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Enabling planetary defense: Science, law, ethics

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ABSTRACT

The need for operationally-ready international agreements for planetary defense was recently highlighted following the discovery of Asteroid 2024 YR4 in December 2024, initially predicted to have a 1.3% chance of colliding with Earth in 2032. While no longer considered to pose a threat, this event highlighted the need for a clear global response protocol for dealing with asteroidal and cometary impact hazards, including explicit guidance regarding who has the mandate to act and what approvals would be needed to create, maintain and activate global defense systems. The United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) has begun the process of multilateral planetary defense by creating the International Asteroid Warning Network (IAWN) and the Space Mission Planning Advisory Group (SMPAG). However, not all countries or relevant stakeholders are members, and recommendations are not enforceable. This article will argue that a more robust and sustainable multilateral agreement for planetary defense and the protection of the astro-geophysical environment would promote space cooperation, protect our space heritage, and mitigate potential conflict arising from planetary defense activities.

1. Introduction

Every day Earth is visited, but not hit, by many small asteroids and occasionally comets. Every day Earth is *hit* by about 50-100 metric tons of meteoroids and fragments of asteroids that are typically so small they cause no damage [1]. Nevertheless, there are a number of historical examples of asteroid impacts that have caused significant concern, including loss of life, such as the Cretaceous-Paleogene (K-T mass extinction) event, which was consistent with a 10 km wide asteroid striking Earth 66 million years ago. Smaller events include the Tunguska incident, thought to be caused by an asteroid airburst of 30-80m diameter in 1908, and more recently the Chelyabinsk incident, caused by the high-altitude airburst of a 20m asteroid in 2013 [2]. The K-T event is deemed responsible for the loss of 70-75% of life on the planet, Tunguska for three human deaths and more than 2000 square kilometers of destroyed Siberian forest, and Chelyabinsk for more than 1500 human injuries, primarily from flying glass caused by the shock wave [3]. It is generally accepted that an impactor of 1 km or larger could cause destruction on a global scale [2], but most surveys suggest there are no hazards of this size on an impact trajectory with Earth predicted over the next century [4]. However, Daly et al. note “the catalogue of near-Earth asteroids is incomplete for objects whose impacts would produce regional devastation” [4]. It is precisely this tension between global and regional interests that makes defense of the planet against asteroidal and cometary impact hazards such a politically fraught issue. While our situational awareness is relatively good for large objects (>1 km diameter) it is less so for threats that are less than 200m diameter, and especially those under 140m [5]. It is also poor for sun grazing comets, such as comet NEOWISE (C/2020 F3) that was discovered on March 27, 2020, and made its closest approach to Earth approximately 3 months later on July 3, 2020, (this is the basis for the 2021 comedy movie, *Don't Look Up*). This comet had an estimated nucleus size of 5 km and would have been an existential threat had it hit. In the near term, there will be a flyby of asteroid Apophis on Friday the 13th of April, 2029. Apophis will come extremely close to Earth, passing inside the Geosync belt, and will be visible by the unaided eye throughout much of the world. Were Apophis to hit the Earth, it would have an energy roughly equivalent to all the world's nuclear arsenals.

The need for operationally-ready international agreements for planetary defense was recently highlighted following the discovery of Asteroid 2024 YR4 in December 2024, initially predicted to have a 1.3% chance of colliding with Earth in 2032 [6]. While no longer considered

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to pose a threat, the impact hazard led to substantial media attention in the first weeks of 2025, including many questions regarding whose responsibility it might be to launch a defensive action to mitigate the threat. Two UN endorsed groups - the International Asteroid Warning Network (IAWN) and the Space Mission Planning Advisory Group (SMPAG) – were mobilized at this time, but there were many matters of authority, capability and cooperation that still needed to be addressed before any hypothetical plan could have been agreed upon, had the predicted threat remained. Ultimately, what the public saw was the activation of a plan to make a plan, rather than clear lines of delegation and responsibility for undertaking any necessary protective actions. Kendal, Milligan and Elvis note that "while their [IAWN and SMPAG's] information gathering activities were unlikely to attract opposition, the planning of defensive actions-had they been warranted-might have been more controversial" [7].

At least one nation state at the time also expressed interest in developing a domestic capability for planetary defense, with China's State Administration of Science, Technology and Industry for National Defence (SASTIND) purportedly advertising for relevant experts to join a new taskforce [8]. Several other countries also possess capabilities in this regard, including the United States of America, Russia and the Republic of Korea to name a few, but have no clear mandate to act in the face of an impact threat [9]. In their workplan, SMPAG has explicitly highlighted the issue that no nation seems willing to take on the responsibility of planetary defense [10]. It is also noteworthy that IAWN and SMPAG do not have representation from all countries or relevant stakeholders, and that their recommendations are not enforceable. This article will argue that a more robust and sustainable multilateral agreement for planetary defense and the protection of the astro-geophysical environment would promote space cooperation, protect our space heritage, and mitigate potential conflict arising from planetary defense activities. For this article, we are conceiving of an agreement that is part contractual, part aspirational, introducing the capacity for legal enforceability for some agreed-upon obligations and prohibitions, while retaining the flexibility of negotiating actions on a case-by-case basis guided by pre-established technical, ethical and legal guidelines. As such, the proposed agreement would bear some resemblance to a space-based treaty, but be able to engage a wider range of stakeholders in establishing the scope of permissible and obligatory contributions to planetary defense, including nation states, corporations and individuals who possess relevant capabilities. While it is beyond the scope of this article to propose specific membership for involvement, existing UN-endorsed groups, influential industry actors, civilian and military space organizations, represent some likely candidates.

2. What is planetary defense?

Planetary defense refers to measures intended to prevent or mitigate the effects of collisions between the Earth and asteroids, comets, or fragments thereof [2]. The classification "near- Earth asteroid" (NEA) applies if an asteroid's distance from the Sun is within 1.3 astronomical units (AU), whereas a "potentially hazardous asteroid" (PHA) refers to an NEA whose minimum orbit intersection distance is within 0.05 AU and absolute magnitude is less than 22 [2]. Despite representing "a very real and potentially much more devastating" hazard – due to their large nuclei and high relative velocity – Lubin and Cohen note comets have been largely neglected in the planetary defense conversation to date [11]. These authors account for this, "partly due to their impact rarity, and partly due to our lack of defense options for extremely large comets" [11]. Other researchers suggest it is due to their unpredictable trajectories impeding detection [2], with Morrison noting that astronomical surveys and orbital calculations must form the "front line" of any effective defense strategy [12]. At its core, improving planetary defense involves developing enhanced detection methods, including for PHAs and comets, and appropriate countermeasures against impact hazards.

2.1. Methods of planetary defense

There are many proposed planetary defense methods, but this article will mainly focus on the ones that have received the most attention in recent scholarship, including deflection using standoff nuclear explosive devices (NEDs), gravity tractors, laser ablation, and kinetic impactors (KIs). A new approach using hypervelocity penetrators that can be passive or explosive, incorporating NEDs in extreme cases, is also currently being studied. This method promises fast reaction using existing launch vehicles, such as a Space X Falcon 9, and may in the future offer a "single launcher solution" [11]. For NED deflection, an explosion near the surface of the asteroid could vaporize (via X-ray ablation) and cause the ejection of some mass, with the resultant forces altering the path of the remaining material [12]. NEDs are widely considered the only currently available option capable of managing an impact hazard discovered on short notice or of greater than 2 km in diameter [2]. Gravity tractors, on the other hand, aim to keep the asteroid body intact but influence its gravitational field to drag it off its current path. This method would rely on large vessels in close proximity to NEAs exerting an attractive force over very long time periods, and thus for practical reasons has not been far developed [1,2]. Laser ablation methods have currently only been demonstrated under laboratory conditions, but operate on a similar principle to NEDs, inasmuch as they aim to ablate part of the asteroid to alter its trajectory [2]. One example is the proposed Directed Energy System for Targeting of Asteroids and Exploration (DE-STAR) system. Laser ablation could be most readily deployed in a "stand-on" approach (DE-Starlite) where a modest 10-100 kW class laser, such as currently exists, would rendezvous and ablate material from the target surface much like the X-ray ablation from an NED, though over a longer time scale. A more exotic and much longer time scale version of extremely long distance "stand-off" laser ablation would use an orbital or lunar-based laser, but the latter is decades away in technological maturity. Meanwhile, "stand-on" laser ablation is relatively mature in terms of technology, as it is similar technologically to a high-power welding laser or the DE (directed energy) tactical defense systems already deployed on some ships, and that are also being deployed rapidly on land assets. One advantage of pursuing "stand-on" laser ablation is the extremely large amount of funding going towards military DE weapons systems; thus, it leverages existing and rapidly evolving technology.

Due to the social and political challenges of pursuing nuclear options, one of the most promising and well-developed planetary defense methods to date involve deflection KIs or the use of hypervelocity penetrators to completely disrupt the threat. KI deflection involves staging an intentional collision at a high relative velocity between a spacecraft and the orbital threat to alter the latter's trajectory [2]. NASA's recent Double Asteroid Redirection Test (DART) mission demonstrated proof of concept, successfully changing the orbit of Dimorphos, the smaller component of the binary NEA, 65803 Didymos, after impact on September 26, 2022 [4]. Daly et al. claim DART represents a "key accomplishment on the path to advancing kinetic impactor technology to an operational capability" for planetary defense [4]. More complex KI systems currently being designed include the use of multiple "hypervelocity penetrators" that would aim to pulverize a NEA into small fragments and then use "the Earth's atmosphere as a shield" to burn up the residual material [11]. According to Lubin and Cohen, the proposed method involves energy transfer, rather than momentum transfer, and could "spatially and temporally de-correlate" the energy of the impact hazard over a large dispersal area, such that a ground observer should only experience a series of acoustic shockwaves and optical pulses," [11] rather than the kind of airburst damage seen in Chelyabinsk. These authors further claim this approach could allow for extremely short-term response if needed, using fewer launch resources than standard KI deflection techniques would require for the same threat. Although not a major focus for this paper, another theoretical planetary defense method involves increasing an asteroid's albedo by painting the surface with a reflective coat of alkali metal to change its Solar reflectivity, thereby reducing the effect of Solar gravity and changing the object's orbital period [3].

3. What are the potential security implications of planetary defense activities?

Planetary defense activities have the potential to exacerbate political tensions, precisely because many defensive space technologies also have offensive capabilities. Outer space is often considered the ultimate military "high ground," with Pražák noting it already provides "[r] econnaissance, secure telecommunications, space surveillance and eavesdropping" to assist terrestrial military operations, even in the absence of active weaponization in the space environment itself [2]. In 2019, the USA established Space Force under its National Defense Authorization Act, and France created its Space Command, similarly within its Air Force department [2]. This trend of extending military responsibility to more explicitly include the space domain has continued in many other countries as well, with De Zwart and Stephens noting space has always been a "dual-use domain," embedded with military technology [13]. Pražák claims "the possibility of space as the next theatre of war should be considered" with continued national militarization of space activities "creating insecurity between actors and increased competition in armament since no actor will run the risk of being left behind" [2]. This next section will consider various risks associated with different planetary defense methods, including astro-political threats to international cooperation in space.

3.1. Risks of deflection

Morrison reminds us that when an impact hazard is detected we will not know exactly where it will hit, but "we will know that the hit will be along a *risk corridor*" that will likely include several countries, while excluding many others [12]. Thus, he notes the risk is "not distributed globally," and deflection attempts may protect one country at the expense of another within the risk corridor, causing "an obvious source for concern or even conflict," during what might be years of uncertainty [12]. This was recently seen with Asteroid 2024 YR4, with the risk corridor initially suggesting a possible impact site in India. The dilemma of globally unequal risk distribution has also featured in SMPAG's legal discussions on the topic, with the consensus that shifting risk from one region to another is "extremely problematic," but noting some deflection attempts may inadvertently do this [14]. When it comes to planetary defense more broadly, Morrison notes: "If we really did have an asteroid headed for the Earth, different nations might have very different opinions about where it should be aimed in a deflection maneuver" [12]. Views on what regions might be sacrificed as alternative impact sites are likely to conflict, with utilitarian calculations, such as how to minimize loss of human and animal life, and avoid damage to infrastructure and the environment, potentially yielding inconsistent results. Beyond utilitarianism, other relevant ethical considerations include whether there is a duty to protect the interests of the less fortunate (for example, nation states or individuals with the capability to engage planetary defense actions might be considered to have a moral obligation to act on behalf of those who lack such capabilities), or whether being in the path of an asteroid is just bad luck, suggesting that attempts to intervene on behalf of others may be supererogatory at best, or in the case that a redirection attempt leads to undesirable side effects, that it may be morally preferable to allow nature to take its course. The latter consideration is often invoked in discussions of "acts versus omissions" – in this case, it could be argued that were an asteroid set to hit one location, failing to intervene would merely be an omission that carries no ethical responsibility (since the agent is not responsible for the asteroidal threat), while intervening and causing it (intentionally or otherwise) to hit a different region, would represent a conscious choice, and thus the agent would be directly to blame for any negative outcomes in terms of potential destruction and loss of life. Early concerns that deflection technologies might be used to redirect an asteroid to an adversary in a terrestrial conflict have mostly been discredited due to practical constraints [12], but another legitimate risk of deflection is unintentionally redirecting the object into a gravitational keyhole, where it could now hit us on a future approach [2].

3.2. Risks of destruction

A possible risk depending on the PD technique is the creation of fragments that survive atmospheric re-entry and still impact the Earth. Lubin and Cohen show that depending on the size of the fragments, this could both be a solution to the problem of planetary defense if the fragments are small enough (<15m) and spread out spatially on the Earth, or if the fragments are too large, they could themselves cause significant damage. The issue of dust creation from small fragments in the terminal defense mode of hypervelocity penetrators (assuming a closing velocity between the asteroid and penetrator of ~20 km s−1 [15]), is generally minor and does not cause a "nuclear winter" scenario [11]. While traditionally NEDs have been seen as the only approach for short-term or terminal defense mode, this may no longer be true with the use of short-term hypervelocity penetrators. However, NEDs remain an important option, particularly for large threats including comets, and could be used for both stand-off deflection or in conjunction with hypervelocity penetrators. In the latter case, the goal would be to use sequential passive penetrators to "drill a hole" with the last penetrator being an NED allowing for a well tamped detonation with subsequent efficient fragmentation, much like an underground nuclear weapon test. Although NEDs are currently important to keep in reserve, and are particularly important for cometary impacts, such as sun grazing comets, Katz notes "nuclear explosions are widely considered undesirable," even if sometimes deemed "necessary" (in the technical, rather than legal sense) [3].

Legally speaking, NEDs are also considered undesirable, and arguably outright banned, with SMPAG's legal issues statement noting NED's for planetary defense would qualify as "nuclear weapons" [14]. The most blatant restriction comes from Article 1 of the Limited Test Ban Treaty of 1963, which restricts the testing of nuclear explosions in space following the USA's 1962 Starfish Prime experiment, which detonated a 1.4 megaton nuclear explosion at an altitude of 400 km, damaging satellites and causing widespread disruption to communication and power systems [2]. Looking at the plain language of the treaty, barring some necessity or suspension of the treaty, this would prohibit nuclear planetary defense, however, looking at the purpose of the treaty there may be some wiggle room for use of NEDs against a near Earth object (NEO). The Limited Test Ban Treaty is meant to prevent the transboundary harm that necessarily stems from nuclear explosions of introducing radioactivity in "man's environment" [16].

The nuclear test committed by the United States was squarely in Earth's orbit, whereas a nuclear intervention for planetary defense would happen in what is often referred to as the third category of space, open outer space. While this distinction may be unpersuasive for some, it is reasonable to interpret the Limited Test Ban Treaty as being restricted to outer space actively being used or likely to be used by humans given the purpose of the treaty is to prevent transboundary harm to the human environment.

Beyond the Limited Test Ban Treaty, other relevant provisions are Article IV of the Outer Space Treaty (OST) prohibiting the stationing of nuclear weapons in orbit, and the Non-Proliferation Treaty which prevents the stockpiling and expansion of nuclear weapons [17]. The issue here is whether the use of a nuclear explosion in this context would be considered a nuclear weapon or a peaceful nuclear explosion. Peaceful nuclear explosions are allowed under the Non-Proliferation Treaty and have been used to mitigate environmental disasters [18]. The obvious issue with this designation is confirming that it is indeed a peaceful nuclear explosion and not a Trojan horse hiding under the guise of dual use. The dual-use fear is not limited to NEDs but is most exacerbated by them. In any planetary defense protocol, we have to be extremely careful not to undermine the nuclear non-proliferation project, which would diminish global security and increase the risk of conflict, both in space and on Earth. However, relying on treaty suspension or necessity arguments for cases where NEDs may be required, as Morrison claims, may be just as detrimental to global security [12]. The best way forward would be for the international community to agree on standards stemming from the current treaty obligations and state practice shown above.

As noted above, it is also important to understand the use case where an NED may be deemed "necessary" [3]. For example, if a country knew a significant threat was expected to hit them unless an effective intervention was launched, and they felt they could not depend on other countries to defend them against this threat, it is likely they would decide to act unilaterally. While a unilateral action scenario may be considered undesirable in a "perfect world," we do not live in such a world. Another issue is that an NED is normally interpreted as a *weapon* from a *stockpile*, or at least a nuclear explosive that could be used as a threat against countries. A useful thought experiment might consider the possibility of designing a nuclear explosive that could not be used against anything except an external threat, i.e., it could NOT be detonated except for planetary defense purposes. Would this be prohibited by law? There are human-made devices in space that utilize nuclear material, and this has been the case for many decades, including small reactors and Radioisotope Thermoelectric Generators (RTGs), etc. Clearly devices using nuclear material are not prohibited in the space domain under current international guidelines. It is nuclear *weapons* that are prohibited. It may be possible to work around this issue with sufficient development, where timeframes for required action allow, or for the UN Security Council to approve a one-time exception for cases deemed "necessary" according to pre-agreed criteria.

3.3. Dual-use technology considerations

Dual-use technologies refer to technologies that have both civilian and military applications and include most planetary defense methods. For example, NEDs for asteroid ablation could be used to disrupt enemy communications, and Pražák reminds us that the rockets and payloads proposed for KI planetary defense activities resemble "direct ascent kinetic energy anti-satellite weapons" and could easily be suspected of that purpose [2]. Laser systems that can ablate asteroids can also damage functional satellites, while asteroid painting technologies could be used on satellites where "the line between painting and accidental dazzling or blinding can be blurry" [2]. As such, it is clear that global cooperation will be necessary when devising effective planetary defense strategies, to avoid conflict and exacerbating political tensions between nations.

3.4. Liability

Liability in the case of planetary defense potentially stems from the Liability Convention, although its application in this context is contested, and arguably also the principles of transboundary harm. In international law, liability is an obligation to provide compensation for harm caused by conducting activities that are not illegal but negligent [19]. Liability without international responsibility is rare but not unheard of in international law with the Liability Convention and Transboundary harm being prime examples. The Liability Convention of 1972 establishes two standards of liability for damage caused by space objects [20]. The first is absolute liability for damage caused on the surface of the Earth by a space object, and the second is fault-based liability for space object on space object damage [20]. For both standards, it is the Launching State(s) that are liable for the damage caused [20]. The Liability Convention is a victim-oriented treaty and as such allows victims to sue any State involved in launching or procuring the launch of an object [21].

First, it is unclear if the Liability Convention would apply to a planetary defense situation.

The damage has to be caused by a space object, and it is unclear what causation rules the Liability Convention operates on. Given the victim-oriented nature of the treaty, a broad interpretation of causation would not be inappropriate, but would still be highly contextual to ensure there is not a break in the causation chain, even for the strict liability standard. Second, the Liability Convention discourages action, both in terms of prevention and mitigation, given there is no obligation to act but once action is taken there is an obligation to act responsibly. Action in this context would be launching, given the only entity that can be liable is Launching State(s) and the only damage covered is damage to the Earth or a man-made space object that was caused by man-made space objects. A further complication is that what it means to act responsibly as an operator of general space activities is unclear, never mind what it means in the context of planetary defense. Fault is undefined in the Liability Convention, while the due diligence and prevention standard in the transboundary harm principles are guided by accepted scientific standards but does not require scientific certainty [19]. The transboundary harm standard could be used to help interpret fault, given that a collision or botched planetary defense operation would likely cause significant transboundary harm, depending on what area of the Earth is struck, but state practice in this regard will be the ultimate interpreter. While some scholars question the direct applicability of such standards to the space context, it remains the case that core principles could be adapted to serve this domain, which may be guided by existing provisions, including good Samaritan laws that protect actors from liability when engaged in genuine rescue operations. Article VI of the OST, which contains the "responsibility regime" enshrining "international responsibility for national activities in outer space" may also be difficult to interpret when the action taken is a transnational collaboration or intended for global, rather than national defense [17]. A new agreement that is not limited by what is currently included in the OST or what is currently interpreted as a potential transboundary harm might help develop guidelines that are fit-for-purpose in a planetary defense scenario. Defining fault is extremely important, given that there can be potentially infinite liability if the chain reaction consequences are foreseeable. Adding the vagueness of fault and the potential breadth of the liability, the Liability Convention may unintentionally impede planetary defense prevention and mitigation activities if actors are concerned that their deflection attempts may inadvertently cause damage on the surface of the Earth or another space asset.

4. What are the potential space heritage implications of planetary defense activities?

As various planetary defense methods focus on deflecting or destroying impact hazards, it is worth considering the heritage implications of these actions. Gorman defines heritage as "basically stuff from the past that people in the present think is important and want to keep for future generations," noting this might include visions of the night sky unencumbered by artificial satellites [22]. This may be particularly important for cultures that use dark space constellations, such as many Indigenous Australian groups [23]. Some visible asteroids and comets may also have cultural significance, such as Halley's comet or 4 Vesta, and interference with these celestial bodies may violate cultural norms. If placing more objects in orbit to monitor and react to impact hazards, there is also the risk constellations may be obscured, as is being seen in observatory images impacted by Starlink's mega-constellations [24]. However, this is less likely to be of relevance to the case of planetary defense monitoring, as the issue is caused by low orbiting satellites. Gorman also notes that some of what is classified as space junk actually carries deep significance in our space heritage, such as the OSCAR 5 satellite launched by Australian university students in 1970, representing an important milestone in "Australia's engagement with space" [22]. If nations or private actors are able to start testing planetary defense methods in space, such heritage items may be damaged in the process in the absence of any guidelines regarding legitimate practice targets.

5. Legal considerations: how the Outer Space Treaty enables planetary defense

The United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) has begun the process of multilateral planetary defense by creating the International Asteroid Warning Network (IAWN) and the Space Mission Planning Advisory Group (SMPAG) [25]. These groups are made up of representatives from UN member states, national civil space agencies, research facilities, and other relevant stakeholders, and as noted previously, were recently activated in response to Asteroid 2024 YR4. The responsibilities of these groups are divided into two parts of planetary defense: detection, and mitigation [26]. The detection under the IAWN, legally speaking, is rather non-controversial, whereas mitigation in general, and under the SMPAG, has many legal questions that must be addressed. The SMPAG's legal working group has analyzed the legality of various planetary defense plans and technologies from the perspective of various legal instruments and following guidance within the Outer Space Treaty. While the OST was not created with planetary defense in mind, thus limiting its direct contribution to these discussions, it still provides a useful framework for discussing interventions in the space environment, based on general rules and aspirational goals for human use and exploration of space. Depending on the procedures of the SMPAG's legal working group, the group itself could help solve many of the fears of dual use, and concerns regarding the Liability Convention discouraging participation in planetary defense activities due to liability risks. If the working group's potential mitigation plans are adopted via consensus with sufficient detail by those seeking its guidance, one could argue that this would be considered collective procurement of a launch, regardless of which country launches the mission. Current legal norms are unlikely to support this interpretation in practice, suggesting a re-imagining of responsibility for actions in space might be necessary for a multilateral planetary defense protocol to truly become operational. If this was achieved, with so many countries subject to the joint and several liability of the Liability Convention, the financial risk would be diffused as well as the interest balanced. Further, multilateral action would quell the fears of dual-use Trojan horses if clear procedures and standards are created within these plans.

As for the legal principles that should guide mission planning, these should be transboundary harm draft principles. The consequences of planetary defense most cleanly fall into transboundary harm. Further, the commentaries for the transboundary draft articles already incorporate the Liability Convention, and the OST incorporates general international law through Article III [17,19]. Transboundary harm principles put an obligation on States to prevent and/or provide reparations for transboundary harm created by its actions. As any harm caused by a planetary defense mission would be devastating, and preparation is the best plan, the prevention obligation is a viable guiding principle for the SMPAG to use.

The Prevention of Transboundary Harm from Hazardous Activities lays out the rules on “activities not prohibited by international law which involve a risk of causing significant transboundary harm through their physical consequences” [27]. The prevention obligation found in Article 3 simply states: “The State of origin shall take all appropriate measures to prevent significant transboundary harm or at any event to minimize the risk thereof” [27]. Article 10 of the same instrument then goes on to expand on what exactly it means to take “all appropriate measures”, with the most relevant part for our purposes being subsection F [19,27]. Subsection F requires state, regional, and international standards to be used to inform the prevention obligation [27]. This obligation is a continuous one and is meant to be guided by the scientific standards available at the time [19]. Without standards, the acting State still has an obligation to carry out due diligence on what would be appropriate if the harm is “serious or irreversible” [19] Planetary defense, obviously, has the potential to be serious and irreversible. Creating international recommendations through SMPAG would serve a similar purpose as the Principles Relevant to the Use of Nuclear Power Sources In Outer Space, providing a technical standard for proper use of technology, lessening the fears of dual-use applicability, and proposing a standard for even unilateral missions.

SMPAG is in the best position to do this as it includes the civil space agencies. While the Planetary defense mission would likely have to be supported by military organizations, the civilian agencies should be the driving organizations and face of the conversation, to underscore a science-based approach to the planetary defense problem and ease negotiations.

6. Practical and logistical considerations

The “ethics of planetary defense” will come down to a decision of what is considered more important. If human life is to be considered more important than objects and their unperturbed orbits, then the ethics of defense becomes a practical question rather than a purely philosophical question. Another critical ethical factor will be the issue of proactive defense vs defense only when absolutely necessary (i.e., imminent threat of destruction of life). Proactive defense is defined as defense for the future prevention of harm to life even if no specific future threat is currently known. In this sense, proactive planetary defense is similar to vaccination in that no immediate threat to the person taking the vaccine is known but there is a probability of future harm (at least to some) if no vaccination is taken. And just as the more developed and efficacious a vaccine, the higher the benefit-risk ratio for those taking it, the more technologically mature and appropriately executed the proactive planetary defense system, the closer it would become to the ultimate goal of producing protection for all with no additional risk of harm. If proactive planetary defense is accepted, then the next issue will be one of degree. Should ALL potential threats be eliminated, or only those considered to be the most dangerous? This will then turn the ethics of planetary defense into one of the economics of planetary defense. As a concrete example, should Apophis and Bennu be eliminated as future threats? Previously considered the most hazardous asteroid when discovered in 2004, the threat level for Apophis has since been downgraded with astronomical observations from 2021 concluding there is no risk it will hit Earth for at least a century [28]. But where should the line be drawn for a proactive response? A secondary level of planetary defense would be that of conventional (whether passive or conventional explosive) vs nuclear explosive methods, with the latter most likely to be needed for impact hazards detected very late. This would represent a reactive model of planetary defense.

A robust planetary defense program would be a layered system of both detection and mitigation requiring both long term detection and mitigation in addition to terminal detection and mitigation. This is similar to an over-the-horizon vs last-minute approach to national defense. A more nuanced approach to planetary defense in the terminal mode would establish acceptable levels of damage, with an emphasis on some property damage being tolerated while loss of human life is not. The loss of animal life will also have to be considered in any full ethical debate. For example, is loss of aquatic life in an asteroid strike in the ocean acceptable? There are also broader environmental concerns and biosecurity implications for impacts, even in nonpopulated areas, such as most of Antarctica, where the majority of rocks from space have previously been recovered [29].

New methods of planetary defense via shock and explosive fragmentation allow for a robust mitigation capability up to certain threat levels. For example, asteroid threats up to about 1 km are currently possible to mitigate, depending on the density, speed and warning time, while an asteroid the size of Ceres 950 km diameter (about the size of Texas) is not currently viable to mitigate even with all nuclear devices available. As another example, comets at 10 km diameter (~Halley's) are conceivable to mitigate [30]. For the larger threats, the use of nuclear mitigation is a desired option to maintain, especially in shorter warning scenarios. Note that the use of "stand-off" NED's is relatively inefficient as the X-ray coupling to the surface that causes ablation is not nearly as effective as would be the same device used in a sub-surface penetration mode, and alternative methods would require multiple NEDs. It would be much more effective to detonate the weapon beneath the surface. The current issue of using the equivalent of Earth penetrating NED's is that at the extremely high closing speeds of an asteroid or comet threat, the weapon would be destroyed in the intercept. Future use of passive hypervelocity sequential penetrators may allow an NED to be much more effectively used by detonating inside the threat, thus allowing much more robust planetary defense for larger threats.

A number of political questions inevitably arise regardless of the method of planetary defense being supported, including "who is responsible and authorized for defending the planet?", with the likely political arguments as to what is a "cover" for a weapons program being immediately invoked. For precisely this reason, ideally, any planetary defense program would be a transnational endeavor rather than a nation state responsibility. A related question will be "is the use of space (for example, lunar deployment) allowed for defense?" While currently this will be highly controversial, there was a time not long ago when any satellite was considered a threat. A 2019 book addressed the possibility of establishing a global consortium for planetary defense that proposed using a future lunar settlement as both a mining facility and a planetary defense platform [31]. This work within international politics is ongoing, including through UNOOSA's Action Team on Lunar Activities Consultation (ATLAC) initiative [32], and various interdisciplinary responses to hypothetical planetary defense scenarios [33].

7. Ethical guidelines informed by legal and practical considerations

One would hope that in the face of a global catastrophe, reason would prevail, though history provides us with little optimism here [11]. As recent concerns around possibly conflicting planetary defense actions to address Asteroid 2024 YR4 have demonstrated, now is the time to develop ethico-legal and practical guidelines for international planetary defense protocols. As a starting point, we suggest the following considerations be included in such a model.

- The preservation of all human life, without discrimination, should be the ultimate priority for planetary defense
- Wherever possible and not in conflict with the above priority, risk of harm to other bioforms should be mitigated as far as possible
- Planetary defense platforms and systems should demonstrate respect for the principles of cooperation, including those outlined in the Outer Space Treaty, recognizing the socio-political harm of undermining global cooperation in the space domain
- Approved planetary defense technologies should demonstrate efficacy and be validated through simulations and live demonstrations, as appropriate
- Planetary defense systems should be subject to international governance to minimize the risk of unauthorized use in terrestrial conflict, where relevant
- Dual-use technologies should be subject to both civilian and military oversight to ensure transparency and to protect the public interest
- Planetary defense guidelines should align with all relevant aspects of space law and reflect relevant liabilities and waivers regarding the destruction of celestial objects, including during testing and implementation of planetary defense responses
- Planetary defense groups should include representation from many countries to ensure international perspectives are considered, including from non-Launch states
- In the event of a predicted impact with Earth, the regions most directly affected should have a right to request and receive support to avoid or mitigate the effects of the impact

While IAWN and SMPAG have contributed substantially to the project of developing appropriate protocols for the global endeavor of protecting Earth from asteroidal and cometary impact hazards, the lack of enforceability and direct capability to implement planetary defense plans demonstrates the need for stronger systems and measures to address impact threats. Similarly, while the OST has achieved outstanding support and remains the most influential agreement directing human interactions with the space environment, changing it to incorporate planetary defense responsibilities could undermine its efficacy by opening it up to other politically-motivated changes.

8. Conclusion

Asteroidal and cometary impact hazards pose a significant threat to life on Earth that justifies the development of robust planetary defense strategies to mitigate these harms. Advanced technologies capable of deflecting or destroying an impact hazard are under development but the lack of an international agreement regarding responsibility for planetary defense means there is no clear mandate for response teams to use these technologies in the event of a predicted collision. Given the political sensitivity of designing and testing planetary defense technologies for use in space, ethico-legal guidelines are needed that clearly outline risks, harms, liabilities and responsibilities for mitigating impact hazards in the future.

Author statement

The authors have not used generative AI.

CRediT authorship contribution statement

Evie Kendal: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Madison Kujawa:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Philip Lubin:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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