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Asteroids: An Exploration Assessment

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Asteroids: An Exploration Assessment

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A workshop sponsored by
NASA Office of Space Science
and held at the University of Chicago
January 19-21, 1978

Co-Chairmen:

Edward Anders, *University of Chicago*
David Morrison, *NASA Office of Space Science*

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FOREWORD

This volume contains the proceedings of an Asteroid Workshop organized by the co-chairmen with the sponsorship of the NASA Headquarters. The workshop was held at the Continuing Education Center at the University of Chicago, January 19-21, 1978. The 15 invited speakers and several observers included scientists specializing in meteorites and/or asteroids as well as representatives from NASA Headquarters and the Jet Propulsion Laboratory.

The workshop was relatively small and was conducted in an informal manner that encouraged discussion of the issues. The presentations and subsequent discussions reviewed and assessed the current state of asteroid science and considered how future programs can best increase our understanding of the nature of these objects and of their relationship to the formation and early history of the solar system. As one element, the workshop considered the contribution that space missions, such as a multiple asteroid rendezvous mission utilizing low-thrust ion drive propulsion, might make to asteroid studies in the late 1980's.

Thanks are due to the staff of Science Applications, Inc. for their assistance with the workshop and the preparation of this volume. Mr. J. Niehoff handled the meeting arrangements, Dr. W. Wells assisted the co-chairmen in the editorial tasks and Ms. K. A. Osadnick typed the final manuscript.

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June 1978

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ASTEROIDS: AN EXPLORATION ASSESSMENT

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INTRODUCTION AND FINDINGS

INTRODUCTION

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The Significance of Asteroid Science

The asteroids appear to represent a largely fragmented remnant of the planetesimals from which the larger planetary bodies accreted in the early history of the solar system. Because of their small size, most of them apparently escaped the drastic thermal and chemical alteration that characterizes the planets and large satellites, such as the Moon. Thus, many asteroids can be expected to contain much chemically primitive material that is characteristic of the original condensation products of the solar nebula. Some asteroids, such as Vesta, have not escaped high temperatures and processes of geochemical differentiation; they may help us understand the early thermal evolution of planetary material. The processes of condensation and accretion may also be revealed by the close study of asteroids, since the repeated collisions that have fragmented most of them should provide natural probes of interior structure. The dynamical families, in particular, can be expected to provide a range of fragments that were initially part of a larger parent body. Therefore, continued study of the asteroids can be expected to yield important and probably unique evidence on both physical and chemical processes associated with the development of the planetary system from the original solar nebula.

Our interest in the asteroids is further stimulated by our conviction that many, and perhaps most, of the meteorites are derived from asteroidal parent bodies. Detailed laboratory investigations of these extraterrestrial materials have revealed a wealth of information about the chemistry of the solar nebula and, to a lesser but still very important degree, about physical processes in the parent bodies. Studies of asteroids and of meteorites are synergistic, with each contributing to our overall understanding of solar system processes and evolution.

It is believed that asteroidal debris has played a major role in cratering the surfaces of the inner planets, so a knowledge of the history of asteroidal breakup and of the dynamical transport of material into the inner solar system is vital for understanding planetary geology and chronology. Such impacts continue today, and the small Earth-approaching Apollo and Amor asteroids constitute a present population of potentially planet-impacting objects. It is important to understand the relationships of the Apollos and Amors to the main belt asteroids and to the comets, as well as to solve the more general questions of interplanetary dynamics needed to relate meteorites to their parent bodies.

Finally, asteroids are important as true planetary objects, to be studied as global entities. Although we have no information at present on their morphology or geology, or on their interior structure, we confidently expect that closer examination will reveal the asteroids as individual worlds of great interest in their own right. An instructive example is provided by the Viking studies of Phobos and Deimos, which indicate that these objects, which are smaller than most of the asteroids that we are likely to visit with spacecraft, are remarkably individual and have been subject to processes that were totally unanticipated before high resolution images were obtained. Particularly exciting are prospects for comparative studies, since the asteroids provide a unique resource of small planets of greatly varying size and heterogeneous chemistry. Nowhere else can we expect so readily to identify the separate processes that have influenced the formation and geologic evolution of planetary bodies.

Purpose of the Workshop

This book is the report of an asteroid science workshop held at the University of Chicago on January 19-21, 1978. The workshop was sponsored by the Planetary Division of the NASA Office of Space Science as a means of assessing current knowledge of the asteroids and developing recommendations for their continued study.

Participants in the workshop were asked to consider the following key questions in preparing their papers:

1. What are the most important things we want to learn about asteroids? How do these goals relate to deeper insights about the solar system and its evolution?

2. What are the crucial experiments needed to obtain the information in (1)? How much can be done from the ground, and what requires a space mission?

3. Are meteorites samples of asteroids, and if so, can meteorites be related to asteroids on a one-to-one basis? Can this be accomplished (now or in the future) by (a) telescopic observations, or (b) dynamical studies?

4. What is the relationship between main belt asteroids and Earth-approaching asteroids? Would a mission to (or sample of) one group tell us much about the other?

5. What type of missions (if any) will most advance our understanding of asteroids in the late 1980's or early 1990's? Are multiple targets required? Is rendezvous necessary? Is sample return necessary?

Much of the discussion centers around these points, and in the next section of this book answers to these questions are suggested as part of the findings of this workshop.

The workshop had two distinct purposes, which in turn dictated its format. First, it was a meeting of scientists who gathered to discuss their own research and to summarize the state of asteroid science as of January 1978. Approximately the first half of this book is devoted to review papers and discussion of these scientific issues, divided into two areas: (1) Meteorites and Their Relationship to Asteroids; and (2) Earth-Based Observational Programs. Second, the workshop addressed programmatic issues of interest to NASA, and these provide the topics for the second half of the book: (3) Future Exploration Options; and (4) Mission Capabilities. In parts 3 and 4 the participants attempt to provide guidance for future research, particularly in regard to the potential of a flight mission to the asteroids.

Overview of the Workshop

Each of the four sections of this book corresponds to a half-day session at the workshop. Each paper was assigned 20-40 minutes for presentation, with time for discussion included. In addition, a general discussion of pertinent issues concluded each of the four sessions. The speakers provided manuscripts reviewing their subjects, and in addition, the discussions were transcribed. The manuscripts, some of which have been revised by the authors after the workshop, are incorporated into this volume together with edited versions of the transcribed discussions.

The first paper, by George Wetherill, introduces the problem of the relationship between the asteroids and the meteorites from the point of view of dynamics. It is clear that asteroidal fragments can be delivered to Earth-crossing orbits and will impact the Earth, but there are serious quantitative discrepancies between the observed amount of meteoritic material and the yield expected from these processes. Wetherill thus emphasizes the complexity of the interrelationships among main belt asteroids, comets, Apollo asteroids, meteors, and meteorites. He suggests that most differentiated meteorites are derived from the belt, but he also favors comets as significant sources for primitive meteorites.

Robert Clayton, in the second paper, explores the exciting new work on isotopic abundance variations among meteorites. Oxygen isotope differences are establishing genetic associations between meteorite classes, which in turn indicate that the parent bodies were formed out of pre-solar material that was not fully mixed at the time condensation occurred within the solar nebula.

The physical as well as chemical properties of the meteorite parent bodies are reviewed by John Wood, who concludes that many differentiated meteorites were likely formed in asteroidal-sized parents. Wood then explores in more detail a new and somewhat speculative model for the formation of the pallasites at the interface between an iron core and olivine mantle in differentiated bodies only about 10 km in diameter, which are later incorporated into a second generation of larger (100 km) parent bodies.

The final paper in the first section is by Edward Anders, who explores the relationship between stony meteorites and the asteroids in the main belt. Anders notes that the presence of trapped solar gas in stony meteorites requires their origin in the regoliths of asteroidal-type bodies, and he argues that the most plausible sources are the C (carbonaceous) and S (siliceous) asteroids, in spite of the differences (discussed in the next section) between the spectra of S asteroids and ordinary chondrites. This problem is a central one for the interpretation of both astronomical observations and dynamical theory, and there were a number of opinions expressed by workshop participants in the discussion.

Part Two of the book is more directly concerned with the observational data on asteroids, most of which have only been acquired during the past few years. The first paper, by David Morrison, briefly summarizes physical observations and then treats in more detail the classification scheme recently developed by a number of the observers to describe asteroid surfaces. The principal classes, distinguished on the basis of a number of parameters involving albedo and color, are called C, S, and M--a terminology used frequently in this book.

The CSM classification serves as the starting point for Ben Zellner's paper on the geography of the asteroid belt. Zellner describes how the raw data on asteroid types are corrected for observational biases (against dark objects, for instance) to derive the distribution of types throughout the belt. He also discusses recent work on family members that indicates that dynamical families have a true physical relationship, presumably indicating common origin in the breakup of a parent asteroid.

Tom McCord's paper deals with the interpretation of asteroid reflectance spectrophotometry in terms of mineralogical types. He gives inferred mineral assemblages for about 60 asteroids, comparing the asteroid surface materials with the similar materials that make up many meteorites, but noting the absence of asteroids with spectra that match identically the ordinary chondrites.

Dennis Matson next reports on infrared observations. He discusses the significance of reflectivity in the 1-4 μm region as an indication of surface mineralogy, and he also treats the thermal models used to analyze infrared observations at longer wavelengths. Matson also discusses Lebofsky's recent discovery of a spectral feature due to water of hydration on Ceres, in apparent contradiction to the mineralogy inferred for this asteroid by McCord from spectrophotometry.

A comprehensive paper on asteroid collisions, cratering, and the evolution of regoliths is given by Clark Chapman. He reports on recent laboratory experiments and computer modeling that predicts the development of regoliths on all asteroids more than a few tens of kilometers in diameter and that allows for a wide range in the intrinsic strength of asteroidal surface materials. Chapman also discusses why the high frequency of inter-asteroidal collisions probably requires nearly all asteroids to be fragments of precursors.

Gene Shoemaker's paper marks a shift of emphasis from the large, main belt asteroids to the smaller and rarer Apollo and Amor objects that pass close to the Earth. He reviews the origin, physical properties, and discovery history of these asteroids, which appear to link the main belt objects, the comets, and the meteorites. The number of these objects can now be estimated with reasonable confidence; the physical observations suggest that a wide variety of compositional types are represented among the near-Earth asteroids.

In the general discussion that concludes this section, several interesting points are raised. The variety of surface mineralogies was stressed, and the expectation is that differences would be even more striking if asteroids could be resolved spatially. Chemical as well as physical evolution may be important on the surfaces of the larger objects. An important question for the Earth-approaching asteroids concerns the apparent rarity of carbonaceous objects; is this effect real or only apparent?

The second half of the book is less science oriented and more speculative in nature. It begins with a section on future exploration options, and then in the final section deals specifically with investigations that could be done from a spacecraft.

Clark Chapman and Ben Zellner review recent observing programs and speculate on the role these observations will play during the next decade. They see a shift from surveys to more specialized, intensive studies of individual objects, but not until the spectrophotometric surveys are extended to many more objects. They also predict an increasing role for radar, mid-infrared spectroscopy, and thermal studies from the IRAS satellite.

Although Earth-based studies will remain important, there is increasing interest in spacecraft observations of asteroids. Fraser Fanale presents a detailed science rationale for an initial asteroid mission that involves rendezvous or orbit with several main belt asteroids. This concept of a multi-asteroid rendezvous mission provides a baseline for much of the material in the rest of the book.

Imaging studies are highlighted by Joe Veverka in the next paper. Using the Viking measurements of Phobos and Deimos as examples, he discusses the wide range of processes that might be revealed on asteroid surfaces by high-resolution photography from a spacecraft.

John Niehoff presents a comprehensive examination of the options for asteroid missions. Within the constraints of existing or planned launch vehicles and low-thrust propulsion systems, a wide variety of missions is possible, including flyby, rendezvous, and even sample return. The multi-asteroid rendezvous concept requires an ion drive low-thrust propulsion system of the type being developed for a comet rendezvous. Niehoff's analysis indicates that there are plentiful opportunities for such missions to visit four asteroids with stay times of 60-90 days each and transit times between rendezvous of the order of a year.

An alternative mission strategy focused on the Earth-approaching asteroids is next given by Gene Shoemaker. He emphasizes the opportunities for sample return and manned visits, which favor the closer Apollos and Amors over the main belt objects.

In the general discussion following these papers, there is a wide-ranging discussion of the relative roles of flight missions and of Earth-based studies during the next few years. While a great deal remains to be done from Earth, it was the consensus that major advances in the 1980's will depend upon flight missions. In particular, only from a spacecraft will it be possible to obtain significant spatial resolution and to study asteroids as individual planetary bodies. This section contains an interesting variety of philosophical discussions on our ability to ask the right scientific questions and to seek answers realistically when extrapolating from our present perspective to the radically advanced capabilities of experiments on spacecraft.

The final section of this book deals with investigations that might be included on spacecraft sent to the asteroids. Tom McCord begins with a review of optical remote sensing, particularly visible and infrared spectrophotometry and multispectral mapping. Instruments of this type have not yet been flown but are under development; they appear to offer the best prospect for determining mineralogy and mapping mineralogical units on an asteroid surface.

Jim Arnold discusses remote geochemical measurements that could be made with gamma-ray spectrometers and x-ray fluorescence spectrometers. These instruments have proved themselves in lunar orbit, and they seem best suited to determining the elemental content of asteroid surfaces.

Imaging techniques are discussed by Joe Veverka, who argues that very high resolution imaging provides the best means of examining geological processes acting on asteroid surfaces. Imaging also may be important for revealing how asteroids accreted and for obtaining some data on their differentiation history. Imaging from rendezvous together with Doppler tracking is also the only way to determine accurate densities and hence place limits on bulk composition.

In the final paper, Thanasis Economou addresses the question of *in situ*, rather than remote sensing, measurements. Hard landers or penetrators could be deployed to make direct measurements of surface composition, providing a much more complete chemical analysis than can be obtained with remote sensing instruments. Such measurements should be considered, even for the initial asteroid rendezvous mission.

In the final general discussion, the main topics concern the possible roles of hard landers and of sample return. While these are clearly areas of great scientific interest, the majority favors giving highest priority for the first mission to remote sensing of a substantial variety of main belt asteroids, in order to truly explore the diversity of these objects.

The final session of the workshop, on the morning of January 21, was devoted to a discussion of the five key questions stated in the previous section, and to formulating mission-related recommendations for NASA. The section on findings and recommendations, which follows, is an edited summary of that discussion, reflecting the collective view of the workshop participants.

It is the hope of the organizers and participants in the Asteroid Workshop that the present volume will be useful to the science community and to NASA alike. The review papers in the first half provide an overview of this discipline and may be read as an informal introduction to asteroid science in 1978. The second half represents the first effort to apply recent advances in spacecraft and experiment capabilities to sketch the outline of an asteroid exploration mission that would have broad scientific appeal and be relevant to important emerging problems of solar system evolution and comparative planetology. Finally, the discussions are included to give some flavor of the friendly give-and-take that characterized what most of us felt to be a very stimulating and successful scientific conference.

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FINDINGS AND RECOMMENDATIONS

Major Research Goals of Asteroid Studies

The primary goals of asteroid science should be to characterize the overall population of minor planets, to relate these objects to the processes of solar system formation and evolution, and to study representative examples as global entities in order to understand the processes influencing their history. Specifically, we desire to determine for a representative sample of objects:

1. Composition (chemical and isotopic)
2. Mineralogy
3. Internal structure and, hence, evidence of accretion and differentiation history
4. Surface morphology and evidence of geologic processes, including thermal events
5. Nature of regolith and fragmentation history.

These data must be related to a statistically representative sample of objects if we are to understand the broader questions of accretional history, subsequent collisions and fragmentation, and orbital evolution of the asteroid population.

As a more detailed set of questions amenable to study through research on asteroids, we summarize the items listed by Fanale in his paper later in this report:

1. What were physical and chemical conditions in the solar system during planetary accretion like?

    a. What were the *physical* interactions among solid bodies of all sizes like during accretion of our planetary system? This includes processes of accretion, fragmentation, and dynamic rearrangement.

    b. What *chemical* fractionation processes operated during condensation/accretion to produce differences in bulk composition among asteroids? How are these processes related to the internal structure of primitive bodies?

2. What magmatic processes operated within asteroids to produce internal differentiation?

    When did these processes operate and what were the energy sources (short-lived nuclides, solar electromagnetic interaction, etc.)? Why did they seemingly affect some asteroids and not others?

3. What are the genetic relationships among small bodies in the solar system?

    Are there parental relationships among (a) various orbital families of asteroids, (b) various spectral classes of asteroids, (c) comets, (d) meteorites, (e) planetary satellites, and (f) interplanetary or interstellar dust? In what context does this place the information we have already accumulated on meteorites and what, in turn, does this tell us about planetesimal/planetary genesis?

In the following two sections we consider what are the crucial Earth-based observations and experiments that will contribute to answering these questions, and then the degree to which further progress may require a space mission.

Earth-Based Investigations

Ground-based astronomical observations have already made substantial progress in defining and characterizing the broad population of asteroids, but a great deal of useful work remains to be done by further application of existing techniques. We expect that, before any space mission can be undertaken, these ground-based surveys will have effectively completed a reconnaissance of the asteroid belt. Thus, it is appropriate for a first space mission to proceed directly to the exploration phase of study, as discussed in the following section.

Because there are so many asteroids and they represent such a heterogeneous population, extensive survey work is essential. Only with such data can we expect to integrate the detailed data obtained for a limited number of objects (either from the Earth or from a space mission) into an appropriate context. For this reason, we would not expect an exploratory space mission to supplant Earth-based studies of the asteroids to the degree that the Mariner flights have done so for the terrestrial planets.

The survey programs of UBV photometry, polarimetry, reflection spectrophotometry, and thermal radiometry that have been carried out during the past few years have transformed our knowledge of the main belt asteroids. Particularly notable is the evidence of heterogeneity and the indications that most asteroid surfaces can be characterized by mineral assemblages similar to those of the meteorites. These surveys now include more than 30% of the named and numbered asteroids, and these data have been brought together in an accessible form in the TRIAD data file. We anticipate that studies of this kind will be continued, and also that more demanding techniques such as infrared spectroscopy and radar studies will be applied to those objects large enough to make them practical.

There are several areas of Earth-based investigation that appear particularly valuable for answering high-priority questions concerning the asteroids. These are:

1. *Survey and Classification with Moderate Spectral Resolution.* Although UBV data have proved exceedingly useful, we note that substantially better characterization of asteroid mineralogy is obtainable with photometric systems that extend to a wavelength of 1.1 μm. We also note that the combination of such spectral data with albedos determined by either thermal radiometry or polarimetry is exceedingly useful for such survey applications. It appears that data of this kind for of the order of 1000 asteroids will be needed to clearly identify the major classes and to search for rare objects of unusual composition that may be the parent bodies of important meteorite classes. Important contributions to this survey work may also be carried out from Earth orbit if appropriate processing of radiometric data from IRAS or other infrared satellites can be done.

2. *Detailed Spectral Observations Coupled with Laboratory Studies.* The interpretation of asteroid mineralogies has progressed greatly in the past five years, but fundamental questions of interpretation remain. One of these relates to the possible identification of certain S asteroids with the ordinary chondrites; another involves the search for the spectral signature of a truly metallic asteroid. Problems of space weathering and regolith formation need additional consideration. A program of detailed spectra from the ultraviolet to 4.0 μm for a representative sample of asteroids, together with

substantial support from laboratory work and theoretical studies, would greatly advance our understanding of asteroid mineralogy. Determination of metal content may also be greatly aided by radar work, since a metallic asteroid is expected to provide an anomalously large radar return.

3. *Discovery and Characterization of Earth-Approaching Asteroids.* The Earth-approaching asteroids are a crucial link between the main belt asteroids and the meteorites. We need to understand the dynamics of these objects and to relate their physical characteristics to those of the better-studied and more accessible objects in the main belt. Our knowledge of these objects has increased greatly in recent years largely as the result of two search programs carried out at Hale Observatory and of efforts to acquire some physical data in the brief time they are accessible after discovery. We strongly support the continuation of these searches, and if possible their expansion through acquisition of a dedicated Schmidt telescope for asteroid work. It is also of great importance that time on large telescopes (both optical and radar) be available on short notice to apply to these asteroids the techniques for physical observations that have been applied so successfully in the main belt.

4. *Meteoritical Investigations.* The study of meteorites is a major branch of planetary science, and the impressive advances being made in this area will surely continue independent of the fate of asteroid research. We will not presume in this report to comment on meteoritical research, other than to note that the connection between asteroids and meteorites is a close one, and that advances in either area should contribute to understanding the other.

Space Missions

The underlying motivation for asteroid missions lies in the eventual need to investigate individual bodies on a detailed scale. General and specific questions are suggested by studies of meteorites, by Earth-based observations of asteroids, by theoretical modeling of asteroids and protoplanets and by experience with studies of other planetary bodies. The demand for such detail stems from the difficult problem of unraveling accretional and fractionation histories and the need to gain further insight into evolutionary processes by comparative studies. Object specific information on surface morphology, composition, mean density, and internal structure, necessary to advance our understanding of these histories, will require space missions to individual targets. Even if there were no presumptive connection between asteroids and meteorites, such studies would eventually be required to understand the role that the asteroids have played in the evolution of the planetary system.

Among the investigations to be accomplished by space missions are high resolution spectral and spatial mapping of the surface, global and regional determination of internal structure, *in situ* verification of remote sensing measurements, characterization of the solar wind interaction, and return of samples for extended Earth-based study. In addition to greatly enhancing the fineness to which comparative studies can be extended, the synergistic combination of these data is required to explore specific asteroids as global entities, be they either relatively intact planetesimals or fragments of some earlier collision process.

It is our consensus, therefore, that space missions to asteroids will be required to continue the progress in our understanding of these bodies as they relate to the total formation and evolution of the solar system. As indicated in the previous section, we feel that the current program of Earth-based observations is formulating a base of asteroid information comparable to reconnaissance mission capabilities. Hence, in order to justify their cost, initial asteroid-dedicated missions should be capable of an exploration level at least comparable to planetary orbiters, with long stay times and the ability to survey entire surfaces. In the case of the larger asteroids, an orbiter is in fact an appropriate approach, but for objects with low surface gravity, simple station-keeping with some maneuver capability is sufficient. For simplicity, we will refer to both of these modes as *rendezvous* missions.

An essential characteristic of the asteroids is their variety. In order to accomplish the scientific goals of a mission, it will be necessary to visit several objects. While this could in principle be accomplished with many separate launches, it seems most cost-effective for each launch to visit as many objects, in succession, as performance limits permit. Consequently, we conclude that *multi-asteroid rendezvous* is the recommended concept for an early asteroid mission. Low-thrust ion drive propulsion provides the capability for this mission concept.

The timing for a first asteroid mission is closely tied to progress in Earth-based observations. Seven years ago, at the time of the Tucson asteroid conference, it seemed to many of us that a mission was premature. Since then photometric surveys have examined about 600 asteroids, and reasonably detailed spectra have been obtained for more than 300. We believe that Earth-based studies of this type are crucial for understanding the asteroids and for intelligent planning of a mission. But this field is rapidly reaching maturity, and it is anticipated that within another five years we may reach a point of diminishing returns in ground-based studies. Thus, it is our assessment that preliminary planning could begin now for a multi-rendezvous asteroid mission for initiation in the early-to-mid 1980's.

We have extended these conclusions to a preliminary consideration of targets and candidate experiments. Each of these areas is discussed below.

The main criteria for targeting relate to investigating a sufficient variety of objects to carry out the broad comparative goals of asteroid exploration. In addition, we feel that efforts should be made to study internal structure by visiting several dynamically related objects that appear to be products of the breakup of a single parent body. We do not recommend specifically seeking to identify meteorite parent bodies; rather, we may learn more by visiting asteroids that are not represented in our meteorite collections. It is understood that practical mission considerations will greatly constrain the actual objects that can be targeted in a single mission, but it also seems clear that there are enough potentially exciting targets that a great many suitable missions can be designed, depending on launch date and the capability of the low-thrust propulsion system. Some examples of asteroids or classes of asteroids considered as suitable targets follow:

1. Ceres (largest, presumably unfractured, relatively primitive but probably experienced some thermal evolution, may have bound H_2O on surface, may resemble original planetesimals).
2. Vesta (third largest, presumably unfractured, differentiated and thermally evolved, may be typical of original parent bodies of differentiated meteorites, may hold important clues to lunar evolution).
3. Two or more members of a Hirayama family (to examine fragments of fractured parent body for data on internal structure and accretion history).
4. A small very dark C type (to examine primitive material, investigate accretion history).
5. Typical members of compositional classes, *e.g.*, an S, a metallic surface, an enstatite chondrite surface (to trace varied differentiation and thermal evolution, study geologic processes on a variety of compositions).

6. An Apollo or Amor (key link between main belt and meteorites, possible dead comet nucleus).

7. A Trojan (unique types, possibly different initial conditions and evolution from main belt).

We stress that these are only examples to illustrate the range of comparative investigations to be carried out. Undoubtedly, continuing observations and interpretations will modify and refine this list before an actual mission commitment is made.

The only priority on such targets we could agree upon was that main belt asteroids are more important for an early mission than either near-Earth objects or the Trojans. The compositional variety, difference in size, and large number of main belt objects collectively argue in their favor as prime targets for an early multi-asteroid rendezvous mission. The possible additions of a near-Earth asteroid flyby or rendezvous, or of a Trojan in the context of an extended mission objective was supported, provided that main belt objectives could be satisfactorily maintained. Examples of such additions will have to be generated along with more main belt multi-rendezvous mission cases to evaluate their impact.

Candidate experiments for potential payloads on an early multi-rendezvous mission were also discussed. In general, the emphasis was upon proven designs that have either already flown or have been proposed for other remote-sensing missions such as Lunar Polar Orbiter. Some proven field and particle detectors were also desired. A typical payload might include the following (the order is not significant):

1. Imaging (multifilter, probably CCD)
2. Reflectance Spectroscopy/Multispectral Mapping (visible to 5 μm)
3. X-Ray Spectroscopy
4. γ-Ray Spectroscopy
5. Altimetry (*e.g.*, radar)
6. Gravimetry (*e.g.*, by Doppler tracking)
7. Micrometeorite Detector
8. Magnetometer
9. Plasma Particle Detector
10. Energetic Particle Detector (low/medium energy).

In addition, the workshop considered a rough lander or penetrator as an additional mission capability. One role for such landers would be to obtain unique data on elemental chemistry by implanting an α, proton-scattering experiment. Another would be to acquire extremely high resolution imaging and measurement of bulk surface properties in support of an eventual sample return mission. Another alternative would be to implant several seismometers on a single asteroid and to stimulate them with active charges to investigate internal structure. The uncertainty in the required mass commitment to conduct such an active seismic experiment made it difficult to assess its value compared to deploying single rough landers at each target. The even more fundamental trade between numbers of landers included versus reduction in total number of targets could not be adequately discussed for lack of mission performance data. Hence, the role of *in situ* experiments in an early multi-rendezvous asteroid mission is left unresolved, pending improved definition of experiment capabilities and mission performance trade data.

We recognize the eventual importance and potential contribution of sample return missions to asteroid exploration. However, we recommend that the exact role and timing of sample return be judged after the results of prerequisite rendezvous missions are available. Nonetheless, the design and planning of an early multi-rendezvous mission should, in turn, consider those objectives which would measurably add to the relevant planning of a possible follow-on sample return mission.

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SECTION I:

METEORITES AND THEIR RELATIONSHIP TO ASTEROIDS

DYNAMICAL EVIDENCE REGARDING THE RELATIONSHIP BETWEEN ASTEROIDS AND METEORITES

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Meteorites are fragments of small solar system bodies (comets, asteroids and Apollo objects). Therefore they may be expected to provide valuable information regarding these bodies. However, the identification of particular classes of meteorites with particular small bodies or classes of small bodies is at present uncertain. It is very unlikely that any significant quantity of meteoritic material is obtained from typical active comets. Relatively well-studied dynamical mechanisms exist for transferring material into the vicinity of the Earth from the inner edge of the asteroid belt on an $\sim 10^{8-9}$ year time scale. It seems likely that most iron meteorites are obtained in this way, and a significant yield of complementary differentiated meteoritic silicate material may be expected to accompany these differentiated iron meteorites. Insofar as data exist, photometric measurements support an association between Apollo objects and chondritic meteorites. Because Apollo objects are in orbits which come close to the Earth, and also must be fragmented as they traverse the asteroid belt near aphelion, there also must be a component of the meteorite flux derived from Apollo objects. Dynamical arguments favor the hypothesis that most Apollo objects are devolatilized comet residues. However, plausible dynamical, petrographic, and cosmogonical reasons are known which argue against the simple conclusion of this syllogism, *viz.*, that chondrites are of cometary origin. Suggestions are given for future theoretical, observational, experimental investigations directed toward improving our understanding of this puzzling situation.

INTRODUCTION

The Earth, Moon, and terrestrial planets are impacted by solid interplanetary bodies ranging in mass from $\sim 10^{-15}$ g to 10^{19} g. The total mass flux is ~ 100 g/km^2/yr, of which ~ 1 g is in the mass range from 100 to 10^7 g. About 10% of the material (*meteoroids*) in this mass range survives entry and passage through the atmosphere. Of this 10%, ~ 0.1% is collected from the Earth's surface and constitutes the collections of *meteorites* housed in museums.

Petrological and trace element investigations are interpreted as implying that prior to the recent onset of their cosmic ray exposure, meteorites were in the interior of bodies ranging from 10 to 500 km in diameter. The chemical and mineralogical differences between the various classes of meteorites are principally a consequence of differences in the composition of these *parent bodies*.

The identification of the parent bodies among various small bodies of the solar system is not definitive at present. Candidate objects include comets, asteroids, the Apollo-Amor objects with perihelia near Earth's orbit, and possibly undiscovered classes of bodies as suggested by the recently discovered Saturn and Uranus-crossing object, Chiron (1977UB). Discussion of evidence for and against the association of particular meteoritic classes with these various candidate objects is the principal topic of this review.

Progress toward more positive identification is essential if we are to make full use of the abundant data relevant to the pre-history, the origin, and the history of the solar system being obtained from laboratory studies of meteorites. Only in this way will it be possible to place these small samples of solar system matter in their appropriate geological and astronomical context. Achieving this goal will require a significant and continuing program of interactive laboratory, observational, and theoretical investigations, and is a major argument in support of space missions to these bodies.

Meteorites are of varied chemical and mineralogical composition, and there is no particular reason why all of them should be derived from the same type of parent body. They can be divided fairly well into two classes: the undifferentiated and the differentiated meteorites. Undifferentiated meteorites are also termed *chondrites*, because they usually contain small (0.1 to 1 mm diameter) spherules called *chondrules*, which are primarily of silicate composition. In the undifferentiated meteorites the relative abundances of the refractory elements (*e.g.*, Mg, Fe, Si, [illegible], etc.) to one another are very similar to those found in the Sun and in averaged solar system material. The more volatile elements are systematically depleted (Ganapathy and Anders, 1974). These volatile elements are least depleted in the carbonaceous chondrites in which the S/Si ratio is nearly the same as in the Sun, and even more volatile elements such as C and N are depleted by only a factor of ∿10. Greater depletions of volatiles are found in the most abundant classes of chondrites, the *ordinary chondrites*. The differentiated meteorites have been even more chemically fractionated relative to average solar system composition. They include objects consisting nearly entirely of nickel-iron, silicate objects which appear to have formed by partial melting processes similar to those which form terrestrial and lunar basalts, silicate objects intruded by veins of nickel-iron, and various other mineralogical assemblages (*cf.*, Wasson, 1974).

Identification of appropriate parent bodies for meteorites of these various classes requires a plausible correspondence between the chemical, mineralogical, and physical nature of the parent body and the meteorite, and cannot be accomplished entirely on the basis of dynamical arguments. The characteristics of possible parent bodies are briefly discussed in the following section.

CANDIDATE SOURCES OF METEORITES

It is conventional to distinguish between comets and asteroids on the operational basis of whether or not they possess a visible coma. Although this definition may sometimes be useful, it also ignores the most important point at issue, namely the ultimate origin of the large and small bodies in the solar system. This discussion will therefore make use of a genetic classification, wherein an object, however gas-free, which was derived from a more typical volatile-rich comet, is considered to be cometary.

Typical comets are small (∿1 to 10 km) objects containing more or less equal quantities of volatile compounds of H, C, N, and O and more refractory compounds, *e.g.*, silicates and metal. The success of the "dirty snowball" model of a comet (Whipple, 1950) has probably accidentally led to a misconception in the minds of some workers, particularly those in related fields of study. This is that comets are principally composed of ice, and can be visualized more or less as a glacier or snowbank. In fact, the material emitted by a comet contains as much dirt as snow (Delsemme, 1977). Furthermore, only the smaller nonvolatile particles can be "blown off" with the volatiles, and presence of larger bodies (*e.g.*, ∿25 cm) in comets cause the fraction of ice to be even smaller. As the ice is volatilized, the fraction of rocky material will increase and will tend to accumulate as residual material.

Fireball studies show that the more massive nonvolatile cometary material is abundant and this conclusion is strengthened by the evidence for nearly-extinct and extinct cometary nuclei. Thus at least half, and possibly 90% of even an active comet may be nonvolatile dust and rocky matter. It is possible that a comet may be more like a breccia than an iceberg, and that pieces of ice may be clasts in this breccia, as a consequence of H_2O and CO_2 being as solid as anything else at the low temperatures which prevailed in the region in which comets were formed. At present, most (and probably all) comets are derived from the outermost regions of the solar system, the Oort cloud at a distance of 10^4-10^5 AU (0.1 to 1 light-year) (Marsden, 1977). They become observable only when they are gravitationally perturbed by passing stars into the inner solar system. The volatilization of their H, C, N and O compounds produces a *coma* $\sim 10^4$ km in diameter, and an ionized tail (up to $\sim 10^7$ km in length), which renders the comet visible.

Comets are definitely associated with much of the interplanetary flux of bodies impacting the Earth, including those in the mass range (100 to 10^7 g) under discussion. This has been established by photographic studies of the orbits of these bodies as they enter the atmosphere (Ceplecha and McCrosky, 1976), and comparison of these orbits with those of known comets. Positive identification with particular comets is possible in many cases. In many additional cases similarity of both orbits and physical properties (as indicated by their ablation or fragmentation in the atmosphere), to objects associated with known comets demonstrates their cometary association. However, only three meteorite falls (the undifferentiated ordinary chondrites Pribram, Lost City and Innisfree) are contained among these photographic meteoroids. As will be discussed further subsequently, their orbits and physical properties, although well-determined, do not define at all well whether or not they are also of cometary origin.

Asteroids are bodies ranging up to 1000 km in diameter which are almost entirely confined to the wide region between Mars and Jupiter. They exhibit no coma of volatile compounds, and most likely consist of mixtures of silicates and metal. Spectrophotometric studies (Chapman, 1976) are interpreted as indicating that different asteroids are of different composition. They primarily fall into two classes: the most abundant C type, presumably containing an admixture of carbonaceous composition, and the S type, probably mixtures of silicates and metal. Unlike the comets, direct association of photographic meteoroids with an asteroidal source is not possible, as the orbits of asteroids do not intersect the orbit of the Earth. However, there are mechanisms by which the orbits of asteroidal bodies can evolve into Earth-intersecting orbits. These will be discussed in the following section.

Apollo-Amor objects are small bodies (typically ~ 1 km diameter, but ranging up to ~ 30 km) with perihelia less than a rather arbitrary value of 1.3 AU, and usually with aphelion in the asteroid belt. These orbits are dynamically unstable on the time scale of the solar system, and like the meteorites they must be derived from sources elsewhere in the solar system, which probably include both comets and asteroids (Anders and Arnold, 1965; Wetherill, 1976). Their Earth-crossing or near Earth-crossing nature identifies them as prime candidate meteoroid and meteorite sources (Anders, 1964; Levin *et al.*, 1976; Wetherill, 1976). However, up to the present no clear-cut orbital identifications have been made, although tentative identification of a few Apollos with known small meteoroid streams has been proposed (Sekanina, 1973). Physical measurements show that all but one (1580 Betulia) of the Apollo-Amor objects studied using these techniques resemble the S-type asteroids more than they do the C-type (McCord, 1978). These statistics are certainly biased in favor of the higher albedo S-type objects. In any case, it is of interest to note that they are not all of the same composition, and this range of compositions includes high albedo, silicate objects resembling differentiated and undifferentiated silicate meteorites.

It is hard to rule out the possibility that more than a negligible fraction of the meteoroid flux is derived from unknown classes of objects, as small, nonvolatile objects are very difficult to observe telescopically. The recent discovery of Chiron is evidence that we have not yet learned even all the more qualitative facts concerning the distribution of small bodies in the solar system. It is possible that there are small bodies stably stored in inner solar system orbits (*cf.*, Weissman and Wetherill, 1973), possibly in resonances, which resemble those in which 1685 Toro is currently trapped (Danielsson and Ip, 1972; Williams and Wetherill, 1973) but which, unlike Toro, are not destabilized by Mars' perturbations. Even an interstellar contribution cannot be entirely ruled out, although orbits of photographic meteors show their proportions must be very small ($\lesssim$0.1%).

During the last century opinion has shifted to and fro regarding with which of these classes of candidate bodies one should associate meteorites. Until the last decade or two, the prevailing opinion was primarily determined by stochastic fluctuations arising from the small number of "experts," rather than from an abundance of relevant data. However, during the last few years there has been a great increase in the quantity of experimental, observational, and theoretical data concerning meteorites, meteors, and their candidate sources. In spite of this, serious problems of identification of Earth-impacting bodies with their solar system sources remain.

It might be thought that the gross difference between typical cometary and asteroidal orbits would make it relatively easy to distinguish between cometary and asteroidal sources once the orbits of meteorites are known. This is not the case. In order for asteroidal material to impact the Earth as a meteorite, it is necessary that it be placed into a more eccentric orbit with perihelion within the orbit of the Earth. On the other hand, comets or cometary residua will have short dynamical lifetimes in the inner solar system unless their orbits evolve into orbits with aphelia inside Jupiter's orbit, *i.e.*, become similar to the orbit of Encke's comet (aphelion = 4.1 AU). Thus asteroidal and cometary meteorites will have similar orbits, with Earth-crossing perihelia and aphelia in the asteroid belt. The distinction will be further blurred as a consequence of perturbations by Earth and Venus which will tend to "equilibrate" the distribution of Earth-crossing orbits. It is known from radiant and time-of-fall statistics (Wetherill, 1971) that at least ordinary chondritic meteorites must evolve from initial Earth-crossing orbits with perihelia near Earth and aphelia near Jupiter. Both asteroidal and cometary sources can have this general characteristic. However, more subtle differences exist which in the future may be helpful in identification of candidate sources.

DYNAMICAL ARGUMENTS FOR AND AGAINST PARTICULAR IDENTIFICATIONS, CONSIDERED IN THE LIGHT OF OTHER EVIDENCE

Asteroids

Purely dynamical considerations. Asteroids are strong *prima facie* candidates because it is known that collisions among the asteroids must provide a quantity of small debris (10^{13}-10^{15} g annually) which would be more than adequate to supply the present flux of Earth-impacting matter, *provided* that there exist mechanisms able to place a sufficient fraction ($\sim 10^{-4}$) of this material into Earth-crossing orbits on the short time scale ($\sim 10^6$ yr) defined by the cosmic-ray exposure history of meteorites. It is also necessary that the shock damage associated with this transfer mechanism usually be limited to that associated with low shock pressures (10-100 Kb).

Difficulties in finding such mechanisms have been a problem in the past. Suitable mechanisms must be primarily gravitational in nature, as collisional shock associated with more than small ($\lesssim$.1 AU) changes in semimajor axis is probably excessive. Gravitational perturbations of Mars-crossing and Mars-grazing asteroidal fragments by Mars have been suggested as such a gravitational mechanism (Arnold, 1965; Anders, 1964) but until recently it appeared that, except for iron meteorites, this mechanism required transit times too long to be reconciled with cosmic-ray exposure histories.

Production of relatively low velocity ($\lesssim$200 m/sec) fragments in proximity to various regions in the asteroid belt in which the motion of fragments is in resonance with the motion of the giant planets has now been semi-quantitatively shown to be an adequate source.

Fairly large ($\sim$100 m) fragments will be produced by collisions in the vicinity of the Kirkwood 2:1 gaps at 3.28 AU, in which the orbital period is commensurable with the period of Jupiter. The resulting resonant motion will at times cause these fragments to be in highly eccentric orbits with aphelia beyond 4 AU and perihelia $\sim$2 AU. These orbits will be stabilized by librational relationships which preclude close encounters to Jupiter. However, statistically probable collisions of these $\sim$100 m bodies with smaller asteroidal debris will produce low-velocity meteorite-size fragments which will escape the libration region and undergo strong perturbations by Jupiter near their aphelion, which can cause their perihelion to random walk into Earth-crossing on a short ($\sim 10^6$ yr) time scale, and hence become meteorites when they impact the Earth (Zimmerman and Wetherill, 1973). This chain of events has been criticized on the grounds that requiring two collisions, close approaches to Jupiter, etc., renders it too complex and by inference *ad hoc* to be taken seriously. Such reasoning is fallacious, as there is no reason to suppose that nature provides meteorites to Earth by mechanisms which are simple for us to describe to one another in preference to those which are probable. The mechanisms described are real phenomena of significant and estimable probability which cannot fail to occur.

The principal problem is a quantitative one, as best estimates of the meteorite yield on Earth from this source are 10^7-10^8 g per year, and this estimate is uncertain by at least an additional order of magnitude. Thus it is not clear if a major or only a minor part of the Earth's meteorites are produced in this way. Scholl and Froeschlé (1977) have presented evidence that the mechanism described above may be more effective for the 5:2 Kirkwood gap than for the 2:1 case. Large asteroids in proximity to these Kirkwood gaps are listed in Tables 1 and 2.

Table 1. Large Asteroids with Semimajor Axis within 0.1 AU of 2:1 Kirkwood Gap (3.28 AU)

Asteroid	a	e	i	B(1,0)	Class	Diameter (km)
106 Dione	3.17	.18	5	8.8	C	139
511 Davida	3.18	.18	16	7.4	C	323
154 Bertha	3.18	.10	21	8.5	C	191
92 Undina	3.19	.07	10	7.9	C	244
702 Alauda	3.19	.03	21	8.3	C	205
758 Mancunia	3.20	.13	6	9.6	C	119
175 Andromache	3.21	.20	3	9.6	C	113
530 Turandot	3.21	.20	8	10.3	C	81
381 Myrrha	3.21	.12	13	9.7	C	126
108 Hecuba	3.22	.09	4	9.7	S	61
122 Gerda	3.22	.06	2	9.2	C	139
895 Helio	3.22	.14	26	9.5	?	
745 Mauritia	3.24	.07	14	11.0	?	
903 Nealley	3.24	.05	12	10.9	?	

Classifications and diameters from Morrison (1977) and Zellner and Bowell (1977), Bowell *et al.*, (1978), and Bowell (private communication, 1978). Absolute magnitudes from Gehrels and Gehrels (1978).

Williams (1973) showed that collision fragments produced at low velocity in the vicinity of certain secular resonant surfaces in (a,e,i) space (Williams, 1969, 1971) can be perturbed directly into Earth-crossing on the necessary short time scale. Again, the quantitative yield is difficult to estimate with certainty.

Table 2. Large Asteroids with Semimajor Axis within 0.1 AU of 5:2 Kirkwood Gap (2.82 AU)

Asteroid	a	e	i	B(1,0)	Class	Diameter (km)
146 Lucina	2.72	.07	13	9.2	C	141
45 Eugenia	2.72	.08	7	8.3	C	226
410 Chloris	2.72	.24	11	9.5	C	134
156 Xanthippe	2.73	.23	10	9.8	C	104
140 Siwa	2.73	.21	3	9.6	C	103
110 Lydia	2.73	.08	6	8.7	[illegible]	170
200 Dynamene	2.74	.13	7	9.5	C	123
185 Eunike	2.74	.13	23	8.7	C	169
247 Eukrate	2.74	.24	25	9.3	C	142
387 Acquitania	2.74	.24	18	8.4	S	112
173 Ino	2.74	.21	14	9.1	C	142
308 Polyxo	2.75	.04	4	9.3	U	138
128 Nemesis	2.75	.12	6	8.8	C	164
71 Niobe	2.76	.17	23	8.3	S	115
93 Minerva	2.76	.14	9	8.7	C	168
356 Liguria	2.76	.24	8	9.3	C	150
41 Daphne	2.76	.27	16	8.1	C	204
1 Ceres	2.77	.07	11	4.5	C	1003
88 Thisbe	2.77	.17	5	8.1	C	210
39 Laetitia	2.77	.11	10	7.4	S	163
2 Pallas	2.77	.23	35	5.2	U	608
148 Gallia	2.77	.19	25	8.5	S	106
532 Herculina	2.77	.17	16	8.0	S	150
393 Lampetia	2.77	.33	15	9.2	C	129
28 Bellona	2.78	.15	9	8.2	S	126
68 Leto	2.78	.18	8	8.2	S	126
139 Juewa	2.78	.17	11	9.2	C	163
446 Aeternitas	2.79	.07	11	10.2	0	40
216 Kleopatra	2.79	.25	13	8.1	M	128
354 Eleonora	2.80	.12	18	7.5	S	153
346 Hermentaria	2.80	.10	9	8.9	S	84
236 Honoria	2.80	.19	8	9.5	S	65
441 Bathilde	2.81	.08	8	9.5	M	66
804 Hispania	2.84	.14	15	8.9	C	141
385 Ilmatar	2.85	.13	14	8.8	?	?
81 Terpsichore	2.85	.21	8	9.6	C	112
129 Antigone	2.87	.21	12	7.9	M	115
47 Aglaja	2.88	.14	5	9.2	C	158
471 Papagena	2.89	.24	15	7.9	S	143
386 Siegena	2.90	.17	20	8.4	C	191
238 Hypatia	2.91	.09	12	9.2	C	154
22 Kalliope	2.91	.10	14	7.3	M	177
16 Psyche	2.92	.13	3	6.9	M	250
674 Rachele	2.92	.20	14	8.5	S	102
349 Dembowska	2.92	.09	8	7.2	0	144

Data from same sources as Table 1.

Wetherill (1974, 1977) and Wetherill and Williams (1977) have proposed a "synergistic" mechanism by which the nonlinear interaction of secular resonance and Mars' perturbations can perturb a rather large yield ($\sim 10^{10}$ g/yr) of meteorite-size asteroidal fragments into Earth-crossing. The typical time required for this material to impact the Earth is $\sim 5 \times 10^{8}$ years, but a significant fraction ($\sim$1%) can impact within 50 million years. The mechanism is proposed as the most probable source of iron meteorites, and of some minor portion of the silicate meteorites, *e.g.*, the differentiated basaltic achondrites. The asteroids which supply this material are those with semimajor axis $\sim$2.25 AU, low inclinations, and with eccentricities which permit the parent objects to come within $\sim$.05 to .1 AU of Mars' aphelion for favorable combinations of the long-period "secular" variations in the orbits of both the asteroids and Mars (Figure 1). Most of these asteroids are S type, which have been suggested to be most likely of "mesosiderite" (mixed iron and basaltic silicate) composition. The massive nickel-iron meteorites must come from somewhere, and the combination of appropriate calculated exposure age, yield, and plausib[illegible]emical composition argues strongly in support of this being the most likely place. [illegible]r, this identification also reduces somewhat the plausibility of obtaining the most [illegible]nt classes of chondrites from this source, as this identification of S asteroids with [illegible]tic silicates argues against their being also of undifferentiated chondritic composit[illegible] However, the largest object of this group (313 Chaldaea, 160 km diameter) is of carbonaceous composition (Chapman, 1977, private communication) and may be expected to produce a small quantity of carbonaceous meteorites, constrained by the association of small yields with short transit times for this source.

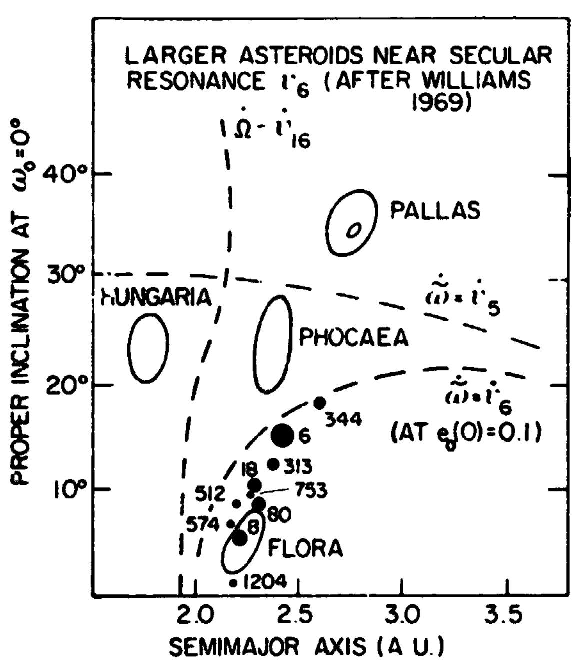

Fig. 1. Observed distribution of large asteroids in the inner portion of the asteroid belt and in the vicinity of the ν_6 resonance. The large open "circles" approximately define the limits of the Hungaria, Flora, Phocaea, and Pallas regions of the asteroid belt.

Recognition of the evidence for meteorites being asteroidal regoliths. A small but significant fraction of silicate meteorites of all classes are rich in inert gases similar in chemical and isotopic composition to the solar wind, contain solar flare cosmic-ray charged particle tracks, in some cases grains exhibiting microcraters, and glassy agglutinates. All of these meteorites are highly brecciated, and the combination of these features strongly suggests an origin similar to that of the lunar regolith (Rajan, 1974). Anders (1975) has carried this argument further and has used the ratio of implanted solar wind and galactic cosmic-ray exposure to infer the heliocentric distance at which this regolithic material was produced. This distance turns out to be 4 to 8 AU, but is model-dependent in a number of ways. Rajan *et al.* (1978) and Schultze and Signer (1977) have identified breccia clasts within both chondritic and differentiated gas-rich meteorites which have radiogenic argon ages markedly younger than the more typical ~4.5 billion year age of other clasts from the same breccia. From this it is plausibly inferred that the breccia was assembled subsequent to the younger of these ages, which in one case is as recent as 1350 million years.

In addition, Turner (1969), Turner and Cadogan (1973), and Bogard *et al.* (1976) have interpreted disturbed radiometric age patterns in relatively highly shocked meteorites as indicating that their parent body was involved in a major impact event 500 million years ago (Heymann, 1967). However, it can also be argued that these events are not well-dated, and could represent a very recent event, associated with the collision which established the recent onset of cosmic-ray exposure, in combination with a small (~3) retention of radiogenic argon from its previous history. Recent theoretical studies of the evolution of Apollo-Amor objects of either cometary or asteroidal origins shows that when secular resonance is included, an asteroidal parent body cannot necessarily be inferred from these ages even if they are interpreted literally (Wetherill, 1978). It turns out that a significant fraction (~15) of Apollos are transferred into the Amor and Mars-crossing region for times as long as 2000 million years, and then returned to Earth-crossing. Thus an Apollo object of cometary origin can have been in the inner solar system 500 million years ago, and have developed some sort of a regolith. However, a small, 1 km Apollo object would seem unlikely to develop a full-fledged lunar-style regolith.

Since there are strong arguments against meteorites being derivable from the regolith of one of the terrestrial planets, and studies of lunar material show they are not from the Moon, the most plausible place to suggest for their source are the surfaces of large (*e.g.*, ≥100 km diameter) bodies in the asteroid region. If so, this regolith cannot be a surficial layer only a few meters deep, as asteroid collision calculations show that the mass yield from asteroidal fragmentation is dominated by deep and even totally destructive impacts (Wetherill, 1967; Dohnanyi, 1969). Whether or not a body with the low surface gravity of an asteroid can be expected to possess such a deep regolith is not clear. Many workers have argued against anything but a very surficial regolith, whereas Anders (1975) has concluded that it is possible that almost the entire asteroid has had a regolithic history. Combined theoretical and experimental work directed toward a detailed understanding of the probable nature of an asteroidal regolith is badly needed. A start in this direction has been made (Housen *et al.*, 1977; Chapman, 1978). Until this is done it cannot be said whether or not the effects observed are compatible with this plausible but undemonstrated association.

The full set of these regolith features are observed in only a few of the gas-rich meteorites. The most clear-cut case is that of the highly brecciated basaltic differentiated meteorites, the howardites (*e.g.*, Kapoeta), for which the "synergistic" mechanism of derivation from the inner asteroid belt is proposed in the previous section. Less complete effects, such as presence of inert gas of solar composition, is less definitive, as unfractionated gas of this type was available over all of solar system history and even earlier. It is probable that formation of a regolith at a well-defined heliocentric distance is not the only way for incorporation of this gas into interplanetary material.

Chemical and mineralogical evidence from meteorites. Even the undifferentiated chondritic meteorites have had a complex chemical history. The volatile-poor ordinary chondrites have in many cases been heated and metamorphosed at temperatures as high as ∿900°C (Van Schumus and Wood, 1967). Subsequent cooling histories several hundred million years in length have been inferred from the extent to which Ni diffuses in the solid state from Ni-poor α-Fe to Ni-rich γ-Fe in the small bits of metallic Fe found in chondrites, as well as in the differentiated iron meteorites. It is not clear how a small asteroidal body could have experienced an early thermal history this extreme. However, the evidence for an asteroidal origin is most strong for basaltic differentiated meteorites, and it has been *demonstrated* that these objects experienced a melting event $\sim 4.5 \times 10^9$ years ago. Therefore, it does not seem extreme to suppose that other asteroids underwent the less severe heating required to explain the textures and mineralogy found in chondrites. If the only alternative source turns out to be comets, it must be remembered that there is no evidence to support a claim that the interior of a comet ever went through such a high temperature stage, or was massive enough to require the long cooling times observed.

An her class of chemical arguments is based upon a presumably known relationship between the temperatures at which meteorites were formed (as deduced from their mineralogy, trace element, and oxygen isotopic composition), and the heliocentric distance at which these temperatures would be found (Larimer and Anders, 1967). However, these calculations require that the present state of knowledge concerning the processes and conditions of star and planetary system origin is more secure than there is any reason to suppose it to be. Such condensation theories also fail to explain how such different classes of asteroids, as inferred from spectrophotometric and polarimetric data, are found at the same heliocentric distance. The variations in oxygen isotopic composition of pre-solar origin found between the different meteorite classes (Clayton *et al.*, 1976; Clayton, 1978) is even more difficult to explain. These phenomena appear to require that asteroids which were originally formed at significantly different heliocentric distance were subsequently mixed by an unknown physical mechanism. This may well have occurred. However, inasmuch as asteroids may have moved since formation this weakens the identification of an asteroidal origin based on an inferred "asteroidal belt" distance of origin.

Relationship of spectrophotometric observations of asteroids to the dynamical evidence. During the last five years a large body of spectral reflection data for asteroidal surfaces has been obtained (Gaffey and McCord, 1977; McCord, 1978). This permits at least tentative identification of the mineralogical nature of these surfaces, particularly the presence of opaque materials such as amorphous carbon, pyroxene and olivine (Fe, Mg silicates), and metallic iron. This has led to an asteroidal taxonomy in which the S and C types, previously mentioned, are the most abundant classes. (See papers in this volume by Morrison (1978) and by Zellner (1978).)

At least one large C type asteroid is located near the ν_6 resonant surface (313 Chaldaea) and others are in proximity to the Kirkwood gaps (Tables 1 and 2). Assuming these asteroids are indeed similar to carbonaceous chondrites, they are strong candidate sources for meteorites. The Apollo-Amor object 1580 Betulia is also of presumed carbonaceous compositions. The high geocentric velocity of fragments of Betulia would lead to a very small yield of material from this particular object. However, the existence of one carbonaceous body among this group, together with the observational biases against such low albedo objects, argues that there are likely to be many more, including some in low-velocity orbits.

The S objects near the resonant regions may also be considered to be excellent parent-body candidates for differentiated silicate and iron meteorites. This is particularly true of those near the ν_6 surface, in view of the agreement between their calculated exposure ages and those measured on iron meteorites. The large asteroid 4 Vesta has frequently been proposed as the source of the basaltic achondrite meteorites. Its reflectance spectrum is in accord with this identification. However, its perihelion is so far from Mars' aphelion and its semimajor axis so far from resonant value that there is no dynamical reason to expect a significant yield of meteorites from this asteroid. It seems more likely that differentiated silicate meteorites (achondrites) are derived from the silicate portion of large S asteroids such as 6 Hebe and 8 Flora, their smaller counterparts (some of which are likely to be their fragments), and Apollo-Amors derived from these bodies. Consolmagno and Drake (1977) have questioned the validity of this inference in view of the near absence among differentiated meteorites of the peridotitic residues of basalt formation, and have proposed Vesta as a basaltic achondrite source for which only the surficial basalt layer is exposed. In view of the dynamical problems associated with this identification, it seems premature to consider this line of reasoning definitive; rather it seems best to leave this matter open at present. It is not at all clear that the collisional fragmentation of even Vesta was sufficiently mild to preclude considerable excavation of its "mantle." It might be that the excess of basaltic achondrites relative to their more ultramafic counterparts is a statistical fluctuation associated with most of these meteorites being derived from a single Apollo-Amor fragment from the Flora region, which happened to be a sample of a basaltic portion of a large S asteroid.

If ordinary chondrites do come from asteroids, it is becoming increasingly puzzling why almost none of the asteroids match the reflectance spectrum of a chondrite. In fact, only one main belt asteroid (the Apollo-Amor objects will be discussed separately) has been held to be of ordinary chondritic composition by spectrophotometric observers, 349 Dembowska. Even this identification has been questioned by recent infrared data (Matson *et al.*, 1977). Various explanations of this discrepancy have been proposed: poor sampling of asteroids, observation of only a surficial layer of the asteroid, changes in reflectance caused by solar wind sputtering or microparticle bombardment. However, plausible reasons for rejecting these hypotheses can be given. 349 Dembowska is a large asteroid (144 km diameter) not too distant from the 5:2 Kirkwood gap, from which meteorites could be derived (Scholl and Froeschlé, 1977). However, there are many other large asteroids similarly well situated which don't look like ordinary chondrites, but are largely normal S- and C-type asteroids. No mechanism is known which would preferentially sample Dembowska relative to these others. Statistical fluctuations in the recent impact history appear inadequate to explain the variety of ordinary chondrite classes or their different exposure histories.

Comets

It is practically certain that no meteorites in our collections have been derived from historically observed comets. The shortest known cosmic-ray exposure age is that of the ordinary chondrite Farmington (19,000 years) and this is unique. In contrast, the volatile content of comets is insufficient to continue the observed volatile loss for more than 10^4 years. Furthermore, it is unlikely that most meteorites are derived from comets during the active stage of their history, as they are usually too massive to be swept along by the outflowing gases. Although meteorites could be freed from comets during more violent cometary outbursts, or following disruption while passing close to the Sun, it seems most likely that cometary meteorites, if they exist, are derived from nonvolatile residues of comets which are likely to survive following the active lifetime of a short-period comet. This could be either from a core which was originally mantled with volatile ices, or a loosely aggregated collection of meteoritic fragments originally scattered through the icy material, or from ice-poor portions of a regolithic breccia.

There is good, if not compelling, evidence that nonvolatile residues of comets exist. There is a gradation in activity between highly volatile comets newly arrived from the Oort cloud, and the short period comets. This trend continues down to apparently severely volatile-depleted short period comets, such as Encke (Sekanina, 1971) and barely active comets such as Arend-Rigaux and Neujmin I. The natural end-members of this series are the nonvolatile Apollo-Amor objects, and it has frequently been proposed that some or all of these bodies are extinct comets (Öpik, 1963; Anders and Arnold, 1965; Wetherill and Williams, 1968; Wetherill, 1976).

One short period comet (Encke) is presently in an orbit with aphelion at 4.1 AU, well within the orbit of Jupiter. An orbit of this kind is relatively stable with respect to gravitational perturbations, in contrast to Jupiter-crossing bodies which will be ejected from the solar system in $\sim 10^5$ years. Sekanina (1971) has shown how the "jet effect" (non-gravitational forces which are the reaction to the comet's emitted dust and gas) has reduced Encke's aphelion to its present value during the last ~1000 years. At present these forces are small, implying relatively little emission of gas, which is compatible with Encke being nearly extinct. On this line of reasoning, it can be predicted that during the next few hundred years, Encke will become an Apollo object. Nor does it appear to be alone. A number of meteor streams are in orbits similar to Encke, often with aphelia even much further within the orbit of Jupiter. Meteors in these streams exhibit physical characteristics very much the same as the Taurid meteors, known to be fragments of Encke (Ceplecha and McCrosky, 1976; Ceplecha, 1977a). It is most plausible that these streams have been recently derived from unobserved extinct comets, because the time required for evolution into orbits as small as, for example, that of the Geminids (aphelion = 2.6 AU), is $\sim 10^6$ years (Wetherill, 1976). In contrast the time during which a stream will remain coherent is $\sim 10^4$ years.

Fragments of extinct comets are not confined to the small, and usually weak, small meteors. Large objects, kilograms in mass, are associated with these streams. There is even evidence that very large (~100 ton) bodies are sometimes found in streams (Table 3).

Table 3. Fireball χ Orionids (Type III)

	a	e	i	ω	Ω	Date
N. χ Orionids	2.22	0.79	2	281	258	12/4-12/15
EN041274 (10^8 g)	1.98 ±.18	0.76 ±.03	3.5	282	252	12/4/74
EN021267 (14 kg)	2.20 ±.02	0.79	3.9	283	250	12/3/67
S. χ Orionids	2.18	0.78	7	101	79	12/7-12/1
PM39469.850 (1 kg)	2.33	0.78	5	93	78	12/10/76

Data from Ceplecha and McCrosky (1976) and Ceplecha (1977b).

So it seems very likely that extinct comets exist and that large meteoroids derived from them impact the Earth. To a large extent the orbits of these meteoroids will be similar to those derived from the asteroid belt by the mechanisms discussed in the previous section. Are these meteoroids ever meteorites, *i.e.*, can they survive passage through the atmosphere and be recovered from the ground? No direct evidence for this exists at present. However, there is circumstantial evidence that this may be the case. Ceplecha and McCrosky (1976) have shown that meteoroids in the 100 g to 10^7 g mass range differ considerably in their physical strength and ability to penetrate deeply into the atmosphere. Although it is possible these differences will prove to be gradational, those observed so far fall into three classes, and can be discussed separately.

Class III, the weakest of all, is associated with a number of well-established cometary meteor streams, and is nearly certain to be of cometary origin. Class II is significantly stronger. Some objects of this class also have definite cometary association (*e.g.*, Taurids and Encke). Ceplecha *et al.* (1977) have obtained a spectrum of one of these bodies which had a terminal mass of 70 g, and hence survived passage through the atmosphere. The spectrum shows strong CN bands and therefore contains carbonaceous matter. It seems most plausible to associate this body with at least some type of carbonaceous meteorite.

The strongest type of fireball meteor is Type I. All three fireballs photographed by fireball networks which have been recovered as meteorites (ordinary ≡ noncarbonaceous chondrites) are of this class. Many fireballs ($\sim$1/3) fall into this class. There is every reason to believe that any of them could have reached the ground if they had been large enough, or had entered the atmosphere at sufficiently low velocity. Their terminal mass distribution (Figure 2) indicates that it is common for both Type I and Type II meteoroids to survive atmospheric passage. Except for the problem that asteroids don't appear to be of ordinary chondritic composition, there is no particular reason why most of these fireballs could not be of asteroidal origin, accelerated into Earth-crossing by one of the gentle resonance gravitational mechanisms discussed in the previous section. If so, this would oppose the present consensus that most meteors, both large and small, are derived from comets.

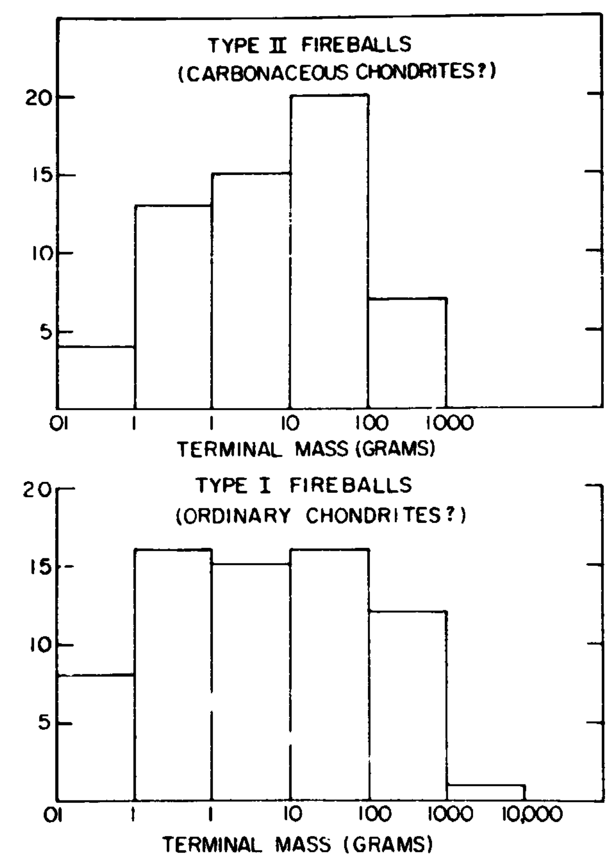

Fig. 2. Observed distribution of Prairie Network fireball terminal masses (Ceplecha and McCrosky, 1976). It is seen that significant terminal masses are found for both Type I and Type II fireballs. Most fireballs belong to these classes.

However, there also seem to be Type I and Type II bodies in *prima facie* cometary orbits, *e.g.*, with aphelia beyond Jupiter or in retrograde motion. Many of these are of high atmospheric entry velocity, >25 km/sec, and scaling to the velocities of the Type I bodies actually recovered as meteorites may have caused them to be erroneously assigned to Type I. But this is not always the case. Six (~3%) of the Prairie Network fireballs (McCrosky *et al.*, 1977) are low velocity (<20 km/sec) Type I bodies with aphelia (Q) beyond Jupiter (see Table 4). These have low terminal masses consistent with their small initial masses. It is very unlikely that this is asteroidal material which impacted the Earth while in the process of being ejected from the solar system, as their number is a factor of ≥100 larger than the number calculated from studies of the orbital evolution of such material. It is certainly possible that these bodies are similar to recovered meteorites, and if so it is only a matter of time before a sufficiently large one falls and is recovered by a fireball network, provided these networks remain operative. Most probably these bodies are of chondritic composition, but they could be either ordinary or carbonaceous chondrites, as many carbonaceous chondrites are essentially as strong as ordinary chondrites, and would be expected to be observed as Type I fireballs.

Table 4. "Strong" Jupiter-Crossing Fireballs with Low Entry Velocity

Number	a (AU)	e	i	Q (AU)	V_{ENTRY} (km/sec)	$M_{INITIAL}$ (g)	M_T (g)	M_T^* (g)	Type
PN39057	4.2	0.76	0.1	7.3	14.7	1400	40	80	I
PN39820B	3.1	0.69	11	5.3	16.7	1100	19	8	I
PN39972	5.5	0.84	3	10.4	18.1	170	1	0.7	I
PN42357C	3.0	0.67	12	5.0	16.0	360	7	20	I
PN42312	3.0	0.69	14	5.1	17.5	430	2	6	I
PN41282	4.5	0.80	2	8.1	17.5	1900	1	20	II

$M_{INITIAL}$ is the initial photometric mass given by Ceplecha and McCrosky (1976).

M_T is the terminal mass calculated by the formal procedure of Ceplecha and McCrosky (1976). M_T^* is the estimated photometric mass near the end point at ~8 km/sec.

If it can be shown that identifiable meteorites are associated with these more unusual orbits of cometary affinity, it will be plausible to associate meteorites of the same class in more ordinary orbits with extinct comets.

Apollo-Amor Objects

The fact that Apollo objects are in Earth-crossing orbits and are exposed to asteroidal collisions near aphelion implies that at least some Earth-impacting meteoroids must be derived from these bodies. Although Amor objects are not Earth-crossing at present, it has been shown (Wetherill, 1978) that evolution of Apollos into Amors and vice-versa is so rapid that many Amors must be former or future Apollos. With regard to their role as meteorite sources, the only questions are the quantitative one of yield, and that of their mechanical strength. Calculations of the yield show that this could be large enough to supply the entire flux of chondritic meteorites (~10^8 g/yr), and is at least high enough to supply ~1% of this material. No definite information regarding their strength is available.

If some fireballs could be associated with known Apollo objects, such information could be obtained from the end heights of these meteoroids. It is not obvious that such identification will be possible, as the exposure ages of stone meteorites are comparable to the time scale for major orbital evolution of Apollo objects. However, in the case of meteorites with very short exposure ages, this could prove possible (Levin *et al.*, 1976).

One problem with identifying the Apollo-Amor objects with ordinary chondrites is that the radiants of chondrites (Astopovich, 1939; Simonenko, 1975) and time of fall (Wetherill, 1968, 1969) are at least at first sight not in agreement with dynamical calculations of the expected distribution of these quantities. This question needs to be examined in the light of more recent work on the aerodynamics of the entry of fireballs into the atmosphere (ReVelle, 1976) and the orbital evolution of Apollo-Amors (Wetherill, 1978).

As discussed previously, Apollo-Amors are not permanent residents of the inner solar system, but are derived from an asteroidal or cometary source, or more likely, both. Thus they can be thought of as big meteoroids which can fragment into small meteoroids, or impact the Earth before fragmentation, forming craters 1-100 km in diameter. Some of these bodies are probably the extinct comets discussed earlier, whereas others can be derived from the inner asteroid belt (Levin *et al.*, 1976; Wetherill, 1976, 1978). The resulting orbits are similar in either case (Wetherill, 1978). Dynamical considerations suggest that the cometary component should predominate. Interpretation of physical observations leads to an ambiguity. All but one of the Apollos for which there are relevant data appear to be related to either ordinary chondritic material or to S asteroids, rather than to carbonaceous material. On cosmochemical grounds, most workers would interpret this to indicate an asteroidal origin. However, this argument could be turned around to imply a cometary origin, as a consequence of spectrophotometric work showing that ordinary chondritic material is rare or absent in the asteroid belt.

All three types of source bodies discussed will lead to the same general distribution of meteorite and meteoroid orbits. These will predominantly be orbits of low inclination, with perihelia near Earth's orbits, and aphelia in the asteroid belt. Full exploitation of more subtle differences in the distributions is likely to require more detailed observational data and improved theoretical techniques. However, as discussed below, some tentative conclusions are now possible and suggestions for advancing our theoretical understanding can be made.

SUMMARY AND SUGGESTED FUTURE WORK

The evidence is very strong that most differentiated meteorites are derived from the asteroid belt, either directly or through the intermediary of Apollo-Amor objects. Spectrophotometric observations show there is opaque material with low albedo in the asteroid belt. It is likely that this is carbonaceous. Some of these asteroids are adjacent to resonances which can gently accelerate their low velocity collision spectra into Earth-crossing. Except for the unlikely possibility that this material is too weak to survive atmospheric passage (Type III fireballs), there should also be carbonaceous meteorites of asteroidal origin.

It is also quite possible that some of our meteorites are cometary, probably derived from extinct comets, most of which will be in orbits such that they would be identified as Apollo-Amor objects. If so, these are likely to be undifferentiated meteorites. They could be carbonaceous chondrites, ordinary chondrites, or both. It seems unlikely that ordinary chondrites are of both asteroidal and cometary origin. However, carbonaceous meteorites are so close to average nonvolatile solar system composition that their composition does not argue for a unique source region. Some classes of carbonaceous meteorites could be asteroidal, others cometary.

One might think that the abundance of observational, theoretical and experimental evidence relevant to the problem of identification of meteorite sources should permit more clear-cut identifications to be made than seems to be the case. The reason is that the evidence does not lead to an internally consistent solution. Thus, by use of only a portion of the available evidence, it is apparently possible to come to more firm conclusions than when all the evidence is considered.

It is likely that an entirely new source of evidence, *e.g.*, returned samples from asteroids and comets, would really clear up the question. However, at the present stage, it would appear useful to understand which line of evidence is leading us astray. This suggests several lines of investigation.

1. Perhaps the most straightforward problem would be to resolve the question of whether or not the distribution of chondrite radiants and time of falls is or is not compatible with derivation of most of these bodies from Apollo-Amor objects. This will require selection of a plausible range of fragment size distributions making use of available or new hypervelocity impact data. This could then be combined with bias-corrected Apollo-Amor statistics (smoothed by theoretical steady-state considerations) and an improved physical theory for meteorite entry, perhaps along the lines of ReVelle (1976) and Padavet (1977). Comparison of the theoretical radiant and time of fall distribution with that observed should then permit us to know whether or not the discrepancy is as serious as appears at first glance.

2. Spectrophotometric measurements on asteroids has led to the conclusion that ordinary chondrites, especially L and LL chondrites, are rare or absent in the main asteroid belt. On the other hand, there are large asteroids adjacent to the 5:2 Kirkwood gap which probably could supply meteorites with the required radiant and time of fall distributions of chondrites. Could these be ordinary chondritic bodies, the spectral signature of which has been obscured by surface alteration processes? Plausible arguments against this possibility have been advanced, but do not seem to be sufficiently definitive to settle the issue. Further laboratory simulation coupled with theoretical studies of the basic physical processes involved may be expected to be of considerable value. These studies should also shed additional light on the origin of other features, such as the absorption feature at $\sim$.65 μm seen in many S asteroids, but which is absent in noncarbonaceous meteorites. Several explanations of this feature have been given, but it is not clear that any of them are correct. When understood, this feature could be important in relating the mineralogical composition of meteorites to that of asteroids.

3. On a sufficiently short time scale, *i.e.*, 10^{2}-10^{4} years, the orbital evolution of planet-crossing bodies is deterministic and can be handled by classical methods of celestial mechanics. However, on longer time scales multiple close planetary encounters occur and minor differences in initial orbits result in grossly different final orbits. Under these circumstances the system is best modeled statistically. Although, like a roulette wheel, it is still in principle deterministic, the information required to make deterministic predictions is not available. Nevertheless, in both cases, valid inferences of a probabilistic nature can be made. Discussion of the long-range orbital evolution of planet-crossing bodies has been entirely dependent on these stochastic methods (Öpik, 1951, 1977; Arnold, 1965; Wetherill, 1968, 1977). However, there are a number of assumptions and approximations made in these stochastic methods which have never been critically

examined using the full range of classical or conventional celestial mechanical understanding which is available. It would be trivial to show that the stochastic methods are not rigorous and trite to say "they should be used with great caution." What is needed is a constructively motivated critical study of these techniques, directed toward placing them on a better theoretical foundation. This could allow us to have more confidence in interpreting second-order differences between observed and theoretical orbit distributions and to more quantitative estimates of expected yields from various sources.

4. A principal basis for the inference that there is meteoritic material of cometary origin is obtained from photographic fireball networks, particularly the Prairie Network (McCrosky *et al.*, 1977). However, the efforts of these networks have primarily been directed toward meteorite recovery, and are strongly biased against the most clear-cut occurrences of cometary origin--the shower meteoroids. Meteoroids identified as belonging to the major showers were not reduced in the Prairie Network investigations, and Canadian Network data is not reduced at all unless a meteorite fall is suspected. There are no continuing fireball studies in the U.S. at present. In fact, all of meteor science in the U.S. is in a state of rapid decline, following withdrawal of both the NASA Ames Research Center and the Smithsonian Astrophysical Observatory from this field. The inferences tentatively made previously strongly suggest that serious treatment of fireball data may force revision of our present concepts of the physical nature of comets, but this cannot happen unless some people work in this field.

5. Many of the arguments used to identify meteorites with their sources are based on regolithic analogs. However, there is very little understanding of how regolithic properties may be expected to vary as a function of heliocentric distance or of mass and composition on the body on which they occur. A start in this direction has been made (Housen *et al.*, 1977; Chapman, 1978). Until we understand much more quantitatively just what an asteroidal or cometary regolith should look like, including charged particle tracks, microcraters, agglutinates, etc., we do not really know if meteoritic evidence favors or disfavors particular regolithic identifications.

6. There is at present no theory adequate to explain even qualitatively the origin of the principal features of the asteroid belt, *e.g.*, its small mass content, relative velocity distribution, Kirkwood gaps and mixed chemical composition. Development of a theory of this kind will require a much more quantitative understanding of the origin of stars and planetary systems in general, and the Sun and planets of our solar system in particular. There has been renewed interest in these problems during the last few years, but the goal is still distant.

One can be hopeful that investigations along the lines suggested above would help considerably in constructing an internally consistent framework in which to view the problem of identification of meteorites with their sources.

This short list of suggestions for future work is in no sense intended to be complete. For example, it is obvious that the full set of chemical, petrological, and isotopic laboratory work on meteorites is essential to a correct understanding of the relationship of meteorites to their sources. Much more needs to be done. It is unlikely, however, that such investigations would lead to the qualitatively distinctive revelations which have followed actual spacecraft missions to the Moon and planets. "Ground truth" and sample return may be expected to be the ultimate answer to the identification of meteorites and their source, and to the realization of the geological context in which these small bits of primordial material should be viewed.

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DISCUSSION

ARNOLD: I tend to trust very much the argument that we don't get meteorites from the Moon because of the 2.3 km/sec required ejection velocity.

WETHERILL: I believe that argument, too. It is difficult to quantify because it requires quantitative knowledge of the impacts of large objects on the Moon. It could be that there haven't been any large impacts on the Moon in the last few million years and therefore this mechanism would not be expected to contribute much to the meteorites in our collections. A skeptic could get around this argument in this way. In our thinking on this problem in the last several years we have looked for more gentle methods for transferring material from the asteroid belt to Earth-crossing regions rather than direct impact and high velocity transfer.

CHAPMAN: What would be the yield of chondrites from Earth-approaching objects if you wanted to assume they were all ordinary chondrites?

WETHERILL: About 10^8 g/yr, but this number is uncertain by at least an order of magnitude. There are more serious problems with an Apollo meteorite source. One is that if you wish to believe that Apollos are derived from the asteroid belt, it is necessary to stretch the estimates of their production rates by a factor of $\sim$10, possibly more.

ARNOLD: Does that problem also extend to the distribution of eccentricities?

WETHERILL: I don't really think so. In your work you had very small semimajor axes and relatively low eccentricities. The ν_6 resonance changes that result a lot. There are slight differences between the orbits of Apollos and orbits derived from the different regions of the asteroid belt or those derived from orbits like Comet Encke. But they are not nearly as extreme as they used to be.

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METEORITES AND THEIR PARENT BODIES: EVIDENCE FROM OXYGEN ISOTOPES

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As a result of the heterogeneous distribution of the isotopes of oxygen in the early solar nebula, the various planets, asteroids and meteorites have isotopic labels which permit recognition of samples derived from common sources. It is thus possible to see genetic associations between meteorite classes, such as group II E irons with H-group ordinary chondrites, and enstatite meteorites with the Earth and Moon. These associations help in defining the complexity of the parent bodies, and in determining their region of origin within the solar system.

INTRODUCTION

In order to understand the implications of all of the detailed measurements which are made on meteorites, we must somehow establish their "field relations" within the solar system. We need to identify their parent bodies, and reconstruct their histories of condensation and accretion. Oxygen isotope "fingerprints" provide a unique method giving information on the number of parent bodies represented by the meteorites. The solar nebula was not completely homogenized with respect to the isotopes of oxygen prior to condensation and accretion of the planets and meteorite parent bodies (Clayton *et al.*, 1973). Materials which condensed in different regions or at different times acquired variable proportions of a component enriched in ^{16}O. This isotopic "fingerprint" remains with the material, and no amount of chemical processing or mass-fractionation can eradicate it.

There are two possible explanations for the isotopic heterogeneity of the nebula: pre-solar solid grains enriched in ^{16}O, or a nucleosynthetically processed gas injected into the nebula followed by rapid condensation. The highest concentrations of the ^{16}O-rich component are found in high-temperature condensate minerals in C3 carbonaceous chondrites. This observation is consistent with the pre-solar grain hypothesis if these grains were refractory minerals which served as condensation nuclei for the solar system condensates. If the ^{16}O-rich component was introduced into the solar nebula from a nearby supernova explosion, then the high-temperature condensates in C3 meteorites were probably formed in the outermost parts of the solar nebula near the supernova shock front.

The oxygen isotopic compositions of the major stony and stony-iron meteorites are shown in Figure 1, on a graph of $^{17}O/^{16}O$ versus $^{18}O/^{16}O$. The oxygen isotopic compositions of matter in the early solar system were modified by at least two processes: (1) addition of the ^{16}O-rich component, which displaces the composition toward the lower left of the graph, along a line of unit slope; (2) mass-dependent isotopic fractionation associated with chemical or physical processes, which displaces the composition along a line of slope 1/2, in either direction, depending on the particular process. The heavy line in Figure 1 is the locus of compositions of terrestrial materials, and illustrates the effect

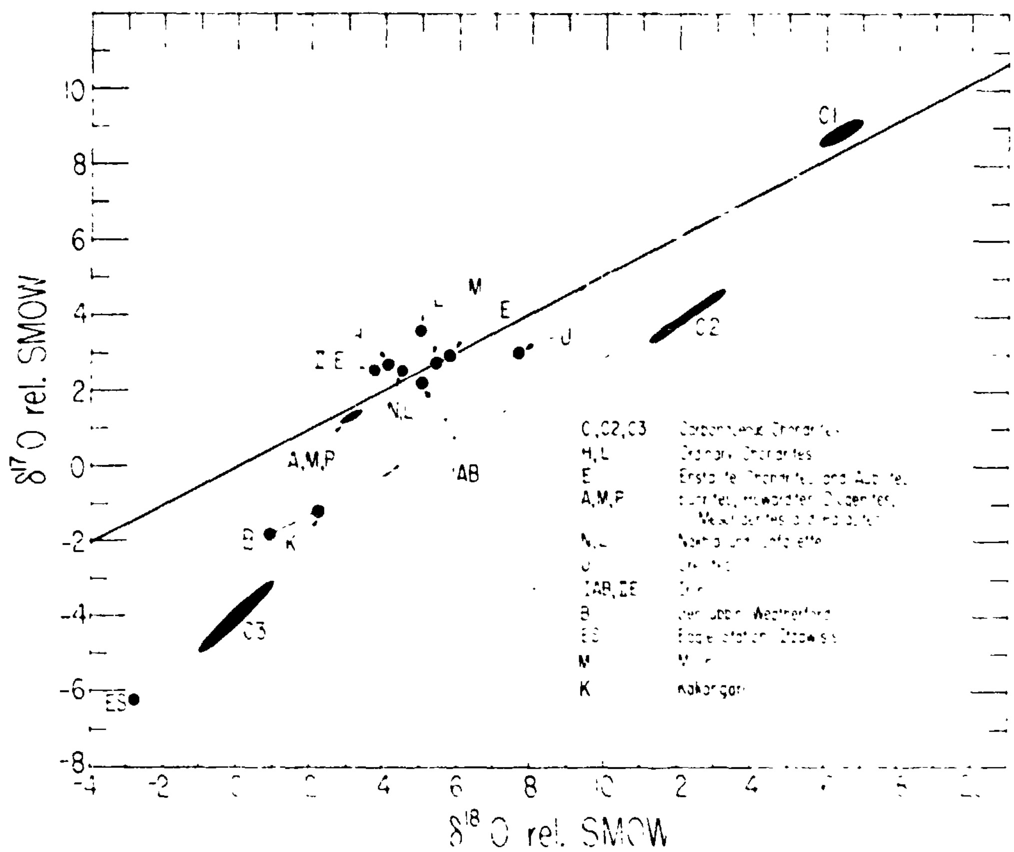

Fig. 1. Oxygen isotopic compositions of various meteorite groups. Ordinate is $^{17}O/^{16}O$, and abscissa is $^{18}O/^{16}O$, both expressed as permil (parts per thousand) deviations from an arbitrary terrestrial standard (SMOW). The heavy line with slope 1/2 is the locus of all terrestrial materials, which spread along the line due to mass-dependent isotopic fractionation. The mean value for the Earth is probably indistinguishable from that for the Moon. The dashed line with unit slope is the extrapolation of the ^{16}O mixing line observed in separated phases of C3 chondrites, most of which are off-scale to the lower left of this figure. Analytical uncertainties in the data are somewhat smaller than the plotted points.

of mass-fractionation processes within a single planet. The actual range of observed isotopic compositions on Earth is about six times as great as the span of Figure 1. The dashed line in Figure 1 is the mixing line of unit slope which is generated by individual inclusions and mineral samples from several C2 and C3 meteorites (Clayton et al., 1977). The observed range of compositions extends well off the diagram to values of $\delta^{18}O$ of -40. The variations in composition of all of the other meteorites are presumably due to a combination of these two processes of mixing and fractionation. Thus meteorites lying above the terrestrial line (C1, ordinary chondrites, IIE irons) contain less of the ^{16}O-rich component than the Earth, whereas the C2, C3 carbonaceous chondrites and most of the differentiated meteorites contain more than the Earth.

It should be considered whether a planet or meteorite parent body might, as a consequence of heterogeneous accretion, be internally heterogeneous with respect to oxygen isotopes (in addition to the obvious effects of isotopic fractionation). The evidence from terrestrial and lunar samples strongly indicates that all materials sampled have come from a single homogenized reservoir, as would be expected for such large differentiated bodies. At the other extreme, it is known that C2 and C3 carbonaceous chondrites are isotopically heterogeneous on a submillimeter scale. The evidence bearing on homogeneity in parent bodies of other meteorites is less direct. For example, all L and LL chondrites appear to be derived from a common reservoir, possibly a single parent body, and all H chondrites are derived from some other reservoir, also possibly a single parent body. It is obviously impossible, in principle, to distinguish between two noninteracting regions of a single parent, on the one hand, and two distinct parents on the other. However, lacking any evidence in favor of large-scale internal heterogeneities, I shall assume that isotopically distinct source reservoirs imply different parent bodies.

In the following sections, the various major meteorite groups will be discussed, with particular reference to the interrelationships among groups and the inferences with respect to their parent bodies.

CARBONACEOUS CHONDRITES

It can be seen in Figure 1 that the C1, C2, and C3 meteorites occupy three distinct regions of the oxygen isotope diagram. The C2s are a special case, since they are composed of approximately equal amounts of high-temperature anhydrous silicates (olivine and pyroxene) and a low-temperature phyllosilicate matrix. The region of Figure 1 labeled C2 is for the matrix material; the data for olivine and pyroxene are distributed along the ^{16}O mixing line determined by the minerals from C3 meteorites. C1 and C2 matrix materials are distinct from one another and, interestingly, lie on opposite sides of the terrestrial fractionation line. They clearly represent different source regions. Since both types are thought to be very primitive solar system materials, and since many asteroids appear to be similar to C1 or C2 meteorites, it is to be hoped that observations of asteroids can be improved to allow distinction between these two types of material.

The difference in isotopic compositions between C1 and C2 matrix requires that they be formed from nebular gases of different isotopic compositions, separated either in space or in time. Since both C1 meteorites and C2 matrix consist of hydrous silicates formed at low temperatures, probably by interaction with water vapor in a nebular gas, the isotopic difference between the two groups implies gaseous regions of the nebula with different ^{16}O abundances. The C1 material could be derived from the same source as the H-group ordinary chondrites, since these two groups appear to lie along a common fractionation line. There is no group of chondrites bearing a similar relation to the C2 matrix material. However, the unique chondrite Kakangari and the achondritic parts of Bencubbin and Weatherford may have such a relationship. In each case, the temperature effect on the isotopic fractionation between gas and solids would account for the enrichments in heavy isotopes in the low-temperature phyllosilicates relative to the higher-temperature olivine and pyroxene. (Note that no low-temperature phyllosilicate counterpart to the L-group chondrites has yet been observed.)

Although the C3 meteorites are isotopically heterogeneous on a submillimeter scale (Clayton *et al.*, 1977), their bulk isotopic compositions are very similar to one another, and only subtle differences between the subclasses C3O and C3V are detectable. Determination of the location and mode of origin of these meteorites is of the utmost importance in deducing solar system history, since they are the principal hosts of the nucleosynthetic isotope anomalies in oxygen, magnesium, calcium, barium and neodymium (Clayton *et al.*, 1977; Lee *et al.*, 1977; Lee *et al.*, 1978; McCulloch and Wasserburg, 1978). In the case of the anomalies in minor elements, their observation in C3 meteorites may simply reflect more favorable conditions for preservation. However, in the case of the oxygen anomaly, the bulk meteorites show a greater ^{16}O-excess than any others, with the exception of the unusual pallasites Eagle Station and Itzawisis. The C4 meteorites Karoonda and Coolidge have oxygen isotopic compositions which are essentially the same as the C3s. The internal isotopic fractionation among minerals in C4s is consistent with metamorphic recrystallization at a temperature near 600°C (Clayton *et al.*, 1977).

A few carbonaceous chondrites have unique isotopic compositions, and do not fall within the three main groups. Al Rais and Renazzo, commonly classed as C2, have distinct compositions unlike the C2 group. Mokoia, usually classed as C3, has an isotopic composition which appears transitional between C3 and C2.

In addition to macroscopic carbonaceous chondrite meteorites, fragments of similar material have been observed as inclusions in other meteorites (Wilkening, 1978). Some of these have been found to have isotopic compositions different from the main carbonaceous chondrite groups, although most are rather similar to the C2 group chemically and isotopically (Clayton and Mayeda, 1978a). Thus, it would appear that conditions for production of C2-like material occurred in many places in the solar system; the observation of many asteroids with C2-like surfaces (Chapman *et al.*, 1975) is, of course, consistent with this observation.

ORDINARY CHONDRITES

Two distinct source reservoirs are required for the ordinary chondrites: one for the H group, another for the L and LL groups. The latter two are not resolved from one another, and could be chemical differentiates from the same source. The two reservoirs are displaced from one another in the direction of ^{16}O mixing, implying condensation under similar conditions from two isotopically distinct parts of the nebula.

Possible association of H-group chondrites with C1 chondrites has been discussed above. They may also have been derived from the same oxygen reservoir as the silicates in type IIE irons (Clayton and Mayeda, 1978b). There is no genetic association between the ordinary chondrites and any of the achondrites. In fact, where chondritic and achondritic fragments are found together in brecciated meteorites, they are found to have distinctly different oxygen isotope abundances, thus requiring derivation from separate parent bodies (Clayton and Mayeda, 1978a).

ACHONDRITES, MESOSIDERITES AND PALLASITES

Most of the differentiated stony and stony-iron meteorites fall into a single group in the oxygen-isotope diagram. This class includes the eucrites, howardites and diogenites, as well as the mesosiderites and pallasites. It also includes the well-studied achondrite Angra dos Reis, the igneous differentiation of which was complete 4.55 Gy ago (Lugmair and Marti, 1977; Wasserburg *et al.*, 1977). Were all of these meteorites derived from the same parent body? Differences in initial $^{87}Sr/^{86}Sr$ imply that they were not. Nevertheless the uniformity of oxygen isotopic composition requires that this large group of differentiated meteorites was derived from a common reservoir in the nebula.

A few achondrites form smaller, separate isotopic classes. The ureilites form a single group with isotopic compositions more like carbonaceous chondrites than achondrites. Nakhla and Lafayette, presumably fragments of the same parent, have a unique isotopic composition not obviously related to other groups. Shergotty and Zagami likewise form a separate group. Bencubbin and Weatherford are metal-rich breccias with a distinct and complex isotopic signature. Eagle Station and Itzawisis are highly unusual in both chemical and isotopic compositions relative to other pallasites. Their parent body appears to have formed with an exceptionally large complement of high-temperature condensates, labeled with the ^{16}O-excess recognized first in the C3 chondrites (Clayton and Mayeda, 1978b).

The aubrites are discussed in the next section.

ENSTATITE CHONDRITES AND ACHONDRITES

The enstatite chondrites and aubrites form a single class (Clayton *et al.*, 1976), consistent with derivation from a common parent body, as has been suggested on chemical grounds by Wasson and Wai (1970). This raises doubts about either the association of the E spectral type of asteroids with the aubrites (Zellner *et al.*, 1977) or the RF and RR spectral type with the enstatite chondrites (McCord, 1978). Such problems are not unexpected due to the lack of characteristic features in the reflectance spectrum of enstatite (Gaffey, 1976).

A remarkable aspect of the oxygen isotopic composition of the enstatite chondrites is that it is very near that of the Earth and Moon. The composition appears to lie squarely on the terrestrial fractionation line, perhaps a little enriched in the heavy isotopes relative to terrestrial mantle rocks. It is curious that the Earth should be so similar in isotopic composition to this meteorite group, since the high degree of reduction of the enstatite chondrites would appear to require their condensation in a region of the nebula in which the C/O ratio was significantly greater than elsewhere (Larimer, 1975). Further chemical and isotopic studies of enstatite chondrites are important to investigate their relationships to the inner planets.

IRON METEORITES

Type IIE irons, which contain coarse-grained silicate minerals, may have a common parentage with the H-group ordinary chondrites, as discussed above. The type IAB irons are breccias containing silicate rock fragments of chondritic composition (Bild, 1977). They fall in a single group in the oxygen isotope diagram, which may be related to the enstatite chondrite group by ^{16}O addition. This association with the enstatite chondrites is also suggested by the low iron content of the mafic silicates in the IAB meteorites. Perhaps these meteorites are good candidates for the RF-type asteroids.

PROSPECTS FOR REMOTE ISOTOPIC ANALYSIS OF ASTEROIDS

The problems in performing sufficiently accurate $^{18}O/^{17}O$ and $^{17}O/^{16}O$ measurements without sample return are formidable. Although ^{16}O is abundant, the heavier isotopes are not. Resolution of the different meteorite classes, for example H chondrites from L chondrites, requires a precision in the $^{17}O/^{16}O$ ratio of better than 5×10^{-4}. Since the absolute value of this ratio is only 4×10^{-4}, the measurement requires determination of ^{17}O concentrations to better than 2×10^{-7} relative to ^{16}O. Mass spectrometry is the only feasible technique, and the elimination of interfering species, such as hydrides, would be exceptionally difficult without the chemical processing used in laboratory analyses. Techniques without chemical sample preparation, such as laser-probe or ion-probe mass spectrometry fall far short of the necessary precision in terms of both random and systematic errors. There is no obvious *fundamental* limitation to such remote isotopic analysis, but a very large amount of instrument development would be a prerequisite.

ACKNOWLEDGMENT

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DISCUSSION

VEVERKA: Why are the H and L chondrites represented by a single point, whereas the C chondrites are represented by an extended area?

CLAYTON: That is what we observe. The Cs really do appear to spread out over some range along the fractionation direction due to small differences in the formation temperatures of the minerals. Because the Cs are formed at lower temperatures, the isotope effects are large and a change of 10 or [illegible] degrees in condensation temperature would give you a substantial spread. Ten or 20 c[illegible]ees at the condensation temperatures of the Hs and and Ls would give a very much smaller spread.

FANALE: Are the data here spurious in the sense that what is analyzed is really a physical mixture of ^{18}O-enriched CI material and ^{18}O-deficient C3 material, which would give points for C2s lying along some mixing line?

CLAYTON: We have gone to a lot of effort to try to be sure that these things are free of impurities, and I think we have satisfied ourselves that we have done that pretty well. We have also managed in one case to do an analysis on a carbonate phase of a C2, where there is one percent of calcite That point lies quite a long way from the matrix but is on the same fractionation line as the matrix. So there is pretty good evidence, I think, that these are not mechanical mixtures and that they acquired this composition by interaction with a gaseous material that lies somewhere along the fractionation line.

FANALE: Is it possible, at least in the case of carbonaceous chondrites, that the ^{18}O-enrichment is due to a nonthermal activation process during an interaction with more ^{18}O-rich vapor at high vapor pressures? Or did we really have a homogeneous nebula where at the surface of a progenitor body, such as Ceres, there was preferential escape of ^{16}O from the base of the exosphere leaving a surface which was, therefore, ^{18}O-enriched?

CLAYTON: You ask whether the low temperature minerals could have been formed from ordinary chondrite material by low temperature exchange with an ^{18}O-enriched gas. I would say that is a possibility, particularly if the gas is a large reservoir compared to the meteorites, so that they ended up with no memory of their original composition. There is one thing that leads us to think that something like that might be going on. In samples from other meteorites we saw points that were near the dashed line for C3s (in Figure 1) and we started taking apart some of the C3 meteorites which contain a lot of iron-rich anhydrous silicates. We find that the olivines with different chemical compositions move up and down the dashed line and as we get to the most iron-rich we have at least one point that is on the fractionation line to the C2 matrix region. I can't cite any similar evidence, connecting Cls with anything else. Your second possibility was that everything was once homogeneous and was subsequently enriched in ^{18}O. Presumably you would have to start with very ^{18}O-deficient material like C3 meteorites. I think it's highly unlikely that all of the planets and the Moon and everything were made by that kind of alteration, at least based on what we have seen so far in Allende which is just a few grams of very peculiar C3 matrix in a very peculiar chemical state. I would be more inclined, so that you don't have to move so many atoms, to say that the materials like the Cl and C2 chondrites are normal and that C3 material is abnormal.

McCORD: If the instrumentation did exist for doing oxygen isotope analysis on the surface of an asteroid, what sort of sample handling would you require?

CLAYTON: If the analysis were done by some kind of a laser probe or an ion probe mass spectrometer, no sample preparation is needed. We are working here on the development of an ion microprobe mass spectrometer, not for extraterrestrial analysis, but for terrestrial analysis, and sample preparation there simply involves using a polished rock surface. We do have to put on a conducting coating to keep it from charging up. That is the only preparation we need.

NATURE AND EVOLUTION OF THE METEORITE PARENT BODIES: EVIDENCE FROM PETROLOGY AND METALLURGY

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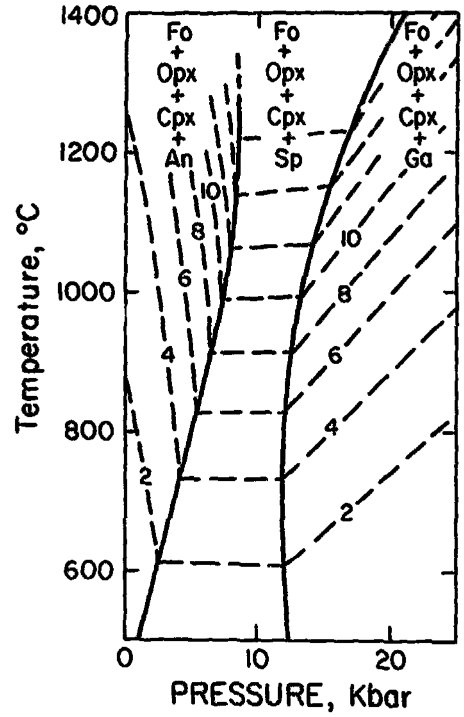
Petrologic and metallurgical properties of the meteorites that specify or limit their depth of equilibration in the parent bodies are noted. Origin of the structure of pallasites is discussed in detail. The pallasitic structure could have formed stably at the core/mantle interfaces of internally melted small planets, where the weight of sunken olivine cumulate layers submerged the lowermost olivine crystals in underlying molten metal. However, the weight of the cumulate layer would also deform the olivine crystals so extensively as to destroy the pallasitic structure, except in the smallest parent bodies (< ∿10 km radius). It appears that melting and differentiation (to produce pallasites, irons, achondrites) occurred in an early generation of small planetesimals, but final cooling of the meteoritic material occurred in larger bodies.

All the evidence from petrological and metallographic studies of meteorites indicates that they evolved and to some degree equilibrated at relatively shallow depths in planets. Most of the evidence from these disciplines does not testify to the total size of the planets, though there is one item of evidence that I believe does constrain the dimension of certain of the parent planets to be very small; most of the present paper will be devoted to a discussion of this point.

So far as evidence constraining depths of origin (not planetary sizes) is concerned, at the simplest level one can cite the ophitic textures of eucritic achondrites, which are reproduced in terrestrial circumstances only by volcanic rocks that crystallized in surface flows or at very shallow depths in feeder conduits. Evidence from textures, microcraters (Brownlee and Rajan, 1973), and fossil tracks (Wilkening, Lal, and Reid, 1971) in other types of Ca-rich achondrite point to their evolution in regoliths, at the surface of one or more bodies.

The meteorites contain no minerals inconsistent with equilibration at very low pressures apart from the occurrence of diamond in the Cañon Diablo iron and in the ureilites (a type of achondrite), the formation of which is clearly attributable to shock pressures upon impact rather than sustained pressure at depth in a planet (Lipschutz and Anders, 1961; Lipschutz, 1964). On the other hand, minerals that *would* be produced by high pressures are not observed. Figure 1 shows a phase diagram relevant to chondrites and mesosiderites. The mineral assemblages of both meteorite classes fall in the left (low-pressure) field; *i.e.*, plagioclase is stable rather than spinel or garnet. The diagram cannot be used to make a quantitative estimate of pressures for these meteorites because it does not include the effect of Na and Fe^{2+}, which are important components of the meteoritic systems. The abundance of aluminum in the M1 sites of orthopyroxene in ordinary chondrites is vanishingly small (0.1 ± 0.1%), which at the apparent temperature of equilibration (∿850°C) indicates very low pressures. Interestingly, the Al_{M1} content of orthopyroxene in a mesosiderite (Patwar) is somewhat higher (0.4%; Weigand, 1975). Because of the approximations mentioned, however, these values cannot be interpreted quantitatively.

Fig. 1. Stable mineral assemblages in the system $CaO-MgO-Al_2O_3-SiO_2$, as a function of pressure and temperature (Obata, 1976). Fo = forsterite, Opx = orthopyroxene, Cpx = clinopyroxene, An = anorthite, Sp = spinel, Ga = garnet. Numbers on dashed lines represent the atomic percent. Al in six-fold coordinated sites in orthopyroxene.



Perhaps the most valuable evidence for depth of equilibration of meteorites is preserved in the metallic minerals they contain. The rates at which metal-bearing meteorites cooled through the temperature interval 600°-400°C in their parent planets can be estimated from the nature of Ni diffusion gradients preserved in their metal alloys (Wood, 1964; Goldstein and Ogilvie, 1965). The slower the cooling rate, the lower the temperature (and hence the higher the Ni content of the γ alloy) when diffusion was immobilized. Characteristic cooling rates for a number of meteorite classes are summarized in Figure 2 (Wood, 1967; Goldstein, 1969; Powell, 1969; Buseck and Goldstein, 1969). This figure also suggests possible cooling sites for the meteorite types, by displaying cooling rates as a function of depth in planets of asteroidal dimension. The cooling rate calculations assume a uniform initial temperature of 1000°C and chondritic long-lived radioactivity, but do not take account of redistribution of heat sources by igneous activity (Wood, 1967).

Many writers have concluded that the meteorites came from differentiated, concentrically layered parent bodies, structurally analogous to Earth. Iron meteorites would represent the cores of these bodies. Others have advocated parent planets with "raisin bread" structure, meaning that relatively small zones of metallic Ni,Fe were dispersed at all depths in them. Urey (*e.g.*, 1963) cites curious reentrant cavities on the surface of the Goose Lake iron meteorite (Henderson and Perry, 1958) and the relatively large abundance of pallasites among meteorites as evidence that the surface/volume ratio of iron masses in the parent planets was high, therefore the iron masses occurred in "raisins." (Pallasites are stony-iron meteorites that consist of roughly equal amounts of coarse olivine (∿1.0 cm) and metallic Ni,Fe. The olivine crystals are in close-packed array, with metal filling the spaces between them. Clearly the solid olivine crystals accumulated stably in this configuration while the metal was molten (*i.e.*, in the temperature range 1600°-1400°C). Properties of pallasites are reviewed by Mason (1963) and Buseck (1977)). Wasson (1972) notes that the

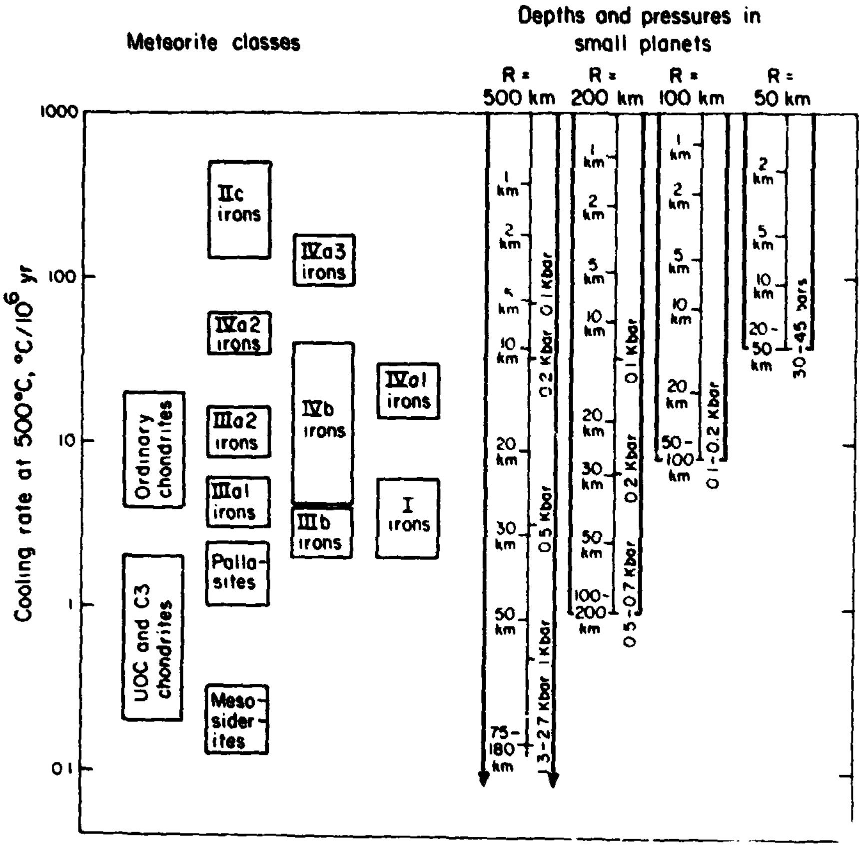


Fig. 2. Left, cooling rates of metal-bearing meteorite classes. Right, depths at which cooling would have occurred at these rates, in four hypothetical planets of asteroidal dimension. Depths >180 km in the 500 km body would not cool to 500°C in 4.6×10^9 yr.

wide range of cooling rates of some geochemically coherent classes of iron meteorites, taken at face value, indicate that the latter evolved in the same parent planet but in discrete bodies at widely varying depths, *i.e.*, in "raisins." (Cooling rates of 33 Group IIIa irons range from 1.5° to $10°/10^6$ yr; 23 IVa irons, $7°$-$80°/10^6$ yr; Goldstein (1969).)

However, a detailed consideration of the chemistry and cooling rates of Group IIIa irons (Figure 3) makes it appear likely that meteorites from two sources, each with cooling rates uniform to within the uncertainty of the method, are lumped in this group. Group IVa can be similarly decomposed into two or three uniformly-cooling components. Figure 2 reflects the subdivision of these two groups. Further, the concept of "raisins" does not really make the Goose Lake cavities any easier to understand, nor does the model when examined in detail help to account for the apparently unstable mixture of high- and low-density components that constitutes pallasites. The "raisin bread" model and others involving

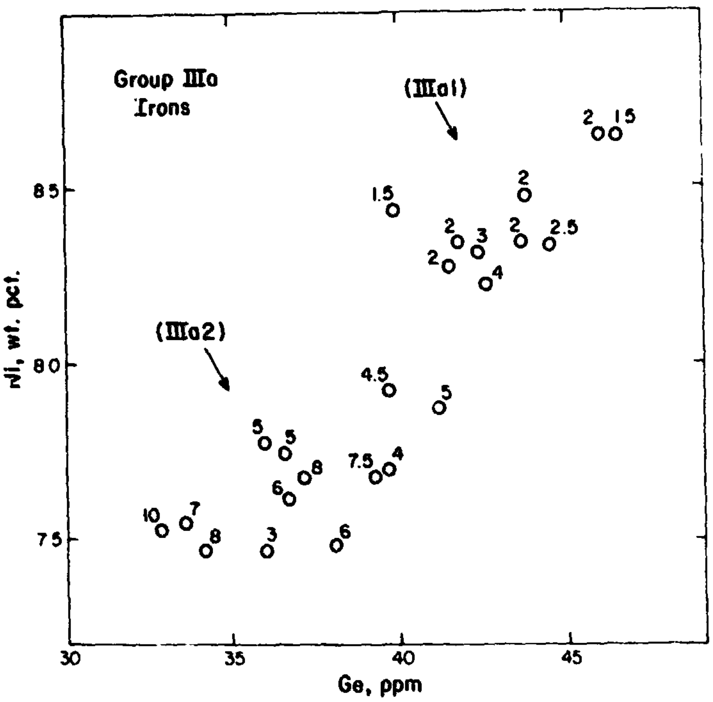


Fig. 3. Ni and Ge contents and metallographic cooling rates of Group IIIa iron meteorites. The number beside each data point is the cooling rate, in degrees C/10^6 yr. All meteorites common to the studies of Wasson and Kimberlin (1967) and Goldstein (1969) are plotted. Two subgroups, probably representing discrete sources, are indicated.

dynamic processes (*e.g.*, Scott's (1977) concept of intrusion of molten metal into olivine cumulates) do not square well with the orderly, close-packed structure of most pallasites.

There is an aspect of melting and differentiation of planetary interiors that would have produced pallasitic material as a gravitationally stable layer at the core/mantle interface. An olivine cumulate layer immersed in mafic silicate magma would press down on the interface between magma and differentiated molten metal/sulfide with a weight proportional to (1) the thickness of the cumulate layer, (2) the difference in density between olivine and magma, and (3) the local value of g. This would submerge the lowermost olivine crystals a certain distance into the molten metal/sulfide (Figure 4a). The depth of submergence would be greater if magma were free to erupt to the surface of the hypothetical planet, meaning that (1) above would embrace all the unmelted substance of the planet whose density was greater than that of the magma (Figure 4b). The amount of pallasitic material that can be formed by the mechanism of Figure 4b can be calculated by assessing the downward weight of solid silicates between R_2 and R_3 and requiring the upward buoyant forces of solid olivine crystals between R_1 and R_2 to equal this value:

$$\int_{R_1}^{R_2} \Delta\rho_{\text{metal, olivine}}\, g(r)\,dr = \int_{R_2}^{R_3} \Delta\rho_{\text{olivine, magma}}\, g(r)\,dr \qquad (1)$$

Results are shown in Figure 5, for a range of possible core sizes. The relative volume of pallasitic material produced is independent of the absolute size of the planet. In principle, the volume of pallasitic material that would form in an internally melted planet (relative to pure Ni,Fe metal) is substantial, larger than the ratio of pallasites to irons in museum collections.

Absolute values of the weight exerted downward by cumulate olivine at R_2 can be estimated, by assessing one side of Equation (1) as a function of R ($\approx R_3$). These are 4, 16, 63, and 390 bars, in planets of total radius 50, 100, 200, and 500 km respectively, for reasonable compositions and internal configurations. These are small stresses, but olivine is extremely weak at the high temperatures of molten iron, and even small directed stresses cause it to yield by the mechanism of power-law creep (Ashby and Verrall, 1977).

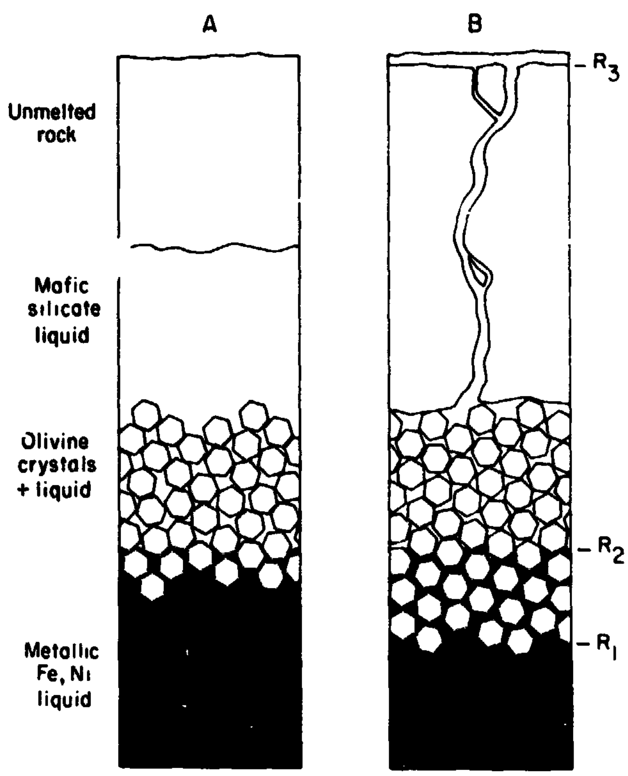


Fig. 4. Radial columns in an internally melted small planet. A: the simple case in which the melted zone is enclosed by an integral shell of unmelted rock. B: the more realistic case where the unmelted shell fractures and founders, resting on cumulate olivine in the melted zone; silicate melt is erupted to the planetary surface. C: the effect of deformation of olivine in the pallasitic layer is to squeeze intercumulus liquids out of it, closing the olivine cumulate layer into pure dunite.

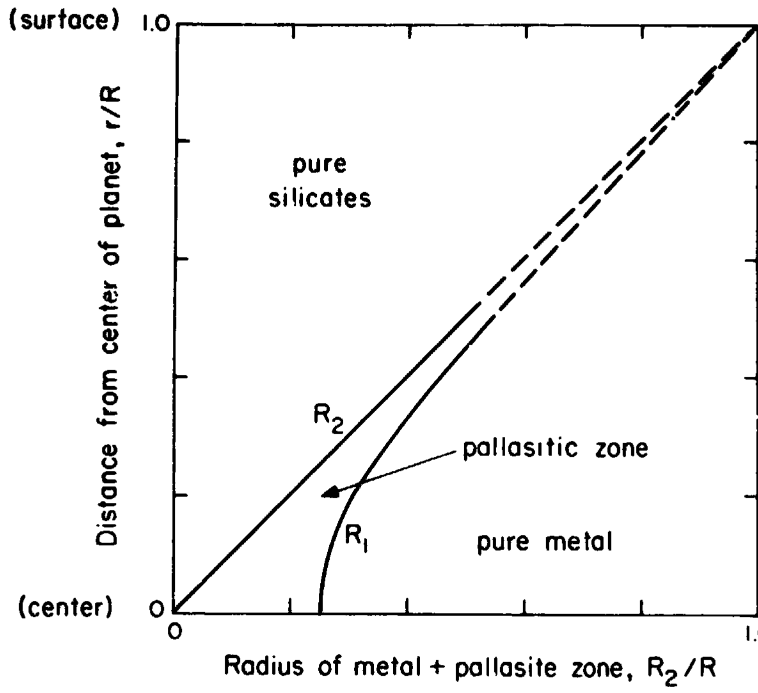


Fig. 5. Positions of the R_2 and R_1 levels (which define the thickness of the pallasite zone), as a function of the total size of the metal + pallasite zone (the core). All values are relative to the overall radius of the planet (R); the relationships are independent of absolute size. Dashed portions of curves correspond to unrealistically large cores, larger than would be produced by total melting and differentiation of ordinary chondrites.

Total deformation (γ, where $\gamma = 1$ corresponds to the shear strain needed to deform a right angle to a 45° angle) equals the strain rate ($\dot{\gamma}$) times the time (ΔT) needed to cool to solidification. Taking

$$\sigma \approx (5 \times 10^{-6})R^2$$

(σ = directed stress in Kbar, R = planet radius in km; from the above calculations),

$$\dot{\gamma} \approx (4.6 \times 10^4)\sigma^{2.91}$$

for olivine in the temperature and shear stress regime of interest (Ashby and Verrall, 1977), and

$$\Delta T \approx (2 \times 10^3)R^2$$

from cooling rate calculations made by the author (ΔT in years; assuming a site at depth = $0.5R$, and cooling through the temperature range 1600°-1400°C), the relationship between planetary dimension and total deformation experienced by pallasitic olivine is found to be

$$\gamma = (3.4 \times 10^{-8})R^{7.82} \tag{2}$$

This relationship is plotted in Figure 6 (uppermost curve).

Deformation great enough to obliterate the characteristic pallasite geometry would be experienced by olivine crystals at the core-mantle interfaces of planets larger than ~10 km radius. Olivine deformation in these circumstances would have the effect of squeezing molten metal out the bottom of the pallasitic layer and molten mafic silicate out the top of the overlying layer (Figure 4c), resulting in a stable layer of virtually pure dunite.

Since Equation (2) applies only to level R_2, and the directed stresses and γ taper to zero at R_1, it might appear that only the upper portion of the pallasitic layer was in danger of obliteration in large planets. However, the dashed curves of Figure 6 make it clear that no significant portion of the pallasitic layer in a planet much larger than 10 km radius would survive destruction.

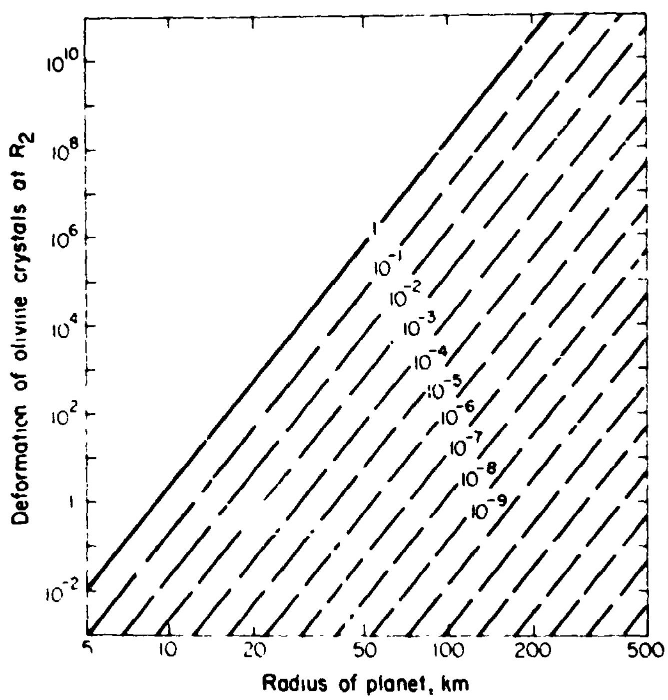


Fig. 6. Total deformation experienced by pallasitic olivine during cooling of a small planet, as a function of the planet's dimension. The curve labeled 1 represents olivine at the R_2 interface, where stresses are greatest; the 10^{-1} curve applies at a level 10^{-1} of the distance between R_1 and R_2, and so forth.

Deformation experienced in >100 km planets (such as Figure 2 appears to require as a cooling site for pallasites) is excessive by such a large factor (>10^8) that even generous allowance for the uncertainties attached to the estimate does not make it possible to reconcile the circumstances of formation with the circumstances of cooling of pallasites. *It appears inescapable that the pallasites solidified in small (~10 km) bodies, but these subsequently must have joined larger (>100 km) bodies before final cooling through 500°C occurred.* The size and energy requirements and the timing of the first generation of bodies are consistent with the Goldreich-Ward mechanism of planetesimal formation by gravitational instability of a dust disk within the primordial nebula (10 yr) and the ^{26}Al content of early solar system material (Lee *et al.*, 1977). Presumably the second generation was accumulated by planetesimal encounters over a longer time period, after the dissipation of the nebula.

Thus it appears likely that the (second generation) parent meteorite planets did in fact have "raisin bread" structures, as a consequence of their assembly from smaller differentiated bodies; but there is no reason to expect that the "raisins" in any particular second-generation body were geochemically related. It is quite possible that most or all iron meteorites went through a similar two-stage history, being melted and differentiated in a small body then cooling as a "raisin" in a larger planet, but there is no obvious way to test this. The iron meteorites may have formed as cores interior to pallasitic layers, or their first generation bodies may have been too large to permit the survival of significant amounts of pallasitic material.

ACKNOWLEDGMENT

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DISCUSSION

GROSSMAN: I would like to know if the boundaries in Figure 1 change depending on the proportions of CaO, MgO, etc.? I am wondering whether the particular section you are showing is sensitive to these proportions.

WOOD: If by proportions you mean changing the modal forsterite to anorthite ratio, no, the boundaries do not change. All the isopleths of Al in the M1 site of orthopyroxene and the boundaries shown in Figure 1 are valid for the mineral assemblages listed, irrespective of the mineral proportions.

GROSSMAN: I wonder if you ought to stretch the point to include up to 12 Kbars on the spinel minerals?

WOOD: It is important to first specify what sort of spinels you are referring to. Mg and Al-rich spinels in equilibrium with olivine and two pyroxenes would indeed reflect very high pressures. In this case plagioclase would no longer be stable with olivine. However, chromite-type spinels can be in equilibrium with olivine, plagioclase, and two pyroxenes at very low pressures (*i.e.*, 0-1 Kbar at about 850°C). The Mg-rich spinels of chondritic Ca, Al-rich inclusions coexist with minerals other than those given in Figure 1; the figure is not applicable to spinel + melilite + fassaite, etc., assemblages.

ZELLNER: Apparently you must have at least one parent body of 500 km diameter.

WOOD: That is what is implied in Figure 2, where the diameter jumps from 200 to 500 km. But I am not sure you couldn't achieve the lowest cooling rates in somewhat smaller bodies.

ANDERS: Isn't it still true that the very lowest cooling rates, below a degree per million years, are a paradox, being found in some of the unequilibrated ordinary chondrites that are volatile-rich and which seem to have had a fairly gentle temperature history? To get these low cooling rates, one has to go fairly deep inside a large body. The second paradoxical category is mesosiderites, where I think you pointed out that they would not cool to a reasonable temperature in the entire age of the solar system.

WOOD: Yes, that is right, if you make the assumption that the mesosiderites have resided at the same position in their parent bodies since the time they were formed. If you are willing to explore more exotic possibilities of relocation of volumes of meteoritic material, and to go through several generations of parent bodies, then these things can be worked out.

ANDERS: Isn't it possible that the method works reliably for irons but occasionally malfunctions for mixtures of silicate and iron? I think your cooling rates for ordinary chondrites certainly are very plausible. But those for the other types of meteorites such as unequilibrated chordrites, mesosiderites and pallasites (again mixtures of stone and iron), all come out suspiciously lower. I wonder if there isn't something in the method that goes sour.

WOOD: I personally don't believe so. The fact is, the first data that indicated a very low cooling rate for a mesosiderite was not gotten by me or Powell on the basis of isolated metal grains. It was gotten by Short on the basis of a nodule in a mesosiderite that displayed integral Widmanstätten structure, and on the basis of the old classical cooling rate method he came up with that slow cooling rate. The work was never published, although it appeared in an abstract for a Meteoritical Society meeting. Short had a small piece of an iron meteorite there; the cooling rate he derived from it should be as reliable as the cooling rates gotten for octohedrites.

ANDERS: I think there is one very important clue that you omitted which can lead to a totally different conclusion. Namely, quite a number of pallasites have olivines at the top and at the bottom and a clear channel of metal in the middle. This configuration is not in hydrostatic equilibrium. In my 1964 review I pointed out one way to get this is to have an olivine zone overlying a core and then mix these two by shock. Obviously such configurations could not have persisted if the materials had remained molten for a long time. It is only the momentarily liquid state after shock, followed by instantaneous freezing, that allows this to survive.

WOOD: I didn't have time to address all aspects of pallasites. There are some properties of pallasites and some types of pallasites that have clearly been affected by dynamic situations, where there was an injection or intrusion of molten metal. Indeed, the fact that some pallasites consist of olivine fragments rather than nicely rounded crystals bespeaks some sort of violent event. The fact is, however, a great many, perhaps most of the pallasites, do consist of rounded olivines in nicely ordered, close-packed arrays, as was shown by no less than Lord Rayleigh. To that you would have to add a caveat to the effect that some of these parent bodies suffered shocks or stresses or techtonic events during the crystallization of their cores that allowed still molten metal to intrude regions that had begun to solidify. The regions of olivine crystals at the two ends of the particular specimen that you speak of are in close-packed array. The violent event that injected metal between them could not really have been the same event that filled in the spaces between these nicely ordered arrays of olivine crystals. The crystals just wouldn't stay together; they would scatter out.

VEVERKA: Two points. First, a crucial question is what is the effective g? We can reduce g by considering rotation. In fact, if the original bodies had very rapid rotation periods ($\sim$2 hrs), then g would have been close to zero, or at least very small throughout the body. Thus for rapidly rotating bodies deformation may have been small even at great depth. As long as g wasn't exactly zero, gravitational settling could still be invoked as Goles, Fish and Anders showed in 1960. Second, a discussion of the uncertainties in the exponent of σ, which is a component of Equation (2), is needed. Two aspects need to be considered. First, in the actual laboratory measurements is the exponent determined to ±0.1, ±0.5, or what? Second, how well can one extrapolate the exponent to the present case? The argument about the need for two generations of "parent" bodies hinges in part on the high exponent of σ. Could the exponent be reduced to 5? Would that change the conclusions? The argument that two generations of parent bodies are needed to account for the pallasites hinges on Equations (1) and (2). In Equation (1) it is essential to make sure that the correct g is being used. In Equation (2) it is essential that the correct exponent is being used.

WOOD: Let me address the second point first. The relationship between stress (σ) and the strain rate ($\dot{\gamma}$) of olivine is based on experimental data by Durham and Goetze (Plastic flow of orientated single crystals of olivine. *J. Geophys. Res.* 82, 5737-5753, 1977), at 1600°C in the stress range 0.2-0.5 Kbar. This corresponds to conditions at the core/mantle interface of planets of approximate total radius 200-300 km. Outside this range, the stress-strain relationship depends upon formulae based on the theoretical analysis of creep mechanisms by Ashby and Verall (1977), which is fitted to the data of Durham and Goetze and also to the data of other authors at lower temperatures and higher stresses. The exponent of σ found by Durham and Goetze is actually higher than the value used by me (3.6 ± 0.3, versus 2.91). This is because my formula is based on a curve I fitted to Ashby and Verall's extrapolation (in an attempt to embrace the stress range 0.01-1 Kbar), rather than to Durham and Goetze's data. I am not really qualified to critically evaluate Ashby and Verall's modeling, but note that if I went with the experimental data instead, the exponent in Equation (2) would be even higher than it is, and the point this paper attempts to make would be even more compelling. The experimental data only goes down to a planetary radius of $\sim$200 km, but even a modest extrapolation of the experimental stress-strain relationship to smaller dimensions suffices to exclude the possibility that the pallasites crystallized in planets as large as their cooling rates indicate. The effects of rotation are interesting to consider. Centrifugal acceleration would tend to offset gravity most beneath a planet's equator, and there the pallasitic structure might be preserved in arbitrarily large planets if they were spinning fast enough (*i.e.*, at just less than the stability limit). The centrifugal acceleration would go to zero at the poles of the planet, though, and there the pallasitic structure would be vulnerable. However, if Equation (2) is valid, the deformative stresses that would act in a nonrotating planet are excessive by such a large factor ($>10^8$, as noted toward the end of the article) that it seems unlikely pallasites could be saved from collapse by rotation. First, if the centrifugal acceleration were less than gravitational acceleration by even as much as 10^{-8}, even pallasites beneath the equator would be doomed. This leaves an extremely narrow window of rotation velocities that would do the job, since the planet would fly apart if the centrifugal acceleration exceeded the gravitational acceleration by very much. Second, even if rotation exactly offset gravity at the equator, one would only have to go to latitudes $>\sim 10^{-8}$ radians above and below the equator to find the component of centrifugal acceleration no longer adequate to preserve the pallasites.

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MOST STONY METEORITES COME FROM THE ASTEROID BELT

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The place of origin of stony meteorites can be determined from their trapped solar-wind gases. "Gas-rich" meteorites of all classes have only 10^{-3}-10^{-4} the solar noble gas content and $\lesssim 10^{-2}$-10^{-4} the surface exposure age of lunar soils. These differences suggest that the gas implantation took place between 1 and 8 AU from the Sun, in a region where the cratering rate was 10^2-10^3 times higher than at 1 AU. Both requirements are met by main belt asteroids, not by long- or short-period comets, by Trojan asteroids, or by stray bodies in thinly populated parts of the inner solar system. The observed prevalence of gas-rich meteorites (up to 100% among carbonaceous chondrites, 2-33% among other classes) requires that the parent bodies be large enough, and remain in the asteroid belt long enough, to develop a substantial regolith. These conditions are more readily met by asteroids than by comets. The young ages of xenoliths in gas-rich meteorites (down to 1.4 AE) show that gas implantation is an on-going process in the solar system, not a relic from a hypothetical "early irradiation."

L chondrites, in contrast to H chondrites, show pervasive evidence of outgassing 500 Myr ago, accompanied by shock heating to 950-1250°C for centuries or millennia. Apparently the L chondrite parent body was not a comet, but an asteroid broken up at that time.

Of 27 xenoliths (foreign inclusions) in meteorites, 20 are carbonaceous (mainly C2) whereas 5 are ordinary chondrites or related meteoritic types. Because xenoliths are a relatively unbiased sample of the asteroid belt, it seems likely that ordinary chondrites and their kin comprise the second-most-abundant type of material in the belt. Thus S asteroids may have chondritic rather than stony-iron composition.

SOLAR GASES: CLUES TO THE ORIGIN OF METEORITES

The most direct evidence on the former location of meteorites comes from trapped solar wind (Anders, 1975). I shall present the argument from that paper in updated but greatly abridged form, omitting various qualifications and supporting arguments. In addition, I shall review a few other lines of evidence bearing on the problem.

Do Gas-Rich Meteorites Come from Regoliths?

Almost every stony meteorite class has several "gas-rich" members that are brecciated and contain a characteristic noble-gas component, of solar isotopic and elemental composition (Table 1). Wänke (1965 and earlier papers) was the first to suggest that this component represents solar wind trapped by meteoritic dust in the regolith of the meteorite

Table 1. Prevalence of Gas-Rich Meteorites[a]

Class	%	Class	%
C1 Chondrites	100	L Chondrites	2
C2 Chondrites	61	LL Chondrites	8
C3V Chondrites	60	K Chondrites	25
C3O Chondrites	0	Howardites	33
H Chondrites	12	Aubrites	33

[a]Mazor *et al.* (1970); Schultz *et al.* (1972), Srinivasan and Anders (1977).

parent body. Because solar-wind ions have very low energies, they penetrate only a few hundred Angstroms into the grain, and hence are trapped only by grains residing at the very surface. A later impact cements these dust grains into a coherent rock, which is then ejected from the parent body by still another impact. All stages of this process have been observed in lunar samples, from fresh, unirradiated soils to welded, gas-rich breccias.

Detailed studies of meteoritic breccias have revealed many additional parallels to lunar breccias: charged particle tracks, microcraters, anisotropically irradiated grains, radiation damage, etc. (Wilkening, 1970; Barber *et al.*, 1971; Macdougall *et al.*, 1973, 1974; Poupeau *et al.*, 1974; Rajan, 1974; Maurette and Price, 1975; Price *et al.*, 1976; Goswami *et al.*, 1976). The consensus that has emerged from this work is that gas-rich meteorites formed in a regolith. Wetherill (1978) has contended, however, that only "a few" of the gas-rich meteorites show "the full set of these regolith features," the most clear-cut case being the howardites. Actually, the above studies included aubrites, H chondrites, C1 chondrites, and C2 chondrites, in addition to howardites, and all showed the full set of regolith features (except that no microcraters have yet been reported from aubrites). By Occam's Razor, all are likely to have formed in a regolith.

Model for the Solar Gas Content of Meteorites

To a first approximation, the mean solar gas content G of soil from a given body depends on two parameters: the solar wind flux, which is proportional to the inverse square of the heliocentric distance a, and the mean surface residence time t. The latter is approximately proportional to the inverse of the cratering rate R, which determines the rate at which the topmost layer is blanketed by ejecta; both old soil and freshly crushed rock (Gault *et al.*, 1974). Thus, using symbols $\circ$ and $\star$ for the Moon and meteorite parent body, we can write

$$\frac{G_\circ}{G_\star} = \left(\frac{a_\star}{a_\circ}\right)^2\left(\frac{t_\circ}{t_\star}\right) \approx \left(\frac{a_\star}{a_\circ}\right)^2\frac{R_\star}{R_\circ} \qquad (1)$$

Because we know the heliocentric distance of the Moon, at least to a first approximation, we can use lunar soil as "ground truth" to determine the formation distance of gas-rich meteorites.

The conditions under which Equation (1) is valid have been discussed by Anders (1975), and will not be repeated here. The principal requirements are (1) that the bombarding fluxes in both regions be "top-heavy" (*i.e.*, the exponent γ in the differential mass distribution $N = Am^{-\gamma}$ must be less than 2) so that the dominant process will be crushing of fresh rock rather than reworking of old dust, and (2) that the Moon and meteorite parent bodies retain about the same fraction of ejecta. The first requirement is met for the Moon and the asteroid belt, judging from the abundance of siderophile elements in lunar and meteoritic breccias (Anders, 1975). It is probably also met for comets, because both comets and their debris (shower meteors) seem to have $\gamma < 2$. The second requirement certainly is not met by very small asteroids or comets, which lose most of their ejecta and hence cannot develop a regolith. But even a 45 km asteroid should lose only 50% of its impact ejecta, according to data by Gault *et al.* (1963), and loss of *average* soil should have no effect on Equation (1). According to a detailed model by Housen (1976), asteroids of r = 100 km and 20 km can accumulate regoliths of ~100 m and ~10 m in 10^9 years.

A referee has questioned the approximate inverse proportionality of t and R in Equation (1), because blanketing* would involve mainly recycled grains on the Moon and mainly fresh grains on an asteroid. In the first place, we are concerned primarily with the relation between G and t, not R, and that relation is exact whether the blanketing is done by a fresh or a recycled grain: the integrated gas content per unit time and area is the same no matter how many grains share in the integrating.

Second, though the relation between t and R does indeed require that the *major part* of the ejecta be freshly crushed rock rather than recycled grains, it can be shown that this condition is met for all practical purposes. A quantitative statement of this condition is that the integrated flux of crater-forming bodies of mass 0 to M (where M = mass of largest body to strike the planet) be large compared to the flux of bodies unable to penetrate the average regolith, of mass range 0 to m:

$$F \equiv I_0^M / I_0^m = [(M^{-c}-0^{-c})/(m^{-c}-0^{-c})] > 2 \qquad (2)$$

where c is the exponent in the *cumulative* mass distribution. On the Moon, the mare regolith is typically about 5 m thick, so $m \sim 10^7$ g. With $M = 10^{19}$ g, corresponding to a 10 km body, and $c \approx -0.17$ (corresponding to γ = 1.83; Dohnanyi, 1971) we obtain F = 110, so the proportionality is good to 1%. For a hypothetical asteroid with a 100 m regolith, $m = 10^{13}$ g and $M = 10^{19}$ g, so F = 10.5 and the proportionality is good to 10%.

Actually the agreement is not quite as good, because the mass distribution steepens below 10^9 or 10^6 g (Chapman, 1972), and the upper limit of integration is not well defined, because the ejecta from the largest craters are not distributed globally, and so do not contribute fully to the *average* regolith (Ganapathy *et al.*, 1970).** However, there is direct evidence for the dominance of juvenile grains in lunar soil cores and especially meteoritic breccias. Charged-particle track studies have shown that grains from a given layer differ in exposure time by $\sim 10^2$-10^3, with the median exposure typically an order of magnitude below the maximum (Poupeau *et al.*, 1974; Price *et al.*, 1975; Goswami *et al.*, 1976, and many references cited therein). And the amount of meteoritic material in lunar soils (1-1.5% in mature soils; down to 0.09% in young soils; Krähenbühl *et al.*, 1973) is comparable to that in gas-rich meteorites (1-4%, Laul *et al.*, 1972; Chou *et al.*, 1976; Hertogen *et al.*, 1978), so that on both bodies, dilution by fresh rock keeps pace with addition of meteoritic material. In any event, since the differences we shall try to explain amount to 2-3 orders of magnitude, errors of even a factor of 2-3 are of no consequence.

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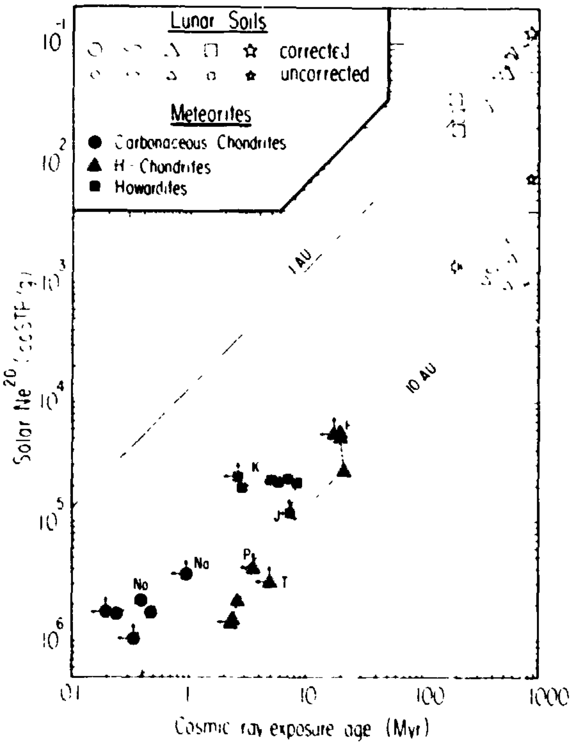
* "Blanketing" is a more accurate term than the widely used misnomer "gardening," because the mixing process is not a simple overturn but a "biased random walk," where many small increments alternate with occasional large decrements (Laul *et al.*, 1971).

**On the other hand, large craters contribute heavily to the total *volume* of the regolith, which is relevant to some aspects of this problem, *e.g.*, the abundance of gas-rich meteorites.

Formation Distance of Gas-Rich Meteorites

According to Equation (1), the gas content G should be proportional to surface exposure age t and the inverse square of the heliocentric distance a (Figure 1). We can calibrate this relation by means of lunar soils (open symbols), which are *known* to have formed at 1 AU. Because lunar soils lose Ne owing to temperature and saturation effects, it was necessary to calculate corrected Ne values from the Xe content, using the Ne/Xe ratio. (This correction has somewhat improved the correlation of G and t, as shown by a comparison of the large and small symbols). The "10 AU" line represents a^{-2} dependence of the solar wind flux.

Fig. 1. Relation between solar-gas content and surface exposure age as a function of distance from the Sun (Anders, 1975). Cosmic-ray exposure age of meteorites is only an upper limit of the surface exposure age, and Ne^{20} content may be too low because of saturation effects; thus all meteoritic points should be shifted toward the upper left. Regardless of class, gas-rich meteorites have systematically lower gas contents and exposure ages than do lunar soils. Their parent bodies must have been located in a region of lower solar wind flux ($1 < a < 8$ AU) and higher cratering rate. Both characteristics point to the asteroid belt.



The surface exposure age can be measured by different radiation effects, and generally increases with the penetration depth of the radiation (Table 2). For our analysis, the solar wind exposure age is relevant, but since it is not known for most meteorites, we shall use the cosmogenic noble-gas exposure age as a substitute. Though these two quantities are by no means equivalent (they measure the residence time in the topmost few hundred Angstroms and topmost meter, respectively), there is evidence that they are proportional to each other.

However, for meteorites this proportionality is less strictly valid, because the cosmic-ray exposure age also includes the transit time to Earth, when the meteorite was again bombarded by cosmic-rays. To minimize this effect, I have selected meteorites of short exposure

Table 2. Different Types of Surface Exposure Age for Lunar Soils and Gas-Rich Aubrites

Effect	Effective Depth (cm)	Age (yr)	
		Lunar Soils[a]	Aubrites[b]
Solar Wind	$\sim 10^{-6}$	10^6-10^7	1-100
Solar Flare Tracks	$\sim 10^{-3}$	10^6-10^7	10^3-10^4
Galactic Cosmic-Ray Tracks	10	10^8	10^6
Cosmogenic Noble Gases	100	1-10×10^8	3×10^7

[a]Lal (1975).
[b]Poupeau *et al.* (1974).

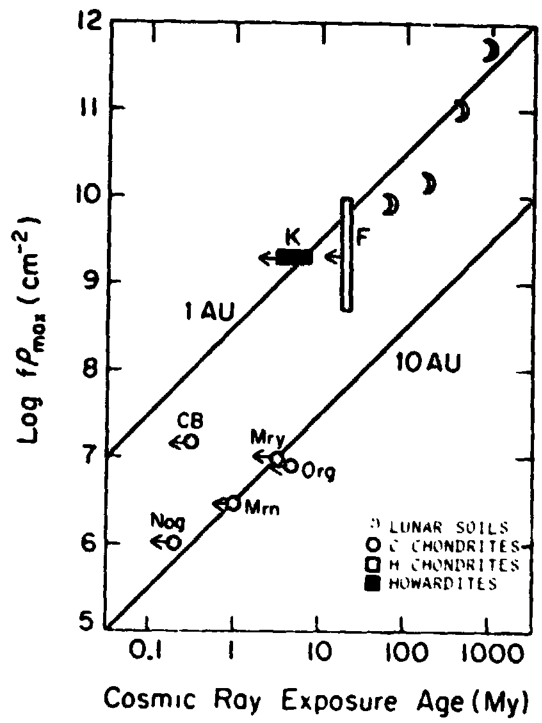
age, but since the transit time is always finite, these ages must be regarded as upper limits of the surface exposure age, which we are after. Arrows are inserted to remind us of this fact. In two cases where the transit time was independently determined from the Al^{26} content (Nogoya, Pantar), the surface exposure age seemed to be on the order of 10^5 years (Anders, 1975). Different samples of the same meteorite are connected by solid lines.

The Ne^{20} contents also may be somewhat too low, owing to diffusion losses. The correction should be much smaller than for lunar soils, because gas-rich grains in meteorites generally lack the radiation-damaged, amorphous surface layers, which are very leaky and are responsible for most of the gas loss from lunar soils (Ducati *et al.*, 1973; Poupeau *et al.*, 1974). Precise corrections cannot be estimated from the Ne/Xe ratio, owing to the presence of planetary Xe, but it seems likely that the correction factors are smaller than 5x or perhaps even 2x. Vertical arrows indicate the direction of the correction.

Gas Content and Surface Exposure Age. In spite of these uncertainties, Figure 1 reveals two stark and simple facts: meteorites have shorter exposure ages and lower gas contents than do lunar soils, by 1-3 and 3-5 orders of magnitude, respectively. Errors in these quantities cannot account for this difference. Exposure ages for meteorites are upper limits because they include the transit time, but any correction for this effect can only enlarge the difference. Ne^{20} contents are lower limits, but are unlikely to be in error by more than a factor of 5. Moreover, Price *et al.* (1975) have shown that this uncertainty can be circumvented by using solar-flare track density rather than Ne^{20} content as an integrator of solar corpuscular radiation (Figure 2). Here the total radiation dose is given by the product $f\rho_{max}$, where f = fraction of track-rich grains and ρ_{max} = maximum track density at the edge of the grain. Two of the most gas-rich, non-primitive meteorites (the howardite Kapoeta and the H chondrite Fayetteville) fall two orders of magnitude below the most heavily irradiated lunar soils, whereas five carbonaceous chondrites fall 3-6 orders of magnitude below.

Taken at face value, the meteorite data suggest a formation distance less than 10 AU, in some cases appreciably less: <2.6 AU for the C2 chondrite Cold Bokkeveld, <1.2 AU for the howardite Kapoeta, and <3.7 AU for the H chondrite Fayetteville. The asteroid belt would seem to be the most likely source.

Fig. 2. Product of solar-flare track density ρ_{max} and fraction of track-rich grains f, a more saturation-proof indicator of surface exposure (Price *et al.*, 1975), correlates with cosmic-ray exposure age in much the same way as Ne^{20} does in Figure 1. Carbonaceous chondrites (circles) again have lower track densities and ages than do lunar soils (crescents), which suggests formation at a greater distance from the Sun, in a region of higher cratering rate. Difference is less marked for howardite Kapoeta (K) and H chondrite Fayetteville (F).



Cratering Rate. These data contain still another, more decisive clue pointing to the asteroid belt: the low gas contents and short cosmic-ray exposure ages of meteorites compared to lunar soils. Apparently meteorites come from a region where the cratering rate is much higher than at 1 AU, so that material stays at the surface for a much shorter time before re-burial. The asteroid belt, with its high flux of rubble, again is the obvious candidate. Indeed, quantitative consideration of cratering rates (Anders, 1975) leads to predicted Ne^{20} contents that agree rather well with observed values (Table 3).

The data in Figures 1 and 2 thus show pervasive, fundamental differences between meteorites and lunar soils: meteorites have consistently smaller gas contents, track densities, and exposure ages than do lunar soils. The differences amount to factors of 10^2-10^6, much larger than the approximations and simplifications involved in Equation (1). Wetherill (1978) maintains that these differences cannot be conclusively interpreted in terms of distance, surface exposure age, and cratering rate until a "detailed understanding of the probable nature of an asteroidal regolith" has been attained. It is not clear, however, what physical parameters other than a, t, and R are capable of accounting for factors of 10^2-10^6, and hence how a more detailed understanding can drastically alter the first-order picture presented here.

Table 3. Predicted Ne^{20} Contents of Lunar and Asteroidal Regoliths

	Moon	Asteroid (r = 100 km)
Heliocentric Distance, AU	1.00	2.5
Cratering Rate, cm/yr	8×10^{-8}	7.3×10^{-5}
Ne^{20} Flux, cc STP $cm^{-2}yr^{-1}$	2×10^{-8}	3.2×10^{-9}
Predicted Ne^{20}, cc STP/g	8×10^{-2}	1.2×10^{-5}
Observed Ne^{20}, cc STP/g	5.6×10^{-2}	2.9×10^{-6}
	(Lunar soils)	(H chondrites)

Depth of Asteroidal Regoliths

There has been some controversy over the thickness of asteroidal regoliths; in particular, whether asteroids can develop thick enough regoliths to account for the great abundance of gas-rich meteorites (Table 1). Let us approach this problem empirically, and see what the meteorites tell us about the regoliths of their parent bodies.

Wänke (1966) has made the important observation that gas-rich H chondrites show essentially the same cosmic-ray age distribution as do all H chondrites, and are present not only in the continuum but also in major peaks such as those at 5 Myr and 22 Myr (Figure 3). This shows that a gas-laden regolith must extend to sufficient depth to assert itself even in the larger and deeper impacts.

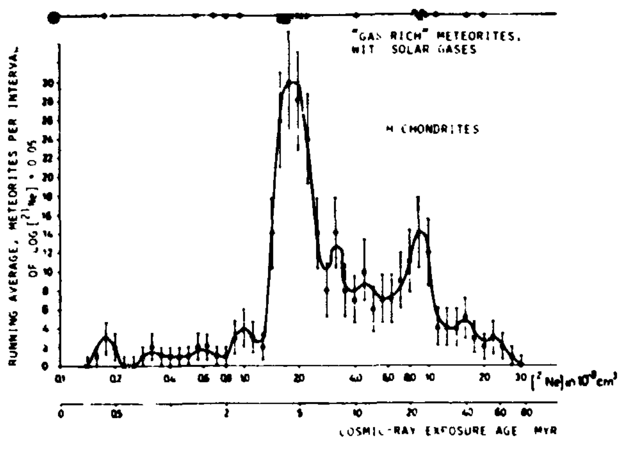


Fig. 3. Cosmic-ray exposure ages of gas-rich H chondrites (top) peak at the same values (5 and 22 Myr) as the ages of all H chondrites, and the proportion of gas-rich meteorites in the continuum is comparable to that in the peaks. Evidently large and small impacts eject about the same proportion of gas-rich meteorites, which suggests that solar-wind irradiated regolith material comprises a roughly constant fraction of the outer layers, down to at least the depth of the largest crater, 0.5-1.2 km. (From Wänke, 1966).

Let us roughly estimate a minimum depth for the largest event in Figure 1, the 5 Myr peak. Some 47% of all dated H chondrites are in this peak, and since H chondrites comprise 37% of all chondrite falls, the 5 Myr peak contributes some 17% of the annual influx of chondrites, $\sim 10^8$ g/yr (Wetherill, 1977). If the dynamical mean life against planetary capture is 30 Myr, and one-third of these meteorites eventually fall on Earth, then the total reservoir of H chondrites from the 5 Myr impact is 1.7×10^{15} g.

This value includes only material in the meteoritic mass range (10^2 g - 2×10^6 g), and we must therefore integrate the mass distribution to larger masses--say 2×10^{12} g, corresponding to a diameter of about 100 m. If we do this for two extreme choices of the population index s in the cumulative size distribution, 2.5 and 3.6, we obtain 2.2×10^{16} g and 2.0×10^{15} g for the total mass.

From these values, we can find the size of the crater. With the Short and Forman (1972) relation for the volume of the crater, and a depth/diameter (h/D) ratio of 0.35, we obtain D = 3.3 and 1.7 km and h = 1.2 and 0.53 km. According to Figure 1, the fraction of gas-rich meteorites in the 5 Myr peak is 10/72 = 0.14, so if this figure is representative, then the regolith thickness would have to be 160 m or 70 m for the two cases.

Actually, the true thickness must be much greater. Wänke (private communication, 1967) has pointed out that each of the larger peaks in the radiation age spectrum (Figure 3) contains chondrites of all petrologic types, from H3 to H6. It does not seem plausible that all these types originated in a shallow zone of ~ 1 km depth. The peak metamorphic temperatures of H3 and H6 chondrites differed by at least 300°C (<600°C vs. 950 ± 100°C; Wood, 1967; Onuma *et al.*, 1972), and it seems very difficult to establish such a steep temperature gradient over a distance of less than 1 km, let alone maintain it over the $\sim 10^{[illegible]}$ yr duration of metamorphism.

The obvious answer is that the H chondrite parent body has been extensively mixed by earlier, larger impacts, so that meteorites of all petrologic types, as well as regolith material, are closely juxtaposed and are ejected together even by small-scale impacts. The original stratigraphy may have resembled that of the L chondrite parent body (Figure 4), as reconstructed from the observed frequency of petrologic types. (There is evidence that the L chondrite parent body was completely shattered in a collision about 500 Myr ago (Anders, 1964; Heymann, 1967; see also section entitled "Outgassing of the L Chondrite Parent Body"), and so the L chondrites falling on Earth may be a relatively unbiased sample of this body.) If so, then mixing and brecciation must have penetrated at least 0.12 r into the H chondrite parent body, to expose the H6 layer.

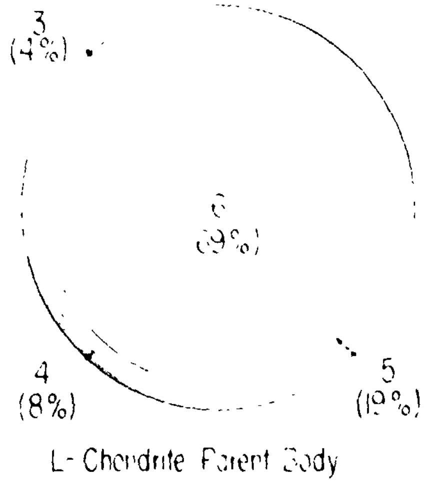


Fig. 4. Cross section of L chondrite parent body, showing volume fraction occupied by each petrologic type. Because L chondrite parent body seems to have completely broken up about 500 Myr ago, volume fraction of each petrologic type should be proportional to its observed frequency.

Apparently, the H chondrite parent body thus has a substantial "megaregolith" (Hartmann, 1975). A rough idea of its average depth may be obtained from the abundance of solar Ne^{20} in meteorites. The mean solar Ne^{20} content of 34 gas-rich H chondrites (Schultz and Kruse, 1977) is 2.9×10^{-6} cc STP/g. With a solar Ne^{20} flux of [illegible] $\times 10^{-9}$ cc $cm^{-2}yr^{-1}$ at 2.5 AU, a 14 km layer of such material could be produced in 4.6 [illegible]. Three observations suggest that this material actually is unevenly mixed through a large volume of the body: the wide variation in solar Ne^{20} content among gas-rich H chondrites ($\sim 10^3$x), the coexistence of H3 to H6 material in a single gas-rich meteorite, and the simultaneous ejection of H3 to H6 material in small cratering events. In the light of these observations, it seems unlikely that the original accretional stratigraphy has been preserved in meteorite parent bodies.

These *observations* (as distinct from inferences) also seem hard to reconcile with the frequent assertion that asteroids can only have thin regoliths. The observations are well-documented, and so perhaps the fault lies with the models that predict thin regoliths on asteroids.

ASTEROIDS OR SHORT-PERIOD COMETS?

Granted that the gas implantation took place in the asteroid belt, was the meteoritic substrate itself asteroidal or cometary? Short-period comets traverse the asteroid belt in the final phase of their history, and could conceivably develop a gas-rich regolith during that period. There are four lines of evidence bearing on this question.

Chemical Composition

Comets appear to have carbonaceous chondrite composition, judging from meteor spectra (Millman, 1972) and from the abundance pattern of the micrometeorite component in lunar soils (Ganapathy *et al.*, 1970). Thus they could indeed serve as a source of gas-rich carbonaceous chondrites. It seems unlikely, however, that they could also furnish the less primitive types of gas-rich meteorites: howardites, aubrites, or ordinary chondrites. All these classes have had a prolonged, high-temperature history under dry conditions, which is hard to reconcile with the volatile-rich composition of comets. Other arguments against a cometary origin have been given by Anders (1971).

Prevalence of Gas-Rich Meteorites

One important constraint is the common occurrence of gas-rich meteorites in nearly all classes of stony meteorites (Table 1). The only exceptions are eight rare classes, with a total of 49 members: E chondrites, C3O chondrites, diogenites, ureilites, nakhlites, angrites, and chassignites.

Thus a fairly large fraction of the source volume of meteorites must have been transformed into a gas-laden regolith. Comets are doubly disadvantaged relative to asteroids in this respect: typically, they are 1-2 orders of magnitude smaller and spend 3 orders of magnitude less time in the asteroid belt. A calculation analogous to that in Table 3 shows that a 30 km comet would develop a regolith of only 4 m thickness in 10^7 yr, corresponding to 4×10^{-4} the mass of the body. This is clearly insufficient to explain the high abundance of gas-rich meteorites. Moreover, since much of this material was near the comet's surface for 4.5 AE, it would show a high cosmic-ray exposure age, contrary to observation

Early Irradiation

The preceding objections against a cometary origin of chondrites at least could be dismissed if cometary matter had acquired its solar gases in a hypothetical "early irradiation" in interplanetary space, rather than on a regolith. But there are numerous objections against this idea.

Owing to the low energy of solar wind ions, the gas must be removed to a residual density of $<10^5$ molecules/cm^3, some 9 orders of magnitude less than the initial density in the solar nebula. It is not obvious how the gas can be removed without carrying the dust along. Also, on this hypothesis, accretion of comets and ejection to the Oort belt still have to take place after irradiation, yet the gas which both processes require is already gone.

Moreover, there exist C2 chondrites without solar gases, and others with gas-rich and gas-poor portions of otherwise identical mineralogy (Nogoya, Murray, Mokoia, etc.). Wetherill (1978), who considers an early irradiation to be a viable proposition, has not explained how these gas-poor materials are to be protected against the early irradiation, how they are to be mixed with irradiated material only of the same mineralogy, and how the correlation in Figures 1 and 2 is to be accounted for.

Most important, the compaction ages of gas-rich meteorites are consistently shorter than 4.55 AE, *e.g.*, 4.22 to 4.42 AE for carbonaceous chondrites (Macdougall and Price, 1974; Macdougall and Kothari, 1976), <1.4 AE for ordinary chondrites (Schultz and Signer, 1977), and <3.6 AE for the howardite Kapoeta (Dymek *et al.*, 1976). Thus, gas-rich meteorites must have been made by processes that still operated in the solar system 1.4 AE ago, not by that durable chimera, the "early irradiation."

Outgassing of the L Chondrite Parent Body

A peculiar trait of L chondrites is the preponderance of short K-Ar and U-He ages, which are discordant between 1 and 4 AE but become concordant at 0.5 AE (Figure 5). These short ages correlate with shock and reheating symptoms, and the obvious explanation therefore is that the L chondrite parent body broke up 0.5 AE ago (Anders, 1964; Heymann, 1967. Taylor and Heymann, 1969, 1971; Turner and Cadogan, 1973; Bogard *et al.*, 1976). The high proportion of strongly heated meteorites (950-1250°C; Wood, 1967, Smith and Goldstein, 1977) implies a high input of kinetic energy per unit mass, and hence a high projectile/target mass ratio. The slow cooling rates of many of the heated meteorites (0.01-1 degree/year) suggest that the primary fragments were of kilometer dimensions.

At least two-thirds of the known L chondrites bear the signature of this 500 Myr reheating event, and hence must have been contained in one or at most two bodies at that time. This is easy to reconcile with an asteroidal but not with a cometary origin, because comets surely did not originate in a single collision, nor were they heated to ~1000° for centuries or millennia afterwards.

Wänke (1966) and Wetherill (1978) have questioned this interpretation. In their view, the gas loss occurred during the final collision that ejected the decimeter-sized meteorite from its parent body, and corresponds to the onset of cosmic-ray exposure. The radiogenic "age" of 500 Myr then does not represent a true age, but merely the fortuitous retention of some 6 of the He^4 and 3 of the Ar^{40}.

This hypothesis does not explain why short gas-retention ages are much more common among L than among H chondrites (Figure 5) and why they occur across the full range of cosmic-ray ages (Figure 6). If the gas loss took place only during the impact corresponding to the cosmic-ray age, why are these impacts always more severe on the L chondrite parent body? Studies at lunar and terrestrial craters show that the major part of the

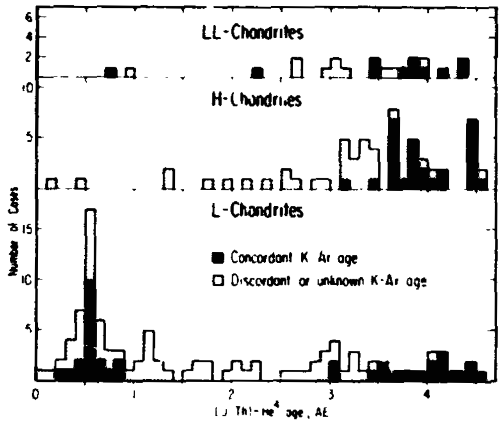


Fig. 5. L chondrites show a large proportion of U-He ages less than 2 AE, accompanied by shock and reheating effects in most cases (Taylor and Heymann, 1969). Because these ages tend to become concordant with K-Ar ages at 0.5 AE, it appears that large portions of the L chondrite parent body were reheated and outgassed at that time, presumably by a collision that produced a Hirayama family.

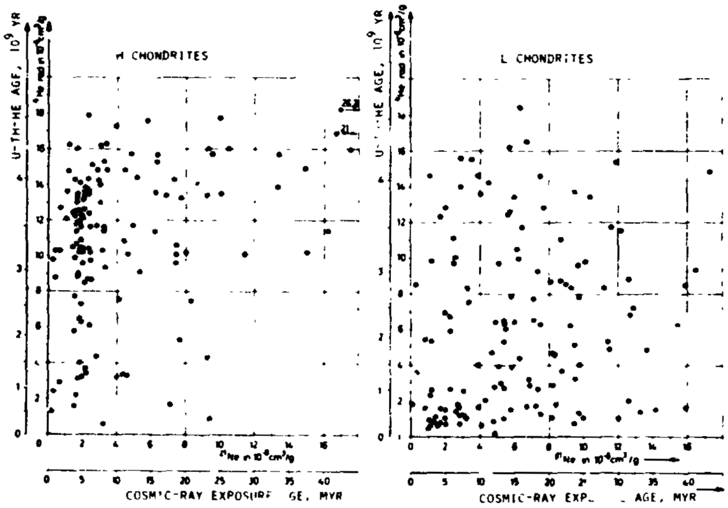


Fig. 6. Regardless of cosmic ray age, short U-He ages are common among L chondrites but rare among H chondrites. Many of these meteorites also were shock-heated to 950-1250°C and cooled at rates of 0.01-1°/yr, corresponding to burial depths of up to 1 km or more. Consequently, the gas loss and reheating cannot have been caused by the impact triggering the cosmic-ray exposure era, but by an earlier, larger event. (From Wänke, 1966).

ejecta is only lightly shocked, and does not have its gas-retention ages reset. Wholesale gas loss, as for the L chondrites (Figures 5 and 6) is very much the exception, and needs to be explained by some exceptional event, such as the collision of two bodies of comparable size.

Moreover, metallographic studies show that many shocked L chondrites cooled at rates of 1 to 0.01 deg/yr, corresponding to burial depths of a kilometer or more. But the impact that started the cosmic-ray exposure by definition must have reduced the meteorite to less than a meter in size, and so cannot be responsible for the heating at 1000 m depth.

METEORITES AND ASTEROIDS

Mineralogy and Accretion Temperature

Evidently, gas-rich meteorites formed as recently as 1.4 AE ago, in a region 1-8 AU from the Sun where the cratering rate was 10^2-10^3 times higher than at 1 AU. These characteristics point uniquely to the asteroid belt. Moreover, asteroid mineralogy, as inferred from spectral reflectivity data, matches chondrite mineralogy to first order. Asteroids, like chondrites, divide into a carbonaceous and a siliceous class, *and since the transition from siliceous to carbonaceous mineralogy occurs at a nebular condensation temperature of 400°K* (Larimer and Anders, 1967; Anders, 1972), it appears that *chondrites and asteroids both condensed in the region traversed by the 400°K isotherm.*

Wetherill (1978) has criticized the condensation theory because it fails to explain why spectrally different asteroids occur at the same heliocentric distance. In the first place, the correlation of mineralogy with distance is not bad, considering that temperatures fell not only with distance but also with time (by some 50-100°; Anders, 1972; Alaerts *et al.*, 1977). Asteroids formed at large distances, where even the initial temperatures were below 400°K, would be carbonaceous througnout; those at small distances, where even final temperatures were above 400°K, would be siliceous throughout; and those at intermediate distances would have siliceous cores and carbonaceous mantles. Breakup of such hybrids would give a mix of C and S objects at the same distance.

Second, there is reason to believe that asteroid orbits have been scrambled since their formation. Whipple *et al.* (1972) have shown that the high inclination of 2 Pallas cannot have persisted throughout the accretion stage, but must be a post-accretional feature caused by an unknown perturbation process. This is also true of other asteroids of high i and/or e. Thus the imperfect correlation between composition and semimajor axis is a problem in dynamics, not cosmochemistry. No matter how this problem is ultimately resolved, the fact remains that both meteorites and asteroids show the distinctive change in mineralogy expected at 400°K. Hence both must have formed in a region of space traversed by the 400°K isotherm.

Xenoliths

All of the objects proposed as meteorite parent bodies--asteroids, comets, Apollos--have orbits that cross at least part of the asteroid belt for at least part of their history. During that time they sweep up a random sample of asteroidal debris, and cement some of it into impact breccias. Meteorites eventually carry this debris to Earth in the form of xenoliths (= foreign inclusions). In this manner, meteorites act as a "poor man's space probe," sampling bodies whose orbits do not allow their debris to reach the Earth directly. (There may be some discrimination against bodies of high encounter velocities, but this will gradually lessen at least for the fine debris, as its orbits become circularized.)

XENOLITHS

HOSTS	C	C1	C2	C3	H	L	LL	Ch	Au
C2				1					
C3			2					1	
H	5	1	5					1	
L	2		1						
LL					1				
Ho			2						
Au								1	
Mes				1				1	2
	7	1	10	2	1			4	2

Fig. 7. Xenoliths (foreign inclusions) in meteorites provide a relatively unbiased sample of material in the asteroid belt. Carbonaceous chondrites, especially C2s, predominate, accounting for 20 out of 27 xenoliths. Ordinary chondrites and their relatives (Ch) are the second most abundant class, with five representatives. None of the meteorite classes tentatively identified with S asteroids (mesosiderites, irons, Fe^{++}-bearing achondrites) have thus far been found among the xenoliths, and so it seems that ordinary chondrites and their kin are more likely candidates for S asteroid material.

Such xenoliths have been studied extensively by several workers, mainly Wilkening and Fodor and Keil (Wilkening, 1973, 1977; Wilkening and Clayton, 1974; Fodor and Keil, 1973, 1976). Their results, augmented by some recent work from Chicago (Leitch and Grossman, 1977; Hertogen *et al.*, 1978) is shown in Figure 7.

All together, 27 xenoliths have been found thus far, within host meteorites representing eight meteorite classes. Of the 27 xenoliths, 20 are carbonaceous, five are ordinary chondrites in an extended sense (having the same mineralogy but different proportions of FeO and total Fe), and two are aubrites.

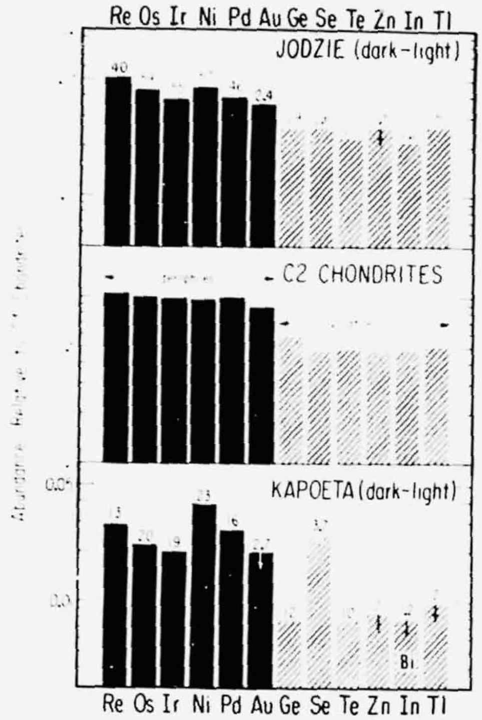
Obviously, these data are of great potential value in characterizing the population of the (inner?) asteroid belt, though at present they are severely limited by statistics and by observational selection. The following tentative conclusions may be drawn from Figure 7 and other evidence.

(1) The ratio of carbonaceous to other chondrites is about 4:1. This happens to match the ratio near the center of the asteroid belt (Zellner, 1978), but the true ratio must be lower because carbonaceous xenoliths are favored by observational selection.

(2) Most of the carbonaceous xenoliths (13 out of 20) resemble known classes, and only a few of the remaining seven are actually new; others merely are insufficiently characterized. Among the identified carbonaceous xenoliths, C2 chondrites greatly predominate, as shown by detailed petrographic studies (Wilkening, 1973, 1978; Bunch, 1975).

The statistical significance of this result is strengthened by noble-gas and chemical analyses of howardites, which provide a comprehensive average of the foreign component in these meteorites regardless of particle size (Mazor and Anders, 1967; Laul *et al.*, 1972; Chou *et al.*, 1976; Hertogen *et al.*, 1978). The foreign component characterized by this comprehensive method closely matches C2 chondrites (Figure 8), and thus proves that material indistinguishable from C2 chondrites dominates in the region of the howardite parent body. Because it is generally conceded that this body is located in the asteroid belt, it follows that C2 chondrites are very abundant in at least one part of the asteroid belt. The spectrophotometric identifications of C2-like material by McCord and his students (McCord, 1978

Fig. 8. Gas-rich portions of howardites contain a foreign component, representing mixed interplanetary debris picked up during their regolith history. Abundance patterns of this component in Jodzie and Kapoeta show some resemblance to C2 chondrites, suggesting that C2 chondrites are the most abundant type of material in the region of the howardite parent body. (From Hertogen *et al.*, 1978).



and references cited therein) thus are strongly supported by tangible samples (Figure 8), and hence hardly need to be prefaced by cautious disclaimers.

(3) "Ordinary chondrites" in the broadest sense comprise the second most abundant group. But only one of five such xenoliths, an H chondr[illegible] actually corresponds to a *known* class. Thus the ordinary chondrites are not rare [illegible], derived from 1-3 yet-to-be-discovered asteroids of the right reflectance spectrum. [illegible], are samples of a rather abundant type of material, of metal content <20%, which is common enough in the asteroid belt to have contributed five out of 27 xenoliths.

Nature of S Asteroids

It is suggestive that the second most abundant group of xenoliths matches the second most abundant class of asteroids, the S asteroids, in gross mineralogy. Both consist mainly of ultramafic silicates and metal. According to some interpretations, however, the S asteroids are much richer in metal (~50% vs. <20%), and thus resemble either stony irons (mesosiderites, pallasites) or coarser-scale (>1 cm) mixtures of silicates and metal, rather than chondrites (McCord and Gaffey, 1974; Chapman, 1976, 1977). This interpretation raises three questions:

1. Why is the second most abundant asteroid class not represented among xenoliths?

2. Why are its meteoritic equivalents so rare among known falls (11 stony irons, or 46 irons and 67 achondrites* among 854 falls)?

3. Why is there no asteroidal equivalent of the most populous class of meteorites, and of the Apollo-Amor objects that resemble them?

The first question has no ready answer. The greater crushing strength of stony irons would cause some underrepresentation, but this is offset by the inconspicuousness of ordinary chondrite xenoliths in ordinary chondrite hosts.

To answer the second question, one might postulate dynamical barriers that prevent the great majority of S asteroids from dispatching fragments to Earth. But this seems unlikely: since S asteroids are the second most abundant class of asteroids, and are fairly evenly spread through the inner half of the belt, they should contribute their share of meteorites and Apollo-Amor objects leaving the belt through various escape hatches. Though their presumably greater crushing strength might cause them to be underrepresented relative to C asteroids, their concentration in the inner half of the belt, where most of the escape hatches are, would offset this factor. Iron meteorites have still higher crushing strengths, and yet about 12 classes of irons (of very diverse chemistry, cooling rate, and hence nebular place or origin (Kelly and Larimer, 1977; Scott and Wasson, 1975)) do get out in copious numbers, although (metallic) M Asteroids are much rarer than S asteroids. And so do various kinds of achondrites, though their asteroidal counterparts are either unobserved, or, in the case of Vesta, unfavorably situated for transmission of meteorites to Earth. Since these rare types are able to assert themselves, and reach Earth in significant numbers, it is not clear how the far more abundant S asteroids are to be prevented from dispatching their fragments to Earth.

Thus we are left with two possibilities. Either the S asteroids are stony irons, in which case we must explain why they are outnumbered in the world's meteorite collections by the meteoritic equivalents of much rarer or unobserved asteroid types. Or they are ordinary chondrites, in which case we must explain why the spectral reflectivity data tell us otherwise. A possible reason is preferential erosion of brittle silicate particles, leaving the surface enriched in metal. I, at least, find it easier to believe that the spectral reflectivity data mislead us than to accept the alternative: that the most abundant meteorite class has no asteroidal equivalent, and the second most abundant asteroid class has no xenolithic and only rare meteoritic equivalents.

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*It is far from clear that coarsely textured, metal-silicate asteroids actually can provide the right environment for the formation of iron meteorites and achondrites.

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DISCUSSION

ARNOLD: The lunar exposure has been comparatively recent, I mean in the last couple of billion years. The exposures that produce these rare gases were older, presumably, and does one not assume that such conditions as the ratio of the age indicating flux to the solar wind flux constant? Certainly the lunar evidence, and common sense also, suggests if we were going back a long time, the cratering rate was considerably higher back at the beginning than at any later point.

ANDERS: Some of these meteorites contain xenoliths and clasts that have been separately dated and some of them are as young as 1.4 billion years. This means the compaction of these rocks happened still more recently and therefore the implantation of these noble gases did not occur at the dawn of the solar system but in recent times, overlapping the formation time of the lunar breccias.

VEVERKA: Are these argon loss ages?

ANDERS: For Kapoeta they are rubidium-strontium ages, for some of the others they are potassium-argon ages.

WETHERILL: I think it is important that you recognize you are talking about entirely different objects here. Kapoeta is a howardite which has all the characteristics of the lunar regolith. On the other hand, ordinary chondrites and carbonaceous chondrites have a very limited regolithic history, and so are not as similar as Kapoeta to the Moon. I think there are problems which are obscured by lumping all these meteorites together.

ANDERS: I am afraid you are entirely mistaken. Ordinary chondrites and carbonaceous chondrites *do* have essentially "all the characteristics of the lunar regolith": microcraters, solar flare tracks, anisotropically irradiated grains, steep track gradients, solar wind gases, etc.--see the paper by Goswami *et al.* (1976) and eight other references cited in my paper. They lack the glassy agglutinates one finds in lunar breccias and in Kapoeta, for the simple reason that they don't contain enough feldspar to make glass--look at any meteorite collection and you'll see that only the feldspar-rich achondrites (like Kapoeta) have shiny, glassy fusion crusts. Ordinary and carbonaceous chondrites have dull, non-glassy crusts, because their principal minerals, olivine and pyroxene, do not readily form glasses.

CHAPMAN: Could you define how the solar wind is being implanted in this top surface layer compared to the meter depth of exposure to cosmic rays? What are the physical requirements that you have for getting implanted gas? Is mixing required?

ANDERS: For solar wind implantation, the grain must be at the very top, with essentially nothing between it and the Sun. As shown by Poupeau *et al.* (1974) in their study of aubrites, meteoritic grains spend much less time at the surface than do lunar grains, *i.e.*, 1-100 years versus 10^6 years. Thus they generally do not develop the amorphous surface layer that is very leaky for light noble gases and prevents lunar grains from building up their full complement of He and Ne relative to Xe. To account for these short ages, some mixing or blanketing process is required. Poupeau *et al.* have shown for aubrites that the solar flare track densities imply a residence time of 10^3-10^4 yrs in the top 10 μm, compared to 10^6-10^7 yrs for lunar grains. Most grains do not show evidence for multiple exposure, and so the process is best described as "blanketing" or "burial," rather than "mixing."

ZELLNER: There are on the order of one hundred S asteroids with diameters larger than 50 km. We have detailed spectra for a little less than half of them. So you cannot exclude that among the S asteroids which have not been studied by more diagnostic techniques there could be ordinary chondritic bodies. And we don't need a lot of them, correct?

ARNOLD: Wetherill's argument is that there are special dynamic means to bring these things to the Earth. If that is true, then it is not the whole collection that is contributing in some proportional way, but three or four objects. There is other evidence concerning bunching of bombardment ages and things of that kind which strengthen those arguments very much, it seems to me. And so it may very well be that most ordinary chondrites are coming from a very limited number of parent bodies which allows, as far as I am concerned, Zellner's point to stand. It may turn out that they are undiscovered.

ANDERS: I agree that the parent bodies of the ordinary chondrites may be just a small subgroup of the S asteroids. But if my arguments are valid, then the majority of the other S asteroids are chondritic with no more than 20% metal.

WETHERILL: With regard to the S asteroids, I don't see why they have to be a mesosiderite of the same sort we have in the laboratory. They could very well be differentiated objects which have mixtures of iron and basaltic materials on the surface, which on a different scale would be a mesosiderite, but they could be in our collections as basaltic achondrites and as iron meteorites.

ANDERS: If that is true, then there should be many basaltic clasts among the xenoliths, and yet not one has been found. According to Figure 7 of my paper, the known meteorite classes comprise some 10 space probes that traverse at least part of the asteroid belt and collect a more or less unbiased sample. Among the first 27 such samples collected, we have found no howardites, no eucrites, and no mesosiderites. I would argue that anything we don't see probably is rare, though this conclusion is limited both by statistics and by observational selection. For example, olivine xenoliths would have been largely overlooked.

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SECTION II:

EARTH-BASED OBSERVATIONS OF ASTEROIDS

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PHYSICAL OBSERVATIONS AND TAXONOMY OF ASTEROIDS

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Since 1970 the physical study of asteroids has been dramatically extended by wide application of four types of observations: spectrophotometry from 0.3 to 1.1 μm; broad-band UBV photometry; visible photopolarimetry; and broad-band thermal radiometry. More than a quarter of the numbered asteroids have been studied with these techniques, and for most of them the data are adequate to determine approximate size and albedo and to provide a rough classification related to mineralogical composition. The specific CSM taxonomic system of Chapman *et al.* (1975) and Bowell *et al.* (1978) is described and used to organize these new data. The CSM taxonomy is also compared with more compositionally specific taxonomies, and some future directions for both observation and classification are indicated.

INTRODUCTION

During the relatively brief span of years from the Tucson Asteroid Conference (Gehrels, 1971) to the present, there has been explosive growth in observational data on asteroids. During the first half of the 20th century and well into the 1960's, asteroid science had been limited almost entirely to searches for new objects and establishment of photographic magnitudes and accurate orbital elements for the fewer than 2000 asteroids that were named and numbered. During the 1960's, the first major efforts to accumulate more physical data (photoelectric magnitudes and lightcurves, with some colorimetric and polarimetric work) were undertaken, primarily by G. P. Kuiper and T. Gehrels at the University of Arizona. Only a few dozen of the brighter objects were studied, however, and the interpretation of the observations was quite limited. The major watershed appears now to have been in about 1970, when C. R. Chapman, T. B. McCord, and their collaborators began a systematic program to obtain spectrophotometry of a large number of asteroids and, perhaps more important, to interpret their observations in terms of composition and mineralogy. Thus for the first time it became possible empirically to test speculations concerning the relationships between distant asteroids and the meteorite samples under intensive study in terrestrial laboratories.

The first interpretation of asteroid spectrophotometry was presented by McCord, Adams, and Johnson (1970), who showed that the reflectivity of Vesta was matched extremely well by that of the rare basaltic achondrites. Shortly thereafter, Chapman, McCord, and Johnson (1973) published reflectivity curves for 23 asteroids and demonstrated the existence of a wide variety of mineralogical types, and about the same time empirical interpretations of these data based on comparisons with meteorite spectra were suggested by Chapman and Salisbury (1973) and Johnson and Fanale (1973).

At the same time that spectrophotometry was emerging as a major diagnostic tool, other new techniques for physical observations of asteroids also were applied. During the 1960's an empirical relation between the shape of the polarization-phase curve and the albedo of a particulate (dusty) surface was recognized, but it was not until a series of papers published beginning in 1971 that J. Veverka applied this relation to derive albedos and diameters of asteroids. At the same time D. Allen first used measurements of thermal infrared radiation (which, unlike reflected light, is greater for a dark asteroid than for a light one) to derive what he called an "infrared diameter" for Vesta, and this work was soon extended to about a dozen asteroids by D. Matson. At the time of the 1971 Tucson conference these new methods for determining sizes and albedos were still suspect to many workers, but within another two years they had clearly demonstrated their value and were being widely applied. An important early result was the discovery by Matson (1971) that at least one asteroid--324 Bamberga--had an albedo about a factor of two lower than that for any previously known object in the solar system. Subsequent studies have shown that most asteroids are in fact members of this low-albedo class.

By 1974 the three techniques of spectrophotometry, polarimetry, and infrared radiometry, as well as revitalized programs of UBV photometry, had been applied to about 100 asteroids. A first attempt to utilize these data collectively to characterize the main belt asteroid population, including the definition of broad classifications based on physical rather than dynamical properties, was published by Chapman, Morrison, and Zellner (1975). This paper has been widely quoted and can be taken to represent a significant benchmark in the rapid recent development of asteroid science. I will use it as the point of departure for the present paper, which is limited primarily to results obtained since 1974.

As of the date of this meeting, physical observations have been made for nearly 600 asteroids--more than a quarter of the named and numbered minor planets. I will discuss briefly the nature of these observations and will then describe several classification schemes that have been used to organize this sudden wealth of data. For the most part, I will be summarizing the original work of Bender *et al.* (1978) and Bowell *et al.* (1978). I am particularly indebted to Ted Bowell, Clark Chapman, and Ben Zellner, who have been responsible for so much of the work discussed here.

THE OBSERVATIONS

Four kinds of physical observations have been widely applied to asteroids in the past four years: UBV photometry; 0.3 to 1.1 μm spectrophotometry; photoelectric polarimetry; and infrared radiometry. Each of these techniques has been applied to at least 100 asteroids. There are, in addition, several other very promising approaches that have not yet had such wide application. Infrared (JHK) photometry has been obtained for about three dozen (Johnson *et al.*, 1975; Chapman and Morrison, 1976; Matson, Johnson and Veeder, 1977; Leake, Gradie and Morrison, 1978); high-resolution infrared spectra exist for Vesta and Eros (Larson and Fink, 1975; Larson *et al.*, 1976; Larson, 1977); Ceres and Vesta have been detected by their thermal radio emission (Ulich and Conklin, 1976; Conklin *et al.*, 1977); and the radar reflectivities of Ceres, Eros, Toro, and Icarus have been measured (*e.g.*, Campbell *et al.*, 1976; Jurgens and Goldstein, 1976). In this paper, however, I will limit discussion to the four most widely applied techniques.

The UBV photometry has been carried out primarily at Lowell Observatory and at the University of Arizona. The principal published sources are: Taylor (1971), Zellner *et al.* (1975, 1977b), and Degewij *et al.* (1978). However, the majority of the data are unpublished observations made between 1975 and 1977 by E. Bowell at Lowell Observatory and referred to by Zellner and Bowell (1977) and Bowell *et al.* (1978).

Spectrophotometry with about two dozen filters between 0.3 and 1.1 μm has been reported for 98 asteroids by McCord and Chapman (1975a,b) and Pieters *et al.* (1976). Three parameters used to date for classification are R/B, the ratio of spectral reflectance at 0.70 μm to that at 0.40 μm; BEND, a measure of the curvature of the visible part of the reflectance spectrum, and DEPTH, a measure of the strength of the olivine-pyroxene absorption feature near 0.95 μm.

Linear polarization of reflected light as a function of phase angle constitutes the third class of data. The observations are all from Zellner *et al*. (1974) and Zellner and Gradie (1976 and unpublished). The parameter P_{min}, the maximum depth of the negative polarization branch, has been measured for 98 objects and is sensitive to grain opacity and hence roughly to albedo. The polarimetry also yields geometric albedo p_V more directly, from the slope of the ascending polarization branch and a recently recalibrated slope-albedo law (Zellner *et al*., 1977c,d). For albedo greater than 0.07, the polarimetric results are in quite satisfactory agreement with albedos and diameters from thermal radiometry. It is now recognized, however, that previously published polarimetric albedos less than 0.07 are inaccurate due to saturation of the slope-albedo law, and furthermore that reliable visual albedos p_V cannot always be inferred from polarimetric data in blue light. Whereas polarimetric albedos were listed for as many as 52 objects by Zellner and Gradie (1976), the elimination of the low albedo objects and those observed only in the blue reduces the number of polarimetric albedos to 24.

The final observational technique is 10 and 20 μm radiometry, carried out primarily by D. Morrison and his collaborators at the University of Hawaii and at Kitt Peak and by O. Hansen at Cerro Tololo. The individual observations have been published by Cruikshank and Morrison (1973), Morrison (1974, 1977a), Hansen (1976), and Morrison and Chapman (1976); all are summarized in a review by Morrison (1977b). In Morrison (1977b), all of the observations have been reduced uniformly with a model based on that described by Jones and Morrison (1974), although entirely equivalent results could also be obtained with the alternative model by Hansen (1977).

In order to use all of these data for classification or any other purpose, it has been necessary to bring them together in a readily accessible format. Thus, beginning in 1976, a number of observers have joined to create a computer file of these data called TRIAD (Tucson Revised Index of Asteroid Data), described by Bender *et al*. (1978). The types of data included and the individuals responsible for the files are given in Table 1. Subject to certain limitations, contents of the TRIAD file can be made available in computer printout or machine-readable form to other researchers with a serious professional interest. Inquiries should be directed to Ben Zellner, who has primary responsibility for upkeep of TRIAD.

Table 1. The TRIAD File

Data Type	Responsibility	No. of Objects[a]
Orbital Elements	D. Bender/JPL	2042
Magnitudes	T. Gehrels/U of AZ	517
Rotational Elements	E. Tedesco/NMSU	150
UBV Colors	E. Bowell/Lowell Observatory	517
Photometric Spectra	M. Gaffey/U of HI	98
Spectral Parameters	C. Chapman/PSI	98
Polarimetric Parameters	B. Zellner/U of AZ	102
Radiometric Diameters	D. Morrison/NASA HQ	165

[a]As of end of 1977.

One of the first projects undertaken with the TRIAD file has been the definition of a simple empirical classification scheme (Bowell *et al.*, 1978). In the following section I will describe this taxonomy, and in the final section I will briefly compare it with more interpretive classifications, based primarily on the spectrophotometric subset of these data, defined by Chapman (1976) and by Gaffey and McCord (1977, 1978).

THE CSM TAXONOMY

The clear separation of many of the larger asteroids into two albedo-color groups was recognized by a number of authors (*e.g.*, Zellner, Gehrels, and Gradie, 1974; Morrison, 1974), and in Chapman *et al.* (1975) this natural division was the basis for the definition of classes called C and S. The C objects are dark and neutral in color and appear to be mineralogically similar to the carbonaceous chondrites, while the S objects appear to contain pyroxene and olivine together with some metallic iron. The terms C (for carbonaceous) and S (for siliceous) were chosen with this compositional identification in mind, but it should be emphasized that these classes were *defined* purely in terms of an empirical clumping of observational parameters. Figure 1, which is a histogram of measured asteroid albedos (Morrison, 1977b), clearly demonstrates the reality of this distinction between high- and low-albedo objects. In fairness it should be noted, however, that the division is less obvious in some other observable parameters.

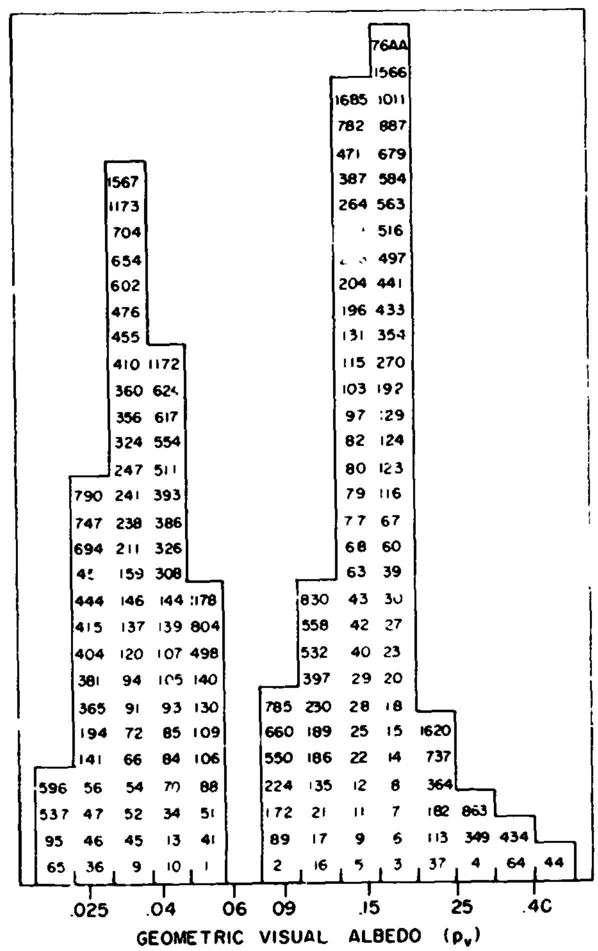


Fig. 1. Distribution of directly determined geometric visual albedos for 187 asteroids. In the CSM taxonomy, the low-albedo peak corresponds to the C asteroids, while the broader high-albedo peak is dominated by the S asteroids. Note the strong bimodality; in spite of a real spread in albedo within each peak, the two albedo populations are distinct and do not overlap (from Morrison, 1977b).

Chapman *et al.* (1975) used five observable quantities in their classification, and they were able to identify several well-observed objects, such as Vesta, that did not fall into the C or S groups. In subsequent papers two additional classes were defined: M objects with reddish colors, intermediate albedos, and little indication of spectral structure near 0.95 μm (Zellner and Gradie, 1976); and E objects, with flat spectra and very high albedos (Zellner *et al.*, 1977a).

The taxonomy of Bowell *et al.* (1978) is a further development of the classification begun by Chapman *et al.* (1975). Seven, rather than five, observational parameters are used to distinguish the classes. It is based on directly observed optical parameters and, compared with other classifications, it is independent of interpretations of asteroid mineralogy. The system depends upon the existence of discrete clusters in parameter space, with genuine gaps (or at least significant depletions) between the clusters. Only where such natural divisions exist are meaningful distributions defined. Following previous usage, this system retains the class names C, S, M, and E, and it adds a new class, R. I call this the *CSM Taxonomy*.

For those asteroids observed in sufficient detail, many different surface types may be distinguished and, indeed, each asteroid may ultimately be recognized as unique. In the CSM taxonomic system, it should be understood that each class contains a substantial spread of mineralogical assemblages; for instance, there is a variation of a factor of three in the albedos of C asteroids, and the S asteroids encompass a wide range of pyroxene and olivine contents as indicated by the depth and centroid of the absorption band near 0.95 μm.

In assigning boundaries between classes for each parameter, Bowell *et al.* adopted the philosophy of *minimizing the number of misclassifications*. Where there is serious doubt as to correct classification of an individual asteroid, the CSM taxonomy carries several possibilities rather than trying to make a questionable unique classification. Note that this philosophy is to be contrasted with one like that of Zellner and Bowell (1977), who attempted to assign the most likely class to each asteroid.

In addition to classes C, S, M, E, and R, Bowell *et al.* introduce a designation U for unclassifiable. The objects designated U are those that are not in the other five classes. I emphasize that U does not simply indicate lack of information or noisy data, but refers to objects that are known to be intrinsically outside the domains of the other classes. It is of interest to note that, of 163 asteroids classified by Bowell *et al.* from both albedo-sensitive and color-sensitive observations, only 16 (10%) are classified U.

The five classes are formally defined by the range of parameters listed in Table 2. As illustrations to help motivate these definitions, however, I now discuss several two-parameter plots taken from the TRIAD file.

Figure 2 displays the geometric visual albedo p_V as a function of UV color index. (This albedo is derived primarily from thermal radiometry, but in a few cases also depends on polarization data.) The plot clearly distinguishes the major C, S, M, and E groups, and it also illustrates the significance of class R, the members of which have high albedo and are distinctly redder in UV than the S objects.

Figure 3 is a similar plot in which the polarization parameter P_{min} is substituted for geometric albedo. It is apparent that P_{min} distinguishes the S and C classes even more strongly than albedo, with only a small group of M asteroids having intermediate values of P_{min} near 1.0.

The easiest observational technique to apply in a survey of physical properties is UBV photometry, which yields colors in the near ultraviolet to visible range. It is thus important to determine to what extent simple color data of this sort, without any albedo-sensitive parameters, can serve to classify asteroids in the CSM system. Figure 4 illustrates UBV colors for 465 objects. Those for which albedo is known independently are denoted by special symbols (*e.g.*, filled circles for C, open circles for S), while the others are

Table 2. Definition of Classes[a]

Parameter	C	S	M	E	R
Albedo, p_V	$\leq$0.065	0.065 - 0.23	0.065 - 0.23	$\geq$0.23	$\geq$0.16
P_{min} %	1.20 - 2.15	0.58 - 0.96	0.86 - 1.35	$\leq$0.40	$\leq$0.70
R/B	1.00 - 1.40	1.34 - 2.07	1.06 - 1.34	0.9 - 1.70[b]	$\geq$1.70
BEND	0.05 - 0.26	0.05 - 0.25	$\leq$0.11	$\leq$0.15[b]	$\geq$0.25
DEPTH	0.95 - 1.00	0.80 - 1.00	0.90 - 1.00	0.90 - 1.00[b]	$\leq$0.90
B-V	$\geq$0.64[c]	d	0.67 - 0.77	0.60 - 0.79	e
U-B[f]	0.23 - 0.46[c]	$\geq$0.34[d]	0.17 - 0.28	0.22 - 0.28	e

a. From Bowell *et al.* (1978).

b. No examples have been measured.

c. Additionally 4.60 (B-V) - 3.17 $\leq$ (U-B) $\leq$ (B-V) - 0.27. Type U allowed $0\overset{m}{.}02$ inside limits when only UBV photometry is available.

d. Additionally B-V $\geq$ (U-B)/7.0 + 0.74; 1.70 (B-V) - 1.12 $\leq$ (U-B) $\leq$ (B-V) - 0.33; (U-V) $\leq$ 1.47. Type U allowed $0\overset{m}{.}02$ inside limits, except for the last, when only UBV photometry is available.

e. (U-V) $\geq$ 1.47.

f. Type U always allowed for U-B $\leq$ 0.28, when only UBV photometry is available.

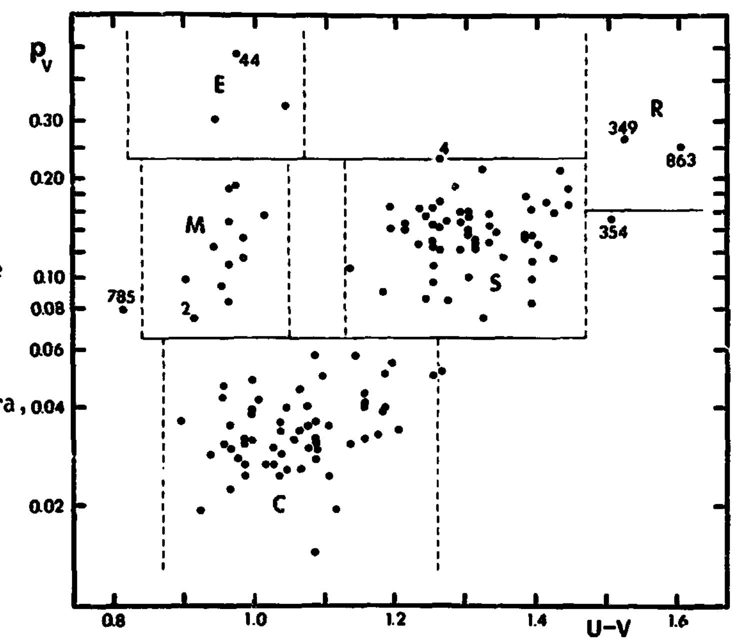


Fig. 2. Geometric albedo (p_V) versus U-V color index for 144 asteroids with semimajor axis less than 3.6 AU. Domains indicate allowable parameters on the CSM classification system for asteroids of types C, S, M, E and R; objects outside these domains are unclassifiable, designated U. The albedo boundaries (solid lines) are those given in Table 2, but the limits in U-V (dotted lines) are more complex, as shown in Figure 5. Unusual objects 2 Pallas, 4 Vesta, 44 Nysa, 349 Dembowska, 354 Eleonora, 785 Zwetana, and 863 Benkoela are indicated by number (from Bowell *et al.*, 1978).

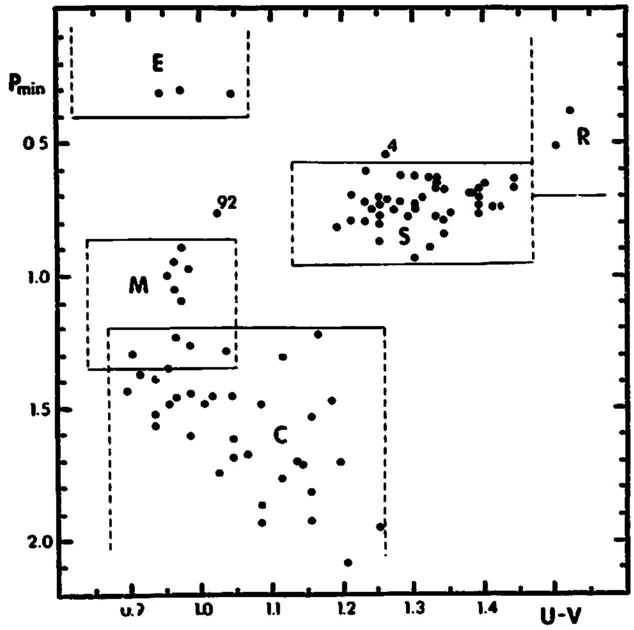


Fig. 3. Depth P_{min} of the negative polarization branch versus U-V color index for 93 asteroids with semimajor axis less than 3.6 AU. Class boundaries are as indicated for Figure 2. Unusual objects indicated by number are 4 Vesta and 92 Undina (from Bowell *et al.*, 1978).

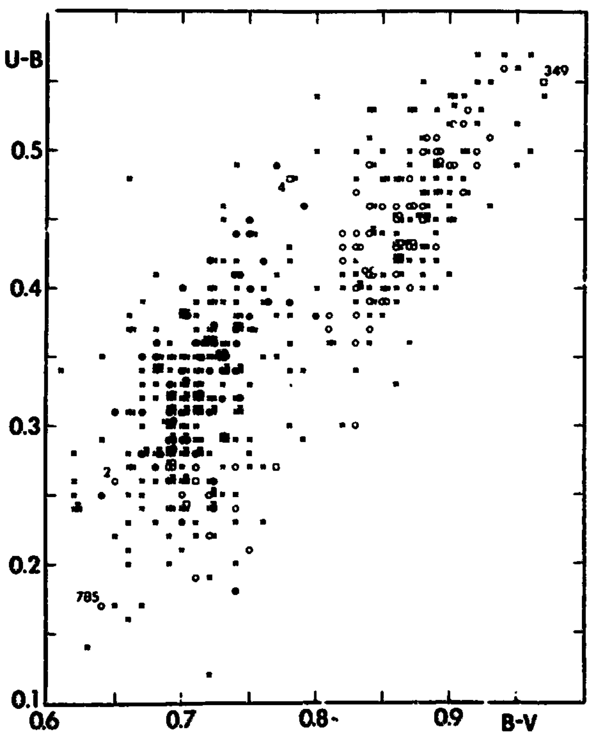
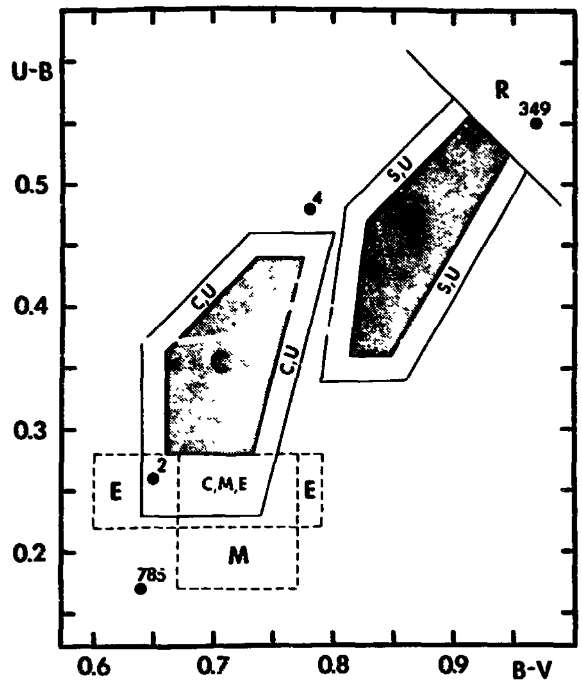


Fig. 4. B-V and U-B colors for 465 asteroids with semimajor axis less than 3.6 AU. Symbols indicate measured albedos, where available, as independent indications of type: ● for p < 0.065; o for 0.065 < p < 0.23; □ for p > 0.23. Where no albedo is known the colors are indicated by x. Two asteroids, 863 Benkoela and 1685 Innes, have colors that are off the scale of this graph. Unusual asteroids 2 Pallas, 4 Vesta, 349 Dembowska, and 785 Zwetana are indicated by number (from Bowell *et al.*, 1978).

indicated by x. The domain of the S objects is clear on this plot, but without albedo it is difficult to distinguish the dark, neutral-colored Cs from the lighter, but still neutral-colored Ms and Es. Figure 5 shows the actual boundaries of the classes in the UBV plane as adopted by Bowell *et al.*

Fig. 5. Similar to Figure 4, but showing adopted domains of types C, S, M, E and R in UBV colors in the CSM taxonomy. Numerical coefficients representing the type boundaries are given in Table 2. Neutral colors plot in the lower left (*e.g.*, 785 Zwetana), red colors in the upper right (*e.g.*, 349 Dembowska). Note that UBV colors clearly separate R from S from C asteroids, but become degenerate for neutral colors where the C, M, and E domains overlap (from Bowell *et al.*, 1978).



Four examples show how the taxonomic definition illustrated in Figures 2-5 and listed in Table 2 can be used to classify asteroids. We begin with a typical, thoroughly observed C asteroid. 19 Fortuna; the observational parameters are given in Table 3. The UBV colors fall within the C domain of Figure 5, and the albedo of 0.030 and the P_{min} of 1.72 also clearly place Fortuna in the low-albedo C class. Of the spectrophotometric parameters, BEND allows either C or S, R/B allows C, M, or E, and the absence of the pyroxene absorption band (DEPTH = 1.00) serves only to exclude membership in class R. Thus the classification would be ambiguous if only the spectrophotometric parameters were available, but is clearly tied down by both UBV colors and the albedo-sensitive observations.

As an example of an S object, Table 3 also lists the parameters for 5 Astraea. This classification could be made unambiguously from UBV colors alone or from R/B alone. The other parameters are consistent with the S classification, but none considered alone is sufficient; the albedo allows types S or M, P_{min} and DEPTH allow S or R, and BEND any type except R. For the S asteroids, UBV colors are particularly diagnostic.

Asteroid 44 Nysa in Table 3 is a prototype E object. The high albedo and small P_{min} suggest E but by themselves are also consistent with the limits for class R. The UBV colors fall within the ambiguous domain allowing C, M, E, or U but not S or R. Thus both color and albedo data are required to place an object uniquely in class E, and the only proven E objects are 44 Nysa, 64 Angelina. and 434 Hungaria. None of these, unfortunately, has as yet been observed spectrophotometrically.

Table 3. Four Examples of Classification

Asteroid	Type	B-V	U-B	BEND	R/B	DEPTH	p_v	P_{min}	Type
19 Fortuna	C	0.75	0.38	0.21	1.09	1.00	0.03	1.72	✓
	S			0.21		1.00			
	M				1.09	1.00			
	E				1.09	1.00			
	R								
5 Astraea	C			0.10					
	S	0.83	0.38	0.10	1.63	0.84	0.144	0.70	✓
	M			0.10			0.144		
	E			0.10					
	R					0.84		0.70	
44 Nysa	C	0.71	0.26						
	S								
	M	0.71	0.26						
	E	0.71	0.26				0.467	0.31	✓
	R						0.467	0.31	
4 Vesta	C			0.14	1.33				
	S			0.14			0.226		
	M				1.33		0.226		
	E			0.14	1.33				
	R					0.74	0.226	0.55	
	(U)	0.78	0.48						✓

Perhaps the most prominent example of an unclassifiable asteroid is 4 Vesta. In Table 3 the relatively high albedo allows classes R or (just barely) S or M, but the very unusual P_{min} of 0.55 excludes types S and M. The spectrophotometric parameters BEND and R/B exclude type R, however, and the UBV colors fall outside the domains of any of the recognized classes. Thus Vesta can only be classified U.

Table 4 lists the adopted classifications for 344 asteroids from the TRIAD data file. Also given are diameters obtained either from direct observation or calculated on the assumption that the object has the albedo of an average member of its class (see footnote to Table 4). The asteroids listed in Table 4 are those used by Zellner and Bowell (1977) and by Zellner (1978) to study the distribution of types, but the actual data are updated to include the TRIAD values as of early 1978. In the expanded classification of 523 asteroids by Bowell *et al.* (1978), there are 189 C objects, 142 S objects, 12 of type M, 3 of type E, and 3 of type R. The classification U is obtained for 55 objects, while 119 (25%) receive uncertain or ambiguous classifications. Most of these ambiguities presumably could be cleared up if additional observational techniques were applied. However, there is no guarantee that smaller and fainter objects will have the same distribution as those already studied, most of which have diameters greater than 50 km.

In the above statistics the C objects are much underrepresented, of course, because of their low albedos and generally larger distances. In the following paper, Zellner discusses corrections for these selection effects. The E and R types, however, must be genuinely quite rare. Zellner and Bowell (1977) have noted that in the whole main belt there appear to be only two E objects with diameters greater than 50 km, and it now appears that R objects must be similarly unusual. In a bias-corrected sample, neither of these classes would constitute as much as 1% of the asteroid population.

Table 4. Asteroid Classification[a] and Diameters[b]

Asteroid	B(1,0)	D (km)	Type	Asteroid	B(1,0)	D (km)	Type
1 Ceres	4.48	1018	U	60 Echo	9.98	50	S
2 Pallas	5.02	629	U	61 Danae	8.90	87*	S
3 Juno	6.51	247	S	62 Erato	9.85	103*	C
4 Vesta	4.31	548	U	63 Ausonia	8.96	89	S
5 Astraea	8.13	122	S	64 Angelina	8.84	56	E
6 Hebe	6.98	195	S	65 Cybele	7.99	308	C
7 Iris	6.84	210	S	66 Maja	10.51	76*	C
8 Flora	7.73	153	S	67 Asia	9.66	61*	S
9 Metis	7.78	153	S	68 Leto	8.22	124	S
10 Hygeia	6.50	450	C	69 Hesperia	8.17	134?	U
11 Parthenope	7.80	151	S	70 Panopaea	8.93	154	C
12 Victoria	8.38	135	S	71 Niobe	8.28	114*	S
13 Egeria	8.15	241	C	72 Feronia	10.15	92*	C
14 Irene	7.49	153	S	76 Freia	9.11	143?	CMEU
15 Eunomia	6.42	245	S	77 Frigga	9.70	61*	M
16 Psyche	6.88	252	M	78 Diana	9.17	139*	C
17 Thetis	9.08	96	S	79 Eurynome	9.25	75	S
18 Melpomonene	7.69	152	S	80 Sappho	9.22	86	U
19 Fortuna	8.45	220	C	81 Terpsichore	9.64	112*	C
20 Massalia	7.73	137	S	82 Alkmene	9.52	64	S
21 Lutetia	8.61	111	M	83 Beatrix	9.76	106*	C
22 Kalliope	7.28	178	M	84 Klio	10.34	81	C
23 Thalia	8.23	114	S	85 Io	8.92	146	U
24 Themis	8.27	209*	C	86 Semele	9.71	107*	C
25 Phocaea	9.30	65	S	87 Sylvia	8.12	224?	CMEU
26 Proserpina	8.80	90*	S	88 Thisbe	8.07	206	C
27 Euterpe	8.44	116	S	89 Julia	8.15	168	S
28 Bellona	8.16	122*	S	90 Antiope	9.41	124*	C
29 Amphitrite	7.13	194	S	91 Aegina	10.00	105	C
30 Urania	8.82	90	S	92 Undina	7.95	150?	U
31 Euphrosyne	7.28	332*	CM	93 Minerva	8.71	167	C
32 Pomoma	8.76	93*	S	94 Aurora	8.71	190	C
34 Circe	9.59	113*	C	95 Arethusa	8.83	165*	C
36 Atalante	9.82	103*	C	97 Klotho	8.75	94	M
37 Fides	8.43	93	S	100 Hekate	9.08	79*	SU
39 Laetitia	7.44	164	S	102 Miriam	10.28	83*	C
40 Harmonia	8.32	121	S	103 Hera	8.84	89*	S
41 Daphne	8.23	176	C	104 Klymene	9.44	121*	C
42 Isis	8.81	96	S	105 Artemis	9.42	124*	C
43 Ariadne	9.19	76*	S	106 Dione	8.80	169*	C
44 Nysa	7.85	72	E	107 Camilla	8.28	209*	C
45 Eugenia	8.31	227	C	108 Hecuba	9.69	60*	S
46 Hestia	9.56	133	C	109 Felicitas	10.13	74	C
47 Aglaja	9.24	134*	C	110 Lydia	8.75	169*	C
48 Doris	7.99	147?	U	111 Ate	9.11	143*	C
49 Pales	8.67	178*	C	113 Amalthea	9.86	47	S
51 Nemausa	8.68	158	U	114 Kassandra	9.46	121*	C
52 Europa	7.62	289	C	115 Thyra	8.84	93	S
53 Kalypso	9.97	96*	C	116 Sirona	8.89	80	SR
54 Alexandra	8.87	177	C	117 Lomia	9.18	138?	CMEU
55 Pandora	8.71	172?	CMEU	119 Althaea	9.82	57*	S
56 Melete	9 49	143	C	120 Lachesis	8.78	174	C
57 Mnemosyne	8.41	108*	S	122 Gerda	9.16	139*	CU
58 Concordia	9.92	96*	C	123 Brunhild	10.13	49*	S

Table 4 (continued)

Asteroid	B(1,0)	D (km)	Type	Asteroid	B(1,0)	D (km)	Type
124 Alkeste	9.39	67	S	216 Kleopatra	8.21	218?	CMEU
125 Liberatrix	9.77	64?	U	219 Thusnelda	10.68	38*	SM
126 Velleda	10.58	40*	S	221 Eos	8.94	97?	U
129 Antigone	7.85	114	M	224 Oceana	9.79	59*	M
130 Elektra	8.46	121?	U	230 Athamantis	8.65	114	S
131 Vala	11.03	35	SM	236 Honoria	9.51	65*	S
133 Cyrene	9.18	78*	S	238 Hypatia	9.23	153	C
135 Hertha	9.24	78	M	241 Germania	8.61	179*	C
137 Meliboea	9.14	142*	C	247 Eukrate	9.31	14?	C
139 Juewa	9.16	139*	C	250 Bettina	8.49	192?	CMEU
140 Siwa	9.58	102	C	258 Tyche	9.54	65*	S
141 Lumen	9.58	115*	C	264 Libussa	9.67	63	S
144 Vibilia	9.15	132	C	268 Adorea	9.76	106*	C
145 Adeona	8.67	175*	C	270 Anahita	10.03	50	S
146 Lucina	9.30	131*	C	275 Sapientia	10.04	94*	C
148 Gallia	8.47	106*	S	276 Adelheid	9.74	106?	CMEU
149 Medusa	11.94	24?	U	281 Lucretia	13.11	15?	U
150 Nuwa	9.33	129?	CMEU	284 Amalia	11.28	52*	C
151 Abundantia	10.53	41*	S	293 Brasilia	11.07	58*	C
152 Atala	9.60	63*	S	295 Theresia	11.41	27*	S
153 Hilda	8.82	99?	U	306 Unitas	10.02	[illegible]2*	S
156 Xanthippe	9.81	103*	C	308 Polyxo	9.28	136	U
159 Aemilia	9.32	133	C	313 Chaldaea	10.10	92*	C
162 Laurentia	10.01	97*	C	324 Bamberga	8.07	251	C
163 Erigone	10.80	65*	C	326 Tamara	10.32	81*	C
164 Eva	9.84	101*	C	335 Roberta	9.93	48?	EU
166 Rhodope	10.91	38?	U	336 Lacadiera	10.96	33?	MEU
170 Maria	10.72	41?	U	337 Devosa	9.90	99?	CS
172 Baucis	10.09	67	S	338 Budrosa	9.78	58*	M
173 Ino	8.82	162*	C	342 Endymion	11.29	52*	C
176 Iduna	9.52	72?	U	344 Desiderata	9.09	145*	C
177 Irma	10.75	67*	C	345 Tercidina	10.15	89*	C
178 Belisana	10.69	38*	S	349 Dembowska	7.2[illegible]	144	R
179 Klytaemnest	9.31	71*	S	350 Ornamenta	9.45	122*	C
181 Eucharis	9.06	79*	S	351 Yrsa	10.30	45*	S
182 Elsa	10.24	47*	S	354 Eleonora	7.48	169	U
183 Istria	10.98	33*	S	356 Liguria	9.27	149	C
185 Eunike	8.75	168*	C	357 Ninina	9.82	104*	C
186 Celuta	10.46	45	U	360 Carlova	9.42	129	C
189 Phthia	10.76	41	S	362 Havnia	10.13	89*	C
192 Nausikaa	8.61	93	S	363 Padua	10.05	94*	C
194 Prokne	8.84	193	C	364 Isara	11.08	31?	SMR
195 Eurykleia	10.07	92*	C	365 Corduba	10.32	99	C
196 Philomela	7.72	160	S	367 Amicitia	12.10	19*	S
200 Dynamene	9.47	121?	CME	370 Modestia	11.72	43*	C
203 Pompeja	10.08	91*	C	377 Campania	10.04	95?	CMEU
204 Kallisto	10.07	50*	S	381 Myrrha	9.68	126	C
206 Hersilia	9.84	101*	C	384 Burdigala	10.81	36*	S
208 Lacrimosa	10.48	42	S	386 Siegena	8.60	174	C
209 Dido	9.47	121?	CMEU	387 Aguitania	8.4[illegible]	112	S
210 Isabella	10.45	77*	C	388 Charybdis	9.52	119?	CMEU
211 Isolda	9.02	167	C	389 Industria	9.40	69*	S
213 Lilaea	10.12	46?	EU	393 Lampetia	9.32	121	C
214 Aschera	10.41	43?	MU	395 Delia	11.49	48*	C

Table 4 (continued)

Asteroid	B(1,0)	D (km)	Type	Asteroid	B(1,0)	D (km)	Type
397 Vienna	10.54	50	S	660 Crescentia	10.60	39*	SM
402 Chloe	10.28	46*	S	674 Rachele	8.65	97*	S
404 Arsinoe	9.99	94*	C	679 Pax	10.40	42	S
409 Aspasia	8.31	207*	C	680 Geneveva	10.68	69?	CMEU
410 Chloris	9.47	124*	C	694 Ekard	10.11	90*	C
415 Palatia	10.54	74*	C	702 Alauda	8.29	205*	C
416 Vaticana	9.24	76*	S	704 Interamnia	7.24	338	C
426 Hippo	9.81	103*	C	705 Erminia	9.55	117?	CMEU
432 Pythia	10.33	45*	S	714 Ulula	10.30	46*	S
433 Eros	12.40	15	S	Marghanna	10.73	67*	C
434 Hungaria	12.45	10	E	737 Arequipa	9.93	54*	S
435 Ella	11.33	51?	CMEU	739 Mandeville	9.79	63?	U
441 Bathilde	9.45	61	M	744 Aguntina	11.25	32?	U
444 Gyptis	9.11	142*	C	747 Winchester	8.81	205	C
446 Aeternitas	10.21	47*	R	755 Quintilla	10.75	37?	MEU
451 Patientia	7.67	326	C	776 Berbericia	8.70	173*	C
454 Mathesis	10.27	83*	C	778 Theobalda	10.58	36?	EU
455 Bruchsalia	9.86	101*	C	782 Montefiore	12.68	15*	SM
462 Eriphyla	10.77	40?	U	785 Zwetana	10.73	45	U
471 Papagena	7.78	148	S	790 Pretoria	9.09	177	C
472 Roma	10.39	44*	S	796 Sarita	10.16	88*	C
476 Hedwig	9.82	103*	C	804 Hispania	8.86	162*	C
478 Tergeste	9.22	75*	S	825 Tanina	13.04	13*	S
481 Emita	9.86	101*	C	830 Petropolita	10.52	41*	S
497 Iva	10.71	38*	M	853 Nansenia	12.61	28*	C
498 Tokio	10.34	72	C	863 Benkoela	10.31	49*	R
505 Cava	10.10	50?	ME	887 Alinda	15.43	5.2	U
508 Princetonia	9.41	125*	C	888 Parysatis	10.82	36*	S
509 Iolanda	9.67	60*	S	911 Agamemnon	9.01	94?	U
510 Mabella	10.96	61?	CMEU	924 Toni	10.45	77*	C
511 Davida	7.36	341	C	932 Hooveria	11.12	55*	C
516 Amherstia	9.37	63	M	946 Poesia	11.53	46*	C
524 Fidelio	10.99	60*	C	963 Iduberga	13.83	9.2*	S
532 Herculina	6.96	230	S	969 Leocadia	13.58	9.1?	EU
537 Pauly	9.94	97*	C	976 Benjamina	10.51	75?	CMEU
540 Rosamunde	12.25	18*	S	977 Philippa	10.76	66*	C
545 Messalina	9.72	107*	C	1001 Gaussia	10.70	38?	MEU
550 Senta	10.53	41*	S	1011 Laodamia	14.24	7.2	S
554 Peraga	9.85	103*	C	1036 Ganymed	10.61	39*	S
558 Carmen	10.08	65	SM	1043 Beate	10.93	34*	S
563 Suleika	10.00	53*	S	1048 Feodosia	10.66	70*	C
569 Misa	11.26	53*	C	1052 Belgica	13.27	11*	S
584 Semiramis	9.82	54	S	1058 Grubba	13.01	13?	SR
588 Achilles	9.73	61?	MEU	1140 Crimea	11.59	25*	S
591 Irmgard	11.77	23?	MU	1143 Odysseus	9.48	62?	EU
596 Scheila	9.98	133	U	1171 Rusthawelia	10.81	64?	CMEU
602 Marianna	9.45	137	C	1172 Aneas	9.35	128*	C
617 Patroclus	9.05	88?	U	1173 Anchises	10.18	87*	C
618 Elfriede	9.38	126*	C	1178 Irmela	12.99	23*	C
623 Chimaera	12.20	34*	C	1212 Francette	7.99	238?	CMEU
624 Hektor	8.65	110?	U	1263 Varsavia	11.75	42*	C
631 Philippina	10.16	49*	S	1266 Tone	10.43	77*	C
654 Zelinda	9.51	72?	U	1268 Libya	10.07	92?	CMEU
658 Asteria	11.70	23*	SU	1314 Paula	13.96	8*	S

Table 4 (continued)

Asteroid	B(1,0)	D (km)	Type	Asteroid	B(1,0)	D (km)	Type
1329 Eliane	12.22	19*	SU	1583 Antilochus	9.76	60?	MEU
1362 Griqua	12.42	31*	C	1620 Geographos	16.67	2*	S
1401 Lavonne	13.53	10*	S	1681 1948WE	12.84	14*	S
1437 Diomedes	9.39	125?	CMEU	1685 Toro	14.60	8?	U
1500 Jyvaskyla	14.43	7*	S	1694 Kaiser	13.73	17*	C
1504 Lappeenrant	13.03	12*	S	1707 1932RL	13.89	8.7*	SU
1547 1929CZ	11.96	24?	U	1864 Daedalus	16.34	3?	U
1566 Icarus	17.62	1.7?	U	1960UA	15.00	9*	CU
1567 Alikoski	10.64	75	C	1976AA	18.40	0.9	U
1580 Betulia	15.80	6.5*	C	1977RA	16.71	2*	SU

[a]Classifications are from Bowell *et al.* (1978) and follow the definitions in Table 2. Multiple classes indicate ambiguity.

[b]Diameters followed by * are computed for the mean albedo of the class, rather than determined directly. Diameters followed by ? correspond to an adopted albedo of 0.1 and could be in error by as much as a factor of three. For a summary of directly measured diameters, see Morrison (1977b).

It is of interest to note that the largest asteroids do not fit into the CSM taxonomy. Vesta, as discussed above, is unique in a number of parameters. Pallas is C-like in some respects and M-like in others, but clearly unclassifiable. Ceres is loosely describable as a C type, but has a rather high albedo (0.054) and an unusual spectrum with uncommonly reddish U-B and uncommonly neutral R/B colors. Thus Ceres is now formally designated as a U object, and should not in any case be thought of as a prototype for the C class. Among the six largest asteroids (Morrison, 1977b), Ceres, Pallas, and Vesta are unclassifiable, Euphrosyne has been observed only in P_{min}, with Pallas-like results, 704 Interamnia is a peculiar C object, and only Hygiea is a normal C. Thus the true C-dominated asteroid population only begins at diameters of 300 km and smaller. Note, too, that well over half the mass in the asteroid belt is accounted for by these unusual asteroids which do not fit the CSM classification system.

COMPARISON OF THE CSM TAXONOMY WITH OTHER SYSTEMS

Taxonomic schemes have an important function in organizing observational data, but because the number of classes and subclasses and their exact boundaries are largely arbitrary, they can also be a source of misunderstanding and dispute. The CSM taxonomy attempts to divide its classes along natural lines with a minimum of interpretation. It is thus of limited use in studies of asteroid mineralogy, and indeed some very different mineralogical assemblages may be grouped together in the CSM scheme. In this final section of my paper, I briefly consider some comparisons between the CSM and two other taxonomies, following the more detailed discussion in Bowell *et al.* (1978).

In the first alternate taxonomy, Chapman (1976) used the available spectrophotometry for 98 asteroids to establish 13 groups, each of which he interpreted to have similar surface composition and mineralogy. For instance, one group is interpreted as being due chiefly to the signatures of nickel-iron plus olivine while another is suggestive of a C2 (CM) carbonaceous chondritic composition.

Even more recently, Gaffey and McCord (1977, 1978) have developed a separate classification for 62 of the spectra, emphasizing interpretations of mineralogical assemblages. This scheme is described in more detail in this volume by McCord (1978). Fifteen groups were defined, mostly consisting of subdivisions of several broader groups symbolized by R (for reddish spectra, both with and without prominent 1.0 μm absorption features), T (for transition), and F (for flat).

In general the Chapman and Gaffey-McCord classifications group asteroids in a consistent manner. However, in a few cases there are real differences as discussed by Bowell *et al.* (1978) and Gaffey and McCord (1978).

A continuing controversy in all three taxonomic systems concerns the significance of the class called M in the CSM classification. The name for this class suggests its interpretations as metallic (Zellner and Gradie, 1976); that is, the characteristic spectral signature of these asteroids is suggestive of nickel-iron. However, it is agreed by both Bowell *et al.* (1978) and Gaffey and McCord (1978) that these objects could be either nearly pure metal or finely divided metal in a neutral silicate matrix (*e.g.*, like the enstatite chondrites). There is clearly a great geochemical difference between these two interpretations, and present observations do not seem capable of distinguishing between them. A complicating factor is that Gaffey and McCord interpret another group of asteroids (their class RF) as also of iron or enstatic-chondritic composition, while Chapman interprets the spectra as indicating a broad, weak absorption feature due to either olivine or olivine-plus-pyroxene. If Gaffey and McCord are right, then asteroids of nickel-iron or enstatite chondrite composition are distributed among both the M and S types of the CSM system, in spite of a wide gap in UBV colors between these classes.

In spite of its low level of direct interpretability in terms of mineralogy, the CSM taxonomy does have some significant advantages. First, it can be applied widely, since it depends upon only a few observational parameters. Second, it involves albedo information directly, and thus it permits investigation of differences in the size distributions and orbital distributions for the separate classes. Through its strict accounting of albedos, the CSM taxonomy permits a reasonable correction for bias to be applied to the available statistics, such as accomplished by Chapman *et al.* (1975), Morrison (1977b), Zellner and Bowell (1977), and Zellner (1978). Third, the CSM system requires no revision when mineralogical identifications are modified or improved, since it is based strictly on observational parameters.

The CSM taxonomy has proved useful for outlining the structure of the asteroid belt, and it will probably be extended during the next year or two to nearly half the numbered asteroids. The usefulness of its applicability to the Earth-approaching asteroids or to those beyond 3.6 AU, where different populations may exist, has yet to be demonstrated, however. The reconnaissance data exemplified by the CSM taxonomy are not sufficient, however, for understanding the mineralogy of asteroid surfaces. It seems clear that detailed analysis of reflection spectra supported by albedo data and by laboratory and theoretical work is required as well, and our understanding of the nature of the asteroids in the next few years will probably be best advanced by a two-pronged attack involving both continuing reconnaissance studies and the intensive acquisition and interpretation of spectrophotometry of a smaller number of representative asteroids.

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DISCUSSION

VEVERKA: Are the magnitudes that are included in the TRIAD file the ones that have been measured recently or are they from some previous compilation?

MORRISON: There are several sources for these magnitudes. Gehrels has provided photoelectric magnitudes for many. A lot more of the magnitudes are only photographic. The goal was to obtain the best magnitude for every numbered asteroid. However, for many individual objects, especially faint objects, these magnitudes can still be very bad--with brightness uncertain by as much as a factor of two.

CHAPMAN: Another advantage of this classification scheme which I think is important is that a relatively simple observing program in which only radiometry and UBV photometry are used can detect the anomalous or unusual objects. The taxonomy alerts us to unusual asteroids we should go out and look at in more detail with spectrophotometry and other techniques.

MORRISON: About 10% are Us, so you can improve the efficiency of observations by a factor of ten for the more elaborate techniques if you decide to concentrate on the unclassified objects.

ANDERS: I wonder if the time hasn't come to analyze this population to see how homogeneous these classes are and whether any of them break up into subsets.

ZELLNER: Remember that the data are extremely heterogeneous and, to do anything that is very formal mathematically, one needs a better set of data.

MORRISON: The number of objects for which we have all seven of those parameters must be well under 100. Most of them are S, of course, because of the observational bias in favor of bright objects. Even so, the high albedo ones, like Vesta, the Es, or the Rs are extremely rare. Zellner will talk about how much rarer they are in the population as a whole when bias corrections are included. It is very curious that we are able to think of these rare objects as having very close relationships to certain meteorite classes. However, the data base is rapidly expanding, and within the next year it may be appropriate to apply more sophisticated statistical techniques, such as cluster analysis.

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GEOGRAPHY OF THE ASTEROID BELT

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Several hundred minor planets can now be classified into broadly defined C, S, M, and other compositional types. Corrections for observational selection bias show that at least 75% of the main belt asteroids are of Type C, about 15% are of Type S, and 10% of other types. The proportion of S objects drops smoothly outward through the belt with an exponential scale length of 0 4 AU. Objects of exceptional type are found throughout the main belt. At least for diameters >50 km, the major types show very similar size-frequency relations.

Several Hirayama families show characteristic optical properties contrasting with the field population, and evidently originated as the collision fragments of discrete parent bodies. The Trojans seem to form a compositionally distinct population. Of a dozen Amor and Apollo objects observed, nine are S-like, one is of Type C, and two show unusual compositions.

INTRODUCTION

Much of the fascination of minor planets lies in their population statistics, that is, the distribution of types over diameter and orbit. In the preceding paper Morrison (1978) has summarized the telescopic techniques that have been used for large numbers of asteroids, and described the classification into Types C, S, M, etc., recognizable in optical polarimetry, thermal radiometry, and UBV colorimetry. The classification system is one step removed from attempts at mineralogical description as described by McCord (1978). The mineralogical description, where available, is to be much preferred over the simple classification by optical type, but only for the latter is a statistically adequate sampling available. At the University of Arizona we are beginning a seven-color survey, using broadband interference filters from 0.36 to 1.05 μm wavelength, with hopes of obtaining mineralogically diagnostic data for a substantial fraction of the numbered asteroid population.

The first attempts at analysis of the population statistics was by Chapman *et al.* (1975), who classified 110 objects into C, S, and U (unclassifiable) types. Corrections for observational selection effects showed that the C asteroids are predominant, especially in the outer regions of the belt. Zellner and Bowell (1977) carried out a similar exercise for 359 objects, incorporating Types M and E and using for the first time a large number of observations of UBV color. The taxonomy has been more closely examined, and applied to data for 521 asteroids, by Bowell *et al.* (1978). Most of the results discussed here are taken directly from the latter two papers. A bias-corrected analysis of the larger data set and more secure classifications of Bowell *et al.* remain to be done.

THE MAIN BELT

Observational Selection Effects

Since minor planets differ in geometric albedo by at least a factor of ten, any discussion of distributions over diameter and distance must begin with statistically reliable diameters and must incorporate corrections for observational selection biases. Also, we must take care that objects of various types or distances are intercompared only for similar size ranges. Failure to observe these precautions can be perilous. For example, Chapman (1976) noted that classified S asteroids tended to fall near Kirkwood gaps, and C objects to avoid the gaps widely. The result is statistically well-established, and there are no obvious biases toward or away from the Kirkwood gaps in the compositional surveys. As shown by Zellner and Bowell (1977), however, Chapman's conclusion was only an artifact of comparing large C asteroids with small S objects, together with a genuine tendency for large objects of any type to avoid the gaps.

Diameters for about 200 asteroids are available from the polarimetric and thermal-radiometric surveys (Morrison, 1977a, 1978; Zellner *et al.*, 1977a; Gradie *et al.*, 1977). In addition we can obtain statistically useful diameter information from geometric albedos assumed according to the compositional type; Zellner and Bowell (1977) adopted albedos 0.035 for C objects, 0.12 for Type M, and 0.15 for Type S.

Corrections for observational sampling bias have been discussed by Chapman *et al.* (1975), Morrison (1977a,b), and Zellner and Bowell (1977). It is assumed that, in any region of the belt, the sampling completeness is a function of apparent magnitude only. Then bias factors are computed for each interval of magnitude and distance as the ratio of the number of objects sampled to the total number of asteroids known to be present. For each classified object at a magnitude and distance associated with bias factor n, we assume that n-1 additional asteroids of identical size and type are present. The bias factors need not be monotonic functions of magnitude, and no distortions are introduced by particular attempts to observe faint objects or members of particular Hirayama families, so long as the sampling intervals are adequately chosen. Clearly the process is limited by the statistics of small numbers.

The bias correction process is also limited by the normalization sample. Figure 1 illustrates the distribution over heliocentric distance for 1978 numbered asteroids. This sample is itself heavily biased, being incomplete for objects fainter than about apparent magnitude 15.5, or diameters smaller than 12 km for inner-main belt S asteroids, 55 km for outer-main belt C objects, and $\sim$150 km for the Trojans. For fainter asteroids we must depend upon some extrapolation of the magnitude-frequency relation, or results from the Palomar-Leiden Survey (van Houten *et al.*, 1970). Since few objects brighter than magnitude 16 were observed in the PLS, its region of overlap with the numbered population is somewhat problematical.

Frequency of Types

According to the bias analysis of Zellner and Bowell, there are approximately 560 main belt asteroids with diameters >50 km, of which 76% are of Type C, 15% of Type S, 5% of Type M and 3% of other types. Similar results, with a somewhat higher proportion of C objects, were obtained by Morrison (1977a,b). Large asteroids of the high-albedo varieties are genuinely quite rare. Zellner *et al.* (1977b) noted that there are apparently no more than two or three E asteroids with diameter >50 km in the entire population. In their sample of 523 objects, Bowell *et al.* (1978) were able to identify no additional candidates for the Vesta type with diameter >25 km. It is a remarkable result that mixed among the predominantly dark, carbonaceous population there can be a very few asteroids of quite exceptional type.

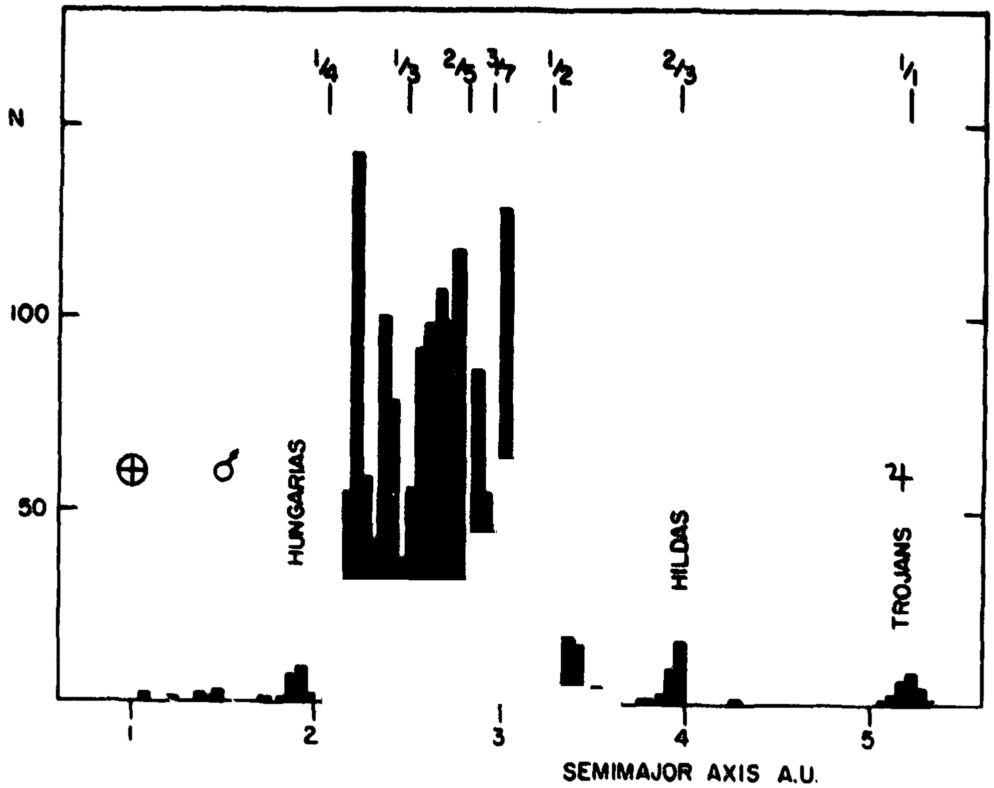


Fig. 1. Distribution over mean heliocentric distance of the first 1978 numbered asteroids, in increments of 0.05 AU. Fractions indicate the ratio of orbital periods for the principal dynamical resonances with Jupiter. Adapted from Zellner *et al.* (1977b). Data are from the TRIAD computer file (Bender *et al.*, 1978).

Distributions Over Heliocentric Distance

Figure 2 illustrates the general decrease of the relative frequency of S-type asteroids with increasing semimajor axis. The departures from a smooth curve are of no statistical significance, and there is no evidence for systematic differences near Kirkwood gaps. The mixing ratio drops exponentially with distance with a scale length of about 0.4 AU. Bias-corrected distributions over orbital eccentricity and inclination have not as yet been derived.

The relatively sharp cutoff in S/C ratio with distance implies great difficulties for any hypothesis involving formation of asteroids of various types in widely differing regions of the solar system and their subsequent relocation in the main belt. (That is not to say, of course, that some asteroids of rare type could not have such a history.) Also let me emphasize that Figure 2 does not represent a progressive darkening of asteroid surfaces with distance, but variations in the relative proportions of distinct types. The situation may have been misunderstood by Whipple (1977). Some tendency for S objects to have more neutral colors at greater distance has been noted (Zellner *et al.*, 1977c), but generally objects of a given type tend to show the same range of optical properties no matter where located.

Distributions Over Diameter

Figure 3 illustrates the bias-corrected distributions of C and S+M Types as derived by Zellner and Bowell (1977). The data are consistent with parallel size-frequency relations, both showing a change of slope near 160 km; however, the statistics are poor for the smaller sizes and also for diameters >200 km due to the small number of objects present. An alternate interpretation of the same size-frequency data is given by Chapman (1977).

FAMILIES

Among the most exciting results of the past year is the evidence that the Hirayama families, consisting of asteroids with strongly clustered orbital elements, are not random collections of field objects but show a high degree of internal homogeneity (Hansen, 1977; Gradie and Zellner, 1977). The families apparently originated as the collision fragments of discrete parent bodies. Thus we can see into the interior of the parent bodies, including possibly differentiated objects, in ways not possible for the major planets and their satellites.

The better-populated families often have only one or two large members or consist entirely of small objects. Thus they were generally overlooked in the bright-asteroid surveys and are only now being explored by UBV and similar techniques. When comparing the compositions of the smaller family members with the non-family field population, we are dependent upon an incompletely-tested assumption, namely that the mixture of types seen for large asteroids is also characteristic of the field population at small sizes.

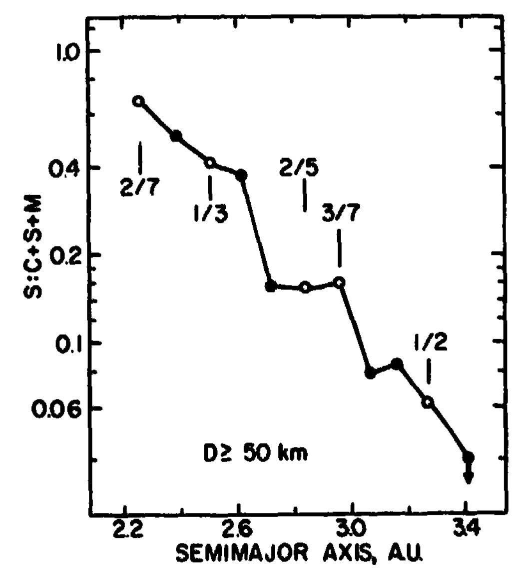


Fig. 2. Ratio of bias-corrected type frequencies, as a function of orbital semimajor axis. Open circles indicate zones containing major Kirkwood gaps. Adapted from Zellner and Bowell (1977).

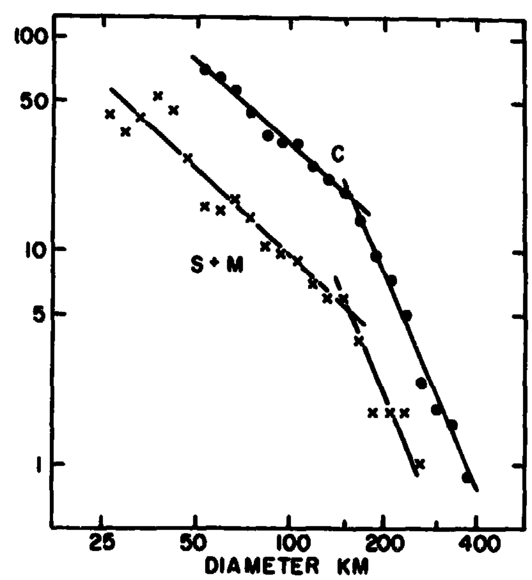


Fig. 3. Bias-corrected number of asteroids of Type C, and Types S plus M, in intervals of 0.05 in log diameter for the whole main belt. Adapted from Zellner and Bowell (1977).

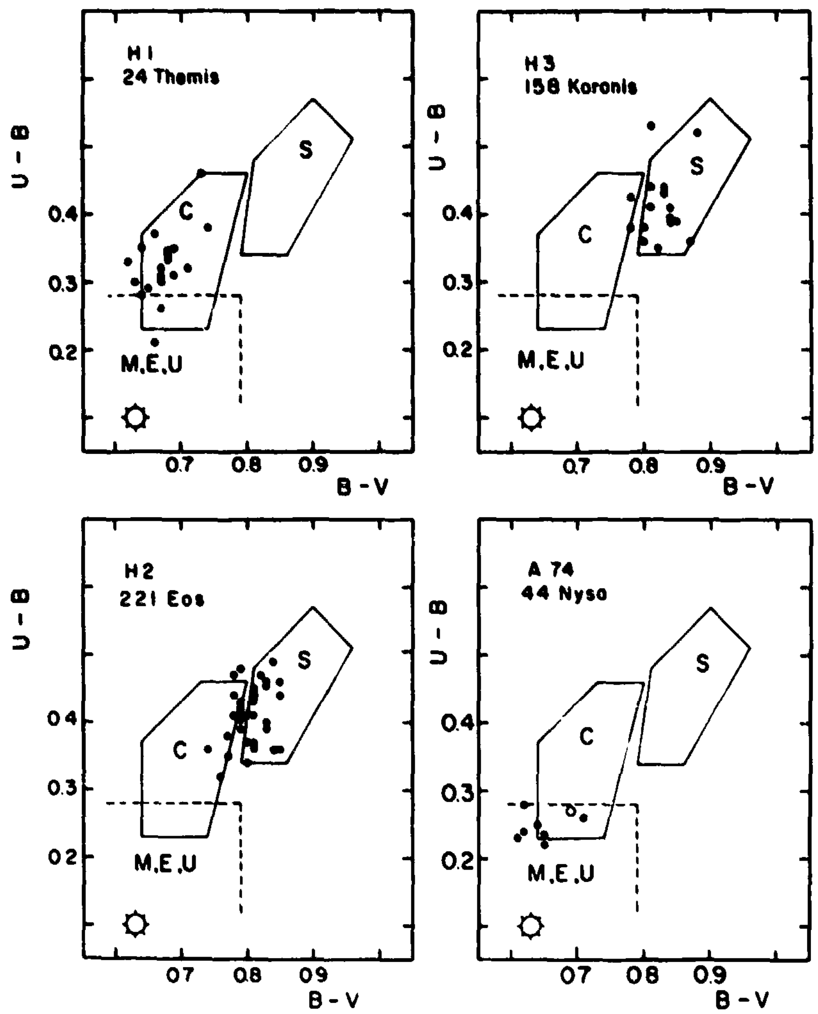


Fig. 4. Observed UBV colors for minor planets in the Hirayama families associated with 24 Themis, 158 Koronis, 221 Eos, and 44 Nysa. Color domains of the C, S, M, and E Types are as defined by Bowell *et al.* (1978). The symbol at B-V = 0.63, U-B = 0.10 indicates adopted colors of the Sun. The open circle in the Nysa family represents the M object 135 Hertha. Data are from the TRIAD file and from Degewij *et al.* (1978).

Figure 4 illustrates UBV data for four families. The family Arnold 74 is located in the inner regions of the main belt but seems to contain no typical C or S asteroids at all. It consists of the irregularly-shaped 80 km E object 44 Nysa, the 80 km M object 135 Hertha, and at least six small fragments of an unidentified but unusual compositional type.

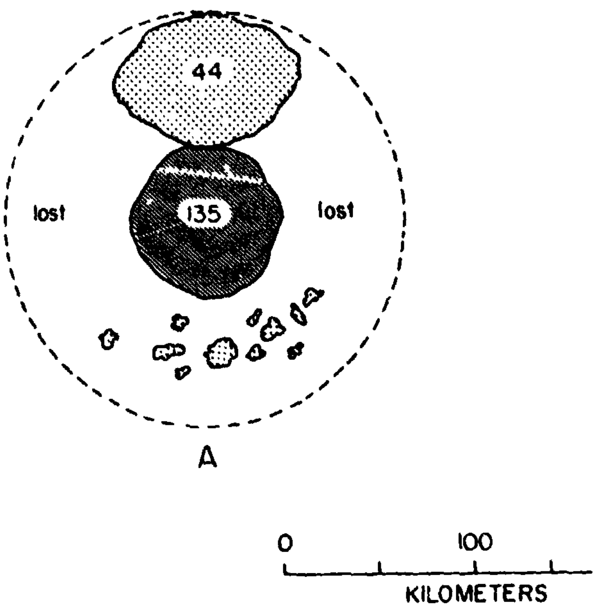
Zellner *et al.* (1977b) attempted to reconstruct this family as in Figure 5, with the hypothesis that the small fragments are also of the E type and that, together with 44 Nysa, they represent the enstatite-achondritic shell collisionally spalled from the iron core 135 Hertha. Alternate interpretations are possible, as for example a forsterite mineralogy for the E objects, or an enstatite-chondritic nature for Hertha and some of the small fragments. Meteoritic evidence tends to favor a common origin for the enstatite chondrites and achondrites (Clayton *et al.*, 1976; Hertogen *et al.*, 1978). In any case a very interesting parent body has been broken open to form the 44 Nysa family.

The families Hirayama 2 (221 Eos) and Hirayama 3 (158 Koronis) are the subject of a survey in progress by UBV and thermal-radiometric techniques (Gradie *et al.*, 1977). The Koronis objects appear to be entirely of Type S, although the field population consists of at least 80% Type C at its heliocentric distance. This family (as does Hirayama 2) has no prominent largest member but at least a dozen objects in the 30-50 km size range, and is clearly the result of a catastrophic fragmentation event. Here we have evidence that S objects are internally homogeneous with no large iron core or other marked compositional inhomogeneity.

The 221 Eos family is similarly distinct from the field population and contains the only known asteroids which appear to be intermediate between C and S types. Preliminary indications are that they in fact form a linear series between typical C and S properties in both albedo and color. A reflection spectrum of 221 Eos itself (McCord and Chapman, 1975) is peculiar and has been interpreted in terms of a mixture of mafic silicates and opaques perhaps resembling the C3 chondrites (Gaffey and McCord, 1977). Further speculations on the nature of this family would be premature.

In UBV colors the 24 Themis family (Hirayama 1) appears to consist entirely of C objects, six of them falling in the 100-200 km diameter range. Here we have a background problem, since the field population at semimajor axis 3.14 AU is at least 90 of Type C. Still the chances are small that no S or other types would be found out of 19 objects sampled, and this family also appears to have a collisional origin.

Fig. 5. Reconstruction of the 44 Nysa family, as suggested by Zellner *et al.* (1977b). 135 Hertha is taken to represent a metallic core, and 44 Nysa and the smaller fragments a mantle of enstatic-achondritic (or other transition-metal-free) material.



It has several times been suggested that C asteroids may consist of S type or other stony-metallic cores which subsequently accreted surface layers of dark carbonaceous material. This hypothesis may be attacked on several grounds, one of which is the evidence from the families. For the Koronis object it would be necessary to assume that the C material was entirely removed before the major collision that produced the family, or else disposed of in some way. For the Themis family the putative core would have to be still concealed in one of the larger members.

Finally, let me note that at least half the asteroid population cannot be assigned to recognizable family groups, but may nevertheless have originated in collisions for which the debris is now widely dispersed. Thus the overall complexion of the belt, including such general trends as seen in Figure 2, may be telling us more about the individual properties of a rather small number of parent bodies than about the continuum properties of the solar nebula.

THE OUTLIERS

Of the 2045 presently numbered minor planets, 1917 move in orbits with semimajor axis between 2.06 and 3.65 AU, eccentricity <0.35, and inclination <30°. Of the remainder, there are 21 numbered Trojans near the equilateral Lagrangian points of Jupiter, 27 Hildas near the 2/3 resonance at 3.95 AU, 16 Hungarias with relatively high inclination orbits inside the 1/4 resonance, and 48 Apollo/Amor objects in Mars- or Earth-crossing orbits (see Figure 1). The sampling is clearly much biased in favor of nearby objects. Sixteen numbered asteroids, including 2 Pallas with its exceptional inclination, fall into none of the above categories. The Hungarias, Hildas, and Trojans may have been formed at their present distances, but the Apollos and Amors appear to need a source of replenishment from the main belt or from the comet population (Wetherill, 1976, 1978).

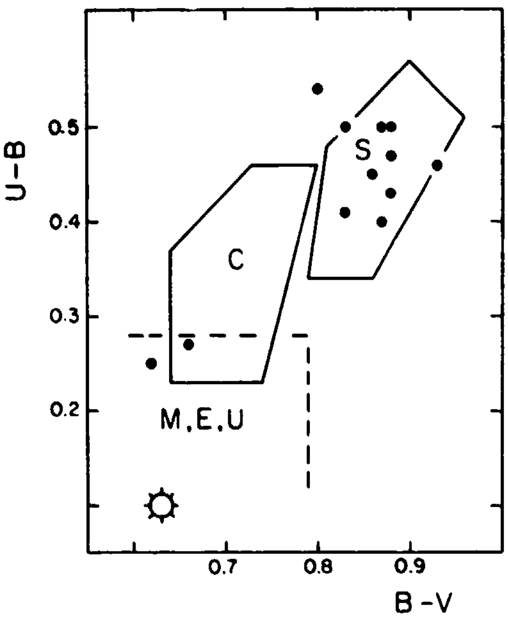


Fig. 6. UBV colors for twelve asteroids in Earth- and Mars-crossing orbits. Data are from the TRIAD file.

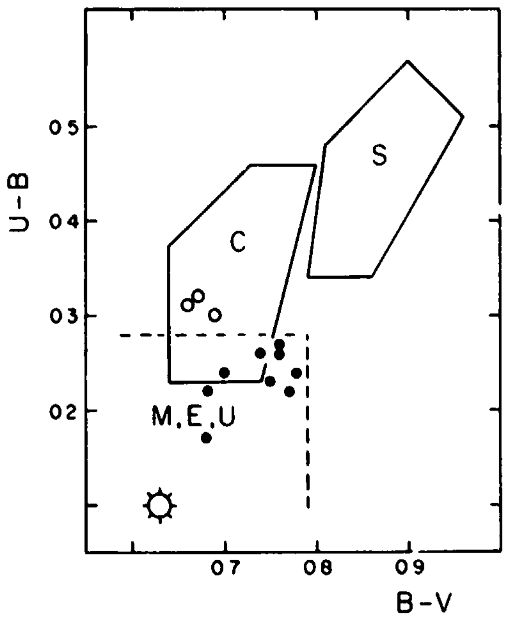


Fig. 7. UBV colors for nine Trojan asteroids (filled circles) and for the outer satellites JVI, JVII, and Phoebe. Data are from Degewij *et al.* (1978) and unpublished results at the University of Arizona.

Figure 6 illustrates UBV data for a dozen small bodies in Earth- and Mars-crossing orbits. Mostly they have S-like optical properties, but bias corrections are difficult. (Actually the distribution of types is very similar to that for the dozen brightest main belt asteroids.) Some of these have been studied in detail, and 433 Eros is perhaps the best-observed of minor planets (*Icarus*, Volume 28, No. 1, 1976). Object 1685 Toro is the best identified candidate for an ordinary-chondritic composition among the asteroids (Chapman *et al.*, 1973). Object 1580 Betulia is the only well-established C type among the Mars-crossers; 1474 Beira has relatively neutral colors of unknown significance.

Figure 7 displays UBV colors for nine Trojans. McCord and Chapman (1975) reported exceptional reflection spectra turning upward in the infrared, unlike anything in the main belt, for the Trojans 624 Hektor and 911 Agamemnon. The available UBV colors and uniformly low thermal-radiometric albedos (Cruikshank, 1977; Degewij *et al.*, 1978) argue a high degree of homogeneity among the Trojans, with an unidentified composition distinct from the rest of the asteroids. Figure 7 also illustrates remarkably similar colors, distinct from the Trojans, for the outer satellites JVI, JVII, and Phoebe.

The Hilda asteroids are poorly explored. UBV colors reported by Degewij *et al.* (1978) are generally Trojan-like, but with wider scatter. Degewij *et al.* find a variety of types among the Hungarias; 434 Hungaria itself is of the very rare E type.

FUTURE WORK

In spite of enormous progress in the last five years, we are only beginning to scratch the surface of the minor planet population with regard to some very interesting questions. Future space missions may be limited by the laws of celestial mechanics to objects which now seem wholly insignificant, and it is vital that we be able to make intelligent choices among such possible targets. Returns from the Infrared Astronomy Satellite will trivialize efforts to date in the art of asteroid thermal radiometry, but radiometry alone is not enough for mineralogical classification. The UBV technique is capable of reaching almost any numbered asteroid, but is also limited in diagnosticity.

Detectors now exist by which it is possible to obtain diagnostic spectral reflectivity data at wavelengths out to 0.10 μm for quite faint objects. A thousand minor planets could be thus observed in three years' work, and I believe that such a dedicated ground-based survey is the critical next step.

ACKNOWLEDGMENTS

This paper was prepared making heavy use of the TRIAD computer file (Bender *et al.*, 1978) and the recent compilation of asteroid types and diameters by Bowell *et al.* (1978). Asteroid work at the University of Arizona is supported by the National Aeronautics and Space Administration.

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DISCUSSION

CHAPMAN: You have looked at several of the most populous families. Previously published data on representatives of other families have shown that they have heterogeneous compositions among the members, so it is not a general rule that asteroid families have members with identical compositions. There are other cases where there are considerable differences.

ZELLNER: We should look at those too.

N78-29014

ASTEROID SURFACE MINERALOGY: EVIDENCE FROM EARTH-BASED TELESCOPE OBSERVATIONS

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Surface mineralogy of asteroids can be inferred in many cases using a variety of spectroscopic remote sensing techniques. Through the application of these techniques, mainly over the past ten years, mineral assemblages analogous to most meteorite types have been found as surface materials of asteroids. Conspicuously rare or absent from the main asteroid belt are ordinary chondrite-like assemblages, while carbonaceous materials are common as are metal-silicate assemblages. The distribution of mineral assemblages with asteroid size and distance from the Sun reveals heterogeneity which is surely informative of early accretionary and evolution processes, but the precise meanings are yet to be agreed on.

Low temperature assemblages are relatively more abundant with increasing distance from the Sun. All assemblages generally can be found inside 3.0 AU and metal plus orthopyroxene assemblages are concentrated inside 2.5 AU.

INTRODUCTION

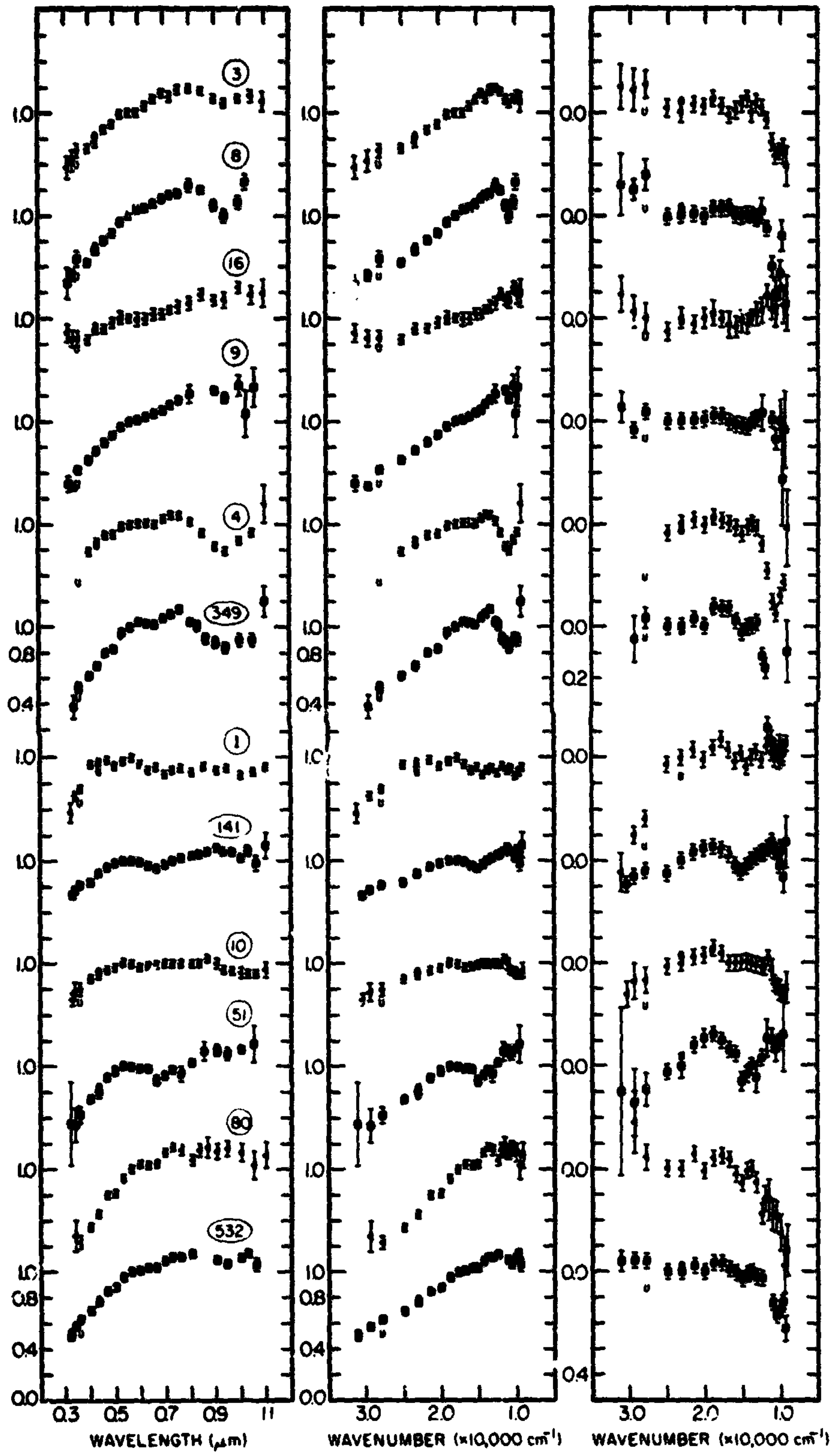
Surface mineralogy is one of the most revealing types of information obtainable about asteroids, since direct evidence of the compositional and thermal evolution of the objects is derivable. The mineral assemblages present are more informative than elemental abundances, for the exact combinations of elements in a mineral and the crystal structure are very sensitive to the composition of the parent material and to the temperature and pressure history.

Near ultraviolet, visible, and near-infrared reflectance spectroscopy is the most definitive available technique for the remote determination of asteroid surface mineralogies and petrologies. Electronic absorption features present in the reflectance spectra of asteroids (Figure 1) are directly related to the mineral phases present (Adams, 1975; McCord *et al.*, 1978).

Polarimetry, infrared radiometry and several other techniques (Morrison, 1978) provide complementary information, such as albedo, which, although not a unique function of mineralogy, is very useful in differentiating between mineralogic groups and in resolving ambiguities.

PREVIOUS CHARACTERIZATIONS OF ASTEROID SURFACE MATERIALS

McCord *et al.* (1970) measured the first 0.3-1.1 μm spectrum of an asteroid, 4 Vesta, and identified an absorption feature near 0.9 μm (see Figure 1) as due to the mineral pyroxene. They suggested that the surface material was similar to basaltic achondritic



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meteorites. Hapke (1971) compared the UBV colors of a number of asteroids to a variety of lunar, meteoritic and terrestrial rocks and rock powders. He concluded that the surface material of these asteroids could be matched by powders similar to a range of the comparison materials but not by metallic surfaces. Chapman and Salisbury (1973) indicated that some matches between asteroid and meteorite spectra were found for several meteorite types including enstatite chondrites, a basaltic achondrite, an optically unusual ordinary chondrite and, possibly, a carbonaceous chondrite. Johnson and Fanale (1973) showed that the albedo and spectral characteristics of some asteroids are similar to C1 and C2 carbonaceous chondrites and others to iron meteorites. The latter two sets of authors noted the problem of defining precisely what constituted a 'match,' and both raised the question of subtle modification of asteroid surface materials by *in situ* space weathering processes. Salisbury and Hunt (1974) raised the question of the effects of terrestrial weathering on meteorite specimens and the validity of matches between the spectra of such specimens and the asteroids.

McCord and Gaffey (1974) utilized absorption features and general spectral properties to characterize surface materials of 14 asteroids. They identified mineral assemblages similar to carbonaceous chondrite, stony-iron, iron, basaltic achondrite and silicate-metal meteorites. At that time it was possible to establish the general identity of the spectrally important minerals in an assemblage, but very difficult to establish their relative abundances.

Chapman *et al.* (1975) utilized spectral, albedo and polarization parameters to define two major asteroid groups. The first group was characterized by having low albedos ($\leq$0.09), strong negative polarizations (>1.1%) at small phase angles and relatively flat, featureless spectral reflectance curves. These parameters were similar to those for carbonaceous chondrites and these asteroids were designated as 'carbonaceous' or C type. The second group was characterized as having higher albedos ($\geq$0.09), weaker negative polarizations (0.4-1.0%) and reddish, sometimes featured spectral curves. These parameters were comparable to those for most of the meteorites which contain relatively abundant silicate minerals so this group was designated 'siliceous or stony-iron' or S types. A small minority (~10%) of the asteroids could not be classified in this system and were designated 'unclassified' or U types. This classification system has been redefined recently by Bowell *et al.* (1978). (In this volume, see Morrison, 1978.)

This simple classification scheme can be quite useful since it does seem to often separate these two major types of objects and the observational parameters on which the scheme is based can be measured at present for objects fainter than those for which complete spectra can be obtained. The choice of terminology is unfortunate, however, since it implies a specific definition of surface materials in meteoritic terms, which was not intended. Any 'flat-black' spectral curve would be designated C type whether or not the surface material would be characterized as carbonaceous by any other criteria. A similar objection can be raised with respect to the 'siliceous' terminology since it implies a degree of specificity not present in the classification criteria.

Thus, while the C and S classification of asteroids cannot be viewed as a description of mineralogy or petrology, it does provide valid characterization with respect to the chosen parameters. Since the groups appear in each of the parameters used (albedo, polarization, color), a single measurement such as UBV color can be used to classify the asteroid (Zellner *et al.*, 1975; Zellner *et al.*, 1977b; Zellner and Bowell, 1977; Morrison, 1977a,b).

Fig. 1. Typical spectral reflectance curves for the various asteroid spectral groups: 3 Juno, RA-1; 8 Flora, RA-2; 16 Psyche, RR; 9 Metis, RF; 4 Vesta, A; 349 Dembowska, A; 1 Ceres, F; 141 Lumen, TA; 10 Hygiea, TB; 51 Nemausa, TC; 80 Sappho, TD; and 532 Herculina, TE. Spectral curve for each asteroid is displayed in several formats: left--normalized reflectance versus wavelength (μm); center--normalized reflectance versus energy (wavenumber, cm^{-1}; and right--difference between spectral curve and a linear 'continuum' fitted through 0.43 μm and 0.73 μm points. (From Gaffey and McCord, 1978.)

This approach can also be utilized to identify anomalous objects (Zellner, 1975; Zellner *et al.*, 1977a) or to establish possible genetic relationships between members of asteroid dynamical families (Gradie and Zellner, 1977). Chapman (1976) utilized the basic CSM classification system but identified subdivisions based on additional spectral criteria ('slope,' 'bend' and 'band depth'; McCord and Chapman, 1975a,b) which are mineralogically significant.

Johnson *et al.* (1975) measured the near-infrared reflectance of three asteroids through the broad bandpass J, H, and K filters (1.24, 1.65 and 2.2 μm) and concluded that these were consistent with the infrared reflectance of suggested meteoritic materials. Matson *et al.* (1977a,b) utilized infrared H and K reflectances to infer that space weathering processes were relatively inactive on asteroid surfaces in contrast to the surfaces of the Moon and Mercury.

A very favorable apparition in early 1975 permitted the measurement of a variety of spectral data sets for the Earth-approaching asteroid 433 Eros. Pieters *et al.* (1976) measured the 0.33-1.07 μm spectral reflectance of Eros through 25 narrow bandpass filters. This curve was interpreted as indicating an assemblage of olivine, pyroxene and metal, with metal abundance equal to or greater than that in the H-type chondrites. Veeder *et al.* (1976) measured the spectrum of Eros through 11 filters from 0.65-2.2 μm and concluded that their spectral data indicated a mixture of olivine and pyroxene with a metal-like phase. Wisniewski (1976) concluded from a higher resolution spectrum (0.4-1.0 μm) that this surface was best matched by a mixture of iron or stony-iron material with ordinary chondritic material (*e.g.*, iron + pyroxene + olivine), but suggested that olivine is absent or rare. Larson *et al.* (1976) measured the 0.9-2.7 μm spectral reflectance curve for Eros and identified Ni-Fe and pyroxene, but found no evidence of olivine or feldspar. The dispute over the olivine content arises because of slight differences in the observed spectra near 1 μm, and the uncertainty in the metal abundance is due to incomplete quantitative understanding of the spectral contribution of metal in a mixture with silicates.

In a comprehensive article, Gaffey and McCord (1977) presented a detailed mineralogical analysis of 65 asteroid reflectance spectra and arrived at the most complete description existing of the mineral assemblages present on asteroid surfaces. They also gave a review of the field and a detailed discussion of the interpretive techniques applied to derive mineralogy. Much of the material in the present article is derived from this paper and the reader is referred to it for more detailed and comprehensive information.

The evolving characterization of the surface mineralogy of the asteroid 4 Vesta is illustrative of the improving sophistication of the interpretative process.

a. McCord *et al.* (1970) measured the reflectance spectrum of Vesta with moderate spectral resolution and coverage (0.40-1.08 μm, ∿24 filters). They identified a deep absorption band (∿0.92 μm) which they interpreted as diagnostic of a pigeonite (pyroxene with moderate calcium content). The spectrum was matched to that of a eucritic basaltic achondrite (pyroxene + plagioclase). A second pyroxene band was predicted near 2.0 μm.

b. Chapman (1972) obtained a spectral curve of Vesta with the absorption feature centered near 0.95 μm which was interpreted to indicate a more calcium- or iron-rich pigeonite.

c. Chapman and Salisbury (1973) compared this spectrum to a range of meteorites and concluded that it was best matched by a laboratory spectrum of the howarditic basaltic achondrite, Kapoeta.

d. Veeder *et al.* (1975) measured a high-resolution (~50 Å) 0.6-1.1 μm reflectance spectrum of Vesta, determined the absorption band position to be 0.92 ± 0.02 μm and interpreted this to represent a calcic pyroxene or eucritic basaltic achondrite.

e. Johnson *et al.* (1975) measured the broad bandpass reflectance of Vesta at 1.65 and 2.20 μm (H and K filters) and concluded that the data matched that expected for a basaltic achondritic surface material. They emphasized the need for higher-resolution spectra beyond 1.0 μm.

f. Larson and Fink (1975) determined the 1.1-3.0 μm reflectance of Vesta relative to the Moon. They identified the predicted second pyroxene band and confirmed the existence of pyroxene in the surface material. They indicated that no absorption bands for olivine, feldspar or ices were seen in the spectrum.

g. McFadden *et al.* (1977) measured the high-resolution (20-40 Å) 0.5-1.06 μm spectrum and determined the band position to be 0.924 ± 0.004 μm. They inferred the presence of a 10-12 mole% Ca pyroxene and suggested that the symmetry of the absorption feature indicated little or no olivine.

h. Larson (1977) presented the 1.0-2.5 μm reflectance curve of Vesta relative to the Sun. The band minimum (2.00 ± 0.05 μm) is within the field of eucrite meteorites, although it may overlap with the howardite field.

Improvements in the mineralogical and petrological characterization of the surface materials of 4 Vesta result partly from improvements in spectral resolution and coverage. Perhaps most important has been the improved understanding of the mineralogical significance of absorption features in reflectance spectra. The recent effort has concentrated on characterizing the mineral absorption features more precisely, but the original interpretation (McCord *et al.*, 1970) still appears valid.

SUMMARY OF ASTEROID MINERALOGICAL INFORMATION

Mineralogical interpretation of the observed spectra of approximately sixty asteroids has been made utilizing the wavelength dependent optical properties of meteoritic and meteorite-like mineral assemblages (see Gaffey and McCord, 1978) and a summary is given in Tables 1 and 2. The albedos (radiometric) and the depth of the negative branch of the polarization-phase curve have been used to provide an indication of the bulk optical density of the surface material, which constrains the interpretation of the surface mineralogy and petrology. A wide variety of mineralogical assemblages have been identified as asteroid surface materials. These assemblages are mixtures of the minerals found in meteorites. However, the relative abundance of mineral assemblage types present on main belt asteroid surfaces differs radically from the relative abundance of meteoritic mineral assemblages arriving at the Earth's surface. The relative abundances of various assemblages as discussed here are uncorrected for observational bias against the smaller, darker, and more distant asteroids as described by Chapman *et al.* (1975), Morrison (1977b), and Zellner and Bowell (1977).

Table 1. Asteroid Surface Materials: Characterizations[a]

Asteroid	Spectral Type	Mineral Assemblage (b)	Meteoritic Analogue (c)	CSM Type (d)
1 Ceres	F	Sil(O), Opq(M)*	C4 (Karoonda)	C (C*)
2 Pallas	F	Sil(O), Opq(M)*	C4 (Karoonda)	U (C*)
3 Juno	RA-1	NiFe $\sim$ (Ol$\sim$Px)	Ol-Px Stony-Iron	S
4 Vesta	A	Cpx	Eucrite	U
6 Hebe	RA-2	NiFe > Cpx	Mesosiderite	S
7 Iris	RA-1	NiFe, Ol, Px	Ol-Px Stony-Iron	S
8 Flora	RA-2	NiFe $\gtrsim$ Cpx	Mesosiderite	S
9 Metis	RF	NiFe, (Sil(E))	E. Chon. Iron	S
10 Hygiea	TB	Phy, Opq(C)	C1-C2	C (C*)
11 Parthenope	RF	NiFe, (Sil(E))	E. Chon. Iron	S
14 Irene	RA-3	NiFe, Px	Px Stony-Iron	S
15 Eunomia	RA-1	NiFe $\sim$ (Ol>>Px)	Ol-Px Stony-Iron	S
16 Psyche	RR	NiFe, Sil(E)	E. Chon. Iron	M
17 Thetis	RA-2	NiFe, Cpx	Mesosiderite	S
18 Melpomene	TE	Sil(O), Opq(C)	C3	S
19 Fortuna	TA	Phy, Opq(C)	C1-C2	C
25 Phocaea	RA-2	NiFe, Px, Cpx	Px Stony-Iron	S
27 Euterpe	RA-2	NiFe, Px, Cpx	Px Stony-Iron	S
28 Bellona	TE	Sil(O), Opq(C)	C3	S
30 Urania	RF (?)	---	---	S
39 Laetitia	RA-1	NiFe $\sim$ (Ol$\sim$Px)	Ol-Px Stony-Iron	S
40 Harmonia	RA-2	NiFe > Px	Mesosiderite	S
48 Doris	TA	Phy, Opq(C)	C1-C2	C
51 Nemausa	TC	Phy, Opq(C)	C1-C2	C
52 Europa	TA	Phy, Opq(C)	C1-C2	C
58 Concordia	TABC	Phy, Opq(C)	C1-C2	C
63 Ausonia	RA-3	NiFe, Px	Px Stony-Iron	S
79 Eurynome	RA-2	NiFe $\sim$ Cpx	Mesodiderite	S
80 Sappho	TD	Sil(O), Opq(C)	C3	U
82 Alkmene	TE	Sil(O), Opq(C)	C3	S
85 Io	F	Sil(O), Opq(M)*	C4 (Karoonda)	C
88 Thisbe	TB	Phy, Opq(C)	C1-C2	C
130 Elektra	TABC	Phy, Opq(C)	C1-C2	U
139 Juewa	TB	Phy, Opq(C)	C1-C2	C
140 Siwa	RR	NiFe, Sil(E)	E. Chon. Iron	C
141 Lumen	TA	Phy, Opq(C)	C1-C2	C
145 Adeona	TA	Phy, Opq(C)	C1-C2	C
163 Erigone	TA	Phy, Opq(C)	C1-C2	C
166 Rhodope	TC	Phy, Opq(C)	C1-C2	U
176 Iduna	TA	Phy, Opq(C)	C1-C2	C
192 Nausikaa	TA-2	NiFe $\sim$ (Px>Ol)	Px-Ol Stony-Iron	S
194 Prokne	TC	Phy, Opq(C)	C1-C2	C
210 Isabella	TABC	Phy, Opq(C)	C1-C2	C
213 Lilaea	F	Sil(O), Opq(M)*	C4 (Karoonda)	C

Table 1 (continued)

Asteroid	Spectral Type	Mineral Assemblage (b)	Meteoritic Analogue (c)	CSM Type (d)
221 Eos	TD	Sil(O), Opq(C)	C3	U
230 Athamantis	RF	NiFe, (Sil(E))	E. Chon., Iron	S
324 Bamberga	TABC	Phy, Opq(C)	C1-C2	C
335 Roberta	F	Sil(O), Opq(M)*	C4 (Karoonda)	U
349 Dembowska	A	Ol, (NiFe)	Ol. Achondrite	O
354 Eleonora	RA-1	NiFe ∿ Ol	Pallasite	S
433 Eros (e)	--	Px ∿ Ol, NiFe	H Chondrite	S
462 Eriphyla	RF (?)	---	---	S
481 Emita	TABC	Phy, Opq(C)	C1-C2	C
505 Cava	TA	Phy, Opq(C)	C1-C2	C
511 Davida	TB	Phy, Opq(C)	C1-C2	C (C*)
532 Herculine	TE	Sil(O), Opq(C)	C3	S
554 Peraga	TA	Phy, Opq(C)	C1-C2	C
654 Zelinda	TC	Phy, Opq(C)	C1-C2	C
674 Rachele	RF (?)	---	---	S
704 Interamnia	F	Sil(O), Opq(M)*	C4 (Karoonda)	U
887 Alinda	TD	Sil(O), Opq(C)	C3	S
1685 Toro (f)	--	Px, Ol	L Chondrite (?)	U

(a) From Gaffey and McCord (1978).

(b) Mineral assemblage of asteroid surface material determined from interpretation of reflectance spectra: NiFe (nickel-iron metal); Ol (olivine); Px (pyroxene, generally low calcium orthopyroxene); Cpx (clinopyroxene, calcic pyroxene); Sil(O) (mafic silicate, most probably olivine); Si(E) (spectral neutral silicate, most probably iron-free pyroxene (enstatite), or iron-free olivine (forsterite); Phy (phyllosillicate, layer lattice silicate, meteoritic clay mineral, generally hydrated, unleached with abundant subequal Fe^{2+} and Fe^{3+} cations); Opq(C) (opaque phase, most probably carbon or carbon compounds); Opq(M) (opaque phase, most probably magnetite or related opaque oxide).

Mathematical symbols ('>', greater than; '>>', much greater than; '∿', approximately equal) are used to indicate relative abundance of mineral phases. In cases where abundance is undetermined, order is of decreasing apparent abundance.

Asteroidal spectra which are ambiguous between 'TDE' and 'RF' are not characterized mineralogically.

(c) Meteoritic analogues are examples of meteorite types with similar mineralogy but genetic links are not established. For example, objects designated as analogous to mesosiderites could be a mechanical metal-basaltic achondritic mixture.

(d) Asteroidal spectral type as defined by Chapman *et al.* (1975) and as summarized by Zellner and Bowell (1977). C* designation from Chapman (1976).

(e) Pieters *et al.* (1976).

(f) Chapman *et al.* (1973).

Table 2[(a)]

Asteroid	Orbital Parameters a (AU)	e	i (deg)	Albedo (b) (%)	Pmin (c) (%)	Diameter (b) (km)
1 Ceres	2.767	0.08	10.6	5.4	1.67	1003
2 Pallas	2.769	0.24	34.8	7.4	1.35	608
3 Juno	2.670	0.26	13.0	15.1	0.75	247
4 Vesta	2.362	0.09	7.1	22.9	0.55	538
6 Hebe	2.426	0.20	14.8	16.4	0.80	201
7 Iris	2.386	0.23	5.5	15.4	0.70	209
8 Flora	2.202	0.16	5.9	14.4	0.60	151
9 Metis	2.386	0.12	5.6	13.9	0.70	151
10 Hygiea	3.151	0.10	3.8	4.1	-	450
11 Parthenope	2.453	0.10	4.6	12.6	0.70	150
14 Irene	2.589	0.16	9.1	16.2	-	158
15 Eunomia	2.642	0.19	11.7	15.5	0.70	272
16 Psyche	2.920	0.14	3.1	9.3	0.95	250
17 Thetis	2.469	0.14	5.6	10.3	0.65	109
18 Melpomene	2.296	0.22	10.1	14.4	-	150
19 Fortuna	2.442	0.16	1.6	3.2	1.65	215
25 Phocaea	2.401	0.26	21.6	18.4	-	72
27 Euterpe	2.347	0.17	1.6	14.7	0.60	108
28 Bellona	2.776	0.15	9.4	13.2*	-	126*
30 Urania	2.365	0.13	2.1	14.4	0.75	91
39 Laetitia	2.769	0.11	10.4	16.9	0.70	163
40 Harmonia	2.267	0.05	4.3	12.3	0.75	100
48 Doris	3.114	0.06	6.5	-	-	-
51 Nemausa	2.366	0.07	10.0	5.0	1.95	151
52 Europa	3.092	0.11	7.5	3.5	-	289
58 Concordia	2.699	0.04	5.0	-	-	-
63 Ausonia	2.395	0.13	5.8	12.8	0.65	91
79 Eurynome	2.444	0.19	4.6	13.7	-	76
80 Sappho	2.296	0.20	8.7	11.3	-	83
82 Alkmene	2.763	0.22	2.8	13.8	-	65
85 Io	2.654	0.19	11.9	4.2	-	147
88 Thisbe	2.768	0.16	5.2	4.5	-	210
130 Elektra	3.111	0.21	22.9	5.0*	-	173*
139 Juewa	2.783	0.17	10.9	4.0	1.30	163
140 Siwa	2.732	0.21	3.2	4.7	-	103
141 Lumen	2.665	0.21	11.9	2.8	1.75	133
145 Adeona	2.674	0.14	12.6	-	-	-
163 Erigone	2.367	0.19	4.8	-	-	-
166 Rhodope	2.686	0.21	12.0	-	-	-
176 Iduna	3.168	0.18	22.7	-	-	-
192 Nausikaa	2.403	0.25	6.9	16.5	-	94
194 Prokne	2.616	0.24	18.5	2.7	-	191
210 Isabella	2.722	0.12	5.3	-	-	-
213 Lilaea	2.754	0.15	6.8	-	-	-

Table 2 (continued)

Asteroid	Orbital Parameters			Albedo (b) (%)	Pmin (c) (%)	Diameter (b) (km)
	a (AU)	e	i (deg)			
221 Eos	3.014	0.10	10.8	-	-	-
230 Athamantis	2.383	0.06	9.4	10.0	-	121
324 Bamberga	2.682	0.34	11.2	3.2	1.45	246
335 Roberta	2.473	0.18	5.1	-	-	-
349 Dembowska	2.925	0.09	8.3	26.0	0.35	144
354 Eleonora	2.797	0.12	18.4	14.8	0.[illegible]	153
433 Eros	1.458	0.24	10.8	17.4	0.[illegible]	23
462 Eriphyla	2.872	0.09	3.2	-	-	-
481 Emita	2.743	0.16	9.8	-	-	-
505 Cava	2.686	0.24	9.8	-	-	-
511 Davida	2.187	0.17	15.8	3.7	1.70	323
532 Herculina	2.771	0.17	16.3	10.0	0.75	150
554 Peraga	2.375	0.15	2.9	3.9*	-	101*
654 Zelinda	2.297	0.23	18.2	3.2*	-	128*
674 Rachele	2.921	0.20	13.6	-	-	-
704 Interamnia	3.057	0.15	17.3	3.3	-	350
887 Alinda	2.516	0.54	9.1	16.6	0.75	4
1566 Icarus	1.078	0.83	23.0	16.6*		1*
1685 Toro	1.368	0.44	9.4	12.4*		3*

(a) From Gaffey and McCord (1978).

(b) Albedos and diameters by the radiometric technique as summarized by Morrison (1977b). Those indicated by an asterisk are regarded as of marginal certainty.

(c) Depth of the negative branch of the phase-polarization curve (P_{min}) as summarized by Chapman *et al.* (1975).

A large fraction (∿40%) of the interpreted spectra indicate surface materials composed of an abundant (spectrally) opaque phase (*e.g.*, carbon, carbonaceous compounds and/or magnetite) mixed with an Fe^{2+}-Fe^{3+} silicate (*e.g.*, low temperature hydrated silicate or clay minerals as found in the C1 and C2 meteorites). A range of subtle variations of these spectra indicates that a variety of these opaque-rich clay mineral assemblages exist on asteroid surfaces.

Approximately a quarter of the interpreted spectra imply surface materials composed of mafic silicates (olivine, pyroxene) mixed with an opaque phase. These materials are comparable to the C3 and C4 carbonaceous chondritic assemblages. The majority (∿15% of total) of these spectra are characterized by a significant but not overwhelming spectral contribution by the opaque phases. These assemblages are comparable to the 'olivine + opaques' C30 and C3V meteoritic assemblages. About 10% of the total objects studied apparently represent similar silicates (olivine) with a spectrally dominant opaque phase. Recent studies of Ceres by Lebofsky (1978) and Gaffey (1978) suggest that anomalous iron-free clay minerals, not yet observed in meteorites, may be an important surface component of these asteroids.

Most of the remaining spectra (about a third of the interpreted spectra) exhibit characteristics of a significant spectral contribution from metallic iron or nickel-iron. The surface materials of these asteroids appear to consist of assemblages of Ni-Fe, either alone or with a variety of silicates, including metal or metal plus a transition metal-free silicate (*e.g.*, enstatite or forsterite), metal plus olivine, metal plus pyroxene and metal plus olivine plus pyroxene. The majority of these metalliferous objects appear to have surface materials with abundant (∿25-75%) metal. The apparent metal abundances in these surface materials are comparable to those in the stony-iron meteorites and represent a significant enrichment over the cosmic abundance.

The range of mineral assemblages present on asteroid surfaces is an indication of the range of processes that have acted on the asteroids and asteroid parent bodies. Most modern cosmological models assume that the solid bodies of the solar system accreted from grains precipitated by a cooling nebula of solar composition (*e.g.*, Cameron, 1973; Cameron and Pine, 1973; Lewis, 1972). The sequence of condensation with decreasing temperature in a solar nebula has been discussed extensively (*e.g.*, Larimer, 1967; Grossman, 1972; Grossman and Larimer, 1974). In a condensation sequence which does not involve the large scale removal of condensed matter from contact and further reaction with the nebular gas (equilibrated or quasi-equilibrated condensation model), the unmetamorphosed chondritic meteoritic assemblages (C1, C2, C3, LL 3-4, L 3-4, H 3-4, E 3-4) and the high temperature calcium-aluminum inclusions of the C-type meteorites (*e.g.*, Allende) can be formed by accretion of direct condensation products. While the detailed sequence of mineral condensation and reaction is a function of nebular pressure, a major factor to bear in mind is that the oxidation of iron (Fe^0) to Fe^{2+} begins to take place near 750°K, well below the temperature at which essentially all the silicate and metal phases will have condensed. In these models, the magnesium end members of the olivine and pyroxene materials condense near 1300°K but do not incorporate the Fe^{2+} cations until the nebula has cooled below 750°K. The sensitivity of final product mineralogy (*e.g.*, Fe^{2+} distribution) to nebular conditions and processes (*e.g.*, isolated regions, gas-dust fractionation) and to accretionary and post-accretionary processes, can provide a key to utilizing mafic silicate mineralogy as a probe of the evolutionary history of certain regions of the solar system.

There is evidence from these remote sensing techniques for three definable asteroid populations, with different condensation, accretion or thermal histories.

1. The opaque + Fe^{2+}-Fe^{3+} assemblages (spectral types TA, TB, TC, see Table 1) and their meteorite analogues, C1 and C2 chondrites, accreted from material apparently condensed at low temperature (<400°K) from the solar nebula. These materials have experienced weak or minimal post-accretionary thermal events.

2. The opaque + mafic silicate assemblages (spectral types TD, TE, F) and their meteoritic analogues, the C3 and C4 chondrites, accreted from nebular condensate between 750°K and 350°K. The C4 meteoritic materials (type F asteroidal surface materials) appear to have experienced some post-accretionary metamorphism.

3. The metal-rich differentiated asteroid surface assemblage (and most of the differentiated meteorites) accreted from material condensed below 750°K, and have experienced intense heating events permitting magmatic differentiation to occur.

DISTRIBUTION OF ASTEROID MATERIALS

The distribution of the types of mineral assemblages with respect to orbital elements or size of body can provide insight into the nature of the asteroid formation and modification processes. Chapman *et al.* (1975), Chapman (1976, 1977), and Zellner and Bowell (1977) have drawn several conclusions based on these distributions of C- and S-type asteroids.

The distribution of the mineralogic groups with respect to semimajor axis is shown in Figure 2. These assemblages can be grouped according to post-accretionary thermal history into two groups: (a) apparently unmodified low temperature, surface materials (Types TA, TB, TC = C2) and intermediate temperature surface materials (Types TD, TE = C3), and (b) apparently metamorphosed or differentiated assemblages (Types RA, A, F). The distribution of these materials with respect to semimajor axis is shown in Figure 3.

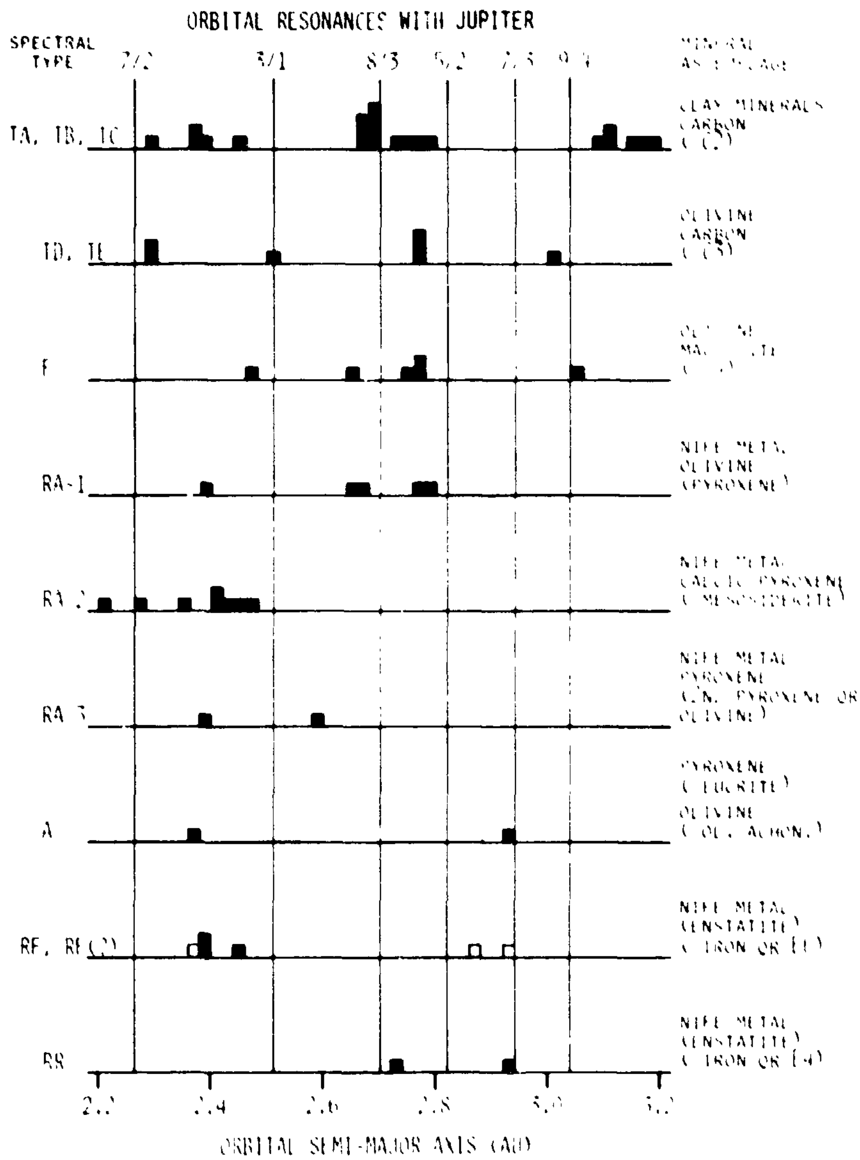

Fig. 2. Distribution of asteroid surface material groups as a function of the semimajor axis of their orbits (uncorrected for observational bias) for the members of each spectral group discussed in the text (from Gaffey and McCord, 1978).

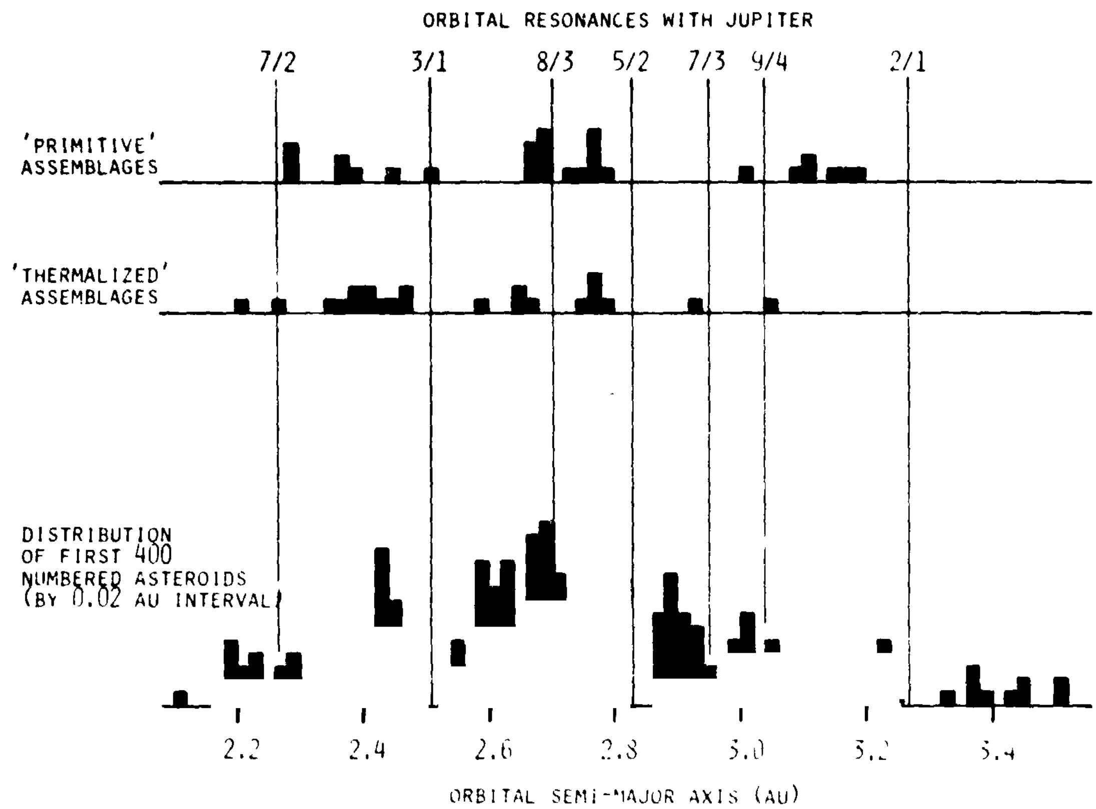

Fig. 3. Distribution of asteroid surface material groups as a function of the semi-major axis of their orbits (uncorrected for observational bias) for groups with diverse thermal histories (Primitive - apparently unaltered by any post-accretionary heating events - TA-TB-TC, TD-TE and Thermalized - apparently heated and modified or melted and differentiated by some strong post-accretionary heating episode) and the distribution of the first 400 numbered asteroids (as a histogram per 0.02 AU) (from Gaffey and McCord, 1978).

These distributions have not been corrected for observational bias, which favors brighter objects over darker objects; that is, objects with high albedos are favored over those with low albedos or objects with small semimajor axes are favored over those with large. Thus, for example, the number of TA-TB-TC objects should be multiplied by some factor depending on size and semimajor axis to compensate for their low albedos. Zellner and Bowell (1977) have discussed this bias correction process in detail.

These distributions verify the increase in relative abundance of the low temperature assemblages with increasing distance from the Sun reported by Chapman *et al.* (1975), but they also show that inside about 3.0 AU, all types generally can be found in a region. The particular concentration of the metal plus orthopy ene assemblage contained in spectra type RA-2 inside 2.5 AU is a distribution which s d be considered in light of models for differentiating these objects.

The distribution of surface mineralogies with respect to the size of the bodies is of interest (Figure 4). Two significant factors should be noted. First, the largest sized

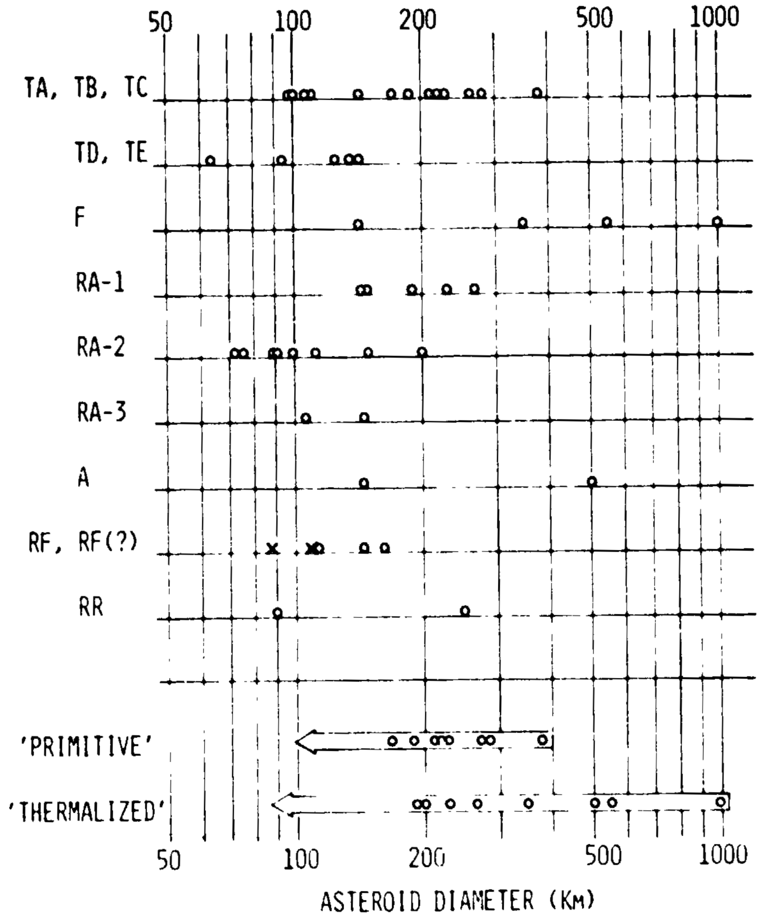

Fig. 4. Distribution of asteroid surface material groups as a function of asteroid diameters (uncorrected for observational bias). Primitive materials (TA-TB-TC and TD-TE) are compared to thermalized materials (RA-1, RA-2, RA-3, A, F) to provide an indication of the upper limits to the size distributions of the original populations (from Gaffey and McCord, 1978).

object of the TD and TE (~C3) groups is significantly smaller than that of the TA-TB-TC (~C2) group. This would tend to support the concept that the C3-type material was isolated in the interiors of bodies with C2-type surfaces (inhomogeneous accretion). Second, the largest sized body among 'thermalized' objects (RA, A, F) is significantly larger than that of the 'unthermalized' or 'primitive' objects (TA-TB-TC, TD, TE). This would imply that the size of the parent body may have an influence over post-accretionary heating. The cut-off in size below which heating did not take place appears to be approximately 300-500 km. Observational bias correction should enhance this discrepancy.

The C2-like surface materials which dominate the main asteroid belt population appear to be relatively rare on the Earth-crossing and Earth-approaching asteroids (Apollo and Amor objects). Spectral reflectance curves have been interpreted for two Amor asteroids

(433 Eros ~ H5-6 or L5-6 assemblage; Pieters *et al.*, 1976 and 887 Alinda ~ C3 assemblage) and for one Apollo asteroid (1685 Toro ~ L6(?); Chapman *et al.*, 1973). Gehrels *et al.* (1970) utilized several indirect methods to define a wavelength dependent brightness curve for the Earth-crossing asteroid 1566 Icarus which indicated the presence of an absorption feature in the region of 1 μm (pyroxene?). Zellner *et al.* (1975) provided the UBV colors for two additional objects (1620 Geographos and 1864 Daedalus), both Type S. Zellner and Bowell (1977) indicate that of about 12 Apollo or Amor objects, one is of Type C. While some have reservations with regard to the meteoritic specificity of the CSM classification system, one can view C and S as approximately 'C2' and 'not-C2.'

It is evident that the dominant C2-type assemblages of the main belt are under-represented among the Apollo and Amor objects by about two orders of magnitude (~1/10 instead of ~10/1). This discrepancy implies that the Apollo and Amor asteroids are not randomly derived from the population of the main belt. If this population anomaly is not a recent or temporary event, then the source region which replenishes this inner solar system population must be both restricted and strongly depleted in C2-type asteroidal materials. This suggests that these asteroids may be derived from the innermost portions of the belt, perhaps inside 2.0 AU. Wetherill (1977) has suggested that objects formed closer in to the Sun (*e.g.*, ordinary chondritic assemblages) may have been stored at the inner edge of the belt and may represent the source of these objects. The cometary hypothesis (Öpik, 1963, 1966; Wetherill and Williams, 1968) for the origin of the Apollo and Amor asteroids cannot be ruled out on the basis of the available spectral data. Chapman (1977) reaches similar conclusions with respect to the origin of these asteroids.

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DISCUSSION

ARNOLD: Is it correct that no two of the spectra in Figure 1 are identical? If so, then I suggest again there is great variety among asteroid surfaces.

McCORD: That is right. It is felt that each one in this sample is significantly different and reveals some difference in the surface material.

MATSON: Your expectation of a continuum of properties seems to be unlike the clear divisions seen in some other parameters, like albedo.

McCORD: In part, you are right. There won't be a continuum between all of the various dimensions.

MORRISON: When you lump the asteroids together into thermalized and unthermalized groups, but without correcting for observational bias, I don't think this really adds much information. One might as well use the bias-corrected C and S data that Zellner reported here.

CHAPMAN: Not true, because it turns out there are both thermalized and unthermalized interpretations within the S classification. In other words, although there is a general association between the McCord/Gaffey groups and the C and S classifications, their individual spectra have been interpreted in such a way that the C and S are heterogeneous with respect to thermal evolution.

McCORD: That doesn't mean the C and S classification is useless. In individual cases it could lead you widely astray, but as a statistical tool probably not.

ARNOLD: I note that you reinforced the conclusion derived by other workers that there are no close analogs of an ordinary chondrite in this group. I also note that the ones which have C3 as the closest meteoritic analogs are Ss, and I wondered if you would comment on that?

McCORD: Well, that is quite possible because C3 is a modified metamorphosed material that can have a spectral continuum which would give you an S classification when you look at it using UBV photometry.

ARNOLD: Do you take albedo into account? A laboratory scientist knows that C3s are dark objects, but not as dark as C2s.

McCORD: That is taken into consideration. In fact, sometimes albedo is necessary in order to resolve ambiguities.

CHAPMAN: The TE class that you associated with C3s falls in the S class defined by Bowell *et al.* I don't think the TE spectra differ substantially from others which you have assigned to other classifications, and secondly, the albedo of those TEs is 0.13, which is pretty bright compared to C3 meteorites.

McCORD: These TEs may be too bright; in any individual classification errors are possible. But I would like to emphasize that the classifications are not capricious and should not be judged according to a single parameter. One has to spend a great deal of time working with both the asteroid spectra and the laboratory spectra before one begins to get a feeling for which differences are important and which are not.

WETHERILL: There is a feature at 0.65 μm. It appears in what others call an S-type asteroid; it does not appear in an ordinary chondrite, nor does it appear in any actual meteorites. So in regard to comparing meteorites with asteroids, I think it is worthwhile to place similar emphasis on the things that don't agree as well as the things that do agree.

McCORD: That feature is not well understood. I think it is real and that it means something. We are going to have to go to the laboratory and work on that. At the very beginning it was felt it might be spurious, a problem with comparison of standard stars, but the calibrations have been checked. It is not as though the feature is uniformly there. It is not there in some, it is there weakly in others, strongly in still others. That indicates it is real.

GROSSMAN: When you look at the broken surfaces of C1 and C2 meteorites in the laboratory, the human eye can certainly see the difference. I'm puzzled as to why the TA-type spectrum stands for C1-C2. Is it difficult to tell the difference spectrally between a C1 and a C2 in the laboratory or is it just that the asteroid spectra fall somewhere in-between them?

CHAPMAN: There are only three C1 samples available, and they are not in pristine optical condition. The problem is that no one has had believable samples of a C1 to measure in the laboratory.

GROSSMAN: What is in store for us as far as an improvement beyond what we see in Table 1? Is there any technological breakthrough that is going to happen?

McCORD: There is not a technological breakthrough, but more hard work. One has to measure the spectrum better with higher signal-to-noise, with larger spectral range, and with higher spectral resolution. It should be done for asteroids which have strong spectral features. Then one has to have available laboratory and theoretical material that allows one to interpret the features. For example, we need data on cold hydrated materials, materials we really don't know very much about. We are setting up to do that now. The emphasis of the work now that this survey is concluded is to do better interpretations for some specific main belt objects as well as for the Earth-approaching objects.

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INFRARED OBSERVATIONS OF ASTEROIDS FROM EARTH AND SPACE

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Infrared observations of asteroids have made possible key steps in our understanding of asteroids. The list of accomplishments includes: diameters, albedos, surface morphology and surface composition. Current topics of interest include the presence of water of hydration on Ceres, the presence of mixtures of silicate and metallic phases, and the state of development of asteroidal regoliths which range from rocky (1580 Betulia) to lunar-like (*e.g.*, Ceres, Vesta). We review these accomplishments critically and assess the advantages which can be obtained by performing infrared observations from Earth orbit and from interplanetary spacecraft.

REFLECTED RADIATION

Introduction

The measurement of reflectances at wavelengths between 1 and 4 μm yields important information about asteroid surface composition and the processes by which these surfaces may have been modified. Further, it more than doubles the wavelength range over which asteroids may be compared with available reflectivity data for meteorites and other laboratory samples. As a result, it is possible to classify asteroids better and to devise more precise tests for hypotheses about their surface compositions.

The need for asteroid photometry at wavelengths longer than 1 μm was first recognized as a result of laboratory investigations into the bulk reflectance properties of meteorite samples (Johnson and Fanale, 1973; Chapman and Salisbury, 1973; Gaffey, 1974, 1976). These works showed that meteorites as a group exhibited a large range in infrared reflectance. This should also be true for asteroids with meteorite-type compositions. Furthermore, it was argued that high spectral resolution would not be essential because for many meteorites the infrared reflectances (particularly those for the carbonaceous chondrites and the irons) do not vary sharply with wavelength in the 1 to 3 μm interval. But, even when bands (arising from solid state transitions in minerals) were present, the features were observed to be typically 0.5 μm or more in width. Therefore, existing astronomical infrared bandpasses and, more important, existing systems of standard stars are suitable for asteroid photometry.

The first asteroid study with this technique was carried out by Johnson *et al.* (1975) who observed Ceres, Pallas and Vesta. They were able to use published V bandpass photometry for these asteroids to derive the asteroidal reflectances at 1.25, 1.65 and 2.2 μm. However, they noted that simultaneous visual wavelength photometry would be necessary for any other asteroids observed by this technique because of the large uncertainties in the instantaneous apparent visual magnitude due to (1) lightcurve, (2) aspect, and (3) phase effects. Chapman and Morrison (1976) and Leake *et al.* (1978) have reported J, H, and K photometry for 433 Eros and about a dozen other asteroids. Veeder *et al.* (1976, 1977, 1978) have observed 30 asteroids at 0.56, 1.6 and 2.2 μm and derived the relative infrared reflectances for these objects. Lebofsky (1977) has extended this technique to 3.45 μm for Ceres.

Photometry and spectroscopy are complementary techniques. For example, over the last several years the sensitivity of infrared astronomical interferometers has increased dramatically. Such an instrument has been applied to the asteroids and high resolution spectra of 4 Vesta, 433 Eros, and 1 Ceres are now available (Larson and Fink, 1975; Larson *et al.*, 1976; Feierberg *et al.*, 1977). These spectra allow precise band centers to be determined and as such are very important for compositional identifications. Based on the statistics of asteroid types (Chapman *et al.*, 1975; Zellner and Bowell, 1977), we estimate that more than 80% of the asteroids will exhibit infrared spectral reflectances which are essentially linear. In these cases the main task is to determine the slope of the spectrum by photometry. The remaining asteroids, especially if they have apparent bands or peculiarities in their photometry or spectrophotometry, become prime candidates for high resolution infrared spectral investigations.

The purpose of this section of this paper is to assess the state of asteroid infrared reflectance measurements and the advantages offered by Earth orbit and spacecraft observations. The second section deals with thermal radiation emitted by the asteroids and the third section discusses future observations of asteroids from space.

Infrared Photometry

The available infrared reflectance data for asteroids have been drawn together in Tables 1 and 2. The only published reflectances at 1.25 μm are those of Johnson *et al.* (1975). However, magnitudes published by Chapman and Morrison (1976), Leake *et al.* (1978), and Lebofsky (1978) are used here together with the observations of the same asteroids by Veeder *et al.* (1976, 1977, 1978) and solar data from Johnson *et al.* (1975) to compute 1.25 μm reflectances. The method by which this was done is described in footnote 3 of Table 1.

Figure 1 shows the infrared results for three asteroids and the 0.3-1.1 μm spectrophotometry published by Chapman *et al.* (1973). Vesta has a relatively high infrared reflectance, while the infrared reflectances of Ceres and Pallas are distinctly flat or low. A high infrared reflectance compared with that at 0.55 μm is typical of many silicate minerals and rocks (Hunt and Salisbury, 1970) and most meteoritic materials (Chapman and Salisbury, 1973; Gaffey, 1974, 1976). On the other hand, flat infrared curves such as those of Ceres and Pallas are unusual for ordinary terrestrial rocks, but are apparently common in the asteroid belt. Johnson and Fanale (1973) found that some carbonaceous chondrites and laboratory mixtures of carbon black and silicates have flat spectral reflectances as well as low albedos. The scaled reflectance plot (Figure 1) allows direct comparison with spectral features of meteorites without confusion from slight overall albedo differences due to laboratory methods, grain size, or sample packing characteristics. Care must be taken, of course, to compare materials with generally similar albedos; for example, pure enstatite and carbon black have similar visual reflectance spectra but greatly different albedos.

Table 1. Infrared Reflectances

Asteroid	R_λ 1.25 µm	R_λ 1.6 µm	R_λ 2.2 µm	Type[6,7]	Footnote
1 Ceres	0.98 ± 0.09	0.99 ± 0.09	1.08 ± 0.09	C	1
		0.94 ± 0.13	1.03 ± 0.10		4
2 Pallas	1.05 ± 0.09	0.97 ± 0.09	1.05 ± 0.09	C	1
		0.79 ± 0.08	0.83 ± 0.08		4
3 Juno		1.19 ± 0.10	1.30 ± 0.10	S	4
4 Vesta		1.18 ± 0.1[illegible]	1.29 ± 0.14		1,8
		1.10 ± [illegible]	1.16 ± 0.07		4
5 Astraea	1.15 ± 0.16	1.25 ± 0.10	1.30 ± 0.15	S	3,4
6 Hebe	1.15 ± 0.15	1.21 ± 0.09	1.30 ± 0.12	S	3,4
7 Iris	1.16 ± 0.10	1.31 ± 0.09	1.44 ± 0.09	S	3,4
8 Flora	1.25 ± 0.12	1.42 ± 0.10	1.55 ± 0.11	S	4,10
9 Metis		1.27 ± 0.09	1.45 ± 0.10	S	4
10 Hygiea		0.96 ± 0.07	1.06 ± 0.10	C	4
12 Victoria		1.51 ± 0.12	1.72 ± 0.13	S	4
14 Irene		1.39 ± 0.08	1.52 ± 0.10	S	4
15 Eunomia	1.21 ± 0.09	1.24 ± 0.08	1.38 ± 0.08	S	4,10
16 Psyche		1.14 ± 0.09	1.37 ± 0.10	M	4
19 Fortuna		0.97 ± 0.11	1.10 ± 0.11	C	4
20 Massalia		1.28 ± 0.09	1.39 ± 0.10	S	4
22 Kalliope		1.14 ± 0.12	1.46 ± 0.14	M	4
27 Euterpe		1.26 ± 0.11	1.37 ± 0.10	S	4
39 Laetitia		1.38 ± 0.08	1.49 ± 0.08	S	4
40 Harmonia		1.38 ± 0.11	1.46 ± 0.11	S	4
43 Ariadne		1.44 ± 0.12	1.47 ± 0.19	S	4
44 Nysa		1.03 ± 0.12	1.15 ± 0.11	E	4
51 Nemausa		1.24 ± 0.13	1.28 ± 0.10	C	4
63 Ausonia		1.50 ± 0.10	1.70 ± 0.12	S	4
129 Antigone	1.02 ± 0.10	1.28 ± 0.07	1.45 ± 0.08	M?	3,4
192 Nausikaa		1.47 ± 0.07	1.62 ± 0.10	S	4
230 Athamantis		1.33 ± 0.15	[illegible] ± 0.14	S	4
349 Dembowska		1.38 ± 0.10	1.57 ± 0.14	-	4,9
354 Eleonora		1.48 ± 0.14	1.69 ± 0.16	S	4
433 Eros	1.3 ± 0.14	1.5 ± 0.1	1.7 ± 0.1	S	2,3
511 Davida	0.85 ± 0.11	1.03 ± 0.08	1.19 ± 0.08	C	3,4
1976AA			1.5 ± 0.3	-	5

[1]Johnson *et al.* (1975).
[2]Veeder *et al.* (1976).
[3]These values of R_λ(1.25 µm) have been computed from the published J-K magnitudes of Chapman and Morrison (1976) using the formula:

$$R_\lambda(1.25\ \mu m) = R_\lambda(2.2\ \mu m)\exp\{-0.4[(J-K)_{asteroid} - (J-K)_{Sun}]\}$$

The values of R_λ(2.2 µm) are those in the above table and $(J-K)_{Sun}$ is 0.36 from Johnson *et al.* (1975). The tabulated errors are estimates only, having been computed upon the assumption that the errors in $(J-K)_{asteroid}$ and R_λ(2.2 µm) are random.
[4]Veeder *et al.* (1978).
[5]Veeder *et al.* (1977).
[6]Type C and S classifications are defined by Chapman *et al.* (1975).
[7]Types M and E have been discussed by Zellner *et al.* (1975), Zellner and Gradie (1976), Chapman (1976), Morrison (1977a,b,c), Zellner *et al.* (1977a,b,c,d), Matson *et al.* (1977a), Zellner and Bowell (1977), Veeder *et al.* (1978), Morrison (1978), Zellner (1978), *cf.*, Gaffey and McCord (1977), McCord (1978).
[8]Basaltic achondritic.
[9]Olivine plus metal; *cf.*, Gaffey and McCord (1977) and Veeder *et al.* (1978).
[10]These values of R_λ(1.25 µm) have been computed from the published J-K magnitudes of Leake *et al.* (1978) as in Footnote 3.

Table 2. Observations of Ceres by Lebofsky (1978)

Wavelength	Magnitudes		Reflectance R_λ			
					Model Limits[2]	
	m_λ	$\sigma_{\bar{x}}$	Nominal[1]	$\sigma_{\bar{x}}$	Upper	Lower
1.25 (J)	6.41	0.02	0.98	0.02	0.98	0.98
2.22 (K)	5.89	0.01	1.07	0.01	1.07	1.07
3.03	6.23	0.05	0.75	0.04	0.75	0.74
3.12	6.19	0.02	0.77	0.02	0.76	0.75
3.43	5.77	0.02	1.12	0.02	1.06	0.97
3.45 (L')	5.74	0.01	1.16	0.01	1.08	0.98

[1]Scaled to 1.0 at V (Johnson *et al.*, 1975). Before thermal flux removed.
[2]Thermal flux removed. The upper and lower limits are due to the uncertainty in the removal of the thermal flux.

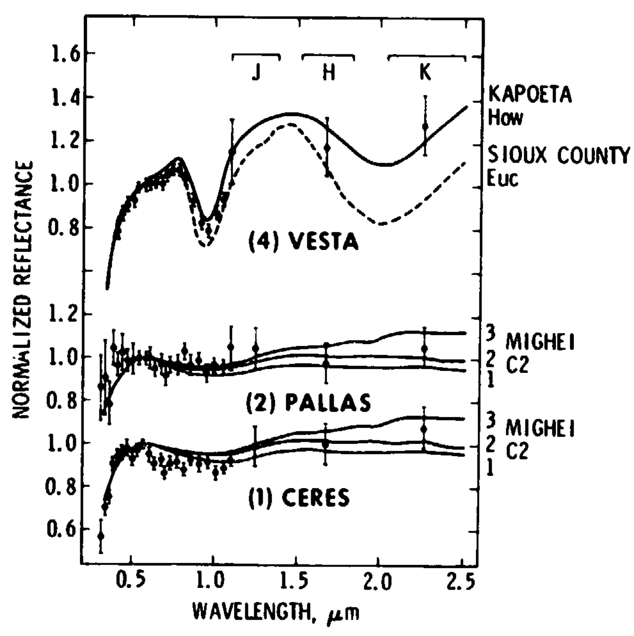

Fig. 1. Normalized spectral reflectances for 1 Ceres, 2 Pallas, and 4 Vesta, compared with laboratory data for several meteorites. The 0.03-1.1 μm asteroid data are those of Chapman *et al.* (1973). Meteorite curves are from Johnson and Fanale (1973), Chapman and Salisbury (1973), and Gaffey (1974, 1976). The bars near the top indicate the full width at half-minimum of the infrared bandpasses.

Infrared reflectance data are quite useful for asteroid classification; *cf.*, Matson *et al.* (1977a). This can be shown in one way by plotting the visual geometric albedo versus $R_\lambda(2.2\ \mu m)$ as in Figure 2. On this plot the C asteroids are clearly separated from the others. The cluster of points to the right contains not only S but also the M asteroids 16 Psyche and 22 Kalliope. Several peculiar asteroids stand out on this plot. 4 Vesta is the best understood in that it is known to have a basaltic surface. E asteroid 44 Nysa has a very high albedo, perhaps in excess of 0.3 or 0.4 (Zellner, 1975; Morrison, 1977a,c), but has an $R_\lambda(2.2\ \mu m)$ otherwise characteristic of C asteroids. Zellner (1975) and Zellner *et al.* (1977c) have suggested that Nysa is of an enstatite-achondrite-like composition. 2 Pallas and 51 Nemausa represent the extremes of low albedo asteroids observed in the infrared. The data of Figure 2 suggest that we are seeing either a surface compositional or a surface morphological sequence within both the C and S classes.

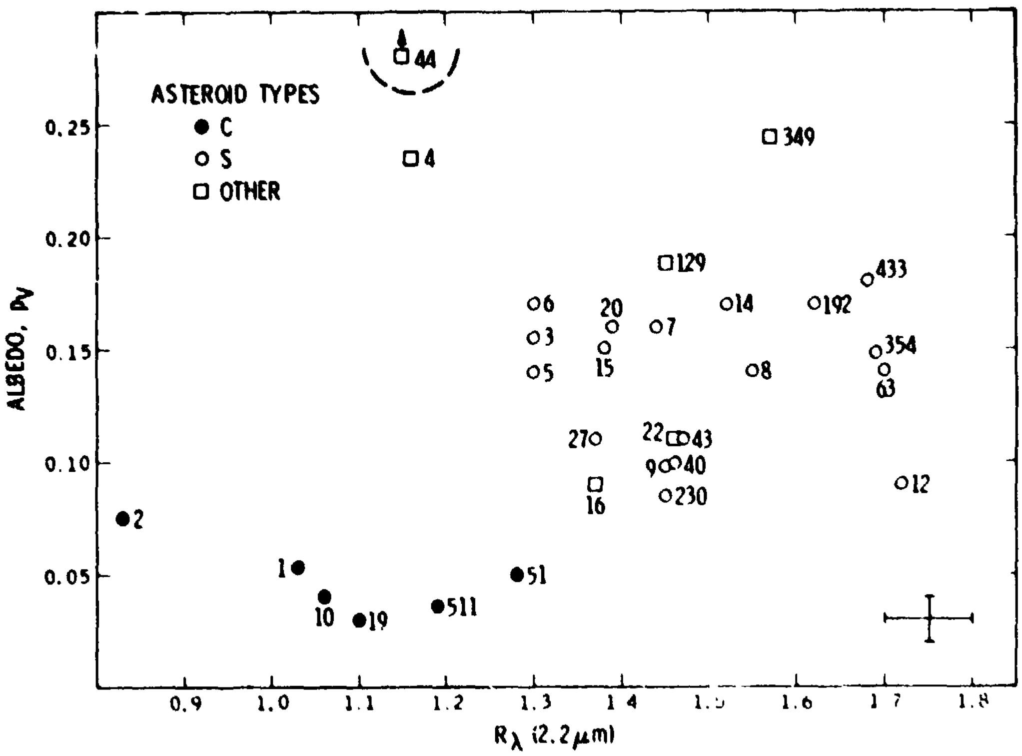

Fig. 2. Geometric albedo vs. relative reflectance at 2.2 μm. The albedos were determined by the radiometric method and are from Morrison (1974, 1977a), and Morrison and Chapman (1976). Typical error bars (estimated relative error) are indicated. The asteroid types are defined by Chapman *et al.* (1975). Use of radiometric albedos from Hansen (1976a, 1977) or polarimetric albedos from Zellner and Gradie (1976) would also result in a similar diagram.

From an inspection of Table 1 it is obvious that asteroids that have large values of $R_\lambda(1.6\ \mu m)$ also have high values of $R_\lambda(2.2\ \mu m)$. This is illustrated by plotting the two reflectances in Figure 3. Once again the C and S objects are separated. The meteorites, which are natural samples from space, provide a logical set of objects for comparison with the telescopically observed asteroids. Using the laboratory data of Gaffey (1974, 1976) we plot the relative infrared reflectances of meteorite samples in Figure 3.

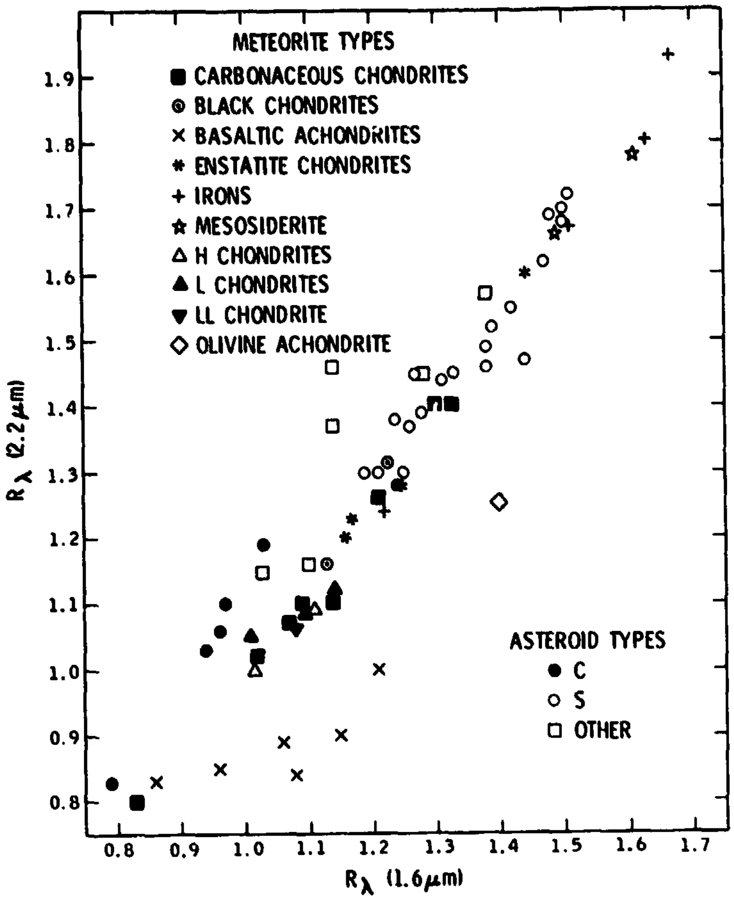

Fig. 3. Comparison of asteroid and meteorite data on a color plot: R_λ(2.2 μm) versus R_λ(1.6 μm). The asteroid data are from Veeder *et al.* (1978). The meteorite data are from Gaffey (1974, 1976). While the meteorites plotted here are unlikely to be fragments from any of the asteroids shown, they do provide a set of natural compositional hypotheses. For example, the reddest asteroids fall among the data for iron and mesosiderite meteorites. It now appears that the known space weathering processes do not operate significantly to redden asteroids. Thus, the presence of a metallic phase is strongly suggested (Matson *et al.*, 1977b). As one can see in the above plot, several compositional hypotheses appear able to explain the 1.6 and 2.2 μm infrared reflectance data. Further optical tests will help to distinguish between them, or perhaps will point to a closely related composition not currently represented in the meteorite sample. This has already proved to be the case for Vesta.

The meteorite data more than span the range of the asteroid data. There are carbonaceous chondrites which are as low in infrared reflectance as 2 Pallas and there are irons and mesosiderites which exceed the redness of the reddest known asteroids. Note that all of the meteorites which are as red as the reddest asteroids have a significant metallic phase. However, when Figure 3 is considered in detail it remains obvious that there are asteroids which do not correspond to any of the meteorites thus far measured. On the other hand, there are clear examples of types of meteorite materials which have not yet been observed telescopically. The olivine achondrites provide a case in point.

It may be significant that the carbonaceous chondrites do not exactly coincide with the C asteroids. The C asteroids tend to be redder, having a higher reflectance at 2.2 μm relative to their 1.6 μm reflectance than the corresponding meteorites. This effect cannot be easily explained by reddening the reflectance curve due to particle or grain size effects. Johnson and Fanale (1973) measured meteorite reflectances as a function of grain size. Examination of their data for the C2 meteorite Mighei, for example, shows that this type of reddening would move the plotted meteorite data along the trend of the meteorite data already plotted in Figure 3 and not perpendicular to it. There is also the possibility that the meteorite spectra have been affected somewhat by Earth weathering (Gaffey, 1976). Of course, the sample of meteorite data is not complete. Furthermore, there are cases of samples of the same meteorite being considerably different. The C1 meteorite Orgueil provides such an example. The effect of phase on R_λ(1.6 μm) and R_λ(2.2 μm) has been investigated by Veeder *et al.* (1978). They find no significant variation. This led them to the conclusion that the 1.6 and 2.2 μm phase coefficients are similar in magnitude to that in the visual. Color dependent photometry calibration, or the H-K solar color, might be in error by 0.1 magnitude and cause the C asteroids not to coincide with the carbonaceous chondrites, but we do not think that this is a very likely possibility. Zellner *et al.* (1975) have also noticed a similar effect in the UBV data. Thus, we are not yet able to detail the nature of the differences in terms of either composition or morphology, although the general agreement in albedo and shape of the reflectance spectrum between C asteroids and carbonaceous meteorites remains evidence that they are compositionally similar.

Space weathering or the alteration of surface optical properties on a planetary object as a result of exposure to the space environment has been a source of concern ever since it was realized that the lunar soils are different from the optical properties of rocks or rock powders. The effect of maturation on the optical properties of lunar soils is a systematic darkening and "reddening," or steepening of the reflectance spectrum continuum. At the optically "young" stage are the fresh crystalline rocks and powders, as seen in the laboratory and in the rims of fresh, young craters on the Moon. These rocks exhibit high albedos and reflectance spectra which are typically flat and have one or more electronic absorption bands (see Adams and McCord, 1971). At the optically "mature" end of the scale are the mare soils having low albedos and very red reflectance spectra without strong bands.

The optical maturation of asteroid regoliths has been studied by Matson *et al.* (1977b) and compared with the lunar example. They found: (1) that space weathering has not significantly altered asteroid optical properties; (2) that the most probable reasons for this fact relate to the lack of optically mature impact regoliths on low gravity objects; and (3) that within this context comparisons of asteroid spectra with powdered (but "unweathered") meteorite and other rock samples are valid.

Recently a search for absorption bands due to H_2O on asteroid surfaces has been initiated by Lebofsky (1977, 1978). In the 3-4 μm wavelength region of Ceres' spectrum he found evidence for the presence of water of hydration (see Table 2 and Figure 4). This spectral feature was confirmed subsequently by Feierberg *et al.* (1977). In Figure 4 the results have been rescaled to $R_{1.25} = 0.98$ ($R_{0.56} = 1.0$) and plotted along with the shorter wavelength data on Ceres (Chapman *et al.*, 1973; Johnson *et al.*, 1975). The normalized reflectances of three different meteorites have also been plotted for comparison. An absorption feature can clearly be seen in the Ceres spectrum and appears to be centered around 3 μm. Also, the general shape and depth of the curves in the 3-4 μm region are fairly similar to that of the Type II carbonaceous chondrite Murchison and differ significantly from the other carbonaceous chondrites. Comparison with other laboratory spectra of meteorites confirms the similarity to the spectra of Type II carbonaceous chondrites. Analogy with C2 composition suggests the presence of about 10-15% water in the form of water of hydration on the surface of Ceres. This is the first evidence of water in the surface material of an asteroid.

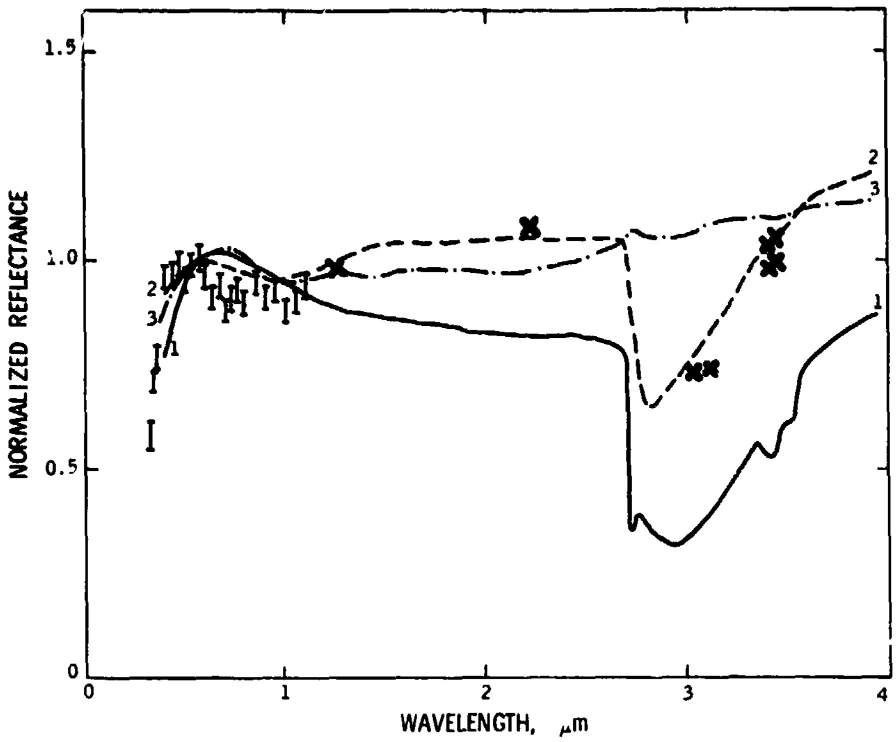

Fig. 4. Comparison of the spectrum of Ceres with three laboratory spectra of carbonaceous chondrites, scaled to 1.0 at V. The 2.5-4.0 μm spectra are unpublished data from Salisbury: (1) Orgueil, C1. 0.3-2.5 μm, Johnson and Fanale (1973); (2) Murchison, C2. 0.3-2.5 μm, Johnson and Fanale (1973); (3) Karoonda, C4. 0.3-2.5 μm, Gaffey (1974). Ceres data from 0.3-1.1 μm are from Chapman *et al.* (1973). Infrared data for Ceres are from Lebofsky (1978). The two sets of points at 3.43 and 3.45 μm give upper and lower limits after removal of thermal flux.

Infrared Spectroscopy

Advances in infrared detector technology and availability of large astronomical telescopes have made it possible to apply the techniques of Fourier transform spectroscopy to asteroids. So far, Vesta (Larson and Fink, 1975), Eros (Larson *et al.*, 1976) and Ceres (Feierberg *et al.*, 1977) have been observed. In the next few years a spectral resolution of 50 cm^{-1} will become available for many asteroids brighter than about eleventh visual magnitude.

The infrared is a key spectral region for absorption bands and the determination of band centers and shapes is essential to precise mineralogical identifications. Partly for historical reasons, the contribution thus far of infrared spectroscopy has been confined to performing detailed checks on compositional hypotheses formulated on the basis of other types of data. In the future the importance of this technique will grow as scientific interest demands ever more precise identifications of surface compositions.

THERMAL EMISSION

Introduction

The study of thermal emission radiation from asteroids has yielded a way to determine their sizes and albedos. Results are now in hand for some 200 objects. Asteroids as a whole are found to be larger and darker than was previously supposed. The typical Bond albedo of an asteroid is a few percent. Objects this dark absorb almost all of the sunlight that reaches their surface. The absorbed power heats the surface and eventually leaves the asteroid as thermal radiation concentrated in the infrared spectral region. Thus asteroids are relatively easy to detect at wavelengths of 10-20 μm.

To a first approximation, the thermal emission from an asteroid surface has a blackbody wavelength distribution (Gillett and Merrill, 1975; Hansen, 1976b). However, for the purpose of size determination, the range of available phase angles is not adequate to determine the angular distribution of infrared radiation, and thus photometric-thermal models must be constructed in order to account for thermal emission in the directions which cannot be observed from the Earth. The size and albedo of the asteroid are derived by using such models to equate the solar insolation with the sum of the total thermal emission power and the power of the scattered sunlight. For a spherical asteroid the balance between incoming and outgoing radiation may be represented by:

$$\pi R^2(1 - A)S_0 = \beta\, \varepsilon\, \sigma\, R^2 \int_0^{2\pi} \int_0^{\pi} T^4(\theta,\phi) \sin\phi \, d\phi \, d\theta \tag{1}$$

where R is the radius of the asteroid, A is the bolometric Bond albedo, S_0 is the solar constant, β is a normalization constant (of order unity) whose value is determined by the angular distribution of the thermal emission, ε is the emissivity, σ is the Boltzmann constant, $T(\theta,\phi)$ is the temperature at a point on the surface at longitude θ and latitude ϕ. The Earth and Sun are both in the equatorial plane of the coordinate system at $\theta=0$, $\phi=0$.

Photometry of thermal emission from asteroids has been obtained by Low (1965, 1970), Allen (1970, 1971a), Matson (1971a,b), Cruikshank and Morrison (1973), Morrison (1973, 1974, 1976, 1977a), Morrison and Chapman (1976), Morrison *et al.* (1976), Hansen (1976a), Cruikshank (1977), Cruikshank and Jones (1977), and Lebofsky *et al.* (1978). Quantitative descriptions of the methods of deriving albedo and diameter from thermal infrared observations have been given principally by Allen (1970, 1971a), Matson (1971b), Morrison (1973, 1977c), Jones and Morrison (1974), Hansen (1977), and Lebofsky *et al.* (1978). The albedos of asteroids determined by the radiometric method compare well with those found by the polarimetric method. (The polarimetric method is an empirical relation between geometric albedo and the slope of the linear polarization at visual wavelengths as a function of phase angle (Zellner and Gradie, 1976).) Earlier differences between many of the radiometric and the polarimetric diameters (*cf.*, Chapman *et al.*, 1975; Hansen, 1977) have been resolved by the recent recalibration of the polarimetric albedo-slope relationship (*cf.*, Zellner *et al.*, 1977b, as well as Morrison, 1977c). Approximately 50 asteroids have been well observed by both techniques (*cf.*, review by Morrison, 1977c). A few diameters obtained from analyses of speckle interferometry, radar, radio, lunar occultation and stellar occultation data agree (within their estimated uncertainties) with the radiometric diameters. The use of radar is a promising new technique in asteroid studies. Diameters have been derived for 433 Eros and 1580 Betulia. The radar and visual polarimetric observations of Betulia are interesting because they do not result in a diameter in agreement with that obtained by the radiometric method. The resolution of this problem is the subject of a section of this paper.

In the following sections, three photometric-radiometric models used for interpreting radiometric data are discussed (see Table 3).

Radiometric Model 1: Lunar-Type Surface

The cratered surfaces of Mercury, the Moon and Mars as well as Phobos and Deimos are evidence of an intensive bombardment history. There is every reason to expect that the asteroids have also been bombarded and that their surfaces are heavily cratered. This type of history was also experienced by some of the meteorite parent bodies as pieces of their surface regoliths have reached the Earth as gas-rich, brecciated meteorites (*cf.*, Wilkening, 1976; Rajan *et al.*, 1974, 1975).

The larger asteroids are expected to possess well-developed regoliths. Once gravity differences are taken into account, these regoliths should resemble in many ways that of the Moon. For example, the asteroid Vesta (~550 km in diameter) has sufficient gravity that more than 95% of the ejecta from impact craters falls back to the surface. There, as on the Moon, material may be reworked by subsequent impacts (Chapman, 1971, 1976, 1978, Matson, 1971b; Gaffey, 1974, 1976). Although asteroids are small, the above statements can be made with considerable certainty because mass determinations are available for Ceres, Pallas and Vesta (Schubart, 1974, 1975; Hertz, 1968) and because laboratory data on impacts into basalt (Gault *et al.*, 1963) can be used to provide a worst case analysis leading to the same conclusions. This reasoning is consistent with the negative polarization branch of the light reflected from asteroids at small phase angles which indicates that their surfaces are covered with dust. Thus, it is reasonable to assume that the surfaces of the larger asteroids are porous or particulate.

The lunar-type model was pioneered by Allen (1970, 1971a) and Matson (1971a,b) and was the first model used to obtain asteroid sizes and albedos from infrared photometry. Further development and extensive application of this model has been done by Morrison (1973, 1976, 1977b,c), Jones and Morrison (1974), Hansen (1976b, 1977) and Chapman *et al.* (1975).

Model 1, whose parameters are tabulated in Table 3, uses the photometric and thermal properties of the lunar mare to define a model for asteroid surfaces. This model corresponds to a slowly rotating body of relatively low thermal inertia. The following assumptions are made: (1) isotropic emission from each surface element, (2) negligible emission from the non-illuminated side, (3) emissivity constant with wavelength, and (4) no conduction of heat to depth. A closely related variant allows for the possibility of nonisotropic emission from surface elements on the asteroid, *i.e.*, emission peaking toward zero phase as has been observed for the Moon by Saari and Shorthill (1972). This can be approximated by setting β = 0.8-0.9 and leaving $T(\theta,\phi)$ unchanged (however, the subsolar temperature increases); *cf.*, Jones and Morrison (1974). A recent remodel due to Hansen (1977) also accounts for some backside emission. The result of such corrections for nonisotropic emission is on the order of 5-10% reduction in the derived diameter of the asteroid.

Table 3. Model Parameters

Parameter	Model 1	Model 2	Model 3
Analogy	Lunar Surface	Rock	Iron Meteorite
Thermal Response	Low Thermal Inertia	High Thermal Inertia	High Thermal Inertia
Rotation	Slow	Rapid	Rapid
β	1.0	π	π
Emissivity, ϵ	1.0	1.0	0.1
$T(\theta,\phi)$, $\lvert\theta\rvert \leq 90°$	$T_{max} \cos^{1/4}\theta \cos^{1/4}\phi$	$T_{max} \cos^{1/4}\phi$	$T_{max} \cos^{1/4}\phi$
$\lvert\theta\rvert > 90°$	0	$T_{max} \cos^{1/4}\phi$	$T_{max} \cos^{1/4}\phi$

The lunar-type model has been used to interpret the photometry of thermal emission from about 200 asteroids. A recent review of this effort has been written by Morrison (1977c). A table of diameters appears in this volume (Morrison, 1978). Diameters of Vesta have been determined by three other methods. The results are compared in Table 4.

Table 4. Vesta's Diameter by Different Methods

Method	Diameter (km)	Reference
Radiometry*	538 ± 54**	Morrison (1977a) Hansen (1977)
Polarimetry	536 ± 54	Computed from data in Zellner *et al.* (1977c)
Radio	597 ± 41	Computed from data and model of Conklin *et al.* (1977)
Speckle Interferometer	513 ± 51	Worden *et al.* (1978)

*Model 1
**Estimated error

Radiometric Model 2: Rock Surface

While the possibility of the failure of some of the assumptions used in the infrared method has been considered previously (Matson, 1971b, 1975), the data recently obtained for 1580 Betulia by Lebofsky *et al.* (1978) provide the first concrete example where Model 1 does not give results consistent with those obtained by other methods. Based on a comparison with the diameters determined from visual polarimetric (Tedesco *et al.*, 1978) and radar data (Pettengill, personal communication), it would appear that Model 2 as described in Table 3 better represents the actual temperature distribution on the surface of Betulia. This model would imply that the surface thermal properties are dominated by material of high thermal inertia (*e.g.*, rock). While at first this would appear to be in disagreement with the polarimetric results which indicate a dusty surface, any discrepancy would be resolved, if, for example, the rock is covered with a very thin layer of dust.

Clearly, it is possible that the surface of such a small asteroid could consist only of bedrock. However, it is more likely that some regolith is present. Blocks as large as the thermal wavelength (~20 cm) or larger can be present on the surface without significantly reducing the thermal inertia. The effect of such boulder fields has been considered previously in studies of lunar eclipse and lunation cooling data, where they provide an effective means to retain heat into the lunar night (Fudali, 1966; Allen, 1971b; Mendell and Low, 1975). If the polarimetric diameter of Betulia is assumed to be correct, it is then possible to use the requirement of high thermal inertia to place a limit on the amount of fine grain material present. The limit on the areal coverage (using a linear combination of Models 1 and 2) of this material is ≲40% (Lebofsky *et al.*, 1978).

Parameters for Model 2 are indicated in Table 3 and the results are shown in Figure 5 for representative objects in the main belt (*i.e.*, P = 2.7 AU). The main differences of these spectra from those of Model 1 are that a significant amount of thermal emission is shifted to large phase angles (in particular to the night hemisphere) so that the apparent infrared flux observed at the Earth is reduced relative to Model 1. In addition, the effective temperature is lowered so that the radiation peak is shifted to slightly longer wavelengths.

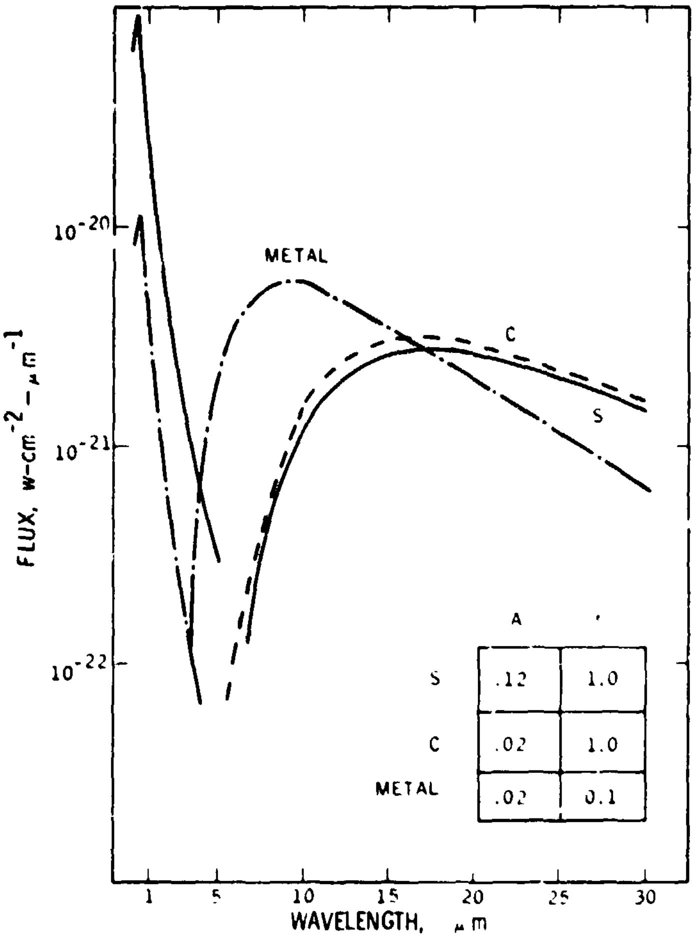

Fig. 5. A comparison of the spectra for C and S asteroids (Model 2) and a metallic asteroid (Model 3) with radii of 1 km at a solar distance of 2.7 AU representative of the main belt Relatively rapid rotation with high thermal inertia results in a significant amount of thermal emission from the night side and a decrease in infrared flux observed at the Earth. Rapid rotation also lowers the effective temperature relative to Model 1 and shifts the peak of the thermal emission to longer wavelengths. The low emissivity characteristic of metallic surfaces increases the effective temperature and shifts the peak of the thermal emission to shorter wavelengths.

Radiometric Model 3: Iron Surface

With modern advances in infrared technology the limiting magnitude to which astronomical objects can be observed has become much fainter. In the future advanced instruments such as the Infrared Astronomical Satellite, Space Telescope and other spacecraft will lead to other significant advances. A few years from now, it will be possible to observe main belt asteroids with diameters as small as tens to hundreds of meters. In this size range it is likely that a number of metal asteroids, analogous to the iron meteorites, will be discovered. In fact, some larger metal-rich objects have already been suggested on the basis of reflection spectroscopy (McCord and Gaffey, 1974; Gaffey and McCord, 1977; Matson *et al.*, 1977a; Veeder *et al.*, 1978).

With these considerations in mind we have started an investigation of Model 3. This model corresponds to a homogeneous metal sphere. As such, it has low emissivity and very high thermal inertia, as indicated in Table 3 and shown in Figure 5. As in Model 2 a significant amount of infrared flux is emitted at large phase angles. The low emissivity raises the effective temperature of the model surface and shifts the radiation peak to shorter wavelengths. The assumption of a low albedo for such an object is as yet only a guess. The chief result of this exercise is to determine the gross characteristics of the thermal spectrum and to develop criteria for recognizing metal-rich asteroids.

DIRECTIONS FOR FUTURE INFRARED RESEARCH

There are a number of problems toward which work can be directed profitably:

a. It is important to determine if the degree of redness (*e.g.*, R_λ(2.2 μm) can be correlated quantitatively with the metal content (*cf.*, McCord and Gaffey, 1974; Gaffey and McCord, 1977).

b. The presence of significant amounts of metal has implications which need to be studied for the radiometric and the polarimetric methods of asteroid size determination.

c. It is important to extend the size of the sample of observed asteroids and meteorites. For example, the Trojan asteroids are known to be significantly different from other asteroids, as well as unlike *any* laboratory sample (McCord and Chapman, 1975).

d. Theoretical studies should be conducted on the origin and evolution of the asteroids using the asteroid reflectance data as well as the meteorite data as boundary conditions.

These and other ground-based efforts will: (1) identify interesting asteroids as potential targets for spacecraft missions, and (2) characterize the asteroids as a whole so that detailed observations from spacecraft visits to a few can be placed in proper context and be used to further understand the origin and evolution of the solar system.

Asteroid observers in Earth-orbit will immediately have the entire thermal emission spectrum available to them as well as all the diagnostic bands in the infrared reflection spectrum. In addition, observations from space have some engineering advantages. It is possible to suppress thermal emission from the telescope and other instrument surfaces by cooling them. Atmospheric emission background no longer floods the detectors, and the limit in performance is lowered to the level of the zodiacal light and of the detectors themselves. The general levels of accuracy and precision are increased because corrections for atmospheric extinction are not needed. The science return from these advances is expected to be great. Observations of the entire thermal emission and reflection spectra will immediately result in improved thermal models and hence more accurate albedos and sizes, and in better interpretations of surface composition. It will be possible to search for compositional information not only via the model emissivity but also directly by measuring any Reststrahling and Christiansen bands present. These bands are related to the Si:O ratio (*i.e.*, the degree of polymerization of the SiO_4 tetrahedron) and the index of refraction, respectively.

Flyby and rendezvous observations will give spatial resolution across the asteroid's surface. This will allow the mapping of geologic units based upon their reflection and thermal properties. Chief goals for spacecraft measurements of the reflected infrared radiation (1-5 μm) are: (1) to map the compositional units on asteroid surfaces at a resolution of better than 1 km for large asteroids (such as Ceres and Vesta) and at better than 1 m for small asteroids (1-10 km diameter), (2) to establish the variety of chemical species present including discrete classes and mixtures of, for example, ices, silicates, oxides, and metals, (3) to study the variation of the degree of hydration within individual units and from one asteroid to another, (4) to map the angular distribution of the scattered infrared radiation and to use this information to infer surface texture and morphological and other properties which are otherwise not directly observable. Emitted thermal data obtained at large phase angles and across the terminator will yield maps of the thermal inertia. Strong constraints on regolith grain size will result. In addition, the amount of bare rock or boulders exposed will be immediately apparent. The detailed study of several asteroids by these methods will give the necessary absolute calibration for future remote infrared observations from the ground or Earth-orbit.

In addition to the foregoing there is an experiment, conceptual in nature, that requires study and development before its implementation can be assessed properly. A small scanning spacecraft at one of the Lagrange points of the Earth-Sun system can be used to search for Apollo asteroids. These objects are relatively bright in the infrared and can be distinguished readily from the celestial background by using their relative motion and spectral signatures. Such an experiment would scan a great circle on the celestial sphere, thus defining a plane. Any object crossing this surface would be discovered, permitting intensive study by all available techniques. A more sophisticated experiment might include the main belt asteroids. The scientific return from this experiment would include a determination of the number density of asteroids as well as identifications according to compositional types.

For the near future, the most important advances from space are likely to come from the IRAS (Infrared Astronomical Satellite) observatory scheduled for launch in 1982. This satellite will be capable of carrying out a total sky survey in a number of infrared bandpasses reaching to a 10 μm N magnitude of about 7 (Aumann and Walker, 1977). If appropriate data processing can be carried out to retrieve the asteroid observations, it may be possible to obtain radiometric diameters of essentially all of the asteroids with known orbits, thus increasing our catalog of diameters by more than an order of magnitude.

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DISCUSSION

McCORD: Can you say whether the H_2O bands observed on Ceres indicate water, or water of hydration? It is a problem not only on the asteroid, but on the satellites as well.
MATSON: Clearly in the laboratory the spectrum of Murchison is due to water of hydration; whether it is water of hydration on Ceres, I don't know.
MORRISON: I would like to make a skeptical comment concerning the use of thermal measurements to obtain compositional data. Although some information on composition is surely present, the fact is that no demonstration of the utility of thermal spectra has been made, largely due to masking of compositional effects in real objects with regolith surfaces. I expect asteroid thermal spectra will turn out to be nearly featureless blackbodies.
VEVERKA: In your thermal models do you allow for nonspherical objects? Couldn't you match Betulia's thermal spectrum by changing the shape?
MATSON: These models assume spherical shapes. Betulia was observed for a long time over several nights, and the infrared lightcurve indicates that shape is not important. The nice thing about these lunar type models, if they work, is that the thermal conductivity is so low that each element is virtually in instantaneous equilibrium with sunlight. If you put shape into the models, there might be only a 10 or 20% difference.
McCORD: Are you sure there is not an error in the flux measurement itself?

MATSON: That was my first question but the observations were so closely linked with standard stars that there is no way to question them. So we had to consider another model based upon the fact that Betulia is a small object and at some size one should start to see rocks instead of regolith.

ARNOLD: Let me ask how thick a dust layer you are assuming in your Model 2?

MATSON: It is too thick if it becomes a thermal impediment and reduces the thermal inertia. So it has to be thick enough, at least a few microns, to get the polarization data but it can't be much more than a millimeter. If you had centimeters of dust, it would be thermally insulating and the lunar type model probably would work.

ARNOLD: As I will say in my paper, if you are doing gamma-ray studies, the scale length which determines whether you are looking at the underlying rock soil or the dust is tens of centimeters. And if you are doing X-ray studies, the scale length is comparable to that for optical measurements.

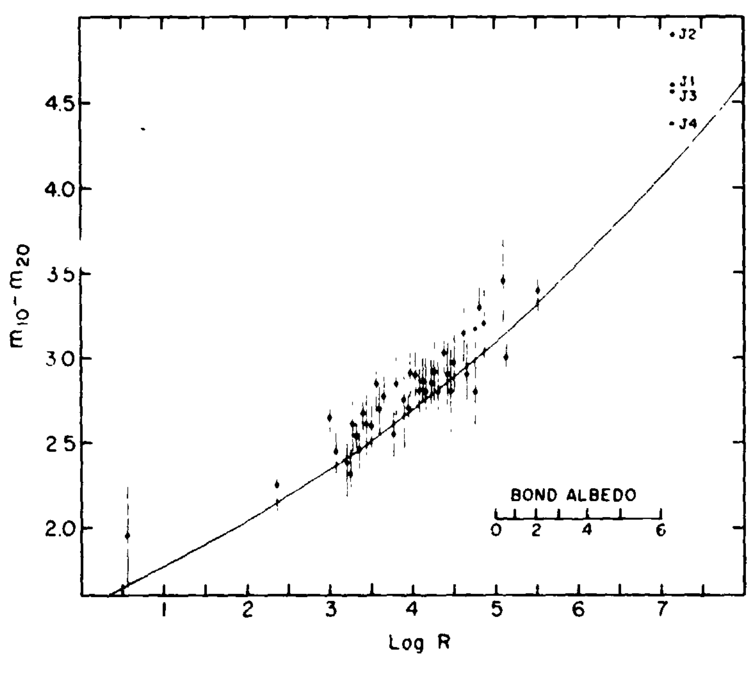
SHOEMAKER: You couldn't distinguish a surface that was broken blocks whose dimensions are typically tens of centimeters from a solid. You can have a regolith of very coarse blocks.

MATSON: We see that on the Moon. A boulder field is seen as a thermal anomaly after dark. It is essentially like bare rock.

CHAPMAN: Isn't it the case that the 10 and 20 μm data, which we have or can obtain, can really distinguish between your Models 1 and 2 and the metal model?

MATSON: Yes. However, you could gain a lot if you could go above the atmosphere or into space and get data at about 7 μm and at 30 or 50 μm. Using 10 and 20 μm data is harder because the effect isn't as large compared to the errors in the data.

MORRISON: I published a graph showing 10 to 20 μm color indices for about 35 asteroids in 1974. There were no anomalies. And since then I have looked at a much larger sample amounting to almost 100 observations and have seen no anomalies of the magnitude that you have calculated for a pure metal model. Clearly smaller anomalies get lost. But it is still interesting that there is a fairly substantial set of data which do not show this effect. (Figure from Morrison (1974) follows.)



MATSON: When you start mixing metals and silicates it gets extremely complicated. But clearly if there is an asteroid with a great deal of metal on or very near the surface, it will be recognized by thermal radiometry.

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ASTEROID COLLISIONS, CRATERS, REGOLITHS, AND LIFETIMES

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Collisional and cratering processes in the asteroid belt fundamentally determine the physical character of the asteroids, including their present numbers, sizes, shapes, spins, internal properties, surface layer textures, and surface topographies. Recent research on these topics is reviewed here, in the context of both asteroidal science and potential mission-planning. Ground-based observational constraints on asteroid collisional processes are relatively weak and indirect. What we believe we understand about these processes results largely from preliminary attempts at theoretical modeling and extrapolation of experiments far beyond laboratory scales. Asteroids, including the larger ones, are a thoroughly fragmented population of bodies if our extrapolations of laboratory experiments to very large scales are at all correct. Interiors of most larger asteroids should be thoroughly fractured. Surface regoliths are probably substantial, except on the smallest and strongest bodies, but should be very poorly mixed in comparison with the lunar regolith. Lateral heterogeneities are probably masked by recent ejecta deposits, except on the smallest and largest bodies. Phobos and Deimos are probably *not* saturated with craters, but in any case do not provide exact analogs for asteroidal cratering. Asteroid crater statistics will provide chronological information pertinent to only very recent epochs of solar system history.

INTRODUCTION

The most important process affecting asteroids subsequent to the early epochs of solar system history has been their collisional interaction with each other and with the complete size-spectrum of interplanetary debris. Of course our knowledge of "geological" processes on asteroids must be based on inferences from remote observation and we may be surprised once we examine an asteroid "up close." But most asteroids are very small and cannot retain atmospheres or generate sufficient internal heat to drive geochemical or endogenic geomorphological processes throughout a major portion of solar system history. Thus we expect that the geological evolution of asteroids has been governed, as has that of the Moon for the last 2-3 AE, by their collisional interactions.

Understanding the collisional evolution of asteroids is now arguably the most important part of asteroidal science for several reasons. First, nearly every observable property of asteroids can be shown to be determined by, or substantially affected by, collisions. Asteroid sizes, shapes, and spins are believed to be due to collisional fragmentation and inferences from telescopic observations concerning asteroid surface compositions and textures depend substantially on the nature and evolution of asteroidal regoliths. A second reason for studying asteroid collisional evolution is that collisions serve partially to mask what asteroids might tell us about the early conditions during the accretionary period of planet formation. A dominant reason for scientific interest in asteroids is, after all, that many of them are--at least compared with the Moon and larger planets--relatively pristine and unaltered objects that preserve clues from the earliest epochs, *provided* we are able to disentangle effects of subsequent collisions. Finally, it is believed that the traits of many meteorites have been shaped by evolution in asteroidal regoliths and that the delivery of asteroidal meteorites into Earth-crossing orbits involves collisional fragmentation in the main belt. The study of asteroid collisional and regolith production processes, as constrained by the properties of meteorites, should help us to interpret meteoritical evidence in a planetological context.

At the high relative velocities in the belt, collisions erode or fracture asteroids as well as create regoliths. Asteroids are ultimately destroyed by catastrophic fragmentations which in turn "create" smaller asteroids. From the known diameters and orbits of asteroids, typical collision rates among objects may be readily calculated. More complicated is specifying the physical outcome of a collision, depending on the relative size of the colliding bodies and on their physical nature (*e.g.*, strength). Gross bounds are provided by conservation of energy and similar considerations. Theoretical and laboratory scale experimental studies of cratering and fragmentation physics have been applied to the problem, but we have no practical experience with collisions of the magnitude that shatter large asteroids. Also, we have only rough ideas about asteroid densities and strengths. Astronomical observations of asteroid sizes, shapes, spins, and inferred surface compositions provide some help in modeling collisional evolution as do meteoritical inferences concerning shock pressures and regolith processing. In summary, some important bounds may be placed on asteroid collisional evolution, but details remain a matter of informed speculation.

Several conclusions and important generalities that will emerge from this paper are summarized here:

1. Collision rates and kinetic energies are sufficient to fragment most asteroids well within the lifetime of the solar system; thus most asteroids, excepting perhaps only the very largest, are of a fragmental nature.

2. Many asteroids in excess of 100 km diameter are probably thoroughly fractured throughout their interiors.

3. Regoliths on asteroids are poorly mixed in comparison with the lunar regolith, except possibly for very large asteroids.

4. Regoliths are thin or absent on small asteroids, especially those of strong rocky composition.

5. Unlike the Moon, for which most crater ejecta are deposited in close proximity to the crater, asteroidal crater ejecta are commonly distributed entirely around the body, tending to mask any underlying lateral heterogeneity.

6. Straightforward approaches to interpreting crater populations on Mars, Mercury, and the Moon cannot be directly applied to craters on Phobos and Deimos, and none of these bodies serves as an exact example of what we might expect on asteroids. Crater populations on an asteroid will reveal the chronology and character of events that have occurred subsequent to the last major fragmentation event in which an asteroid has participated; since such events occur frequently, asteroid cratering records generally will not extend far back in time.

The above conclusions, and others to follow in this chapter, are derived from preliminary theoretical models and gross extrapolations of a few experiments far beyond laboratory scales. Thus, as is the case for any scientific topic for which the observations are mostly indirect, the analyses in this paper should be considered model-dependent and in need of further verification by additional theoretical, experimental and observational work and ultimately by direct examination of asteroids from spacecraft. It would be a mistake, however, to regard the conclusions in this paper as being mere "guesses." Asteroid collision probabilities may be calculated certainly to within a factor of two or three. Given conservation of energy, assessing the possible range of collisional outcomes then becomes a problem in understanding limits on the partitioning of the collisional kinetic energy. Reasonable judgements on this matter constrain the physical nature of asteroids to a considerable degree, but the possibility remains that something is being overlooked.

This paper treats three major topics: collisions and fragmentation, asteroid regolith models, and cratering on small bodies. Much of the paper is based on my own work in progress (in association with D. R. Davis and J. F. Wacker on collisional evolution and with R. Greenberg, K. Housen and L. Wilkening on regolith models). There is little recent literature dealing with asteroid collisional evolution, except for certain specific topics (*e.g.*, Harris, 1978, for discussion of asteroid spins; Wetherill, 1976, for discussion of asteroidal production of meteorite fragments and delivery to Earth). Work on regoliths has dealt almost exclusively with the Moon so far (see review by Langevin and Arnold, 1977). Interpretation of crater populations on small bodies (Phobos and Deimos) is in its infancy; the present paper and comments elsewhere in this volume by Veverka constitute the only extrapolation to asteroids.

COLLISIONS, FRAGMENTATION, AND EVOLUTION OF THE SIZE DISTRIBUTION

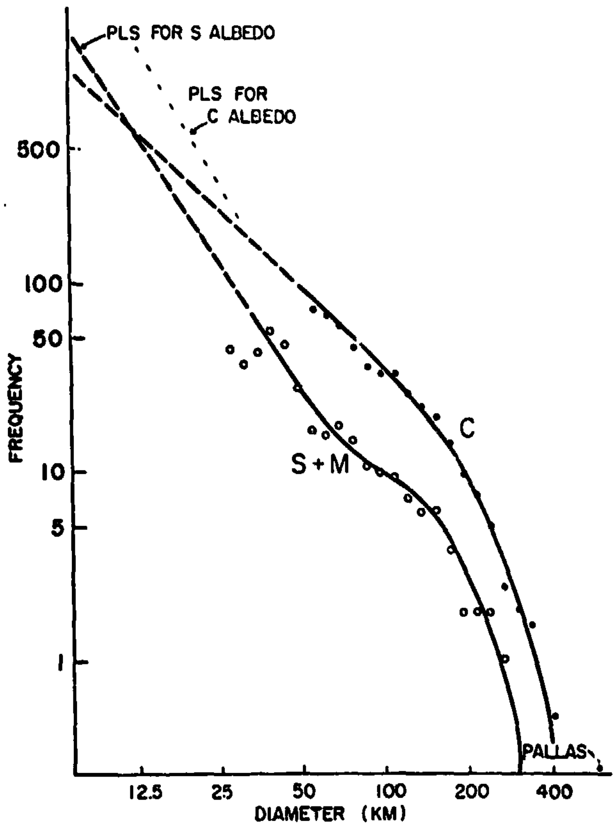
During the past decade, we have learned to measure asteroid albedos and hence diameters with considerable accuracy. Zellner and Bowell (1977) have calculated bias-corrected diameter-frequency distributions for the several spectral types down to 50 km for low-albedo asteroids and down to 25 km for higher-albedo asteroids. The Palomar-Leiden Survey (van Houten *et al.*, 1970) provides data pertinent to asteroids as small as a few kilometers in diameter, but since albedos are not known, the PLS constraints are not very strong (see Figure 1).

The rate of collisions between a target asteroid of diameter D_0 and a field of smaller projectile asteroids of diameters D_1 to D_2 is approximately equal to the collisional cross section of the target ($\pi D_0^2/4$) times the number of asteroids with diameters between D_1 and D_2 (taken from Figure 1) times the mean relative velocities of asteroids ($\sim$5 km/sec) divided by the effective volume of the asteroid belt ($8.5 \times 10^{[illegible]}$ km^3, according to Dohnanyi, 1969). Wetherill (1967) has shown that such particle-in-a-box calculations overestimate collision rates by factors of about 1.5 to 2.

We may usefully distinguish between two types of collisions: (a) those for which the ratio γ between target and projectile diameters is large, resulting in cratering and erosion of the target, and (b) those for which the projectile is sufficiently large (small γ) to result in catastrophic fragmentation of the target (defined as occurring if the largest object remaining after collision is <50% the original mass of the target). Because the exponent of power-law approximations to the incremental diameter-frequency relationship of asteroids has an absolute value <4, most mass (hence most kinetic energy) resides in larger asteroids; therefore the largest collisions are more important in destroying asteroids than the cumulative erosion by small cratering events. But cratering is by no means negligible and, in fact, is wholly responsible for creating asteroidal regoliths.

The fragments resulting from an asteroid collision (whether comprising the entire mass involved in a catastrophic collision or merely the ejecta in a cratering event) may be characterized by the diameter of the largest fragment, the power-law describing the size

Fig. 1. Diameter-frequency distribution for asteroids. Points are bias-corrected counts in increments of 0.05 in log diameter (Zellner and Bowell, 1977). Lines are possible fits and extrapolations, constrained at small diameters by Palomar-Leiden Survey data for two different possible albedos. Figure reproduced from Chapman *et al.* (1978). (Courtesy *Annual Review of Astronomy and Astrophysics*.)



distribution, and the distribution of velocities. The fraction of ejecta traveling at less than the gravitational escape velocity of the target falls back and contributes to the regolith. The remaining ejecta escape and become individual asteroids or smaller debris in their own right.

The previous three paragraphs have parameterized the problem. Let us now consider the collisional physics and what little has been learned from theoretical modeling and Earth-based experimentation. Cratering is somewhat better understood than is catastrophic fragmentation. Not only have more laboratory scale experiments been done on impacts into semi-infinite targets, but nuclear explosion craters provide some basis for extrapolation to larger-scale events. Moreover, computer codes have been written to model hypervelocity cratering, not fragmentation, events. Nevertheless, a catastrophic fragmentation event may be thought of crudely but usefully as the limiting case of a cratering event that consumes a significant fraction of the volume of the entire target. Laboratory-scale fragmentation experiments involving velocities in excess of 1 km/sec are reported by Moore and Gault (1965), Gault and Wedekind (1969), and Fujiwara *et al.* (1977).

The kinetic energy of the projectile is partitioned into several forms of energy upon impact. For rock-into-rock cratering impacts at 5 km/sec, O'Keefe and Ahrens (1977) compute that 20% of the energy goes into heating (including melting and vaporization) of the projectile, another 20% into heating the target, and about 50% into plastic work and comminution. The remaining 10% is partitioned into the kinetic energy of the ejecta. An experiment by Gault *et al.* (1963) shows the distribution of ejecta velocities as a function of mass-fraction. The fraction of ejecta failing to exceed the escape velocity falls back to the surface. It is uncertain to what extent such cratering models are applicable to fragmentation events. But the asteroid size-distribution is such that most catastrophic fragmentation events involve target-projectile ratios only slightly larger than is sufficient for fragmentation, so the events are not grossly dissimilar from large cratering events; hence one might expect roughly similar energy partitioning.

The most important variable, however, is the physical nature of the asteroidal material. Both dimensional analysis and actual experiments demonstrate that the energy (hence projectile mass) necessary to produce a specified amount of damage (*e.g.*, crater of a specified size or fragmentation of a target of specified size) scales roughly as the target strength. Interpretations of spectrophotometry are consistent with some asteroids being similar to carbonaceous chondrites, which have crushing strengths as low as 3×10^6 dynes cm^{-2}; others may be of strong metallic composition with crushing strengths exceeding 2×10^{10} dynes cm^{-2}. Of course asteroids may have bulk strengths much lower than that of their constituent materials if they are already fragmented, which might have resulted from previous collisional history (see below).

Considerable literature exists on energy/diameter scaling laws for craters, especially in rocky and sandy substrates. Much less is known about fragmentation events, but experiments summarized by Greenberg *et al.* (1977) suggest that the effective "impact strengths" of materials are about two orders of magnitude less than crushing strengths; *i.e.*, a basaltic body of crushing strength $\sim 10^9$ dynes cm^{-2} will be catastrophically fragmented if struck by a projectile with kinetic energy $\gtrsim 10^7$ $ergs/cm^3$. Of particular importance to asteroids is the fact that ejecta velocities from impacts into loosely aggregated material (*e.g.*, sand) are ~ 2 orders of magnitude less than velocities from impacts into rocks (Stöffler *et al.*, 1975); a general velocity dependence on strength is suggested and it may apply also to fragmentation events, but the phenomenon has not been well documented.

For 5 km/sec asteroidal impacts, catastrophic fragmentation may be expected to result when $\gamma \lesssim 18$ for hard, rocky bodies, $\gamma \lesssim 7$ for iron bodies (at temperatures above the ductile/brittle transition), and $\gamma \lesssim 50$ for very weak bodies. For "supercatastrophic" collisions, involving γ much less than the limiting values just listed, the excess energy produces more comminution resulting in a smaller diameter for the largest fragment and a larger population index for the fragmental size distribution (see discussion in Greenberg *et al.*, 1978).

In order for an asteroid to be "destroyed," it must not only be fragmented, but the fragments must have sufficient kinetic energy to overcome their mutual gravitational attraction. Roughly, this will happen if the portion of projectile kinetic energy that goes into fragmental kinetic energy (perhaps 5 to 10%) exceeds the gravitational binding energy of the target. In detail, it is required that most of the fragments, especially the most massive ones, are accelerated to velocities exceeding the body's escape velocity. For solid, rocky bodies $\lesssim 100$ km diameter, any impact sufficient to fragment the body will also be sufficient to disperse the fragments. But, for a larger, rocky body, it may be marginally fragmented but fail to be dispersed; such an event converts the body into a "pile of rocks" which no longer has substantial internal strength. Similar behavior would occur for weaker bodies $\gtrsim 10$ km diameter. Such asteroids will not be dispersed until involved in a "supercatastrophic" event that partitions sufficient energy into kinetic energy to overcome the gravitational binding. Of course, when that occurs the largest fragment from such an already broken-up body will be *much* smaller than the original body--to first order one might simply assume the body has disappeared as an observable asteroid and been converted into small interplanetary debris.

Chapman and Davis (1977) and Davis and Chapman (1977) have been investigating asteroid collisional evolution models, employing the parameters and concepts discussed above. In particular, they have considered the simultaneous collisional interaction of two populations of asteroids, one consisting of strong bodies, the other of weak bodies. They have studied the collisional evolution of the present asteroid belt (*e.g.*, the bias-corrected populations of Zellner and Bowell, 1977) as well as hypothetical augmented early asteroid populations. A number of important results are as follows:

(1) The asteroids presently impact each other with sufficient frequency that most large asteroids must be expected to have been catastrophically fragmented within the last several billion years. Provided that 5% to 10% of the kinetic energy is available for fragment dispersal, most large asteroids have lifetimes against disruption shorter than the age of the solar system even with the present low population density. Thus those that we see now must be either (a) fragments of rare larger bodies that chanced never to have been converted into a "pile of boulders" by earlier catastrophic impacts prior to catastrophic disruption; or (b) remnants of rare larger bodies that chanced to escape disruption and have been whittled down by gradual erosion. Since the characteristic lifetime against catastrophic fragmentation varies roughly as the square-root of the asteroid diameter, all small asteroids must be regarded as being multi-generation and/or recent fragments of larger bodies. These expectations are in accord with several observations: asteroid spins are those expected for a collisionally evolved population (Harris, 1978) and asteroid shapes seem to be irregular except for asteroids sufficiently large and weak that gravity induces sphericity.

(2) Asteroid size-frequency distributions are not expected to be linear on a log-log plot. It had been argued previously that all asteroids (Dohnanyi, 1972) or at least collisionally-evolved C-type asteroids (Chapman, 1974) should exhibit such a linear distribution. But two effects lead to nonlinearities: (a) the effects of gravity holding together fragmented objects until supercatastrophic collisions disrupt them, and (b) the interaction of populations of different strengths. Figure 2 illustrates one run of the Chapman-Davis program, resulting in nonlinear size-distributions for two types of asteroids that mimic rather closely the observed distributions for C and S types.

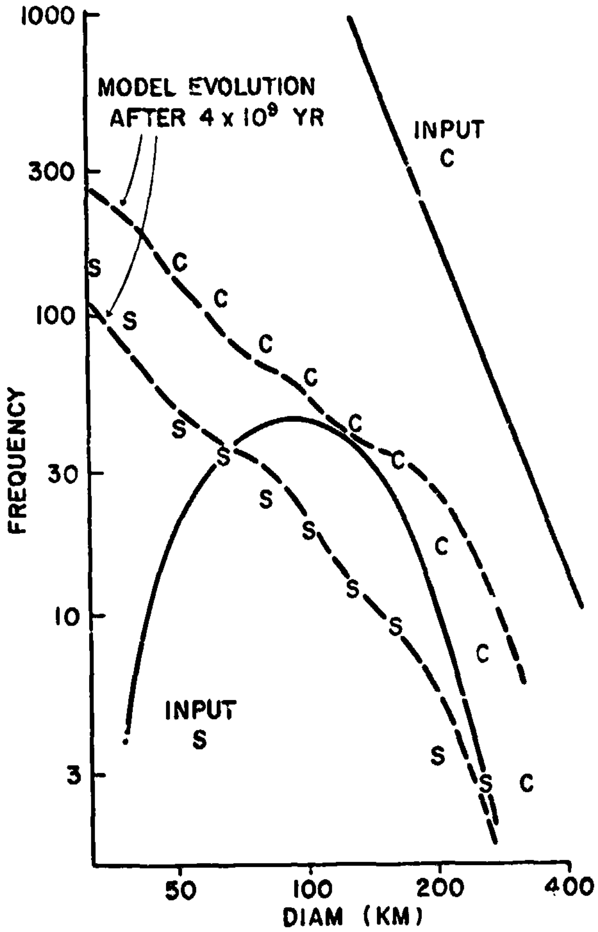


Fig. 2. Comparison of Chapman/Davis evolution model with observations. For this particular run, initial size-distributions were chosen (solid lines) to model the type of scenario described by Chapman (1976). C and S asteroids were taken to have crushing strengths of 5×10^7 and 2×10^{10} dynes cm^{-2}, and densities of 3 and 5 gm cm^{-3}, simulating carbonaceous and iron-rich asteroids respectively. Impact strengths were taken to be 6% of crushing strengths. The mass of the largest fragment involved in a supercatastrophic disruption was taken to be one-eighth the original mass; much smaller fractions, depending on energy density, might be more appropriate and would result in diminished production of middle-sized asteroids. The dashed curves show the evolved C and S populations after 4×10^9 years. Plotted for comparison are bias-corrected frequencies of C and S asteroids observed today (Zellner and Bowell, 1977). The frequencies are per interval of width 0.1 in log diameter.

(3) The present asteroid population *may* be a remnant of a much larger early population (Chapman and Davis, 1975). Figure 2 is typical of virtually all runs of the collision evolution model in that input populations orders of magnitude greater than the present belt (such as "input C" in Figure 2) always decay to distributions approximating the present belt (in both slope and intercept) after several billion years. The only potential large populations that fail to evolve to the present belt are those in which most of the mass is originally stored in bodies substantially larger than Ceres approaching lunar size. Note that result (1), that asteroids are highly fragmented, does not depend on the early asteroid population being more populous than today; *present* impact rates are sufficiently high to lead to high fragmentation rates, even if the asteroid belt originally contained only a fraction more mass than it does today. In fact, the present distribution and nature of asteroids may provide clues as to whether the population truly was greater in the past. Chapman and Davis (1975) argued that the belt might have been ~300 times more populous based on the characteristics of an inferred remnant population of very strong iron-cores of precursor bodies. This inference is highly model-dependent and should not be regarded as a secure determination of the early asteroid population.

Several sources of uncertainty require emphasis. First, because of the relatively large values of γ sufficient for catastrophic fragmentation, the evolution of main belt asteroids of observable sizes depends on the frequency of very-much-smaller asteroids--those too small to have measured surface compositions and often so small as not to have been discovered or sampled at all. Thus future observations pertaining to the frequency and probable bulk compositions of asteroids in the 100 m - 10 km size range would be very important. Second, more experimental and theoretical work is necessary to understand how projectile kinetic energy is partitioned into comminution energy and especially into ejecta or fragmental kinetic energy. Large quantities of energy could be partitioned into heat without necessarily melting major amounts of rock. Should much less than 1% of the energy be available for kinetic energy, asteroid lifetimes might be much longer than we think. Should smaller fractions of energy be available for comminution throughout the asteroidal volume than is true at laboratory scales, asteroids might be less fragmented than we think.

ASTEROID REGOLITHS

Lunar scientists have developed a comprehensive understanding of the lunar regolith (Langevin and Arnold, 1977). Asteroid regoliths have received little attention, however. Most discussion has concerned possible particulates in the optical surface layer that would influence polarimetric properties (*cf.*, Dollfus, 1971, and discussion of that paper by Anders and Chapman; also Dollfus *et al.*, 1977). More recent interest in asteroid regoliths has come from meteoriticists who require environments of substantial volume in which to produce the numerous gas-rich and brecciated meteorities (*cf.*, Macdougall *et al.*, 1974). If asteroid regoliths are, in fact, so thick as to constitute a substantial portion of asteroid volumes (*e.g.*, as argued by Anders, 1975, 1978), then models of the collisional evolution and lifetimes of whole asteroids must take regoliths into account, since crater volumes and ejecta velocities from impacts into regoliths are very different than for impacts into rock (see previous section).

Asteroids differ from the Moon in two important respects. First, in the asteroid belt the flux of impacting objects >10 km diameter is roughly three orders of magnitude greater than in near-Earth space. Second, asteroid gravities are much less than lunar gravity, with escape velocities typically ranging from meters per second to hundreds of meters per second. Lesser considerations are: (a) impact velocities are lower in the belt than for the Moon; (b) asteroid compositions are generally different from lunar composition; (c) most asteroids are more irregular in shape than the Moon; and (d) asteroids spin relatively rapidly.

Housen *et al.* (1978) have developed a model of asteroid regolith evolution. It considers the buildup and erosion of regoliths on asteroids from the time an asteroid is created with a bare surface to the time an asteroid is struck by a sufficiently large impact so that it is catastrophically fragmented. At that point, the whole asteroid, if it is not dispersed, is converted into a "pile of rocks" or a megaregolith. Housen *et al.* distinguish between a "typical region" on an asteroid and atypical localities where occasional sparsely scattered large impacts have occurred. The depth of regolith in the typical region is determined by competition between processes that create regolith and those that erode and eject it. Regolith is created by the deposition of ejecta from the large craters outside of the typical region. Regolith is also created by small craters in the typical region (and elsewhere) that penetrate existing regolith, comminute basement rock, and spread their ejecta around the typical region. Regolith is lost by the ejection of some portion of crater ejecta at greater than escape velocity.

An essential assumption of the Housen *et al.* model, in its present state of development, is that crater ejecta are widely distributed around an asteroid. Figure 3 shows how ejecta distributions are localized on large bodies, such as the Moon, and on smaller bodies of sandy composition. But on still smaller sandy bodies (<10 km diameter), or on rocky bodies smaller than a few hundred kilometers diameter, the predominant ejecta velocities approach escape velocity and the fraction of ejecta that fails to escape surrounds the asteroid with a blanket of roughly uniform thickness.

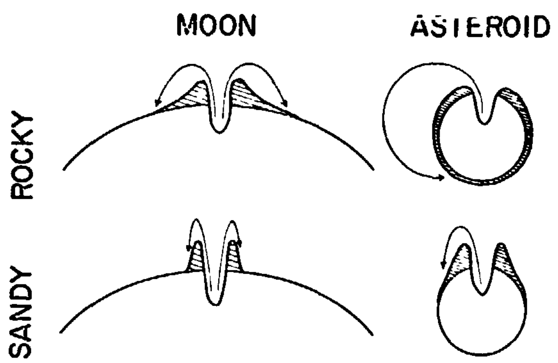


Fig. 3. Schematic illustration of the distribution of crater ejecta on Moon-sized and asteroid-sized bodies with rocky and sandy substrates. Typical trajectories are shown. Ejecta velocities are greater from craters created in rocky surfaces. Ejecta blankets are relatively localized on a Moon-sized body but may completely surround an asteroid, especially a small, rocky one. Vertical relief is exaggerated 10:1.

The incremental size-distribution of interplanetary debris is believed to be roughly described by a power law with an exponent between -3 and -4. Such a distribution is characterized by having the predominant surface *area* in the small size fractions but the predominant *mass* in the large size fractions. Provided that energy-scaling applies (*i.e.*, crater volumes vary as projectile volumes for constant impact velocity), an asteroid surface area is predominantly covered by small craters, yet most of the ejecta are produced by the largest craters. It is for this reason that it is useful to study the "typical region" described above, which is defined as that spatially evolving fraction of an asteroid surface that contains craters smaller than D_s, the diameter of the largest crater that "saturates" the surface of the asteroid. (D_s is obtained by integrating the areas of all large craters formed from t = 0 to the current time-step, from the largest crater down to craters of diameter D_s, constraining the total area to be one-third of the area of the asteroid. Thus, two-thirds of the asteroid surface is deemed to be "typical.") As time evolves, larger and larger craters contribute to saturating the surface, so D_s increases and the "typical region" changes shape to include them and to exclude recently formed craters larger than D_s.

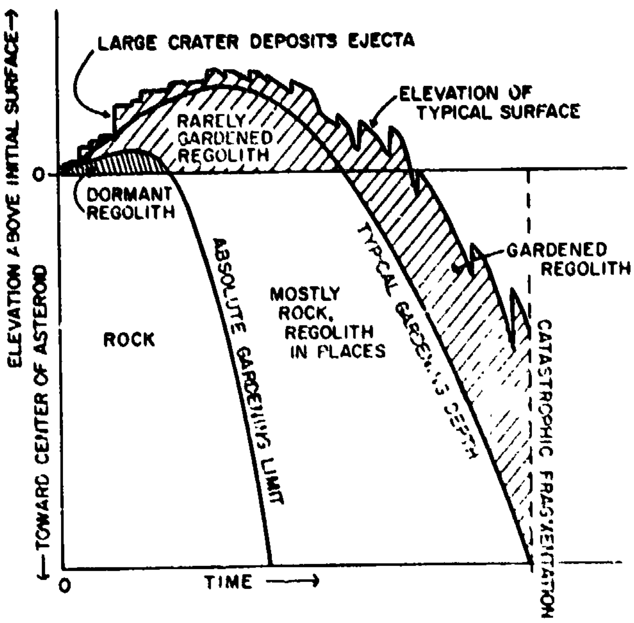


Fig. 4. Schematic illustration of regolith evolution on a typical region of a small asteroid. Regolith is built up mainly by ejecta from occasional large, sparsely scattered craters outside the typical region and is "gardened" by numerous small impacts within the region. The jagged shape of the surface elevation curve is due to discontinuous deposition. In reality, the typical and absolute gardening depth lines, here shown as smooth, would mimic the jagged shape of the elevation line. There may be a dormant zone in which ejecta once deposited is buried too deeply to be gardened for a while. The "typical gardening depth" is the depth at which one turnover occurs per characteristic time scale. Catastrophic fragmentation usually occurs before the asteroid is completely eroded away.

Figure 4 illustrates the evolution of regolith on the typical region. Initially only the smallest craters saturate the surface, hence little ejection of material occurs. Larger craters in atypical regions deposit ejecta all over the asteroid and, in particular, onto typical regions, causing the elevation to rise. The regolith is built up discontinuously, with the biggest jumps being due to the largest craters. During the early period of maximum deposition and minimal erosion, a dormant zone may be created in which ejecta deposits are shielded from the subsequent excavations by craters smaller than D_g. Note that the vertical distance between the curves for the surface and the "absolute gardening limit" corresponds to the depth of a crater of diameter D_g. While regolith or rock can be excavated down to the absolute gardening limit, the material remains undisturbed in most places. The *typical* depth at which material is gardened at least once during typical time scales for deposition or erosion of regolith is the depth of the (smaller) craters that saturate the surface during such short time scales.

With passing time, larger and larger craters are included in the typical region and ejection becomes more efficient. Simultaneously, because there is a maximum size crater that can impact an asteroid without catastrophically fragmenting it, the range of crater sizes that contributes to deposition from afar onto the typical region shrinks. Increasing erosion and decreasing deposition lead to a maximum in surface elevation, followed by net erosion from the typical region. Eventually a sufficiently large impact occurs that the asteroid is fragmented and the regolith evolution model is no longer applicable.

Cases have been run for rocky asteroids ranging from 1-300 km diameter and for weakly cohesive asteroids between 1-30 km diameter. A weakness in the present Housen *et al.* model is that large, rocky asteroids that develop appreciable regoliths are treated as wholly rocky bodies, in calculating ejecta volumes and velocities, rather than as two-layer bodies with a weakly cohesive layer overlying a rocky substrate. Nevertheless, we can qualitatively understand such bodies by recognizing that they respond to smaller cratering events like weakly cohesive bodies. The Housen *et al.* model is especially inapplicable to large, weakly cohesive bodies for which ejecta velocities are insufficient to surround the asteroid with ejecta. Local gardening and erosion must occur on such bodies as on other asteroids, but deposition from large, distant craters is not uniform across the typical region. Instead, there are regions adjacent to atypical regions with much greater deposition and regions far from atypical regions with much less deposition than would be calculated by the model.

Housen *et al.* have varied model parameters. The following conclusions seem to be reasonably secure. Small (*e.g.*, 10 km diameter) rocky asteroids generate virtually no regolith and simply erode away until the asteroid is catastrophically disrupted. Rocky asteroids of >100 km diameter generate regoliths of hundreds of meters in depth, but the regoliths are very poorly mixed compared with the familiar lunar case. Small (10 km), weakly cohesive asteroids generate a few meters of poorly mixed regolith. Large, weak asteroids have not been treated because of the inapplicability of the uniform-deposition assumption, but may be expected to have large but variable depths of regolith. Regoliths on such asteroids are better mixed than on other asteroids, but probably are less well-mixed than the lunar regolith.

The upper couple of meters of lunar mare regolith is the classic regolith. Since Apollo, meteoriticists have recognized some similarities between meteorites and lunar soils and breccias. But there are important differences, mainly in the sense that the regoliths on meteorite parent-bodies are less "mature" than the lunar regolith. This is understandable because meteorites sample greater depths than do lunar samples and because asteroid regolith processes differ from those occurring at the lunar surface.

Although it is beyond the scope of this paper to describe ways that meteorites are produced and delivered from the asteroid belt, suffice it to say that because the asteroid size-distribution contains most volume in large bodies it is required that meteorites must come chiefly from large-scale collisions. The exact scale of collisions depends on the efficiency with which meteorites are delivered to Earth from various collisions, but meteorites must typically sample parent-bodies to depths of kilometers. Thus, the lunar mega-regolith (and examples of it among highland breccias) provides a better analog for meteorites than does the surficial regolith studied from lunar core tubes and other means. The size distribution of lunar cratering projectiles that yield craters with depths greater than a few hundred meters is known to be relatively shallow on a log-log plot, yielding more blanketing and less repetitive gardening than is true at smaller scales; the same should be true of asteroidal regoliths sampled at depth.

Two factors applicable to smaller and rockier asteroids that distinguish them from the Moon are ejection of substantial fractions to space and deposition from afar. Both factors tend to reduce the chances that a grain can be repeatedly bombarded. After participation in only one or a few cratering events, the probability becomes great that a near-surface grain is ejected to space. Also, each sizeable impact anywhere on the asteroid results in deposition of a layer that protects a grain from being involved in a crater-forming event. Another distinction between asteroids and the Moon is that the damage done by an impact at 5 km/sec in the belt is much less than that done at ~15 km/sec on the Moon; thus agglutinate formation should be much reduced on asteroids, compared with the Moon, even if all other factors were equal. Interplanetary comparisons of regolith maturity have been made by Matson *et al.* (1977).

The Housen *et al.* regolith production model for smaller, rockier asteroids implies that any impact in an atypical region would blanket the rest of the body with ejecta from that locality. In effect, such asteroids "paint themselves gray" (or whatever color) during each major impact event, masking whatever compositional heterogeneity may lie beneath. In reality, of course, a crater volume of ejecta is not spread uniformly over an asteroid, but must cluster somewhat due to variable ejection velocities and angular heterogeneities (*e.g.*, lunar rays). Furthermore, the coarser the ejecta are, without a preponderance of fines, the larger a crater must be for its ejecta to mask the entire surface of an asteroid. In the absence of any firm constraints on ejecta trajectories and size distributions, it might merely be noted that virtually all measured asteroids are compositionally homogeneous on a global scale, which may reflect the efficiency of regolith distribution processes or, alternatively, an underlying compositional uniformity for most asteroids (Degewij and Zellner, 1978). Vesta is one asteroid for which regional color and albedo differences are well documented, but it is a large body well outside the range of applicability of the Housen *et al.* model. Crater ejecta are far too localized to mask Vesta's underlying compositional heterogeneity. Lateral heterogeneities would be expected to be absent from all asteroids except the following: very large rocky asteroids, moderate to very large weak asteroids, small rocky asteroids (that lack regolith altogether), and relatively "new" asteroids of any size.

CRATERING ON SMALL BODIES

Most of our experience in studying lunar and planetary cratering processes has involved the Moon and larger planets. With Mariner and Viking imagery of Phobos and Deimos now available, there have been initial attempts to understand the cratering records on much smaller bodies. Some interpretations have been formulated in terms applicable to larger bodies, but which may not be relevant for small bodies. More recently, there has been some thinking about Phobos and Deimos as asteroid analogs and we must bear in mind certain differences between these small satellites, located deep in Mars' gravity well, and heliocentrically orbiting asteroids of various sizes.

Cratering on small satellites and asteroids differs from planetary cratering in several respects. Some differences are discussed in the previous section, including the fact that crater ejecta often completely surround small bodies and much may escape such bodies altogether. Another difference is that although smaller bodies are hit less frequently by very large impacts, when they are hit, they may catastrophically fragment, whereas planets are never hit by impacts sufficient to destroy them. We may compare the evolution of craters on a small body with the evolution of craters on a small portion of the Moon having the same area. To the extent that the local lunar area is affected by very large events occurring elsewhere on the Moon (a basin-forming impact, for instance), the small body would be totally unaffected (*i.e.*, the projectile would miss the body entirely). The small lunar area may, alternatively, be struck directly by a moderately large cratering event (*e.g.*, crater diameter half the diameter of the region) while such an event on a small body would catastrophically fragment it, ending the evolution of that body. Moreover, those projectiles that *do* strike the small body without fragmenting it will produce different effects from those of a similar projectile striking the small lunar region because of different gravity and possible differences in competence of the surface layers. Generally, as argued in the previous section, there is more uniform deposition of ejecta on a small body than on a large one.

There are two major differences between martian satellites and asteroids of similar size. First, the impact rates are far less in the vicinity of Mars than in the asteroid belt. Second, ejecta that escape Phobos and Deimos rarely if ever can escape the gravity of Mars itself. As argued by Soter (1971), the ejecta orbit Mars; eventually most of this may be reaccumulated by the satellites. Because of this effect, the martian satellites may be like the Moon in that most ejecta returns to the body, but unlike the Moon in that ejecta are rather uniformly distributed over the whole satellite.

Craters have been used to address a number of important planetological questions, including the relative and absolute ages of units and the effects of endogenic processes on planetary surfaces. A critical question in all interpretations of cratering populations is whether or not the crater populations are in equilibrium between crater-formation and crater-destruction. The most important crater-destruction process on a body that is geologically "dead" is the cratering process itself (overlap, erosion, and deposition of ejecta). It has been commonly thought (*cf.*, Thomas and Veverka, 1977) that the crater populations on Phobos and Deimos are "saturated" (*i.e.*, in equilibrium with the cratering process) because crater densities approach a lunar "saturation curve" due to Hartmann. But the differences bet martian satellites and the Moon described above yield different expected saturation densities. In particular, one would expect higher saturation densities on martian satellites, for at least two reasons: (1) Marcus (1970) has shown that the equilibrium crater density varies inversely as the logarithm of the dynamic range of the crater dimensions. Since the largest crater on Phobos is much smaller than lunar basins, the saturation density of small craters on Phobos should be higher than for craters of the same size on the Moon. (2) To the extent that crater ejecta are widely distributed, hence thin, on small bodies, moderately large craters on small bodies cannot be obliterated by blanketing, whereas those proximate to cratering events can be obliterated on large bodies.

Further analysis of cratering on small bodies is required, but it seems likely that the apparently sub-saturated crater populations on Phobos and Deimos imply that the surfaces of these bodies are relatively "fresh." This could have resulted from the creation of these satellites by fragmentation of larger precursor bodies at a time sufficiently recent that saturation has not yet been reached. Such a situation is not unreasonable, since the probability of catastrophic fragmentation becomes large as saturation is approached, provided (as seems to be true for craters larger than about 1 km) the slope of the incremental power-law describing the cratering distribution has an absolute value $\lesssim 3$. Surely, in the asteroid belt, and possibly near Mars, the impact rates are so high that the lifetimes of small bodies are much shorter than the age of the solar system. Therefore, crater counts on asteroids will provide information pertinent to recent epochs only and cannot shed light on absolute or relative chronologies of events happening earlier in solar system history.

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DISCUSSION

VEVERKA: Could you summarize for me the physics of breaking up an object?
CHAPMAN: There is a certain kinetic energy in the projectile, which is well defined and gets liberated by the impact into several kinds of energy. It breaks the bonds that are holding the material together. Some of it is converted into kinetic energy of fragments.
VEVERKA: But isn't the problem knowing whether it makes a lot of little pieces or a few big pieces?

CHAPMAN: That is right. What is the size distribution of crater ejecta or fragments of some large broken up asteroid? We don't have any experiments on this scale. Certainly experiments have been done over a range of sizes on a laboratory scale, and I believe the basic physics is understood. When you impact something a shock wave will propagate across the body. You are going to deposit more energy per unit volume near the point of impact than you do farther away. So on a qualitative level, at least, one can be quite sure the target is smashed up into a lot of small particles right at the point where the impact occurred. The far side of the body will split apart into a few big pieces simply because a few fracture planes went through. I would add, however, that the velocity associated with the resulting fragments is also critical. The low gravity of an asteroid is a very fundamental characteristic; unlike the Moon where all the ejecta falls back, for an asteroid some really significant fraction of the ejecta escapes.

ZELLNER: What is the time scale in the present asteroid belt to crater a freshly broken surface?

CHAPMAN: The lunar mare surfaces are saturated with craters less than about 100 m in diameter. So if you are talking about that size crater and if the time scale is three orders of magnitude shorter than for the Moon, then the surface is cratered in about 4 million years.

VEVERKA: There is a difference between an equilibrium density and a saturation density. The latter is determined by seeing how many circles of a given diameter you can fit into a given area. But there will be fewer craters of a given size in the equilibrium situation because in the real world craters are destroyed by a variety of processes which are not modeled adequately by simply drawing circles on a plane. Even on a small asteroid craters are affected by ejecta from other cratering events, but the effect may not be as important as it is in the case of the Moon. Thus we might expect crater densities higher than those in the lunar uplands, but still below the theoretical saturation limit. The important question is how much higher might the equilibrium crater densities on a small body be?

SHOEMAKER: Quantitatively, the lunar crater equilibrium distribution is the result of the smaller craters destroying the big ones by local transport of surface material. Qualitatively, you would expect the same thing to happen on Phobos and Deimos because most of the ejecta that escape from these moons is swept up again. If you are correct about asteroids, that most of the ejecta are lost, the equilibrium density will be higher.

CHAPMAN: What is happening on the Moon happens the way you say it does because of the size distribution of small ejecta. Marcus (1970) discussed the size distribution of larger craters on the Moon for which the production function has a shallower slope. I think his concept is relevant for interpreting the number of moderately large craters on Phobos or on any asteroid. I agree when you get down to the smallest craters, where the size distribution is very steep, then it happens as you describe.

GROSSMAN: You say that the impact rates in the asteroid belt are so high and for many asteroids a very large fraction of impact ejecta may be lost from the body completely. Has very much attention been paid to the possibility that the regoliths on some of those bodies, maybe many of them, may not be from the body itself but from others?

CHAPMAN: Yes, I think that has been thought about. You can apply this kind of analysis to see what happens when a grain of sand or a tiny little pebble impacts a large asteroid. If you are in a regime where you are losing most of the mass by big impacts, you will probably lose most of the ejecta from small impacts, too. The velocity of the ejecta depends mainly on the velocity of the impact and is nearly independent of the mass of the projectile. The small impacts therefore produce erosion, too, and there is a net erosional regime on all asteroid surfaces. On the Moon, where you may or may not have net erosion, meteoritic material accounts for 2% of the regolith. It is going to be less than that on any asteroid.

ANDERS: The amount of extraneous meteoritic material in gas-rich achondrites ranges between 0.3 and about 5%. So, judging from these meteorites, the amount of extraneous material that falls on asteroidal regoliths is indeed a small fraction.

ARNOLD: An effect which is small on the Moon, but which is responsible, I think, for the smoothness of the Moon's surface, is the fact the low velocity ejecta tend to move down slopes rather than up slopes. A fresh surface is rough, but after a while the little hollows fill in. On the smaller asteroids, the difference in gravitational potential between one point and another is comparable with the total gravitational potential. So even though things are thrown around much more widely, there may very well be a strong tendency for things to move down-slope, to move into the lows and to expose the mountains, ridges and high spots. If that is correct, it may well turn out there are high bare patches and filled low patches on small irregular asteroids.

CHAPMAN: I would have thought it would be the other way around. If the gravity were low, wouldn't the ejecta go to any point independent of whether it were a mountaintop or not?

ARNOLD: I am saying the difference between the gravity at the highest point and at the lowest point is a large part of the total gravity. In a situation like that, I don't care how low the total is, the material that doesn't escape is going to accumulate in the lows, whether it starts in the highs or the lows. I think that is a big effect.

WOOD: But the frictional forces that tend to resist down-slope motion are constant, and must more effectively inhibit down-slope movements where g is small than where it is large.

ARNOLD: Well unfortunately it isn't clear but it has an exciting potential. If it were true, it would expose clean surfaces on the highs. It is an experimental fact, whether my model is right or not, that the lunar rocks are clean and stand out. Although fillets are observed they are never very prominent. I don't know whether this effect would be more pronounced on the asteroids, but for now I am prepared to defend it.

FANALE: It is interesting, philosophically, because this is the first time that idea has been mentioned. It may be an example of a whole class of things have haven't been discussed here because they haven't been thought of yet.

CHAPMAN: That is entirely correct, and I want to say again that my comments about asteroid collisions, regoliths, and craters represent, as far as I know, a fair summary of the very limited state of knowledge about these matters. It is theoretical. There are no laboratory observations at appropriate scales.

WOOD: What is the basis for thinking that crater ejecta distributes itself evenly over the surface of an asteroid instead of being concentrated near the crater rim? My physical intuition doesn't lead me to that conclusion.

CHAPMAN: Consider the material which is launched into space and then lands. (I am not talking about crater rim material which has simply been shoved.) It goes much farther if you have low gravity. Clearly if you are losing some substantial fraction of the ejecta entirely to space, the area over which the rest of the ejecta is distributed is going to be pretty large.

SHOEMAKER: Let me describe one feature of an experiment done repeatedly at Ames Research Center--firing shots into a sawn vertical rock face. A tremendous flood of material is ejected from each at high velocity. But if you look at the high-speed pictures. in addition to all the rapidly moving objects, there are very often big spalls that are just barely ejected and fall to the floor of the shot chamber. In the typical crater formed in hard rock, some big chunks of rock are just barely lofted out of the crater. Thus, I expect that even on very small asteroids some material will pile up near each impact crater.

WETHERILL: Generally, I am sympathetic with the idea that the small asteroids are a steady-state population, being produced from their larger neighbors, and destroyed by collisions. I think there are also some observational data that might make one worry about how far this concept should be extended. In particular, the Hungaria region is an isolated region of the asteroid belt fenced off from everywhere else by several resonances. The largest object in there is 434 Hungaria which is a small object, about 10 km. It is not really a family; there is a group of things that are probably fragments from Hungaria gathered around it and some more dispersed objects which are very unlikely to be direct collision ejecta from that object. They are typical PLS objects, 1 km size. So in this region of the asteroid belt, as far as we know, there is no way to replace what gets destroyed. You may say they don't collide much because their semimajor axis is 1.9 AU. That doesn't really hold up too well because a lot of asteroids get into that region and their collisions with the Hungarias occur at high velocity.

You make up for the small number of collisions with very catastrophic collisions. Somehow or other the Hungarias are preserved. You might say it all broke up yesterday and some of the fragments had much more velocity than we thought. Put them all together and most of the mass is still in 434 Hungaria.

CHAPMAN: Another example which is very peculiar is the size distribution of asteroids between the 2:1 and 3:2 commensurabilities with Jupiter. They are outside the main belt but should have fairly significant collision interactions. Yet, there are no small asteroids in this region; they are all large. The PLS turned up almost no new asteroids just interior to the Hildas.

SHOEMAKER: An important issue here is the size distribution of fragments. There is an easy "kitchen experiment" one can do to see what kind of fragment distributions you get when you are right at the threshold between making a crater on an object and knocking the thing apart. All you need is a hunting rifle and a collection of rocks. With a little experimentation you will find the critical rock size. Once you pass the threshold of catastrophic fragmentation, lots of fine fragments are produced. But there is a critical interval, as this threshold is approached, where a peculiar variation in the distribution of large fragments relative to little pieces is found. When I look at the magnitude distributions of asteroids in some of the Hirayama families it reminds me of this critical range.

CHAPMAN: The paper by Fujiwara *et al.* (1977) has some improvements in the theory of size distributions from such marginally catastrophic events and I think that regime is better understood now.

VEVERKA: When I said that the physics might be different in the case of a typical asteroid, what I had in mind is that even before an asteroid suffers the ultimate catastrophic impact which demolishes it, it has already suffered a whole series of slightly less severe collisions which have caused a lot of internal fracturing and weakening. Thus when the big impact does take place, how the asteroid comes apart must be determined in part by how it was pre-fractured.

SHOEMAKER: Gault and Wedekind (1969) did a relevant experiment in which they repeatedly fired projectiles at spheres. Damage was accumulated in the spheres. Their experiment is an idealized version of the problem, but I think that their results give a quantitatively correct picture.

CHAPMAN: It is quite clear that there ought to be many impacts on the larger asteroids, larger than 50 km or so in diameter, that are sufficient to break the object up but insufficient to loft large pieces into space. Before you catastrophically rupture something entirely and disperse it into a Hirayama family, you will have created basically a pile of boulders.

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EARTH-APPROACHING ASTEROIDS: POPULATIONS, ORIGIN, AND COMPOSITIONAL TYPES

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Earth-approaching asteroids are small bodies of stellar appearance which pass close to the orbit of the Earth. Some of these asteroids are the easiest bodies to reach by spacecraft, beyond the Moon. Physical observations suggest they have a broad range of composition and that at least a few may be the most primitive solid bodies that are readily accessible for detailed study. Hence they are of special interest for exploration. At least two different kinds of bodies probably are represented among the Earth-approaching asteroids: (1) fragments of main belt asteroids, and (2) extinct comet nuclei. The number of Mars-crossing asteroids appears to be sufficient to sustain no more than 20% of the Earth-crossing asteroid population in steady-state, and the ratio of the number of Earth-crossers to Amor asteroids (1.02 AU < q $\leq$ 1.30 AU) appears to be an order of magnitude higher than that expected, if all near-Earth objects were derived from Mars-crossers. Hence, although Amor asteroids are approximately in equilibrium with and may be derived mainly from shallower Mars-crossers, the Earth-crossing asteroids are inferred to be primarily of different origin. The supply of extinct short period comets seems to be adequate to sustain the population of Earth-crossers, but little is known about the ultimate state of degassed comet nuclei.

Precise physical observations have been made on somewhat more than a dozen near-Earth asteroids. Observed Amors occupy a broad region in the U-B versus B-V color domain, whereas the observed Earth-crossers have a more restricted range of color. The UBV fields of observed Amors and Earth-crossers exhibit moderate overlap. It is commonly believed that extinct cometary nuclei might resemble C-type asteroids, but no more than two C-type objects have been discovered so far, among the near-Earth objects. If Earth-crossers are dominantly of cometary origin, it appears likely that there are unusually strong observational selection effects which decrease the chances of finding C-type objects or that the expectations concerning the color and other properties of extinct comets are in error.

INTRODUCTION

The term Earth-approaching asteroid is used here to designate small bodies of stellar appearance which are on orbits that allow them to pass near 1 AU. A few of the known Earth-approaching asteroids are the easiest bodies to reach by spacecraft, beyond the Moon. Physical observations of these objects suggest that they have a broad range of composition; some probably are the most primitive solid objects that are readily accessible for detailed study.

Besides their intrinsic scientific interest, the Earth-approaching asteroids are especially attractive for exploration because of their very small size and because of unusually small impulses required for rendezvous at aphelion. Landing and escape from these bodies requires miniscule propulsion. A man could achieve escape velocity from most of them by jumping. For some of the Earth-approaching asteroids, spacecraft trajectories can be found where the sum of rendezvous and Earth return impulses is in the range of 2-3 km/sec. What this adds up to is feasibility of sample return. Much of the story that these small wanderers have to tell concerns the early steps of accretion of solid matter in the solar system. But the full story can be wrung from them only with the aid of powerful techniques applied to samples in laboratories here on Earth. The prospect of sample return missions makes the Earth-approaching asteroids of special interest for exploration.

POPULATIONS OF PLANET-CROSSING ASTEROIDS

Somewhat more than 40 Earth-approaching asteroids have been discovered in the course of the past 80 years of astronomical observation. Those asteroids which approach but do not cross the present orbit of the Earth have been called Amor asteroids. This designation is applied here to all asteroids with perihelion distance, q, between 1.017 and 1.300 AU. A little less than half of the Earth-approaching asteroids are Amors. The remaining objects, with $q \leq 1.017$ AU (the present aphelion distance of the Earth), are referred to here as Earth-crossing asteroids. From the standpoint of potential spacecraft missions, it is convenient to distinguish between Earth-crossing asteroids with semimajor axes, a, greater than 1 AU, here referred to by the conventional term Apollo asteroids, and those with $a \leq 1$ AU, which will be designated 1976AA-type asteroids. All known Amor and Apollo asteroids cross the orbit of Mars, whereas the two known examples of 1976AA-type asteroids do not. In addition, there are about 50 Mars-crossing asteroids with $q > 1.3$ AU. These will be designated here simply as Mars-crossing asteroids or Mars-crossers.

While the line drawn between Amor asteroids and Earth-crossers is useful for discussion of spacecraft missions, it is rather arbitrary from the point of view of orbit evolution and origin of these bodies. As a consequence of secular perturbations, at least three known Amors, Quetzalcoatl, Cuyo, and Betulia, are Earth-crossing during part of their secular variation cycle (Wetherill and Williams, 1968; Wetherill, 1976; Williams, personal communication, 1978). A few other Amors, with q slightly greater than 1 AU, may also be part-time Earth-crossers. By the same token, not all asteroids with $q \leq 1.017$ are full-time Earth-crossers. Most Amor asteroids, over long periods of time, probably evolve into full-time Earth-crossers as a result of strong perturbations during close encounters with Mars and with the Earth (Wetherill, 1976).

Three surveys in which planet-crossing asteroids have been discovered are especially useful for estimating the populations of these objects: (1) the Palomar National Geographic Sky Survey (PNGS), conducted with the 122 cm Schmidt camera at Palomar Mountain, California; (2) the Lick Proper Motion Survey (LPM), conducted with the 51 cm astrograph at Lick Observatory, Mt. Hamilton, California; and (3) the Planet-Crossing Asteroid Survey (PCA) conducted with the 46 cm Schmidt camera at Palomar Mountain. Discoveries of planet-crossing asteroids from these three surveys are listed in Table 1. Omitted from Table 1 is the Mars-crossing asteroid 1949OA, discovered in the LPM survey. Because only objects relatively close to the Earth that produced long trails on the PNGS and LPM plates were followed for orbit determination, neither the PNGS nor LPM observations are suitable for estimation of the population of Mars-crossers.

Combined discoveries from all three surveys are used here to estimate the populations of Earth-approaching asteroids, and discoveries from the PCA survey are used to estimate the population of Mars-crossers. The area of sky photographed as independent fields (excluding overlap of plates) is as follows:

Table 1. Planet-Crossing Asteroids Discovered in Three Systematic Surveys

Survey	Object	Class	a(AU)	e	i	q(AU)	V(1,0)	Discovery Conditions*			
								m_{pv}	Δ(AU)	r(AU)	α
PNGS	Icarus	Earth-crosser	1.078	0.827	22.99°	0.187	16.8	15.0	0.268	1.264	18.0°
PNGS	Geographos	Earth-crosser	1.244	0.335	13.33°	0.827	16.7	14.8	0.264	1.198	32.9°
PNGS	Quetzalcoatl	Amor	2.520	0.582	20.55°	1.052	18.5	13.9	0.077	1.050	29.5°
PNGS	1980	Amor	1.709	0.365	26.84°	1.085	14	14	0.567	1.546	17.0°
LPM	1950DA	Earth-crosser	1.683	0.502	12.15°	0.838	15.5	13	0.150	1.084	47.5°
LPM	Antinous	Earth-crosser	2.260	0.606	18.45°	0.891	15.2	14.0	0.352	1.337	12.0°
PCA	1976UA	Earth-crosser	0.844	0.450	5.85°	0.464	20.7	14.3	0.034	1.024	29.7°
PCA	1976AA	Earth-crosser	0.966	0.183	18.91°	0.790	17.6	13.8	0.130	1.112	14.4°
PCA	1977HA	Earth-crosser	1.601	0.504	23.05°	0.794	18.4	15.2	0.165	1.124	16.5°
PCA	1973NA	Earth-crosser	2.429	0.638	67.99°	0.879	15.6	11.2	0.089	1.100	19.9°
PCA	1977VA	Amor	1.865	0.394	2.97°	1.130	19.6	15.8	0.142	1.132	6.0°
PCA	1974UB	Mars-crosser	2.124	0.359	36.34°	1.361	14.1	14.6	0.687	1.679	5.7°
PCA	1977VB	Mars-crosser	2.304	0.363	26.94°	1.470	15.6	15.7	0.531	1.490	16.1°
PCA	1974UA	Mars-crosser	1.800	0.082	30.08°	1.653	13.4	14.[illegible]	0.695	1.675	9.7°
PCA	197[illegible]SB	Mars-crosser	2.727	0.384	16.76°	1.680	13.6	14.3	0.754	1.752	4.6°
PCA	Cl[illegible]ne	Mars-crosser	2.311	0.251	6.84°	1.730	12.7	14.5	1.061	2.05[illegible]	2.7°
PCA	1973SA	Mars-crosser	2.281	0.234	8.38°	1.746	13.9	14.7	0.756	1.74[illegible]	7.2°

*m_{pv} = apparent visual photographic magnitude, Δ = distance from the Earth, r = distance from the Sun, α = phase angle.

PNGS Survey .... 54,000 square degrees
LPM Survey .... 44,000 square degrees
PCA Survey .... 66,000 square degress (first five years)

Estimates of the populations of given classes of asteroids can be obtained by the following method. The magnitude-frequency distribution of each class of planet-crossing asteroids is assumed to be of the form,

$$N_v = Ke^{bv} \tag{1}$$

where N_v is the cumulative number of asteroids equal in absolute magnitude to v or brighter, v is the absolute visual magnitude, v(1,0), and K and b are constants to be determined by observation. The magnitude-frequency distributions of both main belt asteroids and inactive comet nuclei follow this simple exponential law closely; the size-frequency distributions of large craters on the Moon, Mars, and Mercury indicate that planet-crossing asteroids must also have a magnitude distribution of this form. The coefficient in the exponent, b, is observed to be close to 1 for all classes of small bodies.

The constant K in Equation (1) is determined from the systematic surveys by means of the following equation.

$$K = \frac{P_v}{U^{1/2} \int_{v_{min}}^{v_{max}} bF(v)T(v)I(v)e^{bv}dv} \tag{2}$$

where P_v is the cumulative number of asteroids of a given orbital class observed in a systematic survey, U is the square degrees of sky photographed, and F(v) is a function related to the area searched in each orbit plane, for objects of a given v, when one of the nodes lies at opposition; T(v) is a function related to the mean time spent in the search area by asteroids of a given v, assuming random distribution of the arguments of perihelion; and I(v) is a function related to the mean relative size of the search area, for objects of a given v, with randomly distributed longitudes of the node. A model of the photometric phase function and information on the frequency distributions of perihelion and aphelion for each class of objects are required to solve F(v). Knowledge of frequency distributions of the orbital elements a, e, and i for each class of objects is required to solve the functions T(v) and I(v). The required empirical information is obtained from the sample of known objects in each orbital class.

The lower limit of integration in Equation (2), v_{min}, is set by the single brightest object given by Equation (1) and is found by iterative solution for K. The upper limit of integration, v_{max}, is controlled by the effective magnitude threshold of detection for fast-moving objects for a given telescope and photographic emulsion. As v_{max} is also dependent on the care with which plates are searched for moving objects, it must be determined retrospectively from the objects of highest magnitude discovered in a given survey. The values of K derived from Equation (2) are highly dependent upon the independently estimated values of b; the resulting values of N_v at v = 18, however, are relatively insensitive to plausible uncertainties in b.

Estimates are given in Table 2 for the populations of the different classes of planet-crossing asteroids to absolute visual magnitude 18 (equivalent to about 0.7 to 1.5 km diameter). Errors listed in the table are ± one standard deviation and are derived solely from the statistical uncertainties associated with the small number of discoveries. The next largest sources of formal error lie in the determination of v_{max} and in the estimation of b. All other formal errors are small by comparison.

Table 2. Estimated Populations of Planet-crossing Asteroids

	Estimate from Systematic Surveys; Cumulative Number to V(1,0) = 18	Estimate by Wetherill (1976); Cumulative Number to B(1,0) = 18
Earth-crossers	800 ± 300	∿600
Mars-crossers		
Amor asteroids	∿500	300-700
Moderate to shallow Mars-crossers	10,000 ± 5,000	∿5,000
Mars-"grazers"	∿5,000	

Aside from the formal errors, there is also a systematic bias in the observations. This bias arises in part from the failure of the observers to detect all the fast-moving objects down to a specified minimum length and density of trail on the photographic plates and also from limitations on the ability of the observers to follow the detected objects with sufficient observations for orbit determination. Thus the estimates of the populations of planet-crossing asteroids should be regarded as lower limiting bounds.

Mars-crossing asteroids are subdivided in Table 2 into two categories, moderate to shallow Mars-crossers and Mars-"grazers." This is done because two out of the six Mars-crossers discovered in the PCA survey, Cline and 1973SA, just barely cross the orbit of Mars on rare occasions during the cycle of secular perturbation of their orbits (J. G. Williams, personal communication, 1977). For asteroids of this type there is a very low probability of close encounters with Mars, and there is little chance that they can evolve into Earth-approaching asteroids, except as fragments from collisions.

Also listed in Table 2 are estimates of the populations (cumulative number to B(1,0) = 18) of Earth-crossers, Amors, and shallower Mars-crossers obtained by Wetherill (1976) using different methods. For typical values of B-V near 0.8 for planet-crossing asteroids, the cumulative number of asteroids to V(1,0) = 18 will be about twice the number to B(1,0) = 18, for any given orbital class. Within the uncertainties, Wetherill's estimates agree with those derived here from discoveries in the systematic surveys.

Another check on the population of Earth-crossers is provided by the cratering history of the Earth and the Moon. As shown by Shoemaker (1977) the number of craters 10 km in diameter and larger on 3.3 billion year old mare surfaces on the Moon and the number of large impact structures found on the craton of North America are consistent with the flux of Earth-crossing asteroids calculated from the population of Earth-crossers given in Table 2.

It may be seen from Table 2 that only a few percent of the Earth-approaching asteroids to absolute magnitude 18 and about 1% or less of the Mars-crossers have been discovered. Earth-crossing asteroids may be slightly more numerous than Amors, and Mars-crossers are about an order of magnitude more numerous than either Amors or Earth-crossers.

ORIGIN AND ORBITAL EVOLUTION OF PLANET-CROSSING ASTEROIDS

At least two different kinds of bodies probably are represented among the known Earth-approaching asteroids: (1) objects or fragments of objects which reside in or were derived from the main asteroid belt, and (2) nonvolatile residua or cores of the nuclei of extinct periodic comets. The former category includes objects which were on Mars-crossing orbits to start with or were initially close to regions of secular resonance or of low order commensurability with Jupiter. The second category of bodies is derived ultimately from much more distant parts of the solar system. Periodic comets are captured from the Oort cloud and perhaps nearer regions of the solar system by close encounters with Jupiter; a small fraction of these periodic comets is trapped in very short period orbits with aphelion distances near 4 AU by a combination of Jupiter encounters and nongravitational forces. An example of such a comet is P/Encke. Whatever nonvolatile residue may remain from such objects after 10^3-10^4 years will be asteroidal in appearance. As a consequence of encounters with the terrestrial planets, further evolution of the orbits of both "asteroidal" and "cometary" near-Earth objects, particularly of Earth-crossers, results in an extensive overlap of the orbital characteristics of the two classes of objects.

As Earth-approaching asteroids are derived, in part, from shallower Mars-crossers, it is of interest to examine first the origin of these latter objects, which are the most numerous of the planet-crossing asteroids. Typical dynamical lifetimes of Mars-crossers are of the order of 1-2 AE (Wetherill, 1976). Hence, many Mars-crossers probably have remained on Mars-crossing orbits since the principal period of planetary accretion. Such objects can be viewed as unaccreted planetesimals of Mars. The dynamical lifetime almost certainly exceeds the fragmentation lifetime of most Mars-crossers near V(1,0) = 18; asteroids in this size range probably are produced chiefly by relatively recent collisional fragmentation of larger Mars-crossers. The estimate of the population of Mars-crossers to V(1,0) = 18, given in Table 2, is extrapolated from observations of larger asteroids on the basis of an assumed magnitude distribution law which, as shown by Dohnanyi (1971), corresponds approximately to an equilibrium fragmentation distribution.

Small Mars-crossers may also be derived by fragmentation of asteroids adjacent to surfaces of secular resonance in the asteroid belt discovered by Williams (1969), or asteroids near the Kirkwood gaps, in particular the gap at the 3:1 commensurability with Jupiter. Mechanisms by which meteorite-sized fragments can be injected from these regions in the main belt into planet-crossing orbits have been described by Zimmerman and Wetherill (1973), Scholl and Froeschlé (1977), and Wetherill (1977). Multiple collisions are required for injection from the margins of the Kirkwood gaps at the 2:1 and 5:2 commensurabilities, and it appears unlikely that more than a few kilometer-sized Mars-crossers can be derived in this way. Main belt asteroids near surfaces of secular resonances, on the other hand, may be an important source of small Mars-crossers, and many known Mars-crossers lie close to these surfaces (Williams, 1971). For example, two out of six Mars-crossers listed in Table 1 lie very close to secular resonances; 1974UA lies adjacent to the Hungaria region, near $\dot{\tilde{\omega}} = \nu_5$, and 1974UB is near $\dot{\Omega} = \nu_{16}$ (Figure 1); 1973SA, near the Flora region, is moderately close to $\dot{\tilde{\omega}} = \nu_6$ (Williams, personal communication, 1978). None of the Mars-crossers discovered in the PCA survey are far removed from a secular resonance.

A significant fraction of the Mars-crossers is possibly derived from extinct comets. A list of half a dozen Mars-crossers with aphelion distance, Q, near 4 AU given by Marsden (1971) and a similar list by Sekanina (1971) may include objects of cometary origin. Close encounters with Mars can reduce Q, moreover, so that some Mars-crossers with less eccentric orbits may also be extinct comets.

A large fraction of the Amor asteroids is, evidently, derived from shallower Mars-crossers. If the Amors were in dynamical equilibrium with Mars-crossers, then the ratio of the number of shallow Mars-crossers should equal the ratio of their respective lifetimes (Öpik, 1963). As seen from Table 2, the ratio of Amors to shallow Mars-crossers is about 1/20 to 1/10, whereas the ratio of the lifetimes of Amors to those of shallow Mars-crossers is about 1/10 to 1/5 (Wetherill, 1976). The number of Amors appears to be slightly low for dynamical equilibrium, but the discrepancy is within the uncertainty of estimation.

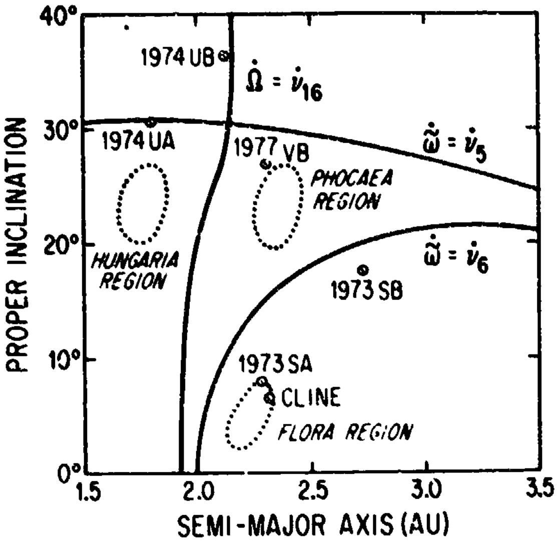

Fig. 1. Surfaces of secular resonance in the asteroid belt (after Williams, 1969) and position of Mars-crossing asteroids discovered in the PCA survey.

A significant number of the Amors, perhaps even the majority (Wetherill, personal communication, 1978) may be of cometary origin. The most likely extinct comet among the known objects is Betulia, which has a maximum Q of 3.9 AU and a present orbital inclination of 52°. Its Jacobi constant with respect to Jupiter suggests it may be a cometary object (Kresak, 1977). It should be noted, however, that Betulia, at times, crosses not only the orbits of Mars and the Earth, but also the orbit of Venus. By close encounter with Mars, Earth, or Venus the Jacobi constant with respect to Jupiter can change abruptly, and the orbit of Betulia can become less or more comet-like with time.

Earth-crossing asteroids, in contrast to the Amors, are clearly not in dynamical equilibrium with shallow Mars-crossers nor are they in direct equilibrium with the Amors. The typical lifetime of Earth-crossers was reported as 0.5×10^8 yr, by Wetherill and Williams (1968) and as $\sim 0.2 \times 10^8$ yr by Wetherill (1976). If Earth-crossers were derived entirely from shallow Mars-crossers and were in equilibrium with Mars-crossers, they should be about 50-100 times less numerous than Mars-crossers and about 10 times less numerous than Amors. The figures in Table 2 show that this is not the case. There are too many Earth-crossing asteroids.

The excess of Earth-crossing asteroids can be seen very simply in another way. If all Earth-crossers were in dynamical equilibrium with Amors, then, with decreasing q, there would be a relatively rapid, order of magnitude drop in the number of asteroids near the threshold of Earth-crossing. The reason for this is that the probability of collision or ejection of an Amor from the solar system as a consequence of encounters with Mars is much smaller than the probability of collision or ejection of an Earth-crosser as a consequence of encounters with the Earth. This is so primarily because the Earth is an order of magnitude more massive, and, therefore, gravitationally an order of magnitude more active than Mars. Contrary to expectation, however, the number of Amors and Earth-crossing asteroids is nearly uniformly distributed as a function of q. There is roughly an equal population of Amors, with q between 1.0 and 1.3 AU, and of Earth-crossers with q between 0.7 and 1.0 AU. Among the discovered objects there are 20 Amors with reasonably well defined orbits in the range 1.0 AU $<$ q $<$ 1.3 AU and there are 14 Earth-crossers with 0.7 AU $<$ q $<$ 1.0 AU.

The distribution of asteroids by q in the vicinity of 1 AU appears to be explicable only if the majority of Earth-crossers have been injected more or less directly into Earth-crossing orbits from some source other than Mars-crossers. Progressive evolution of typical Mars-crossers into Earth-crossers may account for, at most, 10-20% of the

Earth-crossers. The remainder must be derived chiefly from somewhat deeper regions of the asteroid belt or from comets. Collision debris from asteroids near the secular resonances can be injected directly into Earth-crossing orbits (Williams, 1973a,b). For the cases studied so far, a few percent of the ejecta becomes directly Earth-crossing (Williams, personal communication, 1978). Other Earth-crossing objects are derived from perturbation by Mars of Mars-crossing debris which was not initially injected as deeply into a resonance (Wetherill, 1977). The combination of direct injection into resonant Earth-crossing orbits and the secondary perturbations by Mars produces one Apollo for every three Amors derived from the secular resonances (Wetherill, personal communication, 1978). A few tens of percent of the Earth-crossing asteroids may be derived this way. Collision fragments derived from the margins of the 2:1 and 5:2 Kirkwood gaps may be injected directly into Earth-crossing orbits, but, because two collisions are required for this, the yield of kilometer-sized bodies probably is very low. So far as the celestial mechanics of the asteroid belt is presently understood, there appear to be no other likely sources of Earth-crossers among the asteroids. A remaining probable source of Earth-crossing asteroids is the family of short-period comets.

All but a few periodic comets are Jupiter-crossing and have extremely short dynamical lifetimes. The Jupiter-crossing comets are unlikely to be captured into very short period orbits by close encounters with terrestrial planets, although this must happen on rare occasions and may produce a few planet-crossing asteroids. A few comets, such as P/Temple 2, P/Clark, P/Grigg-Skjellerup and P/Encke have aphelia inside the orbit of Jupiter. All of these except P/Encke, however, pass within the sphere of influence of Jupiter, and they have a very high probability of being ejected by Jupiter from the solar system. Evidently from the action of nongravitational forces, the aphelion distance of P/Encke has been reduced to 4.1 AU (Sekanina, 1971), a critical threshold below which comets and asteroids are relatively safe from ejection. Comets entering this safe region have much longer dynamical lifetimes, which will permit a significant fraction to be captured into still smaller orbits by encounters with the terrestrial planets.

Two comets in moderately stable orbits appear to be nearly extinct: P/Arend-Rigaux and P/Neujmin 1 have been asteroidal in appearance during recent apparitions, although observations of P/Arend-Rigaux in 1977 revealed a very weak coma and tail (Degewij, 1978). Secular variation of the nongravitational acceleration of P/Encke suggests it may become extinct in 60-70 years (Sekanina, 1972), leaving a kilometer-sized inactive body. The asteroid Hidalgo is Jupiter-crossing and is very probably an extinct comet. Hence there is little doubt that a few comets, at least, are capable of evolving into planet-crossing asteroids, by progressive loss of their volatile constituents during perihelion passages.

The question remains whether the supply of comets entering safe orbits is adequate to sustain the population of Earth-crossing asteroids. It is difficult to give a reliable answer to this question as there is only one known example of such a comet. The population of Earth-crossers to magnitude 18 is roughly 10^3, and they have a mean lifetime near 2×10^7 years. A new magnitude 18 or brighter Earth-crosser must be supplied roughly once every 2×10^4 years to maintain the population in steady-state. Marsden (1971) has estimated that the lifetime of activity of a short-period comet is of the order of 10^3 to 10^4 years. It would be a matter of luck, then, to discover a short-period comet, with a nucleus brighter than magnitude 18, in the process of decaying into an Earth-crossing asteroid. P/Encke appears to be an example of just such a comet (Sekanina, 1971). Within the lifetime of persons now living, P/Encke may join the group of objects which, by the standard criteria of telescopic observation, we recognize as Apollo asteroids.

Finally, it is of interest to examine the orbits of the known Earth-crossing asteroids to see which ones are most comet-like. 1973NA has an aphelion distance of 4.0 AU and an inclination of 68°. Its Jacobi constant with respect to Jupiter is comparable to that of many periodic comets and suggests a cometary origin for this object (Kresak, 1977). With much less confidence, a similar case can be made for Sisyphus, 1981, and 1974MA. Adonis, Antinous, 1976WA, and PLS 6334 all have Q near 4 AU and might also be relatively unevolved extinct comets. These criteria should be used with caution, however. Some asteroids injected by collisions into the Kirkwood gaps or into secular resonances can acquire aphelion distances near 4 AU. Encounters with the terrestrial planets, moreover, greatly modify the orbits of Earth-crossers. Asteroids with very small orbits can be derived from comets with orbits like that of Encke, and objects originating as typical Mars-crossers can be placed on comet-like orbits.

COMPOSITIONAL TYPES AMONG THE EARTH-APPROACHING ASTEROIDS

Precise physical observations have been made on 14 near-Earth asteroids. On the basis of the available data, the Earth-crossing asteroid population appears to be different from the Amor population. The number of Earth-approaching asteroids for which physical observations are available is still very small, however, and it is premature to draw firm conclusions about the differences or the similarities of physical characteristics between the Amors and Earth-crossers on the basis of this small sample.

UBV photometry represents the most complete set of physical observations obtained on the Earth-approaching asteroids (Figure 2). Amor asteroids are distributed over a

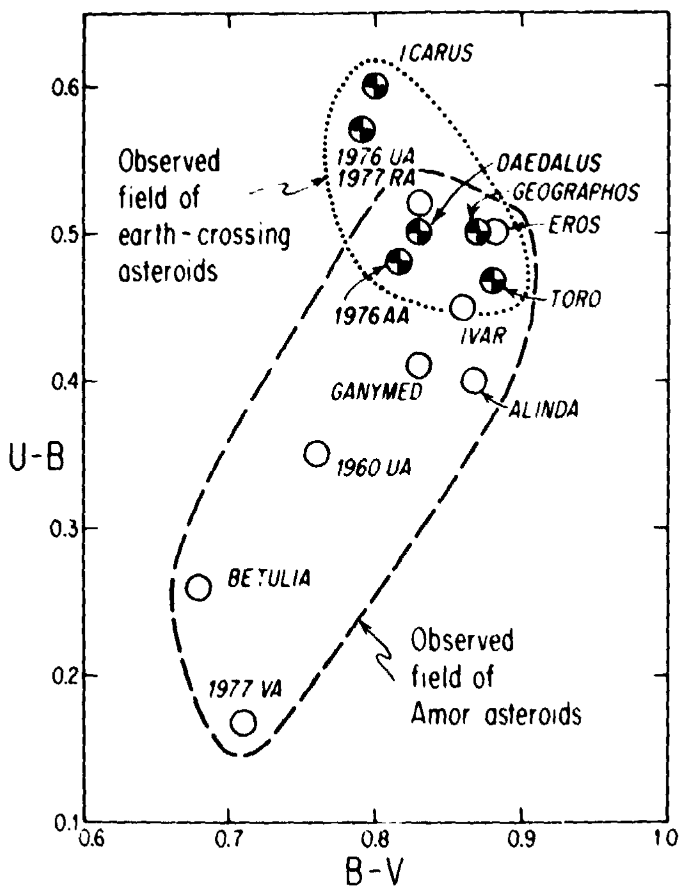

Fig. 2. UBV colors of Earth-approaching asteroids. Amor asteroids are shown with an open circle and Earth-crossers with a target symbol. Data are from TRIAD file and from Degewij (1977), and Degewij *et al.* (1978).

Table 3. Classification of Earth-Approaching Asteroids by Compositional Type

Amor Asteroids			Earth-Crossing Asteroids		
	Compositional Type	Reference		Compositional Type	Reference
433 Eros	S	2	1566 Icarus	0	2
887 Alinda	S	2	1620 Geographos	S	2
1036 Ganymed	S	2	1685 Toro	U	2
1580 Betulia[1]	C	2	1864 Daedalus	0	2
1627 Ivar	S	2	1976AA	S?	5
1977RA	S?	3	1976UA	0?	6
1977VA	M? or E?	4			

[1]Although listed as an Amor asteroid, Betulia is Earth-crossing part of the time. 1960UA may also be Earth-crossing part of the time.

[2]Zellner and Bowell (1977).

[3]Based on data from Degewij, *et al.* (1978).

[4]Based on data from Degewij (1977).

[5]Based on data from Gradie (1976).

[6]Based on data from Zellner and Bowell (unpublished).

broad field in the U-B versus B-V color domain. Earth-crossing asteroids, on the other hand, occupy a smaller field which is characterized by relatively high U-B values (excluding, for the moment, the special asteroid Betulia). Most Amors with UBV colors close to the Earth-crossing asteroid field are classed as S-type asteroids by Zellner and Bowell (1977) and Zellner (1978) (see Table 3). The predominance of S-type asteroids among the Amor group is consistent with the derivation of these objects primarily from shallower Mars-crossers, as suggested by dynamical considerations. As shown by Chapman *et al.* (1975), Morrison (1977) and Zellner and Bowell (1977), S-type asteroids are the dominant type on the inner edge of the main asteroid belt, the principal region from which shallow Mars-crossers are, in turn, derived.

Only one Earth-crosser, Geographos, is certainly an S-type asteroid. Besides Geographos, the Apollo asteroid Toro falls within the Amor asteroid UBV field, but Toro is distinguished on other physical characteristics from S-type Amors. The Earth-crossers 1976AA and Daedalus lie on the margin of the S field as defined by Zellner (1978). Daedalus was classified as an O-type asteroid, along with Icarus, by Zellner and Bowell (1977) although polarimetric albedo determinations used by them in distinguishing this class have now been revised. Icarus and 1976UA, which show extreme values of U-B, near 0.6, and intermediate values of B-V, near 0.8, are clearly distinct from S-type asteroids and from all measured Amors.

It has been widely supposed that extinct cometary nuclei might resemble C-type asteroids. The basis for this expectation is the belief that comets are very primitive objects and that C-type asteroids are similar to carbonaceous meteorites, which are the most primitive meteorites recovered. If many Earth-approaching asteroids are of cometary origin, it is plausible that some or perhaps most carbonaceous meteorites are derived from extinct comets.

Recently, more direct evidence has been obtained which strengthens the supposition that the relatively nonvolatile constituents of comets are carbonaceous. A team of investigators headed by D. E. Brownlee has succeeded in collecting substantial numbers of small particles of extraterrestrial origin from the stratosphere (Brownlee *et al.*, 1976; Brownlee *et al.*, 1977). Most of these particles resemble carbonaceous meteorites in composition but are very different in structure. The presence of large concentrations of ^{4}He (Rajan *et al.*, 1977) shows that they entered the Earth's atmosphere as small particles. Comets are the most likely source for interplanetary particles of this type.

A second and more direct observation linking comets to C-type objects is the UBV photometry of the asteroid Hidalgo reported by Degewij *et al.* (1977). This object, although asteroidal in appearance, is almost certainly an extinct comet (Kresak, 1977); its orbit is Jupiter-crossing and resembles the orbits of active periodic comets. It has a low albedo and its UBV color lies on the margin of the field for C-type asteroids.

No more than two out of 14 Earth-approaching asteroids studied to date are of the C type. Betulia is an unequivocal C-type asteroid (Lebofsky *et al.*, 1978; Tedesco *et al.*, 1978). Because its present perihelion distance is greater than 1.017 AU, it is generally listed among the Amors, but as shown by Wetherill and Williams (1968), large oscillations in eccentricity and inclination of the orbit of Betulia are produced by secular perturbations; more than half of the time Betulia is Earth-crossing. The Jacobi constant of Betulia relative to Jupiter suggests it could be a relatively recent extinct comet.

The Amor object 1960UA may also be a C-type asteroid, but the observations are insufficient for classification. Its UBV color is on the margin of the C field; observation of its albedo will be required to determine whether or not it is of the C type. The perihelion distance of the orbit of 1960UA is less than the maximum aphelion distance of the Earth, and it may be Earth-crossing part of the time. The present aphelion of 1960UA is 3.5 AU; its orbit could have evolved from one more like that of P/Encke by a succession of encounters with the Earth or Mars.

The paucity of C-type asteroids among the Earth-crossers seems to be in conflict with the dynamical arguments for cometary origin of a major fraction of Earth-crossers. This conflict may be more apparent than real, however. Two selection effects discriminate against observation of C-type objects among the Earth-crossers. First, among asteroids of the same size, C-type objects are fainter and therefore are less likely to be observed. This selection effect led to serious underestimation of the abundance of C-type asteroids in the initial studies of the main belt. Half of the Earth-crossers studied to date are, in fact, among the brighter known. However, none of the intrinsically faint objects--Icarus, 1976AA, and 1976UA--are of the C type. Secondly, there is a strong bias in the existing observations of Earth-crossers with regard to the semimajor axes of the asteroids. All of the Earth-crossers for which UBV or other physical observations have been made have semimajor axes less than 1.5 AU (*i.e.*, less than the semimajor axis of Mars). The observed objects all lie within the first 45th percentile of the semimajor axis-cumulative frequency distribution of Earth-crossers (Figure 3). This bias is partly related to the fact that objects with semimajor axes close to that of the Earth tend, on the average, to move slowly with respect to the Earth, and therefore are easier to observe. This circumstance made possible extended observations of 1976AA during its discovery apparition, for example. Part of the bias is also due to the fact that the first three asteroids for which secure orbits were obtained, apparently by chance, had small semimajor axes; because the orbits were well determined, observational campaigns were mounted for these asteroids during close passes to the Earth.

As shown by Monte Carlo simulations of orbit evolution by close encounters with the terrestrial planets (Wetherill, 1977 and personal communication, 1977), asteroids with initial orbits like those of typical Mars-crossers are more likely to be perturbed into orbits with small semimajor axes than are extinct comets with orbits like that of P/Encke. The proportion of Earth-crossers of asteroidal origin, therefore, should be highest among

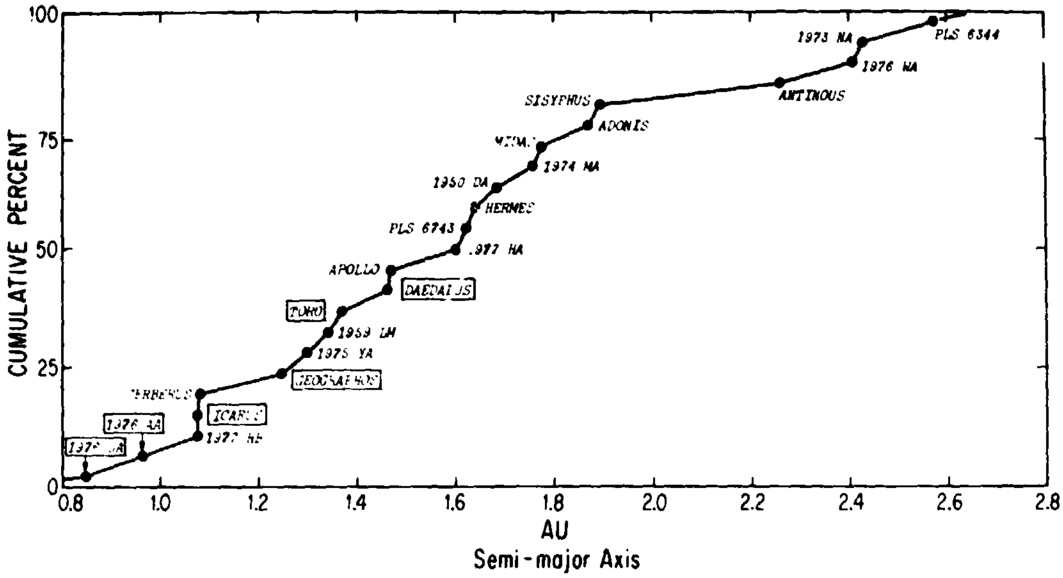

Fig. 3. Frequency distribution of semimajor axes of Earth-crossing asteroids. Names of asteroids for which UBV observations have been made are shown with boxes.

the objects of small semimajor axis, where the S-type object Geographos and possible S-type 1976AA are, indeed, found. A larger fraction of Earth-crossers of large semimajor axis (right-hand side of Figure 3), on the other hand, probably are of cometary origin.

It should be borne in mind that comet nuclei may have much greater spectrophotometric diversity than is commonly supposed. One particular mechanism by which diversity might arise is suggested by the orbital characteristics of Icarus and 1976UA, two objects which have nearly the same UBV color and which have extreme U-B values. At perihelion, Icarus approaches within 0.18 AU of the surface of the Sun. At this distance the peak temperature of a blackbody of low thermal inertia and an albedo of the order of 0.2 or less be about 600°C. Gibson (1976) has shown that about 50% of the carbon is lost from the carbonaceous meteorite Murchison by heating to 600°C for three days. At 900°C (corresponding to a perihelion distance of about 0.1 AU) 95% of the carbon is driven off. Thus, the albedo and color of Icarus may have been altered significantly by repeated close approach to the Sun, especially if its perihelion distance were once somewhat less than it is at present. It is conceivable that Icarus was once a C-type object. 1976UA presently grazes the orbit of Mercury at perihelion (q = 0.464). At this distance, maximum temperatures are of the order of 270°C, which probably are too low to expel much carbon from the surface. It is entirely possible, however, that the perihelion distance of 1976UA was also at one time much smaller.

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DISCUSSION

ANDERS: Is it fair to compare the numbers of Apollos and Amors? Shouldn't one instead compare masses of the two populations, because fragmentation goes on all the time? The number doesn't stay constant during the time the Mars-crosser supposedly evolved to an Apollo. More likely one Mars-crosser gives several Apollos just by fragmentation.

SHOEMAKER: The numbers are all given to the same magnitude (and hence size) limit, and the magnitude-frequency distribution observed for main belt asteroids was used in calculating the number of V(1,0) = 18. it appears that this magnitude-frequency distribution is approximately an equilibrium fragmentation distribution. Hence the effect of fragmentation of Mars-crossers is taken into account.

ANDERS: Then you are integrating to a larger size limit for the Mars-crossers than for the Apollos.

WETHERILL: It is not necessary to consider fragmentation, as the ν_6 resonance has the effect of rapidly equilibrating the Apollo and Amor populations. They should have nearly the same steady-state size distributions, except for objects like 1036 which is in an unusually stable orbit for an Amor. In addition to considering the Amor/Apollo ratio, it is also possible to calculate the rate at which Apollos and Amors are produced from the large main belt asteroids. I think you could make 10% of them without too much trouble. But to make more than half seems very difficult.

ANDERS: The paradox is not as great as it was ten years ago. You should try to apply a correction for fragmentation and see how much of a discrepancy remains. I think your factor of ten will be reduced by fragmentation.

WETHERILL: I think the difference between ten years ago and now is that we have identified new mechanisms to transport objects from the main belt to Earth-approaching orbits. This decreases the discrepancy to something like a factor of ten rather than a factor of 100. On the other hand, I think the factor of ten is much better established; it's a much more sophisticated number.

ANDERS: Part of the problem is that, at the moment, the statistics on Mars-crossers rest on four objects.

SHOEMAKER: There are two estimates in Table 2. One is based upon the four discovered objects, the other on a larger set of arguments. I think the estimates are reasonably congruent, and neither is likely to be off by more than a factor of ten. If Apollos were really derived by a process which generally involves an evolution of Mars-crossers into Amors, although not in every case, then you would expect to see a much larger number of Amors in proportion to the Apollos.

NIEHOFF: There could be another explanation for the discrepancy, and that is when an object becomes an Apollo, its lifetime goes up for some yet unexplained reason.

ANDERS: If the dynamicists are correct, and I think they are, there is no gimmick except a very odd resonance occasionally.

WETHERILL: Apollos are not in that kind of resonance.

SHOEMAKER: You might invoke some resonances like that found for 1685 Toro, which would slightly extend the lifetimes.

ARNOLD: Other possible mechanisms for the origin of Apollos and Amors are also going to be called upon to explain why they are roughly equal in number. These other models might also give you the correct ratio of Mars-crossers to main belt asteroids. Suppose they are made from comets or something; once they cross the orbit of the Earth they are much more vulnerable, their lifetime gets much shorter. So again there is a discrepancy.

WETHERILL: There is something to what you say. However, comets are more likely to have an aphelion near Jupiter, so their lifetime is also shortened by interactions near aphelion as well as by Earth-crossing. To really make it work, you have to say that a comet with a small perihelion is more likely to be decoupled from Jupiter by nongravitational effects into an orbit like that of Comet Encke than are ones with a larger perihelion. This may not be the case because the total amount of gas loss, *i.e.*, the integral of the nongravitational forces, should be the same. But it could be that the process is nonlinear, that getting near the Sun changes the lag angle or something like that in such a way it favorably places extinct comets into orbits with small periods.

ARNOLD: The first explanation is likely to be perhaps a 20% effect. The second may not be right either, but it is well worth investigating.

SHOEMAKER: The anomalous ratio of Apollos and Amors is the principal argument for invoking cometary sources for the majority of those asteroids.

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SECTION III:

FUTURE ASTEROID EXPLORATION OPTIONS

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THE ROLE OF EARTH-BASED OBSERVATIONS OF ASTEROIDS DURING THE NEXT DECADE

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During the past decade, Earth-based observations have led us from ignorance to considerable understanding about the physical properties of asteroids. Candidate targets for space missions can now be chosen using criteria that will not prove trivial in the future; intensive ground-based studies of targets can refine the choices. Present reconnaissance studies of asteroids are now reaching maturity. Ground-based programs are shifting to more specialized, intensive studies of selected individual bodies and special classes (*e.g.*, Hirayama families). Two powerful techniques--radar and mid-IR spectroscopy--have yet to be widely applied to asteroids; high priority should be given to these programs in the future and to (a) search programs with a large Schmidt telescope (especially for Mars- and Earth-approaching bodies), (b) a moderate resolution visible and near-IR spectrophotometric survey of at least half the asteroids, (c) high resolution spectrophotometry and radiometry of unusual objects, (d) radar studies of representative main belt asteroids, and (e) application of the full complement of astrophysical techniques (including polarimetry and intensive lightcurve studies) to objects of high scientific interest and to potential space mission targets. The infrared astronomical satellite (IRAS) also has high potential for contributing to asteroid science. Laboratory and theoretical programs complement observational programs by enabling data interpretation and synthesis. Ground-based programs should continue even in a future era of asteroid space missions in order to extend ground-truth to the diverse and widely dispersed population.

INTRODUCTION

Our present knowledge of the asteroids rests entirely on Earth-based astronomical measurements, bolstered of course by observational and experimental studies of other bodies thought to be related to asteroids. The long history of asteroid discovery, orbit determination, and photographic photometry had yielded by 1970 nearly 2000 known asteroids and a wealth of speculations about their statistical distributions and orbital evolution. But substantial understanding of the physical properties of asteroids awaited the application of modern remote-sensing techniques, using efficient detectors at large telescopes, beginning about 1970.

During the 1970's, reconnaissance measurements of parameters known to be related to surface composition have been made for over one-quarter of the numbered asteroids, although the full range of available techniques has been applied to few objects. We will address in this paper the question of what observations can be made in the near future. We will also attempt to treat the more speculative question of how much return may be expected from continued ground-based observations and whether such data have the potential for ultimately resolving the questions that have been raised in the past decade.

GROUND-BASED TECHNIQUES

The techniques discussed in this section have already been successfully applied to asteroids. It is not our purpose to describe the techniques here; the reader may consult other pertinent references (see papers in Session II of this volume). We will indicate what asteroid properties they reveal (or suggest) without delving into the methodologies and the caveats that always accompany interpretation of observations. The history of each technique is sketched to provide a frame of reference for our guesses about the future application of the technique. Of course, any application of ground-based techniques depends not only on theoretical capabilities of state-of-the-art instrumentation, but also on availability of facilities, funds, and interested observers. The growth in number of asteroids measured by several important techniques is illustrated roughly in Figure 1.

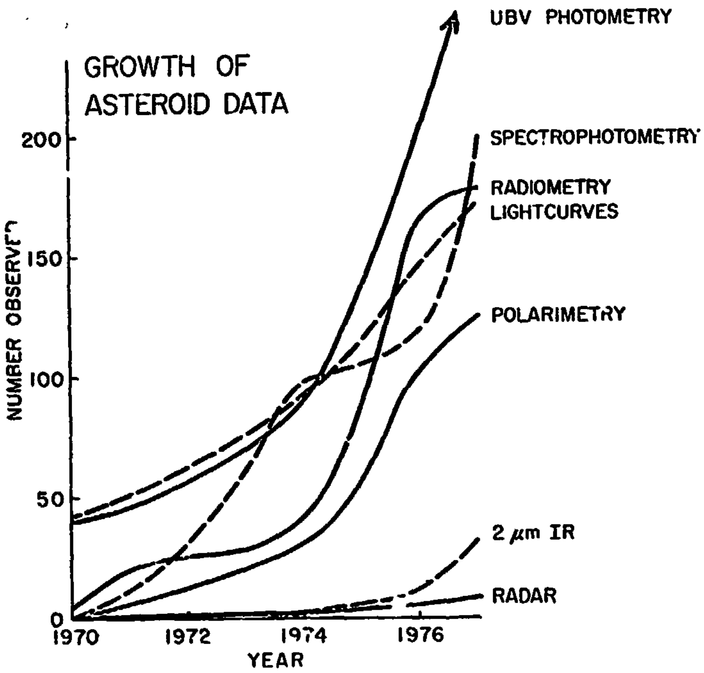

Fig. 1. Approximate growth in the number of asteroids observed using several techniques during the 1970's.

Asteroid Searches and Photographic Surveys

There have been two major photographic surveys of asteroids: the McDonald survey of all brighter asteroids, nearly complete to photographic magnitude 15 or 16, and the Palomar-Leiden survey, which sampled asteroids down to magnitude 20. The sheer number of fainter asteroids and time-consuming nature of photographic surveys prohibits extension of completeness much beyond the current limits. But sampling of the population of much fainter and smaller asteroids could lead to improved understanding of asteroid collisional processes, Hirayama families, and other important problems. Better sampling of asteroids in high inclination orbits and other unusual orbits is particularly important. Current search efforts by E. Shoemaker and E. Helin and by C. Kowal have slowly but substantially improved our knowledge about Mars-crossing and Earth-approaching asteroids. Application of a larger, dedicated instrument could increase the discovery rate by an order of magnitude and help to establish the relationship between Earth-approaching asteroids, the main belt asteroids, comets, and meteorites as well as to establish cratering rates and thus chronologies on the inner planets.

Visible Photometry of Asteroids

The measurement of the apparent brightness of an asteroid as a function of time provides a crude estimate of an asteroid's size; combined with radiometry or polarimetry, the size is much more precisely determined Asteroid photometry as a function of phase angle yields some information concerning surface texture; but the measurements are time-consuming and not of primary importance. Relatively simple photometry over the course of a night (lightcurve photometry) can yield a fundamental property, rotation period, and some indication of asteroid shape. With great difficulty, photometry can yield more precise knowledge about asteroid spin, including pole direction and sense (prograde or retrograde) and better knowledge of asteroid shape. Some photographic photometry has been done for all asteroids; but for many of the fainter objects, the best available magnitudes are highly provisional. Photoelectric magnitudes are known for a quarter of all the numbered asteroids and could be extended to nearly all numbered asteroids within a few years by a single dedicated observer. Lightcurve photometry is a time-consuming program initiated in the 1950's and yielding rotation periods for several dozen bodies by 1970. Expanding interest during the 1970's, especially by foreign observers and some amateurs, has increased the number of known rotation periods to more than 150. The present sample only hints at some possibly very interesting correlations between lightcurve properties and diameter, orbit, and compositional type; yet it is difficult to imagine that the number of accurately known amplitudes and rotation periods will more than double in the next decade. Photoelectric photometry with sufficient aspect coverage to yield reliable pole positions is likely to be limited to a handful of objects for the foreseeable future. Nevertheless it is important to realize that, given time and sufficient motivation such as a planned space mission, the shape, pole, and spin rate can be obtained by ground-based techniques for almost any asteroid.

UBV Photometry

UBV photometry provides reconnaissance data that can be related to asteroid surface composition. While insufficient by itself to specify asteroid surface mineralogy, it does reliably imply membership in a few of the major compositional classes and is a useful tool for identifying anomalous asteroids. The technique was applied to several dozen asteroids in the 1950's and 1960's and has been applied recently to about [illegible]00 asteroids, mainly by E. Bowell at Lowell Observatory and by Degewij, Gradie and Zellner at the University of Arizona. The survey could be extended to virtually all known asteroids within a decade, given a dedicated observer and a telescope in the 2 m class. Color variation with rotation is potentially very important, but color variations discernable in Earth-based disk-integrated data seem quite rare among the handful of objects measured.

Polarimetry

Polarimetry provides information primarily on the texture and opacity of particulates on asteroid surfaces. Measurements as a function of rotational phase for a handful of asteroids suggest, as with UBV measurements, that most asteroid surfaces are homogeneous on a hemispheric scale. More useful in the past have been measurements (mainly by B. Zellner) of polarization as a function of solar phase angle, over the generally available range of 0° to 30°. Individual values at small phase angles are correlated with albedo and more extensive observations at larger phases yield precise albedos, except for the blackest asteroids. Since radiometry (discussed below) is more readily accomplished and yields the same information, the number of polarimetrically-determined albedos and diameters is not likely to increase much in the future. Future application of polarimetry will likely be for special-purpose studies; the technique can be applied, often with difficulty, to perhaps half the numbered population.

Radiometry

Measurement of the thermal radiation from an asteroid at wavelengths near 10 and 20 microns, when combined with visible photometry, yields a determination of asteroid diameter and albedo that is only slightly model-dependent (Matson *et al.*, 1978). The technique was developed less than a decade ago, but by 1976 had yielded more than 150 asteroid diameters. There has been a recent lull in the measurements since the two regular observing programs (those of D. Morrison and O. Hansen) have been discontinued. Work on special objects is continuing at the University of Arizona. The technique is not much more difficult than UBV photometry, at least for main belt objects, although it requires instrumentation that is less readily available. More than half of the numbered asteroids could be measured within a decade. More refined radiometry (as a function of asteroid rotation and phase angle) is correspondingly more time-consuming, but can yield better determinations of asteroid thermal properties and the sense of rotation. Thermal emission spectra are potentially indicative of composition, but so far no spectral features have been found.

Spectrophotometry

Spectrophotometry of asteroids can be accomplished from Earth in several different passbands and with a variety of instruments yielding different spectral resolutions. Such data are, to varying degrees, indicative of asteroid surface mineralogy (see McCord's paper elsewhere in this volume). Most spectral features of interest from 1000 Å to beyond 10 microns are relatively broad and can be detected with spectral resolutions ($\Delta\lambda/\lambda$) of about 0.1; absorption band position measurements made with 10 times better spectral resolution can define certain compositional characteristics reliably but still higher spectral resolution is not demonstrably useful. Filter spectrophotometry in the visible and near-IR (0.3 to 1.1 microns) has been published by McCord and Chapman for 100 asteroids and is available (in varying stages of reduction) for about 150 more. The technique can be applied, with difficulty, to more than half of the numbered asteroids; use of a multiplexing instrument would increase observing efficiency, but it is doubtful that the technique will be applied to more than a quarter of the numbered asteroids within the next decade. Broad-band filter photometry in the JHK region of the infrared has been done for several dozen asteroids, primarily by JPL scientists, and complements the visible spectrophotometry; because of low detector efficiency the technique cannot be applied to the fainter asteroids. Higher resolution studies in the 1-4 micron region, using quantum-efficient interferometric techniques, have been made of several asteroids and--with considerable effort and allocation of major facilities and resources--can be applied to the hundred brightest asteroids; a major effort is underway by H. Larson. This infrared region is rich with diagnostic spectral features, but observations are somewhat hindered by absorptions in the Earth's atmosphere. Spectral features exist in the UV, below 1500 A, that differ for various rocky and metallic materials; it is unknown if such features will prove to be as compositionally diagnostic as infrared features, but in any case, exploitation of this spectral region can be accomplished only from above the Earth's atmosphere and with exceptionally sensitive detectors because of the near-absence of short wavelength sunlight.

Radar

Radar is the one ground based astronomical technique that is known to be powerful but has yet to be widely applied to asteroids. Many Earth-approaching asteroids, and some of the larger main belt asteroids (especially those in the inner edge of the belt) are potentially within the range of the Goldstone and Arecibo observatory facilities. Radar detection provides information on asteroid bulk properties (especially presence or absence of a major metallic component), size, shape, and roughness; more refined observations, potentially applicable to only a few asteroids, could be much more revealing. It is doubtful that radar observations will be made of more than a few dozen asteroids during the next decade. Passive detection of microwave radiation from a few asteroids has been done, but the technique is difficult and unlikely to provide fundamental information.

There are several other techniques, or refinements of the above techniques, that have been, or could be, applied to asteroids. For instance, direct measurement of asteroid diameters by speckle interferometry, lunar occultations, or asteroidal occultations of stars could help calibrate, and give us greater confidence in, the radiometric technique. A combination of highly refined photometry, radiometry, polarimetry, spectrophotometry, and radar measurements of a single asteroid over a range of phase angles and rotational phase can uniquely specify geometric, physical, and compositional parameters that would be indeterminate or less certain from less complete data. Such a coordinated study of 433 Eros in 1975 illustrated the possibilities of essentially all the ground-based techniques in current use (see the May 1976 issue of *Icarus*). Mass determinations are available for three asteroids and estimates may be made of the masses of several more asteroids within a few years.

In combination with known orbital parameters (*e.g.*, membership in a Hirayama family), physical parameters may be statistically treated for all asteroids, or subsets; thereby we may speculate about some asteroid properties not directly measurable (*e.g.*, internal composition, strength, mode of origin). But, fundamentally, ground-based observations are restricted to telling us about the size, shape, and spin of an asteroid and something about the mineralogy and texture of the surface layer as resolved on a global scale. Basic data on sizes and surface properties are now available for several hundred asteroids, could be extended to any known asteroid, and probably will be extended to most known asteroids during the next decade. Basic data on spins and shapes exist for half as many asteroids, could be extended to most, but probably will not be done for more than a few hundred in the foreseeable future. Highly refined measurements of asteroid properties, employing most of the available techniques, have been done for only a few asteroids, could be done for a few Earth-approaching asteroids and perhaps 100 main belt asteroids, but probably will not be done for more than a handful.

OBSERVATIONS FROM EARTH ORBIT

Observations from Earth orbit permit the full resolving power of the telescope to be utilized over the full spectral range, unhindered by atmospheric absorptions. It remains to be seen how helpful such advantages may be. Extended spectral ranges in the UV and IR may provide important constraints on some types of asteroid mineralogical assemblages, but it seems unlikely that our understanding will be dramatically affected. The resolving power of the Space Telescope is probably insufficient to make useful maps of even the largest asteroids.

Observations from Earth orbit may also be made with much greater efficiency than from the ground. For instance, the Infrared Astronomical Satellite (IRAS), a project currently in preliminary stages, would have the capability for doing radiometry of all known asteroids; in fact it will measure such asteroids and thousands of as-yet-unknown asteroids unavoidably in the process of making a catalog of infrared sources. It remains to be established that the IRAS asteroid observations will be made and reduced in ways maximizing the scientific return.

While advantages to asteroid science by the allocation of a major fraction of observing time from Earth-orbiting satellites and observatories would be great, the facilities provide even greater benefits to other astronomical disciplines and are thus unlikely to be allocated for asteroid work except in rare instances. The best prospects are cases such as IRAS in which asteroid observations are made unavoidably in the process of carrying out another program.

THE FUTURE OF GROUND-BASED OBSERVATIONS OF ASTEROIDS

It is not easy to speculate about the future. Certainly during the next decade, new techniques--or at least important variations of present ones--will be developed that may be applied to a sample of asteroids. But any ground-based remote-sensing technique is fundamentally limited to telling us about reflected or emitted radiation from the hemispherically averaged *surface* of the body in question. New ground-based techniques are unlikely to address complementary aspects of asteroids (*e.g.*, concerning asteroid interiors) needed for complete understanding of these bodies.

In the previous section, we guessed at the likely application of present techniques during the next decade, assuming rough maintenance of present resources and priorities. Currently asteroids receive a substantial fraction of NASA-supported ground-based astronomical attention; vastly greater allocation of funds or major telescope time is unlikely. But modest increases are possible if continued asteroid observations are deemed to be important. Asteroids (unlike cometary nuclei, for example) are very profitably studied from the ground. In terms of maximum return from minimum effort, however, it is probably true that we will have soon skimmed the cream from the top of the ground-based asteroid observations. Certainly the less powerful techniques are approaching their limits. At this point, therefore, the critical questions are two-fold: (1) Is the present understanding of the asteroid population adequate for technical planning of space missions and intelligent choice of targets, or is the next decade likely to hold such surprises that any present mission strategy will ultimately seem ill-conceived? (2) What are the most profitable avenues for future ground-based work, both in support of space missions and in pursuit of questions (such as population statistics) that can be addressed only from the ground?

Anders (1971), in the context of the first question, argued as follows: "Ground-based research on asteroids and meteorites is nowhere near exhaustion; on the contrary, it is moving at an impressive pace. If we maintain this pace for another decade or two, we will not only have answered most of the questions posed for an early mission, but will be able to come up with a more worthwhile, more informative mission...Some crucial questions will undoubtedly remain when all ground-based studies have been pushed to their limit, and at that stage, perhaps ten years from now, further progress will require space missions. We do not know what sort of a target will have the highest scientific interest at that time: a Trojan, a Hilda group asteroid, a few nearly spherical asteroids (small or large) in the near or far parts of the belt, a few highly irregular objects, a Hirayama family, etc. Any choice we make now is likely to seem trivial or uninformative a decade hence."

We submit that the ground-based observers have done their homework since Anders' statement was drafted almost a decade ago. Whereas we were then largely ignorant about asteroids and their significance, we now have learned enough about them to formulate some fundamental cosmogonical and planetological questions that exploration of asteroids may answer. Compositional classifications are now adequate for the planning of quite a few multi-asteroid rendezvous missions, each including a variety of important types. To a substantial degree we know which asteroids are likely to be related to known meteorites (by avuncular, if not parental, association) and thus are interesting for *in situ* studies of the meteorite parent bodies. We also know of objects that are not represented in our meteorite collections, and are especially significant on that account. We can characterize asteroids sufficiently to assert that available techniques will likely prove practical for the determination of critical physical and engineering parameters--size, shape, spin, surface type, etc.--for almost any known asteroid. It no longer seems possible that target choices made on the basis of current knowledge will prove trivial. Of course, our understanding will be better when (and if) final target selection is required; a ground-based program dedicated to observing candidate targets could further upgrade target selection.

The second important question concerns the most productive directions for future ground-based programs. Clearly, several of the productive past reconnaissance programs are approaching their limits. As we learn more about the asteroids, there will be an inevitable shift toward more specialized programs addressing problems of high scientific interest. They may involve application of proven techniques (*e.g.*, radiometry) to special classes of bodies (*e.g.*, Hirayama families) or application of past or developing techniques to intensive studies (*e.g.*, lightcurve pole-determination, detailed measurement of absorption bands, or thermal IR studies of rotational and phase effects) of a modest sample of asteroids of exceptional interest. Thus we may expect a diminishing number of new asteroids measured but an increasing sophistication in techniques and results for sampled asteroids. Future programs will increasingly be directed toward well-formulated questions of cosmogony or interrelationships. A concomittant requirement of the ground-based program is that increased attention be given to interpretation and synthesis of data already obtained and to associated theoretical and laboratory research programs. For example, it is important to investigate the role of metal on and within asteroids: how metal reddens asteroid spectra, how metal responds to hypervelocity impact at asteroidal temperatures, and how metal affects thermal properties and interpretation of radiometry.

The progress of science is unpredictable. Nevertheless we can identify the following ground-based programs for high priority during the next few years:

1. A substantially expanded search for Earth-approaching objects, by broadfield photographic techniques, particularly in conjunction with the IRAS survey. A new large Schmidt telescope appears to be needed; the cost will be substantial but the benefits will be great for all of astronomy.

2. A spectrophotometric survey of roughly a thousand minor planets, at resolution comparable to UBV or somewhat higher, but extended to longer wavelength. Detectors now exist for adequate photon count out to wavelength 1.10 microns for the majority of the numbered asteroids. The survey is otherwise routine, using fully proven facilities and techniques.

3. Continued thermal-radiometric studies, especially of newly discovered Apollo/Amors and main belt objects that are found to be spectroscopically interesting. The techniques are fully proven, requiring only dedicated observers.

4. Continued and expanded high-resolution spectroscopy and narrow-band spectrophotometry in the visible and infrared of asteroids found to be especially interesting in the low resolution survey. The 0.8-3.5 micron spectral region is especially important for more sophisticated characterization of the mineralogy. Improved detectors are appearing. Additional laboratory and theoretical work on interpretation of reflection spectra is needed.

5. Radar studies of a small representative sample of main belt asteroids.

6. Application of the full complement of astrophysical techniques, including polarimetry intensive lightcurve studies, for the objects of greatest scientific interest, for those objects (such as Vesta) which are certain to be high on the list for space missions, and for all objects which emerge as good candidates for space missions on dynamical grounds.

We now seem to be passing from the stage of total ignorance about the ground-based observable properties of asteroid surfaces to a state of considerable knowledge. One may imagine that after another few years devoted to the remaining important observations and synthesizing the available data, the broad ground-based perspective on the nature of the asteroids will be largely complete. The scientific approach must ultimately shift from the observational characterization of asteroid surfaces to developing hypotheses concerning how asteroids got to be the way they are.

Beyond those problems that can be tackled from the ground, many fundamental questions about small bodies and implications for solar system history require close-up analysis of their chemical, physical, and geological traits (*e.g.*, minor minerals, trace elements, isotopic compositions, surface topography, compositional heterogeneities, internal structure, etc.). Space missions are required to measure such properties. Since asteroids are so numerous and so widely dispersed in space, missions will necessarily be restricted to only a few bodies. Thus we must ultimately rely on remote-sensing data from the vicinity of Earth to extend insights gleaned from missions to the entire asteroid population.

In conclusion, ground-based asteroid science has made sufficient progress so that we can be confident in designing a space mission exploration strategy that will not seem unintelligent a decade hence. At the same time, there remains high potential for further understanding of asteroids from Earth-based programs that apply state-of-the-art techniques to special subsets of the population and address fundamental problems raised by the early reconnaissance data.

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DISCUSSION

FANALE: About the variations in polarimetric measurements--if nature made asteroids very nonuniform, you wouldn't know which variables are varying, because you're looking at a composite of a thousand variables. But nature makes them quite uniform, so polarimetry is a wonderful technique for spotting something really wild.

MORRISON: Does α_0, the angle of zero polarization, contain much information about regoliths and dusty surfaces, or are these observations difficult or impossible to interpret?

CHAPMAN: It's my view that polarization is telling us something about surface properties, but not enough. It's telling us that there are interesting differences between the asteroids, but there is not enough information in polarization or even polarization combined with photometry and other techniques to specify what these differences are. Once again, perhaps some insight may come with more observations or with better laboratory data which would enable us to understand these differences.

VEVERKA: Let me come back to Fanale's point. Polarization is a useful technique. It can tell you which asteroids are different. It does not necessarily have to tell you why and one shouldn't make the assumption that a lot of people have made, that somehow if you're clever the information is there and you should be able to sort it out uniquely. The parameter α_0 may not have a unique interpretation in terms of regolith properties, yet it may still be useful to know that two particular asteroids do or do not have the same α_0.

FANALE: And it gets you around the problems that come from not knowing the shape of the asteroid.

MATSON: It seems to me that the differences that can be detected with polarimetry are at a smaller scale than the differences that can be detected with radiometry.

CHAPMAN: I think you're right. This is another reason why polarimetry is important.

MORRISON: You mentioned that masses are known for three asteroids, but only two are precise enough to tell us something. I expect we will not get many more with a precision like 10%.

MATSON: With current radar technology, we can get ranges to the larger asteroids, and once you have a record of ranging data to Ceres or Vesta over a period of five years or more, you can start to pull out asteroid masses.

VEVERKA: I think you have a problem there with time scales. It's certainly true that over a long period of time, say 100 years, you could get those asteroid masses.

MATSON: Yes, that's true for the large amplitudes that one must use with ground-based astrometry. But with radar you don't have to go for the maximum amplitudes. You can take some little wiggle.

GROSSMAN: Is the ground-based observational activity leveling off due to money?

CHAPMAN: Yes, it's leveling off due to saturation of several things, including the number of known asteroids, the funding, the available instrumentation, and the available manpower.

MATSON: From the data that are available now we are seeing the main themes, we are seeing the large-scale story. Once one delineates the main themes, then the exceptions to the themes become absolutely crucial. Maybe 10 years from now we may find a peculiar asteroid that really alters our perceptions.

CHAPMAN: We have come a long way and we have a considerable distance further to go with the present techniques, but we are not going to learn everything using only current techniques.

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SCIENCE RATIONALE FOR AN INITIAL ASTEROID-DEDICATED MISSION

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The maturation of our knowledge of asteroid surface mineralogy from Earth-based measurements and the simultaneous advent of a powerful new low-thrust propulsion system (Ion Drive) have brought us to the threshold of identifying a scientifically attractive initial asteroid-dedicated mission. Science requirements dictate rendezvous with several asteroids which should be carefully chosen on the basis of Earth-based observations, and investigated as global entities. Satisfactory execution of the key remote sensing experiments requires long rendezvous/orbit times. The delivery of one or more hard landers to asteroid surfaces is also scientifically desirable and within the capabilities of an Ion Drive system. Such a mission could provide unique insights into: (1) the physical and chemical conditions during planetary formation, (2) the internal differentiation histories of solid planetary bodies, (3) the genetic relationships among small solid bodies of the solar system, (4) the collisional history of the asteroids and its implications for the bombardment of planetary surfaces, and (5) the potential of asteroids as sources of raw materials for space utilization.

CURRENT KNOWLEDGE

Our current knowledge of the asteroids suggests that they may provide a unique source of insights into the formational conditions and subsequent history of the solid bodies of the solar system. There are about 2000 asteroids with well-determined orbits, and with the application of current observing techniques this number could reach 50,000. Most orbit the Sun in modestly inclined and eccentric orbits between 2 and 4 AU. Our strongest source of scientific information about the asteroids comes from observations of their surface optical properties (which strongly imply surface mineralogy) and comparison of these properties with those of meteorites for which a great library of chemical and isotopic data, with genetic implications, is available. A danger in such comparison is that, although most (but not all) asteroids strongly resemble some class of meteorites in their optical properties, hence mineralogical composition, there is no guarantee that this equivalence extends to *other* (trace element, isotopic, chronological, etc.) properties which characterize the meteorites. Other than qualitative inferences which may be drawn from reflectance spectra, we have *no direct information concerning the chemical compositions of asteroid surfaces*. Except for two asteroids for which approximate (±10%-20%) densities are available, we have no direct bulk compositional information whatsoever, let alone information on zonal structure. Finally, even the optical properties refer only to the whole disks; there has been no spectral mapping of the asteroids except for large numbers of lightcurves (albedo at a particular wavelength versus rotational phase) and polarization data.

Still, the Earth-based optical data constitute our "strong suit" as far as scientific information on the asteroids and their relationship to the solar system as a whole is concerned. These data must also serve as the focal point of any attempt to plan intelligently in initial asteroid missions. There are moderate spectral resolution (~24 spectral element) data in the 0.3-1.0 μm range available on about 200 asteroids and broad-band UBV photometry on perhaps another 300 (*cf.*, Morrison, 1978; Chapman and Zellner, 1978). For about 30 asteroids, the 0.3-1.0 μm data have been augmented with observations at two specific wavelengths further into the infrared (1.6 and 2.2 μm). Continuous spectra from 0.3-2.5 μm are available for only a few asteroids.

The first conclusion from these data is that asteroid surfaces tend to fall into one of several rather distinct spectral classes which resemble spectra of each of several major mineralogical/chemical classes of meteorites (Morrison, 1978; Bowell *et al.*, 1978). The data favor the existence of such distinct classes rather than continua in that histograms of the visible albedos (Morrison, 1977) and red:blue ratios of all the studied asteroids are unequivocally bimodal and because other straightforward portrayals of the asteroid reflectances (*e.g.*, visible albedo versus U-B magnitude, etc.) tend to produce distinct clusters of points (Zellner and Bowell, 1977; Bowell *et al.*, 1978). However, some asteroids do not fit well into any familiar meteorite classes on the basis of their spectra, and the frequency of falls of various meteorite types appears to be rather different from the overall population distribution among the asteroids--at least the belt asteroids. Neither of these problems shakes the apparent correspondence between asteroid surface spectral classes and classes of meteorites. In the broadest sense, most of these asteroid surfaces tend to fall into the following classes: C type (corresponding to optical properties of the primitive carbonaceous meteorites), S type (corresponding to stony meteorites made up of ordinary rock-forming silicates), and M type (corresponding to iron, stony-iron, or metal-rich meteorites). For a further discussion of asteroid spectra, see Gaffey and McCord (1977), Chapman *et al.* (1975), Bowell *et al.* (1978), and a current review by McCord (1978). The dynamical arguments allowing derivation of most meteorites from the main belt asteroids (including derivation of some from Apollo and Amor objects which might ultimately have been derived from the main belt) seem strong (Wetherill, 1977; Wetherill, 1978; Anders, 1978).

A second point is that the most populous class of asteroid surface spectra is equated to the most primitive and chemically complete meteorite type: the carbonaceous meteorites. This supports the general notion that asteroids may represent a potential watershed of knowledge about early solar system history because they are minimally altered remnants or incipient subplanets that never modified themselves endogenically (geologically) as has, say, the Earth. This notion--that asteroids are generally primitive--is also supported by the observation that there seems to be some concentration of the (least modified) C asteroids in the outer portion of the belt. The C asteroids still cannot be portrayed as being the most compositionally unmodified or chemically complete objects (in bulk) in the entire solar system; present information suggests both comets and outer planet satellites may be more chemically complete in terms of bulk composition. However, differential sublimation of ices makes cometary surfaces a complex source of information--especially concerning the initial state of the *non-icy component* which was initially available in the *inner* solar system, while endogenic differentiation (it is easy to melt and differentiate a large predominantly icy object) creates similar complexities for the outer planet satellites. Also, the correlation of asteroid composition with heliocentric distance suggests that, despite considerable scrambling, most surviving asteroids seem (unlike comets) to be in roughly their original orbits. Thus asteroids seem most likely to be dominated by material which gives clues to the original nature of solid material which formed the inner planets. (Ironically, the initial notion that this *had* to be so just because they were too small to have any geological (endogenic) histories of their own now seems to be an oversimplification (see below).)

A third point is that, despite their apparent status as an assemblage which *generally* reflects the raw state(s) of the matter which made up the inner solar system, certain of the asteroids appear to have remarkably differentiated surfaces. No asteroid appears large enough to have differentiated by the processes which are usually c[illegible]ted with planetary differentiation, *i.e.*, conversion of gravitational energy to heat or accumulation of heat from decay of long-lived nuclides such as ^{238}U, ^{235}U, ^{232}Th or ^{40}K. In such small bodies ($\lesssim$600 km diameter) the heat would be lost as fast as it accumulated so it would never get hot enough inside to melt most silicates or metal. Does this mean that asteroids represent fragments from a disrupted very large object exceeding the summed mass of all the surviving asteroids by a large factor? More likely, we may have overlooked an important heat source that "works" even (or especially) for small bodies with short thermal lag times. One asteroid (4 Vesta) appears covered with basaltic surface flows. One class of meteorites (the basaltic achondrites) also seems to have been derived from such surface flows. Yet this object (Vesta) has a diameter of only 550 km. How old is the surface of Vesta and of other asteroids which are suspected of having differentiated surfaces? What heat source was responsible? Heating by electromagnetic induction associated with an early stage in the Sun's development (Sonett and Herbert, 1977) has been suggested as one possibility; another may be heating by short-lived nuclides (*e.g.*, ^{26}Al) left over from nucleosynthesis (Papanastassiou *et al.*, 1977). Both could be effective despite the short thermal lag of these small objects. All suggestions are subject to tests by study of the cratering histories of these differentiated surfaces as well as other measurements. A key point is that we may have failed to include such important early heat sources for the large inner planets in our analysis of *their* thermal histories.* The Moon is an example of a suspiciously small body which was rather thoroughly melted very early in its history. But the Moon is a borderline case; accretional energy could conceivably have been sufficient to melt its outer portions. The problem is more sharply etched for Vesta; *it* seems *much* too small for the energy sources proposed for the Moon's differentiation to have been effective. Also it has two neighbors, Ceres and Pallas, which are larger but apparently have primitive carbonaceous surfaces. Clearly, there are some major mysteries involved in our understanding of energy sources in the early solar system, and clearly the asteroids are a potential source of information which may lead to the explication of these energy sources.

A fourth point is that the asteroids also may represent a major source of information concerning the very poorly understood physical processes of planetary accretion. There is some balance today between accretion and fragmentation in the asteroid belt. By examining asteroid surfaces we may be able to recreate this collisional history and understand why a single asteroidal planet apparently never formed. These collisions may also have revealed "cross sections" of the former deep interiors of asteroids. In addition, these collisions and dynamical rearrangements have delivered to the terrestrial planets a good part of the bombarding flux which dominated their early history and the marks of which (craters) serve as a useful chronometer to document that history (Chapman, 1978).

A fifth point is that asteroids represent a wide, even wildly disparate, assemblage of peculiar surface mineralogies ranging from very metal-rich surfaces to surfaces rich in carbonaceous materials. This, together with the fact that these are small bodies (which are small enough to allow comparatively easy ejection of their surface material to space or alteration of their orbits) suggests--at least for the Earth-crossing asteroids--their possible eventual utilization as economically attractive sources of raw materials. Such materials could be used for construction of large space structures as opposed to the possibly more expensive alternatives of launching materials from the Earth or processing them on--and launching them from--the Moon (*e.g.*, see O'Leary, 1977). Thus we are led to the formulation of the following key questions which seem especially approachable via asteroid studies.

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*Even if the planets themselves accreted too late to benefit from such heat sources, the protoplanets that accreted to form planets may have been so differentiated.

QUESTIONS AMENABLE TO ASTEROID STUDIES

1. What where physical and chemical conditions in the solar system during planetary accretion like?

   a. What were the *physical* interactions among solid bodies of all sizes like during accretion of our planetary system? This includes processes of accretion, fragmentation, and dynamic rearrangement. What do these physical conditions imply for the formation and initial state of very large objects like the Earth and their subsequent bombardment history?

   b. What *chemical* fractionation processes operated during condensation/accretion to produce differences in *bulk* composition *among* asteroids and could these same processes account for apparent differences in bulk compositions among the terrestrial planets? Did these condensation/accretion processes produce "ready-made" or *initial* zonal layering *within* asteroidal or planetary bodies in the solar system?

2. What magmatic processes operated within accreted bodies to produce internal differentiation?

   When did these processes operate and what were the energy sources (short-lived nuclides, solar electromagnetic interaction, etc.)? Why did they seemingly affect some asteroids and not others? Did they affect the Earth and the other planets as well?

3. What are the genetic relationships among small bodies in the solar system?

   Are there parental relationships among (a) various orbital families of asteroids, (b) various spectral classes of asteroids, (c) comets, (d) meteorites, (e) planetary satellites, and (f) interplanetary or interstellar dust? In what context does this place the vast library of isotopic, geochemical, textural, and other information we have already accumulated on meteorites and what, in turn, does this tell us about planetesimal/planetary genesis?

4. What is the potential of the asteroids as sources of raw materials?

   What variety of raw materials are available? Is mining from asteroids of any of these materials for any application preferable to mining, processing, and launching from Earth, or mining from non-asteroidal extraterrestrial sources such as the Moon?

The preceding key questions are essentially those which were singled out in the *Report of the Terrestrial Bodies Science Working Group* (Brandt *et al.*, 1977).

SCIENCE STRATEGY AND MISSION TACTICS

What does all this information tell us about how (or indeed whether) to design an asteroid-dedicated mission? Some people might conclude that there are so many asteroids of such varied composition that the design of a valid mission which studies only a tiny fraction of a percent of them is a hopeless task. Others might contend that the ground-based program has provided so much knowledge of the asteroids that we ought to wait until spacecraft reconnaissance of the entire solar system is accomplished before we visit them.

Still others may conclude that our knowledge of asteroids is too meager to permit judicious mission planning or selection of targets.

I disagree with such conclusions and conclude that, thanks to the ground-based program, *we have just now reached the threshold of knowledge where a valid investigation of this enormous population of objects from space may be intelligently planned.* Moreover, I conclude (see next section) that our conceptual designs for low-thrust propulsion systems have also just recently matured to the point where a viable asteroid-dedicated mission so planned may actually be executed. Specifically, based on the information in the previous section, I conclude:

1. A *scientifically* valid initial asteroid mission must visit *several* asteroids and not just one.

2. The task of choosing asteroid targets is not hopeless. Instead, the Earth-based data allow us to select representatives of all *major* spectral classes and to identify other uniquely interesting target objects as well.

3. Such a mission will achieve high scientific status *only* if it fills, for the selected asteroids, the two greatest gaps in our knowledge, namely information on their:

   a. *densities*

   b. *surface chemical composition*, including the maximum amount of accuracy and spatial resolution consistent with achievement of the other listed mission goals.

4. Spectral data should emphasize spatial resolution of two classes:

   a. very broad-band multispectral imaging

   b. high spectral resolution-moderate spatial resolution mapping.

5. Some attempt at investigating the internal zonal structure of the asteroids should be made.

I have made a semi-serious attempt at constructing a specific mission scenario, Table 1, based on these principles. This scenario is intended as an illustration only. In the next section, it will be shown that some specific scenarios nearly as demanding with respect to both targets and encounter conditions (see below) as that given here as an illustration of science desires have already been identified by Bender (1977) as being within the capability of an Ion Drive mission and compatible with the delivery of a satisfactory scientific payload as well. In Table 1, I have listed the demanded or preferred targets, the characteristics of the target (if unique) or those of the class that it represents, the number of dependably identifiable candidates satisfying the description and the reasons why that asteroid or class of asteroid deserves a place in the limited list of targets. To underline the illustrative nature of this scenario, I should point out that there are at least two classes of objects which could profitably be substituted for those I have listed. (1) a member or members of a discrete orbital family (because of the possibility that zones internal to a fragmented progenitor might be exposed; Nysa (Table 1) qualifies as the largest member of a 12-member orbital family), and (2) an asteroid or asteroids known on the basis of its optical properties to be an unlikely source of any meteorites in hand. Finally, it seems unlikely that more than four-to five asteroids per launch could be included in an actual multi-rendezvous mission.

Table 1. An Example Multi-Rendezvous Mission

Priority (not order of encounter)	Description	Examples	No. of Dependable Members	Special Scientific Interest
1. Demand Vesta	550 km diameter; covered with basalt-like material/color varies	Unique	-	Global differentiation/time?/energy source?/source of achondrites?
2. C Types				
a. Prefer Ceres	Largest dark C typ but oddly bright (~6% albedo); water band	Unique	-	Largest object/relic, not disrupted/generally primitive/most populous class/largest thermal lag/regional endogenic effects?
b. Accept other large C substitute for Ceres	C type/albedo <4%; D > 70 km	10 Hygeia 19 Fortuna 324 Bamberga	>10	Primitive?/source of carbonaceous chondrites?
3. S Types				
a. Prefer 349 Dembowska	Very red/deep olivine band	Unique	-	Derived from mantles of differentiated objects?
b. Accept as substitute: other S with olivine and pyroxene bands	An S with substantial olivine and pyroxene bands	12 Victoria 63 Ansonia	>10	Class derived from mantles of differentiated objects?
4. M Types				
a. Prefer 16 Psyche	D > 200 km/low albedo/no bands/no sharp UV dropoff	Unique	-	Huge metal-rich object/from core of differentiated object?/source of mesosiderites?/end member of S-M series
b. Accept any M type	M, smaller than Psyche		>6	Similar, but smaller
5. E Types	High albedo/neutral color/"flat" spectrum	44 Nysa 64 Angelina	-	Bright/surface of enstatite?/deep interior of differentiated object, but different zone than other Ss?
6. Any additional C type small	C type; D < 50 km		>100	Representative of large class/most primitive/chemical composition important/easy to find/source of some carbonaceous chondrites/compare with Mars' moons
7. Any additional S type			>40	Representative of large class/easy to find

C-3

What should the scientific payload be? The measurement of satisfactorily accurate densities requires mass measurement accurate to 1% or better. For a 200 km diameter rocky asteroid this can be done with a closest approach of 10^5 km if the velocity is 1 km sec^{-1}. The other ingredient in the density recipe is the volume, which requires global shape measurement. This is so because small asteroids, unable to reassume hydrostatic equilibrium shapes after large impacts, can have "bites" missing from them which will modify the volume calculations. An approach within 1000 km or less should provide satisfactory resolution for this purpose in the case of a CCD camera. For imaging upon rendezvous or orbit, at least six broad-band filters should be part of the camera system and should be carefully chosen, not only to produce good color pictures of the object, but to create a synergistic base for extension of the results of a high spectral resolution-moderate (km) resolution spectral mapper. A conceptual version of the latter instrument has been proposed for the Lunar Polar Orbiter mission and has already been tentatively accepted for the Galileo mission. Such an instrument can produce definitive moderate to low resolution maps of mineral distribution over the asteroid surface. Also, a prominent H_2O band has just been identified on the asteroid Ceres (Lebofsky, 1978). Maps of H_2O distribution on asteroid surfaces may be produced and constitute an important and obviously exciting produce of this and the gamma-ray equipment: both a gamma-ray and x-ray fluorescence instrument are necessities on the payload because together they will provide definitive chemical analyses of the major element abundances and selected abundances of especially cosmochemically important minor or trace elements. Analyses of H, O, C, Na, Mg, Al, Si, K, Ca, Ti, Fe, Th and U are possible. Of particular interest would be the potential of the gamma-ray instrument for measuring the C and especially H distribution since the history of H_2O and other volatiles associated with C asteroids will be an important area of investigation. These measurements are absolutely essential to the fulfillment of the major science goals as indicated above. The reader is referred to the discussion of remote chemical measurements by Arnold (1978). Nonetheless, the quality of chemical data is enormously dependent on the encounter conditions. Based on the science needs of this mission, and the practicalities involved (see below), low spatial resolution chemical mapping emerges as a requirement. There is no guarantee that vastly different geochemical provinces would be seen since the low gravitational fields allow significant global redistribution of ejecta to result from impacts. Also the albedos of most asteroids show somewhat meager or nonexistent optical variations with rotation of most. Still, these are whole disk data and there is the possibility of some windows in some asteroid crusts that--given the combination of chemical and spectral mapping--could be quite revealing. This might be true for the largest asteroids where impacts have more difficulty in spreading material over most of the asteroid. Piles of large exposed blocks may characterize major impact sites. Also it is generally assumed that smaller asteroids are essentially in the erosional mode. Thus the statement that "asteroids paint themselves grey" may prove more true than false, but the meager state of our knowledge of these objects leaves spatial resolution for chemical and spectral measurements as an important goal. A discussion of some of these problems is given in this volume by Chapman (1978).

A crucial point is that very slow flybys (<200 m sec^{-1}) are vastly preferable to fast flybys of the type offered by typical ballistic multi-encounter missions (*e.g.*, 4-10 km sec^{-1}) in that the latter seem to offer only crude (10-15%) chemical analyses of only a few chemical elements. For a major asteroid a slow (<200 m sec^{-1}) flyby is capable of providing precise elemental analyses owing to the longer integrations times. When the stay time at the asteroid is several days, then not only could precise analyses be obtained for several elements, but this analysis could be extended to cover a large portion of the asteroid and crude analyses could be obtained for each of a handful of spatial elements, affording a crude chemical map. If the orbit could be maintained for tens of days, then a real map, containing perhaps 100 spatial elements, could be obtained. Such a procedure could allow spotting even fairly small regions of unusual chemical compositions--such as the windows mentioned above. Beyond these stay times, field-of-view limitations come into play. Also, the accuracy is likely to be limited by calibration uncertainties rather than precision. Figure 1 gives a very crude back-of-the-envelope representation of the dependence on the quality of chemical information for a typical off-the-shelf instrument

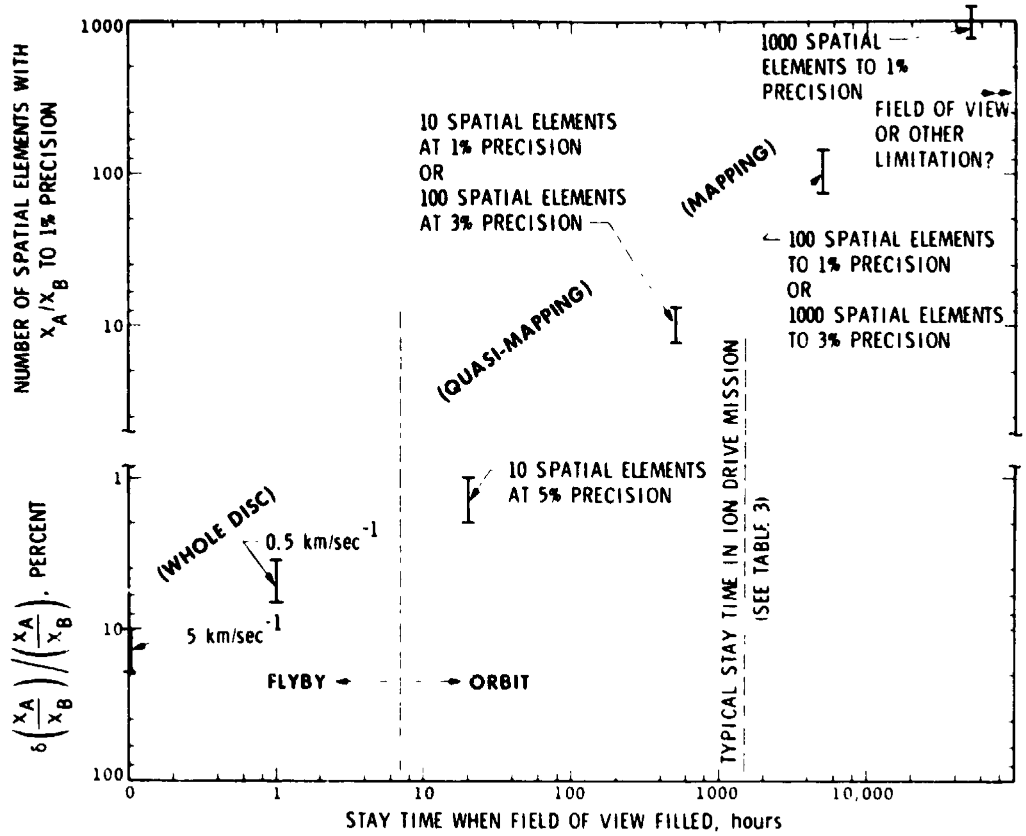

Fig. 1. A highly generalized representation of the typical precision with which the ratio of two major elements might be determined as a function of flyby velocity or orbital stay time at a 500 km diameter asteroid with a 100 km closest approach or orbital attitude. Since neither the elements nor the design of the radiometric instrument (approximately an off-the-shelf instrument) are specified, the absolute values given should not be taken too literally. Also, it is only precision, not (calibration-limited) accuracy which is indicated. However, the strong dependence of the precision of whole disk analyses on flyby velocity, and the sharp dependence of mapping capability on orbital stay time are fairly portrayed. The close, fast flyby shown on the left is not only scientifically unattractive, but it also requires the development and use of precise optical navigation techniques.

in an example encounter. It is true that use of one of the recently developed huge (and heavy) detector arrays would improve the level of performance for a given set of encounter conditions. However, encounter conditions determine coverage and other parameters as well as signal-to-noise, and given any instrument the quality of the result is so steeply dependent on encounter conditions as to militate for <200 m sec^{-1} relative velocities and orbit whenever possible.

Information concerning the thermophysical properties of the regolith could be obtained from infrared radiometric measurements from 8 μm to 40 μm. Some ancillary compositional data might also be obtained. Tracking might provide valuable information concerning lateral mass variations. Considering the possibility of coalescence of several large nuclei and the possibility of the resulting density composite surviving with minimal later internal evolution of some of these objects, and considering the possibility of radial zoning being exposed by fragmentation, such an experiment might provide interesting data. This is especially so since the surface may be coated with a more or less uniform "blend" of material from various regions as the result of impacts. A fields and particles package consisting of a magnetometer, a solar wind plasma analyzer and a low-to-medium energy electron detector could provide valuable information on the existence of intrinsic or fossil magnetic fields and the interaction of the solar wind with the asteroid as an electrically conducting or insulating body.

Although I have emphasized the importance of rendezvous for the chemical measurement, this point can be almost as strongly made for the other remote sensing instruments, including the mapping spectrometer, imaging, radiometer, gravity experiment, and the fields and particles package. In some cases, the experiment benefits mainly from enhanced signal-to-noise, but in others the increase in coverage and variety of positions relative to the satellite-Sun line or even simply increasing the time base for synoptic observation are equally important.

The possibility of including hard landers or penetrators on a mission is attractive, especially considering the massive payloads made possible with an Ion Drive vehicle (see below). A hard lander might weigh ~80 kg and contain perhaps a 12-15 kg science payload. This would allow for a three-axis stabilized seismometer plus the following: a multispectral facsimile camera could provide close-up panoramic imaging of a small domain on the surface. An α/p/x-ray fluorescence device could provide a *complete* chemical analysis including *minor* or *trace* elements. Such data could also help to plan a subsequent sample return mission. However, orbital science should definitely not be sacrificed in any major way for lander science.

Table 2 shows *example* orbiter and lander payloads. I have, for the sake of argument, assumed a hard lander rather than a penetrator for this exercise, but penetrators may be preferable. Penetrators offer a greater chance (but only a chance) of allowing a heat flow measurement and probably better coupling for a seismic experiment. However, their surface payload and data rates are more limited and the problems of emplacing a penetrator into a low G body with no atmosphere introduces some engineering complexities. The choice is not yet clear. In any event, the vehicular capabilities of the Ion Drive propulsion system allow one to consider carrying hard landers or penetrators for several targets in addition to a satisfactory "orbiter" payload.

Achievability of Science Desires

How feasible are missions like that described in Table 1? Detailed discussion of the full assemblage of mission options is beyond the scope of this paper and is available elsewhere in this volume (Niehoff, 1978). However, a short discussion of our ability to carry out a viable multi-rendezvous mission seems appropriate. Multiple rendezvous scenarios involving either ballistic missions or ballistic missions with gravity assists are not compatible with the scientific criteria outlined above. Two typical ballistic mission scenarios (one direct and one Vega) are given in the first two columns of Table 3. They are unattractive primarily, but not exclusively, because of the high relative velocities at encounter and the poor assemblage of targets. As indicated in Figure 1, such conditions would probably provide only rather crude whole disk elemental abundance measurements, with no chance of chemical mapping at all--even in the case of an asteroid much larger than the targets given. All the other measurements would likewise suffer because of the short time base, reduced coverage, etc., as discussed earlier.

The third column gives a scenario based upon the capabilities of a solar electron propulsion system (SEP). This example was identified as the result of a casual preliminary search. Nonetheless it at least provides a rendezvous with Vesta and a slow flyby (200 m sec^{-1}) of the asteroid Io. Although the array of targets is exceedingly limited, this preliminary example serves to show that the future of asteroid exploration from

Table 2. Example Payload for Asteroid Rendezvous

Orbiter

Instrument	Mass	Power (w)
1500 mm CCD Camera (800 × 800), multispectral (∿8 filters) 250 mm CCD Camera (800 × 800), multispectral (∿8 filters)	20	20
x-ray Fluorescence	2	2
γ-ray	17	10
Mapping Spectrometer	10	5
Multispectral Radiometer	7	4
Radar Altimeter	12	30
Fields and Particles Package	10	15
Micrometeoroid Detector	3	2
Tracking	-	-
TOTAL	81 kg	88 w

Lander (Mass = 80 kg*)

Instrument	Mass	Power (w)
Facsimile Camera	1.5	1.0
α-Backscatter/p/x-ray Fluorescence	2.0	1.5
Seismometer	2.0	0.2
Magnetometer	0.6	0.3
TOTAL	6.1 kg	3.0 w

TOTAL MASS OF ORBITAL INSTRUMENT PLUS LANDERS:

81 kg (orbital instruments) + 160 kg (80 kg × 2 landers) = 241 kg

*Each of two.

space was closely bound to the development of some sort of Shuttle-launched low-thrust propulsion system (Atkins *et al.*, 1976).

Since then, NASA has committed to the development of a particular low-thrust propulsion system called Ion Drive, which is based upon the SEP concept, but which has much higher thruster power levels, an improved array of solar cells and other major design

Table 3. Comparison of typical direct ballistic, VEGA ballistic, SEP and Ion Drive asteroid multi-encounter scenarios. The launch year, asteroid name, asteroid radius, asteroid spectral type, years between launch and each asteroid encounter, and flyby velocity or rendezvous conditions are given in order. The mass available for orbital science instruments and lander packages is given below the dotted line. The improvement in the quality of the missions with respect to both selection of targets and encounter conditions which has resulted from the improvement in available (or developmental) propulsion systems is obvious.

1	2	3	4	5	6
Direct 1982	VEGA 1980	SEP 1985	Ion Drive* 1986	Ion Drive* 1984	Ion Drive* 1988
Sappho 41 km, U or S, 0.7 yr, 13 km sec^{-1}	Flora 75 km, S, 1.9 yr, 8 km sec^{-1}	Vesta 376 km, unique, 1.8 yr, rendezvous	Vesta 275 km, unique, 1.7 yr, orbit for 40 days	Ceres 502 km, C, 2.0 yr, orbit for 60 days	Ceres 502 km, 2.3 yr, orbit for 50 days
Dagmar ?, ?, 1.6 yr, 6 km sec^{-1}	Sonneberga ?, ?, 3.4 yr, 9 km sec^{-1}	Jerome ?, ?, 2.3 yr, 5 km sec^{-1}	Fortuna 108 km, C, 4.2 yr, orbit for 70 days	Maja 38 km, C, 4.0 yr, rendezvous for 60 days	Lucina 46 km, C, 40 yr, orbit for 60 days
Flora 75 km, S, 2.6 yr, 10 km sec^{-1}	Stavropolis ?, ?, 3 7 yr, 10 km sec^{-1}	Io 73 km, C, 3.5 yr, 0.2 km sec^{-1}	Eleanora 76 km, S, 5.9 yr, orbit for 57 days	Melpomene 75 km, S, 6.0 yr, orbit for 60 days	Parthenope 75 km, S, 6.3 yr, orbit for 60 days
Photographica ?, ?, 3.6 yr, 11 km sec^{-1}	Fidelio ~30 km, C, 5.0 yr, 6 km sec^{-1}		Irene 79 km, S, 8.3 yr, orbit	Celuta 24 km, M, 8.1 yr, rendezvous	Vesta 275 km, unique, 8.5 yr, orbit
Protogeneia ?, ?, 4.2 yr, 7 km sec^{-1}	1940QC ?, ?, 5.9 yr, 5 km sec^{-1}				
Isara 14 km, S, 5.7 yr, 9 km sec^{-1}					
		~100 kg	200-300 kg	200-300 kg	200-300 kg

*Bender (1977); mass in orbit for initial encounter = 5480 kg.

improvements. Using Ion Drive, a large scientific payload, including possible multiple landers, can be delivered to a wider variety of asteroidal targets for rendezvous lasting several tens of days at each asteroid (Bender, 1977). In the case of asteroids with diameters >50 km, it would not only be desirable, but necessary, to orbit for the duration of the rendezvous. Orbital velocities would be $\sim$100 m sec^{-1} for a major asteroid under the encounter conditions described in the caption of Figure 1. Columns 4, 5 and 6 of Table 3 show two of several example scenarios identified by Bender (1977) which I consider to be especially attractive and which, in fact, are marginally compatible with the science desires stated above. The first of these involves an initial encounter with Vesta, a subsequent encounter with the large C object Fortuna, and two encounters with S asteroids. The second orbits Ceres, a small C, a 75 km S, and a small M object. However, it does not encounter Vesta. The last orbits both Ceres and Vesta, although it does not orbit the latter until 1996. It also orbits a 46 km C object and a 75 km S object, but no M object is encountered. In the Bender scenario over 5000 kg is placed in orbit including $\sim$300 kg of mass dedicated to orbital instruments and lander packages. This allows for several hard landers as well as a generous orbital payload, quite compatible with the example suggested in Table 2. It has been pointed out to the author that NASA is unlikely to commit to the development of an Ion Drive design quite as powerful as that assumed by Bender. Nonetheless, we are getting close.

Despite the tremendous progress that has been made in defining candidate multi-rendezvous missions, none is yet completely satisfactory. For example, none of the multi-rendezvous missions identified by Bender encounter Vesta, a C object *and* an M object. Moreover, even with Ion Drive, a transfer from one asteroid to another still requires about half a revolution ($\sim$2 years), so these missions take an exceedingly long time (>8 years) to complete. Finally, there is no specific provision yet for possible sample return. Some schemes for multiple asteroid sample return have been suggested but have not been the subject of detailed engineering studies. Even if such schemes are shown to be compatible with the Ion Drive payload, they should be carried out on an initial asteroid mission only if they do not seriously compromise the ability of the initial mission to investigate (1) each of several carefully selected asteroids as (2) global or planetary entities. This seems unlikely.

The impressive array of multi-rendezvous missions identified by Bender is, in fact, also the result of a very preliminary and limited survey which was conducted under a rather constraining set of rules. For one thing, it was assumed that the encounter with either Ceres or Vesta had to be the first encounter. Also, the payload mass at first encounter was optimized, which is not necessary. Besides simply continuing the search, the effect of altering these and other constraints should be investigated. The compatibility of an initial spacecraft investigation of an Apollo asteroid with studies of those in the main belt should also be studied. A dual launch mission with nonredundant targets also seems a very attractive option. Finally, the possibility of encountering a Trojan asteroid at the termination of the mission should be considered. In any event, Table 3 shows at a glance that dramatic progress has been made, and that the simultaneous maturation of our knowledge of the asteroids from Earth-based optical measurements together with vast simultaneous improvements in anticipated delivery capabilities has brought us to the threshold of the definition of a viable initial asteroid-dedicated mission.

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DISCUSSION

ARNOLD: I strongly agree that multiple encounters are essential to good science, and that long stay times are needed for the gamma-ray or x-ray sensing systems. Flybys are not attractive, especially for gamma-rays. I will discuss this point further in my paper in this afternoon's session.

ANDERS: In our museums there are howardites that seem to match the spectrum of Vesta. Suppose the measurements on a rendezvous mission to Vesta show that there is a chemical resemblance between howardites and the surface of Vesta. Are we then to assume on the strength of this identification that everything we have ever learned about howardites now applies to Vesta?

FANALE: No, you have to determine the chronology of differentiation independently for Vesta by looking at the cratering history of its surface. You would also want to know what the density is and if there is a density inversion.

ANDERS: The age would be difficult to get because the cratering rate in the asteroid belt is much higher, which means the surface will be saturated.

FANALE: We are going to have to do a lot of thinking about the specifics. I think we have to establish the link between Vesta and the achondrites. Chemical mapping of Vesta can be accomplished and perhaps there are windows where you can see something about the zonal structure and understand something about the magmatic path that was followed in its differentiation as well.

CHAPMAN: If you place too much emphasis on unique targets, such as Ceres and Vesta, you might get no typical C or S objects.

FANALE: You will almost certainly encounter a small one on the way.

ARNOLD: If there have been highly differentiated bodies in the asteroid belt (Vesta seems to be one clear example), one strongly suspects there are now pieces of highly evolved bodies. It can't be that all the Vestas are still intact. In that case one would have the possibility of looking at a vertical section.

FANALE: The most optimistic case for the chemical mapping of the very big asteroids is the possibility of seeing some of these windows. For the very little ones there is a possibility it will be totally in an erosional mode so you are not covered with a patina or any other dust. It is likely that we may not learn much about lateral variations on the rock surfaces of the middle-size asteroids because of their regoliths.

IMAGING ASTEROIDS: SOME LESSONS LEARNED FROM THE VIKING INVESTIGATION OF PHOBOS AND DEIMOS

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There is a good chance that the two small satellites of Mars really are captured asteroids and as such may be representative in many (but not all) ways of other small bodies in the asteroid belt. This paper discusses specific experiences from the study of Phobos and Deimos during the Viking mission and uses them to formulate three basic goals of any serious imaging study of asteroids. These are to obtain: (1) the highest possible resolution, (2) complete coverage of the surface, and (3) data over a wide range of phase angles.

I. INTRODUCTION

The recent investigations of the satellites of Mars by the Viking Orbiters provide some useful lessons on how to plan a detailed imaging study of an asteroid. After summarizing our current knowledge of the two asteroid-like moons of Mars, I will discuss three crucial requirements for any successful imaging study of asteroids:

1. The need to obtain the highest possible resolution of the surface.
2. The need for complete coverage of the surface.
3. The advantages of imaging over a wide range of phase angles.

These points are illustrated using specific experiences derived from the study of Phobos and Deimos during the Viking mission.

Phobos and Deimos in Summary (*cf.*, Veverka, 1978)

Phobos and Deimos are small, very dark grey asteroid-like satellites. They have geometric albedos of about 0.06 in V and B-V colors of about +0.6 (*i.e.*, they are grey). While both are irregular, their shapes can be approximated reasonably well by triaxial ellipsoids. Phobos is about 27 × 21 × 19 km across; Deimos is about half as big: 15 × 12 × 11 km. The two satellites have a similar shape; in each case the ratio of the longest to the shortest axis is about 1.4 to 1.0. The spin periods of both satellites are synchronous with their orbital periods, but it is interesting to note that the actual values are comparable to those of asteroids--7^h39^m for Phobos and 30^h17^m for Deimos.

Both satellites are heavily cratered and are completely covered with a regolith whose surface microtexture appears to be lunar-like, judging from its photometric, polarimetric and thermal inertia properties. On the scale of several hundred meters, the surface of Phobos is homogeneous in albedo, but that of Deimos is not. Bright patches (some 30% brighter than the surroundings) are conspicuous on Deimos. The surface density of craters on both satellites is similar to that in the lunar uplands suggesting that these may be equilibrium surfaces. Using current models of the past cratering rates at the orbit of Mars, one can estimate that the surfaces are at least 2.5 to 3.0 billion years old. The largest crater on Phobos, Stickney, is about 10 km across. The largest known crater on Deimos is about 3 km across.

The most surprising discovery made by Viking is that the surface of Phobos is covered by swarms of trough-like grooves which seem to be surface expressions of deep fractures within Phobos produced by the formation of Stickney. Grooves are not found on the surface of Deimos. In spite of the low surface gravity of the two bodies ($g \sim 10^{-3}$ g on Phobos, and about one-half less on Deimos), much ejecta-like material, including coarse blocks tens of meters across, are evident on the surfaces--especially on Deimos.

A recent mass determination for Phobos leads to a mean density of about 2 g/cm^3. This low mean density, the low albedo, and the Ceres-like spectral reflectance curve of the satellite, suggest that Phobos is made of a low density, water-rich material similar to that which makes up some carbonaceous chondrites. Information on the composition of Deimos is inconclusive. The data suggest that although Deimos is probably *not* identical in composition to Phobos, it may also be made of some sort of carbonaceous material. A mass determination by Viking Orbiter 2 suggests that the mean density of Deimos is similar to that of Phobos, but the determination is very uncertain since we do not know the volume of Deimos very well (see below).

The probable low density, water-rich carbonaceous chondrite composition of Phobos (and Deimos?) suggests that they may have formed in the asteroid belt and were captured by Mars during a comparatively early stage of its accretion (when Mars was still surrounded by an extensive primitive atmosphere) or were perhaps captured collisionally. Thus there appears to be a good chance that the satellites of Mars really are captured asteroids and as such are representative in many (but not all) ways of other small objects that we may encounter in the asteroid belt.

II. THE NEED TO OBTAIN THE HIGHEST POSSIBLE RESOLUTION

The Viking experience in studying Phobos and Deimos provides numerous examples of the need to obtain the highest possible resolution imagery of asteroid-sized bodies.

Discovery of Grooves on Phobos: Their Morphology and Age

While Mariner 9 resolution (several hundred meters) was adequate to show the irregular shape and the heavily cratered surface of Phobos, it took resolution of better than 50 m to discover that the surface of the inner satellite is crossed with grooves (Figure 1). At moderate resolution ($\sim$40 m), the linear features--or grooves--appeared to fall into two distinct categories, first called "striations" and "crater chains" by Veverka and Duxbury (1977). The "striations" seemed to be trough-like depressions, while in many cases the "crater chains" seemed to show similarities to the "herringbone" pattern of secondary crater chains on the Moon (Figure 2). Still higher resolution imagery (<15 m) was needed to make it clear that there is essentially only one type of linear feature, or groove, although some of the grooves have been modified to various degrees by other processes. At the highest resolution achieved on Phobos (5 m) the simplest grooves appear to be fault-like troughs (Figure 3), although local segments are often modified by pitting and have a beaded appearance (Figure 4). Significantly, at these highest resolutions none of the grooves looks like a chain of impact craters. Even the "herringbone" patterns suspected in Figure 2 are ultimately resolved into beaded troughs (Figure 5) which bear no resemblance to chains of secondary craters.

Fig. 1. View of Phobos from Viking Orbiter 2 (Frame 039B84). The large crater at top (Roche) lies close to the north pole of Phobos and is about 5 km across. Range = 800 km.

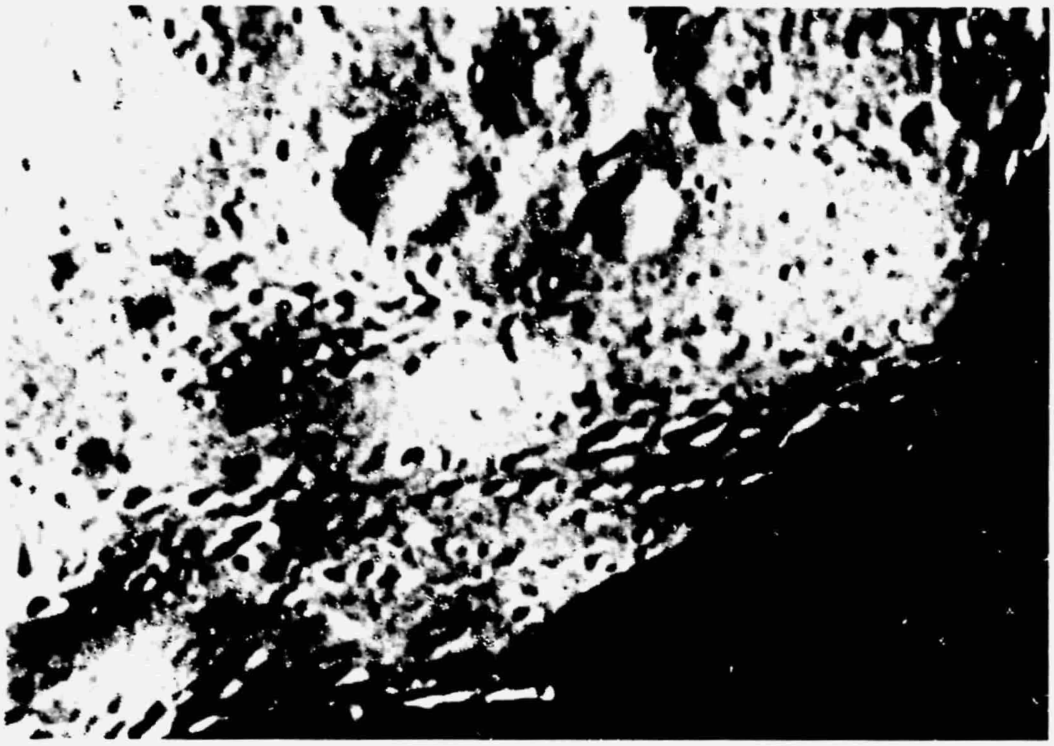

Fig. 2. Enlarged segment of Frame 039B84, showing apparent clusters of irregular depressions arranged in herringbone patterns suggestive of secondary effects.

From a detailed study of the morphology of the grooves, Thomas *et al.* (1977) conclude that they are probably surface expressions of internal fractures--fractures which as we will see below (Section III) appear to be intimately connected with the formation of Stickney, the largest crater on Phobos (*cf.*, Figure 12). This study of groove morphology using the highest resolution imagery available (5-15 m) established the following facts:

a. Grooves are typically 100-200 m wide and 10-20 m deep.

b. They are largest and best developed in the neighborhood of Stickney and taper out toward the point antipodal to Stickney (Figure 12). Some of the grooves near Stickney are 700 m wide and several hundred meters deep.

c. Many groove segments are modified by pitting (Figure 4) and have a beaded appearance.

d. A few segments may have slightly raised rims (Figure 6).

e. At the highest resolution available, no groove segment has the appearance of a chain of impact craters.

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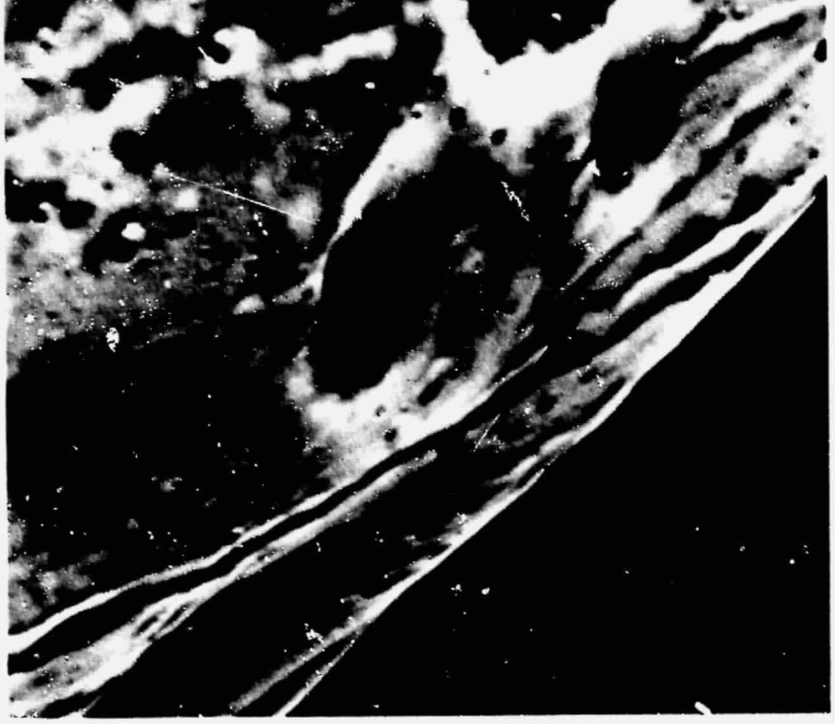

Fig. 3. Close-up of Phobos grooves obtained by Viking Orbiter 1 during February 1977. Range = 137 km. The picture is about 3 km across and shows detail as small as about 5 km. The triplet of large craters is the same as that in Figure 2 (Frame 244A08).

The pitting and the possible raised rims can be explained in terms of a modification of the grooves by internal processes. Veverka *et al.* (1977) suggest that the large impact which produced Stickney not only cracked Phobos, producing the grooves, but heated up portions of the interior enough to outgas some water vapor. It should be recalled that the low albedo, the spectral reflectance curve, and the mean density of Phobos suggest that the satellite is made of a material similar to water-rich low-density carbonaceous chondrite material (Veverka, 1978). By raising the temperature locally to slightly more than 400°K during the formation of Stickney, water vapor should be driven off. It is likely that this vapor will tend to come out along fractures, possibly accounting for the pitting and the possible raised rims on some of the grooves (Veverka, 1978).

Very high resolution imagery has also made it possible to estimate the age of the grooves by counting small impact craters within them. In this way Thomas *et al.* (1977) find that the grooves are probably at least 3 AE old and thus cannot be attributed to any recent event, such as the tidal stretching of Phobos by Mars. This mechanism, proposed by Soter and Harris (1977) should have been most effective during the past hundred million years (Pollack, 1977). Thus, the old age of the grooves is inconsistent with a tidal origin, but is consistent with an origin associated with the formation of Stickney (Thomas *et al.*, 1978).

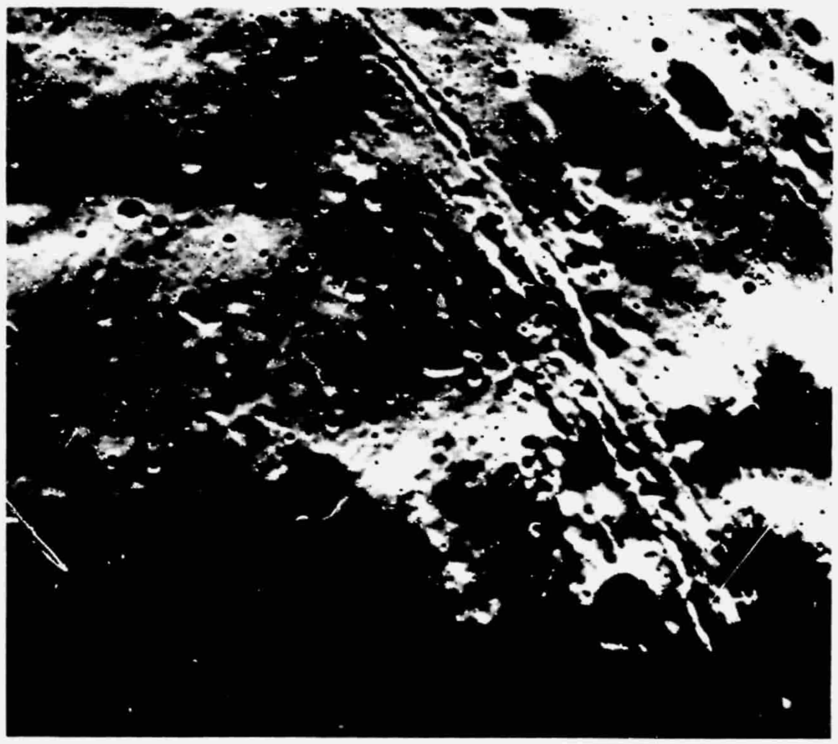

Fig. 4. Portion of Viking Orbiter 1 Frame 246A05 taken from a range of about 260 km. Note the conspicuous pitting of the grooves. The grooves are typically 100-200 m wide.

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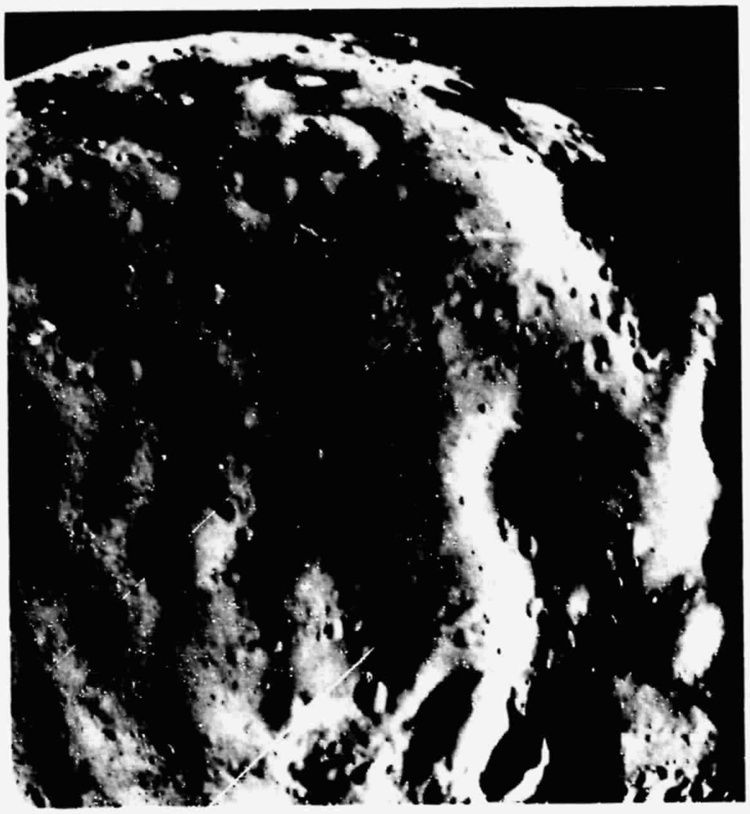

Fig. 5. Viking Orbiter 1 image of Phobos taken from a range of 530 km. The triplet of craters shown in Figures 2 and 3 is seen at center top. Note the different appearance of the groove just below the crater triplet in the three views. Raised rims are visible on some of the craters at top (Frame 243A71).

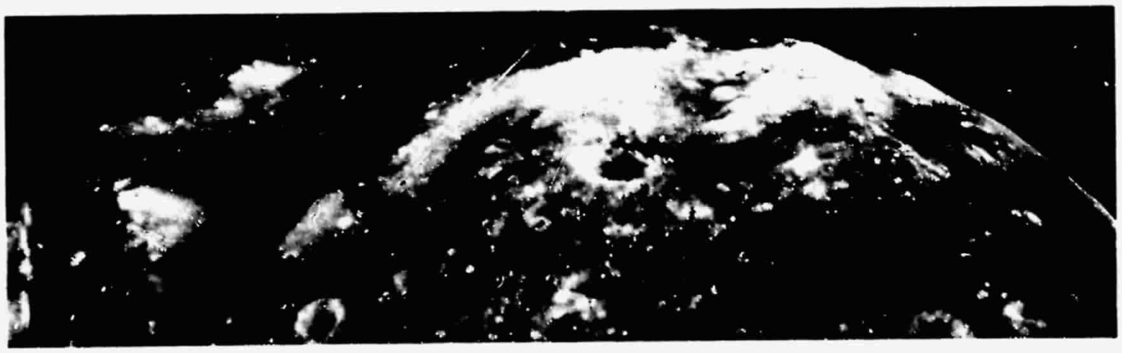

Fig. 6. View of Phobos from a range of 440 km at a phase angle 11°. Several grooves, showing possible raised rims, are seen on the limb (Frame 252A16).

Fig. 7. Viking Orbiter 1 view of Phobos from a range of about 310 km. Note the conspicuous dark marking in the 2 km crater at upper left (Frame 248A01).

Evidence of Small-Scale Surface Inhomogeneities on Phobos

While the surface of Phobos is generally homogeneous both in texture and in albedo on lateral scales of several hundred meters (Noland and Veverka, 1977a), higher resolution imagery does reveal several interesting localized anomalies. For example, at large phase angles, many craters show prominent dark markings on their floors (Figure 7), which have been interpreted as deposits of impact melt (Section IV). Also, in the vicinity of Stickney there occurs a patch (about 3 × 6 km across) of hummocky material whose origin is at present unclear, but which could represent some type of ejecta associated with the formation of Stickney.

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Fig. 8. View of Phobos from about 160 km obtained by Viking Orbiter 1. Note the dark layer in the crater wall at top. The frame is about 3 km across (Frame 244A03).

Layering Within Crater Walls on Phobos

One of the highest resolution pictures of Phobos (~5 m) shows an oblique view of a crater wall which contains evidence of layering (Figure 8). A dark layer, about 50 m thick and some 150-200 m below the surface, demonstrates that there are at least shallow inhomogeneities with depth and may provide evidence for a very deep regolith. Similar evidence should be looked for on asteroids. An effective resolution of better than 10 m is needed.

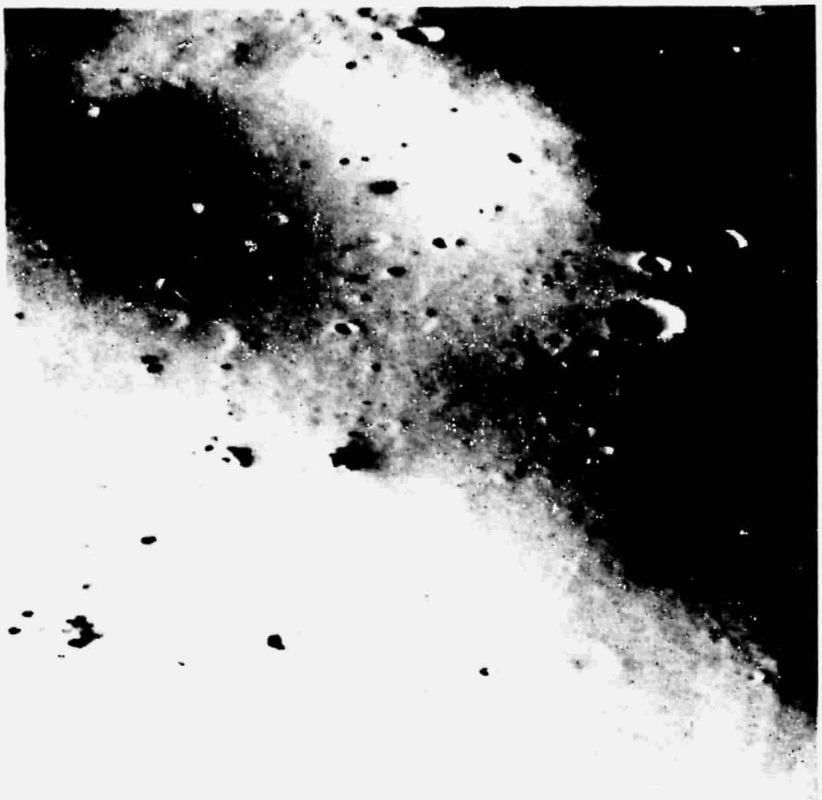


Fig. 9. Viking Orbiter 2 close-up of Deimos from a range of about 60 km. The picture is about 1.3 km across. The smallest visible detail is about 2-3 m. Note the conspicuous dark halo crater near top center (Frame 423B61).

Dark Halo Craters

Another noteworthy discovery made using the highest resolution imagery is that very small (d ≈ 10-20 m) *dark halo* craters appear to be common on both Phobos and Deimos (Figure 9). These craters appear to be similar to their lunar and martian counterparts. Their ubiquitous presence on very different bodies suggests that they may not involve the excavation of dark, subsurface material, as has been proposed in the lunar context, but may instead be attributable to certain characteristics of the impacting body (*e.g.*, composition, high velocity, etc.)

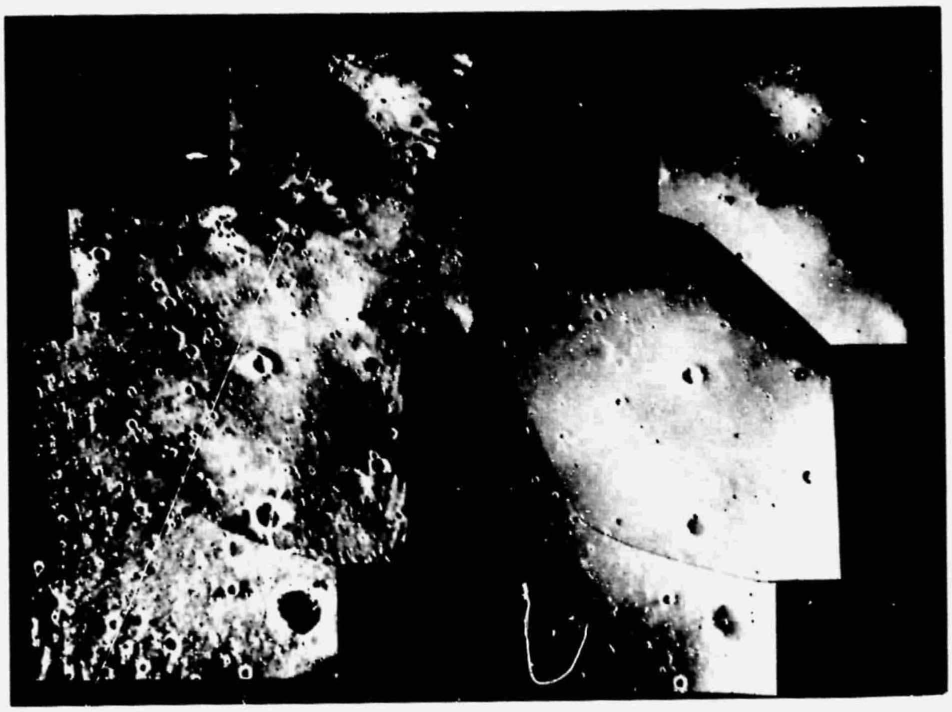


Fig. 10. Viking Orbiter 2 mosaic of Deimos from a range of 60 km. Each frame is about 1.3 km across. Two different enhancements are shown (Frames 4ƨ3B61-63).

Blocks and Ejecta Deposits on Deimos

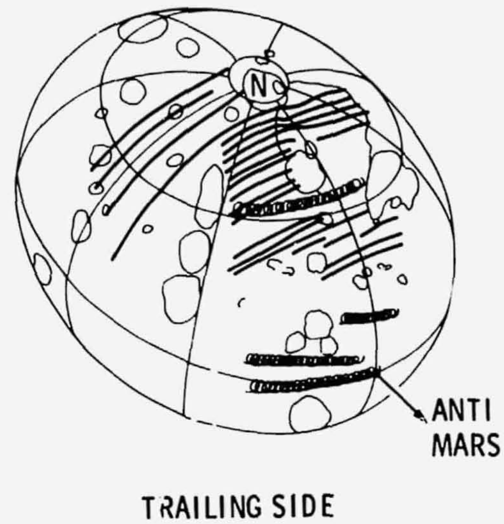
Low resolution images (100-200 m resolution) show that the surface of Deimos has bright patches, and that, compared to Phobos, Deimos appears to be very smooth. The latter observation remained a puzzle for a long time inasmuch as crater counts indicated that Phobos and Deimos have equal surface densities of impact craters. The very high resolution images (resolution about 3 m) obtained by Viking Orbiter 2 in October 1977 have resolved this puzzle and have provided convincing information as to the nature of the bright patches (Figure 10).

The bright patches appear to be deposits of fine-grained ejecta which, in many cases, partially fill craters on Deimos--thus accounting for the relatively smooth appearance of the outer satellite. (Similar bright patches do not occur on Phobos, and there is less evidence of craters being filled in by ejecta.)

The high resolution images also show that the surface of Deimos is littered with numerous isolated, roughly equidimensional positive relief features (typically ∿10 m in size) which have the characteristics of ejecta blocks. How so much ejecta is retained on such a small satellite, and why the process seems to be so much more efficient on Deimos than on Phobos, remain unresolved puzzles.

The high resolution images also show a new, and as yet unexplained surface feature: bright streak-like markings behind positive relief features such as crater rims and blocks. These markings appear to be concentrations of fine-grained ejecta, and it is conceivable that they may be analogous to certain deposits formed by near surface flows that are seen in some parts of the lunar surface, but it must be admitted that the detailed resemblance is not very close.

Fig. 11. Old sketch map of the distribution of grooves on Phobos based on incomplete surface coverage (from Veverka and Duxbury, 1977). Compare with Figure 12.



III. THE NEED FOR COMPLETE COVERAGE AT HIGH RESOLUTION

One of the crucial requirements is that complete coverage of the surface be obtained at the highest possible resolution. Complete coverage of the surface is needed to look for global patterns and to search for regional anomalies. For all missions, the angle of the subsolar latitude determines the extent of the surface that is illuminated. Given the short rotation periods of most asteroids, full coverage at a useful resolution could be realized even for a flyby mission. Rendezvous missions offer an opportunity for higher resolutions with complete coverage.

The Viking investigation of Phobos provides a striking example of the need to have global coverage in order to understand important phenomena on small bodies. As soon as the enigmatic grooves were discovered, many possible explanations were proposed. At first the coverage of Phobos at the resolution needed to see grooves was very limited (Veverka and Duxbury, 1977) and it was impossible to determine the true distribution of the grooves on the surface of Phobos, or their possible connection with other major topographic features. One early and clever suggestion by Soter and Harris (1977)--that the grooves are fractures due to martian tides--was consistent with the then available information (Figure 11). However, as soon as more complete high resolution coverage was obtained, it became evident, from the pattern of the grooves and from their intimate association with the crater Stickney (Figure 12), that the grooves could not be due to martian tides but were probably expressions of fractures associated with the formation of Stickney (Thomas *et al.*, 1978).

As far as regional variations are concerned, none were found on Phobos (other than that in the distribution of grooves). Specifically, there are no significant variations in the surface density of impact craters; thus no large-scale cratering or spallation event has occurred in "recent" times. The entire surface of Phobos, like that of the lunar uplands, has reached an equilibrium state in terms of cratering.

Complete surface coverage is also needed to derive an accurate density from a mass determination. For irregular objects such as Phobos, Deimos, or most asteroids, accurate volumes can only be determined by imaging all of the surface. There is no reliable way of extrapolating beyond the limb. In the case of Phobos, for which our surface coverage is essentially complete, the current uncertainty in the volume is still comparable (about ±10%) to the uncertainty in the mass determination. While further analysis will improve

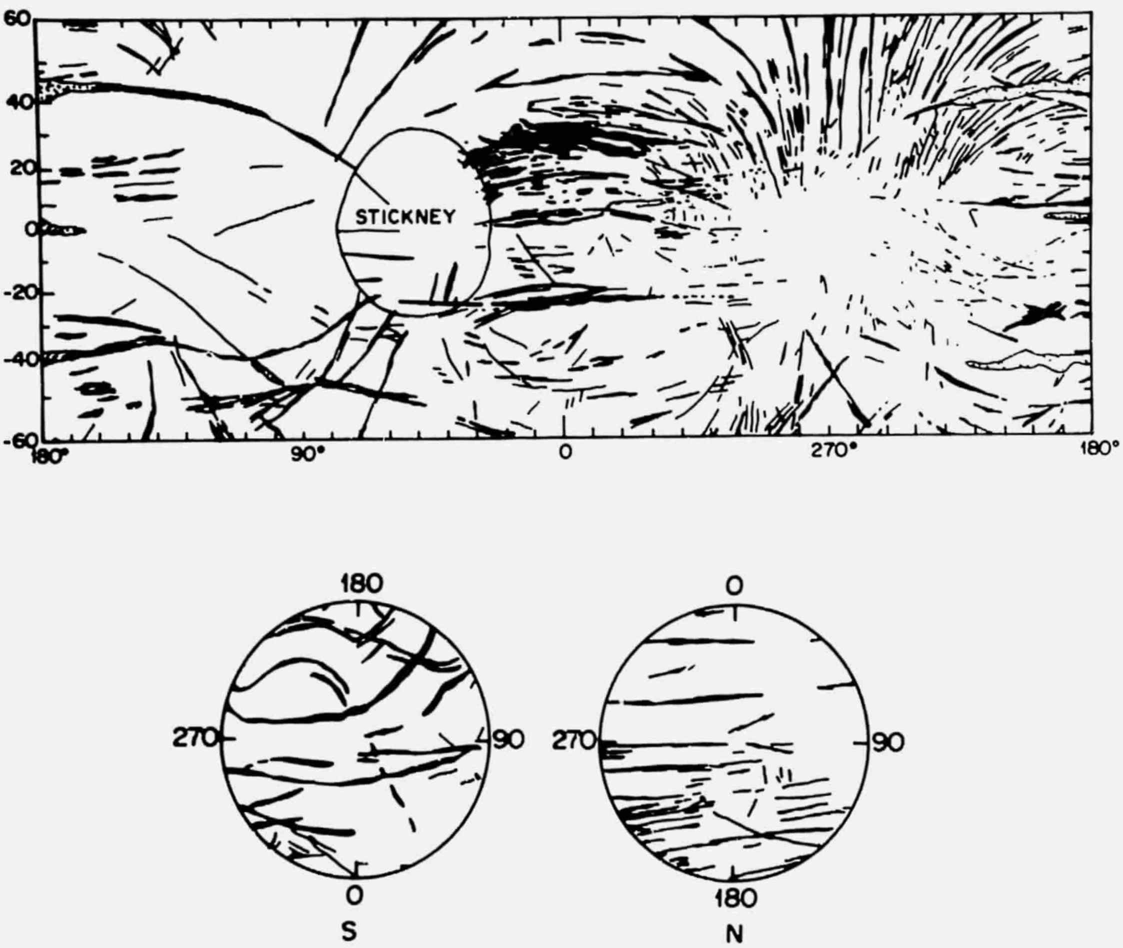


Fig. 12. Sketch map of Phobos showing the location of the grooves and of the largest crater, Stickney. Stippled areas represent hummocky topography within grooves (after Thomas *et al.*, 1978).

our knowledge of the volume, accurately determining the volume of an irregular object is still a difficult problem, even when essentially complete coverage of the surface exists. In the case of Deimos, Viking has imaged only about 50% of the surface, and the volume remains very uncertain. Thus while we know the mass of Deimos about as well as that of Phobos, we cannot determine the mean density of the outer satellite reliably until more extensive coverage of its surface is obtained.

The incomplete coverage of Deimos not only plagues attempts to determine the density, but also makes it difficult to resolve some other important questions. For example, we now know that there are no grooves on Deimos. Why? One possible explanation is that there is no crater large enough (say >5 km) on Deimos to have fractured the satellite. While we know that there is no crater larger than about 3 km on the part of Deimos that has been imaged, it is important to show that there is no much larger crater on the remainder of the surface.

Fig. 13. Viking Orbiter 1 view of Phobos at a phase angle of 14°. The conspicuous bright rings around many of the craters probably represent areas of unusually intricate texture. Range = 370 km (Frame 250A14).

IV. ADVANTAGES OF IMAGING OVER A LARGE RANGE OF PHASE ANGLES

While the optimum phase angle for studying surface morphology (craters, grooves, blocks, etc.) is close to 90°, much significant information about surface texture can be obtained by imaging over a wide range of phase angles. From such data it is possible to construct phase curves for various parts of the surface and search for textural differences. It is possible to determine whether the regolith is laterally homogeneous, and whether or not there are extensive exposures of bare, uncomminuted rock. For example, in the case of Phobos, Noland and Veverka (1977a) used such data (obtained by Mariner 9) to show that the regolith on the inner satellite is essentially homogeneous in texture on scales of several hundred meters.

Recent high resolution Viking images show that significant differences in surface texture do occur over smaller distances on Phobos. For example, near opposition (phase angle $\alpha \approx 10°$), narrow bright rings are seen around many of the craters (Figure 13). At low phase angles these features are about 5-10% brighter than their surroundings; but they are inconspicuous at larger phase angles. They are best explained as regions of circumcrater ejecta whose texture is rougher than that of the surroundings.

Fig. 14. Viking Orbiter 2 view of Deimos from a range of 1000 km. The resolution is about 50 m. Note the absence of grooves and the conspicuous bright markings (Frame 428B60).

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Phase angle coverage allows one to distinguish differences in albedo effects from differences in phase function effects. That is, one can determine *why* a certain region appears brighter than another under a given illumination geometry. Is it because the material is intrinsically brighter (*i.e.*, has a higher normal reflectance), or is it because it has a different phase function (*i.e.*, a different texture or surface roughness)? Two interesting examples can be given:

a. By constructing relative phase curves Noland and Veverka (1977b) proved that the conspicuous "bright" material on Deimos (Figure 14) actually has a normal reflectance about 30% higher than the surroundings, but has a comparable texture (since its phase function is essentially identical to that of its surroundings).

b. By a similar procedure, Goguen *et al.* (1977) have demonstrated that the "ultra-dark" material which is conspicuous on the floors of many Phobos craters at large phase angles (Figure 7), appears darker (contrast $\sim$100% near $\alpha = 90°$) because it has a steeper phase curve (*i.e.*, is much rougher) than its surroundings, and not because it has a significantly lower normal reflectance. Goguen *et al.* found that the normal reflectance of the "dark" material differs by less than 10% from that of the surroundings. Its coarse texture and its location on the bottoms of craters is consistent with its being solidified impact melt which, judging from terrestrial experiments, often has a coarse, vesicular texture.

ACKNOWLEDGMENT

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DISCUSSION

MATSON: How would you describe the blocks on Deimos? Do they tend to lie on their sides or to stand on their ends?

VEVERKA: We have looked at the block height versus block width distribution on Deimos and what is interesting about this is that if the blocks were equidimensional then the data suggest that they are buried in something. Typical blocks are like 10 m or so in dimension.

MORRISON: Do you want to say anything about which of these kinds of features or lessons apply most directly to asteroids? As you pointed out, asteroids have a somewhat different environment.

VEVERKA: In the next session, I am going to talk about imaging objectives and their importance. The best answer to your question is that you are really not smart enough to know what you are going to see on asteroid surfaces. That should be the lesson of these two objects. In neither case were we able to anticipate what we should see at high resolution and the two objects are really very different. Therefore, we should not pretend we can predict what will be seen on any particular asteroid and we must plan our strategy so we can take advantage of whatever is there. That involves doing the best you can to get high resolution, complete surface coverage, and complete phase angle coverage. I left color measurements out of this discussion for a number of reasons. In the case of Deimos, the bright patches, to our 5% sensitivity, don't really have colors different from the surroundings. I am sure they do have smaller color differences and that would be interesting information. If we had only global or hemispheric measurements, we would probably think that Deimos is very homogeneous, but when you get there you do notice these albedo differences.

CHAPMAN: This is entirely right. One does not want to view these observations as saying "let's think about whether we will see grooves on asteroids, etc." If we had Earth-based observations of Phobos and Deimos similar to those we have of asteroids (we don't because of their closeness to Mars), we would have concluded a number of things about these objects having to do with composition, for instance, but not with geology. Then, we go there and look at them and find features that are mysterious, unexpected and different between the two bodies. These features will cause people to think about these bodies in a way they have never been thought of before. Ultimately, this just proves once again that at least as much is going to come from serendipity as can be anticipated and planned for in advance. I think similar comments could probably be made about other scientific methodologies and not just imagery. We may think we know all the questions to address. We may think we have theories that explain what asteroids are all about. But we have never had the intelligence to really know for sure what we are going to find when we go to a planet or a small body. This is an important lesson.

MORRISON: This is perhaps saying the same thing. Once we have spacecraft data from other planets, we deal with a whole universe of questions we never would have asked from the ground. We have less data on individual asteroids now than we had on Mars or Mercury or Jupiter before the first missions to these planets. Surely the same dramatic widening of our perspective will apply to an asteroid mission.

SHOEMAKER: I hope no one in this room thinks that because we have seen the beautiful pictures of Phobos and Deimos, we now know what asteroids look like. There are some very important differences in the environments of Phobos and Deimos and the environments of the asteroids.

VEVERKA: Once we actually look at several comparable size objects, I think there will be a whole host of investigations to be done relating observations to differences in environments, composition, etc. I think we will learn a lot of things from that.

WETHERILL: I agree with what others have said. You have no idea before you go there what you are going to find. One great advantage of imaging is that it allows you to get answers to questions you didn't know enough to ask in advance. Imaging definitely isn't just for public relations. But I think it is worthwhile to make predictions before a mission. It was shocking that so many people were surprised by craters on Mars. And even after finding craters on Mars, I remember arguing with some members of the Mariner 10 imaging teams about whether there would be craters on Mercury. Some of these people were convinced there would not be craters on Mercury because Mercury was too far from the asteroid belt.

SHOEMAKER: It is necessary not only to think about what will be discovered and to try to make predictions, but also to take time to find out what others have predicted. There is a prophetic statement in Öpik's 1951 paper on Mars-crossing asteroids to the effect that it would be worthwhile looking for craters on Mars! Unfortunately, only a few of the predictions in the literature are as well-grounded.

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ASTEROID MISSION ALTERNATIVES

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Six missions are reviewed which cover the three basic asteroid mission concepts: flyby, rendezvous, and sample return, to a variety of objects including Apollos, Amors, main belt members, and Trojans. Mission characteristics and propulsion requirements of each example are provided along with illustrations of flight profiles. A detailed argument is presented for rendezvous encounter as the best alternative for "exploration" level investigation. Assumption of this encounter option leads to the choice of multi-asteroid rendezvous as the best concept option for early mission exploration of asteroids. The propulsion requirements of multi-rendezvous point to the need for the timely development of low-thrust performance capability for NASA's continued solar system exploration program. It is shown that a minimum solar electric propulsion system of 25 kw with array concentrators is needed to perform multiple rendezvous missions of more than two asteroids. This same system is more than adequate for sample return missions as well. A brief discussion of rendezvous maneuvers demonstrates the utility of orbits for objects greater than 10 km in diameter. An encounter strategy is proposed which features adaptability and flexibility; this strategy requires low propulsion expenditure and only basic *a priori* target information. It is concluded that continued mission and systems analyses can bring us to a high state of flight project readiness by the mid-1980's.

INTRODUCTION

NASA-directed studies of asteroid missions have been performed almost since the agency was formed. Initial results, obtained as early as 1963 by IIT Research Institute (Anon., 1964) dealt principally with flyby missions to the well-known objects, *e.g.*, Ceres, Vesta, Eros, and Icarus. As both analytical capability and propulsion technology evolved, more difficult concepts began to receive consideration, *e.g.*, rendezvous and sample return, with some studies including various forms of low-thrust propulsion. By 1972 mission analysts had generated a substantial base of data on requirements for missions to specific asteroids, *e.g.*, Northrup Services, Inc. (Anon., 1972).

Perhaps the earliest serious consideration of the importance of asteroid missions to solar system exploration by the science community occurred during the 12th Colloquium of the IAU, entitled *Physical Studies of the Minor Planets*, held in Tucson, Arizona in March 1971 (Gehrels, ed., 1971). It became apparent during the course of this meeting, particularly owing to a paper by Anders (1971), that serious planning of an asteroid mission would be premature at that time. This position was strongly supported by two important facts: (1) our state of knowledge about asteroids was based on limited data about several larger or close-approaching objects while the potential for much better information through continued dedicated ground-based observations was very high; and (2) mission concepts to date had concentrated on single well-known targets, which seemed to offer a return of information that was comparatively small, in comparison with the vastly more complex goal of asteroid exploration. Consequently, during the decade of the 1970's, asteroids continued to be studied from the Earth, rather than by missions, and rightly so. Out of this research has emerged an impressive systematic cataloging of asteroid characteristics in the form of the TRIAD data file (Zellner, 1978).

Mission concepts also improved. Specifically, analysis of multi-target concepts, introduced initially by Brooks and Hampshire II (1972) and subsequently analyzed by Bender and Friedlander (1975) and others, have shown that several objects (up to six or seven) can be encountered on a single mission, greatly enhancing its potential science return. The purpose of this paper is to present a brief review of recent progress in asteroid mission analysis, and to present arguments for a preferred concept for early exploration of the asteroids. The asteroid targets discussed include Apollos, Amors, main belt objects, and the Trojans. Mission concepts reviewed include fast and slow flybys, rendezvous, and sample return. Both single and multiple target examples are cited. Propulsion requirements of both ballistic and solar electric low-thrust flight modes are included in the mission examples examined. Mission concepts and associated characteristics are presented first by way of typical example summaries, followed by rationale and supporting arguments for selection of the multi-asteroid rendezvous mission concept for early flight exploration. The paper concludes with a brief discussion of rendezvous strategies capable of global and detailed investigations of individual bodies in the presence of the small but not insignificant asteroid gravity fields.

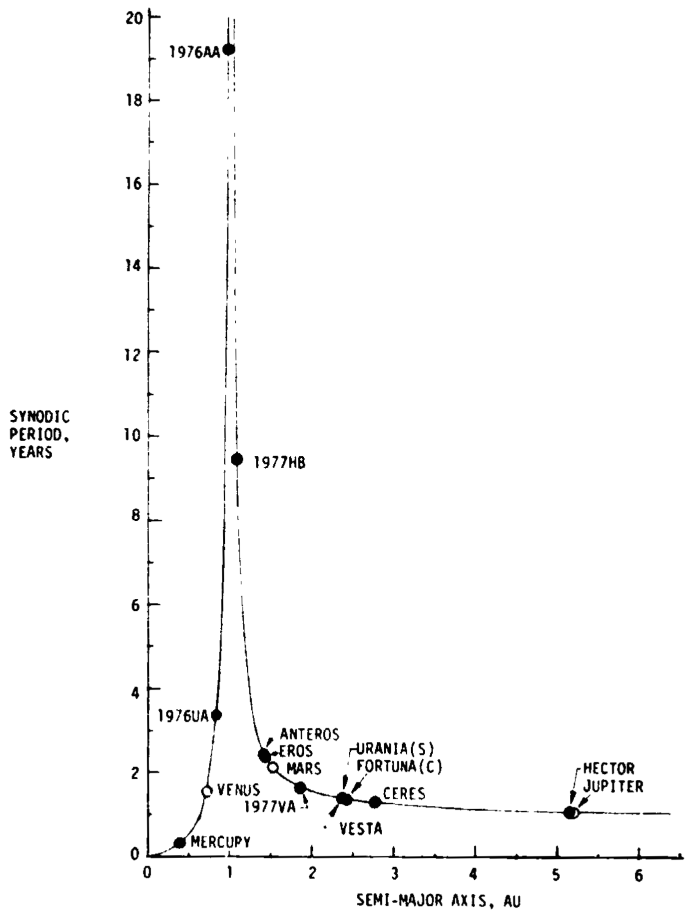


Fig. 1. Asteroid mission opportunity frequency.

ASTEROID MISSION CONCEPTS

Missions to the asteroids, like all other interplanetary flights from the Earth, are constrained to periodic launch opportunities. Although it is theoretically possible to launch an asteroid mission almost any time, owing to the large number of available targets, missions to specific objects have specific launch opportunities, spaced in time by their synodic period with the Earth. Each object's synodic period is controlled by the semimajor axis (a) of its orbit about the Sun. A plot of synodic period (relative to the Earth) versus semimajor axis is presented in Figure 1. The average opportunity interval (*i.e.*, synodic period) of Mercury, Venus, Mars, and Jupiter are shown in the plot as open circles. Various asteroids from the Apollo 1976UA (a = 0.83 AU) to the Trojan Hector (a = 5.15 AU) are also presented in the plot, as solid dots. It is readily apparent from this presentation that missions to all asteroids beyond Mars can be undertaken with a frequency of less than once every two years; main belt missions have an opportunity frequency averaging once every 16.5 months. Only those objects which have orbits approaching 1 AU (the Earth's orbit) exhibit increasingly longer gaps between direct ballistic opportunities, owing to the low relative motion between themselves and the Earth. These objects are primarily the Apollos and some of the closer Amors. The longest interval shown on Figure 1 is for the Apollo 1976AA (a = 0.97), 19.1 years. It should be noted, however, that whereas objects which are accessible on intervals less than every two years exhibit launch windows of approximately a month, objects such as 1976AA which are accessible only once in a great while remain accessible for many months (perhaps even more than a year) when their opportunities do occur. One final point on mission opportunities to bear in mind is that the flight requirements (*i.e.*, launch energy, flight time, and payload performance) can be highly variable from one opportunity to the next because of the eccentricity and inclination of asteroid orbits. Hence, even though mission opportunities recur on average every 16.5 months or so, favorable opportunities occur with less frequency; specific examples will be cited below.

Six asteroid mission concepts will be discussed as a means of demonstrating the characteristics which are available to the mission planner for the development of flight exploration strategies. The identifying features of each of these missions are summarized in Table 1. As can be seen, this mission set includes near-Earth, main belt, and Trojan asteroid targets. Both ballistic and low-thrust flight modes are represented. Four single missions are included--two rendezvous and two sample return missions; and two multi-target missions will be discussed--one flyby concept and one rendezvous concept. All of these missions could be accomplished with current technologies, although certain hardware elements required for some of the missions have, as yet, not been developed. Each of these six examples is presented individually in the following subsections.

Table 1. Asteroid Missions

Asteroid Object Class	Flight Mode		Mission Concept[a]		
	Ballistic	Low-Thrust	Flyby	Rendezvous	Sample Return
Apollo	x			S	
Amor	x				S
Main Belt	x		M		
Main Belt		x		M	
Main Belt		x			S
Trojan	x			S	

[a]S: single target; M: multiple targets

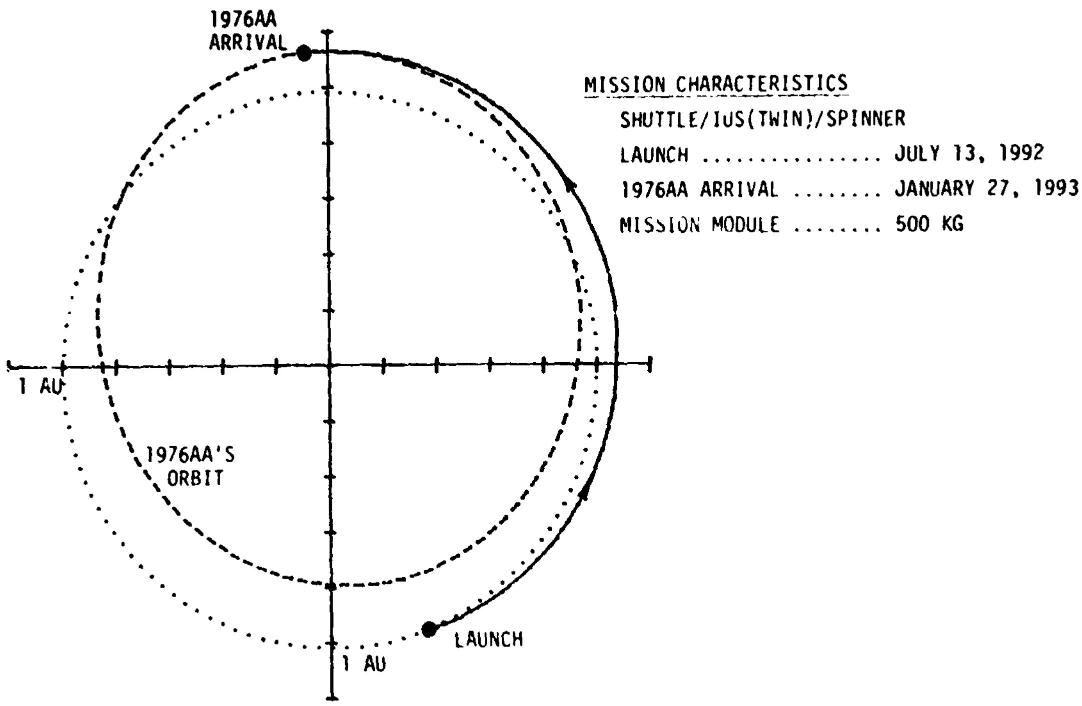


Fig. 2. 1991 1976AA rendezvous mission.

An Apollo Rendezvous Mission

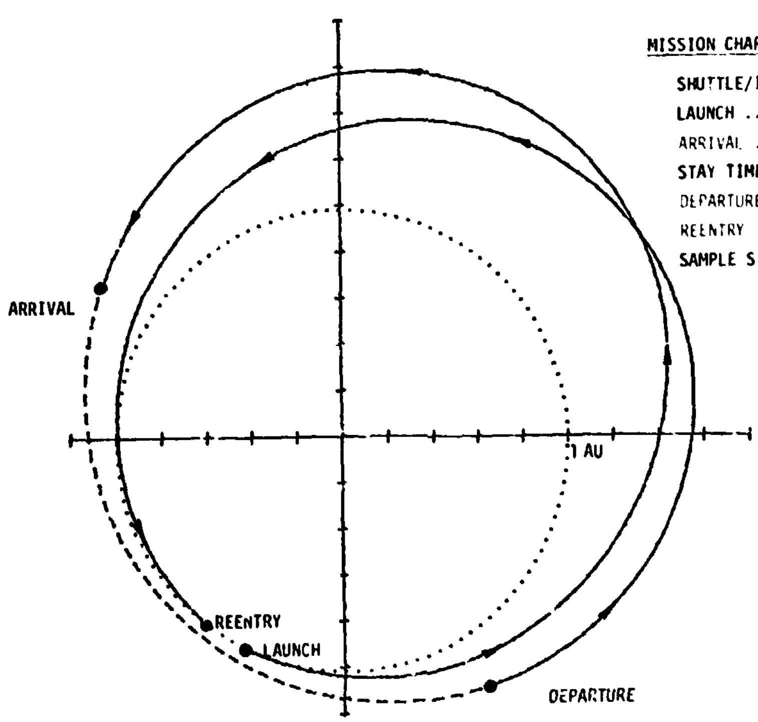
The first example is a ballistic rendezvous mission to the Apollo asteroid 1976AA. 1976AA was discovered two years ago (Shoemaker and Helin, 1978). It is the first asteroid found with a semimajor axis less than the Earth's (0.97 AU). 1976AA's orbit, with a perihelion of 0.74 AU and an aphelion of 1.14 AU, crosses the Earth. Its orbital period is about 347 days. Hence it moves slightly faster about the Sun than the Earth, passing it once every 19 years (note the synodic period of 1976AA in Figure 1). The next window of favorable rendezvous opportunities to 1976AA occurs between 1991-93 (Bender, 1976).

The close proximity of 1976AA to the Earth was immediately recognized as a potentially attractive situation for flight exploration. The asteroid's high orbit inclination of more than 19°, however, was soon realized to be a mitigating factor against low-energy missions. Both unmanned and manned ballistic round-trip missions to 1976AA have been studied (Niehoff, 1977) and both possibilities were found to require multiple Shuttle launches. Yet more practical one-way ballistic rendezvous missions to 1976AA are possible. An example of such a mission is illustrated in Figure 2 with a July 1992 launch date. The Earth's orbit is shown as dots in the figure, with the ecliptic projection of 1976AA's orbit shown as dashes. The heliocentric transfer from Earth to 1976AA is represented by the solid arc marked with arrows. A flight time of [illegible] days is required. Note that the spacecraft would never be more than 0.15 AU away from the Earth during the entire transfer to the asteroid. A rendezvous payload of more than 500 kg could be managed with a Shuttle/IUS(Twin)/Spinner launch system. This would place approximately 100 kg of science instrumentation at rendezvous with 1976AA. By comparison, this mission has approximately the same level of performance difficulty as the Galileo mission, but is accomplished in a much shorter period of time.

On the order of at least 400 Apollo asteroids equal to or larger than 1976AA are thought to exist (Shoemaker and Helin, 1978). If additional objects from this set can be found with lower inclinations than 1976AA, not only will short-time ballistic rendezvous missions be possible, but low-energy short-trip time sample return options can also be considered.

An Amor Sample Return Mission

This example is a low-energy ballistic sample return mission to Anteros. This asteroid, discovered in 1973, is a Mars-crosser with a perihelion of 1.06 AU and an aphelion almost in the main belt at 1.80 AU. Its low inclination of 8.7° contributes significantly to low-energy characteristics of this mission, depicted in Figure 3. Again the dotted orbit is that of the Earth and the dashed orbit is that of Anteros. The outbound and return transfers are shown as solid arcs marked with arrows. Launch is in May 1992 with arrival in August 1993. After a stay time of almost six months, departure on the homeward leg is begun in February 1994. The sample is returned to Earth in May 1995, almost three years after launch. A non-propulsive payload design of 780 kg was chosen for the performance analysis of this mission. It includes a 250 kg interplanetary bus (used both outbound and returning), a 150 kg encounter science payload, a 350 kg lander, a sample acquisition and retrieval system, a 29 kg Earth reentry capsule, and a 1 kg sample. If space-storable propulsion can be used for all the large post-launch maneuvers, then the entire mission module (~1700 kg with propulsion) can be launched with a single Shuttle/IUS(Twin) system. This launch capability results from the low post-launch impulse budget required, which is less than 3 km/sec. The total energy demands of this sample return are less than that of the Galileo mission.



MISSION CHARACTERISTICS

SHUTTLE/IUS(TWIN)

LAUNCH	MAY 26, 1992
ARRIVAL	AUGUST 20, 1993
STAY TIME	177 DAYS
DEPARTURE	FEBRUARY 14, 1994
REENTRY	MAY 14, 1995
SAMPLE SIZE	1 KG

Fig. 3. 1992 Anteros sample return mission.

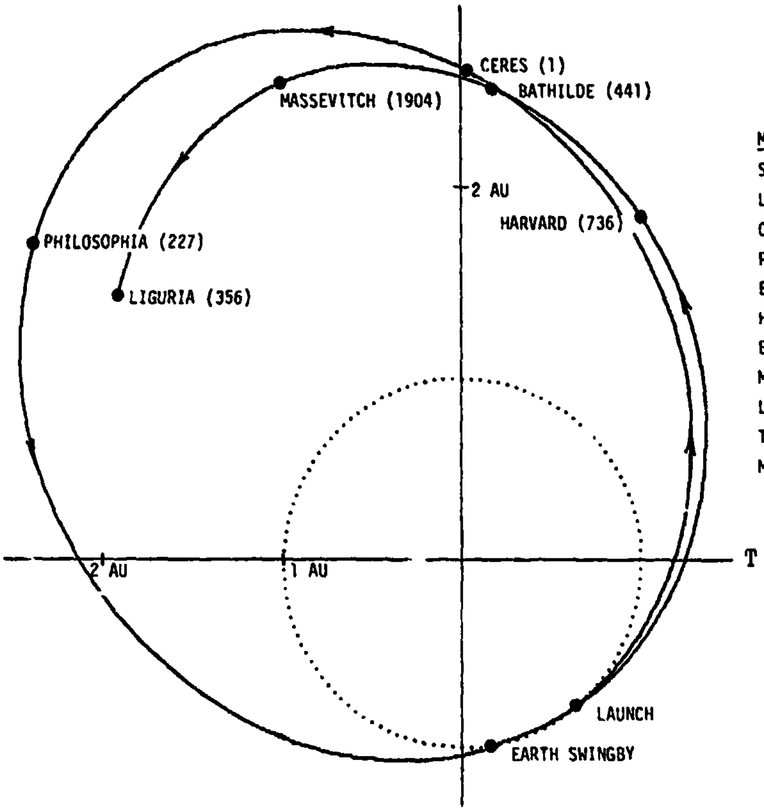
Although the energy required is low, the flight time of three years is comparable to that required for a Mars sample return mission. The stay time alone at Anteros, in this example, is comparable to the flight time of the rendezvous mission to 1976AA presented above. In general, low-energy flight times are proportional to the 3/2's power of the semimajor axis of the object, so that sample return missions require increasingly longer times, the deeper the asteroid belt is penetrated, to reach a desired target. This situation is alleviated somewhat by shorter stay times (Earth is more favorably placed at arrival for immediate departure) of objects in the main belt, and by low-thrust propulsion, but trip times will not decrease for more remote objects.

The rather high eccentricity (e = 0.26) of Anteros, combined with its period of 625 days, results in variable mission energy requirements from one opportunity to the next. With a synodic period of very nearly 2.4 years this behavior is cyclical over a period of five opportunities, or 12 years. In other words, the low-energy sample return examples to Anteros presented above occur only once every 12 years, even though four additional launch opportunities occur during this interval. As it turns out, one of these opportunities occurs with Anteros properly situated in its orbit for a fast one-year sample return mission but the energy requirements are very high. Such mission variability with opportunity is typical of asteroids with eccentric orbits. Additional characteristics of Anteros missions can be found in a recent paper by Niehoff (1977).

A Main Belt Multi-Flyby Mission

Multi-targeted asteroid flyby missions were introduced by Brooks and Hampshire II (1972) as a means of expanding flyby information return for essentially the simple addition of a propulsion system comparable to that of a planetary orbiter. This concept is described generally as a series of several ballistic main belt fly-throughs during which small amounts of propulsion are expended at appropriate points along the trajectory to sequentially acquire targets of opportunity. While there is no way of knowing *a priori* any more than the first target (usually selected to start the search procedure), enough targets present themselves during the course of generating such a mission that some selection is possible. The multi-flyby example selected for discussion here was generated as part of a larger unpublished study at Science Applications, Inc., which specified *a priori* that this particular mission encounter Ceres, at least one M class (metallic) object, and as many other objects as possible. The mission was further constrained to begin during the 1984 launch window for Ceres. The ecliptic trajectory projection of the resulting mission is presented in Figure 4. It consists of two passes through the main belt separated by a reencounter of the Earth, and includes six asteroid flybys. Launch occurs in August 1984 and Ceres (the first target) is encountered in May 1985. No low-energy targets of opportunity were found between Earth and Ceres. An impulse of 390 m/sec is applied shortly after the Ceres flyby enabling an encounter with Philosophia a year later in June 1986. Another impulse of 565 m/sec is applied shortly after Philosophia flyby to reencounter the Earth in July 1987. The Earth's gravity assist along with a 315 m/sec impulse is used to reshape the second main belt fly-through to encounter the M-type object Bathilde in May 1988. One target of opportunity, Harvard, was subsequently found before the Bathilde flyby and two more, Massevitch and Liguria, were found after Bathilde but still on the same orbit revolution. An additional 465 m/sec was needed to add these targets. Liguria, the final flyby, occurs in May 1989, 4.8 years after launch.

The energy requirements of this example are the lowest of the six mission concepts presented. The post-launch impulse requirement is 1735 m/sec plus navigation maneuvers. A 500 kg spacecraft carrying 100 kg of science instruments would require an additional 800 kg of post-launch propulsion to perform this mission. The total injected mass of 1300 kg is easily accommodated by a Shuttle/IUS(Twin) system at the required injection energy (C3) of 54 km^2/sec^2. Note the flyby speeds given in Figure 4, which vary from a low of 5.3 km/sec at Philosophia to a high of 12.4 km/sec at Liguria.



MISSION CHARACTERISTICS

SHUTTLE/IUS(TWIN)

LAUNCH	AUG 84
CERES FLYBY (10.1 KPS)........	MAY 85
PHILOSOPHIA FLYBY (5.3 KPS)...	JUN 86
EARTH SWINGBY (8.2 KPS).......	JUL 87
HARVARD FLYBY (6.7 KPS).......	FEB 88
BATHILDE FLYBY (8.5 KPS)......	MAY 88
MASSEVITCH FLYBY (5.4 KPS)....	NOV 88
LIGURIA FLYBY (12.4 KPS)......	MAY 89
TOTAL TRIP TIME	4.8 YRS
MISSION MODULE	500 KG

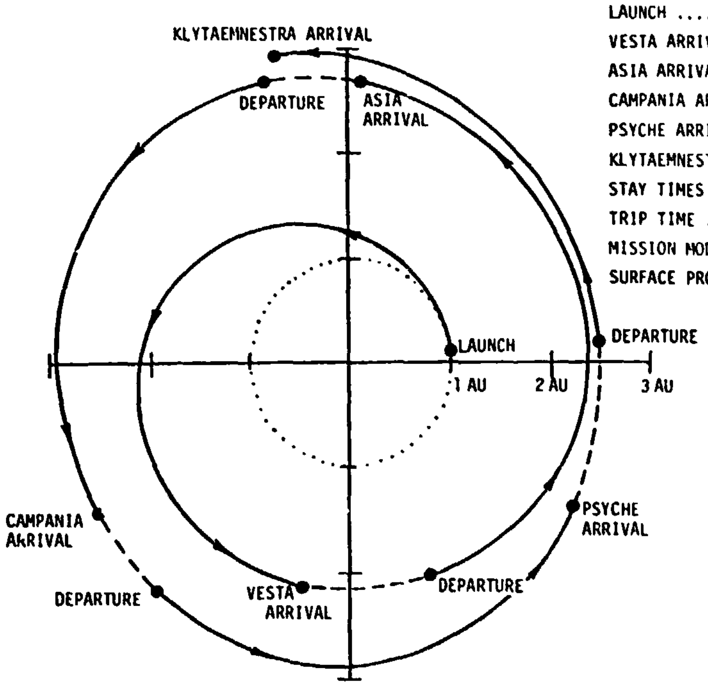
Fig. 4. 1984 multi-asteroid flyby mission.

This example has two encounters on the first fly-through and four on the second. Three encounters per fly-through are usually experienced in generating multi-flyby mission concepts, so we have here some indication of the variability in number of encounters possible per pass, although the encounters still average three per pass. Multi-flyby missions can theoretically be launched anytime. However, if a single specific main belt first target is desired, as was the case here, launch opportunities will occur only once every 16-17 months with some variability experienced in launch energy, and hence maximum payload, regardless of the subsequent targets.

A Main Belt Multi-Rendezvous Mission

This next example capitalizes on the potential advantage of multiple encounters by attaining rendezvous conditions at each target instead of high-speed flybys. Not only do the spacecraft instruments have more than three orders of magnitude more time to study each object, but lighting conditions are controllable, distances remain constant, and surface probes can be deployed with reasonably small expenditures of energy, if desired. The penalty for this added capability is much higher energy requirements and longer total mission time. The multi-rendezvous mission is, in fact, the most difficult mission to perform of the six examples presented, and requires an advanced low-thrust propulsion system to meet the post-launch maneuver requirements.

The example chosen for discussion is a five-target mission that was generated by Bender (1977). Its ecliptic flight profile is depicted in Figure 5. As before, the dotted orbit is that of the Earth, and the solid arcs marked with arrows are the heliocentric transfers between targets. The dashed arcs indicate the periods of rendezvous (stay time) with each target. This time is typically set at 90 days per target, but is slightly longer at the first target, Vesta (112 days) for performance reasons. Two differences are immediately apparent compared to the multi-flyby profile (Figure 4). First, once the flight path reaches the asteroid belt it stays there. Second, the arcs, and hence flight times, between targets are longer. This is a necessary result of reducing the encounter speed at each target to zero for rendezvous, and directly increases total trip time. The five-target example shown in Figure 5 has a 1987 launch and requires almost nine years to complete if the stay time at Klytaemnestra is added to its May 1996 arrival date. The energy-efficient spiral character of the flight path was possible in this example because the four asteroids encountered after Vesta were targets of opportunity. If specific targets are desired, less efficient flight profiles are likely to occur, which could result in fewer targets being accessible within performance capabilities.



MISSION CHARACTERISTICS

SHUTTLE/IUS(TWIN)/ION DRIVE (60 KW)

LAUNCH	OCTOBER 3, 1987
VESTA ARRIVAL	MAY 14, 1989
ASIA ARRIVAL	APRIL 26, 1991
CAMPANIA ARRIVAL	FEBRUARY 15, 1993
PSYCHE ARRIVAL	OCTOBER 7, 1994
KLYTAEMNESTRA ARRIVAL	MAY 31, 1996
STAY TIMES	90 TO 112 DAYS
TRIP TIME	8.7 YEARS
MISSION MODULE	500 KG
SURFACE PROBES	75 KG PER ASTEROID

Fig. 5. 1987 mult. asteroid rendezvous mission.

A 500 kg, non-propulsive mission module carrying 100 kg of science was assumed for determining the performance requirements of this example. A further allowance of 75 kg per target was added to permit the deployment of a penetrator at each of the five asteroids, as well as 100 kg of mercury propellant for low-thrust station-keeping/orbital maneuvers. With these payload assumptions the mission requires a 60 kw Ion Drive low-thrust propulsion system similar to that recently designed by the Jet Propulsion Laboratory (Anon., 1977) for a Halley Rendezvous mission. The payload and this low-thrust system can be launched with the Shuttle/IUS(Twin).

Launch opportunity characteristics are similar to those for the multi-flyby mission discussed above. The average time between rendezvous encounters, in this example, is 1.5 years, which is typical for main belt objects. Hence, each inter-asteroid transfer and encounter is similar to an inner planet mission in time and operations. The benefit of the multi-rendezvous mission is, therefore, not so much in savings in time as it is in savings in hardware costs, since only one system is employed to explore many targets. Additional information on the tradeoff between number of targets, propulsion requirements, and flight time is given in the next section, which presents a rationale for why the multi-rendezvous mission concept should be the baseline approach to flight exploration of the asteroids.

A Main Belt Sample Return Mission

This example, a sample return mission to a main belt asteroid, is presented for several reasons. First, main belt sample return is a very probable element of any comprehensive asteroid exploration strategy. Second, sample return from main belt asteroids is considerably more difficult than from well-placed Apollos or Amors (such as Anteros discussed earlier), an important point relevant to planning exploration strategies.

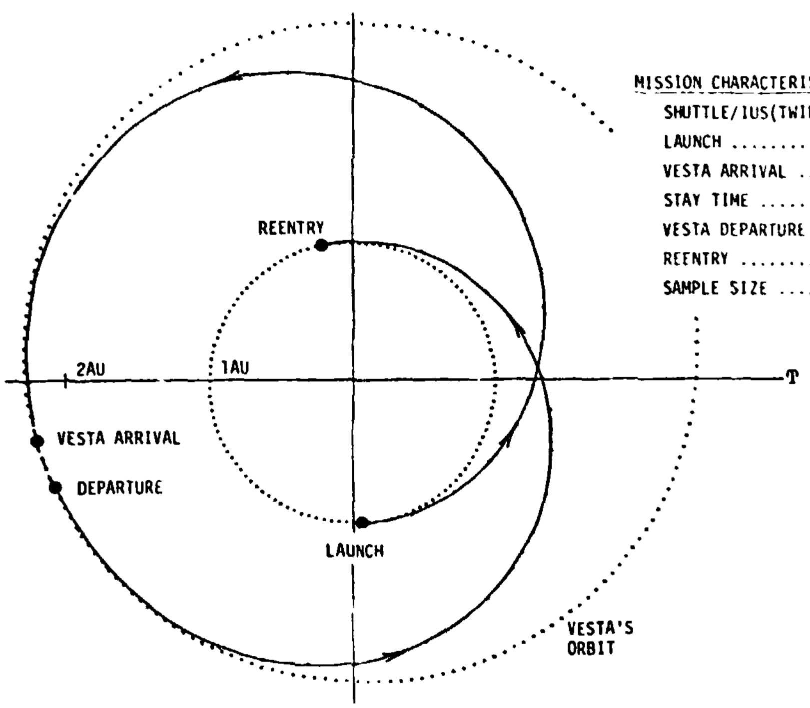


Fig. 6. 1990 Vesta sample return mission.

The specific example chosen for illustration of requirements and characteristics is a 1990 Vesta sample return. The heliocentric flight profile is presented in Figure 6. Launch takes place in June 1990. A low-thrust interplanetary transfer delivers the sample return mission module to Vesta almost two years later in May 1992. A short stay time of 30 days is assumed for sample acquisition on the presumption that the target has already been explored by a precursor rendezvous mission. The same low-thrust system begins a spiral departure of Vesta in June 1992. The 1.5-year return trajectory reencounters the Earth in December 1993 where the sample capsule is released on a direct reentry flight path for surface recovery. The total mission time for this example is 3.5 years, which is typical for missions of this kind.

Payload assumptions for a performance analysis of this mission are similar to those assumed for the Anteros ballistic sample return discussed above. An interplanetary mission module of 400 kg is needed, together with the low-thrust propulsion system. Encounter operations, including initial orbit capture, descent, sample acquisition, ascent, and rendezvous with the waiting interplanetary low-thrust system and mission module are handled by a 495 kg lander/ascent/rendezvous (LAR) module. The final hardware system needed is the sample reentry capsule budgeted at 30 kg including a 1 kg sample. The 30-day stay time is divided into four segments: (1) a three-day approach phase terminated with impulsive capture of the entire system using LAR propulsion into a low circular orbit; (2) one week of orbital reconnaissance for site selection; (3) one week for descent, acquisition, and delivery of the sample by the LAR to the waiting interplanetary spacecraft; and (4) low-thrust spiral escape from Vesta in the remaining 13 days.

A preliminary assessment of interplanetary flight options clearly showed that low-thrust propulsion is needed for main belt asteroid sample returns such as the Vesta example discussed. To perform this mission ballistically, even with optimistic energy and post-launch propulsion assumptions, would require four Shuttle launches. These launches would be used to assemble 11 IUS stages in orbit needed to inject the required payload (including post-launch propulsion) on a ballistic transfer trajectory to Vesta. By comparison, the low-thrust mission can be performed with a single Shuttle/IUS(Twin) launch. A 25 kw solar electric low-thrust propulsion module easily performs the interplanetary transfers. It should be noted that this system is considerably less advanced and less costly than the 60 kw Ion Drive system used in the previous multi-asteroid rendezvous mission example. It follows that single main belt asteroid sample return missions are more easily performed than main belt multi-rendezvous missions, from a propulsion point of view.

A Trojan Asteroid Rendezvous Mission

The final example to be discussed is a rendezvous mission to a Trojan asteroid, captured at one of the stable libration points of Jupiter. Launch opportunities to the Trojans occur at 13 month intervals (see Hektor, Figure 1). Little, if any, mission analysis has been performed on the Trojan asteroids. Therefore, the example presented here was selected to be representative of minimum requirements for Trojan rendezvous, to determine if ballistic flight performance is adequate for this class of asteroid missions.

The selected target is the Trojan asteroid Odysseus, which has the rather small orbit inclination of only 3.2°. Propulsion requirements were further minimized, in the case examined, by selecting an optimum launch opportunity, *i.e.*, November 1988. The ballistic flight profile is shown in Figure 7, using the same orbit profile formats as in the preceding examples. Rendezvous occurs in September 1991, almost three years after launch.

It is apparent from the energy requirements for this flight profile that this would be a difficult ballistic mission to perform, considerably more difficult than the Galileo mission, for example. Hence, the performance analysis was based on the full capability of a Shuttle/IUS(Twin)/Spinner launch vehicle in order to determine maximum payload capability. Using a two-stage, high-energy, space-storable retropropulsion system, the

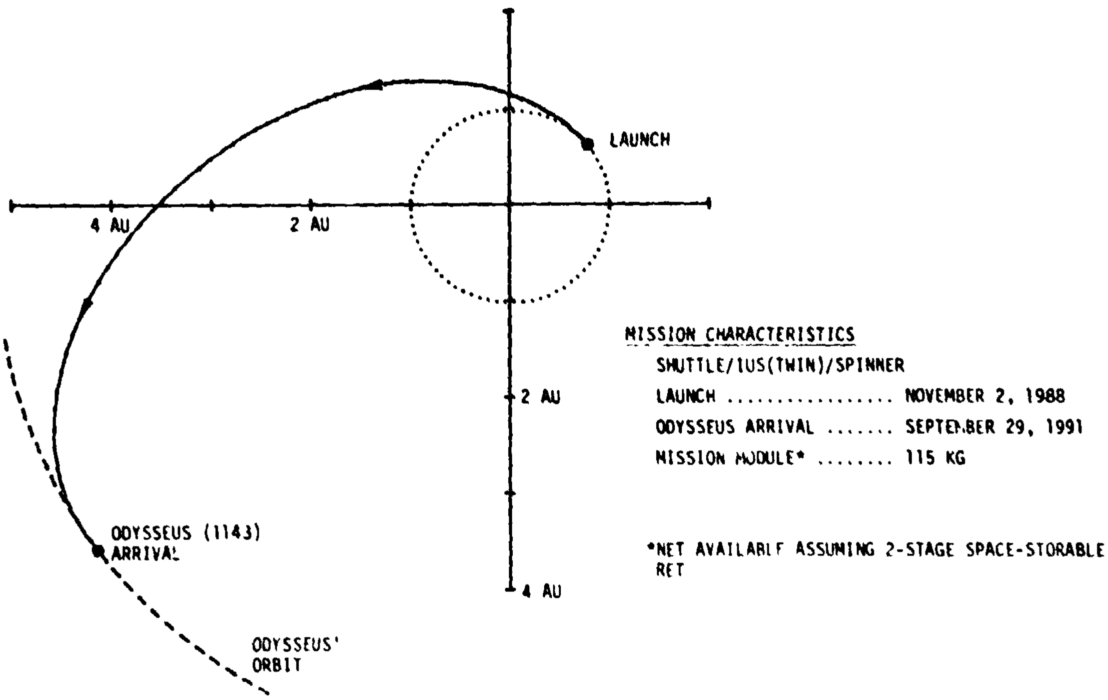


Fig. 7. 1988 Odysseus rendezvous mission.

maximum delivered rendezvous payload was found to be only 115 kg. Without exploring this example any further, two conclusions are apparent. First, even the most accessible Trojan asteroids will require low-thrust propulsion (or gravity-assisted trajectories) for rendezvous. Second, the likelihood of multi-rendezvous Trojan asteroid missions is doubtful in light of these energy requirements and the substantial differences in orbit inclinations of the larger known bodies.

MULTI-ASTEROID RENDEZVOUS: PREFERRED EXPLORATION MODE

The Committee on Planetary and Lunar Exploration (COMPLEX) (Anon., 1976) has defined three levels of planetary investigation which are, in increasing order of comprehension and sophistication: (1) reconnaissance, (2) exploration, and (3) intensive study. The detailed ground-based program of asteroid observations, currently in progress, is often cited as the reconnaissance phase of asteroid exploration. If this premise is correct, then initial flight projects should address "exploration" level questions of asteroid investigation. With this perspective in mind, an important question to be answered prior to the planning of asteroid exploration strategies is: "What is an appropriate mission concept to undertake 'exploration' level investigation of the asteroids?"

Three mission concepts embrace the six asteroid mission examples just discussed: flyby, rendezvous, and sample return. The flyby concept can be further divided into two subconcepts, fast flyby and slow flyby. (Only the fast flyby concept has been discussed above, *i.e.*, the ballistic multi-flyby main belt mission example.) There are, therefore, four basic mission concepts for exploration level study of the asteroid. In planetary exploration strategies, the sample return concept is considered a part of intensive study. The preferred approach is to develop a broad base of "exploration" level knowledge with less costly one-way multi-targeted asteroid missions, then proceed with sample return missions to a few specific representative asteroids, in order to effectively pursue "intensive study" level objectives of asteroid exploration. It should be noted, however, in the specific case of low-energy Apollo and Amor objects, it may be possible to combine "exploration" and "intensive study" with multiple object sample returns. The practicality of such a hybrid approach will depend on additional discoveries of such low-energy objects as well as further engineering studies of mission requirements.

The assignment of sample return to the "intensive study" level still leaves three basic mission concepts to choose from for "exploration" level investigations, *i.e.*, fast flyby, slow flyby, and rendezvous. Assuming that all of these concepts are capable of carrying a comparable comprehensive science payload (on the order of 100 kg mass), then the effectiveness of each can be judged in terms of those payloads' encounter performance. Encounter performance will be assessed here by considering the capability (spatial resolution and time) of a visual imaging experiment, the premise being that if imaging encounter capabilities are unsatisfactory, so also will be most, if not all, of the other remote sensing instruments. In other words, if an asteroid remote sensing payload cannot produce acceptable imaging science because of encounter conditions (primarily velocity), it will not produce good science with its other instrumentation either.

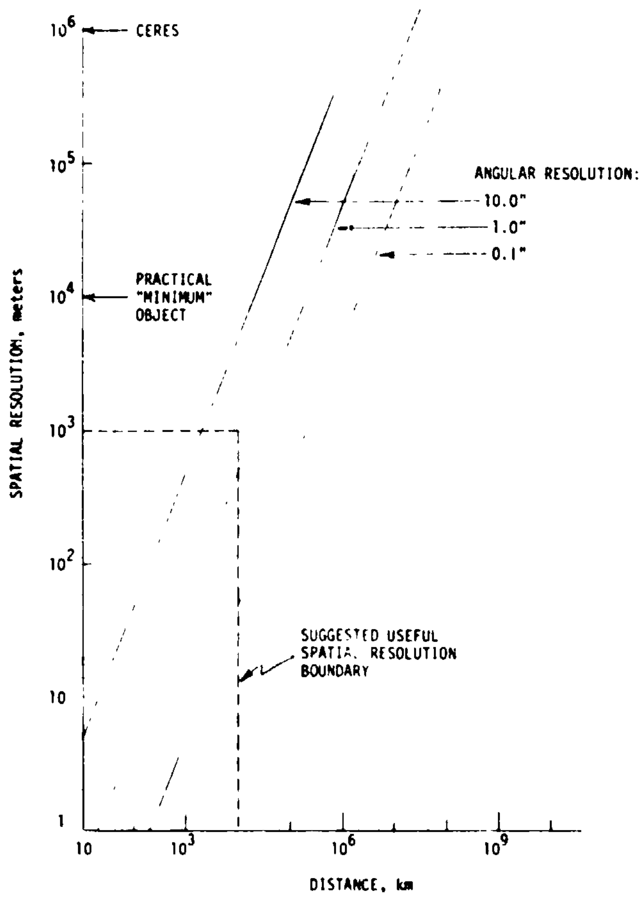


Fig. 8. Spatial resolution.

Spatial resolution is presented in Figure 8 as a function of distance for several effective angular resolutions. The purpose of presenting this graph is not to illustrate the relation between resolution and distance, which is straightforward and well understood, but to use the plot to establish a boundary of productive imaging data for asteroids. The diameter of Ceres, $\sim 10^6$ m, is noted near the top of the abscissa. Except for a few others, most notably Vesta, the remaining asteroids are less than 2×10^5 m diameter with main belt objects as small as 10^4 m being candidate mission targets based on ground-based observational data currently being collected. From this perspective, it seems reasonable to assume that encounter imaging information would always be useful at resolutions greater than 10^3 m, *i.e.*, resolvable picture elements an order of magnitude smaller than the smaller targets of interest. This still leaves the lower limit of resolution at 1 km, certainly quite crude even by comparison with lower resolution planetary imaging capabilities. The limiting effective resolution of spacecraft imaging instruments, based on Viking orbiter and Voyager design, is about 2 arcsec. Hence, for resolutions of better than 10^3 m, the instrument must be within 10^4 km of the target as illustrated by the dashed lines in Figure 8. This then is a suggested boundary on encounter distance. Perhaps more subjective, but just as important, is a secondary boundary for distinguishing surface features on the encountered objects. A suggested limit of 10^2 m as the coarsest useful resolution for these investigations yields an upper distance boundary of 10^3 km. To summarize, assuming that the current planetary spacecraft imaging instruments represent an advanced state-of-the-art, asteroid encounter distances must be within 10^4 km before acceptable data on size and shape can be safely assumed (presuming acceptable phase angle conditions) and within 10^3 km before useful data on surface features can be assumed. These values will now be used to evaluate the effectiveness of the three candidate "exploration" level mission concepts defined above.

Asteroid encounter tradeoffs between flyby velocity and time within specified resolution boundaries are presented in Figure 9. Flyby velocity is shown along the abscissa. Time within resolution boundaries is given on the left ordinate in minutes, with solid curves for the two resolution boundaries defined above, *i.e.*, 10^3 km and 10^4 km, plotted in the graph. For the purpose of computations an encounter of Ceres has been assumed with a closest approach of 100 km. The effect of assuming a smaller target will be mentioned in a moment. Consider first the fast flyby encounters. In the main belt multi-asteroid flyby example discussed earlier (see Figure 4), a minimum flyby speed of 5.3 km/sec was noted for the second target, Philosophia. This value is not much above the theoretical minimum flyby speed of 4.5 km/sec for a main belt asteroid at a mean distance of 2.4 AU, encountered by a ballistic coplanar transfer from the Earth. The average flyby speed of the six encounters is 8 km/sec. The resulting times spent within the resolution boundaries for speeds of 5 and 8 km/sec, found in Figure 9, are as follows:

Flyby Speed	Resolution Boundaries	
	1000 km	10,000 km
Minimum, 5 km/sec	9 min	70 min
Average, 8 km/sec	6 min	45 min

These times are, of course, maximum possible values. Image smear near closest approach, as well as unfavorable solar lighting geometry would reduce these times. For smaller objects the times within the boundaries (measured from the surface) would also be less.

Typical asteroid rotation periods are 5-10 hr. Hence, to obtain full longitudinal coverage of asteroids with remote sensing spacecraft will require *at least* 5 hr (300 min) within acceptable resolution boundaries. A conservative value of 10 hr (600 min) seems more reasonable for planning purposes (assuming the specific mission targets do not have

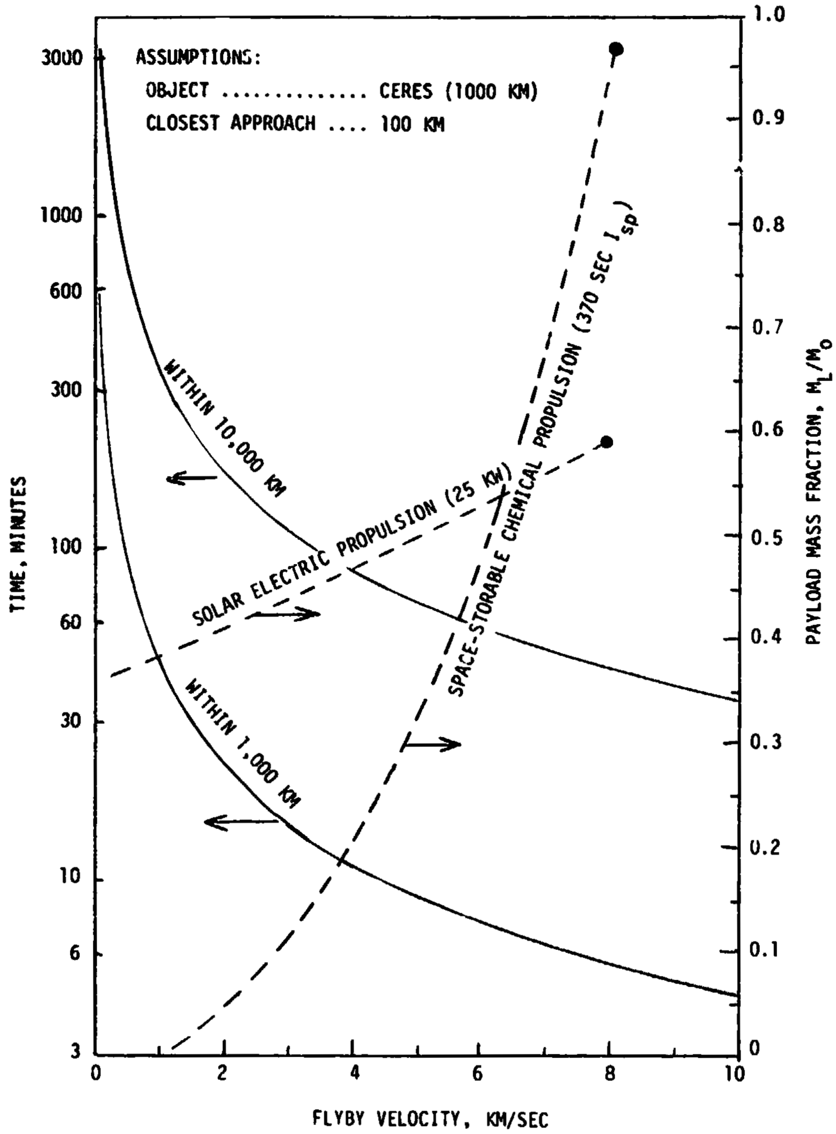


Fig. 9. Asteroid encounter tradeoffs.

known rotation rates before encounter), especially when the extent of possible rotation variations, lighting conditions, object size, and exposure/smear factors are all taken into account. Returning to Figure 9, it is found that the flyby speeds required to provide 60C min within the boundaries of 10,000 km and 1,000 km are 0.58 km/sec and 0.08 km/sec, respectively. These velocities are between one and two orders of magnitude slower than the average speed of the multi-flyby mission example presented in Figure 4. Fast flybys severely restrict the amount of useful data obtained. Hence, it can be concluded that only the slow flyby and rendezvous mission concepts are suitable candidates for "exploration" level asteroid investigation, where slow flyby refers to encounter velocities of less than 1 km/sec.

The key tradeoff which dictates the choice between slow flyby and rendezvous mission concepts for initial asteroid flight exploration is payload performance versus encounter time. The time difference between a 10 hr slow flyby encounter and a 30 day rendezvous is a factor of 72. The question is: "What is the associated propulsion penalty for achieving rendezvous instead of the easier slow flyby?" The answer to this question is also given in Figure 9. Payload mass fraction is shown along the right-hand abscissa as a function of flyby speed, where flyby speed in this case is the speed *after* a propulsive maneuver is performed, assuming that the initial speed (*i.e.*, unbraked encounter speed) is 8 km/sec--the average flyby speed of the multi-flyby mission example discussed earlier. Two dashed curves are shown relating braked flyby speed to payload mass fraction: (1) a space-storable chemical propulsion curve assuming impulsive braking, and (2) a solar electric propulsion curve assuming gradual low-thrust braking. It is apparent that solar electric propulsion is favored for reducing flyby speeds by more than a few kilometers per second, owing to its superior specific impulse. Of even more significance is the fact that the additional performance penalty to bring the encounter speed to zero, *i.e.*, rendezvous, is almost negligible. Hence, the tradeoff between payload performance and encounter time strongly favors rendezvous over slow flyby, assuming the use of low-thrust propulsion. It is concluded that multi-asteroid rendezvous is the preferred mission concept for "exploration" level asteroid investigation.

A preliminary performance summary in terms of required injected mass versus number of rendezvous targets, prepared by Friedlander (1978), is presented in Figure 10. A 40 kw Ion Drive interplanetary low-thrust propulsion system and a 500 kg mission module (~100 kg science payload) is assumed. Injected mass is given along the ordinate and number of targets is shown along the abscissa. The lower curve assumes just the mission module payload which is carried from target-to-target. The upper curve assumes an additional 100 kg small lander system (*e.g.*, penetrator), is dropped at each target. The dashed line across the plot

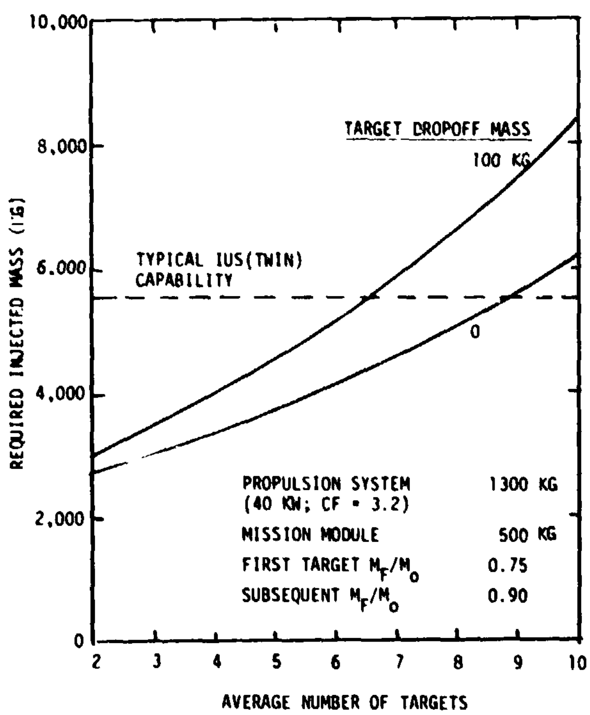


Fig. 10. Capability of advanced solar electric propulsion for multiple asteroid rendezvous missions.

shows the maximum injected mass which can be launched by a Shuttle/IUS(Twin) vehicle at the typical *vis viva* injection energy requirement. Up to eight targets can be encountered without landers, and up to six targets reached with small landers, without exceeding single launch Shuttle capability. Because of certain simplifying assumptions, these preliminary results represent upper limits on number of targets. Also, it should be noted that typically 1.5 years of flight time is required to reach each target. Hence, an eight-target mission would have a trip time from launch to the final target of 12 years. The impact of such long endeavors needs to be assessed both in terms of reliability and planning of science investigator participation.

The results shown in Figure 10 are derived for a 40 kw Ion Drive low-thrust system with solar array concentrators, a design considerably advanced over early low-thrust development plans. Using a less advanced 25 kw design, still with concentrators, would decrease the number of targets to three or four. Further decreasing the design to a 25 kw system without concentration, representative of current SEP technology, would decrease the number of targets to only two. Hence, the potential exploration capability of the multi-asteroid rendezvous concept very much depends upon the level of low-thrust performance available at the time such missions are to be implemented.

RENDEZVOUS OPERATION CONSIDERATIONS

A few remarks on maneuver strategies during rendezvous should be made since the effects of asteroid gravity fields are different from those encountered in planetary experience. The gravity of asteroids larger than 10 km in diameter is greater than that usually assumed for comet nuclei. Hence, station-keeping rendezvous strategies typically assumed for comet rendezvous missions can be very costly at asteroids larger than 10 km, particularly when close approaches (<100 km) are desired. The preferred alternative is to orbit these objects, just as is done on planetary rendezvous missions.

Orbital periods (ordinate) are presented as a function of orbit altitude (abscissa) in Figure 11 for four size (diameter) asteroids: 1, 10, 100 and 1000 km, assuming a mean density of 3 g/cm^3. Two-body equations of motion dictate that all spherical bodies of equal density have the same orbital periods at zero altitude, *i.e.*, 1.9 hr. However, as altitude increases the associated orbital periods about smaller bodies increases more rapidly than for larger bodies. This characteristic is evident in Figure 11. Hence, at 10 km altitude the orbital period about the largest asteroid Ceres (~1000 km diameter) is still only 1.9 hr, whereas for a 1 km object it is 180 hr (from Figure 11). At 100 km altitude the Ceres orbiter would still have a short period of only 2.5 hr, whereas a 1 km asteroid orbiter would have an extremely long period of 5400 hr (225 days). In fact, a 1 km asteroid at a mean solar distance of 2.75 AU would have a sphere-of-influence of only 100 km.

Given the orbital characteristics just described, what should the encounter strategy be for a first remote sensing payload? Many possibilities exist. One attractive scenario, which is sequentially phased in three steps from broad global reconnaissance to very detailed study, goes as follows:

Step 1: Slowly approach the asteroid from a rest position beginning at the order of 50,000 km. During this time (~3 days) continue processing low-resolution imaging to determine object size, shape, rotation rate, and polar axis.

Step 2: Establish a polar observation orbit with a period at least several times longer than the asteroid rotation period for global medium resolution coverage.

Step 3: When global coverage is complete transfer to a low altitude circular orbit which is nearly resonant with the rotating object so that sites of specific interest can be studied repetitively in detail.

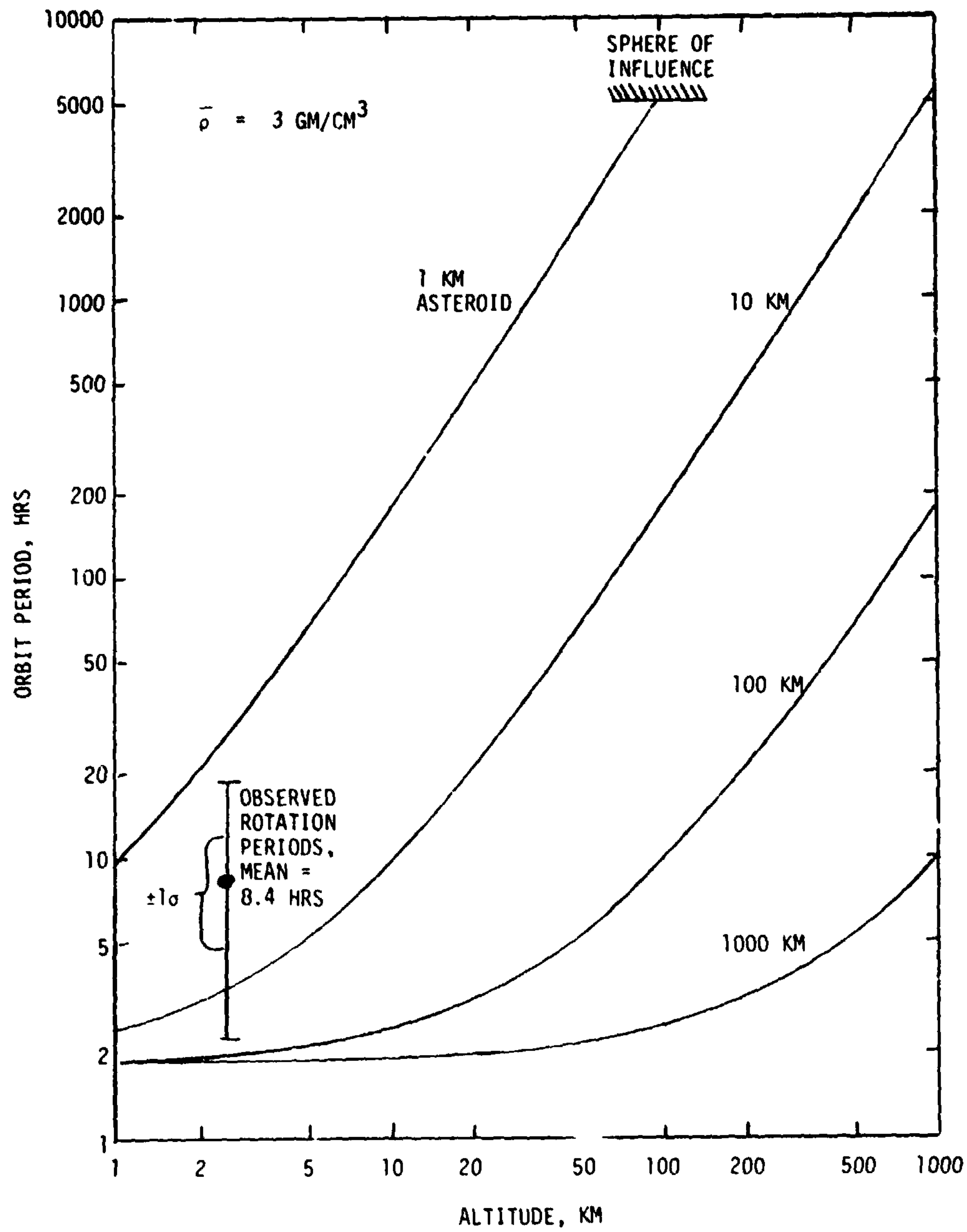


Fig. 11. Orbital characteristics around asteroids.

Three examples of this rendezvous maneuver strategy are summarized in Table 2 for three large asteroids: Fortuna, Urania, and Vesta. Global coverage orbit altitudes near 800 km were chosen to provide 100 m imaging resolution. Minimum coverage times for these objects varied from 1-4 weeks. Resonant low altitude orbits of less than 70 km provide resolutions of better than 8 m with the same camera system. Note also the small amount of impulsive ΔV which would be required to establish these orbits, the most being 141 m/sec for Vesta. Hence, these orbits can be established in a short period of time with the low-thrust inter-asteroid propulsion system, or even with a small auxiliary chemical propulsion system, if preferred. In summary, an adaptive orbital sensing strategy is suggested for asteroid rendezvous payloads which offers considerable investigation flexibility at minimum propulsion cost.

Table 2. Asteroid Rendezvous Profile Example

Parameters	Asteroids		
	Fortuna	Urania	Vesta
Class Object	C	S	U
Diameter (km)	215	91	538
Rotation Period (hr)	7.5	13.6	10.6
Initial Orbit Altitude for Global Mapping (km)[a]	800	800	829
Initial Orbit Period (hr)	48.6	176.8	15.5
Minimum Global Mapping Time (days)[a]	6.1	7.4	29.7
Final Orbit Altitude for Detailed Studies (km)[a]	61	36	66
Final Orbit Period (hr)	3.7	4.6	2.6
Final Orbit Rate: Rotation Rate Resonance	2:1	3:1	4:1
Equivalent Total ΔV for Orbit Capture (m/sec)	52	21	141

[a]These data presented for 250 mm focal length camera with a 49 mrad field-of-view and 120 μrad per line pair resolution; mapping resolutions are $\leq$100 m, detailed studies resolutions are $\leq$8 m.

ACKNOWLEDGMENT

The author would like to express his appreciation to staff members of Science Applications, Inc.'s Space Science Division, particularly Mr. Alan Friedlander, for their contributions, suggestions, and critique of this paper. Also to be acknowledged is Dr. David Bender of JPL, whose persistent interest in small body missions over the last five years has contributed greatly to the sparse asteroid mission data base currently in existence.

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DISCUSSION

CHAPMAN: Does the 500 kg mission module for the Anteros sample return mission include some science instruments?

NIEHOFF: Yes, there is a separate lander vehicle that actually does the acquisition and which has some surface science. There is also an allowance of 50 kg for remote sensing instruments.

VEVERKA: What is the typical ΔV for a multi-asteroid flyby mission?

NIEHOFF: In the 1994 mission shown it is 1700 m/sec. This is the ΔV after Earth escape, making this mission easier than Galileo.

VEVERKA: I am confused between the two Ion Drives. Is the conventional one the same as the one currently being discussed for a possible Comet Encke or Tempel 2 mission?

NIEHOFF: Yes. Twenty-five kilowatts is enough to do Encke or Tempel 2 rendezvous.

WETHERILL: Is there anything essentially difficult about going to the 60 kw instead of 25 kw? Is it just a matter of making it bigger or does the cost go up enormously?

MORRISON: There are some engineering changes with the larger system. One tries for higher efficiencies and that costs extra. For example, the solar concentrator for the 25 kw system is simpler, a factor of two instead of a factor of four.

FANALE: I would like to make two comments. One is that the example you gave of imaging is very useful. However, if you did the same exercise for other instruments which have wider fields-of-view, it is even more devastating. My second comment is that it is not just the resolution that we are concerned with. We mentioned briefly global coverage that you get only if you watch the asteroid rotate. You also want variations in the Sun-spacecraft-object geometry for photopolarimetry, radiometry and fields and particles experiments. I agree the resolution is a basic thing but there are other important things as well, all of which argue for the advantages of rendezvous.

ARNOLD: Usually on missions like this, the gamma-ray spectrometer is the critical item as far as time is concerned and I am delighted to have other people also wanting to be around for a long time. For the gamma-ray spectrometer, and for the x-ray system as well, one really needs to be pretty close. The angular field is typically 30°, which means in your description of the asteroid encounter, the time spent at 100 km from the object is very interesting. Being 800 km away is not. Many things I came here to argue for from one point of view are surfacing as useful from other points of view and it sounds as if a stay time on the order of 60 days is realistic.

NIEHOFF: The reason for that higher orbit was to get a quick global map. It would probably take much longer and be a much bigger burden on the imaging system if the initial map were done at closer range.

ARNOLD: I think if you tried to picture yourself in that room planning the sequence of steps, having that quick map would be very, very valuable before you started trying to think what you were going to do next.

NIEHOFF: One thing I didn't mention was that we are in the process of doing an analysis of gravity mapping with Doppler tracking and the initial results look encouraging. No separate instrument may be necessary to get the mass distribution.

ARNOLD: There is a distinction, which is important to me, between orbiting and station-keeping. I would surely think of orbiting Ceres or any really big object. I would want to get into a polar orbit and look at the whole thing. At smaller objects you do not orbit, but you would try to go to say six or eight close points and hold a position. Where does the transition between these operational modes occur?

FANALE: I indicated that station-keeping is easier than orbit-keeping except for the big ones which have a surface escape velocity of more than 100 m/sec.

ARNOLD: What diameter is that roughly, do you recall?

NIEHOFF: Orbits are possible around asteroids which are surprising small, maybe less than 10 km. As an additional point, for a very small object (less than 10 km), the surface weight of a lander would be measured in grams, not in kilograms; this is an important operational problem for sampling.

EARTH-APPROACHING ASTEROIDS AS TARGETS FOR EXPLORATION

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Primary goals for the exploration of Earth-approaching asteroids will be to determine their chemical and mineralogical composition and especially to determine their structure. Objects derived from the main asteroid belt are likely to be fragments of larger bodies. As such they would provide direct evidence on the internal structure, processes, and history of the larger parent asteroids. Nonvolatile cores of extinct comets, on the other hand, may yield the most direct evidence obtainable concerning the early stages of accretion of solid matter in the solar system, specifically in the outer part of the system. Return of samples would be essential to develop and decipher this evidence.

Study of unmanned missions shows that between 5% and 10% of the Earth-approaching asteroids can be reached by low ΔV ballistic trajectories (ΔV from low Earth orbit less than the 6.4 km/sec required for rendezvous with Mars). Two of the best candidates, from the trajectory standpoint, are 1977VA and 1943 Anteros. Both of these are Amor asteroids. Rendezvous is achieved near aphelion, and the minimum impulse required for sample return to Earth is very low--of the order of 1 km/sec. Because impulses for landing and escape from these small asteroids are of the order of 1 m/sec, many landings could be made to visit and sample different parts of an asteroid in the course of a single mission. An aggressive astronomical search for more near-Earth asteroids will undoubtedly yield many more promising candidates for this type of exploration. Development of the Space Shuttle opens the possibility of an exploration program wherein a single spacecraft could make repeated round-trips between the Earth and different low ΔV asteroids.

The discovery of 1976AA ($a = 0.97$, $e = 0.18$, $i = 19°$) indicates that a few asteroids exist which are very close neighbors of the Earth. The extreme near-Earth objects are Amors and Earth-crossers with semimajor axes near 1 AU that have acquired small e and i as a consequence of repeated close encounters with the Earth. Typically, these objects would be accessible by low ΔV missions of 6 months or a year duration. Manned missions to explore such bodies are technically feasible by utilizing the capabilities of the Space Shuttle. Roughly about 1% of the Earth-approaching asteroids may be sufficiently close neighbors of the Earth to be considered candidates for manned missions based on 7-10 Shuttle launches. The discovery rate for Earth-crossers would have to be increased by a factor of about five, however, in order to achieve a high expectancy of finding a suitable target within 10 years. The primary tasks of exploration of Earth-approaching asteroids are well suited to the capabilities of properly trained astronaut-scientists.

INTRODUCTION

The primary goals for the exploration of near-Earth asteroids (including those bodies which are extinct comets) would be to determine their structure, the diversity of chemical and mineralogical composition of individual bodies, the processes of accretion and subsequent metamorphism or magmatic differentiation of these bodies, and especially the history of these processes. Objects derived from the main asteroid belt are likely to be fragments of larger bodies. As such they would provide direct evidence on the internal structure, processes, and history of the larger parent asteroids. The stony cores or other nonvolatile residua of extinct comets, on the other hand, may yield the most direct evidence obtainable concerning the early stages of accretion of solid matter in the solar system, specifically in the outer part of the system. Return of samples will be essential to develop and decipher much of this evidence.

The Earth-approaching asteroids are especially attractive for exploration because of several favorable conditions. First, some of the Earth-approaching asteroids are the easiest bodies beyond the Moon to reach. Secondly, with the possible exception of a few active comet nuclei, some are the smallest bodies discovered in the solar system. Because of their small size, they have very low escape velocities, of the order of 1 m/sec. This has two important consequences for exploration:

1. On account of the low escape velocities, regoliths on their surfaces should be very thin to locally absent. Sufficient bedrock should be exposed, in crater walls and elsewhere, to determine the structure of these objects from a combination of remote and on site observations and samples. It is of interest, in this regard, that infrared radiometric observations of Betulia suggest that it has a rocky surface, unlike that of larger main belt asteroids (Lebofsky *et al.*, 1978).

2. Because of the low escape velocities, landing and escape from surfaces of these asteroids requires almost negligible propulsion. Landing is roughly comparable to docking with another spacecraft, and it should be possible to achieve landing by means of relatively simple engineering design features.

Third, on the basis of dynamical considerations and existing physical observations, many different kinds of bodies appear to be represented among the near-Earth asteroids. In particular, it seems likely that they include many extinct comets.

It has been argued that, because a large number of meteorites that are presumed to be samples of asteroids are already available for study, missions to retrieve samples from asteroids are unnecessary. Most of what is known about very early conditions and events in the history of the solar system has, indeed, been learned from meteorites. As important as the meteorites are, however, every one of them is a sample out of context. Until asteroids are actually explored and sampled directly, the reconstruction of the parent bodies whence meteorites have come will remain speculative. This limitation of knowledge about the parent bodies, in turn, places severe restraints on our understanding of meteorites and on the relationship of the meteorites to one another. Celestial mechanics and the processes of meteoroid entry into Earth's atmosphere are efficient filters, moreover, and it is clear that meteorites are not a representative set of samples of solid material in near-Earth space.

What are the fragile objects that disintegrate in the Earth's atmosphere? Do we actually have samples among the meteorites of the nonvolatile parts of comets? What is the structure of a comet nucleus or of the nonvolatile parts of the nucleus? What is the structure of a small primitive asteroid? Is it an aggregate of aggregates of solid objects accumulated during accretion? What is the size of the component parts? What is the diversity of constituents in such a body? The answers to these questions can only be obtained by direct exploration. Global surveying of individual bodies, combined with multiple returned samples, is required to obtain definitive answers to questions such as those.

UNMANNED MISSIONS

The accessibility of near-Earth asteroids for exploration by spacecraft can be expressed by the ΔV required for rendezvous, or, in the case of sample return or manned exploration, the combined ΔV for rendezvous and return to Earth. Detailed studies of outbound and return trajectories are required for precise determination of the ΔV for any mission. But a convenient approximate estimate of the minimum possible ΔV may be obtained from the following figure of merit, F

$$F = U_L + U_R \tag{1}$$

where U_L is the impulse required to inject a spacecraft into a transfer trajectory from low Earth orbit to the orbit of the asteroid, and U_R is the impulse required for rendezvous with the asteroid. For simplicity of calculation, both U_L and U_R are normalized to the Earth's orbital speed and are, therefore, dimensionless. Low ΔV trajectories are achieved by rendezvous near aphelion or perihelion of the asteroid orbit. Minimum ΔV missions to Amors and Apollos (where Apollo asteroids are formally defined as having $a > 1$ AU) are achieved by rendezvous at aphelion. The transfer orbit of the spacecraft is taken to be tangent to the orbit of the Earth at perihelion and tangent to the orbit of the asteroid at aphelion. In order to achieve rendezvous under these ideal conditions the asteroid would have to arrive at aphelion at precisely the right time. In actual missions, the asteroid is almost never at the ideal position, so that real ΔVs to rendezvous are always somewhat larger than calculated here for the ideal case.

It is assumed that, in the average case, half the plane change is accomplished at injection into the transfer orbit and half at rendezvous. In the case where the argument of perihelion is 0, and neglecting the finite eccentricity of the Earth's orbit, U_L is then given by

$$U_L = \sqrt{U_t^2 + S^2} - U_o \tag{2}$$

where S is the normalized speed of escape from Earth, U_o is the normalized orbital speed at low Earth orbit, and

$$U_t^2 = 3 - \frac{2}{Q+1} - 2\sqrt{\frac{2Q}{Q+1}} \cos \frac{i}{2} \tag{3}$$

where Q is the aphelion distance of asteroid normalized to semimajor axis of the Earth, and i is the inclination of asteroid orbit. The solution for U_t^2 is obtained from the equation for the encounter speed of an object in eccentric orbit with an object in circular orbit (Öpik, 1951). A term could be added in the computation of U_t for the eccentricity of the Earth's orbit, but the correction is less than 1% in F for all known cases. The impulse at rendezvous, U_R, is given by

$$U_R = \sqrt{U_c^2 - 2U_r U_c \cos \frac{i}{2} + U_r^2} \tag{4}$$

where, for Amor asteroids,

$$U_c^2 = \frac{3}{Q} - \frac{2}{Q+1} - \frac{2}{Q}\sqrt{\frac{2}{Q+1}} \cos\frac{i}{2} \tag{5}$$

$$U_r^2 = \frac{3}{Q} - \frac{1}{a} - \frac{2}{Q}\sqrt{\frac{a}{Q}(1-e^2)} \tag{6}$$

a is the semimajor axis of asteroid normalized to semimajor axis of the Earth, and e is the eccentricity of the asteroid, and for Apollo asteroids,

$$U_c^2 = \frac{3}{Q} - \frac{2}{Q+1} - \frac{2}{Q}\sqrt{\frac{2}{Q+1}} \tag{7}$$

and $$U_r^2 = \frac{3}{Q} - \frac{1}{a} - \frac{2}{Q}\sqrt{\frac{a}{Q}(1-e^2)} \cos\frac{i}{2} \tag{8}$$

For 1976AA-type asteroids ($a \leq 1$ AU), minimum ΔV missions are achieved by rendezvous at perihelion. However, short duration missions are achieved by rendezvous at aphelion. The nominal strategy adopted for rendezvous at aphelion with 1976AA-type asteroids is somewhat different than that used for rendezvous with Amors and Apollos. The semimajor axis of the transfer orbit of the spacecraft is held at 1 AU and is tangent at aphelion with the orbit of the asteroid. This decreases the rendezvous impulse, U_R, at the expense of a minor increase in U_L; the perihelion of the spacecraft orbit no longer corresponds to the point of injection into the transfer trajectory. Equations (2), (4) and (8) apply, and the solutions for U_t and U_c now become

$$U_t^2 = 2 - 2\sqrt{2Q - Q^2} \cos\frac{i}{2} \tag{9}$$

$$U_c^2 = \frac{3}{Q} - 1 - \frac{2}{Q}\sqrt{2 - Q} \tag{10}$$

The figure of merit obtained by means of these equations is compared with the actual ΔV to rendezvous with eight low ΔV objects in Figure 1. The equation

$$\Delta V = (30F + 0.5) \text{ km/sec} \tag{11}$$

yields the actual ΔV for optimum missions within a few tenths of km/sec precision. (Orbital speed of the Earth is 30 km/sec).

Cumulative frequency distributions of F are shown for Amors in Figure 2 and for Apollos in Figure 3. About 30% of the Amors have figures of merit comparable to or lower than that of Mars. About 75% of the Amors have lower figures of merit than "typical" main belt asteroids. (F for a typical main belt asteroid shown in Figures 4 and 5 was computed on the basis of a = 2.5, e = 0.15, and i = 15°.) The cumulative frequency distribution of F for Apollos is displaced toward slightly higher values with respect to the cumulative distribution of F for Amors. About 60% of the Apollos are easier to reach than "typical" main belt asteroids.

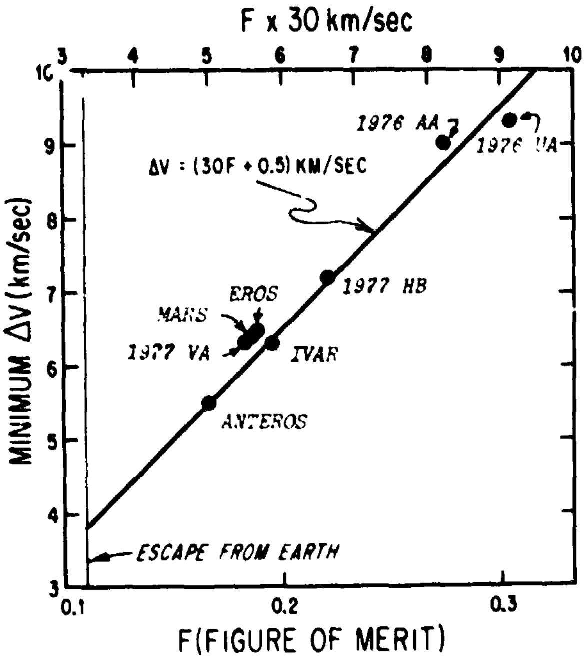

Fig. 1. Correlation of figure of merit with minimum ΔV for optimum low ΔV missions. Minimum ΔVs are from Arnold and Duke (1977) and from Bender (personal communication, 1977).

The most favorable known asteroids for low ΔV missions are Anteros and the recently discovered Amor asteroid 1977VA. Both of these asteroids are easier to reach than Mars, Anteros by a significant margin. Eros, 1960UA, Ivar, and 1972RB all have favorable figures of merit, close to that of Mars. The Apollo asteroid 1959LM has a figure of merit similar to that of Anteros, but the orbit of 1959LM is poorly determined and it is lost. Another Apollo, PLS 6743, also has a very low figure of merit and is lost.

A characteristic of special importance about rendezvous missions at aphelion with low ΔV Amors and Apollos is that the rendezvous impulse is very low, typically of the order of 1 km/sec and, in some cases, less. Under optimum conditions, the departure impulse for return to Earth is about the same as the rendezvous impulse. Hence, missions can be found where the sum of rendezvous and departure impulses required for sample return is in the range of 2-3 km/sec. In this respect, low ΔV Earth-approaching asteroids are substantially more accessible than typical main belt asteroids, where the sum of rendezvous and departure impulses is in the range of 5-6 km/sec or higher. As shown by Niehoff (1977), a simple ballistic sample return mission to Anteros is well within the injection capability of a single Space Tug.

Development of the Space Shuttle opens the possibility of an entirely new type of exploration program. A single spacecraft could make repeated round-trips between Earth orbit and different low ΔV asteroids. Propulsion for such a spacecraft could be provided either by conventional rocket engines or by low-thrust (ion) engines. Samples could be retrieved from the spacecraft in Earth orbit by means of the Shuttle, where the spacecraft itself could be refurbished with new sample containers and propellant for either conventional or additional ion engines. A nominal single mission to each asteroid should include detailed visual, spectrophotometric, and chemical mapping of its surface, determination of its mass and density, and multiple landings, at sites selected from this mapping, with on-site measurements and recovery of samples. Rotation of the asteroid would have to be determined from visual mapping to permit the maneuvers required for landing.

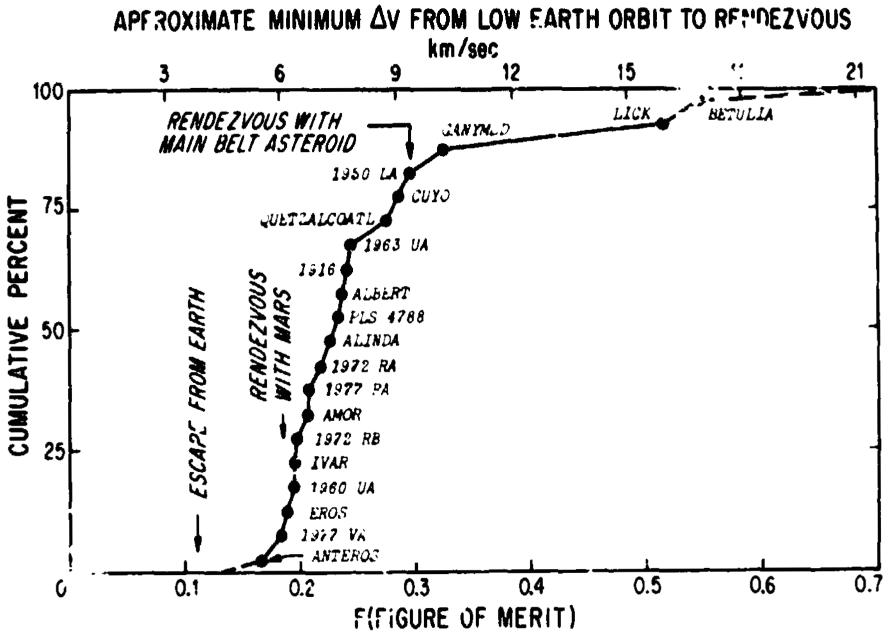

Fig. 2. Cumulative frequency distribution of figure of merit for rendezvous with Amor asteroids at aphelion.

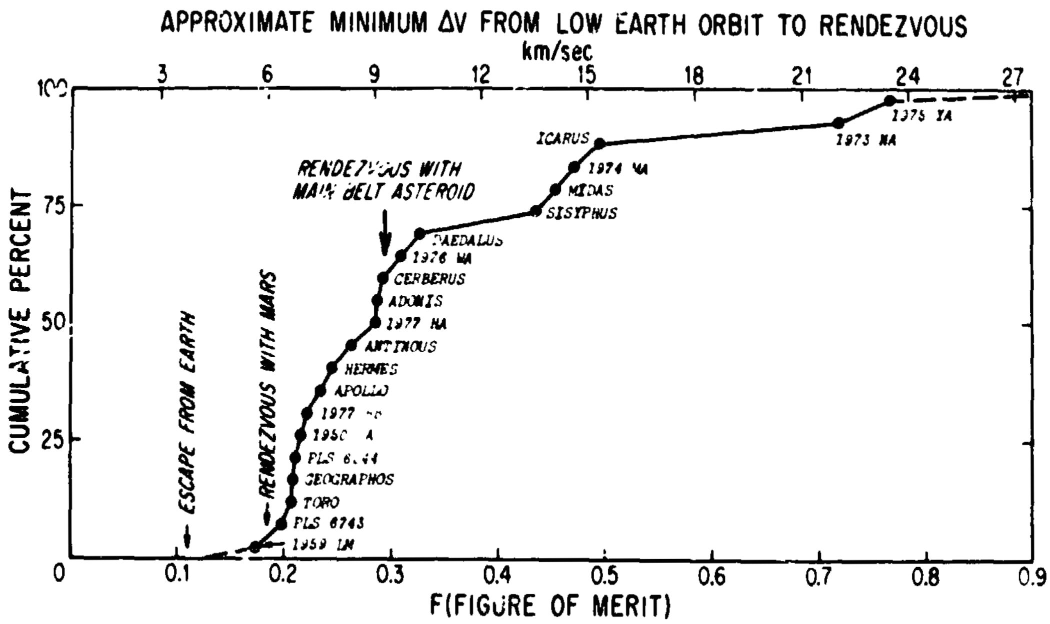

Fig. 3. Cumulative frequency distribution of figure of merit for rendezvous with Apollo asteroids at aphelion.

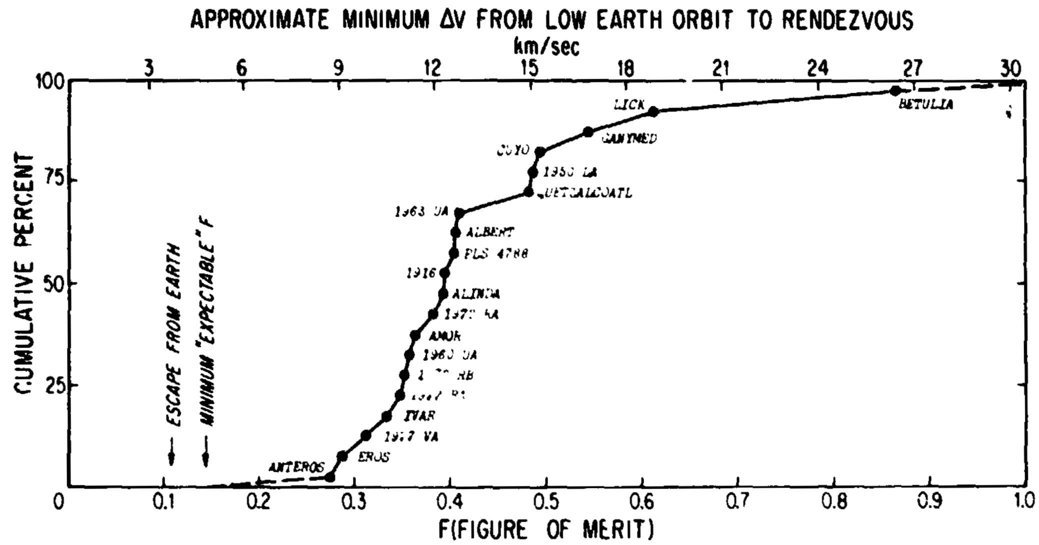

Fig. 4. Cumulative frequency distribution of figure of merit for rendezvous with Amor asteroids at perihelion.

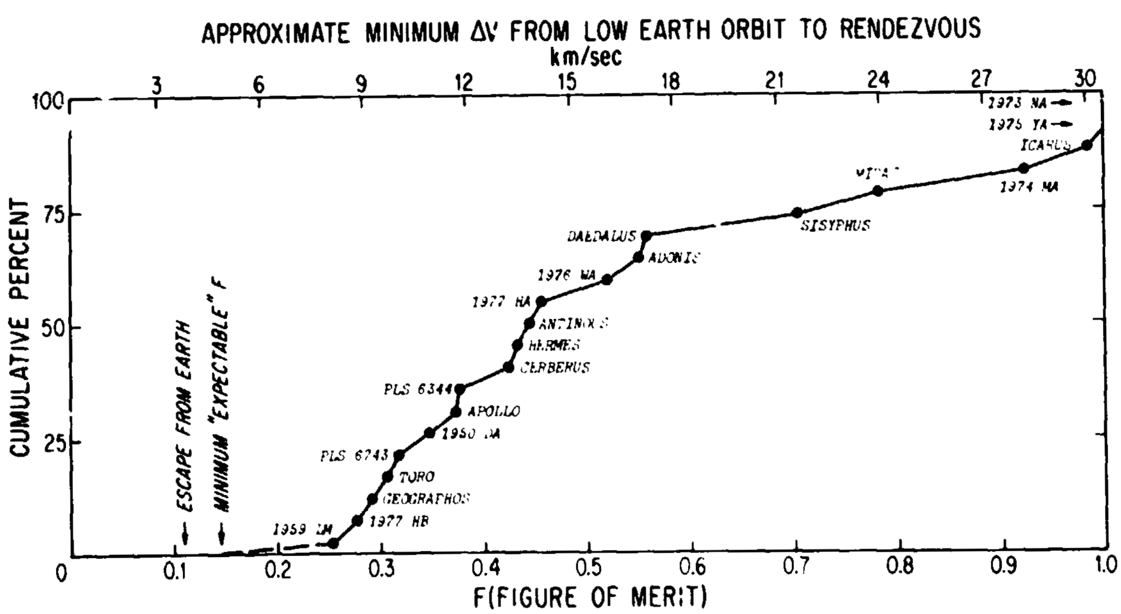

Fig. 5. Cumulative frequency distribution of figure of merit for rendezvous with Apollo asteroids at perihelion.

A broad range of compositional types has already been identified among the favorable low ΔV asteroids. An initial program, for example, might include missions to 1960UA (possible C type), Ivar (S type) and 1977VA (possible M or E type). It is of interest that a possible extinct comet, 1960UA, is among the known low ΔV objects.

Several unnumbered asteroids that have very low apparent ΔV from low Earth orbit to rendezvous, 1946SD, 1949SZ, and 1936UI, are occasionally listed among the Amors. These objects have poorly determined orbits, however, and are lost. In all probability their eccentricities and semimajor axes are higher than has been estimated by preliminary calculation, and they do not have as low figures of merit as suggested by the preliminary elements. The asteroid 1936UI, discovered by Reinmuth, has a nominal figure of merit of 0.17, and it may be worth attempting its recovery.

A continuing survey for new Earth-approaching asteroids will undoubtedly yield more promising candidates for sample return missions. A few percent of the Amors and the Apollos probably have still lower figures of merit than Anteros, and would be especially favorable for sample return missions. An aggressive campaign to find these objects and determine their compositional classification and also to identify more possible extinct comets should be carried out as a prelude to a multiple asteroid sample return program.

MANNED MISSIONS

The discovery of 1976AA ($a = 0.97$, $e = 0.18$, $i = 19°$) indicates that a few asteroids exist which are very close neighbors of the Earth (Helin and Shoemaker, 1977). Asteroid orbits with a near 1 and low e and i have the characteristic that very low ΔV spacecraft trajectories to rendezvous and for Earth return can be accomplished in relatively short periods of time--typically either six months or a year, for a round-trip mission. The discovery of a very near-Earth asteroid raises the possibility of manned exploration utilizing the capability of the Space Shuttle to carry manned spacecraft and the necessary propulsion systems into Earth orbit. Although 1976AA is a close companion of the Earth in space, its moderately high orbital inclination makes it less easy to reach than many other Earth-crossing asteroids and many Amors. Nevertheless, for short duration round-trips, 1976AA is one of the three easiest targets for exploration and, in many respects, is the best known candidate for a short mission.

Low ΔV short duration trajectories are achieved by rendezvous at perihelion for Amors and for all known Apollos and at aphelion for known 1976AA-type asteroids. In computations of the figure of merit for rendezvous at perihelion of Amor asteroids, the perihelion of the spacecraft transfer orbit is taken as tangent with the Earth's orbit at perihelion, and tangent with the asteroid orbit at aphelion. Launch impulse, U_L, is obtained from Equation (2), and the perihelion distance, q, is substituted for Q in Equation (3), *i.e.*,

$$U_t^2 = 3 \quad \frac{2}{q+1} - 2\sqrt{\frac{2q}{q+1}} \cos \frac{i}{2} \qquad (12)$$

Rendezvous impulse, U_R, is given by

$$U_R = \sqrt{U_c^2 + 2U_r U_c \cos \frac{i}{2} + U_r^2} \qquad (13)$$

where $$U_c^2 = \frac{3}{q} - \frac{2}{q+1} - \frac{2}{q}\sqrt{\frac{2}{q+1}} \tag{14}$$

and $$U_r^2 = \frac{3}{q} - \frac{1}{a} - \frac{2}{q}\sqrt{\frac{a}{q}(1-e^2)}\cos\frac{i}{2} \tag{15}$$

For Apollo asteroids, the spacecraft transfer orbit is taken as tangent with the asteroid orbit at perihelion, and the semimajor axis of the transfer orbit is held at 1 AU. Launch impulse is, again, obtained from Equation (2) but U_t^2 is now given by

$$U_t^2 = 2 - 2\sqrt{2q - q^2}\cos\frac{i}{2} \tag{16}$$

Rendezvous impulse is computed by Equation (4),

$$U_c^2 = \frac{3}{q} - 1 - \frac{2}{q}\sqrt{2 - q} \tag{17}$$

and U_r^2 is obtained from Equation (15).

Cumulative frequency distributions of F are shown for Amors in Figure 4 and for Apollos in Figure 5. The approximate minimum ΔV from low Earth orbit to rendezvous at perihelion with Amors and Apollos is approximately 50% higher than the minimum ΔV to rendezvous at aphelion with these asteroids. Velocities of known Amors and Apollos are much higher at perihelion, and the rendezvous impulses are correspondingly higher. For the best candidates for short duration missions among the asteroids discovered so far, the minimum ΔVs to rendezvous are about 9 km/sec (Table 1). The approximate ΔV to rendezvous with 1959LM is 8.1 km/sec, but, because this asteroid has a poorly determined orbit and is lost, it is not listed in Table 1.

Table 1. Best Known Candidate Asteroids for Short Duration, Low ΔV Missions

Asteroid	Orbital Type	F	Approximate Minimum ΔV to Rendezvous (km/sec)
Anteros	Amor	0.27	8.7
1976AA	1976AA	0.27	8.7
1977HB	Apollo	0.28	8.9
Eros	Amor	0.29	9.2
Geographos	Apollo	0.29	9.3
1976UA	1976AA	0.31	9.7
Toro	Apollo	0.31	9.7
1977VA	Amor	0.31	9.8

The two lowest ΔV asteroids in Table 1 are Anteros and 1976AA. Niehoff (1977) has investigated round-trip missions to these asteroids for favorable opportunities. Round-trip ballistic missions of 365 days duration, allowing for 30 days stay time at each of the asteroids, can be achieved with ΔVs to rendezvous of 9.2 km/sec for Anteros and 9.1 km/sec for 1976AA. A six-month duration mission to 1976AA would require more than a 20% increase in the energy requirements. Niehoff estimates that 28 Shuttle launches would be needed for a manned mission to 1976AA and 34 Shuttle launches for the mission to Anteros. The requirement for Shuttle launches could be reduced to 23 for the mission to Anteros, if the stay time were reduced to 10 days.

Whether 23 or 28 Shuttle launches is an acceptable cost for a manned mission to an asteroid depends on the priority and national significance that is attached to such a mission. These missions could almost certainly be accomplished by assembly of spacecraft and propulsion modules transported to Earth orbit by the Shuttle and by fueling in orbit. Significant improvements in cost probably could be achieved by means of more sophisticated strategies than simple ballistic missions. For example, fueled propulsion modules for the departure impulse from the asteroid might be delivered to the asteroid ahead of time by unmanned spacecraft, utilizing either conventional or low-thrust propulsion systems. The most economical attack on reducing the number of Shuttle launches required, however, would be to search for asteroids with more favorable orbits and figures of merit than have been found to date.

Extremely low ΔV Amor asteroids may exist, as a consequence of two different dynamical circumstances. First, it is possible that some small planetesimals have remained in the space between the orbits of Earth and Mars from the time of planetary accretion. Provided that the maximum aphelia of such objects are somewhat less than the minimum perihelion of Mars, 1.309 AU, and that the minimum perihelia of these planetesimals is somewhat greater than the maximum aphelion of the Earth, 1.067 AU, they have indefinitely long lifetimes. Taking account of the forced oscillations of eccentricity, produced mainly by Jupiter, the range of semimajor axes for objects that are safe from collision with Earth or Mars is 1.15 to 1.21 AU (see Friedlander *et al.*, 1977). For these objects to be stable against planetary encounters, they must also have very small proper eccentricity. Fragmentation lifetimes for bodies 100 m in diameter and larger in orbits of this type are greater than the age of the solar system, at the present flux of interplanetary material. The fact that no objects of very low eccentricity have been observed in this region between Earth and Mars may indicate that Mars migrated outward during accretion. Presumably, most of them were swept up by Mars or the Earth or reduced to fine debris by collisions during the period of high bombardment. There is no theoretical basis at present, however, for concluding that these processes completely removed all small bodies.

Secondly, extremely low ΔV Amors can be injected into orbits with aphelia equal to or somewhat greater than 1.309 AU by close encounters with Mars, during the extrema of oscillation of Mars' eccentricity. The probability of this happening is low, but so long as the perihelia of the Amors lie somewhat outside of 1.067 AU, such objects would have very long lifetimes. The figure of merit of an Amor with an aphelion just at 1.309 AU and perihelion at 1.067 AU and with 0° inclination is 0.15, which is equivalent to a minimum ΔV to rendezvous at perihelion of about 4.9 km/sec. This is shown as the minimum "expectable" F on Figure 4. A few percent of the Amors are expected to have figures of merit for rendezvous at perihelion between 0.15 and 0.27, corresponding to ΔVs between 4.9 and 8.7 km/sec.

Two mechanisms may produce extremely low ΔV Earth-crossing asteroids: (1) injection of very low ΔV Amors into Earth-crossing orbits by encounter with Mars, and (2) reduction of ΔV of Earth-crossers by multiple encounters with Earth and Venus. In the first case, the limiting figure of merit is 0.15, as given above for Amors. In the second case, the limiting F is found for a body that just crosses the orbit of Venus, at the maximum Q of Venus, 0.777 AU, and the orbit of the Earth at minimum q of the Earth, 0.933 AU. For rendezvous near the Earth, at aphelion of the asteroid, the figure of merit would by 0.18, corresponding to a minimum ΔV to rendezvous from low Earth orbit of about 5.8 km/sec.

Minimum encounter velocities at the Earth's sphere of influence for very low ΔV asteroids derived either from Amors or from Venus-crossers would be 1.9 km/sec. Multiple encounters with the Earth would be expected to shuffle the orbital elements, while the encounter velocity tends to be conserved. Changes in e and a would be exchanged for changes in i, for example, so that some of these bodies would tend to become exclusively Earth-crossing, like 1976AA. It might be supposed that encounters with the Earth could further reduce the ΔV to rendezvous. While this is physically possible, it is statistically more likely that the ΔV will be increased by such encounters. From the cumulative frequency distribution of F for Apollos (Figure 5), a few percent of the Earth-crossers are expected to have figures of merit between 0.15 and 0.25 corresponding to approximate ΔVs of 4.9-8 km/sec. Both "cometary" and "asteroidal" objects should be present in this group of Earth-crossers.

Finally, there are two possible dynamical classes of near-Earth objects, representatives of which have not so far been discovered. Weissman and Wetherill (1974) have shown that substantial regions of stability in orbital element phase space exist for objects in 1:1 resonance with the Earth. These regions are analogous to the stable L_4 and L_5 libration regions on Jupiter's orbit, which are occupied by the Trojan asteroids. Gehrels (1977) has made a preliminary search of the libration regions on the orbit of the Earth without success. Another region of stable orbit, for objects of low eccentricity, lies between Venus and Earth. This region has never been deliberately investigated. As both the libration regions on the orbit of the Earth and the region of stable orbits between Venus and Earth are more than 90° from opposition, they are very rarely examined for asteroids. We plan to begin such a search in 1978. Trojans of the Earth would represent the ultimate low ΔV asteroids. As the most stable objects, on "tadpole" orbits, can never approach the Earth more closely than ~0.4 AU, however, they would be less accessible on short duration missions than low ΔV Amors and Earth-crossers.

Parametric studies of transfer trajectories in near-Earth space by Niehoff (1977) show that impulse requirements for round-trip missions scale almost linearly with inclination of the target asteroid for i below 20°. A 100% increase in energy is required for every 6-7° increase in inclination. For an asteroid with a and e comparable to 1976AA, about 10 Shuttle launches would be required for a manned mission, if the inclination were 8°, and about seven Shuttle launches if the inclination were reduced to 5°. Encounter velocity at the Earth's sphere of influence for such an asteroid with i = 5° would be 4.2 km/sec, more than twice the minimum velocity for Earth-crossers given above. The discovery of objects which could be reached by manned missions using 7-10 Shuttle launches, therefore, appears entirely possible. Very roughly, about 1% of the Amors and 1% of the Earth-crossing asteroids may fall in this category. There may be a total of 10-20 Earth-approaching asteroids to absolute visual magnitude 18 (diameters in the range of 0.7-1.5 km) with encounter velocities of 4-5 km/sec or less and many more smaller bodies. An intensive search for Earth-approaching asteroids will be needed to find these bodies. At the present rate of discovery of Earth-approaching asteroids of 4-5 per year, it might take 25-50 years to find the first one. The rate of discovery will need to be increased by a factor of at least five to achieve a reasonably high probability of discovering, within the next decade, an asteroid which could be reached with a simple ballistic manned mission utilizing 7-10 Shuttle launches.

The scientific objectives of a manned mission would be similar to those of the unmanned missions. Properly trained astronauts, however, would bring to the task of exploration an enormous advantage in maneuverability and dexterity on the surface of the asteroid, with the attendant advantages for close scientific examination of the surface and flexibility in sampling. They would be able to solve details of the structure of the asteroid that would be very difficult to obtain by unmanned spacecraft and to sample accordingly. It is the structure of the body, with all that this term implies for decipherable history, or, in other words, the geology of the asteroid, which constitutes the primary goal of direct exploration. It is a task made to order for astronaut-scientists.

While the task of exploration of Earth-approaching asteroids is highly appropriate for manned missions, we do not suggest that such missions would be undertaken for scientific goals alone. Earth-approaching asteroids constitute the next nearest worlds in space, beyond the Moon, that can be visited by man. Missions to these objects represent the most readily achievable step in an orderly development of manned space exploration. The value of such missions must be judged in the context of the larger goal of extending man's capabilities in space and in extending the frontier of exploration.

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GENERAL DISCUSSION ON SESSION III

MORRISON: Our topic for this discussion is the future exploration of the asteroids. We should particularly consider the future of Earth-based studies, and the interrelation of these with mission plans for perhaps a decade from now.

CHAPMAN: For a start, I would like to emphasize the importance of laboratory and theoretical studies. Lack of such information limits our ability to interpret the observations we now have; for example, we really don't know what the surface of a metallic asteroid in space should look like.

ANDERS: We argued yesterday about the interpretation of the S asteroids, whether they are stony-irons or chondrites, and the crucial difference is the abundance of metal on the surfaces of the bodies. The question is, then, what are the effects of space weathering in low g? What does the surface look like after bombardment by dust particles and the solar wind? Comerford reported in the mid-1960's that when a chondrite is bombarded with dust particles, the silicates erode preferentially whereas the metal merely flows plastically so that eventually the metal stands out from the surface. How does this compare with the asteroid measurements?

McCORD: And even more fundamental is the study of the optical properties of metal. We don't know for sure how much metal the spectra indicate.

VEVERKA: It is essential to understand the optical properties of asteroid regoliths both in terms of the optical constants of the constituent minerals as well as in terms of the textures involved. In my opinion that is more important at the present time than getting 100 more spectral reflectance curves.

ANDERS: We really need to understand asteroid regoliths. Before Apollo, there was considerable talk about what the lunar surface looked like and there were papers describing electrostatic effects, etc. These effects seem to be small on the Moon, but probably are quite a bit larger on the smaller asteroids. There also was considerable talk about the transport of dust from the highlands to the maria or vice versa. This doesn't seem to be very important on the Moon, because mare-highland boundaries are very sharp even after several billion years of bombardment. To what extent could laboratory programs investigate these questions?

FANALE: I would like to understand theoretically what water has or has not done to asteroid surfaces. We need to know where it came from, how it moved through the parent bodies, and when it escaped, if it has done that.

ARNOLD: With all respect to the last couple of comments about regolith theory and water, I think these things are much easier to understand after a mission than before. Close-up pictures will make a tremendous difference. Right now, for example, it might be very reasonable to discuss the regoliths of Phobos and Deimos; however, I would be quite skeptical about a theoretical program of such studies before the pictures were available. I would like to point out something that I feel is important but which is being done by one person. Brownlee is looking again at a 100 year old subject, namely deep sea spherules. It has been known since 1876 or thereabouts that there are meteoritic spherules in the cores at the bottom of the ocean. They are coming not only from meteorites that are in the collections, but from meteorites that never reached the collections because they burned out high up. Some people like myself have been stimulated to join him. If these arguments of Ceplecha and McCrosky, and now Wetherill, aren't correct, this work can show they are wrong.

MORRISON: The thermal history differences among objects of similar size and similar location in the belt has been pointed out in the past as one of the big mysteries of the asteroids. The program of this workshop is such that we have not discussed this problem. People are doing theoretical and laboratory work on possible selective heating mechanisms to produce a thermally evolved Vesta and a relatively unevolved Ceres. Does anyone have some further input on the progress that is being made in that area?

MATSON: I think to some extent that work has been suffering; few proposals are funded. I think one of the services this workshop can provide is to say that although there have been a lot of thermal models, the possibilities have not been exhausted.

WETHERILL: I think computing thermal models is relatively trivial. But if there were some way to really understand the role of the aluminum-26 or other early heat sources, that would be an important thing.

CHAPMAN: I would like to address the question of how far we are likely to get with ground-based research in the next few years. I think that scientists are capable of stating answers to any question that is asked. The problem is whether those answers are believable. I think we basically couldn't believe any answer concerning the physical nature of the asteroids a few years ago, and now I think we have considerable confidence in answers to a few very specific questions about asteroids. With this base, we can also go on to address speculative answers to a whole host of new problems. I don't think we can have very great confidence in those speculative answers today but if we can augment the data in the future by a factor of ten, we may be able to. Can we associate particular meteorite classes with particular asteroids or particular asteroid families? That's a specific question. I think we can clearly associate, with a high probability of being right, certain meteorite classes with certain asteroid *classes*. But only very speculative papers have been addressed to associating particular meteorite classes with particular bodies. There are a couple of papers about Vesta. One was written regarding the Farmington meteorite. I don't think we will have confident answers based on the ground-based work even in the next decade. I don't personally have confidence that this question will be answered and that the very skeptical people are going to say yes, we know for sure those meteorites are coming from that asteroid.

ANDERS: Maybe to focus the discussion we should take the case of Vesta. Every speaker has mentioned it as being the asteroid with the most characteristic spectrum. It was the first one to be matched up with a specific meteorite class. A number of papers have been written in the last year or two trying to interpret Vesta as the parent body of eucrites and howardites; a particularly interesting example is that by G. J. Consolmagno and M. J. Drake (*Geochim. Cosmochim. Acta* 41, 1271-1282, 1977). The petrology of the eucrites has been very well worked out by Stolper, which in turn has led to detailed compositional models of Vesta. But there are dynamical arguments against getting the howardites from Vesta. Perhaps we have not looked hard enough at some far-out dynamical possibilities. Now I wonder what work is required in order to decide conclusively whether or not eucrites and howardites are likely to come from Vesta or whether we are going to have to look for another source?

WETHERILL: It is very hard to demonstrate that you have thought of all the things that can be thought of. I am hopeful that as more people concentrate an attack on this sort of dynamical problem, we will exhaust the possibilities more than we already have. With regard to Vesta there may very well be mechanisms discovered which will bring some quantity of material from Vesta into the inner solar system. However, other silicate asteroids that are adjacent to the ν_6 resonance, etc., are also potential sources of meteorites. I think it would be very surprising if some selective mechanism were found for Vesta which is enormously more efficient than these others. I don't see how we can get more material from Vesta without getting a lot more from these other asteroids, too.

ANDERS: Let me take the pessimistic possibility first. Suppose after several years of hard work by you and others, there is no known way to get meteorites from Vesta to Earth. Suppose the argument of Consolmagno and Drake still holds, that for every eucrite-howardite, there should be at least ten times as much of the complementary ultramafic differentiate, and since such meteorites do not fall in numbers exceeding those of eucrites, the parent body is not yet broken up; we are just seeing bits and pieces spalled off the surface. Suppose we have nothing but that argument and we are still very eager to learn something about Vesta, so a mission is launched to Vesta. What kind of measurements are needed and what kind of evidence is needed before we can say yes, Vesta is the parent body of eucrites, or no, it is not?

FANALE: If you include a hard lander with its alpha-scatter instrument on the surface, the completeness of your chemical analysis is going to be much greater than with only orbital gamma-ray and x-ray results. I think that with the global chemical information from orbit and the chemical analyses from the hard lander, you would be able to go a long way.

ANDERS: Suppose the chemical analysis that has been sent back is a perfect match to the eucrites. How do I know even then that there wasn't a twin to Vesta that broke up and is actually the source of eucrites? And that twin might be significantly different in some important ways. It could be older, it could be younger, or it could have a different history. So I still would not be justified in concluding that eucrites came from Vesta, just because of a chemical analysis.

FANALE: I think what the eucrites are telling us is that there are objects like Vesta which when studied as global entities could place severe constraints on the early thermal history of planetary objects. Whether the eucrites came from Vesta is an important, but separate question.

ARNOLD: It is an important question because such knowledge would allow you to take meteorites you have, on which you can do these beautifully detailed measurements, and know exactly where in the solar system they came from.

FANALE: I agree, it is important, But there is a separate question about looking at the early chronological history of planetary objects. Almost surely Vesta went through the same history that produced others. But we don't know what it means because we haven't studied Vesta as a global entity, so we don't know what an entire parent body looks like. We should look for things which may be present on the surface that will indicate something about Vesta's differentiation chronology and the magmatic path that was followed.

ARNOLD: I have a little story I would like to tell. I sat in another room, about this size and with about this number of equally distinguished people, when we were trying to select the proposals for the first lunar sample analysis. We weren't able to keep at it all the time, and people insisted on talking science occasionally. One of the discussions involved an argument over whether tektites came from the Moon or whether chondrites came from the Moon. I was chairman trying to get them back to work. To get around this argument, I said: "Perhaps this at least is a proposition we can all agree on: when we get samples from the Moon we will recognize some of them." And every head in the room went up and down. Back to work, and yet this was totally wrong. So you can understand why I keep reemphasizing the point that you have got to go and see. When we can survey the asteroids with the kind of payload Fanale describes, we will know as much about these objects as we know about the Moon from Earth observations and from lunar orbital measurements. In addition, however, we know more about the Moon as an object because we have the lunar samples, and they have given us an enormous amount of information. This combination of global remote sensing coverage, some chemistry, and some detailed mineralogy is certainly not answering all questions. But many of the questions on Fanale's list should be addressable. If you imagine something like several volumes full of hign quality papers about the asteroids visited on a mission, I think you have an approximate estimate of the information you will have.

MORRISON: Let me suggest an analogy, although it may be dangerous. I am sure we would all agree that learning whether meteorites come from particular asteroid parent bodies is extremely important. This is rather like going to Mars to find life there. It is extremely important, but no one would say that not obtaining a definitive answer means we have not learned useful things about Mars. In addition, I think our level of knowledge of the asteroids is so low that we could work ourselves into a dangerous corner. We should say that a mission is desirable because asteroids are intrinsically interesting objects and not because we will get answers to specific Questions A, B and C.

ANDERS: I believe in serendipity, but to justify a mission to the asteroids we need to do more than say "let's see what we discover." Asteroids are unique in more than one way. One of the unique features is that they are less evolved geologically than planets. Another is that we have materials, the meteorites, that either have come from asteroids or are basically similar to asteroids. So we should carefully decide what questions we should ask that would justify a mission to asteroids, and still allow for a bit of serendipity.

FANALE: My point of view is that it's necessary to establish key questions which are important in understanding solar system history and that are likely to be answered by a mission such as we are discussing, rather than by some other mission which is a competitor.

ANDERS: On those terms, yes, I agree. Let me also say I think you presented a magnificent list of questions in your paper. But I am not sure all of these questions can be answered by the kind of asteroid mission we have discussed. It is not clear how the specific measurements can be performed that will actually answer some questions.

VEVERKA: It is really important that we distinguish between interesting questions and answerable questions. You can ask what is the parent body of a certain meteorite type. That is very similar to asking what is the origin of the Moon. It is very interesting but I don't know how you go about answering it. Specifically, in the case of Vesta, if you brought back a sample of the surface and submitted it to all the usual analytical techniques, it is very unlikely that all the measurable parameters will match exactly those of a specific meteorite type. If the parameters are generally similar, but not identical, what are you going to conclude?

FANALE: I made it very clear that a limited mission to a limited number of objects was not going to give you a global context to the meteorite data. But I did point out if you are choosing a mission it should do the best job possible of answering that particular question.

ANDERS: Note that I didn't ask the question, "where did the H chondrites come from?" Presumably there are many bodies of that composition. Vesta appears to be unique, and its connection with the likewise rare howardites may therefore be a more answerable question. I completely agree with Veverka's skeptical point of view that even if samples are brought back and put through laboratory tests that agree in every way, there still remains a lingering doubt.

SHOEMAKER: I would like to submit, and whether it is pessimistic or optimistic depends on your viewpoint, that we will not identify a parent for any single meteorite within the lifetime of anyone in this room. What we can do is go to individual asteroids and find out what they really are. That is the question we should be addressing. Maybe we will be lucky and find the source for one of the known meteorite types. But the important thing is to go to the individual asteroids, study them, ultimately get samples from them, and analyze those samples with the same techniques we have used in the past for the meteorites to get the answers for those samples and those asteroids.

ANDERS: There is a possibility that if we do so, we may bring back samples that are indistinguishable from a known meteorite class. I would be very embarrassed to have spent $400 million dollars for samples that are, for instance, a little different from H chondrites, but not in a very significant way.

NIEHOFF: You wouldn't be spending the whole amount on that one answer, but you would come back, by definition, with a wealth of other information.

MORRISON: I think Anders has just given a pretty good rationale for choosing a mission concept that characterizes several asteroids as planetary objects, rather than just concentrating on sample return from one asteroid.

ARNOLD: It seems reasonable to me that a sample return mission would require for its justification more information than I foresee us deriving from ground-based observations alone. For that reason I agree that the exploration of multiple objects is the first objective. After such a mission, I think we would be in a position to say with some reasonably high probability whether or not sample return is going to yield material different from the meteorites we already have.

NIEHOFF: I would go further. An objective of a multi-rendezvous mission probably ought to be that we do come back with the necessary data to assess what a sample return mission would do.

MATSON: Before we go off on an asteroid mission, the targets of that mission ought to be studied intensively from the ground and also from Earth orbit over the extended wavelength range from ultraviolet into the infrared. Such concentrated studies will provide a very powerful tool.

ARNOLD: The other point I have not heard is that this kind of mission can provide the information needed to interpret the ground-based information we have. If one does have four or five objects which one has explored in detail and really understands, one can go back to the general questions that were discussed earlier and address them in a more sophisticated way. You may be able to say with more certainty than before that the H group chondrites come from this class of object or we think the only possible place the eucrites can come from is from this particular object.

ANDERS: We must not forget that we have a large body of spectroscopic information, thanks to McCord, Chapman, and others. This information is getting more specific and more reliable all the time, and after some necessary laboratory studies have been made, the interpretation, too, will be more conclusive. Looking ahead ten years from now with all this additional work, I wonder if we could justify sending a mission just to see if we are right on five asteroids?

VEVERKA: No one is proposing that. One of the reasons for having an asteroid mission is to go beyond that. Most of the things we have discussed so far tell you about the outermost layers. For example, one of the things people keep talking about, which I don't believe, is that many C objects are coated with something and they are not C objects on the inside. A mission provides the only way I know of to determine masses accurately and to obtain information on internal densities.

CHAPMAN: Further analogy can be drawn with lunar exploration. Many long books were written about the Moon before the Apollo program. They dealt with a whole host of interesting questions, largely of a geological nature, because the data we had on the Moon dealt with whole body geophysics and observable surface geology. Many of the questions addressed in those books were of fundamental importance, such as the creation of basins. Then we actually visited the Moon, and now if one looks at the Proceedings of the Lunar Science Conferences, one sees as a result of the Apollo samples that a whole realm of additional questions are being addressed. In the case of the asteroids and the meteorites, we have lots of samples but what we are entirely lacking is the global planetological aspects of asteroids. Some of us are preoccupied with thinking about the kinds of problems that present themselves from the studies of the meteorites. However, I expect that the asteroids also will be geologically and globally interesting bodies. And understanding the fundamental problems of these bodies, such as collisions, should synergistically help us answer the questions that one asks on the basis of meteoritical evidence. Maybe I should ask you, do you think that global planetological questions can be addressed by an asteroid mission?

ANDERS: Quite possibly if you find asteroids at just the right stage of fragmentation. But you have made the point that the asteroid belt at one time was much more massive, and that there are virtually no asteroids that still have their pristine surfaces. So, will you then be able to make real sense out of fairly detailed mapping of five asteroids? Will you really be able to determine their original composition, the geology, and so on? If the asteroid has lost 80% of its mass, will you really be able to tell what the original asteroid was like?

CHAPMAN: It is my expectation, and I think most people's expectation, that Vesta is not a fragment. So there is one original asteroid. We can visit some that are certainly fragments and we can also visit some like Ceres and Vesta that almost certainly are not fragments. One can then interpolate among the possibilities.

ANDERS: You'll see a cratered surface and perhaps a few basins that allow you to see through the present crust. This would be interesting, but not crucial information. Jerome and Goles and others have already recognized howardites as mixtures of crust and mantle material, *i.e.*, eucrites and diogenites, and both of these are available in pure form.

CLAYTON: Could you convince anyone in this room that all the known eucrites or howardites come from a single asteroid? You can't convince us that any two eucrites are from the same parent body. How can you convince anyone they come from a particular asteroid?

ANDERS: Vesta is the only known source for eucrites, and it meets the requirement that it is not extensively broken up. To turn the question back to you, how would a mission answer this question?

CLAYTON: I wouldn't ask that question of a mission. I have heard much better questions asked here. I wouldn't think Vesta would be a particularly interesting place to go. I would be much more interested in the primitive asteroids than the evolved ones.

FANALE: I don't believe it will be necessary to choose between Vesta and a primitive asteroid in target selection. When I say to demand Vesta, it is because Vesta is unique, so you have to demand Vesta to get it. The whole asteroid belt is full of the smallest and darkest things you can imagine and they are the most primitive ones.

They are the ones you will encounter typically by serendipity after you make those demands for Ceres or Vesta. So while I do think Vesta is very desirable, it doesn't mean I would give up any chance of going to a primitive asteroid in order to go to Vesta.

MATSON: With meteorites we are looking at asteroids from a microscopic point of view. With telescopic observations, we are looking at the macroscopic point of view. I see an asteroid mission filling the size scale between these two extremes.

ANDERS: We have such information for Phobos.

MATSON: No we don't, we don't have any meteorites or samples from Phobos.

ANDERS: When we made out the list of questions for this workshop, the very first one was, "What are the most important things we want to learn about asteroids? How do these goals relate to deeper insights about the solar system and its evolution?" Thus a mission cannot be justified as an end in itself, as a way to obtain information that is trivial or is easily deducible from ground-based measurements with a little bit of inspired speculation. We must instead try to formulate truly important questions that can be answered conclusively only by a mission. Let us bear in mind that we are in a privileged position, relative to people arguing for missions to comets or Jovian satellites. We have at least a few asteroidal samples among our meteorite collections, and that gives us a unique advantage over other planetary scientists. If we want to propose a mission, then we must be able to justify it by four-to-five truly important questions that only a mission can answer. I want to make sure we have done our homework. I believe that this workshop, and this discussion we have had, are important for bringing out just what the questions are that can be addressed by a mission to the asteroids.

SECTION IV:

ASTEROID MISSION CAPABILITIES

OPTICAL REMOTE SENSING OF ASTEROID SURFACES FROM SPACECRAFT

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The application of optical remote sensing techniques to asteroid surfaces using ground-based telescopes has revealed most of what is known about these objects. Transporting the related instruments to the asteroids for close-up study during rendezvous or landing missions has the potential for providing large increases in our knowledge of asteroid surface structures, composition and mineralogy. Reflectance spectroscopy and multispectral mapping are the companion techniques likely to be most useful, for between the two approaches surface units can be determined. Several other techniques should be considered for providing complementary information. The state of instruction is such that no serious technical problem in developing such experiments is expected.

INTRODUCTION

When asteroid exploration is extended by carrying instruments near asteroids and onto their surfaces we will find measurements in ultraviolet, visible and infrared energy regions even more useful than they are now, working from the Earth's surface. A variety of techniques are available which all depend on measuring radiation reflected or emitted by surface material. This article discusses each technique briefly and points out some more obvious experiments which could be performed on flyby, rendezvous or landing missions. As always one must be cautious in assuming that all possible techniques and experiments are known. New and better methods may be discovered in the future and in fact may now exist unknown to the author.

Optical radiation coming from an asteroid consists of two components: passively scattered solar radiation at shorter wavelengths and emitted thermal radiation at longer wavelengths. Figure 1 shows the flux received at the Earth from a square kilometer of a lunar mare region at near-zero phase angle. The case for a low albedo asteroid near the Earth would be very similar. For objects farther from the Sun the wavelength at which emitted thermal radiation becomes dominant shifts to longer wavelengths, to about 4 μm at Mars and 6 μm at Jupiter.

The major techniques available for obs   ing asteroids at optical wavelengths are tabulated in Table 1. All of these could be remotely applied from a flyby or rendezvous spacecraft and the spectroscopic techniques could be applied on the asteroid surface to study samples, as is commonly done in terrestrial laboratories.

Fig. 1. Radiation received from a 1 km² mare area, albedo 0.06, at the mean Earth-Moon distance (Adams and McCord, 1970).

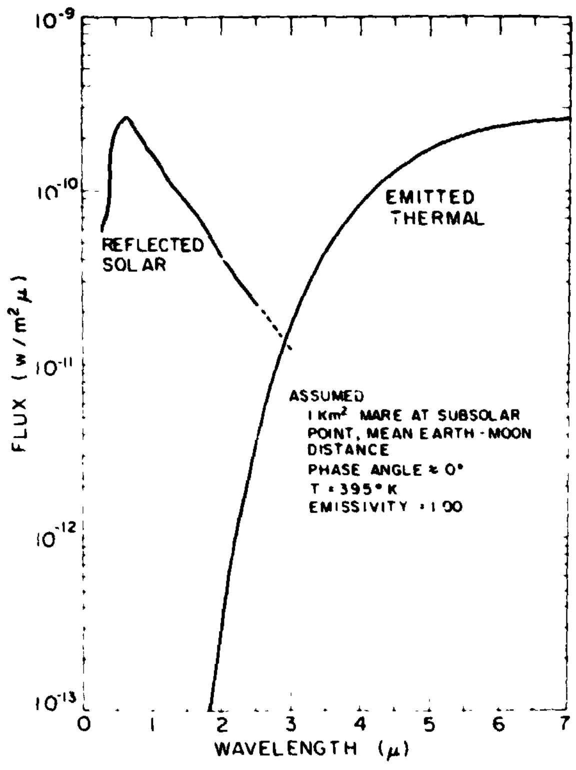


Table 1. The Major Techniques Available for Observing Asteroids at Optical Wavelengths

Technique	Wavelength Region	Property Determined	Physical Phenomenon
1. Reflectance Spectroscopy	0.1-5.0 μm	Mineralogy	Electronic Absorption
2. Emittance Spectroscopy	5.0-1000 μm		Molecular Vibration
3. IR Radiometry	5.0-1000 μm	Diameter, Albedo, Thermal Inertia	Thermal Energy Exchange
4. Polarimetry	0.1-1.0-? μm	Grain Size to Material Opacity Ratio	Specular Reflection and Scattering
5. Broadband Photometry	0.1-1000 μm	(See 1 and 2 Above) Albedo	(See 1 and 2 Above)
6. Multispectral Mapping	0.1-1000 μm	Compositional Unit Extent	(See 1 and 2 Above)

REFLECTANCE SPECTROSCOPY

Technique Description

Spectral reflectance is the fraction of incident solar radiation that is reflected from a surface as a function of wavelength. With sufficient spectral resolution and intensity precision, absorption bands often can be resolved that are diagnostic of surface composition and mineralogy (see Figure 2). For mineralogical interpretation we are concerned primarily with the wavelength dependence of reflectance and to a lesser extent with the albedo or absolute amount of reflected light, and angular dependence, or polarization of the reflected radiation.

The material on the surfaces of solar system objects typically occurs as randomly oriented fragments. When observed in reflected solar light, the particulate material returns two components of radiation: (1) a specular component, which consists of first surface reflections and is described by Fresnel's laws for absorbing dielectrics; and (2) a diffuse component, which is composed of light that has entered at least one grain and has been scattered back into space toward the observer. It is the diffuse component that contains the most compositional information.

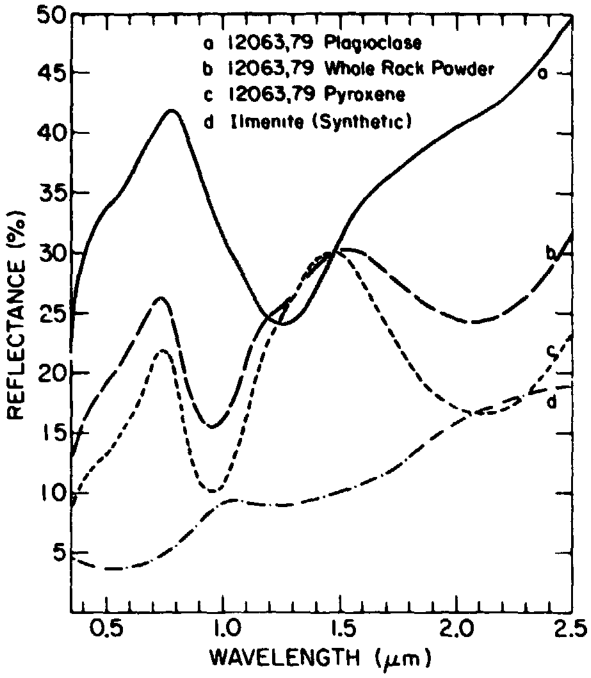
The absorption bands that appear in reflectance spectra are due primarily to (1) electronic transitions and charge transfers by d-shell electrons in transition metal ions (Fe^{2+}, Ti^{4+}, Cr^{3+}, etc.), (2) overtones of molecular vibrations, (3) photoelectronic emission, and (4) photoconduction. The wavelength positions of the absorption band centers depend on the types of ions present and on the dimensions and symmetry of the sites in which the ions are situated. These two factors to a large extent define the mineralogy of a sample. Note that reflectance spectroscopy is a method of remotely sensing *mineralogy*, in contrast to γ-ray spectroscopy and x-ray fluorescence, which remotely sense *elemental composition*.

Reflectance spectra are interpreted using a combination of laboratory and theoretical techniques. Laboratory spectra of a large number of chemically analyzed terrestrial, lunar, and meteoritic minerals and rocks have been analyzed, and their spectra have been studied as functions of particle size, phase angle, mixing ratios, and mixing heterogeneity. Interpretations of absorption bands are based on ligand field theory (interelectronic transitions), molecular orbital theory (charge transfer transitions), band theory (photoconductivity and photoemission), and theories of molecular vibration. Relative modal abundances are determined analytically by comparing the relative strengths of bands contributed by the constituent minerals, and using assumptions about relative grain sizes and homogeneity. Simple comparisons with catalogs of laboratory spectra are not adequate and may be misleading.

For many objects in the solar system, such as the Moon and Mars, telescopic spectra for a large number of locations can be obtained and petrologic units identified. Determination of unit petrology requires high spectral and spatial resolution; however, the spectra often can be characterized in terms of intensities at few diagnostic wavelengths, which can be mapped in two dimensions (using multispectral imaging techniques) to determine the spatial extent of petrologic units.

Problems can arise to make the application of reflectance spectroscopy difficult or impossible. For example, observations can be affected by low light levels and poor spatial resolution. Furthermore, solar system objects have their surface optical properties modified by one or more alteration processes, which have to be understood before accurate interpretations can be made. The optical properties of soils can be strongly altered by masking agents, such as agglutinitic glass on the Moon and Mercury, vegetation and clouds on Earth, and windblown dust on Mars. To a lesser extent, polarization effects and reflection geometry can also complicate interpretations.

Fig. 2. Spectral reflectivity of Apollo 12 basalt powder 12063 and plagioclase and pyroxene separates from the same rock. Ilmenite is a synthetic sample (Adams and McCord, 1971).



These limitations notwithstanding, the technique has been successfully applied using ground-based telescopes; the compositions of nearly 100 asteroids have been determined; the pyroxene composition, titanium content, soil maturity and mare basalt types have been determined for units across the lunar surface; the abundance, type, and water content of ferric oxides in the martian soils have been measured; and the presence of H_2O on the Galilean satellites, and the rings and satellites of Saturn has been detected. Spacecraft experiments should extend the ground-based work and acquire basic information about the composition of solar system bodies.

Instrument System

Remote Measurement. Flyby, orbiter and rendezvous missio asteroids require spectrometers of some sort with telescopic foreoptics to gathe ght and project an image of a surface spot. Several spectrometers have been developed for ground-based telescopic observations. These include multi-discrete interference filters (0.3-2.5 μm), single detector spectrometers (0.6-5.0 μm), and interferometer spectrometers (1.0-2.5 μm). Several broadband photometers have also been used.

Two instruments have been designed for spacecraft use. A cross disperson eschell spectrograph using linear arrays of detectors (0.35-5.0 μm) has been designed for the LPO mission and a modified version was proposed for the Galileo mission. This instrument gives very wide spectral coverage for only one or a few spatial elements (because of optical aberrations).

A second instrument is being designed and built to fly on the Galileo mission. It will be a single dispersion spectrometer using linear arrays of detectors aligned along the slit image, rather than along the spectral dispersion as for the other system. This instrument has narrower spectral coverage (because of order overlap) but it has the ability to image up to 30 or so spatial elements simultaneously.

These two instruments represent the two extremes of design for dispersion spectrometers. Combining the advantage of each has been attempted but not achieved.

An interferometer spectrometer was flown on the Mariner 9 Mars mission but the spectral range did not reach to short wavelengths where electronic absorptions are well developed. A similar system modified to reach to ~1.2 μm was proposed for the Galileo mission. A problem with the interferometer spectrometer approach in general is the close mechanical tolerances required to work at visible and near infrared wavelengths and the unnecessarily high spectral resolution and resulting decreased sensitivity that must be accepted in current designs.

Circular variable filter (CVF) spectrometers have been suggested and they are attractive because of instrument simplicity. But simultaneous measurement of more than one spectral channel is not allowed and this greatly reduces measurement efficiency. For bright surfaces and rendezvous missions one might be able to use such a device.

Considerably more development of these instrument concepts is needed to obtain appropriate devices for actual missions. Different missions will require different devices. Important parameters affecting design are: surface brightness (distance of object from Sun, distance from object, spatial resolution, surface material albedo), integration time spent on one surface spot (ground track speed, spatial resolution), and aerial coverage desired (type of object, total time spent at object).

In Situ Measurement. A landing mission could involve some sample analysis. In this case a reflectance spectrometer could be used to make detailed mineralogical analyses, just as is presently done in terrestrial laboratories. No such instrument has been designed (although many models exist for laboratory use) and problems of light sources, calibration and sample manipulation may exist.

EMISSION SPECTROSCOPY

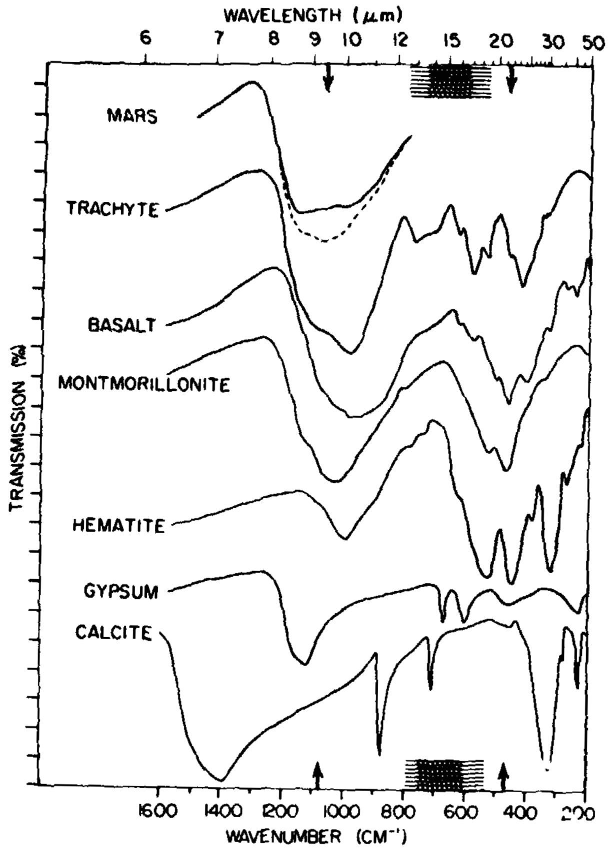
Technique Description

A planetary surface element reaches a certain temperature according to a complex set of energy-balance conditions involving geometry and Kirchoff's laws. The major source of energy is solar radiation which is absorbed by the surface at visible and near infrared wavelengths (Figure 1). A minor but possibly detectable amount of energy may originate in the planet's interior. Some emitted thermal radiation is reabsorbed by other parts of the surface within the field-of-view of the emitting surface element.

The ability of a surface to radiate depends partly on the optical properties (index of refraction and extinction coefficient) of the material, and these properties vary with the wavelength of radiation emitted. Solids are composed of atoms and molecules bound in a crystal lattice. With their associated bonds, these form oscillators which vibrate at preferred frequencies. Near the preferred vibrational frequencies, bands (called reststrahlen bands) appear in the emission spectrum of the solid (Figure 3). For silicates the Si-O bond is responsible for a strong emission near 10 μm, for example. These bands can be diagnostic of composition.

Unfortunately, these emission bands usually can be seen only for surfaces with large particle sizes (100 μm). However, at a wavelength slightly shorter than but related to the reststrahlen band, the index of refraction of the emitting material becomes equal to that of the surrounding medium. At this wavelength (Christiansen frequency) no scattering occurs at particle boundaries and the maximum possible radiation escapes to space. It has been shown that the Christiansen frequency varies predictably with composition and this approach has been used to study lunar and terrestrial samples.

Fig. 3. Transmission spectra of rocks and mineral ground to 0-5 μm and suspended on a mirror. Curves have been separated vertically for clarity. Peak transmission near 8 μm (250 cm^{-1}) is typically about 90% for the rock spectra, and ordinate divisions are 10%. Shaded region of the spectrum is obscured by martian CO_2 lines in Mariner 1971 spectra. Recalculated Mariner 1971 nonpolar spectra are shown here. Vertical arrows indicate position of polar radiance maxima, near which we also expect the nonpolar transmission minima (Logan *et al.*, 1975).



Instrument Systems

Remote Measurements. Several spectrometers of the designs (but with different detectors) described under a previous section have been built and used on ground-based telescopes. The spectral range covered is restricted to the 10 μm and 20 μm terrestrial atmospheric windows.

A CVF spectrometer (2-14 μm) was flown to Mars on the Mariner 6 and 7 missions and an interferometer spectrometer (4-50 μm) was flown to Mars on Mariner 9.

In this spectral range the interferometer spectrometer becomes a more practical alternative because of the increased wavelength of radiation observed. The detectors become more difficult to handle because of the need for cooling to near 0°K. Considerable development of both the techniques and the instrumentation is required to make available a dependable experiment.

In Situ Measurement. As in the case of shorter wavelength reflectance spectroscopy, emission spectroscopy can be applied on landing missions to analyze samples. Spectroscopy at these energies is a standard laboratory technique, as at shorter wavelengths, and instrumentation is equally undeveloped. Probably the *in situ* measurements would be made in transmission rather than emission so that sample preparation becomes a serious problem.

IR RADIOMETRY

Technique

The temperature of an illuminated planetary surface is controlled by insolation (surface area presented to incoming sunlight), surface albedo (amount of sunlight absorbed), and temperature of objects within the field-of-view of the radiating surface element. After sunlight is cut off (*e.g.*, eclipse), the relative importance of subsurface heat exchange increases rapidly as the surface cools. From the solution of the heat-conduction equation one finds that the surface material properties K (thermal conductivity), ρ (density), and C (heat capacity), in the functional form $(K\rho C)^{\frac{1}{2}}$ (called the thermal inertia), control the rate of cooling of a surface, but the temperature of objects in the field-of-view of the emitting surface also has an effect.

Infrared radiometry is the measurement of flux emitted from a surface, perhaps at several broad spectral bands, from which an effective temperature can be derived. Temperatures of an illuminated surface, alone, usually reveal little about the surface except albedo and illumination geometry. When condensates are present some compositional information can be inferred by considering freezing temperatures. Temperature changes during illumination changes such as an eclipse can give additional information from the measurement of thermal inertia.

Instrument System

A large number of IR photometers are in use making ground-based measurements of flux in several broad spectral bands for a wide variety of objects including asteroids. Also, a number of instruments have been flown on spacecraft. Development of such instruments is not difficult given the work already done. One area of difficulty is the detector cooling required to achieve the best sensitivity.

POLARIMETRY

Technique

Reflected radiation can be analyzed into its two orthogonal planes of polarization, one perpendicular ($I_\perp$) to the plane of scattering and one parallel ($I_\parallel$) to this reference plane. The plane of scattering is defined by the source, surface, and observer. The polarization (P) of the reflected radiation is defined as

$$\%P = \frac{I_\perp - I_\parallel}{I_\perp + I_\parallel} \cdot 100$$

Polarization has usually been measured as a function of the angle between source, surface, and observer, or "phase" angle. There is generally a maximum polarization near a phase angle of 110°, diminishing to zero near 20°. A 90° shift in the plane of polarization occurs at small phase angles resulting in a small "negative" polarization which again approaches 0 at 0°.

In the laboratory, the polarization versus phase-angle curve has been shown to be a combined function of opacity (composition), particle size, and surface structure. Within moderate limits, an empirical relation has been shown to exist between the slope of this polarization curve and the geometric albedo of a particulate surface. The negative polarization at small phase angles is characteristic of surfaces covered with some form of dusty semi-opaque soil.

Through computer modeling techniques a recent theoretical analysis of the way light is reflected and scattered from a particulate surface has allowed a better understanding of the physics and optics behind the observed polarization (see Wolff, 1975). This analysis showed that the polarization versus phase curve is the result of several factors, such as the complex refractive index of the particles (determined by composition and defining opacity), porosity of the soil, amount of shadowing, and particle size. For example, if the basic structure of the soil is known or assumed constant over a region, then the observed polarization curve is largely a function of the opacity of the particles and can be used as a measure of albedo within the limits defined by the model.

Instrument System

Systems using crystal or polaroid analyses and single detectors are in common use on ground-based telescopes. Spacecraft polarimeters have been flown as part of imaging experiments. Polaroid filters are inserted in the optical path to measure polarization.

MULTISPECTRAL MAPPING

Technique Description

The basic study of a planetary surface involves defining the boundaries and extent of surface units and characterizing them in terms of physical features, lithology or chemical composition. Multispectral mapping is an effective method for determining the spatial extent of geologic units on a planetary surface. Ground-based telescopic studies of the Moon have been carried out for more than 60 years, but spacecraft missions to objects other than the Earth have seldom included multispectral mapping experiments. Developments in two-dimensional detector technology and image processing techniques are stimulating activity in this field. Increased understanding of the optical properties of planetary surface materials is making multispectral maps more meaningful.

Multispectral mapping is defined here as not just the acquisition of images at several wavelengths but also the processing of images obtained through at least two different spectral bandpasses to produce a single image encoding color information. Physical processes causing color differences across planetary surfaces have recently become much better understood and color differences are becoming a dependable parameter for defining and characterizing geologic units. As discussed above, the reflected and emitted spectra of planetary surfaces contain absorption or emission features which are related to compositional properties. In some cases, the understanding of the surface-material optical properties has reached such a level that direct correlation of optical parameters can be made with compositional parameters. For example, the slope of the reflectance spectrum between 0.40 and 0.56 μm for mature lunar mare soil is directly correlated with TiO_2 content. Basaltic mare units can be distinguished based on titanium content. By mapping the spatial distribution of the slope of the reflectance spectrum using multispectral imaging techniques, a map of titanium content in the mare soil, and thus a map of some mare basalt geologic units, can be obtained. Other optical and compositional parameters are correlated, but this case illustrates the point.

The wavelengths at which a surface is imaged must be chosen with great care in order that the color maps bring out geologic and geochemical features and so that the color images can be interpreted in terms of known physical processes affecting the optical properties. Poorly chosen bandpasses lead to massive data reduction exercises and result in poor unit discrimination. The differences in color properties which signify compositional differences are often small (0.1-10%). The precision of measurement required to map the appropriate optical parameters in two dimensions has strained the available technology.

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DISCUSSION

MORRISON: Some remote sensing techniques are a lot more productive than others and a lot more likely to fly on a mission if we have one. Could you comment on which ones you think are more important?

McCORD: I would list reflectance spectroscopy and multispectral mapping as the main spacecraft techniques for optical remote sensing. I think mineralogy is an important property, and the distribution of units on the surface of a body is important for determining how that body evolved. Emission spectroscopy may turn out to be important as well. It is less well understood and has not been practiced nearly as much. There is a problem in that for the particle size distribution we find existing on the Moon, the emission features are essentially washed out. There are complementary features called Christiansen peaks which do show up. Very little laboratory work has been done on these. Finally, mapping the temperature of the surface is less interesting to me than determining composition

MATSON: Emission spectroscopy is sensitive to a different set of minerals than reflectance spectroscopy. Radiometry is more oriented toward texture and morphology of the surface.

McCORD: If you have a fairly rapidly spinning asteroid, radiometry will be sensitive to physical properties, like exposed rock versus regolith, rather than chemical properties.

MORRISON: Basically, the radiometry is sensitive on a distance scale of millimeters to centimeters, which you don't otherwise probe.

McCORD: Polarimetry is again oriented toward small-scale physical rather than chemical properties.

ARNOLD: This list has all the techniques which you and others have applied from the Earth. What can you learn about a body in general when you are close-up rather than through a telescope?

McCORD: There are two definitions of what close-up is. One is in orbit or in rendezvous at some distance. There one wants to take the geological approach of defining and characterizing units. With multispectral mapping, one would be defining the extent of units and with the spectroscopic techniques, one would be characterizing units in terms of mineralogy. If one knows the extent and characteristics of the units on the surface, presumably one could work out an evolutionary history using the approaches of classical geology. But I would like to go further and say these techniques can be applied *in situ*, the second case. If one had a lander, one would want to carry a reflectance and emittance spectrometer and analyze the material on the surface just as you do in the laboratory. These are very powerful laboratory techniques for mineralogical analysis.

ANDERS: How long would it take you to map an asteroid the size of Ceres if you had an instrument in orbit? Also, could you resolve a 1 km crater and characterize any exposed bedrock?

McCORD: The answer to the second question is a matter of resolution. One kilometer resolution from 1000 km is easy, and if you move closer and keep the focal lengths of your optics the same, you can get much higher resolution.

VEVERKA: If you are orbiting these objects, the orbital velocity is very low, and there are no severe problems with smear. Ten meter resolution is possible.

McCORD: That's right. So characterizing a 1 km crater would be easy. Now the first question was coverage and that depends on what kind of resolution you want. For the Lunar Polar Orbiter mission, we're talking about mapping with a single spot of about 1 km and doing the entire Moon surface in a year. A different instrument being built for the Galileo mission maps spatial elements simultaneously but with fewer spectral elements. Both instruments work at about the same speed.

MORRISON: The Moon is a factor of ten larger than Ceres in surface area, so for a typical 60 day rendezvous time, you could spectrally map all of Ceres at 1 km. Perhaps you'd want higher resolution for selected areas, too.

FANALE: It is within the capabilities of these instruments to do a very exciting experiment to give a detailed map of the distribution of the water and OH on the surface of these objects.

MORRISON: Could I ask one of you involved with the Galileo imaging to comment on the degree to which the CCD imaging system can accomplish the spectral mapping goals and relieve the pressure somewhat on the kinds of instruments McCord has discussed?

CHAPMAN: The CCD has a broader spectral coverage than other cameras that have been flown but not as broad as is needed for good mineralogy. We don't have a CCD camera that goes out to 5 μm.

VEVERKA: I think the other problem is that obviously you are likely to have a limited number of filters on a CCD camera. You do not have the ability to do the kind of spectral characterization we want.

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REMOTE GEOCHEMICAL SENSING OF ASTEROIDS

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The techniques of remote geochemical sensing are substantially the same for any planetary body without an atmosphere, or with an atmospheric column density of less than about 10^{-3} g/cm^2 surface. Thus the paper by Haines *et al.* (1976) provides a proper and current technical basis for the present subject. A few new points will be noted below after a quotation of the abstract from Haines *et al.* (1976).

> Two instruments, the gamma-ray spectrometer and the x-ray fluorescence spectrometer, are uniquely suited to the chemical mapping of planetary surfaces from orbit. Through their detection of characteristic line spectra they measure the concentrations of a suite of elements in each area overflown. Multi-element chemical maps derived from these remote measurements are used in the construction of evolutionary models of planetary bodies and of the solar system as a whole. The NaI(Tl) gamma-ray spectrometer and a gas proportional x-ray spectrometer were flown over 20% of the lunar surface during the Apollo 15 and 16 missions. These instruments measured chemical differences across the boundaries of known lunar provinces and revealed several new features of lunar-surface composition. Advanced spectrometers which are under development for future missions are able to educe much more information in a given time span than the Apollo instruments. They may be used in possible future missions such as Lunar Polar Orbiter, a Mars orbiter, a Mercury orbiter, outer planet satellite missions, rendezvous with asteroids and cometary nuclei, and surface-penetrating planetary probes.

In essence, using the gamma-ray and x-ray techniques together, all major elements, the radioactive elements Th, U, and K, and certain trace elements, especially H, can be analyzed with good sensitivity and reasonable accuracy. This is a sufficient data set for most (but not all) investigations in geochemistry and planetary evolution. For asteroids there are two possible mission modes.

The largest objects, of diameter hundreds of kilometers, appear to be at least rather closely spherical. Their gravitational acceleration is such that injection and maintenance in orbit seems practicable (to a chemist). It also seems worthwhile. Although there are as yet no positive indications of regional differences of composition, our knowledge of the Moon, and of the variations in visible and IR spectra among asteroids, suggests that this is likely.

The smaller asteroids, below some size limit, will not be so easy to orbit. Perhaps they will also be more homogeneous in composition. However, if they are fragments of larger bodies, they may allow us to sample a vertical profile of differentiation. This would be very exciting. Technically, the operations people will have to tell us how to "station-keep" around different parts of the surface, to get the necessary geochemical and geophysical data.

The current experimental technique for gamma-ray spectrometry follows closely that described in Haines *et al.* (1976). Abundances appropriate to less differentiated bodies--closer to or identical with chondritic patterns--would modify their Table 1, which is reproduced here, but yield no surprises. At greater distances from the Sun the cooling of the Ge detector becomes easier. The one new development is the demonstration by Haines and Metzger (1978), using Apollo gamma-ray data, that deconvolution of instrument areal response, to get closer to the true source map, can be made practical. If this can be done with these comparatively noisy, low-resolution data, we should be able to do much better in any future mission. Thus the limitation of areal resolution to a value close to the altitude of the spacecraft above the surface can be removed. Resolutions as good as one-third or one-fourth of the altitude may be attainable, for sharply contrasting chemical provinces.

Table 1. Calculated Lunar Sensitivity Limits with 80-cm^3 Germanium Detector at 100-km Altitude*

Element	Observing Time			Lunar Soil Types		
	1 hr 3σMDL	10 hr 3σMDL	100 hr 3σMDL	Highland (A-16)	KREEP (A-14)	Mare (A-11)
Th ppm	0.52	0.17	0.052	2.11	14.0	2.1
U ppm	0.12	0.039	0.012	0.58	4.0	0.55
K %	0.028	0.0087	0.0028	0.096	0.430	0.115
Fe %	2.2	0.70	0.22	4.0	8.0	12.3
Ti %	0.90	0.23	0.090	0.34	1.0	4.6
Si %	3.4	1.1	0.34	21.1	22.5	20.0
O %	6.5	2.1	0.65	45.0	44.2	41.6
Al %	5.5	1.8	0.55	14.4	9.2	7.10
Mg %	3.0	0.95	0.30	3.3	5.60	4.60
Ca %	20	6.2	2.0	11.2	7.60	8.60
C %	5.4	1.7	0.54	-	-	-
H %	0.75	0.24	0.075	0.0015	0.004	0.007
Na %	1.0	0.32	0.10	0.350	0.470	0.32
Mn %	1.8	0.56	0.18	0.054	0.100	0.1[illegible]
Ni %	1.2	0.38	0.12	0.045	0.040	0.024
Cr %	4.1	1.3	0.41	0.075	0.13	0.195
S %	7.3	2.3	0.73	0.060	0.10	0.10
Cl %	0.26	0.081	0.026	0.0012	0.010	0.003
Lu ppm	11	3.5	[illegible].1	0.5	3.2	1.6
Gd ppm	250	80	25	7	35	17

*Haines *et al.* (1976).

For x-ray spectrometry, proportional counters still appear best, although the other detectors mentioned have not been ruled out. An improved solar monitor, using a glass test panel of known composition, inserted periodically into the field-of-view, should markedly improve precision and ease of interpretation. The resolution element on the surface can be narrowed, as in the Apollo experiments, by passive shielding. The lower flux of solar x-rays found in the asteroid belt will slow up the gathering of statistics, but not in a troublesome way.

A critical fact about the gamma-ray system is that its sampling depth is on the order of tens of grams per cm^2, or tens of centimeters at low density. It is important to establish, if possible, the mean thickness of the regolith on target objects, and the fraction of "bare" area on this scale. There are plausible arguments that the smaller target objects, at least, should have regoliths thinner than this, and perhaps considerable areas with no visible covering. We cannot yet be certain.

It seems to be agreed at this meeting that multiple-target missions are to be preferred. This is certainly true from the geochemical point of view. It is also important that other observations require (or prefer) substantial stay times at each object. This is important for gamma-ray spectrometry--much less so for x-ray analysis.

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DISCUSSION

ECONOMOU: Can you describe the sensitivity and measurement accuracy of the gamma-ray technique for various elements?

ARNOLD: For all the major elements listed in Table 1 and for long stay times, the sensitivities are certainly better than 1% of that element--it differs from element to element depending on the detection limit. I think there will be an improvement in accuracy with the germanium system. If we normalize to an element like silicon or oxygen, the accuracy for the elements that are well-determined is certainly on the order of 5% relative or somewhat better. For asteroids that are irregular in shape, the geometrical corrections are difficult, so placing everything on an absolute basis may be a little tricky. But if we normalize to a major element and note that everything has to sum to 100%, then I think we can get an iron-to-silicon ratio and similar ratios to better than 5%.

ECONOMOU: Do you require ground truth to normalize your results?

ARNOLD: Well, ground truth is always very desirable. The normalization question has to be answered differently for radioactive elements than for the major elements. In the case of the radioactive elements the decay constants are very well known. Thus, one can just normalize them as closely as one pleases without ground truth. In the case of the other elements there are nuclear physical parameters, cross sections, which can be uncertain by 10-15% in the best measurements. I don't know if they will be determined better than that by the time this mission flies. In the case of the Moon we have applied ground truth factors in order to obtain more reliable analytical results. Why not use the Moon as ground truth because we have flown the Apollo mission? You can do that, but we used what is by present day standards a rather inferior instrument, so that correction might not be good enough. For some elements where you have both the x-ray and gamma-ray methods, you can compare one to the other. Were we lucky enough to get a gamma-ray spectrum from orbit and to have an alpha experiment on the ground, such a comparison, I think, would be fruitful for both. So the question of normalization does introduce some potential problems among the major elements. But I think these are the different ways of attacking it.

FANALE: The solar-induced x-ray flux is lower in the asteroid belt. Does this cause problems for the x-ray system?

ARNOLD: The counting limitations of the x-ray system are much less than those of the gamma-ray system. Both can use all the time we can get. I am terribly glad to have optical people say they want to be around for a long time, to take some of the pressure off of us. The unit of x-ray data which was processed on the Moon is e[illegible]

8 or 16 sec. Multiply that by nine, to account for the decrease in solar flux at 3 AU, and you still have plenty of time to collect the desired data. Having both gamma-ray and x-ray experiments is useful for cross-checking and for improving the aerial resolution by passive shielding of the x-ray detectors and for the possibility of comparing the mean composition over a 30 cm depth, to that over a fraction of a millimeter.

FANALE: Would you say something about carbon and hydrogen?

ARNOLD: A very good point. Because people are much more aware of the lunar work we've done, the sensitivity to carbon and hydrogen is perhaps not well known. The sensitivity to hydrogen is enormous for gamma-ray techniques, easily 0.1%. One sees hydrogen in two ways, as a neutron capture line, and it changes the neutron spectrum in a radical way. If you had 1% water of hydration, if you had a rock as wet as the typical crustal basalt or granite on the Earth, then you would have qualitative changes in the ratios and intensities of certain lines. This also extends the depth range. One is really looking down a couple of meters, because the neutron economy is the thing that determines it. We are about as sensitive to carbon as we are to most other elements. There is a 4.4 MeV line. I would say the sensitivity is a percent or a fraction of a percent. The amount of carbon found in the C1 or C2 meteorites would be no problem.

McCORD: This is a case where two techniques, the optical and the higher energy techniques, complement each other. Carbon and opaques, for example, are materials we have difficulty distinguishing optically. Measuring them like this we can very quickly eliminate ambiguities.

CHAPMAN: For the smaller irregular asteroids you are limited in your resolution to something like a tenth [illegible] radius simply by the necessity of being far enough away that you are not hit by a mountain. That resolution nevertheless seems good to me.

ARNOLD: For a larger object like Ceres or Vesta, we would certainly want to map from orbit. That is the way to get the ultimate aerial resolution and to work together with the other techniques. For the smaller ones, if you are doing station-keeping, I think you would want to concentrate on particular interesting features.

NIEHOFF: I would like to comment that the way in which one generates coverage, even though you are orbiting, is not in the traditional sense you think of for LPO, for example. The asteroids are spinning more rapidly than your orbit period, so you essentially peel them like an apple. The same thing happens at a smaller object [illegible] the stat keeping mode. That is, the object won't hold still for you unless you go into a synchronous orbit about it so you can do long duration observations of specific spots.

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SOME IMPORTANT IMAGING GOALS FOR ASTEROID MISSIONS

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This paper discusses five important objectives for any imaging experiment on a future asteroid mission, based on our current prejudices of what asteroids are like. These prejudices are based on extrapolations from other bodies whose surfaces have been studied at close range by spacecraft (most notably the Moon, and the two satellites of Mars) and on numerous indirect inferences. Imaging provides the most direct means of verifying whether actual asteroids conform to our current view of what they ought to be like.

INTRODUCTION

This paper outlines five major imaging objectives of any serious asteroid mission. They are:

1. Determination of volume, mass and mean density
2. Search for surface inhomogeneities
3. Characterization of asteroid regoliths
4. Comparative study of cratering mechanics
5. Characterization of non-crater surface morphology on objects of different compositional types.

Of these major objectives, the first two are of fundamental and crucial importance to our understanding of the nature of evolution of asteroids. The first is properly an imaging objective, since to determine an accurate mean density one needs not only the mass, but an accurate volume.

DETERMINATION OF MASS, VOLUME AND MEAN DENSITY

Probably the most important task of any asteroid mission is to determine the object's mass and volume. If both determinations are made accurately, to within $\pm 10\%$, a useful mean density $\bar{\rho}$ can be obtained. The obvious importance of $\bar{\rho}$ is that it tells us about the interior composition of the asteroid and appears to be the most direct means of remotely determining anything about asteroid interiors.

The Viking experience with Phobos and Deimos (Tolson *et al.*, 1978) as well as studies made by the Comet Halley Science Working Group (Belton, 1977) prove that it is feasible to obtain accurate masses and accurate volumes, even for very small bodies (radius $\gtrsim 1$ km). In the asteroid context it will be essential to image the asteroid at high resolution long enough on either side of encounter to be able to determine its shape and dimensions accurately. (As typical asteroid rotation periods are 6-8 hours, the above requirement should be easy to meet.) High resolution images will also be useful during a flyby for determining the distance of closest approach which is needed in order to determine the mass. Of course, the distance of closest approach can be determined even more accurately given an on-board radar.

Given an accurate value of $\bar{\rho}$, one has obtained some information on the possible bulk composition of the asteroid. As shown in Table 1, knowledge of $\bar{\rho}$ to $\pm 20\%$ or better is very useful for distinguishing differences in bulk compositions. Some of the important questions that can be answered once $\bar{\rho}$ is known are:

1. *How representative are asteroid surfaces of the interiors?* Surface compositions can be inferred from remote sensing; mean compositions from $\bar{\rho}$. What classes of asteroids have surfaces representative of the interiors? What classes of asteroids have differentiated interiors? For a given class this might be a function of asteroid size (radius). What is the critical radius?

2. *Are there large metallic cores among the asteroids?* Chapman (1974) suggested that certain large asteroids were stripped-down metallic cores of larger parent-bodies. Such bodies should have high mean densities. Knowing with certainty that 100-200 km metallic cores did form in the asteroid belt would be important information.

3. *Are there small, low density objects in the asteroid belt?* If some small asteroids ($1 \leq r \leq 10$ km) are present which are not fragments of much larger bodies, then it is conceivable that some may have very low densities ($\bar{\rho} \ll 2$ g/cm^3). For example, finding a $\bar{\rho} \sim 1$ g/cm^3 object would not only indicate that this is probably a primitive object but would provide information about the accretion mechanism of small bodies.

It should be noted that sophisticated measurements could yield data on the mass distribution within the object. It would be of interest, especially for small irregular asteroids, to see whether the mass distribution is homogeneous (*i.e.*, do the centers of figure and of mass coincide?). Large density inhomogeneities in the case of a small, irregular asteroid would indicate that it is a fragment of a larger, differentiated object, or that it is an accretional composite.

Table 1. Densities of Meteorites (after Wasson, 1974)

Meteorite Type	Density (g/cm^3)
Carbonaceous Chondrites	
CI	2.2 - 2.3
C[illegible]	2.6 - 2.9
[illegible]V, CO	3.3 - 3.6
Ordinary Chondrites	3.4 - 3.6
Enstatite Chondrites	3.5 - 3.8
Achondrites	3.1 - 3.4
Stony-Irons	~ 5
Irons	~ 7.9

SEARCH FOR SURFACE INHOMOGENEITIES

High resolution imaging is needed to look for evidence of variation in:

1. morphology
2. texture
3. composition
4. age

over the surface of an asteroid at various scales. Surface morphology can be characterized in terms of the types of surface features visible; differences in surface texture can be determined by photometry; differences in surface composition can be searched for by means of color measurements; differences in age can be found from crater counts.

Such variations could arise from internal activity. It is clearly very important to look for evidence of internal activity on the surfaces of 100-200 km asteroids and to study the style of this activity and determine the time of its occurrence. There is strong evidence that "lava flows" have occurred on the surface of Vesta (Drake and Consolmagno, 1977), but are the surfaces of smaller asteroids totally devoid of any traces of internal activity?

Surface variations could also arise from large cratering events and from spallation (*i.e.*, knocking away a significant fraction of an asteroid during a catastrophic impact). Current prejudice holds that in the case of large asteroids such severe impacts were common only during the first 1 billion years or so of the solar system's history. Thus, we shouldn't expect to see any evidence of "recent" large-scale impacts on the surfaces of asteroids, but this is still worth checking into.

Variations in surface composition could also be evidence for fragmentation from a large parent body. For example it would be of great interest to definitely establish that some 50 km asteroid was once a fragment of a much larger parent body.

CHARACTERIZATION OF ASTEROID REGOLITHS

Our present understanding of how regoliths are generated and maintained on small bodies is very poor. There is good evidence that asteroids as small as 1 km in radius have some sort of regoliths, while the two satellites of Mars are known to have well-developed regoliths even though the objects are only some 10-20 km across (*e.g.*, Veverka, 1978). The ability of a body to retain a regolith should be primarily a function of surface gravity and hence of the body's size. However, laboratory experiments suggest that the nature of the surface may also play an important role in the evolution of regoliths (*e.g.*, Chapman, 1978). Thus, an important advance in our understanding of regoliths would occur if we could compare the surface characteristics of:

1. Two asteroids of similar composition but of vastly different size. For example, two S objects, one with a radius of 5 km, the other with a radius of 50 km;

2. At least two asteroids of comparable size (actually similar g) but of widely different composition. For example, a C object and an M object; or a C object and an S object.

The only small objects for which we have direct information about the surfaces are the two satellites of Mars. However, it has been argued that the surfaces of these two bodies may not be representative of those asteroids of similar size since Phobos and Deimos are in the potential well of Mars. Soter (1972) has argued that this circumstance helps the two martian satellites recapture a significant fraction of the ejecta thrown off their surfaces by impacts. The investigation of a single 20 km C asteroid would resolve this issue once and for all. A second-order investigation which would help our understanding of how regoliths are retained on small bodies would consist of comparing the surface properties of two asteroids of similar size and composition, one of which is nearly spherical and has a long rotation period, while the other is irregular and has a short rotation period.

A first order characterization of regolith properties can be obtained by means of photometry and high resolution images. Photometry will give information on the texture of the surface and on the lateral homogeneity of the regolith. High resolution images should reveal the presence or absence of ejecta blocks, filling-in of impact craters, and possible near-surface layering exposed in crater walls. From the morphology of small craters one should be able to determine the regolith thickness as was done in the lunar context by Quaide and Overbeck (1968).

COMPARATIVE STUDY OF CRATERING MECHANICS

The mechanics of high velocity impact cratering are not perfectly understood. It appears that gravity effects have a dominant influence on crater morphology (given a certain impact energy) but mechanical characteristics of the target material are also important. Hartmann (1972) has proposed a gravity dependent crater morphology sequence in which crater morphology scales essentially as g^{-1}. Thus, for example, Hartmann proposes that central peaks will occur in craters 10 times smaller on a body whose g = 100 cm/sec^2 than on the surface of one whose g = 10 cm/sec^2. Other gravity effects have been discussed by Gault *et al.* (1975) in the case of Mercury and the Moon: for example, semicontinuous ejecta blankets should occur closer to the crater rim if g is high. Comparative studies of the crater morphology on different asteroids provide a unique means of testing such gravity scaling ideas, as well as the possible importance of the mechanical properties of the target material.

Ideally, one would like to compare the morphology of craters (depth/diameter ratio, diameter at which central peaks occur, extent of ejecta blankets, height of crater ramparts, the occurrence and extent of ray systems) on:

a. asteroids of similar surface g, but very different surface composition (*e.g.*, a C object and an M object);

b. asteroids of similar composition (*e.g.*, two S objects) but with very different g's (*e.g.*, 20 cm/sec^2, and 2 cm/sec^2).

Such experiments, especially when compared with previous results on the larger planets and on Phobos and Deimos would provide a crucial test of our understanding of impact cratering.

CHARACTERIZATION OF NON-CRATER SURFACE FEATURES ON OBJECTS OF DIFFERENT COMPOSITIONS

Interesting non-crater surface features almost certainly occur on the surfaces of some asteroids, and contain important information about the evolutionary history of these objects. Three possible examples are:

1. *Lava flows on objects with achondritic surfaces.* The style, extent and age of such flows are of great interest, as is any evidence of the possible flooding of large craters.

2. *Groove patterns associated with large craters on small C objects.* It has been suggested that patterns of grooves similar to those found on Phobos may be common on the surfaces of many small, mechanically weak asteroids (Veverka *et al.*, 1977). Any evidence of internal modification of such grooves would be of great interest.

3. *Unusual surface features on M objects?* In view of the malleability and high tensile strength of nickel-iron, one might expect some unusual morphology on the surfaces of M objects, if they are truly metallic.

CONCLUSIONS

The above list of imaging objectives is seriously limited by our lack of knowledge of what asteroid surfaces are like. It is true that one can extrapolate to some extent from past experience with the Moon and especially with Phobos and Deimos, and one can even bolster these guesses by intelligent theoretical reasoning. Nevertheless, it is this author's opinion that no one is clever enough to imagine what the surface of any particular asteroid is really like. The only way we will ever find out is if we send our instruments there and look.

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DISCUSSION

MATSON: Is measurement of density the only way to get internal structure?

VEVERKA: Density is the only practical way I see in the next 20 years. It is much more difficult to do a seismic experiment. You have to land a seismic net. I don't believe we can do that now.

FANALE: You made a very optimistic statement that we would find out something about zonal structure from tracking.

VEVERKA: It is a difficult thing to do and depends, in part, on being lucky.

MORRISON: Could you put the mass determination in a little better perspective for me? For objects the size of Ceres and Vesta, it is quite easy to determine mass by going into orbit. But for a kilometer-size comet nucleus, it is hard. Where does the crossover take place and how do you go about making accurate measurements for small bodies?

VEVERKA: My impression is that for all rendezvous missions mass determination is a relatively trivial matter. Nor am I suggesting that in the case of Ceres it will be difficult to determine the volume. Most of what I have been saying about the need to measure volume accurately really applies to the smaller main belt asteroids where it is difficult to determine the volume because of their irregular shapes.

ANDERS: Could you distinguish complex accretionary structures from those produced by later, very large-scale brecciation events caused by inter asteroid collisions?

CHAPMAN: There is a big difference in the velocity regime at which the impact has taken place. During accretion the velocity must have been much smaller.

SHOEMAKER: In the context of this meeting, I don't know anything that we could learn about accretionary structures with the optical resolutions that have been discussed here. I am convinced that if you could really investigate a small body with the same techniques used in manned lunar missions, it would be extraordinarily interesting. Many questions could be addressed. You could take a proper sample and images with a wide range of scales which would enable us to address the question of accretionary structures. Right now I can't give you any of the definitive criteria, but I have a hunch that interesting structures at the scales of tens of centimeters, meters, and tens of meters are there to be found.

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EXPERIMENTS ON ASTEROIDS USING HARD LANDERS

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The possibility and desirability of science on hard lander missions to asteroids are examined using the Westphal Penetrator Study as a basis. Imagery and chemical information appear to be the most significant science to be obtained. The latter, particularly a detailed chemical analysis performed on an uncontaminated sample, may be necessary to unequivocally answer questions about the relationships of asteroids to meteorites and the place of asteroids in theories of the formation of the solar system.

INTRODUCTION

A few philosophical comments are perhaps pertinent relative to the general subject of this workshop: the study of asteroids. There is a frame of thinking about all uninvestigated objects of the solar system that relates them to the meteorites that we have available for intensive study in our laboratories. This is certainly a practical zero order framework--meteorites do represent a rather diverse set of objects, and, as previous papers have shown, optical observations provide correlations that allow classification of asteroids into types that might correspond to the meteorites we have in the laboratory.

On the other hand, it may be recalled that none of the three solar system objects that we have investigated intensively--the Earth, Moon, and Mars--have turned out to be simply related to any meteorite class. This, in spite of speculations about the Moon and Mars, previous to their intensive investigations, that tended to follow the same pathways as the present discussions about asteroids.

Thus, without minimizing the meteorite framework of thinking about asteroids, let us keep our minds open for the types of surprises that were uncovered in the investigations of the Moon and Mars.

Similarly, a more detailed framework of thinking about the solar system is built about the idea of volatility, or inversely, condensation. Whether or not this turns out to be fundamental, it is useful in focusing attention on the concentrations of a few key elements. At the same time, here too, we should not restrict ourselves at this stage to analyzing just for these magic key elements, or we run the danger of missing the important new knowledge that the study of new objects may provide.

A second general point, with specific relevance to the topic of this paper, is the role of hard landers in the study of an extraterrestrial object. A general classification of investigations of such objects might be ordered as in Table 1.

Table 1. Classification of Extraterrestrial Object Investigations

1. Earth-based Studies
2. Studies from Near-Earth Orbit
3. Flybys
4. Object Orbiters
5. Hard Landers
6. Soft Landers
7. Sample Return

In this list, there is some experience relative to each of these modes of exploration except for Number 5. Thus, the topic of this paper has less concrete data to support it than many others in this workshop. The authors have knowledge of only one intensive study of th possibility of doing science on hard landers, namely the *Final Report and Recommendations of the Ad Hoc Surface Penetration Science Committee* (Westphal, 1976), which was directed mainly towards Mars exploration.

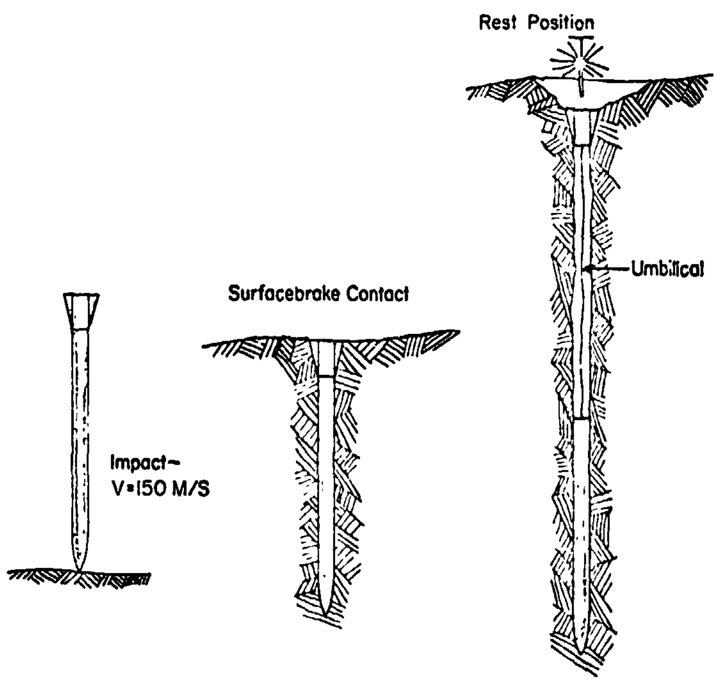

Fig. 1. Sequence for penetrator emplantation.

In addition, there have been less extensive studies of other hard lander types of missions; we will base our remarks on the possibilities of science using penetrators--objects that are dropped from an orbiting or flyby type of vehicle, which have sufficient braking power to reduce their impact velocity to about 0.1-0.2 km/sec. The penetrators typically will consist of two parts--a forebody which is a torpedo-type object which penetrates and comes to rest 1-10 m below the surface and which contains most of the science payload, and an afterbody which remains on the surface, provides communication with the mother vehicle (or Earth), and has minimal science (Manning, 1977) (see Figure 1).

The figure shows a schematic mission sequence considered by the Westphal Committee for a Mars Penetrator. Table 2 (again from the Westphal report) shows nominal Mars Penetrator characteristics. Note the small science payload--7 kg--that presumably will always be characteristic of such hard landers.

Table 2. Nominal Mars Penetrator Characteristics[a]

Complete Penetrator	
Weight	31 kg
Principal Diameter	9 cm
Frontal Area	64 cm^2
Sectional Density	0.5 kg/cm^2
Length	140 cm
Payload[b]	
Weight	7 kg
Volume	4500 cm^3
Power Output (RTG)	0.3 watt
Battery Supplement	1.0 watt hr/day
Data Storage	2×10^5 bits
Forebody Probe	
Weight	28 kg
Principal Diameter	9 cm
Frontal Area	64 cm^2
Sectional Density	0.5 kg/cm^2
Length	123 cm
Detachable Afterbody	
Weight	3 kg
Principal Diameter	23 cm
Frontal Area	350 cm^2
Sectional Density	0.01 kg/cm^2
Length	28 cm

[a]From Final Report and Recommendations of the Ad Hoc Surface Penetrator Science Committee (J.A. Westphal, Chairman, August 1976).
[b]Includes science and supporting electronics.

Obviously, for asteroid missions, some of the characteristics designed for a martian mission would have to be modified (a very obvious example is a replacement for the parachute braking in the case of an atmosphereless asteroid body). The figure and tables are given to provide some general framework for talking about hard landing missions to asteroids. It will be assumed that the type of science that was considered by the Westphal Committee for a Penetration Mission to Mars is representative of the type of science that could be done on a hard landing mission to an asteroid.

One more comment about penetrators as a specific type of hard lander; one of their characteristics is that they examine material that is some distance (1-10 m) below the surface. This has special science implications and is in contrast to the type of information obtained by optical and x-ray techniques, either from Earth or on flyby or orbital missions. The topmost surface of an extraterrestrial object *may* be modified so as to be significantly different from that of the material deeper down. This modification may be due to interaction with the atmosphere or with interplanetary radiations or particles, and may produce both physical and chemical effects. An example is the permafrost expected by many to be present below the surface of Mars, whereas the surface examined by Viking was very dry. Penetrators are especially suited for detecting such effects.

A final general comment might be made about the appropriateness of hard landers in the study of asteroids. An important characteristic that has been established about asteroids is that there are several significantly different types, as judged by the observational techniques available so far (McCord, 1978; Morrison, 1978). Thus, asteroid missions in the foreseeable future are typically thought of as involving investigation of several asteroids--three, four, or more--on the same mission. Since such a mission may very well involve a flyby or relatively short-term encounter with each asteroid, there is a premium on the type of science that can be performed on several asteroids. The emplantation of one or more penetrators on each asteroid as the mother vehicle passes by is an attractive feature of a mission carrying penetrators. It could provide much more information than could be obtained by remote sensing; also, it would not have the weight requirements of landing a Surveyor or Viking type spacecraft on each asteroid.

Before going into the science possibilities, the authors must make the obvious cautionary statement: the only practical and engineering aspects that have been considered are the assumptions that the Westphal Penetrator study--directed toward Mars--represents a zero-th order approximation for the capability of a hard landing science mission to asteroids.

POSSIBLE HARD LANDER SCIENCE

In considering the possible scientific results that might be achieved by a penetrator on an asteroid, this paper starts from the results of the Westphal Committee. Table 3 lists (with a little adaptation) the types of measurements that are considered practical on such a mission.

Table 3. Possible Asteroid Hard Lander Science (after Westphal, 1976)

Probe Forebody	Detachable Afterbody
Seismicity	Imagery
Chemical Composition	Near-Space Environment
Hydrogen/Water Measurements	Magnetic Properties
Heat Flow	

The Westphal Committee considered it practical to have some imaging capabilities on the afterbody, even though the acceleration experienced would be appreciably greater than on the penetrator forebody itself. The height from which pictures could be obtained would be small, but the scientific information would be significant. It would bear not only on the processes occurring on the asteroid surface (*e.g.*, cratering, presence or absence of a regolith) but also could affect the interpretation of remote sensing measurements such as radar reflectivity.

Measurements could also be made in the afterbody on the near-space environment of the asteroid. For example, the steady-state presence of gases and ions could provide information on the degassing of the object even if no, or minimal, mass analyses were involved. Similarly, the presence of magnetic material on the surface of the asteroid could be established (to the level performed by Surveyor or Viking) using primitive imaging capabilities.

The deceleration profile on the forebody probe of a penetrator as it came to rest in the subsurface material should be a very sensitive distinguishing indicator between the different classes of meteorites that are proposed as models for asteroids (pallasites, ordinary chondrites and carbonaceous chondrites). In fact, planning for the complete range of mechanical properties represented by such models may represent a significant constraint on a mission planning to go to different asteroids.

The emplantation of a seismometer by penetrators has, in the past, been a prime reason for advocating such missions to terrestrial type bodies. The usefulness of seismometers on asteroids is not so obvious. The very low seismicity of the Moon, and the paucity (if any) of results from Viking on Mars, make dim the prospects for signals from an instrument on an asteroid. Before dismissing such measurements completely, however, more complete analysis should be made of the possibility that seismic signals on an asteroid would be enhanced due to, for example, an increased frequency of impacts by nearby massive objects. Also, the engineering possibilities of obtaining significant seismic information by setting off explosive charges on an asteroid after seismometer emplantation should be examined (Wood, personal communication, 1978).

Perhaps the most significant scientific result that could come from a penetrator-type mission to an asteroid would be the more complete chemical characterization than can be deduced from either Earth-based, Earth-orbit or flyby observations. As indicated in the introduction, such remote observations provide the first gross classification of an object from information either about the most abundant minerals or about some specific chemical elements that are identified (Haines *et al.*, 1976). The experience on the Moon and Mars has shown that a complete chemical analysis provides surprises and details not obtainable by such remote sensing devices. Of course, the ultimate technique--sample return--can be expected to be even more productive, especially as regards chronological and other isotopic information.

Because of the potential of this chemical approach, it is worth focusing on some practical details as well as on some detailed results that might be expected.

Table 4 summarizes the techniques that have been considered for a penetrator-type mission for studying the chemical composition and chemical state of the material around an emplaced penetrator. In all four cases, there is some evidence that the hardware involved can survive the decelerations involved in emplantation. The first two techniques measure the bulk properties of the material surrounding the penetrator. The last two require the acquisition of a sample. Because the emplantation process modifies somewhat both the physical and chemical state of the material just outside the penetrator, a drill, or other means of obtaining an unaltered sample, is needed. Some work has been done indicating that such a sample acquisition system is practical. In the case of hard landers other than penetrators, this uncontaminated sample acquisition may be even simpler to accomplish.

The *in situ* gamma-ray measurements, if possible, are among the simplest that might be performed on a penetrator (Metzger and Parker, 1976). The presence of a nearby RTG source of neutrons and gamma-rays can be either a hazard or a benefit. In the cleanest experiment of this type, data would be obtained on the potassium and radioactive heavy element concentrations of the nearby material. The results should allow a discrimination at least between the pallasite and chondrite models of the asteroids. More generally,

Table 4. Possible Techniques for Studying Chemical State and Composition on Penetrator Missions to Asteroids

1. *In situ* Gamma-Ray Measurements

   a. "Natural" Radioactivity of Surroundings (K, Th, U)

   b. Nuclear Processes Induced by Cosmic-Rays or RTG Neutrons (*e.g.*, O, Si, Fe, H)

2. Thermal Neutron Measurements

   (Sensitive to H)

3. Chemical Analyses of Procured Sample

   (All principal chemical elements except H; selected minor and trace elements.)

4. Analyses of State of Water in Procured Sample

   ("Free-water," absorbed water, water of hydration, chemically bound water)

they would provide data on the concentration of a relatively volatile element, potassium, and of the refractory elements, uranium and thorium. In addition, the data would bear on the radioactive heat production in the asteroid.

If the gamma-ray measurement could be extended to include, *e.g.*, Si, Fe and H (making use of the neutrons from the RTGs or cosmic-rays), the discrimination between candidate meteorite classes would be complete. Again, in somewhat more basic terms, the characterization of the asteroid in terms of its position in a condensation type scenario of the formation of the solar system bodies would be clarified.

Another measurement that could provide data on the bulk properties of the matter surrounding the emplanted penetrator is that of the thermal neutrons present. The RTG power sources currently considered for penetrators produce some 10^5 neutrons per second. This is the range of intensity that has been used in terrestrial applications of hydrogen determination by neutron moderation techniques (*e.g.*, Long and French, 1967). It is expected that this technique could determine hydrogen with a sensitivity of 0.05% by weight (water content down to 0.5% by weight) although, of course, it would not distinguish between hydrogen in the form of water and that in the form of carbon compounds. Both forms would be indications of carbonaceous chondrite material, or more basically, of the presence of very volatile constituents in the body. In terms of possible eventual uses of asteroids for self-sufficient extraterrestrial activities, the availability of hydrogen is an extremely important resource.

More complete chemical characterization of a sample on a hard lander mission depends on the acquisition of an uncontaminated sample. As mentioned above, this does not appear to be an impossible objective, particularly for a body that is not appreciably harder than a basaltic rock. Miniature hardened instruments appear to be available to perform rather complete chemical analyses of such a sample. A currently considered instrument would use an alpha particle technique for the light chemical elements and x-ray detection for the heavier elements.

Table 5. Chemical Analyses on Hard Lander Missions to Asteroids

(Expected accuracies (at 90% confidence limit) in weight percent for principal chemical elements[a])

Element	α + p + x-ray Modes
C	± 0.2
O	± 0.7
Na	± 0.2
Mg	± 0.8
Al	± 0.4
Si	± 1.2
K	± 0.2
Ca	± 0.2
Ti	± 0.15
Fe	± 0.4

[a]From Economou and Turkevich, 1976.

Table 5 gives the presently considered achievable accuracies of such analyses for the principal chemical elements (Economou and Turkevich, 1976). The accuracies are such that (especially if a separate hydrogen determination is made), more than 99% of atoms in the sample will be identified and determined, a reasonable normative mineral composition can be deduced, as well as the state of oxidation of the system.

Thus, the material examined would be characterized considerably beyond the meteorite classification and even beyond that achieved on the Surveyor missions to the Moon, certainly beyond that achieved on Viking. The establishment of the major constituents would permit more soundly based interpretations of the abundances of the minor and trace elements.

Table 6 gives examples of the sensitivity considered achievable by present day instruments for minor elements (Economou and Turkevich, 1976). These sensitivities depend somewhat on the state-of-the-art of semiconductor x-ray detectors which is continually improving. Better sensitivities may well be achieved by the time an actual asteroid mission is undertaken. Even the present sensitivities provide examples of chemical elements (*e.g.*, C, K, Ti, Zr), whose abundances are used to characterize condensation conditions at the time of formation of solar system bodies.

In conclusion, it is likely that remote sensing measurements will not answer definitively very important questions about the nature of asteroids, their history and relationship to other bodies of the solar system. *In situ* chemical analyses are probably required to establish conclusively the relationships of asteroids to the meteorites with which they are frequently compared. Such analyses will also be needed to place asteroids in the condensation scenario often invoked for the history of the solar system. It is by such more complete chemical analyses that the spectral characteristics of the Moon and Mars have been established and it should therefore be a good bet that asteroids will likewise provide new and intriguing data.

Even such *in situ* measurements, however, are not likely to provide the isotopic data needed to establish the chronology of asteroid formation and of their exposure to the space environment. Nor will it be possible to place them in the hierarchy of oxygen isotope anomaly systematics that is emerging for solar system bodies. For such data, returned samples appear to be required.

Table 6. Chemical Analyses on Hard Lander Missions to Asteroids--Examples of Expected $\alpha + p +$ x-ray Sensitivities for Minor Elements, Evaluated for a Basalt Matrix Using Alpha and Auxiliary Sources[a]

Element	Sensitivity (Weight %)	Element	Sensitivity (Weight %)
H[b]	0.03	Rb	0.001
N	0.2	Sr	0.001
F	0.05	Y	0.0005
P	0.2	Zr	0.0005
S	0.1	Ba	0.001
Cl	0.1	La	0.001
K[c]	0.07	Ce	0.0008
V	0.03	Nd	0.0008
Cr	0.02	Sm	0.0005
Mn	0.03	Pb	0.005
Ni	0.02	Th	0.005
Cu	0.02	U	0.005
Zn	0.02		

[a]From Economou and Turkevich, 1976.

[b]Using thermal neutron detection techniques.

[c]Sensitivity for K expected in the presence of a few weight % of Ca.

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DISCUSSION

ARNOLD: A comment on the list of penetrator instruments. This paper reinforces my impression that the combined alpha instrument is best for penetrator use. There is a potential instrument being developed by Trombka using a pulsed neutron source which I think can make the gamma-ray experiment more attractive than the simple gamma-ray experiment described here. The biggest disadvantage of this gamma-ray experiment is that you can't use a germanium crystal because temperatures are too high (about 150°K).

ANDERS: It seems to me the gamma-ray and alpha-ray instruments are complementary. Gamma-ray spectrometry from orbit does a superb job for uranium, thorium and potassium and gets regional averages. Then the alpha instrument in turn goes below the regolith, and also does considerably better on elements such as calcium.

ARNOLD: I agree if you put the germanium in orbit and the alpha spectrometer down below you would indeed have the best of both worlds. We were really discussing the tradeoff in the penetrator. I think it would be fantastic if you could put both instruments in the penetrator.

NIEHOFF: How about an x-ray diffractometer? There was a Viking proposal for a small device of this type. If mineralogy is that much more important than elemental abundances, then some instrument of this type should be looked at.

FANALE: Mineralogy is in many ways more important because you can take the same mass balance and put it, as nature has, in a thousand different crucibles and produce a variety of mineralogies. We might be better off spending our money doing a mineralogical experiment that is designed to look at the bland materials you find in carbonaceous chondrites and which give no x-ray lines on a laboratory diffractometer. So I think you ought to think seriously about that.

ECONOMOU: There are at least two groups working on diffractometers. Detectors are a problem; they must have good resolution and must survive penetrator emplacement.

ANDERS: Under ideal conditions in the laboratory a diffractometer can identify adequately the two or three most abundant minerals in typical mixtures such as are found in nature. It cannot cope well with the less abundant minerals in such a mixture unless they are first enriched by a separation. It probably cannot cope well with regolith-type material, containing glasses, amorphous materials, and clay minerals that do not give diffraction patterns. I think it would be a complete waste of effort to send such an instrument to an asteroid.

McCORD: Is there a problem getting enough velocity to emplace the penetrator?

NIEHOFF: No, it turns out the same tube from which a penetrator was launched at Mars to make it deorbit provides enough energy for you to get an impact on an asteroid. So it is a fortuitous complementary design. The one system difference is the need for a device to maintain the attitude from the time of launch until impact and that weighs on the order of 10 kg.

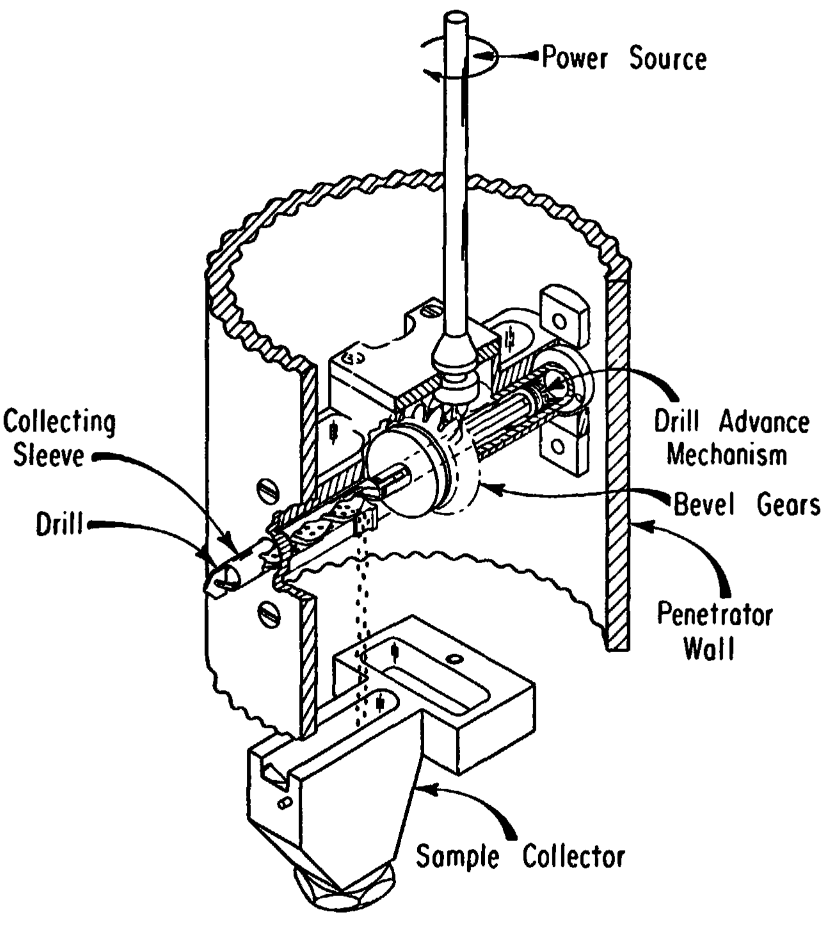
McCORD: If a penetrator impacts one of these unconsolidated objects, will it go too deep and rip the umbilical cord?

NIEHOFF: Yes, it could. There are design alternatives which could alleviate this problem.

SHOEMAKER: How does the alpha scattering instrument look at the soil or rock?

ECONOMOU: The material adjacent to the penetrator is modified by the impact, so to get a sample we must penetrate this boundary layer which is a few millimeters thick. We have a working prototype of a device that goes into the soil and brings a sample back to our instruments. (See figure below from a report by Turkevich, A. L., Economou, T. E., and Franzgrote, E. J. (1977). Adaptation of the alpha particle instrument for penetrator mission. In *Reports of Planetary Geology Program, 1976-1977*. NASA TMX-3511, p. 258.)

PREPROTOTYPE
SAMPLE ACQUISITION SYSTEM
FOR A PENETRATOR



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GENERAL DISCUSSION ON SESSION IV

MORRISON: The final general discussion should focus on mission options and instruments. I'd like to begin with the question of the role of sample return.

SHOEMAKER: We know how difficult it is to land on a planet. It is much easier on the asteroids. We are talking about rendezvous with and orbiting many of these objects. On the smaller asteroids, the additional energy to go down on the surface with a soft landing is trivial. It is not inconceivable to think about landing and retrieving samples in early missions.

NIEHOFF: I think the big problem there is not the energy of doing it, but our technological readiness. We must be careful not to oversubscribe our ability to support instrumentation for both orbital and surface science.

SHOEMAKER: I couldn't agree with you more. We should not try to do the optimum package of all the mapping functions as well as sample return in the same mission. We might conceive of two rather different missions, one a multiple asteroid rendezvous mission, and one a multiple asteroid sample return mission.

FANALE: I agree with the interest in the sample return and what I said in my paper is that it is a great thing to do, providing you can develop a concept for a multiple sample return without sacrificing the major principle of long stay times and visiting a variety of carefully selected objects.

CHAPMAN: It seems to me that sample return is not justifiable for a first asteroid mission. If we limit outselves to what we can do from the Earth, and thinking about meteorites and so on, we would not approach the knowledge necessary to intelligently select a sample. We probably don't know enough even to plan for a mission to successfully return a sample. So I think any discussion of sample return really ought to be in the context of some subsequent mission.

McCORD: I would agree with that, unless sample return were easy to do and unless the public appeal that would be derived from it is necessary to carry the mission. I don't think either of these conditions applies.

WOOD: I think to start with a sample return mission could be embarrassing. It could, as Anders has said, get us a sample exactly like something we have in a museum. This may be exciting to us, but it isn't going to appear very cost-effective to the public.

SHOEMAKER: I would like to take issue with the idea that bringing back a familiar rock would be a terrible embarrassment. In fact, I would consider it a crowning achievement, if we could identify the source of objects that have fallen on the Earth. Suddenly we would be able to relate, unequivocally, two disparate bodies of knowledge, and the sum of those two is much larger than the parts. But I think, frankly, our chance of achieving that is small.

ANDERS: It seems that to some extent the sample return and *in situ* measurements are mutually exclusive in terms of money, payload, etc. Perhaps our first priority should be to design a well thought out mission without sample return, which maximizes significant measurements that are likely to give interesting results. To forego this in favor of sample return at an early stage would be a mistake.

WETHERILL: I agree, but I also feel we should find out what the problems of eventual sample return really are. We must find out what is needed to know to do sample return at a later time, otherwise we are always going to have this hurdle to get over.

NIEHOFF: That is a good point. In evaluating and establishing the science goals of a rendezvous mission, we should consider information needed to plan subsequent missions. The things you do for science in most cases support what you want from an engineering standpoint. There may be a few extra things you may want to consider as the payload is selected. For example, how do I fasten myself to a low-gravity body where there is a large amount of regolith, especially if I want to take a core sample?

MORRISON: We have emphasized the necessity for sampling multiple objects because of the heterogeneity of the asteroids. The conclusion I would draw from what you are saying is that sample return as a first mission is almost automatically precluded. A sample return mission is more complex than a rendezvous, and sending five sample returns costs more than sending one spacecraft that orbits five asteroids sequentially. To shift the subject somewhat, I would like to ask how we feel about penetrators or hard landers on a first asteroid mission?

VEVERKA: Can someone tell me what the tradeoffs are? We've seen a number of missions which included rendezvous with a number of asteroids. When we include penetrators, what do we give up for each penetrator?

NIEHOFF: For the five-target example I showed, you had enough margin that you could carry penetrators to each target and not lose anything. Each penetrator was 75 kg. There is another problem, though, namely the cost tradeoff. Roughly, the cost of five targets without penetrators is comparable to two targets with penetrators. But let me put the cost numbers in the proper context. There is a large cost for the first penetrator ever built, and that cost is included in these values. This is the general problem with penetrators. If we can keep the engineering aspects of the design constant, the repetitive cost, once the first one is made, might be as low as $5 million. NASA is still funding penetrator studies. Primary interest is in a seismology and meteorology network on Mars.

WOOD: It seems to me that the requirements for penetrators vary widely from one application to another, and I wonder if you are not compromising some other things rather badly by insisting on using one standard model for all planets and applications?

NIEHOFF: Briefly, what comes out of the design analysis is the fact that nobody can give us a very detailed model of any surface we are going to impact. Is it some kind of regolith, a vesicular basalt, or some kind of slushy ice? We have to design a penetrator to accommodate a wide uncertainty in what we are going to impact.

WOOD: It seems to me one thing that we could do with an asteroid which would really represent an advance in our knowledge over what we know about meteorites, would be a precise determination of the internal structure of one asteroid. When I say precise, I mean a good deal more precise and less ambiguous than you would get by the means discussed so far. I would not reject seismology as out-of-hand and would like to propose such an experiment with penetrators. I have the impression that penetrators are considered difficult, impractical and unpopular for several reasons. One difficulty is that if it is designed for the exploration of Mars, the penetrator requires considerable deceleration before it impacts the surface. Another is that it was designed to land under any circumstances, including the penetration of hard rock. And the third is that as soon as penetrators were named as a possible mode of planetary exploration, everybody raced to include their instrument on the package. Penetrators would be easier to use in the case of a small asteroid because you wouldn't have to decelerate it in the first place, indeed you would have to accelerate it with a small reaction engine. Secondly, you ought to be able to choose a decent place where you would have some confidence it would go into a regolith rather than hard rock. In the third place, you could exercise some discipline to keep the penetrator very simple; indeed it could contain nothing but a seismometer, the most practical thing to have on a penetrator. It seems to me that without making the mission ridiculously expensive, you could place seismometers in at least three different positions all around the surface of an asteroid, and you could also hit it several times with active charges. Unlike the Moon or Mars, an active charge would be able to send shock waves entirely through a small asteroid. In principle one could define the entire internal structure of it, determine the seismic velocities of the various units, and thereby learn some very important things from such an experiment that you could not get in any other way. This might actually be a practical option as long as you kept it simple and didn't start putting every experiment on Earth into the penetrator.

MATSON: I agree with you. Even one seismometer and one charge on a small asteroid would give the velocity for the direct ray.

ANDERS: What kind of asteroid would you pick? One whose surface shows evidence of differentiation or one that is big and apparently has a compositionally primitive surface?

WOOD: That would require more thought. I think I would prefer one that is obviously layered, like Vesta, that you expect to be layered. Something as big as Ceres would preclude the use of active sources to define the structure of the whole thing.

VEVERKA: Wood is very interested in going to a small object and small objects tend to be irregular. How can you be sure without an elaborate imaging system on your penetrator that you are indeed going to be able to penetrate wherever you like? Is that a problem?

NIEHOFF: It depends on how close you can get before you launch the penetrator. We did a little bit of work on that about two years ago and it seems to me there was no problem. You definitely have to come close, but with rendezvous that is perfectly possible.

WOOD: It is my impression that a lot of the weight and a certain amount of the expense of a penetrator goes into a highly ruggedized device that is designed to penetrate hard rock for great distances at high speeds, and I really don't see the need for this on a regolith-covered asteroid.

NIEHOFF: The high velocity is used to be sure you don't bounce back out again. As the surface gets harder, that possibility becomes greater. If you bounce back, your systems won't be able to collect and send data. So a high impact speed is a necessity and really has nothing to do with the surface gravity of the object.

FANALE: Let me be the devil's advocate. The penetrator alters the environment making it difficult to obtain a proper sample and its payload is small. There is an alternate which is the hard lander. It is something like 80 kg total with 12 kg of science instead of 7 kg and it is much easier to deploy on the surface. The disadvantage is you have to couple it to the ground and we have not explored the possibility of coupling it reasonably with some kind of explosive device.

NIEHOFF: An interesting hybrid of the two systems would contain the probe part of the penetrator for attachment and some kind of a surface package for actually performing the science, which gives you some relief in volume and power requirements.

MORRISON: It appears clear that there is substantial interest in penetrators or rough landers for the asteroids, but that we do not have enough information to understand the costs or the tradeoffs that may be necessary to include them in a first mission. So let me change the subject again to Earth-approaching asteroids. Can Jim Arnold briefly summarize the results of his Summer Workshop for Near-Earth Resources? What was the final recommendation of that group regarding asteroid missions?

ARNOLD: The bottom line was that an early program of missions to promising near-Earth asteroids should be undertaken. The view of the group was that if practical utilization of asteroid resources was possible, it would be from the Apollos and the Amors.

ANDERS: What kind of objects were considered most desirable?

ARNOLD: From the resource point of view, metal and water are the most desired resources. If the Moon is really as dry as everybody thinks it is, and since water is one of the things that human beings use, then carbonaceous chondritic material becomes very interesting. Also, the iron and nickel in some meteorites is more attractive than the 10% iron in lunar rock.

ANDERS: Would we be satisfied merely with remote sensing data?

ARNOLD: If we were actually proposing some large-scale industrial use of these materials, no, certainly we would not be satisfied. As it was put by the two mining engineers present at that meeting, nobody digs a mine without samples. If you contrast the relative cost of an exploratory sample return mission and a mining operation you will see that an exploratory mission is very modest.

MORRISON: To go one step further, there would also need to be pilot manufacturing and mining between the initial sample return mission and the full-scale mining operation.

SHOEMAKER: Another criterion is the effort it takes to get the material back to Earth orbit. The lowest ΔV objects you can find are attractive resources independent of their composition. Mass itself can be a valuable resource.

WETHERILL: I don't think the reports endorsed missions to these objects *per se*, but endorsed them in the context that if NASA decided to go into a resource program involving asteroids, these are the types of things we should do first. That is quite different from possible recommendations from this group on a scientific ground.

MORRISON: Having considered an array of instruments and their capabilities for remote sensing with a rendezvous mission, let us now discuss whether it would be responsible to advocate a remote sensing mission. Could we answer important scientific questions with the instruments we have seen?

CHAPMAN: In this meeting we have had what I have found to be a very exciting discussion of scientific questions dealing with asteroid sciences. I think there is general agreement among the people in this room that asteroids, meteorites, comets, and small bodies are potentially very interesting objects. We have also had presentations that strike me as being nice steps toward designing a plausible asteroid mission based on previous experience with other kinds of missions. I think there has been, however, a minimal amount of discussion about the link between those two. Granted asteroids are fascinating and interesting and important to study; granted that missions can be flown which make lots of measurements. The question you asked, "can a rendezvous mission answer important scientific questions?" has hardly been addressed at all. I think it is very hard at present to address those questions in a reasonable way. We really don't know on the basis of ground-based data enough specifics about asteroids to define very explicit measurements that will be guaranteed to answer questions. A decade ago we probably would not be putting this requirement on ourselves to establish specific mission goals because at that time NASA was in the general exploratory mode of operation and we didn't really expect you would know a whole lot about a body before the first mission. Now most people are talking about what we can do next on Mars and you kind of feel you ought to be very specific and really know where you are and what you have to do. We don't know that much about asteroids, so we cannot develop a detailed rationale for a mission based on a logical progression of reasoning that says you are going to answer these specific questions by going to an asteroid.

MORRISON: I think that is an excellent point. It is asking too much to judge a first asteroid mission by the criteria we would use in going back to Mars or Venus.

CHAPMAN: Before such a mission is launched one would want to do one's homework and specify in as great detail as you could what kind of experiments you could do that would address known questions.

McCORD: I think we can ask these questions now. What is its composition? What is its structure? Does it have a regolith? What are the features on the surface? Aren't those the questions to be answered?

ANDERS: Yes, but I also think some of these questions are more profound that others. I think it is almost a foregone conclusion the big asteroids have regoliths. I certainly agree with Chapman that we should try to pursue these questions and see just what we can do with the tools at hand. For instance, nobody has mentioned a Viking-type mass spectrometer as a possible instrument to be sent to an asteroid. We should ask, is it feasible? Would we be interested in the results? Veverka made quite an impressive argument for the power of imaging. It is likely to turn up some surprises that will be quite interesting, and moreover is the only way to get some first-hand information on physical features and structure. Another step would be for us to begin making up a list of targets that we all agree on, that are likely to be interesting, no matter who of us is right. Ceres is obviously one. I think another one is a Hirayama family member. If you really want to look inside an asteroid, that is an obvious choice. A third one might be an asteroid with very low albedo, presumably more carbonaceous, more primitive than anything that reaches the Earth. Primitive matter of all kinds is of great interest in its own right. A fourth target would be asteroids that for dynamic reasons are very unlikely to deliver meteorites to Earth. That is, asteroids in the main belt with quite small eccentricity and inclination and far removed from resonances. This is just a beginning of a list. I am sure each of you can add several favorites to it. And maybe that is a good way to proceed; first to compile a list of targets, and then ask what experiments make the most sense for each of these asteroids.

MORRISON: I believe this is a good place to end this discussion. We all seem to agree on the desirability of a multi-asteroid rendezvous mission, and I find the scientific arguments presented here quite convincing. Clearly it is not the responsibility of this workshop to define a science payload or to select targets for a mission, but it is a useful exercise to consider these things. Tomorrow, we will try to summarize our position on all of these issues for the "Findings and Recommendations" section of this report.

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16. Abstract

This volume contains the proceedings of an Asteroid Workshop organized by co-chairmen Edward Anders, University of Chicago, and David Morrison, NASA Office of Space Science, with the sponsorship of the NASA Headquarters. The workshop was held at the Continuing Education Center at the University of Chicago, January 19-21, 1978. The 15 invited speakers and several observers included scientists specializing in meteorites and/or asteroids as well as representatives from NASA Headquarters and the Jet Propulsion Laboratory.

The workshop was relatively small and was conducted in an informal manner that encouraged discussion of the issues. The presentations and subsequent discussions reviewed and assessed the current state of asteroid science and considered how future programs can best increase our understanding of the nature of these objects and of their relationship to the formation and early history of the solar system. As one element, the workshop considered the contribution that space missions, such as a multiple asteroid rendezvous mission utilizing low-thrust ion drive propulsion, might make to asteroid studies in the late 1980's.

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