Ground-Based Observation of Near-Earth Asteroids

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An increased ground-based observation program is an essential component of any serious attempt to assess the resource potential of the near-Earth asteroids. A vigorous search and characterization program could lead to the discovery and description of about 400 to 500 near-Earth asteroids in the next 20 years. This program, in conjunction with meteorite studies, would provide the data base to ensure that the results of a small number of asteroid-rendezvous and sample-return missions could be extrapolated with confidence into a "geological base map" of the Aten, Apollo, and Amor* asteroids.

Ground-based spectral studies of nearly 30 members of the Aten/Apollo/Amor population provide good evidence that this class includes bodies composed of silicates, metal-silicates, and carbonaceous assemblages similar to those found in meteorites. It is probable that the full range of known meteoritic materials (if not an even greater diversity) is represented in the near-Earth population. These include water- and carbon-bearing C1 and C2 types and metal-silicate bodies that are 5- to 50-percent metal.

Among the relatively few known members of this large near-Earth population are objects in orbits that require less (sometimes much less) energy to reach from low Earth orbit (LEO) than the lunar surface requires. Their orbits are similar to the orbit of the Earth, though many are inclined to it. And, because they are much smaller than the Moon, they have little gravitational attraction. Thus, only a small amount of propulsive energy is required to approach or leave those whose orbits are both close and in nearly the same plane. Using current propulsion technologies, the vast majority of near-Earth asteroids are practically inaccessible. However, if there are as many near-Earth asteroids as we think there are, many more seem likely to be found that are in favorable orbits.

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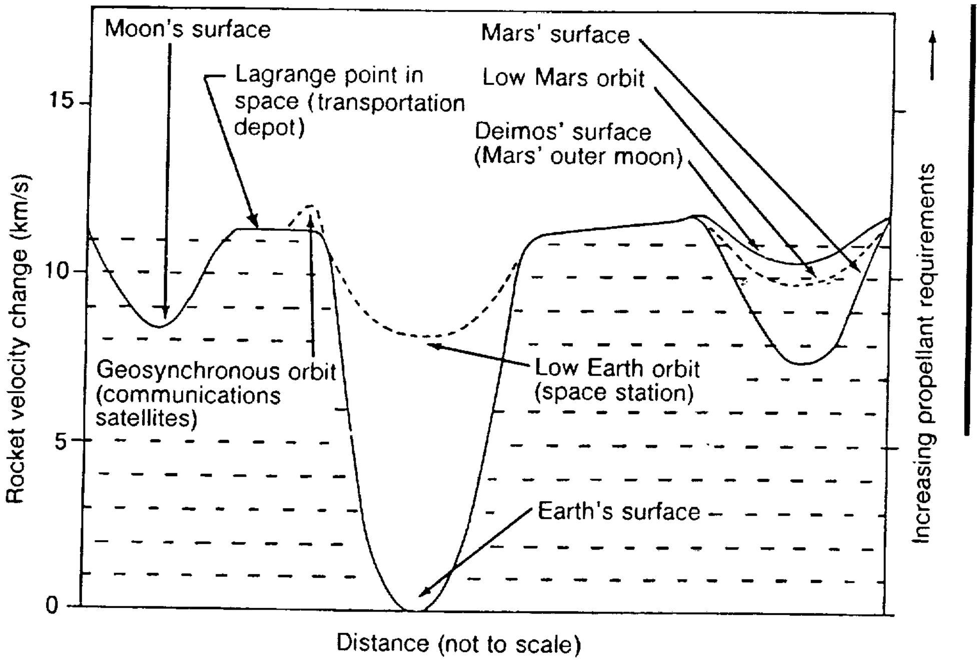
* The Aten asteroids are those whose orbits lie mostly within the Earth's orbit; that is, between Earth and Venus. The Apollo asteroids have orbits that cross the Earth's orbit. The Amor asteroids approach Earth on the Mars side but do not cross the Earth's orbit. These definitions were supplied by Lucy-Ann McFadden, David J. Tholen, and Glenn J. Veeder in their chapter "Physical Properties of Aten, Apollo and Amor Asteroids" in the 1989 book *Asteroids II*, ed. Richard P. Binzel, Tom Gehrels, and Mildred S. Matthews (Tucson: University of Arizona Press).



Velocity Changes (ΔV's) Required To Get to Various Places

Distance to objects in the inner solar system is, in many cases, not as important as the velocity that must be imparted to a spacecraft to enable it to escape the Earth's gravity, reach the object, change direction at the target object, return to Earth, and land softly. The higher the velocity required, the more rocket propellant is necessary to achieve it, and the propellant requirement increases as the square of the velocity change.

The velocity change is dominated by the velocity required to leave a planet's gravitational field. This figure illustrates the effect of "gravity wells" in the inner solar system. Getting off the Earth is the biggest effort, and most models assume that transportation in space starts from low Earth orbit. The Lagrange points and lunar orbit represent the limits of the Earth's gravity well. (Getting to geosynchronous orbit takes a little more energy than getting to lunar orbit.)

The velocity change to get from low Earth orbit to the surface of the Moon is similar to that required to reach orbit around Mars. Some near-Earth asteroids require about the same velocity change as that required to get to martian orbit. The Moon and Mars have significant gravity wells of their own, however; whereas asteroids, being so small, have no significant gravity well. To return to the Earth from the lunar or martian surface requires that the velocity change be reversed.

It is the lack of a gravity well that makes asteroid missions (or missions to Mars' moons, Phobos and Deimos) attractive from an energy standpoint. To return to Earth from an asteroid or Deimos can take as little propellant as that required to go between their orbits and the edge of Earth's gravity well (the Lagrange "plateau" in the figure). From there, aerobraking can take the spacecraft to the orbit of a space station or to the surface of the Earth.

Falling into the gravity well of Mars or the Earth need not take as much propellant as getting out, because the atmosphere can be used to slow down the spacecraft. That was the function of the Apollo heat shield and is the function of the Space Shuttle's thermal protection tiles. Providing such an "aerobrake" to disperse the frictional energy of reentry can reduce the propellant requirement significantly.

Aerobrakes are not "free," as they add mass to the spacecraft going to and returning from the target object. Improving thermal control systems and aerobrake materials will have important consequences for round-trip missions to asteroids.

Figure provided by Paul W. Keaton, Los Alamos National Laboratories.

Table 12 lists the instruments that are being used or could be used to search for near-Earth asteroids. Currently, only a few near-Earth asteroids per year are being found. (See figure 6.) Table 13 lists techniques useful in characterizing asteroids and the types of information obtainable using these techniques. To be confident that usable materials could be recovered from asteroids, we need more specific characterization of their composition. A small commitment of resources (a few million dollars per year) to continue and modestly expand the efforts to find and characterize near-Earth asteroids would enable much greater progress to be made.

TABLE 12. *Near-Earth Asteroid Search Instruments*

Instrument	Detector	Status	Discovery rate per year, current full-time
Large, wide-field telescope (e.g., 48-in. or 120-cm Schmidt) [ground-based]	Photographic with daily plate survey	3-4 days/ month at 1 site	5 / 10s
Large, conventional telescope (e.g., 70-in. or 180-cm Cassegrainian) [ground-based]	CCD with real-time discrimination of fast-moving objects	Half-time operation	1 / 10s?
Infrared satellite (IRAS-type) survey [in LEO]	Liquid-helium-cooled mirror array detector for real-time detection of fast moving objects	Infrared Astronomical Satellite was flown successfully for other purposes	NA / >10s

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Figure 6

Schmidt Telescope

The search for asteroids is conducted with wide-field telescopes known as Schmidt telescopes. A few near-Earth asteroids are being found each year by a team including Eugene Shoemaker, Carolyn Shoemaker (shown here with the Schmidt instrument at the Palomar Observatory), and Eleanor Helin. The telescopes are scanned at the same rate as the Earth turns, so that on photographic plates the stars remain fixed points. Under these conditions, asteroids which are moving across the star field appear as streaks on the plates. The small size and scarcity of near-Earth asteroids makes their discovery a particularly tedious task.

TABLE 13. *Asteroid Characterization Techniques and Information Derived*

Technique	Information derived [Requirements and limitations]
Reflectance spectroscopy and multicolor photometry[a]	Asteroid class[1] [Not a determination of specific composition] Surface mineralogy[2] [Requires broad spectral coverage, high resolution, and high signal-to-noise ratio; knowledge of albedo improves characterization] Detection of water-bearing materials[3] [Data in the 3-μm spectral region required]
Visible photometry and lightcurve photometry[a]	Size[4] [Requires knowledge of albedo] Albedo[4] [Requires knowledge of size] Rotation period[5] [Requires a sequence of closely spaced observations over several nights] Approximate shape[6] [From analysis of lightcurves] Orientation of spin axis[6] [From variation of lightcurve form with viewing geometry]
Visible polarization[a]	Albedo[7] [Requires observations over a range of phase angles]
Infrared photometry[a]	Size[8] [Knowledge of albedo improves determination] Albedo[8] [Derived in combination with visible photometry] Relative emissivity[9] [Model-dependent indication of metal abundance or surface texture]
Radar[b]	Surface conductivity or metal abundance[10] [Model depends on assumptions of surface porosity] Diameter[10] [From duration of returned signal] Rotation rate[10] [From frequency spread and delay in signal] Shape[10] [From temporal variation of frequency spread and time delay]

TABLE 13 *(concluded).*

Technique	Information derived [Requirements and limitations]
Passive microwave radiometry and spectroscopy[a]	Near-surface temperatures[11] Temperature gradients, conductivities, and thermal inertias
Occultations	Diameter[12] [Dependent on obtaining accurate durations from several sites] Shape[12] [Profile for moment of occultation]
Space telescope images	Moderate resolution images[13] [Approximately 30-km resolution in middle of asteroid belt]

[a] The spectral coverage and the spectral resolution of observations depend on the specific instrument and telescope being used. For any particular system, the quality (signal-to-noise ratio) of the resultant data depends on the brightness of the asteroid, which is proportional to the square of its radius and the inverse square of its distance from the Earth and from the Sun. At visible wavelengths the signal is also proportional to the surface albedo, and at infrared and microwave wavelengths it is proportional to 1 minus the albedo.

[b] The strength of the returned radar signal is proportional to the strength of the transmitted signal, proportional to the square of the diameter of the target asteroid, and proportional to the inverse fourth power of the distance to the asteroid. Asteroid distance is the major factor in data quality.

The following references provide detailed reviews of the various techniques listed in this table:

[1] Tholen, David J., and M. Antonietta Barucci. 1989. Asteroid Taxonomy. In Asteroids II, ed. Richard P. Binzel, Tom Gehrels, and Mildred Shapley Matthews, 298-315. Tucson: Univ. of Arizona Press.

[2] Gaffey, Michael J.; Jeffrey F. Bell; and Dale P. Cruikshank. 1989. Reflectance Spectroscopy and Asteroid Surface Mineralogy. In Asteroids II, 98-127.

[3] Lebofsky, Larry A.; Thomas D. Jones; Pamela D. Owensby; Michael A. Feierberg; and Guy J. Consolmagno. 1990. The Nature of Low-Albedo Asteroids from 3-μm Multi-color Photometry. Icarus **83**:16-26.

[4] Bowell, Edward, and Kari Lumme. 1979. Colorimetry and Magnitudes of Asteroids. In Asteroids, ed. Tom Gehrels, 132-169. Tucson: Univ. of Arizona Press.

[5] Harris, A. W., and D. F. Lupishko. 1989. Photometric Lightcurve Observations and Reduction Techniques. In Asteroids II, 39-53.

[6] Magnusson, Per, et al. 1989. Determination of Pole Orientations and Shapes of Asteroids. In Asteroids II, 66-97.

[7] Dollfus, A.; M. Wolff; J. E. Geake; D. F. Lupishko; and L. M. Dougherty. 1989. Photopolarimetry of Asteroids. In Asteroids II, 594-616.

[8] Lebofsky, Larry A., and John R. Spencer. 1989. Radiometry and Thermal Modeling of Asteroids. In Asteroids II, 128-147.

[9] Gaffey, M. J. 1989. Asteroid Surface Metal Abundances. Bull. American Astron. Soc. **21**:963.

[10] Ostro, Steven J. 1989. Radar Observations of Asteroids. In Asteroids II, 192-212.

[11] Webster, William J., Jr., and Kenneth J. Johnston. 1989. Passive Microwave Observations of Asteroids. In Asteroids II, 213-227.

[12] Millis, R. L., and D. W. Dunham. 1989. Precise Measurement of Asteroid Sizes and Shapes from Occultations. In Asteroids II, 148-170.

[13] Zellner, B.; Eddie N. Wells; Clark R. Chapman; and D. P. Cruikshank. 1989. Asteroid Observations with the Hubble Space Telescope and the Space Infrared Telescope Facility. In Asteroids II, 949-969.

A coordinated effort should include the following:

1. An increase in the level of effort, presently that of about 1 person per year to that of 5-10 persons per year. All available time on Schmidt telescopes with apertures 60 cm and larger would be used. Smaller telescopes would not detect enough asteroids to make efficient use of the observers' search time.

2. Construction of a 60-cm Schmidt telescope dedicated to the search for near-Earth asteroids. This facility could be built in 1 year, would cost from $200 000 to $300 000, and should allow investigators to discover 5 to 10 near-Earth asteroids per year. At this rate of discovery, the number of candidate asteroids for near-Earth rendezvous missions would be adequate within just a few years.

3. Construction of a 120-cm Schmidt telescope dedicated to the search for near-Earth asteroids. Such an instrument could photograph approximately 700 fields each year. The development of automatic scanning systems has eliminated the immense task of visually scanning these plates for trailed images. This next-generation search instrument is needed to achieve the goal of discovering 400 to 500 near-Earth asteroids in the next 20 years. The survey would allow the choice of an asteroid for detailed investigation possibly leading to mining operations. This telescope would take about

3 years to complete and cost from $3 million to $4 million. The search program would require the work of about 6 persons per year. Discovery rates with this facility should be from 20 to 30 near-Earth asteroids per year.

4. Assembly and monthly update of a central index of wide-field plates. This cooperative effort would allow rapid access to all images containing the asteroid, including those recorded before the asteroid was recognized, and would thus contribute to the precise determination of its orbit. This effort would require the equivalent of about 1 person's work per year.

5. Application of radar to the study of near-Earth asteroids. Radar has only recently been successfully applied to asteroid studies, primarily from the Arecibo facility (see fig. 7).

   Because signal strength is related to the inverse fourth power of the distance to the target and because the target asteroids are relatively near, radar promises to be a very powerful technique for studying them. Radar can provide information on size, shape, and rotation rate. And radar wavelengths will be responsive to composition (e.g., metal content) and surface structure.

Without an accelerated discovery program, we will probably continue to discover only a few near-Earth asteroids each year. Only a small number of these are easily accessible to spacecraft. Therefore, in order to utilize asteroidal resources within the next 20 to 30 years, we need an expanded search program to find near-Earth asteroids and we need measurements of their physical properties to evaluate their usefulness.

Figure 7

Arecibo Observatory

The Arecibo Observatory, in Puerto Rico, is the premier radio telescope instrument used in the Earth-based study of the planets and small bodies in the solar system. It is capable of beaming a powerful signal into space and receiving the radio waves reflected from the source. The telescope has been used to map the surface characteristics of the Moon, Venus, and Mars, and recently has started to provide data on the physical properties of near-Earth asteroids. The radio wave reflection properties are affected strongly by the surface roughness and by the granularity of surface materials, and to a more limited extent by the composition of the asteroids.