

Review

Technical Challenges and Ethical, Legal and Social Issues (ELSI) for Asteroid Mining and Planetary Defense

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Abstract: Advances in the field of asteroid dynamics continue to yield new knowledge regarding the behavior and characteristics of asteroids, allowing unprecedented levels of accuracy for predicting trajectories and contributing to impact avoidance strategies. Meanwhile, more detailed information regarding the physical composition of asteroids has reignited interest in asteroid mining as a potential new resource sector. This article considers some of the technical, ethical, legal and social issues facing global planetary defense efforts and off-world mining proposals. It considers issues such as claim jumping, weaponization of the space environment and ownership issues for resources extracted from space.

Keywords: asteroid mining; planetary defense; asteroid dynamics; space ethics; green energy transition



Academic Editors: Marta Ceccaroni and Marco Fenucci

Received: 11 March 2025

Revised: 28 May 2025

Accepted: 13 June 2025

Published: 15 June 2025

Citation: Kendal, E.; Milligan, T.; Elvis, M. Technical Challenges and Ethical, Legal and Social Issues (ELSI) for Asteroid Mining and Planetary Defense. *Aerospace* **2025**, *12*, 544. <https://doi.org/10.3390/aerospace12060544>

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1. Introduction

Advances in the field of asteroid dynamics continue to yield new knowledge regarding the behavior and characteristics of asteroids, allowing unprecedented levels of accuracy for predicting trajectories and contributing to impact avoidance strategies. New deflection technologies have demonstrated proof of concept for providing planetary defense from impact hazards. NASA's recent DART project (Double Asteroid Redirection Test) was a world's first deflection impactor trial combining NASA, the US Space Force and the private sector by launching a SpaceX Falcon 9 rocket out of the Vandenberg Space Force Base [1].

Meanwhile, more detailed information regarding the physical composition of asteroids has reignited interest in asteroid mining as a potential new resource sector. The economics of kick-starting commercial asteroid mining are daunting. However, the potential rewards ensure that the prospect continually returns to the discussion table. If return issues can be resolved, then asteroid mining could substitute for terrestrial extraction of dwindling precious metal and rare earth reserves from increasingly hard-to-access places using increasingly intrusive methods to sustain supply [2]. Continuing to rely upon such reserves could be a lose–lose strategy, more costly for extraction and more environmentally damaging. For resources likely to become inaccessible due to geopolitical obstacles, establishing a strategic supply line from space could be a form of insurance. In spite of setbacks for mining companies, such as the failure of the high-profile but under-capitalized Planetary Resources in 2020, the background drivers for considering asteroid mining remain in place,

and new contenders, such as AstroForge (Huntington Beach, CA, USA) and Karman+ (Denver, CO, USA), continue to arise. The option has never gone away.

What is missing from discussions are two things: first, a viable economic strategy, and second, practical and ethical guidelines for the complex task of coordinating public security and commercial activities in the space environment. These two problems are coupled together. If there is no viable economic strategy for asteroid mining, then societal and ethical questions will be moot or at least restricted to the ethics of tracking and a potential market in tracking information. If there is no practical approach that might help to resolve the relevant societal and ethical problems of mining and defense, then the viability of the economics of asteroid mining should not matter. At least in theory. We are well aware that human activities are not always bound by what we should do. This article focuses upon the second set of problems, the ELSI side (short for ‘Ethical, Legal and Social Issues’), although it will include brief commentary upon the first problem—the practicality of asteroid mining and redirection—where appropriate.

Specifically, we shall consider the current state of the science for asteroid mining and planetary defense deflection technologies and apply a transdisciplinary lens to the associated technical challenges and ethical, legal and social issues (ELSI). An opening thought is that the difficulties of justifying some less technologically challenging process in ELSI terms may push us towards a more technologically challenging resolution.

An illustrative case is in lunar mining for ^3He , an option that has gone in and out of favor over the past five decades, with former NASA astronaut Harrison Schmitt proposing and popular fiction picking up on the idea, only to find that surveys of lunar resources bring forward a number of problems [3,4]. Asteroids sit further out from the Sun, and therefore, the density of ^3He in asteroid regolith tends to be much lower than on the Moon. Yet, asteroid mining promises to relieve the pressures of the potential environmental harms of lunar strip mining. In addition to disturbing the natural surface conditions, these risks include kicking up large volumes of surface layer ‘space-weathered’ dust, potentially changing the reflectivity of the Moon’s surface by exposing the brighter material underneath [5,6]. And so ELSI considerations push us towards a preference for the technologically more demanding goal of mining asteroids *rather than* the Moon. The technologically least challenging option is not necessarily the most ethically defensible one. A challenge moving forward will be tilting the incentives so that better options can become less challenging.

This background thought will help to shape our treatment of three main clusters of issues: (1) those related to developing a response to asteroidal impact hazards; (2) environmental concerns regarding off-world resource extraction, and finally (3) fairness in the distribution of risks and rewards associated with asteroid tracking and mining. We can argue about whether or not asteroid mining should serve some larger goal (e.g., making terrestrial arrangements fairer, more equal, or in some sense decolonized), but minimally, we should aim for fair systems of mining in space. From an ELSI point of view, the introduction of new technologies and processes anywhere should not make matters worse. This is a minimal and realizable goal, one that researchers in asteroid dynamics can readily commit to. Nobody wants to find that their work has made the world a worse place, or that it has been used for terrible ends. And while researchers are not exactly in the situation of Richard Feynman working on the Manhattan Project, their warnings about the risks of asteroid mining and redirection do carry over into ethical concerns about doing the preparatory math and contributing to the processes. These warnings may sometimes proceed from a flawed understanding of asteroid mining and redirection, but it would be complacent to imagine that nothing terrible could ever occur. And so, the ELSI side of these issues carries some weight.

2. Methods and Background

2.1. Architecture and Benefits

This article adopts a transdisciplinary ELSI approach that combines an appeal to the architecture concept, which is integral to NASA's Moon to Mars strategy. The technical assessment involves synthesizing current knowledge on asteroid dynamics such that the ethico-legal analysis is fit-for-purpose. The approach might be referred to as a TELSI approach; however, for simplicity, we will use the standard ELSI acronym with the addition of 'Technical' implied. Central to the strategy is maximizing the benefits of space exploration and potential resource extraction for both off-world and terrestrial applications. This is intended to demonstrate the continued translation of space research and development for real-world outcomes and preserve the social license to operate in space. As space operations typically involve (at least some) state-funded architecture, it is important to clearly articulate how these investments are impacting citizens on Earth, including through technological developments made for space exploration that are also implemented in healthcare, communications, disaster responses and sustainability research [7]. This paper particularly focuses on the environmental and security benefits that could accrue to citizens on Earth and off-world by continued support of human space activities, while considering some of the ethical, legal and social issues that would need to be addressed to ensure fair distribution of the associated burdens and benefits.

2.2. The Science of Space Rustling

Space rustlers are those who would, hypothetically for now, 'steal' an asteroid that has been prospected by others who established its value. The hard-won knowledge of composition would identify the 'one-in-a-thousand' truly ore-bearing, i.e., profitable to mine, asteroids [8]. Today, there are very few ore-bearing asteroids in total that could be candidates for mining because we are limited to the energetically-easier-to-reach 50% of even the near-Earth asteroids. Rarity leads to value.

The rustlers avoid the hard work of prospecting. Instead, they would track where you are going and get there ahead of your mining spaceship. They could do this because they could put the funds that 'should' have gone into prospecting into building a more powerful rocket. But they do not mine 'your' asteroid at once. First, they attach their rocket to 'your' asteroid and push it into a different orbit, changing its dynamics. As space is big, the asteroid is then lost to you. That is why they moved it. The rustlers instead know how hard they pushed on the asteroid and in what direction, so they know its new orbit. Even if you did find an asteroid that was likely the one you worked so hard on, how would you prove it? Perhaps your careful assays would provide a chemical 'fingerprint.' But then there is a legal difficulty.

Rustling like this is perfectly legal within the Outer Space Treaty (1967). This treaty says that you cannot own the original asteroid. Your investment in prospecting the asteroid counts for nought. Rustlers can even argue that because they moved the asteroid, it is no longer a celestial body and they can own it outright. That would be consistent with the laws of a growing group of countries that interpret the OST as allowing anything picked up from a celestial body to become property. In this case, the rustlers could 'pick up' half the asteroid and put one in each pocket (or very large bag).

There is no oversight body that can rule on who gets to mine that asteroid. That means that people are likely to resort to force to protect what they see as theirs.

Space rustling is an example of something that seems unfair but is not illegal. Here, ethics must pick up where the law leaves off. If the desire is to promote a just society, and thus fair interactions between members of that society, there must be a method to oppose things that violate those principles of fairness, even if only through social disapprobation.

But what has worked on Earth may not have the same moral force in the vastness of space, possibly requiring the formulation of new or adapted ethical frameworks for dealing with the issues arising from asteroid mining.

2.3. Environmental Impacts of Asteroid Mining on and Off-World

From an environmental perspective, asteroid mining carries many potential benefits for Earth. Ideally, it could reduce the destructive impact of mining on the terrestrial environment, while also providing essential resources to promote the green energy transition or, more modestly, to support hybrid energy systems with a significant green component. However, there is significant disagreement about the future feasibility of such activities. One would have to imagine a scenario where terrestrial mining has become politically and/or financially unmanageable, or restrictions on pollution have become substantially stronger and more consistent globally. Milligan (2015) notes that one of the main drivers for asteroid mining is depleted mineral reserves on Earth and the need to meet global energy needs [2]. As a simple example, the quality of copper reserves has been steadily declining for decades, to the point where almost a third of copper is now recycled. Lower quality reserves, with harder access, raise costs, although not yet near the point where space copper mining would be profitable. Global energy needs have also been rising, driven by population increase, urbanization and politically irreversible expectations of more affluent lifestyles. Awareness of the environmental costs of energy production and of terrestrial mining has not reversed these trends. The upshot is a convergence of strategic, economic and environmental *push* factors that simultaneously motivate and justify research into asteroid trajectories to better understand their dynamics and asteroid composition to provide the technical knowledge needed to support the practicalities of mining and redirection.

Whether asteroid mining ultimately mitigates or exacerbates climate change will depend in part on how carbon-intensive the relevant mining and transportation systems turn out to be, and whether the extracted resources are used to provide in situ resources (e.g., fuel) for space missions or end up returned to Earth where they might feed and sustain environmentally damaging systems. Drawing energy sources or metals from asteroids rather than from damaging terrestrial processes does not tell us how the resulting energy and metal supplies will themselves be used.

At present, these questions tend to be set aside because the cost of transporting resources back to Earth remains prohibitive. It is generally more expensive to bring something back compared to sending something into space. Even a relatively lightweight return of ^3He for fusion reactors (which are themselves still experimental) turns out to be economical only if the return is opportunistic and piggybacks upon other space activities [3]. A dedicated lunar ^3He mining industry remains not just hypothetical but an uneconomic fiction. Nevertheless, there are companies working to realize this potentiality. The economics of asteroid mining are even tougher. There is a first-mover problem. Given the massive initial outlays of capital for basic infrastructure and refinement of the technical process, it will be economically more rational for companies to join as part of the second or third waves of asteroid mining, rather than paying to be part of the exponentially more expensive first wave where hard and costly lessons will also need to be learned.

This can change. A process of what the classical political economists (from Adam Smith to Marx) referred to as ‘primary accumulation’ or ‘primitive accumulation’ could pave the way for more normal economic activity. Extra-market processes paving the way for regular industry and commerce. This process involved heavy initial state outlays to subsidize otherwise uneconomic private sector activity for larger strategic reasons, up to the point where the processes cease to be uneconomic. A comparable process may be required for scaled-up asteroid mining to begin. If it looks like China may initiate large-scale mining,

then the US will also want to do so, and the Europeans will want to be part of the process. The formidable economic obstacles for mining at scale, including the first-mover problem, are a significant barrier but are unlikely to be a permanent barrier. Yet, even if there are substantial environmental benefits in the form of an alleviation of terrestrial extraction pressures, a downside should also be anticipated.

For C-type asteroids with their high concentrations of carbon, this could mean a substantial increase in carbon-based materials returning to Earth, at a time when the ideal option would be to remove carbon from the system. If we think of the Earth as akin to a giant terrarium that has gone wrong, then it is time to pop the lid, open up this closed system, take out some of the more troublesome components, and keep the system open. The excess carbon build-up is an obvious candidate for removal. If it turns out that there is some economically viable way to process the carbon component of asteroids for fuel supply and consumption, this would result in further carbon release into the atmosphere [9]. Rather than being advantageous, the return of materials from C-type asteroids could be something of a nightmare scenario. However, if kept in the space environment, some carbonaceous asteroids could be mined for their water content, providing resources for drinking or growing crops, or separated into hydrogen and oxygen and used for rocket fuel and life-support systems.

For some metal (M-type) asteroids, the dense concentrations of platinum, iridium, gold and other precious metals could also exceed the total supply currently on Earth. This could economically destabilize the existing resource sector for those resources sensitive to supply changes, particularly if a sudden increase in availability is unlikely to motivate the discovery of additional uses [8,10]. The economic impact of even small changes in supply may be hard to predict at the timescales required for mining business decisions, with some markets being more elastic to changing supply levels than others [8]. Asteroids rich in cobalt could supplement or replace terrestrial sources of this resource. Sometimes labeled the ‘blood diamond of batteries,’ this element is required to produce lithium-ion batteries, such as those found in many mobile phones and electric vehicles, with much of the current global supply relying on miners in the Democratic Republic of Congo working in unsafe conditions [11]. Cobalt mining in Russia (the world’s third largest producer) also has a particularly poor environmental record. Yet, our dependence upon supply is absolute. Abandonment of the relevant technologies is unthinkable. There are both environmental and occupational health and safety advantages to finding new sources of this prized element, assuming future off-world mining conditions are sufficiently regulated to protect the workforce. Nickel and platinum mining also have their problems, with the latter contaminating water and land systems and the former adding soil erosion to the list of failings. It is one of the ironies of environmental critiques of mining that they are set down and disseminated through the use of technologies, which themselves draw upon a range of metals whose terrestrial acquisition is at least ethically questionable. Shifting off-world for sourcing would be an ideal fix.

Reflections of this sort have contributed to an environmental case for mining off-world. Pilchman (2015) claims that the potential for asteroid mining to provide cheaper fuels and reduce environmental degradation means: ‘On its face at least, asteroid mining will be good for people’ [12]. However, realizing this potential requires careful implementation to avoid the negative effects of extreme wealth concentration, as seen in the terrestrial mining context. There are also some who are concerned about whether it is ethical to mine in space at all, referencing the Outer Space Treaty’s (1967) principles of non-appropriation and benefit-sharing as grounds for avoiding commercial activity in this region [13]. Less common philosophical concerns focus on the possibility the space environment can or does possess intrinsic rights to non-interference, particularly regarding the extraction of

non-renewable resources, but these tend to focus on lunar mining and potential damage to the Moon, rather than asteroids.

2.4. *The Science of Planetary Defense*

Planetary defense refers to actions taken to avoid or minimize the effects of collisions between Earth and asteroids or comets. The UN Office for Outer Space Affairs (UNOOSA) defines a Near-Earth Object (NEO) as any asteroid or comet with a trajectory that would bring it ‘within 0.3 astronomical units, or approximately 45 million kilometers, of the Earth’s orbit’ [14]. Potentially Hazardous Asteroids (PHAs) are further defined as those near-Earth asteroids with a minimum orbit intersection distance within 0.05 astronomical units and an absolute magnitude of 22 or less [15]. The two most technically established methods for planetary defense are the use of kinetic impactors (such as was demonstrated in the DART mission), where another object is launched to intersect with the impact hazard and alter its trajectory; and the use of nuclear explosive devices (NEDs) to destroy an asteroid discovered at short notice [16]. However, while the technical knowledge for the latter is well advanced, detonating an NED in space is illegal and adopting an NED-based planetary defense strategy is widely considered ethically and socially undesirable due to the potential to de-stigmatize the stockpiling and use of nuclear weaponry by nation states beyond this use case [17]. Less controversial methods for planetary defense include the use of large space vehicles to serve as gravity tractors that could slowly drag an asteroid off an impact trajectory while keeping it intact; and deploying (currently largely hypothetical) laser ablation technologies. However, these methods face substantial technical challenges, with the former method largely abandoned by researchers in the field due to the practical constraints imposed by the size of the craft and the lead time to impact required for an effective intervention to be launched. Schmidt and Ditrych (2022) further note, regarding the latter, that high-energy lasers for space applications also carry significant stigma, again leading to a conflict between the technical, ethical, legal and social dimensions influencing technology uptake [18].

3. Discussion: Analysis of ELSI in Asteroid Mining and Planetary Defense

3.1. *Claim Jumping and Piracy Issues*

The technical demands of understanding and influencing asteroid dynamics mean corporate actors in this space will inevitably be utilizing knowledge and infrastructure paid for through public funds and national space agencies’ research. Even where asteroid orbits are well characterized and the data is ‘freely’ available, this data has typically been obtained and maintained using systems that rely on public funding. If such use is considered exploitative, this may harm the social license under which national space agencies operate—all the more so for off-world mining activities if they yield substantial wealth for individuals, and particularly if these individuals are using the space location as a way to evade taxation. However, this is an argument whose force is significantly weakened if we think again about a process of primary accumulation in which heavy state support is a necessary phase of socially desirable economic development. It is part of the price that has to be paid, but it does grant a good deal of state leverage over the resulting patterns of economic development. And this can be an opportunity to exert some level of democratic control that reaches *beyond* regulations and taxation policies. Given the demonstrated limitations of the latter as levers for social justice on Earth, an additional pathway to democratic influence may be welcome. But here we are in danger of imagining systems of asteroid mining as non-transformative, as mere repetitions of familiar patterns of 20th-century economic development. Now is the time to collectively consider what social

and legal incentives and consequences might be suitable to guide this new mining sector, and particularly how these may be enforced given the complexities of the space industry.

A lack of law and order in space may lead to a lack of security for mining activities in various ways. A space ‘pirate’ would be someone who learns of a payload being transported and hijacks it, stripping it of identifying features and selling it on themselves [8]. Such activities would clearly be illegal but difficult to prosecute. However, a larger concern may be the prospect of repeating even earlier problems, such as claim jumping in space. A simple case, a variant on space rustling, would be where company *a* takes the time to do the research and secure the relevant permission and putting in the required investment to identify a suitable candidate for mining, only to find that company *b* has been tracking their activities instead of doing any of these things, instead using the time to build a bigger mining machine. Yet *b* begins operations and secures the rewards of the work by *a*. As with space rustling, claim jumping is completely legal under the OST, and for now, there is no body to issue permits.

This is a worrying prospect for multiple reasons. While asteroid mining may not require violation of the OST by granting ownership of asteroids, it almost certainly will require security of tenure and security of extraction rights—precisely the safeguards that claim jumping in space would tend to undermine. But what exactly is wrong with claim jumping in space, from an ELSI point of view? As an answer to this question, there are multiple possible knock-on effects, including the noted undermining of systems of tenure and licensing, systems that may be the only hope for effective environmental protection. But this is a rather indirect account of the wrongness of claim jumping.

A more direct account can be given by appeal to a popular, but probably misplaced, worry about space mining. On popular accounts, within fiction, but also within critiques of space mining, the fear is that a wealthy elite will benefit from the work of an underprivileged proletariat of miners facing extreme risks to make others rich. This is unlikely to occur because of developments in robots for mining, and because anyone who actually goes into space for scientific, security or commercial purposes is likely to be highly skilled because of the lethal nature of the space environment. And skilled workers come at a price. Hardly a misused labor force of underprivileged ‘belters,’ to use the vivid imagery of off-world worker exploitation created in the popular television series, *The Expanse* (2015–2022).

Nonetheless, there is a solid idea at the core of this worry. What would be wrong in the underprivileged proletariat scenario is the mismatch between risks and rewards. Those who take the big risks should figure prominently among those who enjoy the rewards of any form of economic activity. This is a basic aspect of fairness, and the reason hazard pay benefits exist. And we do want systems to be fair rather than unfair. Applying this same idea of a mismatch between risks and rewards to the context of claim jumping gives a clear and direct idea about why it would be ethically wrong. The identification of viable candidates for mining is no quick business. It takes years of investment in asteroid dynamics to follow trajectory and gauge composition. Before actual mining takes place, information about appropriate targets will itself be a valuable commodity. Those who make the long-term investments and take the risks involved in such investments ought to be among the main beneficiaries. Claim jumping involves gaining rewards by piggybacking upon someone else’s risks. And this is something that we have already rejected in the hypothetical case of the under-rewarded space miners.

True, the risks would be of a different sort. However, the first-mover problem already illustrates the point that those who become involved in asteroid mining, or any form of mining in space, do so at considerable risk. Multiple failures can be anticipated as under-capitalization or simply the radical underestimation of initial costs, leading to company failure. Planetary Resources, one of the best-known prospective mining companies, failed

before extracting a single ounce of materials, in spite of a good deal of commercial support and an impressive skills base. The prospective commercial rewards may be high, but the risks are also real. Accepting those risks generates a strong claim upon rewards and protection from marauding claim jumpers who do not put in the prior investment and work.

3.2. Dual-Use Concerns for Deflection Technology

In almost a reverse of the claim jumping issue, planetary defense risks becoming a tragedy of the commons—everybody and nobody’s responsibility at once. Developing, testing and maintaining planetary defense technologies is likely to be expensive, and the benefits of having asteroid deflection capability could range from none (if the system is never deployed) to regional (with no guarantee the region that paid for the capability will stand to benefit from it) and global (e.g., in the extreme example of avoiding an extinction level event). There is also considerable disagreement regarding whether the deflection technologies developed should be solely defensive, with some arguing that preventive, *offensive* weapons should be considered, even in cases where the impact hazard has a long lead time or low likelihood of collision. A recent example of this can be seen in the case of Asteroid 2024 YR4, which in January 2025, was initially estimated to have a 1.3% chance of intersecting with Earth in 2032, a risk that was briefly revised up and then plummeted as further observations and calculations were made. Advocates for a more aggressive planetary defense strategy might suggest that this asteroid should be deflected regardless of how low the probability of future impact. But this also highlights that these technologies are not only tools, but also types of *weapons*, and many balk at the further militarization and weaponization of the space environment. Weapons of mass destruction are banned in the OST (Article IV) [13].

It is in the consideration of ethical ramifications for deflection technology that a technologically-informed ELSI approach is perhaps most obviously beneficial. On its own, an ethical evaluation of asteroid deflection must take seriously the extreme possibility of a bad actor using kinetic impactor technologies to redirect an asteroid to hit an adversary. This creates a dual-use dilemma where the technology intended to support planetary defense can be misused in terrestrial conflict. Dual-use dilemmas in ethics are not considered salient only when they are deemed *likely*, and when the negative outcomes (however unlikely) are particularly undesirable, some ethical guidance systems adopt a ‘precautionary principle’ that favors the prohibition of emerging technologies irrespective of the potential benefits this may inadvertently prevent from coming to fruition. Incorporating the technical aspect as part of the ethical analysis here helps elucidate why aiming an asteroid at an enemy would not represent a military advantage. Deflection technologies could be used to nudge an asteroid into an orbit where it would impact an enemy’s territory; however, this plan would take years or even decades to successfully execute, providing plenty of warning for the opponent to mount their own deflection defense. More practically, though, if the opponent came to suspect the cause of the asteroidal impact trajectory, they would also be able to engage conventional weapons in a more direct response well before any threat the asteroid would pose to them. As Elvis (2021) notes, obfuscating the offensive activities would require levels of precision targeting far beyond the current state of the science, and even then, the necessity of orbital correction maneuvers when the asteroid approached close to Earth would likely remove the cloak of anonymity from the aggressor: ‘All in all, it’s far easier to use a bomb on an intercontinental ballistic missile’ [8]. Attempting to use an asteroid as a weapon would be impracticably slow and leave the perpetrator open to direct retaliation, while the timeline of their attack provides years for the intended target to dodge the impact. Opponents lacking deflection capability themselves would likewise

have years to develop or negotiate access to an appropriately effective defense platform, nullifying any asymmetric advantage early access would yield.

3.3. Distribution of Risks and Rewards in Asteroid Mining and Planetary Defense

When we talk about risks in ethics, we are typically including things that can cause physical, psychological, social, economic and/or legal harms. Benefits, meanwhile, are positives across these domains, e.g., pleasure, avoidance of pain, financial gain, autonomy, fulfillment, respect, advanced knowledge, etc. Commercial risks can lead to financial harm or gain, and as previously noted, fairness dictates that benefits should accrue to those who bear the burden of risk—in the case of asteroid mining, that means those who develop the tools, research and facilities should be able to reap the (mineral) rewards. Given the inevitable use of (at least some) nationally funded infrastructure for any commercial space activities, this also demands a fair profit distribution system between private industries and governments. Beyond this, however, is the need to consider the risk of physical, psychological and social harms facing off-world workers who must contend with the health hazards of living in an environment hostile to their survival. This also demands appropriate benefit-splitting and protection of those intangible goods, such as autonomy and respect for human rights. Now is the time to enshrine the formal and informal standards that will protect worker safety and ensure appropriate hazard pay arrangements. As with the dual-use dilemma example above, ethical consideration of potential worker exploitation does not require that maltreatment of workers be *likely*, only that it be *possible*. That an employer could theoretically withhold oxygen from an underperforming miner—with minimal technical effort—is reason enough to build in legal and ethical protections against this possibility.

Regarding asteroid deflection and planetary defense, the potential beneficiaries of avoiding a collision could be all of humanity. However, those with the capacity to mount a defensive strategy in the case of a predicted asteroid impact will represent a relatively small proportion of the global population. An obvious conflict arises when the cost of planetary defense is borne by one (group of) nations, if the predicted impact site is not within their region/s. Would seeking any form of cost recovery be appropriate in such circumstances? This might seem overly mercenary, but where taxpayer funds are used, there is accountability to a specific population expected. Maybe planetary defense could be provided for under humanitarian aid budgets? And this does not even consider that private corporations might one day hold the contracts for planetary defense services. What might an appropriate fee be for saving the world? How would a pro bono case be justified when there is a need to prove to stakeholders that fiduciary duties are being met? Would such a charitable case be absorbed into a company's Corporate Social Responsibility (CSR) framework? The sympathy many may feel toward those whose payoff for investment in asteroid mining is usurped by claim jumpers is perhaps harder to secure when it is one nation's investment in planetary defense being compensated by charging a fee for service from a non-launch state facing an impact hazard. In the immediate term, this might be explained by the fact that mined resources represent a financial gain, whereas avoiding an asteroid strike is preventing a significant harm. We might plausibly demand an ethical obligation to the latter that does not apply to the former, e.g., a more technologically empowered actor may be ethically required to protect the lives and safety of others (even at great personal expense), without necessarily owing any further material benefit (like sharing the spoils of asteroid mining). Intuitively, this falls within the Rule of Rescue, a widely accepted doctrine that imposes a duty to respond to those in peril, which forms the basis of the Rescue Agreement section of the OST. However, in the longer term, if asteroid mining does one day reach its potential in contributing significantly to climate mitigation

efforts and energy security, the distinction between mining providing material gain and mining preventing avoidable harm may start to collapse.

3.4. Building on Existing Frameworks for Globally Regulating Equitable and Responsible Use of Space

When it comes to international governance, Wager et al. (2022) note that the OST is still the ‘principal international agreement governing the appropriation and use of extraterrestrial resources’ [19]. However, these authors note the ambiguity within this treaty regarding ownership of extracted space resources ‘leaves room for individual States to apply their own legal interpretation,’ including whether property rights can be assigned for mining activities [19]. The Moon Treaty of 1979 tried to remove this ambiguity as it related specifically to the exploitation of lunar resources; however, this treaty was never broadly ratified and, in 2023, became the first UN space-related treaty to have a state officially withdraw, with the Kingdom of Saudi Arabia’s removal coming into effect in January 2024 [20]. Going beyond the Moon, the May 2025 draft report addendum from the UN Committee on the Peaceful Uses of Outer Space (COPUOS) on ‘potential legal models’ for global governance of space resource utilization only mentions asteroids once, and this reference merely points to the 2020 Artemis Accords as a ‘useful point of reference for future discussions’ [21]. In this document, the UN Working Group on Legal Aspects of Space Resource Activities is affirmed as an appropriate body to determine international agreement in this area, with suggestions that the International Seabed Authority could serve as a model for governance [21]. This perspective is supported by Hubbard et al. (2024), who draw a direct comparison between outer space and the deep sea’s ‘area beyond national jurisdiction’ definition, but note both are susceptible to the tragedy of the commons if a lack of ownership or authority over the domain leads to a lack of responsibility and care (as noted in the planetary defense example above) [22]. This demonstrates where legal and ethical obligations may come apart, as individuals and states may be considered ethically culpable for showing a lack of respect for the space environment, even in cases where the law is ambiguous. And while the aforementioned Artemis Accords have tried to remove some of the legal ambiguity regarding space mining activities—by articulating that commercial mining would not (in its own interpretation) violate the non-appropriation clause of the OST—for countries who are signatories to both the Accords and the Moon Treaty, the potential for conflicting obligations remain [18,23]. Nevertheless, the Artemis Accords are useful for the current discussion, as they include explicit reference to allowable uses of asteroids and comets, where most similar documents focus primarily on the extraction of lunar resources. A more holistic ELSI approach to asteroid mining would not only consider legal ramifications though, but ethical and social ones as well.

When it comes to existing governance systems for planetary defense, there is arguably even less clarity regarding who on Earth possesses the mandate to act. The UN endorsed International Asteroid Warning System (IAWN) and Space Mission Planning Advisory Group (SMPAG) were both central to preliminary discussions of Asteroid 2024 YR4 in early 2025, but while their information gathering activities were unlikely to attract opposition, the planning of defensive actions—had they been warranted—might have been more controversial. In their ‘Planetary Defence Legal Overview and Assessment’ document from 2020, SMPAG states: ‘Regarding possible decision-making bodies for planetary defence action planning, the United Nations Security Council (UNSC) has extraordinary power to supersede rules of international law through a decision, which requires the votes of nine out of fifteen Members and no opposing vote by one of the Permanent Five (P5) Members of the UNSC. Other international institutions and organizations could provide valuable political support for a planetary defence action, but do not have the authority to permit actions that are contrary to international law, such as using a NED’ [24]. However, this still

leaves significant room for interpretation, particularly for otherwise legal space activities that might have a dual purpose in planetary defense, or for individuals and corporations with the capacity to operate independently in space. It is also relevant to consider that not all UN member states are given equal representation in the above decision-making process, and not all citizens on Earth are affiliated with a recognized member state.

4. Conclusions and Future Directions

This article has considered asteroid mining and planetary defense strategies from an ELSI perspective, taking into account the technical complexities of these emerging fields. By pre-empting issues such as claim jumping, space rustling and environmental and security implications, new ethical and legal frameworks can be developed in advance of off-world mining operations or impact avoidance protocols being established to ensure good ethical guidance. Such an activity would require global consultation and consideration of what kind of values we want to promote for human interactions in space. For this, an ELSI approach allows us to create regulations that can be generally applied, rather than relying on case-by-case analysis.

Author Contributions: Conceptualization, M.E., T.M. and E.K.; methodology, M.E., T.M. and E.K.; writing—original draft preparation, M.E., T.M. and E.K.; writing—review and editing, M.E., T.M. and E.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available in the article.

Acknowledgments: E.K. would like to acknowledge the Scowcroft non-resident fellowship program at the Eisenhower Center for Space and Defense Studies, United States Airforce Academy.

Conflicts of Interest: The authors declare no conflicts of interest.

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