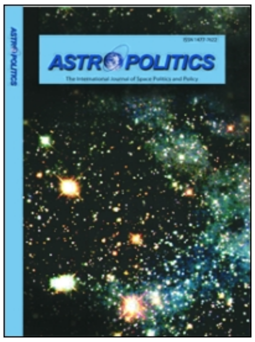

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Rationale, Strategies, and Economics for Exploration and Mining of Asteroids

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The development of off-world sources of critical minerals is creating an opportunity to transform space activity from a consumer of resources into sources of value. This article provides an overview of the rationale for and the feasibility of asteroid mining, based on current technology and information. It concludes that the mining of asteroids is a medium-term to long-term project (20 to 30 years) that requires a stepwise approach. An important step in the development of asteroid mining is the confirmation, through exploration, of the minerals' abundance on the asteroids. A mission capturing and returning to lunar orbit a single 10-meter-diameter asteroid or a rock off the surface of a larger asteroid accomplishes this goal. This mission would also allow the testing of automated mining and processing equipment, reducing the risks of future large-scale asteroid mining operations. Suggested herein is that asteroids' exploration be carried out through a partnership between space agencies and private space companies, whereby the two partners can achieve their strategic interests.

Over the past decades, the number of public and private actors involved in space activities world-wide has increased. The space economy includes many commercial activities. Several mature downstream activities have reached mass markets. They include information technology products and services, such as satellite television and global navigation receivers. In addition, the use of satellite technology in navigation, communications, meteorology, and Earth observation has given rise to a growing stream of applications in such areas as air traffic control, transport, natural resource management, agriculture, environmental and climate change monitoring, and

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entertainment. In 2013, the overall size of the global space economy was $314 billion.[1]

At present, all commercial space activities are carried out in the vicinity of Earth. Within the last decade, a number of private initiatives have surfaced promoting deep space exploration and development. Some of these private initiatives regard the development of space mineral resources, particularly asteroids. This article focuses first on the geology of the asteroids and the rationale behind their mining. A clear understanding of the mineral resources of the asteroids and of Earth's current situation is necessary to evaluate the potential of space mineral resources. Second, it analyzes the economics of these projects. Finally, the last part of the article focuses on the exploration phase and on how cooperation between space agencies and private companies leads to an efficient use of limited financial resources.

GEOLOGY OF ASTEROIDS

While most asteroids are located in a belt between Mars and Jupiter, there are some near Earth asteroids (NEAs) that are highly promising mineral sources. NEAs are asteroids with orbits that regularly bring them close to the Earth. NEAs are grouped into three categories: (1) Amors: asteroids that cross the orbit of Mars, but do not reach the orbit of Earth (Eros is a typical Amor asteroid); (2) Apollos: asteroids that cross the orbit of Earth with a period longer than a year (Geographos is a typical Apollo asteroid); and (3) Atens: asteroids that cross the orbit of Earth with a period shorter than a year (Ra-Shalom is a typical Aten asteroid).

According to the International Astronomical Union, there are currently 10,337 known NEAs, of which 861 have a diameter larger than one kilometer (km). The number of accessible asteroids is much smaller. Accessible asteroids are defined as the ones with low inclination and eccentricity, and with a perihelion distance q equal or less than one astronomical unit (AU). Accessible NEAs are particularly attractive for resource utilization because of the relatively low changes in velocity (Δv) required to reach them and return from them. Many NEAs require less energy to reach than reaching the surface of the Moon, and the return to Earth orbit requires far less Δv than the return to Earth from the Moon.

Asteroid geology has advanced substantially in the last decade by spectroscopic and dynamic studies of asteroids, as well as by analysis of meteorites fallen on Earth. These analyses indicate that asteroids contain valuable elements, like platinum group metals (PGMs), gold, and germanium. Identified natural resources include industrial elements, such as nickel, in the form of metallic nickel-iron, and cobalt. The concentration of PGMs and precious metals varies with the type of asteroid, but they are estimated to be higher than the concentrations in Earth crust (see Table 1).

TABLE 1 Abundance (in parts per million, ppm) of PGMs and precious metals in asteroids

Metals	LL chondrite asteroid	"Good" iron asteroid (90th percentile in Iridium and Platinum)	"Best" iron asteroid (98th percentile in Iridium and Platinum)	Earth crust
Industrial elements				parts per million (ppm)
Cobalt	1.57 percent	0.46-0.80 percent	0.43-0.75 percent	25
Nickel	34.3 percent	5.6-18.0 percent	5,4-16.5 percent	120
Iron	63.7 percent	81.0-94.0 percent	82.0-94.0 percent	55,000
Germanium	1,020	0.06-70	0.05-35	1.8
PGM	ppm	ppm	ppm	ppm
Rhenium	1.1	1.1	2.4	0.0004
Ruthenium	22.2	20.7	45.9	0.001
Rhodium	4.2	3.9	8.6	0.0002
Palladium	17.5	12.6	12	0.0006
Osmium	15.2	14.1	31.3	0.0001

Notes: LL chondrite asteroids are stony (non-metallic) asteroids. They are formed when various types of dust and small particles that were present in the early solar system accreted to form primitive asteroids. PPM is a way of expressing very dilute concentrations of substances. Just as percent means out of a hundred, so parts per million or ppm means out of a million. Usually describes the concentration of something in water or soil. One ppm is equivalent to 1 milligram (mg) of something per liter (l) of water (mg/l) or 1 milligram of something per kilogram (kg) soil (mg/kg). Sources: V. F. Buchwald, *Handbook of Iron Meteorites: Their History, Distribution, Composition, and Structure* (Berkeley, CA: University of California Press, 1975); D. J. Malvin et al., "Chemical Classification of Iron Meteorites, Multi-element Studies of 43 Irons, Resolution of Group IIIE from IIIAB, and Evaluation of Cu as a Taxonomic Parameter," *Geochimica et Cosmochimica Acta* 48:7 (1984): 85-804; M. Hoashi et al., "Palladium, Platinum and Ruthenium in Iron Meteorites and their Taxonomic Significance," *Chemical Geology* 106 (1993): 207-218; and R. P. Mueller et al., "Regolith as a Resource in Solar System Human and Robotic Exploration," paper presented at the 61st International Astronautical Congress, International Astronautical Federation, 2010.

A higher concentration of metals in space than on Earth is explained by the fact that most of these metals sank to the core of Earth at the time when the planet was young. Many asteroids may be bearing water, ammonia, carbon dioxide, methane, and other volatiles. Carbonaceous chondrite meteorites may contain up to 22% of volatiles and water. Stony and nickel-iron asteroids may be also bearing water and volatiles, but in reduced quantities than carbonaceous chondrite asteroids. It is also estimated that asteroid's raw materials are, in general, of excellent quality, which requires a minimum of machining, since the analysis of meteorites indicates that the metals are in free state in the majority of the meteorites, with the exception of carboniferous ones.

RATIONALE FOR ASTEROID MINING

Pressure from increasing world population and limited resources is the most cited argument in favor of asteroid mining. For at least three decades, scientists and economists[2] have debated whether humanity is rapidly depleting the mineral resources on which it depends. The prevailing opinion is that there is no immediate concern about the capacity of mineral resources to match the demand for most metals. Technical progress has continuously extended the amount of mineral reserves. Recycling of existing products is adding to the supply of ores. Moreover, the endowment of mineral deposits in many parts of the world has been poorly explored, so that no realistic assessment of their mineral potential can be made. The limit to growth is thus perceived as a long-term threat and, as such, does not provide a rationale for asteroid mining in the short to medium term. However, there are other, more important arguments for developing asteroid mining.

Minerals from asteroids, marketable to Earth, are essentially PGMs plus some precious metals. The price structure of industrial metals and water and volatiles does not make them commercial on the Earth market, but only in the space market, which at the moment does not exist. PGMs are indicated as critical materials. Critical materials are usually referred to as materials whose demand is high and whose market is global in scope, while supply is constrained. On the demand side, the demand for PGMs has increased on average by about 5.5% per year[3] in the last 60 years. The demand for PGMs derives mainly from the autocatalysis and jewelry industries, but they are also used in an extensive range of other products and applications, which include glass, electronics, non-road emission control equipment, and industrial manufacturing, which collectively account for some 25 to 30% of total PGM demand. PGMs are fundamental to the construction and function of automobile catalytic converters and of other products and applications. Since, at present, there are no viable substitutes for PGMs in these products and applications, constraints of the supply of those minerals could result in costly situations for those industries. Demand is expected to grow by an average annual rate of 4% in the next 10 years. Environmental legislation affecting global emission standards is expected to be extended to emerging countries, like China and India, which will provide the major impetus to demand for PGMs. Demand of PGMs for jewelry will also contribute to total demand growth, but to a lesser degree, due to thrift and substitution between platinum group minerals.

On the supply side, criticality is the consequence of a confluence of factors: (1) physical constraints; (2) the influence of non-primary market actors on the market, such as governments; and (3) the fragility of the resource supply chain to "common mode" disruptions arising from operating dislocations, either stochastic (e.g., natural disasters), organizational (e.g., labor unrest, government policies), or institutional (e.g., non-competitive behavior of firms).

The factors underlying the constraints may vary from one material to another. Sometimes, materials' criticality might derive from physical constraints, but criticality can often be the consequence of supply

TABLE 2 Metal metric comparison

	Ore grade (weight percent)	Energy in GJ/kg (Giga joule per kilogram of material treated)	Prices in U.S. dollars/ kilogram (kg)	Price volatility	Percent of primary produced in one country	Number of companies totaling over 50%of global supply
PGMs	0.0003-0.002	240	31,000	3.05	72.9	4
Gold	0.0005	200	45,731	0.05	15.2	15
Germanium	0.0004	not applicable	1,950	0.66	67.8	7

Notes: Ore grade is usually expressed as a weight percentage of the total rock (weight percent). Energy in GJ/kg is a measure of the energy intensity of a process. Price volatility is a measure for variation of price over time. It is measured as the standard deviation over a period of 60 years. Also, non-reliable data are available on energy intensity in germanium extraction. Sources: W. G. Ernst, *Earth Systems: Processes and Issues* (New York: Cambridge University Press, 2000); Alonso et al., "*Material Availability and the Supply Chain: Risks, Effects, and Responses*," *Environmental Science & Technology* 41 (2007): 6649-6656; and *Mineral Commodities Summary, 2011*, United States Geological Survey (Washington, DC: U.S. Government Printing Office, 2011).

concentration in a few areas of the world or a monopolistic/oligopolistic situation that creates substantial market pressures. Market concentration and other metrics gleaned from the literature can be used as a first-pass comparator for the level of criticality of PGMs, as shown in Table 2.

The first and second metrics consider physical constraints determined by the effort required to obtain each kilogram of a metal. The costs of extracting and refining PGMs are much greater than those for many other metals because of the low PGM concentrations in ore. For example, platinum ore grade is typically 0.5 to three grams (g)/metric ton. This is three orders of magnitude lower than the average grade of copper, nickel, tin, zinc, or lead. The energy needed in PGMs' refining operations is about 1000 orders of magnitude higher than those for the other metals. These factors explain the high prices of PGMs. Looking to the future, PGMs are more likely to experience larger price variations than other metals, because of the changes in energy cost, introduction of environmental regulations related to the high level of pollution generated by these mining operations, and poorer head grade that would impact future production costs and scarcity.

The high concentration of PGMs and gold supplies in a few companies indicates that these are pure oligopolistic markets. Since the largest deposits of PGMs are located in areas of the world that are politically unstable or under the influence of non-primary market actors, the fragility of the resource supply chain to disruptions arising from operating dislocations is high. In the past, labor unrest and energy shortages in South Africa were the main reasons behind the high PGM price volatility. Government policies have affected investment in PGMs' mining in Zimbabwe. Legislation proposed[4] in 2010 that would require that large corporations have 51% domestic ownership has created uncertainties, causing a delay in investments in the expansion of existing mining operations and in explorations of new deposits. In the future, the high concentration of PGMs supply in South Africa, Zimbabwe, and Russia means that any disruptions or uncertainty in those countries could affect over 95% of global PGM supply.

Managers know that they need to protect their supply chains from serious and costly disruptions, but the most obvious solutions—increasing inventory, adding capacity at different locations, and having multiple suppliers—undermine efforts to improve supply-chain cost efficiency. In the last 10 years, companies have carried out policies to improve their supply-chain cost efficiency, but very little was done to mitigate the effects of disruptions. Surveys[5] have shown that, while managers appreciate the impact of supply chain disruptions, they have done very little to mitigate their impacts. The early years of the twenty-first century have been notable for major supply chain disruptions that have highlighted vulnerabilities for individual companies and for entire industries globally. The supply of off-world PGMs could reduce the fragility of these resources' supply chain, thereby reducing the risk to consumers of extraordinary market volatility, both in terms of substantial price excursions and/or restrictions on resource availability at any price and, thus, increasing the efficiency of the world economy and long-term growth.

Recently, a number of private initiatives have surfaced promoting the exploration and development of asteroids, among which Planetary Resources, Deep Space Industry, and Excalibur Exploration are the most prominent. These initiatives follow a growing number of companies interested in the development of the outer space economy (solar base space power, lunar mining, rockets and spacecraft manufacturing, space launching, and space tourism). It is interesting to note that major investors in private space ventures are related to computer/Internet firms, such as Elon Musk (SpaceX, PayPal), Paul Allen (Strato Launch, Microsoft), Jeff Bezos (Blue Origin, Amazon.com), and Eric Schmidt and Larry Page (Planetary Resources, Google). As the electronic/information industry is an important consumer of PGMs, these industries will be affected positively by a reduction in the fragility of the supply chain of these minerals.

ECONOMICS OF ASTEROID MINING

In the technical literature, there are two ways for structuring asteroid mining: (1) moving an asteroid to lunar or a stable Lagrangian point between Earth and the Moon, where the raw material is extracted and sent to Earth; and (2) mining the asteroid directly in its natural orbit. In the first solution, technical limitations and safety considerations restrict the dimension of the asteroid to be moved into lunar orbit or to a stable Lagrangian point. From the technical point of view, we have presently the technology to move an

TABLE 3 Asteroid mass scaling, volumes, and values

Diameter (meter)	Asteroid mass in metric tons	Volume of PGMs and precious metals in metric tons	Value of PGMs & precious metals in millions of U.S. dollars	Volume of industrial metals in metric tons	Value of industrial metals in millions of U.S. dollars	Volume of water and volatiles in metric tons	Value of water and volatiles in millions of U.S. dollars
7	450	0.05	1.4	359	3, 589	91.4	914.9
10	1,309	0.1	4.2	1,043	10, 436	266.1	2, 661.4
15	4,416	0.5	14.0	3,518	35, 205	897.8	8, 978.3

Notes: Asteroid mass has been estimated assuming an average density of the asteroid of 2.5 g/centimeter (cm)^3 The price of water and volatiles has been calculated from their current values plus a mark-up equal to 10,000 U.S. dollars per kg.

asteroid with a maximum diameter of 10 to 20 meters. From safety considerations, it is estimated that an asteroid below a 20 meter diameter will disintegrate into the Earth atmosphere without endangering the safety on Earth. Table 3 reports the different masses of the asteroids and their values in terms of PGMs and precious metals.

The Keck Institute has performed a feasibility study for a mission recovering a small asteroid with a diameter of seven meters and a mass of about 500 tons and bringing it into lunar orbit.[6] The total cost for the recovery of the asteroid and its insertion into a lunar orbit is estimated at about $2.6 billion. Launch costs, including NASA oversight, were estimated to be in the range of $0.5 billion. Even if launch costs could be reduced by using a different launcher (e.g., SpaceX's Falcon Heavy) it is evident that the capture and return of a single 10-meter-diameter asteroid will not cover the costs of the investment, unless a space market for industrial metals and water and volatiles is well developed. At the moment, the only existing space market is the one for the supply of fuel to satellites and to the International Space Station (ISS), which does not make asteroid mining in lunar orbit financially feasible. However, refueling satellites in geostationary orbit adds precious years to the life of the satellites and expands the options of satellite operators who face unexpected emergencies. It will also enable users to decrease the fuel in satellites at launch, increasing the number of instruments on board the satellite.

The second solution has been discussed extensively in the literature. The economic problem of the off-world miner can be described as follows: he has to sustain initially a substantial cost of investment that depends on the costs of constructing and launching the necessary equipment, power supply, cargo container, and instrumentation and control. This is given by Equation (1) below:

$$C = \left(M_{mpe} + M_{ps} + M_{i\&c}\right)^{*} \left(p_e + p_l\right) \tag{1}$$

C is the cost of investment; M_{mpe}, M_{ps}, and $M_{i\&c}$ are respectively the mass of the equipment, power supply, cargo container, and instrumentation and control; and p_e and p_l are costs of construction and of launching. The mass of the equipment, power supply, and cargo container depend on the mass of materials returned to Earth orbit, and on the type of material treated (e.g., loose regolith or hard rock). The amount of the mass returned to Earth orbit depends on the length of the mining season and on the throughput factor, which is the ratio of the kilograms of regolith or rocks treated per kilogram of equipment. Mining season can vary from approximately two months to six months, depending on the eccentricity and orbit inclination of the asteroid. Low eccentricity targets can have longer mining seasons, while high eccentricity targets must have short mining seasons. Longer mining season implies less demanding specifications on mining, processing, and propulsion equipment, and on solar collector. The throughput factor depends on requirements and engineering choices for mining and processing. For a mining mission with the objective of extracting PGMs, precious metals and volatiles, a throughput factor of 200 can be assumed.

The choice of the asteroid is also important, since it will determine the length of the period between the initial investment and the realization of sales. The total time of the mission affects the economics of the project, since the shorter this period, the higher the return on the investment. Depending on the orbital characteristics of targets, there are several mission types that can be identified, which has implications for the type of transfer, choice of the propulsion system, and total mission duration. Low eccentricity asteroids can have non-Hohmann transfer (continuous thrusting), while high eccentricity asteroids must have Hohmann transfer (impulsive transfer). In the first case, non-continuous thrusting propulsion, such as ion rocket propulsion, is allowable, using solar power and deriving its return-journey propellant from the target body. In the latter case, a high-thrust rocket motor is needed and the choices are limited to nuclear thermal rockets. Mission duration can vary from 1.5 to four years, depending on the transfer period and the orbit-matching and synodic period, as it is necessary for the payload on its return trajectory to intersect Earth orbit when Earth is nearby. This implies longer project time lines than indicated simply by use of transfer orbit period.

Once the metals have been returned to low Earth orbit (LEO), the off-world miner has to negotiate with the other firms in the oligopoly for his share of the market to maximize his profits. I assume that each firm in the oligopoly faces an inverse downward sloping demand curve, which depends on the total quantity of the mineral supplied to the market. If the demand for the mineral is price-inelastic in the short term, an increase in the quantity supplied by the off-world miner and the other firms in the oligopoly will have a large negative effect on prices. In that case, the off-world miner would have to act strategically and negotiate its market share with the other firms in the oligopoly. As always, no unambiguous solution exits. The outcome will depend on the specific assumptions made with respect to the other firms' reactions. The economic literature[7] has analyzed these problems. If the annual supply of the new entrant is small compared to the overall size of the market and the information is perfect, an equilibrium solution can be found in which all firms maximize profits, provided that expectations correspond to the actual behavior of the companies in the oligopoly.

It was pointed out that the results would be quite different if the firms chose quantities sequentially. These games are a classic example of bi-level optimization problems, which are often encountered in game theory and economics. These are complex problems with a hierarchical structure, where one optimization task is nested within the other. In a multi-period strategy, when information is imperfect, a sequential equilibrium could prevail, as each company is able to infer information about other companies by their past actions and adjust their next period offers. It is evident that the adjustment would be incomplete in any single period but, over the longer run, some final state of balance would result. In this case, logistically, the off-world miner should reach agreements with a service company, such as Johnson Matthey in London, to deposit the metals returned to Earth and to sell them gradually over time through a series of forward contracts. The service company would then act as liquidity provider and agent for sale. The next section explores the question of if and under what conditions the second solution is financially feasible through a hypothetical case.

HYPOTHETICAL CASE: MINING MISSION TO AN ATEN-TYPE ASTEROID

The mission is the mining of the asteroid 2004 MN4.[8] This mission assumes a Hohmann transfer to rendezvous with the asteroid at its perihelion and a near-aphelion return trajectory to Earth, which are the lowest energy transfers between coplanar, elliptical orbits, tangent to the inner and outer orbits at perihelion and aphelion, respectively. The total time from launch to return in LEO will be roughly the sum of the three orbital half-periods; namely, the outbound transfer orbit, the target asteroid half-period mining season, and the payload return transfer orbit half-period. Based on the above calculations, the total time from launch to the return of the metals in LEO is about 1.4 years. The mining season is estimated at 160 days. It is assumed that it takes 13 months for the construction of equipment and the spaceship. Thus, the total time of the mission from the investment and the return of the minerals in the Earth's orbit is about 2.5 years.

The mass of the metals returned to Earth orbit has been calculated based on the average concentration of PGMs and precious metals presented in Table 1. It is further assumed that the propellant for the return of the spaceship is recovered from the asteroid. As such, the mass departing the asteroid includes both metals and the propellant for the return trip. The net present value of this project is then given by Equation (2):

$$NPV = \left[\left(\Sigma\left(p_t\ q_t\right)\right) - \left(OC\ q_t\right)\right] e^{-\delta t} - C \tag{2}$$

p_t = price of the mineral
q_t = yearly quantity supplied to the market
OC = unit operational costs, including costs of transferring minerals from orbit to Earth
δ = discount rate

The market share of the off-world miner, excluding gold, is assumed to be around 5%. In a Cournot-Nash oligopoly model, the quota of the off-world miner that maximizes its profits, under the simplifying assumption that all firms have equal marginal costs, is equal to:

$$q_t/Q_t = \left[1/\left(OC - 2\beta\right)\right]^* \left(\alpha + \beta q_n\right) \tag{3}$$

In Equation (3), Q_t is the total quantity supplied, β is the price elasticity of the demand function, α is the constant term in the demand function, and q_n is the production of the other firms in the oligopoly.

The dynamics of prices result from the interaction between the supply and demand functions for PGMs. The inverse demand function is a standard one, and it is dependent on a combination of global economic activity and lagged demand and prices. The price elasticity is small in the short run, but it may rise in the long run as substitution takes place. World economic activity is assumed to grow by an average of 3% per year. The total supply is a function of price, cumulative production, and technological factors, in which supply adjusts with a lag and the adjustment is incomplete in any period. These two equations were used in the simulation to determine the dynamics of prices. Prices follow a U-shaped curve, with a large decline in prices in the first year and a smaller fall in the second year, while prices recover in the subsequent years.

Unit operating costs are assumed equal to the cost of transferring to Earth the metals from LEO, estimated at 6,000 U.S. dollars per kg, plus the cost of labor and administrative activities, estimated to be about 2% of the total gross revenues. The metals returned to LEO will need a base in LEO where to be stocked before their transfer to Earth. Pending the construction of a spaceport for the storage of off-world minerals and fuels, a solution to this problem would consist of using the mining spaceship that can remain in LEO as long as necessary for the transfer of metals to the Earth, before leaving for a new mission to another asteroid for the replenishment of metals reserve, which would have decreased over time as a result of the adopted sale strategy. The transfer from LEO to Earth could be made through low-cost space vehicles. The results of the simulation are reported in Table 4.

TABLE 4 Simulation results

Mining season in days	160
Mass returned in metric tons	736
Equipment mass in metric tons	170
Average price changes for PGMs in percent over the period	2.7
Net value of sales in billions of U.S. dollars	26.6
Period of sales in years	11
Discounted net value of sales in billions of U.S. dollars (discount rate of 15%)	9.5
Discounted net value of sales in billions of U.S. dollars (discount rate of 20%)	7.2

These results are based on simplifying assumptions and should be treated with caution. However, they provide some important indications for the project feasibility. First, the results of the simulation depend heavily on the estimated concentration of PGMs and precious metals in the asteroids. The choice of the asteroid is thus determinant for the feasibility of the project. Second, the simulation is sensible to the discount rate, which reflects two elements: the time value of money (interest rate without risk) and a risk premium; i.e., the risk associated with a specific project. Given the risky character of these missions, we have assumed two discount rates of 15 and 20%, respectively.

Third, the cost of the investment, unknown for the time being, must be less than the discounted value of the sales. Since the return on the investment (ROI) for risky projects is generally assumed to be over 50%, we have calculated the levels of the investment costs consistent with a ROI over 50% (see Table 5), which give an indication on the maximum level of the investment costs acceptable to investors. In summary, the simulation indicates that asteroid mining can be financially feasible under certain conditions.

There are three challenges. The first challenge is related to exploration. At present, the concentration of PGMs and precious metals has been estimated via ground-based spectroscopic and photometric analysis of individual bodies, reflecting surface mineralogy and "weathering," and via inferred parallels with meteorites. In the mining industry, these estimates are indicated as "mineral endowment" or "mineral potential." No mining industry would invest in the development of a mine, unless a speculative storehouse of mineral resources is transformed into an actual storehouse through exploration.

TABLE 5 Rate of return on the investments and investment costs

Investment costs in billions of U.S. dollars.	Return on investment (ROI) (discount rate percent)	Investment costs in billions of U.S. dollars	ROI (discount rate 20%)
6.3	50	4.8	50
5.3	79	4.1	76
4.3	12	3.5	10

The same logic will apply to space mining. Exploration is thus the first step for the development of asteroid mining.

The second challenge concerns the costs of investment, which at the moment are unknown, and are driven mainly by the amount of mass returned, by the mission velocity requirements, by the propulsion system characteristics, by the costs of the equipment, and by the launch costs. Due to the inclination of asteroid 2004 MN4, it may require an impulsive transfer and the use of a nuclear propulsion engine. The advantage of the nuclear thermal rocket is that the energy source, high enriched uranium, is of very high energy density, and the reactor can use any non-coking volatile material as its coolant/working fluid/propellant. A study suggests that the development of this technology could cost between 2.5 to three billion U.S. dollars over five years.[9] In order to use an electric propulsion engine, an asteroid with lower inclination must be chosen. Research and development (R&D) of these technologies are well advanced and the next generation of ion engines will offer advanced capabilities with lower development costs compared to nuclear technology.

Launching costs are another important element in the total investment. Whether one uses a nuclear-powered space ship or an electric one, they have to be brought cold into orbit before starting their engines. Until recently, the launch industry in the United States and Europe was dominated by cartels, with space agencies dictating the design of the spaceship. Deregulation would help in reducing launch costs. In this case, national space agencies would act as the federal aviation authority by limiting their activities in certifying the safety of the spaceship, while private space companies would do what they are good at; i.e., reducing the costs through their vertically integrated design, manufacturing, supply chain, and efficiencies in operation. This is happening in the United States, where launch costs are coming down. Pressures are building up in Europe to reorganize the launch industry from the declining of costs in the United States and the low costs of launchers in India and China. Therefore, we feel confident that, in a few years, launch costs will come down globally.

The literature has analyzed the extraction and refining methods for PGMs on an asteroid.[10] These operations are much less massive than on Earth. They do not need heavy machinery for the extraction and the transport of ore to the refining center. On an asteroid, the open cast mining is suitable for the regolith. A cap around the mine site can be used to collect the ore; the rotation of the cap, using centrifugal force, would serve to channel the mineral to the refining center. In the case of extraction of the mineral from a hard rock, the use of a simple excavator is suitable, while a conveyor belt would lead to the ore to the zone refining.

The asteroid minerals require a minimum of machining, since many of the metals are in a free state. The ore is ground and sieved into different sizes. This material is then subjected to magnetic fields for separating the nickel-iron granules from silicates granules. Electrolytic techniques would then be used to remove cobalt and nickel from the metals of the platinum group. Finally, a series of techniques of ion exchange, distillation, and solvent extraction would separate the PGMs from gold. Most of the equipment and related costs can be conceptualized by the mining experience on Earth, to which must be added the cost of developing specific metal refining technologies in microgravity. Initial estimates indicate that the costs of these processes and equipment, including R&D, are around one billion U.S. dollars. These costs could be reduced by building some equipment in situ with 3D printing, using the asteroid regolith. Once in space, most components do not see major loading, save for a few (e.g., pressurized fuel tanks). Hence, space structures could, in fact, be made lighter since they would not need to withstand launch loads. In this way, the cost of the equipment and launching could be reduced.

The third challenge is legal. Uncertainty about property rights and the uses of resources could hinder the funding of these activities by increasing the risk premium. Under the terms of the Outer Space Treaty of 1967, space, including the Moon and other celestial bodies, is not subject to appropriation by a single nation with a claim of sovereignty. Moreover, the parties to the treaty are responsible for ensuring that private entities under their jurisdiction (including companies) legally respect the treaty. This last point is very controversial and is the subject of many disputes among legal experts. One argument raised by some experts is based on the distinction between the word "appropriation" of a celestial body and the word "use" of a celestial body. Another clause of the treaty states: "Outer space, including the moon and other celestial bodies, shall be free for exploration and use by all States." If mining is a use of a celestial body and not appropriation, these experts argue that any material extracted from an asteroid becomes the property of the company that carries out these activities.

Clarification of the property rights is thus important for the development of asteroid mining. Economic theory suggests that property rights are created when it is in someone's interest to do so. A first approach is, for a single nation, to develop an appropriate legal regime, in line with its needs and principles, rather than having to reach compromises with other countries. In view of the growing interest by private companies for mining asteroids, the U.S. Congress is debating a bill, the "Asteroid Act," whose main argument is that "every resource obtained from an asteroid is property of the organization that conducted these activities." However, there are reasons that following a policy of "going it alone" is not desirable. Unilateral actions would be challenged by other nations and would result in a political competition, and potential conflict, among nations in space.

Private companies and financial institutions are not likely to risk their capital and the considerable effort to develop the mineral resources in space if significant legal or political difficulties can disrupt the supply of these assets. Therefore, it is in the interest of all nations to seek an international agreement to provide legal stability and long-term policies. One possible solution to this impasse would be to add a clause of “mutual recognition” to national bills. This would force individual states to sign treaties with other countries concerned with asteroid’s mining, in which each country recognizes the claim of other countries on the use and ownership of the mineral resources of the asteroids. There is precedent for this. Since the early 1980s, the United States has followed this type of protocol when it comes to the rights of extraction of minerals from the deep seabed of the ocean floor. The next section concentrates on the exploration phase of the project

EXPLORATION

On Earth, geological knowledge of an area is usually provided by governments as a public good, and it is widely recognized as an important element for attraction of private companies and for contributing to the continued development of mineral resources. Similarly, the exploration programs of the asteroids from space agencies could open the door to exploitation of natural resources by the private sector, not only through the development of technologies to reach and land on the asteroids, but also through the identification of near Earth asteroids and the verification in-situ of their composition, thus helping to push the commercialization of space beyond low Earth orbit and into deep space.

The key questions in designing exploration are: (1) what is the most important information that one wants to learn about accessible asteroids; and (2) what is required to obtain the information listed in (1); i.e., how much can be done on Earth and what type of space missions are required: manned or robotic, and single or multiple targets. The most important information on the asteroids is a verification for a representative sample of objects of: composition (chemical and isotopic); mineralogy; internal structure; surface morphology; and nature of regolith and fragmentation history. Representative objects should be limited to iron- and chondrite-accessible NEAs, which could be the targets of future mining operations. Ground-based astronomical observations have already made substantial progress in defining and characterizing the population of NEAs, including preliminary estimates of their mineral composition. Algorithms have been developed to define the orbital characteristics, mass of the accessible asteroids, required Δv, length of the missions, and possible launching dates of identified bodies.

National space agencies are designing and planning reconnaissance missions to the asteroids. The 2013 Global Exploration Roadmap of the International Space Exploration Coordination Group (ISECG) reflects the importance of stepwise developments of critical capabilities that are necessary for executing increasingly complex missions to multiple destinations.

Recently, NASA approved a program called Redirect Asteroid Mission (ARM), whose goals are the identification, capture, and transport of an asteroid in a stable orbit around the Moon, and subsequent human missions to this asteroid in lunar orbit. The primary objectives of ARM include the testing of new propulsion systems and the difficult maneuvers of rendezvous with the asteroid, and the verification of the feasibility of long sojourns in space by astronauts, outside the protective shield of the Earth magnetic field, in view of longer-term human missions to Mars. This program will also allow assessing in-situ the mineral resources' composition of the asteroid, and testing methods and systems to carry out these operations. These are valuable sources of information for the development of space mining. This program will thus combine NASA's strategic space exploration interests with those of private entities interested in space mining. NASA plans to launch the spaceship for the recovery of an asteroid in 2019, and to bring it into lunar orbit. Once the asteroid is brought into lunar orbit, the astronauts, aboard the Orion capsule launched by NASA's Space Launch System (Orion and the Space Launch System are currently under development by NASA), will explore it in 2020.

In recent years, the allure of space has once again captured the minds of a generation. Absent from this new wave is the strong government directive of the Apollo era. In its place is the awakening of individuals and private industries who see the possibility of the democratization of space and the expansion of Earth's economic sphere. Private space companies are also designing and planning exploratory missions. Planetary Resources is designing a robotic spacecraft to explore asteroids and to determine the positions, composition, and accessibility of the resources. Deep Space Industries is designing and planning low-cost reconnaissance missions to promising asteroids to analyze key aspects of the asteroids, including their composition, structure, and spin rate, in view of future missions to land on the targeted asteroids and to bring back asteroids' materials. At the moment, little is known about the time frame of these private sector missions and their technical and financial feasibility.

It is important to underscore that national space agencies are operating under tight budget constraints and it is likely that they will continue to operate in such conditions. One possible way out of this conundrum is for national space agencies to identify synergies with private space companies in order to liberate resources for the realization of their strategic mission; i.e., robotically deflecting an asteroid to enable its human exploration in the lunar vicinity. An agreement could be reached with private space companies whereby these companies would carry out robotic exploration missions to targeted asteroids to determine the asteroids' composition, structure, and spin, and to bring back samples. The private companies could share the information with the space agencies for a price, which will be a fraction of the costs for the space agencies to carry out the missions themselves.

Alternatively, they could share the information in exchange for participation in the missions to the small asteroid in lunar orbit to test the mining methods and equipment, thus reducing the risks of future operations on an industrial scale. Both solutions are Nash equilibria, such that each player's strategy maximizes his expected utility pay-off against the given strategies of the other players, and no player can do better by unilaterally changing his strategy. The players' optimal strategy depends on their expectation of what the other player may do. An important step in finding an optimal strategy would be to establish an adequate forum in which space agencies and private space companies can discuss and exchange information on their programs, their affordability, and possible missions' time frames. Identification of synergies and agreements between national space agencies and private space companies brings in the third player in this game: the governments. Governments are ultimately responsible for the allocation of public resources to different programs.

An affordable strategy of asteroid exploration leading to actual asteroid mining should be of interest to policy makers for the following key reasons. Economically, it will provide an effective way to develop mineral resources that are exposed to supply chain fragility. By reducing the risk of extraordinary market volatility to consumers of minerals, representing an important part of the modern economy, it would positively affect long-term economic growth. Moreover, increases in productivity, economic growth, and employment would result because of the investments in the technologies' development and the spill-over effects on a variety of fields, such as artificial intelligence, robotics, new materials, nanotechnology, and computer and communication technologies.

The supply of off-world minerals and the enactment of an international legal framework regulating the use of space could contribute to the elimination of one of the elements behind the present geopolitical instability; i.e., the aggressiveness in the search for the control of natural resources on Earth. Since the end of the Second World War, there were more than 150 wars. Of these, relatively few have been large-scale wars between nations. The majority of wars, about 80%, have been civil wars in the developing-world countries, particularly in sub-Saharan Africa. At present, there are 25 raging wars around the world that have their origins in disputes over local access to critical resources,[11] and there are likely to be many more in the future. Many scholars have analyzed these conflicts in order to understand why violence occurs and how future conflicts can be prevented. There exists an ongoing debate regarding the distribution of raw materials and how this distribution contributes in causing these conflicts. The supply of off-world critical minerals that are free from political risk would contribute to a reduction of tensions in many areas of the world, particularly in sub-Saharan Africa. Geopolitically, access to space mineral resources reduces the risks of conflicts over the access to local resources, creating the conditions for a more stable world.

CONCLUSIONS

The analysis of this report suggests that the exploration of the asteroids by national space agencies will definitely be completed over the next 10 years. From a technical point of view, the capabilities to explore the asteroids exist. The financing of asteroid exploration will not require major increases in the budgets of space agencies from their actual and foreseen funding, if synergies with private companies are found. Asteroid exploration will then open the way to their mining by the private sector, which could most likely occur in the early 2030s. The financing of space mining by private companies can be achieved through financial and equity markets, provided that an international legal framework on the exploitation of space resources is in place, and that some cost issues raised in the previous paragraphs are resolved, particularly the reduction of commercial space transportation costs.

The United States, as the dominant military, technological, and economic power, is in a position to exert a strong influence on these processes. American capabilities remain enormous thanks largely to persistent technological advance. The announcement by the United States of the intention to proceed with the asteroids' exploration in partnership with private space companies, and to collaborate with other nations in the establishment of an international legal framework for the use and extraction of space mineral resources, would give important messages to policy makers, emerging private space companies and financial markets, and other spacefaring nations.

The most important message is that space activities will return economic, technological, and quality-of-life benefits on Earth. The economic benefits come into three broad categories: direct effects, measured by revenues generated by the utilization of space and the performance of related services and products; consumers welfare effects, as measured by the benefits to consumers beyond the value that they have paid for those products and services; and economic effects, arising from the efficiencies generated by those products and services. Political benefits come in one broad category: world political stability. The second important message is that the United States is willing to cooperate with other spacefaring nations in establishing an international legal and institutional framework for a peaceful development of the space economy. In fact, it is only through the establishment of the rule of law that different spacefaring nations could feel secure that their own private companies could participate in these ventures. If commercial space transportation becomes widely available, with substantially lower costs as indicated by recent developments in the United States, then all countries will be able to directly reap the benefits of space resources.

In summary, pushing the human presence and economic activities beyond low Earth orbit opens a new frontier for the benefit of all humanity. Successes in these ventures will revive the interest of the public and policy makers in human space exploration and its eventual colonization.

The scientific knowledge and the technologies to realize the human exploration and colonization of the solar system are already here. Going beyond the solar system will require advancements in science and development of technologies that we do not yet have. The financial resources for the realization of these programs could be found through the collaboration between governments and the private sector.

The history of voyages of exploration and discovery of the modern period teaches us that the strategic interests of governments can align with the interests of individuals in search of knowledge, adventure, and/or to escape political instability; and of businesses looking for new trade routes, raw materials, and new outlets for their products.[12] Voyages of exploration preceded migrations by creating the knowledge and the infrastructure that allowed future settlements. Our own experience creates a precedent, or paraphrasing the poetic expression of Mark Twain: "history does not repeat itself but it rhymes."

NOTES

1. *The Space Report 2014* (Colorado Springs, CO: The Space Foundation, 2014).
2. See S. Kesler, *Mineral Resources, Economics, and the Environment* (New York: Macmillan, 1994); and J. R. Craig et al., *Resources of the Earth* (Englewood Cliffs, NJ: Prentice-Hall, 2001).
3. *Mineral Commodities Summary, 2011*, United States Geological Survey (Washington, DC: U.S. Government Printing Office, 2011).
4. See McMahon et al., *Survey of Mining Companies 2009/2010*, Fraser Mining Institute, http://www.fraserinstitute.org/uploadedFiles/fraser-ca/Content/research-news/research/publications/miningsurvey-2010update.pdf (accessed January 2015).
5. See C. S. Tang, "Robust Strategies for Mitigating Supply Chain Disruptions," *International Journal of Logistics Research and Applications* 9:1 (2006): 33–45.
6. *Asteroid Retrieval Feasibility Study*, Keck Institute for Space Studies, study prepared for the California Institute of Technology and Jet Propulsion Laboratory, Pasadena, California, April 2010.
7. See, for example, D. C. Colander, *Microeconomics* (New York: McGraw-Hill, 2012).
8. 2004 MN4 was discovered on 19 June 2004 by Roy A. Tucker, David J. Tholen, and Fabrizio Bernardi at the Kitt Peak National Observatory. It is an Aten type of asteroid with a diameter of 350 meters and an estimated mass of 40 billion metric tons. It has an orbital period of 323 days, a low eccentricity (0.191), and an inclination on the ecliptic of 3.331 degrees.
9. S. Howe et al., *Ground Testing a Nuclear Thermal Rocket: Design of a Sub-scale Demonstration Experiment,* American Institute of Aeronautics and Astronautics, AIAA 2012-3743, 30 July 2012.
10. See J. S. Kargel, "Metalliferous Asteroids as Potential Source of Precious Metals," *Journal of Geophysical Research Planets* 99 (1994): 21129-21141.
11. See *Stockholm International Peace Research Institute Yearbook 2014* (New York: Oxford University Press, 2014).
12. See A. Sommariva, "Motivations Behind Interstellar Exploration and Colonization," *Astropolitics*12 (2014): 84–92.