Accounting For Violent Conflict Risk In Planetary Defense Decisions

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Abstract
This paper provides the first-ever survey of the implications of violent conflict risk for planetary defense program decisions. Arguably, the aim of planetary defense should be to make Earth safer from all threats, including but not limited to threats from near-Earth objects (NEOs). Insofar as planetary defense projects affect other risks besides NEOs, these other risks should be taken into account. This paper evaluates three potential effects of planetary defense programs on violent conflict risk. First, planetary defense may offer a constructive model for addressing a major global risk. By documenting the history of its successes and failures, the planetary defense community can aid efforts to address other global risks, including but not limited to violent conflict. Second, the proposed use of nuclear explosions for NEO deflection and disruption could affect the role of nuclear weapons in violent conflict risk. The effect may be such that nuclear deflection/disruption would increase aggregate risks to human society. However, the effect is difficult to assess, mainly due to ambiguities in violent conflict risk. Third, planetary defense could reduce violent conflict risk by addressing the possibility of NEO collisions being mistaken as violent attacks and inadvertently triggering violent conflict. False alarms mistaken as real attacks are a major concern, especially as a cause of nuclear war. Improved awareness of NEOs and communication between astronomers and military officials could help resolve NEO false alarms. Each of these three effects of planetary defense programs on violent conflict risk can benefit from interaction between the communities that study and address NEO and violent conflict risks.

Keywords: *nuclear weapons, planetary defense, risk analysis, risk management, violent conflict*

1. Introduction

Planetary defense is commonly understood to refer to the defense of planet Earth against collisions with near-Earth objects (NEOs, which include asteroids, comets and meteoroids). Planetary defense involves the detection of Earthbound NEOs, the deflection of the NEOs onto non-Earthbound trajectories, the disruption of NEO structures into smaller fragments when Earthbound NEOs cannot be deflected away, and possibly also civil defense preparations to aid collision survivors.

Planetary defense programs can have several goals, including scientific discovery, public education, and compliance with domestic and international law. Arguably, the predominant goal is to reduce risks to Earth and its inhabitants. While the focus of planetary defense is on reducing risks from NEO collision, it may be possible for planetary defense programs to also affect other risks. If they do, then these other risks arguably should be accounted for in the design and implementation of planetary defense programs. This can include avoiding activities that decrease

NEO risk but inadvertently increase other risks, and emphasizing activities that decrease (or at least do not increase) NEO risk and also decrease other risks.

This paper examines how to account for violent conflict risk in planetary defense programs. In a sense, NEO collision and violent conflict are very different types of risk: one is astronomical, and the other is social and geopolitical. However, both can involve large explosions that threaten substantial regional or even global damage. Planetary defense programs also utilize military technology, including nuclear explosives. These commonalities create several ways in which planetary defense programs can affect violent conflict risk. This paper examines three:

(1) *Global risk management*: the value of planetary defense as a model for the successful management of a global risk. The value here is for all global risks, including but not limited to violent conflict. The experience of the planetary defense community may contain insights that can be valuable for other efforts to address global risks. Planetary defense programs may be able to realize this value by documenting key aspects of their experience and sharing it with communities working on other risks.

(2) *Nuclear deflection and disruption*: the use of nuclear explosives for NEO deflection or disruption. Nuclear deflection and disruption programs can have several effects on nuclear weapons issues, potentially changing the risk of nuclear war and other violent conflict. Depending on the details, this could give reason for planetary defense programs to favor or disfavor nuclear explosives, or to pursue certain nuclear deflection/disruption program designs.

(3) *Inadvertent NEO conflict*: the prospect of NEO collisions being mistaken as violent attacks, inadvertently triggering violent conflict. Inadvertent conflict triggered by false alarm is a serious concern, especially for inadvertent nuclear war. Planetary defense programs may have opportunities to partner with militaries so as to help militaries correctly identify NEO collisions as such and avoid inadvertent NEO conflict.

This paper is in the tradition of risk analysis and risk management research that seeks to concurrently address multiple risks. This interdisciplinary field endeavors to work across traditional research and policy specializations (or "silos") and develop policies that make the world safer from all risks. The concept of risk-risk tradeoffs has been developed for evaluating actions that could reduce one risk but increase another [1]. Nuclear deflection/disruption may be an example of this. The concept of co-benefits has been developed for actions that could decrease multiple risks and/or have other benefits [2]. Detecting incoming NEOs and reporting them to military authorities may be an example of this; ditto for developing and sharing insights on global risk management.

Some prior research has concurrently studied specific aspects of NEO and violent conflict risks. Implications of nuclear deflection/disruption for violent conflict has gotten the most attention [3-10]. Inadvertent NEO conflict is studied by Refs. [11-12] and has also been discussed by Refs. [13-14]. The idea of planetary defense as a model for global risk management is briefly proposed by Ref. [15]; to the best of the present author's knowledge, the idea has not been pursued further in any prior research.

This present paper synthesizes and extends this prior literature to contribute a more complete study of the implications of violent conflict risk for planetary defense programs. This paper is the first-ever survey of the full range of implications of violent conflict risk for planetary defense program decisions; the prior literature as outlined above is focused on specific aspects of the topic. Additionally, the paper contributes original analysis of the implications of international law, nuclear disarmament, and the taboo against nuclear weapons as they pertain to nuclear deflection. The paper further presents the first-ever quantitative risk analysis of the risk of inadvertent NEO conflict, as well as original discussion of the implications of inadvertent NEO conflict for planetary defense programs. Finally, the paper presents the first-ever extended discussion of planetary defense as a model for global risk management.

The overall aim of the paper is to help planetary defense programs better account for violent conflict in their program decisions. It is not the aim of the paper to definitively resolve which decisions should be made. Definitive resolution would require more detail than can be presented in one paper, including detail specific to a particular decision. Additionally, the decisions can also require the judgments of the decision-makers. It is not the role of this paper to suppose what those judgments should or would be. Therefore, many of the specific recommendations offered by this paper are for more detailed analysis in support of planetary defense decisions.

The paper is organized as follows. Section 2 assesses planetary defense as a model for global risk management. Section 3 analyzes the effect of nuclear deflection/disruption programs on violent conflict risk. Section 4 examines inadvertent NEO conflicts. Section 5 concludes.

2. Planetary Defense as a Model for Global Risk Management

This section presents an initial analysis of planetary defense as a model for global risk management, then describes future work in this direction that the planetary defense community could do. This work would not be a solution to planetary defense challenges per se, but instead would be a more general contribution to the management of global risks, including but not limited to violent conflict. This work is not necessarily worth the investment it would require of the planetary defense community. Whether it is worthwhile depends on factors such as the particular opportunities of members of the planetary defense community, which is beyond the scope of this paper. Nonetheless, one clear conclusion is that the value of this work is strengthened by accounting for its value to the management of violent conflict and other global risks. Members of the planetary defense community should pursue this work where they have good opportunities to do so.

Global-scale risks can be especially difficult to manage because they are not the exclusive responsibility of any one country. The risk management can suffer from "free-rider" effects in which some countries skimp on risk management investment in hopes of benefiting from the investments of other countries. Global risk management can also struggle with the challenge of getting every country to comply with the same standards, or to agree to the same principles of conduct, or to a number of other challenges [16].

Extreme low-probability/high-severity global risks face additional challenges. The high severity can render them quite important in quantitative risk terms [17]. However, policymakers and the lay public may have a tendency to underestimate these risks for at least three reasons [15]. First, non-experts tend to underestimate the risk of events that they have no prior experience of, because such events are not prominently "available" in their minds. Second, non-experts often undervalue harms of extreme severity, a phenomenon known as "mass numbing". Third, extreme global risks are not readily handled by existing institutions, both because they are global and because their extreme severity overwhelms traditional risk management schemes like insurance and liability.

Because of the difficulty of managing extreme global risks, it is of considerable interest to understand cases in which these risks are managed with at least some success. Planetary defense offers one such example, as is proposed (without elaboration) by Wiener [15, p.77]. While the success of planetary defense has only been partial, such that more could have been done and more work is still needed, it is nonetheless valuable as a case study in (partially) successful global risk management. The value here is for other extreme global risks, including nuclear war and other forms of extreme violent conflict, as well as other risks such as supervolcano eruption, pandemic disease outbreak, extreme global warming, and various disasters involving emerging technologies.

2.1 Initial Analysis

This section presents a brief initial analysis of planetary defense as a case study of extreme global risk management. The aim here is to provide some initial insights and demonstrate the sort of analysis that could be extended into a more thorough study of the topic. This section describes how such study could proceed.

In examining the planetary defense case, several questions are pertinent. How was the NEO threat first identified by the scientific community? How did the NEO threat first gain traction among policymakers? What enabled policymaker interest to continue over the years? What difficulties were faced in motivating policymaker interest, and how (if at all) were these difficulties overcome? Has the policy response been adequate given the nature of the threat? What has the role of nongovernmental actors (individuals and organizations) been? Overall, what has worked well, and what could be done better?

Answers to these questions are found in the history of planetary defense. The following briefly summarizes the history, focusing on the early history through the initial policy action. A more detailed history is presented by Chapman [18].

Morrison [19] traces the scientific awareness of the NEO threat to books published in 1941 [20] and 1949 [21]. However, scientific interest was limited until the Alvarez et al. [22] proposal that a large NEO collision caused the Cretaceous-Paleogene extinction and the 1981 Snowmass, Colorado workshop "Collision of Asteroids and Comets with the Earth: Physical and Human Consequences". Public interest grew in the late 1980s following the publication of a trade press book that included a chapter on the NEO threat [23] and a 1989 NASA press release that was interpreted by the press as stating that the large asteroid 4581 Asclepius (1989FC) was a "near miss" event, even though it was only "near" in astronomical terms, not in terms of the danger to Earth.

Formal policy attention appears to have begun with a 26 June 1989 hearing of the US House of Representatives Space Caucus [18]. Attention escalated following the publication of an American Institute of Aeronautics and Astronautics (AIAA) position paper. The AIAA paper described the NEO threat, summarized the scientific study of it, and called for investment in NEO detection and study of NEO deflection and disruption options [24]. Shortly after, the 1990 US House NASA Authorization Report Language calls for NASA to conduct workshops on NEO detection and deflection and disruption. The subsequent detection workshop write-up was published as Ref. [19]. The AIAA paper and the House Report Language both acknowledge the extreme low-probability/high-severity nature of the threat from large NEOs, and they also call for international cooperation while focusing on US leadership. Both also open by noting the

1989FC near miss. Chapman [18] also notes the "pivotal role" played by a sympathetic and well-placed Congressional staffer, Terry Dawson of the House Committee on Science, Technology, and Space.

Some useful insights can be obtained from this brief history. Initial policymaker interest appears to have been generated by a combination of several factors. Scientific scholarship was important to establish the threat, but it may have accomplished little until it was documented and presented to policymakers by the reputable AIAA organization. The 1989FC "near miss", and in particular its documentation in the news media, may have further helped by making the threat "available" in the minds of policymakers and their public constituents. The trade press book [23] and accompanying publicity and Congressional hearing may have played a similar role. And the role of Terry Dawson shows the value of allies within a government. These various factors appear to have combined to persuade the US Congress to take action on what it (accurately) believed to be an extremely low-probability, high-severity risk.

2.2 Further Work

The above history and analysis is just a brief sketch of what could be done on this topic. Further work by the planetary defense community could be of considerable value to broader efforts to address extreme global risks, including (but not limited to) nuclear war and other forms of extreme violent conflict. Further work would combine two lines of research: historical documentation of planetary defense, such as Ref. [18], and analysis of the policy challenges posed by extreme global risks, such as Ref. [15]. The planetary defense community could support further historical documentation, and could partner with policy experts to focus the work on the most pertinent questions and to translate the history into useful insights for other global risks.

The above history and analysis could be developed in greater detail. In addition, here are a few specific topics that could be pursued:

One interesting question is why the planetary defense community has gravitated toward a risk perspective in its assessment of the NEO risk. Risk analysis is often featured in prominent studies of the NEO threat, such as Refs. [19,25], and there is a relatively robust NEO risk analysis literature—see Ref. [12] for a review. In contrast, risk analysis is less prominent in studies of other extreme global risks such as nuclear war—see Ref. [26] for a review. Risk analysis can be valuable for attracting an appropriate amount of attention to extreme global risks and for assessing risk reduction program options.

There are several plausible hypotheses for the prominence of risk analysis in planetary defense relative to other extreme global risks such as nuclear war. First, the NEO threat may be relatively easy to characterize in risk terms. The statistics of NEO collision have a relatively strong empirical basis, whereas the risk of nuclear war depends on ambiguous factors such as the tendency for national leadership to launch nuclear weapons. (NEO risk does have some significant uncertainties, especially regarding the human harms of NEO collisions [12].) Second, the planetary defense community is largely populated by astronomers, who have strong quantitative backgrounds and may thus gravitate toward quantitative risk analysis. In contrast, nuclear war is often studied in more qualitative terms by scholars of political science and related fields. Third, NEOs are a threat from nature in which all human populations have more or less the same interests, whereas nuclear war is a threat from adversarial human activity in which interests vary considerably across populations. For this reason, NEOs may be more readily interpreted as a risk to be managed in more technocratic terms, whereas nuclear war may be treated instead as being in the realm of politics. These (and any other) hypotheses could be explored via more detailed studies of the histories of planetary defense and responses to other extreme global risks.

A second question is on the role played by fictional portrayals of the NEO threat. Wiener [15] proposes that films or virtual reality could make extreme global risks more "available" in the minds of the public. Meanwhile, Chapman [18] cites the major Hollywood films Armageddon and Deep Impact as helping raise awareness of the NEO threat, despite their scientific inaccuracies (especially in Armageddon). This raises the questions of how much the films raised awareness of the NEO threat, how effectively this awareness translated into constructive action to reduce the risk, and whether the interest in the NEO threat diminished as time passed and the films faded out of people's minds. It is possible to study the effects of films on public awareness of global risks—one study examined the effects of the film The Day After Tomorrow on public perceptions of global warming [27]. However, it may be difficult to conduct retrospective studies of the effects of films from multiple years or decades ago. Nonetheless, this may be a fruitful direction for further research to pursue. A related line of inquiry could study the role of NEO simulation exercises, such as the 2019 PDC hypothetical asteroid impact scenario fictional exercise conducted as part of the 2019 Planetary Defense Conference [28].

A third question is on the resources offered for planetary defense and the tension between planetary defense and basic scientific research. Chapman [18] reports that astronomers, including some in NASA leadership, often disfavored planetary defense, instead preferring that scarce funds go to non-applied scientific research. This finding is consistent with the observation that scientists tend to value the "intellectual merit" of research more than its "broader impacts" to society [29-30]. ("Intellectual merit" and "broader impacts" are terminology of the US National Science Foundation.) The finding is also consistent with the classification of planetary defense as a "best shot" global public good, in which success is determined by the quality of the best attempt to address the problem [16]. Essentially, given the availability of a program that could deflect or disrupt an Earthbound NEO, an additional but inferior program is of negligible value, because any given Earthbound NEO only needs to be deflected or disrupted once. Success on "best shot" goods is typically limited mainly by the resources available for the best program, and not by the sorts of adversarial challenges associated with violent conflict risk. Examination of debates over planetary defense funding may thus shed light on broader challenges faced by efforts to address global risks.

3. Nuclear Deflection and Disruption

The exceptionally high energy density of nuclear explosives makes them an attractive option for NEO threat mitigation. For the largest NEO collisions, nuclear explosives may be the only viable option for deflection, provided sufficient lead time; for the most imminent collisions, nuclear disruption may be the only viable option [25]. Disruption is controversial because it does not necessarily eliminate the threat and in some cases may actually increase the damage to Earth by creating a larger number of smaller collisions, though in other cases it may be advantageous [31-32]. Note that some deflection missions can also pose a risk of unintentional disruption.

For smaller and less imminent collisions, non-nuclear options may be viable, such as kinetic impactors. Non-nuclear options can be attractive because nuclear deflection/disruption is interlinked with military nuclear weapons programs and their accompanying implications for violent conflict. Baum [10] presents a quantitative risk-risk analysis of nuclear deflection in terms of its effects on NEO risk and violent conflict risk. This section presents a more qualitative discussion of implications for planetary protection programs.

3.1 International Law

In previous studies on the relationship between nuclear deflection/disruption and violent conflict, an especially common point of discussion is the tension between nuclear deflection/disruption and international treaties. The most detailed studies include Refs. [3-5,8-9]. The implicated treaties include the Outer Space Treaty, the Partial Test Ban Treaty, the Comprehensive Nuclear-Test-Ban Treaty, the Moon Agreement, the Space Objects Liability Convention, the Anti-Ballistic Missile Treaty, the Vienna Convention on the Law of Treaties, and the Draft Treaty on Prevention of the Placement of Weapons in Outer Space and of the Threat or Use of Force against Outer Space Objects. Nuclear deflection/disruption may also be in conflict with the Treaty on the Prohibition of Nuclear Weapons, though this treaty is relatively new and has not yet been the subject of NEO deflection/disruption scholarship. Some of these treaties pertain specifically to nuclear deflection/disruption, whereas others also pertain to some or all other forms of NEO deflection/disruption.

Given the extensive prior literature, this paper will not analyze the permissibility of nuclear deflection/disruption under international treaties. It suffices to note that nuclear deflection/disruption may be in conflict with some treaties, and that the extent of this conflict is a matter of debate among legal scholars. This paper will instead focus on the implications for planetary defense programs, which has received less attention in prior literature. The implications depend on how the legal debate is resolved, with three possible results:

First, nuclear deflection/disruption could be judged to be fully compliant with all international treaties. This conclusion was reached by Kunich [4], but it is a minority view. In this case, planetary defense programs may not need to factor treaty compliance into their evaluations of nuclear deflection/disruption.

Second, nuclear deflection/disruption could be judged to be arguably but not definitively compliant with at least some treaties. For example, the Outer Space Treaty bans weapons of mass destruction in outer space, but Su [9] proposes that nuclear deflection/disruption may fall outside the definition of "weapon", citing a dictionary definition of a weapon as "an instrument used or designed to be used to injure or kill someone". Su nonetheless cautions that "this argument will probably encounter substantial disagreements, as it would weaken norms of existing international space law significantly and run the risk of a nuclear race in outer space" [9, p.2].

Third, nuclear deflection/disruption could be judged to be definitively noncompliant with at least some treaties. For example, the Comprehensive Nuclear-Test-Ban Treaty forbids all nuclear explosions in outer space. This treaty has not yet entered into force, and may be unlikely to do so anytime soon, but if it does, then this could definitively forbid nuclear deflection/disruption.

For the second and third case, decisions on nuclear deflection/disruption must weigh the value of nuclear deflection/disruption against the disvalue of possible or definitive treaty noncompliance. The noncompliance could be addressed by seeking modifications to the treaties, which could take considerable effort and introduce substantial delays, and which is not certain to succeed. The other options would be to abandon nuclear deflection/disruption (and forgo the potential for nuclear deflection/disruption to reduce NEO collision risk), or to push on with nuclear deflection/disruption anyway and accept the consequences of treaty noncompliance.

In the event that an Earthbound NEO is detected that is sufficiently large to require nuclear deflection, and is detected with sufficient lead time for nuclear deflection to be feasible, then treaty compliance is unlikely to be a significant factor. All countries share an essential interest in avoiding large NEO collisions, and they presumably would not protest nuclear deflection missions that are necessary for deflecting a known large Earthbound NEO, regardless of any treaty implications. For more imminent NEOs in which nuclear disruption is the only viable option, the decision may be more difficult, especially if the disruption is likely to result in some NEO fragments hitting Earth. Decisions about the development and testing of nuclear deflection/disruption systems would also be difficult. In the absence of any detected NEO that requires nuclear deflection/disruption, there would be less motivation to pursue test missions, and the downsides of treaty noncompliance would be a proportionately larger factor.

Exactly how the decision would be evaluated is a challenging matter. Treaty noncompliance is difficult to weigh against reduction in NEO risk. Empirical studies of societal decision-making in the face of "tragic choices" between seemingly incomparable societal values (like treaty compliance and risk reduction) find that societies often make inconsistent decisions [33]. Therefore, individuals and countries are likely to be divided on whether to favor test missions. Furthermore, even strictly in terms of risk reduction, there is the possibility that treaty noncompliance could increase other risks, in particular the risk of violent conflict, as suggested by the comment of Su [9] about a nuclear race in outer space. The evaluation of these tradeoffs should be factored into planetary defense program decisions on nuclear deflection/disruption unless nuclear deflection/disruption is found to fully comply with all relevant international treaties. The tradeoffs can be analyzed as multi-criteria decisions [34], with the criteria being NEO risk, violent conflict risk, and treaty implications:

$$D(ND) = -w_{NEO}\,\Delta R_{NEO}(ND) - w_{VC}\,\Delta R_{VC}(ND) + w_{TR}\,\Delta V_{TR}(ND) \qquad (1)$$

In Equation 1, $D(ND)$ is a decision parameter for nuclear deflection/disruption. Nuclear deflection/disruption is deemed worth pursuing if and only if $D(ND)>0$. $\Delta R_{NEO}(ND)$ and $\Delta R_{VC}(ND)$ are the change in the risks from NEOs and violent conflict caused by the use of nuclear deflection/disruption. $\Delta V_{TR}(ND)$ is the change in value from international treaties caused by the use of nuclear deflection/disruption. w_{NEO}, w_{VC}, and w_{TR} are the weights placed on NEO risk, violent conflict risk, and international treaty value in the overall decision. Minus signs appear before w_{NEO} and w_{VC} because increases in risk make nuclear deflection/disruption less attractive.

Planetary defense programs should determine how they believe the parameters of Equation 1 should be set, or the parameters of a comparable decision equation if some alternative to Equation 1 is favored. In risk analysis, it is customary to set $w_{NEO} = w_{VC}$, but it is not strictly necessary to do so. Quantifying $\Delta R_{NEO}(ND)$ and $\Delta R_{VC}(ND)$ is a difficult analytical challenge [10], but it is in principle feasible. Planetary defense programs should invest in this risk analysis. A greater conceptual challenge comes from w_{TR} and $\Delta V_{TR}(ND)$. The value derived from international treaties is not commonly quantified or compared to the value of risks. Planetary defense programs should consult with scholars of international law, moral philosophy, and decision analysis to determine how to quantify w_{TR} and $\Delta V_{TR}(ND)$.

Finally, it should be noted that it may be possible for nuclear deflection/disruption to be compliant with international law even if it is not compliant with one or more treaties. This could occur if nuclear deflection/disruption is authorized by the United Nations Security Council (UNSC). As Su [9, p.3] describes, UNSC decisions may supersede international treaty obligations, such that UNSC authorization for nuclear deflection/disruption may render it compliant with international law regardless of any treaty particulars. In that case, the legality of nuclear deflection/disruption programs may hinge on the willingness of the UNSC to authorize them. UNSC authorization may be more likely in instances requiring nuclear deflection than for nuclear disruption or for program development and testing.

3.2 Nuclear Disarmament

Discussions of nuclear deflection/disruption have occasionally considered implications for nuclear disarmament. Graham and Schweickart [7] express concern that nuclear deflection could interfere with the policy goal of full nuclear disarmament. Conversely, Mellor [6, p.518] quotes one commentator arguing that nuclear deflection/disruption could be advantageous for nuclear disarmament by providing a means for “beating swords into ploughshares”. However, these discussions do not consider the dynamics of nuclear disarmament.

It is possible that, at some future time, nuclear deflection/disruption would be a significant factor in nuclear disarmament, but at present it is not. The world currently has over 14,000 nuclear weapons [35], whereas a single nuclear explosive may suffice for many deflection/disruption missions [25]. Nuclear deflection/disruption could have an inventory of, say, ten nuclear explosives, providing some redundancy and flexibility via different explosive designs, and still be nowhere near current total global inventories. Therefore, nuclear deflection/ disruption programs need to account for their effect on nuclear disarmament only with an eye toward possible future progress in disarmament.

If significant nuclear disarmament progress is eventually made, then nuclear deflection/disruption could become a major factor. One significant concern with nuclear disarmament is that, in a crisis, countries could race to redevelop nuclear weapons. The winner of the race could then gain major strategic advantage by bombing the other side’s nuclear facilities. Thus, nuclear war may be even more probable in a world with zero nuclear weapons than in a world with enough nuclear weapons for effective deterrence [36]. A proposed solution to this is for countries to also eliminate their capacity for developing nuclear weapons, or to place this capacity under strict international control [37]. Nuclear deflection/disruption programs could be a major factor in any such arrangement.

It is important to account for the time scales of nuclear disarmament, which are likely to be decades or even longer. The total global inventory peaked at around 70,000 in the 1980s [35]. Recent progress has been more gradual, prompting some members of the international community to express concern that the nuclear-armed countries intend to keep their arsenals indefinitely [38]. In a high-profile speech in Prague, US President Barack Obama called for a world without nuclear weapons, but acknowledged that this goal “will not be reached quickly—perhaps not in my lifetime” [39]. The NGO Global Zero proposes dismantling all nuclear weapons by 2045 in a plan that aimed to begin in 2018 [40]. These are the sorts of time scales that nuclear deflection/disruption programs should have in mind when factoring in nuclear disarmament.

A question for NEO deflection/disruption program planning is whether nuclear deflection/disruption would still be needed if and when it might factor significantly in nuclear disarmament. By that time, NEO detection and non-nuclear deflection options will have both also progressed. Already, non-nuclear deflection options may suffice for smaller and less imminent collisions, and a large portion of large NEOs have already been detected [41]. Conceivably, a few decades from now, nuclear deflection/disruption will no longer be needed.

Taking all these factors into account, some practical guidance for today's nuclear deflection/disruption programs can be derived. First, disarmament should not factor into nuclear deflection/disruption programs that play out within the next 20-30 years. Within this time period, nuclear disarmament is unlikely to have progressed enough for nuclear deflection/disruption to be a significant factor. Second, nuclear deflection/disruption programs with longer time horizons should seek to partner with groups involved in nuclear disarmament (such as Global Zero) and the corresponding expert communities. The aim should be to craft nuclear deflection/disruption programs that do not increase the risk of nuclear war in scenarios of low-to-zero global nuclear weapons.

The prospect of international control of nuclear deflection/disruption programs should be a focus of policy analysis. Nuclear disarmament scholarship has proposed that international control of nuclear enrichment facilities could permit a civilian nuclear industry while preventing countries from building nuclear weapons [37]. This proposal has in mind non-explosive applications of nuclear technology, especially nuclear power. Nuclear explosives for deflection/disruption may pose additional challenges for an international facility. If these challenges can be resolved, it could pave the way for nuclear deflection/disruption in a world without nuclear weapons. Likewise, this sort of international program may fit well with existing calls for international NEO deflection/disruption programs [25,42].

3.3 The Nuclear Taboo

The nuclear taboo refers to the international stigma against the use of nuclear weapons. The taboo is sometimes credited as an important reason for why nuclear weapons have not been used in violence since Hiroshima and Nagasaki [43-44]. However, nuclear deflection/disruption programs could weaken the taboo, thereby increasing the risk of nuclear war.

The link between nuclear deflection/disruption and the taboo comes from the fact that the taboo is commonly applied to all nuclear explosions, not just the violent ones. There is a long history of "peaceful nuclear explosions" proposed for purposes such as civil canal excavation or steam production for generating electricity. Nuclear deflection/disruption fits into this category. However, these non-violent nuclear explosions are sometimes seen as increasing the legitimacy of nuclear explosives and weakening the taboo, thereby making nuclear war more likely [44].

Prior research has examined the taboo as a factor in the effect of nuclear deflection on violent conflict risk [10]. The effect appears to be negative in the sense that accounting for the taboo makes nuclear deflection less desirable in risk terms, though the magnitude of the effect is unclear. An additional factor to consider is whether nuclear deflection programs could be designed so as to minimize the effect on the taboo. Perhaps nuclear deflection programs could include high-visibility messaging and educational initiatives to emphasize that the programs are of a peaceful, non-military nature and should not be interpreted as any sort of endorsement of the military use of nuclear explosives. However, past debate about peaceful nuclear explosions suggests that these initiatives may have at most a limited effect. Prior proposed peaceful applications (such as civil canal excavation or steam production for generating electricity) are of a clearly non-military nature. If these applications raised concerns, then presumably nuclear deflection would too. In that case, there may be little that planetary defense programs can do to lessen the implications of nuclear deflection/disruption for the nuclear taboo. The only options may be to abandon nuclear deflection/disruption or accept the weakening of the nuclear taboo and the accompanying increase in nuclear war risk. This appears to be a clear case of a risk-risk tradeoff, which should be evaluated to inform planetary defense program decisions. The tradeoff can be evaluated by accounting for the taboo in $\Delta R_{NEO}(ND)$ in Equation 1. Planetary defense programs should consult with experts in international relations and risk analysis to assess this parameter.

4. Inadvertent NEO Conflict

NEO collisions within a certain size range produce explosions with energies comparable to the explosions of military bombs. It is possible for these NEO explosions to be mistaken as military bombings. It is likewise possible that those who make this mistake may then launch an attack that they believe to be a retaliation but is in fact the commencement of hostilities. Such a scenario falls within the broader class of inadvertent conflict. Some international security analysis expresses concern about the risk of inadvertent conflict, especially inadvertent nuclear war [45-47]. NEO collisions are one of the few false alarm types involving actual explosions, and therefore may be especially risky.

This section assesses prospects for inadvertent NEO conflict and implications for planetary defense programs. As detailed in Section 4.2, some prior events contain elements of inadvertent NEO conflict scenarios. However, to the best of the present author's knowledge, no inadvertent NEO conflict has yet occurred, and it has received only limited attention in prior research [11-14]. Therefore, a precise evaluation of the risk and its implications for planetary defense programs cannot be presented. Instead, the analysis in this section is of a more exploratory nature.

4.1 Inadvertent Conflict

While a wide range of inadvertent conflicts are in principle possible, inadvertence is most closely associated with nuclear war. This is due to the design of nuclear weapons systems that some (but not all) nuclear-armed countries have. In particular, some (but not all) countries have nuclear weapons available for launch on short notice, even within just a few minutes [48]. This "hair-trigger" launch posture aims to strengthen deterrence by precluding either side from being able to launch a successful first-strike attack: before the attack would be completed, the other side would be able to launch a large enough counterattack that the first-strike attack would not be considered successful. A downside to this launch posture is that it can result in weapons being launched when there was no incoming attack—essentially, when there might be an incoming attack, it can err on the side of launching.

Over the years, there have been a number of false alarms that are believed to have gone at least partway to inadvertent nuclear war. Ref. [49] documents 15 such incidents. They span from a 1960 incident in which a moonrise was recognized as Soviet missile launch by the then-new US Ballistic Missile Early Warning System to a 2018 incident in which the Hawaii Emergency Management Agency accidentally sent a text message warning the general public of an incoming ballistic missile attack. Three of the 15 incidents were military exercises perceived to be attacks or preparations for attack, while the other 12 involved a mix of non-military events and monitoring system errors. (The Hawaii incident is a unique case because it is the only incident—as documented in Ref. [49]—in which the false alarm went directly to the general public instead of being initially picked up by military monitoring systems.)

Exactly how close any of these incidents came to inadvertent nuclear war is a matter of ongoing expert debate. Lewis et al. [50] argue that at least some of the incidents were close calls, whereas Tertrais [51] argues that they were not close. Closer historical analysis may be able to resolve some of this debate, though it is likely that the publicly available historical record does not provide all of the relevant information, given the classified nature of nuclear weapon systems. Indeed, it is possible that some serious false alarms are not documented in the public record. Given this lingering uncertainty, an objective risk analysis arguably should assign some nonzero probability to the ongoing risk of inadvertent nuclear war. This is to say that the available historical record is insufficient to rule out the ongoing possibility of inadvertent nuclear war. While some effort has been made to quantify the ongoing probability [47], this research is inconclusive on exactly what the probability may be, with plausible estimates spanning several orders of magnitude.

Non-nuclear inadvertent conflict is also possible, though it may be less likely because non-nuclear conflicts tend to not involve hair-trigger launch postures. Absent nuclear weapons, countries could not launch devastating counterattacks on short notice, so there is little value to having a hair-trigger launch posture. An important exception can occur during periods of high tensions between non-nuclear armed countries, especially when opposing armed forces are massed in close proximity. Under these conditions, relatively small false alarms could trigger inadvertent conflict. For example, some analysts have raised the concern that massed autonomous weapons could misinterpret subtle false alarms and fire their weapons before human supervisors could intervene, a type of scenario known as "flash war" [52]. It is proposed that the false alarms could include "sun glint interpreted as a rocket flame, sudden and unexpected moves of the adversary, or a simple malfunction" [53, p.128]. While these non-nuclear inadvertent conflict scenarios may not occur except during high tensions, they are nonetheless worth noting.

4.2 Inadvertent NEO Conflict

Out of all of the 15 nuclear war false alarm incidents documented in Ref. [49], none of them involve the "victim" country sustaining any actual physical damage. Instead, the "victim" merely observes something that appears to be an incoming attack, but is actually something else. In contrast, an NEO collision could cause physical damage. Moreover, that damage could resemble the damage from a nuclear attack. Therefore, NEO collisions may be more likely to cause inadvertent nuclear war than other types of false alarms, though this matter is difficult to resolve due to the lack of precedent for inadvertent nuclear war.

Several recent incidents illustrate the possibility of inadvertent NEO conflict. First, an October 1990 explosion above the Pacific Ocean was detected by US military satellites and initially assessed as a potential nuclear event [11]. Second, a 1993 seismic event in Banjawarn Station, Western Australia was interpreted as possibly a meteorite collision, an earthquake, or a nuclear test detonation by the Aum Shinrikyo terrorist group, which owned land nearby and had an interest in acquiring nuclear weapons [54-55]. Third, a ~100KT 1994 meteor explosion near Kosrae in the Western Pacific was detected by US defense satellites and suspected to be a nuclear explosion, reportedly resulting in US President Clinton being woken up by defense staff [56]. Fourth, a 340T 2003 meteor explosion over suburban Chicago (specifically, Park Forest, Illinois) occurred during the "Operation Iraqi Freedom" military campaign and prompted some witnesses to suspect nuclear attack [57]. Fifth, the 500KT 2013 Chelyabinsk collision occurred approximately 100km southeast of the Russian Snezhinsk nuclear program site. Harris et al. [58, p.838] postulate that the event "could have been misperceived as an act of aggression", especially if cloudy weather precluded visual identification of the asteroid. Sixth, a ~2KT July 2018 collision occurred approximately 43km above the US Thule Air Base. No damage was reported, but the incident nonetheless raised concerns; one nuclear weapons expert wryly commented, "We're still here, so they [the US] correctly concluded it was not a Russian first strike" [59]. Seventh, a 173KT explosion in December 2018 above the Bering Sea may have been initially postulated by the US Air Force to be a nuclear explosion [60]. While none of these incidents appear to have gotten close to prompting inadvertent conflict, they are nonetheless indicative of the possibility.

For planetary defense program decisions, an important question is how large the risk of inadvertent NEO conflict is. The incidents listed above suggest a nonzero risk, but if the risk is vanishingly small, then it may not be worth factoring into decisions. The prospect of inadvertent NEO conflict has been considered in several prior studies [11-14], but not with any quantitative risk analysis. Detailed analysis of the risk of inadvertent NEO conflict is beyond the scope of this paper. What follows is just a simple illustration of how such analysis could proceed, but it is nonetheless the first-ever quantitative risk analysis of the risk of inadvertent NEO conflict. The frequency of inadvertent NEO conflict (F0) may be modeled as the product of three parameters:

$$F_0 = F_1 * P_1 * P_2 \tag{2}$$

In Equation 2, F_1 is the frequency of NEO collisions within a size range conducive to inadvertent NEO conflict. This may correspond approximately to the range of yields of nuclear weapons, which is roughly 300T (the lowest possible yield of the US variable-yield B-61 [61]) to 5MT (the Chinese DF-5A [62]). P_1 is the probability that an NEO collision in the relevant size range would occur in geographically sensitive areas, such as cities and military bases. More detailed research would be needed to accurately assess P_1, but an initial best guess estimate might be ~$1.5x10^{-4}$, corresponding to a 5km radius around each of 1,000 sites worldwide. Finally, P_2 is the probability of a military attack being launched in response to an NEO collision within the relevant size range and geographical area. P_2 is not readily quantified—whether a weapon launch order would be given may depend on the personalities of national leadership and is also a closely guarded state secret. One inadvertent nuclear war risk analysis suggests that the distribution of plausible estimates of P_2 span several orders of magnitude [47].

This illustrative analysis omits several important details. First, national differences in nuclear arsenal size could constrain the applicable NEO size. For example, the largest Russian and US nuclear weapons are smaller in yield than China's [61-63]. Second, launch procedures vary from country to country—Russia and the US have the fastest (most "hair-trigger") launch posture, followed by France and the United Kingdom [48]. Third, the smallest NEOs typically explode harmlessly in the upper atmosphere. These explosions could potentially be mistaken for high-altitude nuclear explosions used for electromagnetic pulse attacks, though this type of false alarm may be relatively easy to resolve [12]. A more careful study of inadvertent NEO conflict should account for these and other details. It should also account for the considerable uncertainty in the parameters in Equation 2, such as was done in the inadvertent war risk analysis of Ref. [47].

Whereas Equation 1 models the probability of inadvertent NEO conflict, a full quantification of the risk would also include the severity. An inadvertent NEO conflict could have a wide range of severities, depending on how the conflict unfolds. However, the lower bound of severity may nonetheless be considerably large, especially if nuclear weapons are involved. In that case, for policy purposes, it may suffice for the probability to be reasonably large, in which case substantial policy measures may be warranted for the sake of avoiding any inadvertent NEO conflict.

4.3 Implications for Planetary Defense Programs

Planetary defense programs may be able to help reduce the risk of inadvertent NEO conflict by helping militaries correctly identify NEO collisions as such and therefore refrain from launching weapons in response. This is equivalent to reducing P_2 in Equation 2. Baum [12] proposes two specific measures for accomplishing this: raising awareness about inadvertent NEO conflict and alerting militaries about incoming NEOs. This section expands upon these ideas to provide further guidance to planetary defense programs.

Perhaps the most attractive audience for raising awareness is the military personnel who are involved in the detection and analysis of information about incoming threats, especially incoming nuclear attacks, and in the communication of this information to political leadership. They have an essential role to play in avoiding inadvertent NEO conflict. They also likely include some people with a more scientific and technical background, making dialog relatively likely to be productive. Furthermore, unlike the political leadership who must make the fateful decisions of whether to launch nuclear weapons, these military personnel are likely to have fewer demands on their time and be more accessible for dialog. These personnel would include people at, for example, the North American Aerospace Defense Command (NORAD) and the US Strategic Command (STRATCOM). Russia and the US are the two most important countries to include because they have the fastest launch postures and by far the largest nuclear arsenals. Dialog with the appropriate military personnel could ensure that they are aware that the explosions they detect can be of extraterrestrial origin. It could further advise them on how to distinguish NEOs from violent attacks, or at least create relationships with NEO experts who can be called on as needed.

Due to the difficulty of connecting directly with the political leadership involved in nuclear launch decisions, it can also be of value to engage with national security policy communities and the public. Policy communities can help inform political leadership and their top staff, potentially including the people who may be consulted when launch decisions are made. Interest from policy communities and the public alike could ensure that political leadership is aware of the possibility of inadvertent NEO conflict if and when they are presented with information about a detected explosion. Recalling the role of Hollywood films in raising public awareness of the NEO threat [18], perhaps new films or other popular media could help raise awareness about inadvertent NEO conflict.

Outreach to these various communities would benefit from involving NEO experts who are from each country that is a focus of the outreach. This is important because of the highly sensitive nature of the activity of identifying the cause of detected explosions. Countries may worry that NEO experts from other countries may have subversive aims. If one country could trick another into believing an attack is instead an NEO event, that would provide a major military and strategic advantage. Therefore, successful outreach about NEOs may require a high degree of trust so that the audience believes the information about NEOs is scientifically accurate and not a strategic trick. This trust is more readily fostered when the outreach involves NEO experts from that country.

Raising awareness sets the stage for the correct identification of NEO collisions when they occur. Correct identification would be further strengthened by establish communications links between NEO detection systems and the military systems that monitor the skies for incoming attacks. Then, militaries can be alerted when incoming NEOs are detected, such as occurred for NEOs 2008 TC3 [64], 2014 AA [65], and 2018 LA [66]. As Tagliaferri et al. [11] explain, these activities may be especially beneficial for militaries with relatively limited space observation capability. Tagliaferri et al. further note that any international NEO alert system must be highly trustworthy to avoid suspicions that false NEO warnings could be used to disguise actual violent attacks. Prior efforts to raise awareness and build mutual trust and understanding between NEO and military communities could go along way to ensuring that, in the heat of the moment, alerts about incoming NEOs are trusted when they should be. Tagliaferri et al. [11] also present some technical analysis of a potential space observation system that could be used for this purpose, though any future plans should be based on a more current accounting of space observation capabilities.

Activities along these lines may have no significant effect on NEO risk. They could even increase NEO risk by diverting resources and expertise away from planetary defense. Therefore, planetary defense program planners must assess whether these activities are worth their time and funding. Militaries could contribute some or all of the funding, though they face their own set tradeoffs between funding priorities. For these reasons, it is important to evaluate the magnitude of the risk of inadvertent NEO conflict. Such risk analysis is likely to be inexpensive relative to the programs that could reduce the risk, and may therefore constitute "valuable information" toward resolving the cost-effectiveness of inadvertent NEO conflict risk reduction measures. (For more on quantifying the value of information for assessing the cost-effectiveness of measures to reduce the risk of NEO collision and other global threats, see Ref [67].)

5. Conclusion

Planetary defense programs can affect violent conflict risk in at least three ways: nuclear deflection/disruption, inadvertent NEO conflict, and as a model for addressing an extreme global risk. This paper examines each of these and its implications for planetary defense program decisions. Planetary defense programs for nuclear deflection/disruption may (or may not) involve a risk-risk tradeoff between NEO risk and violent conflict risk, which could mean favoring other NEO deflection/disruption techniques instead of nuclear explosives. Additionally, planetary defense programs may be able to reduce the risk of inadvertent NEO conflict by helping militaries avoid misinterpreting NEO collisions as violent attacks. Finally, planetary defense programs can help reduce other extreme global risks, including nuclear war, by documenting their successes and failures and relating them to broader themes in the reduction of extreme global risks.

Exactly how planetary defense programs should proceed on these matters depends on details that are beyond the scope of this paper. There are important uncertainties in both NEO and violent conflict risk that impede precise evaluation of planetary defense program decisions. Many specific decisions must also be taken on a case-by-case basis. For example, the value of documenting the successes and failures of planetary defense programs may depend on the extent to which communities working on other global risks are interested in learning from the planetary defense experience. Additionally, the implications of nuclear deflection/disruption for violent conflict risk may depend on the extent to which nuclear deflection/disruption programs are managed internationally, as well as on the future rate of nuclear disarmament. Finally, the merits of planetary defense programs allocating resources to reducing inadvertent NEO risk may depend on how interested militaries are in this particular risk, and on whether the militaries will supply some of the relevant resources (such as funding for detection and communication systems).

One more general and clear conclusion that can be reached from this paper's analysis is on the value of integrated study of multiple global risks—in this case NEO collision and violent conflict. These two risks involve very different processes and expert communities—astronomy for NEO collision and political science for violent conflict. Nonetheless, the multiple effects of planetary defense on violent conflict risk demonstrate the importance of these expert communities reaching across their disciplinary boundaries and working together to make the world safer.

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