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COMETS AND ASTEROIDS: A Strategy for Exploration

REPORT OF THE
COMET AND ASTEROID MISSION STUDY PANEL

May 1972

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Exploration and detailed study of comets and asteroids, therefore, should be a significant part of NASA's efforts to understand the solar system. A comet and asteroid program should consist of six major types of projects: ground-based observations; Earth-orbital observations; flybys; rendezvous; landings; and sample returns. A preliminary listing of the primary objectives of each project type is found in Table I. The Comet and Asteroid Mission Study Panel recommends that planning and implementation of these six types of projects be initiated as soon as practical. Missions of the flyby type could be accomplished with existing conventional propulsion systems. Missions of the other types, however, must be carried out with electric propulsion systems, such as solar-electric propulsion. Some of the scientific instruments for the recommended observations could be adopted from previous planetary and interplanetary projects; some would represent new developments.

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A Strategy for Exploration

Report of a Study by the

Comet and Asteroid Mission Study Panel

to the

National Aeronautics and Space Administration

May 1972

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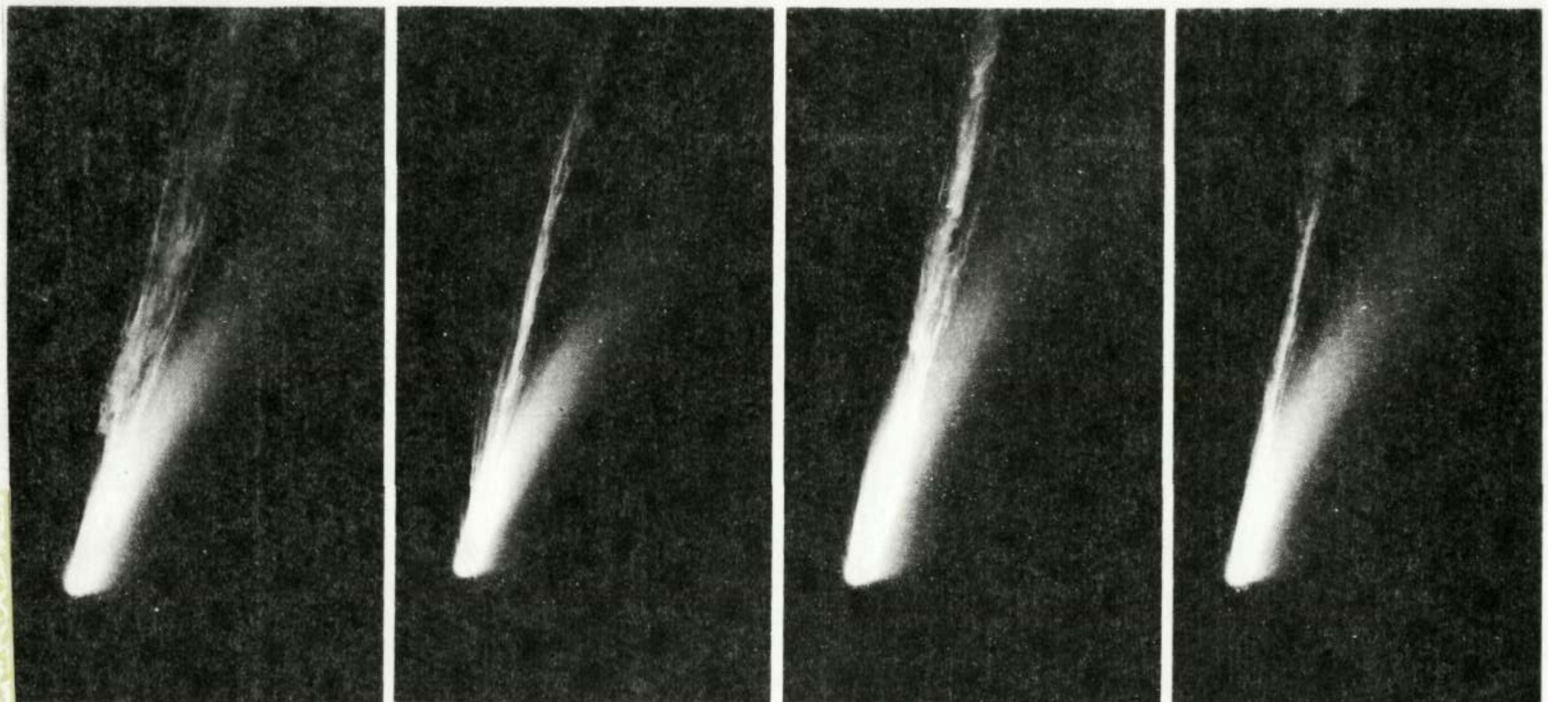

AUGUST 22 AUGUST 24 AUGUST 26 AUGUST 27

Comet Mrkos, 1957. Four views showing dust and gas tails taken with the 48-inch schmidt telescope. (Photograph courtesy of Hale Observatories.)

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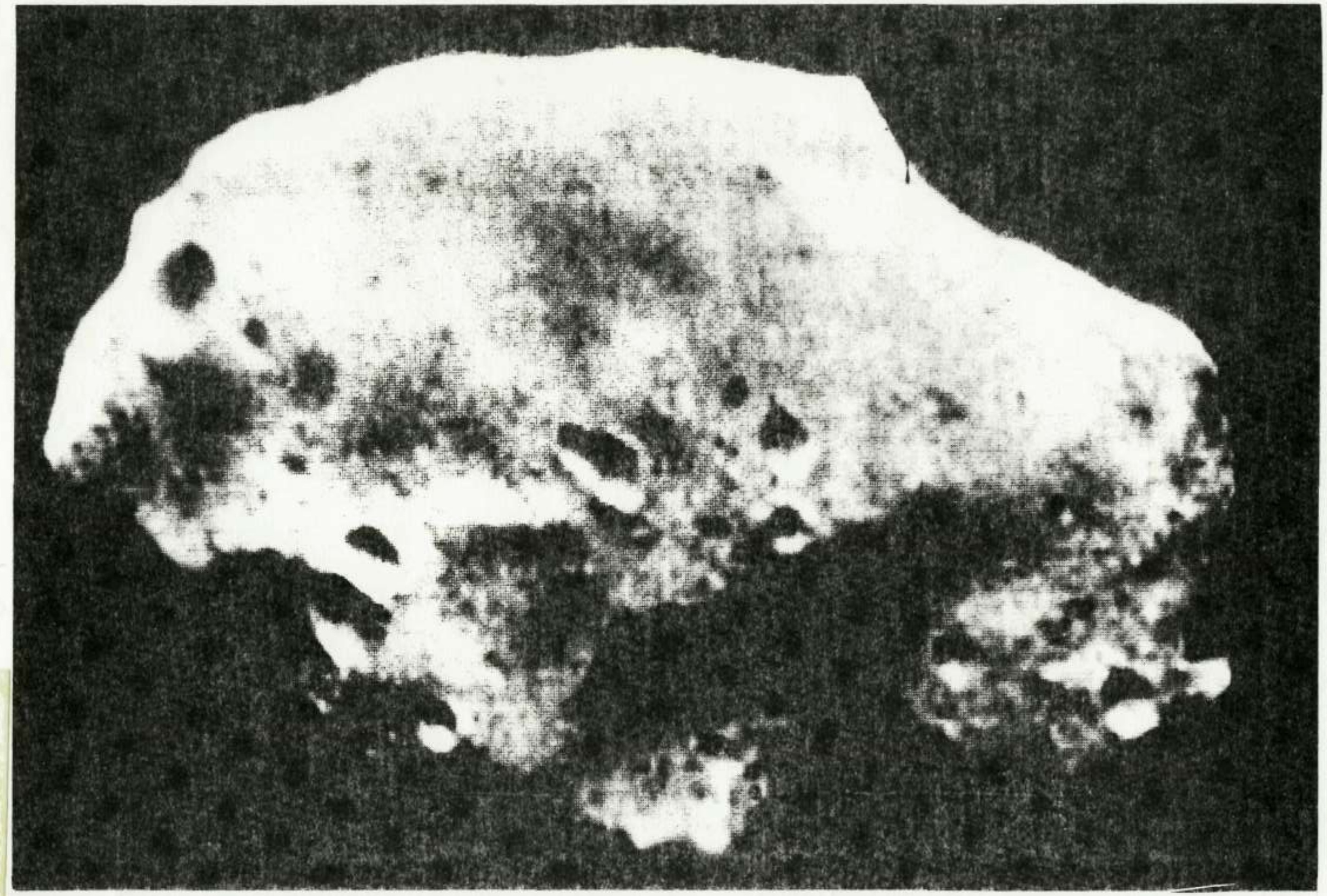

Phobos from Mariner 9
(Photograph courtesy of Jet Propulsion Laboratories.)

COMET AND ASTEROID MISSION STUDY

PANEL MEMBERS

Ernst Stuhlinger, *Chairman*
NASA Marshall Space Flight Center

Hannes Alfvén
University of California, San Diego and Royal Institute of Technology, Stockholm

Gustaf Arrhenius
University of California, San Diego

Roger Bourke
Jet Propulsion Laboratory, Pasadena

Bruce Doe
U.S. Geological Survey, Denver

Steven Dwornik
NASA Headquarters, Washington

Alan Friedlander
Science Applications, Chicago

Tom Gehrels
The University of Arizona, Tucson

Charles Guttman
NASA Marshall Space Flight Center, Huntsville

David Strangway
NASA Manned Spacecraft Center, Houston

Fred Whipple
Smithsonian Astrophysical Observatory, Cambridge

The Panel gratefully acknowledges the continuous assistance from Mr. James K. Harrison, Marshall Space Flight Center, Huntsville, Alabama; and the untiring efforts of Mrs. Mildred S. Matthews, Lunar and Planetary Laboratory, University of Arizona, Tucson, in the editing of this booklet.

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*Hetegonic = "Companion-forming"

PREFACE

Our sun and its system of planets and other objects naturally have a special philosophical importance to us as our home in space. The question of their origin and evolution, therefore, evokes a special interest. Since the time of Copernicus and Kepler the investigation of the planets has sparked numerous advances in physics and has in turn benefited from advancing knowledge of the fundamental laws of nature.

In the past, however, our perspective has been extremely limited. Except for the meteorites, the only body of the solar system to which we had direct access was the earth, the planet on which we live. Now the rocket and the space probe have eased this limitation, returning direct measurements, close-up photographs, and even samples, of other bodies of the solar system to Earth for intensive study. With this new access to the far reaches of planetary space, comparisons among the planets, asteroids, and comets are possible and promise to afford an insight into their nature and history not hitherto attainable.

In seeking the origin and evolution of the solar system, we are also sorely challenged by the fact that eons of time have passed since the formation of the earth and planets, while modern science is only a few centuries old. This is a very stringent restriction that has often led one to observe, half in jest and half in earnest, that we know more about the history of the stars than of Earth, since we can see in the heavens stars and other celestial objects at any stage of evolution that we might want to study. On Earth, we have managed to pierce some of the veil by reading the record of the rocks. But that record is incomplete and shows little about the first eon of Earth's existence.

We are able to peer farther back in time with the Apollo and other investigations of the moon. Lunar soil gives ages of 4.5 eons, more nearly that believed to be the age of the solar system. Our experience with U.S. and Soviet missions to the moon and nearer planets has been remarkably fruitful to date and leaves little doubt that in time we will be able to develop the necessary perspective to understand the origin and evolution of the earth and other planets.

With these new powerful tools, then, we must attempt to discern what the materials accessible to us can tell us about the early days prior to and during the formation of the earth and planets. The earth-like planets can tell us some, but what they do reveal is limited by the fact that these bodies have undergone substantial evolution since their formation. The composition of the giant planets, Jupiter, Saturn, Uranus, and Neptune is likely to be closer to that of the original solar nebula, and much additional information will certainly come from a study of them.

But there are many who feel that it is the small bodies of the solar system, the comets and asteroids, that will afford us the best insight into the early years of the solar system. This is the importance of their investigation and is why discussions like those in this book excite the interest and hold the attention of many scientists.

This new chapter in our study of the solar system has only begun. It will not be completed until our spacecraft have visited every major body of the solar system. It will certainly have to include the investigation of the satellite systems of planets like Jupiter and Saturn. And it most certainly will not be complete until spacecraft have rendezvoused with comets and landed on asteroids to study these important probes of the past. For this to happen, there is much yet to do. It will be necessary to develop and use electric propulsion, to work out suitable mission plans, to devise landing and sample return techniques for the asteroids, and to build, instrument, and launch the necessary spacecraft.

These future missions to the comets and asteroids are extremely challenging. They are bound to be most fruitful and revealing. Moreover, we know that they can be done. It remains only to do them.

HOMER E. NEWELL
Associate Administrator
National Aeronautics and
Space Administration

RECOMMENDATIONS

1. Comets and asteroids are believed to hold decisive clues to the origin and evolution of the solar system. Their study promises to help answer some of the fundamental questions which cannot be answered by the study of the earth, moon, and planets. It is recommended that NASA initiate a vigorous program for comet and asteroid exploration.

2. The Panel recommends that the program contain the following major activities:

a. Ground-based observations (UV, visual, IR, radar), laboratory research, and theoretical studies. High priority should be given to a 1.5 to 2 m telescope dedicated to comet and asteroid observation in order to support and to stimulate investigations in this field.

b. Continuing effort on the development of instruments, equipment, and components, and initiation of the design of subsystems, applicable to a variety of flight missions to comets and asteroids.

c. Investigation of the possibilities of conducting comet and asteroid observations and appropriate model experiments from an orbiting laboratory as represented by the Shuttle sortie module.

d. Continuation of planning and optimization studies concerning a family of flight missions to comets and asteroids ranging from flybys to sample return flights.

e. Selection of individual missions, and implementation of these mission flights, beginning at the earliest time compatible with resources availability.

3. On the basis of present knowledge and capabilities, the Panel recommends a program of missions as follows:

The first mission to be a flyby to a short-period comet (P/Whipple or P/Encke?) and two or more asteroids.

The second mission to be a rendezvous with a comet, possibly including probes toward the comet nucleus.

Further missions to include a rendezvous with an asteroid and a landing on its surface with data return by telemetry, and also missions to asteroids, and possibly to comets, which include the return of material samples to Earth.

The Panel recommends that two or more flights, possibly to different bodies, by planned for each of the missions named.

The Panel further recommends that the program include a mission to Comet Halley. This comet is an ideal representative of comets with longer periods (76 years). P/Halley has been observed for more than two thousand years; a Halley flight mission would have great scientific as well as public appeal. Although valuable information could be gathered on a fast flyby, the Halley mission should preferably be a rendezvous which offers a substantially greater exploration potential than a flyby.

4. The Panel recommends that flight missions in the comet and asteroid exploration program be considered to start during the second half of the decade of the 1970's.

5. Flights of the first mission in this program could be accomplished with flight-proven chemical propulsion systems, but all the other missions, which are more demanding in propulsion requirements than a fast flyby, will require either a complex multi-stage design of chemical rockets, or a propulsion system of advanced design. In view of the great exploration potential of a program of these more demanding missions, the Panel recommends that an advanced system for which the basic technologies already exist, such as solar-electric propulsion, be developed now for application later in this decade.

SUMMARY

Planets and their larger moons, under the forces of heat, gravity, and meteoroid impact, have lost all records of their early formative processes. Their study will be only of limited value for our understanding of the initial phases in the genesis of our solar system. Asteroids and comets, however, have suffered far less of a metamorphic change; very probably, they are still close to the state in which they were formed several billion years ago. Their exploration will help us understand the crucial components and the very early stages in the formation of the solar system. Flight missions to these small bodies, therefore, will provide information on early circumstances and processes which is nowhere else available, not even on those meteorites which reach the surface of the earth.

Many of the asteroids probably formed near the orbits where they are found today. They accreted from gases and particles that represented the primordial solar system cloud at that location. Comets, in contrast to asteroids, probably formed far out in the solar system, and at very low temperatures; since they have retained their volatile components they are probably the most primordial matter that presently can be found anywhere in the solar system.

Exploration and detailed study of comets and asteroids, therefore, should be a significant part of NASA's efforts to understand the solar system. A comet and asteroid program should consist of six major types of projects: ground-based observations; Earth-orbital observations; flybys; rendezvous; landings; and sample returns. A preliminary listing of the primary objectives of each project type is found in Table I. The Comet and Asteroid Mission Study Panel recommends that planning and implementation of these six types of projects be initiated as soon as practical. Missions of the flyby type could be accomplished with existing conventional propulsion systems. Missions of the other types, however, must be carried out with electric propulsion systems, such as solar-electric propulsion. Some of the scientific instruments for the recommended observations could be adopted from previous planetary and interplanetary projects; some would represent new developments.

TABLE I

	Comets	Asteroids
1.	**Ground-based Observations:**	
	Atomic and molecular spectrometry	Photometry (IR; visible)
	Photometry	Polarimetry
	Ephemerides determinations	Ephemerides determinations
	Astrometry	Lightcurve studies (rotation, topography, shape, size)
	Non-gravitational motion studies	Thermal emission measurements
	Polarimetry	Radar backscatter measurements
2.	**Earth-orbital Observations and Experiments:**	
	UV and IR spectrometry	UV and IR spectrometry
	High resolution imaging	High resolution imaging
	Experimental studies in zero-gravity, high vacuum, wall free environment	Experimental studies in zero-gravity high vacuum, wall free environment
3.	**Flyby Missions:**	
	Imagery	Imagery (size, shape)
	Plasma measurements	Mass, density measurements
	Particles in tail studies	IR-sensing
	Magnetometer measurements	Photometry
	Observations of ions	Polarimetry
4.	**Rendezvous:**	
	Imagery	Imagery (size, shape, rotation)
	Physics and chemistry of coma and tail studies	Magnetic field measurements
	Magnetic and electric structure studies	Gas and plasma environment studies
	Ion measurements	Gamma-ray, x-ray and IR spectrometry
	Particle size distribution	
	Mass spectrometry	
	Gamma-ray, x-ray, UV and IR spectrometry	
	Plasma measurements	
5.	**Landing Missions:**	
	Imagery (incl. close range)	Imagery (incl. close range)
	Composition of surface material analysis	Composition of surface material analysis
	Gamma-ray sensing	Gamma-ray sensing
	Alpha-ray scattering measurements	Alpha-ray scattering measurements
	X-ray scattering measurements	X-ray scattering measurements
	Magnetometer measurements	Magnetometer measurements
	Seismometry	Seismometry
	Gravimetry	Gravimetry
	Thermal sensing	Thermal sensing
	Penetrometry	Penetrometry
6.	**Sample Return:**	
	Solid material analysis	Solid material analysis
	Solar wind and cosmic ray studies	Solar wind and cosmic ray studies
	Age determinations	Age determinations
	Chemical analysis	Chemical analysis
	Phase-crystalline analysis	Phase-crystalline analysis
	Magnetic and electric analysis	Magnetic and electric analysis
	Gas probe studies	

And a large number of other measurements of the properties of the returned material contributing to establishing a record of its cosmic history.

Chapter I

BACKGROUND AND BASIS OF COMET AND ASTEROID PANEL STUDY

Under the auspices of the Space Science Board of the National Academy of Sciences, a summer study was held at Woods Hole in 1970 with the objective of suggesting directions and priorities for future space science programs. During this conference, strong arguments were presented for the exploration of comets and asteroids, and the recommendation was made that a program for such exploration be included in the broad NASA program for the study and exploration of the solar system.

Early in 1971, the Program Directorate for Planetary Projects in the NASA Office for Space Sciences and Applications (now Office for Space Sciences, OSS) initiated several study projects concerning flight missions for comet and asteroid exploration. In support of these studies, OSS established an Ad Hoc Comet and Asteroid Mission Study Panel, composed of members of the scientific community, of NASA Headquarters, and of NASA Field Centers (see "Panel Members", page vii). The findings, conclusions, and recommendations of this Study Panel are presented in a condensed form in this booklet.

Two previous specialist meetings served as a valuable source of information and knowledge to the Panel. The first, a symposium on asteroids, took place at the University of Arizona in Tucson in March, 1971 (Gehrels 1971); the second, a symposium on comets, was organized by the Yerkes Observatory in June, 1971 (Roberts 1971).

The desire to explore small interplanetary bodies, such as comets and asteroids, has increased considerably since the 1970 Summer Study, because a unique feature of these small bodies has become increasingly ovbious as the exploration of the moon and of Mars progressed. Comets and asteroids, unlike the earth, the other planets and the moon, have not undergone profound changes in their structures and compositions by such factors as gravity, heat, or volcanism. In all probability, they still consist, at least in part, of the basic material which accreted at the time when planets were formed, about 4.5 billion years ago. The study of these small interplanetary bodies, therefore, may be the only way to learn about the nature of primordial matter, and about the earliest stages in the formation of larger celestial bodies, in the solar system.

A considerable effort in time and funding to be spent on a continuing program of comet and asteroid exploration would appear most appropriate and justified.

The important features of comets and asteroids which should be studied include shape; rotational speed; magnetic properties; surrounding magnetic fields; density; compactness; surface structure; optical properties of surfaces; age;

nature and composition of materials; mineral structure; radioactivity; roles of condensed gases, particularly water; existence of more complex molecules, among them hydrocarbons and amino acids; absorbed cosmic ray and solar wind particles; and others. The physics of emissions from the cometary surface, and details of particle-plasma interactions in the vicinity of the nucleus and within coma and tail, should be investigated. There is a possibility that comets even harbor very primitive forms of live organisms.

It will not be sufficient to study only one comet and one asteroid. In all likelihood, there are several different kinds of comets, distinguished by the compactness and density, and possibly composition, of their nuclei. Also, there seem to be different kinds of asteroids; some may be metallic and compact, others may be of a light and fluffy structure, still others may be carbonaceous-chondritic. Several comets and asteroids should be studied at close range as calibration check points for typical classes of bodies, and also as sources of entirely new information.

Obviously, some of the features of comets and asteroids could be observed from flybys. The more detailed studies, however, require a rendezvous with some time spent flying in close formation. A landing with *in situ* observations and high data rate communications would increase the exploration potential by a large margin. By far the highest information yield can be obtained from material brought back to Earth-bound laboratories for careful and detailed analyses with high precision methods. This value assessment of mission types is borne out by experience with the lunar exploration program.

In addition to a program of flight missions, a continuing effort of ground-based observations in the visible, infrared, and microwave regions should be expended in support of comet and asteroid exploration. Comet tails, responding sensitively to electric and magnetic fields in space, are large-scale indicators of field and palsma conditions in the interplanetary medium. Theoretical studies and laboratory experiments should complement these ground-based observation programs.

The comet and asteroid exploration program will obtain further support from continuing studies of meteoroids and meteorites. Some of the asteroids may be similar in their makeup to those objects which penetrate the atmosphere and reach the earth's surface; other asteroids, however, may resemble those meteoroids which, because of their very low density, burn up completely in the upper layers of the earth's atmosphere.

Another class of interplanetary bodies whose study will support and enhance the exploration of comets and asteroids is represented by the small moons of planets. Several of these, particularly Phobos, Deimos, and some of Jupiter's satellites, currently are, or soon will be studied in connection with the exploration of their mother planets.

The study of comets and asteroids could draw significant benefits from orbital observation capabilities such as offered by the Shuttle. First, telescopic observations from an orbiting laboratory will profit from the higher resolution and the extended wavelength range available to astronomy in orbit. Second, experiments with artificial comet-like structures, deployed in the close vicinity of an orbiting laboratory, can be carried out under combined conditions of vacuum, electric and magnetic fields, weightlessness, and virtually unlimited space which are not otherwise available. Third, an orbiting Shuttle will represent an ideal "receiving laboratory" in which samples retrieved from comets and asteroids can be investigated before they are subjected to the rigor of reentry conditions and earthbound transportation. The structural makeup of many of these samples may bear features caused by weightlessness which should be studied in a zero-gravity laboratory.

A program for the exploration of comets and asteroids should include a number of flight missions of different nature (flybys, rendezvous, landing probes, and sample return flights) to several individual comets and asteroids. A possible planning approach to a program of studies and flight missions is described in the following chapters. All members of the Comet and Asteroid Mission Study Panel have actively participated in the writing of these chapters. The panel members wish to emphasize, though, that this early planning work should be followed soon by more specific studies of mission objectives, flight instrumentation, and individual flight projects. A considerable number of technical reports and proposals concerning these subjects exists already; it should be the panel's endeavor to define those projects which would represent an optimum comet and asteroid program with regard to scientific value, technical feasibility, and funding constraints.

REFERENCES TO CHAPTER I

Gehrels, T. 1971, Editor, "Physical Studies of Minor Planets", NASA SP-267, Washington, D.C.

Roberts, D.L. 1971, "Proceedings of the Cometary Science Working Group", IIT Research Institute Publication.

Chapter II

THE PROMISES OF COMET AND ASTEROID EXPLORATION

The study of the solar system is a study of man's local cosmic environment. We are now in the early phase of general exploration, leading soon, hopefully, to a general picture of the evolution that has taken place. The motivation is still largely curiosity, but as in all exploration, curiosity carries background overtones that involve vital survival instincts – the search for possible unknown hazards that may be overcome, if understood, and for advantageous discoveries that may improve life. The search in space, however, involves even deeper motivations – the desire to "find ourselves" in the universe. How did we develop from the first complicated molecules? Can we expect other such systems to exist? Few? Many? Nearby? If these answers are favorable, can we expect to detect any such systems? If so, can we expect eventually to detect other intelligent life in the universe?

A reasonable goal in the reconstruction of solar system history is to develop a description or theory, consistent with our most subtle observations, tracing physical or *state* parameters as a function of time and position in the solar system back to a time when the system was strikingly different from what it is today. For convenience, call this the *parameter-time-position array* or the PTP array. The exploration becomes necessarily more vague as we go earlier in time. The parameters of state at first might be, for example, temperature, pressure, density, gas and dust composition, motion and plasma characteristics of a large interstellar cloud as it collapses. Physical and chemical processes follow from the starting parameters during the collapse and subsequent development of the sun and planetary system.

II.1. Meteorites and Asteroids

Meteorites provide us with by far our best current information concerning the physical circumstances that prevailed during the early accretion states in the terrestrial part of the planetary system. Much of this information is remarkably specific with regard to physical conditions in the "solar nebula" before the sun's radiation and early "solar gale" eliminated the gases. Many investigators speak confidently of *accretion* processes in the early *solar nebula* and of a *solar gale*, or highly increased solar wind when the sun was young; all this demonstrates the extent to which actual observations are used in support of specific hypotheses.

The wide variety in the characteristics of the meteorites is witness to diverse effects along the temporal sequence in the development of circumsolar matter throughout the accretion process and also carries information about positional effects of varying temperature and physical regimes with respect to the sun. According to some investigators, the meteorites appear to have been formed at temperatures in the range from perhaps 300 to 700° K and probably from Jupiter's neighborhood to Mars, but possibly outside of these limits. We find evidence that the comets must have formed at much lower temperatures and at far greater distances from the sun, very likely being the building blocks for Uranus and Neptune. It is even possible that some of the meteorites we have studied are samples from the inner nuclei of very large comets.

Exploration of the moon gives us invaluable information at one position in the PTP array, but the moon has been so differentiated that the time-coordinate begins too late to give us much detailed information about the accretion or early stages of its development. Even the locale of its origin is in dispute. The earth and Mars give us information largely relevant at even later stages of development after the planets were fully formed.

Presumably most of the meteorites come from comets or asteroids. If asteroids developed in relatively circular orbits with modest orbital inclinations such as they possess today, then samples from a given asteroid should be representative of material accreted in the corresponding region of space with respect to the sun. A cut through the asteroid should then give a temporal sequence of the situation in a narrow range of solar distance. On the other hand, if the "most successful" protoasteroids developed because of highly eccentric orbits about the sun, we might expect evidence for layering. The protoasteroid may have accreted material over a range of radial distances from the sun where conditions were markedly different and certainly over a range in time. Thus it is clear that a sampling with depth in an asteroid will lead to vitally important information about circumstances of early solar system evolution. Exposed areas or strata for such measurements should be expected generally on all sizes of asteroids because of fragmentation by collision on smaller asteroids and because of cratering on the larger ones.

Our situation today is much as though a geologist were given a large number of samples selected randomly from the walls of the Grand Canyon in Arizona and perhaps some other localities in addition without any information as to the original position of the individual samples. His task of reconstructing the stratification history of the Grand Canyon from such samples would be comparable to that facing the meteoriticist today. He must reconstruct both the temporal and the solar positional variables during the period of planetary accretion in the solar system.

There can be little doubt that some of our meteoritic samples represent the type of asteroids or planetesimals that accumulated to form Mars, the earth, the moon and even possibly Venus. These planets tell us a gross or integrated story of the accumulation process. The details can only be gleaned from studies of the more primitive bodies themselves.

Meteorites give exciting glimpses of ancient and gigantic activity in the prehistory of the solar system. There can be no doubt now that newly made atoms were among the building blocks of the solar system. Almost certainly a supernova occurred in or near the cosmic cloud from which our system developed. Otherwise very little iodine 129 (half-life 17 million years) or plutonium 244 (half-life 82 million years) could have contributed to the observed isotopes of xenon in meteorites. Thus our sun and system may have developed with a group of new stars in a huge collapsed cloud such as we now observe in the Orion Nebula. Will we ever be able to identify any of the sun's siblings among the vast star assembly of the Milky Way? And, could the explosion of a supernova have contributed to the collapse of our own solar-system gas-dust cloud?

The grains in some meteorites show the tracks of high-energy particles of the solar-wind variety, as well as of the higher energy cosmic rays. Thus accumulated particles were present, at least in certain regions and certain times before the accretion of the asteroids was complete. Investigation should clarify these regions and times. Residual magnetism is detected in some grains in some meteorites, also indicating magnetic or magnetohydrodynamics processes in the solar nebula at certain times and positions. The loss of a huge gaseous component (mostly hydrogen and helium) from the solar nebula, in the opinion of many investigators, definitely requires most powerful plasma effects by a solar wind magnified perhaps millions of times from the present value. Did such processes heat our asteroids, heat the outer layer of the moon and remove the primitive atmosphere from the earth? We *can* find out if we persist.

Before the first asteroid probe is launched, accelerated meteoritic studies should be coupled with an expanded program of asteroid photometry. The combination of these studies with theoretical work should lead to one or more fairly well substantiated temporal positional models of the inner solar system development. Then it will be possible to produce fairly credible models of the time sequence of developments in the solar nebula with radial position, perhaps from Mars to Jupiter and with some information as to the concomitant central activity involving the sun and the development of the inner terrestrial planets.

From the first space probes, simple photometric studies made at a considerable distance throughout 180° of phase angle would be of extreme value because albedo, surface texture, etc. will correlate with orbital characteristics and with meteorites. These observations coupled with polarization measurements throughout a much wider range in phase angle than is possible from the earth would add another dimension to the understanding of the surface character of asteroids. Spectra of moderate dispersion throughout the range from the far ultraviolet to the infrared would certainly enable us to analyze some specific mineral contents and to suggest some of the meteorite sources. Thus we could make real progress in analyzing the PTP array. Already there is a strong correlation of color with position in the asteroid belt. Detailed information from radiation studies without an actual landing could then serve to identify the origin of a number of classes of meteorites to give us a large step forward in at least locating our samples in the "grand-canyon".

Spot checking of a few asteroids by space probes would provide calibration of our earth-centered studies and would help distinguish among competing models of solar system evolution. The new information provides impetus to a rather reliable reconstruction of these highly important events in the distant past. This information added to the accumulation of vital information from lunar exploration and planetary exploration should consolidate a preliminary yet viable understanding of the circumstances that led to the development of the terrestrial planets and the interplanetary bodies to Jupiter's distance.

II.2. Comets

The role of comets in the evolution of the solar system is only broadly suggested at present. We are still ignorant of any but the grossest structures that exist in cometary nuclei and are even largely ignorant of the parent molecules that lead to the major spectral bands observed in the optical region. The Orbiting Astronomical Observatory and other space platforms have definitely proven that water ice is the major constituent of comets. Therefore, as mentioned before, it seems highly likely that the comets were formed in the region largely beyond Saturn and are the building blocks of the two outer planets, Uranus and Neptune. By the time of the first cometary flyby, an accelerated study of cometary spectra, both from the ground and space, should have resolved some of the major uncertainties with regard to the molecules that are trapped or frozen in the nuclei of comets. Also, it is possible that a true cometary classification would then become available when the space spectral observations are coupled with the orbital and photometric data and the non-gravitational motions of the observable comets. This information should enable us to establish with more confidence the physical circumstances, particularly temperature and pressure, that existed at the time and position of their formation. Undoubtedly, since comets differ greatly, we can eventually define a PTP array of their development.

Accelerated meteor studies can aid materially in our understanding of cometary classification, structure and development. Most meteors come from comets and represent the solid or "earthy" material imbedded in or incorporated in icy cometary nuclei. More research is needed to ascertain which of the tiny particles in the atmosphere actually arise from meteors and/or comets. Thus meteor studies are fundamental to our general problem.

The meteor studies complement the asteroid and comet studies in solving the present-day problems of dynamical processes among the interplanetary bodies. Collisions produce ablation of larger bodies and elimination of smaller ones by reduction of solids to fine particles and gas, which are blown away from the system by solar radiation and by the solar wind, respectively. The Poynting-Robertson effect causes all the moderate sized particles to spiral towards the sun. The quasi-stable equilibrium between input and loss of zodiacal particles requires much more careful research. We believe that comets are the major source of solid particles in the zodiacal cloud, but have no meausre yet of the input from the asteroid belt. This problem is of basic importance today and also historically.

Considerable evidence has accumulated to suggest that some of the asteroids, particularly those in Earth-crossing orbits, represent comet nuclei whose icy shells have become largely exhausted. The close-up study of such potential cometary nuclei should give definitive clues as to their general character and perhaps will tell us, by means of precise photometry and spectral photometry, whether our museums do indeed include samples of these bodies, for example, the carbonaceous chondrites of Type I.

Flybys to reachable comets will then serve as definitive criteria and calibrations for more detailed models of the comet nucleus, which will be developed in the interim. The spectra alone, even though covering a huge available band of frequencies beyond those that can traverse our atmosphere, will always remain unsatisfactory in the detailed analysis of the various parent molecules and others that constitute the gaseous coma of a comet, not to mention the dust component. Detailed studies of both gases and particles in flyby missions will give us invaluable information concerning the detailed physical circumstances under which the comets developed and also considerable information concerning the pre-history of the gases and solids that finally collected to make up cometary nuclei. Thus we can expect to develop from such missions a far more complete concept of the nature of cometary nuclei, the circumstances and positions in the solar system in which they originated, clear-cut indications as to whether such material is already available for laboratory studies in our meteorite collections, and a basic overall reconstruction of evolution in the outer parts of the solar system. We may expect the temperature data alone to tell us whether the solar system developed in a stellar group or in an isolated cloud in space.

A landing on one or two asteroids should enable us to answer extremely fundamental questions about the detailed process of accretion in these bodies as well as to give us additional vital evidence concerning the "grand-canyon" problem. By correlating the orbit with all of the other observed characteristics of the particular asteroid we should make striking progress in establishing a variable two-dimensional scheme of evolution, our PTP array. Thus we could speak with considerable confidence as to how the asteroid grew. Calibration in terms of known meteorite types would then add invaluable information to the general picture of structure and evolution that will have been developed from the flybys and from ground-based observation.

II.3. Comets, Asteroids and the Search for Life

One of the most fascinating questions that space research is trying to answer is the problem of the origin of life; does it exist on other bodies in our solar system, is it unique to our solar system, and if not, can it be transmitted through interstellar space? Much of this interest is at the present time focused on Mars. The reason for this is partly historical and ultimately goes back to the belief that Mars and Venus possibly could support civilizations of intelligent beings. Since the recent exploration of these planets has largely removed the foundation for such beliefs, the question has now been reduced to the presence on Mars of possible primitive forms of life, compatible with very low partial pressure of water vapor, low temperature, high flux of ionizing radiation, and the frequent reworking of the surface layer by dust storms.

In many ways comets and some types of asteroids would seem to offer equally promising or better possibilities for sustaining life, as they are in a more open interchange with possible life reservoirs in space than is Mars.

Both in the case of Mars (at least now) and the comets, any water is most likely present only as ice and as water vapor at low pressure. While the small amounts of water vapor in the thin Martian atmosphere are drawn from the primordial resources of the planets, the large flux of water vapor observed (for instance, 2×10^7 g/s at 1 AU for Comet Bennett) could be due to replenishment of the supply by continued accretion of ice and dust, probably most effective in a cometary reservoir in the outer reaches of the solar system.

With regard to presence of ice and flux of water vapor through the atmosphere, the comets are consequently serious rivals of Mars.

Although the temperature in the comets during most of their orbital period is still lower than that on the Martian surface, the importance of this fact to the question of existence of life is not clear. Even highly evolved organisms such as brine shrimp have been found to metabolize at a measurable rate at very low temperatures. Furthermore, it is possible that some of the matter in comets is being incorporated in a high energy state and that the utilization of this source of spontaneous energy would to some extent offset the lower rate at which life processes involving activation barriers otherwise would proceed at low temperature.

It is not well known to what extent organic molecules occur on Mars, which could support heterotrophic organisms. However, all indications are that the surface layer has a high oxidation state, that it is frequently overturned and hence exposed to considerable depth to short wavelength radiation; hence the probability is low for preservation of unstable organic molecules.

In contrast the parent bodies of carbonaceous chondrites, which in all likelihood are comets, contain a multitude of metastable organic compounds, that even in the fragments recovered on Earth reach concentrations corresponding to terrestrial soils. Cometary surface material, which never arrives on Earth, contains molecules capable of yielding fragments such as ammonia, carbon monoxide, methane, etc. As substrates for heterotrophic organisms, comets would consequently appear to be potentially fertile, particularly in comparison to Mars. The source of the organic molecules in carbonaceous chondrites is most likely chemical synthesis in space, providing a variety of complex organic compounds. Under these conditions plant life would not be a necessary prerequisite to the existence of other forms of life.

On Mars we do not yet have evidence of whether life exists or has existed, the reason being lack of information. In the indurated parts of extinct comets that carbonaceous chondrites possibly represent, this question is also unanswered, but for different reasons. Extensive investigations culminating in the last decade gave abundant suggestions of the occurrence of a variety of life-like forms. But at least as convincing arguments were raised that these "organized elements" were either terrestrial contaminants or aggregations of matter morphologically similar to fossil primitive organisms, but not necessarily identical with such. As a result this fascinating question had to be left open, waiting for the availability of material guaranteed to be free from terrestrial contamination. We must also have such material in large enough quantities to permit us to extract and identify such molecular structures which are considered safe evidence of biological activity. Studies of this kind will be profitable when we can obtain material from the meteorite parent bodies which is not compacted, indurated and fossilized, but which represents an active interface with the source of water.

The time when this will be possible is when we can sample the surfaces of comets and of such asteroids which may be related to them and investigate such samples in the high purity environment of orbiting space laboratories.

The investigation of returned lunar samples has demonstrated that the lunar surface is admixed with a few percent of meteoritic material of carbonaceous chondrite composition, traced by the characteristic inorganic components, which were part of this projectile material. However, the original structures and organic compounds have been utterly destroyed at the high impact temperatures even on such a relatively small body as the moon.

On the other hand, seeding of the planet earth with preserved organic components from space (including returning space travelers) is possible because of the gradual braking by our atmosphere.

Mars presents an intermediate case; the terminal velocity is still higher than the totally destructive terminal velocity toward the moon. But a thin atmosphere exists which may offer partial compensation for this fact. Hence it is not excluded that seeding from outer space can occur also on Mars; however, the probability and efficiency are much lower than on Earth.

In contrast, comets and asteroids with their exceedingly low gravitational fields offer uniquely soft landing surfaces for particles brought to low relative velocities by gas and dust friction or by alignment with the projectile motion.

Present evidence points at the comet-asteroid complex as an object for life research, which should be at least as promising, if not more so, than the surface of Mars or the atmospheres of Jupiter or Venus.

II.4. Summary

Space missions to comets and asteroids, coupled with increased ground-based research, can be relied upon to give us an overall picture of the circumstances and processes that led to our present solar system. Comets should tell us about the outer part of the system, probably beyond Saturn, while asteroids carry the story of the inner system, probably from the Jupiter region inward. Such results cannot be expected from studies of the terrestrial planets or of our moon because the material there has been so highly differentiated by planetary processes that we have lost the evidence of the earlier stages of development. Also, in asteroids there are organic and even biological possibilities that may turn out to be of fundamental interest. In comets, organic molecules are probably omnipresent with a potential biological interest.

Only by including exploration of the comets and asteroids can we gain a definitive understanding of how our earth and the other planets came into being.

Chapter III

THE COMETS AND ASTEROIDS IN HETEGONIC* PROCESSES

III.1. Scientific Aims of Space Research

The first decade of space research mainly concentrated on the exploration of space near the earth. This was found to be not a void and structureless region as earlier supposed, but filled with plasmas, intersected by sheaths, and permeated by a complicated pattern of electric currents and electric and magnetic fields. The knowledge gained in this way is fundamental to our general understanding of cosmic plasmas. This implies that it is also important for the study of the structure of the galaxy and the metagalaxy, and to cosmological problems in general. Our new knowledge in cosmic electrodynamics will make it possible to approach these problems in a less speculative way than is currently being done.

The second decade of space research displays a different character. As several of the basic problems of the magnetosphere and interplanetary space are still unsolved, one can be sure that these regions will continue to command much interest. However, the lunar landings and the space probes to Venus and Mars have supplied us with so many new scientific facts that the emphasis in space research has been moving toward intensified exploration of the moon and the planets.

The first phase of this exploration has been of a character somewhat similar to the exploration of the polar regions and other regions of the earth which have been difficult to reach: a detailed mapping combined with geological seismic, magnetic, and gravity surveys and an exploration of the atmospheric conditions. However, when applying this exploration pattern to the moon and the planets, one is necessarily confronted with another problem, namely, how these bodies were originally formed. In fact, many of the recent space research reports end with speculations about the formation and evolution of the solar system. It seems that this will remain one of the major problems – perhaps the main problem – on which space research will concentrate in the near future.

III.2. The Origin of the Solar System

Astrophysics is essentially an application to cosmic phenomena of the laws of nature found in the laboratory. From this it follows that a particular field of astrophysics is not ripe for a scientific approach until laboratory physics

* Hetegonic = companion-forming

has reached a certain state of development. For example, until the advance of nuclear physics the attempts to understand how the stars generated their energy could not possibly have been more than speculations without very much permanent value.

The problem of how the solar system originated has been subject to a large number of highly divergent hypotheses. The reason for this has been the lack of basic knowledge in the fields of physics and chemistry essential for the understanding of the phenomena. Furthermore it is necessary to define the boundary conditions that a self-consistent theory of the origin and evolution of the solar system should satisfy. In the past too much attention has been concentrated on the formation of planets around the sun. One of the unfortunate results is that many theories of the origin of the solar system have been based on theories of the early history of the sun. This is a most uncertain foundation since the formation of the sun (and other stars) is a highly controversial question. Recognizing that the satellite systems of Jupiter, Saturn and Uranus are very similar to the planetary system, and at least as regular as this system, it now seems more appropriate to aim at a general theory of the information of secondary bodies around a central body, regarding the formation of the planetary system as only one of the applications of such a general theory.

The study of the sequence of processes by which the solar system originated has often been referred to as cosmogony, a term which rightfully, however, has a much more general meaning. As the origin of the solar system is essentially a question of the repeated formation of secondary bodies around a primary body, the term hetegony (from Greek hetairos or hetes = companion) has been suggested to express this general concept.

It is fairly generally agreed that the sequence of events leading to the formation of the solar system is likely to have been as shown in Fig. III-1, expressing what has been called the planetesimal approach. Primeval gas and possibly dust, the former by necessity partially ionized, was emplaced in certain regions around a central body and condensed to small solid grains. The grains accreted to what have been called embryos and by further accretion larger bodies were formed: planets if the central body was the sun, and satellites if it was a planet. The place of the comets, asteroids and meteoroids in the hetegonic diagram is controversial. The asteroids were formerly often considered to be fragments of a broken-up planet, but there are now an increasing number of arguments for the view that they represent – or at least are similar to – an intermediate state in the formation of planets. Similarly meteoroid streams have long been regarded as having been produced exclusively by the decay of comets, whereas some investigators now also consider the possibility of the reverse process that comets may be accreting from meteoroid streams. For the whole asteroid-comet-meteoroid complex, clarification of the relative rates of these two processes, fragmentation and accretion, is an important part of our understanding of the evolution of our solar system.

Even if the diagram of Fig. III-1 is fairly generally accepted as it stands, this does not mean that the different processes are clarified. To a high degree they are still of a hypothetical character. This has necessarily been the case, because, until rather recently, the basic processes have not been well known. To some extent we have been in the same situation as the astrophysicist trying to clarify the energy generation in stars before the advent of nuclear physics.

However, the results of space exploration promises to change this situation so that there is good hope of bringing this important field of research from the state of discussion of more or less bright hypotheses to a systematic scientific analysis.

III.3. Basic Knowledge for the Reconstruction of the Hetegonic Processes

There are some specific fields of research which are basic for the reconstruction of the hetegonic processes.

a. *Plasma physics* has recently advanced very rapidly, mainly due to thermonuclear research. The first application of plasma physics to cosmic phenomena was only partially successful because it was relying on homogeneous models, and the importance of local electric fields and electric currents in space was not fully appreciated. The second approach takes these phenomena into

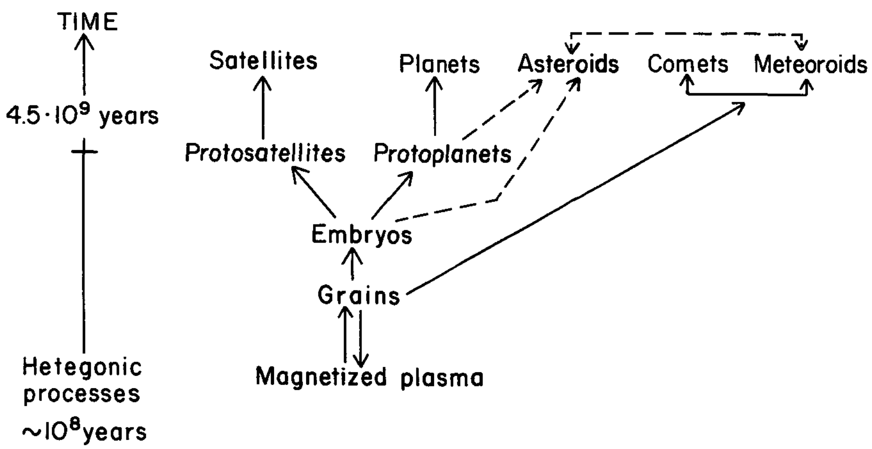

Fig. III-1. The major stages in the evolution of planetary and satellite systems according to the planetesimal approach.

account and tries to achieve a synthesis between laboratory plasma physics, theory, and the space data from the magnetosphere and interplanetary space. Combined with information from other fields, especially solar physics, it is likely to give us as much information on the basic properties of cosmic plasmas as is needed for the understanding of the early plasma phase of the evolutionary chain of Fig. III-1.

b. *Plasma chemistry* is the field of research concerned with chemical reactions in a plasma. These are basically different from the reactions in non-ionized gases. Plasma chemistry also deals with the separation of different elements and molecules in an inhomogeneous plasma due to, e.g. temperature gradients and electric currents. Furthermore, the interaction between a plasma and solid grains condensing from it is highly dependent on its chemical state. The laboratory results and their application to cosmic conditions are relevant for the understanding of the different chemical compositions of the celestial bodies.

For the next process in our evolutionary diagram, namely the accretion of larger bodies from the initial condensates, the following fields of research are essential.

c. *Hypervelocity collision dynamics.* The grains which are the primary result of the condensation will move in Kepler orbits around the central body but their motion will be disturbed by several effects mentioned below. One of them is mutual collisions. The relative velocities at these collisions may have any value from zero up to some ten km/sec. This means that in many cases we are in the region of "hypervelocity" collisions. This is a field which is not yet well understood. Laboratory results are scarce, and their application to cosmic conditions is uncertain because we know very little about the structure of the grains and embryos. Collisions between bodies consisting of fluffy shock-absorbing material or with surface layers of such material are likely to differ from collisions between hard "marbles." Meteorite studies are supplying us with some information. The Apollo observations of meteoroid impact on the lunar surface are another important source of knowledge. In these cases, however, we do not gain very much information about the structure of the grains in space because the particles we recover have either passed the terrestrial atmosphere or been destroyed by impact on the lunar surface.

d. *Celestial mechanics* serves, of course, as a general basis for the whole range of hetegonic processes. This field has been rejuvenated by the application of computer analysis to many of the problems which were formerly impossible to handle. This is especially true for the discovery of the importance of resonance phenomena in the present structure of the solar system. It seems likely that at hetegonic times resonances also played a decisive role in the motions of accreting matter.

e. The study of *Kepler motion in a viscous medium* is essential for our understanding of the evolution of the orbits of the grains and the embryos. From a formal point of view this problem is similar to some basic problems in plasma physics, which is also concerned with a large number of interacting particles. It has been found that the condensed grains have a tendency to equalize their orbits in the neighborhood of a central body thus forming what has been called "jet streams" in space.

f. *The hetegonic processes* culminated 4 to 5 eons ago. The evolution of the direct products of these processes into our present-day solar system has consisted of a number of relatively slow changes: internal forces have transformed the structure of the planets, tidal effects have braked the spins of some of the bodies (especially of the satellites), collisions are continuing in the asteroid belt and on the surface of the planets, comets and meteor streams appear to be in a state of continuous transformation. All these effects are important for the reconstruction of the state of the system immediately after the hetegonic processes ended. It is only after "correcting" for them that the solar system data we observe today are of value for the reconstruction of the formation events. Furthermore the processes governing the present evolution of the comet – cometary asteroid – meteoroid complex probably have many similarities to some of the hetegonic processes.

III.4. Space Observations Relevant to the Hetegonic Problem

From the analysis we have made, it is evident that the background knowledge necessary for the understanding of the hetegonic processes is rapidly increasing through advances in several different fields of research. We shall now discuss the question of what kind of space missions are of particular value for the study of the origin of the solar system.

Let us first emphasize the great value of the space missions which are carried out today or already planned for the immediate future. Increased knowledge of the behavior of cosmic plasmas is gained by spacecraft carrying out particle and field measurements in the magnetosphere and interplanetary space. Further, meteor impacts on spacecraft supply us with information on the very small bodies in our environment, important for understanding of those small bodies out of which our present planets once accreted. Particularly revealing has been the study of meteor impacts on the moon, Mars, and the Martian satellites. Hence these and other investigations automatically contribute to the background knowledge necessary for the solution of the hetegonic problem. But although this is useful there are a number of crucial problems which cannot be solved unless space research is purposely directed towards solving them. We shall now discuss how this could be done.

III.5. Big Bodies versus Small Bodies: Priorities

It is usually thought that, after the lunar landings, the most important missions will be those to Venus, Mars, and the other planets. However, missions to asteroids and comets would be at least as interesting and rewarding from a scientific point of view.

Our analysis has indicated which fields of research will contribute to the clarification of different phases of the hetegonic processes. Plasma physics and plasma chemistry are important for the first phase, including the condensation of small grains. The study of meteroid- and asteroid-sized bodies and of comets will have direct bearing on the accretion processes. We can state as a general rule that the smaller the body the further back in time the study of it will take us. Thus small bodies will be more relevant to earlier periods than large bodies. This means that it is essentially through studying the properties of small bodies in space that we can hope to understand the crucial phase in the formation of the solar system when most of the matter which later formed the planets and satellites was still dispersed.

It is evident that during the formation of the planets and satellites a great deal of information about the formation processes was stored in them. However, to a large extent this information is either obliterated or inaccessible. The planets are likely to have accreted from planetesimals. The earliest phase of this accretion produced a small body, the matter of which may today be in the core of the planet. Thus it is inaccessible even if a manned spacecraft should land on the surface of the planet. Even the nature of the earth's core is still obscure. There is also a possibility that, for example, convection in the interior of the planet has more or less completely obliterated the information once stored there. Concerning the surface layers, planetary processes, including atmospheric effects, have wiped out almost all traces of the hetegonic processes in Earth and probably also in Venus. In other bodies like the moon, and probably also Mars and Mercury, there may be some information left but only referring to the very last phase of the hetegonic processes: the violent and self-destructive accretion of planetesimals in fully developed gravitational fields.

Hence our conclusion is that studies of large bodies like the planets, although fascinating for the study of advanced planetary evolution, have only a limited value for the study of the origin of the solar system.

Small asteroids, comets and meteoroids are different in this respect. Even though they are affected by collisions in space, it is likely that most of them contain considerable information about the condensation and the accretion processes. Because of the small size, there is no heating or convection in the interior which can obliterate the information stored from the time when they were produced, and at least in the very small bodies, their interior is accessible. Degassing by shock and partial or complete melting may have modified some of these bodies, but even in the latter case gravitational separation is ineffective in the size range comparable to Eros or Apollo/Amor asteroids. If some of them are fragments of larger bodies, the internal constitution of these could be determined from the fragments. Hence, in contrast to the planets and to the moon, the small bodies may supply us with planetesimal matter in a low state of metamorphism.

As stated earlier there are two different views of the asteroids and meteoroids: they may be fragments of larger bodies or they may be intermediate products of an accretional process. These views are not contradictory. There is no doubt that fragmentation and accretion both take place in space, and the aim of a study of these bodies should be to estimate the relative importance of fragmentation, condensation and accretion. This should indeed be one of the major tasks in asteroid and meteoroid studies. Similar considerations apply to comets-meteoroids.

III.6. Different Groups of Asteroids

With respect to their orbital parameters, the known asteroids fall into different groups:

a. Main Belt Asteroids. These are orbiting between Mars and Jupiter. Most of them have semi-major axes a in the range $2.0 \leq a \leq 3.5$ A.U.

b. Asteroids outside the main belt form a number of different groups, such as Trojans and Hildas.

c. Amor Asteroids. These are asteroids with perihelia inside the Martian orbit and outside the earth's orbit.

d. Apollo Asteroids. These are asteroids with perihelia inside the earth's orbit. At least one of them, 1685 Toro (see Fig. III-3), appears to be gravitationally captured in resonance with the earth and hence may be a third member of the earth-moon system.

III.7. Specific Interest of Asteroid Exploration

a. Access

Of the astronomical bodies already discoverd, our closest neighbors in space, except for the moon, are members of the Apollo group. One of them, 1566 Icarus, passed very close to the earth in 1968. A flyby mission to members of this group would be relatively simple but probably not particularly rewarding as their relative velocities when close to the earth are very high, on the order of 30 km/sec. A rendezvous with soft landing is a technically challenging project.

Of all the known translunar celestial bodies, the Amor asteroids are the easiest to reach and would therefore be more favorable objects for investigation if the choice must be made on the basis of most favorable trajectories. They have eccentricities which are somewhat lower than those of the Apollo asteroids (although still rather high), and their relative velocities when close to the earth are reasonably small (some < 5 km/sec).

If space activity is planned as a stepwise penetration into outer space, a mission to an Amor asteroid is a logical second step after the lunar landings.

b. An almost unknown group of bodies

Almost nothing is known about asteroid mass, density, chemical composition or structure. Spectral measurements reveal a marked diversity in their surface properties, but the nature of the observed differences is not yet entirely understood. Regular light variations indicate that asteroids spin with periods on the order of 3 - 15 hours.

As compared to the planets, the asteroids have attracted very little interest. The reason seems to be simply that so little is known about them. There is *a priori* no reason why a small body like an asteroid should be less interesting than a body as big as a planet. On the contrary, as discussed above, the small bodies probably have recorded and preserved more information about the early history of the solar system than the planets and satellites which actively destroy their own record.

c. Asteroids – celestial bodies of unique size

The observed asteroids form a group of bodies which in size are intermediate between planets and meteoroids. We may take a diameter of 3000 km (about the size of the moon), as a lower limit for a planetary object, 3 km as representing as asteroid, and 3 m as the size of meteorites from which we have gained our information about meteoroids (Fig. III-2). With these values the masses of asteroids like 433 Eros differ by a factor of one billion from those of the planets and also by a factor of one billion from the masses of meteorites.

Hence, the asteroids that we consider here form a group about in the middle of a vast gap of 18 orders of magnitude in the mass spectrum of celestial bodies.

It should be remembered that natural satellites and comets also are located in the same gap. Comets are not more difficult to reach than is 433 Eros. In fact, the flyby of P/d'Arrest in 1976 is a very straightforward and technically

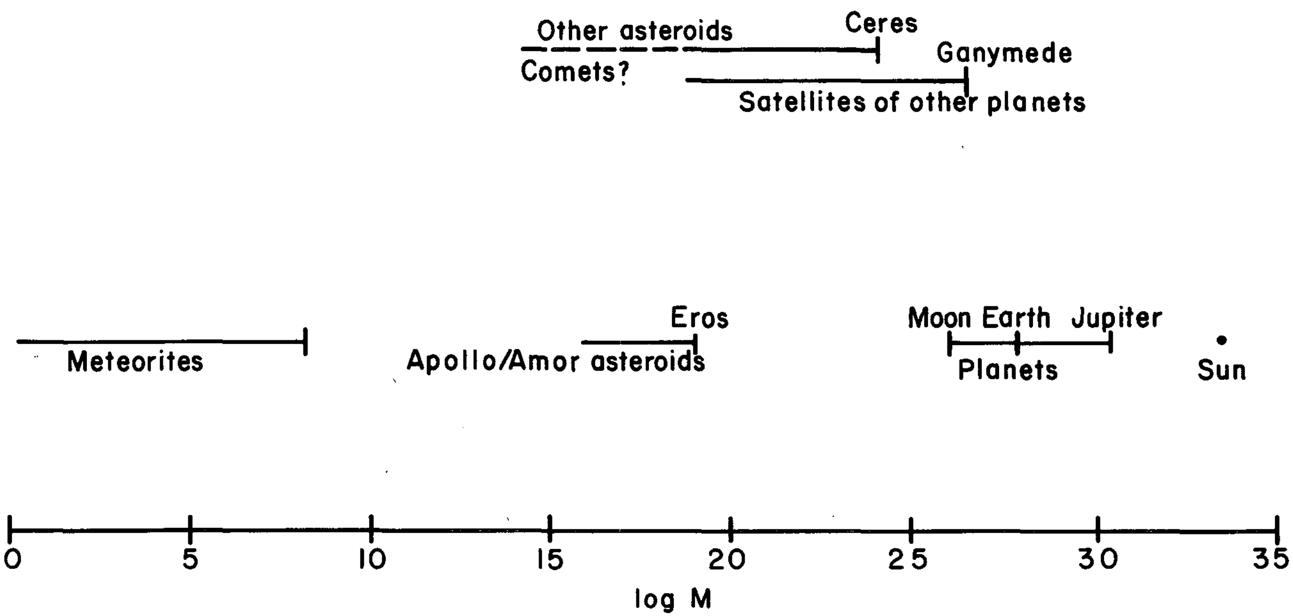

Fig. III-2. Mass Spectrum of Bodies in the Solar System.

Lower Group: Bodies which have been explored are:
Meteorites which have fallen down on the earth,
Moon and planets which have been targets of space missions.

The Apollo/Amor asteroids are located in the middle of a gap of almost 20 orders of magnitude between the meteorites and the planets.

Upper Group: Other bodies, more difficult to explore.

easy mission. The great scientific interest in comets should give high priority to cometary missions as a part of the combined exploration of the small bodies in the solar system.

d. *The uncertain relations between meteorites, asteroids and comets*

The observed asteroids are probably only samples of a large population of bodies, most of which are subvisual. The orbit distribution of the subvisual asteroids is unknown. There have been attempts to estimate the size distribution theoretically, but there is no observational confirmation, and the theories involve a number of uncertain hypotheses. A genetic connection between meteoroids and asteroids is likely to exist, but in view of the fact that the gap in the observed mass spectrum between these groups of bodies is of the order of magnitude of millions or billions, the connection is necessarily uncertain.

It has been claimed that from studies of meteorites we can obtain all the scientific information about asteroids (and comets) that is needed, and that space missions to these bodies hence are unnecessary. "Poor man's space research", consisting of chemical analysis of meteorites which naturally fall down on Earth, is thus sometimes thought to be a satisfactory substitute for space missions. The determination of the orbits of meteorites, which now is beginning to supplement the chemical and mineralogical studies of meteorites, is certainly very important for the exploration of the meteoroid population. Existing dynamic calculations do not support the speculation that a major fraction of the meteorites could be fragments of main belt asteroids deflected into Earth-crossing orbits. Hence comets are considered as a likely major source of meteorites.

Existing results make it clear that meteorites constitute a highly biased sample which is far from representative of the small bodies in space. The latter show a much wider range of orbital and structural characteristics than those of meteorites which depend on low relative velocities and high cohesive strength to survive passage through the atmosphere. In fact, only a very small fraction of the groups of bodies which intersect the earth's orbit are sufficiently tough and slow to be collected on the ground for analysis. Of the small fraction of meteoroids which thus can be studied, many have broken up and all have suffered serious damage by surface heating and ablation. This completely destroys the surface record of the low energy space irradiation and also renders difficult the interpretation of the higher energy exposure record.

e. *The Eros-like asteroids and the early history of the moon*

The asteroids may also contribute to another respect to the clarification of the early history of the moon. Some asteroids such as 433 Eros come very close to the earth with comparatively low velocities. There is a possibility that the pre-capture orbit of the moon was similar. This is a very controversial question of the early history of the moon. Hence, the history of the moon may be related to some of the Eros-like asteroids. For example, it is possible that some of them are planetesimals which escaped accretion by the planet moon. If this type of relationship exists, there should be a direct connection between these asteroids and the bodies which have produced the lunar craters when impacting on the moon. The discovery that the asteroid 1685 Toro is in at least temporary resonance with the earth further empahsizes this (Fig. III-3).

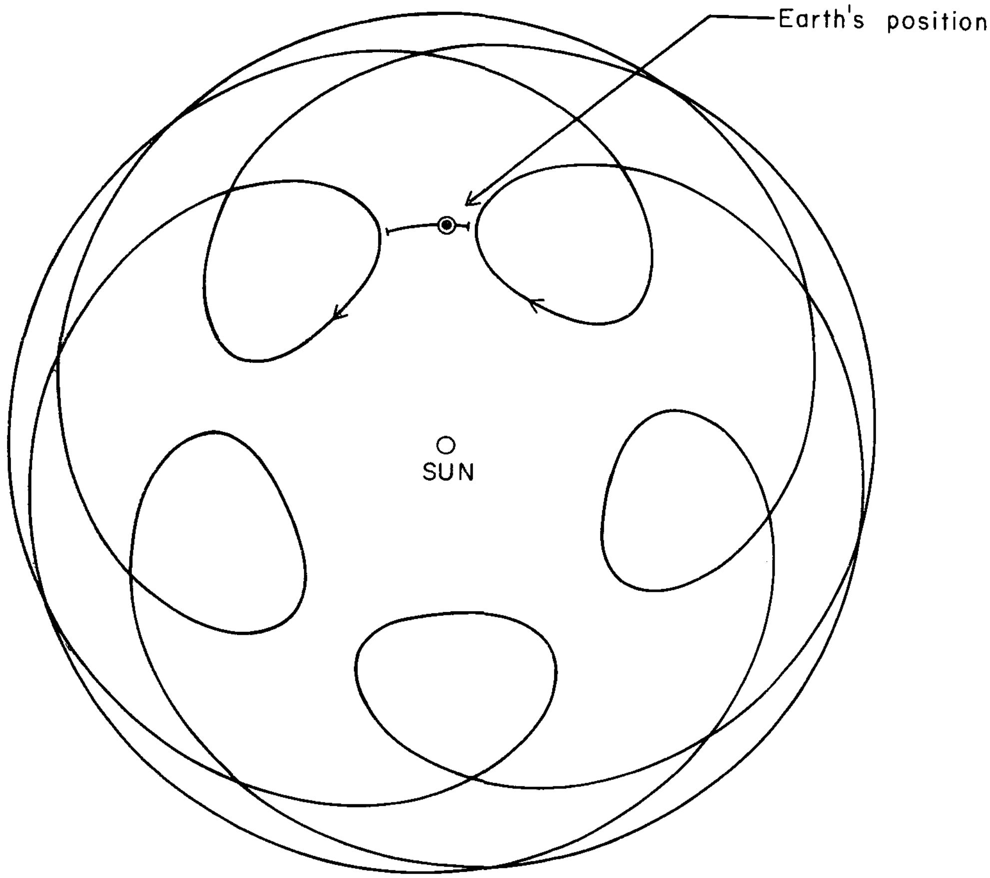

Fig. III-3. Path of the asteroid 1685 Toro in a coordinate system centered on the sun and rotating with the earth. The five loops shown are produced during eight Earth years. In this frame of reference, 1685 Toro's orbit oscillates with a period of 164 years and an amplitude of 9°. This is shown in the figure by letting the earth oscillate along an arc of 18°.

III.8. Meteoroids in Space

The analysis of meteoroids in space is a highly promising field. Among other things, it would reveal to what extent the meteoroids are products of fragmentation and of condensation-accretion. For example, if condensation has taken place on their surfaces, or if they have accreted small grains, one would expect them to contain low density material which would contain valuable information. A study of the structure of meteoroids would also help us to understand the effects of hypervelocity collisions between low density powder aggregates.

With present methods such a study of meteoroids has not been possible. We noted above that the passage through the atmosphere destroys the surface layers of meteorites which are among their most interesting features. Meteoroids impinging on the moon will hit it with at least 2.3 km/sec and are completely destroyed. To recover a meteoroid in space from a spacecraft is probably an extremely difficult operation even for micro-meteoroids.

The meteoroids in interplanetary space are known to orbit preferentially in the prograde direction, and many of the orbits have small eccentricities and small inclinations. For example, the meteoroids called cycloids move in almost circular orbits close to the earth's orbit and reach the environment of the earth with relative velocities which – before the acceleration by the earth's gravitation – in many cases are only a fraction of one km/sec. It is probable that there are also many meteoroids which approach asteroids with very small relative velocities. As the escape velocities of kilometer-sized asteroids are only some meters per second, these meteoroids will make soft landing. Hence there is a good chance of finding fairly undamaged meteoroid material on the surface of asteroids.

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Chapter IV

SCIENTIFIC OBJECTIVES OF MISSIONS TO COMETS AND ASTEROIDS

In chapter III we have discussed the unique characteristics of the asteroids and comets for elucidating the earliest history of the solar system, the fundamental processes governing emplacement of matter around the sun, condensation, and nongravitational accretion. Several pathways are *a priori* possible for this evolution. A choice between these can be made on the basis of specific measurements. The scientific objectives of missions to comets and asteroids comprise definition of these measurements, and their execution. The limits of resolution are essentially set by the closeness of the approach in the sequence: 1) earth-based observations; 2) flyby; 3) rendezvous; 4) landing with *in situ* measurements; and ultimately, 5) sample return, and in a more distant future, exploration by man.

The information yield is expected to increase in each of these steps. As experience from the lunar exploration has shown, the value of actual sample return and also direct observation by man, is enormous in comparison with the other steps. Nonetheless, an orderly progression along the indicated sequence would provide information in each step that would greatly improve the foresightedness in the planning of the following one.

IV.1. Earth-Based Observations

It is clear from the promising progress in Earth-based observations of comets and asteroids, coupled with development of new theory and with insights obtained from lunar exploration, that our knowledge can be considerably advanced by increased efforts in observations from Earth. These might include observations from airplanes, balloons and Earth-orbiting laboratories.

Observations of asteroids and comets from Earth should be planned in such a way as to distinguish between different classes of objects on the basis of their dynamic properties and surface characteristics. Such a classification will be useful for the first missions and for the future systematic exploration in order to choose targets of maximal potential interest.

a. *Statistical orbital dynamics*

One of the most important insights into the question of how repeated encounters between particles in solar orbits could lead to the growth of larger bodies is offered by the statistical-dynamical study of the members of asteroidal families or jet streams, of the interrelation between comets and meteor streams and of computer simulated many-body systems. In many of the cases studied, the conclusions are essentially limited by poor statistics. A large amount of additional information could be obtained by stronger manpower effort in observation, with increased access to more powerful telescopes and to telescopes especially designed and dedicated to comet-asteroidal studies. Figure IV-1 is a photograph of a one-sixteenth scale working model of a proposed asteroid-photopolarimetric telescope (1.8 m diameter). A modest program of discovery of new Apollo and Amor asteroids, which have orbits crossing that of Mars, is being executed with the Big Schmidt telescope at Mount Palomar. It has been estimated that there are 50,000 undiscovered asteroids in the magnitude range down to 20 or 21.

b. Resonance studies

The significance of an individual asteroid is often estimated in terms of its life expectancy. Calculations in the past, based on the assumption of random approach of asteroids near or across the orbits of Jupiter, Mars and Earth, suggested that their lifetimes, given the increased chance of a collision or ejection, would most likely be short in comparison with the age of the solar system. The discoveries of several new forms of resonances, locking asteroids in permanent or long-term orbits with the inner planets, has changed this picture in an important way. An example is the asteroid 1685 Toro (see Fig. III-3), which before its intermittent resonance with Earth was known, was thought to be an object in a temporary orbit with a lifetime against collision or ejection of the order of 10^6 years. The number of resonance possibilities just recently discovered, even by cursory investigations, suggests that the phenomenon is common and extends the recording history of these bodies over long periods perhaps ranging up to the age of the solar system. Consequently, one ground-based objective of comet and asteroid research in preparation for flight missions would be continued search among presently known bodies for potential coupling to the planets; also the search for more, yet undiscovered bodies belonging to the same families or jet streams. Currently this work is constrained due to limited observational facilities, qualified manpower and computer time.

c. Systematic trends in surface properties

By ground-based observations, we have already obtained distinctive criteria from the reflection spectra of different asteroids. With spectrophotometry near 0.94 μm, it has been possible to resolve spectral features characteristic of divalent iron in partial substitution for magnesium in the pyroxene mineral group. Spectrophotometric measurements in visible light give more ambiguous information regarding specific composition of the surfaces. However, this is still

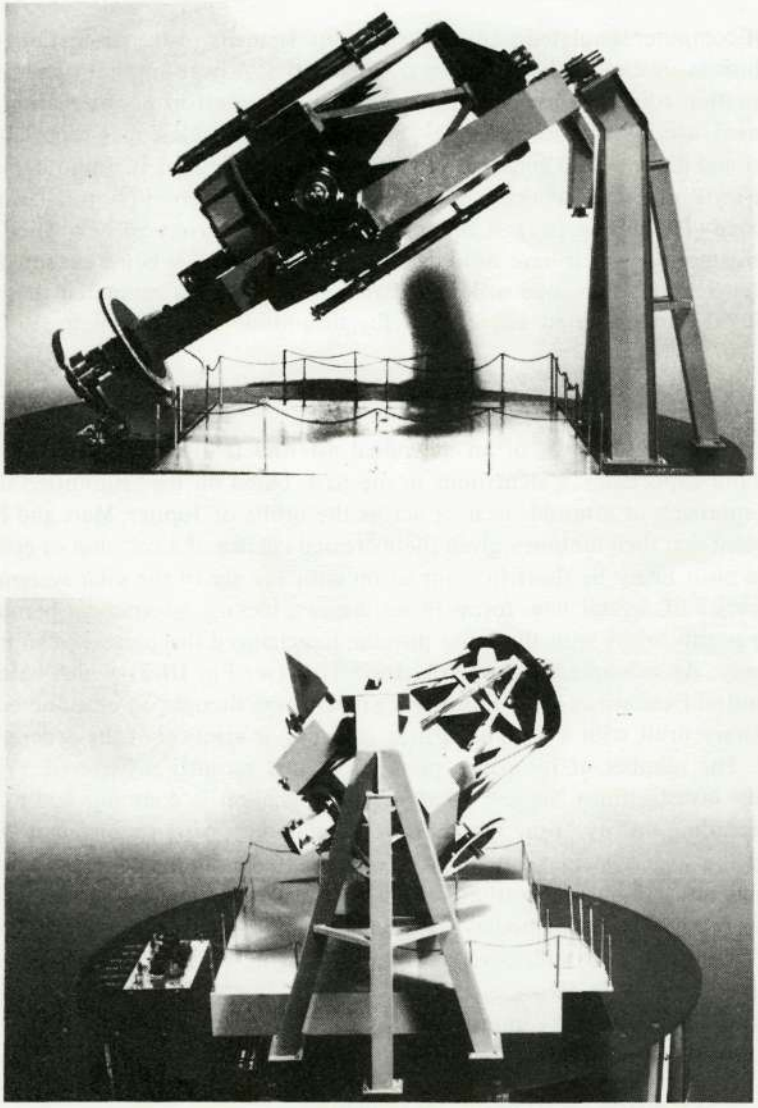

Fig. IV-1. Working model built by Max Kaufman of the 1.8-meter Asteroid Telescope. In particular this model demonstrates telescope balance, the clearance of the tube within the yoke and the percentage of aperture available when the tube is pointed at the north celestial pole, as well as the height of the platform at various telescope orientations. (For details see Kaufman, M. 1971, Sky and Telescope, *42,* 170-173.)

important since distinctive differences have been demonstrated in blue-red reflectivity, correlated with the orbital type. Furthermore the polarization of light appears to be a potentially useful property for distinguishing between bodies with different surface properties.

We consider it important to continue and to refine measurements of this kind in order to widen the base for judgment of suitable objects for flight missions. These can in the foreseeable future comprise only a limited number of objects and hence it is necessary to establish an early basis for generalization.

d. Ground-based mapping of asteroids

Surface features of asteroids cannot be resolved by telescopic observations from Earth. Even so it has been possible to derive much information on surface pattern including shape and on the important question of spin rates from the change in the amount of reflective light with time (Fig. IV-2). In preparation for missions, it is important to expand the exploration effort in this field by improvement of observational facilities, increase in manpower, and extraction of still more detailed information by use of numerical image synthesis techniques. Besides the usefulness of exploring these properties for mission planning, they also expand our basic understanding of the genetic processes involved in formation of asteroids. The spin rate as a function of size is particularly significant in deciding to what extent collisional fragmentation has played a role; exceptionally short periods on the order of three hours or less may be indicative of collisional breakup.

e. Earth-based and Earth-orbital observations of comets

Continued and intensified studies of cometary phenomena would narrow down mission goals and improve our understanding of the origin and development of comets and their relationships to asteroids. Due to the fundamental role of the evolution of the nucleus, an increased emphasis should be placed on the aggregation and changes in aggregation of the solid material in the comets in different stages of the orbits. Special attention should be paid to such comets where the state of subdivision of the nucleus is observed to be changing.

The question whether a solid, icy core is always present, or whether the core material can be loosely aggregated and have a variable state of dispersion, can probably only be solved by flyby and rendezvous missions. However, in preparation for this, it would be highly useful to intensify Earth-based study of these questions in suitable objects.

It is also important to examine by presently available means the composition and excitation in the plasma typically associated with comets, as well as the rate of the processes involved. However, here again, the decisive step in understanding these phenomena will only be taken when they are explored in place, and ultimately, by sampling the solids which are the source or moderators of the observable gas. Awaiting these important developments, progress should be made by further observing the optical emission phenomena from comets by instruments outside the earth's atmosphere; such investigations have already led to the significant discovery of huge Lyman α emission from large cometary envelopes and also to measurement of commensurable OH emission. Further exploration of these and related phenomena would be an important task to be carried out from orbiting laboratories.

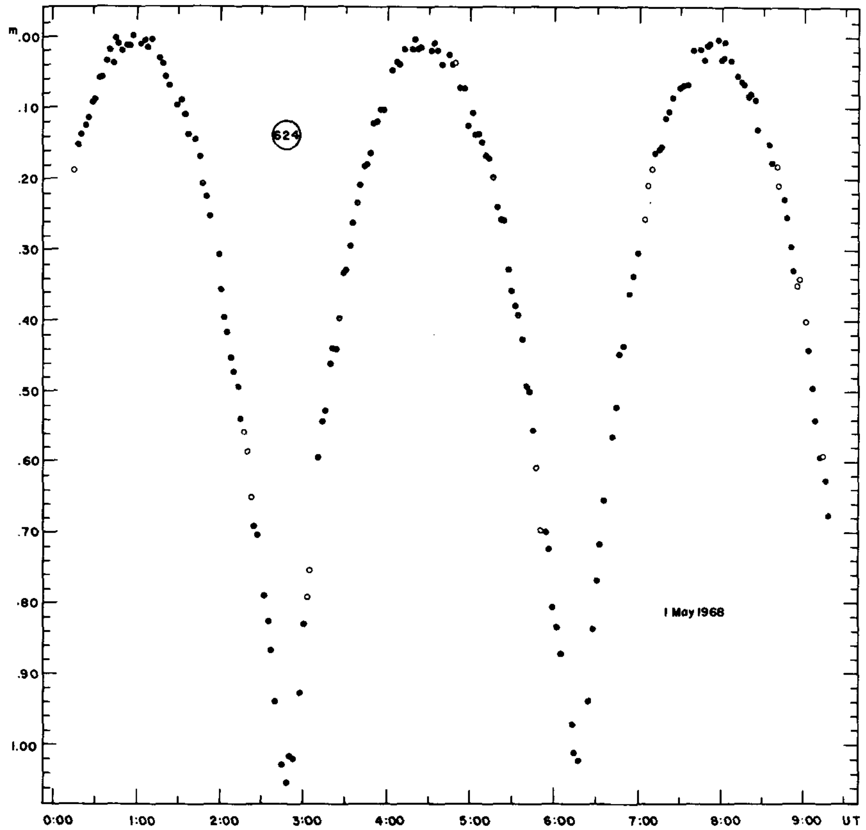

Fig. IV-2. Lightcurve of asteroid 624 Hektor, a Trojan. The observations were made at the Cerro Tololo Observatory. As seen from the figure Hektor has a rotation period of 6^h55^m, with two maxima and two minima. The axis of rotation is nearly perpendicular to the line of sight.

f. Investigation of Earth-intercepted extraterrestrial matter

The possibilities offered by the space program for clarifying the evolutionary history of the solar system has led to a tremendous upswing in the extent and sophistication of the study of meteorites in the laboratory and of meteors penetrating into the atmosphere. These developments have laid the foundation for a wide ranging scientific capability for thorough analysis of the material returned from the moon. The information and suggestions that can be recovered from the study of *meteorites and lunar materials* are still far from exhausted and serve as one of the primary bases for theories concerning the early history of the solar system. Since the meteorites clearly come from small, although as yet unidentified bodies, the results of meteoritic studies are of great importance for delineating the strategy of exploration of small interplanetary bodies. Conversely, however, the conjectures built on meteoritic investigations remain hypothetical and will contain serious uncertainties until complemented by direct observations of material from comets and asteroids. The failure of speculation to predict even some of the more fundamental properties of bodies in space became obvious at the first return of lunar samples. The actual field relationships of the various types of meteorite materials can be safely deduced only by observations in space.

Even so, specific boundary conditions for their origin and subsequent development can be retrieved from these special objects that are intercepted by the earth after surviving passage through the atmosphere as meteorites. Hence we recommend that in preparation for comet and asteroid missions, continued laboratory investigations of meteorites and of processes modeling the origin and evolution of primordial material be further encouraged and supported.

The reconstruction of orbital characteristics of meteorites by stereo photography of the night sky (Meteor Network) bears promise of narrowing down the possibilities with regard to the source of the bodies that reach the surface of the earth from outer space. Equally important, however, is the continuing investigation of the orbital characteristics and, indirectly, the physical nature of the much more abundant material that impinges on the earth's atmosphere but that is too fragile to survive passage through the atmosphere. This matter clearly has orbital and material characteristics which in the extreme range differ dramatically from meteorites. Of great importance is the extraction of as much information as possible by optical and radio measurements for this significant class of interplanetary bodies before the problem of their actual composition and their origin can ultimately be solved by sampling at the source. Hence we recommend that the present investigations in this field be further expanded.

In summary we wish to state that Earth-based studies, although they cannot provide the definitive insight into the formation, configuration and evolution of matter in space, constitute a vital introductory approach in formulating the strategy for space exploration. They also serve as a focal point for realistic discussion of the formative and evolutionary processes and as a rationale for refining the tools ultimately to be used for analysis of extraterrestial matter on comets and asteroids and after return to Earth.

IV.2. Fast Flyby

Although extensive observations are excluded in fast flyby missions, it would nonetheless appear possible by such missions to obtain important information on comets and asteroids which cannot be derived from Earth-based observations. Furthermore, results could be obtained which are desirable for the optimal planning of rendezvous missions and soft landing.

a. Density

Of foremost significance among the observations in evaluating the nature of the solid objects are the determination of volume and mass in order to establish the range of densities. This is particularly desirable among the objects of such a small size ($r < 50$ km) that selfgravitation is negligible. We know that much of the solid matter that intersects the earth's orbit is of low density, ranging down to 0.1 g/cm^3. It is important to search for the origin of this material among the asteroids and the comets. The relative rates of fragmentation and accretion of these bodies is poorly known. Here density data could provide guidance by indicating the maximum size of possibly fragmented bodies. The occurrence of bodies with very low densities (less than 2 g/cm^3) among asteroids and comets would be particularly indicative. Since the densities observed in solids in space spread over a wide range, even rough estimates are useful. Hence, error limits as high as 20% in the determination of volume and mass would still provide significant information. Figure IV-3 shows the relationship between closest approach distance (impact parameter) and asteroid mass for various flyby speeds and accuracy of mass determination. The results have been obtained assuming that the flyby spacecraft is tracked from the earth using conventional S-band Doppler tracking. Additional data types, particularly optical observations from the flyby spacecraft, would improve the uncertainty somewhat.

b. Imaging of shape and surface features

Television and/or spin scan images of asteroids and cometary nuclei would convey important information directly or indirectly related to the origin and evolution of these bodies. The extent to which such deductions can be made is illustrated by the analysis of the image information from the Martian satellites (see Frontispiece) now in progress. The impact response in these is clearly unusual in comparison with the features observed on the moon. The crater density indicates high ages of the surfaces. The spheroidal shapes of both satellites suggest that they are derived by accretion from smaller bodies rather than by fragmentation.

Observations of patchiness in the optical surface properties would be valuable to measure heterogeneity in composition; Earth-based color measurements already indicate that such heterogeneities exist among the asteroids.

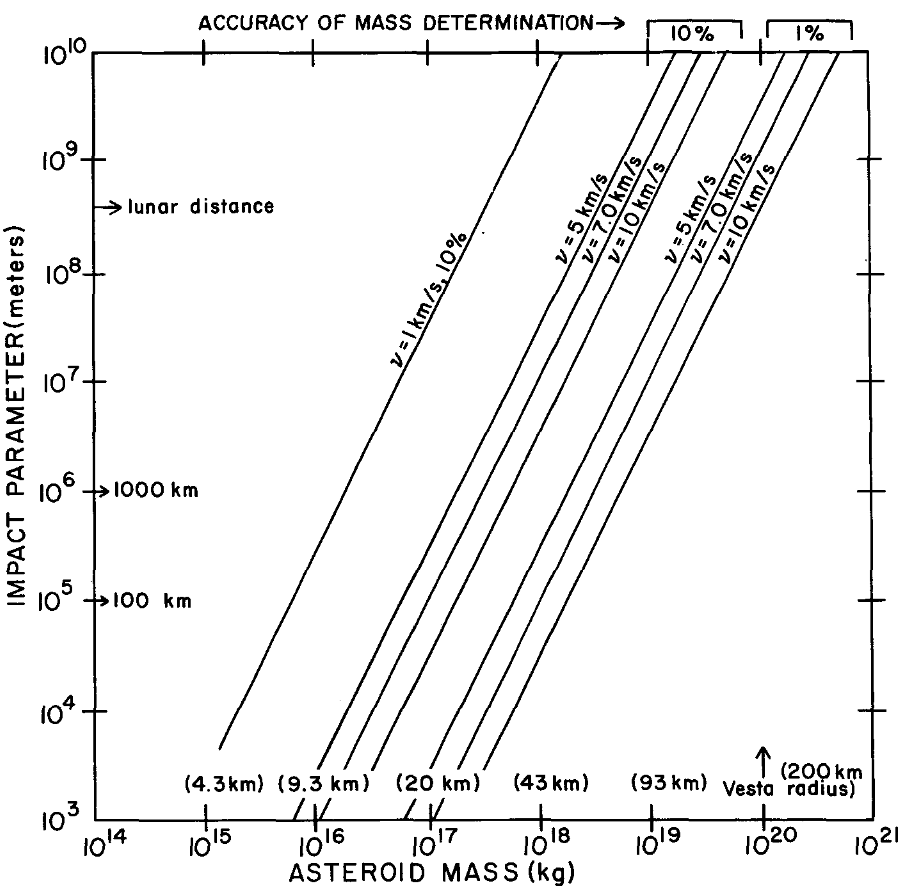

Fig. IV-3. Possibilities of mass determination during flyby of an asteroid (after Anderson 1971, courtesy of V. Eshleman).

c. Particles and fields

Although a fast flyby imposes severe limitations on measurements in the cometary environment, some important information can be obtained which will serve as a guide for more accurate measurements during rendezvous missions. Rather than attempting to resolve fine structures under these conditions, it would appear most useful to emphasize integrating observations, including gradients in total gas pressure and ionization over large regions as well as average abundance of selected species of diagnostic significance.

Also of importance is the use of the fast flyby opportunity to establish the size distribution, concentration and composition of solid particles in the cometary environment. This is crucial for the understanding of the relationship between comets and meteoroids and also for evaluating the risks to space probes during subsequent missions.

The cometary atmospheres are highly interesting as models for plasma processes in space. Our present understanding of them is rudimentary. Their hydromagnetic state should be explored and the electric current systems should be mapped. This can be done by essentially the same methods as are used in exploring the upper ionosphere and the magnetosphere, aiming at measurements of magnetic and electric fields and particle flux including anisotropics in the particle distribution. The region of interaction between the solar wind and the cometary atmosphere is particularly important. During flyby these measurements have to be carried out in an integrating mode and will serve as a basis for planning and executing high resolution measurements during subsequent rendezvous missions.

In summary, fundamental scientific objectives can be pursued by fast flyby missions to asteroids and comets; however, they are limited in comparison with missions permitting extended stays near or on the objects of interest. They represent a necessary preparation for more ambitious missions later and can be achieved at a relatively modest cost. In order to maximize the information return, each mission should include flybys of several targets. The final target might be a comet where penetration as near the nucleus as possible is attempted even at the risk of destroying the spacecraft.

IV.3. Rendezvous Missions

In this stage it should be possible to make sustained measurements and observations in the vicinity of comets and asteroids selected on the basis of the results from flyby missions. The progression to the rendezvous mode should make it possible to solve some of the most central problems associated with these bodies.

a. Cometary atmospheres

In the case of the comets, investigations should focus on the chemical and physical characteristics of the plasma in the coma and the tail. The order of magnitude studies of the magnetic and electric structure of the cometary envelopes, which become feasible during rapid flyby, can during rendezvous missions be followed up with detailed measurements. Such detailed and extended observations are necessary for clarifying the complex and highly inhomogeneous electrodynamic structures which are indicated by present observations.

b. Solids in comets

Furthermore, it will be important to investigate the distribution of solid matter in dense agglomeration as a core and in disperse form as dust. Analysis of gas, collected and concentrated by the spacecraft, will bring us an important step closer to the understanding of the parent material that gives rise to the observed spectra of molecules, radicals and ions. This question in its turn is intimately associated with the general and fundamental problem of how volatile matter is gathered in space and how it is again dissipated. In this connection it would be important to evaluate the use of the new ultrasensitive infrared laser absorption techniques (Kruezer 1971) that for asymmetric molecules promise higher signal-to-noise ratios and greater instrumental simplicity than the mass spectrometric techniques now relied upon for space measurements of this kind.

The distribution of solid particles within the comets and along their orbits is related to the question of the origin and progressive change of these bodies, and of the accretion and dispersion of matter in Kepler orbits. In the most concentrated state, this matter is aggregated into what can rarely be observed as a true nucleus; the answer to the question of its structure, composition and dynamic development could be one of the clues to the primordial development in the solar system.

Experiments made during rendezvous missions aimed at clarifying the nature and distribution of solid matter in comets will include measurements of light scattering, impact rate and composition of impact generated gas, as well as viewing of the central regions of the comet. Aside from its scientific interest, the velocity and density distribution of particulate matter in the central and peripheral regions of the comets is of importance for the evaluation of the possibilities for landing.

Particulate solid material probably occurs in high concentration near the center of active comets, and since size and velocity distributions are unknown, penetration near the center by the rendezvous spacecraft may not be advisable. Instead, the possibility of deploying detachable probes for exploration of the interior regions of the comet should be further investigated. Electrodynamic investigations of the coma and tail might also benefit from the detachable probe concept. which also offers communication advantages.

To obtain maximum information on the dynamics of the central regions, it may be desirable to select for investigation a comet which shows particularly pronounced effects of non-gravitational forces. The relationship between long- and short-period comets is one of the partially solved problems which may hold information on the evolution of circumsolar matter. Another problem is the extreme variation in appearance of the matter in the central region, which in the comet P/Honda-Mrkos-Pajdusakova (HMP) has been reported at times in the form of one, other times as several luminous bodies, whereas at other times again no such bodies could be observed even under optimal viewing conditions. Detailed investigation of both short-period comets with and without marked variability in these respects, such as P/Encke and HMP, is important as well as the investigation of longer period comets such as P/Halley.

c. *Asteroids*

In the case of asteroids, rendezvous missions should be possible that approach the object close enough to observe surface features in some detail and subsurface structure by radar measurement. Relative amounts could be determined of abundant elements which have emission lines in the soft x-ray region, such as sulfur K and longer and the iron $L\alpha$ complex, by observing the fluorescence radiation excited by solar x-rays, protons and the α-particles. Natural and induced radioactivities could also be measured in the rendezvous mode by gamma-ray spectrometry. Other desirable measurements would include irregularities in the internal mass distribution by gradient gravimetry and of possible magnetic fields and field gradients. It is uncertain if the asteroids would have such a magnetic structure as to result in a measurable dipole field. The presence or absence of such a field, together with measurements of shape, surface and subsurface characteristics, and internal distribution of mass would greatly help us to understand the accretion-fragmentation history of these bodies and their possible relationships to comets. From this latter point of view, it would also be desirable during rendezvous missions to measure the plasma environment around asteroids, the extent to which it is determined by solar wind gas release from saturated surface material, and also if internally contained gas components can be discerned. This effect could be particularly important for distinguishing old comet nuclei.

IV.4. Soft Landing and Exploration by Remote Control Instrumentation

Measurements carried out on the surfaces of asteroids and, if possible on the central agglomerations of matter in comets, would provide a breakthrough in the exploration of these bodies. Properties, which in the introductory types of missions can only be studied indirectly, can in this mode be accurately evaluated by direct access to the source materials and by integration over long time intervals. The merits of such studies have been amply demonstrated by the extensive unmanned experiments on the lunar surface carried out as a part both of the U.S. and the U.S.S.R. space efforts.

Aside from the wealth of scientific information that could be obtained, it would seem that important technological advantages would also be gained. The U.S. space program has extensively emphasized and demonstrated the usefulness of man as a decision making operator in space. However, in the next decade exploration beyond the earth's environment will largely have to be carried out in a remote control mode. This would seem to make soft landing on asteroids and comets combined with remote instrumental exploration from Earth-controlled, mobile landing crafts one of the most significant achievements in the next decades of space exploration.

a. Target selection

At the present state of our knowledge, bodies known to lack extensive gas activity would appear to be the most important first targets. These requirements would focus interest on the more easily accessible asteroids including the Amor group and, more remotely, objects suspected to be inactive comets, such as some of the Apollo asteroids. Closeness to the earth would, in addition to scientific interest, appear to be an important consideration from the point of view of remote control and telemetering of data. The Amor group of asteroids offer this advantage since they are closer to us than Mars; also several members of that group appear to be temporary, intermittent or long-term members of the earth-moon system and as such to be of particular scientific interest.The ultimate selection of targets for landing and sample return should await the information that can be gathered by the flyby and rendezvous missions.

b. Surface imaging

The density of impact craters as well as their shapes and sizes would provide information on the age and nature of the surfaces observed. These parameters would give clues to the rate of breakup and erosion compared to the rate of accretion. Images serving this purpose should be obtained both during close approach and on the surface in order to cover the range of crater sizes.

These can, as is now known from the Martian satellites, have upper limits comparable to the size of the object itself.

Other visual observations during approach and while on the surface may give evidence for sturctural changes such as fracturing, faulting and collapse. The topography or albedo features should be surveyed, which are responsible for the irregularities that are already in many cases suggested from lightcurves.

Evidence of variations in albedo would also be of significance as preliminary suggestions of heterogeneity in surface composition. Other features observable by imaging, such as the configuration of material accreted at low relative velocity, surface material rearranged by impact, and the distribution of material on slopes and its competence against sliding, would give us the first information on the mechanical behavior of matter on bodies with minimal gravitational fields. This information would be important in understanding the accretion and growth of the embryonic bodies in the creation of planets and satellites as well as comets and asteroids.

c. *Physical properties of surface material*

The mechanical properties and their change with depth near the surface should be established by probe measurements and would yield information on the compaction processes acting on small bodies in space, and on the possible existence of hard rocks at depth, including ices.

The electrical dipole behavior of the dust found on the moon and suggested on asteroids by polarization measurements can probably be measured in place by xerographic techniques. The electrostatic properties are probably most important in determining the course of beginning accretion in a low gravitation environment, and the response of the surface material to low velocity impact.

d. *Chemical properties and crystal structure of surface material*

In complex materials, such as meteorites and lunar soil, instrumental chemical analysis can be carried out with greater simplicity and accuracy than determination of crystal structure. For this reason, emphasis should be placed on obtaining the maximum amount of chemical and physical information, from which structural interpretation can be indirectly inferred. Simple optical devices providing qualitative information on groups of minerals could also be considered.

The most promising chemical techniques on the basis of present experience are alpha spectrometry coupled with x-ray sensing of heavier elements, and furthermore, gamma-ray spectrometry for the measurement of natural and induced radioactivities. Measurements on surface material should be carried out at several sites on the same body since the variations in composition and other properties are as significant as the absolute values, or they may be even more meaningful. Any such measurements of the heterogeniety of surface and internal properties of asteroids and cohesive cometary nuclei would be most useful for judging the prehistory of these bodies and their integral parts.

e. Atmosphere, gas flux and subsurface sources of gas

One of the central goals for understanding the agglomeration of solid matter in comets and the nature of the cometary atmosphere is the probable existence in these bodies of condensed volatile materials, and their rate and mechanism of escape. This problem is, however, not limited to visibly active comets; one would expect similar conditions and processes, although attenuated, to occur on such asteroids that can be suspected to be comets with highly decreased gas activity. Instruments capable of measuring volatile molecules would consequently be among the most important payload components of soft landed probes on both comets and asteroids. Provisions should be made for subsurface sampling of gas by a tubular probe provided with a heating device for vaporizing ices and other volatile components.

As one of the most versatile and promising methods for assaying trace amounts of asymmetric molecules, the recently developed infrared laser techniques (Kruezer 1971) should be explored for space applications; sensitivities of the order of one part per billion in a one centimeter path is characteristic. Current mass spectrometric techniques, already tested extensively in space, should also be exploited. The use of active seismic experiments for gas release should be investigated. Water vapor probably is the most important volatile determining the cometary (and possibly asteroid) atmosphere. Hence specific techniques (such as dielectric measurement of adsorbed vapor) for the determination of concentration and flux of water should also be considered. Passive seismic experiments could be useful on comets to record effects of high gas fluxes from the interior which may occur there.

f. Internal structure and properties

For the determination of the internal structure and properties, especially their inhomogeneous distribution, seismic, magnetic and gravimetric measurements would be of interest. Active seismic experiments should particularly consider the possibilities for resolving compact, high density regions of ice, rock and metal emplaced in various amounts and configurations associated with low density particulate and welded materials.

Expected values of remanent magnetization could possibly be based on observations from meteorites, which range between 10^{-5} to 10^{-3} emu/g in carbonaceous chondrites. Metallic iron could constitute a variable fraction of asteroids and comets. If this is the case, extreme magnetic and gravitational heterogeneities would be possible; any observalbe contrast in these properties would be of importance in determining the size and nature of the building blocks that make up the bodies.

In general all measurements of internal structure should be carried out from a relatively large number of points on the surface of each body investigated in order to give optimal information; measurement from a vehicle that can hop from station to station would appear to be particularly practical in the low gravitational fields of asteroids and comets.

IV.5. Sample Return

Measurements of physical and chemical properties and their variations on the surface of asteroids and cometary nuclei would bring about an enormous increase in our knowledge of these bodies and of the constructive and disruptive processes in the solar system. However, some of the most crucial measurements can only be carried out with the control possible in Earth laboratories. Other properties of importance can be measured *in situ* only with great difficulty and mostly with inferior accuracy and meaningfulness compared to laboratory analysis. To these groups of measurements belong age determination, particularly in separated crystalline materials, and cosmic ray irradiation features which have provided one of the most successful tools in establishing the early history of the constituent grains and their mode of accretion.

Other such laboratory dependent measurements include intricate magnetic studies which are capable of revealing the magnetic fields prevailing at the time of formation of the material.

Refined chemical measurements, particularly of some minor and trace components of diagnostic importance, are also practical only on material returned to Earth. The dielectric properties of space materials, which determine texture, cohesion, and impact behavior, are also hard to evaluate quantitatively by remote measurements, and they might be studied in Earth-orbiting laboratories where interaction with the atmosphere is precluded. The significance of those critical properties which can be evaluated only by analysis of returned samples can be seen by comparing our state of knowledge of the moon before and after the sample return missions.

Clearly the decisive step in the study of the formative processes in the solar system will be the return of samples with known field relationships from asteroids, carefully selected on the basis of experience from previous mission modes, and from the agglomerations of solids at the center of comets.

Only small amounts of material are needed for the highly sophisticated measurements that can be carried out on Earth; the extensive information from Luna 16 material was, in the U.S., carried out on a total of a few grams. It has already proven possible with the technology now available in the U.S.S.R. to return samples many times larger than the necessary minimum amount. Under these circumstances it would seem to be a realistic and desirable goal to return representative field samples from selected types of asteroids. Cometary nuclei should also be given high priority among the targets for sample return provided that flyby and rendezvous missions demonstrate that one can safely land on them and sample them with the aid of present technological means.

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Chapter V

COMET AND ASTEROID EXPLORATION AS A FOLLOW-ON TO LUNAR STUDIES

Prominent among the reasons for exploration of comets and asteroids resulting from our recent intensive studies of the earth-moon system are:

1. The need to study more primitive bodies to learn about the early history of the earth-moon system.
2. The problem of the mysterious enrichment of refractory elements and depletion of volatile elements in terrestrial and lunar rocks compared to estimated "cosmic" abundances.
3. The desirability of studying the products of the sun and the galaxy at different distances from the sun than the earth-moon system.

Chapter VI-4 further explores these three points.

V.1. Comets and Asteroids are the Most Likely Candidates for Primative Materials

In the broad tripartite scientific reasons for study of the moon – to learn more about the earth, the sun, and the moon itself – use of the moon as a *Rosetta stone* to learn more about the early history of the earth has been the *keystone* justification not only among the scientific community but with the press as well. Although rocks older than 3000 m.y. are far more abundant on the moon than on the earth, the oldest known rocks, whose ages are unequivocal, are about the same age, ~4,000 m.y. Rocks of such old age on the earth have only recently been discovered. Some evidence of altered older rocks exists in lunar samples – famous breccia 12013 may well be 4400 m.y. old and the discovery of extinct plutonium-244 suggests a source again about 4400 m.y. old. Indirect evidence that the moon originated about 4600 m.y. ago is better than the evidence that the earth is 4600 m.y. old, but such an age of origin for both bodies is open to dispute. Although the localities on the moon expected to yield primitive material are yet to be sampled, hopefully by Apollo 17, evidence is mounting that discovery of rocks on the moon with ages incontrovertibly older than 4000 m.y. is not likely. The moon was just too active, from accretion of planetesimals if not from inner energy, to permit primitive material to survive unaltered. The earth, of course, had in its early history all the early accretionary problems suffered by the moon, but in addition has undergone thousands of millions of years of wind and water erosion in addition to dynamical activity generated by inner energy. A more complete understanding of the first half billion years of Earth and moon history must be sought elsewhere.

The existence of very primitive material is known from the examination of meteorites. Lead isotope studies of several meteorites in the early 1950's indicated their age to be 4550 m.y. (Fig. V-1) with a simple isotopic pattern relative to that of the moon (Fig. V-2). This estimate has subsequently been confirmed by potassium-argon and rubidium-strontium studies on prime meteorite material (Fig. V-3) [with a few possible exceptions, most notably that of Kodaikanal, an iron meteorite, at 3800 m.y. (Fig. V-4)]. The youngest features in meteorites are as old as the oldest known materials on the earth and the moon. Meteorites are thought to come from larger bodies. Just which ones is a matter of controversy, but hypotheses have been developed that indicate some meteorites may come from asteroids of various kinds, while carbonaceous chondrites-type I, the most primitive meteorites, possibly come from comets. Few if any meteorites appear to have come from the moon, Mars, Venus, or other planets. Therefore, if we wish to study the most primitive materials in our solar system, we must study comets and asteroids.

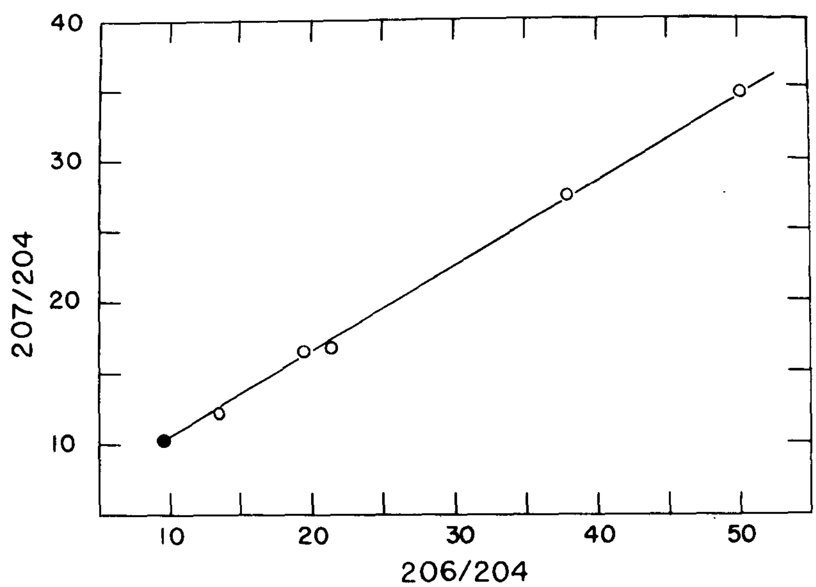

Fig. V-1. A plot of lead-207/lead-204 versus lead-206/lead-204 for 5 stone meteorites (open circles) and the iron sulfide phase – troilite – in meteorites. The lead isotope data lie along a straight line and an age of origin may be calculated from the slope of the line, 4550 m.y. (Figure redrafted from the study by V. Rama Murthy and C.C. Patterson, Primary Isochron of Zero Age for Meteorites and the Earth. Jour. Geophys. Res. *71*, 1161, 1962.)

For convincing dating of materials from comets and asteroids, as well as detailed mineral investigations, returned sample material is probably required. The sample need not be large; the special volume on rock 12013 was based on studies of an aggregate sample weight of 6 grams and the special publication on Luna 16 was based on an aggregate sample weight of 3 grams including full dating and mineralogical studies on a 60 milligram "boulder". Larger samples are desired, however, to provide inclusion of a greater variety of materials.

V.2. Further Exploration of the Significance of Enrichments in Refractory Elements and Depletions in Volatile Elements in Terrestrial and Lunar Rocks Compared to Estimated Cosmic Abundances

Lunar basalts have been found to be enriched in refractory elements, such as uranium and thorium, by as much as a factor of 100 relative to estimated "cosmic abundances" (Fig. V-5) and depleted in "volatile" elements, i.e. – elements that are gases above 1000°C, such as lead and gold, by as much

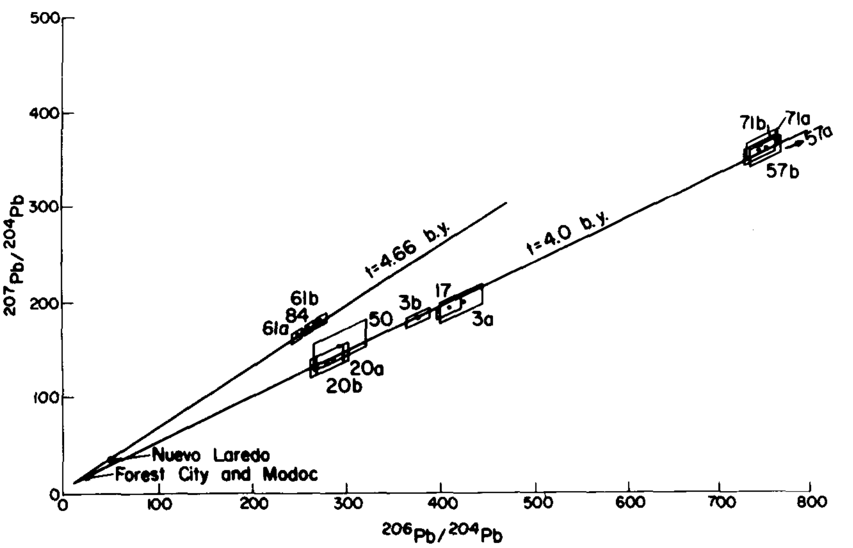

Fig. V-2. A plot of lead-207/lead-204 versus lead-206/lead-204 for lunar samples returned by the Apollo 11 mission. Three meteorite samples – Nuevo Laredo, Forest City and Modoc – are plotted for comparison. Soil and breccia lie near the meteorite line shown in figure V-1. Basalts lie along another line showing that the moon has been an active body since it formed. Addition of Apollo 12 samples complicates the diagram, and addition of Apollo 14 samples further complicates it. Numbers by the analyses are the last two numbers in the Apollo sample catalog. (Figure from M. Tatsumoto, Age of the Moon: An Isotopic Study of U-Th-Pb systematics of Apollo 11 Lunar Samples, II. Proc. Apollo 11 Lunar Sci. Conf., Geochim. et Cosmochim. Acta Suppl. 1, v. 2, p. 1595, 1970, Pergamon.)

as a factor of 10,000. (Cosmic abundances as used here are heavily influenced by carbonaceous chondrites, type I.) Terrestrial basalts (Fig. V-6) also show similar enrichments of refractory elements and depletions of "volatile" elements, but the depletion of volatile elements rarely exceeds a factor of 100. These elemental characteristics of the earth and moon are similar enough to suppose that the two bodies must have formed close together, but different enough such that it is unlikely that the moon was derived from the earth. Contrary to observations on rocks from the earth-moon system, cosmic abundances as represented by carbonaceous chondrites, type-I are quite different so that not all objects in the solar system display the peculiarities of the earth-moon system in elemental abundances. The cause of these elemental peculiarities of the earth-moon system is a matter of vigorous controversy. Some would like to store the "volatile" elements in the cores of the earth and the moon. Others would like to have the "volatile"

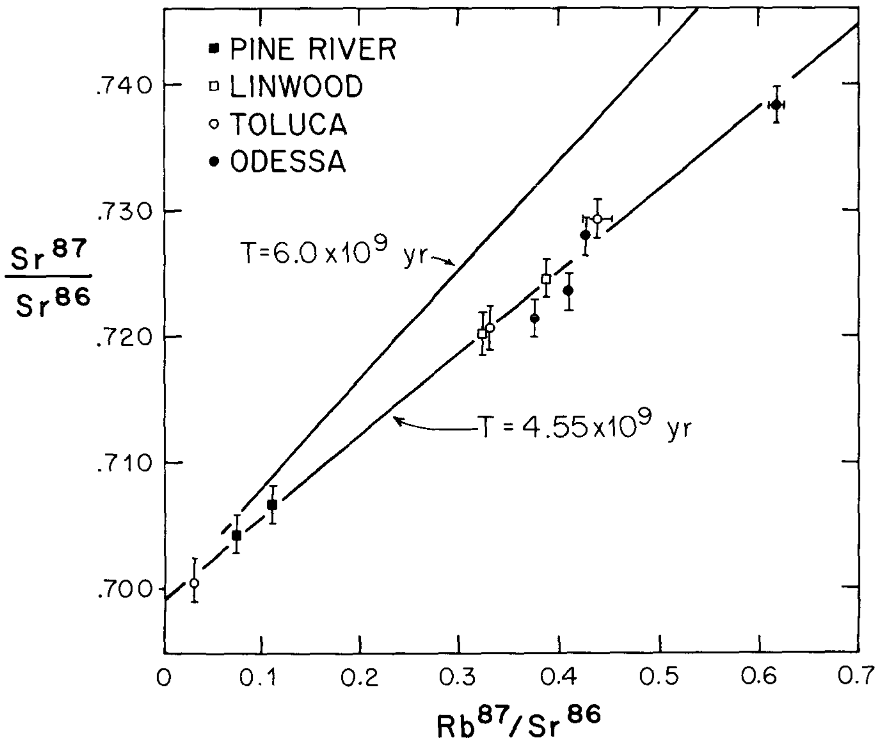

Fig. V-3. A plot of strontium-87/strontium-86 versus rubidium-87/strontium-86 for 4 meteorites – silicate inclusions in iron meteorites. The age calculated from the slope of the line through the data is in excellent agreement with the data from lead isotopes. (Figure from D.S. Burnett and G.J. Wasserburg, ^{87}Rb ^{87}Sr ages of Silicate Inclusions in Iron Meteorites. Earth Plan. Sci. Letters v. 2, p. 397, 1967.)

elements in the atmospheres of the bodies early in their history and then have them blown away by the solar gale associated with the hottest phase of the sun – the Hayashi phase. The study particularly of main belt asteroids as well as of Apollo and Amor asteroids could greatly aid in solving this dilemma in the distribution of the elements and the consequent confusion in the hypotheses concerning cosmic abundances and the evolution of the earth-moon system.

A first approach in this kind of study could probably be performed in a rendezvous mission by gamma-ray spectrometry which could determine

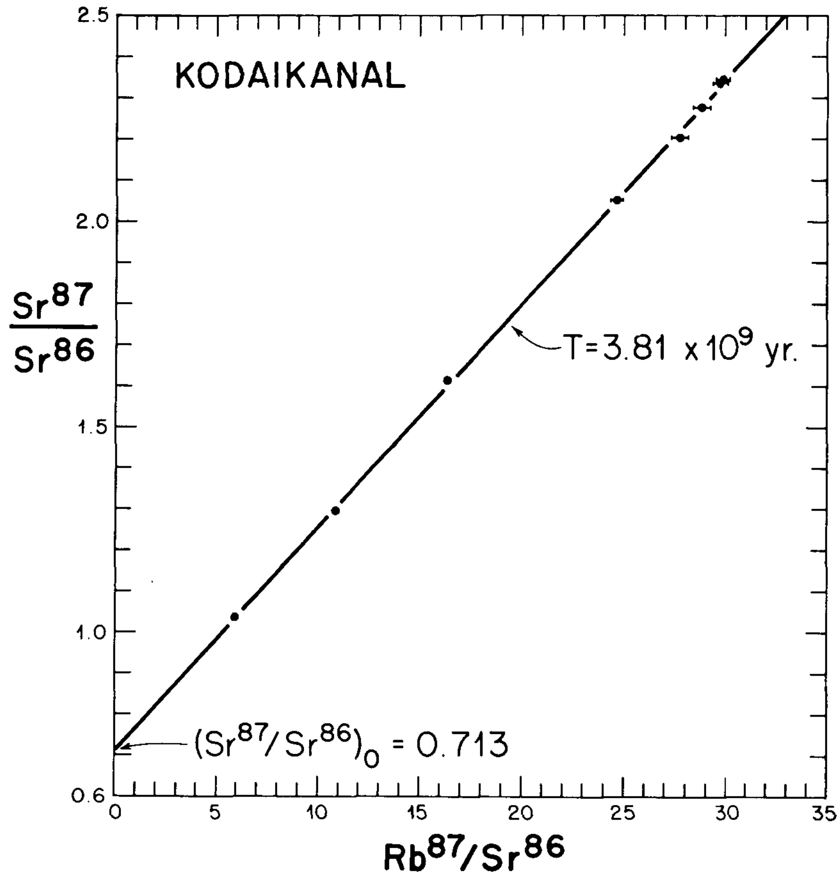

Fig. V-4. A plot of strontium-87/strontium-86 versus rubidium-87/strontium-86 for silicate inclusions in the iron meteorite Kodaikanal. The age determined from the slope of the line through the data is distinctly less than that in figure V-3. This sample is yet to be analyzed for lead isotopes. (Figure from D.S. Burnett and G.J. Wasserburg, Evidence for the Formation of an Iron Meteorite at 3.8 x 10^9 Years. Earth Plan. Sci. Letters v. 2, p. 137, 1967.)

uranium and thorium, refractory elements, and potassium, a "volatile" element. Of further significance, these elements are also the prime heat generating elements. An accompanying x-ray fluorescence study could also provide data on the key elements silicon, aluminum, and magnesium. Preferably a variety of asteroids would be investigated because there is no reason to believe any grouping of asteroids is of uniform composition. Recent infrared studies by Clark Chapman have indicated some asteroids are similar to chondrites of different kinds (some of orthopyroxene; a chain silicate rich in iron and magnesium, others predominately olivine which is a framework silicate rich in iron and magnesium), one of pigeonitic clinopyroxene (a chain silicate rich in calcium and perhaps aluminum as well as iron and magnesium) (4 Vesta), some similar to terrestrial basalts, and others that are black (probably of iron-nickel, carbon, or magnetite). The gamma-ray orbital study made on the mission of Apollo 15 further helps

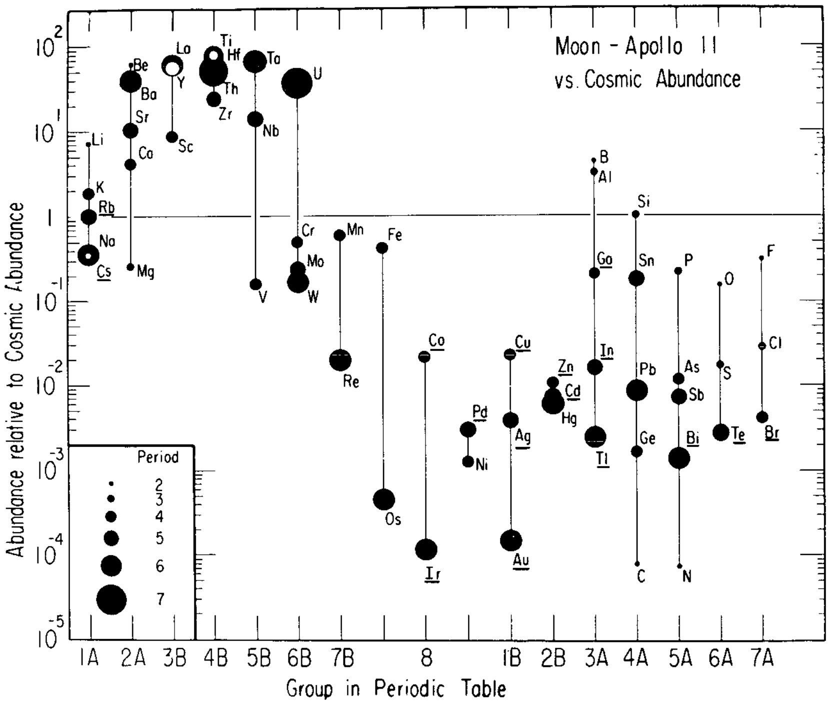

Fig. V-5. Elemental abundances in Apollo 11 rocks normalized to "cosmic abundances". (Figure from R. Ganapathy, R.R. Keays, J.C. Laul, and E. Anders, Trace Elements in Apollo 11 Lunar Rocks: Implications for Meteorite Influx and Origin of the Moon. Proc. Apollo 11 Lunar Sci. Conf., Geochim. et Cosmochim. Acta, Suppl. 1, v. 2, p. 1117, 1970, Pergamon.)

elucidate the need for studies of planetisimals in the solar system. High concentrations of thorium (10 ppm) were found only near the Imbrium Basin and the possibility cannot be excluded that the high thorium concentrations are a property of the impacting planetisimal and not a result of lunar differentiation. If so, the impacting planetisimal must have had 100 ppm thorium or more to allow for dilution by lunar materials. Discovery of asteroids having such great contents of refractory and radioactive elements could only be described as astonishing. The next big step in studying the early chemical evolution of the solar system must come from more primitive bodies than studied so far. The best candidates for such studies are comets and asteroids.

V.3. Study of Products from the Sun and Galaxy at Different Distances from the Sun than that of the Earth-Moon System

Just as the moon has been found to be an ideal repository to study products issued by the sun, comets and particularly asteroids should help in

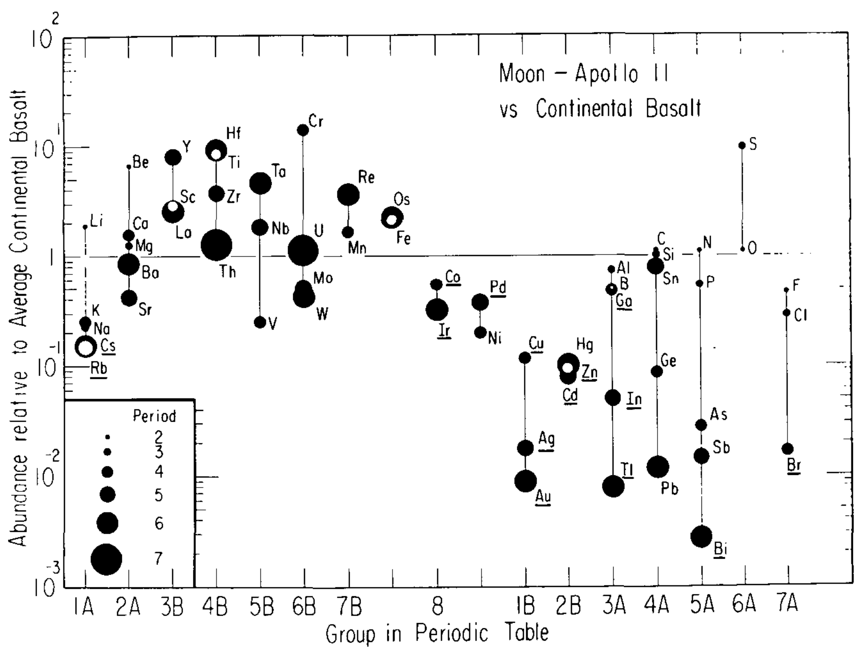

Fig. V-6. Elemental abundance in Apollo 11 rocks normalized to average continental basalt. (Figure from R. Ganapathy, R.R. Keays, J.C. Laul, and E. Anders, Trace Elements in Apollo 11 Lunar Rocks: Implications for Meteorite Influx and Origin of the Moon. Proc. Apollo 11 Lunar Sci. Conf., Geochim. et Cosmochim. Acta, Suppl. 1, v. 2, p. 1117, 1970 Pergamon.)

furthering these studies. Main belt asteroids will give us estimates of the products from the sun that have traveled 2.5 to 3 times as far as those that have reached the moon. Many investigators believe that solar wind action is an important element in erosion on the moon, and the question might well be asked whether the erosion rate of asteroids in the main belt is different from that on the moon. The time-averaged solar flare spectrum in asteroidal material could be measured through comparison with similar data on lunar samples, and the problem of solar flare deceleration could be studied. Lower energy galactic cosmic rays are thought to increase farther out in the solar system beyond Mars and might be an important erosion mechanism of asteroidal bodies. Measurements of the products of galactic cosmic ray exposure in asteroidal materials should allow the age of the most recent major impact event which disrupted the asteroidal surface to be determined and allow estimates of the average macroscopic surface erosion rate to be made. The long flight times for an asteroidal mission offer unique opportunities for long-term exposure of selected detector materials to galactic and solar particles. Important experiments include determination of present-day galactic cosmic ray heavy element compositions in the iron group and greater atomic numbers (e.g. by particle track techniques), present-day solar wind and solar flare fluxes and composition (by surface analysis and mass spectrometric techniques), searches for solar radioactive nuclei (e.g. tritium or manganese-53) and present-day micrometeoroid measurements. Comparison of the micrometeorite impact ("zap" crater) densities on asteroidal materials with lunar materials should help in estimating a mean density of interplanetary matter.

Apollo and Amor asteroids would give us integrated solar wind and galactic ray effects. The integrated effects for solar wind should probably be close to those of closest approach to the sun where the flux is greatest. The galactic ray effects would probably be more representative of the more distant parts of the orbits where comets and asteroids spend most of their time and the galactic ray intensities are the greatest.

Asteroid missions appear to be ideal missions for studies of present-day and time-integrated galactic and interplanetary particle fluxes and would greatly complement similar studies now being made on lunar samples.

Some information relative to solar studies as well as the search for extinct radionuclides, such as plutonium-244, could probably be gained on a lander mission from *in situ* mass spectrometry for rare gases. Micrometeoroid impact studies might possibly be done on a lander mission by high resolution, high contrast imaging. Spallation and fission-track studies and studies involving spacecraft contained detector materials probably require asteroidal sample and detector material return.

C-2

Chapter VI

EXPERIMENTS AND INSTRUMENTS

We shall discuss techniques in a general manner because spacecraft design and trajectory possibilities impose specific restrictions on flight experiments. The sections in this chapter are in order of increasing difficulty. Most techniques applicable to fast flyby also apply to slow flyby or rendezvous, but such repetition of technique discussion is avoided. A detailed discussion of a fast flyby mission for a specific spacecraft, one similar to Pioneer F/G, is given in a special report by Gehrels (1972).

VI.1. Observation from Existing Missions

The recent imaging of Phobos (see Frontispiece) and Deimos by the Mariner mission was impressive. Even though the resolution has been not more than about 300 lines over the surface, much was learned from these pictures. Images have a conceptual value to direct general science and specific detailed studies. A precise measurement of the size and albedo of these bodies was obtained and we learned of their exceptional roughness and saw the effects of bombardment by surprisingly large bodies. We recommend that observations of the satellites be made during the Viking missions, as well as for satellites of Jupiter whenever the opportunity arises.

With spacecraft that travel at random through the asteroid belt the chance of encounter with an asteroid larger than, say, 1 km has a negligible probability. For Pioneer F and G, for instance, none of the numbered asteroids could be found close enough to be observed with a 2.5-cm telescope (that is, to a brightness limit of the 5th magnitude). Without a special mission, therefore, essentially no new input can be expected concerning the larger asteroids.

VI.2. Fast Flyby Missions

The fast flyby missions are the cheapest and least complex. The relative velocities of encounters with asteroids during a mission to Jupiter, or to the Trojans, is generally on the order of 16 km per second while for a trajectory that stays within the asteroid belt, the encounter velocities are lower, on the order of 10 km per second. The trajectories having an aphelion in the asteroid belt are better in this respect. Targets could include an asteroid in the main belt or one of those crossing the Mars orbit, or a comet at distances ranging out to that of Jupiter, or the satellite of an outer planet. An exciting possibility exists of a multi-flyby of a comet and two or more asteroids, during the same mission.

A set of experiments for comet missions, modified from Roberts (1971), is presented in Table VI-1. It is also fairly complete for the asteroid flybys and shows a comparison of fast and slow flybys and rendezvous experiments. Note that interplanetary experiments related to cosmic rays are not listed, but can be flown on an early survey mission at small additional cost in weight and data rate. Further discussion of flyby missions occurs in Chapter VII.

VI.3. Slow Flyby Missions

If the relative velocity is 1 to 5 km/sec and the passage not too distant, it becomes feasible to get infrared data on a small solid body, to detect x-rays from accelerated plasma electrons (if any), and to detect γ-rays from decay of natural and induced radioactivity in the outer meter of the body. Some of the fast-flyby experiments of Table VI-1 gain from increased time resolution. The error in a mass determination from Doppler tracking goes down as the 3/2 power of the relative velocity. Table VI-2 gives a set of instruments to be considered for a slow flyby mission (typically 1-5 km/sec at 100 km distance).

VI.4. Rendezvous Missions

At velocities below 1 km/sec a gravity gradiometer (Forward 1971) can make a precise measurement of mass, including high-order moments. A nucleus or surface probe becomes possible at an approach velocity of a few meters per second, and would provide reconnaissance data as a basis for the design of an "anchor". On the surface, major elements could be probed by backscatter of α-particles, x-ray fluorescence, neutron capture accompanied by α-ray analysis, a seismometer and mass spectroscopy of plasma from a laser pulse. If the anchor is a penetrating boom, a temperature gradient measurement would be important. An accelerometer and strain gauge should record the impact. Microscopic imaging by holography using rotating linear polarization of the reference beam may reveal the structure and proportion of opaque, birefringent, and isotropic phases present in the surface layer.

The dust particle experiments that require high relative velocities may be omitted on a rendezvous mission. Other experiments described in the previous sections are generally significantly enriched by rendezvous. New sensitive laser absorption techniques (Kruezer 1971) might be considered, because of simplicity, as a replacement of mass spectroscopy for analysis of asymmetric molecules. Table VI-2 gives a set of instruments to be considered for a rendezvous mission.

Two primary problems are mentioned by Bender and Bourke (1971) in NASA SP-267, namely that for rendezvous and sample return missions the last

TABLE VI - 1

POSSIBLE EXPERIMENTS FOR A FAST FLYBY TO COMETS AND ASTEROIDS

Instrument	Experiment	Significance
Imager (Spin Scan?)	Mapping surface.	Determine shape and surface features of asteroid and opacity of comet.
Tracking Data Analysis	Determine the influence of gravitational field on trajectory.	Determine mass and, in conjunction with imaging, density.
Magnetometer	Determine magnetic field and variations.	Magnetic field associated with asteroid and its interaction with the solar wind. Nature of cometary tail.
Plasma Probe	Determine nature of plasma.	Nature of plasma in vicinity of asteroids and in comet tail.
Impact Ionization Counter	Determine particle distribution.	Examine distribution of particles in vicinity of comets and asteroids.
Mass Spectrometer	Collect and analyze particles.	Determine chemical composition of cometary material.
Photopolarimeter	Determine brightness, colors, and polarization over a wide range of phase angles.	Determine surface texture and composition of asteroids and particle characteristics of comets.

TABLE VI - 2

SLOW FLYBY – RENDEZVOUS COMETS AND ASTEROIDS

Instrument	Experiment	Significance
X-ray spectrometer	Determine Al/Si and Mg/Si ratio and perhaps others using solar energy as a source.	Major parameter in determining bulk chemistry of body.
Gamma-ray spectrometer	Determine distribution of U, Th, K, and others.	Important to characterize chemistry, differentiation and heat sources.
High resolution imager	Sample surface features in detail.	Look for detailed surface appearance and reconnoiter for a landing.
Photometer and polarimeter	Determine spectral reflectance in opitcal and near IR, polarization-phase curve.	Determine, if possible, a few features of bulk minerology such as iron distribution and particle size distribution.
Electromagnetic sounders	Determine reflection coefficient as function of frequency from a few Mhz to a few hundred Mhz.	Give dielectric constant surface scattering and subsurface layering in upper few 100 meters.
Laser altimeter	Examine roughness of surface and shape of body.	Impact history of the body.
Magnetometer	Measure magnetic field due to body (to about 0.1 gamma).	Establish level of any paleofield frozen into the rocks as well as solar wind character.
Tracking data analysis	Determine mass by disturbance of trajectory.	Knowing size of body, this will give a measure of the density, of fundamental importance to the nature of asteroids.
Gravity gradiometer	Determine mass distributions of asteroid and mass of cometary nucleus.	Map gross heterogeneity in mass distribution of asteroids.
UV Spectrometer		Examine cometary atmospheres.
Mass spectrometer	Analyze gas material.	Analyze cometary atmosphere (Is the asteroid an old comet?)
Plasma probe		Nature of ionized material in cometary atmosphere.
Nucleus probe with imager		Determine properties of cometary nucleus.

thrusting will always have to be done towards the object because the spacecraft must be slowed down with respect to the object, but it might be done at relatively larger distance with subsequent free fall of spacecraft to the surface. This problem will require study because the thrusting causes contamination just prior to the scientific observations. The other problem mentioned by Bender and Bourke is that approach guidance is needed because, even with the best preparations to improve the ephemerides, the uncertainty of the object within the orbit still is estimated to be on the order of a few thousand kilometers. Experience with terminal guidance may be obtained during the early flyby missions.

VI.5. Automated Sample Return Missions

Sample analysis might be made with instruments on the asteroids and by telemetry of the data back to earth. On the other hand, much better analysis can be made with laboratories on earth which requires that the sample be returned to Earth (see IV.5.). Properties such as surface texture, magnetic field, chemical composition, crystal structure and radioactivity could be studied in detail yielding important information on the origin and evolution of the solar system. The recent exploration of the lunar surface should guide us in planning that of the asteroids and comets.

Any sample of a comet would be highly valuable. An asteroid, however, may be inhomogeneous, because of differential erosion effects and/or the sequence of events in formation. The sampling must be sufficiently sophisticated to record the relation of sample to its surroundings in terms of morphology and chemical features determined in the field. It should preferably permit sampling several regions of an asteroid, chosen by the quick-look and ground control.

Sample return missions to the asteroid 433 Eros have been discussed by Mascy and Niehoff (1971) and also by Meissinger and Greenstadt (1971) in NASA SP-267. Table VI-3 lists some experiments. Favorable launch opportunities to 433 Eros occur, for instance in 1977, but also in 1979 and 1981 when launches for sample return missions could occur. The mission times always appear to be approximately three years in length whether the mission is ballistic or with solar-electric propulsion. The stay times on 433 Eros appear to be on the order of 90 days. A sample size of 25-100 kg may be returned by either a Titan IIID-Burner II with a 10 kw solar electrically propelled vehicle or a Titan IIID(7) Centaur/Burner II chemically propelled vehicle. Preliminary investigation indicates that launch opportunities to 1620 Geographos occur in 1976, 1978, etc. and that this asteroid also requires a 3-year total mission time. These considerations are more thoroughly discussed in the following chapter.

VI.6. Manned Landing

The ultimate in small body exploration would be a manned visit. The above discussion of surface inhomogeneity (Sec. VI.5) applies; choice of samples

TABLE VI - 3

SOFT LANDING

Instrument	Experiment	Significance
Surface imaging	High-resolution imaging in visible and infrared light.	Study craters, faulting, collapse features, color, albedo, etc.
Penetrometer	Determine mechanical nature of near surface material; xerographic study of cohesion.	Is the surface hard or covered by regolith and soil?
Chemical analysis	α-particle spectrometer, X-ray sensing, α-ray spectrometry.	Determine bulk chemistry of surface.
Atmospheric composition (mass spectrometer, etc.)	Study gas emitted perhaps after penetration.	Determine composition of trapped gas.
Heat flow	Measure thermal gradient and thermal conductivity probably during a 90-day mission.	Measure of thermal balance at surface and if it is a good insulator get some measure of internal heat generation.
Seismometer (active and passive)	Listen for impacts due to meteorites and determine depth characteristics using active part with a mortar, complete experiment possible in a 90-day mission.	Nature of impacts and determination of internal structure and gas release.
Magnetometer	Measure steady D.C. field and variations associated with solar wind (record field for 90 days).	Measurement of paleofields and study of plasma properties over a period of time.
Plasma probe	Measure density and time fluctuation of plasma.	Correlation with magnetic variation data.

would be made by the astronaut at the site. A paper discussing some aspects of manned landings was written by Alfvén and Arrhenius (1970).

VI.7. Remarks on Selection of Comets and Asteroids for Space Missions

This panel has not as yet made a systematic study of criteria to be used in the selection of targets for space missions, and we made only a few remarks for further consideration.

For the study of primordial material that has had the least amount of metamorphism, the new comets are the most interesting; their chemical composition is more nearly the original one and they show great and varied activity. It is, however, difficult to plan for an unknown event such as that of a new comet, while the orbit of the target should be precisely known for an encounter or rendezvous to succeed. Detailed studies are needed of the possibilities for planning and execution of missions to comets and of the technical limitations to maneuvers and approach guidance.

A periodic comet that does not show nongravitational effects would have the most precisely known orbit and it would be the most interesting object to study the transition from comet to asteroid.

Long-period Comet Halley (p. ~76 yr) is an active comet of great scientific interest and public appeal. This spectacular comet, with next appearance in 1986, comes as a rare event: Mark Twain (1835-1910), for instance, did not see it. The orbit is known well enough to allow advanced planning and it can be observed from the earth long before encounter or rendezvous. Comet Halley is a challenging target, because of its retrograde orbit, and careful technical studies and preparation will be required.

Asteroids need much more study with groundbased telescopes in order to establish which ones are the most interesting targets. Some of them may be special objects because they appear to be extinct cometary nuclei; 944 Hidalgo and 1936 CA Adonis may be examples of this category.

An interesting but inconclusive debate has been published (Alfvén and Arrhenius 1971, Anders 1971) on the merits of having a mission to a Mars-orbit crosser rather than to the asteroid belt, or to specially selected asteroids in the belt. Ceres, Pallas and Vesta appear to be exceptional objects that do not fit the frequency-size distribution of the asteroids as derived in the Yerkes-McDonald Survey (Fig. 5 of Kuiper *et al.* 1958).

The minute study of any comet or asteroid is obviously of extreme interest. The problem that requires a great deal of research, using ground-based telescopes, is to ascertain which objects, as targets for space missions, will lead to the greatest scientific gain.

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Chapter VII
POTENTIAL FLIGHT MISSIONS TO COMETS AND ASTEROIDS

The practical possibility of spacecraft missions to comets and asteroids has been considered for many years. Within the past decade various study groups in the United States and in Europe have carried out investigations of mission feasibility, characteristics and requirements. The motivation for such engineering studies has been reinforced by the growing scientific interest in exploratory missions. Activity in mission analysis has been greatly intensified since 1967 with the availability of a reliable stable of spacecraft, higher energy launch vehicles, the new technology of electric population systems, and the plans for first looks at most of the planets. Existing flight performance data covers a wide range of target classes and mission modes. A partial list of the documented work in this area is given in the bibliography at the end of this chapter. The objective of this document is to summarize characteristics and requirements of potential missions.

VII.1. Definition of Mission and Populsion Modes

It is convenient to define six distinct mission modes which apply to both comet and asteroid targets, with some subtle variations. These are listed below in the order of increasing mission complexity:

1. Fast Flyby
2. Slow Flyby
3. Multi-Target Flyby
4. Rendezvous
5. Rendezvous and Docking/Landing
6. Sample - Return

The designation "fast" or "slow" flyby refers to the spacecraft's approach speed relative to the target body. In the case of the short-period comets, fast flybys have encounter speeds in the range 8-25 km/sec depending upon the comet's orbit shape and inclination. A similar mission to Halley's Comet or to most long period comets have corresponding speeds in the range 30-60 km/sec. In the case of most asteroids which have more nearly circular and less inclined orbits, the fast flyby speeds are 5-12 km/sec depending upon the orbit and the flight time allowed. Slow flyby missions are defined generally as having approach speeds on the order of 1-5 km/sec. An attractive mission mode for early reconnaissance purposes is a multiple-target encounter; i.e., a fast flyby of several comets or asteroids in succession with a single spacecraft possibly terminating with a rendezvous. Such a mission is more complex than a single body fast flyby due to the longer flight times and navigation requirements.

Rendezvous is the limiting case of slow flyby, i.e., the relative speed approaches zero with the spacecraft trajectory and target orbits being matched exactly. Included in this mission mode are the possibilities of circumnavigation of the target body, separable probes to investigate distinct spacial regions and the nucleus of comets, and establishing a gravitational orbit about asteroidal bodies. The addition of a docking maneuver is most appropriate to asteroid targets whereby the entire spacecraft or some major component thereof actually lands on the body to perform *in situ* measurements. Sample return is the most ambitious mission mode. In this case a physical sample from a comet or asteroid would be returned to Earth, either to be recovered in orbit or via a direct atmospheric reentry.

Several flight (propulsion) modes for accomplishing comet and asteroid missions have been investigated, and are listed below in the order of increasing capability and complexity.

1. Single Impulse Ballistic
2. Solar Electric (SEP)
3. Multiple Impulse Ballistic
4. Nuclear Electric (NEP)

The single impulse ballistic mode employs a chemical (or nuclear) rocket to escape the earth and uses only small velocity corrections for navigation purposes thereafter. This mode is generally only applicable to fast flybys. A multiple impulse ballistic system carries with it a large chemical (or nuclear) rocket to make major velocity changes enroute or at encounter.

Electric propulsion systems employ ion thrusters (typically, mercury electron-bombardment engines) which operate at low thrust acceleration ($2\text{-}5 \times 10^{-5}$g) and high exhaust velocities (30-60 km/sec). Although the required mission velocity is attained gradually over a substantial fraction of the total flight time, the propellant expenditure is low relative to chemical systems. Solar electric propulsion derives the required thruster power from lightweight solar arrays. The SEP technology is in an advanced state of development and is expected to be fully flight-proven by the late 1970's. Nuclear electric propulsion employs a reactor with a thermionic converter system for power generation. This technology is under active development with flight readiness projected to the 1980's.

The results quoted here for solar electric missions are based on a propulsion and power system specific mass of 30 kg/kw and thrust efficiencies of 62%. These are felt to be representative of the technology to be flown on early solar electric missions but as the state of the art advances, the performance will improve with the result that flight times will become shorter and/or payloads higher than those shown here.

VII.2. Comet Mission Performance

Comets may be classified into two general groups for purposes of discussion: (1) Short period comets, and (2) Long period, or nearly parabolic, comets. Generally, the short period comets are fainter, less active and not nearly as spectacular as the new comets. However, because of their relatively frequent apparitions, their future returns can be predicted fairly accurately. The short period comets, then, are the most suitable mission candidates in terms of spaceflight planning requirements. These will be described first, followed by a brief discussion of mission opportunities to long period comets.

These are about 70 short period comets which have been observed at more than one apparition having periods in the range 3.3-100 years and perihelion distances in the range 0.34-3 AU. Table VII-1 presents orbital element data for a representative sample of comets having perihelion dates during the time period 1975-90. Also shown is a qualitative rating of Earth-based (telescopic) sighting conditions which account for early comet recovery and observability at moderate brightness near perihelion. These are included because it is assumed that correlations between simultaneous Earth-based and spacecraft measurement will prove valuable. Figure VII-1 illustrates the orbit size and orientation of several comets. P/Halley is distinguished by its large eccentricity and retrograde motion which makes it a very difficult target for rendezvous.

The performance characteristics of selected comet missions in various classes are summarized in Table VII-2. Net spacecraft mass is defined as the spacecraft science and engineering support subsystems delivered to the target; it does not include the propulsion system or propellant required for primary flight maneuvers. Spacecraft and science payload weights for fast flyby missions are expected to be in the range 250-400 kg and 30-70 kg, respectively. The lower values would correspond to a Pioneer-class spacecraft and the higher values to a Mariner-class spacecraft. The reusable space Shuttle, as currently defined, is capable of serving as the first stage for any of the missions listed, i.e. it could replace either the Atlas or the Titan IIID, although an appropriate upper stage (like the Centaur) is still required. The Table indicates that most fast flyby missions can be performed ballistically using Atlas/Centaur launch vehicles with a flight duration of only 3-7 months. Slow flyby missions through the inner coma region would allow increased capability for high resolution imaging and spectrometry. A three-axis stabilized, Mariner-class spacecraft (450 kg) is probably required for this application. Slow flyby missions are achieved at the expense of larger Titan-class launch vehicles, significantly longer flight times, and either low thrust or

TABLE VII - 1

PERIODIC COMETS LISTED BY PERIHELION DATE

COMET	PERIHELION DATE	PERIOD (YRS)	PERI-HELION	ECCEN-TRICITY	INCLIN-ATION	EARTH-BASED** SIGHTING CONDITIONS
d'ARREST	8/13/76	6.25	1.17	0.655	16.8	G
GRIGG-SKJELLERUP	4/ 9/77	5.11	0.99	0.665	21.1	G
WHIPPLE	3/28/78	7.40	2.47	0.352	10.2	F
T–G–K	1/15/79	5.62	1.14	0.641	9.9	P
ENCKE	12/ 6/80	3.30	0.34	0.847	11.9	G
SCHWASSMANN-WACHMANN(2)	3/14/81	6.50	2.14	0.387	3.7	F
GRIGG-SKJELLERUP	5/13/82	5.10	0.99	0.666	21.1	G
d'ARREST	9/18/82	6.40	1.30	0.622	19.6	G
TEMPEL(2)	5/30/83	5.29	1.38	0.545	12.4	X
KOPFF	8/18/83	6.44	1.58	0.545	4.7	G
ENCKE	3/27/84	3.30	0.34	0.846	11.9	G
T–G–K	8/31/84	5.62	1.14	0.641	9.9	P
AREND-RIGAUX	11/22/84	6.82	1.45	0.598	17.9	P
SCHAUMASSE	12/ 4/84	8.25	1.21	0.703	11.8	F
H–M–P	5/24/85	5.33	0.55	0.821	3.3	P
GIACOBINI-ZINNER	9/ 4/85	6.60	1.03	0.707	31.9	G
HALLEY	2/ 9/86	76.0	0.59	0.967	162.2	G
BORRELLY	12/16/87*	6.86	1.35	0.625	30.3	G
TEMPEL(2)	9/13/88*	5.30	1.38	0.545	12.4	G
PONS-WINNECKE	8/12/89*	6.36	1.26	0.634	22.3	F
JOHNSON	11/11/90*	6.97	2.31	0.366	13.7	X

* APPROXIMATE PERIHELION DATE

** G (GOOD) P (POOR)
F (FAIR) X (NOT STUDIED)

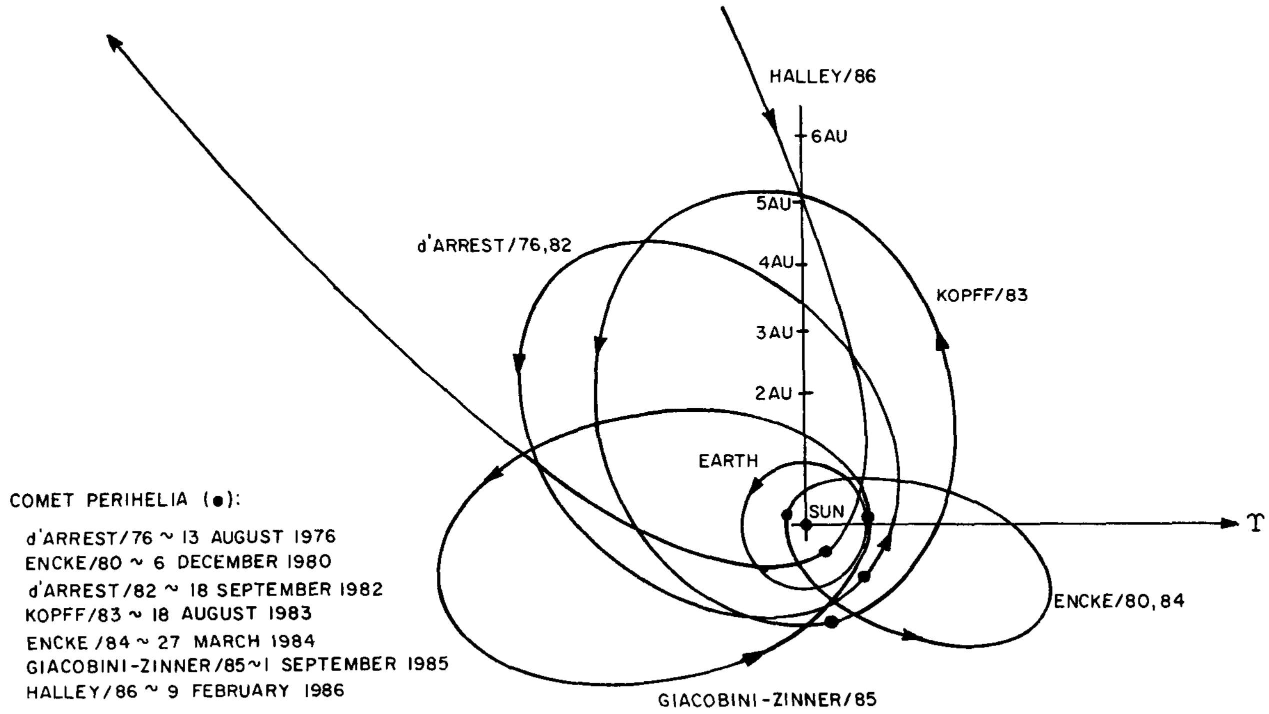

Fig. VII-1. Comparative orbits of several periodic comets.

TABLE VII - 2
COMET MISSION SURVEY

MISSION MODE	COMET/ Apparition	FLIGHT MODE	FLIGHT TIME (Days)	LAUNCH DATE	ARRIVAL DATE	Approach Velocity (km/sec)	LAUNCH VEHICLE
FAST FLYBY							
Net Mass = 250-400 kg	d'Arrest/76	Single Impulse Ballistic	80	5/76	T_p-5^d	13.0	Atlas/Cent
Science = 30-70 kg	Encke/80		80	8/80	T_p-30^d	23.0	Titan IIID/Cent
	Kopff/83		190	2/83	T_p+15^d	8.0	Atlas/Cent
	Giacobini-Zinner/85		170	4/85	T_p+8^d	21.0	Atlas/Cent/BII
	Halley/86		170	6/85	T_p-60^d	55.0	Atlas/Cent
SLOW FLYBY							
Net Mass = 450 kg	Encke/80	Multi-Impulse Ballistic	890	3/78	T_p-85^d	2.0	Titan IIID/Cent
Science = 75 kg		SEP	630	3/79	T_p-10^d	3.0	Titan IIID/BII/10kw
	Giacobini-Zinner/85	Single Impulse Ballistic	1800	11/79	T_p-200^d	4.0	Titan IIID/Cent
		SEP	990	11/82	T_p-50^d	4.0	Titan IIID/BII/10kw
	Halley/86	SEP	900	3/83	T_p-160^d	22.0	Titan IIID/BII/10kw
RENDEZVOUS							
Net Mass = 500 kg	Encke/80	Multi-Impulse Ballistic	1280	2/77	T_p-100^d	0	Titan IIID(7)/Cent
Science = 85 kg		SEP	960	3/78	T_p-50^d	0	Titan IIID/Cent/15kw
	d'Arrest/82	Multi-Impulse Ballistic	1810	8/77	T_p-50^d	0	Titan IIID(7)/Cent
		SEP	740	8/80	T_p-25^d	0	Titan IIID/Cent/15kw
	Kopff/83	Multi-Impulse Ballistic	1443	7/79	T_p-50^d	0	Titan IIID/Cent
		SEP	740	7/81	T_p-25^d	0	Titan IIID/Cent/15kw
	Encke/84	SEP	720	2/82	T_p-40^d	0	Titan IIID/Cent/15kw
	Giacobini-Zinner/85	SEP	1340	9/81	T_p-50^d	0	Titan IIID/Cent/15kw
	Halley/86	NEP	950	5/83	T_p-50^d	0	Titan IIID(7)/Cent/100kw
SAMPLE-RETURN							
Net Mass = 915 kg Science = 52 kg Sample = 5 kg	Encke/80	SEP	2170	2/78	T_p-50^d	0	Titan IIID/Cent/27.5kw

multiple impulse modes. The multiple impulse flight mode generally requires a large midcourse plane-change maneuver (4.6 km/sec for P/Encke in 1980), but, occasionally the same effect can be obtained "free" via a Jupiter gravity-assist or a single impulse trajectory (Giacobini-Zinner in 1985, slow flyby). Trajectory studies performed to date indicate that the SEP flight mode is best for slow flyby and rendezvous missions; for equal payload, major advantages accrue in shorter flight time (1-3 years), arrival closer to comet perihelion and generally simpler mechanizations.

The rendezvous mission requires a spacecraft weight around 500 kg. Science payload is increased to 85 kg and can include instrumentation contained in a small nucleus probe. The advantage of SEP over the ballistic flight mode is even more pronounced. In particular, a 10-15 kw SEP system launched by the Titan IIID/Centaur (or Shuttle/Centaur) vehicle can achieve rendezvous with most short period comets in a flight time of 2-4 years. Figure VII-2 illustrates the trajectory profile for the Encke mission. The top portion is a projection into the ecliptic plane and the exhaust vectors of the solar electric propulsion system are shown at 30-day intervals. The lower portion of the figure shows the same geometry from 20° above the ecliptic. Rendezvous with Halley's Comet is, of course, the exceptional case because of its retrograde orbit. Both SEP and ballistic flight modes are impractical for this mission because of the 7-8 year flight time required. A NEP spacecraft launched by the Titan IIID(7)/Centaur or Shuttle/Centaur can achieve rendezvous in 2.6 years. It would seem then that practical accomplishment of the very difficult Halley rendezvous mission depends upon the development and availability of nuclear-electric propulsion by 1983. Although plans for NEP are still uncertain, a nuclear-electric mission to Comet Halley is listed in Table VII-2.

Sample return from a comet would be an extremely ambitious undertaking. This mission mode has to date been studied only for the P/Encke apparition in 1980, although the data listed in Table VII-2 should apply to later apparitions as well. A 5 kg sample can be returned to Earth and recovered via direct reentry after a total mission duration of 6 years. Note, however, that the SEP power requirement of 27.5 kw is much larger than current design goals for powerplant size.

Several examples of a multiple-comet flyby mission are presented in Table VII-3. The first two comets in the sequence are P/Grigg-Skjellerup and P/Kopff having perihelion passages in May 1982 and August 1983, respectively. A 160-day ballistic transfer to Grigg-Skjellerup can be launched on December 4, 1981, and would have a flyby velocity relative to the comet of 15.8 km/sec. The SEP system would not be utilized until after the first encounter. The transfer from Grigg-Skjellerup to Kopff would be 462 days and the flyby velocity at Kopff 8.8 km/sec. Net spacecraft mass is assumed to be 450 kg. If Kopff were

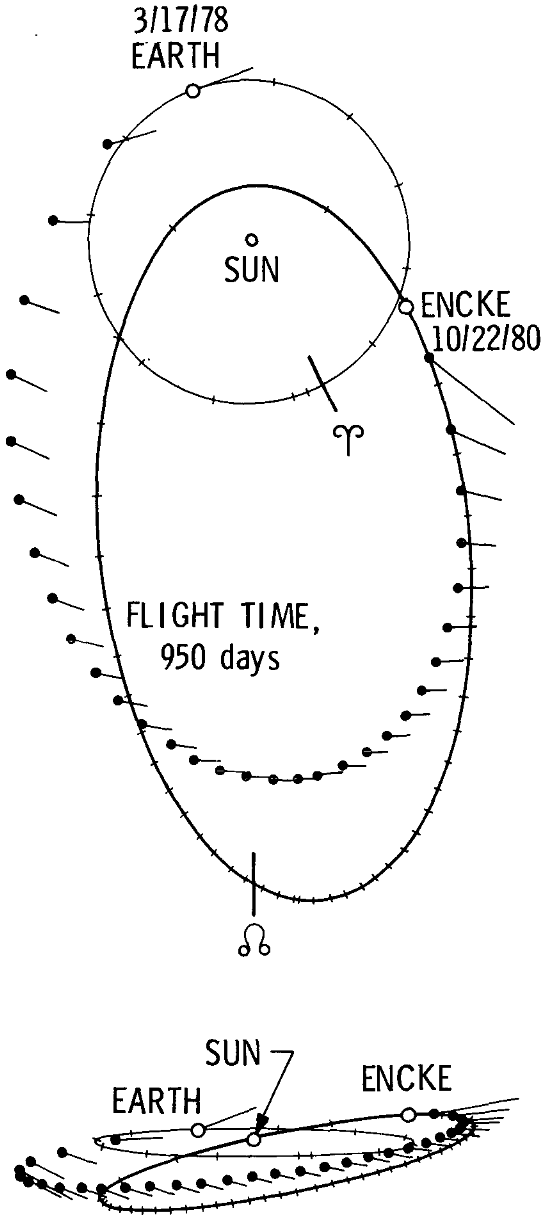

Fig. VII-2. P/Encke rendezvous. Information shown at 30-day intervals.

TABLE VII - 3
EXAMPLES OF MULTIPLE COMET FLYBY MISSION PERFORMANCE

LAUNCH DATE ———————— DEC. 4, 1981
HYPERBOLIC VELOCITY ——— 4KM/SEC
SPACECRAFT MASS——————— 450 KG

COMET SEQUENCE	FLIGHT TIME (DAYS)	FLYBY VELOCITY (KM/SEC)	SEP POWER (KW at 1 AU)	INITIAL MASS (KG)	PROPULSION ON-TIME (DAYS)
GRIGG–SKJELLERUP	160	15.8	0	450	0
GRIGG–SKJELLERUP KOPFF	622	8.8	5	750	236
GRIGG–SKJELLERUP KOPFF TUTTLE–GIACOBINI–KRESAK	957	19.1	5 10	925 1040	590 272
GRIGG–SKJELLERUP KOPFF AREND–RIGAUX	1124	16.1	15	1500	525
GRIGG–SKJELLERUP KOPFF GIACOBINI–ZINNER	1372	21.7	5 10	833 975	440 218
GRIGG–SKJELLERUP KOPFF HALLEY	1428	43.6	5 10	950 1060	615 275

the final target in a 2-comet sequence, the required net mass could be delivered using a small 5 kw SEP system. Four examples of a 3-comet sequence are shown in the table, listed in the order of increasing flight time. The relatively high-energy transfer to P/Arend-Rigaux would require a SEP power rating of 15 kw and an initial mass of 1500 kg. The other three missions can employ a smaller power-plant in the 5-10 kw range. Note that the 10 kw system offers a significant reduction in propulsion on-time (which can reduce wearout and thereby increase reliability) at the expense of a slightly larger initial vehicle mass. Each of the 3-comet missions can be launched with the Titan IIIC or the Titan IIID/BII. The examples shown in Table VII-3 do not necessarily represent the best opportunities from either a trajectory or a scientific standpoint. It is expected that by changing the first and second comets in the target sequence, one should be able to design other, perhaps more interesting multiple encounters. Also, the flyby velocity may be reduced in many instances.

Bright new comets are discovered at an average rate of about 3 to 4 per year, although not all would be accessible to a space probe. To estimate how many would be, a statistical analysis was performed using the 54 new comets observed in the period from 1945 to 1960. The selected criteria imposed are: (1) comet recovery two months before launch, (2) comet observability during this period, (3) launch hyperbolic excess velocity (V_{HL}) less than 11 km/sec ($C_3 < 121$ km^2/sec^2) for a 30-day launch window, and (4) flight time less than 400 days. The following table summarizes the mean parameters and standard deviation of acceptable missions.

Recovery Magnitude	10	15	20
Opportunities per year	0.15	0.7	1.5
Launch Velocity V_{HL} (km/sec)	--	9 ± 2	8.7 ± 2
Flight Time (days)	--	190 ± 80	250 ± 90
Approach Velocity (km/sec)	--	43 ± 20	40 ± 18
Communications Distance (AU)	--	1.6 ± 1.5	1.9 ± 1.2

Recovery magnitude appears to be the most critical parameter. New comets have been recovered, on average, at magnitude 10, but this is inadequate for mission planning purposes. However, if recovery could be made at magnitude 15, the opportunities can be increased to about 2 every 3 years. This may be realistic if a comprehensive comet search program using Baker-Nunn type cameras were undertaken. On this basis, it is concluded that it would not be unreasonable to plan missions to first apparition comets, having a launch vehicle and spacecraft standing by with about two months notice of launch. Assuming a Pioneer-type spacecraft (250 kg) with 30 kg of science instruments, the launch vehicle required could be a Atlas/Centaur/TE-364.

VII.3. Asteroid Mission Performance

At the present time there are about 1800 catalogued asteroids, an equal number of Palomar-Leiden asteroids and a handful of others having reasonably well known orbits. The main asteroid belt extends from about 1.7 AU to 4.0 AU, and contains over 90% of the numbered asteroids. A median asteroid orbit has a semimajor axis of 2.7 AU, an eccentricity of 0.15, and an inclination to the ecliptic of 9°. Table VII-4 presents orbital characteristics of representative asteroids in several orbital groups: (1) Apollo, or Earth crossers, (2) Mars crossers, (3) main belt asteroids, (4) Trojan, or Jupiter related asteroids, and (5) an exceptional asteroid, Hidalgo, having the largest orbital size and inclination. The synodic period indicates the average interval between successive launch opportunities.

Table VII-5 summarizes the performance characteristics of several asteroid mission modes. Flyby missions to individual targets are readily performed in the single impulse ballistic mode using an Atlas/Centaur launch vehicle. Typical flight times range from 150 days for 1566 Icarus to 450 days for the Ceres mission. The exceptionally high flyby velocity of 27 km/sec at Icarus is due to this asteroid's large eccentricity and inclination.

The multiple-asteroid mission can also be accomplished ballistically using the multi impulse technique or with SEP. An Earth-storable propulsion system with specific impulse (I_{sp}) equal to 300 seconds can provide the necessary post-launch impulses for the successive flybys; the total ΔV required is less than 1.5 km/sec. These missions probe the asteroid belt to a maximum distance of about 3 AU and have a total flight time less than 2.3 years. Two of the examples shown include intercept with Ceres. The Titan IIIC/BII launch vehicle provides more than 400 kg net mass for these missions, while the Atlas/Centaur/BII would be adequate for a Pioneer-class spacecraft (250 kg). Using the SEP mode, the Atlas/Centaur and a 5 kw power-plant is entirely adequate for either sized spacecraft.

A sample of rendezvous and docking mission capabilities is also presented in Table VII-5. Comparative data is shown for the SEP and multi-impulse ballistic flight modes, the latter requiring a mild cryogenic space-storable retro-propulsion system (I_{sp} = 400 sec) for reasonable payload capability. For rendezvous missions, including circumnavigation maneuvers but not docking, the net mass requirement is estimated to be 500 kg. The significant advantage of the SEP mode is the smaller launch vehicle requirement and the advanced state of development of SEP systems. Flight times for both modes are roughly comparable. Practical accomplishment of the Ceres rendezvous requires the SEP flight mode. With the addition of docking (landing) maneuvers to the flight profile, the net spacecraft mass requirement increases to about 700 kg. In this case only the SEP

TABLE VII - 4

ORBITAL CHARACTERISTICS OF SOME ASTEROIDS

CAT. NO.	NAME	ABS. MAG.	SEMI-MAJOR AXIS (AU)	ECCEN-TRICITY	INCLIN-ATION (DEG)	SYNODIC PERIOD (YRS)
Apollo Group						
1566	ICARUS	17.7	1.08	0.827	23.0	9.17
1620	GEOGRAPHOS	15.9	1.24	0.335	13.3	3.63
1685	TORO	16.2	1.37	0.436	9.4	2.66
Amor Group						
433	EROS	12.3	1.46	0.223	10.8	2.31
1221	AMOR	19.1	1.92	0.435	11.9	1.60
1627	IVAR	14.1	1.86	0.396	8.4	1.65
Main Belt						
1	CERES	4.0	2.77	0.079	10.6	1.28
2	PALLAS	5.1	2.77	0.236	34.8	1.28
3	JUNO	6.3	2.67	0.257	13.0	1.30
4	VESTA	4.2	2.36	0.089	7.1	1.40
8	FLORA	7.4	2.20	0.157	5.9	1.44
10	HYGIEA	6.5	3.15	0.100	3.8	1.22
20	MASSALIA	7.4	2.41	0.143	0.7	1.37
324	BAMBERGA	8.0	2.68	0.340	11.2	1.30
334	CHICAGO	8.5	3.89	0.057	4.6	1.15
Trojan						
588	ACHILLES	9.3	5.21	0.148	10.3	1.09
617	PATROCLUS	9.1	5.21	0.141	22.1	1.09
659	NESTOR	9.6	5.26	0.110	4.5	1.09
Exceptional						
944	HIDALGO	12.0	5.82	0.656	42.5	1.08

TABLE VII - 5
ASTEROID MISSION SURVEY

MISSION MODE	ASTEROID	FLIGHT MODE	FLIGHT TIME (DAYS)	LAUNCH DATE	Approach Velocity (km/sec)	LAUNCH VEHICLE
FLYBY						
Net Mass = 250-400 kg	1566 Icarus	Single Impulse Ballistic	150	2/78	27.1	Atlas/Cent
Science = 30-70 kg	1 Ceres	Single Impulse	450	6/79	6.4	Atlas/Cent
	433 Eros	Ballistic	175	8/81	6.9	Atlas/Cent
	4 Vesta		325	1/85	5.7	Atlas/Cent
MULTI-FLYBY						
Net Mass = 250-400 kg	632-946-Ceres	Multi Impulse Ballistic	838	10/75		Atlas/Cent/BII
Science = 30-70 kg	1473-Ceres-1153	Multi Impulse	574	7/79	6-12	Atlas/Cent/BII
	1515-1674-561-1720	Ballistic	830	7/81		Atlas/Cent/BII
RENDEZVOUS						
Net Mass = 500 kg	433 Eros	Multi Impulse Ballistic	350	1/75	0	Titan IIIC/BII
Science = 80 kg	20 Massalia	Multi Impulse Ballistic	420	4/75	0	Titan IIID/Cent/BII
		SEP	500	5/75	0	Titan IIID/Cent/15kw
	1 Ceres	SEP	600	11/76	0	Titan IIID/Cent/15kw
RENDEZVOUS & DOCK						
Net Mass = 700 kg	433 Eros	SEP	420	6/81	0	Titan IIID/BII/10kw
Science = 110 kg	20 Massalia	SEP	600	7/83	0	Titan IIID/Cent/15kw
	1 Ceres	SEP	680	6/84	0	Titan IIID/Cent/15kw
SAMPLE-RETURN						
Net Mass = 930 kg	433 Eros	SEP	1080	1/84	0	Titan IIID/BII/10kw
Science = 65 kg	8 Flora	SEP	1360	12/82	0	Titan IIID/Cent/15kw
Sample = 25 kg						

flight mode is considered practical. Note that flight time increases slightly to provide the additional payload (a characteristic of the flexibility of the SEP mode). The rendezvous and docking mission to Ceres is the most difficult example shown and would require a 680-day flight time, a 15 kw power-plant, and the Titan IIID/Centaur launch vehicle.

The most ambitious mode appropriate to asteroid missions is sample return. The net mass requirement of 930 kg now includes the sample recovery system at Earth return; i.e., the aerobraking device for direct reentry or the retro-propulsion system for orbit capture. A 25 kg asteroid sample is assumed. The two examples cited are a 1080-day round-trip mission to 433 Eros and a 1360-day mission to the main belt asteroid 8 Flora. Note that the launch dates shown are just specific examples; launch opportunities to these asteroids recur at intervals of approximately 2 and 1.5 years, respectively. Sample-return from Eros could be accomplished with a 10 kw SEP system and a Titan IIID/BII launch vehicle. The more difficult Flora mission requires a 15 kw system and the Titan IIID/Centaur. Figure VII-3 illustrates the trajectory profile of the Eros mission example, launched in January 1984 with return in January 1987.

VII.4 Combination Missions

The concept of a multiple asteroid-comet flyby with a single spacecraft has been proposed as quite an attractive choice for early exploration. Such a mission is within the capabilities of Atlas-class launch vehicles and the existing Pioneer F/G or Mariner spacecraft technology for both the multiple impulse ballistic and SEP modes. Preliminary trajectory analysis has indicated that numerous target combinations would be available for selection. Table VII-6 describes two of the possible target sequences and trajectory requirements. For the flyby example, comet P/Whipple is selected from a sampling of ten short-period comets having nodes (ecliptic crossings) near perihelion in the late 1970's and early 1980's. P/Whipple arrives at a descending node on February 20, 1978, 35 days before perihelion, at a distance of 2.48 AU. The mission requires a launch hyperbolic excess velocity of about 6.3 km/sec. The maximum injected spacecraft weight of the Atlas/Centaur/TE-364-4 is 650 kg, which is ample for a Pioneer-class spacecraft with the additional propulsion capability to accomplish the ΔV maneuvers near each encounter which sum to approximately 400-500 m/sec. A fourth asteroid can be added to the sequence of three for an additional ΔV of 500 m/sec.

Figure VII-4 illustrates the trajectory profile of the 939 Isberga-P/Whipple-1292 Luce mission launched in April 1977. Asteroid 939 Isberga is encountered 160 days after launch at 1.9 AU from the sun. After encounter a ΔV maneuver of approximately 200 m/sec retargets the spacecraft trajectory to

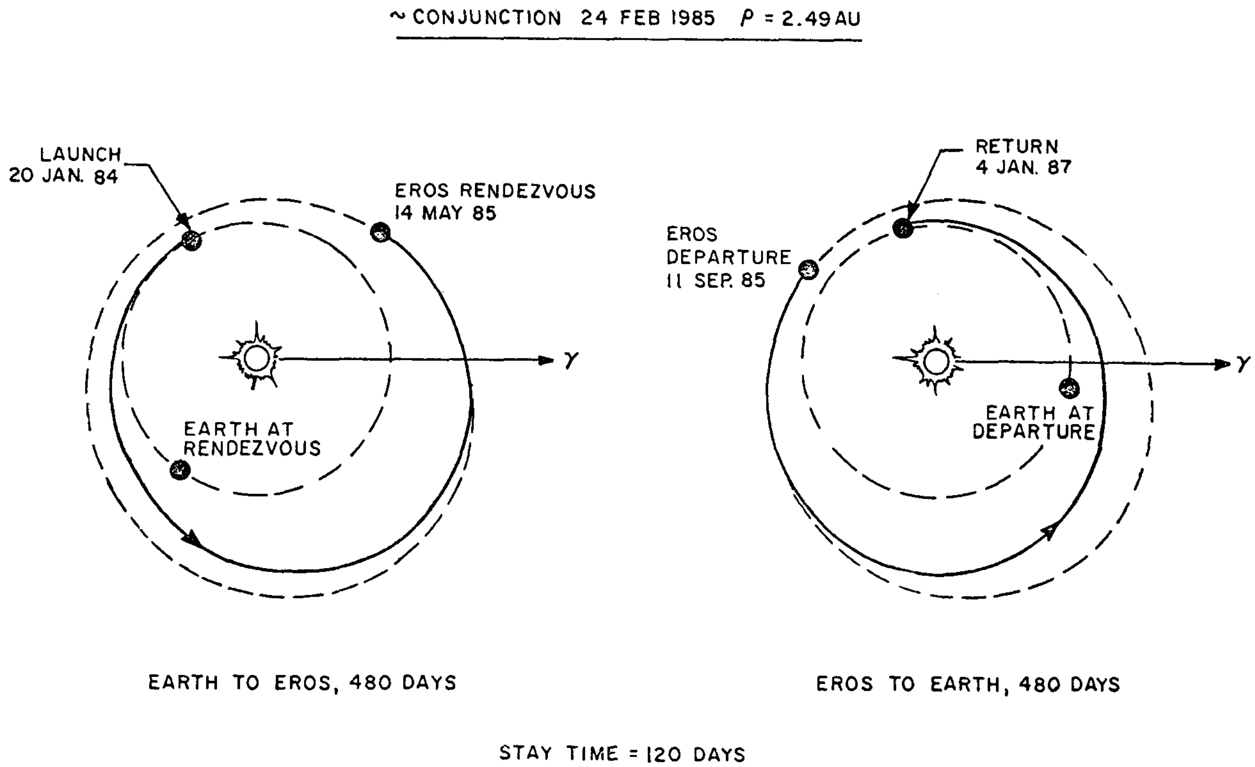

Fig. VII-3. Solar electric transfer profiles for a 1080-day Eros sample return mission, 1984 launch.

TABLE VII - 6

CHARACTERISTICS OF MULTIPLE ASTEROID–COMET MISSIONS

Multi Impulse Ballistic Flybys, 4/26/77 Launch

Bodies	Flyby Speed, km/sec	Date
939 Isberga	11.4	10/ 3/77
P/Whipple	10.5	2/20/78
1292 Luce	5.9	1/10/79

SEP Rendezvous, 3/7/78 Launch

Bodies	Flyby Speed, km/sec	Date
214 Aschera	10.6	12/ 4/78
465 Alekto	8.9	11/11/79
P/Encke	0	10/22/80

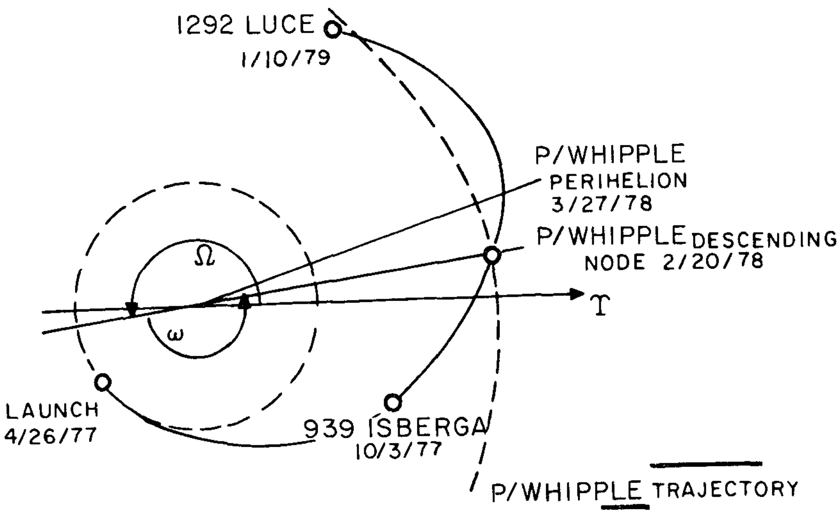

Fig. VII-4. Spacecraft trajectory for the multiple encounter sequence 939 Isberga-P/Whipple-1292 Luce.

encounter P/Whipple 140 days later. Another ΔV maneuver of about 250 m/sec directs the spacecraft to encounter the final target 624 days after launch.

Among the major spacecraft requirements are: (1) a propulsion capability of 800 m/sec, and (2) an optical terminal guidance sensor. Further study of the navigation problem will be necessary to verify that the miss distance accuracy requirements can be met. Total spacecraft weight at launch will be about 450 kg.

An SEP rendezvous to P/Encke which passes two asteroids is also summarized in Table VII-6. It has been found that SEP flights passing through the asteroid belt can be modified to pass by one or more asteroids at very little expense in either capability or complexity. This implies that all such missions should be considered candidates for multiple asteroid/comet flybys. The 214 Aschera-465 Alekto-P/Encke trajectory is illustrated in Figure VII-5 with the SEP exhaust vectors as in Figure VII-2.

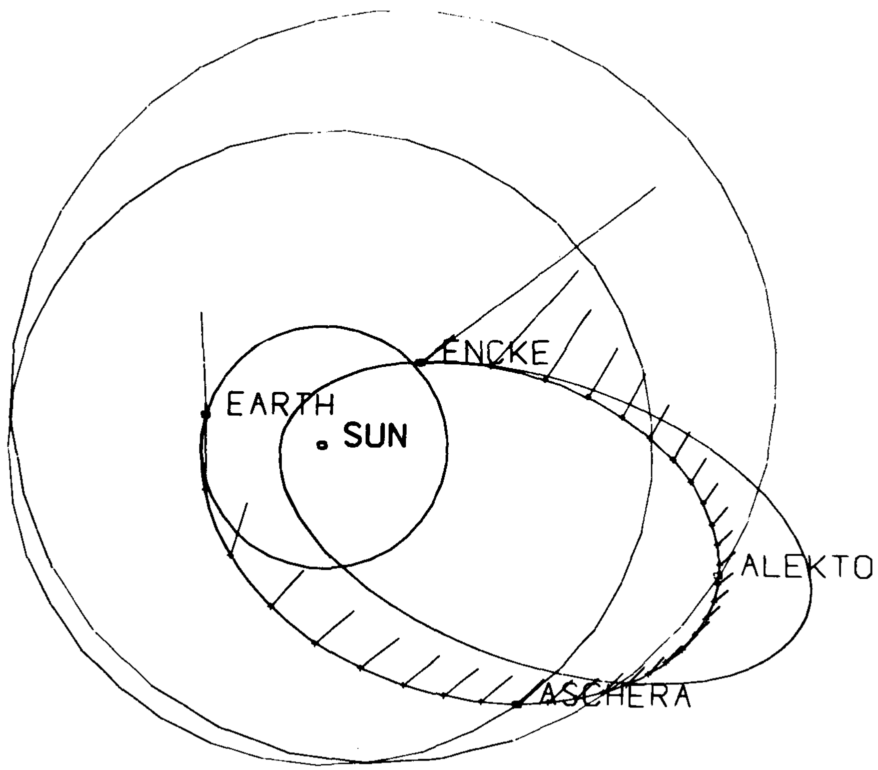

Fig. VII-5. SEP P/Encke rendezvous with asteroid encounters.

Both the P/Encke and P/Whipple missions should be considered representative rather than exceptional. Studies of other short-period comets have revealed other mission opportunities in a variety of years. The reader is referred to the Bibliography for additional discussion of comet/asteroid multiple encounter missions.

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GLOSSARY

a – Semimajor axis of orbit.

Accretion – The growth of celestial bodies from smaller elements or the growing together of small particles or grains by vapor condensation, melt welding, electrostatic and gravitational attraction and other processes.

Amor Asteroids – Asteroids that have perihelion distances between 1.00 and 1.38 AU.

Aphelion – That point of a planet's or comet's orbit most distant from the sun.

Apollo Asteroids – Asteroids with a perihelion distance less than or equal to 1.00 AU.

Apparition – The appearance of a celestial body such as a comet after being invisible for a period of time.

Asteroid – Small solid body that usually is observed at the telescope as a moving object having stellar appearance.

AU – Astronomical unit, equal to mean distance between Earth and sun.

Ballistic Mode – Flight mode where the spacecraft follows a ballistic path unassisted by propulsive forces except for occasional corrections or alterations to the flight path.

BII – Burner II, a small upperstage vehicle powered by solid rocket motors.

C_3 – Hyperbolic excess energy per unit mass on Earth-escape hyperbola, km^2/sec^2.

Comet – A celestial object that has at least once been observed as a nebulous moving object.

Comets of the Jupiter Family	– Comets of short period with orbits of relatively low inclinations and aphelia in the neighborhood of Jupiter.
	– Delta-V, the change in spacecraft velocity required to establish a new trajectory path.
emu	– Electromagnetic unit.
Eon	– 10^9 years.
Fragmentation	– The break up of bodies into fragments.
g	– Grams.
Hetegony	– Theory dealing with the formation of secondary bodies (satellites, planets) around central bodies (planets, sun). (From Greek hetes = companion and goneia = production.)
Hilda Asteroids	– Group of asteroids with orbital period equal to 2/3 that of Jupiter.
Jet Stream	– A collection of particles or bodies moving in Kepler orbits with similar orbital elements.
Long-period Comets	– Comets having periods appreciably longer than those of the Jupiter Family.
Main Belt Asteroids	– Asteroids between Mars and Jupiter mostly with semimajor axes between 2.2 and 3.3 AU.
Meteor	– A phenomenon of a small body entering the earth's atmosphere.
Meteorite	– Meteoroid that escapes total destruction in the earth's atmosphere.
Meteoroid	– A small solid body in the solar system generally ranging in size from a few microns to a few meters.

Micron (m) – 10^{-6} meters.

m.y. – Million years.

NEP – Nuclear electric propulsion.

Perihelion – That point of a planet's or comet's orbit closest to the sun.

Periodic Comet – A comet with elliptic orbit.

Planetesimal – A small body (embryo) later developing into a planet.

ppm – Parts per million.

Primordial – First created.

Prograde – As viewed from the north, counter-clockwise; also direction of rotation or revolution which is most common for bodies in the solar system.

PTP Array – Parameter-time-position array.

Retrograde – As viewed from the north, clockwise.

SEP – Solar electric propulsion.

Shuttle – Reusable rocket powered aircraft.

Solar Gale – The solar wind at a strength greatly exceeding the present strength.

Solar Nebula – A large contracting disc of gas and dust assumed in some theories to be the precursor of the solar system.

Solar Wind – The interplanetary flow of protons and electrons emanating from the sun.

Space Storable	– Propellants with low evaporation rates when stored in space but with excessive rates when stored on the ground.
Synodic Period	– The time between two successive conjunctions with the sun, as seen from the earth.
TE-364; TE-364-4	– Solid propelled upper stages for launch vehicles.
Trojans	– Two groups of asteroids with periods of revolution approximately equal to that of Jupiter. Each group is located at one corner of an equilateral triangle, Jupiter and the sun being at the other two corners.

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