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Prospects for Mining Asteroids: Into this World or Out of the Question

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ABSTRACT
Depletion of minerals and other non-renewable resources has long been a source of worry to industrial economies. This worry waxes when markets are tight and wanes when they are not. However, evidence has continued to mount that there are staggering amounts of minerals in space that are technically within our grasp. Scientific work has considered mineral availability and technical ability to mine on near earth objects. Within the last decade a number of space related industries have gained attention. While availability and technical feasibility are both necessary conditions for this industry to develop, they are not sufficient. Rather sufficiency also requires financial feasibility. Although studies have considered the costs of mining asteroids, we are aware of no papers that model the effects on terrestrial mineral market structure with the injection of extra- terrestrial minerals. Our contribution is to consider the current state of mineral markets and provide a model of firm entry to derive implications to the market from space mined minerals entering the market. We conclude with a simple numerical example to demonstrate that the near term prospects for space minerals are likely out of the question.

JEL **classifications: L72, Q30, Q31**
Keywords: Mining Space, Asteroids, Milling, Smelting, Magnetic Precious Metals, Demand, Cost.

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Prospects for Mining Asteroids: Into this World or Out of the Question[1]

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Abstract: Depletion of minerals and other non-renewable resources has long been a source of worry to industrial economies. This worry waxes when markets are tight and wanes when they are not. However, evidence has continued to mount that there are staggering amounts of minerals in space that are technically within our grasp. Scientific work has considered mineral availability and technical ability to mine on near earth objects. Within the last decade a number of space related industries have gained attention. While availability and technical feasibility are both necessary conditions for this industry to develop, they are not sufficient. Rather sufficiency also requires financial feasibility. Although studies have considered the costs of mining asteroids, we are aware of no papers that model the effects on terrestrial mineral market structure with the injection of extra-terrestrial minerals. Our contribution is to consider the current state of mineral markets and provide a model of firm entry to derive implications to the market from space mined minerals entering the market. We conclude with a simple numerical example to demonstrate that the near term prospects for space minerals are likely out of the question.

Tribute to John Tilton

The authors are honored to have been invited to contribute an article in honor of John Tilton's 80th birthday. John has been a bulwark in the Mineral Economics community for many decades. He set out on his professional path with his Ph.D. thesis on international trade patterns of nonferrous metals in 1966 at Yale University under the tutelage of Bela Balassa. By the time he reached the Colorado School of Mines in 1985 as William J. Coulter Professor of Mineral Economics, his strong economic ability, poised and polished communication skills, and formidable institutional knowledge of minerals markets had made him a leading scholar in the field of Mineral Economics. It is at the Colorado School of Mines, that the authors have all had the pleasure of having John as a valued colleague and mentor. John served as Division Director from 1988 to 1998 and helped to build the distinctive Mineral Economics Program in stature. Of the four U.S. Ph.D. degree granting programs in Mineral Economics when John came to CSM, three (Penn State, Arizona State, and West

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Virginia) have fallen by the wayside. Only CSM's Mineral Economics Program, with Energy added to the title in 2007, marches on in John's shadow. We salute John as a scholar and a gentleman and wish him a Happy Birthday with many more returns of the day.

I. Introduction

Non-fuel minerals are critical building blocks to global material well being. At the millennium it was estimated that global consumption of non-fuel minerals excluding bauxite was on the order of 1.2 billion metric tons amounting to about 200 kilograms per capita increasing to more than 300 kg per capita by 2016 (International Organizing Committee for the World Mining Congresses (2018), Wellmer and Becker-Platen (2007), World Bank (2019)). This consumption is largely satisfied out of production and in some cases from recycled product and stock drawdown. The global distribution across products for this consumption in 1998 is indicated by the production statistics in Figure 1.

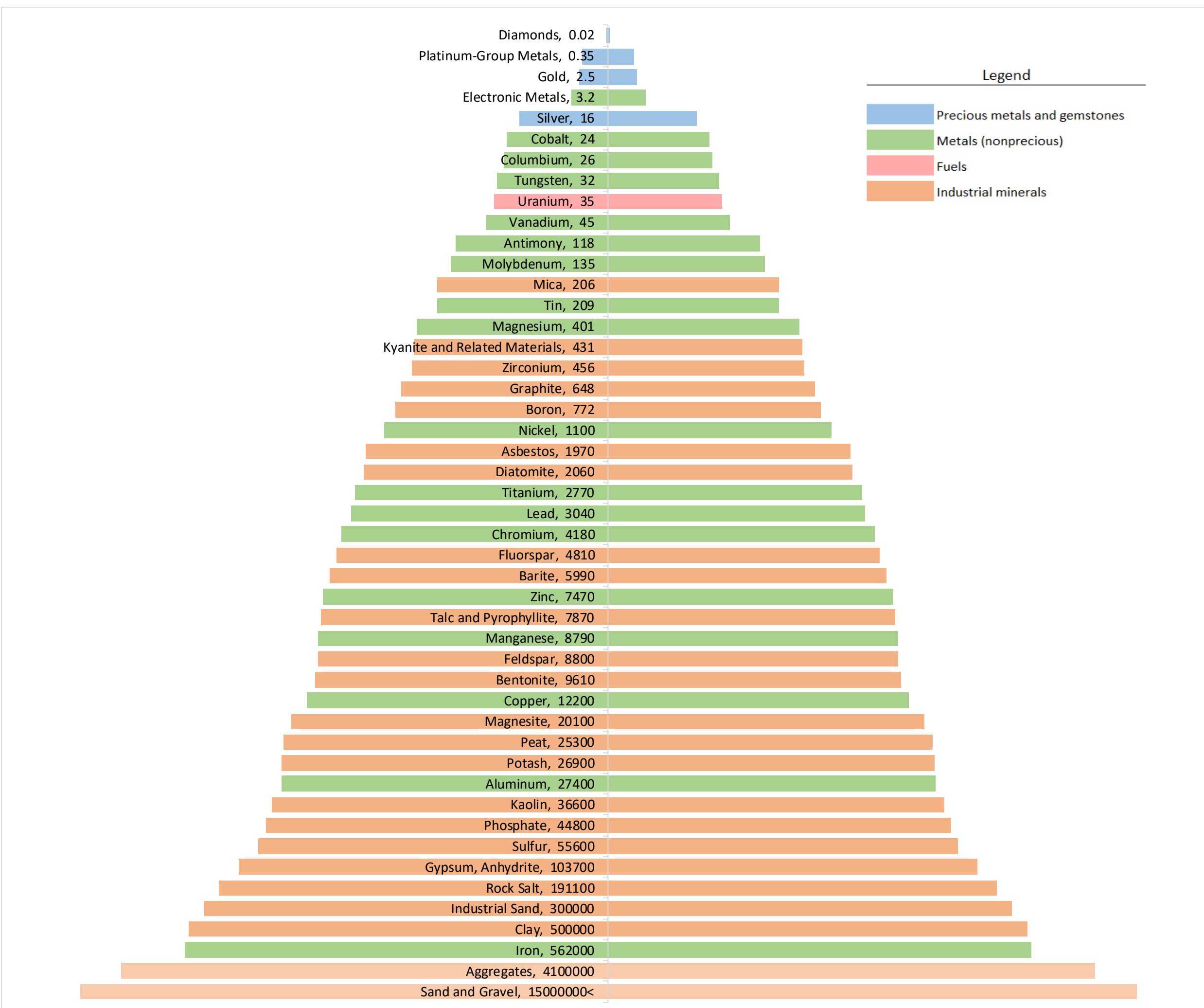

Figure 1: World Primary Production of Mineral Resources (kt) 1998.

Notes: Ores are given as metal equivalences, diamonds include all precious and semi precious gems, and electronic metals are gallium, indium, and germanium. Graphed in logs except for diamonds and electronic metals. Fossil fuels have been eliminated from original graph.
Source: Wellmer and Becker-Platen 2007

For the most part, these minerals are non-renewable. Some are quite abundant and do not seem a cause of concern such as those near the bottom of the pyramid: aggregates (stone, sand and gravel), iron (one of the five most abundant elements on earth), and clay. However, as countries develop, their needs for minerals increase in both quantity and diversity. Since 1900, U.S. consumption of non-fuel minerals has averaged a slightly higher growth rate than that of GDP (Center for Sustainable Systems (2018), World Bank (2019)). Growth in China is even more impressive. Income in most years has grown faster than for most countries in the last two decades with double digit rates in a significant portion of that period. While its mineral growth has typically exceeded GDP growth (Liu (2013), Humphreys (2015), Humphreys (2018)). Diversity of mineral use has increased as well. Few of us had heard of rare earth elements in 1990. Now we hear of them in many uses including computer chips, mobile phones, and future renewable energy uses.

Meanwhile mounting evidence of a seemingly unlimited supply of minerals has been accumulating through moon samples, earth and space telescope images, and even space missions that have orbited, landed, and even brought back samples from an asteroid. Astrorank (Webster (2019)) has catalogued available information on over 600,000 asteroids with estimates of economic potential for some of the more accessible of them. Space travel technology has also been improving. With the International Space Station launched in 1998 and earlier space station and shuttle programs, we have learned much added information that will be needed for space mining. We know more about the needs for humans to survive and thrive in a zero gravity environment, have created reusable rockets, are able to construct and repair equipment in space, and launch satellites from earth orbit. Robotic technological improvements in both the space programs and in terrestrial mining constantly improve our chances of successfully mining space.

Thus, falling costs, improving technology, and a quest for adventure have led to a number private companies joining the fray with stated goals of eventually mining space. Such companies include SpaceX, Planetary Resources, (now part of ConsenSys), and Deep Space Industries (now part of Bradford Space Group) (Dahl (2019b). The dollar value of resources on different near earth asteroids bandied about by proponents are millions, billions, trillions, and even higher. Even after taking away projected costs, the profits can still be quite impressive (Webster (2019)).

In considering if and when to begin tapping such sources, such companies need to be aware of a variety of economic as well as technical issues. First, large size may yield economies of scale in production but injecting huge resources into earthly markets could substantially reduce their prices, changing expected profits into actual losses. Second, if produced under long-term contracts, the 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. Third, there is debate as to how well defined the property rights are in space and problems of the commons may arise.

Our contribution in this paper is to focus on the first issue and provide a general theoretical model for a space mining venture with high fixed and low operating cost with the initial target of marketing minerals on earth. The model described in section II establishes the conditions for a range of possible scenarios for market entry and competition that will need to be kept in mind when developing space projects and contracts. In section III, we develop a simple numerical example using known cost and technology to explore the near term potential for bringing an asteroid back to earth for processing. Conclusions, implications, caveats and suggestions for future work round out our paper in section IV.

II. A Model of Market Entry Incentives

Consider a thickly-traded terrestrial spot mineral market in which, initially, no space mining firms exist. Mineral abundance on asteroids and other bodies is a large part of the value proposition for space mining. A fundamental assumption of our model is therefore that any potential space mining entrant would have access to a large enough mineral resource to be able to exert market power and influence the terrestrial market price. This is equivalent to assuming that, upon entry, the space miner faces a downward-sloping residual demand function for its product denoted by $R(P)$ where P is the price paid by buyers. This assumption applies equally well regardless of whether the existing spot market is perfectly competitive or better approximated by a Cournot oligopoly; for our purposes it only matters that the entrant would face a downward-sloping residual demand function for its product. Take a perfectly competitive terrestrial market as an example. We can derive $R(P)$ from the downward-sloping aggregate market demand function $D(P)$ consisting of price-taking buyers, and the upward-sloping aggregate supply function $S(P)$ composed of pre-existing price-taking firms (not including the space miner). If the space miner enters, it is large enough to determine the market price P through its supply decisions. At that price the terrestrial suppliers offer quantity $S(P)$ to the market, price-taking buyers purchase $D(P)$, and the space miner sells the residual demand, $R(P) = D(P) - S(P)$. The advantage the space miner has is that its scale of production is large enough to determine P while the competitive players take the price as given.[2] In what follows it will be convenient to work with the inverse of the residual demand function which we denote by $P_R(Q_{SM}) = R^{-1}(P)$. Without the space miner in the market, the competitive price is determined by the intersection of supply and demand of the incumbent firms and buyers, i.e., where $S(P_C) = D(P_C)$ and P_C denotes the competitive market price with no space mining firm.

Although there is tremendous potential mineral abundance in space, a major challenge for space mining is the tremendous cost of transporting equipment and minerals to and from space. We therefore assume that the space miner faces two kinds of fixed costs: a very large one-time entry cost denoted by F_e, and an (also potentially very large) annual operating or overhead cost whose present value we denote by F_o. These fixed costs are in addition to the variable costs that depend on the quantity of the mineral that is mined, processed and delivered from space. The one-time entry cost F_e includes all of the initial capital costs associated with constructing the mining facilities in space, constructing or modifying transportation infrastructure such as launch facilities and receiving terminals that will be used over the life of the venture to manage deliveries of equipment, workers, and mineral quantities, the costs of transporting the initial capital equipment to the space mining facilities, etc. The annual operating costs include the maintenance of the substantial capital equipment, the overhead of operating the business, etc. These fixed entry and operating costs are likely to be larger than those associated with opening and operating a terrestrial mine, at least for the first few space mining ventures, simply because of the physical challenges of operating in space. They will also be heavily influenced by the decision of which asteroid or celestial body to target for mining because these bodies differ in their distance from earth, and abundance of minerals.

The space miner also faces variable costs $C(Q_{SM})$ that depend on the quantity Q_{SM} that the space miner extracts, processes, and delivers to the terrestrial market. We assume $C(\cdot)$ is an increasing, convex, continuously differentiable function such that $C' > 0, C'' > 0$. This reflects the fact that once the fixed cost capital investments are made, it may be inexpensive to bring a tiny quantity of the mineral back to earth, but these costs increase at an increasing rate as more fuel is required and larger, more powerful equipment is required to extract, process, and transport larger payloads.

When making the entry decision, the space miner calculates the profit-maximizing quantity it would produce and the maximal profits it would earn at that quantity. In other words, they find the $Q_{SM}^{\star}$ that maximizes

$$\pi(Q_{SM}) = P_R(Q_{SM}) \cdot Q_{SM} - F_o - F_e - C(Q_{SM})$$

[2] In this case, the space miner is acting as a monopolist competing against a competitive fringe. Note that if we were to model the existing market as a Cournot oligopoly, the space miner would still face a downward-sloping residual demand upon entry. This is true regardless of whether the firm enters as an imperfectly competitive Cournot player or a first-mover in a Stackelberg game, as long as the space miner is a large enough player relative to existing market size to exert market power.

and evaluate whether $\pi(Q_{SM}^{\star}) > 0$. The first order condition for a profit-maximizing quantity are the following:

$$P_R'(Q_{SM}^{\star}) \cdot Q_{SM}^{\star} + P_R(Q_{SM}^{\star}) - C'(Q_{SM}^{\star}) = MR - MC = 0$$

where MR and MC denote marginal revenue and marginal cost, respectively. We can now evaluate whether $\pi(Q_{SM}^{\star}) > 0$, or equivalently

$$\frac{\pi(Q_{SM}^{\star})}{Q_{SM}^{\star}} = P_R(Q_{SM}^{\star}) - \frac{F_o + F_e + C(Q_{SM}^{\star})}{Q_{SM}^{\star}} > 0$$

For notational ease, we denote the term $P_R(Q_{SM}^{\star}) = P_{SM}^{\star}$ which is the price that the space miner sets when selling its optimal quantity $Q_{SM}^{\star}$. The second term is the Average Total Cost of producing $Q_{SM}^{\star}$, or *Ex Ante ATC*, that the space miner perceives before entering the market:

$$P_{SM}^{\star} - Ex\ Ante\ ATC > 0$$

If the expected price per unit that the space miner can receive for the mineral exceeds the average total cost of producing each unit, the space miner will enter the market. There is no need for a complicated long-term contract with a buyer beyond standard contracts that are primarily used to coordinate the timing and location of deliveries and formalize the chosen price.

Suppose the space miner enters the market but subsequently their residual demand shifts down, either because aggregate market demand declines or other suppliers have increased output. The key distinction between F_e and F_o is that after entering the market, F_e is sunk. If the space miner is already in the market and $P_{SM}^{\star}$ falls below the *Ex Ante ATC*, the space miner may continue to operate as long as

$$P_{SM}^{\star} > \frac{F_o + C(Q_{SM}^{\star})}{Q_{SM}^{\star}} = Ex\ Post\ ATC$$

First and foremost, the analysis in this section illustrates the folly of valuing space resources at current commodity spot prices because $P_{SM}^{\star}$ is most certainly less than P_C. Further, the analysis shows that even with an abundant resource and the market power to determine the price, there is a range of possible prices over which the space miner would not rationally enter the market ($P_{SM}^{\star} < Ex\ Ante\ ATC$). This range is determined by the pre-existing terrestrial supply and demand conditions that dictate the position of the space miner's residual demand function $R(P)$, and by the fixed and variable cost structure of the space mining enterprise. Within the range $P_{SM}^{\star} < Ex\ Ante\ ATC$, if the space miner had entered the market because of some mistaken beliefs, or if market conditions changed ex post, there is also a range of prices over which the space miner will stay in the market ($Ex\ Post\ ATC < P_{SM}^{\star} < Ex\ Ante\ ATC$), and a range over which they will exit and the venture will fail ($P_{SM}^{\star} < Ex\ Post\ ATC$). These cutoff points are relevant for defining the boundaries for the space miners and can help inform them if they choose to enter into long-term contracts with buyers.

Simple Simulation

In this section, we present some simple numerical simulations using what we know about space technology, asteroid composition, rocket costs, processing costs, and metal markets to determine near term prospects for asteroid mining. Word constraints prevent much detailed discussion of all the model assumptions and simulations but more discussion and simulation results can be found in Dahl (2019a) and Dahl (2019b), while the excel model file is available at Dahl (2019c).

The three most prominent asteroid mining suggestions for metal transfer to earth from space are (1) to mine and process the ore on the asteroid, returning only the final metal product to earth, (2) to bring the asteroid to lunar orbit for processing, returning only the more valuable metals to earth, and leave other metals for lunar use or for outfitting other space exploration, or (3) to capture the whole asteroid or a piece of a larger asteroid and return it back to earth for processing. Since we do not know the technology or cost of processing the asteroids into their component metals in space or in lunar orbit, we choose (3) to return the whole asteroid to earth with its well developed processing system.[3]

Next we choose what to mine. Near earth metallic asteroids are the most likely candidates to be considered for mining to supplement metals on earth. As on earth, the minerals are not pure but often there are a number of metals produced from any given deposit. From meteorites, telescopic images, space craft flybys and even a few samples, information on asteroid content has been slowly accumulating. Using information from Kargel (1994) and Buddhue (1946), we develop a representative metallic asteroid with 89.3 % by weight or 893,000 parts per million (ppm) iron (FE), 93,000 ppm nickel (NI), and 6,000 ppm cobalt (CO) with small quantities of precious metals in the platinum metal group (ruthenium (RU), rhodium (RH), palladium (PD), osmium (OS), iridium (IR), platinum (PT)) and gold (AU) all shown in column 3 of Table 1.

To evaluate the revenue from an injection of these space metals, we need information on market structure as well as demand and supply. We use information in Tilton and Guzmán (2016), Ndlovu (2015), Radetzki and Wårell (2016) and others as explained in Dahl (2019a) for background material and to infer market structure in the form of upper bounds on the Herfindahl Hirschman Indices (HHIs) as shown in column 4, Table 1. The estimates for FE, CO, NI and AU all have HHIs below 1000 suggesting their markets are quite competitive. The platinum group metals have HHIs equivalent to between 3 to 5 equal sized firms and our space miner would add a bit to the competitiveness of the market. Although the platinum metal group suppliers are likely less competitive, we treat them as competitive for our simple simulation recognizing that if they exercised market power, they could likely do a bit better.

We develop demand and supply equations for the current market on Earth from price elasticities of supply (Es) and demand Ed, and price and quantity on Earth in 2018 as shown in columns 5, 6, 8,9 in Table 1.

Table 1: Simulation Inputs and Simulations in 2049 No Space Mining

							$/tonne	tonnes	$/tonne	tonnes
	A#	Weight (g/t)	HHI*	Ed	Es	Ey	P 2018	Q 2018	P 2049	Q 2049
FE	26	893,000.0	995	-0.48	0.24	*1.16*	338	$1,200\times10^6$	1,549	$2,232\times10^6$
CO	27	6,000.0	550	-0.47	0.40	1.21	82519	0.125×10^6	348,041	285,885
NI	28	93,000.0	550	-0.66	0.54	0.95	10559	2.199×10^6	26,435	$4,017\times10^6$
RU	44	21.5	*2271*	*-0.76*	*0.24*	*0.83*	6.1089×10^6	41.99	16.069×10^6	52.94
RH	45	4.0	2708	*-0.76*	*0.16*	*0.83*	54.656×10^6	31.91	143.774×10^6	40.24
PD	46	16.5	1877	-0.70	*0.16*	*0.83*	33.083×10^6	317.82	90.789×10^6	406.51
OS	76	14.5	*2271*	*-0.76*	*0.16*	*0.83*	12.860×10^6	1.50	33.829×10^6	1.89
IR	77	14.0	*2271*	*-0.76*	*0.16*	*0.83*	31.186×10^6	7.18	82.035×10^6	9.06
PT	78	29.0	2765	-0.82	*0.16*	0.83	29.048×10^6	241.58	73.512×10^6	300.75
AU	79	0.6	200	*-1.01*	1.02	1.04	40.245×10^6	4,345.10	81.563×10^6	8,895.42

Source: A more complete description of the development of these inputs are given in Dahl (2019a, 2019b)

[3] Another possibility is to process and use the mineral for lunar or other space applications (avoiding the need to bring the mineral to Earth). Given the relatively larger uncertainties surrounding prices, elasticities, and competitiveness of the mineral supply in space, we do not undertake a simulation for that market.

Notes: A# indicates atomic weight, g/t = grams per metric tonne, HHI = the Herfindahl Hirschman Index, Ed = the price elasticity of the metal demand, Es= the price elasticity of the metal supply, P2018 is the metal's price in dollars per tonne in 2018, Q2018 is the tonnes of the metal consumed 2018, Ey = the income or activity elasticity of demand, P 2049 and Q 2049 are simulated price in quantity in 2019 using the model in http://dahl.mines.edu/SpaceMining.xlsx worksheet ModelDemand and references can be found in worksheet A1_T1. Italicized values are guesstimates as described in Dahl (2019b).

We couple the income growth assumption of 3.6% annually with estimates of income or activity elasticity estimates in Dahl (2019a) as shown in column 7, Table 1. We use these inputs to simulate the price and quantities on Earth without space mining for 2030 and 2049 with the 2049 estimates shown in Table 1 columns 10 and 11.

Our initial estimates of cost are developed from the case study of Brophy, Culick, and Friedman (2012) for returning a 1300 tonne near earth asteroid to lunar orbit. We adapt for the more expensive return to Earth with a smaller asteroid size (1,000 t) We assume contracting and construction of the first ship is paid for at the beginning of 2020 and is launched at the beginning of 2021, with first delivery made and paid for at the beginning of 2030. There are 19 subsequent annual launches with the last asteroid delivery made in 2049. We increase demand with a parallel shift for each metal as income increases but assume that technology and exploration offset any depletion effects leaving the supply equations constant. Given historical developments, this seems pessimistic from historical earthly standards, but optimistic when viewed from opportunities for space mining. A more complete description of the mining costs and assumptions are given in Dahl (2019b)

Under the assumptions in Table 1, we simulate what would happen to price and quantities by mineral in 2030 and 2049 without space mining as shown in Table 2. Total estimated revenue in these ten markets in 2018 is over $600 billion dollars in 2018 about doubling by 2030 and increasing more than 7 fold to about $4.5 trillion by 2049. Iron and cobalt with lower demand elasticities, higher income elasticities and higher supply elasticities see larger revenue gains than the platinum group metals. If we 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%. The ranges are again roughly symmetric but larger for 2049

Table 2: Total Revenue (TR) by Metal for Earth Mines in 2018, 2030, and 2049 (No Space Mining, billions of 2018 $)

No Space Mining						
	TR FE	**TR CO**	**TR NI**	**TR RU**	**TR RH**	
2018 Earth	405.600	10.315	23.219	0.257	1.744	
2030 Earth	928.047	24.039	40.027	0.403	2.740	
2049 Earth	3457.964	99.500	106.200	0.851	5.785	
	TR PD	**TR OS**	**TR IR**	**TR PT**	**TR AU**	**TR**
2018 Earth	10.514	0.019	0.224	7.017	174.867	633.777
2030 Earth	16.965	0.030	0.352	10.766	282.884	1306.254
2049 Earth	36.907	0.064	0.743	22.109	725.543	4455.665

Source: Author's computations using d:\dahl.mines.edu\SpaceMining.xlsx, worksheet ModelDemand.

Notes: For prices and quantities by market for these simulations see d:\dahl.mines.edu\SpaceMining.xlsx, worksheet A2_TR&P&QNoSpace.

Next to get a feel for the market, we consider different space mining deliveries in 2030 with resulting TR by market as shown in Table 3. Our starting project will be returning a 1,000 tonne metal asteroid a year starting in 2030. Although tiny by earth mining standards, we currently have the technical capabilities to make such delivers per space ship. For the most part, it has a very small effect on Earth's metal markets and prices. Earthly mining TR and Q both fall by less than 0.0005%, while space mining revenue is estimated at about 6.3 million dollars compared to over a trillion for mining on Earth. Earth mining revenue fall by less than 0.1% in each separate market except for the two smallest markets – OS (down 0.87%) and IR (down 0.18%). Earth revenues fall by more than the revenues gained by space mining.

Table 3: Total Revenue (TR) by Metal for Earth Mines and Space Mining in 2030. (With space mining, billions of 2018 $)

Space Mining =1,000 t per 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	1306.2475
2030 Space	0.0008	0.0003	0.0006	0.0012	0.0000	0.0063
Space Mining =4,500 t per year (billions of 2018 $)						
	TR FE	**TR CO**	**TR NI**	**TR RU**	**TR RH**	
2030 Earth	928.0443	24.0336	40.0202	0.4021	2.7389	
2030 Space	0.0026	0.0040	0.0062	0.0009	0.0014	
	TR PD	**TR OS**	**TR IR**	**TR PT**	**TR AU**	**TR**
2030 Earth	16.9611	0.0291	0.3492	10.7609	282.8840	1306.2235
2030 Space	0.0037	0.0012	0.0029	0.0054	0.0001	0.0283
Space Mining =10,000 t per 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	1306.1860
2030 Space	0.0082	0.0025	0.0063	0.0121	0.0003	0.0628
Space Mining =100,000 t per 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	1305.5762
2030 Space	0.0813	0.0077	0.0546	0.1198	0.0031	0.5992
Space Mining =1,000,000 t per 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	1300.3707
2030 Space	0.7832	0.0000	0.0000	1.1052	0.0306	5.0983

Source: Author's computations using the model at d:\dahl.mines.edu\SpaceMining.xlsx, worksheet ModelDemand.

Notes: For prices and quantities by market for these simulations as well as simulations for 2049 and 2069 see d:\dahl.mines.edu\SpaceMining.xlsx, worksheet A3_TR&P&Q.

We next consider two other cases of returning one asteroid per year to earth that should be feasible with current space technology. Asteroids weighing 4,500 tonnes and 10,000 tonnes. Again these amounts are so small that prices are only slightly affected. Average revenues for space miners fall slightly as we increase asteroid shipments. Space revenues increase almost in proportion to the increase in asteroid mass. Again earth looses slightly more revenues than the space miners gain and the discrepancy increases as space mining gets scaled up. Now the three smallest earthly markets OS, IR and RU see revenue drops of more than 0.1%. By 10,000 tonnes, space has become more than 8% of the OS market by tonnage.

Since we have not found evidence that current technology can return more than 10,000 tonnes of asteroid per ship, for higher shipments we would increase the number of ships sent per year. We also show two further results for 100,000 and 1,000,000 tonnes of asteroid material returned per year. We see similar patterns with space becoming more significant in smaller markets. With our Leontief production function from space, Osmium from space is about half of the market at 100,000 tonnes and Osmium prices are driven negative by a million tonnes. For a rough cut, we drop it out of the market. Simulations for 2049 and 2069 are also shown in Dahl (2019a). The patterns are similar but since the earthly market is larger, the effect of the space mining additions are smaller.

For a broad view of the market, Dahl (2019a) continues the same simulation for deliveries to 38,400,000 per year as shown in Figure 2. When entry of the metal pushes the price negative, it is dropped out of the market and marginal revenues zig up a bit. These cut offs illustrate markets where space miners could exercise market power as space operations are scaled up beyond our simulations here. Dahl (2019a) also contains simulations showing what space metal tonnage would maximize space revenues in some sample years from 2030 to 2069.

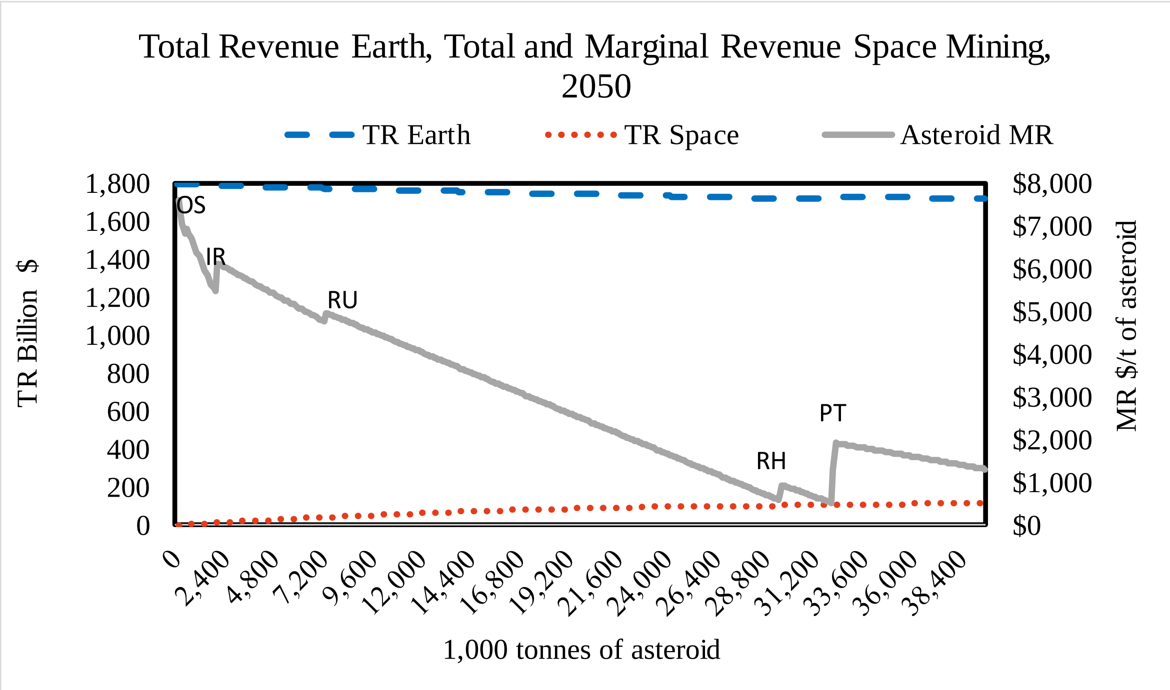

Figure 2 Total Revenue Earth, Total and Marginal Revenue Space Mining, 2049

Notes: The spikes in MR is when the labeled metal drops out of the market. See also d:\dahl.mines.edu\SpaceMining.xlsx, worksheet A4MR2030&2050 for the raw data and simulations for 2049.

For economic feasibility, we turn to the intriguing challenge of developing the cost inputs for our space mining operations. We start with start with Brophy et al. (2012) and a 20 year project. Each ship is assumed to be reusable one time with refurbishment (For more detail on the project and development of cost information, see Dahl (2019b)). Under our assumptions and a very modest 10% interest rate, the levelized cost per tonne of delivered asteroid material is more than $3.0 million dollars and we have not yet included the processing cost of the asteroid into separate metals. Increasing the discount rate to 0.17 about doubles this cost. Meanwhile, if all metals in our 1,000 tonne asteroid are processed, the average space revenues from 2030 – 2049 vary from about $6,300 to $12,200/tonne. The present value for the revenues over this time period is only about $26.4 million, while the present value of the costs is more than $11.5 billion. The NPV of this operation (-$11.5 billion is decidedly unpleasant), see Table 4. Higher discount rates lower our losses while adding in milling and smelting cost will increase our losses.

Table 4 Revenues, Costs, and NPRV of Space Mining

Case	Asteroid	PV Revenues	PV Cost	NPV Space Mining	
1.	1,000	$26,378,759	$11,524,377,974	-$11,497,999,216	base case demand
2.	4,500	$138,412,014	$10,564,304,669	-$10,425,892,656	base case demand
3.	10,000	$306,987,841	$14,405,044,474	-$14,098,056,633	base case demand
4.	10,000	$2,022,053,954	$14,405,044,474	-$12,382,990,520	optimistic demand
5.	10,000	$6,713,535,246	$14,405,044,474	-$7,691,509,228	increased metal concentration, 8×OS, 35×IR, 100×Other precious metals
6.	10,000	$55,921,462,321	$14,405,044,474	$41,516,417,847	optimistic demand & increased metal concentration
7.	10,000	$306,987,841	$305,310,680.43	$1,677,160	cost reduction times 0.17
8.	10,000	$55,264,747	$51,706,742.77	$3,558,005	@ discount rate 0.2 cost times 0.085
9.	10,000	$680,548,762,827		$680,548,762,827	all metal gold
10.	10,000	$72,151,844,400,312	$14,405,044,474	$72,137,439,355,838	half of metal is gold

Source: Authors computations. For more explanation of inputs, addition and more complete simulation results, see Dahl (2019a, 2019b). For the simulation model see http://dahl.mines.edu.SpaceMining.xlsx.

Notes: Case 1: Cost computations do not include milling and smelting costs on Earth, project is 20 years. Cases 2-10: Project is 40 years, cost includes milling at $565 per tonne and revenues have been reduced by 10% to pay for smelting. Cases 1-3: Base case demand assumptions from Table 1. Case 4&6: Optimistic demand case, 0.5 times demand elasticity, 0 supply elasticity, 2 times metal demand incomc elasticity, 1.1 times income growth. Discount rate is 10% for all but case 8. Case 5&6: Increase the concentration for OS by 3, IR by 35 and the rest of the precious metals by 100. The discount rate is 10% for all but case 8. Case 7: Reduction in cost that would push case 3 demand into a profitable zone. Case 8: Reduction in cost that would push case 3 demand with a discount rate of 20% into a profitable zone. Case 9: All of the metal content in the asteroid is gold. Case 10: Gold is increased to half of the metal content at the expense of iron.

Although all precious metals (RU, RH, PD, OS, IR, PT, AU) have prices considerably higher than $3 million per tonne (See Table 1 for the price simulations with no mining), they occur in such trace amounts they can't make the asteroid pay off. Clearly space mining on this scale is out of the question in the next three decades unless we can bring costs down or revenues up. Eight other cases that give higher revenues – increasing content of the more valuable metals, higher income growth, making demand less price and more income elastic and earth supply less elastic even the most optimistic case 9 (increasing metal content by ten fold, income growth by 10%, tripling nickel content, making earthly supply perfectly inelastic, doubling income elasticity of demand, and cutting price elasticity of demand in half) only bring average revenues for earthly mining to about $450,000 per tonne by 2049. Mining for earth delivery is still out of the question.

Next consider a 4,500 tonne asteroid with some cost reduction and technical improvement expected with private mining operations rather than government space missions. Rockets that can be re-used three times extend the mining operations to 2069. Lower overhead, launch cost, and some economies of scale with the larger rocket lower levelized cost to about 630,000 $/t plus earthly milling levelized and operating costs of $565/t (Milling costs are developed from personal conversation with Professor Emeritus Graham Davis, Mineral and Energy Economics Program, Colorado School of Mines and are explained in Dahl (2019b)). However, the NPV for the whole project is almost -$10.5 billion as shown in Table 4, Case 2. Space mining is still out of the question.

In Case 3, we scale the project up to 10,000 tonnes as described in Dahl (2019b). A Saturn V (the most powerful rocket ever built, but retired in the 1970s) would be capable of launching the mass of the ship and fuel required to return this sized asteroid. Levelized cost falls to around $383,000 per tonne. However, in the base case, the NPV of the project is even more depressing at around -$14 billion. We do a little more experimenting with the 10,000 asteroid case. The most optimistic of our demand assumptions shown in Case 4, Table 4 are an improvement over case three but are not enough to turn this project around.

Given how valuable precious metals are, in Case 5, we return to the base case demand but multiply precious metal concentrations by 100 for all except OS and IR. These later two have such small markets their revenues fall with such a large concentration increase and we leave them at concentrations that maximize their revenue in 2030. Losses fall by more than 40% but space mining is still out of the question. However, in Case 6, when we combine the optimistic demand with the higher concentrations, the NPV of our project pleasantly becomes quite profitable at about $41.5 billion. This example suggests that it is theoretically possible to profitably return asteroids to this world at sizes we believe are feasible. However, given what we know about the composition and plentifullness of NEA, the likelihood of even one 10,000 tonne NEA fitting such criteria let alone 40 still suggests to us near term space mining is out of the question (Elvis, McDowell, Hoffman, and Binzel (2010)). Unfortunately doubling the discount rate also drops us back in the red.

Next we experiment a bit with costs. We have seen some pretty striking cost reductions for new technology over the previous decades. For example, solar photo-voltaic costs have fallen by 99% since 1980 (Kavlak, McNerney, and Trancik (2018), Fig. 1). In Case 7, we go back to see what sort of cost reduction would make our base Case 3 profitable. We find that if we can reduce our space mining costs for the 10,000 tonne asteroid across the board to 17% of the base case, we can tip into profitability. If we up the discount rate to 20% we have to drop the costs further down to 8.5% to make our mining profitable. Although these cost reductions don't seem out of the question for the long term (we should probably check this out with some rocket scientists), they don't seem so likely in the near term. The last two simulations are even more fanciful. If all the metal content is gold (Case 9) or the gold content is increased to half of the metal content at the expense of iron, we see NPVs in the billions and trillions.

Since we had to make extremely optimistic assumptions about growth, elasticities, interest rate, and asteroid content to make our venture profitable with existing technology, asteroid mining for near term earth delivery seems out of the question.

Conclusions

Earthly metal markets are large and growing in both quantity and diversity, while these non-renewable resources are gradually depleting. So far with improved technology and new discoveries, earthly producers have generally been able to keep the market adequately supplied. With the optimism of Economists, we assume this is likely to be the case for some time.

However, periodic scarcity and price spikes have caused some to look up and consider the prospects for mining asteroids. Many asteroids contain large quantities of metals and if accessible make it unlikely we will run out of metals for some time. However, to mine these vast resources requires technical and economic feasibility. Our contribution is to develop a general theoretical model of the economic feasibility of space mining. In our model, the mining operation has large upfront capital cost and may or may not have market power in earthly markets. The space mining company would only enter the market, if its expected price would be greater than its expected average total cost, while it would only stay in the market if the price exceeded its variable cost.

The expected model result is easy to derive, but not so easy to implement. Our second contribution is to present some simple market and cost simulations to determine near term mining feasibility using what we know about space technology, asteroids, and earthly metal markets. Given our space accomplishments to date, we believe it is possible to bring asteroids back to earth of up to 10,000 tonnes with current technology. Studies of meteors and asteroids give us some idea of the composition of asteroids and their location. The technology to process metal ore on earth is well known and we have some sample cost information at our disposal. Last from price, quantity, price and income elasticities of demand and price elasticity of supply, we are able to simulate the markets for the metals in our sample asteroid.

For our somewhat optimistic base case scenario to bring back 10,000 tonnes of asteroid or less per year for 40 years and a discount rate of 10%, space mining for bringing back to earth starting by 2030 is out of the question. However, with some heroic assumptions, we could make our 10,000 tonne asteroid case profitable. A 4% annual growth in GDP, reducing the supply elasticity to zero, halving the demand elasticity, and doubling the income elasticity coupled with dramatically higher concentrations of precious metals could make our space mining profitable. Alternatively, dramatic reductions in costs of more than 80% might also turn the tide.

All simulations are predicated on enough metallic asteroids near enough at the right time to feasibly supply our mining operations. Meterorite data suggests that only 5% of NEAs are metallic. Many more are stony with much smaller concentrations of metals. Also NEAs are orbiting and at times may be much further from Earth than our computations allow. Fancy footwork and more fuel than our ships are carrying may be needed to get a spinning asteroid to stop spinning and head off to Earth.

Although unprofitable now, these results suggest that space mining may not be unprofitable forever. As time passes demand will increase, technology will likely improve, earthly supplies will likely get more expensive, space operations will likely get cheaper, and our knowledge of asteroids will increase. Although even more speculative, further research could check the economic feasibility of our mining projects if delayed decades into the future.

As technology evolves, precious metals might be separated out in space for return to Earth, where they are expensive, while leaving FE, NI, and CO in space. These basic building blocks could be abandoned in space or used to support any developing space activities (e.g. spaceships, space dwellings, space industries). These basic metals, all cheap on Earth, are expensive in space. (e.g. currently quoted costs of moving a kilogram from the Earth to the Moon run as high as $1.2 million dollars (Astrobotics (2019)). As separation of metals requires gravity or chemicals and fuel (all in current short supply in space), we are not sure how this will sort out. With the European Space Agency, China, and NASA considering or planning lunar bases in the 2020s (Wall (2019)) our knowledge of technologies to mine and manufacture in space and develop fuels from water and what it will cost should improve. If only precious metals are returned to Earth, future simulations should consider the market power such operations would likely have.

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