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EARTH-APPROACHING ASTEROIDS AS TARGETS FOR EXPLORATION

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Primary goals for the exploration of Earth-approaching asteroids will be to determine their chemical and mineralogical composition and especially to determine their structure. Objects derived from the main asteroid belt are likely to be fragments of larger bodies. As such they would provide direct evidence on the internal structure, processes, and history of the larger parent asteroids. Nonvolatile cores of extinct comets, on the other hand, may yield the most direct evidence obtainable concerning the early stages of accretion of solid matter in the solar system, specifically in the outer part of the system. Return of samples would be essential to develop and decipher this evidence.

Study of unmanned missions shows that between 5% and 10% of the Earth-approaching asteroids can be reached by low ΔV ballistic trajectories (ΔV from low Earth orbit less than the 6.4 km/sec required for rendezvous with Mars). Two of the best candidates, from the trajectory standpoint, are 1977VA and 1943 Anteros. Both of these are Amor asteroids. Rendezvous is achieved near aphelion, and the minimum impulse required for sample return to Earth is very low--of the order of 1 km/sec. Because impulses for landing and escape from these small asteroids are of the order of 1 m/sec, many landings could be made to visit and sample different parts of an asteroid in the course of a single mission. An aggressive astronomical search for more near-Earth asteroids will undoubtedly yield many more promising candidates for this type of exploration. Development of the Space Shuttle opens the possibility of an exploration program wherein a single spacecraft could make repeated round-trips between the Earth and different low ΔV asteroids.

The discovery of 1976AA ($a = 0.97$, $e = 0.18$, $i = 19°$) indicates that a few asteroids exist which are very close neighbors of the Earth. The extreme near-Earth objects are Amors and Earth-crossers with semimajor axes near 1 AU that have acquired small e and i as a consequence of repeated close encounters with the Earth. Typically, these objects would be accessible by low ΔV missions of 6 months or a year duration. Manned missions to explore such bodies are technically feasible by utilizing the capabilities of the Space Shuttle. Roughly about 1% of the Earth-approaching asteroids may be sufficiently close neighbors of the Earth to be considered candidates for manned missions based on 7-10 Shuttle launches. The discovery rate for Earth-crossers would have to be increased by a factor of about five, however, in order to achieve a high expectancy of finding a suitable target within 10 years. The primary tasks of exploration of Earth-approaching asteroids are well suited to the capabilities of properly trained astronaut-scientists.

INTRODUCTION

The primary goals for the exploration of near-Earth asteroids (including those bodies which are extinct comets) would be to determine their structure, the diversity of chemical and mineralogical composition of individual bodies, the processes of accretion and subsequent metamorphism or magmatic differentiation of these bodies, and especially the history of these processes. Objects derived from the main asteroid belt are likely to be fragments of larger bodies. As such they would provide direct evidence on the internal structure, processes, and history of the larger parent asteroids. The stony cores or other nonvolatile residua of extinct comets, on the other hand, may yield the most direct evidence obtainable concerning the early stages of accretion of solid matter in the solar system, specifically in the outer part of the system. Return of samples will be essential to develop and decipher much of this evidence.

The Earth-approaching asteroids are especially attractive for exploration because of several favorable conditions. First, some of the Earth-approaching asteroids are the easiest bodies beyond the Moon to reach. Secondly, with the possible exception of a few active comet nuclei, some are the smallest bodies discovered in the solar system. Because of their small size, they have very low escape velocities, of the order of 1 m/sec. This has two important consequences for exploration:

1. On account of the low escape velocities, regoliths on their surfaces should be very thin to locally absent. Sufficient bedrock should be exposed, in crater walls and elsewhere, to determine the structure of these objects from a combination of remote and on site observations and samples. It is of interest, in this regard, that infrared radiometric observations of Betulia suggest that it has a rocky surface, unlike that of larger main belt asteroids (Lebofsky *et al.*, 1978).

2. Because of the low escape velocities, landing and escape from surfaces of these asteroids requires almost negligible propulsion. Landing is roughly comparable to docking with another spacecraft, and it should be possible to achieve landing by means of relatively simple engineering design features.

Third, on the basis of dynamical considerations and existing physical observations, many different kinds of bodies appear to be represented among the near-Earth asteroids. In particular, it seems likely that they include many extinct comets.

It has been argued that, because a large number of meteorites that are presumed to be samples of asteroids are already available for study, missions to retrieve samples from asteroids are unnecessary. Most of what is known about very early conditions and events in the history of the solar system has, indeed, been learned from meteorites. As important as the meteorites are, however, every one of them is a sample out of context. Until asteroids are actually explored and sampled directly, the reconstruction of the parent bodies whence meteorites have come will remain speculative. This limitation of knowledge about the parent bodies, in turn, places severe restraints on our understanding of meteorites and on the relationship of the meteorites to one another. Celestial mechanics and the processes of meteoroid entry into Earth's atmosphere are efficient filters, moreover, and it is clear that meteorites are not a representative set of samples of solid material in near-Earth space.

What are the fragile objects that disintegrate in the Earth's atmosphere? Do we actually have samples among the meteorites of the nonvolatile parts of comets? What is the structure of a comet nucleus or of the nonvolatile parts of the nucleus? What is the structure of a small primitive asteroid? Is it an aggregate of aggregates of solid objects accumulated during accretion? What is the size of the component parts? What is the diversity of constituents in such a body? The answers to these questions can only be obtained by direct exploration. Global surveying of individual bodies, combined with multiple returned samples, is required to obtain definitive answers to questions such as those.

UNMANNED MISSIONS

The accessibility of near-Earth asteroids for exploration by spacecraft can be expressed by the ΔV required for rendezvous, or, in the case of sample return or manned exploration, the combined ΔV for rendezvous and return to Earth. Detailed studies of outbound and return trajectories are required for precise determination of the ΔV for any mission. But a convenient approximate estimate of the minimum possible ΔV may be obtained from the following figure of merit, F

$$F = U_L + U_R \tag{1}$$

where U_L is the impulse required to inject a spacecraft into a transfer trajectory from low Earth orbit to the orbit of the asteroid, and U_R is the impulse required for rendezvous with the asteroid. For simplicity of calculation, both U_L and U_R are normalized to the Earth's orbital speed and are, therefore, dimensionless. Low ΔV trajectories are achieved by rendezvous near aphelion or perihelion of the asteroid orbit. Minimum ΔV missions to Amors and Apollos (where Apollo asteroids are formally defined as having $a > 1$ AU) are achieved by rendezvous at aphelion. The transfer orbit of the spacecraft is taken to be tangent to the orbit of the Earth at perihelion and tangent to the orbit of the asteroid at aphelion. In order to achieve rendezvous under these ideal conditions the asteroid would have to arrive at aphelion at precisely the right time. In actual missions, the asteroid is almost never at the ideal position, so that real ΔVs to rendezvous are always somewhat larger than calculated here for the ideal case.

It is assumed that, in the average case, half the plane change is accomplished at injection into the transfer orbit and half at rendezvous. In the case where the argument of perihelion is 0, and neglecting the finite eccentricity of the Earth's orbit, U_L is then given by

$$U_L = \sqrt{U_t^2 + S^2} - U_o \tag{2}$$

where S is the normalized speed of escape from Earth, U_o is the normalized orbital speed at low Earth orbit, and

$$U_t^2 = 3 \quad \frac{2}{Q+1} - 2\sqrt{\frac{2Q}{Q+1}} \cos \frac{i}{2} \tag{3}$$

where Q is the aphelion distance of asteroid normalized to semimajor axis of the Earth, and i is the inclination of asteroid orbit. The solution for U_t is obtained from the equation for the encounter speed of an object in eccentric orbit with an object in circular orbit (Öpik, 1951). A term could be added in the computation of U_t for the eccentricity of the Earth's orbit, but the correction is less than 1% in F for all known cases. The impulse at rendezvous, U_R, is given by

$$U_R = \sqrt{U_c^2 - 2U_r U_c \cos \frac{i}{2} + U_r^2} \tag{4}$$

where, for Amor asteroids,

$$U_c^2 = \frac{3}{Q} - \frac{2}{Q+1} - \frac{2}{Q}\sqrt{\frac{2}{Q+1}} \cos\frac{i}{2} \tag{5}$$

$$U_r^2 = \frac{3}{Q} - \frac{1}{a} - \frac{2}{Q}\sqrt{\frac{a}{Q}(1-e^2)} \tag{6}$$

a is the semimajor axis of asteroid normalized to semimajor axis of the Earth, and e is the eccentricity of the asteroid, and for Apollo asteroids,

$$U_c^2 = \frac{3}{Q} - \frac{2}{Q+1} - \frac{2}{Q}\sqrt{\frac{2}{Q+1}} \tag{7}$$

and $$U_r^2 = \frac{3}{Q} - \frac{1}{a} - \frac{2}{Q}\sqrt{\frac{a}{Q}(1-e^2)} \cos\frac{i}{2} \tag{8}$$

For 1976AA-type asteroids ($a \leq 1$ AU), minimum ΔV missions are achieved by rendezvous at perihelion. However, short duration missions are achieved by rendezvous at aphelion. The nominal strategy adopted for rendezvous at aphelion with 1976AA-type asteroids is somewhat different than that used for rendezvous with Amors and Apollos. The semimajor axis of the transfer orbit of the spacecraft is held at 1 AU and is tangent at aphelion with the orbit of the asteroid. This decreases the rendezvous impulse, U_R, at the expense of a minor increase in U_L; the perihelion of the spacecraft orbit no longer corresponds to the point of injection into the transfer trajectory. Equations (2), (4) and (8) apply, and the solutions for U_t and U_c now become

$$U_t^2 = 2 - 2\sqrt{2Q - Q^2} \cos\frac{i}{2} \tag{9}$$

$$U_c^2 = \frac{3}{Q} - 1 - \frac{2}{Q}\sqrt{2 - Q} \tag{10}$$

The figure of merit obtained by means of these equations is compared with the actual ΔV to rendezvous with eight low ΔV objects in Figure 1. The equation

$$\Delta V = (30F + 0.5) \text{ km/sec} \tag{11}$$

yields the actual ΔV for optimum missions within a few tenths of km/sec precision. (Orbital speed of the Earth is 30 km/sec).

Cumulative frequency distributions of F are shown for Amors in Figure 2 and for Apollos in Figure 3. About 30% of the Amors have figures of merit comparable to or lower than that of Mars. About 75% of the Amors have lower figures of merit than "typical" main belt asteroids. (F for a typical main belt asteroid shown in Figures 4 and 5 was computed on the basis of $a = 2.5$, $e = 0.15$, and $i = 15°$.) The cumulative frequency distribution of F for Apollos is displaced toward slightly higher values with respect to the cumulative distribution of F for Amors. About 60% of the Apollos are easier to reach than "typical" main belt asteroids.

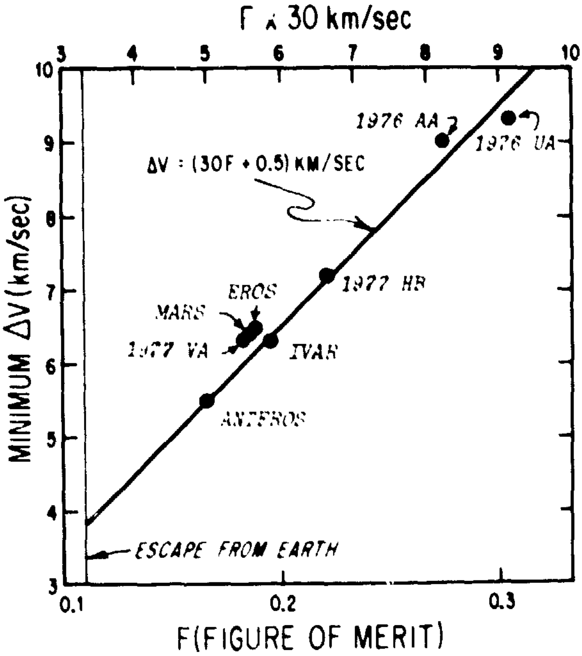

Fig. 1. Correlation of figure of merit with minimum ΔV for optimum low ΔV missions. Minimum ΔVs are from Arnold and Duke (1977) and from Bender (personal communication, 1977).

The most favorable known asteroids for low ΔV missions are Anteros and the recently discovered Amor asteroid 1977VA. Both of these asteroids are easier to reach than Mars, Anteros by a significant margin. Eros, 1960UA, Ivar, and 1972RB all have favorable figures of merit, close to that of Mars. The Apollo asteroid 1959LM has a figure of merit similar to that of Anteros, but the orbit of 1959LM is poorly determined and it is lost. Another Apollo, PLS 6743, also has a very low figure of merit and is lost.

A characteristic of special importance about rendezvous missions at aphelion with low ΔV Amors and Apollos is that the rendezvous impulse is very low, typically of the order of 1 km/sec and, in some cases, less. Under optimum conditions, the departure impulse for return to Earth is about the same as the rendezvous impulse. Hence, missions can be found where the sum of rendezvous and departure impulses required for sample return is in the range of 2-3 km/sec. In this respect, low ΔV Earth-approaching asteroids are substantially more accessible than typical main belt asteroids, where the sum of rendezvous and departure impulses is in the range of 5-6 km/sec or higher. As shown by Niehoff (1977), a simple ballistic sample return mission to Anteros is well within the injection capability of a single Space Tug.

Development of the Space Shuttle opens the possibility of an entirely new type of exploration program. A single spacecraft could make repeated round-trips between Earth orbit and different low ΔV asteroids. Propulsion for such a spacecraft could be provided either by conventional rocket engines or by low-thrust (ion) engines. Samples could be retrieved from the spacecraft in Earth orbit by means of the Shuttle, where the spacecraft itself could be refurbished with new sample containers and propellant for either conventional or additional ion engines. A nominal single mission to each asteroid should include detailed visual, spectrophotometric, and chemical mapping of its surface, determination of its mass and density, and multiple landings, at sites selected from this mapping, with on-site measurements and recovery of samples. Rotation of the asteroid would have to be determined from visual mapping to permit the maneuvers required for landing.

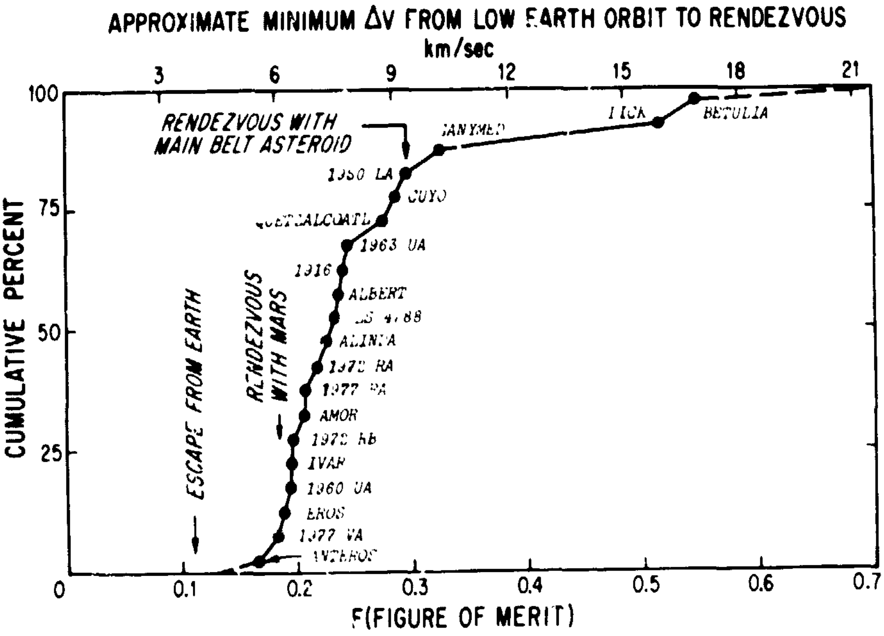

Fig. 2. Cumulative frequency distribution of figure of merit for rendezvous with Amor asteroids at aphelion.

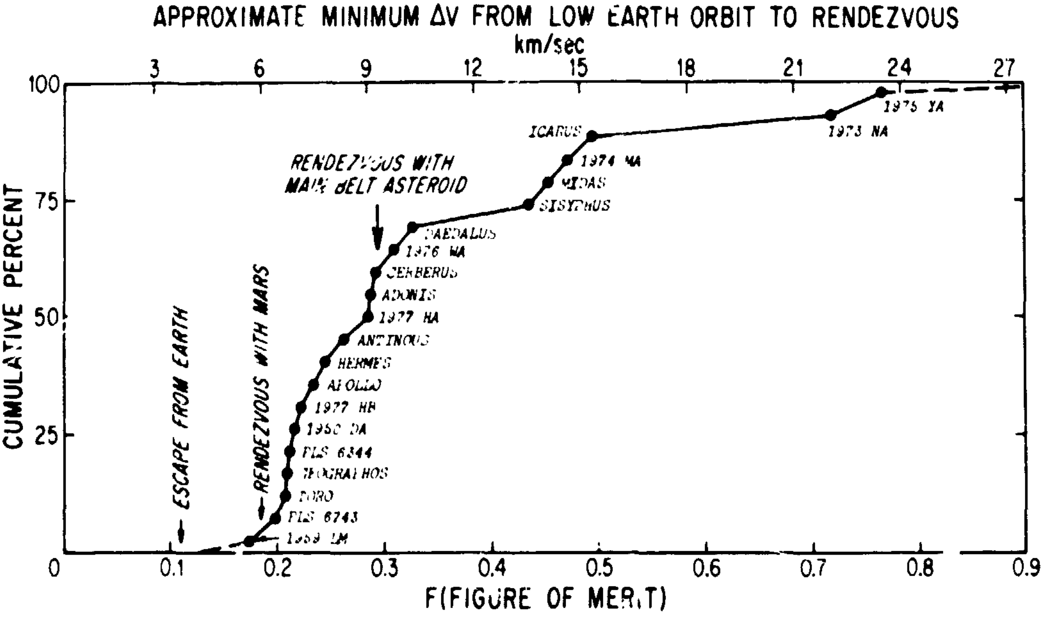

Fig. 3. Cumulative frequency distribution of figure of merit for rendezvous with Apollo asteroids at aphelion.

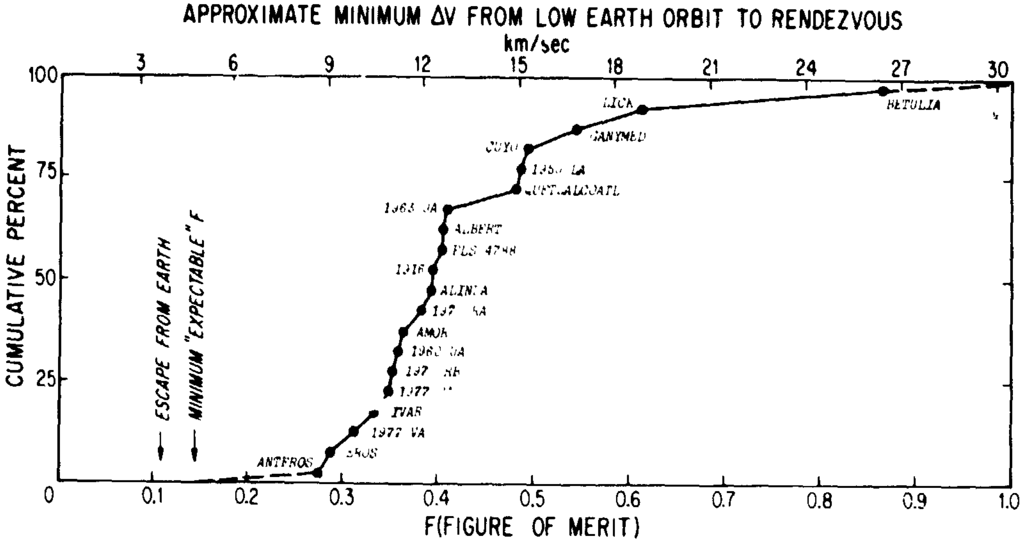

Fig. 4. Cumulative frequency distribution of figure of merit for rendezvous with Amor asteroids at perihelion.

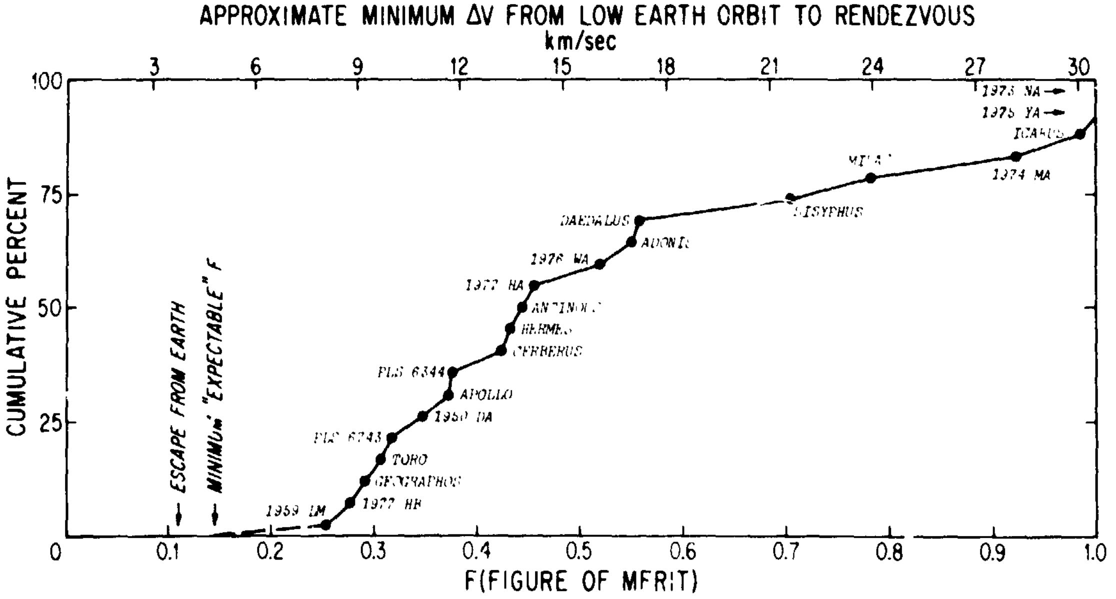

Fig. 5. Cumulative frequency distribution of figure of merit for rendezvous with Apollo asteroids at perihelion.

A broad range of compositional types has already been identified among the favorable low ΔV asteroids. An initial program, for example, might include missions to 1960UA (possible C type), Ivar (S type) and 1977VA (possible M or E type). It is of interest that a possible extinct comet, 1960UA, is among the known low ΔV objects.

Several unnumbered asteroids that have very low apparent ΔV from low Earth orbit to rendezvous, 1946SD, 1949SZ, and 1936UI, are occasionally listed among the Amors. These objects have poorly determined orbits, however, and are lost. In all probability their eccentricities and semimajor axes are higher than has been estimated by preliminary calculation, and they do not have as low figures of merit as suggested by the preliminary elements. The asteroid 1936UI, discovered by Reinmuth, has a nominal figure of merit of 0.17, and it may be worth attempting its recovery.

A continuing survey for new Earth-approaching asteroids will undoubtedly yield more promising candidates for sample return missions. A few percent of the Amors and the Apollos probably have still lower figures of merit than Anteros, and would be especially favorable for sample return missions. An aggressive campaign to find these objects and determine their compositional classification and also to identify more possible extinct comets should be carried out as a prelude to a multiple asteroid sample return program.

MANNED MISSIONS

The discovery of 1976AA ($a = 0.97$, $e = 0.18$, $i = 19°$) indicates that a few asteroids exist which are very close neighbors of the Earth (Helin and Shoemaker, 1977). Asteroid orbits with a near 1 and low e and i have the characteristic that very low ΔV spacecraft trajectories to rendezvous and for Earth return can be accomplished in relatively short periods of time--typically either six months or a year, for a round-trip mission. The discovery of a very near-Earth asteroid raises the possibility of manned exploration utilizing the capability of the Space Shuttle to carry manned spacecraft and the necessary propulsion systems into Earth orbit. Although 1976AA is a close companion of the Earth in space, its moderately high orbital inclination makes it less easy to reach than many other Earth-crossing asteroids and many Amors. Nevertheless, for short duration round-trips, 1976AA is one of the three easiest targets for exploration and, in many respects, is the best known candidate for a short mission.

Low ΔV short duration trajectories are achieved by rendezvous at perihelion for Amors and for all known Apollos and at aphelion for known 1976AA-type asteroids. In computations of the figure of merit for rendezvous at perihelion of Amor asteroids, the perihelion of the spacecraft transfer orbit is taken as tangent with the Earth's orbit at perihelion, and tangent with the asteroid orbit at aphelion. Launch impulse, U_L, is obtained from Equation (2), and the perihelion distance, q, is substituted for Q in Equation (3), *i.e.*,

$$U_t^2 = 3 - \frac{2}{q+1} - 2\sqrt{\frac{2q}{q+1}} \cos \frac{i}{2} \tag{12}$$

Rendezvous impulse, U_R, is given by

$$U_R = \sqrt{U_c^2 + 2U_r U_c \cos \frac{i}{2} + U_r^2} \tag{13}$$

where $$U_c^2 = \frac{3}{q} - \frac{2}{q+1} - \frac{2}{q}\sqrt{\frac{2}{q+1}} \qquad (14)$$

and $$U_r^2 = \frac{3}{q} - \frac{1}{a} - \frac{2}{q}\sqrt{\frac{a}{q}(1-e^2)}\cos\frac{i}{2} \qquad (15)$$

For Apollo asteroids, the spacecraft transfer orbit is taken as tangent with the asteroid orbit at perihelion, and the semimajor axis of the transfer orbit is held at 1 AU. Launch impulse is, again, obtained from Equation (2) but U_t^2 is now given by

$$U_t^2 = 2 - 2\sqrt{2q - q^2}\cos\frac{i}{2} \qquad (16)$$

Rendezvous impulse is computed by Equation (4),

$$U_c^2 = \frac{3}{q} - 1 - \frac{2}{q}\sqrt{2 - q} \qquad (17)$$

and U_r^2 is obtained from Equation (15).

Cumulative frequency distributions of F are shown for Amors in Figure 4 and for Apollos in Figure 5. The approximate minimum ΔV from low Earth orbit to rendezvous at perihelion with Amors and Apollos is approximately 50% higher than the minimum ΔV to rendezvous at aphelion with these asteroids. Velocities of known Amors and Apollos are much higher at perihelion, and the rendezvous impulses are correspondingly higher. For the best candidates for short duration missions among the asteroids discovered so far, the minimum ΔVs to rendezvous are about 9 km/sec (Table 1). The approximate ΔV to rendezvous with 1959LM is 8.1 km/sec, but, because this asteroid has a poorly determined orbit and is lost, it is not listed in Table 1.

Table 1. Best Known Candidate Asteroids for Short Duration, Low ΔV Missions

Asteroid	Orbital Type	F	Approximate Minimum ΔV to Rendezvous (km/sec)
Anteros	Amor	0.27	8.7
1976AA	1976AA	0.27	8.7
1977HB	Apollo	0.28	8.9
Eros	Amor	0.29	9.2
Geographos	Apollo	0.29	9.3
1976UA	1976AA	0.31	9.7
Toro	Apollo	0.31	9.7
1977VA	Amor	0.31	9.8

The two lowest ΔV asteroids in Table 1 are Anteros and 1976AA. Niehoff (1977) has investigated round-trip missions to these asteroids for favorable opportunities. Round-trip ballistic missions of 365 days duration, allowing for 30 days stay time at each of the asteroids, can be achieved with ΔVs to rendezvous of 9.2 km/sec for Anteros and 9.1 km/sec for 1976AA. A six-month duration mission to 1976AA would require more than a 20% increase in the energy requirements. Niehoff estimates that 28 Shuttle launches would be needed for a manned mission to 1976AA and 34 Shuttle launches for the mission to Anteros. The requirement for Shuttle launches could be reduced to 23 for the mission to Anteros, if the stay time were reduced to 10 days.

Whether 23 or 28 Shuttle launches is an acceptable cost for a manned mission to an asteroid depends on the priority and national significance that is attached to such a mission. These missions could almost certainly be accomplished by assembly of spacecraft and propulsion modules transported to Earth orbit by the Shuttle and by fueling in orbit. Significant improvements in cost probably could be achieved by means of more sophisticated strategies than simple ballistic missions. For example, fueled propulsion modules for the departure impulse from the asteroid might be delivered to the asteroid ahead of time by unmanned spacecraft, utilizing either conventional or low-thrust propulsion systems. The most economical attack on reducing the number of Shuttle launches required, however, would be to search for asteroids with more favorable orbits and figures of merit than have been found to date.

Extremely low ΔV Amor asteroids may exist, as a consequence of two different dynamical circumstances. First, it is possible that some small planetesimals have remained in the space between the orbits of Earth and Mars from the time of planetary accretion. Provided that the maximum aphelia of such objects are somewhat less than the minimum perihelion of Mars, 1.309 AU, and that the minimum perihelia of these planetesimals is somewhat greater than the maximum aphelion of the Earth, 1.067 AU, they have indefinitely long lifetimes. Taking account of the forced oscillations of eccentricity, produced mainly by Jupiter, the range of semimajor axes for objects that are safe from collision with Earth or Mars is 1.15 to 1.21 AU (see Friedlander *et al.*, 1977). For these objects to be stable against planetary encounters, they must also have very small proper eccentricity. Fragmentation lifetimes for bodies 100 m in diameter and larger in orbits of this type are greater than the age of the solar system, at the present flux of interplanetary material. The fact that no objects of very low eccentricity have been observed in this region between Earth and Mars may indicate that Mars migrated outward during accretion. Presumably, most of them were swept up by Mars or the Earth or reduced to fine debris by collisions during the period of high bombardment. There is no theoretical basis at present, however, for concluding that these processes completely removed all small bodies.

Secondly, extremely low ΔV Amors can be injected into orbits with aphelia equal to or somewhat greater than 1.309 AU by close encounters with Mars, during the extrema of oscillation of Mars' eccentricity. The probability of this happening is low, but so long as the perihelia of the Amors lie somewhat outside of 1.067 AU, such objects would have very long lifetimes. The figure of merit of an Amor with an aphelion just at 1.309 AU and perihelion at 1.067 AU and with 0° inclination is 0.15, which is equivalent to a minimum ΔV to rendezvous at perihelion of about 4.9 km/sec. This is shown as the minimum "expectable" F on Figure 4. A few percent of the Amors are expected to have figures of merit for rendezvous at perihelion between 0.15 and 0.27, corresponding to ΔVs between 4.9 and 8.7 km/sec.

Two mechanisms may produce extremely low ΔV Earth-crossing asteroids: (1) injection of very low ΔV Amors into Earth-crossing orbits by encounter with Mars, and (2) reduction of ΔV of Earth-crossers by multiple encounters with Earth and Venus. In the first case, the limiting figure of merit is 0.15, as given above for Amors. In the second case, the limiting F is found for a body that just crosses the orbit of Venus, at the maximum Q of Venus, 0.777 AU, and the orbit of the Earth at minimum q of the Earth, 0.933 AU. For rendezvous near the Earth, at aphelion of the asteroid, the figure of merit would by 0.18, corresponding to a minimum ΔV to rendezvous from low Earth orbit of about 5.8 km/sec.

Minimum encounter velocities at the Earth's sphere of influence for very low ΔV asteroids derived either from Amors or from Venus-crossers would be 1.9 km/sec. Multiple encounters with the Earth would be expected to shuffle the orbital elements, while the encounter velocity tends to be conserved. Changes in e and a would be exchanged for changes in i, for example, so that some of these bodies would tend to become exclusively Earth-crossing, like 1976AA. It might be supposed that encounters with the Earth could further reduce the ΔV to rendezvous. While this is physically possible, it is statistically more likely that the ΔV will be increased by such encounters. From the cumulative frequency distribution of F for Apollos (Figure 5), a few percent of the Earth-crossers are expected to have figures of merit between 0.15 and 0.25 corresponding to approximate ΔVs of 4.9-8 km/sec. Both "cometary" and "asteroidal" objects should be present in this group of Earth-crossers.

Finally, there are two possible dynamical classes of near-Earth objects, representatives of which have not so far been discovered. Weissman and Wetherill (1974) have shown that substantial regions of stability in orbital element phase space exist for objects in 1:1 resonance with the Earth. These regions are analogous to the stable L_4 and L_5 libration regions on Jupiter's orbit, which are occupied by the Trojan asteroids. Gehrels (1977) has made a preliminary search of the libration regions on the orbit of the Earth without success. Another region of stable orbit, for objects of low eccentricity, lies between Venus and Earth. This region has never been deliberately investigated. As both the libration regions on the orbit of the Earth and the region of stable orbits between Venus and Earth are more than 90° from opposition, they are very rarely examined for asteroids. We plan to begin such a search in 1978. Trojans of the Earth would represent the ultimate low ΔV asteroids. As the most stable objects, on "tadpole" orbits, can never approach the Earth more closely than ~0.4 AU, however, they would be less accessible on short duration missions than low ΔV Amors and Earth-crossers.

Parametric studies of transfer trajectories in near-Earth space by Niehoff (1977) show that impulse requirements for round-trip missions scale almost linearly with inclination of the target asteroid for i below 20°. A 100% increase in energy is required for every 6-7° increase in inclination. For an asteroid with a and e comparable to 1976AA, about 10 Shuttle launches would be required for a manned mission, if the inclination were 8°, and about seven Shuttle launches if the inclination were reduced to 5°. Encounter velocity at the Earth's sphere of influence for such an asteroid with i = 5° would be 4.2 km/sec, more than twice the minimum velocity for Earth-crossers given above. he discovery of objects which could be reached by manned missions using 7-10 Shuttle launches, therefore, appears entirely possible. Very roughly, about 1% of the Amors and 1% of the Earth-crossing asteroids may fall in this category. There may be a total of 10-20 Earth-approaching asteroids to absolute visual magnitude 18 (diameters in the range of 0.7-1.5 km) with encounter velocities of 4-5 km/sec or less and many more smaller bodies. An intensive search for Earth-approaching asteroids will be needed to find these bodies. At the present rate of discovery of Earth-approaching asteroids of 4-5 per year, it might take 25-50 years to find the first one. The rate of discovery will need to be increased by a factor of at least five to achieve a reasonably high probability of discovering, within the next decade, an asteroid which could be reached with a simple ballistic manned mission utilizing 7-10 Shuttle launches.

The scientific objectives of a manned mission would be similar to those of the unmanned missions. Properly trained astronauts, however, would bring to the task of exploration an enormous advantage in maneuverability and dexterity on the surface of the asteroid, with the attendant advantages for close scientific examination of the surface and flexibility in sampling They would be able to solve details of the structure of the asteroid that would be very difficult to obtain by unmanned spacecraft and to sample accordingly. It is the structure of the body, with all that this term implies for decipherable history, or, in other words, the geology of the asteroid, which constitutes the primary goal of direct exploration. It is a task made to order for astronaut-scientists.

While the task of exploration of Earth-approaching asteroids is highly appropriate for manned missions, we do not suggest that such missions would be undertaken for scientific goals alone. Earth-approaching asteroids constitute the next nearest worlds in space, beyond the Moon, that can be visited by man. Missions to these objects represent the most readily achievable step in an orderly development of manned space exploration. The value of such missions must be judged in the context of the larger goal of extending man's capabilities in space and in extending the frontier of exploration.

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