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Exploring the Scope of Solar Power for Asteroid Mining and Resource Collection Missions

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Abstract: ***Asteroid mining offers the potential to alleviate Earth's resource scarcity by extracting valuable materials from near-Earth objects (NEOs). A critical enabler of this emerging industry is solar power, which provides a sustainable and efficient energy source for space operations. This paper examines the role of solar power in asteroid mining, highlighting advancements in photovoltaic technology and progression in solar sail power systems. It also explores the economic feasibility, environmental considerations, and future challenges of solar-powered mining operations. As space exploration progresses, solar power is poised to play a central role in the development of a space-based economy through asteroid mining.***

Keywords: photovoltaic cells, asteroid mining, solar sailcrafts, propulsion systems, IKAROS, Hayabusa, Hayabusa 2, solar-powered sail

1. Introduction

For decades, humans have known about the existence of valuable minerals in space. In fact, current theories speculate that the vast majority of metals heavier than iron sank down to the Earth's core because they were denser than the hot semi-solid crust of the primordial planet. Much of the heavy metals we see on the Earth's crust were brought to the planet by collisions with asteroids several billion years ago. (University of Toronto)

As human civilisation demands ever-increasing quantities of rare metals with exotic properties, some have turned their gaze from mines underground to asteroids up in interplanetary space. Bringing materials from asteroids to the Earth lay in the realm of science fiction until the launch and return of *Hayabusa* by Japan's Aerospace Exploration Agency (JAXA) in 2010 (Amos). Since then JAXA's *Hayabusa2* and NASA's *OSIRIS-REx* missions have also successfully brought back material from asteroids and comets.

However, these missions were purely exploratory in nature and not designed for commercial mining. Several technological challenges need to be overcome before large-scale mining of asteroids becomes commercially feasible. One significant challenge is the need for energy, both to operate mining equipment and to move the mined ore to a site where it can be refined and utilised. While the *Hayabusa* and *OSIRIS-REx* missions used solar photovoltaic arrays to power their onboard equipment, they used chemical rockets or ion-propulsion systems to travel to and from their target asteroids. These are impractical for long-term commercial mining.

Solar power, due to its abundance and renewability, may emerge as a feasible candidate to meet the energy demands of asteroid mining. In addition to photovoltaic cells for electricity, solar energy can also be harnessed for propulsion in the form of solar sails. This paper will discuss key developments towards utilizing solar energy for asteroid mining, highlighting a growing interest and feasibility in exploiting space resources.

Necessity of Asteroid Mining

Asteroids are rich in metals, including platinum, gold, and rare earth elements, as well as water and other volatiles. These resources could be mined and transported back to Earth or used to support space exploration. Both of these activities will reduce dependence on minerals and organic compounds on Earth. Resources mined from asteroids could be used as feedstocks for factories in outer space, which could in turn be used to build and outfit spacecraft for further exploration. Spacecraft built entirely in outer space will not need large amounts of fuel to overcome Earth's gravity, nor aerodynamic streamlining or strong heat shielding to cut through Earth's atmosphere.

However, as mentioned earlier, the challenges of asteroid mining are substantial and require the development of several technologies including, but not limited to, autonomous mining equipment, efficient energy sources, and the ability to process materials in microgravity (Hellgren, Vide).

Solar power is seen as a critical component of these operations, offering a sustainable and scalable energy solution. The deployment of solar sails can also facilitate the distributed close-range survey of asteroids, allowing a fleet of nano spacecraft to collect extensive data across multiple asteroid families, which significantly reduces mission costs and increases the scientific return (Slavinskis et al.)

Why Solar Energy?

Solar power is the most prevalent energy source for spacecraft and satellites, harnessed through photovoltaic (PV) cells that convert sunlight into electricity. The absence of an atmosphere in space allows solar panels to operate with higher efficiency compared to Earth, making them ideal for powering operations outside of the planet. Solar power is particularly suited for long-duration space missions due to its reliability and the minimal maintenance required for solar arrays in space. Advancements in PV cell architecture mean that solar PV power systems can be successfully used on probes operating very far from Earth, such as NASA's *Juno*, which is currently in orbit around Jupiter. Previously, spacecraft that went beyond the orbit of Mars were almost exclusively powered by radioisotope thermoelectric cells, such as *Voyager*, *Pioneer*, and *Galileo* (Verduci et al.)

While solar PV cells can power mining operations once a spacecraft reaches an asteroid, getting to the asteroid cheaply and efficiently is another matter altogether. Solar sails have been identified as a promising technology for asteroid mining and related missions due to their ability to provide efficient,

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low-thrust propulsion, which is crucial for navigating and manoeuvring in space (Janhunen et al.)

The concept behind the solar sail was proposed by Johannes Kepler back in the 1600s, after observing that a comet's tail curves depending on its orientation to the Sun. Maxwell's studies of electromagnetic fields and Einstein's work on the photoelectric effect gave solar sails their theoretical foundations. Maxwell had shown that electromagnetic waves had momentum, and Einstein showed that the momentum of photons was inversely proportional to their wavelength. Photons can transfer their momentum when they collide with an object. Highly reflective surfaces increase the efficiency of collision and transfer of momentum, rather than absorption of the photon (Encyclopædia Britannica). An object that is lightweight and reflective would therefore be able to move due to the collisions of photons on its surface.

As the name describes them, solar sails are large, lightweight, and extremely thin sheets which can be made of a variety of materials such as carbon nanofibres, metal alloys or synthetic polymers. The Japanese sailcraft *IKAROS* uses a 20-metre-long diagonal square solar sail, with 0.0075 mm thickness made from thermal resistant polyimide resin (Bryant, Robert G. et al). Additionally, they can be crafted out of different materials, the LightSail 2 utilised a lightweight polymer Mylar, coated with a reflective metallic layer (The Planetary Society).

In addition to reflective solar sails such as the ones on *IKAROS*, other kinds of solar sails have been proposed. These include diffractive sails that capture the momentum of photons through diffraction instead of reflection, as well as electric and magnetic sails that use the energy of plasma in the solar wind instead of the photons in sunlight. (Swartzlander; Janhunen et al.)

Case Study: The Hayabusa Missions and Solar Sailcrafts

Given the requirements for asteroid mining, such as the need for an imaging device installed, and landing gear installed for atmospheric re-entry and landing back to Earth. A solar sail possesses multiple advantages over traditional satellites that may be utilised for the same. Taking the example of Ryugu or *1999 JU3* which is located approximately 97,803,867 kilometres away from Earth (TheSkyLive). We can compare the economics and viability of utilising traditional satellites and solar sails.

The *Hayabusa* and *Hayabusa 2* missions executed the first asteroid sample retrieval in the years 2010 and 2020 respectively, with the latter having rendezvoused with the same asteroid being used for comparison, Ryugu.

The *Hayabusa* satellite weighing 510 kg travelling at approximately 1,400 m/s or 5,040 km/hr rendezvoused with the asteroid Itokawa, located 1,960,000 km away from Earth, after two years of deep space flight. The satellite did not rely solely on traditional chemical-based boosters but rather utilised 4 cathode-less electron cyclotron resonance ion engines, µ10 alongside 12 Bi-propellant RCS thrusters. The ion engines were powered by triple-junction cells each producing 2.6 kW at 1 AU. With each ion engine being able to generate 8mN and a maximum of three being able to function simultaneously alongside the thrust generated by 12 chemical thrusters producing 20 N; the maximum acceleration that would be possible for the *Hayabusa* is limited to 0.4706 m/s^2 or 0.0004706 km/s^2 (NASA, "Hayabusa - NASA Science"). Furthermore, the overall weight of the propulsion engines and propellant storage was 369 kg, which meant the payload of control systems, scientific instruments, and sample recovery compartment was limited to 141 kg. This meant that the payload was 26.7% of the total mass of the spacecraft.

The *Hayabusa 2* launched in 2014 was a modified version of its predecessor the *Hayabusa*, it was a 600 kg box-shaped satellite that rendezvoused with its target, Ryugu, after a duration of 2.5 years (an initial revolution around the Earth increased the time to 3 years) (NASA, "NASA - NSSDCA - Spacecraft - Details"). *Hayabusa 2's* average speed was as 3638 km/hr, which was slower than the *Hayabusa*. Like the Hayabusa, the upgraded version was propelled by 4 xenon-ion engines with a maximum thrust of 10 nM per engine, in addition to 12 20-N bipropellant hydrazine thrusters. The total mass comprised by the propulsion for the Hayabusa 2 is 335 kg, comprising of xenon-ion propellant, the engine system mass as well as the chemical propellant (JAXA,"Asteroid Explorer 'Hayabusa2'"). This results in a 44.2 % mass percentage comprised of satellite build and payload. Furthermore, the maximum acceleration that can be generated by the Hayabusa 2 is 4.007 m/s^2 or 0.004007 km/s^2.

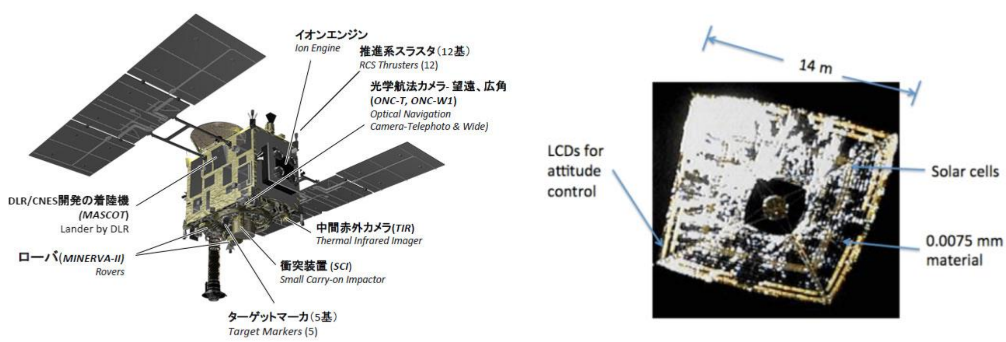

Figure 1: External views of the Hayabusa 2 spacecraft and IKAROS (Globus et al.) & (JAXA, "IKAROS Mission Overview")

Table 1: Statistics of the Hayabusa missions

Satellite	Avg. Speed (km/hr)	Maximum Acceleration (km/s^2)	Mass Percentage[1]
Hayabusa	5,040	0.0004706	26.7
Hayabusa 2	3,638	0.004007	44.2

In comparison, the Japanese solar sail craft IKAROS, while smaller in size, weighed 307 kg and comprised a square polyimide sail weighing an estimated 55 kg. The sail, additionally, contains small thin-film solar cells covering 5% of the total surface area yet supporting the overall thrust of a solar sail with 300 W of power (JAXA, "IKAROS Mission Overview"). In isolation, the solar sails themselves possess the ability to gradually increase in velocity due to the constant momentum gained from photon collisions. While the IKAROS mission was limited to a maximum of 1,410 km/hr, over longer distances and with larger solar sails, greater speeds can be achieved (EoPortal). For example, *Lightsail 2*, while having a maximum acceleration of 5.8×10^{-8} km/s^2 can increase its velocity by 550 km/hr over a month given constant sunlight (The Planetary Society). Consequently, limitations of speed placed on chemical-based propulsion systems do not apply due to the primary energy source for a solar sail being the Sun. Furthermore, given the lightweight nature of the sails, 82% of *IKAROS's* mass was utilised for satellite design and payload. With the increased potential for payload capacity, this increases the economic efficacy of using solar sailcrafts in mining missions, exponentially increasing the quantity of mined resources that can be stored and transported.

What's in the Future?

Recent advancements in solar technology have made solar power more attractive for space applications. Research has shown that flexible and lightweight solar panels, such as those made from perovskite materials, offer higher efficiency and durability in space. These developments are crucial for asteroid mining, where the power needs may be high, and the ability to deploy and maintain solar arrays is limited.

In addition, concepts like space-based solar power (SBSP) systems, which collect solar energy in space and transmit it wirelessly to wherever it is needed, have been proposed as early as the 1960s (Curreri and Detweiler). These systems could provide a continuous energy supply to asteroid mining operations, even when the asteroid is not in direct sunlight.

Challenges and How to Overcome Them?

Environmental concerns associated with asteroid mining, similar to those on Earth such as air quality issues, have been raised, suggesting that existing environmental laws may need refinement to accommodate the unique challenges posed by space mining (Bennett). But solar power offers a clean and sustainable energy solution, producing no emissions or waste. This aligns with the broader goals of minimising the environmental impact of space exploration and ensuring that space activities are sustainable in the long term. The use of solar power in asteroid mining could also reduce the need for transporting fuel from Earth, further lowering the environmental footprint of these operations.

The economic feasibility of asteroid mining hinges on the cost-effectiveness of solar power as an energy source. Solar energy's scalability and low operational costs make it an attractive option for sustained mining activities in space. Experts argue that while the initial investment in solar-powered mining systems is high, the long-term returns could be substantial, particularly as Earth's resources become increasingly scarce and expensive to extract.

The future of solar-powered asteroid mining is promising, but challenges remain. Continued research and development in solar technology, along with advancements in autonomous mining systems and in-situ resource utilisation, will be crucial to overcoming these challenges. As space agencies and private companies continue to invest in space exploration, the integration of solar power into asteroid mining operations is likely to become more sophisticated and widespread.

2. Conclusion

The potential for solar-powered asteroid mining to contribute to the development of a space-based economy is immense. As technologies mature and the economic viability of space mining improves, solar power will play an increasingly central role in powering the next generation of space exploration and resource utilisation.

Furthermore, solar power as a whole will play a crucial role as a steady and constant source of energy accessible during outer space missions. Already explored via missions like the *Mars Orbiter Mission*, *IKAROS* and *Lightsail* sailcrafts, the potential of solar sails as a source of steady and economical energy source is well established. Additionally, supporting the same with advancements in the development of durable lightweight photovoltaic cells may lead to a possibility of self-sustaining sailcrafts not restricted by the limitations of fuel.

In summary, the field of asteroid mining is marked by a blend of technological innovation, legal developments, commercial interest, and environmental considerations, all of which are shaping the future of resource utilisation in space.

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[1] Mass Percentage: percentage of the total mass of the spacecraft that is not used by the propulsion system, i.e. the percentage of the mass that is available for payload and control systems.

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