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Mining Near Earth Asteroids

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ABSTRACT

Asteroid mining has long been a topic of interest and study. Recent advances in launch technologies and reductions in launch costs to low Earth orbit in the commercial crew era, as well as a recent swelling in the known number of Near Earth Asteroids, have made asteroid mining more than just a dream. Companies with substantial financial backing have recently come into existence and are making progress towards making asteroid mining a reality. This paper serves as a survey of proposed asteroid mining strategy, target population and selection, as well as the potential impacts that successful asteroid mining could have for mankind.

Subject headings: Asteroid Mining

1. Introduction

The concept of mining asteroids for resources has been around since the late 1970s ((Gaffey & McCord 1977) and (O'Leary 1977)). Until recently, the development and deployment of space technologies was largely the realm of governments. The advent of the commercial crew and cargo initiatives at NASA have made possible the development of private space technologies as never before.

The successful mining of an asteroid is defined here as the development of a mining program that is both financially self-sustaining and profitable to its investors. While this definition is rather vague, in many cases it refers only to the financial gain provided by the program in the sale of minerals from asteroids. This definition is misleadingly narrow as the deployment of asteroid mines is still far off and yet asteroid mining companies active today still have opportunities to profit through the development and sales of the technologies required to make asteroid mining a reality.

The mining of an asteroid (or asteroids) is a complicated process requiring a serious long term investment. The process leading to the successful mining of an asteroid consists of at least four parts: 1) Viable targets must be identified and confirmed. 2) The target must be either retrieved, or a mining team must be deployed to it. 3) The target must be mined. 4) The materials must be returned to Earth or wherever they are destined to go. Each of these parts is in itself a major undertaking with requirements of its own. These four parts or steps will be discussed throughout this paper.

2. Motivation

The mining of asteroids provides a financial backbone to make commercial space development a reality. Successful operations in the field of asteroid mining will represent mankind's true departure from an Earthbound existence. The excitement associated with making science fiction reality and my own background in aerospace engineering and astronomical instrumentation makes asteroid mining a very appealing target for my study. The associated technologies required to make asteroid mining successful encompass both the development of remote detection capabilities identical to those of astronomy, as well as the development of spacecraft that drove my interest in aerospace engineering many years ago.

3. Asteroid Selection

Before a mining operation can begin, a target body must be selected. The selection of an asteroid for mining requires a number of steps be carried out. First, the desired minerals for mining must be determined. Then, asteroids with the potential of being rich in the target minerals must be found. Before analyzing the details of these two steps, it is necessary to discuss the possible target bodies and minerals that can be found amongst the NEAs.

3.1. Near Earth Asteroid Populations

In the last two decades, the number of known NEAs has ballooned from a few hundred to over twelve thousand, see figure 2. The advent of electronic detectors and robotic telescopes has allowed astronomers to identify a tremendous number of objects in a relatively short period of time. With such a vast number of potential mining candidates, the NEAs must be evaluated for their content in desired minerals. To begin to evaluate the potential resources available in a NEA, they must be carefully classified.

In general, asteroids are categorized in one of two ways. They may be characterized by their orbital parameters or by their reflectance spectra (Nelson et al. 1993). Since this discussion already focuses on the NEAs as viable mining targets and further target selection relies upon selecting a target mineralogy, it is more appropriate to focus on the reflectance spectra classification. While there exist numerous taxonomical systems for classifying asteroid spectra, this discussion will use only the Tholen taxonomy system (Tholen 1984). The original Tholen taxonomy consists of 12 classes each with a different reflectance spectrum. A few additional classes have been added as new types of asteroids have been discovered. At the time of its development, only visible spectra were available, thus the original standards are in visible wavelengths. At present, infrared spectra provide more accurate classification based on absorption features. Specifically, composite absorption features primarily due to olivine and pyroxene at $\sim 1\mu m$ and $\sim 2\mu m$ provide a powerful tool for classifying asteroid spectra (Dunn et al. 2013).

Rather than providing an exhaustive review of each of the asteroid classes in the Tholen system, a focused discussion of distribution of Tholen type those types that are of particular interest to asteroid miners will be provided here. Should the reader desire a more comprehensive discussion of the entire classification system (Nelson et al. 1993) is recommended.

There are three main groups of asteroids, the Carbonaceous Chondrites (C-type), the Stony (S-type), and the Metallic (M-type). Asteroid miners are particularly interested in the C-type and M-type asteroids for reasons that will be presented in section 3.2. Figure 1 shows the distribution of Tholen taxonomical type in the NEAs from Binzel et al. (2002). The taxonomical classes P, E, X, and M are the M-type asteroids and make up approximately 10% of the NEA population. The C-types, consisting of the C,B,F,G, and Q classes, comprise approximately 34% of the NEAs. The S taxonomical class refers directly to the S-type asteroids which make up the bulk of the NEA population making up approximately 50% of the population (Binzel et al. 2002). The remaining taxonomical types are either uncategorized, or conglomerate types.

The general mineralogical profiles for the taxonomical classes are included in table 2. Specifically, the M-types include mostly Iron and Nickel, the C-types include carbon, organics, opaques, and silicates, and the S-types contain combinations of the components of both C and M type asteroids. The mineralogical profiles for the asteroid types do not come from spectra alone. In order to accurately identify the elements present in the different asteroid types, their spectra are compared to the spectra of meteorite samples found on Earth.

As an example of the classification process, figure 3 shows the classification spectra of an asteroid that was observed in space and hit the Earth in 2009 from Jenniskens et al. (2009). A piece of the resultant meteorite was recovered and studied. In panel a, the spectrum of the meteorite sample measured in the lab is shown as open circles and the black line. The poor quality spectrum of the asteroid observed in space is represented by the vertical bars. While clearly the two spectra are fit each other quite well, the poor quality of the spectrum of the asteroid shows the difficulty in clearly identifying asteroids spectroscopically. Panel B then shows the Tholen classification fitting for the asteroid. Again the meteorite spectrum is represented by open circles and a black line, and the asteroid spectrum by the vertical bars. This time, the standard spectra of various Tholen types are shown. The best match to the shape of the curve reveals the asteroid and meteorite to be F class (Jenniskens et al. 2009).

Evidenced by the previous example, identifying an asteroid as being of a certain type does not guarantee that the asteroid will be rich in the targeted minerals. It has been in both C-type and M-type asteroids that there exists substantial mineralogical variation (Jones et al. 1990). This requires potential asteroid miners to obtain as much information about a target as possible before launching a mining mission in order to maximize their potential profits. Before discussing the prospecting operations required to select an optimal target, miners must select what a target based on the minerals they are interested in.

3.2. Mineralogical Targets

Asteroid miners are particularly interested in two groups of elements and compounds from asteroids, volatiles and Platinum Group Metals (PGMs). Volatiles are molecules such as H_2O, N_2, O_2, and CH_4 that are common reactants found incorporated into silicates. The PGMs consist of semiconductors such as Germanium, Indium, Antimony, etc and precious metals such as the namesake Platinum, as well as Silver and Gold. A list of the PGMs is provided in table 1, to be addressed below.

Locked in the silicates that compose some C-type asteroids are the volatiles. These molecules have potential uses for life support, rocket fuel, agriculture, refrigerant, and metallurgy (Ross 2001). Asteroids containing volatiles are estimated to compose $9.8 \pm 3.3\%$ of the near earth asteroid population, but only 1 in 1100 of the total NEA population is expected to contain high amounts of water incorporated in silicates called hydrated minerals(Elvis 2014).

Second, the PGMs are found in some M-type asteroids. The M-type asteroids are comprised primarily of Iron and Nickel, these two elements will be valuable in space as construction materials. However it is the PGMs which are found in high concentrations in some of these asteroids, that are of particular interest to asteroid miners. Roughly 1 in 2000 NEOs are expected to be rich in PGMs (Elvis 2014). In table 1 a breakdown of the value of PGMs in a 1-km sized asteroid in the 90^{th} percentile in PGM richness is presented. Driven primarily by the value of Platinum and Germanium, a company could expect over 38 billion dollars in revenue per $10^6 m^3$ mined just in PGMs (Ross 2001). Furthermore, it is important to note that despite the huge potential profit from PGMs, they account for only 0.2% of the asteroid by number.

PGMs are so valuable due to the fact that they are relatively rare on Earth and that demand for them is high as they are used in the manufacture of many modern electronics components. The semiconductors that make up part of the PGMs are used in the integrated circuits and CCDs in many consumer electronics in the market today and demand for these minerals is high. In table 1, the semiconductor Germanium is second in potential value only to the Platinum in a PGM rich asteroid.

Despite the tremendous potential profits from the M-type asteroids, the mining of volatiles from C-type asteroids represents the most practical near-term target for asteroid miners as fuel and life support concerns will provide the best short term profitability scenario for would-be miners

3.3. Asteroid Targeting

Once a mineralogical target has been identified, asteroids containing the larges concentrations of that target must be identified and evaluated for their accessibility. As discussed in Section 3.1, the classification of asteroids is accomplished using visible and near infrared spectroscopy. Also discussed was the uncertainty in guaranteeing that an asteroid will contain specific elements in high abundance. To reduce the uncertainty, higher quality spectra are required for asteroid miners to be successful. Within the astronomy community, the classification of asteroids has been dependent upon observational programs at observatories where campaigns must compete for observing time. Because aspiring asteroid miners do not want to compete with scientists for observing time, they plan to deploy their own space based telescopes to study promising target asteroids. Planetary Resources, an asteroid mining company, has developed a small space telescope system called the Arkyd in 3 different iterations to study mining targets. In its first iteration, the Arkyd 100 will be placed in orbit where it will conduct observations of NEAs that represent possible targets for the first generation of asteroid mining. The second iteration, the Arkyd 200, will integrate propulsion with the telescope allowing it to intercept targets in Earth-crossing orbits. Finally, the third iteration, Arkyd 300, telescopes will be outfitted with additional propulsion and deep space communications equipment (Lewicki et al. 2013). These final stage craft will be dispatched in swarms to various targets. These swarms will be able to map the surfaces of target asteroids and obtain the highest resolution spectra maximizing the certainty that the target chosen for mining will contain the ideal mineralogy.

Multiple craft will be dispatched to maximize the likelihood that the most productive target will be identified. In Elvis & Esty (2014), it is estimated that 228 probes will be required to guarantee a profitable target will be identified to the 99% confidence level. The primary argument behind the need for multiple probes to be dispatched is that the spectra taken of target asteroids indicates the general compositional characteristics of the asteroid, but does not yield definitive measurements of the abundance of specific valuable minerals within the asteroid (Elvis & Esty 2014).

Should spectroscopic evaluation in orbit of target asteroids fail to provide specific data on the content of a potential mining target, the remaining alternatives rely on capturing part of the target for study. One such mission has already been successful and more missions are planned. The Japanese Hayabusa mission successfully returned samples from the surface of the NEA 25143 Itokawa to Earth (Tsuchiyama et al. 2011) and another mission, Hayabusa 2, is in the planning stages (Tsuda et al. 2013). Additionally, the ESA mission MarcoPolo will visit the NEA 1996 FG3 and return samples from it sometime in the 2020s (Michel et al. 2014). With the plans already laid out by asteroid miners, it is not unreasonable to think that they would devise a similar sample return mission before settling on a specific mining target.

4. Asteroid Mining

This section contains mostly conjecture on asteroid mining strategies based on plans indicated by Planetary Resources and others.

4.1. Mining Operations

Once an asteroid has been targeted for mining and before mining can begin, the necessary equipment must be transported to the mining site. Two strategies have been proposed as possible methods for accessing target asteroids. The first method involves changing the orbit of the asteroid and maneuvering it into orbit around the Earth. The second method relies on the deployment of a remote operation, either manned or robotic. Both methods offer interesting implications for human spaceflight development as well as serious potential pitfalls, making the choice of mine deployment an extremely important decision for a company.

The asteroid capture scenario is a pleasing option as it offers a pleasant future where human miners could work in orbit around the Earth quickly turning an asteroid into valuable materials for orbital construction project. The logistics of changing the orbit of a massive object like an asteroid pose a tremendous and potentially dangerous problem for engineers. Altering the orbit of an asteroid would require the attachment of thrusters to the surface of an asteroid and then using them to perform an orbital transfer maneuver to place it in orbit around the Earth. Figure 4 shows an example 2 maneuver transfer calculated for NEA 1999 RA32 from Hasnain et al. (2012). Panel a shows the first stage of the maneuver where the orbit of the asteroid being slowly changed over a 2.3 year period where an acceleration of $20\frac{\mu m}{s^2}$ is applied by electronic or chemical thrusters. Panel b shows the second maneuver where a large impulse of $2300\frac{m}{s}$ is applied very suddenly as the asteroid nears its desired orbit around the Earth.

A recent study of current thruster technologies suggests that a two stage transfer mission is possible(Hasnain et al. 2012). Such a maneuver would involve the placement of some electronic or chemical thrusters on the asteroid for the first stage of the transfer where the orbit would be changed by small amounts over months or years as in the example above. The second portion of the maneuver would involve the use of heavy rocket boosters to inject the asteroid into a target orbit around the Earth. Considering the masses of asteroids that could be targeted, the impulse required from rocket boosters has not advanced to the required level at present. The danger of capturing an asteroid into Earth's orbit is that any error could result in the target asteroid impacting the Earth. Despite the potential danger, the capture method's relationship with the problem of deflecting hazardous asteroids from impacting the Earth, makes this scenario the target of much interest at NASA and their Asteroid Initiative Program.

Once in orbit around Earth, a mining base could be established on the surface of the asteroid and miners and equipment could be launched from Earth using conventional technologies. A mining operation in orbit around Earth would allow for shorter term manned mining missions. The proximity to Earth would also mitigate some of the risks inherent in mining far from the Earth where rescue would be next to impossible. Additionally, having materials near to the Earth would eliminate the requirement for transportation of materials from a remote asteroid to the Earth.

The deployment of autonomous mining systems requires a substantial amount of technological development that is not necessarily required for the capture scenario. Despite the substantial amount of money that would be required to develop such remote systems, the systems themselves represent a potential source of income for the company developing them. Advanced robotic systems could find use in any number fields on Earth. For example, one might imagine that such autonomous systems involving numbers of individual workers and some kind of central processing facility could be deployed for large scale farming, terrestrial mining, mapping, and other tasks.

Both strategies would benefit from the development of remote ore processing, technology that could provide construction materials and fuels on demand. A fully operational facility might act as a fuel depot for outbound space missions, or provide the semiconductors and support materials for the construction of space based solar power stations, or shipyards.

5. Discussion

The development of a successful asteroid mining industry has the potential to alter the economy on Earth and provide the platform from which mankind will jump into interplanetary exploration, exploitation, and colonization.

The outposts created by miners will serve as refueling depots and launch points for exploratory missions throughout the solar system. One might envision that fueling craft could be launched from outposts to meet up with and refuel exploratory craft on their way to Mars or other locations in the Solar System. The capability of refueling mid trip would allow missions to reach their destinations much quicker than currently possible.

Furthermore, the samples of asteroids that will be provided by asteroid miners will allow planetary scientists to completely define the populations of asteroids in the Solar System. Equipped with a complete set of asteroid samples, scientists will be able to accurately catalog the asteroids by specific composition. Such knowledge will advance our understanding of the formation of the Solar System.

The development of asteroid mining in the NEAs will require the development of many technologies. From mineral extraction to processing, to zero gravity manufacturing, these technologies will directly translate to mining asteroid out in the Main Belt and potentially to the mining of objects farther out in the Solar System such as moons of the giant planets and Trans-Neptunian Objects. Just as mining and agricultural opportunities spurred human expansion across the globe, the exploitation of mineral resources will fuel a leapfrog expansion of humanity throughout the Solar System.

The impact of asteroid mining on terrestrial mining also has important implications for Earth's environment. Once asteroid mining becomes practical, the PGMs available in asteroids are more accessible and more plentiful than found on Earth. The amount of PGMs found in the hypothetical 500 km asteroid could contain 174 times the World's output in platinum (Ross 2001). This amount of PGMs could shutdown the terrestrial mining of these elements. The elimination of mining of these elements will reduce the ecological impact that large scale mining operations cause.

The availability of raw materials in space opens the door for construction and manufacturing in orbit. Eliminating the cost of putting materials into orbit will tremendously reduce the overall cost of space-based construction. The capability of constructing large space stations as habitats and construction facilities fundamental for the further expansion of the human race. Orbital space construction yards will be able construct vast solar panel arrays in orbit around Earth could provide clean energy for the entire planet. Such facilities could also construct space craft far larger than can be constructed on Earth. These large ships will be able to serve as transport for large scale missions and even colonization to other planets and moons in the Solar System. It is a logical, though fanciful, conclusion that if humanity is to expand outside of our Solar System, vast generational spacecraft must be constructed and that the only viable way to create craft large enough to provide for large numbers of humans crossing the vast interstellar void is to construct them in space.

6. Conclusion

Even though the reality of asteroid mining as a commercial reality is decades off, it is clear that the development of technologies associated with asteroid mining is an important step on the way to colonizing space. Despite the time yet required for asteroid mining to become a viable industry, the development of technologies required in space and useful on Earth will provide financial support for companies as they continue to march towards the deployment of asteroid mines. Although much of this discussion on asteroid mining relies on conjecture, the possible benefits to humanity are tremendously enticing. As a result, the prospect of asteroid mining taking humans into space on a more permanent basis has created a great deal of public interest. The idea of a literal gold rush on a new frontier is very exciting and will garner support for fledgling asteroid miners. While risky, both financially and to human life, the potential gains and apparent importance of human expansion into space are sure to bring asteroid mining into reality.

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Table 1. Composition and Estimated Value of a Metal-Rich Asteroid. Updated from Ross (2001). Market values of semiconductors and precious metals from a 1 km diameter M-type asteroid with Iridium richness in the 90^{th} percentile mined at $10^6 m^3/yr$. Elemental prices have been updated from the 1994 values to those of 2010 (USGS 2013). The final column of yearly sales assumes "in orbit" value which adds an additional $\$3,000$ per kilogram to material value. The average of the listed cost per kilogram to low Earth orbit of SpaceX's Falcon 9 and Falcon Heavy Rockets is $3130\$/kg$, so the assumed value from the original is now an appropriate figure to add. Additionally, it is worth noting two additional things. First, the PGMs make up only $\sim 1711ppm$ and the remaining bulk of the asteroid will also have considerable value. Second, at 1 km in diameter the asteroid could be mined for 500 years before running out of material.

Element	Price[a] ($\$/yr$)	Concentration(ppm)	Mine Capacity (tonnes/yr)	Tonnes sold per year	Sales ($\$M/yr$)
Semiconductors:					
Phosphorous (P)	0.08[b]	1300	10100	722	2167
Gallium (Ga)	600.00	60	468	468	1684.8
Germanium (Ge)	1200.00	210	1,640	1640	6888
Arsenic (As)	2.64	3.7	28	28	84
Selenium (Se)	83.40	36	281	281	866
Indium (In)	564.57	0.46	4	4	14
Antimony (Sb)	3.92	0.0047	0.4	0	0
Tellurium (Te)	57.32	0.45	4	0	0
Total for Semiconductors	-	-	-	3143	11703
Precious Metals					
Ruthenium (Ru)	6365.85	13.0	101	101	946
Rhodium (Rh)	79058.70	4.8	38	38	3118
Palladium (Pd)	17072.05	1.3	10	10	201
Silver (Ag)	649.45	0.46	4	4	15
Rhenium (Re)	4720.00	3.7	28	28	216
Osmium (Os)	14467.84	9.0	70	70	1223
Iridium (Ir)	20640.78	33.0	257	257	6076
Platinum (Pt)	51955.61	35.0	273	273	15003
Gold (Au)	39465.36	0.5	4	4	170
Total for Precious Metals:	-	-	-	583	26967
Grand Total	-	-	-	3726	38670

[a]Prices are average prices from 2010 from USGS (2013) unless otherwise noted

[b]Price is average price from 1994 as in original table in Ross (2001)

Table 2. Tholen Taxonomic asteroid types, their surface mineralogy, and Meteorite Analogs from Nelson et al. (1993)

Type	Surface Minerology	Analogs
A	Olivine or olivine-metal	Brachinites
B, C, F, G	Hydrated silicates, carbon, organics, opaques	black/gas-rich ordinary chondrites
E	Enstatite	Enstatite achondrites
M	Metal, trace silicates	Irons (enstatite chondrites)
Q	Olivine, pyroxene, metal	Ordinary chondrites
R	Pyroxene, olivine	none
S	Metal, olivine, pyroxene	Pallasites, mesosiderites CV/CO chondritex (K-type), ordinary chondrites
T	Organic-rich silicates, carbon	none
V	Pyroxene, feldspar	HED association

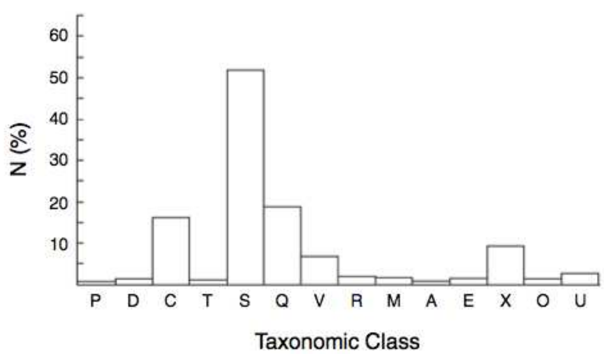

Fig. 1.— Taxonomic Class of 300 NEAs from Binzel et al. (2002). The taxonomical classes presented here are an expanded Tholen scheme where a few additional classes have been added. The C class contains the B, F, and G types. Additionally, the Q class are lumped into the C-type asteroids which contain volatiles. The M-types consist of the P,E,X, and M classes and contain Iron, Nickel and valuable PGMs

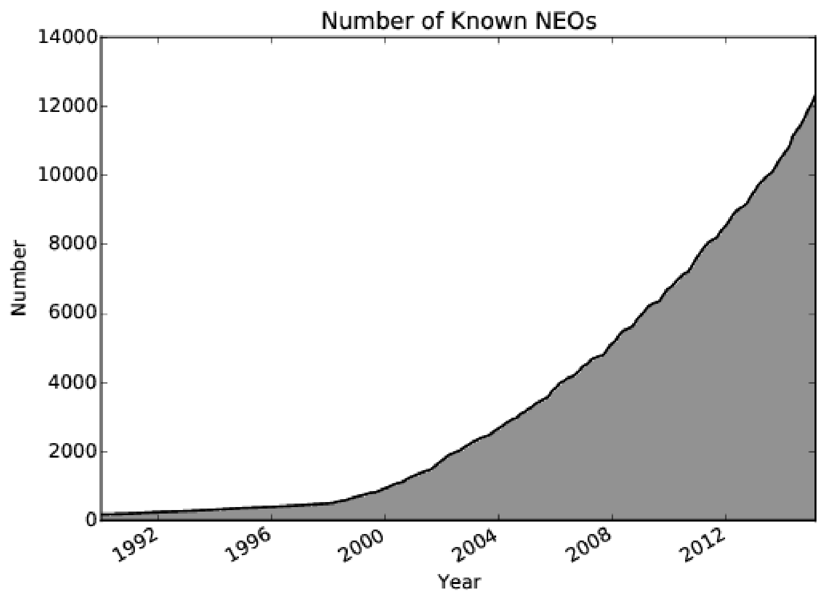

Fig. 2.— Cumulative number of known NEOs up until 2014. Data from JPL database (http://neo.jpl.nasa.gov/stats/). While NEAs are specifically the Near Earth Asteroids, NEO refers to any Near Earth Object. The NEO group contains the NEAs, as well as comets, and space junk.

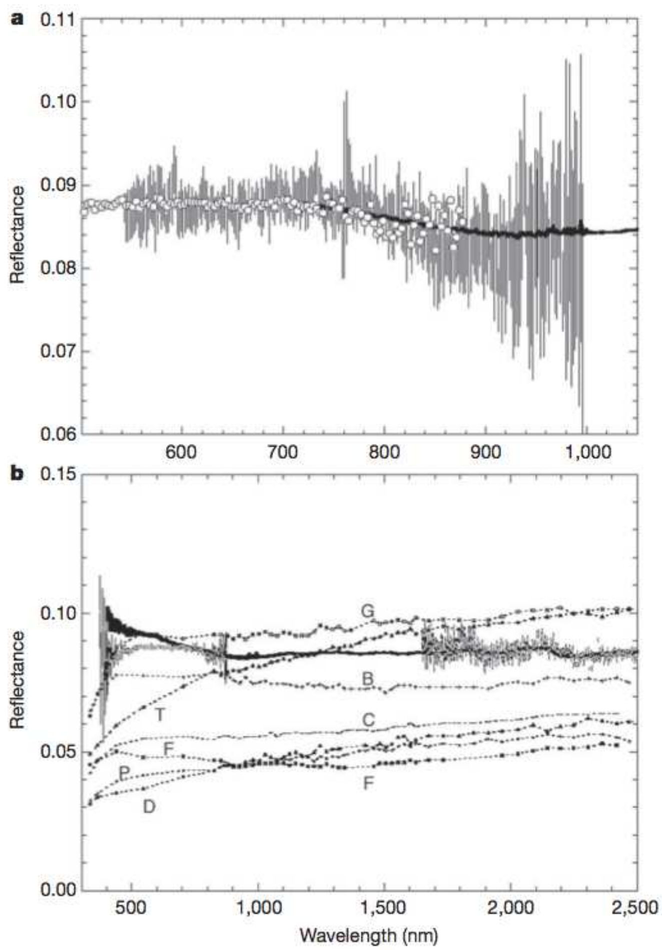

Fig. 3.— Reflectance spectroscopy comparison between a meteorite and asteroid 2008 TC_3. In both panels, the circles and black line represent the spectrum of the meteorite sample and the vertical lines represent the spectrum of the asteroid. Panel a shows the matching of the meteorite spectrum to the noisy spectrum of the asteroid in space exemplifying the difficulty of obtaining high quality spectra of asteroids. Panel b shows the taxonomical determination, where the spectra of the meteorite and asteroid are shown along with the spectra of various Tholen type asteroids. The shape of the spectra reveal asteroid 2008 TC_3 to be a B or F class asteroid. Analysis of the meteorite in a laboratory classifies the asteroid as a F class asteroid devoid of hydrated minerals. With no water present, it would not have made a good mining target. From Jenniskens et al. (2009) .

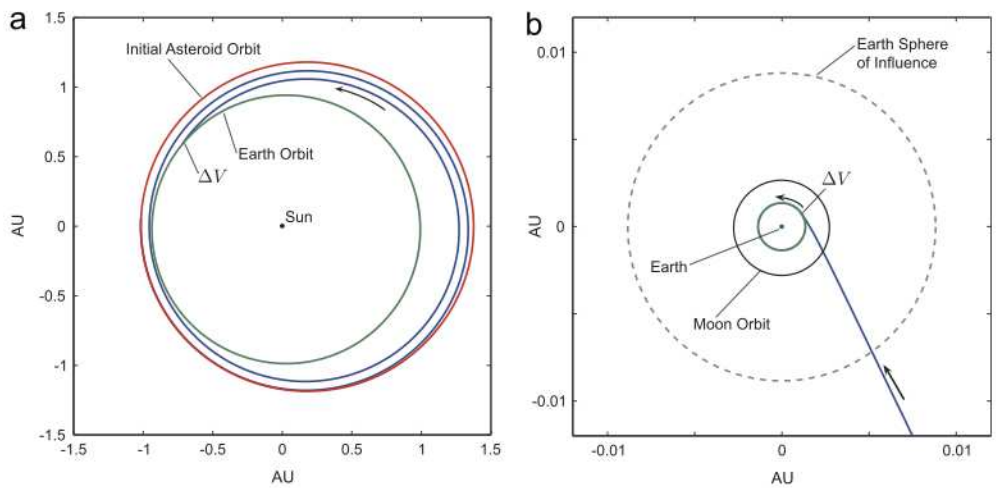

Fig. 4.— Simulated capture of an asteroid into orbit around Earth using a two phase transfer maneuver. From (Hasnain et al. 2012). The two panels represent the two stages for injecting an asteroid into orbit about the Earth. Panel a shows the first stage of the maneuver where the asteroid orbit is gradually changed by applying thrust over a long period of time so that it comes near to the Earth. Panel B show the final injection maneuver that places the asteroid into orbit around the Earth within the Moon's orbit. This second maneuver represents a tremendous impulse over a short period of time.