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What are possible technologies that can be used to make asteroid mining affordable, and reliable?

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Abstract:

Asteroid mining is the process of harvesting resources from near-earth asteroids (NEA). The process involves researching and cataloging all near-earth asteroids using remote sensing techniques such as spectrophotometry and thermal modeling and selecting the suitable NEA for resource exploitation on various factors: Delta V, size, tumbling rate, available resources, distance, and type of orbit, following that launching a fleet of specialized space crafts to detumble, mine the asteroid, and lastly transport ores. These processes are relatively theoretical and have multiple technological and economic constraints which needs to be overcome to make asteroid mining feasible. In this paper we will discuss, these technological and economic constraints, such as the high cost of rockets, high cost per kg of transportation of the payload, the low reliability of current CubeSats used for detumbling, and the low accuracy of remote sensing techniques. The paper also recommends possible solutions such as using redundant thrusters to detumble, replacing current stage 3 propulsion systems with ion propulsion systems, and using low wavelength infrared waves for thermal modeling. Lastly, the paper will discuss possible future technologies currently being researched and how they can be used to further asteroid mining.

1.Introduction:

In today's modern world, resources such as water, platinum, and iron are indispensable. They are essential for the development of much of the technology humans enjoy today, such as phones, pacemakers, catalytic converters. However, the reserves for precious metals are only expected to last around 30 years at the expected rate of consumption (Kifle et al.). The usage of these materials extends beyond gadgets. These metals will also be crucial for building the new frontier in space; in the race to colonize space, the prohibitive cost to transport these resources is one of the most prominent issues that hinders progression. The cost per kg to launch to near earth orbit can range from $1,400 to $30,000 depending on the type the fuel and the rocket used (Jones). However, a breakthrough may come from an idea that has riveted science fiction for decades: asteroid mining. Asteroid mining is the process of extracting metals, and minerals from the surface and core of asteroids. The large pool of resources available in asteroids may satisfy the growing demand for rare earth elements such as platinum, while on-site resource extraction of iron for the development of infrastructure may facilitate exploring and colonizing other planets more plausible. As technology rapidly advances, and knowledge about the different properties of asteroids increases, humans may be able to harness asteroids for resources sooner than expected. Currently the main components of this process can be separated into four different stages: discovery, exploration, detumbling, and mining.

1.1 Available commodities in Asteroids

1.1.1 Platinum Metal Group (PMG).

PMGs are inaccessible due to a process called differentiation. During Earth’s formation heavy metals with higher densities such as platinum, palladium, and iridium sank to the bottom forming Earth’s core. For this reason, the primary modes of platinum extraction are deep underground mines or locations of meteorite impacts. Platinum reserves are estimated to be 69,000 ("Global Platinum Reserves 2020 | Statista") metric tons, compared to 560,000 metric tons of silver reserves ("Global Silver Reserves 2020 | Statista"). The low amount of platinum reserves is not sustainable for the increasing rate of consumption due to technological development. Platinum is used for fuel enhancement, glass, medical devices, chemical production, electrical components and catalysts (Hellgren).

As the consumption of platinum grows, especially in the electrical and medical fields, the demand will exceed global supply. Asteroid mining will be essential to meet the future demand. Due to the low gravitational force of attraction, asteroids have a lower magnitude of differentiation, and platinum is present in much higher concentrations on the surface making it more accessible. A single M-type asteroid 500m in diameter has platinum reserves estimated to be equivalent of half of the Earth's reserves (Hellgren).

1.1.2 Nickel and iron

Unlike platinum, nickel and iron are available in large quantities on earth. However, the process of mining nickel and iron requires removing substantial quantities of muck. This necessitates large scale deforestation, habitat destruction, and carbon and sulfur emissions. A study published in PLOS One ranked nickel as the 8th most potent metal contributing to global warming Asteroid mining is a viable solution to decrease these externalities. A singular asteroid such as Psyche 16 has over 10 quadrillion dollars' worth of iron and nickel, which is enough to sustain the global demand for thousands of years (scotii). Additionally, nickel and iron are some of the main ingredients in construction. While it may not be economically feasible to send iron and nickel back to Earth, it may be environmentally more sustainable to use asteroids as a clean source for mining them. Additionally, they could be used to develop the next frontier in space, avoiding the high cost of transportation from Earth.

1.1.3 Water

Water is arguably the most important commodity available in space. Weight is a significant barrier for space exploration. In order to sustain deep space missions' water will be a key resource for two reasons.

The first reason is water can be spilt into H2 and O2. (Zacny et al.) H2 can be used as a fuel and O2 can be used as a source of oxygen for the crew and as an oxidizing agent for the fuel. Harvesting them on site can reduce the amount of fuel, which is typically the heaviest component of a spacecraft, that future missions need to carry because they can use asteroids as refueling stations (Colvin et al).

The second reason is abundant supplies of water are necessary to sustain life and create colonies, however water is a scarce resource on most planets like Mars. Water is easier to transport from asteroids to other planets compared to transporting it from Earth. Asteroids have a lower gravitational force allowing rockets to launch with low fuel consumption and cost kg for the payload. The water can then be purified and used for drinking (Zacny et al).

1.2 Limitations in current technology

Before the process of mining asteroids can commence, many impracticalities have to be resolved. One of these is the high cost to propel payloads to space. While the cost to propel payloads has decreased from $1 million per Kg (Vanguard rocket) to $1,400 per Kg (Falcon Heavy), (Jones) these costs are only for low Earth orbit, i.e., 160 to 1000 km above the surface of the Earth. Near-earth asteroids (NEA) are less than or equal to 1.3 astronomical units (AU: distance Earth to Sun), approximately 200 million km (Mclure). For comparison the Perseverance rover with a weight of 1025kg at a distance of 2.4 astronomical units had a launching cost of $243 million leading to an approximate cost of $237,000 per kg of payload ("Cost Of Perseverance").

Another constraint for asteroid mining is the low reliability of methods to evaluate the composition of asteroids. Today's techniques compare asteroids with meteorites on Earth. However, these techniques encounter problems when analyzing heterogeneous asteroids as their surface does not match the core(Zacny et al.).

Additionally, because many asteroids rotate around their axis at high velocities mining will be difficult. While current technology can be used for detumbling an asteroid, such as using multiple CubeSats, it is inefficient, and unreliable. (Gaffey et al.)

Furthermore, due to the low gravity of asteroids, the mining process is significantly different compared to that on Earth. The drilling and blasting process used will cause material to be ejected from the asteroid's orbit. Moreover, the lack of manpower and communication will require all processes to be automated. To make asteroid mining more feasible and reliable, new technology has to be developed to combat these issues.

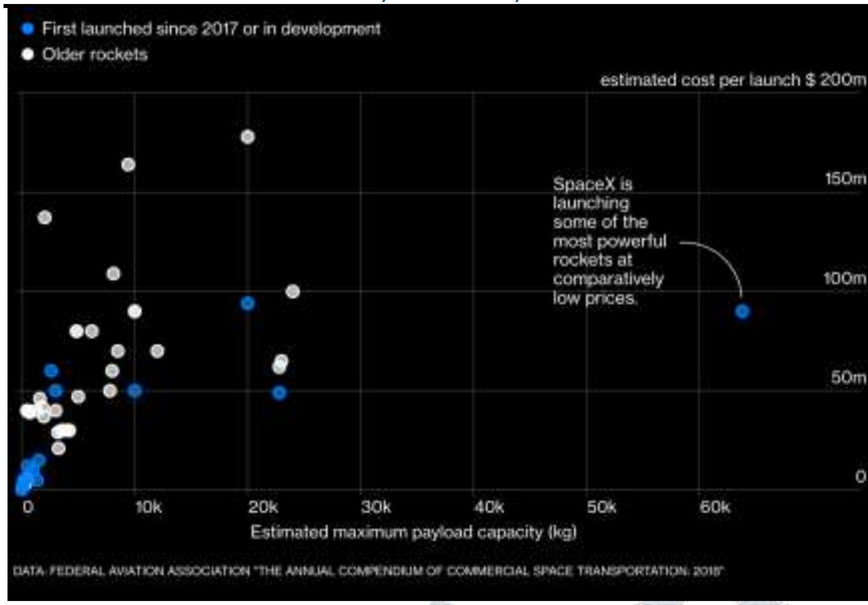


Figure 1(Tartar) Summary of the cost per kg of payload compared to their launching cost.

1.3 Developing new technology to address limitations

Due to current technological restrictions, researchers must develop more efficient rocket propellants (such as electric engines) and improve different remote analysis methods, like spectrophotometry, radiometry, and hyperspectral imaging. Techniques such as melting and centrifugation still need to be tested and perfected in microgravity conditions, and cluster engines and vaporization need to be explored for the detumbling of asteroids to increase reliability (Jones). This leads to my research question: What are possible technologies that can be used to make asteroid mining affordable, and reliable?

2. Methods

Before new technologies are developed it is important to understand the current technologies in use. The following paragraphs will discuss remote sensing techniques used to detect and analyze asteroids, methods to detumble asteroids, and rocket's propulsions systems.

2.1 Remote Sensing Techniques

Until the 1970s, analyzing the composition of a singular asteroid was impractical; however, by using different combinations of remote sensing techniques, it is now possible to accurately determine the composition, size, rotation, along with the texture, and contour of an asteroid. As many of these methods use meteorites on Earth and compare them to asteroids, they lack accuracy when analyzing heterogenous asteroids. (Jones)

2.1.1 Spectrophotometry

Spectrophotometry is a more precise way to determine the physical composition of an asteroid. Unlike planets, asteroids do not have an atmosphere, which facilitates accuracy in the data received as there is no reflectance from gasses in the atmosphere. A spectrophotometer uses a charged couple device (CCD) to capture multiple photos with different filters and then creates a spectrum. (Mainzer et al.) The process works on the principle that materials always reflect the same wavelength of sunlight. The light reflected from materials on meteorites can be compared with the light reflected from the asteroid. Through this method, the surface composition can be accurately deciphered. However, as light is reflected from the surface, the process is only accurate for homogeneous asteroids whose core and surface have the same composition and not for heterogeneous asteroids whose core composition may be different (Zacy) .

2.1.2 Thermal modeling

The heat signature of asteroids can provide essential information. Currently, at NASA's JPL, the Near-Earth Object Camera (NEOCAM) is being developed. The camera has been difficult to manufacture due to the need for a long-wavelength infrared sensor. The telescope uses infrared wavelengths between 4–5.2 and 6–10 μm. The telescope uses thermal modeling, which takes advantage of the nature of C- type asteroids to absorb light and reflect it as thermal energy in the IR spectrum instead of visible light. Thermal models use spherical geometry and beaming parameters to find the composition of heterogeneous asteroids along with their diameter and albedo. (Mainzer et al.)

2.2 Detumbling

Tumbling occurs due to a collision between two or more asteroids, causing each to rotate around their axis. NEAs, if rotating, have varied rotational time periods between 6 minutes and 17 hours. If an asteroid is to be secured and brought to the Lagrange point between the Earth and Sun or the Earth and moon, detumbling needs to occur. This process can be achieved through the use of low-cost CubeSats.

Bazzocchi and Emami have developed a method to determine the optimum locations where low-cost thrusters should be placed along with their orientations in order to detumble an asymmetrical asteroid. Thrusters have the highest failure rate among the subsystems of a spacecraft, (Jafari Nadoushan et al.) so the proposed method of altitude determination and control subsystem (ADCS) has a higher probability of failure. Instead, this issue can be addressed by using redundant thrusters as suggested by Mahdi Jafari Nadoushana , Mahdi Ghobadib, and Maziar Shafae. (Jafari Nadoushan et al.) This method uses a swarm of CubeSats with joint action to detumble the asteroid. However, this mechanism requires the magnitude of tumbling to be less than 1 degree per second. For such cases, Trevor Bennett, Daan Stevenson, Erik Hogan, and Hanspeter Schaub suggest a touchless method using electrostatic actuation of asteroids. This process uses an electron gun or an ion gun to control the charge of a singular servicing satellite while using laser beams to attract the closest receding part and repel the closest approaching part in order to detumble it over time (Daan Stevenson et al.).

2.3 Propulsion systems

Traditionally most rockets use three types of propellants: liquid, solid, and hybrid. Liquid fuel is the most frequently used among the three and is the main source for NASA space shuttles, the Falcon 9, ATLAS, Titan, and Delta rockets. These are bi-propellant rockets as they use two propellants: fuel and oxidizer. These materials are stored in two different tanks and are pumped into a combustion chamber by a turbopump. Liquid oxygen (LOX) is the most common oxidizer, and liquid hydrogen, liquid nitrogen, and kerosene are the most commonly fuels. While liquid fuel-based rockets are safer to use, the fuel tends to react with the outside environment and have to be stored at low temperatures and high pressures. ("Liquid Rocket Propellants") As an alternative, solid fuel may also be used. Solid fuels defleorgate, which is a slow burn, and they have a grain structure usually made of ammonium perchlorate, ammonium nitrate, and HTPB (Hydroxyl-terminated polybutadiene). (Galfetti et al.) Recently hybrid rockets have gained popularity with companies such as Virgin galactic basing their design on them. Hybrid rockets use solid fuel with a liquid oxidizer. This mixture allows hybrid rockets to control their speed by modulating the rate of injection of liquid oxidizer into the solid fuel via a valve. For these rockets the most popular oxide is N2O, and the solid fuel is usually paraffin wax.

2.4 Mining methods

Methods of mining an asteroid will differ from here on Earth, due to the smaller gravitational force of attraction holding the asteroid together. Methods such as drilling, blasting, and crushing will be adapted for microgravity situations. The method for extraction will vary for different types of asteroids and resources. Ice mixture asteroids would require equipment to blast, heat, and distill the water to create rocket fuel and access materials. For hard rock asteroids, the mining process would involve a disc cutter, chemical separation, and magnetic separation.

2.4.1. Processing of Nickel and Iron:

Nickel and iron are common in asteroids, and since these metals are important in construction, mining them from asteroids may be less expensive than transporting them from Earth. The Mond process, also known as the carboxyl process, is used to extract nickel and iron in a highly pure state. The reaction works by heating nickel in the presence of Syngas, a mixture of carbon monoxide and hydrogen, to remove oxygen and leave impure nickel. The impurities mainly consist of cobalt and iron. In the next step, the impure nickel reacts with carbon monoxide to form nickel tetracarbonyl. The reaction takes place at 330 K - 350 K. In the next step of the reaction, the nickel tetracarbonyl is subject to high-temperature ranges from 450 K - 470 K, causing it to break into pure nickel and carbon monoxide, which can be reused. On Earth, these temperatures are achieved using large furnaces powered by coke or HFO (heavy fuel oil) or LNG (liquefied natural gas). However, these methods might not be feasible in space since the raw materials would be difficult to transport.

2.4.2 Processing of Platinum group metals

Platinum group metals consist of ruthenium, rhodium, palladium, osmium, iridium, and platinum. These metals have high densities, and, over time, they sank into the Earth's crust through a process known as differentiation. However, due to asteroids' low gravity, the magnitude of the differentiation effect is much lower and thus these metals are more accessible. Due to the difference in the locations, different techniques will be applied to mine platinum group metals.

Currently, most platinum is mined using underground mining methods. After the ore is mined and the particles are sized properly, a froth flotation process is used to separate metal and gangue Here the air is passed through the mixture of rubble and water. This process allows platinum-rich particles to surface in the froth, which is skimmed off and collected. Once this froth is filtered to form a cake, the cake is heated at high temperatures to remove impurities like sulfur. Copper and iron are also removed by heating at high temperatures in the presence of coke. ("Platinum Mining And Refining | Education")

3. Results

These technologies have now come to the fore front of scientific research. The following paragraphs discuss the data and its significance. The paper will cover the environmental impact of asteroid mining as discussed by Andreas Makoto Hein, Michael Saidani, and Hortense Toll; new methods of asteroid detection; and possible asteroids to mine.

3.1 Environmental impact of mining on earth

According to the EPA, the mining industry is a source of more toxic and hazardous waste than any other sector. As shown in Fig .2, the mining industry was responsible for 1.6×10^{10} tons of carbon dioxide emission in 2015. In addition, depending on the mining method, entire ecosystems can be destroyed, displacing flora, fauna, and indigenous societies. With asteroid mining, while the pollution due to the refining process would still remain, the carbon dioxide emissions and water pollution due to the direct mining process would be significantly lower. However, the process of launching the required spaceships and the emissions caused by the combustion of the fuel uses significant energy and fuel.

3.1.1 Environmental benefits of platinum through asteroid mining

Platinum is one of the most precious metals in the world and has uses in medicine, technology and even fuel. However, platinum's production mechanism uses large sums of water and emits high levels of greenhouse gases. Open cast mining and blasting techniques generate a large amount of solid waste. As the demand for platinum in technology increases, these negative externalities will increase. However, with asteroid mining, solid waste can be significantly reduced. Moreover, techniques such as mirror reflection can be used. This process has low water usage, and because there are no known habitats in space, it will avoid any damage to ecosystems. In their paper “Exploring Potential Environmental Benefits of Asteroid Mining,” Andreas Makoto Hein, Michael Saidani, and Hortense Toll analyzed the differences in CO2 between traditional mining and potentially mining asteroids. They compare the life cycle inventory of space systems and the mining process to compare the carbon emissions. They evaluated the primary carbon emissions from extraction to factory as well as emissions from the launch and assembly of the spacecraft. Their results indicate that a kg of platinum through asteroid mining will emit 150 Kg of CO2 while a kg of platinum from on-earth mining will emit 40,000 Kg of CO2. (Hein et al.)

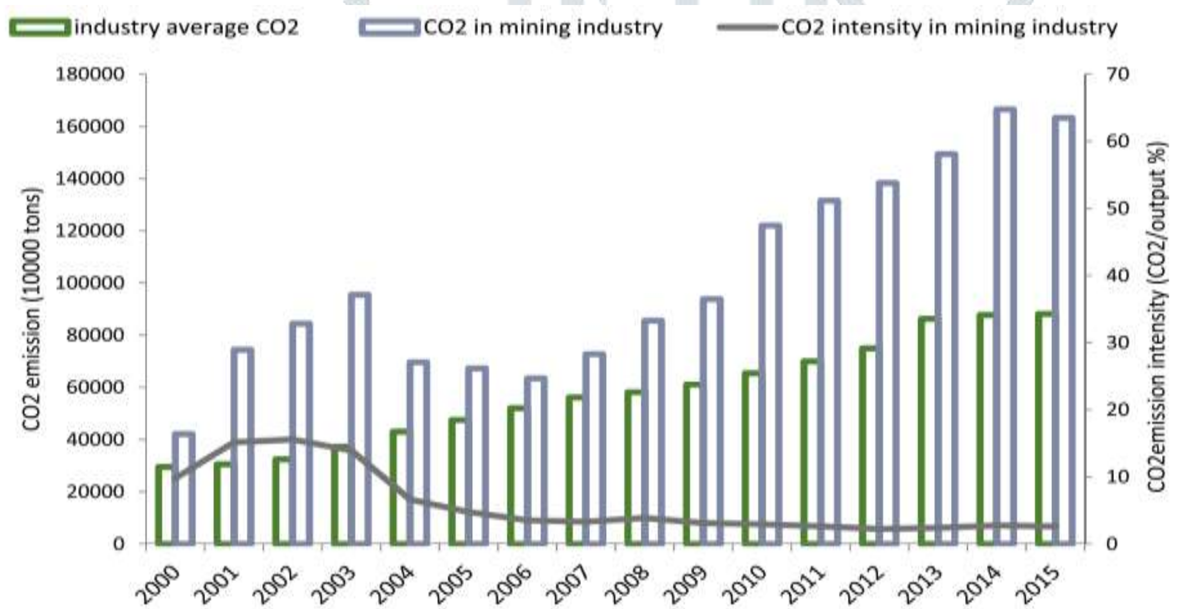


Fig. 2. CO2 emission of industrial average and mining industry and CO2 emission intensity in mining industry.
Data source: Statistical Yearbook of each province (2000–2015)

Figure 2

3.2 Asteroid detection

The German Aerospace Center (DLR) Institute of Planetary Research has classified the spin of an asteroid using the standard thermal model.

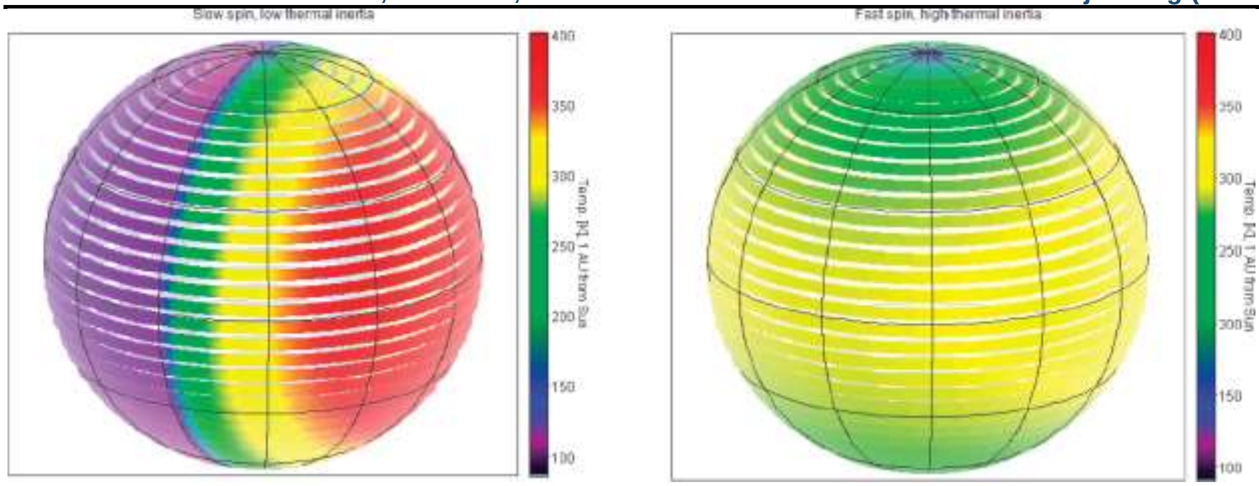


Figure 3 Thermal inertia over a period of time for a perfectly circular slow and fast spinning body (National Academies of Sciences)

In the researchers' modeling, they assumed the asteroid to be spherical, as seen in Fig. 3. The amount of solar energy incidents on the surface of a prospecting asteroid can be determined from information about its orbit and the Sun's radiation output. Following the calculation, an iterative procedure is used to calibrate the model's prediction luminescence of the asteroid. From this, a best-fit value of the diameter is obtained. The variance in the thermal inertia can also be measured with the large differences suggesting a lower spin rate. The spin axis can also be modeled using a similar technique where the locations of the higher temperatures are used to find out the axis of rotation, as seen in Fig. 4. (Jones)

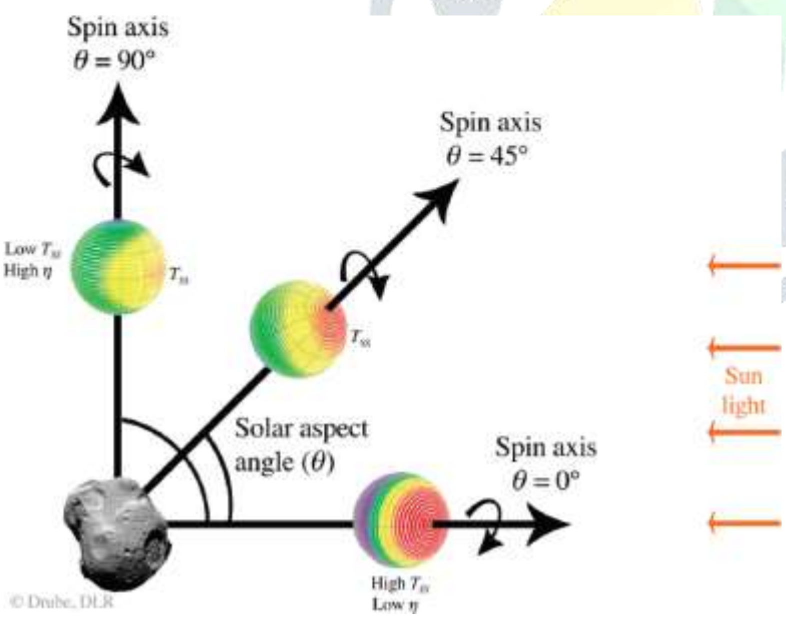


Figure 4 thermal inertia of perfectly circular bodies with different spin axis's of rotation (National Academies of Sciences)

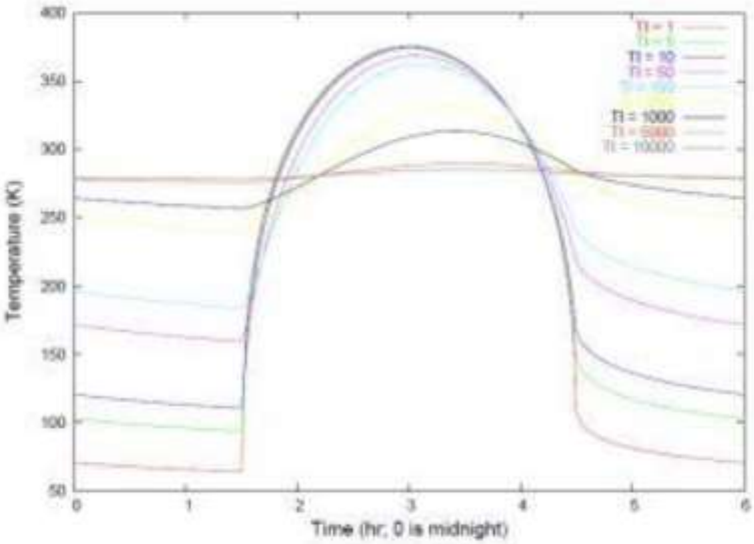
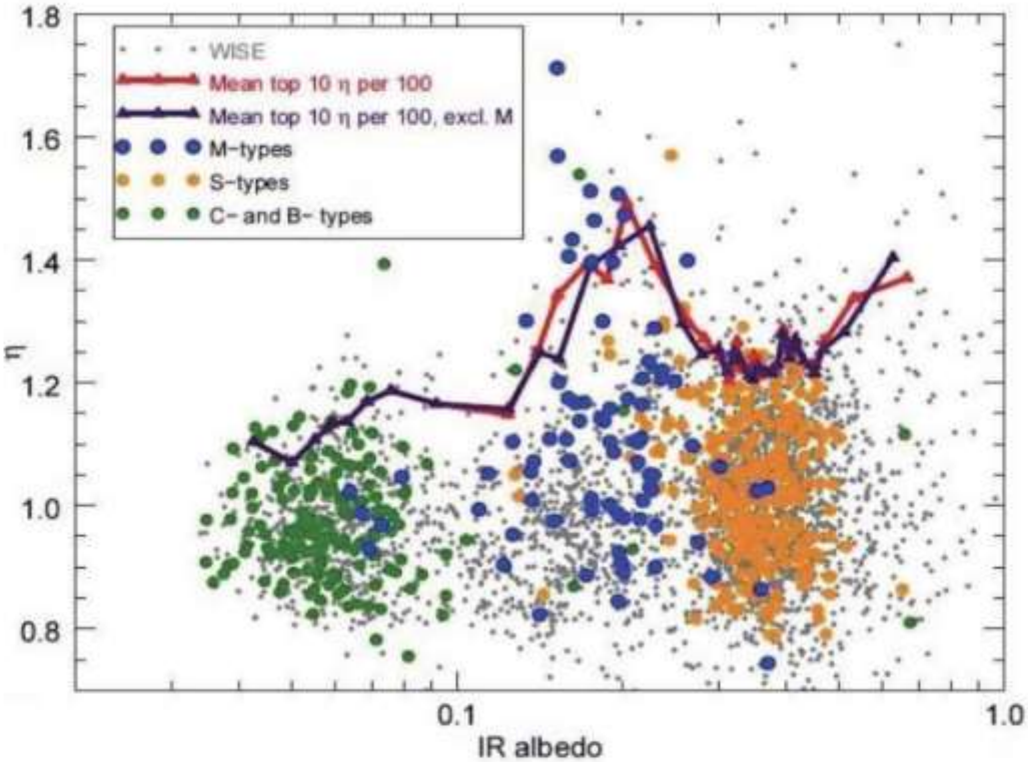


Figure 5 change in the temperate of objects with different thermal inertias 6 hours after midnight (Jones)

The temperature changes over time can also be modeled as seen in Fig. 5 because different elements have different thermal inertia. The change can be modeled and compared with elements on Earth to classify the composition of the asteroid. Additionally, using this data, Harris and Drube (2014) state that "the best-fit η value is a measure of the departure of an asteroid's temperature distribution from that of an object with a smooth surface and zero thermal inertia or spin in thermal equilibrium where η = 1". (Myhrvold) Additionally, the total thermal inertia of an asteroid can then be used to estimate its size because thermal inertia is inversely proportional the diameter.

These models were then applied to data collected by Mid-Infrared Interferometric Instrument (MIDI) and the Very Large Telescope Interferometer (VLTI) at the European Southern Observatory (ESO) about the asteroid Daphne with a systematic uncertainty of 4% and 7% respectively. These results were used to further calibrate data from the Wide-field Infrared Survey Explorer (WISE) telescope, to plot η against IR albedo setting parameters for M,S,C type asteroids as shown in Fig 6.



(Myhrvold)

Figure 6 Compares value of η and the IR albedo of different types of asteroids (National Academies of Sciences)

3.3 Asteroid Selection

Currently, NASA has cataloged over 15000 NEOs. This research has focused on different parameters to select asteroids to exploit. The first of these conditions is having a low ΔV. ΔV is a measurement of energy needed, calculated through the Tsiolkovsky rocket equation. The ΔV for any prospecting asteroid should be less than five km/s. The second parameter is the tumbling or spin rate. Higher spin rates increase the complications for landing and mining on an asteroid as well as transporting it to high lunar orbit. The size of an asteroid is also vital. If an asteroid is quite large, detumbling and transportations may be too difficult to occur. If it is too small, the asteroid may not have sufficient resources to make the mission economically viable. According to Planetary Resources, the ideal asteroid would be around 300m in diameter. The orbit of an asteroid is also significant in deciding its feasibility for exploitation. NEOs can be classified into having three types of orbits as shown in Fig 7.

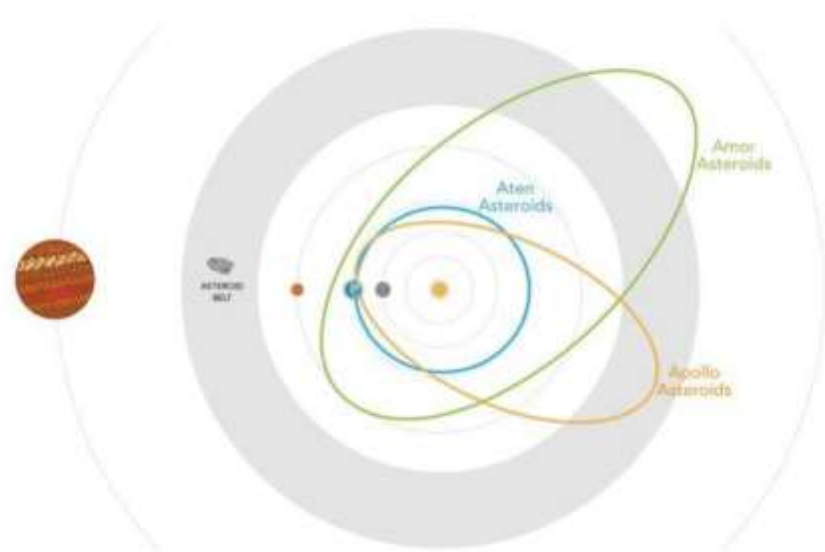


Figure 7 illustrations of the different types of orbits for NEAs (National Academies of Sciences)

The three types of orbits are classified as Aten, Amor, and Apollo. Aten Asteroids are asteroids crossing Earth with semi-major axes smaller than 1 AU. Apollo Asteroids are asteroids crossing Earth with semi-major axes larger than 1 AU. Amor Asteroids are Earth approaching asteroids with orbits that are between the Earth and Mars. (Gaffey)

3.3.2 Possible Asteroids:

The niche parameters lead to a very small number of asteroids that are within reach, easily accessible, have enough resources for profit, and do not have a high spin rate. However, some asteroids have passed most if not all parameters. While short, the current list of possible asteroids includes Ryugu, 1989 ML, Nereus, Bennu, Didymos, 2011 UW158, Anteros, 2001 CC21, 1992 TC, 2001 SG10, and Psyche 16. ("Asteroid Database And Mining Rankings - Asterank")

Asteroid	Est. Value (US$billion)	Est. Profit (US$billion)	Δ V (k m / s)	Composition
Ryugu	83	30	4.663	Nickel, iron, cobalt, water, nitrogen, hydrogen, ammonia
1989 ML	14	4	4.889	Nickel, iron, cobalt
Nereus	5	1	4.987	Nickel, iron, cobalt
Bennu	0.7	0.2	5.096	Iron, hydrogen, ammonia, nitrogen
Didymos	62	16	5.162	Nickel, iron, cobalt
2011 UW158	7	2	5.189	Platinum, nickel, iron, cobalt

Anteros	5,570	1,250	5.44	Magnesium silicate, aluminum, iron silicate
2001 CC21	147	30	5.636	Magnesium silicate, aluminum, iron silicate
1992 TC	84	17	5.648	Nickel, iron, cobalt
2001 SG10	3	0.5	5.88	Nickel, iron, cobalt
Psyche	27.67	1.78	-	Nickel, iron, cobalt, gold

Table 1 summary of possible asteroids to mine along with estimated value , profit delta v and composition ("Asteroid Database And Mining Rankings - Asterank")

4. Discussion

While many methods to pinpoint usable asteroids and potentially extract resources have been developed, significant advancements need to occur before the first resources can be mined. Some of the most important will be the development of a specialized fleet of spaceships, more efficient rocket propellant, optimized mining methods, and inexpensive payload return techniques.

4.1 Electric engines

Chemical rockets require large amounts of fuel and oxidizer to propel payloads to space. The most efficient rocket currently is the Falcon Heavy. The 500-ton rocket with payload contains approximately 400 tons of propellant. Additionally, the burn time for stage one is 162 seconds, and for the second stage, it is 397 seconds, (Colvin) giving a total burn time of approximately 9.5 minutes. Due to the high fuel costs, acceleration in space is mainly dependent on gravitational assists, and maneuvers are very rarely conducted to conserve fuel. However, ion thrusters can overcome these short bearings. While they do not produce enough force to propel rockets into space, once in space, ion thrusters can be more efficient than solid or liquid propellants. Ion thrusters propel ions at 90 km per second compared to 5 km per second of the most efficient chemical thrusters. The difference enables a 90% efficacy of ion thrusters compared to the 35% efficiency of chemical thrusters. (Colvin)

Ion thrusters work by ejecting positively charged ions by bombarding a gas like xenon with electrons generated from plasma. This bombardment creates electrons and positive ions. These positive ions are then siphoned out from a grid at the end of the thruster and propelled by strong magnetic fields to a speed of up to 90km per second. These ion thrusters have already proven successful on many missions. First introduced in the Deep Space One mission, ion thrusters have also been used in the Dawn mission and on the Japanese Hayabusa spacecraft. (Jones)

4.2 3D Printing heat shields

Once a successful mining operation has occurred, the next step is to return payloads of ore. With current technology, the most efficient method would use spaceships. However, as technology develops, the iron, nickel, and silicates extracted from asteroids, which have low-profit margins, can be utilized to 3D print a pod with a heat shield. This pod would be able to land in the ocean and be retrieved by a ship. Regolith has insulating properties, and when coupled with the silicates on asteroids, the mixture can be used to fabricate thermal-protection materials to create a heat shield. The heat shield has to be resilient against high temperatures due to the speeds of up to Mach 14, around 14 km/s reached during reentry. (Thomas) This resilience is achieved by using a silicate gangue to separate silicate from the target metals; the silicates will then be used to form a single-use heat shield for the shuttle cargos to bring the metals to Earth's surface. Arc test jets performed by NASA have suggested these have high reliability for one-time use. (Jones)

5. Conclusion

If humans want to become a space-bearing civilization, researchers must develop and understand technology to make asteroid mining technologically and economically sustainable. In the efforts to colonize and explore different planets like Mars, the development of technology for asteroid mining will allow for faster and safer missions. Through these technologies, asteroids might be used as space stops for refueling and repairs one day. Additionally, with growing concerns over greenhouse gas emissions and an increase in the usage of rare earth elements in everyday lives, finding a sustainable method to provide large quantities of metals like platinum will become an exceedingly important goal. To reach this goal, scientists need to improve their detection methods and combine spectrophotometry and thermal modeling to increase accuracy. Additionally, detumbling mechanisms for asteroids rotating at high velocities need to become more reliable and eclectic engines need to be developed to decrease fuel consumption and increase the distances rockets can travel. However, if this goal is achieved humans will take a big step towards becoming a space bearing civilization cementing our place in the history of the universe.

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