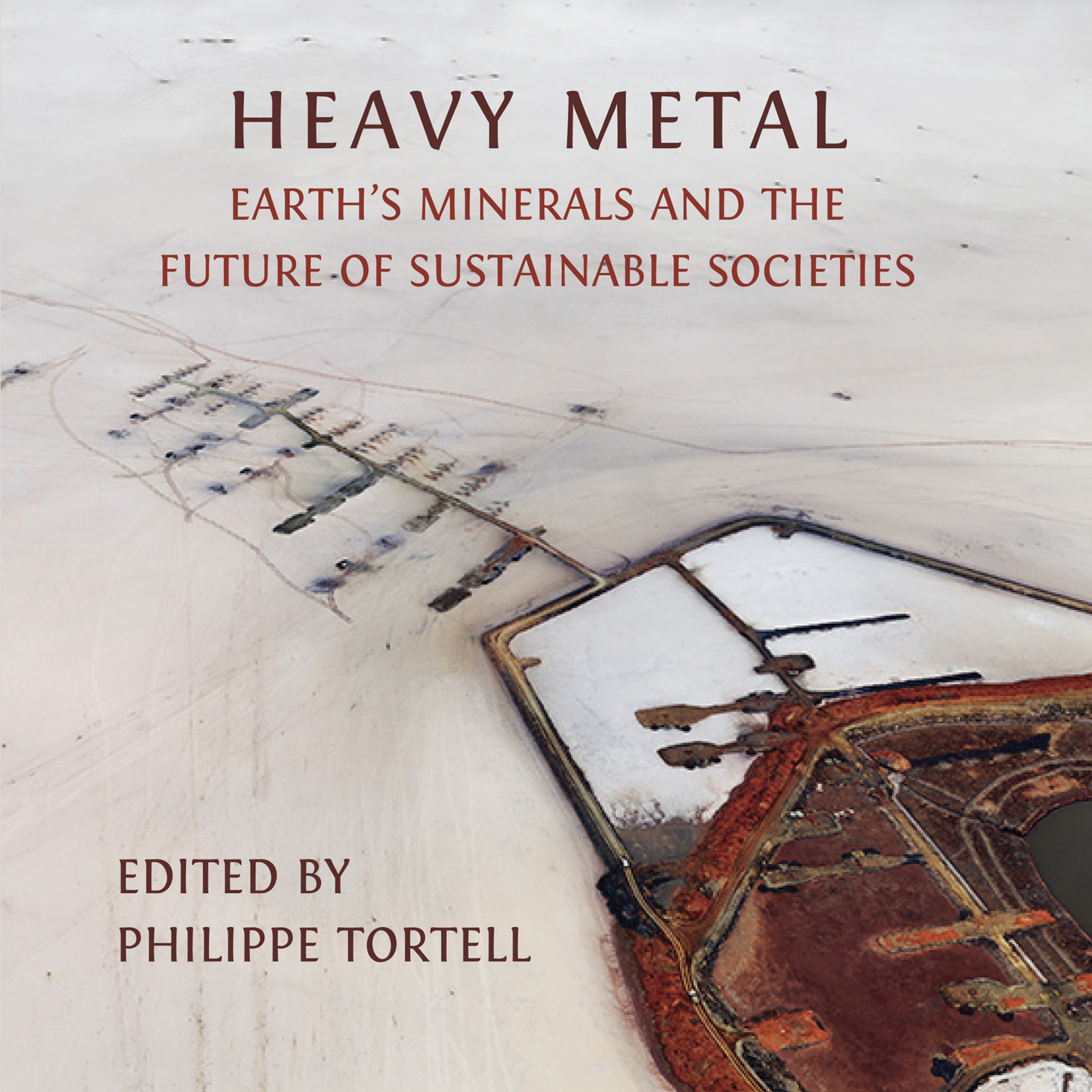
HEAVY METAL

EARTH'S MINERALS AND THE FUTURE OF SUSTAINABLE SOCIETIES



EDITED BY
PHILIPPE TORTELL

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Mines in the Sky

Sara Russell and Riz Mokal

As resources on our planet dwindle, the gaze of writers, scientists, governments and entrepreneurs has turned upwards to consider whether space might supply some of our ever-growing mineral requirements. Before the mid-twentieth century, this idea lay exclusively in the realm of science fiction, and was often cautionary. Garrett P. Serviss' 1898 novel *Edison's Conquest of Mars* imagined Thomas Edison visiting an asteroid near Mars, only to discover it was made entirely of gold and mined by unfriendly Martians.[1] Sci-fi notions of outer space mining persisted well into the twentieth century. According to *The Encyclopedia of Science Fiction*, an entire subgenre of space opera written over the 1930s to the 1960s imagined the Asteroid Belt as the site of a new gold rush, with 'lawless asteroids' serving as 'the perfect place for interplanetary skullduggery'.[2] The 1979 movie classic, *Alien*, imagined a future where commercial space tugs carried mineral ores around the Solar System. In that story, things did not turn out well.

Life imitated art. As the Space Race kicked off in the 1950s and 1960s, voyages of discovery beyond Earth were motivated, at least in part, by a nebulous promise of untold riches. In 1962, US Vice President Lyndon B. Johnson declared 'Someday we will be able to bring an asteroid containing billions of dollars' worth of critically needed metals close to Earth to provide a vast source of mineral wealth to our factories'.[3]

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LBJ may have been drawing on Arthur Radebaugh's comic strip 'Asteroid Arrester', published only a week earlier, which explained that the National Aeronautics and Space Administration (NASA) would one day use powerful rockets to capture asteroids and harness them both for pure science and for commercial activity.[4] Serious academics were also on board, but it was only in 1997 that the distinguished planetary scientist John S. Lewis made the first careful attempt to quantify potential mineral wealth beyond Earth. In his book, *Mining the Sky: Untold Riches from the Asteroids*, Lewis estimated that a single small asteroid, 3554 Arum, could supply twenty trillion dollars' worth of metals.[5] Today, many people, including Texas senator Ted Cruz and the astrophysicist Neil deGrasse Tyson agree that the first trillionaire will be an entrepreneur in the asteroid mining sector. Such claims have motivated the growth of privately owned space exploration companies, like Elon Musk's SpaceX, seeking to exploit a new economic frontier. Underpinning all this activity is the assumption that space mining is a viable approach to help meet humanity's growing need for critical mineral resources. The reality, it turns out, is perhaps not quite so simple.

The story of outer space mining begins a long time ago. The universe was formed about fourteen billion years ago with the Big Bang, a cataclysmic event that produced all the matter we see today. The Big Bang itself generated only the elements hydrogen, helium and a relatively minor amount of lithium. All other elements have subsequently been synthesized from these simple precursors, mostly through nuclear fusion reactions inside stars, with lighter elements coming together to form heavier ones. (Replicating such a fusion process on Earth is a 'holy grail' for clean renewable energy.) The products of these intra-stellar fusion reactions are dominated by the lighter elements including helium, carbon, nitrogen and oxygen, along with the so-called 'transition' metals, such as iron, cobalt and nickel, which have the most chemically stable nuclei. In contrast, the heaviest elements, such as gold and platinum, are formed mainly in energetic supernova explosions, and as a result, these heavy metals have a significantly lower cosmic abundance.

The overall cosmic abundance of different elements is only one factor that influences their availability on Earth. Elements are divided into iron-loving ('siderophile') and rock-loving ('lithophile') types. In the early history of Earth and all other large bodies in the inner Solar System, heavier siderophile elements sank downwards due to gravity to form a core, leaving lithophile elements to rise to form a mantle and crust. As a result of this partitioning, the siderophile elements such as iron, copper and cobalt are relatively scarce in the accessible parts of Earth's crust (the upper few kilometers). It is this top layer that we currently mine for resources, literally scratching the surface of Earth.

In contrast with Earth, some asteroids may constitute a richer source of concentrated metal deposits. These rocky space objects formed from the early dust and gas precursors of our Solar System, and many are expected to preserve the cosmic abundances of different elements. In our Solar System, asteroids are bodies smaller than planets orbiting the Sun, and are concentrated in the Asteroid Belt, between Mars and Jupiter. A small, but significant number of Near-Earth Asteroids (NEAs) also exist. These objects are much more accessible than bodies beyond Mars, and are the likely target of any initial attempts at space mining.

In total, the combined mass of the Asteroid Belt is believed to be around 0.05% of the mass of Earth; there are over a million known asteroids with sizes exceeding one kilometer, and likely billions of smaller ones. Remote spectroscopic measurements and various space missions have demonstrated a remarkable diversity in asteroid size and composition, with distinct types identified based on various observed properties, including the potentially carbon-bearing C-type asteroids, the rocky S-type asteroids and the dark D-type asteroids, which reflect little light and are difficult to observe. Among these groups, the so-called M-type ('Metal') asteroids are most attractive as potential targets for outer space mining. These asteroids make up around 10% of the Asteroid Belt and are believed to be composed of iron and nickel, although some controversy remains regarding their exact mineral composition. Unlike Earth, which has sequestered enormous amounts of its metal inventory into a deep planetary core, M-type meteorites have near uniform compositions, which are assumed to be comprised almost entirely of metals.

The chemical composition of asteroids can be studied on Earth using meteorites that land on our planet's surface. At present, there are around 75,000 known meteorites, the vast majority of which originally derived from asteroids. Linking a meteorite to its extra-terrestrial parent can be complex, but with careful analysis, these objects provide important clues about the potential outer space mineral resources. For example, some meteorites contain high concentrations of transition metals such as cobalt, iron and nickel. These meteorites (and hence likely their parent M-type asteroids) also contain as much as 1% cobalt, as compared to approximately 0.003% in Earth's crust. The more common chondrite meteorites contain between 0.05 to 0.1% cobalt by weight, values similar to the richest deposits on Earth. Assuming a cobalt abundance of 0.05%, it has been estimated that there are approximately 10^{15} metric tons of cobalt in the Asteroid Belt, enough to supply humanity's needs for ten billion years at current rates. A single metal asteroid with a mass of around three billion metric tons could supply thirty million metric tons of cobalt, along with many other useful metals such as iron and nickel. By comparison, the known cobalt resources on Earth amount to around eight million metric tons, with the majority coming from the Democratic Republic of Congo.[6] Cobalt mining in that country has been associated with a wide array of human rights abuses, political corruption and armed conflict.[7] Some have suggested that asteroids could therefore present an attractive alternative supply for this metal, which is a critical element in the rechargeable batteries needed to support low-carbon economies.[8]

Other metals, including the so-called platinum-group metals (PGMs)—ruthenium, rhodium, palladium, osmium, iridium and platinum—are used widely as catalysts in various technologies, including the automotive and medical industries and consumer electronics. Like iron and nickel, these heavy elements are sequestered deep within Earth's planetary core, and only trace quantities are present in near-surface crustal environments. Earth's crust contains about 0.001 parts per million (ppm) of iridium, meaning that every kilogram of rock holds about one thousandth of a gram of this element. By comparison, M-type asteroids can contain up to 60 ppm iridium, sixty thousand times more than that found in Earth's crust. In chondrite meteorites, platinum group elements exist as tiny nuggets of pure metal.[9] Some of the PGMs on the Earth's surface are believed to have been delivered by meteorite impacts after the formation of the planet's core. As a result, the most productive PGM mining regions on Earth are those that have previously experienced giant meteorite impacts, including Vredefort in South Africa and Sudbury in Canada.[10]

Compared to asteroids and other small extra-terrestrial bodies, planet-sized bodies may prove more challenging for heavy metal mining. Like Earth, these larger bodies are differentiated into distinct density layers, with most of their metals buried deep in an inaccessible core. Mars, for example, may have usable ore deposits, but these are likely similar to those on Earth, and more relevant for potential colonists on the Red Planet than as a source to be shipped back to our Blue Planet.

However, there may be one instance where a larger body—the Moon—could supply some much-needed metals. Rare-earth elements (REEs), such as neodymium and dysprosium, are used for batteries, electronics, lasers, magnets and catalysts, among other applications. The future supply of these elements is of concern, mainly because present-day sources on Earth are restricted to a small number of countries, including China, the United States, Myanmar and Australia.

Unlike iron, nickel and PGMs, the REEs are lithophile elements, meaning that they do not concentrate in planetary cores. As a result, they are not particularly abundant in metal-rich asteroids, but parts of the Moon could provide significant reserves of these important elements. When the Moon first formed, its surface rocks melted entirely, slowly crystallizing into a layered structure with light minerals at the top and dense rocks at the bottom. During this process, the REEs partitioned preferentially into the melt phase rather than solid minerals, becoming increasingly concentrated in the upper layers of the Moon as it slowly cooled and solidified. One of the upper layers of material on the Moon, the last to crystallize, formed a highly unusual rock called KREEP (an acronym built from the letters K for potassium, REE for rare-earth elements, and P for phosphorus), first identified during the NASA Apollo space missions of the late 1960s. If significant deposits of this material are identified on the lunar surface, they could potentially provide a source of much-needed REEs. The upcoming NASA Artemis missions to the Moon aim to address this question, among others.

Beyond the significant challenges of identifying and recovering outer space sources of raw minerals, extra-terrestrial mineral deposits must also be processed into forms that are usable in a variety of applications. Different mineral processing options include the return of raw materials back to Earth, processing metal deposits in space, or transporting asteroids to a safe orbit in the Earth–Moon system for longer-term extraction. In metal-rich asteroids, the elements of interest may already be in a chemical form needed for various applications (i.e., pure metal states), reducing the requirements for downstream processing. In this case, metals can more easily be returned to Earth in usable forms, using non-chemical approaches such as raking and magnetic separation. In other cases, metals may exist in a range of different chemical states that require significant treatment prior to utilization. Any necessary processing will be subject to constraints not experienced on Earth, notably low gravity and the lack of air. For this reason, fundamentally new approaches will be needed to recover usable forms of metal from outer space deposits. Such work may include novel methods of 'biomining', in which bacteria are used to leach metals of interest from a rock.[11]

Growing interest in space minerals has ignited a new twenty-first-century Space Race, with a particular focus on the study of asteroids, and the exploration of the Moon and Mars. In 2010 and 2020, the Japanese spacecraft *Hayabusa* and *Hayabusa2* returned to Earth with material from the asteroids Itokawa and Ryugu, respectively. And just last year, in 2023, NASA's *OSIRIS-REx* space probe returned samples from the asteroid Bennu. Over the past decade, several countries including the US, Russia, China, Japan and India have landed autonomous missions on the Moon or Mars (though some of these were crash landings). Recent interest in the Moon has focused on a region on its South Pole known as Aitken Basin, where suspected frozen water could sustain lunar mining operations and provide rocket fuel for travel deeper into the Solar System. Recently, India became the first country to safely land a probe on the lunar South Pole, marking a significant scientific and geopolitical shift in the new Space Race.

The current surge in outer space exploration is occurring against a backdrop of significant legal and regulatory uncertainty. The 1967 Outer Space Treaty, and the subsequent 1979 Moon Agreement adopted by the United Nations General Assembly, set out broad guidelines for activities conducted in outer space. However, both treaties are of limited effect and uncertain interpretation. By way of illustration, the Outer Space Treaty states that Space is not subject to 'national appropriation' or claims of sovereignty, without explicitly addressing the issue of property rights over resources extracted from outer space.[12] Further, accession to these treaties is patchy, particularly amongst states which are likely to develop the relevant travel and mining capabilities over the coming decades. In fact, many states have argued that space mining should be subject to national laws. In 2015, the US passed the Commercial Space Launch Competitiveness Act, signed into law by President Barack Obama. This Act gives US citizens and companies rights of ownership over resources obtained from outer space 'in accordance with applicable law'.[13] Five years later, US President Donald Trump signed an executive order supporting 'the public and private recovery and use of resources in outer space'.[14] Other states, including Luxembourg, Japan and the United Arab Emirates have since passed similar laws, opening the door to a patchwork of potentially competing national regulations. Such an approach could enable outer space mining companies to operate under a 'flag of convenience', as occurs in international shipping. The present legal framework is thus incomplete and unfair, and international regulations would allow commercial operators to self-servingly choose to operate under a national framework with weak environmental and ethical standards.

In response to the growing influence of national interests, there has been a call for new multi-lateral approaches to the regulation of outer space mining. The United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) recently established a Working Group on Space Resources, which has been endorsed by over 130 nations, including Russia and China. Any international treaties developed by this group will not only need to consider property rights for future space mining, but also the potential negative environmental and other impacts of such activities. These include the creation of outer space debris fields, which could pose hazards to satellites and other spacecraft, and potential changes in the orbits of asteroids, which may increase their chances of Earth impact. Other considerations include the inadvertent introduction of novel life forms to planetary bodies, and disturbances that could compromise future scientific studies.

In the not-too-distant future, asteroids and other extra-terrestrial bodies might well become a viable source for at least some of the heavy metals we will require. These outer space objects are remarkably diverse in size, location and composition, but they are all typically metal-rich compared to Earth's near-surface environments. At the extreme, asteroids represent concentrations of almost pure metals orbiting near our planet. It therefore seems logical that they could, in time, be a useful resource. The current economic value of asteroid mining is lower than the huge costs involved in mounting a space mission. But this could change in the future, as technological barriers are overcome and innovative practices reduce costs, while growing scarcity of metals on Earth increases their prices. For now, the logistics and economics of asteroid mining are not established, and any serious discussion of space mining remains part of a long-term solution to the mineral supply issue. In the meantime, missions like NASA's *OSIRIS-Apex* and *Psyche* are visiting asteroids to learn more about our metal-rich neighbors. This type of basic research, combined with investment from the private sector, will enable asteroid mining to become ever closer. Any scientific progress will have to be understood in the context of economic, social, ethical and legal considerations, as humanity seeks to expand its ever-growing footprint beyond Planet Earth.

Endnotes

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