The Exploration of Near-Earth Objects

Committee on Planetary and Lunar Exploration
Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications
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Dedicated to the memory of
Eugene M. Shoemaker (1928-1997),
who was instrumental in the formulation of this report

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Foreword

Comets and asteroids are in some sense the fossils of the solar system. They have avoided most of the drastic physical processing that shaped the planets and thus represent more closely the properties of the primordial solar nebula. What processing has taken place is itself of interest in decoding the history of our solar neighborhood. Near-Earth objects are also of interest because one or more large ones have been blamed for the rare but devastating events that caused mass extinctions of species on our planet, as attested by recent excitement over the impending passage of asteroid 1997 XF_{11}.

The comets and asteroids whose orbits bring them close to Earth are clearly the most accessible to detailed investigation, both from the ground and from spacecraft. When nature kindly delivers the occasional asteroid to the surface of Earth as a meteorite, we can scrutinize it closely in the laboratory; a great deal of information about primordial chemical composition and primitive processes has been gleaned from such objects.

This report reviews the current state of research on near-Earth objects and considers future directions. Attention is paid to the important interplay between ground-based investigations and spaceborne observation or sample collection and return. This is particularly timely since one U.S. spacecraft is already on its way to rendezvous with a near-Earth object, and two others plus a Japanese mission are being readied for launch. In addition to scientific issues, the report considers technologies that would enable further advances in capability and points out the possibilities for including near-Earth objects in any future expansion of human exploration beyond low Earth orbit.

Claude R. Canizares, *Chair*
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Preface

Asteroids and comets continually pass by Earth, sometimes at uncomfortably close distances. Impacting objects in the geologic past have created large craters and may have caused the extinction of many living organisms. Over the past decade, scientific and popular interest has grown in assessing the likelihood that Earth may be struck in the future by large meteoroids, commonly known as near-Earth objects (NEOs). In 1990, Congress asked the National Aeronautics and Space Administration (NASA) to study the danger. NASA responded with two reports in 1992, calling for increased efforts to locate NEOs and to address issues of hazard mitigation.[1,2] A second request from Congress to NASA in 1994 sought a plan for discovering all NEOs larger than 1 km in diameter within a time period of 10 years, as a cooperative effort among NASA, the U.S. Air Force, and international partners. A responding report was released in 1995.[3] Several telescope facilities and new instruments now coming into operation will dramatically increase the rate of discovery of NEOs and determine their orbits. This program of intensified discovery efforts offers a unique opportunity to broaden scientific understanding of the distribution, composition, and origin of the population of small bodies in interplanetary space.

Previous reports of the National Research Council have stated that asteroids and comets offer important constraints on the early history of our planetary system, and comets, in particular, have highest priority for scientific study.[4] Moreover, the Space Studies Board and its committees have stressed the appropriateness of initiating a program of asteroid and comet study that includes both reconnaissance and exploration phases.[5] The most accessible of these bodies, both for observation by ground-based telescopes and for study by spacecraft, are to be found among the NEOs.

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[1] D. Morrison, ed., *The Safeguard Survey: Report of the NASA International Near-Earth Object Detection Workshop,* Jet Propulsion Laboratory, Pasadena, Calif., 1992.

[2] J.G.D. Rather, J.H. Rahe, and G. Canavan*, Summary Report of the Near-Earth Object Interception Workshop,* NASA, Washington, D.C., 1992.

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[5] Space Science Board, National Research Council, *Strategy for the Exploration of Primitive Solar-System Bodies—Asteroids, Comets, and Meteoroids: 1980-1990*, National Academy Press, Washington, D.C., 1980.

Against this background of renewed interest in the study of near-Earth objects, the Space Studies Board charged the Committee on Planetary and Lunar Exploration (COMPLEX) to review current knowledge of NEOs derived from ground- and space-based studies and to answer the following questions:

- What is the present understanding of the origin, composition, and physical characteristics of near-Earth objects?
- What is the expected level of understanding of NEOs in the next decade?
- What levels of ground-based telescopic observation are needed to increase our understanding of targets of high scientific interest?
- What are the likely opportunities for low-cost flyby, rendezvous, landing, and sample return missions to these bodies, and to what degree will these missions address fundamental scientific issues?

This project was formally initiated in May 1996, and the bulk of the material was written in early and mid-1997. This material was extensively revised and updated in the late summer of 1997. Although many COMPLEX members past and present worked on this report, the bulk of the task of assembling their many individual contributions was performed by Harry Y. McSween and Eugene Shoemaker with the assistance of James Arnold, Richard Binzel, and Alan Tokunaga. The work of the writing team was made easier thanks to the invaluable assistance rendered by Alan Harris (Jet Propulsion Laboratory).

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The contents of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. COMPLEX thanks reviewers Donald Hunten (University of Arizona), Clark Chapman (Southwestern Research Institute), Margaret Kivelson (University of California, Los Angeles), George Wetherill (Carnegie Institution of Washington), and John Wood (Harvard-Smithsonian Center for Astrophysics) for many constructive comments and suggestions. Responsibility for the final content of this report rests solely with the authoring committee and the NRC.

Contents

Executive Summary

Near-Earth objects (NEOs) are asteroids and comets with orbits that intersect or pass near that of our planet. About 400 NEOs are currently known, but the entire population contains perhaps 3000 objects with diameters larger than 1 km. These objects, thought to be similar in many ways to the ancient planetesimal swarms that accreted to form the planets, are interesting and highly accessible targets for scientific research. They carry records of the solar system's birth and the geologic evolution of small bodies in the interplanetary region. Because collisions of NEOs with Earth pose a finite hazard to life, the exploration of these objects is particularly urgent. Devising appropriate risk-avoidance strategies requires quantitative characterization of NEOs. They may also serve as resources for use by future human exploration missions. The scientific goals of a focused NEO exploration program are to determine their orbital distribution, physical characteristics, composition, and origin.

Physical characteristics, such as size, shape, and spin properties, have been measured for approximately 80 NEOs using observations at infrared, radar, and visible wavelengths. Mineralogical compositions of a comparable number of NEOs have been inferred from visible and near-infrared spectroscopy. The formation and geologic histories of NEOs and related main-belt asteroids are currently inferred from studies of meteorites and from Galileo and Near-Earth Asteroid Rendezvous spacecraft flybys of three main-belt asteroids. Some progress has also been made in associating specific types of meteorites with main-belt asteroids, which probably are the parent bodies of most NEOs. The levels of discovery of NEOs in the future will certainly increase because of the application of new detection systems. The rate of discovery may increase by an order of magnitude, allowing the majority of Earth-crossing asteroids and comets with diameters greater than 1 km to be discovered in the next decade.

A small fraction of NEOs are particularly accessible for exploration by spacecraft. To identify the exploration targets of highest scientific interest, the orbits and classification of a large number of NEOs should be determined by telescopic observations. Desired characterization would also include measurements of size, mass, shape, surface composition and heterogeneity, gas and dust emission, and rotation. Laboratory studies of meteorites can focus NEO exploration objectives and quantify the information obtained from telescopes. Once high-priority targets have been identified, various kinds of spacecraft missions (flyby, rendezvous, and sample return) can be designed. Some currently operational (Near-Earth Asteroid Rendezvous [NEAR]) or planned (Deep Space 1) U.S. missions are of the first two types, and other planned U.S. (Stardust) and Japanese (Muses-C) spacecraft missions will return samples. Rendezvous missions with sample return are particularly desirable from a scientific perspective because of the very great differences in the analytical capabilities that can be brought to bear in orbit and in the laboratory setting.

Although it would be difficult to justify human exploration of NEOs on the basis of cost-benefit analysis of scientific results alone, a strong case can be made for starting with NEOs if the decision to carry out human exploration beyond low Earth orbit is made for other reasons. Some NEOs are especially attractive targets for astronaut missions because of their orbital accessibility and short flight duration. Because they represent deep-space exploration at an intermediate level of technical challenge, these missions would also serve as stepping stones for human missions to Mars. Human exploration of NEOs would provide significant advances in observational and sampling capabilities.

The Committee on Planetary and Lunar Exploration (COMPLEX) has considered appropriate baseline research efforts, as well as a number of augmentations to existing programs for the discovery and characterization of NEOs. With respect to ground-based telescopic studies, the recommended baseline is that NASA and other appropriate agencies **support research programs for interpreting the spectra of near-Earth objects (NEOs), continue and coordinate currently supported surveys to discover and determine the orbits of NEOs, and develop policies for the public disclosure of results relating to potential hazards.** Augmentations to this baseline program include, in priority order, that relevant organizations do the following:

1. **Provide routine or priority access to existing ground-based optical and infrared telescopes and radar facilities for characterization of NEOs during favorable encounters, or**
2. **Provide expanded, dedicated telescope access for characterization of NEOs**.

The baseline recommendation with respect to laboratory studies and instrumentation is that NASA and other appropriate agencies should **support continued research on extraterrestrial materials to understand the controls on spectra of NEOs and the physical processes that alter asteroid and comet surface materials.** An appropriate augmentation to this baseline is to **support the acquisition and development of new analytical instruments needed for further studies of extraterrestrial materials and for characterization of returned NEO samples.**

Spacecraft missions and the development of the associated technology and instrumentation are essential components of any program for the study of NEOs. The baseline recommendation in this area is to **support NEO flyby and rendezvous missions**. Appropriate augmentations include, in priority order, the following:

1. **Develop technological advances in spacecraft capabilities, including nonchemical propulsion and autonomous navigation systems, low-power and low-mass analytical instrumentation for remote and in situ studies, and multiple penetrators and other sampling and sample-handling systems to allow low-cost rendezvous and sample-return missions.**
2. **Study technical requirements for human expeditions to NEOs**.

Although studies evaluating the risk of asteroid collisions with Earth and the means of averting them are desirable, they are beyond the scope of this report.

1

Introduction to Near-Earth Objects

The recognition that Earth resides in a swarm of small orbiting objects (Figure 1.1) and that the collision of these bodies with our planet poses a finite hazard to humanity has led to a flood of new discoveries and a significant increase in research on the nature and origin of Earth-approaching objects. These discoveries present an opportunity to investigate extraterrestrial bodies while also providing an indirect assessment of the hazard to life on Earth that they pose. Although studies specifically evaluating the risk of asteroid collisions with Earth and the means of diverting them are desirable, they are beyond the charge of this committee.

Appreciation of the fact that some near-Earth objects (NEOs) can collide with Earth has led to increased support by NASA for systematic surveys of potentially hazardous objects.[1-3] Currently, about 400 NEOs have been discovered; the rate of discovery is expected to increase in the next few years as additional charge-coupled device (CCD) detection systems are installed at dedicated search telescopes in the United States and abroad. At the expected level of support, thousands of NEOs probably will be discovered in the next decade. A possible cooperative program between NASA and the U.S. Air Force, with the goal of discovering about 90% of NEOs larger than 1 km in diameter (estimated to be about 3000), could increase the rate of discovery by nearly two orders of magnitude.

Approximately 5% of NEOs are the most readily accessible extraterrestrial bodies for exploration by spacecraft. The energy requirements to rendezvous with and land on these bodies are less than those to land on the surface of the Moon. In some cases, the energy requirements to return samples to Earth are very low. The combination of the diversity and accessibility of these bodies presents new opportunities and challenges for space exploration and indicates a need for sufficient ground-based observations of NEOs to identify targets of highest scientific interest.

Understanding the orbital and size distributions and the physical characteristics of NEOs may be useful for devising appropriate strategies for mitigating impact hazards. Furthermore, these tiny worlds are scientifically interesting because they carry records of the origin and evolution of planetesimals such as those that accreted to form the planets. A well-planned program for the study of NEOs can lead to an understanding of the following fundamental questions:

- How many objects are there?
- What are their size distribution and composition?
- How often do they strike Earth?

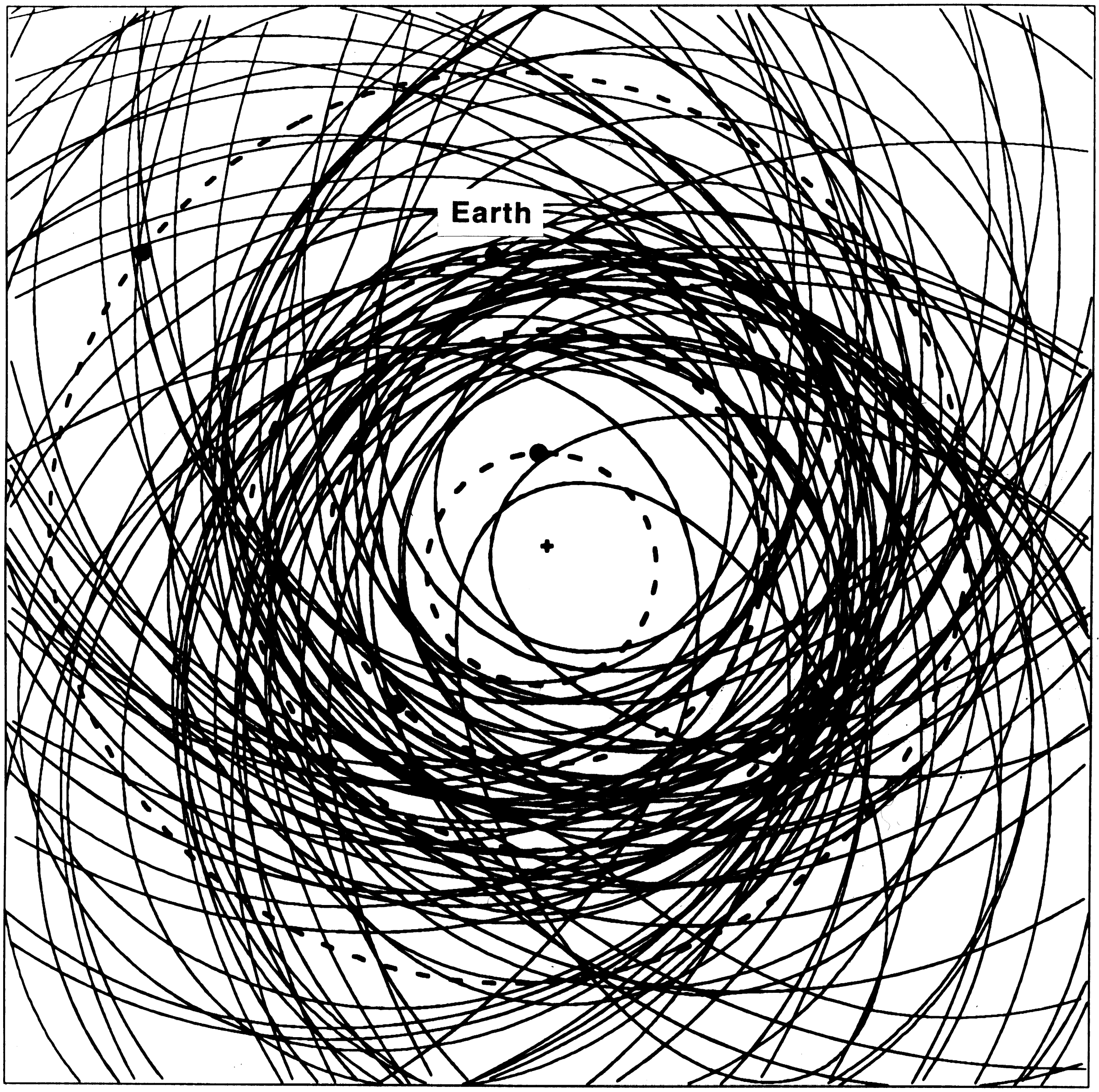

FIGURE 1.1 Orbits for 100 representative near-Earth objects with estimated diameters of 1 km or larger, representing only about 5% of the total estimated population in this size range. All orbits included have perihelion distances of 1.10 AU or less, and the orbits have been projected into the Earth-Sun (ecliptic) plane. Also shown by dashed lines are orbits for the terrestrial planets Mercury through Mars, with their positions on January 1, 1997, indicated. Vernal equinox is to the right. (Courtesy of R.P. Binzel.)

- What are their thermal and collisional histories, and their relationships to meteorites and other bodies in the solar system?

SCIENTIFIC GOALS FOR THE STUDY OF NEAR-EARTH OBJECTS

The scientific goals of an NEO research program can be stated succinctly: ***To understand the orbital distribution, physical characteristics, composition, origin, and history of near-Earth objects.*** These goals are responsive to scientific objectives for the exploration of small bodies in the solar system previously articulated by the Space Studies Board and its committees.[4,5]

Orbital Distribution

Asteroids in near-Earth space are categorized as Amor, Apollo, or Aten objects, depending on whether their orbits lie outside that of Earth, overlap that of Earth with periods greater than 1 year, or overlap that of Earth with periods less than 1 year, respectively (Box 1.1). Comets are classified as short period or long period, depending on whether their orbital periods are less or greater than 200 years. This report focuses specifically on Amor, Apollo, and Aten objects (collectively referred to as NEOs), some of which may be currently inactive short-period comets. Most NEOs probably originate when collisions in the main asteroid belt eject fragments into resonances with Jupiter and Saturn. They may also derive from the Oort Cloud or the Kuiper Belt. A systematic inventory of NEOs will permit a better understanding of their orbital distribution, as well as the relationships among asteroids, comets, meteorites, and interplanetary dust.

Physical Characteristics

An assessment of the physical characteristics of these objects includes determining their shapes, sizes, albedos, spin characteristics, and masses. Shapes, sizes, and spin characteristics are central to understanding collisional histories; albedos (as functions of wavelength), reflectance spectra, and calculated densities provide information on asteroid and comet compositions and internal structures. Their magnetic and thermal properties relate to composition and thermal history. Studies of surface morphology and materials, including craters, fractures and other structural features, regoliths, and bedrock outcrops, allow the geologic evolution of these objects to be reconstructed.

Chemical and Mineralogical Compositions

Determining the chemical and mineralogical compositions of NEOs provides critical constraints on their formation and evolution, as previously emphasized by the Space Studies Board.[6] Their bulk chemistries relate to condensation and other processes thought to have occurred within the solar nebula, and their mineralogies are functions of temperature, pressure, and geologic history (or orbital history, in the case of comets). Quantification of mineralogy provides a bridge between asteroid spectroscopy and studies of meteorites. Returned samples would also allow determination of their times of formation and fragmentation based on their radiogenic and cosmogenic isotopic compositions, as well as studies of processes resulting from interactions with the space environment (solar wind implantation, space weathering, and so on). The petrology of returned samples would reveal details of accretional, thermal, and regolith-forming processes.

Origins

The origins of NEOs must be inferred from their physical characteristics, compositions, and orbital properties. All of these objects are thought to be relics from the early solar system. Meteorite studies tell us that many bodies retain primordial characteristics and thus provide unique opportunities to constrain presolar and solar nebula events. Others may be geologically processed and differentiated, and the relative importance of subsequent

BOX 1.1 Orbital Evolution of NEOs

All near-Earth objects (NEOs) are in chaotic, planet-crossing orbits; their orbits evolve as a consequence both of long-range (secular) perturbations, due chiefly to the gravitational attraction of Jupiter and Saturn, and of close-range perturbations due to infrequent close encounters with one or more of the terrestrial planets.[*] Long-range perturbations drive precession of the long axis of the orbit relative to the line of the nodes and related variations in the eccentricity and inclination of the asteroid's orbit. The orbits of NEOs that overlap Earth orbit can intersect Earth's orbit, typically four times, during a complete cycle of precession of the long axis. Also, many orbits that currently lie outside that of Earth (orbits of the Amors) can become overlapping as a result of secular changes in eccentricity and can intersect Earth's orbit during precession. An example is the orbit of the fairly large Amor asteroid (1580) Betulia, whose orbit can intersect Earth's eight times during one cycle of precession. NEOs whose orbits can intersect Earth's as a result of secular perturbations and thus can collide with Earth, therefore, are called Earth crossing. It should be noted, however, than many Earth crossers cannot collide with Earth because the phase symmetry of their free oscillations causes their perihelia to be outside Earth's orbital plane when their eccentricities are high enough for their perihelia to be inside 1 AU.

Occasional close encounters with one or another terrestrial planet lead to long-term chaotic evolution of the orbits of NEOs. Hence, over time, noncrossing Amors can become crossing or evolve into Apollos, Apollos can become Atens, and vice versa. Ultimately, many NEOs can become Jupiter crossing and then generally are ejected from the solar system, or they may evolve through perturbations into small, extremely eccentric orbits and be vaporized during close encounters with the Sun.

NEOs are thought to be derived primarily from fragments produced by collisions between asteroids in the main asteroid belt. Studies of the physics of collision and the observed disposition of orbital elements of asteroid families suggest that the changes in velocity imparted to kilometer-size fragments during catastrophic collisions generally do not exceed a few hundred meters per second. These changes are an order of magnitude smaller than those required to inject main-belt asteroid fragments into Earth-approaching orbits. In many cases, however, the small changes in velocity imparted to collisional fragments are sufficient to shift them into a dynamical resonance, such as a mean motion commensurable with the mean motion of Jupiter or a secular resonance. Resonant amplification of the orbital eccentricity of the fragment can then lead to a planet-crossing orbit. Synergistic interplay between resonant perturbations and perturbations due to encounters with Mars probably plays an important role in delivering NEOs to Earth-crossing orbits.

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[*] E.M. Shoemaker, J.G. Williams, E.F. Helin, and R.F. Wolfe, "Earth-crossing asteroids: Orbital classes, collision rates with Earth, and origin," pp. 253-282 in *Asteroids*, T. Gehrels, ed., University of Arizona Press, Tucson, Ariz., 1979.

processes (e.g., collisional and thermal histories, surface alteration, fluid-rock interactions) can be assessed. However, such modified bodies may have made up a substantial portion of the planetesimals that accreted to form the terrestrial planets,[7] thereby providing information related to the early stages of planet growth.

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2

Status of Current Research Programs

MEASURING THE PHYSICAL CHARACTERISTICS OF NEAR-EARTH OBJECTS

By virtue of their close approaches to Earth, NEOs are the smallest observable solar system bodies (Box 2.1) for which ground-based physical and spectroscopic studies can be conducted. In the past, low discovery rates, lack of rapid access to large-aperture telescopes, and the state of astronomical detector technology made it a challenge to measure physical characteristics for any but the brightest NEOs. Prior to the 1990s, only about 20 NEOs had been measured for their compositional, rotational, or thermal properties.[1]

With the widespread application of sensitive CCD detectors in the 1990s, telescopic measurements of physical or mineralogical characteristics are currently available for about 80 NEOs, where the most common data are measurements of spectral properties. Time series measurements of the brightness variations of NEOs produce light curves revealing rotation rates in the range of several hours to days, similar to known rotations for main-belt asteroids. More limited data on the rotation rates of comet nuclei suggest that comets rotate more slowly than most asteroids, making rotation a possible discriminator between asteroidal and cometary sources for NEOs. Light curve data for NEOs suggest that they generally rotate in the plane of their principal axes. An exception is (4179) Toutatis, which is a non-principal axis rotator with rotation and precession periods of 5.41 and 7.35 days, respectively.[2] Thermal properties have been measured for a few NEOs; the data suggest that many such small objects do not have substantial regoliths.

These measurements[3] reveal that most short-period comets have diameters in the range of 1 to 10 km. Their shapes are inferred to be irregular ellipsoids, with the ratio between the two largest principal axes falling in the range of 1.1 to 2.6. Their surfaces have low albedos, with most albedo estimates being <4%. Typically, only a small fraction (<10%) of the surface is active during perihelion passage, which suggests that most of the surface may consist of a mantle of nonvolatile material. Although the internal properties of comets are unknown, low densities are inferred from their slow rotations (5 to 70 hours), the frequent occurrence of splitting during perihelion passage, and the tidal breakup of Shoemaker-Levy 9. These results suggest that the physical structure of comets may be described as strengthless agglomerations of gravitationally bound planetesimals with a bulk density between 0.5 and 1.0 g/cm^3. Most of this decade's physical measurements of NEOs have been made as target-of-opportunity observations obtained shortly after an object's discovery. Figure 2.1 shows an example of the circumstances that favor observations shortly after discovery. Historically, discoveries most often have occurred when an object made a close approach to Earth. In many cases, these apparitions are followed by a

BOX 2.1 Asteroid Magnitudes and Sizes

The absolute magnitude H of an asteroid is a constant that represents its intrinsic brightness due to reflected sunlight in the V spectral band (the yellow-green region centered near the peak of the solar energy spectrum). The observed magnitude V of an asteroid depends on H and on the asteroid's distance from Earth (Δ), its distance from the Sun (r), and the angle (α) between the lines of sight to Earth and the Sun as seen from the asteroid:

$$V = H + 5 \log (\Delta^* r) + f(\alpha).$$

H is determined from observations of V at times corresponding to specific values of $\Delta^*$and r (in astronomical units); $f(\alpha)$ is the phase function (a function of α that can be estimated in various ways).

The absolute magnitude depends on the size of the asteroid and its albedo (its reflectivity in a given spectral band). Thus, the asteroid's size can be estimated from H if the albedo can be measured or inferred from other observations (e.g., its spectral type). At absolute magnitude 18, an average S-type (relatively bright) asteroid is about 0.8 km in diameter, and an average C-type (dark) asteroid is about 1.6 km in diameter. There is, however, a factor-of-three uncertainty in the measured albedos of S-type asteroids and a similar uncertainty for C-type asteroids. Thus, the 0.8-km object cited above could reasonably be anywhere between 0.5 and 1 km in diameter. This factor-of-three uncertainly corresponds to a factor-of-eight uncertainty in volume.

decades-long interval during which no additional close approach will occur. Fainter-magnitude limits being achieved by CCD surveys conducted to discover NEOs are reducing the bias toward discovering objects only when they are in the near vicinity of Earth.

Prospects for progress in measuring NEO physical characteristics, especially their spectral properties, are illustrated in Figure 2.2, which shows the apparition circumstances for known near-Earth asteroids through the end of the twentieth century. With the commissioning of the Keck II 10-m telescope and NASA's participation in the project, there is the potential for pre-mission physical measurements at visible and near-infrared wavelengths of specific NEOs of high scientific interest. A dedicated 2-m-class telescope would permit most discovered NEOs to become accessible for physical characterization.

Perhaps the greatest progress and potential for direct physical measurements of NEOs will occur through radar observations that complement spectral studies.[4] Of the 37 near-Earth objects detected as of 1997 by radar, 4 were first observed before 1980, 20 were first observed during the 1980s, and 13 were first observed during the 1990s. The Goldstone antenna of NASA's Deep Space Network is responsible for the sole detections of nine NEOs and the most informative observations of three others. Images with several tens of meters of resolution have been obtained for three objects—(1620) Geographos, (4179) Toutatis, and (6489) Golevka—and shape models have been constructed for those objects and (4769) Castalia.[5] At least 100 of the currently known NEOs are expected to be detectable by the Arecibo telescope during its first decade of operation following the completion of a major upgrade in 1997. Given current NEO population estimates, a thorough survey could reveal a sufficient number of close Earth approaches to allow Arecibo to construct 1000-pixel images of about one object per month. Thus, radar offers tremendous potential for achieving detailed shape models for a large number of NEOs.

UNDERSTANDING THE MINERALOGICAL AND CHEMICAL COMPOSITIONS OF ASTEROIDS

Visible and near-infrared reflectance spectroscopy provides the most sensitive and broadly applied remote sensing techniques for characterizing the major mineral phases present within asteroids.[6] At visible and near-

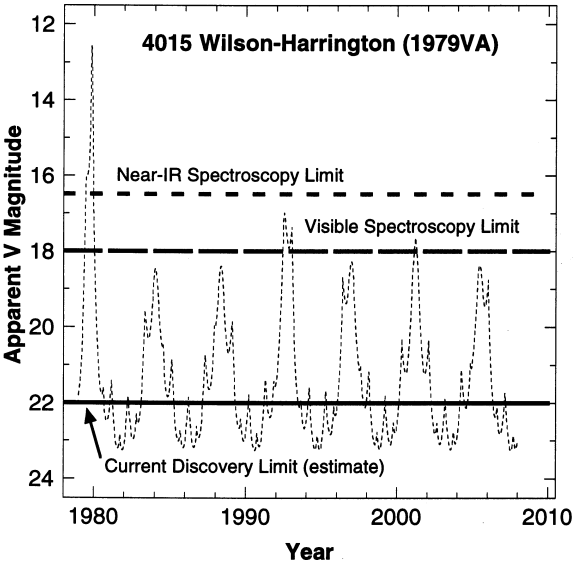

FIGURE 2.1 Observability of asteroidal or cometary near-Earth object (4015) Wilson-Harrington. Maxima in brightness correspond to closest Earth approach. As indicated by current limits for visible and near-infrared spectroscopy, NEOs such as Wilson-Harrington make infrequent, close approaches that allow measurements of their physical properties with 2-m-class telescopes occasionally available for NEO studies. Previously, the best opportunity for physical measurements often coincided with the discovery apparition, where discovery was enabled by an extremely close approach to Earth. Most modern NEO discoveries by CCD surveys are at magnitudes well below the physical measurement capabilities of telescopes generally available to NEO observers.

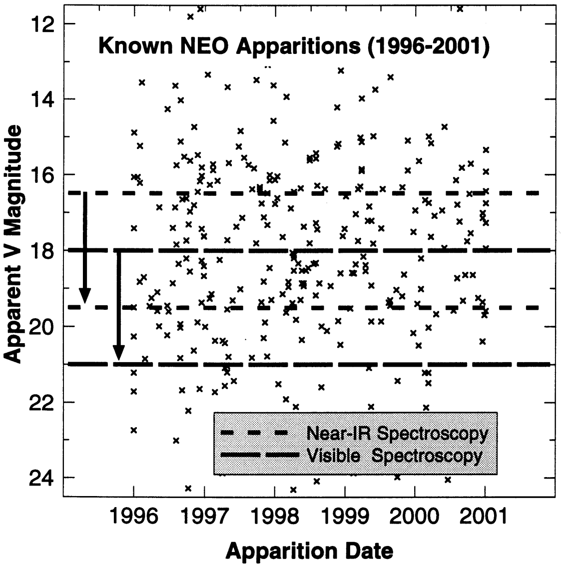

FIGURE 2.2 Apparition circumstances for known near-Earth objects over the years from 1996 to 2001. Lines on top indicate current limits for physical measurements. Arrows indicate potential new limits for NEO physical measurements arising from NASA's participation in operation of the Keck telescopes.

infrared wavelengths, recognizable spectral absorptions arise from the presence of the silicate minerals pyroxene, olivine, and sometimes feldspar, as well as nickel-iron metal, spinel, primitive carbonaceous assemblages, and organic tholins. Water-bearing minerals such as phyllosilicates also exhibit distinct absorption features at near-infrared wavelengths. Seemingly dormant comets can have their activity revealed through the detection of fluorescence emission bands. Complementing these optical techniques are radar albedo measurements, which give primarily diagnostic information on the presence and abundance of metal phases.

At visible wavelengths, multiple-filter photometry measurements in the 1980s have given way to CCD spectrographs in the 1990s. The transition to CCD spectrographs is occurring more slowly at near-infrared wavelengths, where new instruments with capabilities for mineral spectroscopy are only now becoming available. Currently, visible-spectrum observations are the most common physical measurements being made of near-Earth objects. Access to larger telescopes, which improve the observational limits for visible-spectrum physical measurements, will correspondingly provide the opportunity for compiling a substantial sample of measurements at wavelengths other than visible.

Although the most reliable mineralogical interpretations require measurements extending into the near infrared, measurements in the visible wavelengths allow preliminary characterization according to the taxonomic groups established for main-belt asteroids. Many near-Earth asteroids fall into taxonomic categories over the same range as asteroids in the inner main belt. Most common in the inner asteroid belt and among NEOs are objects having S-type asteroid spectra, which are interpreted to be olivine-pyroxene assemblages with a wide range of olivine-to-pyroxene abundance ratios. Spectral types corresponding to C-type asteroids are also seen within the NEO population. At least one metal-rich NEO is inferred from a very high radar reflectivity and supported by spectroscopic and radiometric observations.

Short-period comets are composed of roughly equal mixtures (by mass) of ice and dust, with the ice component consisting primarily of water (H_2O), carbon monoxide (CO), and carbon dioxide (CO_2). Although the ice component is inferred from daughter products measured in cometary comae, the chemical composition of the dust has been directly measured through mass spectrometers on board the Giotto and VEGA spacecraft sent to comet Halley and interplanetary dust particles (IDPs) collected in Earth's upper atmosphere.[7] The dust for comet Halley consists of two major components: a refractory organic phase composed of carbon, hydrogen, oxygen, and nitrogen (CHON) and a magnesium-rich silicate phase. Within CHON particles, carbon and oxygen approach cosmic abundances, whereas nitrogen is intermediate between cosmic abundances and those found in C1-chondrites. The abundance of hydrogen is more like that in C1-chondrites. For rock-forming elements, the abundances are found to be within a factor of two with respect to cosmic abundances.

DECIPHERING THE RELATIONSHIPS AMONG ASTEROIDS, COMETS, AND METEORITES

Many meteorites are thought to be samples of NEOs, most of which are, in turn, derived from main-belt asteroids. The difficulty lies in determining exactly what kinds of meteorites are related to which asteroids or asteroid classes (Box 2.2). The few advances in unraveling asteroid-meteorite connections relate to main-belt rather than near-Earth asteroids, since the latter are generally faint and must be observed within a rather narrow window of opportunity. Because of the spectral similarities and apparent relationships between many main-belt and near-Earth asteroids, however, these discoveries also serve as linkages between NEOs and meteorites. However, it should be noted that some recent research suggests that a large fraction of meteorites may be derived directly from the main asteroid belt, without near-Earth intermediaries.[8]

The main-belt asteroid (4) Vesta is now usually acknowledged as the parent body for HED (howardite-eucrite-diogenite) meteorites. Rotational reflectance spectra for Vesta indicate a surface dominated by eucrite basalts, excavated locally in large craters to reveal plutonic rocks similar to diogenites. Howardites are regolith breccias composed of mixed eucrite and diogenite. New CCD spectra of small bodies with orbits between Vesta and the adjacent 3:1 mean orbital resonance with Jupiter (known to be a dynamical "escape hatch" that allows asteroid fragments to arrive in Earth-crossing orbits) indicate that they also have compositions similar to HED meteorites.[9] Thus, these igneous meteorites can be assigned with some confidence as samples of Vesta, the third-largest asteroid (500 km in diameter), although other parent bodies are possible. Several NEOs have the same taxonomic classification as (4) Vesta.

In contrast, spectral analogs for the parent asteroids of ordinary chondrites (the most common types of meteorite falls) have proved elusive. A possible relationship between these meteorites and S-type asteroids has been debated for decades. Part of the problem in tying S asteroids to meteorites lies in the fact that S-type asteroids exhibit a wide range of properties, probably reflecting a correspondingly wide range of compositions. Present evidence suggests that space weathering (a kind of optical alteration due to exposure to the space environment and shock) has modified the spectral properties of asteroid surfaces, thus masking their true compositions.[10] Shock due to impacts has been shown to lower albedo and modify spectral character, and shock-blackened chondrites are relatively common. Spacecraft rendezvous and sampling missions to S asteroids should resolve the issue of whether spectral masking occurs. It is likely, however, that the S asteroid class also contains nonchondritic objects.[11] Spectral variations observed during asteroid rotation indicate that the surfaces of some S asteroids are compositionally heterogeneous (Figure 2.3), implying either that they may be differentiated or that they may have accreted from compositionally diverse chondritic materials. Both of the main-belt asteroids encountered during Galileo spacecraft flybys—(951) Gaspra and (243) Ida—are of the S class, as is the NEAR mission target (433) Eros.

The C-type asteroids have low albedos and relatively featureless spectra and are conventionally thought to be spectral analogs for carbonaceous chondrite parent bodies.[12] Some carbonaceous meteorites have suffered aque-

BOX 2.2 Asteroid Taxonomy and Meteorite Classification

The asteroid taxonomic groups are derived from studies of a great variety of visible and near-infrared spectra and albedos of main-belt asteroids, which are relatively large and easy to observe.* The earliest recognized and largest groups are S (siliceous), C (carbonaceous), and M (metallic). Each of these taxonomic groups consists of a diverse collection of objects; for example, the S group has now been subdivided into numerous subgroups. Asteroid (4) Vesta and a large number of small, nearby asteroids compose the V group. About a dozen other letters of the alphabet have been used to categorize main-belt asteroids. This same system is utilized for near-Earth objects (NEOs) when sufficient spectral information is available. However, classification into one of the taxonomic groups is only a first stage, and compositional interpretation commonly requires more detailed spectral information.

Meteorites are more accessible, and laboratory investigations of their chemistry and petrology have resulted in an even more detailed classification system. Most meteorites are chondrites, stony objects of roughly solar chemical composition (minus the most volatile elements). Of these, nearly all fall in the broad ordinary chondrite class, which has been further subdivided. Other, highly reduced chondrites fall in the enstatite chondrite group, whereas those containing appreciable organic matter are the carbonaceous chondrites. Most other stony meteorites are achondrites, of which the HED (howardite-eucrite-diogenite) group is prominent. The achondrites are igneous rocks or, in the case of the so-called primitive achondrites, residues after the extraction of small quantities of melt. Iron meteorites are samples of differentiated asteroid cores or segregated small pods of metal. They exist in many forms, distinguished by their compositions and cooling histories. Pallasites and other stony-iron meteorites are metal-silicate mixtures that also formed in other differentiated bodies.

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*M.J. Gaffey, T.H. Burbine, and R.P. Binzel, “Asteroid spectroscopy: Progress and perspectives,” *Meteoritics*, 28:161-187, 1993.

ous alteration at low temperatures, resulting in the formation of complex assemblages of hydrous clay minerals, carbonates, sulfates, and organic molecules. The spectral signature for water of hydration in phyllosilicates is particularly diagnostic for asteroids that have suffered aqueous alteration. A few carbonaceous chondrites have been dehydrated at high temperatures, and controversy exists concerning whether meteorites of this type are commonly represented among the main-belt C asteroid population. The NEAR spacecraft imaged C-type asteroid (253) Mathilde during a flyby in June 1997. C-type asteroids are also recognized among the NEOs.

The terminal stages of a comet’s life are not well understood, but it is likely that progressive loss of volatiles during repeated passages close to the Sun causes depletion of surface volatiles, creating an inert mantle that seals off the interior. Without the presence of a coma or tail, such a body will resemble an asteroid. At least one NEO, (4015) Wilson-Harrington, has exhibited one episode of cometary behavior,[13] and the orbital similarity between (3200) Phaeton and the associated Geminid meteor stream suggests that this body may also have been a comet. Although it is generally thought that cometary materials are sampled as interplanetary dust particles but are not represented in the world’s meteorite collections, this view may reflect ignorance about the nature of the nonvolatile (rocky) components of cometary nuclei. Comets, as well as dark D- and P- type asteroids located in the outer main belt, may have been sampled as interplanetary dust particles, or micrometeorites.[14]

Some main-belt and Earth-approaching asteroids have nondiagnostic (relatively featureless) spectra. Included in this category are E and M types, which spectrally resemble enstatite achondrite and iron meteorites, respectively. A spectral and dynamical link has been made between NEO (3103) Egar and enstatite achondrites.[15] Although such connections are implied in most asteroid classification schemes, they have not been rigorously demonstrated, and several of these asteroids exhibit absorption bands due to water of hydration which appear to make these particular objects incompatible with nominal analogs. There are also asteroid classes (e.g., T- and F-

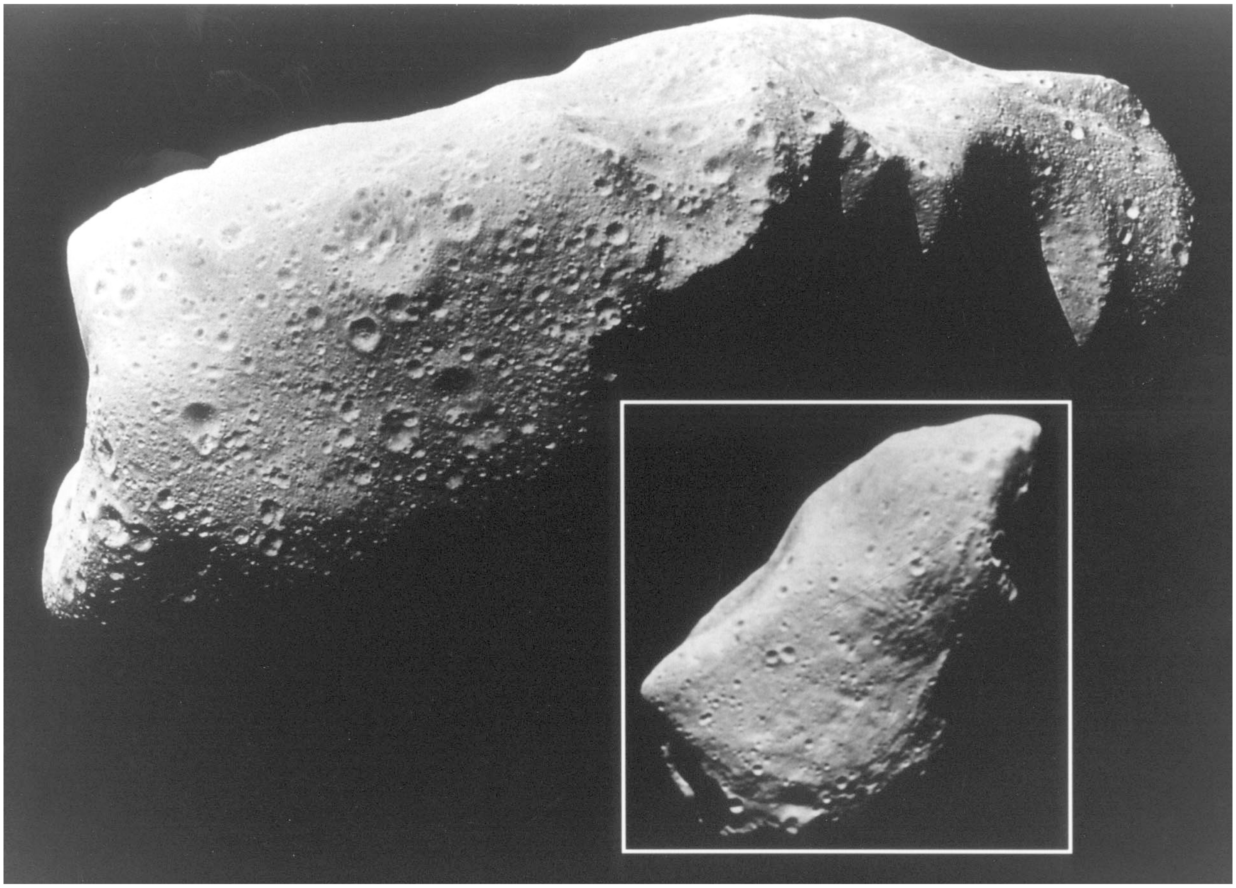

FIGURE 2.3 Galileo spacecraft images of main-belt asteroids (243) Ida and (951) Gaspra (inset), to approximately the same scale. (Courtesy of NASA.)

type asteroids) for which no analogous meteorite types are recognized, as well as meteorite types (e.g., ureilites) for which no asteroidal parents have been suggested.

Further information on linkages between various kinds of meteorites and their asteroidal parents may be provided by the identification and study of asteroid families, which are probably disrupted fragments of larger bodies. Families thought to represent chondritic asteroids tend to be homogeneous in composition, whereas those from differentiated asteroids are not. Precise connections between families and known meteorite types, however, remain problematical.

UNDERSTANDING THE FORMATION AND GEOLOGIC HISTORIES OF NEAR-EARTH OBJECTS

A wealth of information regarding the geology, age, and evolution of asteroidal bodies can be obtained from spacecraft, as clearly illustrated by Galileo observations of the main-belt asteroids (951) Gaspra[16] and (243) Ida[17] (see Figure 2.3). The Galileo mission provided the first observations of the populations of small impact craters on asteroids, evidence for the probable presence of large spall surfaces, qualitative information on the thickness and development of asteroidal regoliths, support for the idea of optical maturation of surface materials, hints of possible internal structure, and the discovery of a co-orbiting moonlet around Ida. Gaspra was found to have a low crater density suggestive of a young surface age on the order of a few hundred million years. The inferred young age of Gaspra is consistent with a short collisional lifetime as expected for asteroids of this size (Gaspra has a mean diameter of approximately 14 km). Ida was found to have a crater density five times higher than that found on Gaspra, suggestive of an age near 1 billion years. Presumably this age reflects the time of collisional disruption of the parent body of the Koronis asteroid family, of which Ida is a member. Both Ida and Gaspra are elongate irregular bodies that have been interpreted as individual collisional fragments formed by the catastrophic disruption of larger objects, although other interpretations have been offered.

Craters smaller than 1 km on Ida exhibit a complete range of erosional form and a size-frequency distribution indicative of a steady-state or equilibrium population. This, together with the downslope orientation of chutes and bright stripes and the presence of dark-floored craters and fresh craters with bright rims, points to the existence of a regolith. From the depths of flat-floored craters, the regolith is inferred to be a few hundred meters thick in places. On the younger surface of Gaspra, on the other hand, there is little direct evidence of a regolith. However, bright materials associated with fresh craters along ridges on Gaspra have a stronger 1-micron absorption band than darker materials found in interridge areas. Observations suggest that both Ida and, to a lesser extent, Gaspra have undergone moderate optical maturation.

The geologic information obtained by spacecraft observations of main-belt asteroids is complemented by radar observations of a few NEOs. Among the three NEOs best observed by radar, (1620) Geographos is a single, coherent splinter, (4179) Toutatis is an aggregate of debris, and (4769) Castalia consists of two objects in contact.[18,19] Radar data strongly suggest the presence of craters on Toutatis (Figure 2.4), but no NEO has yet been studied with high enough spatial resolution to determine details of its geology such as the presence of a regolith. Because of the expected young ages and very low surface gravity of NEOs, some researchers suspect that regoliths on these objects may be generally thin, patchy, or in some cases, absent. Diverse thermal properties deduced from infrared observations of a number of these objects may be consistent with these expectations.

To the extent that asteroid-meteorite connections can be considered firm, studies of meteorites provide quantitative information on asteroid formation and geologic evolution. From HED meteorites,[20] the mineralogy and chemistry of (4) Vesta—the probable HED parent body—are now reasonably understood; the timing of its

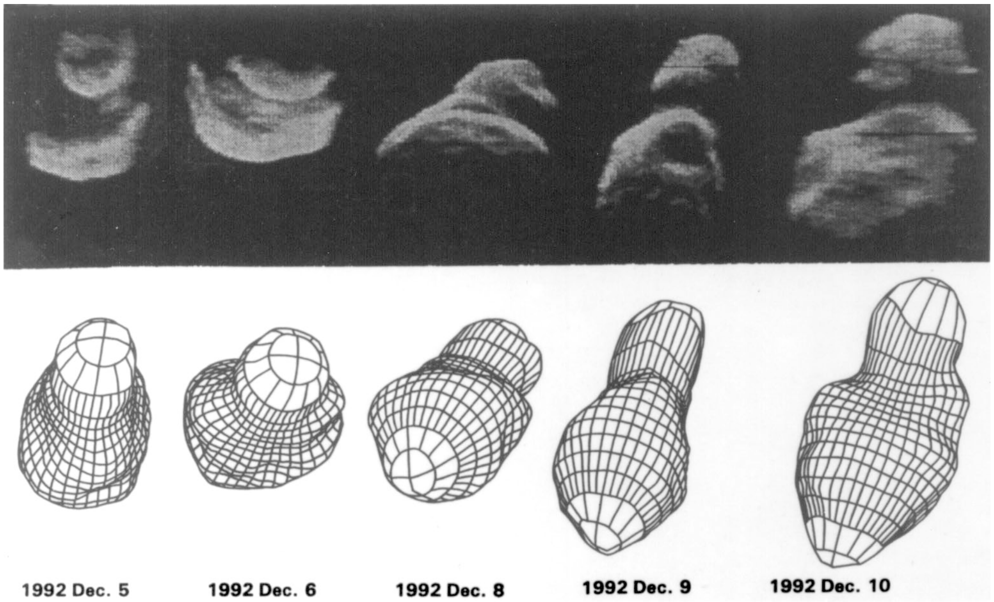

FIGURE 2.4 Radar images of asteroid (4179) Toutatis, showing apparent craters and its irregular shape. Accompanying sketches illustrate its change in appearance with time. (Courtesy of NASA.)

melting has been constrained by radiometric dating; geochemical evidence for core formation has been discovered; and models for its thermal evolution are being formulated. The thermal histories of ordinary chondrite parent bodies are also interesting. Most ordinary chondrites have been metamorphosed, and detailed thermal models for their parent asteroids have been constructed based on decay of short-lived radionuclides.[21] Chondrite cooling histories, determined from nickel diffusion profiles in metal grains, suggest that many bodies were disrupted by impacts and subsequently reaccreted into "rubble piles."[22] Earth-approaching S asteroids, possibly representing fragments of bodies heated to varying degrees, may be especially instructive for understanding asteroid thermal evolution and accretionary structure. Many carbonaceous chondrites have suffered aqueous alteration, and the source of the fluids that caused alteration in C-type asteroids was probably ice, originally accreted along with rocky material and later melted by decay of short-lived radionuclides, electromagnetic induction heating, or impacts.[23] Information on the maturity of asteroid regoliths and the duration of their exposure has also been gained from studies of meteorite regolith breccias.

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3

Future Research Activities

DETECTING NEAR-EARTH OBJECTS

The estimated population of NEOs[1] includes approximately 1400 Earth crossers (Atens, Apollos, and Earth-crossing Amors) of at least 1-km size and an additional ~1500 noncrossing Amors. As of April 1998, about 140 known Earth crossers and some 120 noncrossing Amors were of this size. Thus, the discovery of NEOs is estimated to be about 9% complete for objects larger than 1 km in diameter. Although the task is well begun, the vast majority of NEOs remain to be found.[2]

In the past few years the annual rate of discovery of Earth crossers larger than 1 km has been at about 1% of the estimated remaining population.[3] However, new CCD detection systems that are becoming available for dedicated search telescopes will permit an increase in the discovery rate by an order of magnitude. Three systems (Table 3.1) whose development is being supported by NASA include the Near-Earth Asteroid Tracking (NEAT) CCD camera, developed by the Jet Propulsion Laboratory (JPL) and currently in use on a U.S. Air Force Ground-based Electro-Optical Deep-space Surveillance System (GEODSS) 1.0-m telescope; the Lowell Observatory Near-Earth Object Survey (LONEOS), which utilizes a dedicated 0.6-m Schmidt telescope; and the Spacewatch system of the University of Arizona, currently operating a 0.9-m telescope, with the addition of a 1.8-m telescope now under construction.

The LONEOS system, which began test observations in 1997, has an instantaneous field of view of 3° × 3° and an expected threshold of detection of about *V* magnitude 19.5. In full operation, LONEOS will be capable of

TABLE 3.1 NASA-Supported Surveys of NEOs

Program	Survey Telescope	Aperture (m)
Spacewatch, University of Arizona	Existing telescope	0.9
	Telescope under construction	1.8
LONEOS, Lowell Observatory	Schmidt telescope (near completion)	0.58
NEAT, Jet Propulsion Laboratory	U.S. Air Force GEODSS telescope	1.0

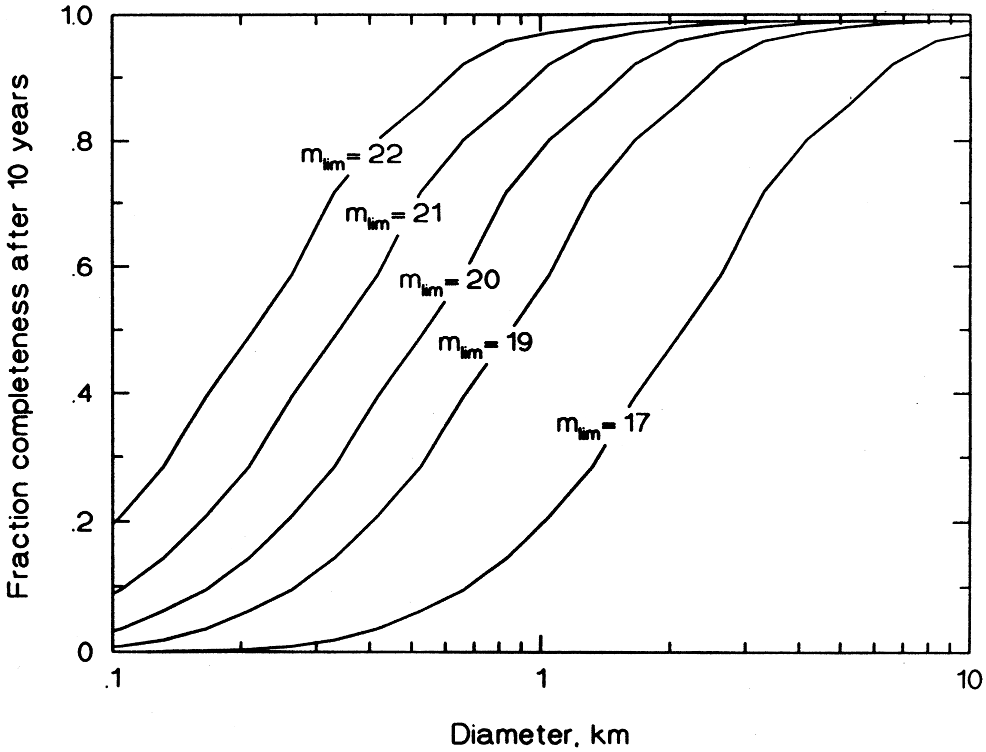

FIGURE 3.1 Survey completeness after 10 years versus diameter of NEOs for various system-limiting magnitudes. All-sky coverage (approximately 15,000 degree^2) is assumed each month. The photographic Schmidt telescope on Palomar Mountain (~0.5-m aperture) is capable of all-sky coverage to a limiting magnitude of 17. A single 0.5-m CCD system (e.g., LONEOS) should be able to achieve all-sky coverage to a limiting magnitude of 19. A system of one or two 1-m telescopes should be able to survey to about limiting magnitude 20. To reach limiting magnitude 21 will probably take a system of several 2-m telescopes.

covering the entire accessible sky (about 15,000 degree^2) each month to detect all observable asteroids to apparent magnitude 19.5. It is expected that about 80% of the Earth-crossing objects of 1-km diameter or greater could be detected by LONEOS in 10 years of full operation (see Figure 3.1). It must be noted, however, that LONEOS by itself could not carry out sufficient astrometric follow-up observations to obtain reliable orbits on the NEOs detected. To do this would require an approximate doubling of telescopic resources (either a second dedicated telescope of comparable aperture or the use of multiple smaller telescopes).

If the 1.8-m Spacewatch telescope under construction were to be instrumented with appropriate large-format CCDs, it could be operated in a program similar to that of LONEOS. Such a program would lead to detection of about 95% of Earth crossers of 1-km size in 10 years (see curve for limiting magnitude 22 in Figure 3.1). The LONEOS and Spacewatch systems used in a coordinated program of detection and orbit determination could yield the orbital elements for about 1000 new Earth-crossing asteroids larger than 1-km diameter, as well as thousands of smaller NEOs, in 10 to 15 years. Continued support of these projects would be necessary to achieve this goal. Participation of the NEAT system and international observers would ensure that high-precision orbits were obtained for most of the bright NEOs discovered. COMPLEX supports the coordination of ongoing NEO search programs.

There is a possibility that the U.S. Air Force, as an expansion of the NEAT project, will undertake a more intensive survey of NEOs in collaboration with NASA, using the U.S. Air Force's GEODSS satellite-tracking network upgraded with large-format CCD cameras. Such a program would have a capability similar to that of the combined LONEOS and Spacewatch surveys. COMPLEX supports the U.S. Air Force's involvement in this effort.

ISSUES RELATED TO INCREASED DISCOVERIES OF NEAR-EARTH OBJECTS

Given the greatly increased rate of NEO discoveries that will follow from the surveys described above, a database system that will not be overwhelmed with new information must be developed. The role of the Spaceguard Foundation, at present an international advocacy organization for the study of NEOs and the hazard they pose, is undefined and unclear. The Minor Planets Center had already demonstrated its capability in handling a similar, though smaller, database. The same organization could potentially handle the task of cataloging all new NEO discoveries, with augmented funding.

The survey will probably find a few objects that, for a period of time (a few weeks to a few years), have a significant probability of hitting Earth, before it eventually is shown (in all probability) that they will not. NASA and the astronomers engaged in discovering NEOs must address the question of how to behave responsibly in the public arena, in terms of reporting and explaining any potentially threatening discoveries. Some preliminary work on this problem has already been published,[4] but this difficult and important issue requires that protocols be established. Organizations such as the International Astronomical Union and COSPAR may have a role to play in this task.

OBSERVATIONS NEEDED TO IDENTIFY OBJECTS OF HIGH SCIENTIFIC INTEREST

The Space Studies Board has stated previously that reconnaissance and initial exploration of asteroids by spacecraft constitute a high-priority goal.[5] Three classes of observations are required to identify targets of sufficient scientific interest to justify exploration by spacecraft:

1. ***Identification,*** which includes detection and astrometry to determine orbits. When possible, astrometric observations by radar are effective in securing highly accurate orbits because the precision of these measurements is greater than that of optical observations.
2. ***Classification*** by use of photometric data and orbital parameters to assign the object to one of several broad categories: Earth approaching or not, taxonomic category, and asteroidal or cometary behavior.
3. ***Quantitative description*** requiring characterization of the object in as much detail as possible using a diverse set of observations, such as size, shape, rotation, and composition. A full set of physical parameters desired for NEO quantitative description includes the following:
   - ***Size*** is best determined by measuring both visible and thermal infrared flux densities. Albedo and mean-diameter estimates can be obtained if both visible and thermal properties are determined. If only visible observations are obtained, as in most cases, the diameter can be estimated from an assumed albedo based on spectral classification.
   - ***Rotation*** is determined from repeated observations at a single wavelength, providing a light curve from which the object's spin rate can be obtained. If coupled with radar or thermal infrared observations, information on the shape of the object (spherical or elongate) can be obtained.
   - ***Surface roughness and shape*** can be characterized by radar.
   - ***Emission of gas and dust,*** such as seen in faint comae, may be detected. Such emissions can potentially distinguish objects of a cometary nature.
   - ***Surface composition*** in a global sense requires spectrophotometric or spectroscopic observations over the range 0.3 to 2.5 microns. With higher spectral resolution, the mineralogical composition can be obtained for certain classes of asteroids. Regolith properties and aspects of the space "weathering" of NEOs can be determined from multiangle photometry and thermal-infrared measurements.

In favorable cases, surface mapping can be carried out by radar observations, allowing the recognition of features of geologic interest such as craters, stratification, or possibly fracture systems. As the asteroid rotates and different parts of its surface come into view, spatial variations in its spectral properties can be determined if the telescope is large enough or the object is close enough. These spectral variations can be related to spatial differences in surface composition.

- ***Asteroidal satellites*** can be sought using occultations, adaptive optics, or coronagraphic techniques.

These observations should provide the basis for selection of NEO targets of high scientific interest for exploration by spacecraft.

OPPORTUNITIES FOR LOW-COST MISSIONS

Advantages of Robotic Missions to Near-Earth Objects

Laboratory studies have shown that meteorites (and hence the asteroids from which they may have been derived) display a great variety of mineral assemblages, chemical and isotopic compositions, and physical properties, but these studies have also told us much more. A few examples of important measurements possible only, or best done, in the laboratory are quantitative age determination; thermal, shock, and irradiation histories; detailed mineralogy; trace element and isotopic measurements; and the inclusion of interstellar grains. All of this information is critical for reconstructing an object's geologic history. Laboratory studies have obvious advantages over telescopic and spacecraft observations, particularly in the far richer variety of instruments, the flexibility of experimental designs to meet the needs of specific samples, and the possibility of successive experiments. This rich store of information can be transferred to our knowledge of asteroids as soon as one question is answered: Which asteroid types are the parents or siblings of which meteorite classes? Telescopic observations of NEOs, particularly by visible and near-infrared spectroscopy, likewise reveal a rich variety of objects.

Meteorites are important geologic materials, but they are samples out of context. Spacecraft data on NEOs and returned samples provide this critical context for relating diverse lithologies and understanding the processes that formed them. Since most NEOs are fragments of larger objects, they also allow direct sampling of otherwise inaccessible interiors of differentiated objects. NEOs are, in reality, small planets with distinctive structures and geologic histories, and these can best be understood by close-range observations from spacecraft, complemented with returned samples.

Although most meteorite classes presumably originate from some asteroid type, not all asteroids supply meteorites. That is, in our present state of understanding, the variety of asteroids is almost certainly greater than that of meteorites now in collections, and NEOs may represent unsampled types and dormant comets. Nevertheless, we should expect new knowledge and new opportunities as our mission-based science database grows.

Current and Planned Robotic Missions to Near-Earth Objects

The Space Studies Board has previously noted that Discovery-class spacecraft missions to asteroids and comets provide great scientific return for the funds invested.[6] Spacecraft missions to NEOs can be classified into three types with progressively greater complexity, scientific yield, and cost: flyby, rendezvous, and rendezvous with sample return. There can be no doubt that rendezvous, with a well-selected instrument set and close approach capability, makes possible much more definitive study of a given object than does a flyby. The added value provided by sample return is likely to be great, and the Space Studies Board and its committees have repeatedly noted that the return of asteroid samples for laboratory analysis will be necessary to meet the objectives of continuing solar system science.[7,8]

The following ongoing or already approved spacecraft missions relate directly to the exploration of near-Earth objects:[9]

- ***Near-Earth Asteroid Rendezvous*** is the first of NASA's Discovery class and will be the first spacecraft to orbit an asteroid. The spacecraft flew by (253) Mathilde, a main-belt asteroid, in June 1997 and will rendezvous with (433) Eros, one of the largest Earth-approaching asteroids, in February 1999. The encounter with Mathilde, the largest asteroid (approximately 60 km in diameter) ever visited by a spacecraft, provided the first close-up images of a C-type object. Eros, with dimensions of 14 × 14 × 40 km, is an S-type asteroid with heterogeneous surface composition. Data to be obtained for Eros include measurement of bulk properties (size, shape, volume, gravity field, spin state), surface properties (elemental and mineralogical composition, texture, topography, geology), and internal properties (mass distribution, magnetic field).

The NEAR spacecraft, launched in February 1996, carries an instrument payload that includes a multispectral imaging system, an x-ray/gamma-ray spectrometer, a near-infrared spectrometer, a magnetometer, a laser rangefinder, and a radio science experiment. After insertion of the spacecraft into polar orbit around Eros, the science payload should provide sufficient data for nearly complete topographic and geologic maps showing features as small as a few meters across. Spectral types will be mapped at a resolution of a few meters, mineral abundances at a resolution of several hundred meters, and major and minor radioactive elements at a similar or coarser scale. Thus, the NEAR mission should provide a major advance in our knowledge of the composition and geologic evolution of this asteroid.

- ***Deep Space 1,*** NASA's first New Millennium program deep-space technology demonstration mission, is planned for launch in July 1998. Although this mission will be driven by the requirements of technology validation (especially solar electric propulsion), it will encounter an asteroid, a comet, and the planet Mars. The first encounter will be with the Amor asteroid (3352) McAuliffe in January 1999, and the second with the periodic comet West-Kohoutek-Ikemura in June 2000. No physical studies have yet been carried out on McAuliffe. The asteroid may be about 2 km in diameter if it is an S type, or about 5 km in diameter if it is a C type. An integrated camera-spectrometer will be used to determine the sizes and shapes of both bodies, as well as the spectral reflectance of their surface materials.

- ***Stardust,*** the fourth of NASA's Discovery missions, will be launched in February 1999. It will capture a sample of dust particles from comet P/Wild 2 and return it to Earth for laboratory analysis. A deflection of this comet during an encounter with Jupiter in 1974 reduced its perihelion distance from 5 to 1.5 AU, and so this object is now Earth approaching. The spacecraft will approach the comet nucleus within 50 km, using on-board optical navigation, and a particle mass spectrometer provided by Germany will obtain in-flight data on very fine particles. During interplanetary cruise, a second set of collectors will collect dust grains currently entering the solar system from interstellar space. The samples will be returned to Earth in January 2006.

- ***Muses-C*** is an asteroid sample-return mission to be carried out by Japan's Institute of Space and Astronautical Science, with participation by NASA. Its scheduled launch is January 2002. It will rendezvous with (4660) Nereus (approximately 1 km in diameter, probably either a C-type or an M-type asteroid) in September 2003. Nereus is one of the most accessible NEOs so far discovered. In addition to a ballistic sampling device, the nominal instrument payload of Muses-C includes a CCD camera, an x-ray spectrometer, a secondary ion mass spectrometer, a dust collector, and a laser rangefinder. Prior to sampling, the asteroid will be mapped with the on-board instruments. After two months on station at Nereus, the spacecraft will return a sample to Earth, arriving in January 2006. Muses-C is also intended to demonstrate a solar electric propulsion system, autonomous guidance and navigation, and direct hyperbolic reentry of the sample capsule.

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4

Technological Aspects of Studies of Near-Earth Objects

SUPPORT AND DEVELOPMENT REQUIRED FOR GROUND-BASED OBSERVATIONS

Telescope Technology and Observations Needed

Observations of NEOs are governed by the short time available to study them. Because they traverse near-Earth space very quickly and are intrinsically very faint, the window of opportunity for physical studies of most objects is measured in days to about a week at most. However, for some objects the observations can be planned. New technology need not necessarily be developed, but access to existing facilities (optical and infrared telescopes, radar facilities) or development of search and observational telescopes for more or less continuous use is desirable.

Routine or priority access to optical and infrared telescopes and radar facilities requires strong and focused coordination. However, because observing time on large-aperture telescopes generally is scheduled long in advance, there is little flexibility for observing most newly discovered objects during the short period that they are sufficiently bright. Moreover, the appropriate instruments may not be available on short notice. Data that can be expected for most objects will be of uneven consistency and quality except for NASA-related facilities, such as the Infrared Telescope Facility (IRTF) and Goldstone.

A dedicated 2-m-class telescope situated at a good site could provide a vast amount of highly consistent data on the physical characteristics and mineralogical compositions of NEOs. Such a telescope should have a visible-wavelength charge-coupled device (CCD) and a suite of instruments for physical observations. A minimum set of instruments would include the following:

- ***Visible- and near-infrared-wavelength CCDs with broad-band filters operating in the range of 0.3 to 2.5 microns*** that would provide the basic set of observations, including light-curve studies, on most discovered objects. This instrument could be a dual optical-infrared photometer to obtain multicolor photometry of the faintest objects;
- ***Spectrographs covering 0.3 to 2.5 microns*** that would obtain the surface mineralogical composition of some of the brighter objects; and
- ***A 10-micron radiometer*** that would provide thermal infrared observations to establish the size and albedo of the brighter objects.

Laboratory Studies and Technology Needed

A number of laboratory investigations will aid in understanding NEO spectra and processes even in advance of sample-return missions. Such investigations are also important for defining the scientific objectives and sampling strategies for future sample-return missions. Asteroid spectra, for example, depend critically on the nature of the outermost surface layers. Regolith breccias contain materials that once resided on the surfaces of meteorite parent bodies, and some interplanetary dust particles may also be surficial materials. Further study of regolith breccias and their relation to asteroidal soils is valuable, but emphasis should be on understanding the processes involved in soil formation and space weathering and on identifying those that produce optical and compositional effects. A direct comparison of the spectral properties of regolith breccias and soils has been done in the case of the Moon, revealing that breccias have flatter spectra and stronger absorption than do soils. The question of weathering by long-term exposure to space is important for the determination of asteroid-meteorite connections. Systematic searches for space weathering products in chondrite regolith breccias, as well as experimental studies of possible space weathering processes, should be undertaken. Quantitative information on the mineralogical effects of shock blackening is also needed to interpret some NEO spectra.

Although the identities and compositions of the minerals composing different meteorite groups are well known, quantitative data on relative mineral proportions commonly are not available. These data are critical for interpreting asteroid spectra. Also, more rigorous methods for deconvolving spectra to obtain information on mineral proportions and composition, as well as physical properties, have to be pursued.

The petrogenetic connections between meteorite types must be explored more fully, so that the coexistence of different types on asteroids can be predicted and sought in spectral data. Thermal models for asteroids provide a powerful way to relate meteorites with different metamorphic grades or aqueous alteration histories; petrologic and geochemical studies allow the relationships among igneous meteorites to be understood. These studies are also critical for determining whether complex NEOs have inherited accretional structure or have acquired heterogeneity by internal geologic processing or by chance collisions that resulted in rubble pile objects.

Finally, the development of new microanalytical instruments will benefit the chemical and mineralogical characterization of returned samples from NEOs. NASA's Cosmochemistry program, especially those parts devoted to the study of interplanetary dust particles collected in the stratosphere and interstellar grains separated from meteorites, has greatly expanded the ability to handle and analyze very small samples. However, some analytical techniques are not currently applicable to the characterization of very small samples. Continued development of such instrumentation, and acquisition of existing instruments for use in providing access and training, are necessary steps that should precede sample return.

TECHNOLOGY STATUS AND DEVELOPMENT FOR ROBOTIC MISSIONS TO NEAR-EARTH OBJECTS

The missions currently planned, along with ground-based spectroscopy, radar, and meteorite studies, should greatly increase our understanding of NEOs by the year 2000. It is virtually certain that important questions will be suggested by the new data. However, only a small subset of these bodies will be explored, and the diversity of NEOs will require, for further progress, either a spacecraft cruising among them or multiple missions targeted on individual objects. Learning how to conduct more, and more effective, missions for less money seems particularly urgent in this particular area of planetary exploration.

The three main types of small-body missions (flyby, rendezvous, and sample return) are discussed briefly above. Because no one mission of any type can characterize the variety of NEOs, the goal of technology development must be to reduce costs and increase capabilities. Experience so far is very limited, but the paths available for progress seem to be many. One possible path is the use of one of the various types of nonchemical propulsion systems that can allow multiple encounters with a large number of objects, thereby lowering unit costs. In an earlier report, the Space Studies Board concluded that the value of electric propulsion systems for missions to comets and asteroids would be immense.[1]

Among the many nonchemical propulsion methods discussed to date, the most fully developed and most likely to be used soon for multiple targets is solar electric propulsion (SEP),[2] that is, ion engines powered by solar arrays. These have been designed, built, and tested in several forms since the 1960s. NASA's Space Electric Rocket Test (SERT) program, for example, launched an ion engine on a sounding rocket (SERT 1) in July 1964 and on an orbital flight (SERT 2) in February 1970. To date, however, SEP has not yet been employed to accomplish an actual deep-space mission. Ions can be accelerated across an electric potential, which in most concepts is provided by solar power, to a much higher velocity than chemical fuel systems can reach. Thus, massive quantities of fuel are not necessary. The disadvantage—that these systems provide low thrust (typically a few millinewtons or less) for any reasonable power level—is balanced by the fact that such engines can be run continuously, not merely for a few minutes but for periods comparable to the flight duration. Later legs of such a mission can even be retargeted, within broad limits, based on new information derived from the mission itself or otherwise. Deep Space 1 will test the utility of SEP as a propulsion system for small spacecraft.

Another path is the use of multiple penetrators or small landers on one spacecraft, which could provide knowledge of surface and subsurface properties. Additionally, miniaturization, which could allow reduction of the required mass of spacecraft and science payload, may permit the launch of multiple spacecraft at one time. A more detailed discussion of attractive lines of progress follows for each of the three main mission types.

Flyby Missions

The simplest mission type is the flyby, without provision for matching velocities to achieve rendezvous. A variety of scientific goals can be achieved, as already illustrated by Galileo's flyby imaging of Gaspra and Ida and NEAR's flyby observations of Mathilde. In addition to imaging and broad spectral characterization, other instruments such as magnetometers and spectrometers could yield important information about the magnetic properties, composition (particularly the presence and proportion of metallic iron), and thermal evolution of NEOs.

Flyby missions to individual objects probably will not be as attractive as other mission types for scientific exploration of NEOs, except for special high-priority objects or unless they can be done very inexpensively. With the anticipated massive increase in the number of NEOs known, *multiple* flyby missions[3] may be attractive as a cost-effective means for increasing our understanding of the variety of taxonomic groups represented among NEOs and perhaps making new, secure asteroid-meteorite connections.

Rendezvous Missions

Rendezvous requires matching the velocity as well as the position of the spacecraft with the NEO and hence is a more difficult task with respect to both energy and precision performance. Attractive mission opportunities, such as those for multiple flybys, are relatively rare but will increase with the number of known NEOs. When the number of known interesting objects reaches the thousands (and probably before), this should not be a problem.

The NEAR mission should demonstrate the special opportunities created by the weak gravitational field of small objects. When the local gravitational acceleration (g) is on the order of a few cm/sec^2, attitude jets are sufficient to permit maneuvering close to the asteroid. Automated "landing" at multiple targeted sites should be achievable, and the distinction between an orbiter and a rover becomes blurred. Among other advantages, this will widen the range of instruments available to satisfy a given objective such as chemical analysis.

Sample-Return Missions

Creating a system capable of robotically collecting and returning material from a small body would be a major advance in capability for asteroid and comet research. The only robotic space missions to date that have accomplished such a task were three Soviet missions (Lunas 16, 20, and 24), which returned core samples of lunar regolith. Stratigraphic detail was not preserved as well as in core samples collected by the Apollo astronauts.

A recent study of a mission involving two spacecraft on a single launch vehicle gives an example of the opportunities and problems associated with the use of solar sails for sample-return missions. The only use of chemical rockets in this mission, after launch, is for a small lander/penetrator to take the sample and transfer it robotically to the spacecraft. The two asteroids chosen for the study were both large main-belt asteroids, with escape velocities of hundreds of meters per second, so that conventional rocketry is still needed for landing and takeoff from the asteroid. Similar missions to smaller objects, particularly NEOs, would be technically much easier. Solar electric propulsion, proposed years ago for the Halley-Temple 2 mission, would be an alternative option. Although the use of a single spacecraft might be preferable for multiple flyby or rendezvous missions, use of multiple spacecraft is preferred for sample-return missions because it would increase the likelihood of successful sample acquisition.

HUMAN EXPLORATION OF NEAR-EARTH OBJECTS

It would be difficult to justify the human exploration of NEOs on the basis of any cost-benefit analysis of the strictly scientific results obtained.[4] As stated in the National Academy of Sciences' 1988 space policy report, "the ultimate decision to undertake further voyages of human exploration and to begin the process of expanding human activities into the solar system must be based on non-technical factors."[5] If, for other reasons, the United States should choose to utilize human exploration beyond low Earth orbit, a strong case can be made for starting with NEOs. Missions to these bodies could serve effectively as stepping stones or "waypoints," in the language of the Synthesis Group's report.[6]

A few percent of NEOs are the most accessible bodies beyond Earth for both robotic and human exploration. In the case of human expeditions, a primary concern would be to keep the total mission times as short as possible in order to minimize the hazards and attendant risks to which astronauts are exposed. These include, but are not limited to, weightlessness, a high-radiation environment, meteoroid impact, and equipment failure. NEO missions can reduce the requirements for life support and total mission costs. Short-duration, low delta-V missions to NEOs require either six-month or one-year round trips, since return to Earth occurs at either the ascending or the descending node of the transfer trajectory. Still shorter "sprint" missions (i.e., of a few months' duration) are conceivable with a large commitment of additional propulsion. Among the currently known NEOs, at least two and perhaps more can be reached in six-month or one-year round-trip missions with realistically achievable delta-V. An example of a six-month mission profile to asteroid 1991 JW is shown in Figure 4.1.[7] With the anticipated accelerated discovery of NEOs, the number of potential targets for human expeditions can be expected to increase by an order of magnitude in the next 10 to 15 years. Hence, there most likely will be opportunities for launch to one or more accessible asteroids in any given year, and there could conceivably be a diversity of physical types from which to choose.

The range of geologic problems to be solved by astronauts on NEOs would depend on the type of body. In nearly all cases, the distribution, depth, and physical and petrologic characteristics of the regolith, the original locations of fragments in the regolith, and the structure of the underlying body of the asteroid repesent basic problems to be solved. Studies of bedrock or regolith will provide clues to its origin and evolution.[8]

The advantage that human explorers bring to the study of NEOs is the ability to conduct on-site observations at a great range of scales, from the hand specimen to the entire body, coupled with the ability to manipulate materials and take diverse samples in the context of complex field relationships. Although some of these tasks can be done robotically with difficulty, the human observer has a great advantage in dexterity and in integrating diverse observations.[9] Humans can also adapt to new situations quickly and effectively, enabling real-time decisions to be made. The field aspects of scientific investigation of the surface of an asteroid are, in many ways, analogous to field geology. The surface of a 1-km asteroid is a geologic field area well suited for study during the stay times of two weeks to a month that are possible on a six-month human expedition.

Expeditions to NEOs represent the easiest and least expensive next step in human exploration of space beyond Earth. Scientific exploration of these bodies could provide the experience and technology needed for fruitful human exploration of Mars and even deeper space.

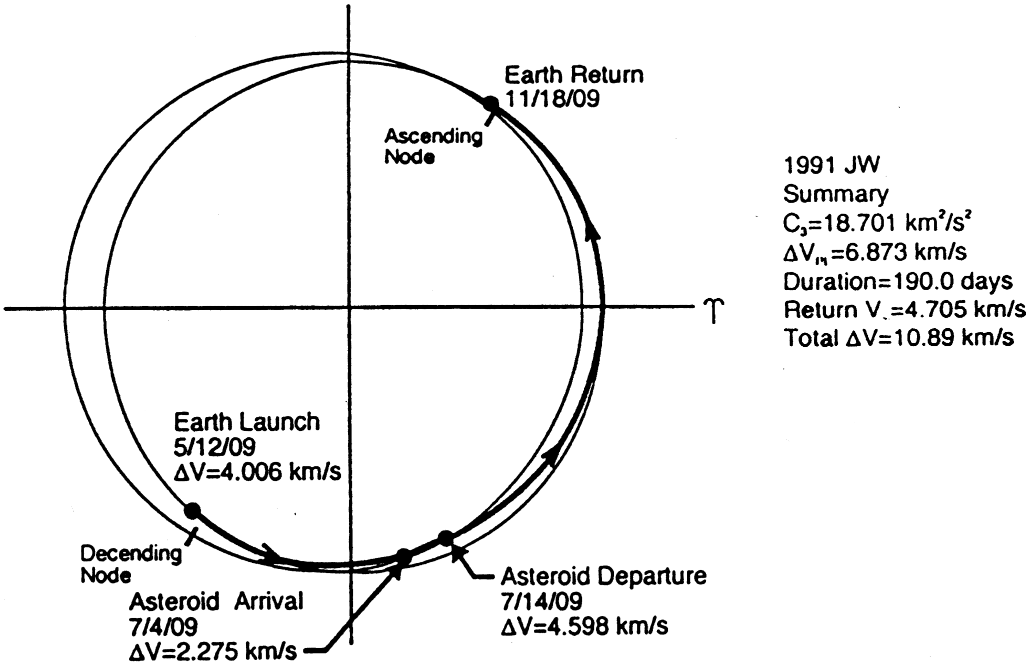

FIGURE 4.1 Six-month round-trip mission profile to NEO 1991 JW. This mission requires a lower delta-V than does a one-way trip to the lunar surface. (SOURCE: T.D. Jones et al., "Human exploration of near-Earth asteroids," *Hazards Due to Comets and Asteroids,* University of Arizona Press, Tucson, Ariz., 1994, p. 683.)

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5

Conclusions and Recommendations

COMPLEX has identified alternatives for the continued discovery and characterization of NEOs. These are summarized below, and some advantages and disadvantages of each are discussed. Under each heading, the baseline program describes the current or necessary level of activity, and augmentations describe more ambitious levels of activity that could be combined with the baseline program. Availability of funding and programmatic priorities will determine whether augmentations can be implemented. These recommendations are consistent with priorities articulated previously by the Space Studies Board and its committees for the scientific study of asteroids and comets.[1,2]

GROUND-BASED TELESCOPIC OBSERVATIONS AND INSTRUMENTATION

Baseline Recommendation: Support research programs for interpreting the spectra of near-Earth objects (NEOs), continue and coordinate currently supported surveys to discover and determine the orbits of NEOs, and develop policies for the public disclosure of results relating to potential hazards.

Interpreting the spectra of NEOs already cataloged in NASA's Planetary Data System should continue. The NEAT, LONEOS, and Spacewatch systems, when used in a coordinated program of detection and orbit determination, could discover and characterize perhaps 1000 new Earth-crossing objects larger than 1 km in diameter, as well as thousands of smaller NEOs over a 10- to 15-year period. The baseline program, however, will not provide information on physical properties, compositions, and origins of newly discovered NEOs. NASA should undertake a study of how to communicate these findings to the public, especially the discoveries of potentially threatening NEOs, and appropriate protocols should be established.

Augmentation 1: Provide routine or priority access to existing ground-based optical and infrared telescopes and radar facilities for characterization of NEOs during favorable encounters.

Frequent access to existing facilities would allow most objects discovered in any given month to be observed. Alternatively, access could be granted contingent upon discovery of an object using a system perhaps analogous to the Hubble Space Telescope's (HST's) target of opportunity program This augmentation would allow a subset of NEOs to be classified, and their sizes, shapes, rotation, and surface compositions would be characterized. The current level of effort in spectral classification of NEOs is perhaps 20 objects per year, although access to appropriate instruments may decrease. Prioritized access to telescopes could increase this level by an order of magnitude. The present rate of NEO characterizations by radar, approximately 1 per year, might be increased by a factor of 10. Infrared measurements of size and albedo require large-aperture instruments and could double or triple from the present rate of fewer than 10 per year. Priority access would affect ongoing observation programs (depending on the number of participating facilities). The quality and consistency of data might be uneven, depending on the instrumentation available, and the cooperation and flexibility of observers would be required.

Augmentation 2: Provide expanded, dedicated telescope access for characterization of NEOs.

With the construction and planned commitment of national operational resources to large (4- to 10-m) telescopes, consideration is being given to decommissioning several national facility telescopes in the 2-m class.[3] If funds for NEO research were provided for maintenance of an existing telescope of at least 2-m aperture (including the cost of necessary support personnel) in order to ensure more or less full-time access, use of such a facility would allow physical and mineralogical characterization of as many as half of the NEOs discovered each year. A minimum set of instruments would include CCDs with broad-band filters, a 10-micron photometer, and a near-infrared array spectrometer. Funding would be required for instrument construction.

LABORATORY STUDIES AND INSTRUMENTATION

Baseline Recommendation: Support continued research on extraterrestrial materials to understand the controls on spectra of NEOs and the physical processes that alter asteroid and comet surface materials.

Meteorite regolith breccias and some interplanetary dust particles potentially provide samples of asteroidal and cometary surface materials. Mineralogical, chemical, textural, and spectral studies of such materials can constrain the interpretation of NEO spectra and help quantify the proportions of phases that dominate their spectra. The discovery and characterization of altered surficial layers in regolith breccias would greatly assist in solving the question of space weathering. Laboratory studies would also be useful in addressing this problem. The occurrence of different meteorite types on the same asteroids can be understood from petrologic studies, as well as theoretical models of the accretional, thermal, and collisional histories of asteroids and comets. An advantage of continuing such work is that it tends to be an inexpensive aspect of NEO research. However, it is often difficult or impossible to make connections between specific NEOs and meteorites or interplanetary dust particles.

Augmentation 1: Support the acquisition and development of new analytical instruments needed for further studies of extraterrestrial materials and for characterization of returned NEO samples.

Materials research provides important information used in defining NEO exploration targets and the instrumentation required for spacecraft missions.[4] State-of-the-art instruments in laboratories on Earth are necessary to develop and maintain scientific expertise in readiness for asteroid sample-return missions. Even adapting existing instrumental technologies for the analysis of extraterrestrial materials requires a great deal of time and effort, and so laboratory facilities and protocols must be in place long before they are needed to analyze returned NEO samples. The development of new and improved microanalytical techniques and instruments will also be necessary for characterization of organic compounds, isotopes, and other constituents of tiny meteoritic and interplanetary dust samples, as well as the modest-sized samples to be collected on NEO sample-return missions. An advantage of supporting instrument development is that laboratory equipment is versatile and can be used in many research programs (e.g., the search for evidence of life in martian meteorites and returned martian samples); additionally, facility instruments can be shared among many investigators.

SPACECRAFT TECHNOLOGY, INSTRUMENTATION, AND MISSIONS

Baseline Recommendation: Support NEO flyby and rendezvous missions.

Spacecraft such as NEAR and Deep Space 1 are already capable of NEO flyby and rendezvous missions. The high spatial resolution afforded by such missions provides important information on NEO physical characteristics, composition, formation, and geologic history that is otherwise unobtainable. Some flight instruments for remote sensing are already in a reasonably advanced state of development but require miniaturization. An advantage of supporting further reconnaissance missions is that they can draw on the technological heritage of previous spacecraft and thus have lower costs.

Augmentation 1: Develop technological advances in spacecraft capabilities, including nonchemical propulsion and autonomous navigation systems, low-power and low-mass analytical instrumentation for remote and in situ studies, and multiple penetrators and other sampling and sample-handling systems to allow low-cost rendezvous and sample-return missions.

The definition and development of new analytical instruments to be flown on flyby, orbital, and landed spacecraft must be a high priority. In situ imaging and measurements of physical and chemical properties are the justification for NEO spacecraft missions that do not return samples, and the severe mass and power limitations imposed by smaller spacecraft will demand a new generation of instruments. With increased emphasis on low-cost, rapid-pace, and highly competitive missions, new instrument development is a difficult challenge, and programs such as NASA's Planetary Instrument Definition and Development Program (PIDDP) have to be supported. However, in the case of some NEOs, it may be easier to collect and return samples than to do adequate in situ analyses.

Flight instrument development focused on sampling devices and on autonomous navigation and control systems would enable NEO sample-return missions. Spacecraft and instrument miniaturization and multiple penetrators or landers are among other potential mission-enhancing developments. Nonchemical propulsion concepts hold particular promise for NEO missions. Sampling missions would be most effective if focused on collecting samples from well-characterized geologic units or the subsurface of NEOs and from an object exhibiting cometary behavior. Sample return involves many complex manipulations that pose engineering challenges.

Augmentation 2: Study technical requirements for human expeditions to NEOs.

Human exploration of NEOs would provide considerable improvement in understanding because of the ability to make intensive geologic observations and take carefully chosen samples. The technical requirements for human expeditions to NEOs, although undefined, are intermediate between those for lunar and martian missions. A particularly attractive aspect is that human spaceflight beyond the Moon will probably require incremental steps, and an expedition to a NEO would be of considerably shorter duration and risk and lower in cost than one to Mars.

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Glossary

Absorption features Minima in spectra produced by absorption of certain wavelengths of light by surface materials

Accrete To combine materials physically to form a larger object

Achondrite A stony meteorite that crystallized from molten liquid

Albedo The proportion of incoming light that is reflected from a surface

Aqueous alteration A process by which minerals react with liquid water or a hydrothermal fluid

Asteroid family Asteroids with similar orbital elements that were probably once parts of a larger asteroid

Asteroids
  Main-belt Small bodies with orbits between those of Mars and Jupiter
  Near-Earth Small bodies whose orbits approach that of Earth

Astronomical unit (AU) Measurement of distance equal to the mean distance from Earth to the Sun

Breccia Rock composed of broken fragments cemented together

Chondrite A common class of meteorites that has not been melted or differentiated

Coma The atmosphere surrounding the nucleus of a comet, produced by gas and dust expelled from the nucleus

Condensation A process by which solids form directly from a cooling gas

Cosmogenic See **Isotopes**

Delta-V Impulse (change in velocity) required to accomplish a specific manuever in space

Differentiation Internal stratification of a body, caused by heating and usually resulting in a core, mantle, and crust

Ecliptic The plane defined by Earth's orbit around the Sun

Electromagnetic induction heating Method proposed for asteroid heating, using electric currents induced by variations in a strong solar wind

Emission band Radiation emitted by an object at a particular range of wavelengths

Interplanetary dust particles Tiny particles that once orbited in the spaces between planets, normally collected in the stratosphere by high-flying aircraft

Iron meteorite One composed primarily of iron-nickel alloy

Isotopes
  Cosmogenic Isotope produced by exposure to cosmic rays
  Radioactive Unstable isotope that decays spontaneously
  Radiogenic Isotope formed by radioactive decay

Kuiper Belt Zone of presumably icy planetesimals located outside the orbit of Neptune

Light curve Variations in amplitude observed as an asteroid rotates

Metamorphic grade Relative intensity of heating and recrystallization

Nodes Two points at which an object's orbit intersects Earth's orbital plane

Oort Cloud Spherical halo of icy planetesimals located between approximately 1,000 and 50,000 AU from the Sun

Orbital precession Slow, periodic rotation of the long axis of an orbit

Parent body Object of asteroidal size from which meteorites were derived

Petrology Study of the mineralogy, texture, structures, and origin of rocks

Photometry Measurement of light intensities

Phyllosilicate Silicate mineral with layered crystal structure

Plutonic Rocks that crystallized from magma at depth

Radioactive See **Isotopes**

Radiogenic See **Isotopes**

Radiometric dating Determining the age of a sample from measurement of its radionuclides

Radionuclide Radioactive isotope

Regolith Layer of fragmented, incoherent rocky debris on the surface of an object

Solar electric propulsion Reaction drive that utilizes solar energy to power an ion engine

Space weathering Alteration of an asteroid's surface materials by exposure to the space environment

Spall surface Dislodged slab of rock

Spectra Reflection or absorption of different wavelengths of incident light

Spectroscopy Measurement of spectra

Thermal
  Inertia Parameter indicating the rate at which a body's temperature responds to changing heat input
  Model Calculated history of temperature variations with time

Tholin Complex organic compound producing a dark reddish spectrum

Trace element Element present in small abundance

Ureilites Complex igneous rocks composed mostly of pyroxene, olivine, and carbon

Volatiles Elements that condense from or exist as a gas at low temperatures

Water of hydration Water bound into crystal structures of hydrated silicate materials, such as clays