Prospecting for Minerals in Space: What's Out There and Can We Get to It?

by

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Abstract: Ever since Captain Kirk took command of the Enterprise, we have known that space is the final frontier. With minerals on Earth finite, do we want to move mining operations to space, where no one has mined before. Booming metal markets and improvements in space technology have kindled interest in this very question. In a companion background paper, I reviewed nonfuel mineral markets on Earth and noted the periodic paranoia about running out. In each case, adjustments on demand and supply have come to the rescue; higher prices stimulated buyers to find substitutes, conserve the factor and buy less, while higher prices stimulated sellers to dig deeper, squeeze marginal resources harder, and search in frontier areas. In this background paper, I consider whether space might be such a frontier soon to be within our economic reach. In any large mining operation, there are legal, social, political, economic, geological, and technological implications. I outline some of these and conclude with a numerical simulation of the cost competitiveness of bringing asteroid material back to Earth for processing.

Introduction

For space to be a mineral frontier with near term development prospects, a number of criteria must be satisfied – there needs to be minerals we want in space, we need to be able to exploit them, and some capable entity needs to want to exploit them. I explore aspects of all three of these requirements. In section II, I consider the information on the availability of economically desirable minerals in space, especially those nearby. In section III, I explore the history of space flight and the technology available to make space mining a reality. In other words, can we do it? In section IV, I highlight a few legal and economic issues relating to space mining, and in section V, I dive deeper into space mining prospects with some back of the envelop computations on the costs and returns to mining given what I have gleaned about current technology and costs from publically available literature.

II. Minerals from space: What's out there?

Information on mineral availability in space though not abundant has been improving. We've come a long way since Galileo first turned his primitive telescope towards the sky in 1610. The European Space Agency and NASA launched the first space telescope (the Hubble) in 1990. After some initial repair, it began sending back images in late 1993. With additional periodic repair, it has continued to return images to this day (nasa.gov/mission_pages/hubble/story/index.html).

Since 1985, more than 5 missions from four space agencies (U.S. – NASA, E.U. – ESA, Japan – JAXA, China – CNSA) have made it to asteroids and have included flybys, orbiting, landing and returning samples (https://nssdc.gsfc.nasa.gov/planetary/planets/asteroidpage.html).The two most recent asteroid orbiting probes were scheduled to land and take samples and return them to Earth. (Osiris-Rex (USA) and Hayabusa-2 (Japan)) https://nssdc.gsfc.nasa.gov/planetary/chronology.html), (https://nssdc.gsfc.nasa.gov/planetary/planets/asteroidpage.html) Hayabusa II successfully returned a sample to Earth in December, 2020 (https://www.bbc.com/news/science-environment-55201662). Osirus-Rex landed and took samples in October of 2020 and is scheduled to return to Earth in 2023 (https://www.nasa.gov/osiris-rex).

Our knowledge of asteroid composition comes from the study of meteorites, telescopic imaging, along with space mission photos, landings, and samples. Asteroids that have not been sampled, which is practically all of them, are typically categorized by their spectral type. Although there are a number of such categories (http://curious.astro.cornell.edu/about-us/72-our-solar-system/comets-meteors-and-asteroids/asteroids/295-how-are-asteroid-compositions-and-classifications-determined-intermediate), Metzger (2013) indicates that three types are of relevance to space mining – C, S, and M. Type C is likely to contain water, metal, and organic or carbonaceous compounds. Their components might be converted into hydrogen, oxygen, and methane for rocket fuel and Co_2 to grow plants, create plastics and rubber that might be crafted along with metal into parts, perhaps with the use of 3D printers. Type S may contain the platinate group of metals – ruthenium, rhodium, palladium, osmium, iridium, and platinum. These precious metals sell for millions of dollars a metric tonne on Earth, so make them candidates to mine and return to Earth where their most important current and potential uses include vehicle catalytic converters; catalysts in petroleum refining and the chemical industry; health applications; and fuel cells among other applications (https://www.thermofisher.com/blog/metals/what-are-the-platinum-group-metals-and-why-do-they-matter/). Type M may include some metals in the platinate groups but with more prevalent quantities of iron and nickel. The last two less valuable but plentiful minerals will more likely be used in space for colonization or as hardware for larger missions as they are very expensive to get to space but comparatively cheaper to mine on Earth. However, if earth shortages and costs provided the right incentives, they might be sold on Earth as well. The evidence to date suggests that space objects are well endowed with minerals were we to run out on Earth. A 2017 USGS study promisingly concluded "that the water and metal resources in near-Earth asteroids are sufficient to support humanity should it become a fully space-faring species" (Keszthelyi et al. (2017)). For more on detecting, population estimation, identifying and characterizing asteroids see Anthony and Emami (2018)).

Not only asteroid composition but location will also be an important determinant of cost. The moon, our nearest celestial neighbor, though technically not an asteroid (too big and it doesn't orbit the sun), may have some possibility for mining. It is thought to contain large amounts of titanium (an important alloy for spacecraft but abundant on Earth), Helium 3 (that might power fusion reactors), water (that could be used to produce rocket fuel, to support life, and to shield humans from cosmic radiation) and rare earth minerals (https://www.space.com/13247-moon-map-lunar-titanium.html. https://www.space.com/28189-moon-mining-economic-feasibility.html). See https://www.jpl.nasa.gov/infographics/infographic.view.php?id=11272 for a brief discussion of how moon mining might work. As the moon has been hit by numerous meteorites, it may have abundant other minerals as well. For more on the moons chemical composition from lunar samples taken on the eight Apollo and Luna lunar missions, see https://www.permanent.com/lunar-geology-minerals.htm.

Targeting the moon for mining has already begun. Moon Express founded in 2010 has a stated goal of mining the moon (http://www.moonexpress.com/, https://spacenews.com/moon-express-raises-12-5-million/). In 2016, it was the first commercial company to receive U.S. government permission to travel out of earth's orbit. However, the company missed the target of winning Google's Lunar XPRIZE in 2017, as did all the other entrants. When a major investor pulled out in 2017, they struggled until receiving a NASA contract in 2018. They are now focusing their attention on landers that could take about 450 pounds to the moon. (https://www.cnbc.com/2017/01/31/billionaire-closer-to-mining-moon-for-trillions-of-dollars-in-riches.html, https://www.jpl.nasa.gov/infographics/infographic.view.php?id=11272. https://www.orlandosentinel.com/business/space/go-for-launch/os-bz-moon-express-update-20181114-story.html).

Next come the asteroids. The two most prominent companies targeting asteroid mining have been Planetary Resources, which announced its intensions to mine asteroids in 2012 and Deep Space Industries, which announced its intensions in 2013. Planetary Resources strategy to bring down costs would be to use water and resources in space to avoid having to port all materials from Earth. Their first focus was to be on water and ice, which would be converted to fuel and sold as rocket propellant. They made their first successful earth satellite demonstration launch from the International Space Station in 2015 and a second demonstration launch of an earth satellite with technology to detect water on nearby celestial bodies in 2018 (https://www.planetaryresources.com/company/timeline/, https://space.skyrocket.de/doc_sdat/arkyd-3.htm, https://www.planetaryresources.com/2018/04/mission-success-arkyd-6-tests-key-technologies-for-commercial-space-resource-exploration/). As NASA switched their focus from near earth asteroids to moon exploration and mineral prices tanked, Planetary Resources switched their focus to earth observation (https://www.geekwire.com/2019/bradford-buys-deep-space-industries-shifting-focus-asteroid-mining-green-propulsion/). Suffering from funding issues, they were acquired by ConsenSys, Inc., a block chain company, in late 2018 (https://spacenews.com/asteroid-mining-company-planetary-resources-acquired-by-blockchain-firm/). Although their future within ConsenSys is uncertain, the acquisition was accompanied by vague pronouncements of democratizing and decentralizing private-ordering and commerce in space.

Deep Space Industries was also first focusing on water, but in their case it was on a water propulsion system to reduce the cost of asteroid mining. In 2016, they announced plans to visit a near Earth asteroid by 2020 (https://www.geekwire.com/2016/deep-space-industries-asteroid-2020-prospector-1/, https://www.geekwire.com/2019/bradford-buys-deep-space-industries-shifting-focus-asteroid-mining-green-propulsion/). However, as the times changed, they too needed to switch their focus away from asteroid mining to endeavors closer to Earth. They turned to their water propulsion system, called Comet, which is now being used by four small satellites. This system uses electricity to heat water to steam and create propulsion. In early 2019, they were acquired by Bradford Space, which manufactures satellite control systems and will continue to support the comet propulsion technology. (https://www.geekwire.com/2019/bradford-buys-deep-space-industries-shifting-focus-asteroid-mining-green-propulsion/, http://bradford-space.com/about-bradford-engineering-history.php).

Although these asteroid mining pioneers have put us closer to asteroids, these latest developments suggest that space mining is not as close as they had hoped. However, technical change and the move toward green energy applications could dramatically increase the demand for certain metals. For example, gallium (#31), germanium (#32), selenium (#34), indium (#49), and tellurium (#52) are used in electronic and solar energy application; cobalt (#27), hafnium (#72), and rhenium (#75) are used in alloys that can withstand high temperatures with applications in aerospace, military, and medical industries; the rare earth elements praseodymium (#59), neodymium (#60), terbium (#65), dysprosium (#66), and lutetium (#71) have uses in wind turbines, efficient lighting, electric vehicles, digital equipment and in medical devices, and lithium (#3) is important for batteries where light weight is important (https://www.metabolic.nl/publications/metal-demand-for-renewable-electricity-generation-in-the-netherlands/, https://www.angelo.edu/faculty/kboudrea/periodic/trans_transition.htm, https://www.carbonbrief.org/explainer-these-six-metals-are-key-to-a-low-carbon-future (Haque, Hughes, Lim, and Vernon (2014)). Arrobas, Hund, Mccormick, Ningthoujam, and Drexhage (2017) summarize the uses for some of these metals in table 1.

Table 1 Important Metals for Low Carbon Uses

	Wind	Solar photovoltaic	Concentrating solar power	Carbon capture and storage	Nuclear power	Light-emitting diodes	Electric vehicles	Energy storage	Electric motors
Aluminum	X	X	X	X		X		X	X
Chromium	X			X	X	X			
Cobalt				X	X		X	X	
Copper	X	X		X	X	X	X		X
Indium		X			X	X	X		
Iron (cast)	X		X			X		X	
Iron (magnet)	X								X
Lead	X	X			X	X			
Lithium							X	X	
Manganese	X			X			X	X	
Molybdenum	X	X		X	X	X			
Neodymium (proxy for rare earths)	X						X		
Nickel	X	X		X	X	X	X	X	
Silver		X	X		X	X	X		
Steel (Engineering)	X								
Zinc		X				X			

Source: Arrobas et al. (2017)

When earthly sources become too sparse and the time comes, as with any green field mining venture, asteroid mining will require prospecting to find the commercial grade possibilities. Such discovery will eventually require orbiting, landing, and sampling. To pick our prospects for further investigation, we can first turn to the mounting information on where the near-earth asteroids are, what is their composition and their orbits. In 1997, a near earth asteroid (1997 XF11) almost a kilometer in diameter was discovered that might potentially hit the Earth in 2028. Although this asteroid was later found to be non-threatening, the scare led to the founding of the NASA's Center for Near-Earth Object Studies in 1998. Since then they have found more than 18,000 near earth objects greater than 1 km in diameter with orbits that come within 195 million km of the sun and 50 million km of the Earth (https://www.jpl.nasa.gov/news/news.php?feature=7194). The majority of these near earth objects (NEOs) are asteroids or rocky debris from the beginning of the solar system and a small percent are comets, which are made of ice, gas, and dust that can melt when the sun shines on them (hence the tail)(https://solarsystem.nasa.gov/asteroids-comets-and-meteors/overview/).

NEOs proximity to Earth make them likely candidates to begin a space mining venture after the moon or perhaps even before as many are easier to access than the moon. These asteroids are also being watched to indicate whether they are potentially harmful object (PHAs). Such is the case if they are on a near collision course with Earth and considered large enough to cause significant damage from such a collision (For a more precise definition see https://cneos.jpl.nasa.gov/about/neo_groups.html). Near-earth asteroids are also categorized by orbital groupings – Ateras, Atens, Apollos, Amors. These groupings depend on the length of their orbital axes and their relationship to earth's orbit

(http://astronomy.swin.edu.au/cosmos/N/Near+Earth+Asteroids, https://cneos.jpl.nasa.gov/about/neo_groups.html)

The most numerous asteroids within our solar system are in a belt further out between Mars and Jupiter. They are called the main belt asteroid (MBA). Although even more technically and economically challenging to mine, they are immensely plentiful with more than a million specimens with diameters greater than one kilometer (https://solarsystem.nasa.gov/asteroids-comets-and-meteors/asteroids/in-depth/). They are unlikely to be our first mining targets. However, were we to colonize space, particularly Mars, these mineral sources become much more appealing.

Even more massive but less known is the Kuiper belt of objects (KBOs) beyond Uranus (orbiting the sun at more than 30 Au or 30 times the distance from Earth to the sun).It contains Pluto (sadly defrocked as a planet as of 2006, shame on you Neil deGrasse Tyson) (https://spaceplace.nasa.gov/kuiper-belt/en/). Demoted to dwarf planet status, Pluto has more happily gained some sibling dwarf planets (Ceres, Haumea, Makemake, Eris) (https://www.space.com/16144-kuiper-belt-objects.html). Surface study of objects in the Kuiper Belt suggest they consist mostly of frozen volatiles including methane, ammonia, nitrogen, and water in varying degrees. Larger objects are more likely to be able to keep hold of more of the most volatile compounds while smaller ones may have surfaces that contain more water ice. (Brown (2012), https://www.annualreviews.org/doi/full/10.1146/annurev-earth-042711-105352). So the amount of minerals and water in asteroids is pretty amazing and the information about them is slowly and steadily mounting.

NASA's New Horizon Space probe launched in 2006 reached its closest approach to Pluto in 2016 with equipment to measure atmospheric composition, color mapping of the surface, atmospheric emissions, solar wind around Pluto, and its moons (http://pluto.jhuapl.edu/Pluto/The-Pluto-System.php). New Horizon is currently sending back information on an even more distance KBO (Ultima Thule) (http://pluto.jhuapl.edu/Ultima/Ultima-Thule.php). You can link to an animated gif file with the movements of these asteroid belts along with planetary motion at https://minorplanetcenter.net/iau/Animations/Animations.html. So the technology exists to get us to the furthest asteroid belt to have a look. We can even get beyond as NASA's Voyager I and II launched in 1977 left the solar system into interstellar space in 2012 and 2019, respectively. However, New Horizon with a payload of about 30 km, a price tag of $800 million and a one way trip to Ultima Thule of 13 years, suggests we will not be mining this asteroid just yet.

To come up with a representative asteroid for the simulations in Dahl, Gilbert, and Lange (2019)and Dahl, Gilbert, and Lange (2020), the most useful information came from work done to assay meteors. This data has been collected over many years. NASA (2019) indicates that "more than 50,000 meteorites have been found on Earth." Almost all of them are from asteroids (99.8%) with a few from the Moon and Mars (https://solarsystem.nasa.gov/asteroids-comets-and-meteors/meteors-and-meteorites/in-depth/).

From near earth objects, Kargel (1994) considers metalliferous asteroids as promising candidates for asteroid mining, surveys work on the metal content of these asteroids, and cites the value for some of these asteroids if the precious metals could be brought back to Earth. Wasson (1974) suggests that about 5% of meteorites are in this category. Dahl (2020) uses information from Kargel (1994) and Buddhue (1946) to come up with a representative metallic asteroid as reproduced in Table 2.

Table 2 Representative Metal Meteorite

	A#	**Weight (g/t)**	**<=Sources (Concentration)**	**Density g/ct^3 =t/m^3**
Fe	26	897,000.0	Buddhue (1946), p 247, Table 1	7.87

Co	27	6,200.0	Buddhue (1946), p 247, Table 1	8.90
Ni	28	93,000.0	Buddhue (1946), p 247, Table 1	8.91
Ru	44	21.5	Kargel (1994), p. 21,133, Table 1, column 4	12.37
Rh	45	4.0	Kargel (1994), p. 21,133, Table 1, column 4	12.41
Pd	46	16.5	Kargel (1994), p. 21,133, Table 1, column 4	12.02
Os	76	14.5	Kargel (1994), p. 21,133, Table 1, column 4	22.60
Ir	77	14.0	Kargel (1994), p. 21,133, Table 1, column 4	22.40
Pt	78	29.0	Kargel (1994), p. 21,133, Table 1, column 4	21.45
Au	79	0.6	Kargel (1994), p. 21,133, Table 1, column 4	19.32
Asteroid	(10 metals)	996,300.1	Kargel (1994), p. 21,133, Table 1, column 4	7.92

Source: Density for metals: https://www.angstromsciences.com/density-elements-chart. Density for asteroid, authors computations in http://dahl.mines.edu/SpaceMining.xlsx, worksheet AsteroidMass&Dens&Vol, cells I12:S14.

Notes: g/ct^3= grams per cubic centimeter also equal to t/m^3 = metric tonnes per cubic meter.

More recently, rare earth metals have been cause for concern and more meterorite assays for them have cropped up as well. Because these elements are so similar, they are difficult to separate and were identified later than others. For a fun romp through the history of their separation, see https://www.periodni.com/history_of_rare_earth_elements.html. The first three rare earths separated into elemental form were lanthanum, cerium, and ytterbium in the late 1830's and early 1840's. Most of the rest were separated out by 1910. However, the last, promethium, was only separated out in the 1940s from byproducts of nuclear chain reaction technology (https://cen.acs.org/articles/95/i34/whole-new-world-rare-earths.html). Meteorite assays for them seem to have come later. some highly cited early examples of rare earth elements in meteors include Haskin, Frey, Schmitt, and Smith (1966), Nakamura (1974), and Evensen, Hamilton, and O'Nions (1978).

Carbonaceous chondrite asteroids are thought to be possible targets for space mining partly for their water content, which can be a source of fuel. They typically contain some precious and rare earth elements. Martínez, Moyano-Cambero, Trigo-Rodríguez, Alonso-Azcárate, and Llorca (2017) use inductively coupled plasma mass spectrometry on 38 carbonaceous chondrite meteor samples to determine their treasures for 14 of the rare earth elements. Their meteor samples come from the following carbonaceous chondrite groups: CH, CI, CK, CM, Co, CR, CV, and some meteors that are not yet grouped. From their assays, information they provide from other studies, and other sources, I put together the following representative carbonaceous chondrite asteroid in Table 3. The remaining 2/3 for this asteroid's composition would likely contain some carbon but is mostly silicate (Ibiblio (1996)).

Table 3 Representative Carbonaceous Chondrite Meteor (content in ppm)

Category	**Material**	**ppm**	**Source:**
FerroMag	Fe	215,312.00	Martinez et al. (2017), Table 3
	Cr	312.50	Wasson, Kallemeyn, Runcorn, Turner, and Woolfson (1988) quoted from Martinez et al. (2017), midpoint of range in Table 5
FerroMag	Co	0.59	Martinez et al. (2017), Table 3

FerroMag	Ni	1,205.00	Martinez et al. (2017), Table 3
	Cu	0.11	Wasson et al. (1988) quoted from Martinez et al. (2017), midpoint of range in Table 5
	Zn	0.22	Wasson et al. (1988) quoted from Martinez et al. (2017), midpoint of range in Table 5
REE	Sc	8.60	Wasson et al. (1988) quoted from Martinez et al. (2017), midpoint of range in Table 5
REE	Y	1.92	Wasson et al. (1988) quoted from Martinez et al. (2017), midpoint of range in Table 5
PGM	Ru	0.95	Wasson et al. (1988) Averages from Table 2
PGM	Rh	0.10	Wasson et al. (1988) Averages from Table 2
PGM	Pd	0.65	Wasson et al. (1988) Averages from Table 2
	Ag	0.14	Wasson et al. (1988) Averages from Table 2
REE	La	1.93	Martinez et al. (2017), Table 2
REE	Ce	6.53	Martinez et al. (2017), Table 2
REE	Pr	0.50	Martinez et al. (2017), Table 2
REE	Nd	2.22	Martinez et al. (2017), Table 2
REE	Sm	0.52	Martinez et al. (2017), Table 2
REE	Eu	0.14	Martinez et al. (2017), Table 2
REE	Gd	0.55	Martinez et al. (2017), Table 2
REE	Tb	0.09	Martinez et al. (2017), Table 2
REE	Dy	0.62	Martinez et al. (2017), Table 2
REE	Ho	0.13	Martinez et al. (2017), Table 2
REE	Er	0.48	Martinez et al. (2017), Table 2
REE	Tm	0.06	Martinez et al. (2017), Table 2
REE	Yb	0.37	Martinez et al. (2017), Table 2
REE	Lu	0.06	Martinez et al. (2017), Table 2
PGM	Os	0.66	Wasson et al. (1988) quoted from Martinez et al. (2017), midpoint of range in Table 5
PGM	Ir	0.61	Wasson et al. (1988) quoted from Martinez et al. (2017), midpoint of range in Table 5
PGM	Pt	1.10	Wasson et al. (1988) quoted from Martinez et al. (2017), midpoint of range in Table 5
	Au	0.16	Wasson et al. (1988) Averages from Table 2
	Water	110,000	Ibiblio (1996)
Rest		673,140.51	

Notes: FerroMag=ferro magnetic, PGM=platinum group metal, REE=rare earth element. Highlighted rare earth elements are the ones considered critical (U. S. Department of Energy (2011)).

Martinez et al. (2017) suggest that the rare earths in the above asteroid would not be profitably mined for return to Earth, but that the platinum group elements might be. Sommariva (2015) also suggests that platinum would be an early asteroid mining target in decades to come. She urges a public private partnership in the early stages to develop the technologies for mining asteroids and furthering space markets and goals.

From this limited discussion, we have some idea of what is out there. There are precious metals and rare earth elements out there, much coveted on Earth. Given the number of estimated asteroids, which is likely growing as I type, there is lots to be had. However, they have low concentrations and it is difficult to fetch and bring these valued cargoes back home to Earth. In the next section, I turn to exploring whether we have the capability to so.

Mining Space: Can We Do It?

Not just distance determines how difficult it will be to get to an asteroid for mining operations. There is one further complication. I guess that's why they call it rocket science. First, you need to accelerate enough to escape the gravity of Earth. How much you need to accelerate depends on whether you are launching in the direction the Earth is moving or the more difficult task of launching in the opposite direction. You can launch into low earth orbit (LEO), but if you accelerate further you can go to more distant places. This acceleration or change in velocity, is designated as delta v or Δv and is measured in kilometers per second (km/s). We have numerous estimates of Δv for various celestial objects of interest. Figure 1 contains some common examples. Δv to low earth orbit starts at about 9.4 km/s. With another 6.4 Δv, we could land on the moon. With 8 or so more Δvs from LEO, we could get to the potential mining targets in the main asteroid belt between Mars and Jupiter (Taylor, McDowell, and Elvis (2018)).

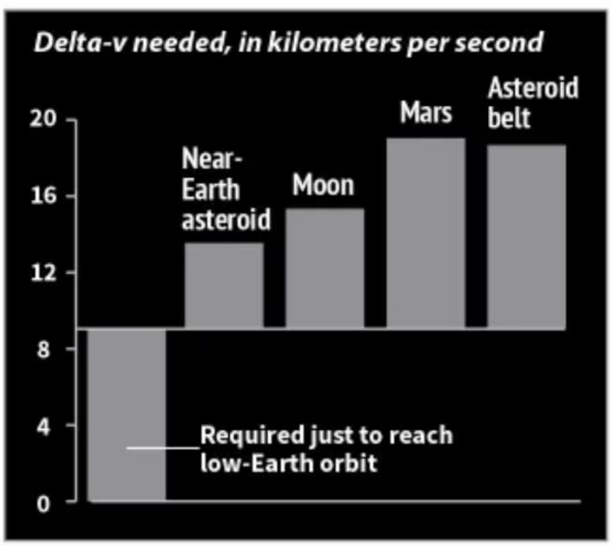

Figure 1: Δv for some well known objects.
Source: https://www.space.com/26572-how-it-worked-the-apollo-spacecraft-infographic.html

We can look more closely at some Δvs for some intermediate targets. Δv to LEO is around 9.4. With more acceleration, we can go into a higher orbit synchronized with the earth's rotation (geosynchronous orbit (GSO)) putting us above the same spot on Earth at all times. If this GSO is over the equator, not only is the same spot always below, but the whole visible area is always the same. Such an orbit is called geostationary (GEO). GEO requires an additional Δv of 3.8 from LEO. GSO and GEO are orbits typically used for communication satellites and surveillance. An orbit that gets us into GSO or GEO with the lowest Δv, which typically minimizes fuel burn, is the Hohmann transfer orbit indicated by GTO. With more acceleration yet you can attain a transfer orbit that does not remain in orbit but reaches escape velocity to "slip the surly bonds of Earth" entirely. This Δv is typically called earth transfer and designated as C3. Similarly, there is a Mars C3.

A last handy category of orbits I mention here are Lagrange points. These refer to orbital positions of an object relative to other bodies also in orbital relationships. They are somewhat similar to geosynchronous orbits, but they magically remain over the same position with respect to more than one celestial body. For example, the moon orbits the Earth and the Earth in turn orbits the sun. There are five points in orbit around the Earth that remain in a fixed spot over both the Earth and the Moon. Two of them are stable. If a satellite is orbiting at either of the stable two points, called L4/L5, and wobbles off course, there are forces to push it back on track. If located over the unstable points (L1/L2/L3) more guidance systems would be required to keep them on course https://solarsystem.nasa.gov/resources/754/what-is-a-lagrange-point/. Such Lagrangian points are logical points for refueling and resupply depots servicing space mission. Figure 2 shows the Δvs to more of these intermediate destinations.

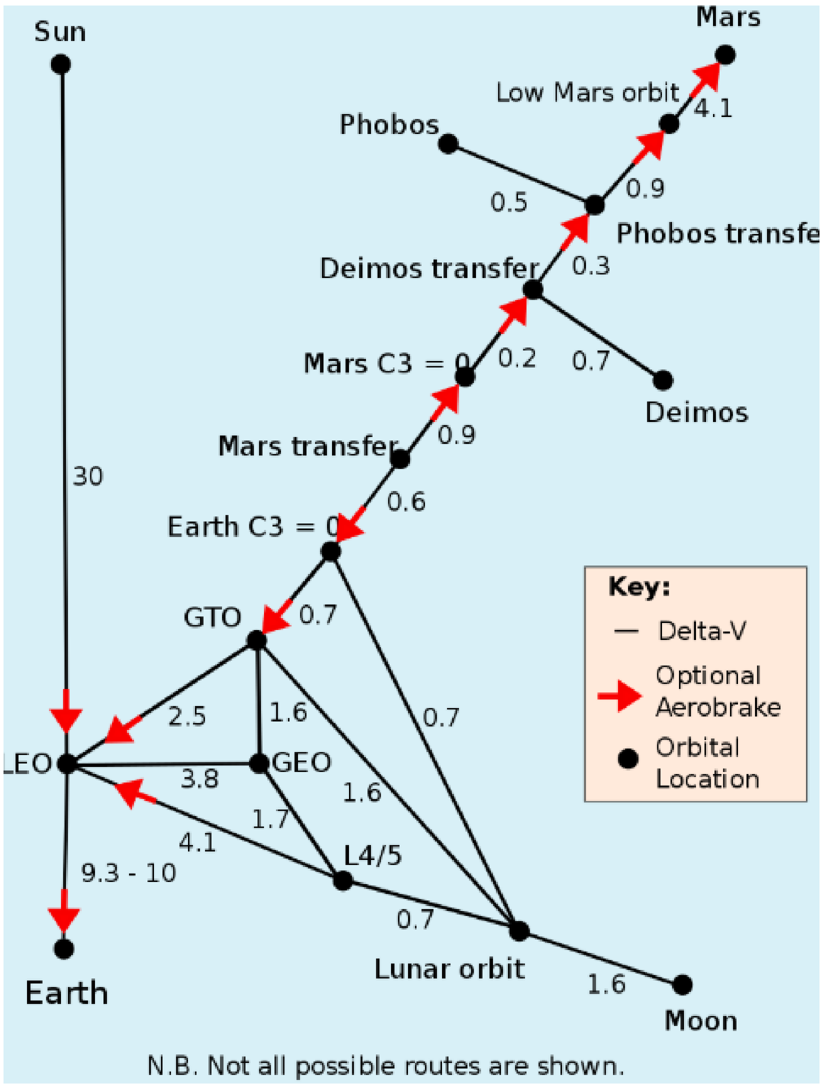

Figure 2 Approximate Δvs for Earth/Moon/Mars Destinations
Source: https://infogalactic.com/info/Delta-v_budget

With space exploration and study, we have been accumulating more information about the difficulty or Δvs to get to different objects. Asterank, acquired by Planetary Resources in 2013, has collected available information and has a database of more than 600,000 asteroids. Based on spectral composition, orbital information, and mineral prices, they list names, information on the asteroid's orbit, asteroid group, nearest pass to Earth, and Δv's. For some, they estimate mineral values and mining profits (http://www.asterank.com/, http://digg.com/2017/asterank-interactive-asteroid-mining-map); https://echo.jpl.nasa.gov/~lance/delta_v/delta_v.rendezvous.html) gives the Δvs from LEO for more than 17,000 Near Earth Objects (NEO). About 2,000 have a Δv of 5.5 or less, which is less than that of going to the moon. Coming back is even cheaper, as we do not have to escape gravity from the asteroid, while once near enough, earth's gravity is working for not against us. Although if we want to land on Earth we will need to slow down. Here atmospheric drag or aerobraking can help provided we have enough shielding to not incinerate the asteroid at reentry as temperatures can reach over 2600 °C (https://www.nasa.gov/mission_pages/constellation/orion/orionheatshield.html).

When travelling in space inertia is important, every time you want to change directions, speed up, or slow down you will need to change velocity, where velocity is both a speed and a direction. If you want to orbit or land on an asteroid or other celestial body, you also need to synchronize your movement and direction with the other object requiring more changes in velocity. These Δs can be added up across all the maneuvers required to reach a required space destination.

Tsiolkovsky's rocket equation, which shows how Δv is related to the rocket mass (M_{s0}), fuel mass (F_0), and the exhaust velocity of the rocket (v_e) assuming no drag and constant fuel burn over time, is

$$\Delta v = v_e \ln\left[\frac{Ms_0 + F_0}{Ms_0}\right] \tag{1}$$

(https://infogalactic.com/info/Tsiolkovsky_rocket_equation, https://web.mit.edu/16.unified/www/SPRING/propulsion/notes/node103.html).

The velocity (v_e) we get from a ship of given weight and fuel burn depends on physical principals relating to fuel use and design. You can see more on that at https://www.grc.nasa.gov/WWW/K-12/rocket/rktthsum.html. The amount of fuel needed per kg of payload to reach these destinations depends on the rating of the particular rocket. Rocket ratings are typically the amount of velocity change it can manage by burning its entire fuel supply. The Δv may be influenced by gravity, if the rocket is operating near large objects or drag if the nearby object is large enough and cool enough to have an atmosphere (http://www.astronomynotes.com/solarsys/s3.htm). For example, the return to Earth from the moon would require a lower Δv as the moon has less gravity to oppose the lift off and Earth has more atmosphere to slow the ship down. Drag from an atmosphere and gravity adds Δv when accelerating or moving away and decreases Δv when decelerating or moving towards a large object.

If the interest is on fuel burn, solve the above equation for fuel to get:

$$\frac{\Delta v}{v_e} = \ln(\frac{Ms_0 + F_0}{Ms_0}) \rightarrow \exp(\frac{\Delta v}{v_e}) = \frac{Ms_0 + F_0}{Ms_0} \rightarrow Ms_0 \exp(\frac{\Delta v}{v_e}) = Ms_0 + F_0$$

$$Ms_0 \exp(\frac{\Delta v}{v_e}) - M_{S0} = F_0$$

Fuel use increases linearly with the mass of the ship but exponentially with Δv. We can use this equation to scale up or down fuel with changes in the mass of the ship and the Δvs. Assume v_e constant for two ships (0 and 1) of different mass (Ms_0 and Ms_1) and going to different places (Δv0 and Δv_1). Divide the rocket equation of one by the other:

$$\frac{\Delta v_0}{\Delta v_1} = \frac{v_e \ln\left(\frac{Ms_0 + F_0}{Ms_0}\right)}{v_e \ln\left(\frac{Ms_1 + F_1}{Ms_1}\right)} \rightarrow \Delta v_0 \ln\left(\frac{Ms_1 + F_1}{Ms_1}\right) = \Delta v_1 \ln\left(\frac{Ms_0 + F_0}{Ms_0}\right)$$

Rearrange to

$$\ln\left[\left(\frac{Ms_1 + F_1}{Ms_1}\right)^{\Delta v_0}\right] = \ln\left[\left(\frac{Ms_0 + F_0}{Ms_0}\right)^{\Delta v_1}\right]$$

Take the exponential of each side of the equation

$$\exp\left\langle \ln\left[\left(\frac{Ms_1 + F_1}{Ms_1}\right)^{\Delta v_0}\right]\right\rangle = \exp\left\langle \ln\left[\left(\frac{Ms_0 + F_0}{Ms_0}\right)^{\Delta v_1}\right]\right\rangle \rightarrow (\frac{Ms_1 + F_1}{Ms_1})^{\Delta v_0} = (\frac{Ms_0 + F_0}{Ms_0})^{\Delta v_1}$$

Take each side of the equation to the $1/\Delta v_0$,

$$\frac{Ms_1 + F_1}{Ms_1} = (\frac{Ms_0 + F_0}{Ms_0})^{\frac{\Delta v_1}{\Delta v_0}}$$

Solve for F_1

$$F_1 = (\frac{Ms_0 + F_0}{Ms_0})^{\frac{\Delta v_1}{\Delta v_0}} Ms_1 - Ms_1 = Ms_1\left[(\frac{Ms_0 + F_0}{Ms_0})^{\frac{\Delta v_1}{\Delta v_0}} - 1\right]$$

Then fuel use when we send the same ship to different destinations ($M_{S0}=M_{S1}$ and $\Delta v_0 \neq \Delta v_1$) is

$$F_1 = Ms_0\left[\left(\frac{Ms_0 + F_0}{Ms_0}\right)^{\frac{\Delta v_1}{\Delta v_0}} - 1\right] \qquad (2)$$

So fuel use goes up at the exponential of the velocities. Fuel use if we ship different masses to the same destination ($M_{S0} \neq M_{S1}$ and $\Delta v_0 = \Delta v_1$) is

$$F_1 = (\frac{Ms_0 + F_0}{Ms_0})Ms_1 - Ms_1 = (\frac{Ms_0 Ms_1 + F_0 Ms_1}{Ms_0} - \frac{Ms_0 Ms_1}{Ms_0})$$

$$=(\frac{Ms_0 Ms_1 + F_0 Ms_1 - Ms_0 Ms_1}{Ms_0}) = (\frac{F_0 Ms_1}{Ms_0}) \rightarrow \frac{F_0}{F_1} = \frac{Ms_1}{Ms_0} \qquad (3)$$

Fuel use goes up as the ratios of the ships mass. While information about asteroids has been collecting, spacecraft technology and research equipment that helped with the data collection has been moving forward as well. The space race started when the Soviet Sputnik reached low earth orbit (LEO) with its altitude varying from about 230 km to 950 km, with a payload of about 85 kg. It lasted in orbit about 3 months (https://www.u-s-history.com/pages/h1716.html). Soviet and U.S. projects continued to compete. U.S. Apollo 11 in 1969 put men on the moon using the most powerful rocket ever build the Saturn V. At lift-off it weighed around 3300 tonnes with a payload of 50 tonnes landing on the moon. (https://www.nasa.gov/audience/forstudents/5-8/features/nasaknows/what-was-the-saturn-v-58.html**).** This demonstrated a capability to put equipment and miners on the moon and probably the capability to reach near earth asteroids but unlikely at a scale that would make space mining profitable. Typical current earthly mining equipment can be gargantuan. For example, a drag line that removes overburden in open pit mines and scoops up ore can weigh on the order of 2000 tonnes. For a sampling of modern coal mining equipment see http://www.coaleducation.org/technology/modern_equipment.htm.) Getting such large equipment to an asteroid or space and having humans operate them with no gravity seems an unlikely business mode. However, earthly technology has been edging towards robotics to improve safety, increase productivity and reduce costs. Current thinking is that much of space mining will be done with robotics. However, current moves towards self driving trucks and robotic drilling machines on Earth still involve large pieces of equipment. Then again there is the problem of no gravity and also atmosphere if the equipment is smaller but must be used in conjunction with rather than in place of human proximity (https://www.nbcnews.com/mach/science/robots-are-replacing-humans-world-s-mines-here-s-why-ncna831631, https://www.distrelec.de/current/en/robotics/how-robots-are-changing-the-mining-sector/). However, with time and tenacity, infrastructure and materials to mine in space will likely be developed for space as well.

With successive unmanned missions, human capability extended to all nine original planets and interstellar space. Mission and date of first flyby's in chronological order are as follows: Venus (U.S. Mariner 2, 1962), Mars (U.S. Mariner 4, 1965), Jupiter (U.S. Pioneer, 1973), Mercury (Mariner 10, 1975), Saturn (U.S. Pioneer 11, 1979), Uranus (U.S. Voyager 2, 1986), Interstellar Space (U.S. Voyager 1, 2012) and Pluto (U.S. Voyager II, 2015) (https://www.popularmechanics.com/space/a16443/solar-system-planets-pictures/). These missions demonstrate a capability to get to even the more far flung objects in the solar system that might be potential mine sites as well as the communication abilities to control the vessels from Earth. However, the expense and time to get to some of these objects is quite large and long. It took more than $1 billion and about 2 years for the U.S. Gallileo space craft with payload less than half a tonne to get to the asteroid Gaspra. On the way to Jupiter, Gallileo passed by this asteroid located in the inner region of the main asteroid belt between Mars and Jupiter. Yet, the seeds of the technology we need to mine space have been planted and they continue to grow.

In between some of these feats, the technology was extended to unmanned flights landing on Mars (Soviet Mars 3, 1971), reaching Mars and returning with samples (U.S. Viking Lander 1976), and reaching Venus and returning with samples (Soviet Venera 1982). There have been multi-year orbiting of five of the eight planets in our solar system with first accomplishments: of Mars (U.S. Viking 1, 1976-1980), of Venus (U.S. Pioneer Venus, 1978-1992), of Jupiter (U.S. Gallileo, 1995-2003), of Saturn (U.S. and European Space Agency Cassini–Huygens, 2004-2017) (https://aerospace.org/story/brief-history-space-exploration, https://www.britannica.com/science/space-exploration/History-of-space-exploration). Only Earth has been orbited by humans, and only one human has orbited for longer than a year – Russian cosmonaut Valery Polyakov remained on the Russian Mir space station, from January 1994 to March 1995 (https://www.space.com/11337-human-spaceflight-records-50th-anniversary.html).

Meanwhile, more countries were joining the USSR and the U.S. in developing satellite launch capabilities often to provide commercial communication. The first communication satellites were launched by the U.S. and U.S.S.R. in the 1960s. They were soon followed by Canada, France, Germany, and Indonesia in the 1970's, and the European Space Program and about a half dozen other countries by the 1990s (https://www.esa.int/About_Us/Welcome_to_ESA/ESA_history/The_launch_of_MARECS_B2, https://en.wikipedia.org/wiki/List_of_communications_satellite_firsts). In 2019, out of around 8400 total launches from Earth, there are around 5,000 objects still in orbit around Earth. Another seven are in orbit around other celestial bodies. Some of these are space debris, but about 40% of these objects are in working order providing a variety of services - communication, earth observation, research facilities, and global positioning (https://www.pixalytics.com/satellites-orbiting-earth-2019/, http://www.unoosa.org/oosa/osoindex/search-ng.jspx?lf_id=). As of August, 2020 the website, (https://www.ucsusa.org/resources/satellite-database), indicates there are roughly 2800 active satellites circling the globe owned by more than 50 countries. Greshko (2018) notes that historically there have been 29 spaceports with the capability to launch vehicles into space with 21 still active in 2018. Roberts (2020) lists launch facilities by country. Such orbital technology for observation and communication will help move any space mining program forward.

Global positioning satellites systems (GPSS) are important navigation aids for terrestrial and likely will be for celestial mining ventures as well. The U.S. system had its genesis in the 1960s with the U.S. Navy using positioning satellites to keep track of submarine location. The U.S. Department of Defense continued the U.S. system designated as Global Positioning System (GPS) with twelve experimental GPS satellites that provided continuous signal launched between 1974 and 1985. Between 1989-1995, 24 fully functional GPS satellites plus 3 spares were launched for a complete global system. They are positioned so that at least 4 satellites are accessible from any point on the Earth (https://www.pcworld.com/article/2000276/a-brief-history-of-gps.html). Free public access to a degraded less accurate signal from the satellites was made available in the 1980s, while free public access to an accurate signal from the non-coded signal was made in 2000 with a reserved system for the U.S. military and government (https://www.space.com/19794-navstar.html). The latest version of the system, GPS III, had its first satellite launched in 2018. These satellites will be more accurate, have a 25% longer design life, and be more compatible with other GPSS systems around the world (https://www.lockheedmartin.com/en-us/products/gps.html .

In the meantime, the Soviet Union and then Russia developed the completely operational GPSS system called GLONASS, between 1982-1995. It functioned only a short time but with upgrades and repair it became fully functional again by 2011 (https://www.gpsworld.com/innovation-glonass-past-present-and-future/, https://www.glonass-iac.ru/en/guide/, https://www.gps.gov/systems/gnss/). China's Beidou 1 system provided service to all of China by 2000, its Beidou 2 system provided service to the Asian-Pacific region by 2012, and the preliminary version of its Beidou 3 system provided full global service by late 2018 (https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/cnss, http://en.beidou.gov.cn/, https://www.gps.gov/systems/gnss/). To not have to rely on the U.S. GPS or Russian GLONASS system, the Europeans have developed their GPS system, named Galileo. It is the only civilian controlled GPSS with its first satellites put in orbit in 2016 and with the target of 24 satellites in orbit and 6 spares in service. As of November 2020, 24 are operational (https://ec.europa.eu/growth/sectors/space/galileo, https://www.gsa.europa.eu/european-gnss/galileo/galileo-european-global-satellite-based-navigation-system; https://www.gsc-europa.eu/news/latest-batch-of-galileo-satellites-enters-service; https://gssc.esa.int/navipedia/index.php/Galileo_Space_Segment#:~:text=The%20Galileo%20constellation%20comprises%20of,distributed%20evenly%20round%20the%20equator, https://www.gsc-europa.eu/). Both India and Japan are developing their own regional GPSS. India launched their first of currently seven operational satellites in 2013 and the last in 2018 (https://directory.eoportal.org/web/eoportal/satellite-missions/i/irnss). Japan launched the first of currently four satellites in 2010 and the last in 2017. (https://www.unavco.org/projects/project-support/gnss-support/gnss-modernization/gnss-modernization.html, https://www.japantimes.co.jp/opinion/2018/11/12/editorials/japan-positions-future/#.XIMi4yhKhPY)

Orbiting space stations are likely to be needed for space mining to become feasible. By 1995, there had been a number of successful space stations. The first was the Russian Salyut 1, which was launched in 1971. It remained in orbit for 6 months and humans were successfully placed on the station for a stay of a few weeks by the Soyuz 11 shuttle. However, the crew of the Soyuz 11 were sadly killed on reentry to Earth (http://www.astronautix.com/s/salyut.html, https://www.esa.int/Our_Activities/Space_Transportation/Launch_vehicles/The_Russian_Soyuz_spacecrafthttps://www.britannica.com/technology/Salyut, https://en.wikipedia.org/wiki/Salyut_1). Four of the next six Russian Salyut space stations successfully reached and maintained orbit and had human inhabitants transferred to and from them: Salyut 4 (1974-1977), Salyut 5 (1976-1977), Salyut 6 (1977-1982), and Salyut 7 (1982-1991). In the meantime, the United States had put its first space station in orbit (Skylab 1973-1979). It was damaged on launch but repaired in orbit by human inhabitants. Its life ended when its orbit decayed and it crashed into the Pacific. Numerous scientific experiments were done on these stations including investigating the effects and needs for human space habitation (http://www.scienceclarified.com/scitech/Space-Stations/Modest-Beginnings-Salyut-and-Skylab.html).

Another likely need for commercial space mining is for the transfer vessels to and from such space stations be reusable. None of the vehicles for human transfer to and from the above mentioned space stations were capable of being reused. That honor fell to the U.S. Space Shuttle program also called the Space Transportation System (STS). The five shuttles that flew the 135 successful missions were Columbia (1981-2003), Challenger (1983-1986), Discovery (1984-2011), Atlantis (1985-2011), and Endeavor (1992-2011) (https://evert.meulie.net/faqwd/how-many-space-shuttles/ https://www.boeing.com/history/products/space-shuttle-orbiter.page). The shuttles consisted of an orbiter, which carried humans and cargo. It returned from orbit by gliding to Earth with a parachute to slow its descent for a soft landing. To get the orbiter into low earth orbit required considerable thrust, which came from three re-usable rocket engines, and two detachable reusable booster rockets, which parachuted back to Earth. Although the booster rockets and main engines were reusable, they required considerable refurbishment after each use. The rockets were fueled with liquid oxygen and liquid hydrogen carried in a huge (non-reusable) fuel tank (https://www.britannica.com/technology/space-shuttle, https://www.space.com/12085-nasa-space-shuttle-history-born.html).

As Skylab was no longer in orbit, the first space shuttle missions were not to dock with a space station but were used in orbit for test missions, scientific experiments in space and to deploy satellites. It was also used to deploy and repair the Hubble Space Station (https://video.nationalgeographic.com/video/news/00000144-0a26-d3cb-a96c-7b2fa33d0000). The first Space Shuttle visit to an actual space station was to the Russian Mir Station in 1995. The Mir station, which orbited from1986-2001, was modular. Its core was launched by the Soviet Union with other modules built on in space. The Russians, who inherited MIr, completed it in 1996 (https://history.nasa.gov/SP-4225/mir/mir.htm). Later generations of the Soyuz space crafts, that had served the Salyut space stations, made transfers to and from the station but none were reusable. U.S. Space Shuttles had nine missions to the MIr from 1995-1998. Over its life, the MIr had hosted 125 cosmonauts from 12 nations (https://spaceflight.nasa.gov/history/shuttle-mir/spacecraft/s-mir-15yrs-main.htm).

The fifteen nation International Space Station (ISS) – USA, Russia, Canada, Japan and the European Space Agency – was completed between 1998-2011. As with the MIr, it is modular. The joint American/Russian built control module was put into orbit first (https://www.space.com/16748-international-space-station.html). You can see a time line of the building process at http://www.esa.int/Our_Activities/Human_and_Robotic_Exploration/International_Space_Station/Building_the_International_Space_Station3. The first crew was delivered to the station in 2000. The ISS has 16 pressurized habitable modules contributed by various participants (http://howthingsfly.si.edu/ask-an-explainer/how-big-international-space-station. Supplies and equipment to build the ISS were delivered by un-crewed Russian Proton Rockets and a few other spacecraft. However, only two crafts could also deliver humans to the station –the Russian Soyuz

Space Craft, which can carry 3 humans or the U.S. Space Shuttles, which could carry 7 humans (https://howthingsfly.si.edu/ask-an-explainer/how-many-people-fit-spaceship).

Although it was thought that the U.S. Space Shuttle would save money over expendable space craft, it turned out to be quite expensive because operating and refurbishment cost between launches were so high. NASA reports that the whole program flew 135 missions between 1981 and 2010 at a cost of $210 billion not adjusted for inflation putting the average mission cost adjusted for inflation at well over $1.5 billion. Further, they reported the marginal cost in 2011 at the close of the program at $450 million per flight.

Falling budgets, high costs, safety difficulties, and a desire to promote the private sector into space travel led NASA to develop its Commercial Orbital Transportation Services (CoTS) in 2005 to allow the private sector to provide transport to and from the ISS. The initial successful partner chosen by NASA in 2006 was SpaceX and the second successful partner chosen in 2008 was Orbital Sciences Corp, part of Northrup Grumman as of 2018. In the first phases, NASA helped with some seed money to develop the commercial spacecraft. Upon successful demonstration of their ability to resupply the ISS, both were awarded contracts.

SpaceX founded by Elon Musk in 2002 has a number of private sector firsts including reusable rockets and numerous supply missions to the international space station. SpaceX's Dragon, powered by a Falcon 9 rocket, made a successful demonstration in 2012, when it became the first private company to berth with the ISS. SpaceX was awarded a contract for $1.6 billion for 12 missions for a total of up to 20 tonnes of cargo through 2016. A subsequent 8 missions were also awarded to SpaceX that would last through 2018. In 2017, with a goal to build a reusable spaceship and rocket, SpaceX reused a recovered Dragon for a mission for the first time in 2017. It also recovered the core stage of a Falcon 9 rocket (https://www.nasa.gov/sites/default/files/files/SP-2014-617.pdf, https://en.wikipedia.org/wiki/SpaceX_Dragon, https://www.sciencefocus.com/space/how-does-spacex-build-its-falcon-9-reusable-rocket/, https://www.theverge.com/2018/5/9/17254384/spacex-falcon-9-block-5-upgrade-rocket-reusability-savings). Although the government owned Space Shuttle, which was retired in 2011, cost around $500 million a launch, SpaceX has managed to bring that cost down to around $60 million a launch (Quora (2018)).

Orbital's non-reusable Cygnus spacecraft, powered by an Antares rocket, succeeded in docking with the ISS in 2013. Orbital was awarded an original contract of $1.9 billion for 8 missions totaling up to 20 total tonnes. Northrop Grumman received follow up contracts for 9 missions with total cargo up to 30,000 kg of cargo to the ISS (https://www.northropgrumman.com/Capabilities/CRS/Documents/Cygnus_Factsheet.pdf, https://www.nasa.gov/sites/default/files/files/SP-2014-617.pdf).

While these advances are encouraging, the market for space mining took a step back in 2018 and 2019. Two other often cited companies, who had signaled their entrance into space mining, have scaled back or eliminated plans for space mining when they were acquired by other companies. Planetary Resources (founded in 2009 as Arkyd Astronautics and acquired by ConsenSys in 2018) has an eventual goal of mining asteroids. Their emphasis is now on water that can be used to produce fuel as well as support life and provide radiation shielding for space activities (Planetary Resources (2018a), Planetary Resources (2018b)). Deep Space Industries (founded in 2012 and acquired by Bradford Space Group in 2019) started with a stated goal of asteroid mining but has most recently focused on their water based propulsion systems, they call Comet (Deep Space Industries (2019)).

These missions have demonstrated the ability of the private sector to deliver transportation to and from the ISS. Not including any of the seed money, the average cost per mission varies from around $130 to $240 million. Although this is considerable less than the $450 marginal cost of the last space shuttle flights or the average cost of over a billion dollars, the payload for Cygnus is only 3.75

tonnes and the payload for the Dragon is 6 tonnes to the station and 3 tonnes return. Neither can carry humans. The Space Shuttle could carry up to 7 humans with a payload of 27.5 tonnes to the ISS with return payload of 14.4 tonnes (https://www.google.com/search?rlz=1C1GCEA_enUS776US776&ei=LB-IXJaVOKjujwTthL3QCw&q=cygnus+to+iss+payload+-wiki+kg&oq=cygnus+to+iss+payload+-wiki+kg&gs_l=psy-ab.3...24188.24769..25111...0.0..0.80.156.3......0....1..gws-wiz.iYmwiSq_kiE, http://spaceflight101.com/spacecraft/dragon/tonnes, https://en.wikipedia.org/wiki/Space_Shuttle).

Without the Space Shuttle, the U.S. has had no capacity to launch humans into orbit and has had to hire seats on the Russian non-reusable Soyuz Spacecraft. Soyus can transport 3 humans at a time and as of 2018 charged more than $80 million per seat. (https://www.nbcnews.com/mach/science/how-much-does-space-travel-cost-ncna919011, http://www.spaceref.com/iss/spacecraft/soyuz.tm.html). The cargo version of the Soyuz called Progress M has a payload to the station of about 2.4 tonnes and can return with about 2 tonnes of waste (http://spaceflight101.com/spacecraft/progress-m/).

Another part of NASA's program to commercialize space travel was the transportation of human's to the ISS. The commercial crew development program (CCDev) began in 2009. By 2014, NASA had chosen SpaceX with $3 billion in additional funding for its Crew Dragon and Boeing with around $4.7 billion funding for its CST-100 Starliner. There were to continue to develop these ships for human transfer to the ISS with first flights by 2017. Neither company made the 2017 deadline but SpaceX launched its first successful test mission in March of 2019, which docked at the ISS and successfully returned to Earth but did not yet carry human cargo. Boeing was targeting an April, 2019 test launch date for its un-crewed CST-100 Starliner. (https://www.fromspacewithlove.com/commercial-crew-development/, https://www.space.com/how-to-watch-spacex-crew-dragon-demo-1-mission.html, https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/ccdev, https://www.space.com/43207-boeing-starliner-ready-march-2019-test-flight.html). As of December 2020, Starliner has failed to dock at the station with a new target test flight date of March 2021. (https://www.theverge.com/2020/3/6/21167883/nasa-boeing-passenger-spacecraft-cst-100-starliner-flight-test.; https://spacenews.com/next-starliner-test-flight-scheduled-for-late-march/).

Since NASA's access to Soyus seats expired at the end of 2019, they were hoping one of these space crafts would be ready for commercial crew delivery soon (https://spacenews.com/commercial-crew-test-flight-schedule-slips-again/). That date seems to have been extended as a Soyuz capsule returned astronauts in April 2020. SpaceX had successfully completed a demo flight of their Crew Dragon spacecraft on a Falcon 9 rocket on May 30, 2020. It delivered two American astronauts to ISS for the first private commercial U.S. flight putting humans into space. (https://blogs.nasa.gov/spacestation/2020/04/17/touchdown-expedition-62-returns-to-earth-completes-station-mission/, https://www.theverge.com/2020/3/16/21181681/nasa-human-spaceflight-soyuz-rocket-launch-iss-spacex-coronavirus, https://www.nasa.gov/press-release/nasa-astronauts-launch-from-america-in-historic-test-flight-of-spacex-crew-dragon). In November, 2020, SpaceX and NASA delivered four occupants to the ISS in the first of six crewed mission (https://www.nasa.gov/press-release/nasa-s-spacex-crew-1-astronauts-headed-to-international-space-station/).

From this brief discussion, this newbie has decided that we can mine asteroids. At least we do seem to be able to move stuff around in space and bring samples back to Earth. For full scale mining operations, the stages we will need to follow are prospecting to find the target asteroid we want to mine, excavating the raw materials we want, concentrating and separating the valuable material enough to be sent to refineries, further refining and separating needed for metals to be sent to final market for processing into useable products. Transportation and storage may be needed at various points along this supply chain (Hein, Matheson, and Fries (2018)). National Research Council (2002) summarizes these processes on Earth.

Early on, many have suggested that asteroid mining will begin with water, regolith and other materials for space use with only the most valuable metals brought back to Earth. Sonter (1996) reviews some of these proposals from the 1980s on. Although abundant on Earth, such mundane products are expensive to move into space. Figure 3 shows a timeline of costs per kilogram to launch from Earth to low earth orbit. Thus, a tonne of rolled steel priced at around $540 per tonne on Earth in 2019, would cost more than a hefty $950,000 if transported to space on a Falcon Heavy rocket. Water practically free on Earth, by comparison, would be almost as pricey. To take water into a Lagrange point in cis-lunar orbit for use on a lunar construction project might cost $40,000 per tonne (Jones, Klovstad, Judd, and Komar (2019)). Precious metals, if processed at the asteroid and brought back to Earth might be frosting on the cake.

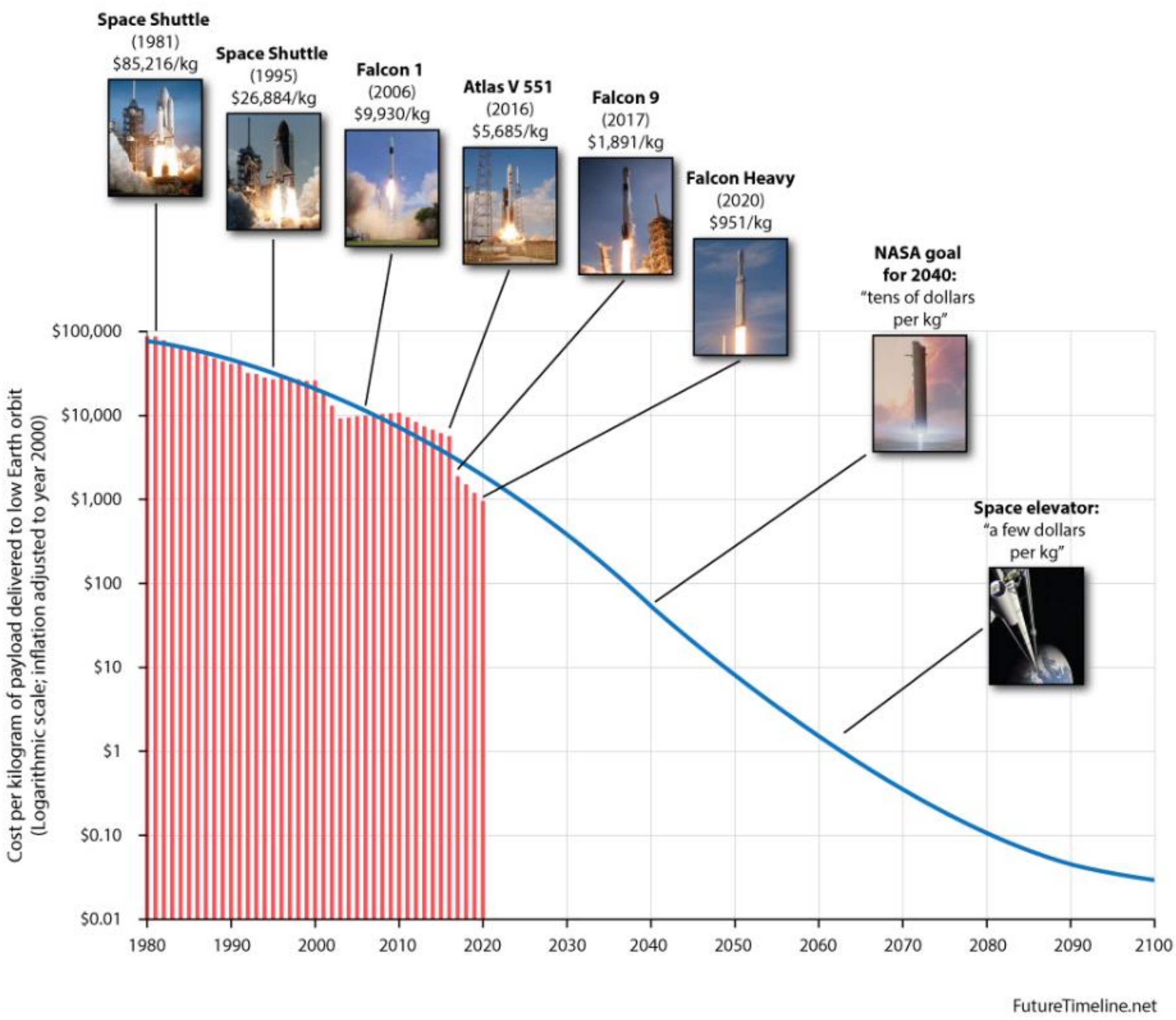

Figure 3: Cost per kilogram to launch from Earth to Low Earth Orbit
Source: https://www.futuretimeline.net/data-trends/6.htm

For the representative metal asteroid above, concentrating and refining these metals are well known processes on Earth. Crundwell, Moats, Ramachandran, Robinson, and Davenport (2011) have detailed descriptions of some of these processes for nickel, cobalt and the platinum group metals, all contained in our representative metallic asteroid above. The Mond process has been well known for more than a century to separate nickel from iron and other metals (Morrison et al. (2018)). However, Gertsch (1992) in McKay, McKay, and Duke (1992) suggest we do not know how to separate out precious metals at the asteroids, as problems would be encountered in keeping equipment on the asteroid for excavating, collecting, materials and to keep fugitive dust from interfering with operations. Kargel (1994), Zacny et al. (2013), and others suggest that for platinum to be successfully mined, it would need to be mined in situ with only the platinum returned to Earth.

Andrews et al. (2015) develop a mission to return water and metals to space stations where the water can provide fuel and cheaper metals can be used for manufacturing. The manufacturing of fuel, products and services for companies and tourists would provide just over half of their revenue in the 20th year of the project with PGMs providing the rest. Their project calls for nuclear power to provide the energy for magnetic beneficiation, the Mond process, and separation of volatiles. From the Mond process, the cheaper metals (iron, nickel, cobalt) along with water would be delivered and used at the earth orbiting space station, while the PGMs would be transferred down to Earth. In the 20th year of their project, about half of their revenues come from platinum sales with water priced at the space station at $1500/kg and an implied cost per tonne of PGMs of about $21 million.

Their results rely on optimistic assessments of technology and a space market. Spudis (2014) notes that may be the residue from the Mond process. However, he questions our current ability do this remotely in zero gravity. The whole process requires temperatures up to 280 °C, and we would have to be able to trap the gaseous iron and nickel laden products between processes. He alternatively suggests magnetic field separation works in no gravity but is also doubtful of that because it requires lots of energy and complicated equipment to claim the valuable products and discard the dross. Lewis (2015), a well known expert on mining asteroids, suggests that we will begin by mining water for fuel in space, followed by materials for space habitat and operations and platinum will be a byproduct sent back to Earth. Thus, he implies an ability to separate out the platinum.

Hein, Matheson, and Fries (2020) do not consider manufacturing of equipment in space except for heat shield production for platinum mining. They return water to cis lunar orbit with water priced at $40 million per tonne with platinum separated out and returned to Earth, where the assumed price is $30 million per tonne. They find that platinum mining for earth return is only profitable under rather unlikely conditions.

Martínez et al. (2017) indicate the technology to excavate and refine metals in situ in a near zero gravity setting is yet to be developed. Martinez et al. (2017) and Andrews et al. (2015) hypothesize the following. Loose surface rubble might be pushed into a strong bag by a spinning blade. Drilling, blasting, cutting and crushing will need to be adapted to the new environment. Separation could take on a variety of forms: Distillation to recover water, Co_2, and hydrocarbons; electrolysis to recover iron, oxygen, and other metal alloys from silicates; and the Mond process to recover nickel. Andrews et al. (2015) further suggest using magnetic beneficiation to separate ferro-magnetic products (in their case iron and nickel) from other materials. They power their operations with water from the asteroid and nuclear power. Their ships for transporting materials to and from the asteroid would also be nuclear powered.

Many studies now seem to agree that water used in space as fuel for space travel and eventually for other uses will be our first asteroid target. Although Hein et al. (2020) note that none of the suggested water recovery techniques have been tested in space, many seem to think this is a fairly surmountable problem. Dreyer et al. (2016) suggest an in situ process they call optimal mining. It uses concentrated sunlight for the process without the need for complicated robotic instruments. Calla, Fries, and Welch (2019), Wasson (1974) table 1) show the pros and cons of 10 different asteroid water mining technologies. They select microwave drying and vapor collection as best for their small craft missions to return 100 kg of water to a convenient orbit for space fuel depots.

Rare earths along with PGMs are also mentioned as potential targets for return to Earth. Lewis (2016) does not think this feasible as asteroids tend to have little rare earth elements. Martinez et al. (2017) study the composition of carbonaceous chondrite asteroids, often cited as promising targets for mining for use in space because of their water and metal content. Recall the representative sample based on Martinez et al. (2017) above in Table 3. They cite studies that compare REE concentrations on carbonaceous chondrite asteroids to the concentrations on the earth's crust and find them to be lower. Given the difficulties in separating rare earths, this is hardly an endorsement for commercial development and they do not expect REE metals to be mined from asteroids for return to Earth.

Being an optimist, I believe that technology does exist or will be developed to return asteroids to Earth. So having considered a brief look at technology, the next question is to ask about mining asteroids for Earth return is: Do we want to? I turn to exploring the answer to this question by looking at the economics in the next section.

Economic Issues

Far flung space activities to date have been government sponsored. Closer in, private companies and governments own communication satellites. If the private sector moves in where heretofore only governments have tread, there will be a number of economic issues. Both legal and commercial risks will need to be taken into account,

The legal framework for space mining is not well established. The most relevant international treaty is the 1967 UN Outerspace Treaty (United Nations (1966)). It stipulates that no one owns any celestial body and they should all be used for peaceful purposes to benefit humankind. This treaty does not prohibit space mining, but does not necessarily sanction it either (Greenspon (2016)).

Another agreement, more specifically relating to the moon is the "Agreement Governing the Activities of States on the Moon and Other Celestial Bodies" adopted by the U.N. General Assembly in 1979. With five countries signing, it went into affect in 1984 (United Nations (1979)). It currently has 21 country signatories or ratifications (https://treaties.un.org/doc/Publication/MTDSG/Volume%20II/Chapter%20XXIV/XXIV-2.en.pdf). It reserves the moon for peaceful uses, forbids weapons and military bases on the moon, and makes the moon and its resources a common heritage of all humans with no private ownership by individuals or states (https://www.worldatlas.com/articles/which-countries-have-been-on-the-moon.html, https://en.wikipedia.org/wiki/Moon_landing). However the only countries that have soft landed on the moon (Russia, first landing Luna 9, 1966, U.S. first landing Surveyor I, 1966, China (Chang'e 3, first landing 2013) have not signed the agreement leaving its authority over the moon rather equivocal.

Two counties have passed laws relating to celestial property rights. The U.S. in 2015 and Luxembourg in 2017. Both seem to confer the law of capture. The company that mines a celestial body will get to keep what they mine. As space is a commons, this lack of assured long term property rights poses some risk to potential entrants and may need more clarification and international agreement before private parties will undertake space mining ventures (https://www.economist.com/the-economist-explains/2018/06/12/who-owns-what-in-outer-space).

There are many uncertainties involved in such projects that make them risky. In studies cited above, technologies are assumed that may only have been conceptualized or tested in the lab. Space markets are assumed to exist at the comparable price of getting the product from Earth. I would argue we don't really know what longer term demand equations for most materials are in space. If it is just to supply government funded projects to the Moon and Mars, the demand might be quite small. Only if we start to truly colonize space will such a market take off.

Costs information is also highly speculative. Given the riskiness of asteroid mining, private funding initially might be problematic. Heintzen and Harrison (2016) outline the process on Earth for greenfield metal mining projects. Such projects are typically funded by consortiums of banks or government development agencies. The technical requirements for such projects are monitored by technical consultants hired by the lender to monitor and report on the status of the project. These consultants monitor the overall project, its environmental implications (probably not an issue at the asteroid but could be so when metal is returned to Earth), construction progress, mechanical completion, startup timeliness and performance, completion testing, and final certification. These reports often require site visits, which are unlikely to be possible, if such mining operations are done by robots. If lenders seriously doubt the ability to monitor such projects, they may not be forthcoming with their funds. Although a Goldman Sach's report argues that "Space mining could be more realistic than perceived"(http://www.parabolicarc.com/2017/04/10/goldman-sachs-bullish-asteroid-mining/).

Another source of risk is market volatility. The preponderance of studies consider water for space and PGMs for Earth. Although I don't know so much about water prices in space (I will leave that to the space experts), I do know something about earth prices for PGM's. For example, Figure 4 shows the real price volatility in Earth's platinum market since 1986. There were the doldrums in the 1990s and the dramatic run up from 1999 to 2008 and recovery after the 2009 dip to an all time high in 2011 of over $60 million dollars a tonne in 2019 dollars. Around this time some start up companies started talking about and investing in research on mining platinum on asteroids. With the equally dramatic price run down through 2019, the talk and investment has turned more to water and servicing the existing space activities nearer to home. Hein et al. (2020) also question whether platinum space miners could survive such volatility in Earth's market.

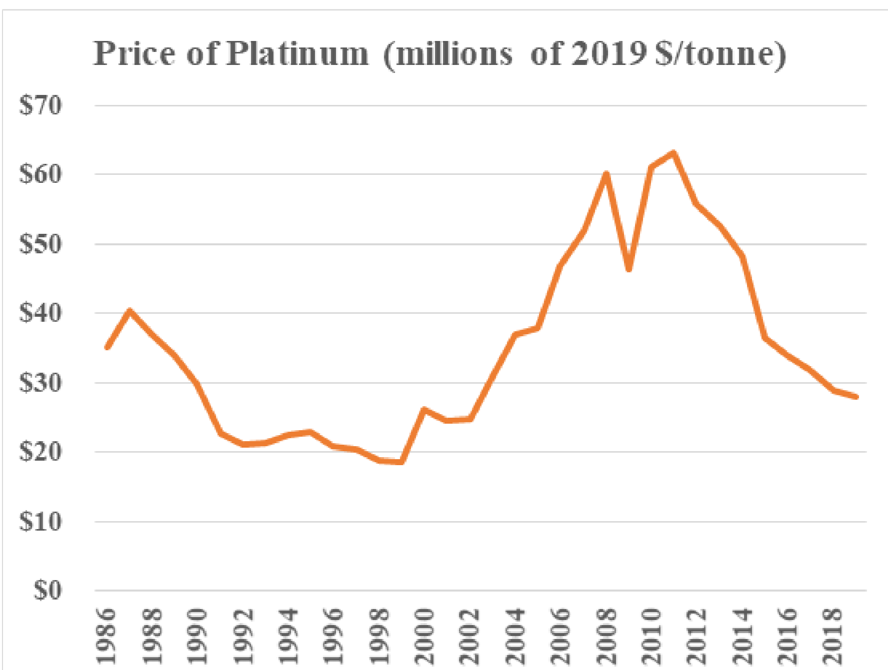

Figure 4: Price of Platinum (millions of 2019 $/tonne)

Notes: Precious metals are often price in troy ounces with about 32,151 Troy ounces per metric tonne.

Source: https://www.macrotrends.net/2540/platinum-prices-historical-chart-data

A further looming risk to the PGM market is electric vehicles. Large chunks of these markets are for use in catalytic converters in internal combustion engines (41% of platinum, 85% of palladium, and 84% rhodium) (https://www.bloomberg.com/news/articles/2018-03-26/shrinking-platinum-sector-adds-to-ramaphosa-s-economy-challenge, Cowley and Ryan (2018), p 3). If electric vehicles do take over much of the transportation sector, it is not clear whether fuel cell vehicles or other uses will fill in the slack.

Another economic unknown relates to market structure. The platinum group metal's market is somewhat concentrated by company and country. For example, the top four companies produce over 90% of the platinum and about 2/3 of all PGMs (Dah20a, Table 5). South Africa produces more than 90% of Earth's platinum, 35% of the Earth's palladium, and 80% of the Earth's rhodium. If this concentration means these companies are earning excess profits they can afford to lower prices more in responses to space mining competition than if these markets were competitive.

If produced under long-term contracts, transaction cost literature suggests that the risk of hold up or companies on Earth refusing to pay the initially agreed upon price once the investment has been made are not trivial. Further, large size may yield economies of scale in production but injecting huge resources into earthly markets could substantial reduce their prices, changing expected profits into actual losses. Third, property rights are not well defined in space and problems of the commons may present themselves. To understand these risks we need to gauge the projects potential impacts on existing procurement contracting and market structures.

Market Simulations (supporting documentation for Dahl et al. (2019) and Dahl et al. (2020)

My goal in this first simulation is to assume known technologies and markets. Given the uncertainties expressed about separating out metals in space or on the moon, and what a water and metal markets in space might look like, I chose to start my mining venture with the representative metallic asteroid shown in Table 2 and bring it back to Earth. The ppm of the asteroid is shown in column 3 in table 4. The model can be changed to accommodate mining of other types of asteroids, processing in space, and delivering some products to space by changing the demand and supply equations for different drop off nodes. Transport and processing cost would need to be changed accordingly.

Dahl (2020) used information in Tilton and Guzmán (2016) and Ndlovu (2015) to infer market structure in the form of upper bounds on the Herfindahl Hirschman Indices (HHIs) for 25 minerals. The HHIs for the metal markets are shown in column 4 of table 4. The platinum group metals are somewhat concentrated with HHIs equivalent to around 4 to 5 equal sized firms. For now, I will assume they have supply functions and do not retaliate and lose money to drive the space miners out of business.

Next, I develop demand and supply equations for the current market on Earth using the best information I have located so far. I create these demand and supply equations from estimates supplemented with guesstimates for price elasticities of supply and demand. Fally and Sayre (2018) survey such elasticities for numerous natural resources including a number of the metals in our meteorite. From their estimates, I develop the demand elasticities for Fe, Co, Ni, Pt, Pd and Au and the supply elasticities for Fe, Co, and Ni. With no estimates for demand elasticities for the other 3 platinum group metals (Ru, Os, Ir), I use the estimate for the platinum group.

I fill in the missing supply elasticities as follows. Since the platinum group metals on Earth are largely byproducts of the production of Ni or CU, I assume their supply elasticity is low and set it as one third the average for Ni (0.54) and CU (0.43) created from Fally and Sayre (2018). These supply and demand price elasticities are given in column 5 and 6 of Table 1. I create supply and demand from the elasticities around the reported prices and quantities in 2018 shown in columns 7 and 8 in Table 4.

Table 4: Base Case Simulation Inputs and Simulations in 2050 No Space Mining

		(g/t)				\$/tonne	tonnes		tonnes	\$/tonne
	A#	**Weight**	**HHI***	**Ed**	**Es**	**P 2018**	**Q 2018**	**Ey**	**Q 2050**	**P 2050**
Fe	26	893,000.0	995	-0.48	0.24	338	$1{,}200\times10^6$	1.16	$1{,}593\times10^6$	799
Co	27	6,000.0	550	-0.47	0.40	82519	0.125×10^6	1.21	194,657	198,935
Ni	28	93,000.0	550	-0.66	0.55	10559	2.199×10^6	0.85	$3{,}349\times10^6$	20,781
Ru	44	21.5	*2271*	*-0.76*	*0.16*	6.1089×10^6	41.99	*0.83*	47	10.650×10^6
Rh	45	4.0	2708	*-0.76*	*0.16*	54.656×10^6	31.91	*0.83*	36	95.288×10^6
Pd	46	16.5	1877	-0.70	*0.16*	33.083×10^6	317.82	*0.83*	359	59.612×10^6
Os	76	14.5	*2271*	*-0.76*	*0.16*	12.860×10^6	1.50	*0.83*	2	22.421×10^6
Ir	77	14.0	*2271*	*-0.76*	*0.16*	31.186×10^6	7.18	*0.83*	8	54.370×10^6
Pt	78	29.0	2765	-0.82	*0.16*	29.048×10^6	241.58	0.83	269	49.175×10^6
Au	79	0.6	200	-1.01	*1.02*	40.245×10^6	4,345.10	1.04	6158	62.344×10^6

Sources: Dahl (2019a), Fally & Sayer (2018), Kargel (1994). Buddhue (1946). For more detail on sources see http://dahl.mines.edu/SpaceMining.xlsx worksheet A1_T4-Ref.

Notes: Fe=iron, Co=cobalt, Ni=nickel, Ru= ruthenium, Rh= rhodium, Pd=palladium, Os=osmium, Ir=iridium, Pt=platinum, and Au=gold. A# indicates atomic weight, g/t = grams per metric tonne, HHI = the Herfindahl Hirschman Index, Ed = the price elasticity of the metals demand, Es= the price elasticity of supply, tonne=metric tonne. P2018 is the metal's price in dollars per tonne, Q2018 and estimate of global metal consumption in 2018, Ey = the income or activity elasticity of demand, 2050 values for price and global consumption are author simulations. Values in italics are author's estimates. Sources for prices and quantities are shown in the supporting model file A1_T4_Ref. The above elasticities, asteroid concentrations, coupled with income growth averaging 3.6% a year provide the base case for demand estimates. g/t also equals parts per million (ppm).

Since any space mining venture is more than a decade into the future, we need to make some assumptions about how the earthly demand and supply will grow between now and when the mining venture comes online. From 1980 to 2015, global GDP grew an average of 3.5% per year with numbers closer to 4% since the turn of the century (IMF International Monetary Fund (2019)). The IMF forecasts, growth will average 3.6% from 2018 to 2023. I assume an initial income growth of 3.6% over the life of the project. I couple the income growth with estimates of income or activity elasticity estimates. Income elasticity of demand for Fe (taken from the estimates for steel) and for Ni are taken from Fernandez (2018), p 15. That for nickel are taken from the weighted average for the free world from Fernandez (2018). Those for Pt and Au are taken from TIAX (2004), p. 20 and Evans and Lewis (2002), p. 104. The remaining estimates for the other platinum group metals estimates are taken from those for Pt. I use these inputs to simulate the price and quantities on Earth without space mining for 2030 and 2050. The 2050 estimates are shown in Table 1, columns 10 and 11.

Assume construction of the mining operation begins at the end of 2020 with metal deliveries starting in 2030 and lasting for 20 years and make a parallel shift in demand for each metal accordingly. I assume that technology and exploration offsets any depletion effects leaving the supply equations constant. Given historical developments this seems pessimistic from earthly standards, but optimistic when viewed from opportunities for space mining.

Under the assumptions in Table 4, I simulate what would happen to price (P) and quantities (Q) and total revenues (TR) by mineral without space mining as shown in Table 5. The model for these computations is accessible at d:\dahl.mines.edu\SpaceMining.xlsx. Running this model with no space mining yields the total revenues on Earth in 2018 and simulates them for 2030 and 2050.

Table 5 Total Revenue (TR), Price (P) and Quantities (Q) by Metal (No space mining), 2018, 2030. 2050.

	Earth 2018 (Space mining 0 t/year)			Earth 2030 (Space mining 0 t/year)			Earth 2050 (Space mining 0 t/year)		
	TR ($\$10^9$)	**Q tonnes**	**P $/t**	**TR ($\$10^9$)**	**Q tonnes**	**P $/t**	**TR ($\$10^9$)**	**Q tonnes**	**P $/t**
FE	405.60	1,200,000,000.0	338	928.05	1,455,348,966.5	638	3712.95	2,292,199,871	1,620
CO	10.31	125,000.0	82,519	24.04	163,879.8	146,685	107.53	295,493	363,897
NI	23.22	2,199,000.0	10,559	40.03	2,692,417.4	14,867	112.17	4,113,255	27,271
RU	0.26	42.0	6,108,633	0.40	45.1	8,935,608	0.89	53	16,566,897
RH	1.74	31.9	54,656,190	2.74	34.3	79,950,177	6.03	41	148,230,127
PD	10.51	317.8	33,083,070	16.96	343.0	49,461,532	38.50	411	93,674,435
OS	0.02	1.5	12,860,280	0.03	1.6	18,811,806	0.07	2	34,877,677
IR	0.22	7.2	31,186,179	0.35	7.7	45,618,630	0.77	9	84,578,367
PT	7.02	241.6	29,048,157	10.77	258.4	41,668,126	23.00	304	75,735,149
AU	174.87	4,345.1	40,244,639	282.88	5,538.2	51,078,629	766.55	9,145	83,825,963
Total	**633.78**	**1,202,328,987**		**1,306.25**	**1,458,211,492**		**4,768.45**	**2,296,618,583**	

Source: Author's computations using d:\dahl.mines.edu\SpaceMining.xlsx, worksheet ModelDemand. These estimates and sensitivity tests for these and other years are in worksheets A2_TR&P&QNoSpace and DGL20_T_4.

Total estimated revenue in these ten markets in 2018 is over $600 billion dollars more than doubling by 2030 and more than septupling by 2050. But there is quite a lot of variation across the metal markets. Table 6 which shows 2030 and 2050 values of these variables divided by their 2018 values makes it easier to compare across metals. Income elastic iron and cobalt lead the revenue charge and both see more than a 9 fold increase in total revenue by 2050. Their average annual continuous growth rate over this period nears or exceeds 7%. The platinum group metals are the least dynamic and total revenues less than quadruple for all of them by 2050.

Both prices and quantities increase in all markets, but their percentage changes are more modest. The total tonnage increase from 2018 to 2030 is about 20% and to 2050, it is about 90%. For income elastic iron, cobalt, and gold, the quantity increases are more than 90% by 2015. Iron and cobalt prices more than double. Most other products have a price increase of between 80 and 90%, Demand and supply are price elastic for gold and it shows the lowest price increase at about 65% by 2050.

Table 6: Simulated 2030 and 2050 values for total revenue, quantity and price divided by 2018 values

	TR2030/2018	**TR2050/2018**	**Q2030/2018**	**Q2050/2018**	**P2050/2018**	**P2050/2018**
Fe	2.29	9.15	1.21	1.91	1.89	2.54
Co	2.33	10.42	1.31	2.36	1.78	2.48
Ni	1.72	4.83	1.22	1.87	1.41	1.83
Ru	1.57	3.45	1.07	1.27	1.46	1.85
Rh	1.57	3.45	1.07	1.27	1.46	1.85
Pd	1.61	3.66	1.08	1.29	1.50	1.89
Os	1.57	3.45	1.07	1.27	1.46	1.85
Ir	1.57	3.45	1.07	1.27	1.46	1.85

Pt	1.53	3.28	1.07	1.26	1.43	1.82
Au	1.62	4.38	1.27	2.10	1.27	1.64
Total	**2.06**	**7.52**	**1.21**	**1.91**		
minimum	**1.53**	**3.28**	**1.07**	**1.26**	**1.27**	**1.64**
maximum	**2.33**	**10.42**	**1.31**	**2.36**	**1.89**	**2.54**

Source: Author's computations using d:\dahl.mines.edu\SpaceMining.xlsx, worksheet ModelDemand. These estimates and sensitivity tests for these and other years are in worksheets A2_TR&P&QNoSpace.

As the inputs to model are highly speculative, I invite interested readers to enter their own inputs for other simulations into SpaceMining.xlsx, worksheet ModelDemand and present some limited sensitivity testing here on income, price elasticities and income growth. If I multiple all income elasticities or income growth by 0.9 or 1.1, the change in total revenue in 2030 is about +/– 7%. Multiplying demand elasticities by 0.9 or 1.1 changes total revenues around +/– 3.5%, and multiplying all supply elasticities by 0.9 or 1.1 changes total revenues around –/+ 0.2% as shown in Table 7 shows simulated 2030 and 2050 values for total revenue, quantity and price divided by 2018 for each metal market for these sensitivity tests.

Table 7: Simulated 2030 and 2050 values for total revenue, quantity and price divided by 2018 for each metal market.

Edp×0.9 Earth 2030				**Edp×1.1 2030**			**Edp×0.9 Earth 2050**			**Edp×1.1 Earth 2050**		
	TR ($\$10^9$)	**Q tonnes**	**P $/t**	**TR ($\$10^9$)**	**Q tonnes**	**P $/t**	**TR ($\$10^9$)**	**Q tonnes**	**P $/t**	**TR ($\$10^9$)**	**Q tonnes**	**P $/t**
Fe	1.047	1.013	1.034	0.960	0.989	0.971	0.092	0.034	0.057	-0.078	-0.030	-0.049
Co	1.039	1.014	1.025	0.966	0.988	0.978	0.079	0.033	0.044	-0.068	-0.030	-0.040
Ni	1.027	1.011	1.017	0.976	0.991	0.985	0.063	0.027	0.035	-0.055	-0.024	-0.032
Ru	1.035	1.006	1.028	0.971	0.995	0.976	0.077	0.019	0.057	-0.064	-0.016	-0.048
Rh	1.035	1.006	1.028	0.971	0.995	0.976	0.077	0.019	0.057	-0.064	-0.016	-0.048
Pd	1.036	1.007	1.029	0.970	0.994	0.975	0.079	0.020	0.057	-0.065	-0.017	-0.049
Os	1.035	1.006	1.028	0.971	0.995	0.976	0.077	0.019	0.057	-0.064	-0.016	-0.048
Ir	1.035	1.006	1.028	0.971	0.995	0.976	0.077	0.019	0.057	-0.064	-0.016	-0.048
Pt	1.034	1.006	1.028	0.972	0.995	0.977	0.076	0.019	0.056	-0.063	-0.016	-0.048
Au	1.023	1.011	1.011	0.980	0.990	0.990	0.055	0.027	0.027	-0.049	-0.025	-0.025
Total	1.040	1.013		0.965	0.989		0.085	0.034		-0.072	-0.030	

Esp×0.9 Earth 2030				**Esp×1.1 Earth 2030**			**Esp×0.9 Earth 2050**			**Esp×1.1 Earth 2050**		
	TR ($\$10^9$)	**Q tonnes**	**P $/t**	**TR ($\$10^9$)**	**Q tonnes**	**P $/t**	**TR ($\$10^9$)**	**Q tonnes**	**P $/t**	**TR ($\$10^9$)**	**Q tonnes**	**P $/t**
Fe	1.004	0.988	1.016	0.996	1.011	0.985	-0.006	-0.033	0.027	0.004	0.031	-0.026
Co	1.007	0.987	1.021	0.993	1.012	0.981	0.003	-0.033	0.037	-0.005	0.030	-0.034
Ni	1.003	0.990	1.014	0.997	1.010	0.987	0.002	-0.027	0.029	-0.003	0.024	-0.027
Ru	1.000	0.994	1.006	1.000	1.006	0.995	-0.007	-0.018	0.011	0.006	0.017	-0.011
Rh	1.000	0.994	1.006	1.000	1.006	0.995	-0.007	-0.018	0.011	0.006	0.017	-0.011
Pd	1.000	0.994	1.006	1.000	1.006	0.994	-0.007	-0.019	0.012	0.006	0.018	-0.012
Os	1.000	0.994	1.006	1.000	1.006	0.995	-0.711	-0.215	-0.631	-0.711	-0.215	-0.631
Ir	1.000	0.994	1.006	1.000	1.006	0.995	-0.007	-0.018	0.011	0.006	0.017	-0.011
Pt	0.999	0.994	1.005	1.000	1.005	0.995	-0.007	-0.017	0.010	0.007	0.017	-0.010
Au	1.000	0.989	1.011	1.000	1.010	0.990	-0.001	-0.027	0.028	-0.001	0.025	-0.025
Total	1.003	0.988		0.997	1.011		-0.005	-0.033		0.003	0.031	

Edy×0.9 Earth 2030				**Edy×1.1 Earth 2030**			**Edy×0.9 Earth 2050**			**Edy×1.1 Earth 2050**		
	TR ($\$10^9$)	**Q tonnes**	**P $/t**	**TR ($\$10^9$)**	**Q tonnes**	**P $/t**	**TR ($\$10^9$)**	**Q tonnes**	**P $/t**	**TR ($\$10^9$)**	**Q tonnes**	**P $/t**
Fe	0.926	0.980	0.946	1.079	1.021	1.057	-0.191	-0.075	-0.125	-0.191	0.031	-0.026
Co	0.908	0.967	0.939	1.080	1.028	1.051	-0.241	-0.110	-0.147	-0.005	0.030	-0.034
Ni	0.952	0.981	0.970	1.069	1.026	1.042	-0.141	-0.063	-0.083	-0.003	0.024	-0.027
Ru	0.956	0.992	0.964	1.046	1.008	1.038	-0.120	-0.031	-0.092	0.006	0.017	-0.011
Rh	0.956	0.992	0.964	1.046	1.008	1.038	-0.120	-0.031	-0.092	0.006	0.017	-0.011
Pd	0.954	0.992	0.962	1.048	1.009	1.039	-0.124	-0.033	-0.094	0.006	0.018	-0.012
Os	0.956	0.992	0.964	1.046	1.008	1.038	-0.120	-0.031	-0.092	-0.711	-0.215	-0.631
Ir	0.956	0.992	0.964	1.046	1.008	1.038	-0.120	-0.031	-0.092	0.006	0.017	-0.011
Pt	0.958	0.993	0.965	1.044	1.008	1.036	-0.117	-0.030	-0.090	0.007	0.017	-0.010
Au	0.959	0.979	0.979	1.058	1.029	1.028	-0.130	-0.068	-0.067	-0.001	0.025	-0.025
Total	0.935	0.980		1.073	1.021		-0.180	-0.075	0.000	0.003	0.031	

Source: Author's computations using d:\dahl.mines.edu\SpaceMining.xlsx, worksheet ModelDemand. These estimates and sensitivity tests for these and other years are in worksheet DGL20_T_4

Next I consider the effect of space mining on earth's metal markets. Brophy, Culick, and Friedman (2012) costed towing a 1,300 tonne near earth asteroid to the moon. If we can get it to the moon, I assume we can get it back to Earth with appropriate increases in cost. As part of the cost adjustment I lower the asteroid weight to 1000 tonnes.

To get a feel for the markets, I consider different space mining deliveries in 2030 with resulting TR by market shown in Table 8. Our 1,000 tonne metal asteroid for the most part has a very small effect on Earth's metal markets. Earthly mining TR falls by less than 0.0005%, while space mining revenue is estimated at about $6.4 million compared to over a trillion for mining on Earth. Earth mining revenue falls by less than 0.1% except for two markets – Os (down 0.7%) and Ir (down 0.14%). Next increase space mining by a factor of 10 to 10,000 tonnes of space ore per year. Because this amount is still small by Earth standards, prices are again little affected and space revenues go up by only a bit less than 10 times with earthly revenues falling by a larger dollar value than space miners gain. Revenue on Earth is reduced by less than 0.001%. At another 10 fold increase, space mining equals 100,000 tonnes, space revenues increase to more than half a billion dollars, but space still earns less than 0.01% of earthly mining revenues. Increasing by another factor of 10 to 1,000,000 tonnes of space metal, space revenues rise again but by less than 5 fold.

Since some of these markets are rather small, a large enough influx of a metal can drive model prices negative. This happens for Os by the time we get to 200,000 tonnes of asteroid material in 2030 (representing only 2.9 tonnes of Os) and for Ir by 700,000 tonnes of asteroid material (representing less than 10 tonnes of Ir). When prices turn negative, I drop that metal out of the market and continue the simulation. It is not realistic to assume that a metal will always stay in the market provided its price is positive, it merely shows us that the size of some of these markets may be quite small. At a million tonnes of asteroidal material, space revenues increase to more than $5 billion dollars, still relatively small by earthly standards. Running the model out to 2050, with a million tonnes of space asteroids and earth mining revenues increase about another 58%, while space mining revenues more than double. Prices and quantities for these simulations as well as simulations for 2049, 2050, and 2069 can be accessed at d:\dahl.mines.edu\SpaceMining.xlsx, worksheet A3_TR&P&Q.

Table 8 Total Revenue (TR) by Metal for Earth and Space Mining in 2030 with Different Asteroid Size Return to Earth

Space mining 1,000 t/year (billions of 2018 $)						
	TR FE	TR CO	TR NI	TR RU	TR RH	
2030 Earth	928.0468	24.0376	40.0258	0.4028	2.7400	
2030 Space	0.0006	0.0009	0.0014	0.0002	0.0003	
	TR PD	TR OS	TR IR	TR PT	TR AU	TR
2030 Earth	16.9640	0.0300	0.3514	10.7648	282.8841	1,306.2475
2030 Space	0.0008	0.0003	0.0006	0.0012	0.0000	0.0063

Space mining 10,000 t/year (billions of 2018 $)						
	TR FE	TR CO	TR NI	TR RU	TR RH	
2030 Earth	928.0405	24.0273	40.0112	0.4011	2.7372	
2030 Space	0.0057	0.0088	0.0138	0.0019	0.0032	
	TR PD	TR OS	TR IR	TR PT	TR AU	TR
2030 Earth	16.9565	0.0277	0.3458	10.7548	282.8839	1,306.1860
2030 Space	0.0082	0.0025	0.0063	0.0121	0.0003	0.0628
Space mining 100,000 t/year (billions of 2018 $)						
	TR FE	TR CO	TR NI	TR RU	TR RH	
2030 Earth	927.9777	23.9238	39.8654	0.3844	2.7093	
2030 Space	0.0569	0.0877	0.1379	0.0185	0.0317	
	TR PD	TR OS	TR IR	TR PT	TR AU	TR
2030 Earth	16.8812	0.0072	0.2916	10.6545	282.8811	1,305.5762
2030 Space	0.0813	0.0077	0.0546	0.1198	0.0031	0.5992
Space mining 1,000,000 t/year (billions of 2018 $)						
	TR FE	TR CO	TR NI	TR RU	TR RH	
2030 Earth	927.3493	22.9006	38.4210	0.2290	2.4346	
2030 Space	0.5692	0.8528	1.3483	0.1190	0.2900	
	TR PD	TR OS	TR IR	TR PT	TR AU	TR
2030 Earth	16.1341	0.0303	0.3520	9.6662	282.8536	1,300.3707
2030 Space	0.7832	0.0000	0.0000	1.1052	0.0306	5.0983

Source: Author's computation. Notes: The model used for these simulations can be accessed at d:\dahl.mines.edu\SpaceMining.xlsx, worksheet ModelDemand. Prices and Quantities for these simulations as well as simulations for 2050 can be accessed at d:\dahl.mines.edu\SpaceMining.xlsx, worksheet A3-TR&P&Q.

I experiment a bit further to see what happens if I expand space mining by increments of 100,000 tonnes in 2050. As above when asteroid mining pushes the price of a metal negative, I drop it out of the market to see when different metals would drop out and at what tonnage marginal revenue (MR) of space mining goes negative (MR in this case is for a tonne of the asteroidal material with the Leontief fixed coefficients measured in ppm in Table 4.) With growth, the markets are larger and metals drop out at higher tonnage than in 2030. Os drops out by 300,000 tonnes of asteroid mining (representing 4.35 tonnes of Os), Ir by 1,300,000 (representing 18.20 tonnes of Ir), Ru by 4,900,000 (representing 105.4 tonnes of Ru), Rh drops out by 20,000,000 (representing 80 tonnes of Rh), Pt drops out by 21,000,000 (representing 618 tonnes of Pt), Pd drops out by 47,000,000 (representing 775 tonnes of Pt). The marginal revenue per tonne of space mining becomes negative by 41,000,000 tonnes when space mining is still less than 2% of the total world market as measured by revenues. These simulations are shown in Figure 5. The simulations for 2030, when the market is smaller, find space mining marginal revenue going to zero when space is only 1% of the market.

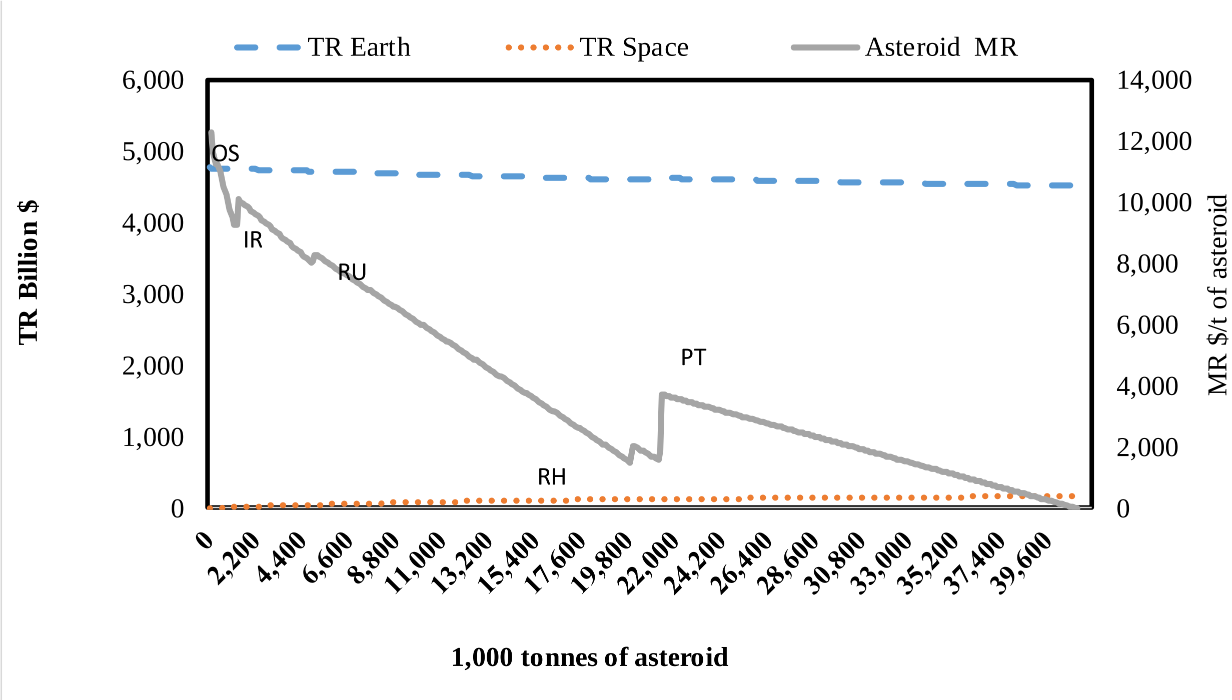

Figure 5 Total revenue (TR) Earth, total (TR) and marginal revenue (MR) space mining at various asteroid sizes in 2050
Notes: The spikes in MR is when the labelled metal drops out of the market. See also d:\dahl.mines.edu\SpaceMining.xlsx, worksheet A4MR2030&49&50&69 for the data for figure 5 with more detail and years.

Figure 5 demonstrates how small space mining is compared to Earth, even when space mining is ramped up to more than 50 million tonnes a year. Further. we will see in the next section that moving so much material in space will present challenges. Marginal revenue for a tonne of asteroidal material starts out around $12,300 per tonne and becomes negative by 41 million tonnes. These numbers will vastly improve if we can separate the metals at scale and leave or use the low valued metals Fe and Ni, and perhaps even Co, in space.

Gold is an interesting case. It is a very small part of our asteroidal material (0.6 ppm). To drive the market price to zero, we have to bring back more than 30 billion tonnes of asteroidal material (considerably larger than the Earth's total current or forecasted market for these metals). With so much asteroid material, the model projects negative prices in all markets. However, what is interesting is that the space injection into Earth's market has to exceed around 18,000 tonnes to drive the gold price negative. With more elastic demand and supply, than for the other precious metals, it is able to absorb a larger percent of tonnage. Thus, if gold can be separated out and brought back on its own, it may have a larger market than the other precious metals in this simulation.

Revenues are only half of the story. To make profits for the company, these revenues must be high enough to cover costs and provide a return commensurate with the high risk for such ventures. I turn to these costs in the next sections beginning with costs on Earth

Cost for Earth Mining, Milling and Smelting

My research into the cost and technology for separating our metal in space have not yet led me to any conclusions. Nor am I yet able to develop supply and demand equations for use of these materials in space. Hence, I decided to start by simulating cases that bring all the asteroid material back to Earth for processing and use. Although this is fraught with its own set of difficulties (e.g. can we get the asteroid back safely and undamaged to Earth's processing facilities?), I set them aside for the moment because I have been more successful at coming up with guesstimates of supply and demand equations and sample processing cost for these metals on Earth. Even if these simulations should be viewed with healthy dose of skepticism, the earthly costs do show what space miners may be up against.

Since the metal in this first case will be processed on Earth, table 9 shows some representative earthly costs for an open pit mine compiled in Dahl (2020). The un-italicized numbers show actual costs for a representative mine (Davis, 2019), while italicized values are computed in Dahl (2020) using extrapolations and economies of scale parameters from the actual cost data. At the top of the table, mining costs are shown for comparison purposes. We expect that the return of 1,000 tonnes or 4,500 tonnes per trip are doable. The mines with actual data vary from 182,500 t/y to 730,000 t/y and are much larger than our starting asteroid values of a paltry 1,000 or 4,500 tonnes per year. To find the cost per tonne of metal divide these costs by the percent of metal in the mined ore. Since my asteroid is almost pure metal, I do not bother adjusting the costs for metal content, whereas earthly metal ore contents are typically much lower (e.g. concentration of platinum group metals in our asteroid are ten times the level of economic concentrations on Earth). These costs show the huge advantage that earthly mines would likely have over returning very small quantities from asteroids and the large economies of scale with levelized mining capital (capex) plus operating cost (opex) per tonne falling from $15.72 per tonne at 182,500 t/y to $5.36 at 730,000 t/y. Earthly mines the size of my initial space ore delivery amount (1,000 t/y and 4,500 t/y) have levelized mining capex plus opex per tonne of about $114 and $64. However, some typical ore concentrations on Earth compared to our asteroid are typically lower: 280,000 on Earth versus 893,000 ppm for Fe, 1,000 versus 6,000 ppm for Co, 40,000 versus 93,000 ppm for Ni, and 9.85 versus 99.5 ppm for the platinum group metals. The exception is gold with 2.5 to 9 ppm on Earth but only 0.6 ppm in the asteroid (Dahl (2020a)). Thus, our asteroid concentrations tend to be 2 to 10 times higher than on Earth, but even multiplying our earthly costs by ten to adjust for metal concentration still leaves a very wide gap compared to what small scale mining might cost in space.

Table 9: Sample mining and processing costs on Earth

Mining	ore	ore	ore	ore	ore	ore	ore
t/day ore	3	12	500	1,000	2,000	2,740	13,699
t/per year ore	**1,000**	**4,500**	182,500	365,000	730,000	**1,000,000**	**2,360,000**
OPEX/t (ore)	$93.29	$52.80	$13.00	$10.00	$4.00	$2.64	$0.31
CAPEX × $\$10^6$	$0.06	$0.20	$4.00	$7.00	$8.00	$8.50	$11.59
CAPEX LC/t ore	$7.42	$5.55	$2.72	$2.38	$1.36	$1.05	$0.61
Processing	**ore**	**ore**	**or**	**or**	**or**	**ore**	**ore**
t/day (ore)	3	12	20	50	100	2,740	13,699
t/year	**1,000**	**4,500**	7,300	18,250	36,500	**50,000**	**118,000**
1 metal							
OPEX/t (ore)	$619.29	$248.24	$185.00	$106.00	$75.00	$14.37	$9.36
CAPEX × $\$10^6$	$3.37	$4.54	$5.00	$6.00	$10.00	$12.61	$23.74
CAPEX LC/t ore	$417.78	$125.23	$85.00	$40.80	$34.00	$31.30	$24.97
2 metals							
OPEX/t (ore)	$685.68	$271.97	$202.00	$115.00	$80.00	$14.14	$9.02
CAPEX × $\$10^6$	$2.49	$4.84	$6.00	$9.00	$13.00	$15.36	$24.23
CAPEX LC/t ore	$308.95	$133.57	$102.00	$61.20	$44.20	$38.13	$25.48
3 metals							
OPEX/t (ore)	$819.44	$302.98	$220.00	$120.00	$85.00	$72.68	$47.41
CAPEX × $\$10^6$	$4.01	$6.76	$8.00	$11.00	$16.00	$18.97	$30.17
CAPEX LC/t ore	$497.51	$186.47	$136.00	$74.80	$54.40	$47.08	$31.73
4 metals							
OPEX/t (ore)	$872.73	$322.68	$234.31	$127.80	$90.53	$77.41	$50.50
CAPEX × $\$10^6$	$5.06	$8.53	$10.10	$13.88	$20.19	$23.94	$38.08
CAPEX LC/t ore	$627.91	$235.35	$171.64	$94.40	$68.66	$59.41	$40.05
5 metals							
OPEX/t (ore)	$929.49	$343.67	$249.54	$136.11	$96.41	$82.44	$53.78
CAPEX × $\$10^6$	$6.39	$10.77	$12.74	$17.52	$25.49	$30.21	$48.06
CAPEX LC/t ore	$792.49	$297.03	$216.63	$119.15	$86.65	$74.99	$50.54
6 metals							
OPEX/t (ore)	$989.93	$366.01	265.7707	$144.97	$102.68	$87.80	$57.28
CAPEX × $\$10^6$	$6.80	$11.47	$13.57	$18.66	$27.14	$32.18	$51.18
CAPEX LC/t ore	$844.03	$316.35	$230.72	$126.89	$92.29	$79.86	$53.83
7 metals							
OPEX/t (ore)	$1,054.30	$389.82	$283.05	$154.39	$109.36	$93.51	$61.00
CAPEX × $\$10^6$	$8.58	$14.48	$17.13	$23.55	$34.26	$40.61	$64.60
CAPEX LC/t ore	$1,065.26	$399.27	$291.19	$160.15	$116.48	$100.80	$67.94
8 metals							
OPEX/t (ore)	$1,122.86	$415.16	$301.46	$164.43	$116.47	$99.59	$64.97
CAPEX × $\$10^6$	$10.83	$18.27	$21.62	$29.73	$43.24	$51.26	$81.53
CAPEX LC/t ore	$1,344.47	$503.92	$367.51	$202.13	$147.01	$127.22	$85.75
9 metals							
OPEX/t (ore)	$1,195.88	$442.16	$321.06	$175.13	$124.05	$106.07	$69.19
CAPEX × $\$10^6$	$13.67	$23.06	$27.29	$37.52	$54.57	$64.69	$102.90
CAPEX LC/t ore	$1,696.87	$636.00	$463.84	$255.11	$185.54	$160.56	$108.22
10 metals							
OPEX/t (ore)	$1,273.65	$470.92	$341.94	$186.51	$132.11	$112.97	$73.69
CAPEX × $\$10^6$	$17.26	$29.11	$34.44	$47.35	$68.87	$81.65	$129.88
CAPEX LC/t ore	$2,141.63	$802.70	$585.42	$321.98	$234.17	$202.64	$136.59

Source: Computations are described in Dahl (2020). Computations for the version in above table are shown in http://dahl.mines.edu/MetalMarkets2020.xlsx worksheet T1_EarthMineCost.

After mining comes milling. This accomplishes the initial concentration of the metal removing much of the dross called gangue. Milling is typically done near the mining operation to reduce the transport and smelting costs for the concentrated ore. Table 9 shows milling cost to be more expensive but also to have large economies of scale. Unit costs fall considerably as operations are scaled up but increase for each additional metal separated out. Sample milling cost and economies of scale elasticities for up to three metals have been used to extrapolate to more metals. For example going from extracting 2 to extracting 3 metals raised operating costs by 7% and capital costs by 26% in the sample data. These same percentage increases are added to the costs for each additional metal up to the 10 metals. If all ten metals are separated out and our earthly mill processes the 4,500 tonnes per year, the unit opex and capex cost per unit of ore for milling is about $1,273 per tonne, if we can contract to process our asteroid in a larger earthly mill that processes 365,000 t/y, we can drop that cost down to around $511/tonne.

Although I later assume operating costs for the space portion are contracted out for the life of each ship mission, I assume earthly costs accrue on a yearly basis. Once the ore has been milled to concentrate the metal, the final process to get almost pure metal is smelting. Smelters typically charge 10% of the revenue, which I can handle by computing total revenues to the space mining company as 90% of the revenue in each market. So now 0.9 times our average revenue has to beat levelized cost per tonne including milling.

Cost of returning Asteroids Material to Earth

Next let's consider space travel cost, which is trickier yet. Brophy et al. (2012) estimate the cost of sending a mission to a NEA and returning with a 1,300 tonne asteroid to lunar orbit converted to 2018 dollars is $2.935 billion. To start with, I make the heroic assumption that lowering the weight of the asteroid from 1,300 tonnes to 1,000 tonnes will compensate for the extra Δv to get the asteroid back to the surface of the Earth instead of into low lunar orbit.

Their total launch weight is 18.8 tonnes with 12.9 of that weight xenon fuel. With solar propulsion their ship will take ten years to make a round trip. With one launch per year starting at the end of 2030, the subsequent 9 launches are reduced by development costs of $1.128 billion. Brophy et al. (2012) do not address the issue of reusability, but I initially assume that the space vessel that captures and delivers the asteroid can make two ten year trips with maintenance or refurbishment cost averaging 3% of initial cost per year during its first voyage for a total of 30% before commencing on its 2nd voyage (https://reliabilityweb.com/best-practice-maintenance) with no salvage or disposal cost. Thus, the second journey for each of the ten ships will cost about $770 million each. These costs are summarized in Table 10. In the initial runs, it is assumed this refurbishment is completed on Earth. These costs are summarized in Table 10.

Table 10 Base Case Mission Costs @ 10% Discount Rate

Cost Case 1 asteroid	**mission 1**	**mission 2-10**	**mission 11-20**
weight 1,000 t	**2018 10^6 $**	**2018 10^6 $**	**2018 10^6 $**
NASA insight/oversight (15% prime contractor)	225	56	17
Phase A (5% of B/C/D costs)	75	19	6
Spacecraft Design, Development, Demonstration, Testing	1128		
Spacecraft Hardware	371	371	111

Launch Vehicle (Atlas 551)	318	318	318
Mission Operation and Guidance (10 year mission plus set up)	129	129	129
Reserves (30%)	674	268	174
Xenon Fuel 12.9 tonnes@1.2×10^6 \$/t	15.48	15.48	15.48
Total	**$2,935.08**	**$1,174.75**	**$769.91**
	2018 $	**2018 $**	**2018 $**
PV(missions)	**$11,524,377,974**		
LC $/t	**$3,191,834**		

Source: Brophy et al (2012), Fig. 8, p. 29, Fig. 16, p 40, and Fig. 17, p. 41 and author's computations. PV = present value as of 2020 in 2018 dollars, and LC = levelized mission cost per tonne.

Under these assumptions and a very modest 10% interest rate, the levelized cost per tonne of delivered space metal is more than $3.0 million dollars per tonne of metal, and I have not yet included the processing cost of the ore. See http://dahl.mines.edu/SpaceMining.xlsx, Worksheet ModelSpaceCost, cell B22, contains the final computation to arrive at this value. Increasing the discount rate to 0.17 in cell B19 about doubles this cost. The reader is invited to change the value in B19 or any value in red font in the workbook to change underlying assumptions.

Meanwhile, if all metals in our 1,000 tonne asteroid are processed, the average space revenues from 2030 – 2050 vary from about $6,300 to $12,200/tonne (see http://dahl/mines/edu/SpaceMining.xlsx worksheet A5SpaceAR.xlsx, column C for all the average revenue per year for all the years. Other columns contain results from the subsequent sensitivity cases mentioned below). Although all precious metals (Ru, Rh, Pd, Os, Ir, Pt, Au) have prices considerably higher than $3 million per tonne (See Table 4 for the simulations with no mining), they occur in such trace amounts they can't make the asteroid pay off. Clearly space mining on this scale for earthly markets is out of the question in the next three decades, unless we can bring costs down or revenues up. So let's give it a try.

I consider 8 more demand cases for a 1,000 tonne asteroid that makes deliveries for 20years with the last delivery at the end of 2049 and the beginning of 2050. Increasing the share of precious metals, increases our revenues, but even increasing all platinum group metals by ten fold (10×PFM) at the expense of iron does not make the average revenues by 2050 more than $72,000 per tonne. If I also increase income growth (Yg) by 10% (1.10*Yg), I still do not exceed $77,500 per tonne by 2050. Nor does additionally tripling the nickel concentrations (3×Ni) at the expense of iron plus making earth supply perfectly price inelastic (Es=0), doubling income elasticities (2×Edy) and cutting our price elasticities in half (Edp×0.5) cause the average space revenue for 1000 tonne asteroid to break $450,000 per tonne by 2050. Mining for Earth delivery is still out of the question. The net present values for the whole project for each of these cases is shown in Table 11.

Table 11: Present Value of Revenues, Costs, and NPV per tonne (t) for 1000 t annual asteroid material return for 20 years, 2030 to 2050

i=0.1	**D_Case 1 Base**	**D_Case 2 2×PGM**	**D_Case 3 2×PGM, 1.1×Yg**
PV Revenue	29,016,635	44,549,997	47,502,253
PV Cost	11,524,377,974	11,524,377,974	11,524,377,974

NPV $/project	-11,495,361,340	-11,479,827,977	-11,476,875,722
	D_Case 4 10×PGM	**D_Case 5 10×PGM,1.1×Yg**	**D_Case 6 10×PGM, 1.1×Yg, 3×Ni**
PV Revenue	168,005,020	178,506,693	191,004,257
PV Cost	11,524,377,974	11,524,377,974	11,524,377,974
NPV $/project	-11,356,372,955	-11,345,871,281	-11,333,373,717
	D_Case 7 10×PGM, 1.1×Yg, 3×Ni, Esp=0	**D_Case 8 10×PGM, 1.1×Yg, 3×Ni, Esp=0, Edy×2**	**D_Case 9 10×PGM, 1.1×Yg, 3×Ni, Esp=0, Edy×2, Edp×0.5**
PV Revenue	218,688,623	467,195,829	683,380,403
PV Cost	11,524,377,974	11,524,377,974	11,524,377,974
NPV $/project	-11,305,689,351	-11,057,182,145	-10,840,997,571

Notes: Case 1 is the demand base case as indicated in Table 4. Notes for demand cases 2 – 9 indicate the following changes from base case: 2×PGM = doubling the concentration of platinum metals, 1.1×Yg = increasing income growth rate 10% = 1.1*3.6=3.96, 3×Ni= tripling nickel concentration, Esp=0 gives earthly supply elasticity for all metals of 0, and Edy×2 doubles the income elasticity of demand for all metals. For more detail on these computations see http://dahl/mines/edu/SpaceMining.xlsx worksheet A5SpaceAR.xlsx. PV = present value as of 2020 in 2018 dollars with discount rate 10%, NPV = net present value as of 2020.

Next I scale up the missions to 4,500 and 10,000. I chose these two additional sizes because I believe they can be accomplished with existing technology. I adjust the fuel needed and mass of the ship as follows. I believe the Falcon 9 has the power to conduct the Brophy et al (2012) mission. Its dry weight, mass and fuel use from their publication are given in the Table 12. The Falcon Heavy and the Saturn V should be powerful enough to complete the 4,500 and 10,000 tonne asteroid missions, respectively. The available dry weight, launch cost and payload to LEO are the non-italicized values given in the table. I compute the remaining italicized information. Launch cost for the Saturn V is extrapolated up by the changing weight of the asteroid relative to the change in cost going from 1,000 to 4,500 or

$$90+(90-62)/(4500-1000)*(10,000-4500)=134.$$

Ship mass is scaled up by the dry weight of the ships. Fuel to NEA is scaled up by the ship mass and the amount of fuel needed to return. Xenon fuel is assumed to cost $1.2 million per tonne. The mass return is the ship mass plus the asteroid mass. The fuel return is scaled up by the mass return. Total fuel and launch mass are computed from the appropriate summations.

Table 12 Launch Cost, Mass and Fuel Needed for Three Different Sized Asteroid Mining Missions

Existing rockets	Dry Weight (t)	Launch cost (10^6)	Payload to LEO	Ship M from existing	Fuel 1 to Nea	Mass return	Fuel Return	Total Fuel	Launch mass
Falcon 9	25	62	18.3	5.500	5.2	1005.50	7.7	12.9	18.40
Falcon Heavy	66	90	63.8	*14.520*	*8.8*	*4514.52*	*34.6*	*43.3*	*57.84*
Saturn V	179	*134*	140.0	*39.380*	*13.2*	*10039.38*	*76.9*	*90.1*	*129.45*

Sources: Brophy et al. (2012), https://forum.nasaspaceflight.com/index.php?topic=18906.0, https://www.quora.com/What-is-the-dry-mass-for-Falcon-Heavy, https://en.wikipedia.org/wiki/Falcon_Heavy, https://www.universetoday.com/129989/saturn-v-vs-falcon-heavy/.

Notes: Italicized numbers are computed by author with the computations shown in http://dahl/mines/edu/SpaceMining.xlsx worksheet AsteroidsMass&Mass&Dens&Vol in the Table starting at cell B1. These estimated fuel values are optimistically low, as the Δv to Earth is higher than to the low lunar orbit of Brophy et al. (2012) even with aero braking, while fuel use goes up at the exponential of Δv as seen in equation 1. Further work could try to quantify this optimism.

The above assumptions yield two cost cases as shown in Table 13. Cost case 2 is for the return of a 4,500 tonne asteroid and cost case 3 is for the return of a 10,000 tonne asteroid.

Along with the above changes in fuel and ship mass and asteroid size, I assume some cost reduction and technical improvement that will likely come with private mining operations rather than using the cost estimates for government space missions. The above launch computation had launch costs of $318 million for a payload of 18.8 tonnes to low earth orbit (LEO) and an asteroid payload return to Earth of 1,000 tonnes. The new Falcon Heavy by SpaceX is expected to be able to deliver of 63.8 tonnes to LEO with a best case towback of a near earth asteroid of 70*68.3 = 4,781 tonnes, which I round down to 4,500 tonnes (Brophy et al., 2012). SpaceX's cost per launch to LEO is estimated at $90 million (Tartar and Qiu, 2018). The space ship launched from LEO, needs to carry more fuel and be larger. The ships are improved and each will make four deliveries in 40 years with refurbishment cost before each new mission of 30% of initial capital cost. I remove the NASA oversight of 20% of contractor cost.

Table 13 Space Mining Costs Case 2 and 3 (including milling on Earth)

Cost Case 2 asteroid weight =	**mission 1**	**mission 2-10**	**mission 11-40**
4,500	**2018 10^6 $**	**2018 10^6 $**	**2018 10^6 $**
Spacecraft Design, Development, Demonstration, Testing	1128.4		
Spacecraft Hardware	538.2	538.2	161.4
Launch Vehicle (Atlas 551)	90.0	90.0	90.0
Mission Operation and Guidance (10 year mission plus set up)	129.1	129.1	129.1
Reserves (30%)	565.7	227.2	114.2
Xenon Fuel	52.0	52.0	52.0
Total cost of missions	**$2,503.3**	**$1,036.4**	**$546.7**
	2018 $	**2018 $**	**2018 $**
PV(missions) $	**$10,657,457,563**	**PV milling**	**$6,830,557**
PV with milling $	**$10,664,288,120**		
discount rate	**0.10**		
LC $/t	**$628,161**		

Cost Case 3 asteroid weight =	mission 1	mission 2-10	mission 11-40
10,000	**2018 10^6 $**	**2018 10^6 $**	**2018 10^6 $**
Spacecraft Design, Development, Demonstration, Testing	1128.4		
Spacecraft Hardware	801.3	801.3	240.4
Launch Vehicle (Atlas 551)	134.0	134.0	134.0
Mission Operation and Guidance (10 year mission plus set up)	129.1	129.1	129.1
Reserves (30%)	657.8	319.3	151.0
Xenon Fuel	108.1	108.1	108.1
Total cost of missions	**$2,958.7**	**$1,491.8**	**$762.6**
	2018 $	**2018 $**	**2018 $**
PV(missions) $	**$14,598,882,474**	**PV milling**	**$15,179,016**
PV with milling $	**$14,614,061,490**		
discount rate	**0.10**		
LC $/t	**$387,213**		

Source: Authors computations. Model for these computations can be found in http://dahl.mines.edu/SpaceMining.xlsx, worksheet ModelSpaceCost starting in column G. Cell J3 can be changed to be 4,500 or 10,000 for the two cases.

Notes: PV=present value as of 2020. This value including milling cost is in cell H18. LC = levelized cost @ discount rate 10 %. LC can be read in cell H22 and the discount rate can be changed in cell H20. Milling cost per tonne can be changed in cell J19.

Levelized mining cost per tonne falls dramatically to about $628,161/t and $387,213/t, for cost case 2 and 3 respectively. Net present values for projects for these the two cost cases and the nine demand cases are summarized in Tables 14 and 15

Now in our most optimistic demand case 9 (10×PM, 1.1×Yg, 3×Ni, Esp=0, Edy×2, Edp×0.5), average revenues exceed the levelized costs in some years after 2040. However, the net present value at 2020 shows losses of more than $6 billion (supply case 2=4,500 tonne asteroids) and more than $2 billion (supply case 3=10,000 tonne asteroids).

Table 14: Present Value of Revenues, Costs, and NPV per tonne (t) for Cost Case 2 4,500 t annual asteroid material return for 40 years, 2030 to 2070

i=0.1	D_Case 1, Cost Case 2	D_Case 2 2×PGM, Cost Case 2	D_Case 3 2×PGM, 1.1×Yg, Cost Case 2
0.9*PV Revenue	152,253,215	231,844,254	251,016,269
PV Cost	10,664,288,120	10,664,288,120	10,664,288,120
NPV $/project	-10,512,034,906	-10,432,443,867	-10,413,271,851

	D_Case 4 10×PGM, Cost Case 2	D_Case 5 10×PGM,1.1×Yg, Cost Case 2	D_Case 6 10×PGM, 1.1×Yg, 3×Ni, Cost Case 2
0.9*PV Revenue	851,576,660	918,503,271	983,928,178
PV Cost	10,664,288,120	10,664,288,120	10,664,288,120
NPV $/project	-9,812,711,460	-9,745,784,849	-9,680,359,943
	D_Case 7 10×PGM, 1.1×Yg, 3×Ni, Esp=0, Cost Case 2	**D_Case 8 10×PGM, 1.1×Yg, 3×Ni, Esp=0, Edy×2, Cost Case 2**	**D_Case 9 10×PGM, 1.1×Yg, 3×Ni, Esp=0, Edy×2, Edp×0.5, Cost Case 2**
0.9*PV Revenue	1,144,454,733	3,050,773,068	4,572,068,146
PV Cost	10,664,288,120	10,664,288,120	10,664,288,120
NPV $/project	-9,519,833,388	-7,613,515,052	-6,092,219,974

Notes: See notes under Table 11, 0.9 of revenue is taken to allow for smelting. Unit operating and capital costs are taken from earthly milling costs for an operation processing 36,500 tonnes per year separating out 10 metals taken from Table 9. Rounded to the nearest dollar per tonne milling cost milling cost equals $366/t. Models to compute these costs and more information on cost per year are available in http://dahl.mines.edu/SpaceMining.xlsx, worksheets ModelSpaceCost, ModelDemand, and A5SpaceAR. Cells in red font can be changed to model these and other cases.

Table 15: Present Value of Revenues, Costs, and NPV per tonne (t) for Cost Case 3=10,000 t annual asteroid material return for 40 years, 2030 to 2070

i=0.1	**D_Case 1 Base, Cost Case 3**	**D_Case 2 2×PGM, Cost Case 3**	**D_Case 3 2×PGM, 1.1×Yg, Cost Case 3**
0.9*PV Revenue	337,686,625	512,632,195	555,236,674
PV Cost	14,614,061,490	14,614,061,490	14,614,061,490
NPV $/project	-14,276,374,865	-14,101,429,295	-14,058,824,816
	D_Case 4 10×PGM, Cost Case 3	**D_Case 5 10×PGM,1.1×Yg, Cost Case 3**	**D_Case 6 10×PGM, 1.1×Yg, 3×Ni, Cost Case 3**
0.9*PV Revenue	1,828,266,373	1,976,992,176	2,122,324,513
PV Cost	14,614,061,490	14,614,061,490	14,614,061,490
NPV $/project	-12,785,795,117	-12,637,069,314	-12,491,736,977
	D_Case 7 10×PGM, 1.1×Yg, 3×Ni, Esp=0, Cost Case 3	**D_Case 8 10×PGM, 1.1×Yg, 3×Ni, Esp=0, Edy×2, Cost Case 3**	**D_Case 9 10×PGM, 1.1×Yg, 3×Ni, Esp=0, Edy×2, Edp×0.5, Cost Case 3**
0.9*PV Revenue	2,465,515,373	6,701,778,341	12,375,827,111
PV Cost	14,614,061,490	14,614,061,490	14,614,061,490
NPV $/project	-12,148,546,117	-7,912,283,149	-2,238,234,379

Source: Author's computations

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Notes: See notes under Table 11 and 14.

Next I consider what sort of demand changes could put cost case 3 in the black. These cases are summarized in Table 16. Case 10 does not contain any higher concentrations of metal, but only has all the more favorable demand elasticities included in some of the first nine demand cases. It yields two billion more in NPV revenues than the base case demand assumptions for 10,000 t asteroids (case 3) but still leaves us seriously in the red losing more than 11.5 billion dollars.

Table 16: Revenues, Cost Case 3, and NPV for 10,000 t annual asteroid material return for 40 years 2030 to 2070 Additional Demand cases.

	Case 10 D_Case 3 but 1.1×Yg, Esp=0, Edy×2, Edp×0.5, Cost Case 3	**Case 11 D_Case 3 but 1.1×Yg, Esp=0, Edy×2, Edp×0.5, 10×PGM, Cost Case 3**	**Case 12 = Demand Case 3 but 1.1×Yg, Esp=0, Edy×2, Edp×0.5, 10×Co, Cost Case 3**
0.9*PV Revenue	$2,783,273,974	$10,638,404,211	$10,239,240,988
PV Cost	$14,614,061,490	$14,614,061,490	$14,614,061,490
NPV $/project	-$11,830,787,516	-$3,975,657,279	-$4,374,820,502
	Case 13 Demand Case 3 but 1.1×Yg, Esp=0, Edy×2, Edp×0.5, 10×Co, 10×PM, Cost Case 3	**Case 14 Demand Case 3 but 1.1×Yg, Esp=0, Edy×2, Edp×0.5, 953×Au, Cost Case 3**	**Case 15 Demand Case 3 but solid gold asteroid, cost case 3**
0.9*PV Revenue	$18,094,371,225	$14,629,836,051	$748,603,171,617
PV Cost	$14,614,061,490	$14,614,061,490	$14,614,061,490
NPV $/project	$3,480,309,735	$15,774,561	$733,989,110,128
	Case 16 Demand Case 3 Cost Case 4 =0.02209×Cost Case 3	**Case 17 Demand Case 3, but i=0.2, Cost Case 5 = 0.00646×Cost Case 3**	
0.9*PV Revenue	$337,686,625	$66,317,697	
PV Cost	$337,668,330	$66,257,577	
NPV $/project	$18,295	$60,120	

Source: Author's computation.

Notes: See notes under Table 11 and 14. 10×Co indicates that cobalt concentrations in the asteroid have been increased 10 times at the expense of iron. 10×PM indicates that all platinum metal concentrations have been increased 10 times at the expense of iron. 953×Au indicates that gold concentrations have been increased 953 times at the expense of iron.

Table 17 shows the prices and total revenues simulated in case 10 for year 2030 and 2069. Prices for most of the metals increase between 3 and 4 fold. The ranking of prices are relatively similar over the time period except gold becomes cheaper than iridium and platinum. The platinum metals as a group tend to be the most expensive and I start by increasing their concentrations to see what they do to the bottom line.

In case 11, Table 16 the concentrations of all the platinum metals are increased 10 fold. The present values of revenues increases by more than 3.5 fold, but do not yet put us in the black. Next increase the concentration of cobalt by 10, case 12. It is not as expensive as any of the platinum metals, but with a considerably higher concentration 60 tonnes versus about a tonne of the platinum metals per asteroid, the increase in revenues is almost as great as case 11. If I increase both the platinum metal and cobalt concentrations, as in case 13, I finally find a case that puts the project in the black by about 3.5 billion dollars.

Table 17 Simulated Metal Prices and Total Revenues for space mining under optimistic demand case 10 for 2030 and 2069, 10,000 t asteroid

	2030			2069	
	P $/t	**TR ($\$10^6$)**	**Q tonnes**	**P $/t**	**TR ($\$10^6$)**
FE	**3,069**	**27.4046**	**8,930.000**	**136,520**	**1,219.1262**
CO	**821,285**	**49.2771**	**60.000**	**43,019,256**	**2,581.1554**
NI	**56,477**	**52.5238**	**930.000**	**1,384,951**	**1,288.0047**
RU	**24,956,246**	**5.3656**	**0.215**	**429,033,169**	**92.2421**
RH	**223,848,902**	**8.9540**	**0.040**	**3,839,274,005**	**153.5710**
PD	**144,341,945**	**23.8164**	**0.165**	**2,520,314,254**	**415.8519**
OS	**25,711,515**	**3.7282**	**0.145**	**152,994,731**	**22.1842**
IR	**126,229,283**	**17.6721**	**0.140**	**2,189,148,313**	**306.4808**
PT	**112,393,282**	**32.5941**	**0.290**	**1,893,288,405**	**549.0536**
AU	**170,334,088**	**1.0220**	**0.006**	**4,834,827,393**	**29.0090**
Total		**222.3578**	**9,921.001**		**6,656.6788**

Source: Author's Computations using http://dahl.mines.edu/SpaceMining.xlsx, worksheet ModelDemand.

The next experiments I do are for gold concentrations. The ore concentrations for the metals in the representative asteroid tend to be larger than profitable ore concentrations on Earth, except for gold. Table 18 reviews some typical ore concentrations on Earth with those in the asteroid.

Table 18 Sample Metal Concentrations in Earth Ores and in the Representative Asteroids

Substance	Ore grade ppm	Asteroid
Fe (Iron)	377,000	893,000.0
Ni (Nickel)	25,000	93,000.0
Co (Cobalt)	1,000	6,000.0
Au (Gold)	2.5 to 9	0.6
Pt (Platinum)	3	29.0
PGM	10	14.1

Source: Dahl (2020a), Table 4 for Earth ore grade and Table 4 above for asteroid concentrations.

Notes: PGM = platinum metal group. Asteroid concentration for PGM is the sum for the non-platinum metals in PGM.

Because of the low gold concentration, increasing the gold concentration by 10 times does little to move the project into the black. Indeed it took an increase in gold concentration of more than 950 times for project to break even at the 10% discount rate (case 14). For another bit of fun with concentrations, I simulate the effect of a 10,000 tonne asteroid that is solid gold. This could represent a case where gold is separated out in space and only the gold is sent back. The increase in revenues at more than 260 times demand case 10 or more than 350 times revenues in demand case 3 is quite dramatic. However, with no idea yet of the cost of space separation with delivery of the pure metal, it is unclear whether such a project would be profitable or not.

For the penultimate case (Case 16 in Table 16) considered here, I take the more realistic demand case 3 and experiment to see what sort of cost reduction would be needed to make this case profitable. I find that multiplying mission plus milling costs by 0.02209 gives a slight profit at the 10% discount rate. Such a cost reduction is not unimaginable. See for example, Kavlak, McNerney, and Trancik (2018). Their figure 1 shows that solar photo-voltaic costs have fallen by 99% since 1980. However, also recall that I have computed costs at a 10% discount rate and probably severely underestimated the mission cost of returning the asteroid to Earth.

Last take a look at Case 17, Table 16, which has the more realistic discount rate of 0.2. At this higher discount rate, multiplying mission plus milling costs by a much lower value is required to yield the 20% required profit rate. For example, if I multiply costs by 0.00646 as shown in the table, the project yields only slightly more than the 20% discount rate. The reader can do their own experimenting with these changes in the excel file http://dahl.mines.edu/ worksheet ModelSpaceCost, cells H20 and J23.

Conclusions and Where to Next

From my initial romp above the clouds, I come to a number of tentative conclusions. Numerous historical studies consider metal markets on Earth from which demand and supply elasticities have been estimated and equations can be formulated. Although simple summaries of past markets, they do present a place to start an analysis of Earth's metal markets that have some statistical basis. More studies have looked at demand than supply elasticities and I suspect demand studies, which tend to have better statistical fits, likely provide better summaries of past metal demand behavior than supply studies. More work clearly can be done to update these results and to try to capture some of the intricacies of these markets such as joint products and better matching the economic activity to each metal use. Further, as we transition to a more sustainable future, the future may look less and less like the past. Thus, we need to speculate how these demand elasticities might change with these newer technologies.

Although asteroid fever has cooled some from when I started this investigation, there is still interest in using space resources to supplement those on Earth or to provide building blocks as space activities escalate. There is some debate as to whether the moon or near Earth asteroids provide a better starting point. Prado (1983-2020) provides a fairly comprehensive summary of the pros and cons of the two option. For example, the moon is closer in terms of travel time, more familiar, and with some gravity it is easier to imagine mining options. However, many near earth asteroids although further away are cheaper to get to and from. As the rocket does not need to resist gravity on its approach to or escape gravity on departure from the asteroid, the asteroid retrieval transportation system is simpler and fuel costs lower. Asteroids do not typically suffer from the moon's extreme temperature changes from 14 days of night followed by 14 days of day except at the lunar poles and the quality of resources may be higher with more free metal concentration than on the moon. Prado argues that absence of gravity is not a severe problem as it can be manufactured by the mission using the centrifugal force of spinning objects. Given the earlier interest by the private sector in asteroid mining, I chose to first consider asteroid mining in support of my co-author's funded project for asteroid mining (Dahl et al. (2019, (2020)).

Although there is still a lot to learn about asteroids, there is already quite a lot of available information that keeps steadily growing. What is clear from my brief review of asteroid resources is there are a lot of resources stored in a multitude of asteroids and comets– some fairly near and others far, far away. Some of these resources are scarce and very valuable on Earth such as the PGMs and gold. Others are rather plentiful and cheap on Earth but very expensive to transfer from Earth to space. Given the number of nearby objects it seems there are gold and other valuables in "them thar" asteroids and they might be ready to be mined. Out of the three main asteroid types, Type C (carbonaceous chondrite with water, metal, and organic compounds), Type S (LL chondrite with platinum group metals) and Type M (metallic mostly iron and nickel with some precious metals), I chose metallic asteroids to investigate and developed a representative asteroid.

I considered three asteroid mining options:

> (1) mine and separate the metals at the asteroid, returning only the final desirable metal products to Earth,
>
> (2) tow the asteroid back to lunar orbit for processing, returning only the more valuable metals to Earth, while leaving the metals with low Earth value for space use, or
>
> (3) capture and tow a small asteroid or a piece of a larger asteroid back to the earth's surface for processing.

My first choice was 2. However, I could not figure out the technology or how to cost for lunar processing. Nor was I able to imagine what the market for metals would be in space. So like the drunk searching for lost keys near the lamppost because that was where there was more light, I changed to case 3 for my initial investigation. However, if the announced plans by NASA, the European Space Agency, and SpaceX to build space stations on the moon come to pass, we will learn more about the technologies and costs of building in Space (https://www.bbc.com/future/article/20190201-how-easy-will-it-be-to-build-a-moon-base).

Next I considered what was technologically feasible. From my historical review of space technology, I concluded we likely have the technology to bring back up to 10,000 tonnes of asteroidal material from near Earth asteroids to the Earth's surface. I ignore the potential hurdles of finding enough appropriate asteroids to feed multi year missions and getting them back safely to the appropriate processing facilities. I continue to determine whether we would want to mine asteroids for Earth return. Making some very optimistic cost assumptions, I first considered a 1,000 tonne mission with deliveries over 20 years without milling or smelting costs. Rockets were assumed to be reusable once with refurbishment. For all cases considered, the NPV of losses exceeded 10 billion dollars.

The initial costs were based on a government mission through NASA. I next scaled up the missions to 4,500 tonnes of asteroidal material and then 10,000 tonnes. For these missions, I assumed potential costs reductions we might expect if the private sector takes over, making rockets more reusable (3 times instead of once) with missions making deliveries for 40 years instead of 20, and also added in mining and milling costs on Earth. Even under the most optimistic assumptions tried, the NPV of losses were never less than $2.2 billion, although unrealistically optimistic demand assumptions and increasing the platinum metal content of the 10,000 tonnes asteroid ten fold reduced losses considerably.

The last set of experiments were conducted to see what sort of demand improvements or cost reductions would it take to make the 10,000 tonne per year for 40 year asteroid project starting deliveries in 2030 to break even. Very optimistic demand elasticities coupled with increasing platinum metals and cobalt metal concentrations at the expense of iron by ten fold would make the project profitable at a 10% discount rate. Very optimistic demand elasticities coupled with increasing gold concentrations at the expense of iron times 953 would suffice as well. On the cost cost side with base case demand elasticities, mission costs would have to be reduced to about 2.2% of base case cost for the mission to be profitable at a 10% discount rate, and would have to be reduced to about 0.65% at a 20% discount rate. It doesn't take a rocket scientist to see that returning whole asteroids to Earth are currently out of the question.

The above cost estimates do not adequately adjust the Brophy et al. (2012) costs for the change in Δv for Earth rather than Lunar return. However, as this would only increase the costs, it would not change the conclusions of the paper. However, as our information on material demand in space, new technology to process in space, and what it will cost, the model could quite easily be modified. Nodes for iron and nickel or other low value products, now rooted on Earth could be moved to LEO or lunar orbit or other space locations with only the more valuable metals returned to Earth. As water is now widely touted is being one of the first products targeted for space use, carbonaceous chrondite asteroids with much higher water content could become the target. As these asteroids are much more abundant than metallic asteroids, this increases the chances that appropriate asteroids will be available. The models also could be rewritten in a programming language that would be more flexible and could include optimization as well as simulation.

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