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Origin and Future of Astrometallurgy

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Abstract: The evolution of material usage has been a pivotal factor in human progress, beginning with the use of copper-based tools in the Chalcolithic Era and advancing to today's high-tech materials like high-entropy alloys and conductive polymers. While ancient materials were sourced from nature, modern materials are the result of extensive research, yet the challenge of resource management persists. This review explores the emerging field of astrometallurgy, which focuses on the extraction and processing of metals from extra-terrestrial sources to support human space exploration and colonization, starting with clay, discovering bronze, and moving into space with today's technology. The present study examines the potential of utilizing resources from celestial bodies such as the Moon, Mars, and asteroids, and highlights the technological advancements necessary for metal extraction in space. The concept of astrometallurgy is closely linked with in-situ resource utilization (ISRU), aiming to make space exploration more sustainable and economically viable. The review also discusses the challenges of adapting traditional metallurgical processes to the unique conditions of space and proposes modifications to optimize metal extraction on the Moon and Mars. The findings underscore the importance of astrometallurgy in the future of space exploration and its potential to revolutionize material production beyond Earth.

Keywords: Astrometallurgy, extra-terrestrial resource, metal production, space.

Astrometalurjinin Kökeni ve Geleceği

Özet: Malzeme kullanımının evrimi, Kalkolitik Çağ'da bakır bazlı aletlerin kullanımıyla başlayıp günümüzün yüksek entropili alaşımlar ve iletken polimerler gibi yüksek teknolojili malzemelerine kadar uzanan insanlık ilerlemesinde önemli bir faktör olmuştur. Antik malzemeler doğadan elde edilirken, modern malzemeler kapsamlı araştırmaların sonucudur, ancak kaynak yönetimi zorluğu devam etmektedir. Bu inceleme makalesi, insanoğlunun uzayın keşfi ve kolonizasyonunu desteklemek için dünya dışı kaynaklardan metallerin ekstrakte edilmesine ve işlenmesine odaklanan astrometalurji alanını araştırmaktadır. Mevcut çalışma, Ay, Mars ve asteroitler gibi gök cisimlerinden kaynakların kullanılma potansiyelini ve uzayda metal ekstrakte etmek için gerekli son teknolojik gelişmeleri paylaşmaktadır. Astrometalurji kavramı, uzay keşfini daha sürdürülebilir ve ekonomik olarak uygulanabilir hale getirmeyi amaçlayan yerinde kaynak kullanımı ile yakından bağlantılıdır. Ayrıca, incelemede geleneksel metalurjik süreçlerin uzayın benzersiz koşullarına uyarlanmasının zorlukları ele alınmakta ve Ay ve Mars'ta metal çıkarımını optimize etmek için değişiklikler önerilmektedir. Bulgular, uzay araştırmalarının geleceğinde astrometalurjinin önemini ve Dünya'nın ötesinde malzeme üretimini devrim niteliğinde değiştirme potansiyelini vurgulamaktadır.

Anahtar Kelimeler: Astrometalurji, dünya dışı kaynak, metal üretimi, uzay.

Review

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1.Introduction

Human beings began using copper-based tools around 5000 BC, marking the onset of the Chalcolithic Era a period characterized by the concurrent use of copper (chalco) and stone (lithos) as primary materials for daily tasks. This era lasted nearly two millennia until the discovery of copper alloying techniques around 3000 BC, which led to the Bronze Age (The British Museum, n.d.; Radivojević et al., 2010). During this transition, relatively soft copper tools and brittle stone implements were replaced by more durable bronze-based tools. Throughout history, each era has been defined by the interaction between humanity and materials, alongside the continual advancement of material technologies. Today, humans have access to a vast array of advanced materials, including high-entropy alloys and conductive polymers, which serve in state-of-the-art technologies.

The fundamental distinction between materials used in antiquity and those of the present lies in their origin. While ancient materials were discovered through exploration of natural environments, modern materials including conventional metals are developed through systematic research and innovation (Klemm et al., 2001). Nonetheless, efficient resource management remains essential for ensuring material affordability. For example, rising oil prices lead to increased polymer costs, just as iron ore shortages drive up steel prices (Jiang et al., 2024; Prasad, 2016). During the Age of Discovery, the pursuit of abundant resources including metals and other valuable goods motivated European expeditions seeking new trade routes to Asia, ultimately resulting in the accidental discovery of the Americas. This newly encountered continent provided Europe with valuable resources such as silver, gold, and potatoes commodities previously unknown in Europe (D. Arnold, 2013). However, this wealth came at a devastating cost for the indigenous populations, who faced violence and cultural extinction (Britannica, 2025; Edwards & Kelton, 2020).

In engineering and technological disciplines, the primary focus remains on the development of novel materials and the optimization of their production methods. Simultaneously, supply chains play a critical role in determining the final cost of a material, device, or product (De Koning et al., 2024). It is evident that companies account for techno-economic considerations when developing new materials or processes (Chai et al., 2022). However, experimental scientists are often encouraged to prioritize the exploration of new technologies that offer improved properties over existing alternatives.

It would be overly simplistic to claim that all early explorers were merely driven by the pursuit of precious resources. In fact, a profound sense of curiosity and wonder has historically motivated numerous explorers just as it continues to inspire modern scientists who gaze at the sky in search of answers.

Space travel has become increasingly accessible. Technological advancements, particularly in spacecraft propulsion systems such as pulsed plasma and ion thrusters, are expected to further reduce costs in the near future (Howe et al., 2022; Melnikov et al., 2024). The cost of sending cargo to space has also significantly declined from approximately $100,000 per kilogram during the 1960s Apollo Program (using Saturn V rockets), to about $3,000 per kilogram with SpaceX's reusable Falcon 9. Projections indicate this cost may fall below $100 per kilogram in the future (Aerospace Security, 2022; Jones, 2018). As space travel becomes more affordable, the prospect of colonizing celestial bodies such as the Moon, Mars, the Asteroid Belt, and Europa becomes increasingly plausible. Such colonization may offer long-term solutions to existential risks including uncontrolled artificial intelligence, climate change, and nuclear conflict. Thus, identifying alternative habitats through space colonization is of critical importance (Ćirković, 2019; Gottlieb, 2022; Munevar, 2019). Beyond colonization, the utilization of extra-terrestrial resources presents several strategic advantages, as outlined below:

Capital generation to fund future missions: Although scientific curiosity is a significant motivator, space colonization represents a large-scale initiative requiring substantial initial investments. Profitability is essential to attract stakeholders.

Self-sufficiency of space colonies: While early infrastructure and basic needs might be supplied from Earth especially for nearby locations like the Moon or Mars long-term sustainability requires local resource utilization, particularly for distant sites such as the Asteroid Belt or Europa.

Establishment of inter-colony trade networks: Historically, trade networks facilitated not only the exchange of goods and wealth but also human mobility and cultural interaction. Despite modern digital communication, physical trade routes may remain essential for in-person engagement.

Employment opportunities in extra-terrestrial colonies: Initial jobs will likely be scientific in nature. However, a sustainable colony will eventually require diverse professions miners, technicians, farmers, construction workers, and others. Effective resource management could become a major employment sector. Moreover, purposeful engagement in work may help inhabitants adapt mentally and emotionally to the new environment.

While the above projections assume the physical presence of humans in space colonies, it is important to acknowledge alternative proposals suggesting that space colonization may proceed via autonomous systems and robotic technologies (Campa et al., 2019).

In summary, the local valorization of extra-terrestrial resources processing them at the mining site will be beneficial for multiple reasons, including reduced energy consumption and lower processing costs compared to transporting raw materials back to Earth.

The concept of space mining, particularly asteroid mining, has been examined extensively in the literature (Andrews et al., 2015; Dallas et al., 2020). However, the term astrometallurgy, which encompasses the extraction of metals from extra-terrestrial sources, remains relatively novel and underexplored. Chapters 4 and 5 provide a detailed discussion on the emergence and scope of astrometallurgy. For clarity, the definition proposed by the authors is presented below:

"Astrometallurgy is a discipline that encompasses mineral processing and extraction of metals and metal compounds from their primary and secondary extra-terrestrial sources beyond Earth's atmosphere."

The term astrometallurgy is also etymologically appropriate, as the prefix astro- refers to stars or outer space. Hence, it can accurately describe metallurgical activities conducted outside Earth's atmosphere, including metal extraction (Astro-, 2024). Nevertheless, once permanent settlements are established on celestial bodies (e.g., Mars), it is likely that astrometallurgy will gradually be referred to simply as metallurgy by local inhabitants. Until then, the use of the term astrometallurgy remains suitable to reflect the unique conditions of such environments.

This review centers on astrometallurgy, discussing its conceptual origins and practical applications through selected case studies involving the Moon and Mars. The authors acknowledge existing challenges related to space travel and colonization, including solar radiation, microgravity, water scarcity, extreme temperature variations, propulsion limitations, and psychological effects (Balistreri & Umbrello, 2022; Gottlieb, 2022). All projections in this study are made under the assumption that these barriers can eventually be addressed. In addition, foundational information regarding the formation of the universe and the origins of extra-terrestrial matter is provided to offer readers conceptual clarity.

2. Formation of The Universe and The Matter

Big bang model is the current opinion that most of the physicist defend as the most probable model. It describes the formation of the universe approximately 13 billion years ago (Mathews, 2008). Regarding that theory, universe evolved to the current form of it from an infinitely dense dimensionless point to a hot spot and a vast space filled with many objects of interest, such as black holes and giant stars (Figure 1). Galaxies with billions of stars, and celestial objects that either orbits around them or moves more freely, creates billions of giant clusters scattered all through this vast void space.

The formation of the universe in its current state has taken billions of years. In the earliest moments, the universe was characterized by extremely high temperature and density, allowing the existence of only subatomic particles such as photons and quarks. It was not until approximately one ten-thousandth of a second after the Big Bang that protons and neutrons began to form. Within the following minutes, the first atomic nuclei emerged through the process of nucleosynthesis, resulting in the creation of the simplest elements, including hydrogen, deuterium, and helium (Pagel, 2000). However, the formation of complete atoms required several hundred thousand years. As the universe continued to expand and cool, gravitational forces became increasingly influential, leading to the condensation of atoms into gas clouds. These gas clouds gradually accumulated, forming denser regions with stronger gravitational pull, which further enhanced the aggregation process. This mechanism eventually led to the formation of massive, high-temperature celestial bodies known as stars. The immense pressure in the cores of these stars enabled the synthesis of various elements, starting from the primordial hydrogen and helium produced during the early stages of the universe.

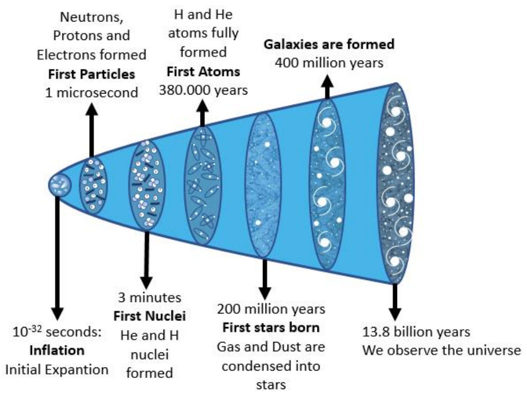

Figure 1. History of the universe.
Şekil 1. Evrenin tarihi.

The generation of elements varies depending on their atomic structure. For instance, relatively light elements such as lithium and beryllium are synthesized within active stars like the Sun as part of their energy production processes (Spite & Spite, 1982). In contrast, elements such as carbon and oxygen are formed during the late stages of a star's lifecycle. When a star exhausts the hydrogen in its core, it enters a phase of decline and expands into a red giant. During this phase, the fusion of helium atoms gives rise to heavier elements, extending up to iron (Cowan & Sneden, 2006).

Nevertheless, the internal conditions of stars are not sufficient for the synthesis of elements heavier than iron, such as gallium or bromine. The formation of these heavier elements typically requires the extreme conditions produced during a supernova. Additionally, neutron-rich elements like gold and uranium are formed through a process known as neutron capture, which involves the bombardment of atomic nuclei by neutrons. This bombardment causes a rapid increase in the size of the atomic nucleus, ultimately leading to the formation of heavier elements (Cowan & Sneden, 2006).

Recent research has identified alternative pathways for the formation of certain heavy elements. In particular, the collision of two neutron stars approximately 140 million light-years away resulted in the synthesis of an estimated five Earth masses of strontium (Watson et al., 2019). Although such events occur with low frequency, which might appear inconsistent with the relatively high abundance of heavy elements on Earth and in other celestial bodies, the overall composition of the universe supports these findings. Observational data and theoretical models suggest that the universe consists primarily of hydrogen (approximately 74% by mass) and helium (approximately 25% by mass), with all other heavier elements comprising only a small fraction of the total mass. Despite their limited abundance in the universe, these heavier elements constitute the fundamental building blocks of the planets and celestial bodies observed within our solar system.

3. The Types of The Objects in The Solar System and Their Chemical Contents as an Extra-Terrestrial Resource

Currently we are well aware of the chemical composition of the planets and their moons in our solar system. For instance, we know that Venus has a very similar composition with earth, except the extreme amount of carbon dioxide in its atmosphere (Figure 2). Or Mars has a crust that is composed of mostly iron, magnesium, aluminium, and potassium. Utilizing these extra-terrestrial resources on these celestial bodies is one of the most exciting ideas in the history of the mankind. Although, it seems possible to extract resources from the objects in space with our current technology, we are currently limited with the near earth objects within the reach. However, the mining concept in space is quite different from its earth-base equivalent. In mining operations around the world, mostly conventional techniques that are created with the experience of thousands of years is combined with currently available high-tech tools and methods in order to perform extraction from challenging environments, such as obtaining oil by drilling from the ocean bottom, obtaining gas from the air, and even obtaining valuable minerals from the ocean bottom. However, advancing mining studies under lower gravity or microgravity conditions has become a separate research and development issue.

	Carbon Dioxide	Nitrogen	Oxygen	Argon	Methane	Sodium	Hydrogen	Helium	Other
Sun							71.0 %	26.0 %	3.0 %
Mercury			42.0 %			22.0 %	22.0 %	6.0 %	8.0 %
Venus	96.0 %	4.0 %							
Earth		78.0 %	21.0 %	1.0 %					< 1.0%
Mars	95.0 %	2.7 %		1.6 %					0.7 %
Jupiter							89.8 %	10.2 %	
Saturn							96.3 %	3.2 %	0.5 %
Uranus					2.3 %		83.5 %	15.2 %	
Neptun					1.0 %		80.0 %	19.0	

Figure 2. Chemical composition of all planets in the solar system (NASA, a; NASA, d; NASA e).
Şekil 2. Güneş sistemindeki tüm gezegenlerin kimyasal bileşimi.

Among the various alternatives, asteroids with orbits close to Earth are considered among the most promising candidates for accessing extra-terrestrial resources, a concept referred to as astromining. These celestial bodies, which traverse the interplanetary space, are generally classified into three main types: carbonaceous (C-type), siliceous (S-type), and metallic (M-type) asteroids. Our solar system contains millions of asteroids, most of which are located in the region between Mars and Jupiter, commonly known as the Asteroid Belt. C-type asteroids are composed primarily of clay and silicate rocks, and they also contain volatile substances such as water and carbonaceous compounds. These asteroids are among the most prevalent and are typically found in the outer regions of the belt, farther from the Sun. Due to the low temperatures in these regions, carbon-based compounds are preserved effectively on their surfaces. Some C-type asteroids are estimated to contain up to 22% water. They hold significant potential for the extraction of volatile resources and may even be utilized in applications such as horticulture and air production in future space missions. S-type asteroids mainly consist of silicate minerals such as olivine and pyroxene, along with notable amounts of nickel and iron. These asteroids are more frequently found in the inner parts of the main Asteroid Belt and are regarded as the most common type. It is estimated that approximately 85% of all meteoroids that fall to Earth originate from S-type asteroids. They are particularly promising as potential sources of nickel and iron. M-type asteroids are rich in metallic elements, primarily composed of nickel, iron, and cobalt, and they may also contain precious metals such as gold. Additionally, they are known to harbor elements from the platinum group, including palladium, rhodium, ruthenium, osmium, and iridium. M-type asteroids are typically located closer to the central region of the Asteroid Belt (Mhatre & Mhatre, 2020).

4. Transition from Asteroid Mining to Astrometallurgy

In the context of global mining activities, two critical parameters for ensuring sustainable operations are safety and environmental cleanliness. From this perspective, it is essential to anticipate and mitigate potential accidents in order to protect both environmental and human health. In gold production, incidents such as the leakage of cyanide into water sources, which can result in serious water pollution, as well as other events leading to resource loss or endangering the lives of workers and nearby residents due to excavation activities that may induce destruction or seismic events, are often the result of non-standard mining practices. These types of incidents, which may be classified as preventable, can generally be avoided through the implementation of rigorous safety protocols. However, the prediction and monitoring of parameters related to complex phenomena such as natural disasters or rock collapses remain challenging. Due to the unpredictable nature of such events, providing early warnings or implementing preventive measures is significantly more difficult. The environmental risks and safety concerns associated with terrestrial mining have led to increased interest in alternative approaches such as marine mining and extraterrestrial mining. The extraction of rare and precious metals, including platinum, often requires deep subsurface operations and high energy consumption on Earth. In contrast, these metals are found in relatively higher abundance within near-Earth asteroids (NEAs), making asteroid mining an appealing prospect (Dong et al., 2020). Nevertheless, it is essential to assess the economic viability and profitability of asteroid mining initiatives. For a mission to be viable, it is necessary to evaluate both technological readiness and relevant economic factors. In terms of profitability, attention must be given to the potential extraction of volatile compounds such as water, which could support space missions, as well as valuable metals like platinum, which hold significant value in global markets (Hein et al., 2019).

In particular, volatile mineral extraction provides clear economic and logistical advantages for space exploration. To advance these efforts, it is recommended to focus on developing scalable, efficient processes for water extraction and transportation. Asteroid Mining for metals is currently not economically viable under typical market conditions. Further research is required to reduce costs and better understand market dynamics. In order to increase the profitability and facilitate the viability of future efforts, it is necessary to design modular, reusable spacecraft, investigate in-space manufacturing to reduce logistics costs, and develop policies to address legal and financial risks (Hein et.al. 2019) Nevertheless, these analyses and developments show that asteroid mining missions are pioneering in-situ resource utilization (ISRU) technologies and paving the way for deep space industrialization (Xie et al., 2021).

Although human activities in extra-terrestrial environments, such as mining operations, are of growing importance, they carry the risk of significant and long-lasting environmental impacts. These impacts include the alteration of natural landscapes, disruption of scientific exploration, and the potential loss of future resource sustainability. In contrast to Earth, extra-terrestrial landscapes do not possess natural mechanisms for recovery, such as tectonic activity or vegetation, which means that human-induced disturbances may persist indefinitely. While environmental assessment frameworks on Earth have demonstrated effectiveness in mitigating damage, equivalent systems have not yet been established for space activities. One of the principal challenges is the absence of regulatory frameworks for commercial operations in space. In addition, the space industry has shown limited recognition of environmental risks, and the possibility of irreversible damage in extra-terrestrial settings further complicates the issue. Although international agreements, including the Outer Space Treaty (1967) and the Moon Treaty (1979), emphasize shared governance of space resources, they lack binding provisions for environmental protection. Therefore, there is a pressing need for a customized assessment framework that addresses the specific requirements of space industries. The development of such a framework would require active collaboration among governments, private sector stakeholders, and international organizations. Without voluntary adherence to environmental standards, the introduction of regulatory enforcement may become necessary as public awareness regarding extra-terrestrial environmental concerns continues to grow (Kramer et al., 2020).

For sustainable mining in space, the implementation of low-gravity vehicles that stabilize equipment and isolate extracted materials may help prevent contamination and support safe mining operations. In addition, lightweight and solar-powered smelting and beneficiation units could enable on-site processing of resources, particularly on asteroids. This would reduce the financial and logistical burdens associated with transporting materials over long distances (Dong et al., 2020).

In addition to environmental challenges, the history of terrestrial resource exploitation and colonization raises concerns about the potential for similar conflicts in space. As terrestrial resources become increasingly scarce, extra-terrestrial mining is expected to play a vital role in maintaining industrial productivity and global economic stability. Existing space law provides general guidelines for space activities but lacks specific regulatory structures related to resource extraction and taxation. The establishment of taxation mechanisms is critical for the equitable distribution of profits and for reducing the likelihood of conflict over resource ownership and control (Semerad et al., 2023).

Recent advancements in space research and resource extraction capabilities have given rise to the concept of astrometallurgy as a natural extension of astromining. A significant proportion of the energy required for a spacecraft to reach the Moon is consumed merely in reaching low Earth orbit, which lies within the first 400 kilometers. This illustrates the importance of launching missions from locations where gravity is considerably lower, such as the Moon, to improve energy efficiency in space travel. However, transporting all the materials necessary for such missions from Earth is not a feasible option. As a result, the utilization of nearby resources, including asteroids and lunar materials, has become essential. This approach, known as in-situ resource utilization (ISRU), has strengthened the relevance of astrometallurgy as a distinct field of study (Shaw et al., 2022).

Numerous studies have focused on the on-site use of space resources, including the extraction of valuable metals such as platinum and the provision of accessible water sources to support long-term human presence on the Moon. Consequently, in-situ resource utilization has emerged as a multidisciplinary concept encompassing the identification, extraction, and processing of a wide range of extra-terrestrial resources. Alongside astromining, which focuses on resource prospecting and exploration, astrometallurgy plays a pivotal role in the development of industrial-scale processes, particularly for lunar applications. These efforts contribute to the advancement of metal production technologies and the overall specialization of in-situ resource utilization strategies for future space missions.

5. Origin of Astrometallurgy

Extractive metallurgy, which originated as an ancient practice involving the transformation of ores into metals, has evolved into a modern scientific discipline through advances in chemistry (Habashi, 1997). Within this context, astrometallurgy refers to the extraction of minerals and production of metals from celestial bodies, as well as the development of metallurgical processes designed for application in space environments (Astrometallurgy.com; Shaw et al., 2022). The concept of astrometallurgy emerged at the intersection of space exploration technology and speculative scientific literature. It was initially introduced by visionary authors such as Arthur C. Clarke, H. G. Wells, and Robert A. Heinlein, who popularized the idea long before it became a subject of scientific inquiry. Over time, astrometallurgy developed into a recognized scientific field, driven by the necessity to explore and utilize extra-terrestrial resources in support of human activities beyond Earth. The progress of space missions in the mid-twentieth century, especially the Apollo program, demonstrated the feasibility of extra-terrestrial resource utilization and contributed to the rising interest in this area (Shaw et al., 2022). The potential to access abundant metals from asteroids and other celestial bodies has since become a primary motivator for continued research and development.

The advancement of astrometallurgy is closely associated with the concept of in-situ resource utilization, which reflects humanity's objective of achieving sustainable deep space exploration. In-situ resource utilization involves the exploitation of local materials available on planetary bodies such as the Moon, Mars, and asteroids to generate essential resources including water, oxygen, and fuel (NASA, f). This approach is particularly important because it offers a sustainable alternative to transporting materials from Earth. Launching payloads from Earth is costly, with current expenses starting at approximately 3,000 United States dollars per kilogram for low Earth orbit missions using reusable Falcon 9 rockets developed by SpaceX (Our World in Data, 2021). The cost of delivering one kilogram of material to the Moon can reach up to 1.2 million United States dollars (Shaw, 2022), while the projected budget for a human mission to Mars is estimated at around 500 billion United States dollars (Jones, 2016). By enabling the extraction and utilization of local resources, such as water and oxygen from lunar or Martian regolith, in-situ resource utilization offers a way to significantly reduce overall mission costs. This reduction not only lessens financial burdens but also increases operational flexibility and reduces dependence on Earth-based supply chains. Furthermore, in-situ resource utilization facilitates the construction of infrastructure on other planetary bodies, including habitats and life support systems, through the use of local materials. This capability is essential for maintaining long-term human presence on the Moon and Mars, and it also serves to mitigate risks arising from logistical disruptions in the supply chain.

The transition of astrometallurgy from conceptual speculation to practical implementation is exemplified by NASA's Lunar Surface Innovation Initiative. Through this program, NASA aims to develop core technologies and strategies necessary to support the Artemis mission, which serves as preparation for deeper space expeditions (NASA, c). Among the six priority areas identified in this initiative, two are directly related to astrometallurgy: in-situ resource utilization and excavation, construction, and outfitting.

Astrometallurgy involves the extraction and processing of metals from lunar and Martian regolith and from asteroids. This encompasses technologies for excavation, material transport, and storage, with the aim of producing structural components, tools, and systems required for life support. Innovations in additive manufacturing, such as three-dimensional printing, further contribute to this process by enabling the conversion of regolith into usable construction materials. This approach significantly reduces the need to transport large quantities of equipment and building materials from Earth (In-Situ Resource Utilization – NASA).

At present, astrometallurgy remains in the experimental and early developmental stages. Ongoing initiatives, including NASA's Artemis program and private sector ventures, play a critical role in advancing the technological readiness and economic feasibility of space-based metal production. It is projected that within the coming decade, significant progress will be made, and milestones such as metal production on the lunar surface are expected to be achieved. By the anticipated date of NASA's Artemis III mission in September 2026 (NASA, b), astrometallurgy is likely to transition from a theoretical concept to a tangible reality. Furthermore, according to Matthew Shaw, a leading researcher in the field, the production of metals on the Moon using Earth-derived processes could become achievable within five to ten years (CSIRO, 2023). These developments invite the scientific community to consider further innovation beyond existing terrestrial models and to envision more novel approaches tailored specifically for extra-terrestrial environments.

6. How to Modify Metallurgical Processes to Extract Metals from Extra-Terrestrial Resources

Developing mineral processing and metal extraction technologies for space applications requires reconsidering conventional methods due to the significant differences between Earth and space conditions. Traditional Earth-based processes, which use gravity, pressure, and abundant water, may prove ineffective on the Space due to its reduced gravity, low pressure, and limited water availability (Shaw, 2022). Consequently, there is a critical need to adapt existing technologies or devise new processes optimized for the space environment. Currently, the primary objective is to adapt these technologies, particularly for use in lunar conditions, in anticipation of the ongoing Artemis Mission (Shaw, 2022). Furthermore, future objectives include developing similar extraction technologies for Martian conditions and potentially other celestial bodies (Khetpal et al., 2002; Nababan et al., 2022). Therefore, this work will concentrate the extraction of metals in Moon and Mars.

A point that needs to be addressed is that human dependence on oxygen for life support and its use as rocket propellant directs current space exploration initiatives to prioritize oxygen extraction from the surfaces of Mars and the Moon (Hinterman & Hoffman, 2020; Schlüter & Cowley, 2020). It is noteworthy that oxygen extraction from lunar minerals frequently results in the production of metal by-products, which makes this process of interest as a potential metallurgical extraction technique (Shaw et al., 2022). In light of the above, it is evident that while the traditional extractive metallurgy industry has historically focused on the recovery of metals, in the case of astrometallurgical processing, oxygen recovery is also a key factor in determining the economic viability of the process (Shaw et al., 2022).

Current comminution, beneficiation, and metal extraction processes have all been developed and refined over time with base assumptions that come inherently from the physical and chemical conditions found on Earth. To address the question of how to modify metallurgical processes to extract metals from extra-terrestrial resources on Mars and the Moon, it's essential to consider the unique environmental factors on these celestial bodies (Table 1).

Table 1. Comparison of Earth, Moon and Mars (N. S. Arnold et al., 2022; Benison et al., 2008; Nababan et al., 2022; *Safe on Mars*, 2002; Shaw et al., 2022).
Tablo 1. Dünya, Ay ve Mars'ın karşılaştırılması (N. S. Arnold vd., 2022; Benison vd., 2008; Nababan vd., 2022; *Safe on Mars*, 2002; Shaw vd., 2022).

Factor	Earth	Moon	Mars
Gravity	9.8 m/s^2	1.62 m/s^2	3.72 m/s^2
Average Surface Temperature	14 °C (Day and Night)	123 °C (Day) −178 °C (Night)	−127 °C to +17 °C
Pressure	1 atm	Unmeasured (Day) 3x10^{-15} atm (Night)	7x10^{-3} atm
Solar Flux	1368 W/m^2	1361 W/m^2	590 W/m^2
Human Access	Abundant	Severely Restricted	Severely Restricted
Day/Night Cycle	24 hours	708.7 hours	24.66 hours
Water Availability	Plentiful	Rare resources	Iced water and possible subglacial water bodies
Dust	Easily suppressed	Electrostatic, abrasive, and everywhere	Electrostatic, abrasive, and magnetic

Lunar and Martian regolith share common characteristics, containing abundant oxides such as Silicon dioxide (SiO_2), Aluminum oxide (Al_2O_3) and Iron oxide (FeO or Fe_2O_3) (Kalapodis et al., 2020). Therefore, metal extraction on the Moon and Mars focuses to reduction of oxides (Table 2).

Chemical reduction techniques, such as hydrogen and carbothermal reduction, offer feasible options for metal extraction on the Moon. However, their main limitation lies in the cost associated with the supply chain due to the need for chemical reagents (Shaw et al., 2022). Hydrogen reduction, which involves the reaction between iron monoxide and hydrogen to produce metallic iron and water, is theoretically applicable using hydrogen sources present on the Moon. Nonetheless, the limited availability of hydrogen on the lunar surface renders this method resource-intensive and economically challenging. Similar obstacles are encountered in other chemical reduction methods, including carbothermal, lithium, and acid-based reduction techniques, primarily because they require the import of reagents from Earth, thereby increasing logistical and operational costs.

On Mars, carbothermal reduction presents a more advantageous approach due to the possibility of producing carbon monoxide locally from the abundant carbon dioxide in the Martian atmosphere (Nababan et al., 2022). The MOXIE system, developed as part of Martian exploration technologies, has demonstrated the capability to split carbon dioxide into carbon monoxide and oxygen, thus offering a reliable in situ source of reductant for metal extraction. The local production of carbon monoxide significantly enhances the feasibility of carbothermal reduction on Mars. Furthermore, once metal production is established on the Martian surface, the application of metallothermic reduction methods could be considered. For instance, if silicon metal can be produced, it may serve as a reducing agent to extract magnesium from its oxide.

Electrochemical reduction techniques, including Molten Regolith Electrolysis (MRE) and solid-state electrolysis, are also regarded as promising methods for lunar applications. These techniques offer the advantage of utilizing lunar regolith directly, eliminating the need for extensive pre-processing or beneficiation (Shaw et al., 2022). MRE utilizes molten regolith as the electrolyte, thereby avoiding the use of imported chemical reagents. Solid-state electrolysis, which operates at relatively lower temperatures, has the potential to reduce overall energy consumption. Both techniques are compatible with the lunar environment and facilitate the direct processing of local materials. However, the development and implementation of long-lasting inert anodes remain a critical requirement for the success of these technologies. MRE is generally considered more advantageous than solid-state electrolysis, as it does not require additional electrolyte materials and minimizes the complexity of resupply logistics. Electrochemical methods may also be adapted to Martian conditions, expanding their applicability beyond the Moon (Nababan et al., 2022).

Thermal reduction, also known as pyrolysis, is another promising technique for extra-terrestrial metal extraction, particularly on the Moon. This method leverages the high solar flux and natural vacuum present on the lunar surface to enable energy-efficient thermal decomposition of oxides (Shaw et al., 2022). Concentrated solar energy can be used to achieve the high temperatures necessary for the dissociation of metal oxides, as the absence of atmospheric interference ensures unattenuated solar input. Although this technology is currently at an early stage of development, it holds significant potential due to its minimal reagent requirements and compatibility with a wide range of feedstocks. In addition, the vacuum environment of the Moon and outer space contributes to lower energy demands compared to terrestrial systems. On Mars, similar advantages exist due to the planet's low atmospheric pressure, which allows thermal decomposition to occur at reduced temperatures. This environmental benefit enhances the feasibility of thermal reduction techniques for Martian metal extraction processes (Nababan et al., 2022).

In summary, the adaptation of metallurgical processes for extra-terrestrial resource extraction necessitates the strategic utilization of the specific environmental conditions and available resources of both the Moon and Mars. On the Moon, electrochemical and thermal reduction techniques offer considerable potential, primarily due to the feasibility of directly processing lunar regolith and the beneficial effects of the natural vacuum environment (Shaw et al., 2022). On Mars, carbothermal reduction using carbon monoxide produced from the local carbon dioxide-rich atmosphere presents a particularly effective solution. Additionally, electrochemical and thermal reduction methods may also be applicable on Mars, supported by the planet's low ambient pressure and the abundance of carbon dioxide (Nababan et al., 2022).

When comparing these methods, hydrogen reduction emerges as a theoretically feasible but practically limited approach on the Moon, mainly due to the scarcity and high cost of hydrogen sourcing. Carbothermal reduction, while constrained on the Moon by reagent availability, becomes significantly more viable on Mars because of the ease of generating carbon monoxide in situ. Molten regolith electrolysis offers substantial advantages for lunar conditions by eliminating the need for additional reagents, while solid-state electrolysis, although requiring lower energy input, depends on the availability of an added electrolyte material. Thermal reduction techniques benefit from the unique environmental conditions of both celestial bodies, including high solar flux and vacuum on the Moon and low atmospheric pressure on Mars, enabling efficient oxide decomposition. Overall, molten regolith electrolysis and thermal reduction are better suited for lunar applications, whereas carbothermal reduction stands out as the most promising method for Martian environments.

Ongoing research and technological development remain essential for refining these metallurgical approaches and enabling their practical implementation in future space missions. Despite the promising advancements, several critical technical and environmental challenges must still be addressed before sustained human activity in deep space becomes a realistic and viable goal.

7. Conclusion

Astrometallurgy constitutes a pivotal development within the field of materials science, offering significant contributions to the advancement of sustainable space exploration and the potential establishment of extra-terrestrial settlements. The capability to extract and process metals from extra-terrestrial sources minimizes dependency on terrestrial resources and provides solutions to the economic and logistical difficulties associated with prolonged space missions.

This review has emphasized the considerable potential of utilizing materials such as lunar and Martian regolith, as well as asteroid-derived resources, for on-site metal production. Nevertheless, the shift from conventional terrestrial metallurgical practices to astrometallurgical applications necessitates substantial modifications due to the distinctive environmental conditions encountered in space. These conditions include reduced gravitational forces, low ambient pressure, and limited access to water.

Among the methods evaluated, electrochemical and thermal reduction techniques, particularly molten regolith electrolysis and carbothermal reduction, have demonstrated promising applicability for operations on both the Moon and Mars. As research in space science continues to progress, sustained innovation and scientific inquiry into astrometallurgical processes will be indispensable for overcoming existing technical barriers and ensuring the effectiveness of future space missions.

In conclusion, astrometallurgy holds the potential to significantly reshape human activities beyond Earth by enabling the economically viable and technologically feasible colonization of other celestial bodies.

Table 2. Possible extra-terrestrial metal extraction methods for moon and mars.
Tablo 2. Ay ve Mars'ta olası dünya dışı metal çıkarma yöntemleri.

Application	Requirements	Advantages	Disadvantages	Overall Assessment for Lunar Application	Overall Assessment for Mars Application
Hydrogen Reduction	Hydrogen	Feasible using lunar hydrogen sources	Scarcity of hydrogen, high cost	Resource-intensive and costly	Not suitable due to hydrogen scarcity
Carbothermal Reduction	Carbon	In situ production of CO on Mars	High supply chain costs if importing reagents	Challenging due to reagent import needs	Highly viable with in situ CO production
Molten Regolith Electrolysis (MRE)	Inert Anode	No additional reagents needed; uses lunar regolith	Need durable inert anodes	Promising due to no reagent need	Potentially adaptable
Solid Electrolysis	Electrolyte material Anode	Lower energy requirements	Requires an electrolyte material	Potential due to lower energy needs	Potentially adaptable
Thermal Reduction	High solar flux	Energy-efficient; uses high solar flux and vacuum	Low technology readiness level	Highly promising due to energy efficiency	Viable due to low ambient pressure and vacuum

8. References

Aerospace Security (2022). Space Launch to Low Earth Orbit: How Much Does It Cost? https://aerospace.csis.org/data/space-launch-to-low-earth-orbit-how-much-does-it-cost/

Andrews, D. G., Bonner, K. D., Butterworth, A. W., Calvert, H. R., Dagang, B. R. H., Dimond, K. J., Eckenroth, L. G., Erickson, J. M., Gilbertson, B. A., Gompertz, N. R., Igbinosun, O. J., Ip, T. J., Khan, B. H., Marquez, S. L., Neilson, N. M., Parker, C. O., Ransom, E. H., Reeve, B. W., Robinson, T. L., … Yoo, C. J. (2015). Defining a successful commercial asteroid mining program. Acta Astronautica, 108, 106-118. https://doi.org/10.1016/j.actaastro.2014.10.034.

Arnold, D. (2013). The Age of Discovery, 1400-1600. Routledge.

Arnold, N. S., Butcher, F. E. G., Conway, S. J., Gallagher, C., & Balme, M. R. (2022). Surface topographic impact of subglacial water beneath the south polar ice cap of Mars. Nature Astronomy, 6(11), 1256-1262. https://doi.org/10.1038/s41550-022-01782-0

Astro-.(2024). https://dictionary.cambridge.org/dictionary/learner-english/astro

Astrometallurgy.com (2023). What is Astrometallurgy? Why are we here? https://astrometallurgy.com/what-is-astrometallurgy%3F

Balistreri, M., & Umbrello, S. (2022). Should the colonisation of space be based on reproduction? Critical considerations on the choice of having a child in space. Journal of Responsible Technology, 11, 100040. https://doi.org/10.1016/j.jrt.2022.100040.

Benison, K. C., LaClair, D., & Walker, J. (2008). Physical sedimentology experiments with sulfuric acid solutions: Implications for Mars? Earth and Planetary Science Letters, 270(3-4), 330-337. https://doi.org/10.1016/j.epsl.2008.03.036.

Britannica (2025). Potato - Definition, Plant, Origin, & Facts. https://www.britannica.com/plant/potato

Campa, R., Szocik, K., & Braddock, M. (2019). Why space colonization will be fully automated. Technological Forecasting and Social Change, 143, 162-171. https://doi.org/10.1016/j.techfore.2019.03.021

Chai, S. Y. W., Phang, F. J. F., Yeo, L. S., Ngu, L. H., & How, B. S. (2022). Future era of techno-economic analysis: Insights from review. Frontiers in Sustainability, 3, 924047. https://doi.org/10.3389/frsus.2022.924047

Ćirković, M. M. (2019). Space colonization remains the only long-term option for humanity: A reply to Torres. Futures, 105, 166-173. https://doi.org/10.1016/j.futures.2018.09.006

Cowan, J. J., & Sneden, C. (2006). Heavy element synthesis in the oldest stars and the early Universe. Nature, 440(7088), 1151-1156. https://doi.org/10.1038/nature04807

CSIRO (2023). Room on the Moon: Building our future in space. https://www.csiro.au/en/news/All/Articles/2023/September/mining-moon-famelab

Dallas, J. A., Raval, S., Gaitan, J. P. A., Saydam, S., & Dempster, A. G. (2020). Mining beyond earth for sustainable development: Will humanity benefit from resource extraction in outer space? Acta Astronautica, 167, 181-188. https://doi.org/10.1016/j.actaastro.2019.11.006

De Koning, I., Kassahun, A., & Tekinerdogan, B. (2024). Benchmarking circularity in supply chains: A systematic literature review. Journal of Environmental Management, 366, 121676. https://doi.org/10.1016/j.jenvman.2024.121676

Dong, Y., Zhao, Y., Li, W., Zhang, Y., & Liu, J. (2020). Safe and clean mining on Earth and asteroids: A review. Journal of Cleaner Production, 256, 120398. https://doi.org/10.1016/j.jclepro.2020.120398

Edwards, T. S., & Kelton, P. (2020). Germs, Genocides, and America's Indigenous Peoples. Journal of American History, 107(1), 52-76. https://doi.org/10.1093/jahist/jaaa008

Gottlieb, J. (2022). Discounting, Buck-Passing, and Existential Risk Mitigation: The Case of Space Colonization. Space Policy, 60, 101486. https://doi.org/10.1016/j.spacepol.2022.101486

Habashi, F. (1997). Handbook of Extractive Metallurgy. Wiley.

Hein, A. M., Matheson, R., & Fries, D. (2019). A techno-economic analysis of asteroid mining. Acta Astronautica, 168, 104–115. https://doi.org/10.1016/j.actaastro.2019.01.048

Hinterman, E., & Hoffman, J. A. (2020). Simulating oxygen production on Mars for the Mars Oxygen In-Situ Resource Utilization Experiment. Acta Astronautica, 170, 678-685. https://doi.org/10.1016/j.actaastro.2020.02.043

Howe, S. D., Howe, T., Bennett, F. G., Blaylock, N., Jackson, G., & Cassibry, J. (2022). Pulsed plasma rocket-developing a dynamic fission process for high specific impulse and high thrust propulsion. Acta Astronautica, 197, 399-407. https://doi.org/10.1016/j.actaastro.2022.03.020

Jiang, H.-D., Liu, Y., Wang, H., Li, H., & Jiang, Y. (2024). An economy-wide and environmental assessment of an imported supply shortage for iron ore: The case of China. Economic Analysis and Policy, 83, 606-617. https://doi.org/10.1016/j.eap.2024.07.002

Jones, H. W. (2016). Humans to Mars Will Cost About "Half a Trillion Dollars" and Life Support Roughly Two Billion Dollars. 1-11.

Jones, H. W. (2018). The Recent Large Reduction in Space Launch Cost. 1-10.

Kalapodis, N., Kampas, G., & Ktenidou, O.-J. (2020). A review towards the design of extraterrestrial structures: From regolith to human outposts. Acta Astronautica, 175, 540-569. https://doi.org/10.1016/j.actaastro.2020.05.038

Khetpal, D., Ducret, A. C., & Sadoway, D. R. (2002). From Oxygen Generation to Metals Production: In Situ Resource Utilization by Molten Oxide Electrolysis. 2002 Microgravity Materials Science Conference, Huntsville, AL, USA.

Klemm, D., Klemm, R., & Murr, A. (2001). Gold of the Pharaohs – 6000 years of gold mining in Egypt and Nubia. Journal of African Earth Sciences, 33(3-4), 643-659. https://doi.org/10.1016/S0899-5362(01)00094-X

Kramer, W. (2020). In Dreams Begin Responsibility: Environmental Assessment and Outer SpaceActions. Society for Social and Conceptual Issues in Astrobiology (SSoCIA) Conference. 5.

Mathews, G. J. (2008). Big Bang Cosmology. AIP Conference Proceedings, 1016(1), 7-14. https://doi.org/10.1063/1.2943636

Melnikov, A. V., Abgaryan, V. K., Peysakhovich, O. D., & Demchenko, D. S. (2024). Promising methods for improving the radio-frequency ion thruster performance. Acta Astronautica, 215, 534-547. https://doi.org/10.1016/j.actaastro.2023.12.031

Mhatre, P., & Mhatre, P. (2020). Asteroid Mining: Future of Space Commercialization. International Journal of Latest Technology in Engineering, Management & Applied Science, 9(4), 19-30.

Munevar, G. (2019). An obligation to colonize outer space. Futures, 110, 38-40. https://doi.org/10.1016/j.futures.2019.02.009

Nababan, D. C., Shaw, M. G., Humbert, M. S., Mukhlis, R. Z., & Rhamdhani, M. A. (2022). Metals extraction on Mars through carbothermic reduction. Acta Astronautica, 198, 564-576. https://doi.org/10.1016/j.actaastro.2022.07.009

NASA, a. About The Planets. https://science.nasa.gov/solar-system/planets/

NASA, b. Artemis III Mission. https://www.nasa.gov/event/artemis-iii-launch/

NASA, c. Lunar Surface Innovation Initiative. https://www.nasa.gov/space-technology-mission-directorate/lunar-surface-innovation-initiative/

NASA, d. The Sun. https://science.nasa.gov/sun/

NASA, e. The Composition of Planetary Atmospheres. https://www.nasa.gov/wp-content/uploads/2015/01/yoss_act_4.pdf

NASA, f. In-Situ Resource Utilization. https://www.nasa.gov/overview-in-situ-resource-utilization/

Pagel, B. E. J. (2000). Helium and Big Bang nucleosynthesis. Physics Reports, 333-334, 433-447. https://doi.org/10.1016/S0370-1573(00)00033-8

Radivojević, M., Rehren, T., Pernicka, E., Šljivar, D., Brauns, M., & Borić, D. (2010). On the origins of extractive metallurgy: New evidence from Europe. Journal of Archaeological Science, 37(11), 2775-2787. https://doi.org/10.1016/j.jas.2010.06.012

National Research Council. 2002. Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface. Washington, DC: The National Academies Press. https://doi.org/10.17226/10360.

Our World in Data (2021). Cost of space launches to low Earth orbit. https://ourworldindata.org/grapher/cost-space-launches-low-earth-orbit

Schlüter, L., & Cowley, A. (2020). Review of techniques for In-Situ oxygen extraction on the moon. Planetary and Space Science, 181, 104753. https://doi.org/10.1016/j.pss.2019.104753

Semerád, P. (2023). Asteroid mining tax as a tool to keep peace in outer space. Space Policy, 65, 101559. https://doi.org/10.1016/j.spacepol.2023.101559

Shaw, M. (2017). Artemis 1 is off – and we're a step closer to using Moon dirt for construction in space. The Conversation. http://theconversation.com/artemis-1-is-off-and-were-a-step-closer-to-using-moon-dirt-for-construction-in-space-191852

Shaw, M., Humbert, M., Brooks, G., Rhamdhani, A., Duffy, A., & Pownceby, M. (2022). Mineral Processing and Metal Extraction on the Lunar Surface—Challenges and Opportunities. Mineral Processing and Extractive Metallurgy Review, 43(7), 865-891. https://doi.org/10.1080/08827508.2021.1969390

Spite, M., & Spite, F. (1982). Lithium abundance at the formation of the Galaxy. Nature, 297(5866), 483-485. https://doi.org/10.1038/297483a0

The British Museum. Chalcolithic. https://www.britishmuseum.org/collection/term/x13740

Watson, D., Hansen, C. J., Selsing, J., Koch, A., Malesani, D. B., Andersen, A. C., Fynbo, J. P. U., Arcones, A., Bauswein, A., Covino, S., Grado, A., Heintz, K. E., Hunt, L., Kouveliotou, C., Leloudas, G., Levan, A. J., Mazzali, P., & Pian, E. (2019). Identification of strontium in the merger of two neutron stars. Nature, 574(7779), 497-500. https://doi.org/10.1038/s41586-019-1676-3

Prasad S. (2016). What is Relationship Between Crude Oil and Polyethylene Prices? https://www.linkedin.com/pulse/what-type-relationship-exists-between-prices-crude-oil-sakthi-prasad/

Xie, R., Bennett, N. J., & Dempster, A. G. (2021). Target evaluation for near-Earth asteroid long-term mining missions. Acta Astronautica, 181, 249–270.