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Space Resources: Physical Constraints, Policy Choices, and Ethical Considerations

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Introduction and outline

For over 50 years, technology has dominated the discussion of human expansion into space. This is for the very good reason that without proven technology there can be no space exploration. The question of "can it be done?" is now all but answered in the affirmative. New questions of "should it be done?" or at least "how should it be done?" are coming to the fore. In this chapter, we discuss such questions in the light of an important assumption about current actions and their later impact. For this, we use the familiar idea of a founder effect: "even a few score, initial colonizers can mean much more for the cultural geography of a place than the contributions of tens of thousands of new immigrants a few generations later" (Zelinksky 1972, pp.13-14). Adapted to the context of humanity's expansion into space, the formulation becomes:

Founder effect*: while we cannot hope to dictate terms to future generations, decisions implemented at the beginning of humanity's exploitation of space resources can have disproportionate and lasting impact.*

This effect is likely to operate as a significant societal constraint upon future patterns of economic and social development. The upside of this effect is a special kind of influence upon future events, allowing us to shape our projects in ways that might encourage them to be continued by others. For example, responsible practices adopted early can create enduring precedents that shape future conduct for many generations. The downside of the founder effect is that beginnings cannot be made again. They are irreversible or difficult to reorient in ways that later actions are not. Mistakes made now have a disproportionate likelihood of rippling indefinitely and unfavorably into unintended future outcomes. This downside reflects physical constraints as well as social ones. The future expansion of a space economy will face constraints of both sorts. Here, we consider only a few that we regard as important and foreseeable. The substantial constraints of our human physicality (which is difficult to accommodate in space) will be set aside in order to focus upon the limiting factor of finite resources. Section 2 will consider such physical constraints upon the emergence of competitive markets, but also as a factor pushing human space expansion towards a systematic presence at multiple interconnected places, rather than merely at the sites with the material resources of more direct interest. Given the potential of these resources, Section 3 addresses the policy questions that now confront governments, highlighting the ways in which the decisions made in the near term will shape whether, when, and how markets for space resources emerge over the medium to long terms. Section 4 will then tentatively frame these possible policy responses within a larger ethical dilemma concerning our obligations to current and future generations: the dilemma of having to continually trade off *near-term justice* against *the interests of future generations*. Near-term justice may enabled by economic expansion in space, but at a cost to those future generations who live closer to the edge of resource depletion and, ultimately, exhaustion.

Economic Prospects and Strategic Resources

Over the past decade the idea that there could be a large and dynamic space economy involving humans working, and possibly living, in space has revived after long pause and several false starts (Sonter 1997; Lewis 1996). Such an economy was widely anticipated during the Apollo era and formed part of the economic rationale for the US Congress to fund NASA's Space Shuttle program, as a way to make spaceflight routine and thereby help bring the cost of space flight down to the point where commercial activity could flourish (NASA 1976). The anticipated reduction in costs, and the economic flourishing it promised, failed to materialize. There are, however, signs that this is finally changing. The cost of launching a kilogram of anything into low Earth orbit (LEO) has now dropped from some $20,000 to about $3000, with the advent of the reusable Falcon 9 rocket from SpaceX (https://www.spacex.com/media/Capabilities&Services.pdf). There are at least three private companies developing their own space stations to lease out to a rapidly growing number of start-ups that plan to manufacture products in space that require micro-gravity or a virtual absence of gravity for their construction; these products range from greatly improved optical fibers to human organs, even human hearts (Elvis 2021). Other customers for private space stations include research organizations, be they space agencies from smaller countries, rich universities and foundations, or biotech companies. The first paying customers are already known; they are tourists (Kooser 2021). Not all of these ventures will succeed, and there are good reasons to be cautious about participating in first waves of economic activity. Nonetheless, the move towards a large-scale and thriving space economy now looks more promising than ever. At this point, no government or international body could stop it from continuing, even if they wanted to do so as a matter of policy or principle.

Such a thriving in-space economy will need supplies of raw materials. The most obvious of which is water. Tourists paying millions for a space ride are likely to choose the space companies with the best safety record and the space station with the best facilities. That includes showers and (at some point) flushing toilets. Water is also effective as protection against radiation and can become rocket fuel when electrolyzed into hydrogen and oxygen. Conveniently, it turns out that water can be found abundantly in some locations in space, and energetically it is cheaper to supply that water from space than to bring it from Earth; it may even become financially cheaper although it will initially be more expensive. As the in-space economy expands, other raw materials will be needed in quantities that are prohibitive to bring up from the ground. Methane for rocket fuel can be made from the large organic molecules found in space. Iron for large scale construction can be sourced from asteroids. Even ordinary silicate rock can be a source of oxygen as well as being used for radiation shielding. These are in-situ resources which are also likely to be used in-situ. The only space resource worth bringing down to Earth, at least in the near future, is precious metals, such as platinum and palladium. But, eventually, some of the dozens of minerals found only in asteroids (the "meteorite minerals", named for how they were discovered) may turn out to have economic value.

Where will all these resources come from? The Moon and, as indicated, the asteroids. Though Mars is also a prime target for human exploration, at the moment it does not seem to be a likely source of resources that could easily be used elsewhere, and any time soon. Below we look at each source location more closely.

The Moon

The Moon is an appealing source for resources. We have already mapped the whole Moon in quite some detail, down to kilometer resolution in most cases (e.g. the compilation in Elvis, Krolikowski, and Milligan 2020, EKM20). As a result, we already know the best places to go prospecting for the richest deposits. The Moon is also only about 400,000 kilometers from Earth; a 3-day trip for astronauts, (NASA 2021) a roughly 1 second trip for light and radio waves. If there is an emergency involving astronaut miners or prospectors on the Moon, they can be rescued and may get home in a time that could be medically useful. On the other hand, the 2 second round trip delay in getting radio signals out and back is short enough that humans may not need to be physically present on the Moon in order to operate machinery there. Efficient tele-operation is plausible once the equipment is smart enough to avoid dangers which lie only a few seconds ahead.

An advantage of the Moon over asteroids for mining is that the Moon has stronger gravity, albeit only 1/6 of Earth's gravity. While that does mean expending more rocket fuel to bring supplies from the Moon to where they will be used in space, gravity makes lunar mining operations much more similar to those on Earth than they would be for the asteroids. Gravity is also useful to separate out the valuable materials from the tailings (Lewis 1996), and implicitly to settle the dust and debris from mining, which does not happen on asteroids.

What are the lunar resources that we might use? Water has already been mentioned, and many players have begun to explore options for use (Wall 2021; Foust 2021; EKM20). However, over most of the Moon, water is present only in trace quantities (ppm, Milliken and Li, 2017). However, there are a few locations where water seems to be present in large-ish quantities (Li et al., 2018). Places where water and volatiles deposited by comets and asteroid impacts remained in total darkness and did not heat up enough to escape (Berezhnov et al., 2012, Lawrence 2017). These "permanently shadowed regions" (PSRs) are primarily located near the poles. The obliquity of the Moon – the inclination of its axis to the plane of its orbit around the Sun - is just 1.5 degrees, compared with 23.5 degrees for the Earth (Allen 1973). As a result, there are almost no seasons on the Moon and at the poles the Sun traces a course around the horizon, rising and falling by only 1.5 degrees each day. As at sunset or sunrise on Earth, any peak casts long shadows at the lunar poles. The raised walls of craters cast shadows against the opposite side of the crater rim, leaving the floors of the craters in permanent shadow. The crater floors are illuminated only by starlight and by light reflected off the rims. This makes these regions very cold. Below 110 K (-163 C) water ice is stable even in a vacuum (Paige et al., 2010). Other volatiles are stable at lower temperatures (Paige et al., 2010).

Lunar resources are cataloged by Crawford (2014) and EKM20. Besides water they include: ^{3}He, a fuel for potential future nuclear fusion reactors; uranium and thorium that are fuels for current nuclear fission reactors; iron, probably remnants of asteroid impacts; and a unique location rich in rare earth elements, the KREEP terrane, which was likely the last place on the Moon to solidify after its creation from the impact of a Mars-sized planet with the proto-Earth (Ćuk and Stewart 2012).

For the near future lunar resources will be plentiful relative to the size of the nascent in-space economy. Measurements indicate that as much as a billion metric tons of water may be present in the PSRs (Crawford 2015). That is a lot compared with the ~50 mt that would be needed to refuel a rocket (Kutter 2018), or the 1 mt/year used by an astronaut aboard the International Space Station (Jonathan McDowell, 2020, private communication), but is still only the volume of a small lake[1]. New York City uses about this much water every day[2]. Lunar resources are plentiful, relative to the anticipated near-term needs of economic expansion, but they are still finite, and far from inexhaustible. They are also highly concentrated into a modest number of locations that are typically only a few kilometers in extent (EKM20). For example, there are just a half dozen PSR areas 50 km across that are colder than 110 K, and a just few dozen larger than about 5 km diameter (Paige et al. 2010). What we draw from this is a simple point: as the in-space economy grows, lunar resources will prove to be inadequate. Although asteroid mining presents considerable logistical difficulties, sooner or later, the asteroids will beckon as alternative storehouses of resources.

Asteroids

Near-Earth Asteroids. The next accessible source for space resources is the population of near-Earth asteroids (NEAs[3]). There are about 20,000 NEAs larger than 100 m diameter (Mainzer et al., 2011). NEAs have orbits within that of Mars and, as the name implies, come close to the Earth, some of them crossing the Earth's orbit, occasionally coming close enough to impact the Earth. Small ones do not reach the ground intact, such as the 17-meter sized asteroid that exploded above the Siberian city of Chelyabinsk in 2013 (Kring and Boslough 2014), but they do lead to

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[1] Lake Mead, behind the Hoover dam, has a capacity about 30 times larger.

[2] "nyc's reservoir system". http://www.nyc.gov/html/nycwater/html/drinking/reservoir.shtml (accessed 30 May 30, 2021.)

[3] Strictly they are the near-Earth objects (NEOs) because the population includes an ill-determined number of dead comets besides true asteroids.

showers of small remnant rocks that we call meteorites. From the analysis of the composition of meteorites we know that some asteroids contain large concentrations of valuable materials, including water and the precious platinum group metals (PGMs[4]). There are three main types of meteorite and asteroid. Each has its own value as resources:

1. First, a metallic nickel-iron asteroid 100 m in diameter that is PGM-rich may contain 20 mt of platinum, about 10% of the yearly production on Earth, with a nominal sales value of $1 billion (Elvis 2014). The million tons of iron left behind might be slowly moved to a high orbit around the Earth; there this iron could provide a relatively cheap source of building material for large-scale habitats, or space hotels, or for the long-dreamed of space based solar power.
2. Second, a carbonaceous water-rich NEA just 10 meters across could have a similar mass of water. Its value, once comparable to the $50 M of platinum, goes down as launch costs per kilogram decrease. Presently in LEO it would cost about $20 M to launch from the ground. In a high Earth orbit, or anywhere else near the top of, or outside, the Earth's gravity well, it could be worth twice as much.
3. The third class of asteroids are called "stony" and are made mostly of silicate rocks. Their value is less obvious. Like lunar regolith, 40 percent of their mass is made up of oxygen atoms. Solar power could be used to liberate this oxygen for use as life support or the oxidizer of rocket propellant. The rock itself, perhaps turned into concrete and formed into convenient shapes, can be used for radiation shielding.

Unfortunately, only about 1 in a hundred NEAs is rich in either water or PGMs (Elvis 2014). The number that we can reach with a payload large enough to undertake mining is limited by our current rockets to a few percent of that, leaving only a few dozen that might be mineable at present and worth a billion dollars each (Elvis 2014). With more powerful rockets, notably with the SpaceX Starship, this mineable number could become several hundred. However, the crucial point is that NEAs in themselves, do not hold greater water resources than the Moon[5]. NEAs could, however, be a profitable training ground for mining the far larger asteroid resources found farther

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[4] The PGMs are: platinum, palladium, rhodium, osmium, iridium, and ruthenium. The six are called siderophiles, as they dissolve in liquid iron. This property is why they are scarce in the Earth's crust as they were efficiently carried down into the iron core of the Earth when the Earth was still largely molten (REF).

[5] "Accessible NEAs", NASA, https://cneos.jpl.nasa.gov/nhats/ (accessed 3 June 2021).

from the Sun. There is much to be learned. Mining without gravity will require new techniques, from attaching to an asteroid and excavating the loosely bound rubble that most asteroids appear to be made of, through to drilling and blasting in order to extract the valuable ore while keeping the dust and debris generated out of the machinery.

Main Belt Asteroids. Beyond the orbit of Mars there is a far larger store of resources. There are a million of asteroids larger than about 300 m in size in the "Main Belt" of asteroids that lies between the orbits of Mars and Jupiter (Jedicke et al., 2015). As on the Moon, most of the resources lie in a relatively small number of larger asteroids. The resources of the Main Belt dwarf those available on Earth or the Moon. To give one measure of this abundance, the total amount of iron in the Main Belt asteroids is some 10 million times that of Earth's proven reserves (Elvis & Milligan, 2019). Economically, the special challenge of mining Main Belt asteroids is that they are so far from Earth. Transit times on energetically efficient Hohmann transfer orbits are a year or so, and in commerce time is money. It may be that, with the profits from NEA mining, companies will be able to afford to set up a shipping system that is economically viable for this more ambitious project. Without it, any space economy would be severely restricted. With it, the physical resources would still be exhaustible, even within a 500 year period if exponential growth, at even modest rates, is not kept within control (Elvis & Milligan 2019). However, for a time, this would allow for a closer approximation to the kind of expansive commercial presence, superprofits, and rapid economic growth that make space mining such an attractive prospect. It is, however, difficult to imagine large scale Main Belt mining as a standalone process, rather than part of a system of activities encompassing both lunar presence and the use of Mars or its (gravitationally weaker) moons as a base for operations (Milligan & Elvis 2019). Periodic raids upon Main Belt resources will hardly overcome the combined resource limitations of the Earth, Moon and NEAs. A functioning space economy capable of overcoming these resource limitations is far more likely to be systemic than opportunistic, i.e. something that involves sustained and expansive presence rather than mere periodic raiding to correct resource deficits closer to Earth.

Mars

Mars itself has many resources, including water, and the red planet is the main hope of those who wish to establish self-sustaining settlements beyond Earth. There is, however, no obvious material resource on Mars that is not found among the asteroids, although exploration may reveal some in the future. The 1/3 of Earth gravity on Mars also imposes an energy penalty on exporting resources from there, compared with the negligible gravity of the asteroids. Nonetheless, it may be that mining the asteroids and the settlement of Mars will be mutually enabling processes which develop as parts of a systemic, rather than opportunistic space economy, for three reasons.

First, among the near-Earth asteroids we already know of a dozen or so that we could move into Mars cycler orbits with today's technology (Strange et al. 2015). A spacecraft in a Mars cycler orbit crosses Earth orbit when the Earth is there, and Mars orbit when Mars is there, without need for any expenditure of propellant (Byrnes et al. 1993). A traveler to Mars would be ferried to the Mars cycler as it passed by Earth, then would take another ferry down from the Mars cycler on arriving at Mars. As no fuel is required[6] the Mars cycler spacecraft can be enormously massive, and that mass can be used for radiation protection. That solves the biggest problem for Mars-bound travelers. A large spacecraft also allows for more space per traveler and a richer more entertaining ride; it could be closer to a somewhat constrained cruise ship rather than a lifeboat. A thriving asteroid mining business could well have Mars cycler building, first as a way to transport large masses to cis-lunar space, and later as a personnel carrying sideline.

Second, following on from the theme of systematicity above, the two moons of Mars, Phobos and Deimos, may be valuable as bases for Main Belt mining (Taylor et al. 2021). They may host repair and supply depots for expensive mining equipment, or they may become sites for refining partially beneficiated ore into purer form. Once there is a profitable human presence on Phobos and Deimos, the cost and difficulty of reaching Mars' surface itself will be much reduced. Explorers and, later, settlers will have an easier journey with much more equipment than higher cost dedicated missions. Miners may want to take rest and relaxation trips to the surface to enjoy real gravity for a while, and to see the sites. They would then provide customers for services provided by Mars settlers.

Third, in order to mine the Main Belt profitably, faster rockets powered by nuclear fusion would be highly desirable because time is money. At least two designs for near-term fusion rockets are now being developed[7] (Cohen et al., 2015; Thomas et al., 2019). They would cut the journey time to Mars to about one month, making radiation much less of an issue. This point is a little more

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[6] No doubt this is an approximation. Perturbations to the orbit will occur and will need to be corrected. This may be done slowly using ion engines to avoid carrying large masses of fuel.

[7] NASA MSFC, Pulsed Fission Fusion: https://www.nasa.gov/puff (accessed 3 June 2021).

speculative given the slow pace at which we are advancing towards economically viable fusion technologies, but it is included because it helps to draw out an important point about the prospective space economy. However, it is a further way to highlight the systematicity point, given that an economically viable large-scale return of Helium 3 from the Moon or from asteroids to Earth is difficult to achieve and may be impractical for the foreseeable future. Earlier use of fusion technologies in space is far more likely, being considerably more viable from an economic point of view (Crawford 2015). This would again involve a systematic linkage of human activities between Earth, the Moon, Mars and the Main Belt. Effective use of the available, and limited, resources points towards a broader systematicity than that between the Earth and a single location from which materials would then be extracted. The limitations of accessible resources, and the combination of (a) their dispersal across multiple locations; and (b) concentration *at* those locations, are drivers for systemic organization.

Policy Choices and the Emergence of Markets for Space Resources

As this survey of resources on the Moon, near-Earth and Main Belt asteroids, and Mars suggests, they are both abundant and becoming accessible enough to one day sustain an economic system that compromises significant nodes off Earth. While these factors provide the conditions that make such a long-term outcome possible, in the short and medium terms, whether, when, and how markets for space resources in fact develop will depend to a significant degree on policy choices by national governments and international bodies.

Some of the relevant policies are already being developed and adopted by the world’s leading spacefaring countries, creating elements of national legislation and policy upon which future generations may build a global regime to govern space resources. Such a regime would consist in a configuration of national and international policy measures governing conduct directed at space resources, including various regulatory and legal instruments. In addition to national measures, international efforts at articulating principles and concepts for governing conduct directed at space resources have also made headway, creating the basis for future global deliberation and negotiation in this issue-area (ISECG International Architecture Working Group, 2010; *Security and sustainability in Outer Space*, 2015; *Vancouver Recommendations on Space Mining*, 2020; Neto *et al.*, 2020). Given the founder effect discussed above, or the path-dependent nature of regimes and associated institutions, early policy choices are likely to have outsized effects on long-term outcomes: decisions being made today could shape the prospects for space resource markets for many decades.

In this section, we consider some of the most fundamental and consequential policy choices before governments and international bodies for the development of markets for lunar and near-Earth asteroid resources in the medium term. As we have seen above, within this timeframe, which we define as the next 30 years, the Moon and proximate asteroids are the most likely targets of resource exploitation. Moreover, the policies adopted to govern resource activities at these initial sites are likely to inform, if not provide templates for, those eventually adopted for Mars, the Main Belt, and other destinations beyond the orbit of Mars.

We understand "markets" here to mean figurative spaces where supply and demand for space resources meet, creating exchanges where at least one party to the transactions is a private, or non-governmental, for-profit actor. Within the medium term we have specified, we postulate as unlikely the emergence of so-called "normal" markets, i.e. those gathering sellers and buyers so numerous that no single actor or subset of actors has a significant influence on price. Instead, within this timeframe, we are more likely to observe the emergence of oligopolies, monopolies, oligopsonies, and monopsonies in contexts where government actors still play significant, if not decisive, roles. For example, we envision a scenario in which the U.S. Artemis program helmed by NASA, a European Moon Village managed by European Space Agency, and a Chinese government-led lunar base program will form the backbone of exploration and settlement activities. These activities would in turn drive demand for lunar resources and associated industries, such as solar power and regolith processing, supplied by perhaps one to at most three firms per product.

An important feature of such strategic markets is that they lack normal competition, the force touted as fostering efficiency and propelling innovation in ideal-typical markets on Earth. Instead of prices set by the interplay of supply and demand as in competitive terrestrial resource markets, in markets for space resources we may for at least a period witness administrative pricing by government monopsonies, prices distorted by generous subsidies to national champions in states with active programs, price gouging by monopolies, and/or price setting by cartels. In addition, during at least an initial period of growth, some of these emerging firms will likely operate at the edge of commercial viability, their business hinging on tenuous models that are highly sensitive to new costs or risks. Insofar as policies add or diminish the costs, risks, or other burdens facing firms, even if only slightly, they could prove to be the difference between the emergence or not of these new industries.

Four sets of policy choices will likely influence whether, when, and with what characteristics markets for space resources, however imperfect, emerge in the medium term.

Government Programs that Create Anchor Demand

The first set of policy factors hinges on the extent to which public agencies pursue ambitious exploration and settlement programs that create anchor demand for space resources. Given the resources characterized in the previous section, it is plausible that the first large-scale buyers of lunar resources, such as power harvested from the Peaks of Eternal Light on the Moon or in-space water retrieved from asteroids, will be long-term government-sponsored exploration programs. While private space resource ventures exist, there is scant evidence that they are opening new frontiers. Rather, the limited private efforts attempted so far have responded to government-led initiatives. Indeed, even in more mature areas of commercial space exploration activity, such as the U.S. launch and transportation industries, private firms' projects are closely tied and responsive to government programs. For example, Space X's commercial cargo and crew businesses for now serve mainly NASA's International Space Station program, though the company has plans for space tourism.

Government Support to Emerging Firms

A second set of policy choices revolves around state support to emerging space resource industries (Krolikowski and Elvis, 2019, p. 13). Many observers regard space resource firms as "strategic," or capable of contributing to a country's national interests in space beyond generating economic value, so enhanced state support in the future is plausible. State support to budding firms can take multiple forms, both indirect and direct. Indirect measures aim at creating a landscape of supportive policy, legal, and regulatory measures for all firms active within a jurisdiction. An example of indirect support that observers frequently describe as a precondition to the emergence of a viable asteroid mining industry is national legislation to confer upon private firms' property rights over abiotic materials they recover from asteroids, subject to certain limits. Property rights of this sort would entail, at minimum, the freedom of disposition over recovered materials, including the right to buy and sell these at will. In the absence of international agreement, the main instruments through which elements of such property rights have been established to any extent are national laws, enforceable in domestic courts. An example is found in the *U.S. Commercial Space Launch Competitiveness Act* of 2015 (U.S. Congress, 2015). A similar form of policy support might be the creation of a licensing body to regulate efforts at space resource extraction, a step that may pave the way for indemnification or insurability, either or both of which might also prove necessary to the emergence of a viable industry.

In contrast to these indirect measures, direct forms of support entail conditional transfers to specific companies. Such transfers could consist of research and development grants to companies creating technologies needed for mining, comparable to the development programs that nurtured the U.S. commercial space launch and transportation industries. These direct forms of support may also entail government agencies' promises to purchase given volumes of space resources at set prices, providing emerging firms with anchor clients for their otherwise too-risky business.

Trade-Offs in the Design of New Regimes

A third set of policy choices concerns the character of the national and international policy regimes that governments may establish to govern activities targeting space resources, another process already underway. Different activities directed at space resources will survive and thrive under distinct policy regimes. We distinguish between three types of activities directed at space resources, set apart by their primary goal: activities aiming at scientific discovery, at establishing a human presence at or settlement of new destinations in the solar system, and at for-profit sales of space resources. For short, we label these "science," "settlement," and "sales" activities (Krolikowski and Elvis, 2019, pp. 10–14). While particular programs or missions will often aim at a combination of these objectives, they will nonetheless tend to be guided by a primary goal that dictates their overall orientation. On one level, these different activities might present technological synergies if, for example, they jointly benefit from the development of a common core of new systems. Specific groups of missions might also be complementary in other ways. For instance, scientific discoveries could help locate resources for commercial exploitation, while commercial activities could drive down the cost of science missions. However, in a more general sense, these different types of activity in practice make distinct and often incompatible demands on policymakers, presenting tensions and trade-offs, rather than complementarities.

In this sense, science, settlement, and sales activities are distinct endeavors facilitated by distinct policy regimes (Krolikowski and Elvis, 2019, pp. 10–16). Science activities are best served by a policy regime that fosters the responsible sharing of space resources, both protecting them from casual or unnecessary modification to preserve their integrity as research materials and enhancing their accessibility to a global community of researchers. Strict protocols for how to modify or act upon asteroid or lunar material will benefit science activities over the long run. In contrast, settlement activities are best served by a policy regime that subordinates the protection of space resources to the goal of supporting a human presence at new celestial destinations. Space resources have value insofar as they serve such missions – by, say, acting as cycler transports or supplying fuel for human habitats – rather than their intrinsic potential to yield scientific knowledge. Restrictions intended to limit the human impact on space resources to preserve their scientific value might in fact complicate or limit human settlement projects. Finally, a policy regime supportive of sales activities would be one that maximizes net rewards to firms in this emergent industry. One means to this end is granting these firms enhanced proprietary claims over extracted resources. Another is limiting protocols for the protection of space resources as scientific assets, since such requirements are likely to inflict burdens on resource-extraction operations. For example, requirements to adopt modes of conduct toward resources that limit contamination and maximize protection of nearby environments, as well as rules requiring extensive documentation or data sharing, are likely to inflict costs, delays, or risks on operations that imperil new companies' already tenuous business prospects. In short, a policy regime that is most conducive to for-profit resource exploitation will likely have features at odds with a regime most supportive of scientific activity.

As policymakers in various countries adopt policies to govern conduct toward space resources, they may create regimes that are more conducive to either science, settlement, or sales activities. In some respects, policies may serve all three of these activity types, but in other ways they are likely to advantage some forms of activity over others. Governments that prioritize nurturing nascent domestic commercial space-resource industries are more likely to adopt policies that benefit a handful of early-entrant firms, based in rich countries with large space industries, at the expense of a global scientific endeavor to study the Moon or asteroids. On the other hand, governments that prioritize scientific activities will likely support the establishment of global governance structures and mechanisms aimed at preserving the value of space resources to research (Krolikowski and Elvis, 2019, pp. 14–15). Acknowledging and negotiating the trade-offs presented by the distinct policy demands of scientific, settlement, and sales activities will be a precondition to effective long-term international policymaking for space resources.

The Collective Management of Crowding and Interference

A fourth set of policy questions confronting decision makers in various countries revolves around how to manage crowding and interference challenges at resource-rich sites in space. As discussed in Section 2.1, this challenge likely presents in its most significant and pressing form on the Moon, where attractive resources and topographical features appear concentrated in relatively small areas, but also exists for the asteroids. This concentration has attracted multiple forthcoming lunar missions to a handful of finite areas, creating the risk of crowding and interference between them. Unmanaged crowding and interference could result in outcomes that leave all actors worse off. An example of such an outcome consists of a scramble for a finite, high-value lunar resource between private firms that unnecessarily degrades the surrounding environment, reduces the value of the resource to science, and inflicts losses of opportunity upon emergent commercial firms.

The most promising means to addressing these risks lies in the creation of collective rules for conduct at these resource-rich sites, yielding a form of governance (Elvis, Krolikowski and Milligan, 2020, pp. 12–15). Governance mechanisms could include a registry to coordinate a timeline of activities by multiple actors that target the same thorium deposits or cold traps on the Moon. They might also include rules for actors' placement of solar panels to harvest power from the Peaks of Eternal Light, such that these do not interfere with each other or with human habitats installed nearby (Elvis, Milligan and Krolikowski, 2016, Ross et al., 2021). If crowding and interference begin to present appreciable risks to new space-resource firms, then concerted action to address them may become a crucial enabling factor for this new industry.

In sum, then, in the medium term, the governments of major spacefaring states, in potential partnership with other stakeholders, are poised to decide four sets of questions that will help shape whether, when, and how markets for space resources emerge. *First*, they will decide to what extent their public agencies will pursue ambitious exploration and settlement programs that create anchor demand for space resources. *Second*, they will consider whether to lend public support to emerging space resource industries and what forms this support will take. *Third*, participants in the creation of emerging regimes for space resources will negotiate the trade-offs between measures support of science, settlement, and sales activities. *Fourth*, these actors will decide whether and how to create governance arrangements to manage crowding and interference challenges at resource-rich sites in space, including on the Moon and at near-Earth asteroids.

Unfolding Policy Developments

At present, these different policy questions range from hypothetical to actual. National laws, such as the 2015 *U.S. Commercial Space Launch Competitiveness Act*, and Luxembourg's 2017 law on the exploration and exploitation of space resources, indicate that governments around the world are already contemplating and even taking steps to foster the emergence of these new industries (U.S. Congress, 2015; Le Gouvernement du Grand-Duché de Luxembourg, 2017). Moreover, the U.S.-led Artemis Accords illustrate one pathway by which the elements of a global regime for space resources could coalesce. The Accords are a collection of bilateral agreements between the United States and other governments that outline "Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids for Peaceful Purposes" (NASA 2020). Although the Artemis Accords have multiple purposes, they commit parties to an understanding of space resource exploitation that supports the emergence of commercial firms engaging in these activities. This position is at odds with a more restrictive understanding of what forms of space resource exploitation are permissible under the Outer Space Treaty, promulgated by other governments. While reaffirming a commitment to the non-appropriation principle in the Outer Space Treaty, the Accords also define a space for national legislation and instruments that would support such private-sector activities. To date, ten countries with active space programs have become signatories to the Accords, with Brazil and New Zealand reportedly intending to join the group (Park, 2021). As the numerous international lunar missions planned for the next decade develop and their implications for space resources grow more apparent, it is likely that more governments will begin an active consideration of these policy questions.

Out of such national and bilateral efforts at governing conduct toward space resources, a global regime may emerge. This regime will not have evolved in the same way as in the past, when the locus of governance development was in United Nations bodies focused on establishing landmark international treaties, such as the Outer Space Treaty. Instead, a coming regime for governing space resources may emerge out of an initial accretion of national and bilateral measures, evolving to include multilateral processes only later, if ever.

In this sense, in responding to the four types of medium-term policy questions discussed above, the governments of key spacefaring states may already be shaping the foundations of an emerging regime. Not only will their choices help shape whether, when, and how markets for space resources evolve, but they will also steer these potential markets toward outcomes that are more or less legitimate and desirable to a global community of stakeholders.

These medium-term choices will influence whether publics, both within these major spacefaring states and in other societies and across multiple generations, come to regard the exploitation of space resources as just and ethically defensible or as an extension of the injustices and harms wrought by market-driven resource exploitation on Earth. It is to these considerations that we turn in the next section.

Two Problems of Ethics for an Expanding Space Economy

Because of the founder effect, decisions taken at the beginning of a venture can have long-lasting effects, and the processes envisaged are not those guided only by the hidden hand of the market but are influenced by governmental agencies and policy, we also raise some ethical issues that should be addressed to limit the negative effects of humans expanding into space to live. These do not constitute a critique of space expansion, but an indication that it is a normal process with a downside as well as several upsides. Our presupposition is that it is also a process which can be deliberately and favorably influenced *to some degree*. If such deliberate influence were impossible, and the negative outcomes inevitable, talk about its ethical dimensions would have at best a diminished and indirect standing. However, given the assumptions of a founder effect, together with the picture of state involvement and policy choice, we will take it that ethical questions are salient, practical and can be of direct significance as one consideration among many during discussions about policy. Here, we focus upon two ethical problems in particular. Both concern justice, and both have a clear economic dimension.

The first is the ‘tenure and entitlement problem.’ This is a familiar problem, attention to which should help to emphasize that we are not attempting to present a generalized ethical critique of mining, but rather focusing upon the ethical problems which occur in the course of mining. The problem is internal to the practice, and not an outside judgement upon it. Justice in this particular case will concern fairness, and so we are not stretching the concept of justice beyond familiar grounds (Rawls 1985). But neither are we denying that justice has other dimensions.

The second problem is what we term the 'near-term justice problem,' and is a newer ethical problem, although it draws upon familiar themes of finite resources and distributive justice. Fairness is again an issue

The 'Tenure and Entitlement' Problem

The high costs and high risks of investment in space, and in mining (asteroid mining especially) raise concerns about 'piggy backing' upon the hard work and investment of others. It takes a good deal of time to identify a suitable target for mining, to map its trajectory, check its composition, even (given technologies available in the near future) to alter its trajectory. Because no state is allowed appropriate an asteroid, under space law [Outer Space Treaty (OST), Article II[8]], others may take advantage of all of this expensive hard work. At first, this may appear to be only an economic issue, or an economic issue with a marginal ethical component. A lack of security in investments may make it harder to grow the space economy, however there is no guarantee that what is economically optimal and what is ethical will coincide. Sometimes they diverge. And even if they did not diverge here on Earth, there is no ultimate guarantee that will continue to coincide in space. Economic rationality and ethics might coincide *here*, but not *there*. And so, a brief thought experiment to draw out what is ethically wrong about such free-riding may be a useful addition to the point that it free-riding is economically problematic.

Imagine a scenario in which space miners face a heartless corporation. Let us call it 'the company.' The miners take the bulk of the risks, but the company takes the lion's share of the profits. This is, of course, unlikely to occur; we are unlikely to see anything like a space proletariat emerging. But the scenario may still be useful as a thought experiment, and useful because we have a strong sense that *something* is wrong here, but may be unsure about exactly what. Would the wrongness be a matter of 'the bosses' exploiting 'the workers'? That is possible, but may overstate the continuity of space concerns and 20th century politics. Moreover, there is another way of seeing the issue: what is unfair in our thought experiment is simply the way in which risks and rewards have become divorced from one another (Athanassoulis and Ross 2010). Under a fairer (more just) arrangement, those who take the risks should at least share significantly in the

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[8] UNITED NATIONS TREATIES AND PRINCIPLES ON OUTER SPACE, Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies ("OST", 1967), Article II: "Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means." http://www.unoosa.org/pdf/publications/STSPACE11E.pdf (accessed 28 May 28, 2021.)

rewards. And the reason offered is independent of questions about what is economically optimal. The scenario would still describe an ethically problematic state of affairs even if it turned out to be economically optimal for a space economy. But this is also not to suggest that ethics and what is economically advantageous must conflict. Rather, the relation between the two is contingent. Abiding by ethical constraints can be economically advantageous *under some circumstances, but not all*.

Framed in these terms, the point is also no longer just about traditional patterns of labor relations. Rather, it generalizes out and applies as readily to mining interests, to one company in its relations with other companies. It is *unfair*, from an ethical point of view, if company x puts in the investment, does the research and initial work, and risks its investment in some mining venture but company y then takes advantage of this *at the expense of x*. Risk takers and the beneficiaries of risks should not be two entirely different groups of people. Tackling this ethical problem will involve not just claims upon extracted materials, but also claims upon secure *tenure*. With security of tenure understood in the light of the insecurities of space, rather than as something absolute. (Over-riding considerations may still apply, cases in which compensation may be due for lost opportunities if entitlement to mine is withdrawn.) These matters are all the more important given the insecurity of start-ups in the space sector. Justice points towards securing tenure in cases where other normal ethical conditions for mining have been met, and where the preliminary work has been put in by the company in question.

The Near-Term Justice Problem

Even if we are happy about the manageability of ethical concerns about the commercial use of resources in the near term, there remains a strong likelihood of conflict between the interests of near generations and those of future generations who will live at a time closer to resource depletion or exhaustion. Assuming that the latter are likely to live at a point in time that we can reasonably worry about (say within a 500 year period), then there may be a case for saying that we should not always prioritize near-term justice. Or, that our deliberation and decisions ought to be framed by an awareness of possible later harms. Near-term rules we establish to encourage a nascent space resource industry characterized by strictly limited available resources, may be carried forward into the completely transformed context of a mature industry in which the abundance of the Main Belt asteroids is available.

The problem itself arises in the following way. Access to space is currently limited to a small number of major powers. This is problematic in terms of entitlements. The Outer Space Treaty (1967) captures a strong moral intuition when it classifies “the exploration and use of outer space” as the ‘province of all mankind.’ (Article I.[9]) Here, we may set aside the question of whether or not outer space can be an actual commons, and focus upon the idea that all are entitled, but few can go. The entitlement remains a dead letter unless there is a ‘democratization’ of space, not simply in terms of the number of economic players, but in terms of access for all nations and peoples. (Even if access for each and every individual remains permanently beyond us.) To help achieve democratization, we might (in theory) radically redistribute resources in order to set access on a fairer footing. We are by no means opposed to this, but it is easier said than done. It would certainly be unfortunate if the democratization of space (however limited) had to wait until we have achieved some broader system of distributive justice on Earth. This idea also seems to be back to front given that it is familiar for newer fields of human activity to offer greater (if still constraind) opportunities for justice. Opportunities which may be more readily denied in established fields (such as those of heavy engineering or political representation) where there is a pre-existing structure geared to resisting certain kinds of change.

Another way to bring about broader access would be to accelerate the process of economic expansion and the process of cost reduction. Doing so would increase the range and extent of opportunities, as well as the range of participants, broadening the space economy out beyond its initial big players. This also looks like the most plausible pathway towards democratization. Near-term justice would be served.

However, this would occur at the expense of a more rapid use of the large, but (as we have seen) both finite and exhaustible resources that the Solar System has to offer. The more rapidly expansion occurs, the more rapidly the resources begin to be used up. And while recycling may alleviate the problem (and would presumably be standard practice in space) it will also become

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[9] OST Article I:
The exploration and use of outer space, including the Moon and other celestial bodies, 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.
Outer space, including the Moon and other celestial bodies, shall be free for exploration and use by all States without discrimination of any kind, on a basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies.
There shall be freedom of scientific investigation in outer space, including the Moon and other celestial bodies, and States shall facilitate and encourage international cooperation in such investigation.

incrementally harder except on a local level, as we expand over larger areas of space. Recycling on Earth is comparatively easy because we are gathered together, in a small area with nowhere beyond a short flight away. The area bounded by Earth, the Moon, Mars and the Main Belt, is simply not like that. The more rapidly we bring resources into use, the fewer new resources there are for future generations to call upon. In the absence of a stable state economy, a point of 'super-exploitation' will eventually be reached, a point at which new resources are no longer accessible in sufficient quantities to meet the needs which the economic system has helped to generate. Rapid expansion will take us towards this problematic state of affairs more rapidly, but it is a state of affairs which will be far more problematic for those who face it than for those of us who merely worry about it.

Conclusions

There are, of course, multiple unknowns about space expansion and the development of an extensive space economy. Unpredicted developments will, no doubt, transpire, and we may expect surprises along the way. In spite of this, we have tried to show that the in-situ space economy has the greatest chance of developing sustainably if it evolves in a systemic way, rather than a merely opportunistic way.

We would do well to anticipate systematic interconnection of ongoing activities across several in-space environments, rather than periodic raids upon NEAs or the Main Belt. The large scale of infrastructure already points towards processes and expenditure which are likely to remain well beyond the means of any group of private players, and will involve strong state involvement, at least during an initial phase. (Whatever occurs later on.)

These conditions point towards the salience of policy making. The magnitude and distribution of space resources raises both policy and ethical issues, to which the priorities of different stakeholders dictate different approaches. Recognizing these tensions and trade-offs is a precondition to making effective policy for space resource exploitation. In the medium term, whether, when, and with what characteristics markets for space resources emerge will to a significant degree depend on key policy choices, some already under way in major spacefaring countries. More fundamentally, ethical choices embedded within these policy measures will influence whether eventual space resource activities are regarded as just and defensible or, instead, as the next iterations of a historical pattern of harmful exploitation established over centuries on Earth.

The salience of policy is strengthened if we assume a “founder effect” such that those of us at the start of the process are likely to have a disproportionate influence upon the later, overall, pattern of development. The prospect of such influence, though far short of making actual decisions *for* future generations, will strongly influence them, pointing to the need to take our ethical obligations towards those future generations seriously, and not simply to dismiss them as beyond our control. This awareness raises unsettling questions that demand our attention today. With regard to the pace of expansion of the space economy, and with regard to the use of the finite resources of the Solar System, we face an ongoing trade-off. A trade-off between the interests of near-term justice (which may be best served by rapid expansion and resource utilization), and justice towards those generations of humans who will come afterwards, and who will live closer to the edge of expansion’s physical limits.

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