PART III

POSSIBLE SPACE MISSIONS AND FUTURE WORK

https://doi.org/10.1017/S0252921100089326 Published online by Cambridge University Press

ARGUMENTS FOR A MISSION TO AN ASTEROID

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GROUPS OF ASTEROIDS

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

(1) *Main belt asteroids* orbit between Mars and Jupiter. Most of them have semimajor axes a in the range $2.0 < a < 3.5$ AU.
(2) *Asteroids outside the main belt* form a number of different groups, such as the Trojans, Hildas, etc.
(3) *Mars-crossing asteroids* are bodies with low a values and perihelia inside the Martian orbit; in several cases they are inside Earth's orbit. They are the closest neighbors in space of the Earth-Moon system. A list of them is given by Marsden, table II.[1] We select from these the ones with eccentricities in the range 0.2 to 0.4; they will be referred to as the Eros group, named after its largest member. The arguments for a mission to an asteroid refer especially to the Eros group as a first target.

SPECIFIC INTEREST OF ASTEROID EXPLORATION

Access

Of the celestial bodies yet discovered, our closest neighbors in space, except for the Moon, are members of the Apollo and Amor groups. One of them, Icarus, passed very close to Earth in 1968.

A flyby mission to members of these groups would be relatively simple, but probably not very rewarding because their relative velocities when close to Earth are very high, on the order of 30 km/s. A rendezvous and soft landing is for this reason a technically difficult project.

Of all the translunar celestial bodies, the Eros asteroids are the easiest to reach and therefore would be more favorable objects for investigation. They have eccentricities that are definitely lower than the other Apollo and Amor asteroids (although still rather high), and their relative velocities when close to

[1]See p. 419.

Earth are reasonably small (some < 5 km/s). This means that they are not very difficult objects with which to rendezvous by means of a soft unmanned landing or—in the future—a manned landing.

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

An Almost Unknown Group of Bodies

Very little is known about the asteroids. Except for Ceres and Vesta, almost nothing is known about their mass, density, bulk chemical composition, structure, or albedo. Polarimetric and infrared measurements have given some information on their surface properties. Regular light variations indicate that they spin with periods on the order of 3 to 15 hr.

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, 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.

The asteroids traditionally have been considered to be fragments of one or several "exploded planets," but this view encounters serious difficulties (e.g., it cannot adequately explain the distribution of orbits). Moreover, it is reasonable to assume that they were accreted by the same process as planets and that the assembly of asteroids is similar to the "planetesimal" state preceding the formation of planets. As such they would be products of concurrent accretion and breakup processes. The development of theories for either one of these processes encounters the difficulty that we know next to nothing about the collective behavior of a population of orbiting small bodies of asteroid size.

Asteroids: Celestial Bodies of Unique Size

The observed asteroids form a group of bodies that 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 an Eros asteroid, and 3 m as the size of meteorites from which we have gained our information about meteoroids (fig. 1). With these values, the masses of the Eros group of asteroids differ by a factor of 1 billion from those of the planets, and also by a factor of 1 billion from the masses of meteorites.

Hence the Eros asteroids, which we are particularly considering 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. Our knowledge of these is also very deficient, but they are more distant in space than the Eros asteroids. Our hope of filling this gap in the near future is connected with missions to members of this latter group.

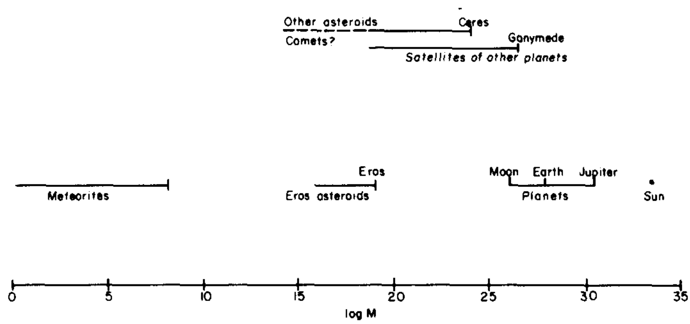

Figure 1.–Mass spectrum of bodies in the solar system. Lower group: Bodies which have been explored are (1) meteorites that have fallen to Earth and (2) the Moon and planets that have been targets of space missions. The Eros asteroids are located in the middle of a gap of almost 20 orders of magnitude between the meteorites and the planets. Upper group: Other bodies, more difficult to explore.

It is sometimes claimed that the region of the mass spectrum which the asteroids occupy is unimportant. In reality there are a number of fundamental questions that can be solved only by a closer study of this region. One of these questions is how the accretion of planets took place, because the accreting embryos (or planetesimals) must have passed through this range. Furthermore, in this mass region, the accretive process must change its character from nongravitational to predominantly gravitational. Exploration of the Moon has demonstrated that all new material accreting on bodies of this large size impacts with such a high energy that practically all traces of the original structure are obliterated.

The Relations Between Asteroids, Comets, and Meteoroids

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. Attempts have been made 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 some asteroids is likely to exist, but because the gap in the 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 at the present time. "Poor man's space research," consisting of analysis of meteorites that automatically fall to Earth, is thus sometimes thought to be a satisfactory substitute for real space missions.

The determination of the orbits of meteorites, which now is beginning to supplement the chemical and mineralogical studies of these objects, is certainly very important for the exploration of the meteoroid population. Existing results make it clear, however, that meteorites constitute a highly biased sample that is far from representative of the small bodies in space. These 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 ($< 10^{-3}$) of the groups of bodies that intersect Earth's orbit are sufficiently tough and slow to be collected on the ground for analysis. Of the small fraction of meteoroids that thus can be studied, many have broken up and all have suffered serious damage by surface heating and ablation. This completely destroys the loose material and the skin, which contain the record of the low-energy space irradiation. The ablation also makes it difficult to take full advantage of the higher energy exposure record in meteoroids.

It is possible that the meteorites are related to some groups of asteroids (especially the Apollo group) and to the comets, but these relations badly need observational confirmation. It is doubtful whether there is any direct connection with main belt asteroids, because it is very difficult to deflect these bodies into Earth-crossing orbits. The Eros asteroids are intermediate. Some of them are Earth-crossing, and may be associated with meteors, some are not. A clarification of these questions is possible only with increased knowledge of asteroids.

There is a possibility of finding soft-landed cosmic dust and meteoroids preserved on the surface of asteroids because their gravitation is so small and because alteration by impact gardening proceeds at a much lower rate than previously inferred (Arrhenius et al., 1971). Hence, asteroid investigations may also clarify the in-space structure of these materials.

Both the comets and the natural satellites of other planets are very interesting objects, some in the same mass range as asteroids. In comparing missions to asteroids with missions to comets or satellites, one can give good arguments for consideration of the latter two classes of bodies. However, the technical difficulties connected with scientifically rewarding missions to these bodies are very much larger at the present time.

Eros Asteroids as Space Probes Clarifying the History of Earth-Moon System

Investigation of an Eros asteroid could give us an important point of reference for clarifying the history of the Earth-Moon system. For example, an event like the heating of the Moon 3.5 billion yr ago can either be associated with some event specific to the development of the Earth-Moon system (for example, the capture of the Moon) or it could possibly be produced by some external cosmic phenomenon affecting this whole region of space. If the thermal history of Eros asteroids is clarified, a decision between these alternatives is possible.

The Eros Asteroids and the Early History of the Moon

The asteroids may also contribute in another respect to the clarification of the early history of the Moon. Some of the Eros asteroids come very close to Earth with reasonably low velocities. There is a possibility that the precapture orbit of the Moon was similar. Hence, the history of the Moon may be related to some of the Eros asteroids. For example, it is possible that some of them are planetesimals that escaped accretion by the planet Moon. If this type of relationship exists, there should be a direct connection between these asteroids and the bodies that produced the lunar craters when impacting on the Moon.

The First Undifferentiated Bodies To Be Investigated

Both Earth and the Moon are large enough for high-temperature planetary evolution including volcanism and radial differentiation. This means that it is impossible to draw any certain conclusions about their bulk chemical composition from studies of samples from their surfaces.

Among the asteroids we are much more likely to find materials that have never been melted since the accretion. Although degassing and partial melting by shock have modified parts of them, gravitational separation is ineffective in the mass range covered by the Eros asteroids. If some are fragments of larger bodies, the internal constitution of these could be determined from the fragments. Their composition and structure may in part be similar to some types of meteorites. However, the loose surface deposits (which must necessarily be found locally) and the exposed hard rock surfaces must have characteristics that have never been sampled in meteorites or on the Moon. This surface layer is likely to contain a unique record of the accretion and ablation processes active in the planetesimal environment. In general, the exploration of asteroids would provide the real configuration and interrelation of the component materials (which may be of known or unknown type) and hence for the first time a direct record of how the most primitive bodies develop in the solar system. No new minerals in a strict sense were found on the Moon, yet their configuration and alteration provided completely new and largely unpredicted information.

In contrast to the planets and to the Moon, the Eros asteroids may supply us with planetesimal matter in a very primitive state. This does not mean that they are samples of homogeneous "primordial" matter because the proportions of condensable elements in the primordial plasma most likely have undergone significant fractionation during the emplacement and condensation processes. However, we would approach the primordial state one step farther.

ACKNOWLEDGMENTS

In preparing this review, we have profited from the discussion at this colloquium. Support from NASA grants NGL-05-009-154 and NGL 05-009-002 is gratefully acknowledged.

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