9th IAA Planetary Defense Conference – PDC 2025
5-9 May 2025, Stellenbosch, Cape Town, South Africa

IAA-PDC-25-09-207

Legal and Policy Considerations for Multi-Action Deflection of Hazardous Near-Earth Objects

Brent W. Barbee[(1)], David A. Koplow[(2)], and Alissa J. Haddaji[(3)]
[(1)]*NASA Goddard Space Flight Center, Code 595, 8800 Greenbelt Road, Greenbelt, MD, 20771, USA, (301) 448-5681*
[(2)]*Georgetown University Law Center, 600 New Jersey Ave NW, Washington, DC, 20001, USA, (202) 662-9567*
[(3)]*The Space Consortium, 10 Agassiz Street, Suite 26, Cambridge, MA, 02140, USA, (617) 710-5722*

Abstract

Deflecting a hazardous near-Earth object (NEO) away from Earth impact may be undertaken using a variety of techniques. Deflections may be categorized according to whether they are designed to be accomplished, in principle, with a single action or are designed to require multiple actions spread across time. Any multi-action deflection (whether impulsive or slow push/pull) gradually moves the NEO, in a premeditated manner, away from its original natural Earth impact location. This necessarily, in effect, places the NEO's impact point at locations not originally directly threatened by the NEO, as part of the gradual process of fully deflecting the NEO. We present an analysis of the legal and policy issues pertaining to multi-action NEO deflection, considering both impulsive and slow push/pull options. Our analysis considers existing treaties and other law, policies, existing legal and political precedents and analyses, theoretical / possible motivations and intentions of the launching state(s), whether the launching state(s) had a single-action deflection or disruption option available (including one that would employ a nuclear explosive device) but nonetheless selected a multi-action deflection option, and more. We discuss findings and conclusions, recommending the articulation of an effective and appropriate legal and political framework for proper handling of multi-action NEO deflection options prior to being confronted with an actual emergency.

Keywords: Asteroid Deflection, Comet Deflection, Space Law, Planetary Defense Law, Planetary Defense Policy

1. Introduction

Earth impacts by near-Earth objects (NEOs)—asteroids and comets whose orbits closely approach that of Earth—have shaped life on our planet since the earliest days of the solar system. NEOs provide both the clues to understanding our ancient past and the keys to securing our prosperous and safe spacefaring future. The applied science of Planetary Defense is aimed at securing our future by leveraging our scientific understanding of NEOs to build our capability to defend ourselves against impacts.

It was a particularly large impact ~66 million years ago that caused the Cretaceous-Paleogene (K-Pg) extinction event [1,2], wiping out the non-avian dinosaurs and 76% of all other species alive at the time. A variety of notable smaller but still consequential impacts have occurred since then, the most recent of which was the ~0.5 Mt explosion of a ~20 m asteroid above Chelyabinsk, Russia on February 15, 2013, injuring ~1,600 people and causing ~$33 million worth of damage. Current population models predict that there are at least several hundred thousand NEOs around the size of the Chelyabinsk impactor that have not been discovered yet.

Spurred onward by witnessing comet Shoemaker-Levy 9's spectacular impact of Jupiter in 1994, NASA and other space agencies around the world have been steadily developing and advancing capabilities for detecting and tracking NEOs, continually improving our ability to find Earth-impacting NEOs before they find us. In 2022, NASA performed the first-ever flight demonstration of a spacecraft system to deflect the orbit of an asteroid, with its Double Asteroid Redirection Test (DART) mission [3]. The year after DART made history by changing the orbit of an asteroid for the first time, NASA's Origins, Spectral Interpretation, Resource Identification, Security - Regolith Explorer (OSIRIS-REx) spacecraft made history again by returning samples of the potentially hazardous near-Earth asteroid (NEA) Bennu to Earth [4]. NASA is currently building an infrared space telescope, named NEO Surveyor[1], that is scheduled for launch during the fall of 2027. It will be tasked with cataloging the undiscovered NEOs and identifying any future Earth-impacting NEOs as far in advance as possible.

When a hazardous NEO on an Earth-impacting orbit is deflected away from Earth impact, the deflection may be performed in a variety of ways and using a variety of techniques. A deflection may be categorized according to whether it is designed a priori to be accomplished, in principle, with a single action or to require multiple actions spread across time, to include a long-term gradual deflection operation. The manner in which the NEO's Earth impact location is moved across the surface of the Earth gradually or in discrete steps during the act of deflecting it completely off the Earth raises a variety of challenging legal and policy questions.

In this paper, we present an analysis of the issues associated with gradual or multi-action NEO deflection and associated recommendations for developing approaches to handle those issues. One of our primary aims in this work is to help prevent those issues from becoming impediments to carrying out a successful NEO deflection mission during a time of need.

2. Risks, Threats, and Hazards

The discussion of potential NEO impacts on Earth involves proper treatment of the concepts of risks, threats, and hazards. Here we provide additional context about how to properly regard these concepts in the context of NEOs and the risks, threats, and hazards they pose to Earth.

---

[1] Jet Propulsion Laboratory, "Near-Earth Object Surveyor," https://www.jpl.nasa.gov/missions/near-earth-object-surveyor/, accessed 2025-04-23.

A risk is defined as a probability that a hazard will happen [5]. The notion of "risk" is often defined as an equation: either that of 1) the probability of a negative event happening multiplied by the damage such an event would cause, or 2) an unforeseen turn of events multiplied by what is at stake. The determination of risks can be brought back to the determination of an "uncertainty." The terms "risk" and "uncertainty" are often used synonymously.

A risk may also be defined as something that is potentially harmful. It is, says Le Breton, "a quantified uncertainty, a potential danger likely to be created by a coincidence." [6]. The definition given to the word "risk" also determines its usage and will depend on whether it is used as a synonym of "choice", "danger", "challenge" or a synonym of "anticipation of the future."

An NEO impact could be considered an existential risk, i.e. a risk that could either annihilate intelligent life or permanently and drastically curtail its potential. On the other hand, when discussing the potential for Earth to be impacted by an NEO large enough to cause meaningful harm but not large enough to have direct global effects, the word "hazard" is used. Terms such as "threat" are only used when a specific object has been identified on a potential impact course towards Earth. This distinction helps us distinguish the following two types of statements:

- When talking hypothetically about an Earth impact, the term "hazard" is to be employed.
- Conversely, when it has been determined that there is potential for an actual Earth impact by a particular NEO, then the term "threat" is to be employed.

In other words, in Planetary Defense, near-Earth objects (NEOs) can generally be considered *potentially* hazardous. Furthermore, there is a specific definition for a Potentially Hazardous Object (PHO), which is an NEO that has a Minimum Orbit Intersection Distance (MOID) with Earth that is less than or equal to 0.05 au (roughly 7,480,000 km or 4,650,000 mi or 20 lunar distances)[2]. However, a particular NEO (or PHO) becomes a "threat" if and when the object is determined to actually have the potential to impact Earth at a particular time. Then, Earth would be at "risk" of an "NEO threat." Moreover, the term "threat" also carries the significance that one wants to be protected from it. The concept of threat is thus underpinned by the idea that one has become aware of the danger posed by a hazard and wants to be protected from it [5] .

Making the distinction between the term "threat" and the term "disaster" is also important. A natural disaster, unlike a threat, refers to a major adverse event that populations have experienced in the past, by being directly or indirectly affected by it. Furthermore, the term "disaster" suggests that the event exceeds the capacities of local management [7]. For example, if/when an NEO is on its route to impact Earth, the term NEO "threat" will be used. Once it has impacted the Earth, the term "disaster" will be used. A major NEO impact is something unprecedented in human experience. Consequently, when talking about NEO research and detection, the terms "threat" and "disaster" may be more appropriately replaced with the term "hazard."

[2] Jet Propulsion Laboratory Center for Near-Earth Object Studies, "NEO Basics," https://cneos.jpl.nasa.gov/about/neo_groups.html, accessed 2025-04-23.

3. Summary of NEO Deflection Physics

The required amount of velocity change (i.e. delta velocity or “ΔV”) that must be imparted to the NEO to deflect it away from Earth impact depends on how far in advance of Earth impact the ΔV is applied to the NEO, the nature of the NEO's orbit (in particular, its orbit eccentricity), and how near or far the NEO's original Earth impact location is from the limb of the Earth. Earlier deflection times and/or fortuitously near-limb Earth impact locations tend to reduce the required deflection ΔV, which also always has local minima at the NEO's perihelia (the depth of those minima are more significant for more eccentric NEO orbits). Overall, deflection ΔV requirements will be unique to a given scenario.

Whether single-action deflection of an NEO is possible depends on whether the required deflection ΔV can be imparted to the NEO via a single impulse, given the size of the NEO, the limits of available technology, and whether the NEO can withstand the impulse without unwanted fragmentation that could pose intolerable secondary risks to Earth. Note that a fortuitously small deflection ΔV requirement can change impact prevention method performance regimes for single-action deflection and avoidance of unwanted NEO fragmentation. For example, a very small deflection ΔV requirement could potentially make single-action deflection possible for smaller/weaker NEOs while avoiding unwanted fragmentation risk, and for larger NEOs that might otherwise have required multiple deflection impulses even using the most performant methods available.

The amount of ΔV that an NEO can tolerate before the onset of unwanted fragmentation depends principally, but not exclusively, on the NEO's mass and bulk cohesive strength. Higher strength may enable a smaller (lower mass) NEO to tolerate a substantial amount of deflection ΔV without unwanted fragmentation, but this is difficult to predict even with state of the art computer models, and NEO bulk strength is difficult to measure even by a spacecraft that has rendezvoused with the NEO.

4. NEO Deflection Techniques

An NEO might, in principle, be deflected away from Earth impact with a single kinetic impactor (KI) or a single standoff detonation of a nuclear explosive device (NED). A KI is a spacecraft that collides with the NEO at very high speed (e.g. >5 km/s) and imparts its momentum to the NEO [8]. Additional change of the NEO’s momentum may be provided by ejecta coming off the NEO in consequence of the kinetic energy imparted to the NEO, but this is challenging to predict [3]. Detonating an NED at some standoff distance from the NEO’s surface (also called the Height of Burst (HOB)) causes radiation from the NED detonation, principally x-rays, to irradiate and ablate a thin layer of NEO surface material, which then blows off the NEO rapidly towards the vacuum of space, causing the NEO to recoil strongly in the opposite direction [9].

Note that while NASA’s DART mission has provided a flight demonstration of the KI technique [3], uncertainty remains about the contribution of ejecta produced by the KI to the total momentum change of the NEO. Furthermore, NEDs have yet to be tested against an NEO. Therefore, while these techniques are regarded as conceptually mature and feasible in principle, work remains to make them fully operational. It is also worth noting that an NEO's response to applied ΔV from an NED may differ from the NEO's response to the same ΔV applied by a KI.

KIs and NEDs are examples of impulsive, or “fast push” deflection techniques that change the NEO’s velocity extremely rapidly, typically in well under a second. That means that the NEO is instantaneously deflected, for practical purposes. By contrast, “gradual” or “slow push/pull” deflection techniques apply a very small continuous acceleration to the NEO over a long period of time to accomplish the total required deflection of the NEO. Potential examples of slow push/pull deflection techniques are ion beam deflection (IBD) and the gravity tractor (GT). A GT spacecraft continuously thrusts with a solar electric propulsion (SEP) system to maintain its position near the NEO, but without pointing its ion beam thrusters at the NEO, allowing the gravity of the GT spacecraft itself to apply a small continuous acceleration to the NEO [10,11]. An IBD spacecraft instead points its SEP ion beam thruster directly at the NEO (and simultaneously points an identical thruster in the opposite direction, so as to maintain its position relative to the NEO) and uses the ion beam itself to apply a small continuous acceleration to the NEO [12].

Like NEDs, neither IBD nor GT has been tested on an NEO and therefore neither are yet operational. Because the acceleration on the NEO is very small, many months or years would usually be required to fully deflect an NEO using either of those techniques. Additionally, because the acceleration on the NEO is most effective when the NEO is near its perihelion, and because more solar power is available for thrusters near perihelion, a gradual deflection will generally be applied during a several month arc centered on each of the NEO perihelion passages available between the start of the deflection mission and the NEO’s Earth encounter date. When not near perihelion, the GT or IBD spacecraft will generally move away from the NEO and cease thrusting, to conserve precious propellant for use when most efficacious (near NEO perihelions). Because there are generally one to several years between NEO perihelion passages, this can have the effect of stretching a gradual deflection out over quite a few years, depending on the size of the NEO, the total deflection distance required, and the number of spacecraft deployed.

Assuming the availability of a reliable technique, single-action deflection is possible when the nature of the NEO’s orbit, the amount of warning time, and the mass and strength of the NEO are all such that 1) a single KI or NED is sufficient to give the NEO the amount of ΔV required for deflection, and 2) the NEO’s mass and/or strength enable it to tolerate that ΔV without unwanted fragmentation of the NEO. However, if those criteria are not met then a series of multiple smaller ΔVs may be imparted to the NEO such that their total effect eventually deflects the NEO away from Earth impact, without intolerable amounts of NEO fragmentation. There would necessarily be some amount of time between the applications of those multiple deflection ΔVs, for various reasons, including to allow time for small debris to clear, to allow time for the effects of the previous deflection ΔV on the NEO to be assessed, and because of the physics governing the launch and flight of multiple spacecraft towards the NEO. Thus, such a multi-action KI or NED deflection campaign might span weeks, months, or even years.

5. Liability

Whether a multi-action deflection is done via a fast push or slow push/pull technique, the important point here is that a multi-action deflection mission is designed to spread the deflection out across a substantial amount of time (e.g. months or years) before full deflection of the NEO is eventually achieved. A consequence of this deflection design strategy is that the NEO will be moved, in a premeditated manner, away from its original natural Earth impact location in an incremental fashion. This means that the NEO will necessarily be redirected towards various locations that were not originally directly threatened[3] by the NEO's natural orbit, as part of the gradual process of moving the NEO entirely off the Earth, and those locations newly at elevated risk would be known in advance. Should the deflection mission fail to complete for some reason, such as underperformance of the deflection system, malfunction or system failure, or abandonment of the mission by the launching state, then the NEO will be left on a trajectory to impact at a particular location that was not originally at risk.

Incomplete deflection during a single-action deflection is also possible. Even though a single-action deflection mission is designed to instantly move the NEO entirely off the Earth in a single action if all goes according to plan, unanticipated problems such as underperformance or system failures may result in the NEO not being moved fully off the Earth. In that situation, the NEO would accidentally be moved away from its natural Earth impact location to some new impact location that was not originally at risk. The legal and political aspects of this situation have been studied, and a summary of the liability for failures resulting in partial deflections follows. This discussion of liability in the case of an incomplete deflection presumes that a backup mission is not sent to the NEO to complete the deflection, for whatever reason (e.g., insufficient time and/or resources).

The current international law regime regarding tort liability for damage inflicted by space activities is strong, clear, and globally-accepted, although it has very rarely been implemented in practice. Space activities have been regarded as ultra-hazardous, so the applicable treaties [13,14] seek to indemnify a country and its inhabitants for harm caused by another state's space activities. In the case of damage suffered on the surface of the Earth, this liability is "absolute," meaning that the acting state is responsible, even if its behavior was in no way wrongful or negligent.

In its 2020 report [15], the Legal Working Group established by the Space Mission Planning Advisory Group (SMPAG)[4] determined that these rules would mean that if a state deflected an NEO (as in a good faith effort to prevent it from impacting Earth) but was unsuccessful in avoiding an Earth impact altogether, so the

---

[3] Note that early in a planetary defense scenario, the uncertainty in the NEO's Earth impact location will generally be so large as to span the entire impact risk corridor. In that sense, all nations crossed by the corridor could be regarded as having been initially threatened by the impending NEO impact. However, in this paper we are primarily concerned with the NEO's actual natural Earth impact location, which is unknown early in the scenario but becomes known later in the scenario, after additional ground-based observations and/or a spacecraft reconnaissance mission have reduced uncertainties sufficiently that we know exactly which nation would be impacted if the NEO were not deflected at all.

[4] The European Space Agency, "SPACE MISSION PLANNING ADVISORY GROUP," http://smpag.net/, accessed 2025-04-23.

NEO, or a portion of the NEO, struck a state other than where it would normally fall without any intervention, the acting state would incur liability. That is, even though it was the NEO that was the immediate cause of the harm, the acting state would be liable for moving the NEO into the damaging position, even if the state's intention had been precisely the opposite. Note that during a multi-action deflection, the foreknowledge of which locations would be in harm's way (and any refusals to agree to the mission) would not affect the nature of liability for an incomplete deflection.

The resulting financial exposure could be enormous. Depending on the circumstances, an NEO might inflict extensive damage, and the acting state would be liable to the impacted state, its persons, and its corporations. Such exposure might deter any state from undertaking the planetary defense mission.

One possible strategy for mitigating the problem could be for potentially impacted states to execute legally-binding waivers of the right to seek compensation. Another approach could be for the United Nations Security Council to exercise its authority under the United Nations Charter to, in effect, suspend the legal obligations of the relevant treaties, to relieve the acting state of liability, and to create some other international mechanism for assisting the recovery of the impacted state.

6. Threat or Aggression Under International Law

A potentially significant legal and political issue regarding the multi-action or gradual deflection scenario arises from the fact that, at any particular time, the planetary defense mission will deliberately expose one country (or a few countries) to increased danger. That is, as the NEO's potential impact point is foreseeably dragged along the impact risk corridor across the surface of the Earth, a sequence of countries will temporarily be at heightened risk. Whenever the multi-action process is paused (for example, when the NEO moves past and away from perihelion), the exposure of a particular country will be sustained for a predetermined period of time. Even when a gradual deflection is operated continuously, i.e. without pauses, it may take a long time for the NEO's Earth impact location to be dragged all the way through a particular country.

It should be anticipated that a state would not favor being placed in such a higher-risk situation for an extended duration. The state may accordingly raise political objections to any such strategy in a variety of global fora. Could a country in this position also raise cognizable complaints under international law?

One such claim could be to characterize the planetary defense process as constituting an "illegal threat," and the country conducting the mission as an "aggressor," behaving in violation of international law. The affected state might argue that the NEO was being "aimed" at its territory and note that if for any reason the multi-action or gradual deflection process were halted, the result would be catastrophic for its territory and population. The country might further assert that if its exposure were sustained, the country would suffer economic damage long before any physical impact. The state might foresee that people and businesses would disfavor remaining in locations along the NEO risk corridor; their flight to safer sites would immediately depress economic activity and property values.

The most applicable international law standard arises from article 2(4) of the U.N. Charter, which prohibits “the threat or use of force against the territorial integrity or political independence of any state, or in any other manner inconsistent with the Purposes of the United Nations.” Surely, if a state were to deliberately corral an NEO and direct it against another state, such a hostile act would be manifestly illegal. However, there is no direct precedent for evaluating these standards as applied to a state undertaking a planetary defense mission that led to the temporary or extended placement of a NEO’s Earth impact location into a place that jeopardized another state. This effect of the planetary defense would be known in advance and the choice of tactics and timing would be deliberate. But the intention of the actor would, ostensibly, be benign rather than aggressive or warlike.

For comparison, currently, many states do maintain military forces and arsenals that are developed, sized, deployed, and trained with an eye toward future armed conflict. Some sustain long-range missiles that are perpetually aimed at each other and ready to fire on short notice. Many subscribe to a theory of deterrence, undertaking to retaliate against a neighbor who undertakes unwelcome acts. Yet none of those measures is ordinarily regarded as constituting “aggression” or an illegal “threat.” The concept of "anticipatory self-defense" would enable a state that has not yet been the victim of an illegal attack—but that has a valid basis to fear that such a use of force is imminent and unavoidable—to strike first, by undertaking measured force to pre-empt the attack it foresees.

If a state did assert that a multi-action or gradual planetary defense deflection mission that paused at the moment when that state was exposed did constitute an illegal act, the U.N. Security Council would constitute the world’s primary dispute resolution authority. Under the Charter, “The Security Council shall determine the existence of any threat to the peace, breach of the peace, or act of aggression and shall make recommendations, or decide what measures shall be taken.” Absent some extraordinary circumstances, it seems unlikely that a disaffected state’s unhappiness about a prolonged exposure via a multi-action or gradual planetary defense mission would be successfully elevated from a political dispute into a valid international legal claim about aggression.

7. Discussion

As described in the preceding sections, planetary defense techniques may be notionally divided into two broad categories: a) fast or strong or impulsive techniques that import a great deal of ΔV suddenly (in less than one second) and cause an abrupt change in the NEO’s trajectory; and b) slow or weak techniques that alter the NEO’s path incrementally, bit-by-bit over a long period of time. KIs and NEDs are prototypical examples of the first category, while IBD spacecraft and GT spacecraft would be concepts of the second sort.

In addition, we identify three kinds of planetary defense applications or scenarios: a) single-step operations, in which sufficient ΔV is created all at once, so only one intervention is necessary to alter the NEO’s trajectory enough to cause it to miss Earth; b) multi-step operations, in which several discrete interventions are required, with some time gaps between the sequential applications; and c) continuous operations, in which the force exerted on the NEO is small but constant, with no gaps or pauses, over an extended period of time.

In principle, the strong methods (KI or NED) could be applied in either the single-step scenario (if the NEO were relatively small but large enough or strong enough to remain intact, or its projected impact point was near the limb of the Earth, so just one small hit would suffice to change its trajectory sufficiently to cause it to miss the Earth) or in a multi-step scenario (if a few or several punches were needed to alter the NEO's trajectory sufficiently). In (partial) contrast, the weak methods (IBD or GT) could be employed in either the multi-step scenario (for example, if the technique were applied when the NEO is near its perihelion, but is then switched off at other times, to save propellant, waiting for the next perihelion, and several such iterations might be required) or in the continuous mode (when the IBD spacecraft or GT spacecraft was kept functioning all the time, even if it was less efficient or effective when far away from perihelion).

It should be noted that any of the three scenarios could be subject to unforeseen problems. For example, the equipment might fail to operate as planned; the effects of the technique might be different than anticipated; or the state(s) conducting the planetary defense mission might run out of money or interest and pause the operation. The effects of those disruptions would be axiomatically unpredictable, and no one could anticipate which state(s) along the risk corridor would be disadvantaged by suddenly being exposed to the NEO danger for a longer period of time than originally expected.

In addition to those possible errors, the multi-step scenario also requires that a state (or several states) would be exposed to extra risk whenever there was a planned pause between the steps. That is, the key feature of the multi-step scenario is not the fact that it has multiple steps; rather, the key feature is that there is a hiatus between those steps. Probably, those pauses would be part of the original concept for the planetary defense mission—the planners would know in advance (for the strong scenarios) when the series of KI or NED strikes would occur, and how much of an interval would be appropriate; or (for the weak scenarios) when the IBD or GT system would be halted while away from perihelion. On the other hand, perhaps there would be some flexibility regarding the timing of the required steps, as the state(s) conducting the planetary defense mission could survey the progress made with the first interventions and decide later when to employ the next steps in the sequence.

In any event, the possibility of a pause (or several pauses) in the multi-step scenario could have significant consequences. A particular state or states would experience heightened danger, sustained for a longer period of time, whenever there was a gap in the conduct of the planetary defense operation.

A particular state would also experience heightened danger for a longer period of time even during a truly continuous deflection with no pauses at all, because that approach still drags the NEO's impact location across individual nations one at a time. So, there will be some (potentially long) amount of time from when the NEO's impact point enters a nation's borders to when the NEO's impact point eventually exits that nation's borders. Throughout that time interval, that particular nation is at elevated risk, and that condition can persist for months, even with no pauses in the continuous deflection. This feature makes even truly continuous (i.e. no gaps or pauses) gradual deflection very distinct from single-action impulsive deflection.

A state in such a situation would have a reasoned basis for objecting to the intervals in the multi-step process or the continuous gradual process. To be clear, the state is not objecting simply to being at risk of an NEO impact – that risk is inevitable, due simply to the unlucky geography of being located on the risk corridor. But the state could complain about having to endure an elevated risk for a sustained period of time, when its neighbors are not similarly exposed. The pause in the planetary defense mission, or the slow nature of the gradual deflection, causing the NEO to hover for some time on a trajectory that would impact a particular nation, is not due solely to astrodynamics, but also to the human decisions about when to undertake the multiple steps and when to pause them.

Accordingly, a state could plausibly complain, for example, that the NEDs should be fired more rapidly, or more powerful NEDs should be used, or the KIs should be launched every week instead of every month. Or a state could complain that two (or several) IBD or GT spacecraft should be employed simultaneously, or that the system should be kept active for a longer time, even as the NEO leaves perihelion, because even though the process is less efficient at that point, it is still having at least having some positive effect.

These judgments about the timing of the several steps in the multi-step process are partly or mainly science-based (depending, for example, on how long it will take the debris to clear the impact zone around the NEO after a KI or NED strike, or on the amount of propellant remaining on the IBD or GT spacecraft). But the decisions may also be perceived as being partly political or economic in nature (asking which states should be exposed for how long, or how much would it cost to build and launch two IBs instead of just one).

A state that was exposed to a heightened or prolonged risk is not being irrational or just selfish; it may have a basis for arguing that the better tactic is to intervene more/faster. Additionally, a state that was affected by a pause in the planetary defense mission would likely suffer some degree of immediate harm, long before any NEO impact. If it were known that a particular state would be exposed for a lengthy time (and especially if there was any doubt about whether the next step in the multi-step process would actually be undertaken), there would be immediate social and economic repercussions. It would be predictable that people in the potential impact area would experience increased psychological stress; that people and corporations would decide to relocate away from the danger zone; that property values in that location would decline; and that the overall economy would suffer.

The next question we pose is: Who should make decisions about what planetary defense method would be used, including about whether and when there would be pauses in the multi-step scenario? Should the key choices be delegated entirely to the state(s) undertaking the PD mission? Should the state(s) that would encounter heightened risks have a special voice in the decision-making? How and under what authority would any associated protocols be enforced?

We note, for example, that if the state undertaking the planetary defense mission was seeking some sort of “waiver” of tort liability before undertaking the operation, then a state facing the prospect of sustained risk might decline to sign – and that refusal might jeopardize the entire mission. Moreover, a state that was particularly agitated by being exposed during a pause might assert that the operators of the PD mission had deliberately selected that state as the location to be affected by a pause – it might assert that the judgments about when to pause and whom to jeopardize were made for political or hostile reasons, and that such a motivation constitutes illegal aggression.

8. Conclusion

In this paper, we have described how the deflection of an NEO to prevent Earth impact may be performed as single-action, multi-action, or gradual and continuous operation, using any of several candidate deflection techniques and technologies. We have pointed out that a multi-action or gradual deflection may expose nations along the NEO impact risk corridor to elevated risks, and that this could significantly complicate the execution of such a deflection campaign in ways that are peculiar to multi-action or gradual deflection and therefore not fully treated by tort liability (as is the case for incomplete deflection occurring during a planned single-action complete deflection).

Specifically, we identify the planned pauses during a multi-action deflection campaign, or the slow manner in which the NEO’s impact location is continuously moved across a given nation during a gradual deflection, as being the key features of multi-action or gradual deflection that distinguishes them from single-action deflection.

The planned pauses and gradual motion of the NEO’s impact location result in particular nations along the impact risk corridor that were not originally naturally threatened by the NEO’s impact being placed at elevated risk for prolonged periods of time. This, in turn, raises difficult legal and political questions regarding how to handle the rights and complaints of those states, the obligations of the launching state(s), and how protocols should be organized so as to facilitate prompt and effective action during a planetary defense scenario to save lives and prevent infrastructure damage. We also note that additional legal and political issues may be uncovered after further analysis; this paper is intended to be a starting point rather than a comprehensive treatment of the problem.

Finally, we recommend that the legal and policy issues surrounding multi-action and gradual NEO deflection be sufficiently studied to illuminate approaches to carrying out those types of planetary defense missions from the legal and policy perspectives should the need arise. Unresolved legal and policy issues could significantly delay the execution of an NEO deflection mission, and any delays to such missions could severely compromise our ability to defend ourselves from cosmic impacts that are capable of doing us grave harm.

References

[1] Alvarez, Luis W., Walter Alvarez, Frank Asaro, and Helen V. Michel. "Extraterrestrial cause for the Cretaceous-Tertiary extinction." Science 208, no. 4448 (1980): 1095-1108.

[2] Schulte, Peter, Laia Alegret, Ignacio Arenillas, José A. Arz, Penny J. Barton, Paul R. Bown, Timothy J. Bralower et al. "The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary." Science 327, no. 5970 (2010): 1214-1218.

[3] Cheng, A. F. , Agrusa, H. F., Barbee, B. W. et al. Momentum Transfer from the DART Mission Kinetic Impact on Asteroid Dimorphos. Nature (2023). https://doi.org/10.1038/s41586-023-05878-z

[4] Lauretta, D.S., Connolly, H.C., Jr, Aebersold, J.E., Alexander, C.M.O., Ballouz, R.-L., Barnes, J.J., Bates, H.C., Bennett, C.A., Blanche, L., Blumenfeld, E.H., Clemett, S.J., Cody, G.D., DellaGiustina, D.N., Dworkin, J.P., Eckley, S.A., Foustoukos, D.I., Franchi, I.A., Glavin, D.P., Greenwood, R.C., Haenecour, P., Hamilton, V.E., Hill, D.H., Hiroi, T., Ishimaru, K., Jourdan, F., Kaplan, H.H., Keller, L.P., King, A.J., Koefoed, P., Kontogiannis, M.K., Le, L., Macke, R.J., McCoy, T.J., Milliken, R.E., Najorka, J., Nguyen, A.N., Pajola, M., Polit, A.T., Righter, K., Roper, H.L., Russell, S.S., Ryan, A.J., Sandford, S.A., Schofield, P.F., Schultz, C.D., Seifert, L.B., Tachibana, S., Thomas-Keprta, K.L., Thompson, M.S., Tu, V., Tusberti, F., Wang, K., Zega, T.J., Wolner, C.W.V. and (2024), Asteroid (101955) Bennu in the laboratory: Properties of the sample collected by OSIRIS-REx. Meteorit Planet Sci, 59: 2453-2486. https://doi.org/10.1111/maps.14227

[5] Dupont, Dictionnaire des risques, Armand Colin, Paris, 2004.

[6] Le Breton, Sociologie du risque, Que sais-je, Paris, 2017.

[7] Pigeon, P. 2017. “Dike Risk: Revealing the Academic Links Between Disaster Risk Reduction, Sustainable Development, Climate Change, and Migration,” in *Identifying Emerging Issues in Disaster Risk Reduction, Migration, Climate Change and Sustainable Development*, K. Sudmeier-Rieux et al. (eds.), DOI 10.1007/978-3-319-33880-4_5

[8] Barbee, B. W., Bruck Syal, M., Dearborn, D., et al, Options and uncertainties in planetary defense: Mission planning and vehicle design for flexible response, Acta Astronautica, Vol. 143, pp. 37-61, 2018, doi: https://doi.org/10.1016/j.actaastro.2017.10.021

[9] Dearborn, D. S. P., Bruck Syal, M., Barbee, B. W., et. al., Options and uncertainties in planetary defense: Impulse-dependent response and the physical properties of asteroids, Acta Astronautica, Vol. 166, pp. 290-305, 2020, doi: https://doi.org/10.1016/j.actaastro.2019.10.026

[10] Lu, E., Love, S. Gravitational tractor for towing asteroids. *Nature* 438, 177–178 (2005). https://doi.org/10.1038/438177a

[11] Wie, B. Dynamics and Control of Gravity Tractor Spacecraft for Asteroid Deflection, Journal of Guidance, Control, and Dynamics 2008 31:5, 1413-1423, https://doi.org/10.2514/1.32735

[12] Frazier, W., Chodas, P., Brophy, J., Chesley, S., Johnson, S., Sims, J. "Comparison of Planetary Defense Deflection Methods." 2024 IEEE Aerospace Conference, DOI: 10.1109/AERO58975.2024.10521323

[13] 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, art. VII.

[14] 1972 Convention on International Liability for Damage Caused by Space Objects, art. II.

[15] Ad-Hoc Working Group on Legal Issues to SMPAG, Planetary Defence Legal Overview and Assessment, SMPAG-RP-004, April 8, 2020, https://www.cosmos.esa.int/documents/336356/336472/SMPAG-RP-004_1_0_SMPAG_legal_report_2020-04-08+%281%29.pdf/60df8a3a-b081-4533-6008-5b6da5ee2a98?t=1586443949723