The Wealth of Asteroids:

Incorporating Near-Earth Resources
into the Human Economy

Chapter 2.

Asteroid population, characterization, and accessibility

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Chapter 2. Asteroid population, characterization, and accessibility

"Small asteroids are not nuggets of rock. They have more in common with sedimentary basins, abyssal plains, and river channels."

—Erik Asphaug [2007]

2.1 Asteroid population

There are lots of asteroids. Main belt asteroids (MBAs) orbit the sun on courses that lie between Mars and Jupiter. Two million objects larger than a kilometer inhabit the main belt, as well as a vast hoard of smaller objects [Tedesco 2005]. Near-Earth asteroids (NEAs) also orbit the sun, but come "near" Earth at some point in their orbit.[1] There are roughly half a million NEAs larger than 50 meters in diameter,[2] and it is thought that 1000 to 1100 of these are larger than a kilometer [Bottke 2007]. The reference NEA described in Chapter 6 is 500 meters in diameter; there are an estimated 6000 NEAs of this size or larger orbiting the sun today.

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[1] NEAs, of which 85% are in fact asteroids (15% are extinct comets), orbit the sun with perihelion distances (q) < 1.3 AU and aphelion distances (Q) ≥ 0.983 AU [NASA 2009]. The Astronomical Unit (AU), roughly 150 million kilometers, is the mean distance between Earth and the Sun.

[2] Schweickart [2007] notes that if the NEA size-frequency distribution holds to a strict power-law curve, we have ~1 000 000 NEAs D ≥ 50 m. Bottke [2005] argues that the distribution varies from a power-law function, which leads to an estimate of NEAs with D ≥ 50 m in the hundreds of thousands.

The economically important very-near-Earth asteroids (VNEAs)[3] constitute a subset of the NEAs. VNEAs are accessible with an expenditure of energy (or change in velocity, ΔV) less than that required to reach the surface of the Moon. Of the roughly 6000 known NEAs, some 15% (just over 900) are VNEAs [Benner 2009].

When the planets formed, the total mass of the main belt was equal to several Earth masses. Today, less than one thousandth of an Earth mass remains. Asteroids are constantly migrating from the main belt to, and through, near-Earth orbits on their way to an impact with the sun or, less frequently, with one of the inner planets (or, even less frequently, they are ejected from the solar system entirely) [Bottke 2002].

Thanks to security concerns regarding possible asteroid-Earth impacts that emerged in the late 1990s, the number of identified NEAs has risen at an accelerated pace over the last decade (Figure 1). Today, orbital data for just over 6000 objects is on file, or roughly one percent of the NEAs larger than 50 m in diameter. This number is increasing, currently at a rate of about 650 discoveries a year. As new telescopes that are already under construction come on line, the pace of discovery is expected to increase dramatically.

[3] Nolan and Bottke [1996] use this term, but intend a more general meaning.

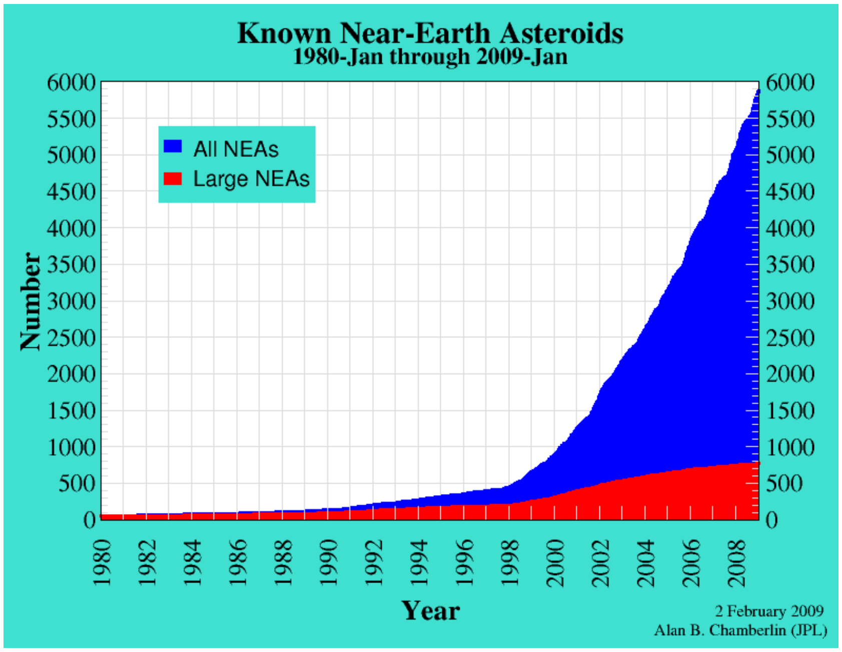
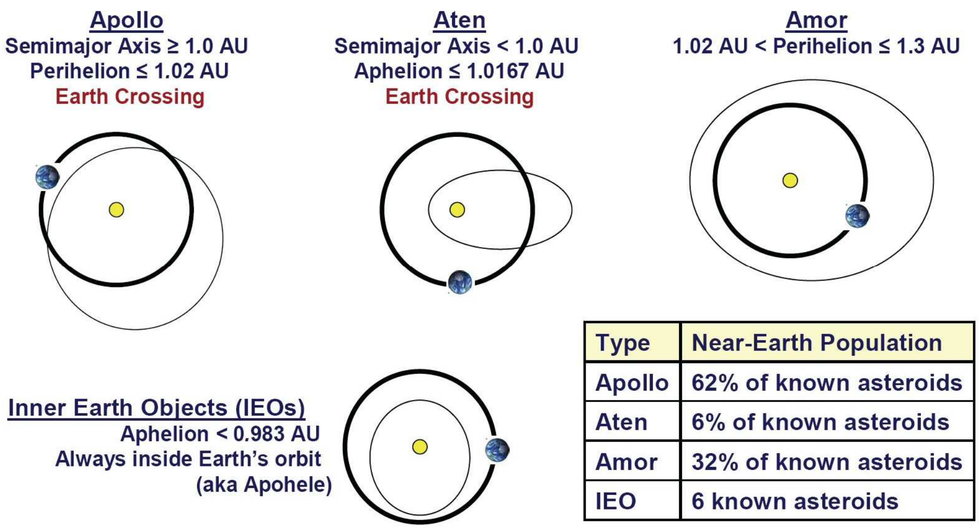


Figure 1. Identified near-Earth asteroids through February 2009. The blue area shows all discovered NEAs (> 6,000). The red area shows the subset of large (D ≥ 1 km) identified objects. Source: [NASA 2009].

NEAs are subdivided into groups based on orbital shape (Figure 2). Named after the first identified asteroid of its type, the Apollo and Aten asteroids have orbits that cross Earth's orbit, and Amor asteroids remain wholly outside of Earth's orbit. The observationally rare Inner-Earth objects (IEOs) travel wholly inside Earth's orbit. The IEOs are difficult to observe; their population is thought to be much larger than is revealed by current statistics.



Type	Near-Earth Population
Apollo	62% of known asteroids
Aten	6% of known asteroids
Amor	32% of known asteroids
IEO	6 known asteroids

Figure 2. Orbital types of near-Earth asteroids. Source: [NASA 2007].

The Catalina Sky Survey [Catalina 2009], run by the Lunar and Planetary Laboratory at the University of Arizona, is responsible for the bulk of recent NEA discoveries [Larson 2006]. All-sky survey telescopes currently under development, such as the Large Synoptic Survey Telescope [LSST 2009] and Pan-STARRS [Pan-STARRS 2009] [Kaiser 2007], will open new windows on deep space and our local solar system [Tyson 2005]. This new generation of ground-based telescopes is expected to "accelerate the rate of asteroid observation by two orders of magnitude. Within the next decade, good orbits should be secured for … several million main-belt asteroids, and tens of thousands of NEAs" [Bowell 2005]. There is a growing consensus that "advances in observing technology will lead to the detection of over 500,000 [NEAs] over the next 15 years" [Schweickart 2008]. Space-based telescopes, such as the European Space Agency's Gaia telescope, scheduled for launch in 2011 [ESA 2009], will also increase the rate of NEA and MBA discoveries [Cellino 2007].

3.2 Asteroid characterization

> "In the beginning (ca 1801), asteroids were points of light in the sky.... The first true compositional investigations of asteroids began in 1970 ... supported by spectral studies of [asteroid] minerals ... and meteorites."
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> —Michael Gaffey, et al. [2002 at 183]

There are three ways to study asteroids: visit them, look at them, and analyze them in the lab after they fall to Earth as meteorites.[4] Fortunately, quite a few meteorites are available for study. More than 35 000 are maintained in collections around the world.[5] Of these, over 1200 have been observed to fall, "and so are free from the highest levels of terrestrial contaminants that can obscure results from analysis" [Grady 2006 at 8]. Meteorite "finds" constitute a larger but more biased sample: terrestrial rain can dissolve softer meteorites after they land.

Ordinary chondrite (OC) meteorites are the most common falls (68%), and come in three types, H, L, and LL, depending on metals content (high, low, and very low). H and L type OC meteorites together constitute more than half of all falls (60%), with each type contributing almost equally (H type: 28% and L type: 31%).

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[4] The first NEA that was observed to impact the Earth, for which samples were subsequently retrieved and sent to the lab, occurred in late 2008 and early 2009. Asteroid 2008 TC3 was first observed on 6 October. The next day, it entered the Earth's atmosphere over the Nubian desert in Sudan, where meteorite fragments were discovered in early December 2009 [Kwok 2009].

[5] The following calculations are drawn from data presented at The Meteoritical Society's online database which offers statistics on over 36 000 meteorites (as of 3 April 2009) [Meteoritical Society 2009].

Given the meteoric data, it is reasonable to assume that the most common near-Earth asteroids would present ordinary chondrite mineralogy. But, until recently, this did not appear to be so. It was a conundrum that the most common, S type asteroids present spectral data that is unlike ordinary chondrites. This puzzle was finally resolved through a careful study of asteroid 433 Eros and new understanding of an aging process of asteroid surfaces called "space weathering."

Today, the "longstanding gulf between the spectral properties of S-type asteroids and ordinary chondrite meteorites appears to be bridged, where the observational data are consistent with a space weathering type process" [Binzel 2006 at 207]. While it is clear that "space weathering is not a simple process" [Moretti 2007 at 260],[6] the first NEA visited by spacecraft, 433 Eros, has been shown to be "a space-weathered ordinary chondrite,"[7] and a growing body of research data, coupled with increasingly robust theory, now secures the link between the two sets of in-space-observed and on-earth-examined extraterrestrial objects.

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6 See also [Paolicchi 2007] and [Vernazza 2007].

7 "Our results provide definitive evidence that Eros is a primitive body with composition and mineralogy similar to ordinary chondrites, but with a surface heavily modified by interactions with the solar wind and micrometeorites, processes collectively termed space weathering" [Foley 2006 at 338]. Itokawa and Apophis, two other carefully observed NEAs, have also been shown to be mineralogically similar to ordinary chondrites.

For asteroid mining, one of the most interesting types of asteroids are those associated with the H type ordinary chondrites, as they offer the highest metal content .[8] Analytical data for ordinary chondrites have been compiled by Lodders and Fegley [1998 at 317-319].[9] Table 1 shows platinum group metal abundances for H type ordinary chondrites.

Platinum group metal		Parts per million (ppm)
44 Ru	Ruthenium	1.100
45 Rh	Rhodium	0.210
46 Pd	Palladium	0.845
77 Ir	Iridium	0.770
78 Pt	Platinum	1.580

Table 1. Platinum group metal abundances in H type ordinary chondrites. [Lodders 1998].

One might assume that the population of near-Earth asteroids that are similar to ordinary chondrite meteorites would mirror the distribution of mineralogical types that

[8] M type asteroids may contain much higher levels of metal, although this remains uncertain. (Some argue that the M of this classification type should suggest “muddle” rather than “metal.”) Moreover, “confirmed M-types ... are relatively rare among the NEOs” [Binzel 2002 at 263].

[9] See also [Horan 2003] and [Fischer-Gödde 2007] for more recent confirmation of these data.

occur in observed fall meteorites, and that 28% of NEAs would show H type mineralogy. But it turns out that this is not the case. A recent study of a small sampling of NEAs (count: 38) shows that the NEA distribution is skewed towards the LL end of the metal "richness" scale, with 63% of this small set of NEAs matching the spectrographic characteristics of an LL type ordinary chondrite. "This result is surprising, because LL chondrites are the least abundant ordinary chondrites (they represent only 10% of all ordinary chondrites, and 8% of all meteorites)" [Vernazza 2008]. In this study, roughly 5-10% of the set of NEAs appears to have an H type ordinary chondrite mineralogy. This is clearly one area where more study is required.

The good news is that our understanding of the relationships between asteroid spectra and meteorite mineralogy can now give us a good idea of the general composition of an NEA, before sending out a spacecraft to examine it more closely. For example, studies of the potential Earth-impactor, near-Earth asteroid 99942 Apophis have shown that researchers can leverage asteroid spectral data to identify NEA mineralogy with a high degree of confidence.[10]

Today, about 10% of identified NEAs have had their spectra analyzed in detail.[11] This percentage has remained constant for several years, as a growing number of NEAs have been identified. For a lucid description of the challenges involved with obtaining these "elemental windows" on asteroid mineralogy, see Michelsen [2004].

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[10] "Apophis is found to be an Sq-class asteroid that most closely resembles LL ordinary chondrite meteorites in terms of its spectral characteristics and in terms of its interpreted olivine and pyroxene abundances" [Binzel 2007a at 4]. Or, more directly, "Apophis *is* an LL Chondrite" [Binzel 2007b at 16].

[11] See [Binzel 2004], [Davies 2007], and [Fevig 2007].

In addition to visible and infrared spectra, ground-based radar can also be used to characterize NEAs. Radio telescopes, such as the Arecibo Observatory in Puerto Rico and the Goldstone Observatory in California, “can produce detailed information about the sizes, shapes, spin states, and surface characteristics of [NEAs]” [Ostro 2007 at 143]. For example, the Arecibo and Goldstone observatories where both used to track and image the close approach (1.4 lunar distances) of asteroid 2007 TU24 on 29 January 2008 [Ostro 2008].

Over two hundred NEAs, and one hundred MBAs, have been detected and imaged with radar telescopes [Benner 2009b], some with remarkable morphological precision.[12]

3.3 Asteroid accessibility

The first, hardest, and most expensive part of any space mission is getting to Earth orbit. The difficulty of escaping Earth’s gravity well is widely recognized, and several efforts are underway to make this first step into space somewhat easier.[13]

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[12] The Apollo NEA, 4179 Toutatis (4.5 × 2.4 × 1.9 km), was imaged with radar during its 1992 [Hudson 2003] and 1996 close approaches to Earth. The data were used to build a striking animation of the asteroid [DeJong 1997].

[13] The company SpaceX is working to develop “a family of launch vehicles which will ultimately reduce the cost … of space access by a factor of ten” [SpaceX 2009]. Sackheim [2006] outlines recent difficulties in the U.S. space industry; Worden and Sponable [2006] proposes a strategy for evolving U.S. launch systems; and Hertzfeld and Peter [2007] outline a multinational, private sector strategy, with reference to SpaceX. A possible disruptive technology is also on the horizon:

While reaching orbit remains a significant hurdle, NEA development can proceed with current launch capabilities [Webb 2006] [FAA 2009]. Moreover, by increasing the demand for launch capabilities, the economic incentive of asteroid mining may help drive the evolution of this recalcitrant technology.

Reaching Earth orbit, however, is just the beginning. Many factors effect a spacecraft's voyage to an NEA: The velocity increment (ΔV) imparted by the launch vehicle, post-launch propulsion systems onboard the spacecraft, the number and type of planetary fly bys, as well as the trajectory design, all effect asteroid accessibility. So far, two NEA rendezvous missions have orchestrated all of these variables successfully.[14] Both returned a wealth of information. In 2010, one mission is due to return to Earth the very first mineral samples collected from an asteroid.

The first NEA rendezvous mission was carried out by the Near Earth Asteroid Rendezvous (NEAR) spacecraft. Launched in 1996, NEAR reached asteroid 433 Eros in early 2000, becoming the first spacecraft to orbit an asteroid. After a year of observation with half a dozen scientific instruments, NEAR executed an initially unplanned soft landing on Eros [Cheng 2002] . Designed and built by The John Hopkins University Applied Physics Laboratory (APL), under contract to NASA, the cost of the spacecraft turned out to be even less than their original low bid, which won them the initial contract (beating out JPL) [Westwick 2007 at 212]. APL agreed to build the spacecraft in 36 months for $122 million; they delivered the completed craft after only 26 months, and

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space elevators would radically reduce launch costs [Aravind 2007] [Elevator: 2010 2009]. If, that is, the legal issues can be sorted [Nase 2006].

[14] In addition, a dozen asteroid fly-bys and a few comet fly-bys have also been executed, each of which gathered a handful of images.

presented NASA with a refund check for $3.6 million. "By contrast, the Mars Observer spacecraft launched in 1992 for an orbital rendezvous with the red planet had cost $479 million to develop" [McCurdy 2005 at 1].

The second NEA rendezvous mission began in 2003 with the launch of the Hayabusa (Falcon) spacecraft by JAXA, the Japanese Aerospace Exploration Agency. Hayabusa was built "to acquire samples from the surface of near-Earth asteroid 25143 Itokawa (1998 SF36) and return them to Earth" [Fujiwara 2006 at 1330]. The spacecraft was also designed to demonstrate several new technologies, including "ion engines, autonomous navigation, [and a] high-speed reentry into the Earth's atmosphere." With the successful completion of its rendezvous with Itokawa, Hayabusa has "delivered a treasure trove of knowledge that enhances our understanding of near-Earth objects" [Asphaug 2006].[15] When it returns to Earth, in June 2010, we will discover the extent to which the sample-return portion of the mission was successful. The Hayabusa mission, like NEAR before it, was carried out at remarkably low cost. For "about $170 million (about one-third the cost of a NASA Discovery mission)" [Rayl 2005], the Hayabusa mission demonstrated multiple technical successes that will inform all future NEA missions.

Several technologies from past and current space missions can be adapted for asteroid mining. For example, NASA's Dawn spacecraft, which was launched in 2007, is intended to rendezvous with 4 Vesta and 1 Ceres, two MBAs, in 2011 and 2015. Nearly all of Dawn's technology can be used for NEA analysis, sample-return, and mining missions [Russell 2007].

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[15] JAXA published all mission data on the Web in 2007 [JAXA 2007].

NEAR and Hayabusa both utilized planetary flybys to boost their kinetic energy [Anderson 2007], which allowed them to reach their targets with much less fuel than would otherwise have been required. Such maneuvers do add to the time of flight (usually about one year), but gravitational assists (from Earth and/or Venus), make it possible to reach essentially any NEA, even if a spacecraft's initial velocity is quite low [Berinde 2005].

The field of spacecraft trajectory design has seen a number of innovations since the success of these two missions. Several new techniques have been developed for designing gravity assisted missions [Vasile 2006] and missions with multiple planetary flybys [Pisarevsky 2007]. Xu [2007] describes techniques for optimizing NEA sample-return missions using single and multiple gravity assists. Genetic algorithms have also been used to evolve efficient flyby trajectories [Conway 2007]. All of this new work has lead to comparative surveys of the different optimization methods that can be used to design low-thrust, low-cost missions to multiple asteroids [Alemany 2007].

Beyond simple gravity assist flybys, more mathematically exotic techniques can dramatically reduce the energy costs of NEA missions. Nonlinear dynamics and the chaotic interactions of n-body gravitational systems allow for surprisingly efficient trajectory design.[16] These trajectories, which have been called "interplanetary superhighways," can lead to spacecraft journeys that require 20%, or less, of the energy increment (ΔV) of more traditional techniques [Remo 1997] [Lo 2006]. Such seemingly abstruse techniques have produced very practical, mission saving results [Case 2004].

Attacking accessibility from the other direction, the current generation of solar-electric propulsion (SEP) systems are powerful enough to make most NEAs directly

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[16] See [Lo 2001], [Belbruno 2004], [Marsden 2005], and [Koon 2007].

accessible.[17] Indeed, the thrust available from today's SEP systems can give survey-type spacecraft sufficient velocity to escape the solar system entirely (ΔV = 12.34 km/sec) [Rayman 2007]. This puts nearly 90% of NEAs within reach—*without* a planetary flyby. Next generation SEP systems, which dispense carbon nanotube particles rather than ionized xenon [Liu 2007], open the exciting possibility of refueling a spacecraft with carbon that has been extracted from an asteroid under mining operations.

New trajectory design technologies and increasingly powerful propulsion systems, coupled with an accelerating rate of asteroid discovery, provides a large and rapidly growing population of accessible NEAs. The challenge now arises of how to rank and prioritize this substantial and expanding set of potential targets. Twenty years ago, analyzing a known population of less than a hundred NEAs, Lau and Hulkower [1987] introduced a "measure of accessibility"[18] that has been used to establish a fundamental baseline for asteroid access costs. At JPL, Benner [2009] calculates and maintains an up-to-date rank ordering of all known NEAs according to their ΔV access cost.[19] Roughly 15% (902 of 6021, as of April 2009) of all known NEAs are VNEAs, or "very-near-Earth asteroids." The ΔV required to reach them is less than that required to reach the lunar

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[17] See [Oh 2005], [Chesta 2006], [Clark 2006], and [Woo 2006].

[18] "One measure of accessibility … is the global minimum total ΔV for a two-impulse transfer of less than 360 deg from standard Shuttle orbit [~300 km] to rendezvous with the target body" [Lau 1987].

[19] Until recently, Benner's reference for these baseline calculations was Lau and Hulkower's 1987 paper. Benner now sites an earlier source for this calculation: [Shoemaker 1978].

surface.[20] Another planning tool, the Hohmann plot or H-plot, based on Hohmann transfer orbits,[21] can be used to visually compare a set of possible NEA targets [Perozzi 2001].

Research teams with scientific agendas have created multiple lists of particularly interesting NEAs,[22] contemplated specific targets in detail,[23] and proposed several rendezvous and sample-return missions.[24]

In 2007, the European Space Agency completed a comprehensive study of the technologies required to complete an asteroid sample return mission [Agnolon 2007]. In early 2008, the Planetary Society, one of the largest space advocacy organizations, awarded $50,000 in prize money for the three best mission proposals (of 37 submitted) to rendezvous with and subsequently track the potentially hazardous asteroid Apophis [Planetary Society 2008].

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[20] Due to orbital phasing (the relationship between Earth's orbit and that of an NEA), only a subset of these NEAs are accessible at any one time. However, due to the large and growing population, multiple NEA targets are regularly available.

[21] Walter Hohmann published his energetically efficient trajectories in *Die Erreichbarkeit der Himmelskörper* (The Attainability of Celestial Bodies) in 1925. "Hohmann's great contribution to astronautical progress was the discovery of a new use for an old object, the ellipse" [McLaughlin 2000].

[22] See [Christou 2003], [Perozzi 2003], and [Qiao 2007].

[23] See [Mueller 2007] and [Vilas 2007].

[24] See [Sears 2004] and [Wells 2006].

We can now see that near-Earth asteroids are quite numerous, that we can determine their elemental composition with a high degree of certainty, and that we have built a substantial knowledge base regarding the several technologies that are required to reach them. In the next chapter, we begin to examine the particular technologies that are available for carrying out an actual asteroid mining mission.

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References: http://www.abundantplanet.org/files/WoA-references.pdf

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