An Introduction to Near-Earth Objects

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On 13 April 2029, an object the size of the APL campus (≈300 m across) will make its closest approach to Earth. At the beginning of January 2029, the object will be a dot visible only in large telescopes that know exactly where to point, 250,000 times too faint to be seen even by the sharpest-eyed person. In early February it will reach its aphelion and begin its return toward the Sun. The Earth, closer to the Sun and moving faster, will overtake the object: already the Earth and this asteroid will have closed the gap between them by nearly 40% since New Year's Day, and the asteroid will have brightened by a factor of roughly 3. At the end of March, the incoming asteroid will have brightened by a factor of 100 since January. The next factor of 100 will take only 2 weeks. As clocks switch over on the East Coast to 13 April, a Friday, the Moon will briefly no longer be our nearest neighbor. As the morning rush hour winds down in the east, sharp-eyed people in dark sites on the other side of the globe will be able to discern the visitor. It will continue to brighten, moving north and west at tens of degrees per hour, reaching a peak brightness comparable to stars in the Big Dipper. Then the geometry between the Sun, Earth, and asteroid will have changed so the asteroid will first become gibbous, then quarter phase. Its brightness will decrease even as it draws closer for the last hour. Finally, during the evening rush, our visitor will be at roughly the distance of the geosynchronous satellites that will be broadcasting news of its arrival. Its phase will become new as it moves into the daytime sky and will recede as quickly as it approached. This object's name is Apophis, and for some time in 2004, it was thought that the scenario described here could end with a collision.

INTRODUCTION

Apophis (or more properly 99942 Apophis) is one of thousands of the known near-Earth objects (NEOs), asteroids and comets with orbits around the Sun that are similar to ours. Their proximity to Earth ranges anywhere from a non-perilous 45 million km (or 0.3 astronomical units [AU], where 1 AU is the average distance between the Earth and Sun) to objects like Apophis. The first known NEO, 433 Eros, was visited by the APL-built Near Earth Asteroid Rendezvous (NEAR) Shoemaker spacecraft in 2001. A second NEO, 25143 Itokawa, was visited by the Japanese Hayabusa spacecraft in 2005. The compositions of NEOs cover a range from icy objects that have spent billions of years at temperatures of 50 K or less to metallic shards that originated at the heart of a molten mini-planet. There is obvious interest in NEOs in order to understand the threat they pose and the resources they promise, but they carry a rich bounty of scientific information as well.

Asteroids and comets preserve information about the earliest times in solar system history, information long lost from larger planets that have experienced volcanoes, erosion, and tectonic events. However, comets and main-belt asteroids are difficult to reach with spacecraft for rendezvous or sample return missions, and ground-based studies are usually restricted to whole-disk observations. We have material from asteroids in our laboratories in the form of meteorites, which can be subjected to precise measurements that give details about their formation and history. The vast majority of this material, however, lacks the context that accompanies knowing the original setting of the sample, and generalizing results from hand-sized scales to kilometer scales (or larger) can be controversial. Furthermore, many meteorites are contaminated to some degree by exposure to elements on Earth before their collection, and those effects need to be disentangled from the true nature of the parent body.

NEOs provide a bridge between the macroplanetary-scale studies of small bodies and the microlaboratory-scale studies of meteorites. All meteorites are NEOs until they enter the atmosphere (and at least one object in 1972 skipped off the atmosphere to live another day; see Fig. 1), so NEOs offer the opportunity to study much

Figure 1. The one that got away. This picture, taken on 10 August 1972, shows the close approach of a 5- to 10-m object to within 60 km of the Earth's surface. At the time it was traveling north at upwards of 14.5 km/s before skipping off the Earth's atmosphere over Idaho. This picture shows it passing over Jackson Lake, Wyoming. (Source: http://fireball.meteorite.free.fr.)

larger versions of meteorites under pristine conditions. Some NEOs are easier to reach than the Moon, and a typical NEO is much easier to reach than a typical main-belt asteroid.[1] Objects that formed at a variety of solar distances currently find themselves in near-Earth space, and a current orbit, combined with physical properties, can give a good sense of where an object originated, which allows study of these nearby objects to gain insight into the outer reaches of the solar system.

As noted above, the NEO population is thought to contain two types of objects: asteroids and comets. While the distinction between them is traditionally based on their visual appearance, the two groups differ significantly in typical composition. In simplified (or perhaps oversimplified) terms, asteroids are largely composed of rock, with varying amounts of metal and/or clays, and are thought to have originated between Mars and Jupiter. Comets, on the other hand, are thought to be largely composed of ice and rock and to have originated beyond Neptune at the outermost reaches of the solar system. For historical reasons, each type of object is named differently. Asteroids, when discovered, are given provisional names related to the year and month of their discovery (for instance, 2002 NY40 or 1998 XF11). When their orbits are sufficiently well known, they are given a number and may also be given a new name (e.g., 99942 Apophis was once known as 2004 MN4), though many maintain their provisional names even after they are numbered (e.g., 54509 2000 PH5). Comets are named after their discoverer(s) (Kohoutek, Hyakutake, Hale-Bopp) along with an official number. In the NEO population, asteroids are thought to be much more numerous than comets, though exact figures are a matter of longstanding debate. Other articles in this issue concentrate on comets in general, and therefore I will focus here on the asteroidal NEO population.

Figure 2. Eros as seen from the NEAR Shoemaker spacecraft. Its surface is covered in craters, with smaller boulders littering the surface. The morphology of the craters, as well as the highest-resolution images, shows clear evidence of up to 100 m of a pulverized regolith rather than bare rock over most of its surface. Eros' dimensions are roughly 35 × 11 × 11 km, and it appears to be an intact, although highly fractured body rather than an unconsolidated rubble pile. (Image courtesy of NASA.)

AN NEO CENSUS

The first NEO, 433 Eros, was found in 1898 (Fig. 2). Astronomers immediately recognized its unusual orbit and the scientific possibilities created by its discovery. Simultaneous observations across the globe during close approaches in 1901 and 1930 were able to measure a distance to Eros using parallax, which was used to calculate the distance from the Earth to the Sun. Until radar was developed, the results of these measurements were the most precise values available. Similarly, perturbations on the orbit of Eros from its close passes allowed the first good measurements of the mass of the Moon to be made.

Many of the techniques used in observing small bodies today were pioneered on Eros: the first light curve was taken in 1900 (and arguments about whether Eros was a single or binary object ensued). Its mass was estimated to within 25% of the value found by the NEAR mission, and a reasonable calculation of its size and a very accurate calculation of its albedo (the fraction of light reflected from an object) were made by Watson in 1937 using data taken in the first third of the 20th century. Indeed, even the concept of a "precovery" was pioneered as Harvard College Observatory astronomers realized in 1900 that Eros was present on photographic plates in their collection from 1893 to 1896 (that is, before its discovery) and that knowledge of its orbit could be improved significantly if those data were included.

Roughly 20 more near-Earth asteroids were found in the 75 years following Eros' discovery. The intervention of two world wars and a turning away from solar system astronomy toward stellar and galactic studies meant that small bodies research suffered, with asteroids considered "vermin of the skies" by astrophysicists. Indeed, some objects were even lost, including 711 Albert, the second known NEO, which was discovered in 1911 and recovered in 2000, and the asteroid 69230 Hermes, lost in 1937 and recovered (and finally numbered) in 2003.

By the early 1980s, there was some greater recognition of small bodies in general and NEOs in particular. Mission proposals to NEOs started to appear in the

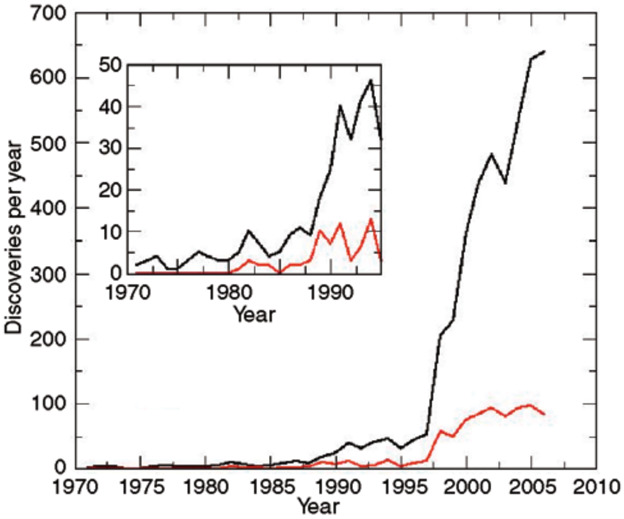

Figure 3. The NEO discovery rate has rapidly increased over the last 20 years. The black curve shows the number of discoveries per year for all NEOs, and the red curve represents potentially hazardous asteroids that pass within 0.05 AU of Earth. Obvious on the main graph and the inset are two critical times: the introduction of charge coupled devices (sensor chips in cameras) and automated object location in the late 1980s, and the inception of MIT's LINEAR (Lincoln Near Earth Asteroidial Research) survey in conjunction with increased efforts due to the late-1990s Congressional mandate to discover 1-km NEOs.

literature as early as 1971, with Eros as an early favorite target. In 1973, the first dedicated survey for planet-crossing asteroids was begun by Eugene Shoemaker using a small telescope at Palomar Observatory. What focused more attention on small bodies, however, was a discovery here on Earth: the realization in 1980 that the K-T (Cretaceous-Tertiary) extinction was caused by an impact[2] and that an inventory of nearby objects was necessary to understand the size of the threat we faced. In the decades since, several search programs were established in the United States (and sporadically in other countries, notably Australia), often sharing facilities with military projects. The discovery rate has skyrocketed (Fig. 3), fueled in part by a mandate by the U.S. Congress to find 90% of all 1-km-dia. NEOs by 2008, with 1 km representing the rough size of an object capable of effecting global disaster with an impact. As that deadline approaches, Congress is considering a follow-on goal to find 90% of the "potentially hazardous asteroids" (which approach within 0.05 AU of Earth) down to a size of 100–200 m.

THE LIFE CYCLE OF NEOs

Studying the paths of fireballs and the meteorites that sometimes result has led to the conclusion that most objects that strike Earth have orbits originating in the main asteroid belt, between Mars and Jupiter. The largest asteroids, like Vesta and the dwarf planet Ceres, are hundreds of kilometers in size and are thought to have been at their current sizes since they formed billions of years ago. The gravitational influence of their rowdy neighbor Jupiter kept any full-sized planet from forming and also ejected a large amount of material from the asteroid belt, perhaps 99% of what was once present.

Jupiter's presence is still felt in the asteroid belt today through a variety of resonances, most notably the 3:1 mean motion resonance. Objects with semi-major axes near 2.5 AU have orbital periods one-third that of Jupiter, and consequently have closest approaches to that planet at only two different points in their orbits. The extra pull at these two points quickly alters the orbit, increasing the eccentricity to the point that, within a million years, an initially circular orbit at 2.5 AU becomes Mars- and Earth-crossing.

Another important resonance is due to the precession of Saturn's perihelion. Certain combinations of semi-major axes, eccentricities, and inclinations in the main asteroid belt create orbits whose perihelia precess is at the same rate as Saturn's. This resonance, called the $\nu 6$ secular resonance, is also very effective at removing mass from the asteroid belt, with objects lasting in the $\nu 6$ resonance for about a million years or so before their eccentricities change and their orbits cross Earth's.

Once reaching near-Earth space from the asteroid belt, NEOs take a bit longer to meet their ultimate fate, but not much longer. Typically, within 10 million years or less, an NEO's orbit continues to evolve until it has a close pass to a planet that ejects it from the solar system or it hits a planet or the Sun. Surprisingly, this latter case, impact into the Sun, is the fate of a majority of NEOs.[3] Given the rapid depletion of the areas near resonances into near-Earth space and the rapid removal of NEOs from near-Earth space, the question becomes how the NEO population is resupplied to give us the objects we see today.

Jupiter was not only instrumental in ejecting most of the mass in the asteroid belt, but it also increased the eccentricities and inclinations of many of the objects that remained behind. This has had the effect of increasing the median impact speed between objects in the asteroid belt to roughly 5 km/s. Impacts between asteroids can put ejecta directly into the main resonances, which can account for some of the supply. But it appears that a recently rediscovered force called the Yarkovsky effect helps to explain much of the rest. The Yarkovsky force is due to thermal inertia and is most effective on rocky objects 1–10 m in size, though over billions of years it can have an appreciable effect on objects as large as 10 km. This force slowly moves material in toward the Sun. So in addition to ejecta directly put into resonances, ejecta throughout the asteroid belt is slowly moved toward resonances via the Yarkovsky effect, accounting for the constant supply.[4]

NEOs AND EARTH IMPACTORS

The most interesting endgame for NEOs, at least for most humans, is Earth impact. The Earth is under constant bombardment from a rain of extraterrestrial material. In a typical year, Earth is impacted by 54 tons of material, most of it the size of dust grains, that does not penetrate deeper than the high atmosphere. However, Earth is hit with objects the weight of dollar coins or heavier roughly 100 times a day. Objects the size of marbles burn up in the atmosphere and are responsible for meteors, or "shooting stars," which can occur either randomly or in periodic, predictable meteor showers. Chair- to table-sized objects often strike Earth after spectacular fireballs, and fragments can survive to reach the ground as meteorites. Meteorite falls with recovery have occurred in Peekskill (New York), Monahans (Texas), and Tagish Lake (Canada) in the last 15 years. Earth bears ample evidence of even larger impacts. Every few decades, on average, we are impacted by an object of 10 tons or so—the mass of the Hubble Space Telescope. A house-sized piece of iron blasted an 0.5-mile-wide hole in the Arizona desert less than 50,000 years ago (Fig. 4). An impact near the Washington Monument from Apophis or a similarly sized cousin would leave a crater that would stretch from the Pentagon to the Capitol, with an ejecta blanket reaching the APL campus and destruction resulting across the eastern United States. Craters dot the American landscape and locations throughout the world. An impact in Mexico is thought to have resulted in the extinction of a large fraction of life on Earth, including the dinosaurs, 65 million years ago. It has been proposed that other so-called mass extinctions are also associated with impacts. Luckily, such large impacts appear to be relatively rare. However, unlike meteor showers, these impacts are not periodic.

As described in other articles in this issue, the study of meteorites has given us profound insights into the earliest times of solar system history and the processes that continue on parent bodies to this day. Because meteorites were necessarily NEOs for some period of time until they impacted Earth, the NEO population should reflect the meteorite population as well as the asteroid (and comet) populations from which they were originally drawn. The extent to which the NEO population differs from these other populations can be used to understand the biases in discovery and the relative importance of delivery mechanisms. Dynamical studies have recently provided a statistical means of tracing NEOs back to their source regions.[5] The result is a set of probabilities associating a given object with a given part of the solar system, which can be combined with other evidence to provide a most likely formation location for each body. This, in turn, allows scientific study of NEOs to provide context for both the meteorites studied in terrestrial laboratories and the regions of the solar system where they originated.

Figure 4. This meteor crater in Arizona resulted from the impact of a roughly 50-m-dia. iron object traveling at about 15 km/s. The crater is 1.2 km in diameter.

SIZE DISTRIBUTION OF NEOs

Critically important to characterizing NEOs for both scientific applications and the hazards they pose is understanding their sizes, which cannot be directly measured save for the few that are observed via radar. Instead, their brightnesses are measured, and these measurements are converted to sizes via measurements or estimates of the albedo, or how bright/dark the objects are. The cumulative size distribution of the NEO population fits a power law with an index of roughly −1.75, so each decrease of a factor of 10 in size adds a factor of roughly 56 in number. This distribution has been fit to the data from asteroid surveys, suggesting there are roughly 1100 NEOs 1 km or larger (and several tens of thousands in the range relevant for the possible new Congressional mandate). The largest potentially hazardous asteroid is 1866 Sisyphus, estimated to be 9 km in diameter, large enough to devastate civilization on Earth if it impacted and roughly the size of the Chixculub impactor that wiped out the dinosaurs. The smallest known and cataloged NEOs are roughly 10 m in diameter, small enough that they would not cause damage to Earth save for the exact area they impacted, assuming they could penetrate the atmosphere. However, even objects that do not make it to the ground could potentially have devastating consequences if they entered over the wrong place: an object roughly 20 m in diameter exploded with the force of a 10-megaton bomb nearly 10 km above Siberia in 1908, felling trees over thousands of square kilometers. Named the "Tunguska event," the impact caused changes in atmospheric pressure detectable in Britain with the primitive equipment available to scientists at the time. A small change in the orbit of the impactor would have resulted in an impact site over Russia's capital, St. Petersburg, rather than the sparsely populated swamps of Siberia.

The albedos necessary to turn brightnesses into true sizes have typically been obtained through observations in the middle (or "thermal") IR. This has been done for roughly 100 NEOs. Albedos can also be measured using polarimetric techniques, popular in the 1970s and 1980s and currently experiencing a revival of interest. Measuring sizes directly using ground-based imaging is theoretically possible for objects that are of a large enough angular size, but this has only been done for main-belt objects. Radar observations can also be, and have been, used to measure sizes.

COMPOSITION OF NEOs

Both indirect and direct information has been used to determine NEO compositions. Evidence from meteorites shows the minimum range of compositions to expect in the NEO population—from completely metallic iron-nickel alloys (iron meteorites), to fragile water- and organic-rich collections (carbonaceous chondrites), to rock types more familiar on Earth.[6] The meteorites most commonly seen to fall to Earth are relatively pristine mixtures of rock and metal called ordinary chondrites. Dust-sized particles (interplanetary dust particles, or IDPs) have been collected by research aircraft and have compositions that share some similarities with larger meteorites, though there are also some important differences. At least some of these IDPs are thought to have come from comets, a relationship that will become clearer as cometary samples returned by the Stardust mission are analyzed more fully in the coming years.

The collection of meteorites on Earth, while critically important, gives an incomplete picture of NEO characteristics. The distribution and proportions of objects that survive passage through the atmosphere and are recognized as meteorites on the ground may not be the same as that found in orbit. Remote sensing techniques are required to understand and catalog the diversity of NEO compositions.

Very preliminary estimates of NEO composition can be derived from their colors (or spectra) measured over visible wavelengths. Historically, asteroid colors (and albedos) have been grouped into major classes denoted as C-, S-, M-types, etc. (Fig. 5). Generalizations about

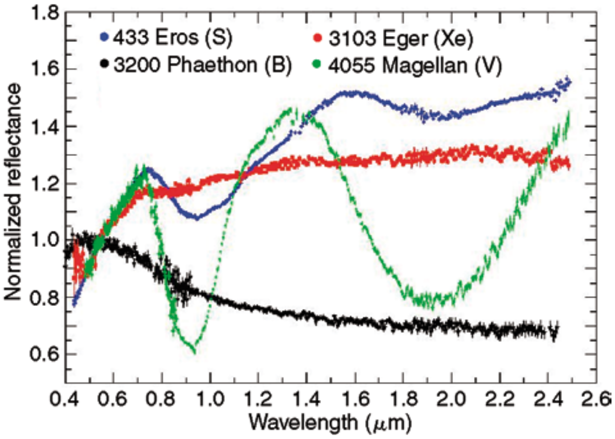

Figure 5. The reflectance spectra of asteroids can take a number of distinctive shapes, forming the basis for commonly used classification schemes. The S- and V-class objects here show deep absorption bands near 1 and 2 μm, indicative of olivine and/or pyroxene. These are associated with silicate-rich meteorites ranging from the primitive ordinary chondrites to the igneous HED meteorites (igneous rocks from basaltic flows after the formation of their parent bodies). The B-class asteroid 3200 Phaethon has a distinctive spectral slope reminiscent of some carbonaceous chondrites, primitive volatile-rich bodies believed to originate in the outer asteroid belt. The Xe asteroids are part of a group that is concentrated in the inner half of the asteroid belt and include objects suspected of being disrupted cores of differentiated bodies. All of the objects seen here are found in the NEO population, highlighting the great diversity of this sample.

the most likely compositions are based on these taxonomic classes, and comparison of these spectra with similar measurements of meteorites can be made as a first step toward estimating the nature of any NEO. However, within any given taxonomic class, ambiguities remain as to making a unique compositional association. These ambiguities can be reduced by having spectral data extending from the visible wavelengths to the near-IR as well as albedo measurements. In particular, spectral absorption bands in the 0.8- to 2.5-μm region can be diagnostic of minerals commonly found in stony meteorites. Measurements of about 3 μm can reveal the presence of water, usually bound into minerals.[7] The spectroscopic evidence suggests that the most common NEOs (S-class objects) have similarities to ordinary chondrites, though with some apparent differences in the details. These differences have led to divergent and controversial interpretations of the S-class asteroids, discussion of which is beyond the scope of this article.[8] Additional insight was gained recently when the elemental compositions of two targets were measured in great detail during spacecraft visits. Both targets (433 Eros by NEAR Shoemaker, 25143 Itokawa by Hayabusa) were found to be very similar to ordinary chondrites, strengthening the above interpretation for S-class objects.[9,10] Other meteorite types also appear to be present in the NEO population, though many spectral types can have multiple interpretations, as noted previously. Several hundred NEOs have been spectrally classified in this manner.

Radar observations can also provide a measure of compositional information in addition to size, shape, and positional information. There is a correlation between radar albedo and spectral type, with the lowest radar albedos tending to correlate with objects believed to be more carbonaceous, all the way to high radar albedos belonging to bodies with high metal fractions. Using this technique, a handful of objects have been found in the NEO population that are believed to be analogs of the iron meteorites. Determining radar albedos is not straightforward; however, and it is not generally done for most objects.

Compositional information about NEOs is particularly important for questions of mitigation as well as the possibility of extracting resources. The two most important factors in determining the density of meteorites are the metal content and the amount of water- and hydroxyl-bearing minerals. These also are the types of minerals of most interest for resource extraction. In particular, water and OH are potential sources of material for life support and fuel. Commonly found in carbonaceous chondrite meteorites, there are currently only a handful of objects in the NEO population known to have these minerals.[11] However, additional observations and access to larger telescopes hold the promise of identifying many more such objects.

ROTATION AND SHAPES OF NEOs

Asteroids and NEOs were known to have irregular shapes long before radar or spacecraft imaging was able to resolve them. Even as unresolved points of light, NEOs reveal information about their shapes through their rotations. If a body is irregular in shape, as it rotates it will reflect differing amounts of light toward an observer on Earth. The variation in brightness (or lightcurve) repeats every time the object completes one of its days, changing slowly as the orientation of the Sun and Earth change relative to the object through its year. For an ellipsoidal body, the lightcurve has two minima (corresponding to the "ends") and two maxima (corresponding to the "broad sides") per rotation. The maxima and minima may be unequal because of irregularities between the opposite sides. Lightcurves thus provide basic information on the overall range of rotation rates and shapes, where the greater the amplitude of variation, the more elongated the body. Ambiguities remain in that an observer does not know *a priori* whether he or she is looking down on the pole of the object (which would result in little or no lightcurve variation), edge-on at the equator (maximum variation), or some aspect angle in between. Usually ambiguity is resolved by repeated observations over a wide range of viewing geometries.

Results derived from NEO lightcurves show that these objects display shapes ranging from spherical bodies to elongated cigars. Radar observations of NEOs can have sufficient spatial resolution to show their shapes, confirming the wide range indicated by the lightcurve observations.

The additional resolution given by the radar data reveals that such extremes in lightcurve variations can also be created by separated binary components in orbit about the object's center of mass. Binaries can have very unusual properties, as with 1999 KW4, the system shown in Fig. 6. Radar imagery yields evidence of a ridge along the equator of the primary. The gravity of the satellite makes the primary's equator the region with the lowest gravitational potential on the body, so regolith (fine granulated rocks and dust) moving "downhill" goes toward the equator.[12] Objects orbiting one another also have the potential to undergo eclipses, allowing lightcurve measurements to be used to detect and measure the binary components. Up to 15% of all NEOs may be binary systems, and there is some evidence that systems with three or more components may also exist. Understanding the diversity of binary systems in the NEO population will be critical for developing mitigation techniques. It is not completely clear how binary asteroids form. Promising theories, like tidal disruption during close planetary passes, are proving less able to explain NEO binaries than once hoped.

Rotation periods for NEOs also show wide diversity, ranging over 4 orders of magnitude from more than 200 h to less than 2 min. In nearly all cases, the

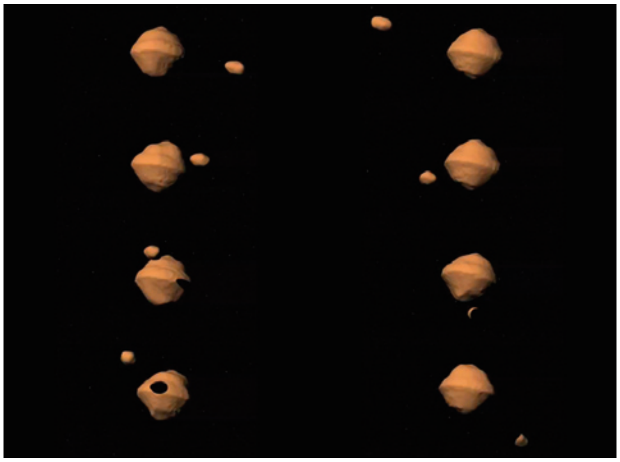

Figure 6. This sequence of images shows the 1999 KW4 system generated from shape models derived from radar observations. This binary NEO has two components of sizes 1.5 and 0.5 km separated by 2.5 km. The gravitational effect of the secondary on the primary has apparently caused the regolith on the primary to migrate to its equator. Roughly 15% of all NEOs are suspected to be binary systems. (Images courtesy of NASA/JPL-Caltech.)

lightcurve variation repeats with a single period, indicating the body is in a stable rotation state about its principal (shortest) axis. However, several objects are known to “tumble” in their rotations, much like a rock tossed into the air. Most likely an object reaches a tumbling state when an off-axis collision occurs. Over time, internal stresses will re-align the rotation axis with the principal axis to restore a nontumbling state to the body. Objects observed to tumble may have experienced a recent collision (recent on geologic timescales) or have interior properties that do not damp out the induced stress. Most revealing for the internal state of NEOs are the fastest rotations observed, with periods as short as a few minutes. Research shows that the fastest rotating NEOs also are predominantly smaller than 180 m in diameter. This size may represent the beginning of the transition between “rubble piles” held together by their own gravity and “intact monoliths.” The latter are coherent rocks with some likely internal tensile strength that holds them together. They are strong enough to remain intact when spun up to fast rotations. In contrast, a rubble pile would fly apart if spun up to rotation periods of just a few minutes. Thus knowledge of the rotation period appears to provide the best preliminary estimate of the internal strength of the NEO.

MASSES AND DENSITIES OF NEOs

Of critical importance for hazard assessment and mitigation are the mass, density, and internal structure of the NEO. While the internal structure is difficult to determine remotely, the porosity of an object, or how well packed it is, can be determined for some bodies. Inferences of composition and likely meteorite analogs can provide critical input in the absence of other available information. Classically, the mass of an object is determined if it has an observable satellite or by a close flyby or rendezvous by a spacecraft. These data are available for roughly a dozen NEOs.

When discussing porosity, it is important to distinguish between microporosity and macroporosity. Microporosity denotes small void spaces, on the microscopic scale, within the material that makes up the body. Macroporosity refers to void spaces between the rocks or blocks that make up the object. According to current interpretations, the macroporosity of an object is the parameter most relevant when considering the internal structure and coherent strength of a body. Surprisingly large macroporosities are found for NEOs (as well as small solar system bodies in general), forming the basis for inferring a rubble pile structure for their interiors. A pile of sand dispensed from the back of a dump truck has a macroporosity of about 20% (i.e., spaces between the grains). A similarly dispensed pile of boulders has a macroporosity exceeding 40%. If the estimated values of 20–40% macroporosity are correct for most NEOs, it implies they have no coherent tensile strength whatsoever. Quite literally, they appear to be piles of rubble weakly held together by their own mutual gravity—most likely having reached this state through collisions that have thoroughly shattered their interiors. Such weak interior strengths have important implications for any mitigation method intended to deliver an impulse force. Close-up imagery by Hayabusa (Fig. 7) shows Itokawa to be a rubble pile under the most straightforward interpretation. Eros, on the other hand, seems to have some strength in NEAR Shoemaker data, though it may be

Figure 7. This view of 25143 Itokawa, taken by the Hayabusa spacecraft, shows a surface very different from Eros (Fig. 2). While some areas are relatively smooth, Itokawa’s surface is covered with boulders of all sizes, with few if any well-identified craters. The structure and morphologies visible here are consistent with an unconsolidated rubble-pile structure. (Image courtesy of the Institute of Space and Astronautical Science [ISAS] and Japan Space Exploration Agency [JAXA].)

thoroughly fractured. The only objects that must be single and unbroken are the extremely rapid rotators, as discussed above.

OPTICAL PROPERTIES AND SURFACE STRUCTURE

The analysis of photometric, polarimetric, and radiometric data on NEOs, as well as direct imaging of Eros and Itokawa, shows that most observed NEOs are covered with regolith. Despite their low surface gravities, even small NEOs appear able to retain some regolith or dust coating. Gravitational effects may still be important; however, the data indicate that NEO regoliths tend to be coarser grained than interpreted for main-belt asteroids, which are still more coarsely grained than the lunar regolith. Images direct from the surfaces of Eros and Itokawa show a complete variety of characteristics ranging from boulders to smooth "ponds" of fine-grained material—with this entire diversity being present on a single body. This smoothness is apparently driven by the seismic shaking of small bodies during impacts. Over the minutes to hours that the body vibrates, small-scale shifts of the regolith can fill in small craters, erasing the record of small impacts. Levitation of dust grains by electric fields has also been suggested for asteroids and has been reported on the Moon. Finally, radar studies have shown promise for determining the density and porosity of near-surface layers (as distinct from the porosity of objects as a whole) and perhaps the presence/absence of a regolith.

The thermal properties of NEOs are potentially quite important for mitigation reasons and unquestionably important for long-term calculations of their orbits. The Yarkovsky effect, mentioned above, is a nongravitational force on objects that depends on how quickly they heat and cool. While it acts on all objects, this effect is too weak to noticeably change the orbits of bodies larger than some tens of kilometers, even given billions of years to act. For the size range of the NEOs of concern, however, the Yarkovsky effect can be important, and positional predictions for at least one 1-km object (1950 DA) cannot be improved further without accounting for the Yarkovsky effect, which requires knowledge of that object's thermal properties. In most situations, the short timescale influence of the Yarkovsky effect will not be critical, although if an object is in a particular type of Earth-approaching orbit, uncertainties due to the Yarkovsky effect could mean the difference between forecasting a possible impact and predicting a clean miss.

EXTINCT COMETS IN THE NEO POPULATION

As discussed earlier, both asteroids and comets are believed to contribute to the population of bodies we discover and catalog as NEOs. However, the question remains: What fraction of NEOs are "asteroids" and what fraction are "extinct or dormant comets?" Observationally, any object that does not display a fuzzy head (coma) or tail is catalogued as an asteroid, regardless of its genesis. From a mitigation or space resource utilization viewpoint, there may be a substantial difference in response or interest, as we presently presume a cometary body is more likely to have a high content of water and other ices.

Measured physical properties of cometary nuclei indicate low albedos, typically reflecting less than 7% of the light that hits them. As this value is substantially below the average of all NEOs, possible comets in the NEO population are less likely to be discovered. This "bias" results because for two objects (one dark, one bright) of the same size, the brighter object is more likely to be detected and catalogued. Given the available data on search statistics and NEO physical properties (taxonomic distributions and their corresponding albedos), "bias-corrected" models for the NEO population can be generated.[5,13] Within this bias-corrected population, 30% of all NEOs reside in highly elliptical orbits that are strongly perturbed by Jupiter—the identical orbital characteristics of many short-period comets. Half of this subset of objects in "comet-like orbit" have the same low albedo characteristics of comet nuclei. Multiplying these factors (30% × 50%) yields 15% as the current estimate for the fraction of all NEOs that are extinct or dormant comets, somewhat higher than most previous recent estimates (typically in the 5–10% range), but much lower than the 50% that dynamical models in the 1980s[14] required.

FUTURE DIRECTIONS IN NEO RESEARCH

In the coming years, expected advances in ground-based and mission work will revolutionize our understanding of the NEO population. Large-scale all-sky surveys such as Pan-STARRS will discover most of the objects 300 m and larger that are in near-Earth space, and designs have been proposed for space-based surveys that would complete the inventory to much smaller sizes. The Discovery Program typically has a healthy number of mission proposals targeting NEOs, and an asteroidal sample will likely be returned to Earth within the next decade, whether by Hayabusa or one of its successors. As additional binary objects are discovered, the number of NEOs with known masses will steadily increase. Apophis has, unsurprisingly, generated much interest from mission planners, including proposals to land a transponder on its surface to improve our knowledge of its orbit, and covering its surface with seismometers to measure its tidal distortion during the 2029 close pass to Earth, which would generate a wealth of data about its interior. The European Space Agency is considering a mission called Don Quijote, which would attempt to actually deflect an asteroid. This mission would include both an impactor and an orbiter, which would assess the effectiveness of the deflection (Fig. 8). While of obvious

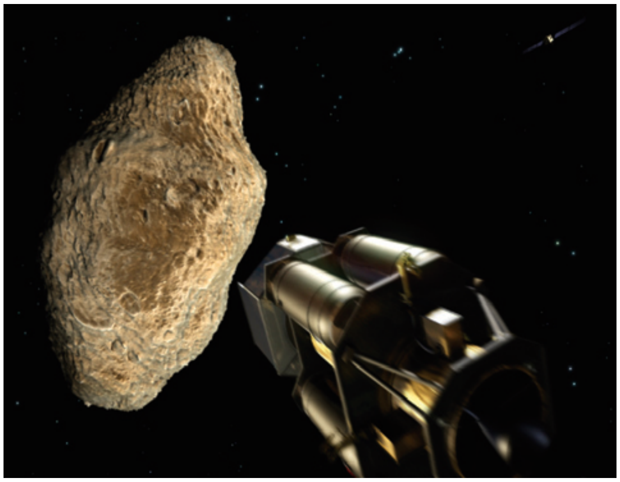

Figure 8. This artist's conception visualizes the final stages of the proposed Don Quijote mission. The impactor, Hidalgo, is in the foreground hurtling toward the target object, while the orbiter Sancho is in the upper right monitoring the results. This attempt to deflect an NEO will produce data giving unprecedented insights into asteroid interiors. (Illustration courtesy of the European Space Agency.)

interest for mitigation of NEO impacts, the characterization of the asteroid would greatly benefit science as well. Finally, there is the possibility of sending humans to visit an NEO as part of the path to visiting Mars. Although not in the baseline plan, studies have been performed to determine the feasibility of such missions. Certainly, given the number of NEOs that have visited the Earth, it only seems polite that we should return the favor.

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