Asteroid Mining and Prospecting

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1 Abstract

There has been a recent increase in interest in the idea of mining asteroids, as seen from the founding of multiple companies who seek to make this science fiction idea science fact. We analyzed a number of prior papers on asteroids to make an estimate as to whether mining asteroids is within the realm of possibility. Existing information on asteroid number, composition, and orbit from past research was synthesized with a new analysis using binomial statistics of the number of probes that would be required to find a valuable asteroid. This information, combined with data on the prices of potentially valuable materials found in asteroids and the past cost of NASA missions, allows us to make a guess as to the financial feasibility of locating asteroids to be mined. Ultimately it appears that finding valuable, ore-bearing asteroids will require a fleet of dozens of small, low cost prospecting probes that are on the border of economic feasibility with current spaceflight potential.

2 Why Mine Asteroids?

For many years, space-based industry has been a staple of science fiction, from stories of people dragging asteroids to Earth to build spacecraft in orbital stations and drydocks to galactic empires sustained by vast interstellar trade networks. While these ideas have long been considered the realm of fantasy and imagination, the last year has seen the founding of two different companies who aim to begin mining asteroids and building the beginning of a space-based industrial infrastructure. With the launching of Deep Space Industries [7] and Planetary Resources [14], the idea of asteroid mining has been returned to the public eye, this time as a question: are these companies serious? [6] What would it take to make asteroid mining possible and profitable?

3 Water and Cheap Metals?

The first question that must be answered when asking about the profitability of asteroid mining is that of the material that would be mined. There are two sets of valuable products to be extracted from asteroids: those that would be used in space and those that are valuable on Earth. The first group includes materials like iron and other metals used in construction as well as water, which is required for a host of industrial applications, can be split into hydrogen and oxygen to create fuel in situ, and is necessary for a variety of purposes for human habitation in space. This group is composed of materials that have little cost on Earth compared to their value in space because of the difficulty of getting any mass into orbit. At current levels of technology, the cost to bring one kilogram of mass to low Earth orbit (LEO) is about $10,000(Atlas V rocket, Falcon 9 rocket) [5]. Thus, for materials like iron and water, which have little significant cost on Earth ($0.5/kg for iron and negligible cost for water) the cost of getting the material to orbit dominates the terrestrial cost. This puts a price floor on any material to be used in space- the cost to orbit. Therefore, any ability to extract one of these useful materials at a cost of less than the cost to orbit would be profitable. However, the problem lies in demand. There is no significant demand for these goods at the present time. No great volume of water, nor of low-cost metals is needed, as there is no permanent habitation in space and no construction of large structures that would require building materials. Therefore, there is no profit, as of the present, to be found in mining asteroids for water or cheap metals.

The future, however, may offer some demand for these materials, and therefore it is prudent to perform a preliminary analysis of the potential for mining these materials (it also offers a useful comparison to the second group which will be discussed). The most important attribute of water and iron is that they are common, making up significant components of the asteroids where they are found. Water is found in C-type asteroids, carbonaceous asteroids that are the most common in the solar system, making up 75% of all asteroids. [2] It can also make up a significant fraction of these asteroids, up to 10-20%. Here, due to the significant bulk fraction of the asteroid made of the desired material, extraction would likely be an easy task compared to that of extracting more rare materials that make up only a small fraction of the asteroids in which they reside. Iron is found in Ni-Fe asteroids (classified as M-type), and makes up the bulk of such asteroids. These asteroids are far less common, while they are the third most populous group, the Ni-Fe group make up only 2.5-5% of all asteroids. In contrast to the high-value materials that make up the other potential income source, both of these material groups are much more easily identifiable by telescopic observation and make up a much greater proportion of the asteroids that they reside in.

4 Platinum Group Metals

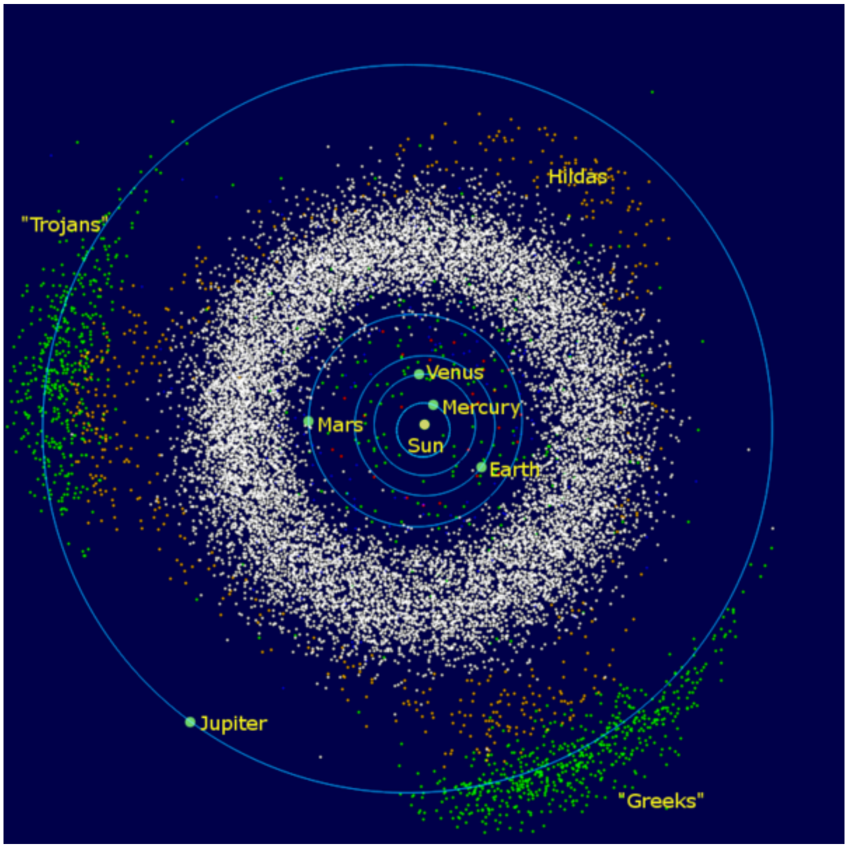
If not materials to be used in space, then what is potentially profitable? Clearly, something that is so valuable that it could be extracted from an asteroid and then returned to Earth for less than the cost of buying it. There are such valuable materials found in asteroids, the platinum group metals (PGMs). These 6 metals–ruthenium, rhodium, palladium, osmium, iridium, and platinum–are all rare on Earth and extremely valuable. They are also found in potentially much higher concentrations on asteroids, specifically the same M-type asteroids as the cheap metals. To get a sense of whether these rare metals could be extracted profitably, it makes sense to look at their current prices. [8]

Element	Value in \$/kg
Platinum	50,000
Rhodium	40,000
Osmium	13,000
Iridium	30,000
Palladium	25,000
Rhenium	10,000

For all of the PGMs, their value is greater even than the value derived from cost to LEO of cheap materials. The high value of these metals means that they are the top candidate for a valuable ore to extract from asteroids for profit. Furthermore, the concentration of these metals in the most rich asteroids far exceeds that on Earth.

5 Where are the asteroids?

Now that we know the identity of the ore (use of the word ore will denote any valuable material that we wish to extract from an asteroid, hereafter referring to PGMs) that would make the best potential target for asteroid mining, we can analyze which asteroids should be targets and how to find them. First, we must identify the asteroid population from which we should select targets. The greatest number of asteroids reside in the "Main Belt", between the orbits of Mars and Jupiter, and coincident with the orbit of Jupiter at the L4 and L5 Lagrange points, the Jupiter Trojans.



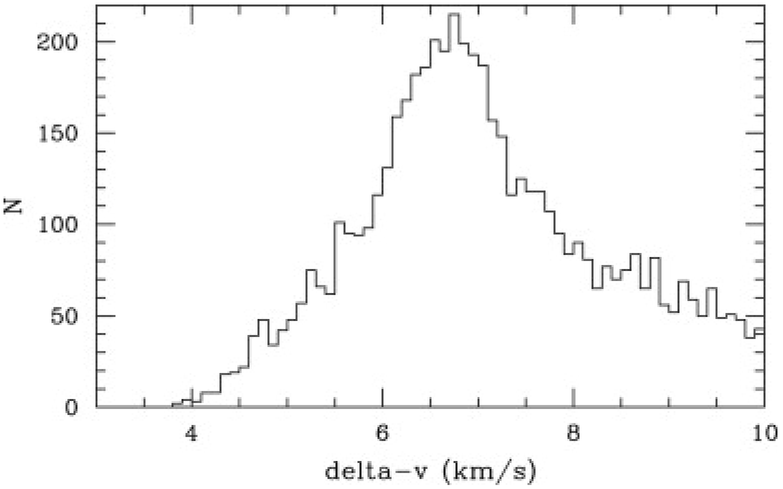
[13]

While the asteroid belt and the Trojans make up the vast majority of the asteroids in the solar system, their distance from Earth makes them poor candidates for mining. Far easier to reach are the near-Earth objects (NEOs). The ease of reaching a body in the solar system is based on a quantity called Δv, a measure of the velocity change needed to move from one's initial orbit to the desired final orbit. Before we analyze which NEOs may be targets we must explain the concept of Δv. The method of calculating delta-v and determining the composition of a rocket is the Tsiolkovsky rocket equation.

$$\Delta v = v_e ln \frac{m_0}{m_1}$$

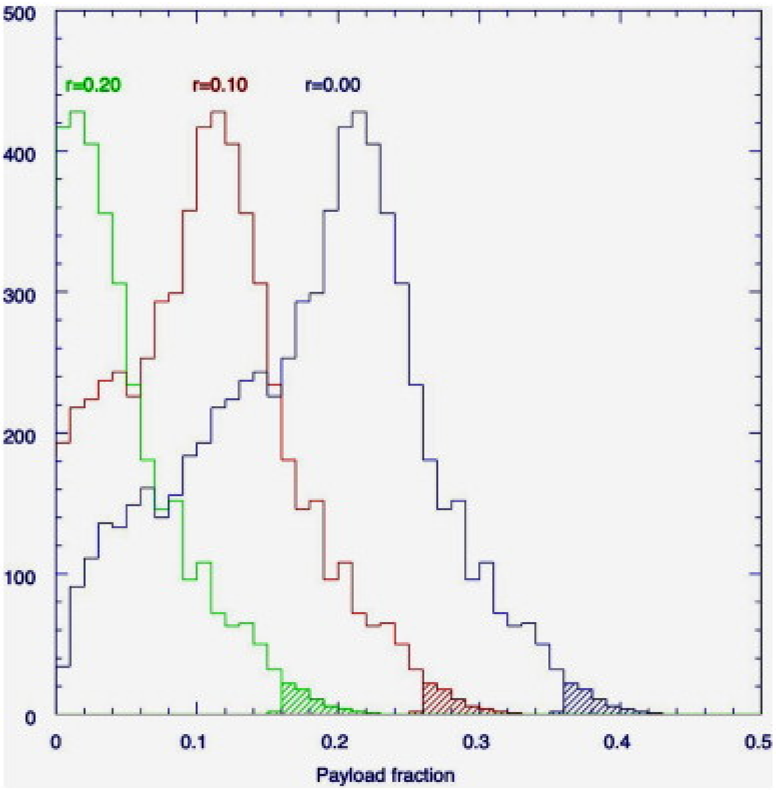
Δv is the maximum change in velocity that will be allowed by the rocket, v_e is the exhaust velocity of the propellant material, and m_0 and m_1 are the initial and final masses of the rocket(before and after fuel consumption). The importance of this equation is that the mass fraction that must be propellant is exponential in the demand for delta-v, therefore ensuring that delta-v remains low is a priority for any mission.

NEOs have Δvs that can be as low as 3.8km/s, though the majority are 6-7km/s as can be seen in a graph from an article on low-Δv NEOs. [4]



Here we can see that, though the typical NEO has a Δv of around 6.5km/s, there is a population below 4.5km/s (ultra-low delta-v objects). For reference, the Moon and Mars require Δv of 6.0 and 6.3 km/s respectively. With the cheap energy budget of a trip to these objects, they mark the easiest targets for potential exploration and exploitation.

With a correction for r, the inert non-payload mass(eg. rocket structure vs. fuel), a measure of the mass ratio from the rocket equation, one can graph the number of available NEO targets against the potential payload fraction.



[4]

The shaded region is the < 4.5km/s ultra-low delta-v set of objects. Here we see the importance of selecting the low delta-v objects. If r is, in fact, about 0.2, then the most common NEOs would allow less than 1 part in 20 payload to reach them. By contrast, the ultra-low objects guarantee at least 15% and possible as much as 30-40% payload fraction.

6 How many profitable asteroids are there?

Now that we know the population of objects that we are selecting from, it is time to determine how many objects are out there that have the potential to be profitable targets. This is determined by a simple multiplication of probabilities (with assumption of independence): [3]

$$N_{ore} = P_{type} * P_{rich} * P_{\Delta v} * N(> D_{min})$$

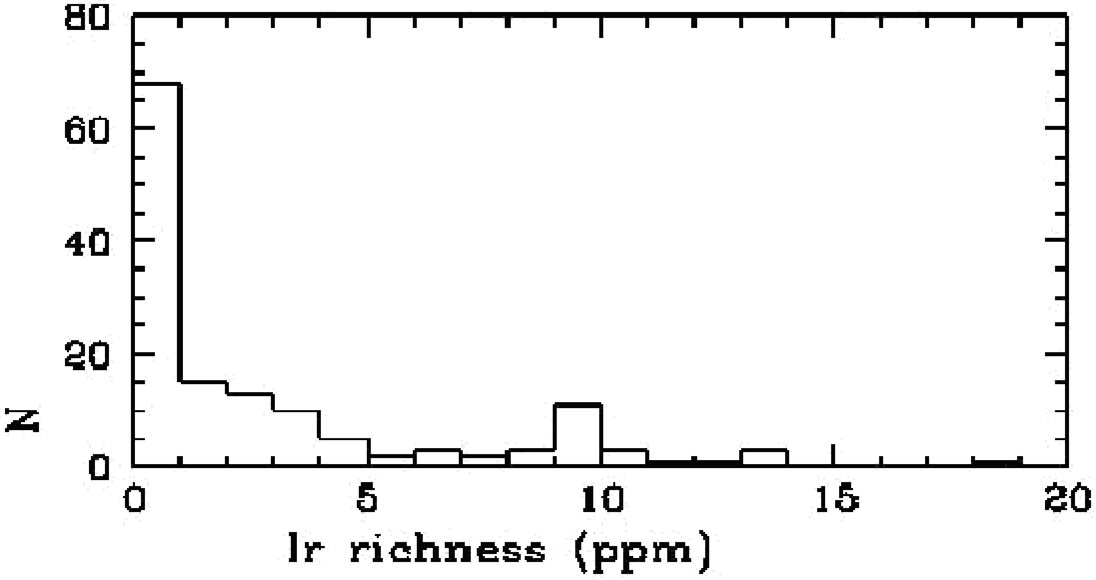
Here, N_{ore} is the number of profitable ore-bearing asteroids, P_{type} is the fraction of asteroids of the desired type (the M-type Fe-Ni for our PGMs, C-type for water), P_{rich} is the fraction of asteroids that have sufficient richness of the ore to be worth mining, $P_{\Delta v}$ is the fraction of asteroids that are at sufficiently low delta-v to be worth pursuing, and $N(> D_{min})$ is the number of NEOs that are of sufficient size (minimum diameter) to warrant pursuit. Each of these factors must be considered to find current feasibility of asteroid mining.

The first factor, P_{type} is a number that is simply taken from observational astronomy as well as analysis of meteorite fragments that have ended up on Earth. This is estimated by Kargel as 2.5-5% of all NEOs. [9] Therefore, we take this number as the estimate for P_{type}.

The next estimate is for $P_{\Delta v}$. Here, we will use a cutoff of 5.5km/s, not quite as harsh as the ultra-low delta-v of 4.5km/s, but one that still guarantees a mission easier than the Moon or Mars which require over 6km/s. Using this level we can consult a database of known NEOs to determine what fraction of them have a delta-v value this low. This is almost exactly 10%, relying on a table compiled by Lance Benner of JPL. [1] This table lists all known NEOs with estimates of a number of their characteristics including delta-v by absolute amount and percentile.

The next factor in the equation in P_{rich}. This is again a factor with some degree of arbitrary decision though it should obviously be significantly greater than the Earth's fraction of these metals. Iridium is used as a marker for the other PGMs, being generally indicative of all of their fractions, and the richness of NEOs is estimated from existing Ni-Fe meteorite fragments. This is found to be a broad distribution, spanning 4 orders of magnitude, from 0.01 to 100 parts per million. [9] The distribution is more fully seen in a table and graph from Elvis' paper on ore-bearing asteroids using data from Scott, Wasson and Buchwald. [15] [3]

Percentage	Mean Ir richness (ppm)
90	10.7
80	5.57
70	3.88
60	2.08
50	0.968
40	0.503
30	0.2571
20	0.0677
10	0.0236



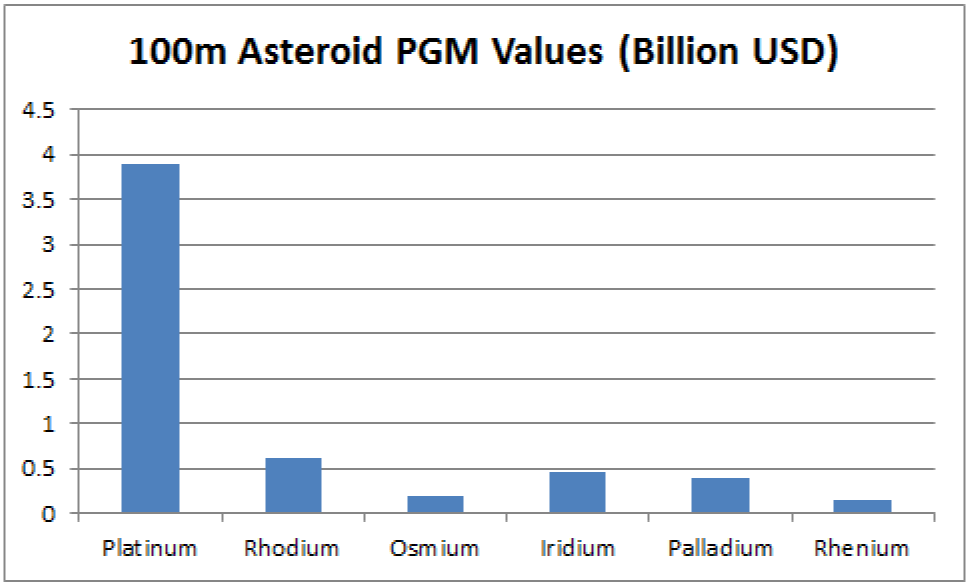
For comparison, the Earth's crustal iridium richness is estimated at 0.001ppm. Even the most resource-poor of the iridium-bearing asteroids is richer than the Earth's crust, while the best candidates would have as much as 10^5 times as much of the PGMs (6 of the 8 most rare elements on Earth). Here we will take P_{rich} to be 10-20%, giving some flexibility in what richness is necessary for profitable extraction but assuming orders of magnitude above Earth fraction as a baseline.

The final number depends on the size of the asteroids that we think will be big enough to warrant mining from. Given that there are upfront costs per asteroid (finding it, sending a ship to bring it back), it is simply not worth dragging every potentially rich asteroid back to Earth to mine, they must be sufficiently large. If we only consider the largest asteroids, greater than 100 meters in diameter, we are left with a population of around 20,000. [12]

With all of these number together, we can estimate the likelihood of any given asteroid being a target: $(0.025 - 0.05) * (0.1 - 0.2) * (.1) = (2.5 - 10) * 10^{-4}$ or 1 in 1000 to 1 in 4000. With the estimate of 20,000 NEOs of the appropriate size we have a guess of 5 to 20 target asteroids.

7 Is it worth it?

Now, with our selection of targets narrowed down quite significantly, we can speak as to the potential value of an asteroid. This depends on a variety of parameters–the size of the asteroid (seen by a telescope so volume rather than mass), the density (telling us how much material we are getting per volume seen in the telescope), and the richness of the various ores. The size we will put at 100m, the cutoff point for our profitable size. Asteroid densities have been estimated by a variety of surveys, and the best guess for the density of M-type asteroids is 5.32 grams per cubic centimeter. [10] This gives a spherical asteroid of 100 meter diameter a mass of $2.79 * 10^9 kg$. We will put the estimated iridium richness of the asteroid at the 80% level (5.57 ppm), and scale the estimated richness of the other elements according to their richness on Earth (5 times as much platinum as iridium, the other metals roughly equal in fraction to iridium). With the value of each metal taken from the table above in section 3, we can calculate the total yield of the asteroid. This gives a value of \$5.7 billion. The breakdown of this value between the different PGMs is shown in the following chart.



The value of an asteroid scales with the cube of the diameter, so a larger asteroid of 1km in diameter would yield 1000 times as much ore while one half the diameter at 50m would yield only one-eighth as much.

The idea of the 1km asteroid having a nominal valuation of $5.7 trillion brings up the question of economics, that of altering the existing market through a glut of new asteroid-originating PGMs. In the original 100m asteroid case, 78,000kg of platinum would be yielded through full processing. The world production of platinum was 192,000kg in 2010. [11] If the processing of the asteroid takes several years, the additional production of platinum would make up only around 10% of world production, which would be unlikely to overwhelm the market and dramatically crash the price. For asteroids of this approximate size consumed at a rate of one every few years, this effect would remain small. When thinking about larger asteroids, the question becomes whether finding the asteroids or processing them is the dominant factor determining the timescale of mining. The giant 1km asteroid, if consumed fast enough, does have the potential to dwarf the current market. This would, however, require the mining to be quick. If this mining were at the same speed as a smaller asteroid, the larger would simply provide a knowledge of significant future reserves rather than a disruption of the current market. A significant increase in the yearly production would certainly lead to a drop in price, though such a price drop from a supply glut could potentially lead to increased demand and use of these metals as industries that cannot at present prices afford PGMs would find themselves able to at a lower price point. Another hopeful sign for the economics of asteroid mining is that PGMs are used often in electronics, a manufacturing field that has been expanding for decades. This rising demand would hopefully at least partially offset the growing supply provided by asteroid mining.

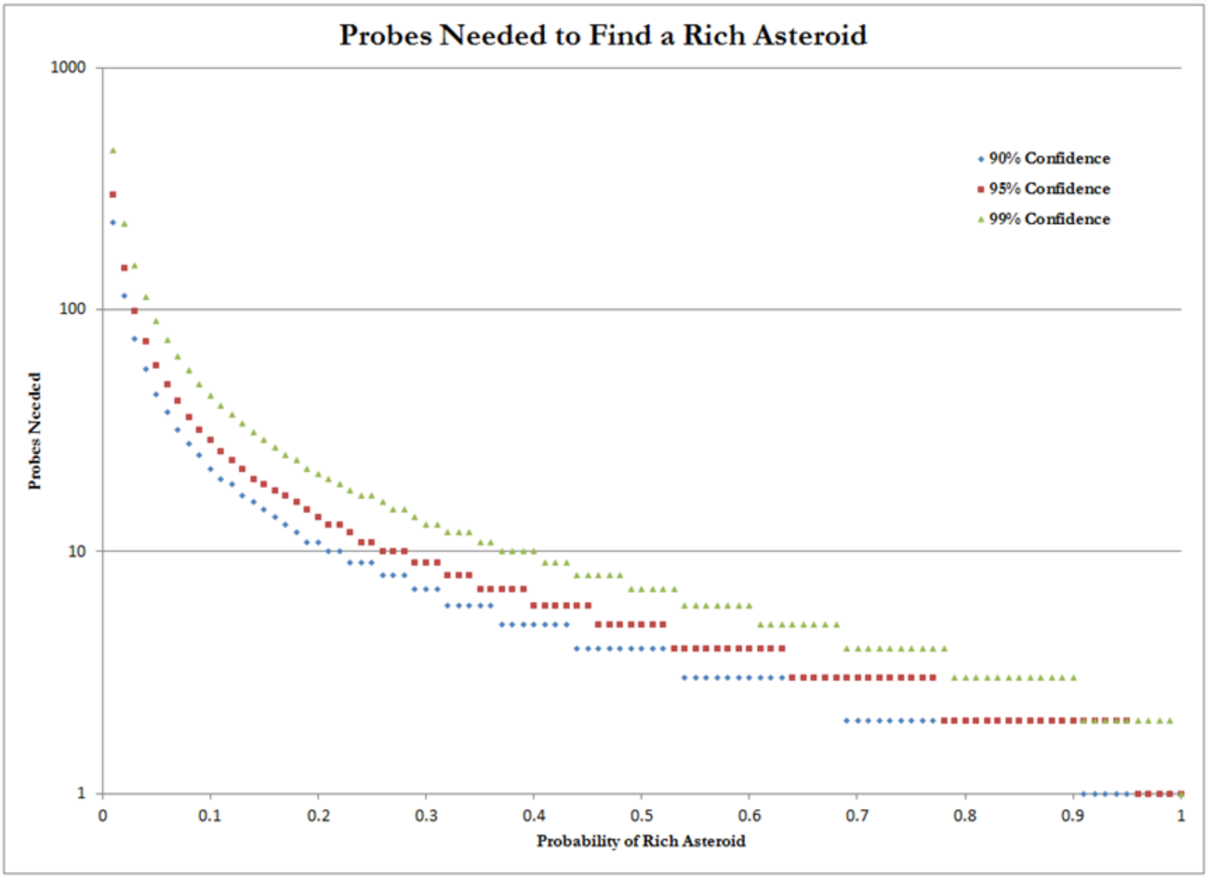
8 Locating a Target

Some of the determination of what makes a good target can be done from Earth via telescopic observation- the size of the asteroid, its orbit, and its spectral type. These correspond to three of the factors from our initial equation–P_{type}, $P_{\Delta v}$, and $N(> D_{min})$. We cannot, however, determine PGM richness within the Ni-Fe asteroid type remotely. This can only be determined remotely by X-ray spectroscopy (or in-situ by direct sampling of the asteroid material) and is not feasible from Earth-based observatories. This leaves the P_{rich} factor as an outstanding problem. It is too expensive to try to capture all of the potential targets while ignoring the richness factor- for every successful target, 5 to 10 would be a waste. Therefore, prospecting missions must be done to determine the composition of potential targets before they are towed back to Earth for mining.

The next question is how many prospecting missions are necessary. This is based on simple binomial probability, the asteroids can be viewed as a bag of white and black balls (non-ore bearing, and ore-bearing), and each prospecting mission grabs a ball and looks at the color. We are hoping to find at least one black ball (rich asteroid). The binomial distribution is as follows:

$$P_B(x;n,p) = (n/x)p^x q^{n-x} = [\frac{n!}{x!(n-x)!}]p^x(1-p)^{n-x}$$

We will be finding any value x>1, as finding more than one target would be fine. The statistics give the following numbers for missions needed to have 90%, 95%, and 99% confidence of finding at least one rich asteroid plotted on a log scale against p, the remaining uncertainty as to whether a potential target is ideal (we assume this is dominated by uncertainty in richness).



This graph shows the binomial statistics for different levels of probability that any one mission will be a success. For each value of p, the number of probes needed to have different confidence levels of finding at least one valuable asteroid are shown. This converges to one for high values of p, but explodes at low values. We can see that the number of probes remains below 10 even for high (99%) confidence above a p value of 0.4, but that at low p, the number of missions climbs to an infeasible level. We can be thankful that while the estimates of p are not high, they do not correspond to the hundreds of probes suggested by values less than 1%. Given that we believe p to be around 0.1-0.2, the following chart displays the required number of trials for some selected values around that estimate of p.

p	90% confidence	95% confidence	99% confidence
0.02	114	149	228
0.05	45	59	90
0.1	22	29	44
0.15	15	19	29
0.2	11	14	21
0.25	9	11	17
0.3	7	9	13
0.35	6	7	11
0.4	5	6	10
0.45	4	6	8
0.5	4	5	7

The result is quite different from the naive expectation that 10 trials is enough if p=0.1 (as appears possible given estimates of P_{rich} plus any other potential uncertainty). The binomial distribution probability of finding at least one in the top 10th percentile with ten trials is 65%. To reach 90% we must make 22 trials. Forty-four trials are needed to reach 99% probability.

9 Mission Design Implications

What is clear is that improving the accuracy of asteroid identification from Earth-based observations is critical for keeping the costs of finding rich asteroids manageable. The difference between p=0.1 and p=0.5 for example: the 99% confidence level is at 44 and 7 missions respectively. Even increasing p from 0.1 to 0.2 would halve the number of missions necessary. Given that any direct assay technique is liable to be costly and time-consuming, significant effort must be focused on pushing existing telescopes to their observational limit in order to bring up the p value as high as possible.

Given current technological limitations however, the value of p looks to be closer to 0.1 or 0.2. This places boundaries on what methods should be employed in looking for asteroid mining candidates. A single mission, or even single digit numbers of missions will likely be insufficient to gain the statistical likelihoods demanded. A better estimate would be that dozens of asteroids would require direct assays (in the form of in situ scanning or even physical assays) in order to better locate the most valuable specimens.

Two to four dozen good NEO candidates must be investigated to have an acceptable chance of finding one ore-bearing asteroid. Because the transit time from one of the rare good asteroid candidates to the next is likely to be a year or so, serial investigations of a few dozen by one spacecraft will take too long. We must consider a parallel approach. A fleet, or swarm, of smaller spacecraft could investigate a number of NEOs simultaneously.

The cost of obtaining this information needs to be a modest fraction of the value of the resources ultimately retrieved, perhaps 10%. For the nominal \$5 B value of the PGM-rich 100 m diameter NEO considered above, that would cap the local prospecting cost at \$500 M. With requirements on the order of 50 probes this gives us in the neighborhood of \$10 million per probe. This means that we need to launch cheap, and surely small, spacecraft.

For NASA missions to asteroids, the launch cost has been between one-fifth and one-third of the total mission cost. With our half billion dollar assay mission, this gives enough to launch at least one rocket fully dedicated to hauling the probes. An example would be the Falcon Heavy, estimated at a launch cost of \$80-125 million with a lift capability of around 50,000kg to LEO. This gives a mass budget for the fleet of probes plus whatever packaging would be needed to fit them in the payload capsule. A design would likely follow the Cold War era idea of MIRV, a system for deploying multiple warheads from a single missile. The launch vehicle would deliver a capsule with many probes to LEO, where they would eject and begin burning toward their respective target asteroids. Assuming that 20% of the mass is tied up in a frame to hold the probes, we are left with 40,000kg or roughly 800kg per probe. Previous NASA missions with similar characteristics (asteroid and comet missions) have had spacecraft between 300 and 1500kg. This is encouraging; if mass could be kept to this low level, then 50 or so could be launched at once. Unfortunately for looking at precedent, no past mission is exactly like this one; there has never been a spacecraft that flew to a NEO and did not return (the return requires additional delta-v and engine capacity). This is, however, actually good news for our potential mission as the cost and difficulty of a one-way trip to a closer object is less than that of all prior missions.

A good sign for the feasibility of this fleet of probes is that NASA missions have historically had significant cost tied up in very high error tolerance beyond that of everyday industrial projects. This is necessary when building one-shot missions, as any failure is a failure of the entire project. With a fleet of identical spacecraft, the error tolerances can be lower as losing 1 or 2 probes is unlikely to compromise the mission. Additionally, design need only be done a single time, then replicated dozens of times rather than redone for each mission as scientific missions must do due to different goals and parameters.

An individual probe for this mission would need several instruments. First, it would require a basic optical camera for navigation upon reaching the target asteroid. This would be used to track it when nearby and align the other devices. The second, and main, instrument would be an X-ray spectrometer. This would use the existing X-rays from the sun to find the PGM density near the surface of the asteroid. A similar project, REXIS, was designed by Harvard and MIT students and put on NASA's OSIRIS-REx mission. The fact that the primary investigative tool that the spacecraft will require is similar to one that was designed and built in conjunction with an undergraduate class gives hope to the idea that the instrumentation may be cheap and easy to build. The individual propulsion for each probe would likely be provided by an ion drive. This propulsion method has been used by previous asteroid missions like Hayabusa, and is currently employed by the Dawn probe to Vesta and Ceres. These have historically been xenon ion thrusters based on a design developed by the Deep Space 1 program (perhaps the closest analogue asteroid mission to the prospecting probes, having been a flyby mission of an asteroid whose orbit crosses that of Mars). Finally, the probe would need some type of power source, likely solar as most spacecraft employ, particularly in the inner solar system, and an antenna to relay data back to Earth.

10 Conclusion

Ultimately, the conclusion drawn from this analysis is that asteroid mining appears to be on the border of feasibility. The best guess that we have for any given asteroid of a desirable size, type, and feasible orbit being ore-bearing is based on the richness parameter, estimated to be around 0.1. This is the remaining uncertainty after telescopic observations are complete. Based on this number and the rules of binomial statistics, this suggests a fleet of several dozen probes with prospecting capability would be necessary to have a high confidence of finding at least one rich asteroid. Given the potential value of an asteroid and the costs associated with launching spacecraft, this suggests a per-probe cost of around $10 million and a mass of around 8000kg. Based on existing and planned launch capability this mass estimate is promising, though the cost remains a challenge as no mission has every been done at such a low cost. However, due to the differences between the prospecting missions and past NASA missions, particularly design costs, (economies of scale) location in the solar system, and error tolerance, it is possible that the costs are within current technological reach. Existing launch systems and spacecraft design systems would be pushed to their limit, but not dramatically exceeded except in raw numbers of craft (each one is not beyond our capability). There is further research to be done on the specifics of instrumentation and design of probes, including significant engineering constraints and analysis of existing technologies and potential capabilities. This result is not surprising given the current interest in companies in asteroid mining, one would expect that at the moment where profitability is on the horizon, that those interested in making money would make themselves know. Any earlier, and the technology would not be there for profitable exploitation, and any later and someone else would have already done it.

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