

The Role of Near-Earth Asteroids in Long-Term Platinum Supply

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Abstract

High-grade platinum-group metal concentrations have been identified in an abundant class of near-Earth asteroids known as LL Chondrites. The potential existence of a high-value asteroid-derived mineral product is examined from an economic perspective to assess the possible impacts on long-term precious metal supply. It is hypothesized that extraterrestrial sources of platinum group metals will become available in the global marketplace in a 20-year time frame, based on current trends of growth in technology and increasing levels of human activities in near-Earth space. Current and projected trends in platinum supply and demand are cited from the relevant literature to provide an economic context and provide an example for evaluating the economic potential of future asteroid-derived precious and strategic metals.

Introduction:

Since the launch of Sputnik in 1957, mankind has traveled a road of increasing dependence on the space frontier, rapidly advancing technology and creating industries that have become a vital part of global economic activity. Commercial activities in Earth orbit include broadcasting, telecommunications, remote sensing, weather monitoring and global positioning. Future commercial activities are expected to include microgravity manufacturing, entertainment and tourism. The bold and highly successful Apollo lunar missions have given way to a steady and growing human presence in orbit, as the International Space Station becomes the second operational facility with a permanent crew. The recent sale of the Russian MIR space station to a U.S. entrepreneur signals the serious intent of private enterprise to build and operate commercial human space facilities. Future trends in the development of space include the possibility of commercial lunar facilities (McKay, 1992 and O'Donnell, 1996) and associated lunar and asteroidal resource extraction. Long-term space-derived mineral product sales are expected to satisfy demand for fuel and construction materials in the growing orbital market as well as specific markets here on Earth.

The Near-Earth asteroids are being catalogued at an increasing pace, and represent a source of materials with high geological diversity. Two classes of asteroid contain high concentrations of platinum group metals (PGMs): Metallic Asteroids and LL Chondrites. Members of both groups have been identified in orbital trajectories close to Earth, having the potential for significant transportation cost leverage. Up to 1000 times the payload can be inserted into low-earth orbit from a spacecraft departing one of these asteroids as an equivalent launch vehicle leaving the surface of Earth. O'Leary (1977), Lewis (1996) and Sonter (1998) have suggested mining products contained on these asteroids which have a high-value per unit mass. Platinum, rhodium, iridium, palladium and gold are found in significant concentrations (total PGM content exceeds 50 grams per ton) in meteorite samples attributed to the LL Chondrites, and enjoying high grades in certain

other classes of asteroid (Kargel, 1996). Mining methodologies appear to be simple, requiring the separation of finely pulverized soil in a low gravity, high vacuum environment.

Platinum Demand Factors:

Two primary market categories exist for platinum: Industrial and precious metals, each having distinctly different demand characteristics (Christian, 1997). Primary industrial uses include emissions-control catalysts or ‘autocatalysts,’ chemical refinery components, and manufacturing of electronics and hard disks. Precious metal uses include jewellery and investment products, such as the US platinum eagle coin.

Current Demand:

Consumption of platinum in jewelry and autocatalysts accounted for over 70% of demand last year, and form the primary consumer base for the metal (Johnson Matthey, 1999). Platinum jewelry has been increasingly fashionable in China and parts of Europe, following a strong lead in Japan. The Japanese market has the strongest jewelry demand internationally, with over five times the annual consumption of any other country. This ‘platinum fever’ could easily spread to other parts of Asia in the short and medium term, exerting an upward pressure on demand. Autocatalyst consumption is on the rise (projected at 5% annual growth – Christian, 1999) and has the potential for sustained long-term growth as developing nations adopt emissions standards similar to the U.S. and Europe.

Table 1. Platinum end use by category (‘000 oz, Johnson-Matthey, 1999).

Year	1998	1999
Autocatalyst	1,415	1,220
Jewelry	2,410	2,730
Industrial	1,250	1,340
Investment	315	200
Total Demand	5,390	5,590

Manufacturing:

Industrial uses of platinum include chemical reaction catalysts for nylon and silicon production, electronic component manufacturing (thermocouples and high density capacitors), extrusion dies for thin-sheet glass manufacturing (used in laptop computer displays), and metal refining electrodes (Johnson Matthey, 1999). Use of platinum in specialty electronics has benefited from trends in miniaturization and the rapid growth of markets for electronic devices. A growing industrial use (projected at 10% per year – Johnson Matthey, 1999) is in hard disk drives, where storage density is increased by the deposition of a thin platinum layer. Finally, a minor use of platinum is in fuel cells – an alternative power storage technology that is gaining popularity. The sale of fuel cells has the potential to boost the platinum market significantly due to their preferred use in electrically powered automobiles. Fuel cells offer significant potential for future growth of platinum sales, particularly if metal prices drop. They offer significant weight savings

compared to lead-acid batteries, are more environmentally friendly, and have long service lifetimes.

Substitutes:

Numerous substitutes exist for platinum. Their use depends on market and price behavior. Other platinum-group metals such as rhodium and palladium can substitute for specific catalytic reactions along with iron and cobalt. Gold is a common substitute for jewelry and investment-grade coins or bars. Palladium has been used as a substitute autocatalyst since 1995 due to low relative prices (Johnson Matthey, 1999). In general, the chemical similarity among PGMs governs the potential for substitution among many of the metallic members, with pricing trends typically dictating the exact substitution characteristics. However, it should be noted that specific platinum-group metals generate optimal chemical performance for a given reactor design, limiting substitution where manufacturing changes are difficult to implement in the short term.

Platinum Supply Factors:

The Republic of South Africa is the world’s largest producer of platinum, accounting for over 75% of 1999 supply. Other major producing countries include the former Soviet Union, the U.S.A., Canada, Chile and Zimbabwe. Minor producers include Colombia, Australia and Brazil.

Current Production:

Annual primary production estimates by Johnson Matthey (1999) for platinum are reported for the year 1999. South African production was conducted by four companies: Amplats produced 928,000 oz; Impala produced 1,065,000 oz; Lonmin produced 564,000 oz; And, Northam produced 333,000 oz of PGM ‘concentrate.’ It is interesting to note that South Africa produced over 75% of the world’s platinum in 1999, with 57% of global production coming out of four South African companies. The high concentration of platinum production in one country creates a natural opportunity for substantial market power, hinting at the presence of a cartel. Russian exports of platinum, produced or market through Noril’sk nickel, totaled 800,000 oz (this number could also include the sale of stockpiled platinum – Johnson Matthey, 1999). Within the U.S., the Stillwater Mine produced 206,000 oz. The Hartley mine of Zimbabwe has an estimated production of 150,000 oz for 1999, but is expected to close in the year 2000. Table 2 shows the annual production of platinum for 1998 and 1999 by country or region.

Table 2. Platinum supply by country (‘000 oz, Johnson Matthey, 1999).

Year	1998	1999
South Africa	3,680	3,820
Russia	1,300	800
North America	285	275
Other	135	165
Total Supply	5,400	5,060

Reserves:

The majority of platinum reserves worldwide are found in a deposit known as the Merensky Reef, located in the Bushveld complex of South Africa. Estimated reserves for the Merensky Reef are 333 Million troy ounces (Anstett, 1980), with an average grade of 0.25 ounces per ton. A similar geologic occurrence can be found in the Great Dyke of Zimbabwe, with estimated reserves of 139 Million ounces of platinum at an average grade of 0.10 ounces per ton. It is noted that production of Zimbabwe platinum continues to be stifled by political problems. Estimated Russian reserves within the Noril'sk deposit are 50 Million ounces. The primary platinum producing area in the U.S. is the Stillwater complex in Montana, with an estimated reserve base of 7 Million ounces at a grade of 0.6 ounces per ton. Minor U.S. platinum deposits can be found along the Salmon River in western Alaska as well as in the Duluth Gabbro of northeastern Minnesota. An important Canadian platinum deposit at Lac de Iles, Ontario contains an estimated 3 Million ounces at a grade of 0.125 ounces per ton. Canadian byproduct platinum is produced in Sudbury, Ontario. Several Chilean copper deposits also produce byproduct platinum. Estimated worldwide platinum reserves total 513 Million ounces (Anstett, 1980).

Byproduction:

Platinum group metals are a byproduct of nickel and copper mining, especially in Canada and Chile. Because of high unit prices for platinum-group metals, byproduction is significant at many mines, capturing a small but important part of the platinum market.

Recycling:

The primary source of scrap platinum is spent autocatalysts. A secondary source is recycled jewelry. Johnson Matthey estimates 430,000 oz will be recovered from autocatalysts in 1999, around 8 percent of the annual market. Autocatalyst recycling exhibits a lagged supply behavior, reflecting the amount consumed in the year of automobile production combined with the average service lifetime of the automobile (Christian, 1999).

Refining:

Most platinum mines produce a PGM concentrate, with product separation occurring at a handful of specialized precious-metals refineries. Current and historical refining has been done at sites that include: Rustenberg, Germiston and Lohrno, South Africa; Krasnoyarsk and Monchegorsk, Russia; Acton and Royston, England; Kristiansand, Norway; the Englehard mill in New Jersey, U.S.A.; And, the Metallurgie Hoboken-Overpelt refinery in Belgium (Fogg, 1990 and Anstett, 1980). Hydrometallurgical and pyrometallurgical processes are used to concentrate PGM ores at most mines. Separation of purified platinum-group metals is done using one of two processes. Analytical chemical methods based on selective precipitation have dominated purification in the past, with a newer process of solvent exchange and electrowinning gaining favor in the 1990's (Fogg, 1990).

The 20-Year Platinum Outlook:

There appears to be a strong potential for an expansion in demand should platinum price drop in coming years. Current high-technology manufactured products that depend on platinum include fuel cells, chemical reactors, refractory metal components, glassmaking equipment, medical devices, electronics, hard disks, and many others. Each of these uses could easily expand to fill a void left by lower prices and increased supply. Other uses of platinum are possible, especially with increased supply.

Technological Factors:

The link between platinum and high technology is strong. The metal has made its way into a variety of industrial uses, forming a strategic cornerstone of our modern technical economy. A high melting point combined with its ductility and mechanical strength gives platinum an advantage over many refractory metals (Yamabe-Mitarai, 1998). PGM chemical inertness can be useful in caustic or other extreme environments requiring high reliability equipment. It is an excellent conductor with good thermal stability. Like gold, platinum will not oxidize in the atmosphere. The metal finds use in automobiles and petroleum refining due to its powerful catalytic properties in the reforming of hydrocarbons. Many platinum-based products form critical links in the U.S. techno-economic system. Examples include gasoline production, modern plastics and chemical processes, emissions reduction, as well as special aerospace and defense industry uses. The strategic importance of platinum has prompted the Defense Logistics Agency to stockpile over 200,000oz of the metal to assure U.S. industrial productivity in case of an interruption in supply (Christian, 1997). Note that North America imported 970,000 ounces to meet 1999 demand, underscoring U.S. dependence on foreign supply (Johnson Matthey, 1999).

Platinum Demand Projections:

Industrial demand for platinum stems from its special physical and chemical properties. Many additional industrial uses of platinum are waiting should prices drop and quantity expand, given the quality and properties of the metal. Autocatalyst consumption is currently on the rise (projected at 5% annual growth – Christian, 1999) and has significant potential for long-term growth as developing nations adopt emissions standards similar to the U.S. and Europe. Specialty electronic devices are becoming more popular in U.S. markets, especially computer and communication system components where platinum offers superior thermal and mechanical performance over other metals. Hard disks, a good example of a growth sector for platinum, are expected to consume the metal at a rate of 10% or higher annual growth (Johnson Matthey, 1999). Fuel cells also have significant growth potential, although somewhat more difficult to quantify for the short-term. General Motors expects to be “mass producing” fuel cell vehicles by 2003, according to industry sources (Robinson, 2000). Worries about carbon emissions combined with aggressive promotional programs in states like California are driving expectations of expanded electric vehicle sales. Chrysler-Daimler and Ford are investing in fuel cell manufacturing, and GM and Toyota have teamed up to work on hybrid electric vehicles and fuel cell technology (Zesiger, 1999). Another potential market for fuel cells is in solar powered buildings that use coated glass panels to produce power, storing the excess power in banks of fuel cells (Brown, 1999). Due to their high

power density per unit weight, the aerospace and defense industries are primary consumers of fuel cells.

High prices limit demand to technical applications where platinum or other rare and expensive metals are required to meet performance specifications. Platinum-group metals could experience significant market growth if prices drop, providing a higher quality substitute for many less expensive industrial metals. In fact, relatively inelastic demand is expected for the metal in the 20-year time frame. A large expansion in supply could easily foster expanded industrial metal usage with only a modest decrease in price.

Platinum Supply Projections:

The conservative assumption that mining costs increase through time is noted in government-generated economic reserve models such as reported in the previous section. These models show constrained supplies in the future, and the 20-year old data reported is felt to be highly conservative. A simple comparison of the USBM platinum supply reports (Anstett, 1980 and Fogg, 1990) with the Johnson Matthey report for 1999, shows that many previously 'condemned' mining districts are currently in production at much lower costs than originally estimated. Clearly mining and metallurgical extraction technologies have advanced. There also remains a significant probability of the discovery of new platinum deposits, particularly as exploration technology advances for tropical areas with heavy vegetation and thick soil cover.

Technology for mining as well as mineral processing continues to advance across many sectors of the industry. Benefits to the platinum business have accrued, dropping the cost of producing concentrate in the process, particularly with the relatively low commodity prices experienced in recent years. Advances in both surface and underground mining equipment include lifetime and serviceability (maintenance) improvements, better durability and automation. Mechanical excavation technology offers special promise for underground platinum mining, as higher durability cutting elements are introduced (better suited for the hard and abrasive source rocks). Longwall mining is already the preferred method in the Merensky Reef (Fogg, 1990). Automation of mineral processing circuits has advanced industry-wide, lowering labor requirements and improving productivity of mineral product concentration. Improved access to the high-grade but deep underground mines in South Africa may be possible through the use of advanced mining technology, helping to transcend current limits due to low labor productivity because of excessive heating and the distance to the mining face.

South African reserves are expected to last 300 years (Dhliwayo, 1999), indicating a substantial amount of platinum supply. In fact, some of the world's largest platinum mines are currently undergoing expansions in mine production (Dhliwayo, 1999 and Christian, 1999). Because of these industry projections and the other factors mentioned above, it is felt that platinum reserves are more than sufficient to meet increasing demand in the 20-year time frame. There is also strong evidence from other metals that a reduction in overall mining costs is likely in the future as well. In other words, prices are expected to continue dropping and mine output is expected to be able to keep up with demand well into the future.

Platinum from the NEAs:

Fueled by fears of a planetary impact catastrophe, asteroids are being catalogued at an accelerating pace. Nearly half of the 816 known near-Earth asteroids (NEAs) were discovered during the last two years (Evans, et. al., 2000). Much work remains, however, as less than 16% of the estimated population of asteroids greater than one kilometer in size have been located. The identification of mineral products including high-grade platinum has caused excitement in the planetary science community, pointing toward a source of low-cost materials for industrial space development (Cox, 1964, O'Leary, 1988, Lewis, 1996 and Sagan, 1998). While asteroid mining is clearly not feasible today, there are indications that rapid growth in aerospace technology and infrastructure could make commercial mining possible in the 20-year time frame.

Geology of Asteroidal Platinum Resources:

The geological characteristics of NEAs are governed by the environment in which they formed. Most asteroids condensed just after the formation of the solar system, as reflected by their age (~4.7 Billion Years). The environment allowed larger bodies, especially planets, to differentiate gravitationally - pulling PGMs as well as iron and nickel to the core. There is a strong correlation to the thermal environment as well. Bodies forming at the edge of the solar system cooled more rapidly, slowing or stopping this differentiation process. Smaller bodies did not develop sufficient mass for gravity separation, and reflect the original distribution of elements from the supernova event. PGMs are quite abundant in these small bodies, called Chondrites after their agglomeritic nature, and hinting at the original distribution of elements in the solar nebulae. Note the similarity to the formation of Earth, especially the sequestering of heavy elements in the planetary core. While PGMs may have been abundant during stellar formation, they are highly depleted in Earth's crust, and are found in only a few locations on its surface.

Meteorite samples are the primary source of detailed data for asteroid chemical composition, especially trace metals. Platinum, rhodium, iridium, rhenium, osmium, ruthenium, palladium, germanium and gold are found in significant concentrations (ranging from 1.1-30.7 grams per ton for each metal) across a variety of meteorite samples attributed to the LL Chondrites (see Table 3). Up to 63.8 grams per ton of platinum is found in the top two percent of iron meteorite samples (both the 90th and 98th percentile PGM concentrations are reported for the 'best' iron meteorites in Table 3). Strong statistical continuity exists for the Chondrites examined by the planetary science community, providing a basis for the expectation that certain large asteroids match the chemical abundance of the meteorite samples (it is hypothesized that these asteroids are the source of the meteorites). However, without a sample returned from an asteroid, the evidence remains circumstantial. Detailed asteroid reconnaissance by spacecraft is has dramatically improved geologic models, but has only been carried out recently for a handful of asteroids. Spectral analysis of data from telescopic observation can sometimes be used to infer general geological characteristics such as bulk composition for newer asteroid discoveries.

Table 3. Average PGM concentrations by meteorite class (ppm – Kargel, 1996).

Metal	Avg. LL Chon.	90 th % Fe	98 th % Fe
(precious metals)			
Ge	1020	70	35
Au	4.4	0.7	0.6
(platinum group)			
Re	1.1	1.1	2.4
Ru	22.2	20.7	45.9
Rh	4.2	3.9	8.6
Pd	17.5	2.6	1.2
Os	15.2	14.1	31.3
Ir	15.0	14.0	31.0
Pt	30.9	28.8	63.8

Orbital Characteristics:

Many asteroids lie much ‘closer’ to Earth than the Moon. The orbital alignment of the near-Earth asteroids brings them alarmingly close to Earth’s orbit on a regular basis. During the period of alignment, the amount of energy required to reach Earth orbit can be as little as 1/1000 the energy as an equivalent spacecraft launched from Earth’s surface. For example, a Russian Proton launch vehicle departing Baikenour Cosmodrome in central Khazakstan can place 20 tons into low-Earth orbit (LEO), while an equivalent Proton leaving the surface of the right NEA at the right time could hypothetically place 20,000 tons into LEO. It is noted that asteroids with the lowest departure energy present the higher danger of Earth impact (the U.S. Department of Defense is examining tactics for their potential diversion). It is precisely this ‘energy leverage’ that makes these asteroids candidates for the lowest-cost supply of materials into the growing Earth orbital market. Lewis (1996) estimates a population of 2,000 NEAs larger than 1-kilometer and 100,000 or more 100-meter diameter asteroids.

Feasibility Considerations:

The technical feasibility of mining asteroid resources has been studied extensively by Sonter (2000) and Kuck (1992). The development and testing of lunar mining technology for extraction of fuel and construction materials has been underway at NASA for at least 20 years (Bock, 1979, Criswell, 1980 and McKay, 1992). However, with the exception of scoops, drills and sample collection devices used during the Apollo missions, no mining equipment has been tested in the appropriate space environment. While engineering data collected in a relevant environment will be required to develop robust mining systems for space, important conclusions can be drawn by simply examining the asteroid environment. The key to the success of early asteroid mining endeavors will be the advantageous use of the unique environmental characteristics.

Two primary mining and processing strategies emerge: Sift through the pre-crushed regolith from a large NEA, or retrieve an entire small NEA for delivery to an Earth-orbital facility. The optimal choice will depend on technology, cost, risk and revenues. One recurring suggestion is the use of a magnetic rake to comb through the finely-

pulverized regolith soil, collecting and concentrating PGMs in the process (Kargel, 1996). Another method could loft a stream of soil through the almost nonexistent gravitational field, deflecting PGMs through a ring or net made of magnetic materials.

Given the estimated population density of LL chondrite NEAs, there are over 8000 candidate bodies less than 100 meters that are high enough in grade to host platinum production. It is important to note that a 100-meter sphere of rock weighs in at almost 1.4 million metric tons, and could contain over 40 tons of platinum at grades measured in meteorite samples. Lewis (1996) estimates that the minimum size that could completely disintegrate during accidental Earth entry is 100 meters, providing an upper size limit for assurance against damage.

Costs and Revenues:

The capital and operating costs for asteroid mining depend on the price of equipment, space launch and operations. Clearly the need for automated robotic mining systems of advanced robustness will cause capital costs to dominate operating costs. A ‘typical’ asteroid mining mission would launch the mining equipment at the first orbital phasing opportunity and expect delivery of materials at the next, 2-5 years later. The requirement for automation stems from the cost and difficulty of sending a rescue mission when the orbit is out of phase. Maintenance equipment must be included in the original package. Capital costs for asteroid mining equipment should be estimated using custom aerospace industry models. Detailed cost models for lunar mining equipment (Christiansen, 1988) should also be consulted.

Sonter (1997, p.144) estimates the equipment mass to move a 20 meter “arjuna” type asteroid (very low orbital transfer energy) into low-Earth orbit to be less than two tons. This would include mining equipment, a power supply and simple thrusters to maneuver the asteroid into Earth orbit using water extracted from the asteroid. A simple calculation using the Advanced Missions Cost Model (Cyr, 1988 – developed to estimate costs for human planetary exploration missions) yields an estimated cost of between \$500 Million and \$1 Billion to construct a two-ton prototype spacecraft. Determination of reliability and equipment service lifetimes will require engineering studies and full-scale equipment testing in a relevant environment.

Revenues will depend on market characteristics at the time of delivery, the uniqueness of products sold and the nature of any contracts signed for product sales. If cartel behavior exists in the platinum market, the negotiation of a sales agreement through existing South African channels could significantly boost revenues. Table 4 below shows projected revenues at a platinum price of \$500 per ounce, and assumes complete recovery of platinum from an LL chondrite with a specific gravity of 3.0g/cc and platinum grade of 30.7 g/ton. Note that the price quoted is above the current commodity market value, and assumes a slight escalation in price due to depletion of reserves. Given the liberal nature of the model assumptions, estimated revenue values represent an upper bound and could easily fall short of expectations.

Table 4. LL Chondrite size –vs- contained platinum (spherical model).

Diameter (meter)	Mass (metric ton)	Contained Pt (kg)	Contained Pt (oz)	Value \$M (at \$500/oz)
10	1,396	43	1,381	0.69
20	11,170	345	11,045	5.5
50	174,533	5,393	172,578	86
100	1,396,262	43,145	1,380,624	690
200	11,170,098	345,156	11,044,993	5,522
500	174,532,778	5,393,063	172,578,011	86,289
1000	1,396,262,222	43,144,503	1,380,624,085	690,312

Market Considerations:

Problems with revenue may also occur due to high price volatility. Indeed, price could easily be driven down just before arrival of the first shipment, provided a marketing agreement has not been negotiated through existing sellers. The potential for space-manufactured products could insulate this somewhat (the PGM concentrate must pass through Earth orbit on its way to market). One advantage of ore refining and product manufacturing in orbit is access to high vacuum and zero gravity. The likelihood of orbital manufacturing facilities in the 20-year time frame is high, and is strongly linked with the growth required to enable asteroid mining endeavors. Specialized niche-market products that could benefit from orbital manufacturing include exotic alloys, metallic-foam based catalysts or high-purity electronic components.

An examination of Table 4 provides some insight into the potential path for asteroid utilization. A 200-meter LL Chondrite contains twice the annual output of platinum mines worldwide. A more practical limit of 20% of the annual market size would be more likely to minimize price disruption, indicating a maximum returned mass of unprocessed asteroid of 100 meters, and a maximum revenue of \$690 Million. However, current launch vehicle technology limits the practical size for transfer to orbit of 20 meters, consistent with Sontner's estimate above. This limit, combined with the relatively low revenue estimate (\$5.5 Million) for a 20-meter LL Chondrite, indicate a lack of economic justification for the option of maneuvering a high-grade platinum asteroid into Earth orbit to extract and sell platinum.

Regolith mining and concentration represents the other possibility for asteroidal platinum, but would incur a much higher risk value due to the complexity of the required mining operations. It would likely take place on a 1 kilometer or larger body (statistical evidence suggests that as many as 160 LL Chondrites may exist at the 1 kilometer size) with sufficient gravity to allow mining equipment some grip. Roughly 4 million tons of material can be extracted per meter of regolith from a 1-kilometer sphere. Assuming complete extraction from the top 1 meter, this implies roughly \$2 Billion in revenue from an extracted mass of 130 tons of platinum. Note that this is again close to the annual world platinum production level, seriously challenging the assumed price of \$500 per ounce. The challenge, of course, is to design mining equipment that can extract and concentrate the product for a total cost of under \$2 Billion. It is clear from this analysis that both options for mining asteroidal platinum lack economic justification. However, it

is noted that existing launch vehicle technology is more than adequate to ship enough concentrate to totally disrupt the world market for platinum. Provided other products provide additional economic incentive, platinum from asteroids appears to have the potential to significantly alter the long-term characteristics of the terrestrial platinum market.

Other Asteroidal Products:

The key to asteroid mining can only be found in the other potential mineral-based products. A brief examination of these other products is in order, and serves to underscore the conjecture that platinum will be a potential player in terrestrial markets in the long-term. To illustrate this point, the example of the 20-meter asteroid will be used. It is also important to point out that the current launch price is around \$10,000 per kilogram to place payloads into low-Earth orbit (LEO). This cost is remarkably close to the current price of platinum of \$12 per gram. The implication is that the entire asteroid may be valued as if it were made of pure platinum (\$111.7 Billion!). However, significant caveats exist. First, there are no existing markets for the other products that could be extracted. Second, the technology for material handling and product fabrication has not been developed.

A typical LL Chondrite contains 10% water, 7% iron and 30% organic hydrocarbons, as well as significant silicate minerals. Given a hypothetical LEO processing facility, a percentage of the available minerals could be converted into useful products that could underwrite an industrial economy in Earth orbit. Note that this example is but one very small 20-meter asteroid of specific composition that could cost as little as \$1 Billion to retrieve and that could generate a maximum revenue of roughly \$100 Billion, provided the technology to make useful products in space existed.

Government Participation:

As part of strategic planning for activities after the completion of the International Space Station in 2007, NASA engineers are designing spacecraft and human support equipment for a series of human exploration “campaigns” in near-Earth space, maximizing the flexibility of systems developed for the eventual exploration of Mars. It is recognized that a human Mars mission without sufficient practice at closer targets would increase risks beyond tolerable levels. The initial baseline is to support a 100-day human exploration mission. This could be achieved through the continuation of the annual ISS budget of \$6 Billion per year. Candidates for a human exploration mission currently include certain NEAs with favorable orbital parameters (Cook, 1999).

Indeed, NASA has a strong commercialization agenda, specifically including the use of space mineral resources (NASA, 1999). Many NASA insiders are proponents of infrastructure development, as evidenced by the “campaign” human exploration architectures, with the expectation of future participation of private interests in space development. Current NASA expenditures in excess of \$10 million per year are creating the technology base for lunar and Mars in-situ resource utilization. Spacecraft exploration of asteroids and comets is also on the rise (the Near Earth Asteroid Rendezvous spacecraft was successfully inserted into orbit around the asteroid Eros on

February 14 of this year), increasing the scientific data available on asteroids. Clearly, the value of government participation in infrastructure and technology development is required at this time. The costs and risks of a private initiative to develop the systems needed for successful asteroid mining are simply too high. A simple spacecraft placed on the surface of an asteroid could provide important data to support the engineering of mining technology (depending on experimental payload choice), and could easily be achieved for \$250 Million or less under the current Discovery program. It would clearly fall under NASA's stated intent to provide tools for commercial space development.

Conclusions:

Raw platinum ore alone is not currently economic for return to Earth. However, the potential for other mineral-based products extracted from asteroid resources is sufficiently good to justify a detailed examination of multi-product economic feasibility. The future of asteroid mining will depend on transcending our current technological barriers. Provided the current NASA logistical plan for human exploration of an asteroid bears fruit, the potential for the development of this technology is high, without an excessive burden being placed on private research and development funds. The NEAs offer several candidates for a more secure medium-duration human mission as a stepping stone to Mars, and offer the key to the successful and profitable use of space mineral resources.

The future utilization of space resources depends foremost on their profitability in the terrestrial economy, and will be used as a stepping stone to the formation to a space-based economy. The identification of specific space resource products with profit potential in existing markets is therefore critical to the opening of the space frontier to human commerce and migration. Asteroidal platinum-group metal deposits offer strong supporting products which have the ability to generate cash flow in the terrestrial economy.

Recommendations:

Future economic work should include econometric estimation of short and long-term demand elasticity for platinum, and extend the above analysis to the other platinum-group metals offered by asteroids. Other markets must be found and thoroughly examined as well. The breakthrough for space resources will come about when a sufficiently large market is found that justifies mining from a lower cost mineral source located in space. The most commonly cited potential market is transportation fuels for Earth-orbiting vehicles. Significant potential exists for markets related to items manufactured in space. Construction materials, glass and ceramics, solar panels and advanced plastics can be made by extending our current manufacturing infrastructure into orbit, and provide the foundations of our current terrestrial economy.

The importance of engineering design of mining and extraction equipment cannot be understated. There is a real possibility that mining equipment masses could be extremely compact, provided elegant ways are found to use the benefits of the unique space

environment. Testing of equipment in the relevant environment is a critical step toward feasibility, and should focus on bringing reliability requirements to levels currently accepted by industry. The potential synergy of public-private cooperation should not be underestimated. NASA has significant experience with complex operations in space, and could provide a tremendous leap forward by sending humans to an asteroid, enabling private space development in the process.

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