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Technological importance of asteroid mining

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Abstract: With the ever-growing demands of the population and the ever-growing world of consumption and technology, the resources of the planet Earth are limited. Some of the Earth's major resources, such as metals and minerals needed to develop the technology and food industries, may be depleted within the next 40-50 years, based on known terrestrial reserves and increased consumption. For industrial and technological development of humanity, new discoveries are needed in future realization as well as future discoveries. Asteroids are celestial bodies of scientific importance to reveal the formation, chemical composition and evolution of the Solar System. As the name implies, "Near Earth Asteroids", metal have been found to be potentially close to possible because they are sufficiently close and can be found in precious metals and minerals. The reservoirs of important substances such as water, metals and semiconductors can be found in these celestial bodies. Although the Asteroids and the Earth are composed of the same elements, the Earth's relatively stronger gravity has attracted all the heavy elements to its core over time. An asteroid rain deprived of such valuable elements results in the formation of gold, cobalt, iron, manganese, molybdenum, nickel, osmium, palladium, platinum, rhenium, radium, ruthenium and tungsten elements (from the core to the surface). Today, these metals are extracted from the Earth's crust and are required for economic and technological advancements. Therefore, the geological history of the Earth can be a very good step for the future of asteroid mining.

Keywords: Asteroid mining, REEs, technology, metals, valuable asteroids.

1. Introduction

Asteroids are celestial bodies that are of fundamental scientific importance for uncovering the formation, composition and evolution of the solar system (Badescu 2013). Mining an asteroid is a concept that even predates space programs, as an idea initially proposed in the early 20th century by Konstantin Tsiolkovsky. Recent analysis suggests that specially Near-Earth Asteroids (NEAs) are close enough and could contain billions of dollars worth of precious metals and minerals. Reservoirs of important substances such as water, metals and semiconductors can be found in these celestial bodies (Hellgren 2016).

The extraction of volatiles is currently the most realistic near-term asteroid mining application. Therefore, several concepts for extraction and supply of water were developed recently (Badescu 2013). These concepts consider water extraction for refueling of spacecraft, radiation shielding, and potable water for life support systems in outer space (Hellgren 2016).

In the last twenty years, a vast amount of data and results from space missions have been collected. Observations from spacecraft are mainly used to complement theories and findings which were deduced from ground based asteroid data (Badescu 2013). Although a full-scale exploitation of space resources has not been achieved yet, some minimal asteroid samples have been retrieved for analysis and testing on earth. The number of discovered NEAs goes beyond 15000, with an average of 30 new asteroids discovered per week (https://www.nasa.gov/planetarydefense/faq/). However, estimates from ground-based observations do not guarantee the accurate composition of asteroid candidates. Therefore, spacecraft are required for in-situ measurements complementing the data and establishing a clear candidate for exploitation. Current missions for asteroid mining consider spacecraft prospection as a first step before the extraction process. Prospection itself usually falls into three different phases (Badescu 2013): discovery, remote characterization, local characterization. These last two characterization phases are endeavors are endeavors currently pursued by asteroid mining companies using small spacecraft (https://www.planetaryresources.com/missions/arkyd-301/). However, recent advances in the miniaturization of spacecraft components and mining equipment may allow for a more cost effective and reliable approach to mine NEAs overall (Calla et al., 2018).

In this article we briefly discussed the need for asteroid mining for materials required by technology.

The Keck Institute of Space Studies mentions that there are five categories of benefits from the return of an asteroid sample or a full asteroid retrieval, which are:

1) Synergy with near-term human exploration,

2) Expansion of international cooperation,

3) Synergy with planetary defense,

4) Exploitation of asteroid resources,

5) Public engagement.

Two major companies, Planet Resources (PR) and Deep Space Industries (DSI), plan to evaluate, explore and collect space resources. These resources include metals, water, and many useful elements for development and construction, both in space and on Earth. Both companies make credible claims about how they will achieve their goals (Hellgren 2016).

Although the history of the idea of asteroid mining is a hundred years old, realistic and concrete studies on this subject have started in our very recent past. Although its foundations were laid primarily with official institutions such as NASA, ESA and JAXA, private companies are currently directing and supporting serious studies on this issue.

For nearly 60 years, NASA dominated space, but a revolution began when they gave up low-earth orbit to private companies like SpaceX and Planet Labs. Fast-moving startups have increased innovation and lowered costs in unprecedented ways.

Planetary Resources Corporation runs the world's first commercial deep space exploration program. The aim is to determine the critical water resources necessary for human civilization to have a say in a wide region in space.

Water as a resource is the first step towards creating a civilization in space. Water is used for life support functions and can also be refined for propellants used in rockets. PR Company's primary goal is to identify asteroids containing the best water source and simultaneously provide vital information needed to construct a commercial mine that will collect water for use in space (https://www.planetaryresources.com/).

Planetary Resources Company aims to be the leading resource provider for astronauts and needed resources in space with the aim of detecting, extracting and refining resources in near-Earth asteroids. The company's first technological satellite, Arkyd-3, was launched from Cape Canaveral in 2015 and deployed to the International Space Station. This spacecraft data collection will include global hydration mapping and underground extraction displays to determine the amount of water and the value of available resources. The information gathered will allow the PR company to design, build and operate the first commercial mine in space

(https://www.planetaryresources.com/missions/arkyd-301/).

Fig. 1 Arkyd-3 satellite

Deep Space Industries, or DSI, is a privately owned American company operating in the space technology and space exploration industries. Deep Space is the second company established to deal with asteroid mining. DSI develops and builds spacecraft technology that enables private companies and government agencies to access their destinations throughout the solar system. The stated goal of DSI is to democratize deep space access by fundamentally changing the deep space access paradigm and greatly reducing cost (http://deepspaceindustries.com/).

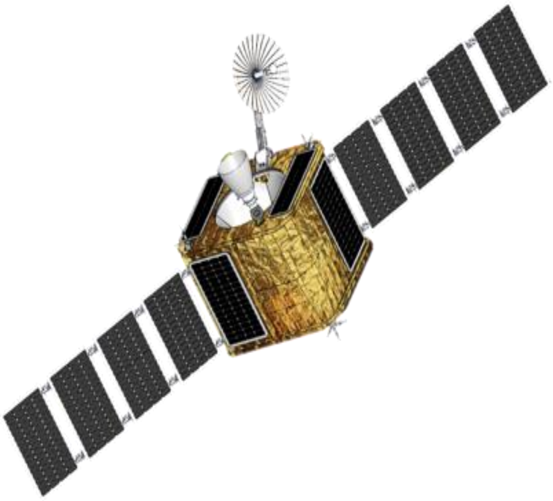

Fig. 2 Xplorer spacecraft

The first of DSI's 2 major projects, Xplorer is designed to do something that no spacecraft has ever done: it uses its propulsion system to autonomously navigate from a given coordinate on Earth from low Earth orbit (LEO). This spacecraft is designed to be deployed in low earth orbit to take advantage of its relatively low cost and high commercial value. With this capability, it provides many research and high delta-V applications for geosynchronous orbit, as far away as Mars and near-Earth asteroids (http://deepspaceindustries.com/).

2. What is An Asteroid?

Asteroid, any of the many small rocky or metallic objects in the Solar System, mostly lying in a zone (the asteroid belt) between the orbits of Mars and Jupiter; also known as a minor planet. They range in diameter from almost 1000 km for Ceres down to less than 10 m for the smallest so far detected. The total mass of all asteroids is 4x1021 kg, about one-twentieth the mass of the Moon (Oxford, A Dictionary of Astronomy, 2018). They are made from different kinds of rock and metals, with the metals being mostly Ni and Fe. Some of them called "minor planets" but they are smaller than the planets or their moons. Since Chladni (1794) published "On the Origin of the Pallas Iron and Others Similar" to it, and on "Some Associated Natural Phenomena" and made plausible the hypothesis that rocks could fall from the sky, the definition of the word meteorite has remained essentially unchanged, as reflected in the ten quotations given above. Nearly all modern reference works use a similar definition. Meteorites are almost always defined to be solid bodies that have fallen through the Earth's atmosphere and landed on the Earth's surface (Rubin and Grossman 2010).

3. Classification of Asteroids

The first more complete asteroid taxonomy was based on a synthesis of polarimetry, radiometry, and spectrophotometry, using a survey of 110 asteroids. The defined a class C for dark carbonaceous objects, a class with the label S for silicaceous objects, and X for objects that did not fit either class. This system has the disadvantage that it was not detailed enough and is based on the exclusion principle. The groundwork for the most complete taxonomy, that significantly expands the previous taxonomy has been proposed by Tholen (Tholen 1984).

Asteroids are divided into three categories according to their structure.

3.1. C-type

C-type (carbonaceous) asteroids are the most common variety, forming around 75% of known asteroids. They are distinguished by a very low albedo because their composition includes a large amount of carbon, in addition to rocks and minerals. They occur most frequently at the outer edge of the asteroid belt, 3.5 astronomical units (AU) from the Sun, where 80% of the asteroids are of this type, whereas only 40% of asteroids at 2 AU from the Sun are C-type. The proportion of C-types may actually be greater than this, because C-types are much darker (and therefore less detectable) than most other asteroid types except and others that are mostly at the extreme outer edge of the asteroid belt (Binzel et al., 1989).

The C symbol in the asteroid species represents carbon and the surface of such asteroids is almost as black as coal. This type of asteroid contains large amounts of rock and metals, as well as large amounts of carbon molecules. They are very similar in composition to carbonaceous 'chondrite' meteorites. Hydrated minerals are present in C-type asteroids. These meteorites are thought to be fragmented during collisions between C-type asteroids.

3.2. S-type

Accounts for about 17 percent of known asteroids. Relatively bright with an albedo of 0.10-0.22. Composition is metallic iron mixed with iron- and magnesium-silicates. S-type asteroids dominate the inner asteroid belt (https://nssdc.gsfc.nasa.gov/planetary/text/asteroids.txt).

The S-asteroid class includes a number of distinct compositional subtypes [designated S(I)-S(VII)] which exhibit surface silicate assemblages ranging from pure olivine (dunites) through olivine-pyroxene mixtures to pure pyroxene or pyroxene-feldspar mixtures (basalts). S-asteroid absorption bands are weaker than expected for pure silicate assemblages, indicating the presence of an additional phase, most probably FeNi metal, although the abundance of metallic or feldspar components is not well constrained. The diversity within the S-class probably arises from several sources, including the coexistence of undifferentiated, partially differentiated, and fully differentiated objects within the general S-asteroid population and the exposure of compositionally distinct units from within metamorphosed and partially and fully differentiated parent bodies (Gaffey 1993). These asteroids have abundant Fe, Ni, Mg, Mo, Al, Ti and Co elements on their surface. In addition, Au, Pt and Ra are also very abundant. Because its composition resembles our planet, It is possible to build structures in space without taking material from Earth.

3.3. M-type

M-type asteroids are asteroids of partially known composition; they are moderately bright (albedo 0.1–0.2). Some are made of nickel–iron, either pure or mixed with small amounts of stone. These are thought to be pieces of the metallic core of differentiated asteroids that were fragmented by impacts and are thought to be the source of iron meteorites. M-type asteroids are the third most common asteroid type (Rivkin et al., 2000).

M-type spectra are flat to reddish and usually devoid of large features, although subtle absorption features longward of 0.75 µm and shortward of 0.55 µm are sometimes present (Bus and Binzel 2000).

16 Psyche is the largest M-type asteroid. 21 Lutetia, probably non-metallic object, was the first M-type asteroid to be imaged by a spacecraft when the Rosetta space probe visited it on July 10, 2010. Another M-type asteroid, 216 Kleopatra, was imaged by radar by the Arecibo Observatory in Puerto Rico and has a dog bone-like shape (Lupishko et al., 1982).

There is abundant evidence, from telescope observations and meteorite samples, that the strength and porosity of near- Earth objects (NEOs) is related to taxonomic type and mineral composition, with carbonaceous C-type asteroids expected to be more porous and less robust than silicaceous S types or M types. Impact events also suggest that there is wide diversity in the structural robustness of impactors, with airbursts caused by objects that disrupt violently in the atmosphere, while similarly sized objects with a largely metallic composition have a relatively high density and strength and can reach the ground to form a crater (e.g., Barringer Crater, Arizona), thus causing much greater damage. Furthermore, there is currently considerable interest in the potential of NEOs as sources of rawmaterials, including various metals, for future activities in space and, eventually perhaps, for use on Earth. NASA's Asteroid Redirect Mission concept involves capturing a small asteroid and returning it to lunar orbit for investigations of relevance to planetary defense and resources exploitation.

For these reasons it is important to improve our knowledge of the mineralogical compositions of asteroids, and their potential as future sources of economically valuable raw materials. In this context we note that while the missions Hayabusa (Fujiwara et al., 2006) and Stardust (Brownlee et al., 2006) have returned material samples to Earth from the S type NEO Itokawa and comet 81P/Wild 2, respectively, and further sample-return missions (e.g., Hayabusa-2: Saiki et al., 2013; OSIRIS-REx: Lauretta et al., 2012), are currently under development, no object thought to be metal rich is amongst their targets. Furthermore, due to their robustness and ability to survive passage through the atmosphere, metallic objects are disproportionately well represented in meteorite collections on Earth. Understanding the true number of metal rich objects in the solar system remains a longstanding problem.

4. Asteroid Mining

Asteroid mining offers the possibility to revolutionize supply and availability of many resources vital for human civilization. Analysis suggests that Near-Earth Asteroids (NEA) contain enough volatile and high value minerals to make the mining process economically feasible (as shown in Table 1). Considering possible applications, specifically the mining of water in space has become a major focus for near-term options. Most proposed projects for asteroid mining, however, involve spacecraft based on traditional designs resulting in large, monolithic and expensive systems (Calla 2018).

Asteroid mining has been proposed as an approach to complement Earth-based supplies of rare earth metals and supplying resources in space, such as water. However, existing studies on the economic viability of asteroid mining have remained rather simplistic and do not provide much guidance on which technological improvements would be needed for increasing its economic viability. Both, in-space resource provision such as water and return of platinum to Earth are considered (Hein et al., 2018).

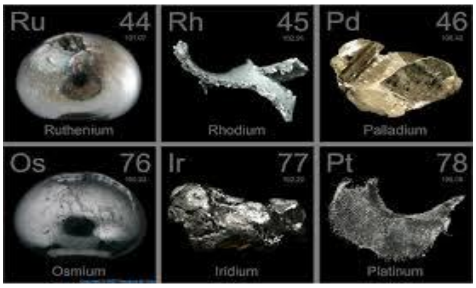

Fig. 3 Platinum Group Metals (PGMs)

Existing research on asteroid mining has mainly looked into its economic viability technological feasibility, cartography of asteroids and legal aspects. More recently, environmental arguments for asteroid mining have been made, in particular with regards to platinum group metals (Hein et al. 2018).

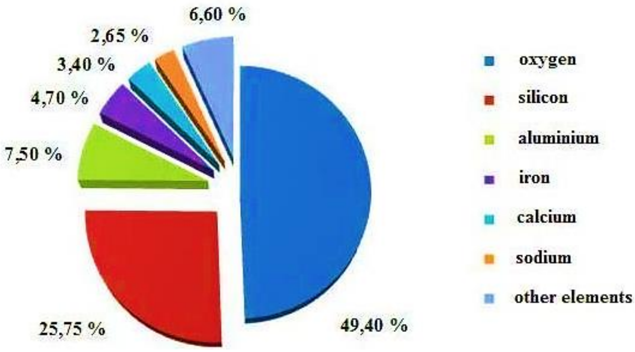

Fig. 4 Percentage distribution of elements on earth (Helešicová M., 2014)

Although the asteroids and Earth were composed of the same elements, the relatively stronger gravity of the Earth attracted all the heavy elements to its core in its molten youth more than four hundred years ago. An asteroid rain, deprived of such valuable elements, produces gold, cobalt, iron, manganese, molybdenum, nickel, osmium, palladium, platinum, rhenium, radium, ruthenium and tungsten (in a flow from the core to the surface) (Brenan and McDonough 2009). Today, these metals are extracted from the Earth's crust and are essential for economic and technological advances. Therefore, the geological history of the Earth can be a very good stage for the future of asteroid mining.

Earth-approaching asteroids could provide raw materials for space manufacturing. For certain asteroids the total energy per unit mass for the transfer of asteroidal resources to a manufacturing site in high Earth orbit is comparable to that for lunar materials. For logistical reasons the cost may be many times less. Optical studies suggest that these asteroids have compositions corresponding to those of carbonaceous and ordinary chondrites, with some containing large quantities of iron and nickel; others are thought to contain carbon, nitrogen, and hydrogen, elements that appear to be lacking on the moon. The prospect that several new candidate asteroids will be discovered over the next few years increases the likelihood that a variety of asteroidal resource materials can be retrieved on low-energy missions (O'Leary 1977).

5. Why is Asteroid Mining Needed?

The exploitation of asteroids, and in particular Near Earth Asteroids (NEAs) has been repeatedly proposed as a source of resources for Earth and space (Lewis 1996). Ross (2001), distinguishes between metals and volatiles as resources along with their use in a variety of applications such as construction, life support systems, and propellant. In particular, volatiles have received attention for in space use, due to their relative ease of extraction. For example, Calla et al., (2018) explored the technological and economic viability of supplying water from NEAs to cislunar orbit.

Table 1 10 most valuable asteroids according to ASTERANK (Asteroid Database and Mining Rankings) database

Name	Type	Value ($)	Est. Profit ($)	Group
Davida	C	>100 trillion	>100 trillion	MBA
Chicago	C	>100 trillion	>100 trillion	OMB
Alauda	B	>100 trillion	>100 trillion	MBA
Diotima	C	>100 trillion	>100 trillion	MBA
Palma	B	>100 trillion	>100 trillion	MBA
Winchester	C	>100 trillion	>100 trillion	MBA
Kreusa	C	>100 trillion	>100 trillion	MBA
Stereoskopia	C	>100 trillion	>100 trillion	OMB
Chiron	Cb	>100 trillion	>100 trillion	CEN
Siegena	C	>100 trillion	>100 trillion	MBA

Only resources with a high value to mass ratio are interesting, due to the high cost of returning such material. Therefore, high-value metals such as rare earth metals and in particular the subgroup of platinum group metals have been the subject of mining studies (Andrews et al., 2015). The supply of rare earth metals is crucial for many "green technologies" such as fuel cells, catalyzers, high capacity batteries, and solar cells. As as shown in Table 2 more accessible than the Moon, near-Earth asteroids are comprised of natural resources that will accelerate humanity's exploration and development of deep space.

Table 2 Semi-major axis (a), eccentricty (e) and Minimum-Orbit Intersection Distance (MOID) values of the 10 most valuable asteroids (Asteroid Database and Mining Rankings database)

Name	a (AU)	e	Δv (km/s)	MOID (AU)
Davida	3.165	0.188	11.145	1.593070
Chicago	3.890	0.024	11.704	2.782950
Alauda	3.192	0.017	12.758	2.120800
Diotima	3.066	0.036	11.224	1.942490
Palma	3.150	0.259	11.988	1.446870
Winchester	3.006	0.339	10.423	1.088250
Kreusa	3.167	0.158	10.791	1.704160
Stereoskopia	3.376	0.119	10.768	1.978950
Chiron	13.669	0.380	11.922	7.471030
Siegena	2.900	0.169	11.557	1.440160

The rare earth elements (REE) form the largest chemically coherent group in the periodic table. Though generally unfamiliar, the REE are essential for many hundreds of applications. The versatility and specificity of the REE has given them a level of technological, environmental, and economic importance considerably greater than might be expected from their relative obscurity.

High-technology and environmental applications of the rare earth elements (REEs) have grown dramatically in diversity and importance over the past four decades. As many of these applications are highly specific, in that substitutes for the REEs are inferior or unknown, the REEs have acquired a level of technological significance much greater than expected from their relative obscurity. Although actually more abundant than many familiar industrial metals, the REEs have much less tendency to become concentrated in exploitable ore deposits. Consequently, most of the world's supply comes from only a few sources (Haxel et al. 2002).

The diverse nuclear, metallurgical, chemical, catalytic, electrical, magnetic, and optical properties of the REEs have led to an ever-increasing variety of applications. The material required by all technological devices to be developed in these areas will not be able to meet the needs of the growing population. At this point, demands can be met by asteroid mining.

Extraterrestrial resources should be the basic sources of materials for the development of humankind civilization in space as well as they could replace the Earth's resources when they would be exhausted. They can be obtained from the planets, their moons or asteroids, primarily NEOs but also from the asteroid belt. Taking into account the homogenous spatial distribution of metallic grains (proved by author's microscopic observations) and knowing the amount of FeNi minerals in rocks with H chondrite composition, the amount of potential FeNi resources on H parent bodies can be calculated. It was estimated that the iron resources from Hebe's FeNi minerals would cover 1.3 million years of terrestrial mining production whereas nickel resources would last for approximately 100 milion years. A small NEO asteroid like (143624) 2003 HM16 (2 km in diameter) has resources comparable with 15 months of mining iron production and over 100 years of nickel production at present rate (Blutstein et al., 2018).

Many applications of REE are characterized by high specificity and high unit value. For example, color cathode-ray tubes and liquid-crystal displays used in computer monitors and televisions employ europium as the red phosphor; no substitute is known. Owing to relatively low abundance and high demand, Eu is quite valuable—$250 to $1,700/kg (for Eu2O3) over the past decade.

Fiber-optic telecommunication cables provide much greater bandwidth than the copper wires and cables they have largely replaced. Fiber-optic cables can transmit signals over long distances because they incorporate periodically spaced lengths of erbium-doped fiber that function as laser amplifiers. Er is used in these laser repeaters, despite its high cost (~$700/kg), because it alone possesses the required optical properties (Haxel et al. 2002).

6. Conclusion

We need to learn about the mineral ratios of asteroids and those that are future economically valuable raw materials. In this context, the Hayabusa (Fujiwara et al., 2006) and Stardust (Brownlee et al., 2006) projects returned material samples from the S-type NEO Itokawa and comet 81P /

Wild2 to the Earth and took more samples, respectively. These tasks (eg Hayabusa-2: Saiki et al., 2013; OSIRIS-REx: Lauretta et al., 2012) are currently under development and are not intended to generate economic profit. The approximate number of metal-rich asteroids has been investigated for a very long time.

Permanent magnet technology has been revolutionized by alloys containing Nd, Sm, Gd, Dy, or Pr. Small, lightweight, high-strength REE magnets have allowed miniaturization of numerous electrical and electronic components used in appliances, audio and video equipment, computers, automobiles, communications systems, and military gear. Many recent technological innovations already taken for granted (for example, miniaturized multi-gigabyte portable disk drives and DVD drives) would not be possible without REE magnets.

Environmental applications of REE have increased markedly over the past three decades. This trend will undoubtedly continue, given growing concerns about global warming and energy efficiency. Several REE are essential constituents of both petroleum fluid cracking catalysts and automotive pollution-control catalytic converters. Use of REE magnets reduces the weight of automobiles. Widespread adoption of new energy-efficient fluorescent lamps (using Y, La, Ce, Eu, Gd, and Tb) for institutional lighting could potentially achieve reductions in U.S. carbon dioxide emissions equivalent to removing one-third of the automobiles currently on the road. Large-scale application of magnetic-refrigeration technology also could significantly reduce energy consumption and CO2 emissions (Haxel et al., 2002). These rare earth elements can be abundantly obtained through asteroid mining and used for future technology.

Although it will reduce employment within the traditional labor-intensive mining industry, it will also provide the opportunity for a technological development boost that will spawn entirely new job sectors. Society will also benefit from new capabilities arising from increased access to previously rare materials (Welch 2010).
There are more than 16,000 asteroids close to Earth. Asteroids serve as a station for life in space and include resources to carry a new journey and the continuation of the human generation to different planets. With asteroid mining technologies, not only the Earth, but also planets from every corner of the universe will be candidates to be our home.

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