A Bridge to the Future

SpaceTech White Paper

Image Source: Bloomberg

Asteroid Mining: Key to Large-Scale Space Migration or Rocky Road?

Contents

INTRODUCTION TO ASTEROID MINING

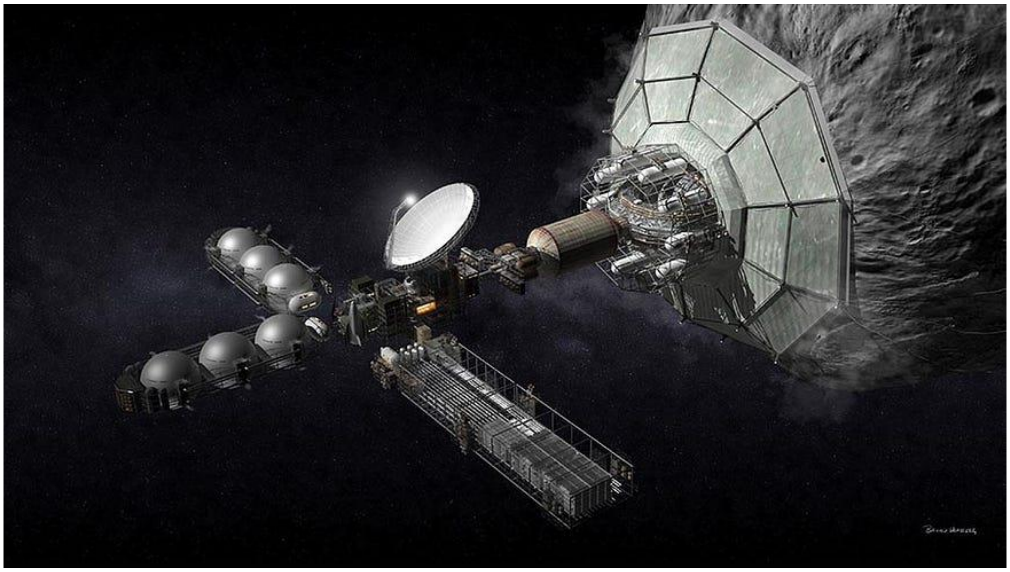
The Dream

The idea of asteroid mining first entered the realm of possibility with the dawn of the Space Age in the mid-20th century. Initial discussions were largely theoretical, rooted in science fiction rather than scientific feasibility. Authors such as Isaac Asimov and films like "Alien" and "The Empire Strikes Back" popularized the concept, imagining a future where humanity harvested the solar system's resources. However, it wasn't until the latter part of the 20th century that scientists and engineers began to seriously consider the challenges of creating an industry out of an idea. The realization that asteroids could contain vast amounts of valuable materials—such as water, precious metals like platinum and gold, and rare minerals—provided a tangible incentive to explore the feasibility of mining operations beyond Earth.

In the 1970s and 1980s, Gerard K. O'Neill, a physics professor at Princeton University and founder of the Space Studies Institute, developed a bold plan for human expansion into the solar system that included asteroid mining as a key component. O'Neill's basic premise was that building a new human civilization beyond Earth should not focus on planetary surfaces, but rather on communities built in "free space." The primary building blocks would be materials mined from the asteroids and the Moon. O'Neill envisioned these habitats being located at the LaGrange Points between the Earth and the Moon, where the gravitational pull of the two planetary bodies balances out, keeping these "islands in the sky" perpetually in place. The O'Neill communities might be envisioned today as very large space stations that would be Earthlike environments, with an atmosphere and variable gravity from weightlessness to "One-G" (the same as Earth). If achieved, his vision could eliminate many of the hazards to human health of the space environment, and make off-world living far more tolerable for large numbers of people.

Today, entrepreneurs like Jeff Bezos are following the vision laid out by O'Neill. The main difference is that Bezos has the financial resources to realize the dream, whereas O'Neill did not. Today's concerns about damaging the lunar environment make the Moon far less attractive for mining, but the asteroids continue to intrigue space advocates and entrepreneurs, and the motivations for mining them now include not only Large-Scale Space Migration, but also the opportunity to make a profit.

Chart 1: What Mining Would Look in the Future



Source: Intro Act, [The Medium]

ECONOMIC AND MARKET ANALYSIS

The Reality

Asteroid mining has shifted from science fiction to a potential industrial reality in the minds of many. Advances in space technology, robotics, and remote sensing have made the prospect far more plausible. Several companies, including Planetary Resources and Deep Space Industries, were founded with the explicit aim of pioneering the asteroid mining industry. These companies focused on developing the technology needed to prospect, land on, and extract resources from asteroids. However, neither company has been successful in achieving its goals and both were acquired by other entities.

In addition, Luxembourg decided to make itself a center of asteroid mining development, welcoming companies with plans to exploit this extraterrestrial natural resource.

Challenges

The **economic and technological challenges, however, have proved to be significant**. Identifying suitable asteroids, reaching them, and then successfully extracting and returning materials to Earth, or using them in the outer space environment, presents a complex array of engineering and logistical hurdles. The asteroid belt is far from Earth, between Mars and Jupiter. Getting there, conducting mining operations, and returning home is not an easy or inexpensive task. While there are asteroids known as near-Earth objects (NEOs), finding and reaching them is also challenging. However, there is a strong consensus among knowledgeable observers that the primary value of asteroid mining will be in helping to build an off-world infrastructure, rather than returning extremely valuable materials to Earth. For example, blogger Casey Handmer states that "There are no known commodity resources that could be sold on Earth." His primary argument focuses on how long it will take for off-world supply chains to compete with terrestrial ones.

Moreover, the **legal and regulatory framework** for space mining remains underdeveloped. The Outer Space Treaty of 1967, which establishes a legal framework for international space law, states that outer space, including the Moon and other celestial bodies, is not subject to national appropriation by "claim of sovereignty, by means of use or occupation, or by any other means." This wording raises questions about what the private sector can and cannot do, who has the right to mine asteroids, and how the resources should be shared. To get around some of these questions, the US Congress passed a law in 2015 stating that companies could extract the materials in an asteroid without claiming ownership of the asteroid itself. The Space Resources and Utilization Act states:

"Any asteroid resources obtained in outer space are the property of the entity that obtained such resources, which shall be entitled to all property rights thereto, consistent with applicable provisions of Federal law." This idea is something like owning the mineral rights under a plot of land without owning the land.

Despite the challenges, there have been notable advancements, led largely by government space programs. Missions like NASA's OSIRIS-REx and Japan's Hayabusa2 have successfully collected samples from asteroids, demonstrating the feasibility of rendezvousing with and extracting materials from these celestial bodies.

Asteroid mining remains a complex and costly endeavor. Here are some of the associated costs:

- ✓ **Exploration**: Identifying suitable asteroids for mining is a significant part of the cost. Companies like **Planetary Resources** and **Deep Space Industries** designed satellites that identified about 15,000 asteroids with significant potential for mining This was an important step for the industry, but only the first step.

- ✓ **Development**: The development of asteroid mining technology is expensive. Similarly, asteroid research missions are complex endeavors and return a tiny amount of material relative to the size and expense of these projects. For example, the Hayabusa missions (1 and 2) cost hundreds of millions of dollars, while the cost of OSIRIS-REx amounted to $1.16 billion.

- ✓ **Operations**: The operational costs of asteroid mining missions are also high. It currently costs hundreds of millions to billions of dollars to build and launch a space mission, so innovations that would make these costs fall dramatically are needed before it is profitable to mine asteroids for the value of their metals alone. Despite these high costs, the potential payoffs could be enormous.

Factors Driving Growth

Even though the topic of economic viability of asteroid mining is currently debatable, some of the factors supporting its growth are listed below:

Abundant Resources: Asteroids harbor vast quantities of valuable metals, water ice, and other materials, exceeding Earth's reserves in some cases. Mining raw minerals from outer space holds **immense economic potential**, with asteroids in our solar system containing valuable metals like gold, platinum, cobalt, palladium, and iron. Estimates from sources like Asterank suggest that the **ten nearest and most viable asteroids** for mining could **hold approximately $1.5 trillion worth of resources**, rivaling the annual value of the entire global mining industry. This opportunity hints at a vast frontier for both terrestrial and in-space manufacturing endeavors. As noted earlier, however, the in-space component appears to be the more realistic application. Additionally, there is a lot of room for growth. It has been estimated that one asteroid, 16 Psyche, has **$700 quintillion** worth of gold and other precious metals, which is equivalent to around **US$93 billion** for each person on Earth! While this is an awe-inspiring number, the economic value of the resources on Psyche will depend on the costs of accessing the asteroid and transporting its cargo to a market.

Chart 2: What Mining Could Look Like in Future

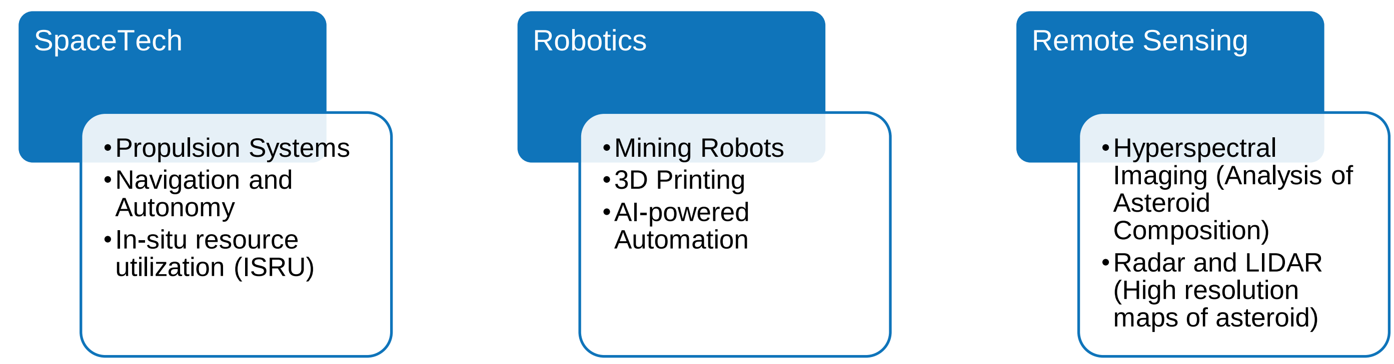
Mineral	Average Abundance g/mt in Metallic Asteroids	Earth's Crust Average Abundance g/mt
Iron (Fe)	893,000	41,000
Cobalt (Co)	6,000	20
Nickel (Ni)	93,000	80
Ruthenium (Ru)	22	<1
Rhodium (Rh)	4	<1
Palladium (Pd)	17	<1
Osmium (Os)	15	<1
Iridium (Ir)	14	<1
Platinum (Pt)	29	1
Gold (Au)	1	1

Source: Intro Act, PNAS, C. Dahl, B. Gilbert, I. Lange, Mineral scarcity on earth: Are asteroids the answer. Miner. Econ. 33, 29–41 (2020).

High Demand: Asteroids are rich with the metals used in clean energy technologies. As demand soars, advocates argue that mining them off-world might be better than mining them on Earth. This remains to be seen, but companies and researchers are actively developing mining and spacecraft technologies needed for asteroid missions. Companies like **AstroForge, Trans Astronautica Corporation,** and **Karman+** are preparing to test their tech in space before venturing toward the asteroids themselves. Also, growing private and government investments in space exploration create a supportive environment for asteroid mining ventures.

Space-Based Manufacturing: Advances in space technology, robotics, and remote sensing are laying the groundwork for its future potential. The combined impact of these is **reducing the technical and economic barriers to asteroid mining**. This can be seen in the form of efficient travel and operations, autonomous resource extraction and processing, detailed characterization of asteroids and reduced reliance on Earth-based resources.

Chart 3: Contribution of SpaceTech, Robotics, and Remote Sensing to Asteroid Mining



Source: Intro Act

Potential Industries for Asteroid-Derived Resources

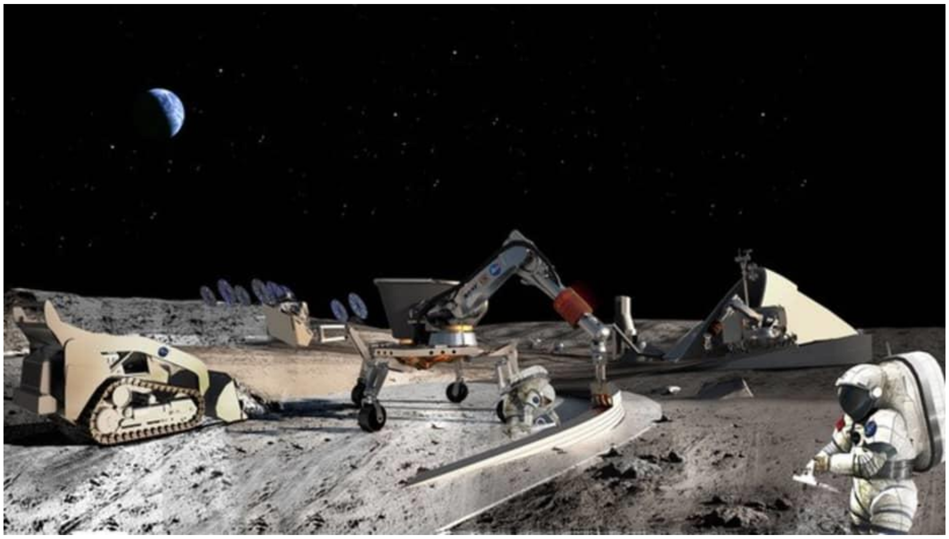
Several industries are actively involved in developing the technologies and capabilities needed for future asteroid mining, and they stand to see potential benefits once it becomes a reality.

Aerospace and Space Exploration: Companies like **SpaceX, Blue Origin**, and **Rocket Lab** are developing reusable launch vehicles that could significantly reduce the cost of transporting equipment and personnel to asteroids. Space agencies like NASA and ESA are conducting research missions and developing technologies relevant to asteroid mining, such as advanced robotics and navigation systems**.**

Mining and Resources: Traditional mining companies, like **Caterpillar** and **Komatsu**, are developing mining equipment and machinery that could be adapted for use on other planetary bodies. Resource companies, like **Rio Tinto** and **BHP**, are interested in the potential of platinum group metals and other valuable resources found in asteroids.

Renewable Energy and Green Technologies: Rare earth elements (REE) are widely dispersed and found in low concentrations that are not economically exploitable. Asteroids contain abundant REEs critical for clean energy technologies like wind turbines and electric vehicles. Mining these elements in space could alleviate supply chain issues and environmental concerns associated with terrestrial mining.

Chart 4: A NASA Rendering of Building a Permanent Base on The Moon Using Autonomous Vehicles



Source: Intro Act, CNBC, NASA

Healthcare and Pharmaceutical: Platinum-group metals are used in medical devices and cancer treatments. Asteroids might contain unknown biomaterials with medical applications for tissue regeneration, drug delivery, and other advancements.

Robotics & AI: Companies like **Astrobotic** and **Intuitive Machines** (which recently landed a spacecraft called Odysseus on the Moon) are developing autonomous robots for space exploration and potential asteroid mining tasks. Advances in AI and machine learning are crucial for automating various aspects of mining operations in the harsh space environment. These advancements could have broader applications in terrestrial robotics and automation, contributing capabilities to various industries.

Asteroid Exploration Missions

The Asteroid Mining industry is still in its early stages, and while there have been several significant government-sponsored missions paving the way, they have primarily focused on sample return rather than full-scale resource extraction.

Hayabusa (JAXA) - Japan's **Hayabusa** was the first spacecraft to take samples from an asteroid, and was also the first mission to successfully land and take off from an asteroid. It brought samples from asteroid 25143 Itokawa to Earth on June 13, 2010. Other scientific objectives of the mission included detailed studies of the asteroid's shape, spin state, topography, color, composition, density, photometric and polarimetric properties, interior and history.

Hayabusa 2 (JAXA) - **Hayabusa2** is a Japanese spacecraft that studied asteroid Ryugu, collected samples, and brought them to Earth for analysis. The spacecraft is now on an extended mission to asteroid 1998 KY26. On December 6, 2020, Hayabusa2 delivered the asteroid sample to Earth. The spacecraft swooped by Earth to drop a landing capsule containing the asteroid sample.

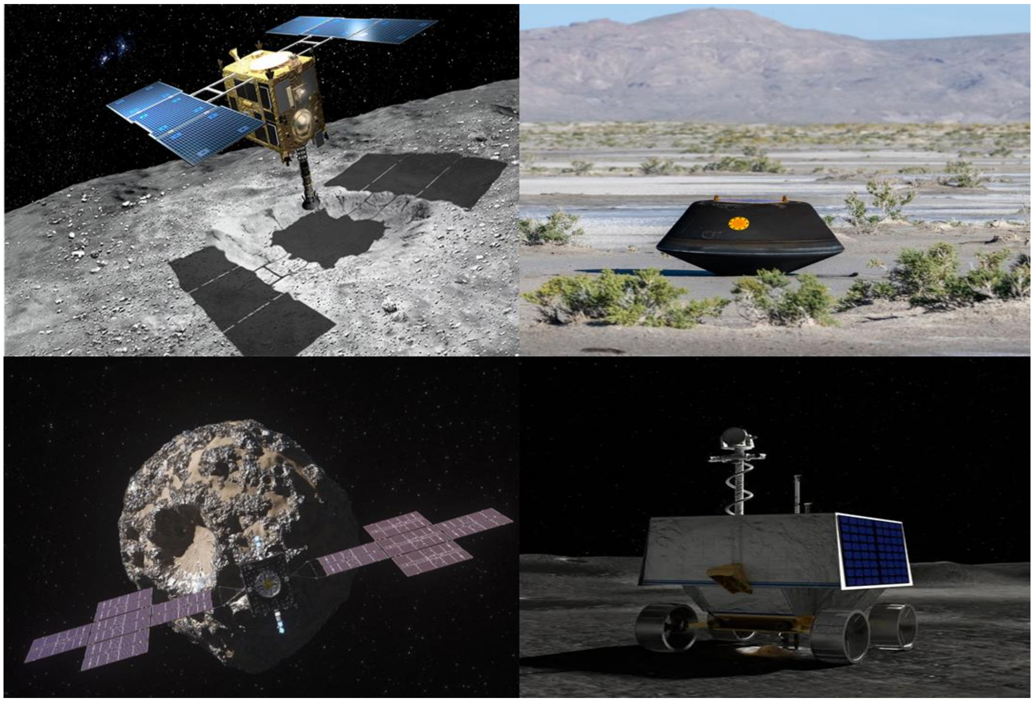
OSIRIS-REx (NASA): OSIRIS-REx is the first U.S. mission to collect a sample from an asteroid. It returned to Earth on September 24, 2023, to drop off material from asteroid Bennu. The spacecraft didn't land, but continued on to a new mission, **OSIRIS-APEX**, to explore asteroid Apophis. Meanwhile, scientists hope the

Bennu sample OSIRIS-REx dropped into the Utah desert will offer clues to whether asteroids colliding with Earth billions of years ago brought water and other key ingredients for life here.

Psyche (NASA): Psyche, launched on October 13, 2024, is a NASA mission to study a metal-rich asteroid located in the main asteroid belt between Mars and Jupiter. This is NASA's first mission to study an asteroid that has more metal than rock or ice. The Psyche spacecraft is traveling to a unique metal-rich asteroid with the same name, orbiting the sun between Mars and Jupiter. By August 2029, the spacecraft will begin exploring the asteroid.

Viper (NASA): NASA's Artemis lunar rover, the **Volatiles Investigating Polar Exploration Rover, or VIPER**, will explore the relatively close but extreme environment of the Moon in search of ice and other potential resources. This mobile robot will land at the Moon's South Pole in late 2024 on a 100-day mission. This lunar rover will search for water ice and other resources on the lunar surface, demonstrating technologies applicable to future asteroid mining.

Chart 5: Illustrative Images of Hayabusa (JAXA) (Top Left), OSIRIS-REx (NASA) (Top Right), Psyche (NASA) (Bottom Right) and Viper (NASA) (Bottom Left)



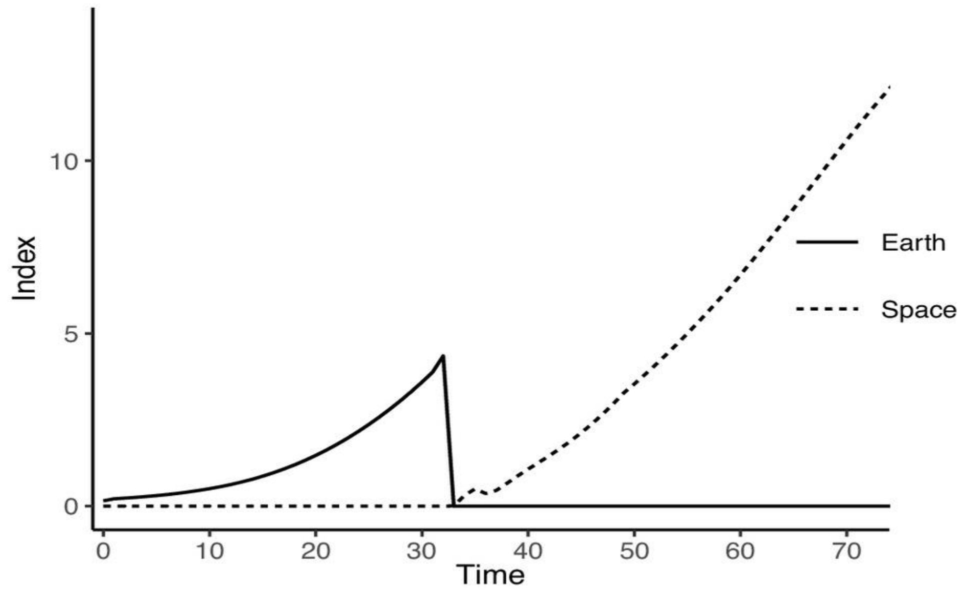
Source: Intro Act, NASA

Asteroid Mining Market Size and Funding Landscape

[Fact.MR](), in its newly published research report, reveals that the global space mining market has **reached a size of $1.7 billion in 2023**. Further, worldwide revenue from space mining is projected to increase rapidly at a **CAGR of 16.1%** and reach a market value of **$7.6 billion** by the end of 2033. A [Bloomberg]() article highlights that despite numerous setbacks and failures, asteroid mining companies have persisted in their pursuit of extracting valuable metals from space, drawing substantial investments from notable figures like James Cameron and Larry Page. However, success has remained elusive, with most ventures either going bankrupt or being absorbed by larger corporations. For instance, Planetary Resources, a promising startup backed by over $50 million, met its demise and was eventually acquired by a blockchain firm in 2018.

Nevertheless, the allure of space mining continues to attract fresh funding. Recent advancements, such as NASA's **Osiris-REx mission**, and NASA's funding initiatives for asteroid-mining research, have bolstered confidence in the burgeoning industry. More money from private investors, more rules from governments, and more missions into space are creating big chances for companies in the asteroid mining game.

Chart 6: Transition of Investment in Mining from Earth to Space



Source: Intro Act, PNAS

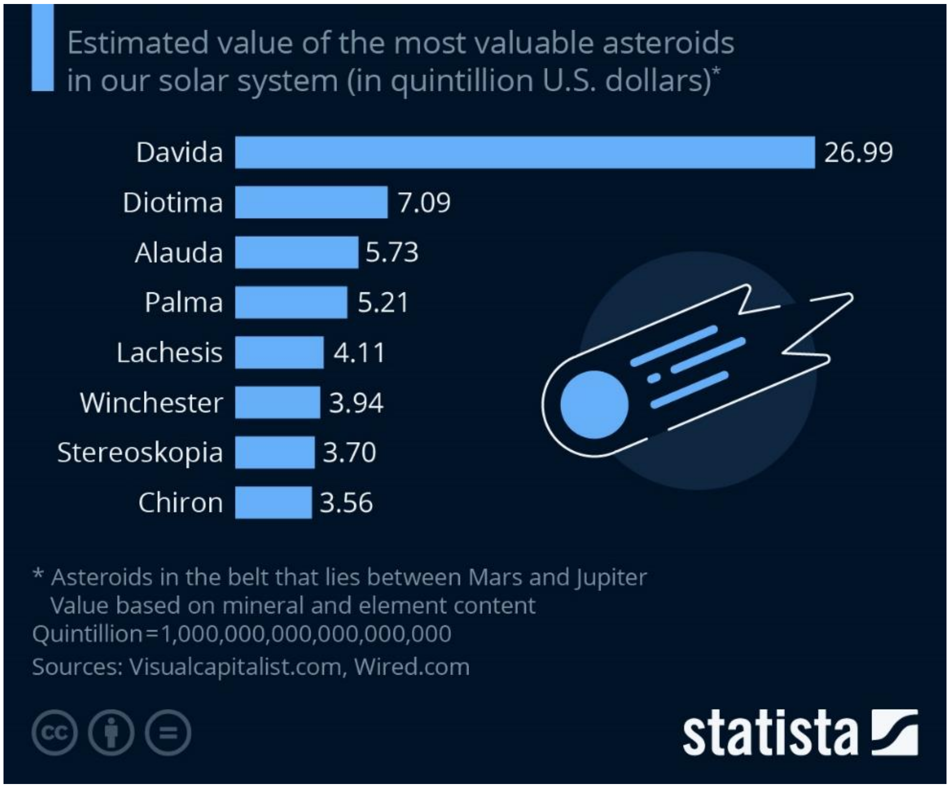
Asteroid Mining Future Outlook

In the coming decades, experts anticipate that space mining will prioritize resources crucial for space missions, not for returning materials to Earth. Rather than traditional metals, such as gold, water could emerge as the most valuable asset in space exploration. As launch expenses decrease and commercial ventures flourish, space-bound rockets will require refueling. According to Phil Metzger, a planetary physicist and former NASA engineer, typical rocket fuel consists of approximately 80% oxygen and 20% hydrogen or methane. Both oxygen and hydrogen can be derived from water through separation. The prospect of mining and refining oxygen and hydrogen directly from the Moon and asteroids appears to offer a more cost-effective solution compared to transporting these resources from Earth.

The evolution of space mining will likely be a slow burn, gaining traction as space exploration expands and extraterrestrial industry and supply chains emerge. **Robotic swarms are anticipated to revolutionize lunar mining operations**, leveraging similarities in chemical composition between Earth and the Moon, as per the Giant Impact Hypothesis. This method holds promise for extracting rare earth metals crucial for modern technologies, titanium for specialized alloys, precious metals like gold and platinum, and the scarce helium-3, potentially fueling future nuclear power plants. However, the energy and water demand of lunar mining poses significant challenges, prompting a University of Arizona team to develop innovative space-mining techniques utilizing collaborative autonomous robots. The team was backed by NASA with funding of $500,000 in 2021. Further, the **exploration of near-earth asteroids (NEAs) may represent a lucrative investment opportunity**, with estimates **exceeding $11 trillion** in valuable resources. Capturing a small Near-Earth Object (NEO) or a portion of a larger celestial body holds significant scientific and technological promise in the coming decades. These findings contribute to the development of an energy-cost framework, or resource map, offering insights into the future utilization of asteroids. Meanwhile, data from the Minor Planet

Center, the internationally recognized clearinghouse for small-body position measurements, shows that 2,818 near-Earth asteroids were discovered as of December 12, 2023. In all, 33,884 near-Earth asteroids have been discovered by NASA up till 2023. Aside from the great scientific value of metal-rich asteroids, they can also have colossal as-yet untapped economic value, too.

Chart 7: The Colossal Untapped Value of Asteroids (As on October 12, 2023)



Source: Intro Act, Statista, Visualcapitalist, Wired.com

Collaboration among nations plays an essential role as space exploration and mining are huge challenges that no single country or company can overcome alone. As noted earlier, Luxembourg decided to make itself a center of asteroid mining development, welcoming companies with plans to exploit this extraterrestrial natural resource. Along with Luxembourg, the US and China see the potential of space mining and are supporting its research and development. They're joined by others in the Artemis Accords, a set of rules for responsible space exploration and mining. NASA's Artemis program, aiming to establish a lasting presence on the Moon by 2024, includes plans for mining and resource use. Canada, Japan, and Europe are among the international partners.

COMPANIES TO WATCH

Following the flurry of activity by **Planetary Resources** and **Deep Space Industries**, the asteroid mining segment has been relatively quiet. The concept still holds great promise, both for building habitats and extracting valuable materials for a profit. However, investors will need to be patient and willing to give companies time to develop the technologies needed for successful implementation of the dream. One company appears to be among the leaders in the field at this time, and it brings a unique approach to the challenge of mining, both on Earth and in outer space.

OffWorld Inc

OffWorld offers a paradigm shift for the entire space exploration and migration enterprise. The company suggests that sending humans out in the first wave of development of space communities is a limited approach. Instead, we should start with swarms of highly intelligent robots who can prepare the way for human beings. This makes sense, because humans are fragile entities when faced with the weightlessness and radiation of outer space, whereas robots can manage both handily.

When it comes to asteroid mining, sending robots to the asteroid belt rather than people is a rational choice. While robots cannot ignore the radiation hazards along the way, they can make the trip without being as concerned about environmental hazards as humans have to be. Once at the Belt, they can carry out the mining, and then return to Earth or Earth orbit with their cargo. In a way, government space program efforts already cited have demonstrated that this is a realistic idea. However, it will be some time before materials mined on the asteroids will be competitive with terrestrial mining.

OffWorld's technology is also applicable to Earth-based mining, offering the possibility of using its robots to work underground, dramatically reducing the number of human miners who have to be exposed to the dangers of this type of work. The company has developed a fleet of robots that can work together to autonomously mine for materials.

Chart 8: Swarm Robotic Mining

Source: Intro Act, OffWorld Inc

In a strategic development, in April 2023, **OffWorld Europe** and the **Luxembourg Space Agency (LSA) signed a pivotal agreement** to launch a comprehensive, multi-year development program for an In-Situ Resource Utilization (ISRU) processing system focused on ice resources. This system will play a vital role in facilitating sustainable lunar exploration by enabling the extraction, processing, and storage of vital resources directly from the Moon's surface. OffWorld has secured a **total of $5.3 million in funding across two funding rounds**. Their most recent funding of $30+million, acquired on February 24, 2022, was obtained through a Grant round.

A number of other space mining companies are still in business, and most, if not all, of them take an approach similar to that of OffWorld, focusing much of their attention on robotic technology.

AstroForge Inc.

AstroForge is an asteroid mining company that was founded in 2021 and is headquartered in Huntington Beach, California. The company develops spacecraft payloads for extracting and refining materials in zero gravity, focusing on platinum-group metals, including platinum and iridium. Their mission is to mine asteroids to extract valuable minerals in outer space at a lower cost and smaller carbon footprint than the current terrestrial mining methods. AstroForge has made significant strides in its mission.

On April 15, 2023, they successfully launched their first mission, Brokkr-1, which aimed to validate AstroForge's full-system engineering team, flight-test critical subsystems in preparation for deep space, and extract platinum from an asteroid simulant. Despite facing challenges such as difficulties in identifying their satellite among others and issues with the magnetic field generated by their refinery system, the company persevered and achieved their first positive signal. The objective of the second mission remains the same: get to deep space, perform a flyby of the asteroid target, and take high resolution images of the surface. The company expressed that meeting just one of these objectives would be a groundbreaking achievement, not just for AstroForge but also for commercial space at-large. Meanwhile, mission 3 planning, design, and prototypes are being tested and the company plans to release more on that soon.

Chart 9: Brokkr-1

Source: Intro Act, [Nanosats Database]

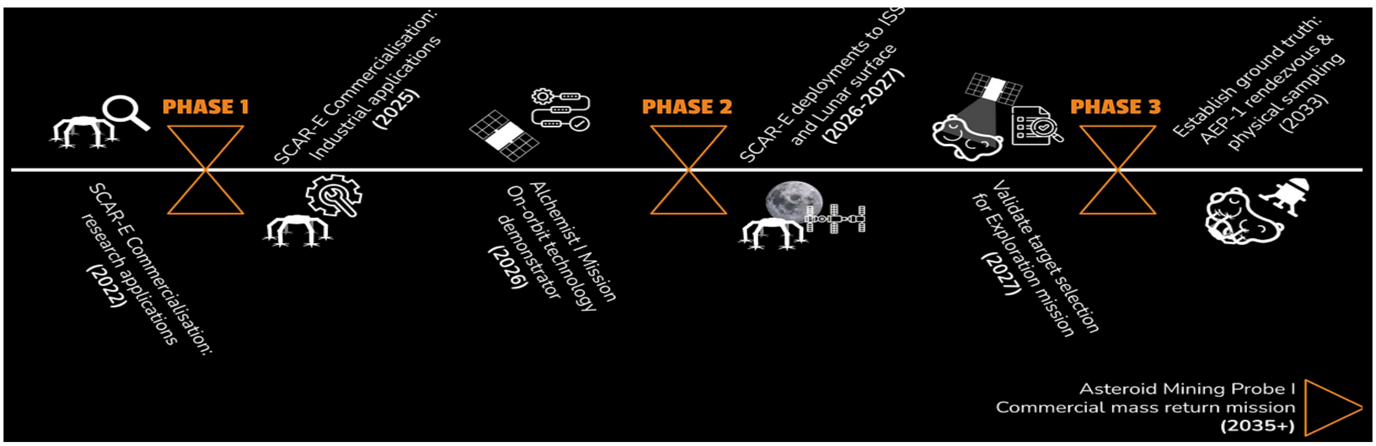
Looking ahead, AstroForge expects 2024 to be as full of challenges and opportunities as 2023. They plan to continue pushing boundaries in the field of asteroid mining and are committed to expanding humanity's capabilities in space. They are planning more missions into deep space, and their progress suggests that they may become **the first commercial company to mine an asteroid and bring the materials back to Earth**. AstroForge **has raised $13 million in total**, in its latest funding round in 2022.

Asteroid Mining Corporation

Asteroid Mining Corporation (AMC) is a **private British space mining company** that is currently developing robotic and satellite platforms to enable the exploration and extraction of off-world resources, including those from asteroids. Founded in 2016 by Mitch Hunter-Scullion, AMC is building on a series of technological innovations that will pave the way toward the profitable mining of space resources from the reduction of launch costs to an expansion of robotic capabilities. The convergence of these factors will enable the company to establish an extraterrestrial economy. AMC aims to approach the asteroid mining process in three stages: prospect, explore, and extract.

AMC will emphasize concurrent commercialization of its technology as it develops its capabilities, generating revenue from the outset. In February 2023, Asteroid Mining Corporation expanded its operations through formulation of US-based subsidiary, Asteroid Mining Co USA, LLC. With establishment of a subsidiary in America, AMC plans to take advantage of the favorable regulatory environment, the rapid growth of space sector funding, and higher opportunities to partner within the launch and space services industry.

Chart 10: AMC's Three-Stage Approach for Asteroid Mining



Source: Intro Act, Asteroid Mining Corporation

In October 2023, Asteroid Mining Corporation announced **SCAR-E Robot** (Space Capable Asteroid Robotic Explorer) which is a six-legged, 20-kilogram robot developed in collaboration with Tohoku University's Space Robotics Lab (SRL) in Japan. SCAR-E can navigate rough terrain, collect samples, and perform basic mining operations in the harsh environment of space. Beyond asteroid mining, SCAR-E can be used for tasks like in-orbit asset maintenance and lunar crater exploration. SCAR-E's hexapedal design allows access to locations inaccessible to previous missions, and its built-in universal attachment point enables precise delivery of a range of payloads to their desired location. The robot is still under development, with ongoing testing and refinement of its technologies. While offering SCAR-E for commercial industrial applications, the company will also develop Alchemist-1, a materials-processing satellite.

Asteroid Mining Corporation has raised a total of $1M in funding over one round. This was a seed round raised on May 4, 2022.

CONCLUSION

Looking to the future, asteroid mining could have profound implications for the development of human civilization beyond Earth, and there may also be benefits to Earth's economy. However, the latter development seems farther in the future than the former. The ability to extract water from asteroids could support long-duration space missions, providing life support and fuel for deep-space exploration and migration. The extraction of metals and other materials could lead to the construction of space-based infrastructure, including habitats, solar power stations, and even manufacturing facilities.

Economically, the potential return on investment may well be enormous, but could take longer to realize than many advocates believe. The value of precious metals and rare minerals contained within a single asteroid could run into the trillions of dollars. If realistic, and if costs of access can be reduced, such economic prospects could drive further innovation in space technology and potentially trigger new levels of competition focused on resource extraction.

Moreover, the technologies invented for asteroid and lunar mining are likely to prove lucrative on Earth, making terrestrial mining more efficient and profitable.

And if asteroid mining technology can be perfected, it would make Large-Scale Space Migration far more realistic, because it would hold out the promise of creating habitats that are Earthlike, inviting, and enticing to individuals and families looking for a new start in life.

However, the future of asteroid mining also hinges on overcoming significant challenges. These include technological barriers, the need for substantial initial investment, the development of a regulatory framework, and concerns about the environmental impact of space mining operations. Moreover, the ethical and equitable distribution of space resources remains a contentious issue that must be addressed.

In conclusion, asteroid mining represents a tantalizing frontier for both space exploration and economic development. From its origins in the realm of speculative fiction, it has evolved into a serious scientific and commercial endeavor. As technology advances and legal frameworks evolve, the mining of asteroids could become a key component of humanity's future in space, offering both challenges and opportunities as we extend our reach beyond Earth.

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