DEFENSE, EMERGING TECHNOLOGY, AND STRATEGY PROGRAM

The Future is Stellar

How Asteroid Mining Can Resolve the Climate Crisis, Expand the Economy, and Ensure the United States Retains Its Dominance in Astropolitics

Alexandra Arneri

HARVARD Kennedy School
BELFER CENTER

50 YEARS OF RESEARCH, POLICY, AND LEADERSHIP

STUDENT PAPER
DECEMBER 2024

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About the Defense, Emerging Technology, and Strategy Program

The Defense, Emerging Technology, and Strategy (DETS) program has a dual mission to

1. advance policy-relevant knowledge and strategy on the most important challenges at the intersection of security and emerging technology; and
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Table of Contents

Introduction

Asteroid mining is a tangible opportunity that the United States should actively pursue to mitigate climate change, the environmental destruction from terrestrial mining and attendant human rights abuses, leapfrog technological advancement and jumpstart its economy. While there are inherent risks and challenges, including navigating ambiguous international law, current geopolitical tensions, technological deficits and mitigating space debris and collisions, they can be addressed by and inform policy that promotes and protects a domestic industry. Asteroid mining is also instrumental in building a space-to-space supply chain, allowing for further space exploration and settlement- and ensuring that the United States is not left behind in the new space race.

Asteroid Mining May Resolve Climate, Environmental and Economic Crises

We are reaching critical climate tipping points and urgently and rapidly need to decarbonize. While this is termed the "clean energy transition" it is rather a dirty affair as "renewable" energy relies on critical, finite minerals and drives increasing extraction[i]. The energy transition requires 17 rare earth elements, the 15 lanthanides, scandium and yttrium[ii]. These elements include cobalt, graphite, lithium and nickel, essential for lithium-ion batteries. Copper, crucial for conductivity[iii]. Rare earth elements ("REE") such as dysprosium, neodymium, praseodymium and terbium, essential for the operation of wind turbines[iv]. Gallium, used in high-efficiency photovoltaic cells, tantalum (coltan), used in electronic capacitors in solar systems and wind turbines, manganese, used in wind turbines, and palladium and platinum, used in hydrogen fuel cell technology[v]. Their extraction pollutes local land, water and air with processing chemicals, dust, aerosols and radioactive waste[vi]. REE mining has a particularly high waste-to-yield ratio – every ton of REE produces 2,000 tons of mine tailings, including 1-1.4 tons of radioactive waste[vii]. Worse, the more we mine, the deeper we have to go[viii], which exacerbates the destructive environmental impact and has spurred seismic activity from unstable faults[ix].

In pursuing our current transition, we are exacerbating historic injustices as the majority of critical element extraction is occurring in the Global South, leading to land grabs, human rights abuses and environmental destruction in "sacrifice zones"[x]. From "artisanal" miners in the Democratic Republic of the Congo, a euphemism for miners, including children as young as five, mining without any operational protocols or equipment, poisoned each day from contact with cobalt and risking amputation and death as makeshift tunnels collapse[xi], to mountains being razed and rivers polluted in Burma[xii], to amplification of desertification in the Atacama[xiii], to the destruction of Tibet[xiv] – it is the Global South and vulnerable communities that are bearing the burden of our transition. More than half of transition elements, and 80% of lithium reserves are in or adjacent to indigenous lands[xv]. Within the United States, all lithium deposits are within thirty-five miles of indigenous territory[xvi]. Extraction in or near indigenous territory is continuing and exacerbating historic injustices. The clean energy transition is saving us from a climate crisis but leading us to an environmental and human rights crisis – and the demand for transition elements is only increasing. To reach net-zero targets by 2050, we need six times the mineral input in 2040 than we have today[xvii]. It is expected that there will be a 2500% increase in demand for dysprosium alone by 2035[xviii] and a 400-600% increase in REEs[xix]. The demand for copper is expected to increase by 275-350% by 2050[xx]. The demand for lithium is expected to increase by 1500% by 2050[xxi]. It is expected that to meet rising demand over the next couple of decades, we will need to open 384 new mines for graphite, nickel, lithium and cobalt, wreaking even more environmental destruction and misery[xxii].

The national security interest of the United States is compromised by its current energy transition as the U.S. is a net importer of transition elements and reliant on the vicissitudes of a foreign supply chain[xxiii]. The U.S. has identified 50 "critical minerals" or non-fuel materials instrumental to energy with a high risk of supply chain disruption[xxiv]. There is a concentration of deposits of critical elements in a few states and an even higher concentration in processing which poses several risks to supply chains, including natural and political disasters and export restrictions[xxv]. The U.S. remains vulnerable to foreign states intentionally delaying or denying minerals. The U.S. is particularly vulnerable due to its increasing tensions with the People's Republic of China, which processes nearly 90% of rare earth elements, 100% of dysprosium (used in wind turbines and electric vehicles), 70% of cobalt, nearly 60% of lithium and manganese and nearly 100% of natural graphite[xxvi]. China, in seeming retaliation against U.S. export controls respecting chips, has limited the export of gallium and germanium, required for their manufacture[xxvii]. The U.S. needs to find a source of supply that is not controlled and cannot be thwarted by geopolitical rivals or is otherwise disrupted, including by natural stochastic events, which are getting more extreme and more frequent from climate change[xxviii].

A solution to energy security, climate, environmental and human rights crises must be found. One approach- and one that is already a policy of the United States - is through substitution and recycling[xxix]. Lithium iron phosphate (LFP) batteries do not use cobalt and avoid its problematic environmental and human rights impact, and also have more thermal stability than lithium-ion batteries- but the latter have higher energy density, are lighter and quick charging[xxx]. Moreover, LFPs still require extraction of iron ore, nickel and lithium[xxxi]. Development of non-lithium batteries, such as sodium-ion batteries (SIBs), using seawater, present challenges due to lower energy density, which leads to larger batteries that cannot be used in smaller devices or restricted spaces[xxxii]. Moreover, while SIBs avoid the environmental destruction wreaked by lithium extraction, SIBs require the processing of more materials, and hence contribute to more greenhouse gases[xxxiii]. Recycling transition materials also presents numerous challenges. While some elements such as cobalt, copper, nickel and gold, have low degradation and high capacity for circular use, others, such as REEs and lithium, degrade easily and moreover, require energy intensive separation and extraction[xxxiv]. Additionally, there is insufficient stock for recycling and demand continues to increase[xxxv]. Substitution, recycling and resilient design, which domicile and reduce the need for extracting critical elements in addition to depleting e-waste, are necessary but are insufficient to meet our energy security and sustainability, particularly if we wish to grow the economy rather than pursue de-growth[xxxvi].

Another proposed avenue for greater supply is seabed mining, which would allow access to abundant required elements[xxxvii]. Seabed mining in international waters is controlled by the International Seabed Authority ("ISA"), under the 1982 U.N. Convention of the Law of the Sea ("UNCLOS")[xxxviii]. However, the US is not yet a party to UNCLOS[xxxix] and ISA has not authorized any exploitation licenses as it reviews requirements thereof[xl]. The U.S. has asserted that it has the right to mine in international waters without ISA authority[xli]. If it accedes to the treaty, it denies its persistent objection, and may also weaken argument that the international regulation of asteroids should not follow seabed mining. Moreover, deep sea mining may be another environmental catastrophe[xlii]. The seabed covers 65% of the earth's surface and more importantly, makes up 95% of the earth's biosphere[xliii]. Damaging or destroying this ecosystem, which is already stressed from ocean acidification, contamination, including microplastics and loss of biodiversity, may have unparalleled environmental effects[xliv]. Worse, we don't have a comprehensive understanding of the deep-sea ecosystem and face unknown risks from mining that we cannot yet mitigate[xlv]. A better path is space mining – and asteroid mining in particular.

The moon is far closer than asteroids and contains materials that are useful both on earth as well as for in-situ utilization. The moon has large deposits of water and helium-3, the latter a possibility for clean fusion, with high energy yield and minimal residual radioactivity[xlvi]. Lunar regolith is oxygen rich, which extraction can be used both for refueling and providing air to lunar residents[xlvii]. Additionally, lunar regolith can store and supply solar energy to any lunar base[xlviii]. The moon also has some deposits of KREEP (potassium, rare earth elements and phosphorous) but asteroids have far more critical elements[xlix]– from lithium, to cobalt, to palladium[l].

There are currently 1,413,275 identified asteroids in our solar system and the vast majority are in the asteroid belt between Mars and Jupiter[li]. There are also about 20,000 near-Earth asteroids, or within 1.3 au (astronomical units- equivalent to 120 million miles/195 million km)[lii]. There are three types of asteroids – C-type, S-type and M-type[liii]. C-type or chondrite carbonaceous asteroids are the most common and are composed of water, silicates, clay and other organic compounds[liv]. Water is not only vital to life on Earth, particularly as freshwater is a finite resource and increasingly polluted or depleted, but vital for any space missions or established space colonies, and can be separated into hydrogen and oxygen for in situ refueling and further space exploration[lv]. Carbon and phosphorous can be used for fertilizer to grow food in space[lvi]. S-type or "stony" asteroids contain metals including nickel, gold, platinum and magnesium-silicate mixtures[lvii]. M-type asteroids or "metal" asteroids contain the most metal but are the least common[lviii]. Psyche 16, an M-type asteroid in the asteroid belt between Mars and Jupiter, is about 85% metal and is valued more than the entire global economy[lix]. Hence, asteroids not only contain volatiles required for astronauts to replenish supplies in space and refuel, but also critical elements that could obviate the need for destructive terrestrial and marine mining.

Asteroid mining presents a solution to several current and pernicious energy issues. If the United States pursued asteroid mining, it would no longer rely on a global supply chain for critical elements and achieve energy security. It would not be subject to geopolitical restrictions on supply or price volatilities. More importantly, the United States would be able to secure sufficient supply for the energy transition and prevent the current environmental destruction and human rights abuses prevalent in the current extraction of critical elements. Space mining will radically aid the feasibility of space-based climate solutions which lack the environmental impact of terrestrial and marine mining. Space based shades or lunar dust at a stable LaGrange point with the sun, could block sunlight and decrease global temperatures[lx]. These solutions may not only be cleaner, but more effective than current renewable energy infrastructure, which require a massive land print, compromising biodiversity and decreasing terrestrial carbon uptake[lxi].

Asteroid mining can also catalyze economic growth. Weinzierl argues that it may be the best solution to secular stagnation, as it addresses demand side issues, via the massive public investment required to nurture and cultivate the industry and on the supply side, through the innovation spurred by exploration (and exploitation) of the "new frontier"[lxii]. Asteroid mining can spur a new space economy, including space-for-space industry, as it allows for in situ utilization of resources, including refueling, making longer space ventures more feasible[lxiii]. This will indubitably have spillover effects, such as occurred with the moon program, creating new jobs, new businesses and developing new technologies[lxiv]. Numerous technologies, some that we use on a daily basis, were developed during the space program including MRI and CAT scans, infrared thermometers, reflective (emergency) blankets, phone cameras, wireless headphones, temper (memory) foam and enriched baby formula[lxv].

The Legality of Space Mining

The Russian Federation and China have proclaimed that space mining violates the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies ("OTS")[lxvi]. Due to the large number of states that have ratified OTS, consistent state practice, lack of persistent objection and coupled with supporting *opinio juris*, its principles, such as the non-appropriation principle at issue here, has arguably become customary international law[lxvii], and hence extends to all states, irrespective of whether they are signatories or not[lxviii]. That states view non-appropriation as obligatory can be seen from the unsuccessful Bogotá Declaration of 1976. Not only were the equatorial states unsuccessful in their attempt to claim sovereignty over geostationary orbit which continually lies above their territories, but their declaration affirmed rather than rejected the non-appropriation principle as they conversely claimed (unsuccessfully) that geostationary orbit, a product of Earth's gravitational force, should not be deemed a part of space[lxix]. Hence, if the United States were to withdraw from OTS, it would remain obligated by the principle of non-appropriation under customary international law.

The issue, however, is that the principle of non-appropriation is ambiguous as to whether extraction and exploitation of space resources is appropriation. The United States has taken the valid, viable and possibly stronger position that it does not.

The United States ratified OTS in 1967 with unanimous senate consent, providing it status under domestic law[lxx].The United States has never repudiated OTS and has consistently affirmed it, even declaring that its Artemis Accords should be interpreted subject and in accordance with OTS[lxxi].

The operative provisions are Articles I and II of OTS. Under Article I the exploration and use of space "shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind"[lxxii]. Under Article II, there is a prohibition of "national appropriation by claim of sovereignty, *by means of use or occupation*, or by any other means" (emphasis added)[lxxiii]. This is supported by the following language in the preamble: "that the exploration and use of outer space should be carried on for the benefit of all peoples irrespective of the degree of their economic or scientific development"[lxxiv].

While the United States has signed but not ratified the 1969 Vienna Convention on the Law of Treaties ("VCLT")[lxxv], its Article 31, is largely accepted as codifying customary international law[lxxvi]. Under its Article 31 (1), treaties should be interpreted "in good faith and in accordance with the ordinary meaning to be given to the terms of the treaty"[lxxvii]. A plain understanding of the words "exploration and use" covers mining. What constitutes national appropriation is ambiguous, as the sentence can be read in a cumulative fashion, which would denote how a state could claim appropriation but requires a claim to be made, or disjunctive, implying that use would be deemed to be national appropriation *per se* and prohibited. The use of the comma between "sovereignty" and "by means of use…" implies that it should be read in a disjunctive manner[lxxviii]. The language of the preamble that space and celestial bodies are to be explored and used "for the benefit of all peoples" supports this reading[lxxix]. One could also argue that allowing use by private companies is an extension of national sovereignty because such private companies would be licensed by the state and would pay taxes to such state. This reading supports Russia and China's position, and space mining should be hence regulated like deep sea mining under an equivalent agency to ISA, as it would fulfil the dictates of OTS due to its royalties aiding less developed states.

However, under Article 31 (3) (b) of VLCT, we must take into account subsequent state practice as to how states view their obligations respecting "non appropriation"[lxxx]. The OTS cannot be read without the successive 1979 Agreement Governing the Activities of States on the Moon and other Celestial Bodies ("MTS")[lxxxi] - and more importantly, the fact that the only independent spacefaring nations to sign it have been France and India, who are also signatories to the Artemis Accords[lxxxii]. Despite Russia and China's protestations, neither have ratified MTS[lxxxiii], which implies they also reject it. Additionally, despite their protest that unilateral space mining violates international law and their opposition to the Artemis Accords, they are likewise exploring mining options which practice rather affirms the position of the United States[lxxxiv]. MTS clarifies OTS under Article 11 by affirming that no party shall claim sovereignty by use or other means, and expressly denotes that celestial bodies are the "*common heritage of all mankind*" (emphasis added) and subject to equitable sharing of extracted resources[lxxxv]. The rejection of any spacefaring state with an independent program of these provisions implies that the *opinio juris* rejects a reading that extraction requires equitable sharing and is subject to international authority.

Additionally, it's important to note that the principles of common heritage or *res communis*, and national appropriation are separate and that only the latter has developed into international customary law binding all states, the former at odds with state practice. Further, ironically, MTS rather supports the position of the United States on the issue of whether extraction is deemed to be national appropriation. While MTS Article 11 (2) tracks OTS Article 2, MTS Article 11 (3) includes an important qualification, stating that- "neither the surface nor the subsurface of the moon, nor any part thereof or *natural resources in place*, shall become property of any State (emphasis mine)". A plain reading of that sentence is that natural resources that are extracted from a celestial body can become the property of a state (and by extension, of a corporate citizen of such state). State practice also supports this view. NASA and other space agencies have extracted samples from the moon, and recently from asteroids, and have shared their samples with other states, but in a manner that asserts their right to the samples and no state has proclaimed an interest in any NASA samples (or samples from other space agencies)[lxxxvi].

UNCLOS is instructive. UNCLOS designates two areas as international and open to common use – the high seas and the seabed of the high seas[lxxxvii]. The former codifies the customary law of "freedom of the high seas" and any state has freedom to traverse, explore and exploit the natural resources thereof[lxxxviii]. The seabed, denoted as the "Area" and non-biological resource extraction is however deemed the "common heritage of mankind" and subject to international regulation by ISA and equitable sharing[lxxxix]. The "common heritage of mankind" respecting the seabed tracks MTS – and importantly, all independent spacefaring states rejected MTS. This allows for two interpretations – that mining asteroids should be regulated akin to fishing in the high seas or that it should be regulated akin to deep sea mining. The argument in favor of the latter is that there is a clear distinction between biological and mineral resource extraction, and that asteroid mining falls in the latter category. However, another argument – and one that is more viable – is that as there is no such distinction in space, and as asteroids are unconnected unlike the seabed, the former should prevail, and they should be viewed as fish in the high seas. In any case, there is at least a viable argument that the United States is interpreting -and by its practice developing – an area of international law that is currently not *lex lata* prohibited.

The Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids for Peaceful Purposes or Artemis Accords[xc] ("AA") drafted by the United States is therefore not in opposition to international law as protested by Russia and China but a well needed refinement of international law. As of October 2024, there are 44 signatories to AA, and importantly, the vast majority of spacefaring states. Conversely, there are currently only 18 ratifications to MTS and 6, including Australia, Mexico and the

Netherlands, are parties to both. This supports the position of the United States[xci]. AA affirms the principles of peaceful use and cooperation of OTS and affirms the prohibition of non-appropriation but allows for unilateral exploration and extraction[xcii]. This is akin to the freedom of the high seas under UNCLOS, whereby a state provides a fishing license to its flagships and taxes such ships but does not thereby denote a claim of sovereignty through such use. AA affirms that OTS should be interpreted so that no state could claim sovereignty over any area in space and that "extraction of resources does not inherently constitute national appropriation"- allowing for space mining[xciii].

The most controversial provision is Article XI's "deconfliction" provisions which create "safety zones"[xciv] somewhat akin to Exclusive Economic Zones ("EEZ") under UNCLOS. Jurists are conflicted on whether these "safety zones" violate OTS and the customary law principle of non-appropriation. On the one hand, as AA expresses, it is squarely within and develops OTS's non-interference principle as it seeks to prevent conflict between exploring parties and clearly limits the safety zones to that purpose. On the other hand, it arguably violates the non-appropriation principle. This ambiguity allows for state practice to develop the interpretation in one form over the other. The fact that 44 states have acceded to AA and both Russia and China are actively pursuing space exploration and bases, affirms that any position that the U.S. is violating international law is arguable at best.

This is also supported by current state practice whereby several states have enacted domestic legislation to support domestic commercial space industries, including providing property rights for extracted space resources. In 2015, the United States enacted the Commercial Space Launch Competitiveness Act which expressed that the U.S. would facilitate a burgeoning private space industry and allow U.S. citizens (encompassing its entities) exploration and "commercial recovery of resources" in space[xcv]. In 2017, the Grand Duchy of Luxembourg enacted the Exploration and Utilization of Space Resources Law which established a licensing scheme for exploration and extraction of extraterrestrial resources[xcvi]. In 2019, the United Arab Emirates enacted Federal Law No. 12, On the Regulation of the Space Sector, which provides for a permitting scheme for space activities and the ability to extract, acquire and exploit space resources[xcvii]. In 2021, Japan enacted the Act on the Promotion of Business Activities for the Exploration and Development of Space Resources[xcviii]. The act provides for a licensing scheme for launches and commercial space activity and property rights to extracted resources[xcix]. Saudi Arabia's draft legislation will establish a licensing scheme for space resource exploration and extraction and property rights therewith[c]. Saudi Arabia withdrew from MTS and acceded to AA to support its "new space" ambitions. As more states view "new space" as an industry they want to promote, they will likewise enact similar laws, which would further weaken MTS. There is no clear impediment to the United States pursuing a unilateral asteroid mining strategy and pursuing it aids in the development of international law in its interest.

Meeting Challenges and Mitigating Risks

There are several impediments and risks to space mining, and asteroid mining in particular. There are known risks, but there may also be unknown risks and if we are to pursue any cultivation of the asteroid mining industry, we must do so prepared to mitigate the known risks and be vigilant in identifying and navigating unknown risks.

Asteroid mining may require astronomical costs. It may cost as much as $2.6 billion per mining mission, excluding the added substantive cost of processing[ci]. Past missions have been expensive and have retrieved only grams, from missions to Hayabusa ($300MM), Hayabusa2 ($800MM) and the OSIRIS-REx mission to101955 Bennu ($1.16B)[cii]. Asteroid mining will need to transport, extract, possibly process and return vast amounts of material-at prodigious cost[ciii].

Asteroid mining presents unique and gargantuan challenges- and far more than any moon mining[civ]. This is because asteroids are more distant than the moon- the majority farther than Mars- and because asteroids have much weaker gravity. The distance alone creates several substantive issues. It is energy intensive, and we currently lack cost-effective propulsion systems to travel to the asteroids and return[cv]. The distance also complicates communication due to delay, and consequently prevents real time control over machinery[cvi]. The distance requires long operational times for the spacecraft and attendant machinery[cvii]. The lack of atmosphere exposes machinery to high amounts of radiation and extreme temperatures that can cause machinery to malfunction or degrade[cviii]. Microgravity complicates extraction because machinery may not be able to anchor and may float away[cix]. OSIRIS-Rex had difficulty anchoring to Bennu and retrieving a sample, and its attempts led to fugitive regolith and the creation of more space debris[cx].

The development of these technologies requires massive amounts of investment and continued capital injections, but investment is impeded by the uncertainty of the regulatory environment and increasing geopolitical tensions[cxi]. Even if technically feasible, asteroid mining may not be economically competitive against cheaper terrestrial mining. Additionally, there is an economic catch-22 at play. If asteroid mining is an economic bonanza because it allows us to obtain vast amounts of critical elements, then the increased supply, according to standard economic theory, plummets the price and destroys the market. Why would any investor want to invest money in a scheme that may be unfeasible and if feasible may either not protect ownership rights or otherwise not obtain any profit? Yet, without this investment, asteroid mining will never develop.

The collapse of the critical elements market is not merely a tragedy for any putative investor but for millions of people who are currently employed in the terrestrial sector who would lose their jobs and who would lack a skillset transferable to space mining[cxii]. It may not only exacerbate inequality within states by the collapse of the mining sector, but between states, as states in the Global South primarily rely on resource extraction[cxiii]. A simulation conducted by Tel Aviv University concluded that if gold plummeted to half of its price because of the increased supply from asteroid mining, there would be an escalation of global tensions[cxiv].

Asteroid mining contains inherent risks of creating an oligopolistic or monopolistic market. While Neil DeGrasse Tyson predicted that asteroid mining would make the world's first trillionaire[cxv], the running joke is that to be that trillionaire, you have to start out as a billionaire[cxvi]. Asteroid mining is highly capital intensive and presents significant first mover advantages. A first mover can scale and create supply chains that minimize costs creating a higher barrier to entry for later entrants. Additionally, a first mover will likely patent their technology which will create an additional barrier of entry for later movers. Moreover, and perhaps more importantly, a first mover can leverage the uncertainty of the regulatory landscape to lobby regulation in their favor. This will exacerbate already escalating inequality which has also resulted in stagnated overall growth[cxvii].

Asteroid mining necessitates more rocket launches, which release greenhouse gases, carbon dioxide and water vapor at launch and nitrogen oxide during re-entry. Water vapor and nitrogen oxide released at high altitude can deplete the ozone layer, and so can the release of unburned hydrocarbons and aluminum oxide released from solid rocket boosters[cxviii]. Depletion of the ozone layer reduces our protection against solar radiation, leading to deleterious epidemiological effects, including decreased immune system function and skin cancers, and intensifies global warming[cxix]. A recent study of Rocket Propellant-1 (RP-1), a highly refined kerosene, concluded that these rocket launches collectively expel 1 gigagram of black carbon into the stratosphere[cxx]. Chemicals in the stratosphere have a more deleterious impact because they are retained longer in the atmosphere[cxxi]. Space X's methane engines also produce carbon dioxide and water vapor, but produce more water vapor due to methane's higher concentration of hydrogen over carbon[cxxii]. However, there is a risk that methane may be released from the engine, and it is 80 times more potent as a greenhouse gas than carbon dioxide[cxxiii]. Rocket launches also release toxic and carcinogenic chemicals, creating health risks for local populations.

Asteroids have weak gravity and mining them contains the inherent risk of releasing debris[cxxiv]. This will add to the more than 170 million pieces of debris that we already need to remove[cxxv]. The more debris, the more chances of a collision, which collisions would cause more debris and lead to the cascading effect of Kessler's syndrome[cxxvi]. Satellites, particularly for the United States, which is the country most reliant on them, are critical to navigation, communication, observation, intelligence, critical infrastructure management and the financial system and their destruction or disruption could have catastrophic impact[cxxvii]. Moreover, satellite destruction could lead to debris falling onto the earth, causing personal and property damage[cxxviii]. It is also a risk to space sustainability as too much space debris may prevent launches as they would not be able to avoid collisions.

If we bring asteroids to geosynchronous orbit, in order to mine them there more efficiently, or otherwise move their trajectory, we risk destabilizing their orbit and causing massive collisions – perhaps even an impact on Earth[cxxix]. This could have catastrophic, even existential consequences.

There is also the risk of disrupting microbes, as it appears that some extremophile organisms may be able to survive in the harsh environment of asteroids, including in particular the subaqueous environments of larger asteroids[cxxx]. We may also disturb precursors to life and thereby thwart it. Samples from Bennu were rich in carbon and water – the building blocks of life[cxxxi] while samples from Ryugu contained prebiotic molecules[cxxxii]. Worse, we may accidentally transfer some of these extraterrestrial microbes to earth which may have grave consequences for planetary health, perhaps causing epidemics[cxxxiii].

The United States may inflame already rising geopolitical tensions if it were to pursue asteroid or any space mining. In fact – it already has, as Russia and China have protested that AA violates international law. A space race may foment terrestrial rivalries, intensifying the "chip war" and trade war between China and the U.S.[cxxxiv]. It is also bringing China and Russia closer, and they are not only increasing trade between each other but undertaking space missions together, which alignment threatens the national security interests of the United States.

None of these challenges and risks should arrest the cultivation and nurturing of a domestic asteroid mining industry. Rather, these challenges and risks should inform policy that cultivates the industry to appropriately meet the challenges and mitigate the risks.

The *potential* for disturbing extraterrestrial life should not be an inhibiting reason, because terrestrial mining has a *certain* detrimental impact on the local environment and attendant water sources, destroying habitats of known organisms that share our planetary home- in addition to contributing to the global climate crisis. The potential for microbial back contamination may be alleviated by preparing for such risk.

We should not fear, but embrace, technological challenges as they present leapfrog opportunities for innovation with pregnant potential for spillover effects across wide sectors. The moon mission, for instance, had numerous technological spillovers across a wide variety of sectors and boosted the economy. Human ingenuity should be harnessed – it was a challenge to get to the moon, but we did it, and it was a challenge to reuse rockets, but we did that too -and why should we stop here? Innovation spurs innovation. While we don't have commercially ready technology, we already have companies that have developed ingenious prototypes for responsible and sustainable mining, including Trans Astra, which has developed equipment for optical mining (using focused sunlight to extract resources rather than excavation tools to better navigate microgravity) and its "flytrap" capture bag which would cover an asteroid and prevent fugitive regolith[cxxxv]. Generative AI will escalate these technological innovations, including with better spectrographic detection of suitable targets. Developments in robotics and autonomous systems will also aid innovation in this area – and likely this will be a synergetic and dynamic process with numerous spillovers across various industries.

The investment required should also not be an impediment to cultivate this industry. It could rejuvenate our economy. While vertical integration and market control are pertinent risks, they can be navigated and eliminated if the government expressly cultivates competition by structuring the market in a way that fosters entrants. Additionally, the astronomical figures required to cultivate this industry may very likely decrease under Wright's Law – or the thesis of "learning by doing"[cxxxvi]. The cost of production is reduced through production[cxxxvii]. The importation of space resources can be structured in a way that allows for profit but also prevents global market collapse, for instance, by restricting supply.

The loss of the extraction economy for the Global South should also not be an impediment as such economy is exploitative and colonial, causing environmental and social catastrophe and fomenting conflict[cxxxviii]. A more equitable system rather requires that we stop the pillage of Global South resources and allow access to low-cost capital and opportunity. A wealthier United States from asteroid mining would be able to provide more access to capital and the development of new space economies will provide new opportunities for innovation that the Global South could exploit.

While the climate impacts of increased space launches and re-entry are pertinent issues to address, as the impact only escalates with more launches, the greenhouse gases of terrestrial mining – taking into account the substantive increased demand for critical minerals and increased extraction- far exceed the greenhouse gases from launches[cxxxix]. Moreover, the environmental destruction from terrestrial and marine mining exceeds the environmental impact of launches and reentry[cxl]. Hence, while we should aggressively pursue climate and environmental mitigation strategies for launches, we should not let their impact stop launches as space mining has a net lower carbon and environmental footprint than terrestrial mining.

Space debris, orbital destabilization and contamination are pertinent risks that need to be mitigated. While at first blush space mining- and asteroid mining in particular- may seem contradictory to the goals of space debris mitigation and active removal, they are in fact complementary. Cultivating a space mining industry requires that we minimize the risks of collision in space and remove debris while mitigating risks of further debris creation.

Geopolitical tensions may rather impel the United States to pursue asteroid mining. If it developed an asteroid mining industry, it would no longer be vulnerable to global supply chain issues, including China's export restrictions. It would also not fall behind any other state in the space race as asteroid mining is also a foundation for space-to-space industry, and space settlements. Despite the protestations against space mining by China and Russia, they are also aggressively pursuing space exploration and it is in the national security interest of the United States to ensure that it does not get left behind in this race. Indeed, it should lead it.

The United States should focus on asteroid mining rather than lunar mining because they contain critical elements that the moons lacks. Additionally, the proximity of the moon makes it an easier target for mining and settlement, and hence, presents fertile ground for rife competition. The distance between asteroids reduces the probability of two states targeting the same asteroid, as opposed to competing over the same sites on the moon. Additionally, the United States should take advantage of its capital and technology to take the lead in asteroid mining to gain a first mover advantage, for instance by developing refueling stations that later movers become dependent on, providing the United States with a dominant position in developing astropolitics.

Promoting and Protecting Asteroid Mining

The United States should actively cultivate and nurture a domestic asteroid mining industry, spurring a space economy. As Mazzucato has so well analyzed, the United States is no stranger to being entrepreneurial[cxli]. The vast majority of technological and medicinal breakthroughs have resulted from government-backed funding such as the internet, GPS, speech recognition, touch screen technology, all funded by DARPA, new chemical entities (NMEs) funded by the National Institute of Health[cxlii] and COVID vaccines under Operation Warp Speed[cxliii]. The government has not only created new products and services, but created whole new industries, such as the aerospace industry[cxliv].

The U.S. government should act as a prolific and experimental VC fund that provides much needed capital injection into mission-aligned companies that are at stages too risky for private financiers, including at the initial conceptual technological readiness level and sustain productive companies through the Valley of Death. Investment should be subject to strict accountability and transparency (with confidentiality agreements executed to protect proprietary non-patented information), via tranches of capital injections conditioned upon meeting established targets[cxlv]. The government should set clear requirements for development- but be technologically agnostic- directing results but not mandating means[cxlvi]. In this way, the government should ensure that it cultivates mission-aligned technologies from productive and competitive companies.

In adopting Mazzucato's "mission economy" approach, the government thus needs to set a clear and concrete asteroid mining mission and invest in mission-aligned entities throughout various disciplines and sectors[cxlvii]. It should use regulatory forcing to spur mission-aligned innovation, to mitigate or alleviate climate and environmental risks of asteroid mining technologies, including making investment dependent on meeting (i) advances in limiting environmental and climate impacts of launches and re-entry (ii) mitigating the risk of fugitive regolith and escalation of space debris (iii) preventing orbital destabilization (iv) preventing back contamination and (v) enhancing security of autonomous systems and remote controlled systems from malicious actors. It will also have to nurture an attendant active debris removal industry to allow space for more launches. There are many innovations that could aid these aims from developing potent electric propulsion systems that limit greenhouse gases and air pollution from launches, to utilizing nets to cover asteroids prior to mining and even utilizing biomining or using microorganisms to process critical elements from regolith in space, with promising results from ESA's Biorock study on the ISS[cxlviii].

The government should ensure that it is shaping and structuring markets in the public interest. Rather than nurture and bolster a space economy that will be vertically and horizontally integrated, the U.S. should ensure it shapes a competitive and productive market. Arguably, the U.S. has been the most successful V.C. fund in everything but in its internal rate of return – which is absurd and unjust. The U.S. government created the internet- but has failed to establish a digital public infrastructure[cxlix]. The U.S. government, via the National Institute of Health, funds the majority of NMEs, but has failed to exercise its march-in rights to ensure its funded medicine is available at reasonable prices- albeit the Biden administration has promoted their exercise[cl]. The government cannot socialize risk but not returns. Just like any other angel investor, the government should reap its return commensurate with its level of investment and risk. Opponents that argue this is akin to "double taxation" hold a fallible position. First and foremost, return on investment and taxation of income are independent of each other and serve different purposes. Second, even if that argument held any weight, it nevertheless fails to address the issue of regulatory arbitrage which has caused tax flight.

All asteroid mining technology is dual use technology because it could have military capability and should be subject to export controls. Additionally, prior to any license, the U.S. should ensure that space mining technology is secure against nefarious actors, with regular pen-testing of systems and red-teaming of any AI systems used.

The United States should also actively pursue a bifurcated multilateral strategy to develop international space law to limit geopolitical tension on the one hand and on the other protect its dominant position in space. The United States should promote a bifurcated approach to use of the moon and asteroids, with the former treated akin to the seabed, with an international body governing exploitation licenses and tracking UNCLOS, obtaining royalties from extraction – which in this instance, the United States should argue should fund the recently established United Nations Green Climate Fund for climate mitigation and adaptation in the Global South. The moon should be a place for international scientific exploration and cooperation, establishment of space tourism and refueling stations. The latter should be asserted as akin to fish in the high seas and the United States should be the first mover in this space to assert a dominant position. Additionally, the United States should develop international law (and enact attendant enabling domestic law) to transform the principles of the Artemis Accords into a detailed multilateral treaty that delineates rights and liabilities of both states and corporate entities, granting the latter express personality, mandatory mitigation of hazards, including space debris (and an easier international system of mitigating it)[cli] and a dispute mechanism for fair and quick dispute resolution. The development of an easily navigable regulatory space will promote investment and participation and decrease conflict, while being a first mover in the space, can allow the United States to develop international law in the interest of its own industry and security.

Conclusion

The United States needs to actively nurture and cultivate a domestic asteroid mining industry that addresses and is informed by its known risks. It should shape the market via Mazzucato's "mission" approach, investing in mission-aligned entities that meet performance standards and milestones and bolster competition. It should also ensure that it is financing innovation in mitigating climate and environmental risks of launches, preventing space debris, orbit destabilization and mitigating back contamination. Asteroid mining should be pursued as an avenue to obtain control of the supply chain of critical elements needed for the energy transition and prevent the environmental destruction and human rights abuse of terrestrial mining as well as avoiding the potential environmental catastrophe of mining the seabed. It should also lay the foundation for space-for-space industry and establish a new frontier for exploration. The United States can leverage the ambiguity of current international law to assert its position that asteroid mining is akin to the high seas and the moon is akin to the seabed, to both ease geopolitical tensions and be viewed as a multilateral player, while on the other hand concomitantly leveraging its capital and technological capacity to assert its dominance in an avenue that may be critical for future generations.

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