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Metalliferous asteroids as potential sources of precious metals

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Abstract. Recent discoveries of near-Earth asteroids (NEAs) and chemical analyses of fragments of asteroids (meteorites) suggest that there may be a gold mine, literally, in near-Earth space. Judged from meteorite analyses, two types of asteroids offer particularly bright prospects for recovery of large quantities of precious metals (defined as Au, Pt, Ir, Os, Pd, Rh, and Ru), the ordinary LL chondrites, which contain 1.2-5.3% Fe-Ni metal containing 50-220 ppm of precious metals, and metallic asteroids, which consist almost wholly of Fe-Ni phases and contain variable amounts of precious metals up to several hundred ppm. The pulverized regolith of LL chondrite asteroids could be electromagnetically raked to separate the metallic grains. Suitable metallic asteroids could be processed in their entirety. Statistically, there should be approximately six metallic NEAs larger than 1 km in diameter that contain over 100 ppm of precious metals. Successful recovery of 400,000 tons or more of precious metals contained in the smallest and least rich of these metallic NEAs could yield products worth $5.1 trillion (US) at recent market prices. If marketed over 20 years, this would represent a 10-fold increase over the recent global production rate of all precious metals combined. The market response to the hypothetical introduction of such large quantities of precious metals is difficult to predict, because these metals historically have not obeyed normal economic laws of the market. An empirical model suggests that the effects on market prices of a hypothetical increase in production of a given metal can be predicted given existing knowledge of the metal's present market value and production rate. This model suggests that the total value of 400,000 metric tons of precious metals, if marketed over 20 years, would decline to about $320 billion ($16 billion per year). Except for Au, for which production and prices would be marginally affected, the market prices of precious metals may decline by 1 to 2 orders of magnitude if one of the six asteroids were to be mined to depletion over 20 years. Less conservatively, there is a 50% chance that the richest metallic NEA contains at least 1.9 million metric tons of precious metals; this quantity, if marketed over 40 years, may be worth approximately $900 billion at collapsed market prices ($22.5 billion per year). The actual economic and technological impact of asteroidal metals may be considerably greater due to the increased availability and reduced prices of these resources. Despite this great potential, first-order technological, scientific, and economic uncertainties remain before the feasibility of exploitation of asteroids for precious metals can be ascertained.

1. Introduction

The metal mining industry, no less than the rest of the global economy, is facing acute shortages of many nonrenewable natural resources. As the world's demand for these resources is rising, and ever larger quantities of decreasing grades of ore are mined, a deteriorating environment is bringing increasing pressure to limit our harvest of remaining resources. Optimistically, we may be clever enough to adapt to drastic changes in the supply and quality of natural resources and still maintain a semblance of a stable and healthy environment. One possible adaptation may involve the use of resources from outer space [*Lewis et al.*, 1993]. Most work concerning utilization of extraterrestrial resources has focussed on development of the means to "live off the land" during humanity's early thrust into the Solar System. This paper concerns metalliferous near-Earth asteroids (NEAs) as potential sources of precious metals (defined as Au, Ru, Rh, Pd, Os, Ir, and Pt) that could be imported and used on Earth for the benefit of terrestrial civilization. The author does not wish to trivialize the enormous expense, dedication of technological expertise, and risk that would be entailed in an effort to tap asteroidal resources. Rather, the purpose is to point out that such an endeavor could allow us to reap a proportionately valuable reward. The value would lie not so much in the potential cash profits (which could be tremendous), but in new technologies that hitherto have been prohibitively expensive to develop or implement because of the limited availability and high prices of precious metals.

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The technological developments and capital investments that would be required to enable asteroid mining are so formidable that only governments of wealthy nations, or a consortium involving the public and private sectors, could consider such an endeavor. Besides the uncertain cost of developing and operating the mining and transportation infrastructure, many first-order questions must be answered before the technical and economic feasibility of asteroid mining can be fully evaluated. This contribution (1) presents an estimation of the quantities of precious metals that could be recovered in an initial mining venture, (2) offers an empirical model that permits an estimation of the market value of precious metals during a possible future era of asteroid exploitation, and (3) considers possible technologies for mining, refinement, and transportation of asteroidal metals.

2. Historic Production and Possible Future Uses of Precious Metals

Cumulative world production of gold projected through the end of 1994 is about 170,000 metric tons (adjusted for recent production from statistics of the *U.S. Department of the Interior Bureau of Mines* [1993] and *Govett and Harrowell* [1982]). In 1989, world production of Au was about 1900 tons, and production of all platinum group metals (PGM) and Au combined was 2175 tons. The world's nonjewelry industries in 1989 used about 500 tons of Au and PGM, or 23% of production. Most of the remainder went into jewelry and strategic stockpiling.

Wide-ranging technologies use Au and PGM in pure form; alloyed with one another; or alloyed with Cu, Ag, Ni, rare earths, and other relatively inexpensive metals. Among other uses, Pt and Pd are extensively used as catalysts and electrodes in the automotive, petroleum refining, chemical, and electrochemical industries; Au and PGM alloys are widely used as components in the electronics and computer industries and in thermocouples; thin films of Au and PGMs have applications in astronomical instrumentation and fiber optics; PGMs are widely used as corrosion-resistant high-temperature coatings; and Pd, Ir, and PGM alloys are used in high-strength turbine blades and critical wing joints of high-performance military jet aircraft.

The prices of Au and Pt, and to a lesser extent the other PGM, historically have not obeyed normal economic laws of the market [*Robbins et al.*, 1979]. This failure is caused by the special role ascribed to these metals by (1) individual consumers (the gold cult and, in Japan, the platinum cult) and (2) governments (e.g., hoarding, dumping, and the old gold standard), and by the partial control of supplies by a few major producers (South Africa today; formerly Spanish colonial America). Aside from these special factors in the economics of precious metals, a geochemical viewpoint is that the maintenence of the extraordinary market values of the precious metals is fundamentally due to their rarity and extremely nonuniform distribution in Earth's crust, especially in the upper continental crust. Regardless of the special role of Au in society, Au would be expensive simply because it is rare and useful.

Empirical evidence (Figures 1-3) suggests that the condition of high prices and inhibited practical usage of precious metals would be discontinued if their availability was greatly increased. The correlations in Figures 1-3 indicate that availability (which generally is related to a metal's abundance in Earth's upper continental crust) is the principal underlying factor that ultimately controls the price, production, and consumption of any metal. The dispersion of data about the correlation lines in Figures 1-3 can be attributed to secondary factors, such as the magnitude of geochemical tendencies of the metals to concentrate in ores, the cost of separation of metals from ores, the industrial versatility of the metals, and their toxicity. These correlations are not the same as those associated with normal market forces of supply-demand-price. Rather, it is thought that the rough correlation between price and crustal abundances (availability) of various metals (Figure 3) has developed over the long

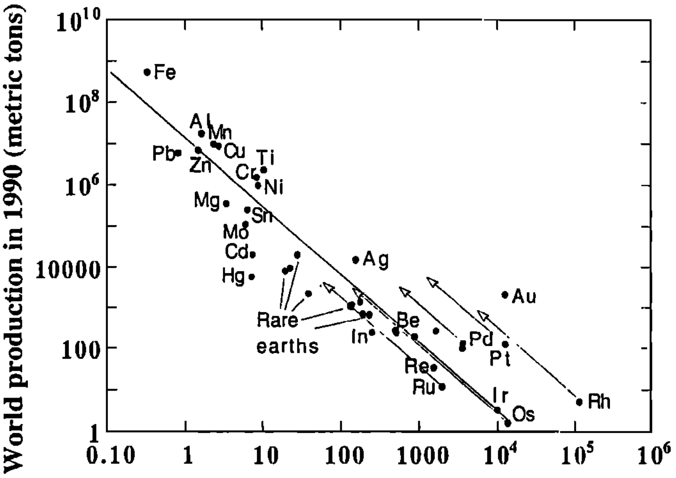

Figure 1. Global production and recent prices of metals. Arrows show possible responses of market values of gold and platinum group metals to an influx of asteroidal metals as described in the text and in Table 1. Data from *U.S. Department of the Interior Bureau of Mines* [1993].

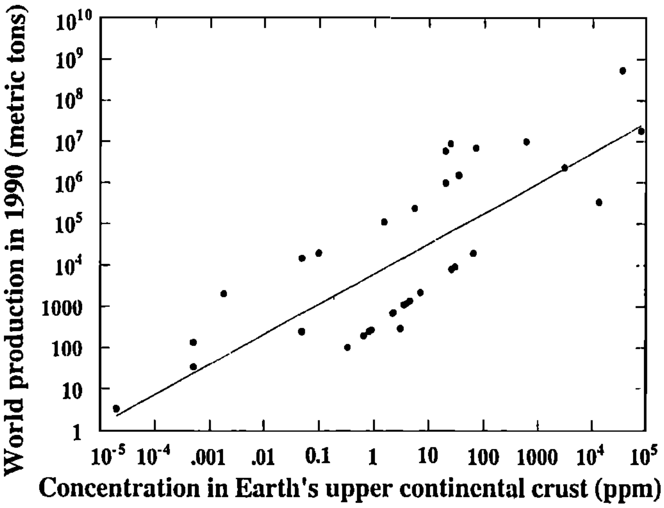

Figure 2. Correlation between global production of metals and the abundances of these metals in the Earth's upper continental crust. Abundance data are from *Taylor and McLennan* [1985]. Production data are from the *U.S. Department of the Interior Bureau of Mines* [1993].

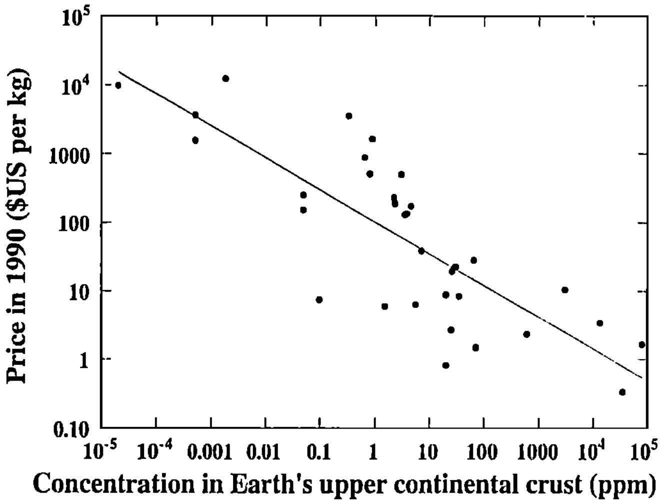

Figure 3. Correlation of average recent market prices with crustal abundances of metals. Abundance data from *Taylor and McLennan* [1985]. Prices from statistics of the *U.S. Department of the Interior Bureau of Mines* [1993].

term as technological applications of metals have evolved to reflect the availability of metals in the crust. Given these technological applications and levels of use, relatively short-term market forces of global economics tend to take over and dictate year-to-year and day-to-day fluctuations in price (as noted above, precious metals have their own peculiar market forces).

The economic history of Al exemplifies the empirical link between availability and utilization of resources, but it also shows that crustal levels of element abundances and availability have not always been nearly equivalent. Aluminum is the third most abundant element in the Earth's crust (after O and Si), but it does not exist on Earth as a native metal. Aluminum was unknown as an element until 1824 (therefore, it was unavailable) because the technology for its isolation from silicates and other minerals did not exist until then [*McGraw-Hill Book Company*, 1982]. During the decades between the discovery of Al and its first commercially successful separation in 1854, this metal had scientific but no industrial importance. The first products of commercial Al production were so valued as a precious metal that Al was displayed next to the crown jewels at the Paris Exposition of 1855, and Al cutlery was used on state occasions by Emperor Napoleon III [*Greenshaw and Earnshaw*, 1984]. By 1858 the price of Al had dropped from $600/kg to $25/kg. Further technological developments caused the production of Al metal to increase by many orders of magnitude and its market value to decline to just $0.40/kg by 1950, finally reflecting the fact that Al is extremely abundant and highly available (given the necessary technology) in Earth's crust. Many 20th Century technologies involving Al no doubt would not have been supported nor even imagineable at the Al prices and production levels prior to the mid 1850's. The case of Al offers grounds for speculating that asteroidal sources of precious metals may in the future offer a comparable technological boon to society.

The availability of any metal (generally related to crustal abundance) cannot be tightly controlled by a single major producer or cartel. The availability of metals throughout history has been imposed on society by nucleosynthesis in stars, processes responsible for the origin of the Earth and its core and crust, and sedimentary and hydrothermal processes near Earth's surface. Thus, availability is not the same economic concept as supply, which can be controlled in the short term by an important group of producers. Though a producer may control access to a rich crustal source of metals, other ores (perhaps of a slightly lower grade) are always accessible to other potential producers.

The vision of asteroid mining would mean that, for the first time, the special geologic circumstances unique to Earth's history would no longer control the availability and economics of precious metals. Instead, it is the conditions of asteroid origin and evolution (and, as always, our ability to obtain these metals) that would matter. If extraterrestrial precious metals are eventually mined and, in response, market prices decline, there is no doubt that existing industrial applications of these metals would be expanded. For example, cheaper PGM alloys could be used in civilian as well as military aircraft, possibly enabling lighter, stronger airframes and more powerful engines to transport larger payloads with better fuel efficiency; catalytic converters in internal combustion engines could be produced with less expensive Pt catalysts, reducing the cost of the converters and making these pollution-control devices available to poor nations that otherwise may do without them; and PGMs could be used to densify penetration-type munitions. Many entirely new technologies, though difficult to predict specifically, could become economically feasible. Though it may require decades for scientists, engineers, and businessmen to imagine and implement these new technologies, such unforseen applications likely would be realized with the importation of asteroidal metals, as suggested by the correlation of global metal production with availability (Figure 2) and historic experience with Al production.

3. Exploitation of Asteroids for Their Precious Metals

Fourth-period transition metals, especially Fe, dominate current world metal production (Figure 1) because of their diverse chemophysical properties and high abundances in Earth's crust (Figure 2) and the consequences of these abundances for low prices (Figure 3). As discussed above, Au and PGMs are so rare and expensive that their industrial uses are sharply limited. The high prices of precious metals motivated the first attempt to mine an asteroid. D.M. Barringer, early this century, believed that precious metals could be extracted profitably from the iron meteorite that formed Meteor Crater, Arizona. He thought that the main body of the meteorite was still buried, intact, beneath the crater. After expending a considerable personal fortune in drilling, Barringer failed in his attempt, because (1) the impactor had a mass of only ~3×10^5 tons instead of the 10^7 tons that Barringer had predicted, and (2) much of the impactor had blown itself to bits on impact [*Hoyt* 1987].

Au and PGMs are rare mainly because geochemical processes have sequestered ~99.8% of them in the most inaccessible part of our planet, the core [*Kargel and Lewis*, 1993]. These metals can be economically extracted from

Earth's crust only where igneous, hydrothermal, and sedimentary processes have re-enriched them by 3 to 4 orders of magnitude. Typical ores contain ~10 ppm Au; some of the highest grade contain 30 ppm (compared with about 0.001 ppm in the average silicate portion of Earth). These ores commonly also contain 0 to 20 ppm of PGM, for a total of 10 to 50 ppm Au and PGM. It is assumed that asteroidal ores would have to be substantially richer to warrant consideration for exploitation; fortunately, many asteroids are vastly richer.

Meteorites, Asteroids, and Possibilities for Importation of Their Metals

The orbits of over 4000 asteroids have been catalogued [*Binzel*, 1989], and the age of space-based asteroid exploration has begun, but no asteroid has yet been directly sampled in space. However, meteoritic fragments of asteroids have been extensively studied and analyzed. Many stony meteorites, including most carbonaceous chondrites, contain their metals entirely or almost entirely in oxidized form, but others contain metallic alloys [*Dodd*, 1981]. Meteoritic metal is composed chiefly of Fe-Ni phases, especially kamacite and taenite, suggesting that metalliferous asteroids could eventualy become major sources of these and other ferrous metals. Some meteoritic metal also contains potentially valuable traces of precious metals (Table I, columns 1-4). Hence, asteroids have been considered as possible rich sources of precious metals [*Gaffey and McCord*, 1977; *Lewis and Hutson*, 1993].

Iron meteorites are thought to be the metallic Fe-Ni-rich cores of asteroids that differentiated early in the history of the Solar System [*Scott*, 1972; *Wasson*, 1985; *Hirata and Masuda*, 1992; *Morgan et al.*, 1992; *Taylor*, 1992; *Keil and Wilson*, 1993]. Ordinary chondrites (and certain rare meteorite types, such as enstatite chondrites, C3-chondrites, and Renazzo-type CR-chondrites) did not differentiate, so that their native metal is still dispersed among silicates. Metalliferous chondritic meteorites (mostly ordinary chondrites) contain ~1% to 20% free metal by mass [*Muller et al.*, 1971; *Dodd*, 1981]. Some igneous silicate-rich meteorites, such as the pallasites and other stony-irons, also are metalliferous, either because their metal and silicate phases did not completely segregate or because they were derived from the core/mantle boundaries of differentiated asteroids. It is only the parent bodies of metalliferous meteorites (irons, stony-rons, and metal-bearing chondrites) that are potential economic sources of precious metals.

Galileo images of two spectral S-type (stony-irons? [*Granahan et al.*, 1993]) main-belt asteroids, Gaspra and Ida, revealed highly nonspheroidal, faceted shapes, suggesting that they are remnants or fragments of larger objects that were broken by large impacts. It is possible, according to one interpretation, that Gaspra may consist of two large, gravitationally bound objects (*C. Chapman*, personal communication, 1994); such "contact binaries" may be common among asteroids; an unambiguous contact binary asteroid, 4179 Toutatis, recently has been imaged by radar [*Jet Propulsion Laboratory*, 1993]. A recently discovered natural satellite of Ida has been explained as a fragment of the same impact that disrupted the proto-Ida, adding further support to the hypothesis that many asteroids are fragments of once-larger objects. Although Ida and Gaspra may be composites of several objects, their shapes suggest that they are not the "rubble piles" [*Veverka et al.*, 1993] that most asteroids were once thought to be. However, the high areal densities of small, superposed impact craters indicate histories of relentless bombardment and formation of thick surface layers of pulverized regolith. Catastrophic impacts and gradual impact pulverization and impact erosion have probably dominated the geologic histories of most asteroids in the Solar System for perhaps the past 3 billion years. These processes may have eroded the silicate crusts and mantles of some differentiated asteroids, thereby exposing their metallic cores, pieces of which have subsequently reached Earth as iron meteorites. Although remote spectral data and radar observations indicate that such metallic asteroids exist, no closeup spacecraft images of such objects have yet been acquired.

There are practical (economic) and environmental reasons to consider the near-term exploitation of metalliferous asteroids for precious metals, but probably not for ferrous metals. *Gaffey and McCord* [1977] estimated that 1 km^3 of asteroid metal would contain enough Fe to supply the world for 15 years and enough Ni for 1000 years. However, these authors calculated that satisfaction of 50% of the world's demand for Fe from asteroidal sources would require transport of 650,000 metric tons per day! Such a rate probably could not be achieved in the near term regardless of the ingenuity and efficiency of space transportation systems of the early 21st century.

Aside from the technological challenge of delivering bulk asteroid material to Earth in quantities sufficient to satisfy the world's demand for ferrous metals, there exist potentially severe environmental problems. The most formidable of these relates to NO_x production by atmospheric shock heating and resulting ozone destruction (*J. S. Lewis*, personal communication, 1994). The quantity of imported extraterrestrial material envisioned by *Gaffey and McCord* [1977], 650,000 metric tons per day, would require the dissipation of ~4 x 10^{23} ergs per day (equivalent to a 10-megaton (MT) nuclear explosion each day) during atmospheric entry. For small-scale objects, the efficiency of NO_x generation during hypersonic flight is roughly 10^{-12} g of NO_x per erg, for a total yield of ~400,000 metric tons of NO_x per day. Certainly much larger quantities of cosmic material than those considered by *Gaffey and McCord* [1977] have entered Earth's atmosphere many times throughout geologic history: on average, one kilometer-sized object has entered every 250,000 years [*Shoemaker et al.*, 1990]. However, NO_x production caused by some of these events probably had catastrophic ecologic effects.

It is unclear exactly how much asteroidal material could be imported without Earth's incurring significant environmental damage. The quantities considered by Gaffey and McCord could be catastrophic for modern agriculture and many species. *Chamberlain and Hunten* [1987], for example, cited calculations that a 100-MT atmospheric nuclear test series would inject into the stratosphere an amount of NO_x equivalent to 10-25% of the ambient atmospheric abundance, and that this injection should result in a 4-5% depletion in the stratospheric ozone abundance; clearly, if these calculations are correct, the Earth's ozone

Table 1. Abundances and Potential Value of Precious Metals in Meteorites and Asteroids

Metal	Abundance in Metal of H-Chondrite,* ppm	Abundance in Metal of LL-Chondrite*, ppm	Abundance in Good 90th Percentile Iron Meteorite†, ppm	Mass in Good 1-km Metallic Asteroid, metric tons‡	Value, Billions $US, Recent Prices§	Value, Billions $US, Deflated Prices#
Ru	5.8	17.8	21.5	87,000	171	5
Rh	1.1	3.3	4.0	16,000	1838	89
Pd	4.5	14	16.5	67,000	246	35
Os	3.9	12.1	14.5	58,000	778	9
Ir	3.9	12.0	14.0	56,000	554	10
Pt	8.0	24.7	29.0	117,000	1474	146
Au	1.1	3.5	0.6¶	2400¶	30¶	29¶
SUM	28.3	87.4	100.1	407,400	5091	323

* Abundances in ordinary H-chondrite metal are based on the assumptions that the bulk meteorite contains 0.72 ppm Ir [*Müller et al.*, 1971], chondritic relative abundances of Au and PGMs [*Morgan et al.*, 1985; *Anders and Grevesse*, 1989], that these precious metals are contained entirely in a free metal phase constituting 18.7% by mass of the meteorite [*Müller et al.*, 1971; *Dodd*, 1981]. The element abundances in the metal of LL chondrites was calculated in the same way, using the average values of 2.96% metal, 0.35 ppm Ir in bulk meteorite [*Müller et al.*, 1971].

† Richness for a "good" 90th percentile meteorite was determined from Ir abundance-frequency curve in Figure 1 coupled with knowledge that PGM maintain C1-chondrite ratios [*Anders and Grevesse*, 1989] in iron meteorites. The abundance of Au, however, is negatively correlated with PGM abundances; the abundance of Au in the tabulated "good" meteorite is based on abundance correlations given by *Wasson* [1985]. Abundances in the probable "best" metallic object are two to three times the listed concentrations.

‡ Assumed to contain 100 ppm of precious metals in the abundances listed in column 2 for the "good" meteorite.

§ Value is based on average 1990 prices on world commodities exchanges: Au $12,405 per kg ($385 per troy ounce), Ru $1,966 per kg ($61 per troy ounce), Rh $114,890 per kg ($3565 per troy ounce), Pd $3,674 per kg ($114 per troy ounce), Os $13,406 per kg ($416 per troy ounce), Ir $9,894 per kg ($307 per troy ounce), Pt $12,601 per kg ($391 per troy ounce). Prices from statistics of the *U.S. Department of the Interior Bureau of Mines* [1993].

Value is based on deflated prices expected to result from flooding the metals market with the metal from one 1-km 90th-percentile asteroid over a period of 20 years. Deflated prices were calculated as explained in the text and as illustrated in Figure 1. Deflated prices are Au $11,988 per kg ($372 per troy ounce); Ru $56.16 per kg ($1.74 per troy ounce), Rh $5535 per kg ($171.75 per troy ounce), Pd $522 per kg ($16.20 per troy ounce), Os $152.63 per kg ($4.74 per troy ounce), Ir $172.40 per kg ($5.35 per troy ounce), Pt $1250.10 per kg ($38.79 per troy ounce).

¶ Due to the negative correlation between PGM and Au [*Wasson*, 1985], a 90th-percentile meteorite selected on the basis of PGM richness is in the 10th percentile of gold richness.

layer could not be sustained with the equivalent of a 10-MT explosion occurring every day caused by the engineered importation of bulk asteroidal material. By contrast, the normal level of atmospheric entry of cosmic matter is ~140 metric tons per day [*Love and Brownlee*, 1993], which generates a roughly equivalent mass of NO_x. The scenario of *Gaffey and McCord* [1977] involves a nearly 5000-fold increase in the daily rate of entry of cosmic material, a potentially serious threat to the ozone layer and biosphere.

The possibilities for near-term recovery of Au and PGM from asteroids are more promising than for ferrous metals, because (1) some asteroids probably contain the high concentrations of precious metals that would be required to permit economic recovery [*Lewis and Hutson*, 1993], and (2) a comparatively small mass of precious metals from asteroids could have a large economic and industrial impact and a smaller environmental impact than present-day Au and Pt mining.

4. The Potential of Asteroids as Sources of Precious Metals

Abundance of metalliferous near-Earth asteroids

Transport to Earth of precious metals from near-Earth asteroids (NEAs) generally would require little change in velocity, hence little energy expenditure and relatively modest propulsion requirements compared to the return of metals from main-belt asteroids [*O'Leary*, 1977, *Davis et al.*, 1993]. NEAs are also more attractive than main belt asteroids in that the former are easier to reach from the Earth; in fact, about 15% of NEAs are energetically easier to reach than the Moon's surface [*Davis et al.*, 1993]. We can assume, at least in the near term, that practical asteroidal sources of precious metals are among the NEAs.

There are ~1700 to 2000 NEAs larger than 1 km in diameter [*Shoemaker et al.*, 1990; *Davis et al.*, 1993; *D.Morrison*, unpublished report, 1992]. The numbers of metalliferous NEAs can be estimated on the basis of the total number of NEAs, statistics on meteorite falls, and spectral and radar surveys of NEAs (Table 2). The estimates based on the percentage of iron meteorite falls are biased by meteor strength; i.e., the fraction of incoming metallic objects tends to be overestimated, while the fraction of fragile carbonaceous objects is underestimated. Estimates based on spectral and radar studies are biased by asteroid albedo and radar reflectivity; again, this bias causes an overestimation of the fraction of metallic asteroids, because it is easier to observe and spectrally analyze the brighter metallic objects and to obtain a radar reflection from them.

Spectral studies and statistics on meteorite falls approximately agree that 2-5% of NEAs are metallic (Table 2). The approximate convergence of estimates for metallic NEAs does not extend to the estimated abundance of stony-iron and metal-bearing chondritic asteroids. The spectral surveys indicate that ~35% of NEAs are S-type objects. S-type objects are thought to consist of variable proportions of silicates and metal, including some fraction of ordinary chondrites, enstatite chondrites, and possibly pallasites, among others. *Gaffey et al.* [1993] suggested that ~10% of the S-type asteroids in the main asteroid belt are consistent with the spectral reflectance of ordinary chondrites. If this fraction also characterizes the NEAs, then one concludes from the spectral studies that as few as 3.5% of NEAs may be ordinary chondrites. In an apparent conflict, the statistics on meteorite falls suggest a much higher fraction of ordinary chondrites, 81%. This conflict can be reconciled only if there are large real differences in the study samples. The sample of observed meteorite falls probably does not randomly sample the entire population of NEAs. Petrologic families of NEAs that have a large percentage of their mass on or very close to collision courses with Earth no doubt are oversampled, whereas other NEA groups are probably undersampled. This problem is similar to the nonuniform delivery of asteroids from the main belt to Earth-crossing orbits [*Gaffey et al.*, 1993]. The spectral survey by *McFadden et al.* [1989] probably comes closest to a complete sampling of the NEAs, but there are large ambiguities in the petrologic interpretation of remotely sensed data [*Gaffey et al.*, 1993].

Radar observations provide an independent means to determine the fraction of metallic asteroids. Of several NEAs studied by radar, apparently one is metallic [*Ostro*, 1989]. The selection bias favoring the detection of metallic objects is similar to that of spectral reflectance studies, and in any case the statistics are poor. Nevertheless, the radar studies have critically validated a basic inference provided by the spectral studies that metallic NEAs do, indeed, exist.

The frequency of achondrite falls offers another way of estimating the abundances of metallic objects. Achondrites are silicate igneous material (solidified lavas, crystal cumulates from magmas, or residual mantle solids left after partial melting). Some achondrites have lunar or Martian origins, but most were probably derived from the crusts and mantles of differentiated asteroids; the complementary components of these parent objects are their metallic cores. The asteroidal achondrites constitute 7.9% of falls [*Sears and Dodd*, 1988]. This fraction is probably not strongly biased by mechanical strength, because achondrites tend to be intermediate between the chondrites (weak) and irons (strong). Achondrites show geochemical indications that they equilibrated with metal, which presumably segregated to form a core (or other isolated metallic bodies) in each achondrite parent body. The metal contents of ordinary chondrites and the core:mantle mass ratios of Earth and Venus suggest that the metal:silicate ratio of basaltic achondrite parent bodies was probably in the range from 0.1 to 0.5. If we assume that differentiated NEA parent objects had a nominal metal:silicate ratio of 0.25, then the fall rate of asteroidal achondrites suggests that metallic objects constitute ~2% of NEAs (Table 2).

If we consider selection biases and the statistical uncertainties in each estimate, the estimated fractions of metallic asteroids given in Table 2 are roughly consistent (2-5%). A nominal 3% metallic NEAs is adopted. Hence, of ~2000 NEAs larger than 1 km, perhaps 60 are metallic. At least two 2-km metallic NEAs have been identified from spectroscopic studies [*Tedesco and Gradie*, 1987], a finding which has radar confirmation [*Ostro*, 1989].

The fraction of metal-bearing silicate-rich objects among the NEAs is unclear; anywhere from about 3.5% to 35% is possible. (The fraction of ordinary chondrites among observed meteorite falls, 81%, is thought to be unrepresentative of the NEAs, as discussed by *Gaffey et al.* [1993] and others.) Therefore, the number of metalliferous silicate-rich NEAs larger than 1 km apparently is anything from 70 to 700. However, as discussed below, few metalliferous silicate-rich NEAs would be desirable as sources of precious metals; it is primarily the LL chondrites that would be of great interest, and only about 2% of ordinary chondrite falls are LL chondrites; this implies that there should be about 1 to 14 LL chondrite NEAs larger than 1 km.

Abundances of precious metals

The selection of an asteroid to be exploited will involve trade-offs between the number of NEAs of each desirable type, their abundances of metallic phases and the average concentration of precious metals in the metallic phases, the difficulty of extraction and manipulation of the metallic ore, the time of flight and propulsion requirements to achieve mass transfer between the asteroid and Earth (hence, the orbital parameters of the asteroid), and the size of the object.

The most abundant type of meteorite (81% of all observed

Table 2. Estimated Percentages of Near-Earth Asteroids (NEAs) That are Metalliferous

Type of asteroid	From 832 Meteorite Falls (Observed %)*	From 832 Meteorite Falls (Calculated as 25% of Achondrites)†	From Spectral Surveys‡	Adopted
% metallic NEAs	5.0 ±0.8	2.0±0.3	4.7 ±3.3	3.0
% metal-bearing stony and stony-iron	81.0 ±4.0	—	3.5 ±0.6 to 35 ±6	3.5 to 35
% LL chondrites	2.0±1.0	—	—	0.07 to 0.7§

* From *Sears and Dodd* [1988].

† The basis for this calculation is described in the text; the survey of falls is that of *Sears and Dodd* [1988].

‡ The percentage of metallic NEAs is the fraction of M-type objects in a spectral survey of 43 NEAs [*McFadden et al.*, 1989]. The higher estimate of the fraction of metalliferous stony objects is the fraction of S-types reported in the spectral survey by *McFadden et al.* [1989]. The lower estimate of metalliferous stony objects is derived from the fraction of S-type NEAs [*McFadden et al.*, 1989] and the interpretation of *Gaffey et al.* [1993] that only 10% of main-belt S-type asteroids have spectra that are consistent with ordinary chondrites or a closely similar silicate-metal mixture. To this lower estimate should be added the other spectral types of asteroids that *Gaffey et al.* [1993] believe are stony-irons, such as pallasites and enstatite chondrites. This addition would probably bring the lower estimate much closer to 35%.

§ These values are the observed fraction of LL chondrite falls (~2%) multiplied by the adopted percentage of metal-bearing stony and stony-iron meteorites.

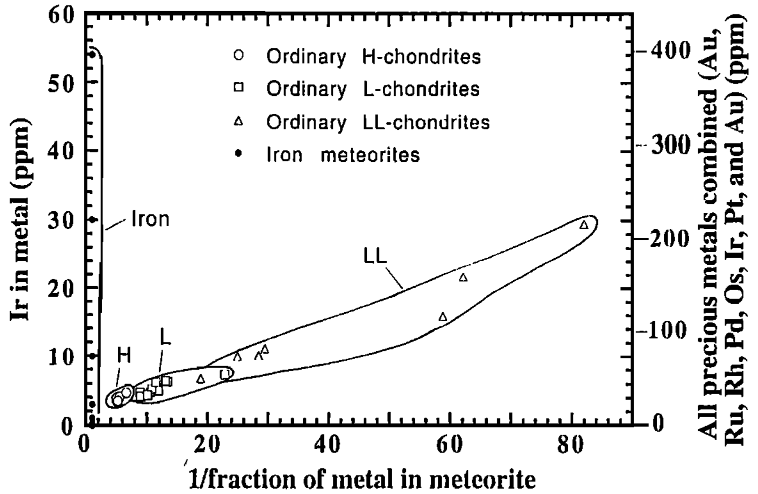

Figure 4. Inverse relationship of the content of Fe-Ni metal in ordinary chondrites and the Ir content of that metal. The figure shows that the richest metal of LL chondrites has an amount of Ir (and presumably other PGMs) comparable to that in the metal of some of the richest iron meteorites; however, the richest LL chondrites contain only ~1.2 mass % metal. Data calculated from *Müller et al.* [1971] on the assumption that Fe-Ni metal contains all of the meteorites' Ir.

falls; [*Dodd*, 1981]) are the ordinary chondrites (including H-, L-, and LL-chondrites). Ordinary chondrites contain 1%-20% metal dispersed through silicates and sulfides, and this metal is rich in precious metals in many instances. There is an inverse relation between the abundance of free metal in ordinary chondrites and the metal's content of Au and PGM (Figure 4). The average ordinary H-chondrite contains about 18.7% (by mass) Fe-Ni metal. This metal contains an average of ~3.9 ppm of Ir [*Müller et al.*, 1971]. Assuming chondritic ratios of Au and the PGMs, this average H-chondrite metal should contain 28 ppm of precious metals (Table 1), whereas the metal in ordinary LL-chondrites may contain 50-220 ppm of precious metals in a smaller fraction (1.2-5.3%) of free metal (Figure 4). If magnetic raking is an efficient process, then LL-chondrites could be an attractive target for exploitation if one of them can be identified and certified to be rich in precious metals. A problem is that LL chondrites are comparatively rare; they can be distinguished from H chondrites on the basis of spectral data, but they are probably not readily spectrally distinguishable from L chondrites [McSween *et al.* 1991].

Ordinary chondrite asteroids are mineralogically heterogeneous and brittle, which would make ordinary chondritic "bedrock" fairly easy to disaggregate. In fact, ordinary chondrite asteroids probably have thoroughly impact-pulverized regoliths; the metal may be easily separable from nonmetallic phases by electromagnetic raking so long as a large fraction of the regolith is comminuted into virtually monomineralic grains (grain sizes are commonly 100-1000 μm). Few observational constraints are available concerning the grain size distribution of asteroidal regoliths; however, the basaltic achondrite asteroid 4 Vesta is thought to have a predominant grain size in its regolith of <25 μm [*Hiroi et al.*, 1994].

An important factor that may favor the selection of an ordinary LL chondrite asteroid for exploitation is that a few ordinary chondrite parent bodies apparently are in very favorable orbits (low geocentric velocities) for the natural delivery of ordinary chondrite meteorites to Earth. This is indicated by the large percentage of ordinary chondrite meteorite falls (Table 1); such favorable orbits should also assist the engineered transfer of mass from these objects into Earth-intercept orbits.

Metallic asteroids consist virtually entirely of Fe-Ni-dominated phases. Their abundances of precious metals is much more variable in iron meteorites than in ordinary chondrites, so that selection of the best metallic asteroid will require detailed exploration if such asteroids are to be exploited. Metallic asteroids are relatively homogeneous and ductile, which would make them more difficult to disaggregate and process than ordinary chondrites (unless their metal were cooled below the brittle/ductile transition); their ductility also would make it less likely that a thick regolith exists on metallic asteroids. Some metallic asteroids apparently contain much higher concentrations of precious metals than in the highest grade metal of ordinary LL chondrites, possibly making the exploitation of metallic asteroids more cost effective than stony-iron bodies.

The abundances of Ir and other PGM in iron meteorites correlate linearly with one another and inversely correlate with the abundances of Ni and Au [*Scott*, 1972; *Buchwald*, 1975; *Wasson*, 1985; *Hirata and Masuda*, 1992; *Morgan et al.*, 1992; *Keil and Wilson*, 1993]. Element-abundance plots have been used to delineate several large classes of iron meteorites; each class apparently was derived from a single parent asteroid, although the parent objects may have been broken by impacts into many smaller asteroids and meteorites.

The total range of Ir abundances in iron meteorites spans 4 orders of magnitude. In most groups of iron meteorites this range appears to have been produced by fractional crystallization, shortly after the origin of the Solar System, of metallic solid phases in the molten cores of asteroids [*Scott*, 1972; *Hirata and Masuda*, 1992; *Morgan et al.*, 1992; *Taylor*, 1992; *Keil and Wilson*, 1993; *Taylor et al.*, 1993; *Jones*, 1994]. Fractional crystallization helped to create some meteorites and asteroids that are spectacularly rich in PGM (conversely, other metallic objects are grossly depleted). Although one can imagine several modes of origin of fractionally crystallized asteroidal cores, perhaps the simplest scenario involves formation of a completely molten core followed by its progressive solidification. *Taylor et al.* [1993] suggested that, because of cooling of asteroidal cores from the outer surface and because of the lack of a strong radial (pressure) dependence of the metal liquidus, the metallic cores of asteroids crystallized in a very complex way different from the concentric accretion of Earth's core. The cores of asteroids would solidify by the inward radial growth of huge metallic dendrites, eventually resulting in the formation of numerous closed magma chambers. In this scenario, the solidified metallic cores of asteroids should be compositionally heterogeneous, with substantial radial and lateral chemical zonation, rather than a simple concentric zonation. This scenario could have important implications for asteroid mining and resource exploration, because it raises the possibility that individual metallic asteroids (whether they are small fragments of cores or virtually intact cores) may be extremely heterogeneous in their abundances of precious metals.

Despite the fact that the concentrations of each precious metal may differ by 4 orders of magnitude among the individual meteorites of a given class, the abundance ratios of PGM are close to chondritic in almost every case [*Hirata and Masuda*, 1992; *Morgan et al.*, 1992]. These chondritic ratios indicate similar geochemical behaviors of PGM during core formation and solidification in the parent bodies. These ratios also imply that the abundances of all the PGM may be estimated if only one PGM is measured.

Figure 5 shows the percentile rankings of Ir contents in 275 iron meteorites encompassing 12 classes. The median iron meteorite contains ~2 ppm Ir; the richest contains over 50 ppm Ir. If they have chondritic ratios of PGM, some of the richest meteorites should contain 75 ppm Ru, 14 ppm Rh, 59 ppm Pd, 51 ppm Os, 50 ppm Ir, 103 ppm Pt, and

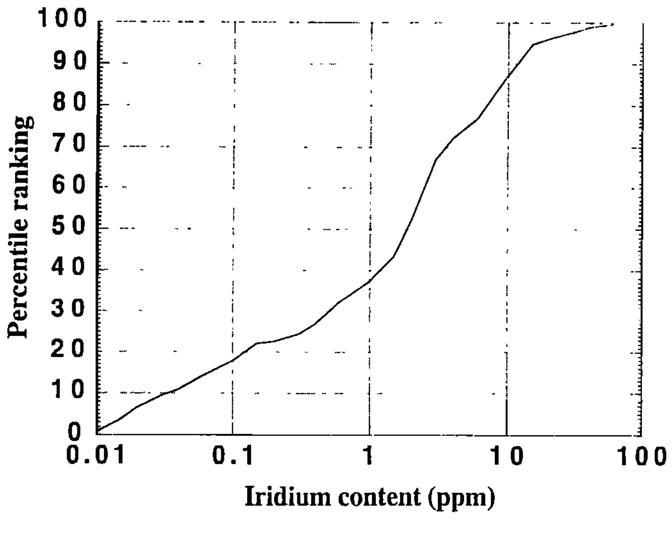

Figure 5. Cumulative plot showing percentile ranking of iridium contents of 275 iron meteorites. Data from *Buchwald* [1975].

0.5 ppm Au, or a total of 353 ppm of precious metals; this value is in the 99th percentile in meteorite richness. A meteorite near the 90th percentile is about one-fourth as rich, but still it contains 14 ppm of Ir and a respectable 100 ppm of Au and PGM combined (Table 1). The lower limit of richness that would be required for profitable recovery is unknown, partly because the cost of the endeavor is unknown. A profit threshold at 100 ppm is just a guess, but it serves to frame a baseline model.

If there are 60 metallic NEAs larger than 1 km in diameter, as discussed above, then about 6 are in the top 10% of richness (above the 90th percentile, the "good" asteroids). In addition, there should be $\sim 10^4$ highly enriched metallic NEAs larger than 100 m in diameter. The quantities of Au and PGM in just one good 1-km asteroid are given in Table 1. It is probable that some asteroids, or parts of some asteroids, are 2 to 3 times more enriched in PGM and are significantly larger than assumed for calculation of the values in Table 1; hence, Table 1 is conservative in terms of the potential yield of precious metals.

Table 1 also lists the potential value, at recent market prices, of precious metals that may be contained in one good asteroid. Production on the suggested scale would exert substantial downward forces on market prices, an effect which is considered in the section below. One metallic asteroid measuring 1 km in diameter has a mass $\sim 4 \times 10^{15}$ g. One asteroid of this size bearing 100 ppm of Au and PGM would contain 400,000 metric tons of precious metals worth over $5 trillion at recent market prices! Other less expensive precious metals, including Re, Ge, Mo, and Ag, also could be produced on large scales depending on the economics of the venture. Because the precious metals constitute only ~0.01% of the mass of the asteroid, it would be most efficient to refine the ore in situ and to return only the precious metals to Earth. If the precious metal content of a 1-km asteroid was mined, returned, and marketed over 20 years, the return rate would be a relatively modest 20,400 metric tons per year, or about 56 tons per day, a rate seemingly achievable with existing propulsion technologies.

The return rate of precious metals in this scenario is less than half the accretion rate (140 tons/day) of cosmic debris that naturally rains onto the Earth [*Love and Brownlee*, 1993]. This rate of importation of mass into Earth's atmosphere would have a negligible impact on the ozone layer. Indeed, the total negative environmental impact and hazard of such an endeavor, including launch of the mining infrastructure, entry hazard, and other aspects, may well be substantially less than the environmental impact of modern Au and Pt mining.

Downward Forces on Market Prices

Production from a good asteroid. The economic feasibility of asteroid mining would hinge partly on the response of the metals market to importation of asteroidal metals. This response would depend on, among other things, the development of new industrial uses of the metals, something that is not easily predicted. As discussed above, production of nearly all metals is in rough proportion to their abundances in Earth's crust, indicating that availability drives production, consumption, and market price to a large extent.

The correlation in Figure 1 was used to estimate the value per unit mass of Au and PGM after asteroidal metals would begin to arrive on Earth (indicated by the arrows in Figure 1). According to the slope of this correlation, deflated prices, p', would be related to current prices, p_o, by

$$p' = p_o(P'/P_o)^{-0.60},$$

where P' is the rate of production of asteroidal plus terrestrial metal and P_o is the rate of current production. If one assumes production levels equivalent to depletion of one good 1-km asteroid in 20 years, the value of Au and PGM would fall to the values indicated in the last column of Table 1. The market value of Au is hardly affected, because asteroidal Au would amount to just 5% of current world production, but the market values of PGM would crash.

Economic potential of the best asteroid. The estimated market value and tonnages of precious metals given above and in Table 1 are based on a conservative set of calculations for the smallest and least rich of the six good metallic NEAs. According to the estimated number of NEAs (Table 2) and the Ir abundances in meteorite falls (Fig. 5), the best metallic NEA may contain about 33 ppm of Ir (corresponding to the 98th percentile in Figure 5), and it may have twice the mass of the asteroid discussed above. There is a 50% chance that one such NEA exists; it could contain a total of 1.9 million metric tons of precious metals. The total deflated market value of the precious metals, if marketed over 40 years, may be approximately $900 billion. Because the best metallic NEA is twice as massive as the 1-km object, the annual rate of processing of raw Fe-Ni metal is the same as in the analysis for the 90th-percentile good asteroid. The annual yield of precious metals from the best asteroid, about 47,000 tons, would be 2.3 times greater that from the good asteroid.

Metals Exploration of Asteroids

Recovery of the metals from NEAs would require the prior detection and assaying of metallic and other metalliferous NEAs. An expanded program of Earth-based radar and spectrophotometric telescopic observations might be used to distinguish metallic from nonmetallic NEAs and L/LL chondrites from H, E, and C chondrites. Following or concurrent with this, fly-by "Discovery"-class or Clementine probes could be sent past several dozen suspected metallic and L/LL chondrite NEAs. The probes could be equipped with imaging systems and imaging spectrometers that are sensitive in the infrared, visual, and ultraviolet. Several NEAs could be explored by each probe over a period of several years, thus acquiring data on their size, mass, density, composition, and regolith characteristics. The fly-by program might be accomplished with about 10 spacecraft, each costing less than $150 million to build, launch, and operate, if these missions could be accomplished under the guidelines of the Discovery program. If the Clementine spacecraft were used, the cost might be as low as some tens of millions of dollars per probe.

Asteroid rendezvous missions, comparable to Near-Earth Asteroid Rendezvous (NEAR), could be sent to several promising NEAs. These spacecraft could be equipped with gamma-ray spectrometers and high-resolution visual and infrared-imaging systems, which could provide global mapping and better data on the abundances of Fe, Ni, Co, and precious metals.

Landers, with or without sample-return capabilities, but certainly with drilling (perhaps laser drilling) and chemical-analysis capabilities, then could be deployed to some of the asteroids that seem to have the highest economic potential. Besides returning precise compositional data, the landers could provide important information on the mechanical engineering properties of the regolith and surface metals. Finally, one NEA could be selected for initial exploitation.

Metals recovery

The energy cost of transferring mass from the orbit of a favorable NEA to a trajectory providing direct entry into Earth's atmosphere is ~10^6 J kg^{-1}, an order of magnitude less than the energy that typically is expended in smelting operations for terrestrial Fe. Of course, this comparison does not include the great challenge in developing and supporting a large mining operation on a NEA. As discussed above, delivery of raw Fe-Ni-rich asteroidal material to Earth probably is not a near-term possibility. However, in situ processing and recovery of the precious metals would reduce the mass of recovered metals transported to Earth by four orders of magnitude, such that the most challenging task would be in the delivery of hardware to the asteroid.

Mining could begin by extraction of metal in manageable quantities. In situ processing of extracted metal might follow a four-step process:

1. Fusion of asteroidal metal.
2. Fractional crystallization to concentrate PGMs and Au.
3. Application of the Mond (carbonyl) process to separate Fe-Ni from PGMs.
4. Reheating of carbonyls to release CO and to yield PGM-rich metal extracts.

Processing would be preceded by isolation and extraction of ore. Metallic asteroidal metal could be fused and drawn off in the molten state or sawn in large pieces. Explosive pulverization might not be effective because of the ductility of the metal, unless the metal were first cooled below the brittle-ductile transition temperature, ~ 167 - 200 K [*Ryan and Davis*, 1994] either by natural night-time cooling or passive artificial shade-cooling. Melting may be the most efficient means of extraction of ore, because later processing of the metal might require it to be melted anyway.

Ordinary LL-chondrite asteroids may possess enormous volumes of regolith that is almost ready made for processing. Electromagnetic rakes might be used to separate metallic from rocky phases in the regolith if it includes a large fraction of fine-grained material. A large NEA, ~3 km in radius, has a surface area of ~100 km^2. If the crater densities and estimated regolith thicknesses on Ida and Gaspra are any guide, then we can expect that stony and stony-iron NEAs commonly possess regoliths ~100 m thick (if, indeed, they are not rubble piles throughout). Thus, a large NEA may contain ~10 km^3 of regolith on its surface, of which ~1-2 km^3 generally would be metal, including up to several hundred thousand tons of precious metals.

Nothing is expected to be simple in the deep-space environment, but the work expended in moving large masses of ore to a processing facility would be far less than in terrestrial mining. The low-gravity environment on asteroids (e.g., ~10^{-4} g on a 1-km metallic asteroid or a 3-km ordinary chondrite object) means that machines of relatively low mass could move hundreds of times their own mass in one operation. Rather than moving and dumping depleted waste to a site adjacent to a processing facility, which is usually an expensive and cumbersome job on Earth, waste could be entirely ejected from an asteroid by propelling it at speeds of only 2 to 6 m s^{-1}.

The initial fusion of asteroid metal (stage 1) would be the most energy expensive step in recovery of precious metals. Approximately 5×10^5 J kg^{-1} of asteroid (~5×10^9 J kg^{-1} of precious metal) would be expended in warming and fusing the metal in this step. Production of 20,400 metric tons of precious metals per year would require a minimum of 3 GW of energy. Likely energy consumption would be ~10 GW, if we consider that there would be less than 100% efficiency over thermodynamically ideal energy use, and that energy would be used in additional processing beyond the initial fusion. The required energy could be supplied by a solar electric plant covering 25 km^2 and having an efficiency of 30%, by solar reflectors covering 8 km^2, or by a nuclear power station. In watts per dollar of economic output, asteroid mining could be competitive with major Earth-based industrial endeavors; an advantage of asteroid mining is that the energy would be produced and used in space with no terrestrial environmental impact. Of course, this comparison does not convey the technical difficulties that would be encountered in the construction and operation of a large power plant in deep space. If a 10-GW power plant should prove too difficult to establish, there are alternative means of processing the metal that could greatly reduce the energy demand. Application of the Mond process to raw ore would entail use of far less energy than fractional crystallization, though the Mond Process would require a large mass of catalytic CO.

In one mining scenario, solar electric or nuclear energy would power electrical resistance heating and fusion; or electrical energy could be converted to laser light, which would impinge on and melt part of the asteroid's surface; liquid from a molten metallic lake then would be processed in situ or it could be drawn off and processed in a plant on the solid surface of the asteroid. In another scenario, solar radiation could be directly reflected onto the asteroid's surface, thereby inducing fusion.

Fractional crystallization (stage 2) could help to concentrate the precious metals in a smaller mass of Fe-Ni-PGM alloy. This step may be required to reduce the mass of industrial equipment and CO used in the carbonyl process (stage 3); otherwise, it would be necessary to apply the carbonyl process to the entire mass of the asteroid.

Fractional crystallization requires mechanical separation (e.g., filtration) or acceleration to cause density separation of phases. Acceleration could be provided by gravity or centrifuge. Filtration of solids from a mostly molten metallic slurry may offer a means of controlled fractional crystallization; ceramic sieves could be passed through the mush at specified intervals or temperatures. Alternatively, gravitational segregation of solids could be effective. Surface gravity on a 1-km metallic asteroid, ~0.11 cm s^{-2} (~10^{-4} g), is sufficient to produce Stokes settling rates ~ 2 cm s^{-1} for grains or solid aggregates 3 cm in size. (The viscosity of liquid metallic Fe-Ni is very low, ~ 10^{-2} poises [*Jeanloz*,

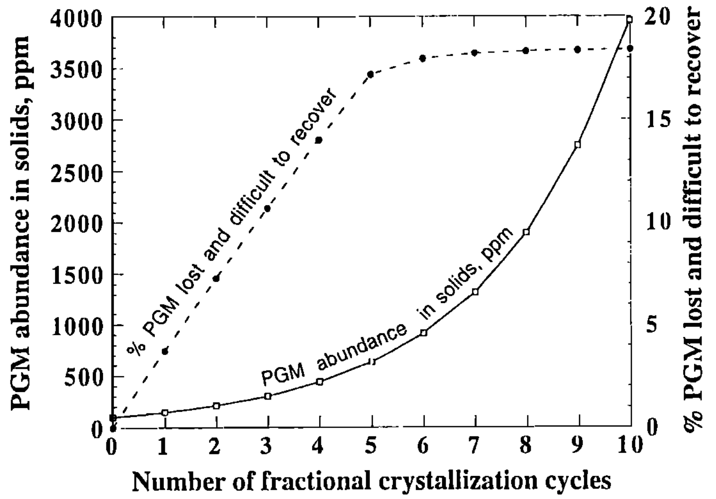

Figure 6. Model of fractional crystallization of asteroidal metal. Solid curve gives the concentration of PGM in the solid; dashed curve gives the cumulative percentage of PGM that is lost in the residual liquids as a result of fractional crystallization and that cannot be easily recovered.

1990].) If thermally driven convection prevents the settling of small grains, then a molten metallic lake could be seeded with large grains that could quickly grow to a size that would settle. Alternatively, thermal convection could be prevented if the surface of the lake were maintained at the liquidus temperature and cooling and crystallization occurred at the solid base of the lake as heat was conducted into the cold mass of the asteroid.

The first solids to crystallize would contain higher abundances of precious metals than the residual liquid except for Au, which would be concentrated in the last residual liquid. Fractionally crystallized PGM-enriched solids could be removed gravitationally for further processing. The last residual liquid could be processed to extract Au and to produce S, P, and C for use as additives to increase the efficiency of further fractional crystallizations. A drawback of fractional crystallization is that some precious metal would be lost in the residual liquid. The amount of lost metal could be minimized by employing several fractional crystallization/fusion cycles and by recrystallizing some of the residual liquid.

Figure 6 illustrates of the effects of multiple Rayleigh fractional crystallization cycles. In the first cycle, about 2/3 of the initial mass would be fractionally crystallized. The solid/liquid partition coefficients for PGM are ~3, appropriate for Fe-Ni-rich metal cooled well below the liquidus and initially containing 0.2% P, 0.2% S, and 0.1% C [*Willis and Goldstein*, 1982]. In reality, the partition coefficients are not constant with the changing composition of the metal [*Willis and Goldstein*, 1982; *Jones*, 1994], but for simple purposes of illustration the assumption of constant partition coefficient serves well. In each subsequent crystallization cycle, the solid from the previous cycle would be completely fused and then 2/3 of its mass would be fractionally crystallized. Roughly 3% of the PGM would be lost in the liquid during each crystallization cycle. Eventually, the solids would become so enriched in PGM that the residual liquids would be richer in PGM than the asteroid was initially; by this time, nearly all the PGM in the residual liquid could be recovered if the liquid itself were fractionally crystallized. Hence, the "% lost" curve in Figure 6 becomes horizontal after several crystallization cycles. The usefulness of fractional crystallization could be extended for several steps beyond that shown in Figure 6. According to binary Fe-Pd and Fe-Pt phase diagrams [*Elliott*, 1965], it should be possible to obtain a Fe-Ni-PGM alloy containing ~20% by mass of PGM after about 20 melting and fractional crystallization cycles.

Although the number of fractional crystallizations that would be required to concentrate the PGM makes it seem energy intensive, it really would not be as bad as it appears, because the mass of material would diminish at each step. The entire sequence of crystallizations would require approximately the same amount of energy that would be consumed in the initial fusion of raw asteroidal metal; all subsequent stages of processing would involve an almost trivial amount of energy, because the amount of mass involved would be relatively small. The efficiency of fractional crystallization in isolating PGM could be increased beyond that illustrated in Figure 6 if the solid/liquid partition coefficients of these metals were increased; this could be accomplished if P, S, and C were extracted from the final residual liquid and added to the PGM-rich material, because P, S, and C have substantial effects on metal partitioning [*Willis and Goldstein*, 1982].

In stage 4 (the carbonyl process), hot, condensed PGM-rich metal fragments would be reacted with CO to form gaseous carbonyls, which would then be distilled to separate Co-PGM-rich material from Fe-Ni [*Lewis and Lewis* 1987]. Reacted CO would be liberated during step 4 of processing, so that CO would effectively be a catalyst and could be recycled. Nevertheless, a substantial quantity of CO might need to be imported to the mining site, perhaps from a carbonaceous asteroid. If the quantity of metal subjected to this process could be reduced by prior fractional crystallization then the mass requirements for catalytic CO also would be reduced. However, the chief advantage of the carbonyl process, especially if applied to the entire mass of the raw metal, is that it is a fairly low-temperature process, so that energy requirements would be far less than if fractional crystallization was applied to the entire mass of the asteroid. Following liberation of CO and deposition of PGM alloys by a final heating, the PGM alloys could be shipped to Earth, where the PGM alloys could be further refined to produce pure native metals.

5. Conclusions and Future Directions

Some near-Earth asteroids (NEAs) may be considered for exploitation of their contents of precious metals (defined as Au, Pt, Ir, Os, Pd, Rh, and Ru). Observational knowledge of the compositions and physical nature of these objects stems mainly from chemical studies of meteorites (believed to be mainly samples of NEAs); Earth-based photometric, spectroscopic, and radar studies of asteroids; and spaceborne imaging of two asteroids. It is estimated that there are ~2000 NEAs larger than 1 km in diameter. Two types of NEAs, metallic asteroids and ordinary LL chondrites, are attractive as possible future sources of precious metals.

Specific asteroidal sources of LL chondrites are not known, but may include some spectral S-class objects. LL chondrites contain 1.2-5.3% (by mass) of metal, which may contain from 50-220 ppm of precious metals. Specific asteroidal sources of iron meteorites likewise are not yet known, but they are widely thought to be among the spectral M-type objects, which may constitute ~3% of the NEA population. Analyses of iron meteorites suggest that some metallic NEAs are highly enriched in Au and PGM. Statistically, there should be about six highly enriched metallic NEAs that are larger than 1 km in diameter and contain over 100 ppm of precious metals. The total value of 400,000 metric tons of Au and PGM in one such asteroid, at current market prices, would be over $5 trillion; the actual market value, at collapsed prices in a flooded market, may be closer to $320 billion (if marketed over 20 years). The very richest metallic NEA, containing 200 to 300 ppm of precious metals, might yield 1.9 million tons of PGM and Au worth $900 billion at deflated prices.

There are many unanswered technical questions. Exactly how could raw metal from metallic asteroids be crushed or fused and then manipulated? How effectively could electromagnetic rakes separate metallic particles from the regoliths of chondritic asteroids? What mass of catalytic CO would be required for a reasonably efficient and closed carbonyl process, and what would be the least expensive source of this CO? What type of deep-space transportation system would be required, and how much would it cost to develop and operate? How much human involvement (hence, expensive life support facilities) would be required? Could the deep-space part of the operation be automated in its entirety? If not, could mining and metal refinement be semi-automated and controlled by on-site telepresence involving few human operators? And the bottom line, what would be the cost of asteroid mining?

There remain major scientific questions pertinent to the engineering aspects of an asteroid exploration and mining venture. How effective and reliable are Earth-based spectrophotometric methods of asteroid compositional classifications? Exactly how did fractional crystallization and other processes concentrate the precious metals in asteroids, and how large were the parent bodies? Is each metallic NEA chemically zoned, so that high-grade ores exist in only a small portion of certain objects? Or does each metallic NEA represent a nearly homogeneous piece of a formerly much larger asteroid core?

Economic issues are perhaps the least understood, particularly the magnitude of market responses to introduction of a vastly increased supply of precious metals. Would there be legitimate industrial uses for the large quantities of precious metals considered in this report? Would these uses justify the enormous capital investments and devotion of technical expertise that would be required to make asteroid mining a reality? Finally, international law and the potential international political response to adjustments in the metals market and the rest of the global economy are matters that must be handled with proper concern.

It is unclear whether the financial return of asteroid mining could yield a profit, but there is a possibility that profits could be tremendous. Probably more important, the importation of abundant, cheap, new sources of precious metals could have an economic and technological impact that may be well beyond the market value of the metals.

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