SCIENCE RATIONALE FOR AN INITIAL ASTEROID-DEDICATED MISSION

FRASER P. FANALE

Space Sciences Division
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91104

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

CURRENT KNOWLEDGE

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

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

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

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

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

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

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

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

QUESTIONS AMENABLE TO ASTEROID STUDIES

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

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

   b. What *chemical* fractionation processes operated during condensation/accretion to produce differences in *bulk* composition *among* asteroids and could these same processes account for apparent differences in bulk compositions among the terrestrial planets? Did these condensation/accretion processes produce "ready-made" or *initial* zonal layering *within* asteroidal or planetary bodies in the solar system?

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

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

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

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

4. What is the potential of the asteroids as sources of raw materials?

   What variety of raw materials are available? Is mining from asteroids of any of these materials for any application preferable to mining, processing, and launching from Earth, or mining from non-asteroidal extraterrestrial sources such as the Moon?

The preceding key questions are essentially those which were singled out in the *Report of the Terrestrial Bodies Science Working Group* (Brandt et al., 1977).

SCIENCE STRATEGY AND MISSION TACTICS

What does all this information tell us about how (or indeed whether) to design an asteroid-dedicated mission? Some people might conclude that there are so many asteroids of such varied composition that the design of a valid mission which studies only a tiny fraction of a percent of them is a hopeless task. Others might contend that the ground-based program has provided so much knowledge of the asteroids that we ought to wait until spacecraft reconnaissance of the entire solar system is accomplished before we visit them.

Still others may conclude that our knowledge of asteroids is too meager to permit judicious mission planning or selection of targets.

I disagree with such conclusions and conclude that, thanks to the ground-based program, *we have just now reached the threshold of knowledge where a valid investigation of this enormous population of objects from space may . intelligently planned.* Moreover, I conclude (see next section) that our conceptual designs for low-thrust propulsion systems have also just recently matured to the point where a viable asteroid-dedicated mission so planned may actually be executed. Specifically, based on the information in the previous section, I conclude:

1. A *scientifically* valid initial asteroid mission must visit *several* asteroids and not just one.

2. The task of choosing asteroid targets is not hopeless. Instead, the Earth-based data allow us to select representatives of all *major* spectral classes and to identify other uniquely interesting target objects as well.

3. Such a mission will achieve high scientific status *only* if it fills, for the selected asteroids, the two greatest gaps in our knowledge, namely information on their:

   a. *densities*

   b. *surface chemical composition*, including the maximum amount of accuracy and spatial resolution consistent with achievement of the other listed mission goals.

4. Spectral data should emphasize spatial resolution of two classes:

   a. very broad-band multispectral imaging

   b. high spectral resolution-moderate spatial resolution mapping.

5. Some attempt at investigating the internal zonal structure of the asteroids should be made.

I have made a semi-serious attempt at constructing a specific mission scenario, Table 1, based on these principles. This scenario is intended as an illustration only. In the next section, it will be shown that some specific scenarios nearly as demanding with respect to both targets and encounter conditions (see below) as that given here as an illustration of science desires have already been identified by Bender (1977) as being within the capability of an Ion Drive mission and compatible with the delivery of a satisfactory scientific payload as well. In Table 1, I have listed the demanded or preferred targets, the characteristics of the target (if unique) or those of the class that it represents, the number of dependably identifiable candidates satisfying the description and the reasons why that asteroid or class of asteroid deserves a place in the limited list of targets. To underline the illustrative nature of this scenario, I should point out that there are at least two classes of objects which could profitably be substituted for those I have listed. (1) a member or members of a discrete orbital family (because of the possibility that zones internal to a fragmented progenitor might be exposed; Nysa (Table 1) qualifies as the largest member of a 12-member orbital family), and (2) an asteroid or asteroids known on the basis of its optical properties to be an unlikely source of any meteorites in hand. Finally, it seems unlikely that more than four-to five asteroids per launch could be included in an actual multi-rendezvous mission.

Table 1. An Example Multi-Rendezvous Mission

Priority (not order of encounter)	Description	Examples	No. of Dependable Members	Special Scientific Interest
1. Demand Vesta	550 km diameter; covered with basalt-like material/color varies	Unique	-	Global differentiation/time?/energy source?/source of achondrites?
2. C Types a. Prefer Ceres	Largest dark C typ but oddly bright (~6% albedo); water band	Unique	-	Largest object/relic, not disrupted/generally primitive/most populous class/largest thermal lag/regional endogenic effects?
b. Accept other large C substitute for Ceres	C type/albedo <4%; D > 70 km	10 Hygeia 19 Fortuna 324 Bamberga	>10	Primitive?/source of carbonaceous chondrites?
3. S Types a. Prefer 349 Dembowska	Very red/deep olivine band	Unique	-	Derived from mantles of differentiated objects?
b. Accept as substitute: other S with olivine and pyroxene bands	An S with substantial olivine and pyroxene bands	12 Victoria 63 Ansonia	>10	Class derived from mantles of differentiated objects?
4. M Types a. Prefer 16 Psyche	D > 200 km/low albedo/no bands/no sharp UV dropoff	Unique	-	Huge metal-rich object/from core of differentiated object?/source of mesosiderites?/end member of S-M series
b. Accept any M type	M, smaller than Psyche		>6	Similar, but smaller
5. E Types	High albedo/neutral color/"flat" spectrum	44 Nysa 64 Angelina	-	Bright/surface of enstatite?/deep interior of differentiated object, but different zone than other Ss?
6. Any additional C type small	C type; D < 50 km		>100	Representative of large class/most primitive/chemical composition important/easy to find/source of some carbonaceous chondrites/compare with Mars' moons
7. Any additional S type			>40	Representative of large class/easy to find

 C-3

What should the scientific payload be? The measurement of satisfactorily accurate densities requires mass measurement accurate to 1% or better. For a 200 km diameter rocky asteroid this can be done with a closest approach of 10^5 km if the velocity is 1 km sec^{-1}. The other ingredient in the density recipe is the volume, which requires global shape measurement. This is so because small asteroids, unable to reassume hydrostatic equilibrium shapes after large impacts, can have "bites" missing from them which will modify the volume calculations. An approach within 1000 km or less should provide satisfactory resolution for this purpose in the case of a CCD camera. For imaging upon rendezvous or orbit, at least six broad-band filters should be part of the camera system and should be carefully chosen, not only to produce good color pictures of the object, but to create a synergistic base for extension of the results of a high spectral resolution-moderate (km) resolution spectral mapper. A conceptual version of the latter instrument has been proposed for the Lunar Polar Orbiter mission and has already been tentatively accepted for the Galileo mission. Such an instrument can produce definitive moderate to low resolution maps of mineral distribution over the asteroid surface. Also, a prominent H_2O band has just been identified on the asteroid Ceres (Lebofsky, 1978). Maps of H_2O distribution on asteroid surfaces may be produced and constitute an important and obviously exciting produce of this and the gamma-ray equipment: both a gamma-ray and x-ray fluorescence instrument are necessities on the payload because together they will provide definitive chemical analyses of the major element abundances and selected abundances of especially cosmochemically important minor or trace elements. Analyses of H, O, C, Na, Mg, Al, Si, K, Ca, Ti, Fe, Th and U are possible. Of particular interest would be the potential of the gamma-ray instrument for measuring the C and especially H distribution since the history of H_2O and other volatiles associated with C asteroids will be an important area of investigation. These measurements are absolutely essential to the fulfillment of the major science goals as indicated above. The reader is referred to the discussion of remote chemical measurements by Arnold (1978). Nonetheless, the quality of chemical data is enormously dependent on the encounter conditions. Based on the science needs of this mission, and the practicalities involved (see below), low spatial resolution chemical mapping emerges as a requirement. There is no guarantee that vastly different geochemical provinces would be seen since the low gravitational fields allow significant global redistribution of ejecta to result from impacts. Also the albedos of most asteroids show somewhat meager or nonexistent optical variations with rotation of most. Still, these are whole disk data and there is the possibility of some windows in some asteroid crusts that--given the combination of chemical and spectral mapping--could be quite revealing. This might be true for the largest asteroids where impacts have more difficulty in spreading material over most of the asteroid. Piles of large exposed blocks may characterize major impact sites. Also it is generally assumed that smaller asteroids are essentially in the erosional mode. Thus the statement that "asteroids paint themselves grey" may prove more true than false, but the meager state of our knowledge of these objects leaves spatial resolution for chemical and spectral measurements as an important goal. A discussion of some of these problems is given in this volume by Chapman (1978).

A crucial point is that very slow flybys (<200 m sec^{-1}) are vastly preferable to fast flybys of the type offered by typical ballistic multi-encounter missions (*e.g.*, 4-10 km sec^{-1}) in that the latter seem to offer only crude (10-15%) chemical analyses of only a few chemical elements. For a major asteroid a slow (<200 m sec^{-1}) flyby is capable of providing precise elemental analyses owing to the longer integrations times. When the stay time at the asteroid is several days, then not only could precise a alyses be obtained for several elements, but this analysis could be extended to cover a large portion of the asteroid and crude analyses could be obtained for each of a handful of spatial elements, affording a crude chemical map. If the orbit could be maintained for tens of days, then a real map, containing perhaps 100 spatial elements, could be obtained. Such a procedure could allow spotting even fairly small regions of unusual chemical compositions--such as the windows mentioned above. Beyond these stay times, field-of-view limitations come into play. Also, the accuracy is likely to be limited by calibration uncertainties rather than precision. Figure 1 gives a very crude back-of-the-envelope representation of the dependence on the quality of chemical information for a typical off-the-shelf instrument

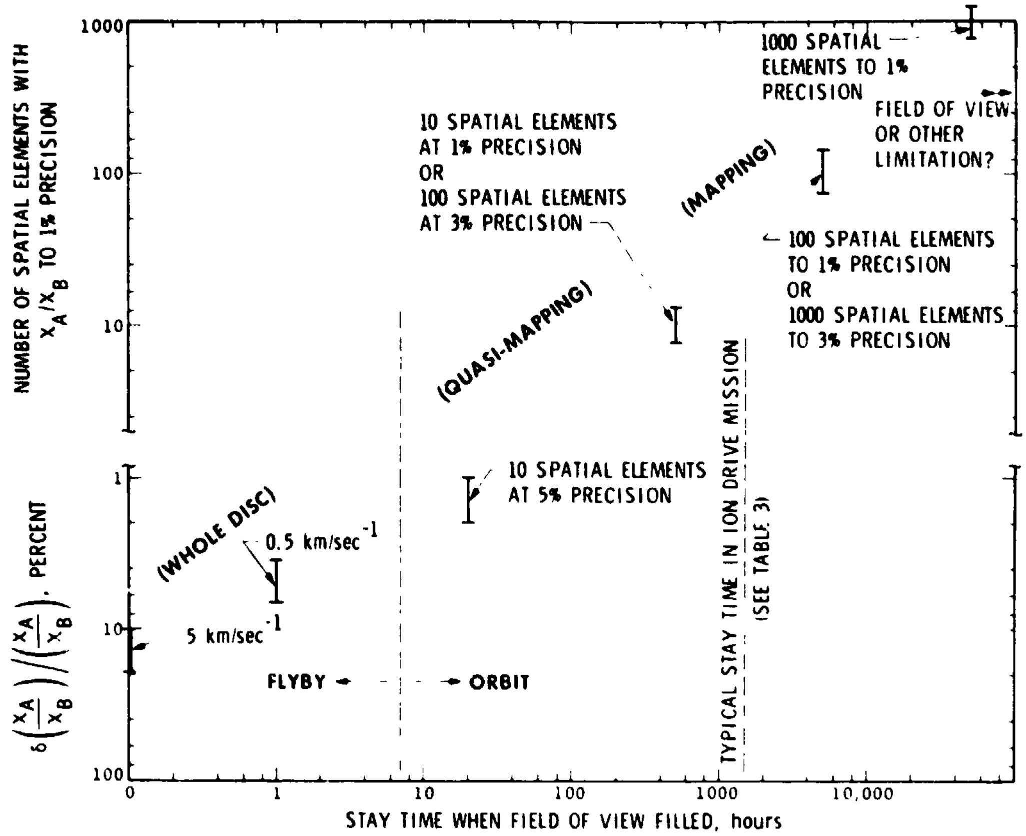

Fig. 1. A highly generalized representation of the typical precision with which the ratio of two major elements might be determined as a function of flyby velocity or orbital stay time at a 500 km diameter asteroid with a 100 km closest approach or orbital attitude. Since neither the elements nor the design of the radiometric instrument (approximately an off-the-shelf instrument) are specified, the absolute values given should not be taken too literally. Also, it is only precision, not (calibration-limited) accuracy which is indicated. However, the strong dependence of the precision of whole disk analyses on flyby velocity, and the sharp dependence of mapping capability on orbital stay time are fairly portrayed. The close, fast flyby shown on the left is not only scientifically unattractive, but it also requires the development and use of precise optical navigation techniques.

in an example encounter. It is true that use of one of the recently developed huge (and heavy) detector arrays would improve the level of performance for a given set of encounter conditions. However, encounter conditions determine coverage and other parameters as well as signal-to-noise, and given any instrument the quality of the result is so steeply dependent on encounter conditions as to militate for <200 m sec^{-1} relative velocities and orbit whenever possible.

Information concerning the thermophysical properties of the regolith could be obtained from infrared radiometric measurements from 8 μm to 40 μm. Some ancillary compositional data might also be obtained. Tracking might provide valuable information concerning lateral mass variations. Considering the possibility of coalescence of several large nuclei and the possibility of the resulting density composite surviving with minimal later internal evolution of some of these objects, and considering the possibility of radial zoning being exposed by fragmentation, such an experiment might provide interesting data. This is especially so since the surface may be coated with a more or less uniform "blend" of material from various regions as the result of impacts. A fields and particles package consisting of a magnetometer, a solar wind plasma analyzer and a low-to-medium energy electron detector could provide valuable information on the existence of intrinsic or fossil magnetic fields and the interaction of the solar wind with the asteroid as an electrically conducting or insulating body.

Although I have emphasized the importance of rendezvous for the chemical measurement, this point can be almost as strongly made for the other remote sensing instruments, including the mapping spectrometer, imaging, radiometer, gravity experiment, and the fields and particles package. In some cases, the experiment benefits mainly from enhanced signal-to-noise, but in others the increase in coverage and variety of positions relative to the satellite-Sun line or even simply increasing the time base for synoptic observation are equally important.

The possibility of including hard landers or penetrators on a mission is attractive, especially considering the massive payloads made possible with an Ion Drive vehicle (see below). A hard lander might weigh ~80 kg and contain perhaps a 12-15 kg science payload. This would allow for a three-axis stabilized seismometer plus the following: a multispectral facsimile camera could provide close-up panoramic imaging of a small domain on the surface. An α/p/x-ray fluorescence device could provide a *complete* chemical analysis including *minor* or *trace* elements. Such data could also help to plan a subsequent sample return mission. However, orbital science should definitely not be sacrificed in any major way for lander science.

Table 2 shows *example* orbiter and lander payloads. I have, for the sake of argument, assumed a hard lander rather than a penetrator for this exercise, but penetrators may be preferable. Penetrators offer a greater chance (but only a chance) of allowing a heat flow measurement and probably better coupling for a seismic experiment. However, their surface payload and data rates are more limited and the problems of emplacing a penetrator into a low G body with no atmosphere introduces some engineering complexities. The choice is not yet clear. In any event, the vehicular capabilities of the Ion Drive propulsion system allow one to consider carrying hard landers or penetrators for several targets in addition to a satisfactory "orbiter" payload.

Achievability of Science Desires

How feasible are missions like that described in Table 1? Detailed discussion of the full assemblage of mission options is beyond the scope of this paper and is available elsewhere in this volume (Niehoff, 1978). However, a short discussion of our ability to carry out a viable multi-rendezvous mission seems appropriate. Multiple rendezvous scenarios involving either ballistic missions or ballistic missions with gravity assists are not compatible with the scientific criteria outlined above. Two typical ballistic mission scenarios (one direct and one Vega) are given in the first two columns of Table 3. They are unattractive primarily, but not exclusively, because of the high relative velocities at encounter and the poor assemblage of targets. As indicated in Figure 1, such conditions would probably provide only rather crude whole disk elemental abundance measurements, with no chance of chemical mapping at all--even in the case of an asteroid much larger than the targets given. All the other measurements would likewise suffer because of the short time base, reduced coverage, etc., as discussed earlier.

The third column gives a scenario based upon the capabilities of a solar electron propulsion system (SEP). This example was identified as the result of a casual preliminary search. Nonetheless it at least provides a rendezvous with Vesta and a slow flyby (200 m sec^{-1}) of the asteroid Io. Although the array of targets is exceedingly limited, this preliminary example serves to show that the future of asteroid exploration from

Table 2. Example Payload for Asteroid Rendezvous

Orbiter		
Instrument	Mass	Power (w)
1500 mm CCD Camera (800 × 800), multispectral (∿8 filters) 250 mm CCD Camera (800 × 800), multispectral (∿8 filters)	20	20
x-ray Fluorescence	2	2
γ-ray	17	10
Mapping Spectrometer	10	5
Multispectral Radiometer	7	4
Radar Altimeter	12	30
Fields and Particles Package	10	15
Micrometeoroid Detector	3	2
Tracking	-	-
TOTAL	81 kg	88 w

Lander (Mass = 80 kg*)		
Instrument	Mass	Power (w)
Facsimile Camera	1.5	1.0
α-Backscatter/p/x-ray Fluorescence	2.0	1.5
Seismometer	2.0	0.2
Magnetometer	0.6	0.3
TOTAL	6.1 kg	3.0 w

TOTAL MASS OF ORBITAL INSTRUMENT PLUS LANDERS:

81 kg (orbital instruments) + 160 kg (80 kg × 2 landers) = 241 kg

*Each of two.

space was closely bound to the development of some sort of Shuttle-launched low-thrust propulsion system (Atkins *et al.*, 1976).

Since then, NASA has committed to the development of a particular low-thrust propulsion system called Ion Drive, which is based upon the SEP concept, but which has much higher thruster power levels, an improved array of solar cells and other major design

Table 3. Comparison of typical direct ballistic, VEGA ballistic, SEP and Ion Drive asteroid multi-encounter scenarios. The launch year, asteroid name, asteroid radius, asteroid spectral type, years between launch and each asteroid encounter, and flyby velocity or rendezvous conditions are given in order. The mass available for orbital science instruments and lander packages is given below the dotted line. The improvement in the quality of the missions with respect to both selection of targets and encounter conditions which has resulted from the improvement in available (or developmental) propulsion systems is obvious.

1	2	3	4	5	6
Direct 1982	VEGA 1980	SEP 1985	Ion Drive* 1986	Ion Drive* 1984	Ion Drive* 1988
Sappho 41 km, U or S, 0.7 yr, 13 km sec^{-1}	Flora 75 km, S, 1.9 yr, 8 km sec^{-1}	Vesta 376 km, unique, 1.8 yr, rendezvous	Vesta 275 km, unique, 1.7 yr, orbit for 40 days	Ceres 502 km, C, 2.0 yr, orbit for 60 days	Ceres 502 km, 2.3 yr, orbit for 50 days
Dagmar ?, ?, 1.6 yr, 6 km sec^{-1}	Sonneberga ?, ?, 3.4 yr, 9 km sec^{-1}	Jerome ?, ?, 2.3 yr, 5 km sec^{-1}	Fortuna 108 km, C, 4.2 yr, orbit for 70 days	Maja 38 km, C, 4.0 yr, rendezvous for 60 days	Lucina 46 km, C, 40 yr, orbit for 60 days
Flora 75 km, S, 2.6 yr, 10 km sec^{-1}	Stavropolis ?, ?, 3 7 yr, 10 km sec^{-1}	Io 73 km, C, 3.5 yr, 0.2 km sec^{-1}	Eleanora 76 km, S, 5.9 yr, orbit for 57 days	Melpomene 75 km, S, 6.0 yr, orbit for 60 days	Parthenope 75 km, S, 6.3 yr, orbit for 60 days
Photographica ?, ?, 3.6 yr, 11 km sec^{-1}	Fidelio ~30 km, C, 5.0 yr, 6 km sec^{-1}		Irene 79 km, S, 8.3 yr, orbit	Celuta 24 km, M, 8.1 yr, rendezvous	Vesta 275 km, unique, 8.5 yr, orbit
Protogeneia ?, ?, 4.2 yr, 7 km sec^{-1}	1940QC ?, ?, 5.9 yr, 5 km sec^{-1}				
Isara 14 km, S, 5.7 yr, 9 km sec^{-1}					
		~100 kg	200-300 kg	200-300 kg	200-300 kg

*Bender (1977); mass in orbit for initial encounter = 5480 kg.

improvements. Using Ion Drive, a large scientific payload, including possible multiple landers, can be delivered to a wider variety of asteroidal targets for rendezvous lasting several tens of days at each asteroid (Bender, 1977). In the case of asteroids with diameters >50 km, it would not only be desirable, but necessary, to orbit for the duration of the rendezvous. Orbital velocities would be $\sim$100 m sec^{-1} for a major asteroid under the encounter conditions described in the caption of Figure 1. Columns 4, 5 and 6 of Table 3 show two of several example scenarios identified by Bender (1977) which I consider to be especially attractive and which, in fact, are marginally compatible with the science desires stated above. The first of these involves an initial encounter with Vesta, a subsequent encounter with the large C object Fortuna, and two encounters with S asteroids. The second orbits Ceres, a small C, a 75 km S, and a small M object. However, it does not encounter Vesta. The last orbits both Ceres and Vesta, although it does not orbit the latter until 1996. It also orbits a 46 km C object and a 75 km S object, but no M object is encountered. In the Bender scenario over 5000 kg is placed in orbit including $\sim$300 kg of mass dedicated to orbital instruments and lander packages. This allows for several hard landers as well as a generous orbital payload, quite compatible with the example suggested in Table 2. It has been pointed out to the author that NASA is unlikely to commit to the development of an Ion Drive design quite as powerful as that assumed by Bender. Nonetheless, we are getting close.

Despite the tremendous progress that has been made in defining candidate multi-rendezvous missions, none is yet completely satisfactory. For example, none of the multi-rendezvous missions identified by Bender encounter Vesta, a C object *and* an M object. Moreover, even with Ion Drive, a transfer from one asteroid to another still requires about half a revolution ($\sim$2 years), so these missions take an exceedingly long time (>8 years) to complete. Finally, there is no specific provision yet for possible sample return. Some schemes for multiple asteroid sample return have been suggested but have not been the subject of detailed engineering studies. Even if such schemes are shown to be compatible with the Ion Drive payload, they should be carried out on an initial asteroid mission only if they do not seriously compromise the ability of the initial mission to investigate (1) each of several carefully selected asteroids as (2) global or planetary entities. This seems unlikely.

The impressive array of multi-rendezvous missions identified by Bender is, in fact, also the result of a very preliminary and limited survey which was conducted under a rather constraining set of rules. For one thing, it was assumed that the encounter with either Ceres or Vesta had to be the first encounter. Also, the payload mass at first encounter was optimized, which is not necessary. Besides simply continuing the search, the effect of altering these and other constraints should be investigated. The compatibility of an initial spacecraft investigation of an Apollo asteroid with studies of those in the main belt should also be studied. A dual launch mission with nonredundant targets also seems a very attractive option. Finally, the possibility of encountering a Trojan asteroid at the termination of the mission should be considered. In any event, Table 3 shows at a glance that dramatic progress has been made, and that the simultaneous maturation of our knowledge of the asteroids from Earth-based optical measurements together with vast simultaneous improvements in anticipated delivery capabilities has brought us to the threshold of the definition of a viable initial asteroid-dedicated mission.

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DISCUSSION

ARNOLD: I strongly agree that multiple encounters are essential to good science, and that long stay times are needed for the gamma-ray or x-ray sensing systems. Flybys are not attractive, especially for gamma-rays. I will discuss this point further in my paper in this afternoon's session.

ANDERS: In our museums there are howardites that seem to match the spectrum of Vesta. Suppose the measurements on a rendezvous mission to Vesta show that there is a chemical resemblance between howardites and the surface of Vesta. Are we then to assume on the strength of this identification that everything we have ever learned about howardites now applies to Vesta?

FANALE: No, you have to determine the chronology of differentiation independently for Vesta by looking at the cratering history of its surface. You would also want to know what the density is and if there is a density inversion.

ANDERS: The age would be difficult to get because the cratering rate in the asteroid belt is much higher, which means the surface will be saturated.

FANALE: We are going to have to do a lot of thinking about the specifics. I think we have to establish the link between Vesta and the achondrites. Chemical mapping of Vesta can be accomplished and perhaps there are windows where you can see something about the zonal structure and understand something about the magmatic path that was followed in its differentiation as well.

CHAPMAN: If you place too much emphasis on unique targets, such as Ceres and Vesta, you might get no typical C or S objects.

FANALE: You will almost certainly encounter a small one on the way.

ARNOLD: If there have been highly differentiated bodies in the asteroid belt (Vesta seems to be one clear example), one strongly suspects there are now pieces of highly evolved bodies. It can't be that all the Vestas are still intact. In that case one would have the possibility of looking at a vertical section.

FANALE: The most optimistic case for the chemical mapping of the very big asteroids is the possibility of seeing some of these windows. For the very little ones there is a possibility it will be totally in an erosional mode so you are not covered with a patina or any other dust. It is likely that we may not learn much about lateral variations on the rock surfaces of the middle-size asteroids because of their regoliths.