
The Near-Earth Asteroids on the Pathway to Earth's Future in Space

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ABSTRACT

Near-Earth asteroids and comets, collectively the near-Earth objects (NEOs), represent a large population of minor planetary bodies whose orbits lie mostly within the zone between Venus and Mars. Many of these objects cross Earth's orbit, providing relatively easy access from Earth for manned or robotic sampling and exploration missions with fewer propulsion requirements than trips to the Moon or to Mars. This chapter provides a review of NEOs in the context of supporting, through in-situ resource utilization, an active and expanding space exploration and resource development program capable of becoming self-funding and supporting a solar systemwide expansion program. The NEO compositions range from highly metallic asteroids composed predominantly of iron, nickel, and cobalt to cometlike objects composed of frozen water and gases of various compositions. The NEOs are the most easily accessible objects in near-Earth space, and they are numerous. As of January 2011, a total of 7872 NEOs had been identified. The number of NEOs with diameters greater than 1 km (>0.6 mi) reached 1269 by June 2012. Moreover, 1176 have been identified as potentially hazardous Earth impactors by the National Aeronautics and Space Administration's Near-Earth Object Program, approaching Earth to within 0.05 astronomical units or approximately 7,480,000 km (4,647,860 mi).

The value of NEOs for space exploration may far exceed the immediate scientific information that they provide on the origin of the solar system: NEOs have the potential to provide fuel for rockets; oxygen and life support materials for explorers; valuable materials and metals for construction in space; and critical, strategic, and highly valuable materials for Earth. Water ice derived from extinct NEO comets or water-rich asteroids can be refined to provide liquid oxygen and liquid hydrogen for rocket fuel and the oxygen necessary for life support. Carbonaceous chondrites contain kerogenlike compounds that can support the

immense carbon chemistry developed for our petroleum industry, and metallic asteroids contain platinum-group and rare-earth elements that have been conservatively valued in the hundreds of billions to trillions of dollars if they were made available in Earth markets. These resources are accessible using existing rockets and boosters, but these existing systems and technologies are nearly 50 years out-of-date. Active space exploration and development programs require highly efficient nuclear rockets and space-based nuclear power systems to reduce launch costs to economically tolerable numbers and to provide the heavy-lift capacity and highly efficient rocket engines for crew health and safety and minimum duration missions. Once flight launches are outside Earth's atmosphere, the NEOs can provide nearly unlimited resources for further exploration.

INTRODUCTION

"We were wanderers from the beginning This zest to explore and exploit, ..., has clear survival value. It is not restricted to any one nation or ethnic group. It is an endowment that all members of the human species hold in common." (Sagan, 1994, p. xii, xvi)

"That we are on the threshold of an explosive human renaissance in space is clear. It is no longer a question of whether or not mankind moves into space; it is a question of when, how and by whom it will be done." (astronaut Brian O'Leary, 1988, p. 457)

During the last 400 years of space exploration, humans have dreamed of entering space (Burns, 2010). From Johannes Kepler's novel *Somnium* (or *Dream*, about 1630; see Burns, 2010, p. 575–584), describing an imaginative look at Earth from the perspective of being on the Moon, to William Olaf Stapledon's (1930) *Last and First Men* that describes the hypothetical 2 m.y. of future human history as it expands throughout the cosmos, the human aspiration has been to explore and occupy space. Now, at the beginning of the 21st century, we have sufficient experience to progress beyond merely exploring space and to proceed to planning, designing, constructing, and operating permanent human colonies outside of Earth's atmosphere. Unfortunately, the hard realities of entering space and our own tentativeness in addressing these hard realities have kept these dreams from being fully realized. The space shuttle transport system (Figure 1) was a triumph of engineering, but that could only achieve low Earth orbit (LEO). Unfortunately, the initial launch costs of \$15,000 to \$20,000 per kilogram in United States (US) dollars did not improve with

experience, and the cost per kilogram to LEO via the shuttle remained over two orders of magnitude more than what was originally hoped for or planned for economical space access. The successes of the shuttle transport system must not be forgotten, but manned space exploration must overcome the energy cost of transporting all fuel and life-support necessities from Earth's surface to the planned destination and for the return mission to Earth. We are constrained by the self-imposed limitations of existing chemical rocket boosters and by the duration of flights imposed by these boosters on missions beyond the Moon's orbit. These limitations can be overcome by building larger heavy-lift boosters, by developing new and more powerful propulsion systems, and using the resources that are available in space. Of these three achievable solutions, the effective use of in-situ resources allows a much greater degree of flexibility in the requirements imposed on the heavy-lift boosters or propulsion systems that are the foundation upon which to build a sustainable space exploration and resource development program.

With these assumptions as a starting point, the issues to be addressed are how and why we should undertake this goal. Are there energy and minerals outside Earth's atmosphere available to us? Can these resources be accessed using existing and near-term technology? Can humans survive and prosper in the environments of near-Earth space or on the Moon or Mars? What must be done to ensure not just human survival, but enhanced productivity in low- or zero-gravity environments? Can profitable commerce be developed between Earth and extraterrestrial activities that justifies and sustains this obviously expensive and risky endeavor?

Many of these questions have been examined in great detail, and a surprising array of viable options have been developed, and the overriding conclusion



FIGURE 1. The space shuttle Discovery on a crawler moving to the launch pad for Mission STS-121 (photograph courtesy of Lockheed Martin Space Systems from National Aeronautics and Space Administration Archives).

for a sustained human presence in space is the requirement for energy and minerals that can be exploited outside of Earth's gravity well.

ENERGY AND MINERAL RESOURCES BEYOND EARTH'S ATMOSPHERE

Where then are the energy and minerals necessary to support our exploration and development efforts? Well-considered and defensible arguments exist for prioritizing missions to Mars (Zubrin, 1996), to the Moon (Bakhtian et al., 2009), or to the asteroids (Lewis, 1996) (Figure 2). Mars is the most Earth-like planet that has the greatest potential for discovering extraterrestrial life and for early development of a self-supporting colony. The Moon is closer; it represents a good laboratory for space science, and it may be the best near-Earth reservoir for helium-3 (^3He) to support future nuclear fusion power generation without significant radioactive waste production. Even if fusion-generating technology is not available in the near future, recent results from the Kaguya spacecraft identifying uranium, thorium, samarium, and iron on the Moon may make power generation using proven modular fission reactors an easy and reliable choice for Moon-based power plants (Campbell and Ambrose, 2010; Kobayashi et al., 2010; Campbell et al., 2013).

The two persuasive arguments for the near-Earth objects (NEOs) as the primary destination for space development are the available supply of varied natural resources and the accessibility as a destination from Earth orbit and as a source of materials to be returned to Earth. The Moon and Mars are attractive

destinations, but the NEOs represent the most accessible (in terms of propulsion requirements and process chemistry) source of strategic materials and volatile compounds to support space activities as well as have essential keys to understanding the formation and evolution of the solar system. Moreover, the NEOs provide the option of supporting a low- or high-orbit space station supply depot, where mission materials to all destinations can be assembled, tested, and readied for flight. Ice and volatiles derived from the NEOs could be processed into fuels and life-support materials (such as breathing oxygen); metals could be refined and shaped into structural elements or solar panels; and all of these products can be used for development activities on the Moon or Mars. Processing and refining metal concentrates from the NEOs at an orbital supply depot for use on Mars or the Moon and for return to Earth provide the profitable economic base that supports the broader program of space exploration and development and also produces the economic return and justification for human expansion beyond Earth.

The first step to space beyond Earth's surface is low Earth orbit (LEO), which ranges from 140 to 2000 km (87–1243 mi) above Earth's surface. The International Space Station (ISS) orbits approximately 350 km (~218 mi) above the Earth's surface, whereas the Hubble Space Telescope's elevation is, on average, approximately 600 km (~373 mi) (Figure 3). Within this range of elevations, drag from the outer reaches of Earth's atmosphere causes a gradual orbital decay, but satellites can remain in this zone for extended periods if they have the ability to restore their lost altitude with onboard boosters. Geosynchronous orbit is much higher, approximately 42,000 km (~27,000 mi) above Earth's surface. At that elevation, the orbital period of a satellite is equal to the rotational period of the Earth, and satellites having an equatorial orbit will appear to remain stationary above one area of Earth's surface.

The energy cost, in terms of acceleration to achieve geosynchronous orbit, is 3.2 km/s (1.98 mi/s) in addition to the 8 to 9 km/s (4.97–5.59 mi/s) necessary to achieve LEO from Earth's surface. Having the ability to refuel and reprovision either in LEO or in geosynchronous orbit would provide a tremendous benefit to any scientific or exploration mission, whether a manned mission or a robotic explorer. Fuel weight for chemical propulsion systems typically amounts to 10 to 15 kg (22–33 lbs) for each kilogram of nonfuel mass when launched from Earth's surface. Rocket fuel, in the form of volatile compounds (such as methane, liquid oxygen [LOX], and liquid hydrogen

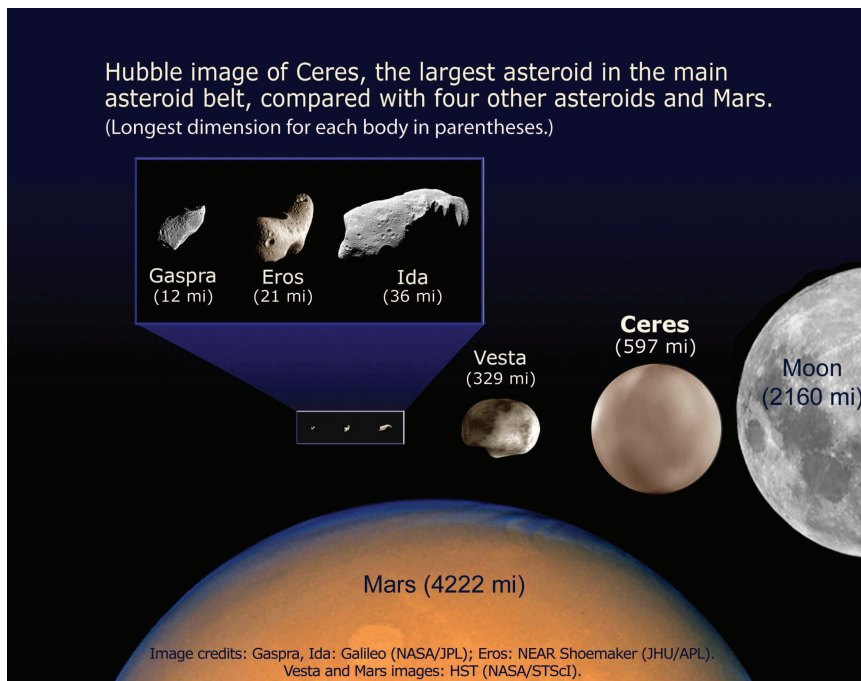


FIGURE 2. Relative sizes of Mars, the Moon, and important main belt asteroids (photographs courtesy of Jet Propulsion Laboratory/National Aeronautics and Space Administration).

[H₂]) could be derived from icy asteroids, dormant comets, lunar soils, or lunar polar ice for extraterrestrial missions. The energy cost to manufacture these fuels is essentially the same for wherever they are derived, but the energy to move these fuels from their origin to Earth's orbit is the distinction: it is much easier to derive these fuels from the nearly zero-gravity environments of the NEOs than it is to loft them from Mars or from the lunar surface to Earth's orbit, and it is substantially easier to derive these fuels from NEOs than it is to launch them from Earth's surface.

Near-Earth objects may prove to be significantly more important than rest stops and refueling stations for travel beyond Earth. Near-Earth objects can be a source of critical and strategic materials for Earth's economy; for materials support to manned bases on the Moon and Mars; and for permanent orbital stations in high Earth orbit or at gravitationally stable points between the Earth and the Moon, the Lagrange points. If the NEOs have these advantages over the Moon and Mars, it is crucial to know more about the origin of NEOs and about their physical and chemical characteristics and accessibility from Earth. Is the best approach to go out to the NEOs, mine the resources, and return to Earth's orbit with the refined product? Or is it more efficient to retrieve an entire NEO and bring it back to near-Earth space where specialized mining and refining operations could be conducted? The following sections address the accessibility and discuss the important properties of NEOs relevant to supporting space exploration and development.

NEAR-EARTH OBJECTS: ORIGIN, NUMBER, AND CHARACTERISTICS

Near-Earth objects are those minor solar system bodies that orbit the Sun with their perihelion less than 1.3 AU and their aphelion greater than 0.983 AU. (An AU, or astronomical unit, is the average distance of the Earth from the Sun, approximately 150 million kilometers. Perihelion is the closest approach to the Sun, and aphelion is the farthest point in an object's orbit from the Sun.) Thus, NEOs are in the zone between Venus and Mars, with many of these objects having orbits that cross Earth's orbit. Binzel et al. (2004) examined the population of NEOs and identified 234 that were easily reachable from Earth's orbit with a best-case delta-v of 7 km/s or less.

Most asteroids classified as NEOs originate through an evolutionary process, whereby objects in the main asteroid belt are gradually diverted from their orbits by gravity resonances with Jupiter and Saturn and move into near-Earth or Earth-crossing orbits within the region between Mars and Venus (e.g., Michel et al., 2005). Those NEOs whose orbit crosses Earth's orbit are classified as Apollo or Aten asteroids (Figure 4). Amor asteroids orbit between Earth and Mars and may cross Mars's orbit but do not cross Earth's orbit. Inner Earth asteroids have similar orbits as those of the Amors except they stay between Venus and Earth (instead of between Earth and Mars).

The main asteroid belt between Mars and Jupiter is home and birthplace for most NEOs, where dust and

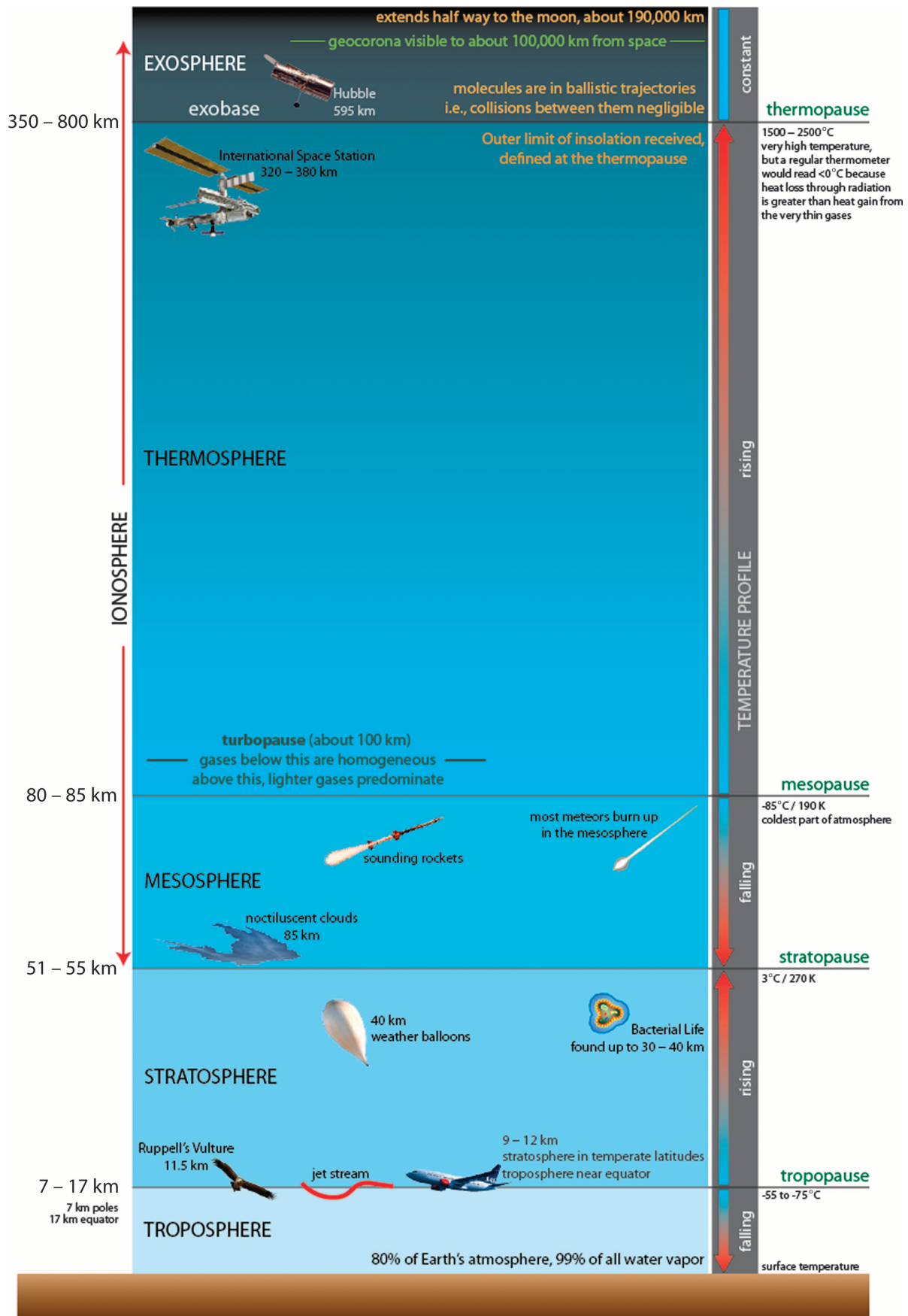


FIGURE 3. Illustration of low Earth orbit to the outer reaches of the atmosphere.

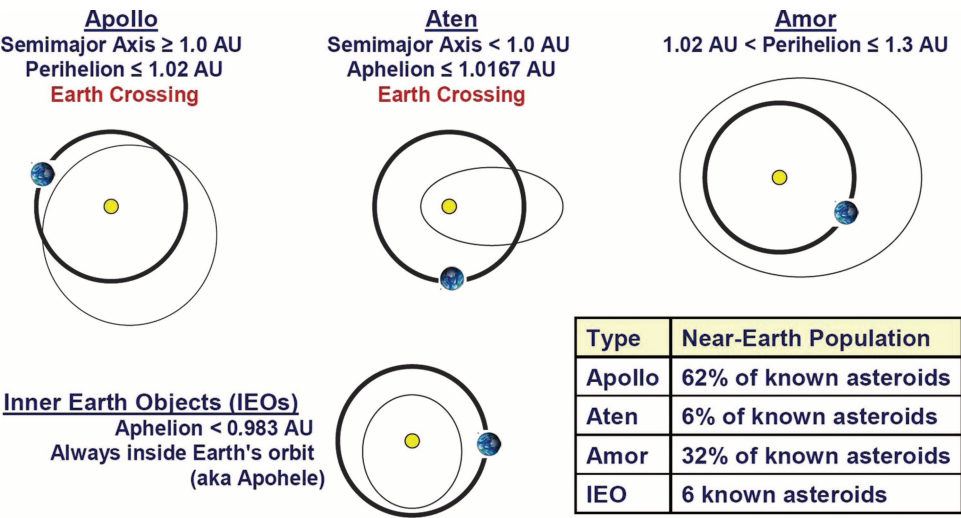


FIGURE 4. Classification of near-Earth objects by their primary orbital element (courtesy of National Aeronautics and Space Administration Minor Planet Center). AU = astronomical unit: average distance of Earth from the Sun.

gas from the primordial solar nebula coalesced but failed to reach the stage of a major terrestrial planet (Asphaug, 2009). Jupiter, and to some extent Saturn, was a primary factor in stirring the gravitational pot to keep the asteroids of the main asteroid belt circulating (instead of clumping together into one entity). Krasinsky et al. (2002) used the gravity perturbations on Mars and 300 of the largest asteroids as well as high-precision ranging measurements on the Viking and Pathfinder Mars landers to derive the total mass of objects in the main asteroid belt. This amounted to approximately 3.6×10^{18} t or about 5% of the mass of the Moon. The size of these objects ranges from sand grains to minor planets, approximately in an inverse power law relationship of the form $N(> D[km]) = CD^{-b}$ where N is the number of objects greater than a diameter (D) in kilometers, C is a constant equal to 942, and the exponent b is equal to 2.345 (Sanchez and McInnes, 2010). An estimated 1 to 2 million objects in the main asteroid belt are greater than 1 km (0.6 mi) in diameter, and Ceres, Pallas, and Vesta, which have mean diameters of 952, 544, and 529 km (592, 338, and 329 mi), respectively, are the largest objects discovered to date.

The NEOs that originated from the main asteroid belt were gradually tweaked out of their comfortable orbits by gravity resonances with Jupiter and moved inward toward the Sun aided by these gravity imbalances and by the Yarkovsky effect (Chesley et al., 2003). The Yarkovsky effect is a sunward thrust created by the anisotropic re-radiation of thermal photons absorbed on the sunward side during the day and re-radiated as infrared radiation on the night side. This effect is more pronounced on objects that have slower rotation rates and diameters smaller than a few tens of kilometers, but it is significant in contributing

to a steady movement and replenishment of NEOs from the main asteroid belt. The total mass of NEOs is uncertain but can be estimated based on an assumed average bulk density of approximately 2.6 and using the power law size distribution discussed previously. Sanchez and McInnes (2010) set the lower diameter limit at 1 m (3.3 ft) and the upper limit equal to the largest known NEO, 1036 Ganymed (diameter equal to 32 km [20 mi]). With these assumptions, the total mass within the NEO population can be calculated to be approximately 4.38×10^{13} t, which is approximately five orders of magnitude smaller than that found in the main asteroid belt. Bottke et al. (2000) estimated that 64% of the NEOs originate from the inner main asteroid belt, 24% originate from the central asteroid belt, and 8% come from the outer asteroid belt.

The important point is that the NEOs are a dynamic class of objects that continuously gain new members by contributions from the main asteroid belt and also lose members by collisions with the inner planets, the Sun, or through encounters with other NEOs. Surprisingly, the mean residence time once an object enters near-Earth space is only a few million years to a few tens of millions of years before an NEO encounters one of the terrestrial planets or the Sun or is ejected out of this zone. This (relatively) short residence time for an NEO implies that the frequency of impacts is common enough to be a concern to planet Earth residents. The discovery of the K-T boundary Chicxulub Crater's correlation with the demise of the dinosaurs and the spectacular demonstration of Comet Shoemaker-Levy impacting Jupiter in 1994 also helped support this conclusion (Chapman et al., 2001). In 1998, the National Aeronautics and Space Administration (NASA), in conjunction

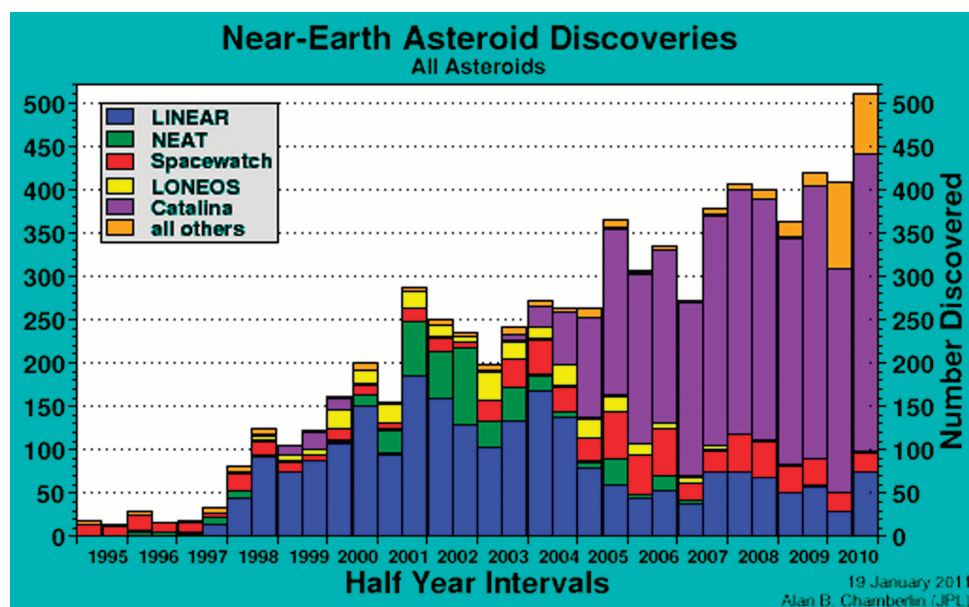


FIGURE 5. Near-Earth asteroid discovery statistics as of January 19, 2011 (Spahr, 2011). LINEAR = Lincoln Near-Earth Asteroid Research program; NEAT = Near-Earth Asteroid Tracking; LONEOS = Lowell Observatory Near-Earth Object Search.

with several other independent, international, and NASA-associated agencies, initiated a 10 yr program to identify 90% of NEOs greater than 1 km (>0.6 mi) in diameter. This size range was selected because impactors greater than 1 km (>0.6 mi) in diameter have the potential to cause global disruption of Earth's ecosystems and potential obliteration of nations. The Lincoln Near-Earth Asteroid Research (LINEAR) program (Evans et al., 2003), the Catalina Sky Survey (2011), the Lowell Observatory Near-Earth Object Search (LONEOS) and Spacewatch® Project (McMillan, 2010), among others, are all conducting broad sky searches for NEOs greater than 1 km (>0.6 mi) in diameter. Although their search process is incomplete, they are now also focusing on identifying NEOs that have inferred diameters greater than 140 m (>460 ft) (this size range would wipe out large cities or cause widespread coastal damage if the impact occurred in an ocean).

The intent of these surveys is to discover, identify, and track those NEOs that represent a potential impact hazard to Earth, but the beneficial by-product of these surveys is a detailed catalog of their orbits and some information on their composition from spectroscopic analyses.

Near-Earth objects also include dormant or extinct comets. Near-Earth comets are considered to have orbital periods less than 200 yr and perihelion distances less than 1.3 AU. Recent evidence suggests that as comets age and no longer emit gas and dust plumes (the distinctive tails of comets as they enter the inner solar system), they may be mistaken for asteroids. Dust and carbonaceous material coating a comet's exterior

give them a dark appearance that is similar to asteroids and insulates the interior ices from volatilization. Weissman et al. (1989) examined the evolution of comets as their orbits subject them to the more energetic environments of the inner solar system and concluded that as many as 6% of objects in the NEO population may be extinct comets.

Numbering the Multitude

Scientific literature reports a wide range of estimates of the total number of NEOs that have diameters greater than a few meters. Jones et al. (2002) estimated 10,000 to 12,000 objects greater than 100 m (>328 ft), whereas Lewis et al. (1993) estimated approximately 70,000 objects greater than 100 m (>328 ft) in diameter. A reassessment by Rabinowitz et al. (2000) that incorporated the initial results of the sky survey programs concluded that the number of NEOs with diameters greater than 1 km (>0.6 mi) is most likely closer to 1000 versus some of the higher estimates. Figure 5 illustrates discovery statistics for NEOs from the Minor Planet Center, which cataloged 7872 identified NEOs as of January 2011 (Spahr, 2011). By June 2012 (Spahr, 2012), the number of NEOs with diameters greater than 1 km (>0.6 mi) had risen to 1269, but new discoveries are added to this list each day.

Surface Characteristics

Missions such as Japan's Hayabusa (Fujiwara et al., 2006) Sample Return program, the European Space Agency's (ESA's) Rosetta program (Montagnon and

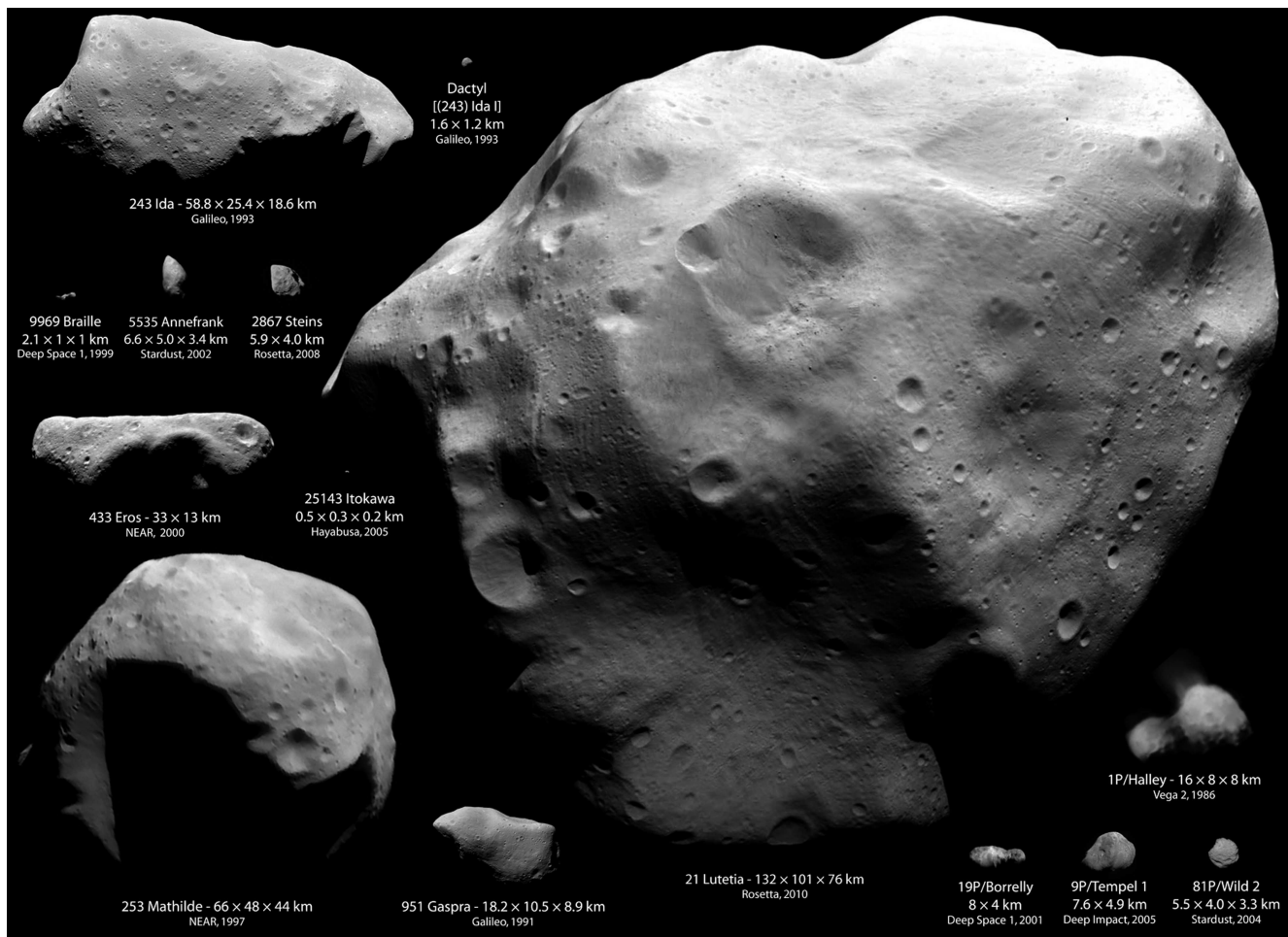


FIGURE 6. Surface physical characteristics of several asteroids and comets taken by various space missions (photographs compiled by Jet Propulsion Laboratory/National Aeronautics and Space Administration [NASA], courtesy of NASA Archives). NEAR = Lincoln Near-Earth Asteroid Research program (LINEAR).

Ferri, 2006), and NASA's Deep Space 1 (Rayman, 2001) and the LINEAR and Stardust programs (Matzel et al., 2010) have provided close-up photography of a few of the near-Earth comets and asteroids as well as information on the physical properties of the comets and asteroid bodies themselves. Close-up pictures of asteroids Itokawa, Eros, Gaspra, Ida, and of Ida's companion, Dactyl, reveal nonspherical bodies of complex configuration and surface characteristics having a definite dust or regolith surface cover (Figure 6). Initial speculation was that because of their small size and low escape velocity, micrometeorite-weathering impacts would not result in the generation of a regolith as is the case with the Moon but would accelerate impact debris to greater than escape velocity. Direct observation by photography of these asteroids revealed a consistent covering of dust and granular material similar to the Moon, in contrast to the initial assumptions.

Chemical Composition

Approximately 5000 chemical analyses of meteorites provide a large database of the chemical makeup of asteroids and NEOs and have assisted in developing a much greater understanding of their origin and physical characteristics. The NEOs are an interesting amalgam of protoplanetary debris that range from essentially undifferentiated solar nebula material (minus the lightest volatile compounds) to melted and differentiated planetary mantle and core material composed mostly of elemental iron, nickel, and cobalt. The detailed understanding and classification of the asteroids is derived from inspection and analysis of meteorites that have fallen to Earth and modified somewhat by recent ground-based radar observations, satellite photographs, and spectroscopic analysis from NASA's, ESA's, and Japan's deep space missions. The most important end members are the carbonaceous chondrites representing the least differentiated and

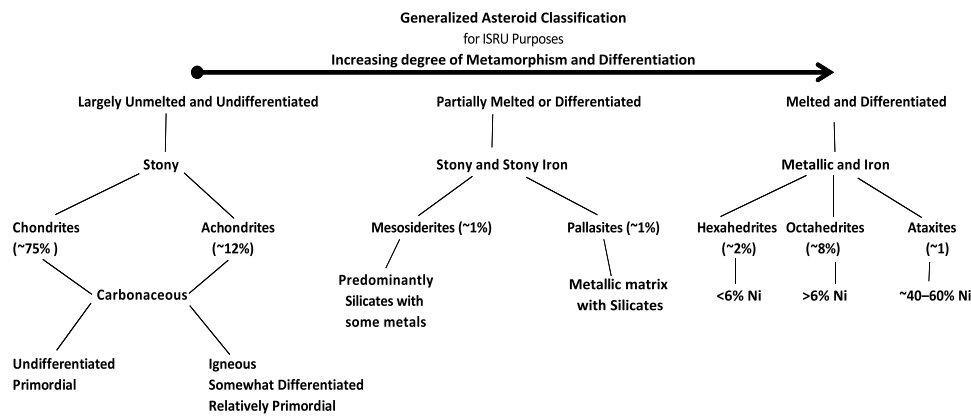


FIGURE 7. Major classifications of asteroids for ISRU purposes based on the composition of meteorite falls on Earth (Modified from Lewis, 1992; Gerlach, 2005; and Gertsch et al., 2006). ISRU = in-situ resource utilization.

primordial of the asteroids and metallic asteroids, representing the differentiated metallic cores of proto-planets. The stony and stony-iron asteroids are intermediate between the two end members. Figure 7 illustrates the general breakdown of asteroid classes derived from inspection of meteorite finds on Earth.

Considering NEOs only from a resource perspective, four main classes of objects are of interest: extinct comets (or cometary-like objects), carbonaceous chondrites (C-type asteroids), stony (S-type) asteroids, and metallic (M-type) asteroids. (Gertsch et al. [2006] identified these same classes for mining purposes but labeled them Class 0 to Class 3, respectively.)

Cometary objects in NEOs are composed of at least 40% or more of ice (ice of varying compositions: methane ice, ammonia ice, carbon dioxide, and water ice), with the remaining mass consisting of carbonaceous material and generally unaltered primordial rock and dust similar in composition to the chondrites or stony asteroids. Cometary objects may comprise from 1 to 6% of NEOs.

Carbonaceous chondrites (C-type) asteroids are considered more pristine—unaltered by early differentiation—than S-type or M-type asteroids and contain significant quantities of carbonaceous material, water, phyllosilicates, oxides, and sulfides, with iron, magnesium, and calcium present. The C-type asteroids are the most common type of the total number of minor planetary objects discovered. The carbonaceous chondrites are so named because of their carbon content and their composition of rounded grains or aggregates of silicate material that may be glasslike or rocklike similar to (weathered) igneous rocks on Earth (except with a high carbon content). The composition of the C-type asteroids is similar to the original raw material that formed the solar nebula before the Sun and planets coalesced into solid (or gaseous) bodies but these asteroids have lower concentrations

of the light gases such as hydrogen and helium. Phyllosilicates or clays are present and are similar in composition and structure to that of a weathered igneous feldspathic rock. Also present are achondrites that have chemical compositions very close to those of the chondrites but without the grain- or aggregate-type structure that gave the chondrites their name.

The key components of this class are their content of carbonaceous material, clays, and water in the form of hydrated minerals. Nichols (1993) compared the carbonaceous and volatile components of C-type meteorites with oil shale, coal, and petroleum and demonstrated their similarities. The nonorganic kerogen-like compounds in carbonaceous asteroids are very similar to those organic carbon compounds found in oil shales and, with the right refinery processes and cracking procedures, can produce the wide range of useful petroleum-derived products that we use today (fuels, plastics, and fertilizers). Table 1 presents the results from Nichols's (1993) study.

Water in both free and chemically bound forms may comprise up to 30% of the C-type asteroids. A 1 km (0.6 mi)-diameter asteroid or comet containing 30% ice would have approximately 150 million tons of ice available for use. The carbonaceous component of these asteroids may also range up to 30%. Thus, these C-type asteroids are the water, fossil fuel reservoirs, and fertilizer plants for the new millennium.

Stony (S-type) asteroids are, as their name implies, predominantly mafic, siliceous, or rocky in composition and are the second most common in occurrence in the NEO region, accounting for 15 to 17% of the total number identified. The S-type asteroids are metamorphosed but unmelted, having lost some or all of their carbonaceous material and volatile components. The stony asteroids have a much lower percentage composition of carbonaceous material and demonstrate a greater degree of differentiation than

Table 1. Comparison of elemental composition of ash-free organic phases from two carbonaceous meteorites, oil shale, coal, and petroleum.*

	<i>C</i>	<i>H</i>	<i>O</i>	<i>N</i>	<i>S</i>	<i>Total</i>	<i>Reference</i>
C1 Orgueil carbonaceous meteorite	73.6	4.6	10.3	1.66	7.23	97.39	Hayes, 1967
C2 Murchison carbonaceous meteorite	78.0	3.1	13.0	1.7	4.2	100	Zinner, 1988
Oil shale, Kentucky	82.0	7.4	6.3	2.3	2.0	100	Smith and Jensen, 1987
Oil shale, Utah	80.5	10.3	5.8	2.4	1.0	100	Smith and Jensen, 1987
Bituminous coal, Pennsylvania	82.4	5.6	9.0	1.6	1.3	100	Smoot, 1979
Anthracite coal	89.4	3.8	4.6	1.1	1.1	100	Smoot, 1979
Heavy petroleum	85.3	11.0	0.5	0.4	2.8	100	Perry and Chilton, 1973; Grayson and Eckroth, 1982
Light petroleum	85.7	12.7	0.3	0.2	1.1	100	Perry and Chilton, 1973; Grayson and Eckroth, 1982

*Modified from Nichols, 1993. Units are presented as weight percent.

the C-type asteroids. A generally consistent gradational composition exists between the S-type and the M-type asteroids. The S-type asteroids are composed predominantly of the oxides of iron, nickel, other metals, and magnesium silicates, with olivine and pyroxene minerals common. These asteroids are rich in platinum-group metals and rare-earth elements and can provide the raw materials for space-based construction of solar power stations and orbiting habitats.

The metallic (M-type or iron) asteroids are believed to be the fractured cores of larger bodies that were originally large enough and heated sufficiently for core differentiation to occur and then later were broken apart by collisions with other objects. Some evidence exists that the iron asteroids may have formed early within the inner solar system and then were ejected outward toward the main asteroid belt. Based on radiogenic age dating, the iron asteroids may have formed up to 100 m.y. before the C-type or S-type asteroids consolidated. The original diameters of the parent bodies of the M-type asteroids are believed to have ranged from 20 to 200 km (12–124 mi). The primary source of heating was the radiogenic heat produced by the decay of ^{26}Al and ^{60}Fe and other short-lived isotopes during the first few million years of solar system history. The M-type asteroids are composed of 10 to 60% of elemental (nonoxidized) iron, nickel, and cobalt, with lesser amounts of other metals and some rocky material. The percentage of rocky material varies, based on examination of meteorite falls, from near zero to a composition similar to the S-type asteroids. Where the icy asteroids and dormant comets are sources of water and volatile compounds with some

organics, the metallic asteroids are sources of primary structural steel, precious and platinum-group metals, and rare-earth elements. Table 2 (O'Leary et al., 1979) presents the mineral and elemental composition of the main asteroid types compared with samples from the lunar regolith.

Economic Value of a Single Near-Earth Asteroid

The question, then, is the effort justified to seek, mine, or retrieve an NEO? Development of NEOs as a resource base would require either manned missions or robotic emissaries to intercept, assess, and mine these bodies or somehow diversion of NEOs from their existing orbits to rendezvous with Earth in a safe stable orbit, where mining can be conducted closer to home. Are these objects actually valuable enough to justify such an effort or should our resources be devoted to building larger booster rockets to support space activities with resources only from Earth?

To put all of these in perspective, it is worthwhile comparing the economic value of metal reserves available from one NEO with its value if it were to be mined and the products sold on Earth. Lewis et al. (1993), Kargel (1994, 1996), Lewis (1996), Sonter (1997, 2001), Gerlach (2005), and Campbell et al. (2009) have comprehensively addressed mining of NEOs. Campbell et al. (2009) addressed NEOs as well as other solar system resources and provided valuable insight on the availability of nuclear fuels as well as strategic materials. From a mining perspective, ore is only valuable if it can be sold for more than the fully loaded costs to produce the end product. For platinum alone, the average concentration in chondritic to metallic

Table 2. Mineralogical, chemical, and physical properties of asteroids.*

<i>Type</i>		<i>C2-type**</i> (wt. %)	<i>C1-type</i> (wt. %)	<i>S-type</i> (wt. %)	<i>M-type</i> (wt. %)	<i>Lunar Regolith</i> (wt. %)
<i>Mineral</i>						
Free metals	Fe	10.7	0.1	6–19	88	0.1
	Ni	1.4	—	1–2	10	—
	Co	0.11	—	0.1	0.5	—
Volatiles	C	1.4	1.9–3.0	3	0.1–23	0.014
	H ₂ O	5.7	12	0.15	2.6	0.045
	S	1.3	2	1.5	~0.1–7	0.12
Mineral oxides	FeO	15.4	22	10	3–15	15.8
	SiO ₂	33.8	28	38	21–54	42.5
	MgO	23.8	20	24	5.9–31.9	8.2
	Al ₂ O ₃	2.4	2.1	2.1	1.4–10.6	13.8
	Na ₂ O	0.55	0.3	0.9	0.12–1.8	0.44
	K ₂ O	0.04	0.04	0.1	0.01–0.22	0.15
	P ₂ O ₅	0.28	0.23	0.28	0.03–1.39	0.12
	CaO	1.15–2.0	1.36	3.36–11.0	1.09–8.12	12.1
	TiO ₂	0.11–0.13	0.07	0.31–1.23	0.11–0.77	7.7
Physical properties	Density (g/cm ³)	3.3	2.0–2.8	3.5–3.8	7.0–7.8	1.5–1.9

*Note that, for illustrative purposes, this table depicts four characteristic types of asteroids based on four meteorite types. Sources include Jarosewich, 1990; O'Leary et al., 1979; and Compston et al., 1970, for Apollo 11 lunar soil sample data (National Aeronautics and Space Administration).

**C1- and C2-type, carbonaceous; S-type, stony; M-type, metallic.

asteroids ranges from 8 to 60 ppm by weight (Kargel, 1996). Using Kargel's (1996) concentration values, an average stony to metallic asteroid that is 1 km (0.6 mi) in diameter might contain from 32,275 to 117,000 t of platinum. Applying year-end 2010 market prices of \$1677 to \$1771.4 per troy ounce in United States [US] dollars (Wall Street Journal Market Data Center, 2011), this would be valued at US \$1.8 to \$6.4 trillion (Table 3).

An accessible ore deposit on Earth with a gross reserves value of US \$2 to \$6 trillion would be viewed as an attractive prospect, but applying this estimate without modification to an asteroid may be overly optimistic. The cost of a mission to mine an asteroid is currently unknown. For comparison, a single launch of the space shuttle costs an average of US \$450 million, whereas the entire Apollo Moon program cost an estimated US \$190 billion in present-day dollars. O'Leary et al. (1979) and Blair (2000) estimated that a mission to mine an asteroid (in place) might cost from US \$5 billion to \$150 billion, although both these estimates are substantially inflated because of unknown risks and uncertainties. If the US \$150 billion is taken as the maximum anticipated cost including unknown risks and the negative

impact on the market value of the imported resources is considered because of a sudden increase in supply, a more realistic/conservative assessment on the total return value can be derived.

From Kargel's (1996) study, if platinum and its associated platinum-group metals were to suddenly become available in unrestricted quantities, market prices would be expected to drop rather sharply, perhaps by 50 to 90%. Lower market prices would also produce new and innovative ways to use these elements so the market demand would be expected to grow, but for the moment, it is assumed that this would not affect the prevailing prices in a positive manner. This ready availability of formerly rare and highly valued metals could reduce the value of asteroid platinum reserves from US \$1.8 to \$6.4 trillion (assuming a 90% reduction in price) to US \$180 to \$640 billion. This would still leave a US \$20 to \$480 billion residual profit after subtracting the assumed maximum cost of the mining and return mission and incorporating the maximum price reduction of 90%. If the value of other associated metals is considered (but also assumed to suffer a 90% reduction from present-day prices), the minimum profit would rise to an estimated US \$140 billion. Table 3 illustrates

Table 3. Concentrations and potential value of rare-earth elements, precious metals, and platinum-group metals in typical asteroids derived from chemical composition of meteorite finds on Earth.*

<i>Element</i>	<i>Concentration in Average LL Chondrite</i>	<i>Concentration in Good Iron Asteroid (90th percentile in Ir and Pt)</i>	<i>Concentration in Best Iron Asteroid (98th percentile in Ir and Pt)</i>	<i>Mass in 1 km-Diameter Good Asteroid (t)</i>	<i>Market Value in Late 2010 Prices (US \$/kg)</i>	<i>Value if Sold at Today's Market Price (US \$)**</i>	<i>Deflated 2010 Market Value (assumed to be 10% of full 2010 value)</i>
Semiconductors							
Phosphorous (P)		1300 ppm		2.25E6	0.06	1.24E8	1.24E7
Gallium (Ga)		60 ppm		1.04E5	480.00	4.98E10	4.98E9
Germanium (Ge)	1020 ppm	210 ppm	0.05–35 ppm	3.63E5	950.00	3.45E11	3.45E10
Arsenic (As)		3.7 ppm		6.39E3	2.02	1.29E7	1.29E6
Selenium (Se)		36.0 ppm		6.22E4	50.60	3.15E9	3.15E8
Indium (In)		0.46 ppm		7.95E2	500.00	3.97E8	3.97E7
Antimony (Sb)		0.047 ppm		8.12E1	5.06	4.11E5	4.11E4
Tellurium (Te)		0.45 ppm		7.78E2	145.00	1.13E8	1.13E7
Platinum and precious metals							
Ruthenium (Ru)	22.2 ppm	13.0 ppm	45.9 ppm	2.25E4	6515.99	1.46E11	1.46E10
Rhodium (Rh)	4.2 ppm	4.8 ppm	8.6 ppm	8.29E3	79,751.86	6.61E11	6.61E10
Palladium (Pd)	17.5 ppm	1.3 ppm	1.2 ppm	2.25E3	24,595.32	5.52E10	5.52E9
Silver (Ag)		0.46		7.95E2	954.88	7.59E8	7.59E7
Rhenium (Re)	1.1 ppm	3.7 ppm	2.4 ppm	6.39E3	3100.00	1.98E10	1.98E9
Osmium (Os)	15.2 ppm	9.0 ppm	31.3 ppm	1.56E4	14,467.84	2.25E11	2.25E10
Iridium (Ir)	15.0 ppm	33.0 ppm	31.0 ppm	5.70E4	19,871.73	1.13E12	1.13E11
Platinum (Pt)	30.9 ppm	35.0 ppm	63.8 ppm	6.05E4	55,022.79	3.33E12	3.33E11
Gold (Au)	4.4 ppm	0.16–0.70 ppm	0.06–0.6 ppm	8.64E2	45,076.31	3.89E10	3.98E9
Other important metals							
Copper (Cu)		100 ppm		1.73E5	9.24	1.60E9	1.60E8
Cobalt (Co)	1.57%	0.46–0.80%	0.43–0.75%	4.32E6	39.60	1.71E11	1.71E10
Titanium (Ti)		14.0%		2.42E6	0.56	1.35E9	1.35E8
Chromium (Cr)		5.0%		8.64E5	10.00	8.64E9	8.64E8
Nickel (Ni)	34.3%	5.6–18%	5.4–16.5%	1.04E6	14.91	1.55E10	1.55E9
Molybdenum (Mo)		0.50%		8.64E0	50.00	4.32E5	4.32E4
Total						6.2E12**	6.2E11
						\$6.2 trillion	\$620 billion

*Modified from Kargel (1996).

**Note that 6.2E12 is shorthand scientific notation for US \$6.2 trillion or 6.2×10^{12} or US \$6,200,000,000,000. Sources: Modified from Ross (2001), Kargel (1996, 1994), and Jarosewich (1990). Metal prices from U.S. Geological Survey Commodity Statistics and Information, 2011, data and Wall Street Journal Market Data Center, 2011.

these statistics using Kargel's (1996) elemental concentration ranges but substituting 2010 commodity prices (U.S. Geological Survey-Mineral Industry Surveys, 2010).

High-risk capital investors might be interested in a space opportunity if the return on investment were within the range of 100 to 1000%. If an investment of US \$150 billion yields a return of US \$6 trillion for 30 yr, the total return on investment would be 3900% or an annualized return for 30 yr of 130%. If costs remained the same but returns were only US \$1.65 trillion for 30 yr, this would result in a 1000% total return, with a 33.3% annual return on the investment. The total return would have to decline to US \$600 billion for 30 yr before the annual return on investment would decline to 10%, equivalent to a respectable high earning bond fund that any conservative investor would be happy to hold.

The Near-Earth Objects as a Source of Strategic Materials

The economic value of rare-earth elements and platinum-group metals is an important consideration that could provide for commerce between Earth and space-based operations and support high-technology manufacturing in space. If valuable materials derived from space-based activities such as mining the asteroids can be returned to Earth to offset the cost of Earth-based governments supporting space exploration, the arguments for space exploration gain a direct economic base. Relocation of a part of Earth-based mining activities to space would also reduce the environmental impacts and consumption of energy, mineral, and water resources on Earth currently dedicated to mining operations, thereby providing a very strong environmental and sustainability argument for space-based mining. Rare-earth elements and platinum-group metals are strategic and critical materials that are essential to the United States economy and to the strategic and economic security of the nation. Although trade-offs with market prices, consumption rates, and economic reserves always exist, critical materials are not infinite in supply and, as high-valued deposits are depleted, lower concentration deposits (or deposits more difficult to extract, and therefore, more expensive) must be addressed. Therefore, development of asteroid resources has a strong national security supporting argument as well.

Mudd (2009) and Prior et al. (2010) provided a recent assessment of the reserves of critical elements being mined in Australia based on the growing demand for specialty metals, catalysts, and high-technology

materials. They found that, although adequate supplies and reserves were available, reserves were not being added at a rate to match or exceed consumption. Mudd (2009) and Prior et al. (2010) were able to derive target dates where the cost of developing local Australian resources of critical minerals would exceed the cost of meeting required supplies completely from imports. This does not imply that Australia is running out of critical materials but rather that the cost to deliver an equivalent quantity of a critical material from an Australian source will increase in the future to a point that importing these materials becomes less expensive than mining them locally. Australia serves as a microcosm of the world market demand and supply for rare-earth elements and platinum-group metals, illustrating that supply and demand alone may be sufficient to drive the development of space-based reserves of critical minerals.

At the present time, the world demand for rare-earth elements is estimated at 134,000 tons/yr, whereas global production is approximately 124,000 tons/yr (Humphries, 2010). The deficit is supplied by reserves from aboveground stockpiles and by some recycling, but this situation cannot continue indefinitely. Demand is expected to increase to more than 180,000 tons/yr by 2012. The time required to bring a new mine online and into production normally requires at least 10 yr. A strong expectation that there will be a shortfall between demand and supply for the near term exists. Whether this can be met from new or expanded Earth-based resources for the medium- to long-term remains to be seen.

No more important group of compounds for industrial chemistry than the catalysts derived from platinum-group metals exists—the United States imports nearly 100% of these metals that are required for manufacturing purposes. The United States also currently imports 100% of the rare-earth elements (but the reopening of the Molycorp mine in California scheduled for 2011–2012 will begin to provide a part of United States needs). Rare-earth elements are required in the production of permanent magnets used in high-energy physics research, electric cars, wind generators, high-performance aircraft, video displays for television and computers, medical imaging equipment, and automotive catalytic converters. Telecommunications and renewable energy industries are based on the ready availability of rare-earth and platinum-group metals. Platinum-group metals are essential for pollution-control equipment and as catalysts in the production of fertilizers, explosives, and petrochemicals.

Humphries (2010) reports that the U.S. Geological Survey-Mineral Industry Surveys (2010) expects global reserves and undiscovered resources to be sufficient to meet the worldwide demand, but this is a conclusion based on assuming that the additional costs for production of increasingly more expensive deposits will be borne by world markets accepting higher prices as less expensive reserves decline. As Campbell et al. (2009) indicated, the availability of important mineral deposits will decline and the cost of extracting sufficient quantities to meet the needs of high-technology industries will increase. The anticipated result will be a demand to develop NEO resources to meet the demands of Earth's mineral needs.

Development of the NEO mineral resources will require the existence of some level of confidence that the mineral commodity prices will remain relatively stable and sufficiently high during a period of at least 20 years to justify the investment, effort, and risk. The market value of the metal content of an average NEO is obviously subject to change based on supply, demand, and normal market forces. Two factors are important now and for the foreseeable future in maintaining and increasing the value of the rare-earth elements and platinum-group metals in asteroids and in sustaining the potential return on investment for an asteroid mining venture for years (as is necessary to plan and conduct a mining operation).

The first issue is that the energy and technology sectors of the world economy are critically dependent on the availability of an adequate supply of minerals (Burke, 2009). Eggert (2008) estimated that the annual need for nonfuel minerals in the United States is more than 11,300 kg (24,912 lbs) per person. Rising expectations in developing countries will increase the demand on the available world reserves of these elements. The U.S. Department of Commerce (2007) and the U.S. Geological Survey (Jackson and Christiansen, 1993) estimated that the existing contribution of the mineral industry to the U.S. Gross Domestic Product exceeds US \$2 trillion, and this dependency of the United States economy on mineral resources is expected to continue and grow.

The second issue is that national leaders whose countries control the known resources recognize the importance of these elements in sustaining the growth of national economies in both basic and high-technology industrial sectors. Many nations are taking steps to protect their existing resources by limiting exports and establishing national reserves and internal price controls. All of these actions will serve to decrease the availability of critical materials on the

world market and, as a result, serve to increase the price of those supplies that are available through imports only (Platts Inside Energy Newsletter, 2010). The United States relies on imports predominantly from South Africa, the Democratic Republic of the Congo, China, Chile, and Australia for its existing supplies. Growing demands of developing countries, political instability in resource-rich nations, and critical supply levels in the United States are anticipated to increase demands on available supplies and increase prices for the future, thus providing an incentive and opportunity to develop asteroid sources of minerals.

Is it practical to consider investing US \$150 billion in an asteroid mining operation? Although this is a substantial investment, it is not out of line for other historic public or private investments. The Alaska Pipeline was a mostly private investment of US \$8 billion in 1977 (~US \$30 billion in 2010 dollars), and the ISS will be an estimated US \$100 billion at completion. Brazil and its partners will be investing an estimated US \$200 billion in developing the pre-salt petroleum reservoirs off the coast of Brazil during the next 10 yr that will yield an estimated 9.5 to 14 billion bbl of oil, which at an average US \$50 per bbl, would yield a return of approximately US \$475 to \$700 billion. Brazil's development of the pre-salt reservoirs is as expensive and as risky as any space exploration effort; they are drilling at depths of 7000 m (22,966 ft) below sea level into zones that are highly pressurized and hotter than many other areas of exploration. The intervening thick layers of bedded and deformed salt make interpretation of the geologic environment below the salt very difficult and risky for the drilling team and highly uncertain for those responsible for making investment decisions. There will be accidents, and there will be lives lost in the development effort. But the project will go forward, and those involved will learn from their efforts and mistakes and will make every new effort they undertake faster, less expensive, and safer. These lessons should not be lost on those that consider space mining opportunities.

From the perspective of an Earth-based entrepreneur or a country short of rare-earth and platinum-group metals, mining an asteroid for high-value materials has the potential to generate significant returns and fully justifies the risk. However, if we exploit the NEOs and then leave them like an abandoned ghost town of the old America West, we are not taking full advantage of the range of resources available from the NEOs. Fortunately, more than valuable metals make the NEOs attractive. There must be plans for the

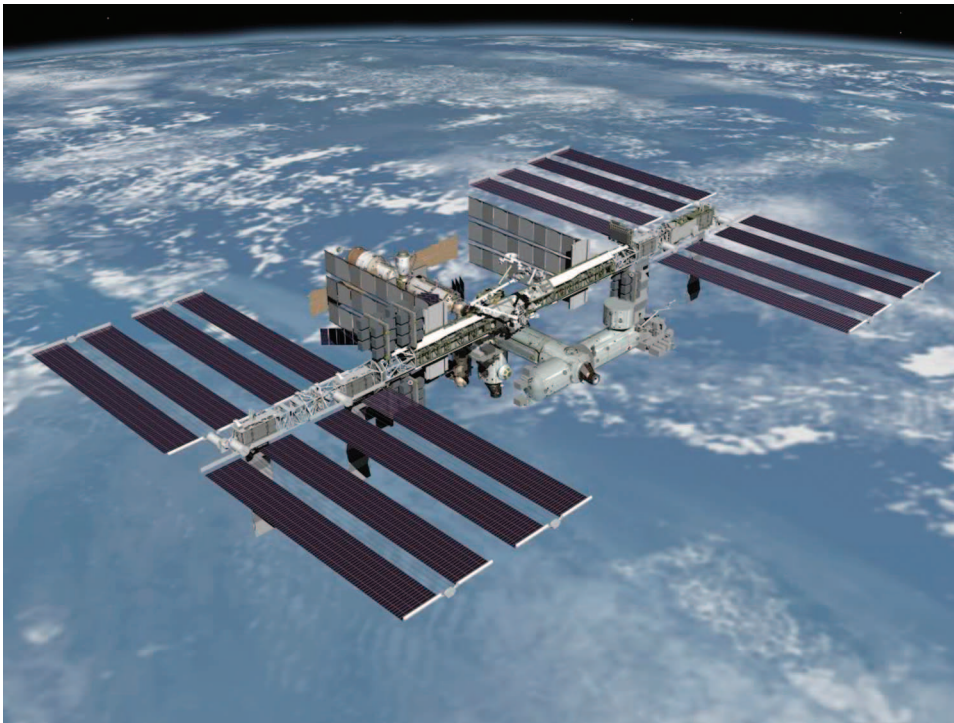


FIGURE 8. International Space Station (artwork courtesy of National Aeronautics and Space Administration Near-Earth Object Program Discovery Statistics, 2010).

long-term development and sustainability of an active space program, and the volatiles and organics from the NEOs provide the necessary resources to make this possible. Other valuable materials include ice for use in producing rocket fuel and breathing oxygen; iron, cobalt, and nickel to produce structural steel; silicon and associated materials for solar panels; and complex carbonaceous material for industrial chemistry. These materials would provide for a growing and self-sustaining space economy and are the full spectrum of elements and compounds that can support space exploration and development from outside Earth's gravity well.

IN-SITU RESOURCE UTILIZATION

"NEAs Near-Earth asteroids may be the most attractive source of shielding, propellants, metals, and refractories in orbits around the Earth." (Lewis et al., 1993, p. 9)

"The purpose of in-situ resource utilization (ISRU) is to harness and utilize these [in-situ] resources to create products and services which enable and significantly reduce the mass, cost, and risk of near- and long-term space exploration." (Sanders and Duke, 2005, p. 5)

In-situ resource utilization (ISRU) is essential for effective exploration of space. Consider the use of

solar panels on the ISS, as shown in Figure 8. These panels produce the necessary power supply for the station from ambient solar radiation. Without the use of solar panels, power for the ISS would have to be provided by some type of electrical generator such as fuel cells, radioisotope thermal generators, or something similar that would require considerable mass, periodic refueling, and regular maintenance. Early activities on the ISS were constrained because the full complement of solar panels were not installed until 2009, which was 11 years after the initial launch of the first module of the ISS in 1998. The S- and M-type asteroids contain ample supplies of silica, carbon, iron, nickel, cobalt, gallium, germanium, and other associated elements that are the raw materials to manufacture solar panels in space, as well as all the necessary materials to construct the habitation modules and the structural supports for all the laboratory modules and associated facilities attached to the ISS.

Glaser (1968, 1977) described how solar power satellites could be constructed in Earth's orbit to beam power to Earth using materials derived from either the Moon or NEOs. Although this concept seemed fanciful in 1968, it has recently been updated by Komerath (2009), who developed supporting calculations that indicate space solar-power stations can economically compete with wind power generators for the cost of delivered electricity. The most important consideration is that solar panels can be launched for a one-time use in space (as was done for the ISS) or the

facilities can be launched to construct and service solar panels in space and provide for an expanding and sustainable worldwide power grid.

Applying this concept to the Moon and Mars, adequate power, life-supporting atmosphere, fuel and water supply can be produced from the lunar regolith or from the atmosphere and soils of Mars. For the Moon, the limiting resource is power; it takes considerable energy to evolve oxygen and water from basaltic rock or the mineral ilmenite, and incident solar energy is absent every 14 days (out of the 28 days) of the lunar day-night cycle. For Mars, resources are easier to develop, but likewise, power constraints exist. Incident solar energy on Mars is approximately 590 W/m^2 , whereas that on Earth is approximately 1000 W/m^2 .

Long-term occupation of the Moon and Mars will require more than just water, air, and fuel. Under long-term occupation, it would be desirable and probably necessary to produce nitrogen fertilizers to grow crops and to manufacture at least some of the hundreds of compounds and commodities that we derive from industrial manufacturing on Earth. All of this is possible in space but only comprehensively possible in combination with the NEOs. The Moon has metals and trace quantities of water but no organics; Mars has metals, an atmosphere, and plentiful water, but it is unlikely that it has any viable organic resources. The NEOs could provide requisite metals, organics in the form of the carbonaceous chondrites, water, and numerous gases in frozen forms—all the raw materials necessary for survival, support, and expansion for development.

Ice from a dormant comet or from an ice-rich asteroid could provide rocket fuel through a process as simple as dissociation of water by electrolysis, yielding (after chilling) LOX and liquid H_2 . These fuels for the space shuttle's main engine are capable of generating an exhaust velocity of 2435 m/s (7989 ft/s) and specific impulses from 390 to 450 s. A reservoir of these fuels in orbit could shorten the travel time for a Mars mission by half by refueling the spacecraft in orbit and thereby providing greater fuel reserves for faster acceleration from Earth and deceleration at Mars without or in conjunction with the significant danger of deceleration by aerobraking only. Greater availability of fuel could increase the allowable mass of the transit vehicle and allow greater radiation shielding, more mass for consumables, or larger living space for the astronauts. An adequate power source on the Mars landing vehicle can also serve to produce fuel while on Mars from conversion of the mostly carbon dioxide atmosphere via the Sabatier process to methane and oxygen. Again, if water ice is

available, LOX and liquid H_2 could also be produced, but the difficulties of storing liquid hydrogen would favor the LOX-methane fuel mix (Zubrin, 1996).

An important use for ice in space that is commonly neglected is to serve as a counterweight for tethered gravity generation. Long-term exposure to microgravity or zero-gravity environments is debilitating. Flight times from the Earth to the Moon are approximately three days, but flights to Mars or to NEOs might extend from 18 months up to three years. During this period, mission crews will be subjected to lack of gravity and exposure to solar and cosmic radiation. For astronauts, a lack of gravity saps muscle strength, degenerates bone mass, and degrades the immune system beginning from the first moment they step outside Earth's atmosphere. A round-trip journey to Mars could subject the flight crew to two years of a zero-gravity environment, the impact of which would result in the muscle strength, bone density, and immune response of a 90-year-old person in a 45-year-old body.

To address this issue, artificial gravity can be created by extending a tether from the crewed vehicle to a secondary mass and rotating the crew and counterweight around their common center of gravity (Figure 9). Ice, with minimal supporting structural elements, could serve as the counterweight and would provide a reserve fuel supply should an emergency abort event occur that requires the crew to return to Earth. (The specifics of the mass ratios between the crew quarters and the counterweight and the length of the tether to minimize the intensity of vertigo-inducing Coriolis forces and force gradients are detailed in Jokic and Longuski [2005] and in Young [2006]). The additional mass required for the counterweight must also be accelerated along with the main crew vehicle, but the ice counterweight can be discarded at any time and does not have to be decelerated at the destination.

Exposure to solar and cosmic radiation outside Earth's atmosphere is also an issue that can be resolved by having a supply of ice in orbit. Cosmic radiation exposure amounts to approximately 1 rem/day in space, whereas, for humans on Earth, the recommended maximum limits for a monitored radiation worker are 5 rem/yr and 0.1 rem/yr for the general public. Intense solar flares can produce radiation levels that can result in severe radiation sickness and death of the crew unless adequate shielding is provided. Evidence now shows that cortical cataracts are more common in astronauts than the general population and more common in astronauts having greater radiation exposure than those astronauts having limited exposure to cosmic



ARTIFICIAL GRAVITY CONFIGURATION

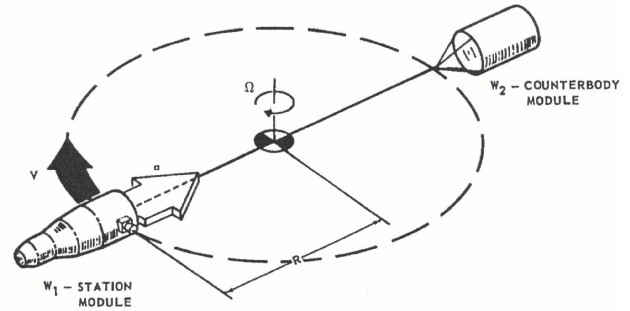


FIGURE 9. Illustration of tethered gravity generation via rotation around a common center of gravity using a counterweight (courtesy of National Aeronautics and Space Administration Archives). v = rotational velocity; Ω = angular momentum of the combined unit; R = radius of the combined unit.

rays (Cucinotta et al., 2001). Ice is an ideal radiation shield and can be shaped in orbit to enclose and protect the crew quarters or, in liquid form, fill an annular space between an inner and outer wall of the crew capsule or a smaller safe room within the crew vehicle.

Retrieval of a Near-Earth Object or In-situ Mining, Refining, and Return to Earth's Orbit

The previous discussion has presented the justifications for development of the NEOs for economic

returns and to support space exploration. Whereas traveling to an asteroid for mining and refining ores is a reasonable approach, an alternate procedure would be to move an NEO to near-Earth orbit for refueling and reprovisioning for activities both within and beyond the Earth-Moon system. However, note that metal mining and production of oxygen and fuels can occur either at the NEO's existing orbit or, using fuel and mass from the NEO, move the object to near-Earth space (Figure 10). Numerous



FIGURE 10. Illustration of mining and construction activities in space (courtesy of Ames Research Center, National Aeronautics and Space Administration images, June 1977).

Table 4. Velocity change (or delta-v) requirements for various destinations from Earth's surface, LEO, lunar surface, or NEA.*

Earth's surface to LEO**	8.0 km/s
Earth's surface to escape velocity	11.2 km/s
Earth's surface to GEO**	11.8 km/s
LEO to NEA** (varies based on target and on rendezvous orbit)	1.5–5.5 km/s
LEO to escape velocity	3.2 km/s
LEO to lunar landing	6.3 km/s
LEO to Mars or Venus transfer orbit	3.8–4.5 km/s
NEO** to Earth transfer orbit (varies)	≈1 km/s
Lunar surface to LEO with aerobraking	2.4 km/s

*Sonter, 1997; Perozzi et al., 2001.

**LEO = low-Earth orbit; NEA = near-Earth asteroids; GEO = geosynchronous orbit; NEO = near-Earth objects.

authors (e.g., Lewis, 1996; Sonter, 2001; Gerlach, 2005) have examined both options and have concluded that in-situ mining at the NEO's orbit is probably more practical for objects greater than 500 to 1000 m (>1640–3281 ft) in diameter. However, moving the object to near-Earth space using mass drivers or nuclear thermal propulsion with in-situ ice as the ejected mass is certainly possible, but that decision would be based on the object's mass and the required velocity change necessary to bring the object to near-Earth's orbit.

Mining NEO materials requires sufficient propulsion capacity to lift tools, mining, and refining equipment from Earth's surface to an NEO, sufficient energy to extract and refine the target minerals, and the propulsion capacity to return or distribute the refined products to their point of use (the Moon or Mars) or back to Earth. The problem is how to access these resources, how to mine and refine these elements in space, and how to use the derived materials for building and manufacturing in space. Energy, in the form of propulsion and power, provides the answers to these issues.

Table 4 presents minimum delta-v requirements for destinations from Earth's surface to LEO and to destinations beyond LEO. (Note from this table that the least energy requirement destination is the NEOs).

Escaping from the bottom of Earth's gravity well to LEO requires that every ounce, pound, kilogram, or ton be accelerated by a minimum of 8.0 km/s (4.97 mi/s). Existing chemical rockets (e.g., the space shuttle main engine or the Saturn V JS-1 engine) that use LOX or H₂ or RP-1 fuel are capable of producing high thrust and a specific impulse (Isp) of 245 to 390 s. However, chemical-powered rockets are just not powerful enough to economically support the mass budgets required for effective development of space resources. As well as high thrust requirements, engines must produce specific impulse values in excess of 800 s and ideally in excess of 5000 s.

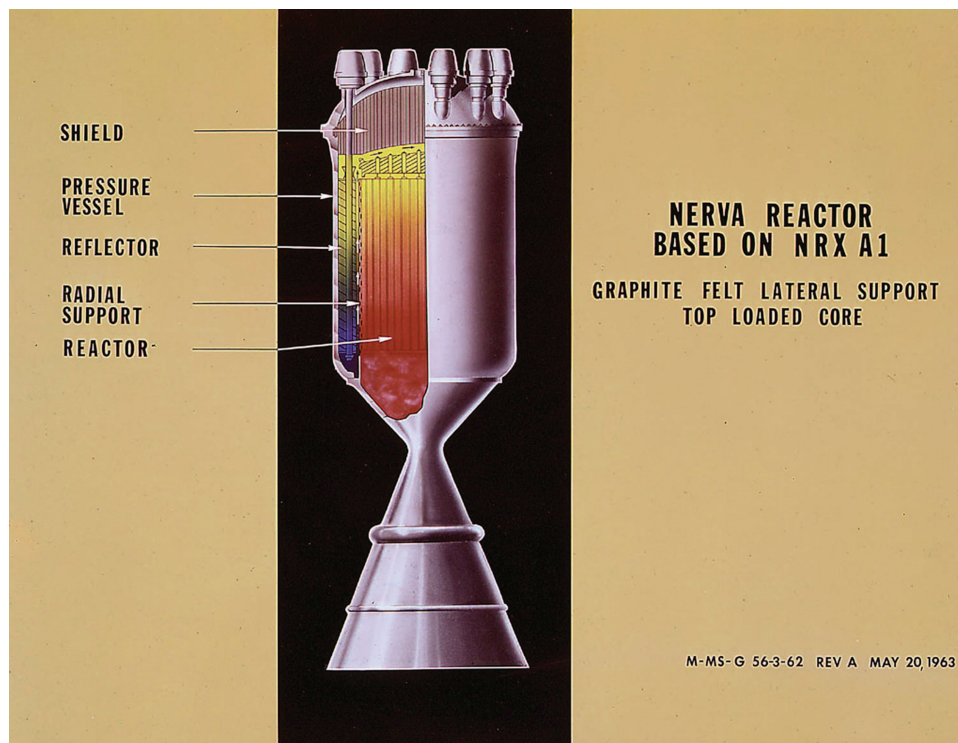


FIGURE 11. The NERVA nuclear thermal rocket engine using hydrogen as the primary fuel (Robbins and Finger, 1991). NERVA = nuclear engine for rocket vehicle application.

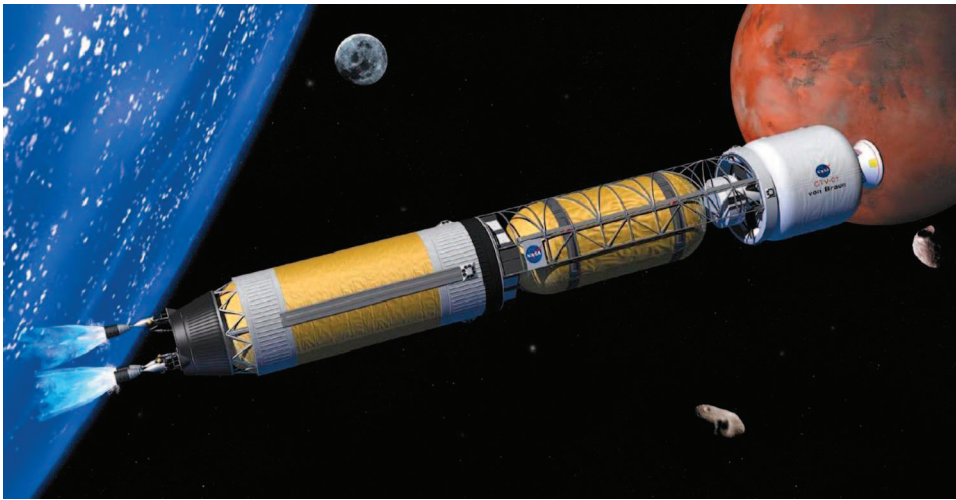
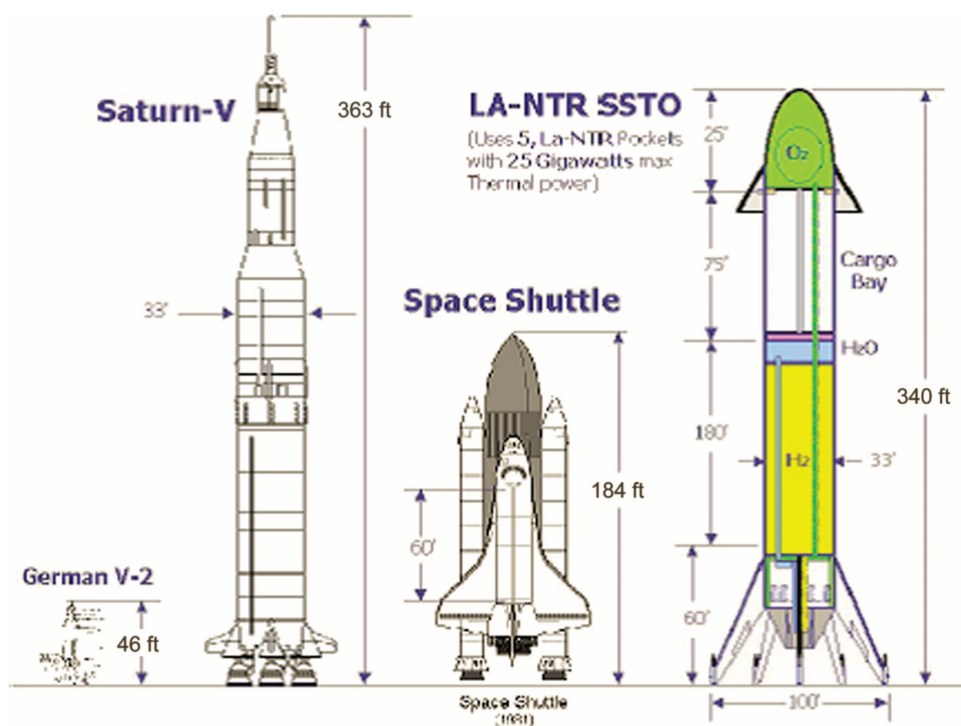


FIGURE 12. Illustration of the LANTR engine (from Davis, 2004, courtesy of NASA Archives). LANTR = liquid oxygen-augmented nuclear thermal rocket; SSTO = single stage to orbit.



Furthermore, the desirable launch costs of US \$150 to \$500/kg have never been approached: the current launch costs for a Space Shuttle payload are still in the range of US \$10,000 to \$15,000/kg.

What is required is a rethinking of how to efficiently reach space to effectively mine the NEOs and how to produce sufficient power in space to support mining, refining, and crew support or asteroid retrieval to Earth. Sackheim (2006) reviewed the development of NASA's propulsion systems and concluded that a new propulsion system has not been produced since the space shuttle's main engines were developed in the late 1960s and early 1970s. Encouraging inno-

ventions exist—the VASIMR® ion engine (Variable Specific Impulse Magnetoplasma Rocket, manufactured by Ad Astra Rocket Co.), and the development of new boosters by Space Exploration Technologies Corp., or Space X. But the ultimate goal of having a heavy-lift, single stage to orbit, reusable launch system has not been approached since the original Orion nuclear-pulse propulsion system or the NERVA (nuclear engine for rocket vehicle application) engine in the 1960s and 1970s. The NERVA engine had been extensively ground tested and was ready for a full orbital flight test when the program was canceled in 1972. The engine weighed 10.4 t, was designed to

operate at 1500 MW (megawatts) thermal and provide 333 kN (kilonewtons) of thrust, and had a specific impulse of 825 s. It was designed to have a 10 hr life and be capable of 60 operating cycles, far beyond any engine available today. Potential modifications and enhancements to the NERVA design indicated that engines capable of specific impulse values of 1000 to 10,000 s were possible with 1970s technology and materials (Figure 11).

The underlying issue of why nuclear energy must be incorporated into the space program is energy density. The best chemical fuels available have an energy density of 1×10^7 J/kg, whereas nuclear fission has an energy density of 8×10^{13} J/kg. Davis (2004) conducted an extensive analysis of existing and speculative propulsion systems and concluded that the LOX-augmented nuclear thermal rocket (LANTR), as defined by Borowski et al. (1994) and Borowski (1995) (Figure 12), was capable of meeting the manned flight certification requirements within 5 yr (from 2004) with a single stage to orbit configuration that also included vertical takeoff and either vertical or horizontal landing. Preliminary design studies also estimated a payload launch cost of US \$150/kg in 2005 dollars. Davis's (2004, p. 54) final concluding statement was that

"Nuclear DC-X (LANTR) has such far-reaching capabilities that it represents a new and vital way of realizing the benefits of space. This advanced propulsion concept can be implemented within 5 yr to meet all manned and unmanned space mission requirements."

Heavy-lift, high-efficiency, refuelable rocket engines are half the problem. Once in space, sufficient power must be available to support whatever mining or refining operations are required, and for asteroid retrieval, power is needed to support mass drivers (Snow and Dunbar, 1982). A mass driver operates using electromagnetic force converted to kinetic energy by ejecting mass in any form in one direction and thereby producing acceleration in the opposite direction. The material that provides the mass can be anything including rock or ice. The mass is loaded in a bucket that is accelerated by an electromagnetic driver similar to a rail gun. At the end of the acceleration ramp, the bucket stops and the mass is thrown into space, producing acceleration in the opposite direction. In this manner, a mass driver mounted on an asteroid can use the asteroid's own mass to gradually move the asteroid from its present orbit into an orbit

that will be easily accessible from Earth. Power in the megawatt to hundreds of megawatts range is required. Solar panels are useful but impractical for any high-power demand mission element that requires acceleration or maneuvering. Solar power certainly has a function to play, if not the central role, in development of space resources, but initially, power is needed from a compact high-energy density source, and nuclear power is the only technology that can meet these requirements. Large solar arrays, initially constructed using nuclear power sources, are an effective method of supporting later development efforts in static orbits or on planetary surfaces, but the initial energy sources need to be nuclear, and for mobile sources, nuclear power generation systems are proven, compact, and reliable.

CONCLUSIONS

The Mercury, Gemini, and Apollo programs have demonstrated that seemingly impossible difficulties to launch both unmanned and manned missions beyond Earth's surface can indeed be overcome. However, sustainable operations in space are not feasible if all supporting supplies and materials must be launched from the Earth by existing chemical rocket boosters. The NEOs contain all the elements to make space exploration and resource development feasible, economically achievable, and profitable. The next phase of space exploration must incorporate in-situ resource utilization, nuclear thermal engines, and nuclear power production for the critical purposes of reducing launch costs, increasing crew safety, and reducing mission durations. Organic materials for supporting a broad-based chemical industry are present. Both mundane and critically essential materials such as iron, cobalt, platinum-group metals, and rare-earth elements are widely available. Platinum-group metals and rare-earth elements are essential for advanced technology industries but are sufficiently rare or costly on Earth as to make mining the NEOs a viable market opportunity. Water, which is easily converted to fuel and breathing oxygen, is readily available. Icy asteroids and dormant or extinct comets can provide the water ice as fuel for refueling in orbit, thereby radically reducing the fuel requirements at launch for any subsequent missions. By having refueling available in orbit, missions would have the capability to plan least-time trajectories, would have material for adequate shielding, and would have discardable mass for artificial gravity generation during transit for substantial improvements in crew health and safety. By taking advantage of NEOs, we have the capability

to conduct an extended and self-supporting exploration and development of the Moon and Mars—an exploration renaissance that has not been seen on Earth since the European discovery of North America.

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