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The First Line of Defense: Long-term Planning for Planetary Defense and its Policy Challenges

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Abstract: The primary nontechnical obstacle to defending against Potentially-Hazardous Near Earth Objects is the political difficulty of achieving support for an active threat mitigation system. The low-probability nature of the threat and limited perceived incentives for politicians to tie themselves to multi-administration projects whose product will likely emerge outside their term of office continue to complicate meaningful steps toward planetary protection. Using John W. Kingdon's Multiple Streams Framework, we identify which mitigation strategies might serve as technically sound and politically viable first steps, as well as policy elements or supportive measures. Together, these factors may provide planners and policymakers a path to creating the circumstances in which their favored planetary defense proposals are best suited to succeed. This structure allows us to explore policy-relevant characteristics of these various approaches and seeks to offer supportive strategies to enhance the political viability of planetary defense as a national (or international) priority. Important insights include the strong viability of kinetic impactors as the first asset towards a Baseline Mitigation Capacity, the importance of public image to both methods and a threat mitigation campaign, and the compatibility of planetary defense with American commercial and security goals set forth in the last decade's space policy and legislation.

1.0 Introduction

1.1 The Danger

The Earth is constantly vulnerable to impacts and airbursts from Near-Earth Objects (NEOs), usually consisting of asteroids and comets, with historical damage ranging from harmless meteor showers as the objects burn in atmosphere, to the multi-kilometer masses which threaten all life. While much effort has gone into cataloging the latter threat, with most NEOs above one kilometer surveilled and documented, it is objects closer in scale but larger than the harmless lightshows with which we are most familiar that pose the greatest practical threat. A National Academy of Sciences survey concluded that an object previously estimated at 70 meters but posited to be as small as 30 meters may have been responsible for the mass devastation in Siberia during the 1908 Tunguska event and would be capable of flattening a major metropolitan area in other circumstances [77].

The capacity for even relatively-small NEOs to produce multi-megaton explosions highlights the importance of attention and consideration of a defensive response, made more apparent by the periodic near-misses by objects which would have devastated extensive regions if they had impacted Earth. With some threats capable of even continental damage discovered mere hours before their flyby, any further delay in response only increases the chances that in the event of a true disaster what might have been a mitigatable threat with preparation will be limited to damage control. There do exist a variety of options for preparation and defense against future NEOs, allowing preemptive defenses which provide far greater security than ad hoc fabrications.

But while these options may all provide some measure of defense, they all involve important trade-offs which policymakers must consider in order to determine which path best supports contemporary needs without requiring unpredictable risks or incurring unacceptable costs.

1.2 Background on Planetary Defense:

Planetary defense is a difficult procedure, primarily due to the numerous uncertainties involved. Because potential oncoming hazards vary in characteristics such as composition, mass, shape, dynamics (e.g., rotation), and trajectory, so too must defensive efforts accommodate the variations and unpredictability. These programs may benefit from drawing primarily on maximizing the adaptability of the infrastructure which supports any hypothetical future defensive campaign. For example, a nuclear explosive device, despite its political baggage, remains a method of great interest due to its capacity to mitigate threats ranging from small rubble piles to multi-kilometer global threats [77]. However, accounting for the various uncertainties involves major burdens, including time, expense, and several case-specific qualifiers (e.g., political controversy) that may deter the application of a technically effective means of defense. Similarly, the risk of damage from failed or improperly deflected threats can require planners to incorporate redundancy mechanisms which further add to the costs of pursuing planetary defense [11]. Even beyond technical considerations, certain mitigation options (most notably nuclear weapons but generally including any alternative with a military application) carry strong stigmas on their use or else risk incurring undesirable political consequences, adding a new dimension beyond purely-scientific-mechanical feasibility. Regardless of the specific method chosen, any planetary defense effort is most effective, and therefore safer, if available as early into a real-world campaign as possible, but would necessitate preemptive investment to provide this capacity, especially to defend against short-warning threats. However, the aforementioned burdens of mitigation, particularly as the time of need for this capability remains unpredictable, continue to limit meaningful progress towards a practical mitigation capacity which might provide true security.

Contemporary estimates predict that the time between a national leader’s order to deflect and the actual launch of the mitigator could take up to 64 months, and this estimate does not even incorporate the time it takes for a threat to reach sufficient perceived threat level to justify a launch [11]. Additionally, the example campaign therein used took a further 25 months to simply reach the oncoming NEO, assuming that there remained enough time to redirect the trajectory and that the utilized method succeeded without any degree of mission failure throughout. As such, any realistic mitigation mission would need to account for both how early mitigation capability becomes available, to facilitate the earliest allowed launch, and the ideal degree of redundancy to account for mission risks. However, the clearest takeaway from the report is that there exists no functional platform to mitigate threats discovered only briefly before their close approach to Earth. Even as the current paper was written observatories discovered a 57-130m “city killer” asteroid only hours before it passed within a fifth of Earth’s distance to the moon, highlighting the potential benefits of investment toward a foundation for defense before an urgent need arises [23].

Within this paper, we seek to provide a preliminary survey of the most applicable proposed methods for planetary defense within a preliminary framework of phased stages of development and utilization. Phase 1 begins with those methods well-suited to serve as the foundation of a planetary defense program, providing a Baseline Mitigation Capacity (BMC). In Phase 2, the model also considers methods prospectively appropriate to serve as the next steps toward an increasingly comprehensive and affordable program. These, along with long-term projective options in Phase 3, offer constructive or profitable secondary uses which can help motivate research and investment. Variable-phase and “exotic” options are also considered for their potential merits and secondary functions, though neither are likely first options. Together, this phased framework, by matching method to their ideal circumstances, may allow policymakers to determine which may best serve as their policy stream when promoting the next stage of effective defense and the expansion of humanity’s capabilities in space.

2.0 Multiple Streams Framework

To undertake the expense of a foundational capability, planners must persuade government(s) of the worth of such an effort and provide clear opportunities to pursue the policy goals. In 1972, Cohen et al. posited a model of “organized anarchies” as bodies shaped by “problematic preferences, unclear technologies, and fluid participation” [24]. Within this context, policymakers do not enter the forum with fixed predetermined opinions, instead “discovering” their preferences through interaction and debate. These policymakers are aware of their own role but not necessarily the full scope of how their responsibilities here will relate to the impact on the system as a whole. And lastly, nearly all decision-making authorities function on the basis of rotating membership, each round of which may have differing time or willingness to invest their resources into the specific issue at hand. Together these circumstances constitute a chaotic policymaking forum, marked by pragmatism and random alignment of favorable factors [86]. Later, John W. Kingdon’s work translated these characteristics to the sphere of U.S. political decision-making as the Multiple-Streams Framework, observing that American policymaking reflects the principles of organized anarchies [40]. The emergent framework organizes the context of any policymaking into “streams” which must converge within a limited-time “policy window” of circumstances to pass; a process which is facilitated by capable “policy entrepreneurs”. Our own observation of the degree of uncertainty, room for competing interests, and lack of obvious path for the advancement of planetary defense efforts leads us to extend this policy structure to the context of planetary defense to help identify opportunities to recognize or produce the convergent conditions in which these useful advancements might come to pass.

We take for granted that advocacy to any participant government would need to occur within the correct context (policy window) and under the right constituent circumstances (streams). However, these conditions differ greatly depending on the type of mission proposed. While we cannot guarantee which circumstances will arise in coming years, organizing the possibilities should reveal patterns upon which policy options can be planned to best facilitate viable routes to planetary defense for policymakers to choose from once complementary contexts emerge. The provision of clearer options can likewise help bridge the obstructive ambiguity which has limited past progress, in order to facilitate investment determined as appropriate into meeting planetary defense needs and prepare our nation and others and overcome the major difficulties of that path.

The primary structure of analysis for the political feasibility of each route of planetary defense is drawn from political theorist John W. Kingdon's "Multiple Streams Framework" [40]. The format draws from Cohen et al.'s theory to posit that policymakers do not simply legislate policy on personal preference and fully rational grounds, but rather only succeed within complementary conditions based on the political environment, elements of policy proposed, and the nature of the underlying problem addressed. Overall, a successful policy proceeds when the "streams" of its problem requirements, policy options, and political conditions combine within the context of a viable opportunity for proposal, known as a "policy window," which well-situated "policy entrepreneurs" may facilitate. The model is well-suited to account for the intrinsic ambiguity which continuously permeates planetary defense efforts domestically and internationally.

Practically all major advancements in planetary defense so far demonstrate the limited conditions in which participants may achieve concrete milestones towards a more comprehensive defense, most notably with the formation of the specialized UN-endorsed agencies the International Asteroid Warning Network (IAWN) and Space Mission Planning Group (SMPAG) within months of the 2013 Chelyabinsk airburst by a 20m asteroid. Understanding the manner in which policy windows have affected planetary defense is critical to planning for further developments, particularly if proponents of expanding current efforts seek opportunities to actively create the conditions for progress.

2.1 Problem

The Problem Stream consists of the nature of the NEO threat and the manner in which affected populations, both policymakers and the public, interact with the issue. Overall, attention to the problem is determined through "indicators," referring to the basis for policymakers' measurements of the threat [85]. This element is specifically important for planetary defense, where the low-likelihood/high damage dynamic is not conducive to commonplace damage-overtime estimates, as the resultant averages are miniscule [53]. Instead, problem indicators for planetary defense considerations could alternatively be predicated on the basis of atmospheric bolides/fireballs detected yearly, which demonstrate the actual ubiquity of meteor interceptions with the Earth [19]. In parallel, extraordinary occurrences, called "focusing events" can bring greater attention to a problem, increasing support for resolution even if the nature of the problem itself is unchanged [4, 34, 86]. Examples of this phenomenon vary extensively but range from near-misses by substantial

NEOs [23], which can briefly spark public attention and serve as supporting evidence in proposals, to major events which can bring about even top-down support from governments, as seen in post-Chelyabinsk in 2013 [7,8].

Likewise, “feedback” from comparable situations or attempts at policy solutions can inform policymakers of the opportunities for improvement of new policy [86]. For example, the 1978 launch of the first step of the Global Positioning System convinced President James Carter to support the program’s growth towards the ubiquitous platform it stands as today [30]. In planetary defense, the clearest source of feedback consists of mitigation demonstration programs (e.g., NASA’s ongoing Double Asteroid Redirection Test [DART]) which reveal the viability of specific methods. One can also observe relevant features in projects of comparable scale and timeframe to suggest elements leaders may seek to replicate. Strong models in this vein might include the Space Transportation System program ($196 billion over 39 years) and the International Space Station (ISS, > $150 billion since 1998) [18, 42]. Both projects included international cooperation and required significant political bargaining to attain consensus, serving as a guide for what joint-efforts may be most acceptable to prospective partners, but also took longer than predicted to reach functionality and return valuable research, requiring careful avoidance of their pitfalls as well [32, 46].

Lastly, “load”, or the amount of difficult issues facing the government at the time of consideration, may greatly impact what policies appear viable at the time [85]. High government load may sometimes lead policymakers to adopt policy based on inefficient engagement with available information, pursuing superficial policies that may not best solve the underlying issue [84]. As such, planners for planetary defense may consider that policymakers may more easily support approaches which incur the least vulnerabilities towards proposers and allow for simplified adoption. At the time of writing, government load, at least within the United States and with respect to space policy load in particular, remains a complex issue. Manned exploratory spaceflight has assumed a forward position within the national priority, with over half of the 2020 budget dedicated to assets and support infrastructure for lunar missions and manned spaceflight and programs in active competition for limited funds through the coming decade [27]. Two possibilities therefore exist: either planetary defense may be kept small enough to avoid budgetary cannibalization in favor of larger projects, or else can draw enough support to achieve the level of funding available to priority projects despite the burden of competition.

2.2 Politics

The Politics Stream consists of the contextual environment in which policy is proposed and is based on common public opinion changes (“national mood”), the perceived influence of interest groups, and the need to account for turnover of policy overseers and legislators [86]. The national mood’s importance is self-evident, serving as one of the foremost indicators for policymakers. The degree of public awareness of the NEO threat undoubtably affects efforts to defend against it through demands for policymakers to enact an acceptable solution. A perceived lack of immediacy of the hazard has likely contributed to the lack of outright pressure on policymakers or any widespread demand for deeper cooperation [56]. However, recent polls have indicated that, at least within the United States, citizens are in fact highly receptive to planetary defense efforts, listing them as the second-highest preferred priority for American space policy (after only terrestrial environmental monitoring). Support also transcends political parties, with 61% of Republicans and 63% of Democrats even listing asteroid monitoring as their preferred top priority for NASA and a further 29% average between the two parties supportive of the measure as an important secondary priority [67]. This suggests that even if public demand does not yet exist, there is a strong foundation for domestic mobilization by capable policy entrepreneurs in support of a viable policy.

Measuring the pressure from specific interest groups factors in differently from general interest in reform. Currently, non-governmental interest groups concerned with planetary defense consist of awareness groups such as Asteroid Day and also more action-oriented organizations such as the B612 Foundation [47]. Such interest groups may lack the magnitude of public support but can provide unique access or expertise that augments any proposal with credibility or singularly valuable supporters. Achieving stronger support from these two sectors is particularly critical as without evidently broad public or specialized support some policymakers have, despite recognizing the scope of the hazard, remained hesitant to introduce the topic for concern of impacting their reelection campaigns [68]. Addressing this concern may increase policymakers’ freedom of action and facilitate an address reflecting the opportunity for popular support.

Compensating for governmental turnover is a critical element in planetary defense policy planning, primarily due to the realities of the problem stream and both time and expense which characterize the policy stream [86]. Any policy proposal will require capacity for flexible reform to fit new requirements or conditions not considered at the onset of implementation to preclude the instigation of new opponents who might seek budget cuts or cancellation. In parallel, successful policy will require consistently demonstratable utility to maintain support from administrators, legislators, the public, and interest groups. Otherwise, policies that tend towards a partisan inclination, perhaps to enjoy support from an accordant administration, may see rapid dissolution of sponsorship upon turnover towards an ideologically-opposed successor. In parallel, an established and durable support base may eventually result in sunk-costs bias, self-sustaining project elements, or strong ties to other important policy, stratifying a specific planetary defense program as a consistent priority for participants throughout each phase. Overall, the politics stream serves as a measure of how much unity policymakers can expect from the public and their peers in authority during deliberations on planetary defense.

2.3 Policy

The Policy Stream consists of the various competing policy proposals offered to a specialized decision-making community to address the problem stream, each of which is judged comparatively on its value acceptability, technical feasibility, and resource sufficiency [85, 86]. Within the planetary defense context, value acceptability factors into the legitimacy and permissibility of both the format for planetary defense and the methods used in pursuit of its goals. Any effort which cannot attain and maintain international consent will suffer major obstructions against cost-sharing and efficiency optimization, potentially hindering capacity-building or a mitigation campaign, or even endangering the long-term viability of the planetary defense project. Likewise, any methodology considered risks major setbacks if nonconforming to contemporary norms -- a danger most evident in considerations of any mitigation method with a “dual-use” capacity for militarization.

Technical feasibility is another key factor in determining the ideal mitigation technology, as policymakers must balance the option of achieving a functioning defensive infrastructure sooner with the parallel interest in managing R&D costs. Resource sufficiency similarly complicates any policy proposal due to the conditions under which planetary defense efforts perform. There is undoubtably overall resource sufficiency for a threat mitigation mission, but with contemporary distributional legislation favoring high-cost manned spaceflight to the Moon and Mars, the question is where planetary defense can fit within a very crowded field [62].

2.4 Policy Window

The policy window is the specific period, or range of conditions, in which a specific policy becomes viable for proposal where its merits might otherwise go ignored [4, 85]. Within these intervals, greater supportive attention may uniquely situate policymakers to begin implementation, or new capabilities may become available, such as when new legislation provides funding where past national fiscal budgets did not. In the specific case of planetary defense, useful examples for policy windows appear in historical periodic bursts of progress in planetary defense, most notably during the 1990s series of congressional investigations and in the wake of the 2013 Chelyabinsk bolide-airburst. The first consisted of major congressional backing for investigation of the threat and planning efforts toward detection and mitigation capabilities, in large part prompted by the 1994 Shoemaker-Levy impacts on Jupiter. The second exemplifies the effect of a major focusing event in the problem stream, prompting political attention from below and pressure from above to seek stronger protection [34]. Predicting when a policy window will become available is difficult; instead, ex ante planning may allow prediction of what form of policy windows may facilitate advances in planetary defense in order to allow policymakers to recognize these opportunities and take full advantage when they arrive.

There does remain the possibility of having to choose between multiple policy windows, and therefore the risk of choosing the wrong opportunity. Just as “defining bioterrorism as a security rather than a public health issue” may leave policymakers unable to “institute broad based reforms that would… meet other public health needs” [9], defining planetary defense as a security centric issue may similarly limit its prospects available within other possible policy windows. Naturally, the most viable policy window depends largely on the available pool of powerful supporters, and therefore their preferred selection criteria. As such, proponents of planetary defense may consider preparing to appeal along commercial and capability-building lines in addition to securitization arguments for increased investment, keeping in mind the alternatives in order to avoid jumping to an imperfect option.

2.5 Entrepreneurs

Policy entrepreneurs are often one of the foremost catalysts in aligning the streams and opening the policy window. This factor is one of the most critical to understand because, where most of the streams relegate policymakers to preparation for the possibility of alignment, policy entrepreneurs offer a tangible means of shaping this process. Such figures are characterized by their access to contemporaneous decision-making authorities and resources to combine streams or even open policy windows [85, 86]. Entrepreneurs can be individuals who use their position or high profile to advocate and support policy expansion efforts, such as Apollo astronaut Russell Schweickart, or composite actors within an increasing number of involved organizations such as B612 (which was co-founded by Schweickart), the Association of Space Explorers, The Planetary Society, and the Safeguard Foundation [65].

Key domestic policy entrepreneurs in maintaining a stable program across administrations are primarily members of the executive and legislative branches of U.S. government. Historically, nearly all major space projects including ICBMs, satellite development, Apollo, STS, Skylab, the International Space Station, and currently Artemis all acquired presidential endorsement. Securing the backing of the chief executive is a significant factor, as they propose the fiscal budget, oversee the executive agencies who actually execute policy, and have significant formal (budget request, executive orders, and executive arrangements for international cooperation) and informal agenda-setting capacity (i.e., the “bully-pulpit”). However, the president is an unlikely candidate for the first policymaker to convince, as historical attempts to bypass broader support in favor of top-down demands have met considerable opposition, most notably in the case of an ill-fated attempt to secure a manned mission to Mars through Vice President Spiro Agnew [32]. Nonetheless, the executive branch remains a critical advocate required for any large-scale expansions. Rather, aligning the president’s advocacy can perhaps occur through bottom-up support from proponent cabinet members and agency heads who advise from within the executive branch or else once advancements within the legislature naturally draw the executive’s own attention.

Within the legislature, Congress maintains specialized subcommittees which are best equipped to link greater attention to practical advances due to their policymaking jurisdiction and budgetary approval duties. In particular, the Senate Subcommittee on Aviation and Space and the House of Representatives Subcommittee on Space and Aeronautics are critical for their oversight of NASA and long-term planning, Committees on Appropriations in both houses are needed to secure steady funding, and the Committees on Armed Services in the event of utilization of military or dual-use infrastructure [6]. Support from either branch of government can provide access to the other, offering proponents who secure backing as early into the planning process the opportunity to maximize resources and strengthen the foundation on which to request more generalized support for expansion.

3.0 Strategies

Within their work, where a proposal would not pass on its own, policy entrepreneurs can make use of strategies to combine the streams and/or open a policy window, implementing their resources and access through several methods of policy promotion. These tactics tie the policy that addresses the problem to the political context, drawing the disparate elements together so that policymakers select the specific policy that recognizably befits the climate. Overall, this procedure is known as “coupling” and can take two primary forms. Most familiarly, a change in the problem stream can allow “consequential coupling,” requiring policymakers to find a solution to their newly salient problem, while alternatively, a change in the politics stream may invoke “doctrinal coupling,” leading policymakers to find a problem to which they can apply an available solution [84]. Either may be possible for planetary defense priorities, and policymakers may consider preparing to employ relevant strategies once complementary changes open the fleeting path to a policy window.

For planetary defense, the challenge is to tie specific mitigation options, in addition to the field as a whole, to tangential - but relevant - issues and goals. Situating planetary defense efforts within the larger scope of national security is important but requires careful management to prevent the possible negative consequences of topic securitization [73]. Likewise, identifying opportunities for commercialization (e.g., asteroid mining) can allow planetary defense to expand as a complementary section meeting the goals delineated in the 2018 executive Space Policy Directive-2 and the U.S. Commercial Space Launch Competitiveness Act [1, 76].

3.1 Framing

As paradoxical as it may sound, one approach to furthering planetary defense is to emphasize the non-planetary defense products of an expansion of effort. For all the costs required to prepare and conduct a planetary defense campaign (in addition to the political pressures on its advocates) there may be alternate means of presenting (framing) the program to either build support more easily or avoid making new opponents. Framing a planetary defense effort purely as an expenditure will inevitably stagnate its progress under the pressure of fiscal conservatives and the historically frugal Office of Management and Budget. Instead, advocates may consider presenting planetary defense as an opportunity for investment, growth, and compliance with national goals. The major recognized applications for space activities include foreign policy, national security, expanding the knowledge base, advancing technology and the comparative national advantage, improving terrestrial services, supporting private enterprise, and a generalized expression of “world leadership” [30]. Framing has concrete benefits beyond supporting the policy acceptance and implementation phases of planetary defense, serving the survivability and expansion of the program in the long-term as well.

One especially relevant form of framing may be to tie a policy to other programs. One may secure a common fate for the policies, so that the individual policy can survive through complementary association with a broadly-supported programmatic umbrella. For our purposes, in addition to the deflection-exclusive mindset of a short-warning campaign, there is also opportunity for long-term scientific and commercial advancements which might convince those who remain hesitant to continue the initial investment into a multi-decade program. The same programs which identify and characterize NEO may also contribute to future efforts to study or exploit those specific objects, particularly in anticipation of commercialized mitigation options such as mining via mass-drivers. This approach, predicated on the “no-regrets” logic which has seen much use in climatological management research due to its usefulness for accounting for uncertain risks [12, 31], also allows planners to continuously preclude accusations of wasted missions, as they may repurpose any observatory mission set to analyze a NEO whose threatening status becomes negligible into a scientific mission which can help set standards for future missions and provide greater insight into the NEO and others like it. Altogether, tying planetary defense to a broader goal may allow the program to draw new supporters and avoid budget cuts or opposition on the basis of its recognized relationship to national interests. However, framers may remain cautious to some degree as tying planetary defense to specific programs may alternatively sink both projects if either accrues too much opposition. As such, it may be useful to frame within indisputably desirable objectives which help accrue support instead of inviting criticism [73].

Before any mission-specific benefits, planners may present the planetary defense program itself as a path through which to achieve broader goals set forth in the 2010 National Space Policy, 2011 National Security Space Strategy, and the current administration's Space Policy Directives. Consistent between all these documents are the goals of safety, stability of use, and the advancement of the American position in space, all of which planners may incorporate into planetary defense to frame the program as not just protection from disaster, but also a vital next step for the space program as a whole. For safety, planetary defense can play a role in setting procedures and norms of safe use. Any coordination effort can guide the procedures for planetary defense missions by partners and later participants, allowing for both standardization and a foundation for coordination of future space activities. In particular, cooperative overtures here can serve as a forum for planning to prevent accidents and set the U.S. as a leader in space situational awareness (SSA) promotion and organization.

For stability, a planetary defense mission can provide an example of responsible campaigns and guide comparable missions that may take place under the auspices of another capable spacefaring power under NEO threat. Many analyses present planetary defense mission considerations from the American perspective, considering how its use of specific mitigation methods might impact others. However, the same concerns governing controversial methods can just as easily play a reversed role if another power takes an agenda-setting position and determines the trends for these approaches first. As such, planetary defense may provide the opportunity for a first-mover advantage with American planetary defense programs instead setting norms for peaceful uses of outer space, thus limiting routes to militarization and saving the cost of an arms race in space.

As for the advancement of the national position, planetary defense may provide domestic services to help meet contemporary national security needs and serve as a catalyst for the space industry and the emerging trans-atmospheric economy. For example, the longstanding Space Launch System (SLS) lifter program has persisted despite controversy and costs [61]. However, the model could benefit from an assured market for implementation as a planetary defense capable lifter, providing super-heavy payload capability in support of any weight/redundancy heavy mitigation option. In parallel, the same infrastructure may provide opportunities for domestic industries to emerge in support and create an international demand for an American provided service.

For new domestic industry, studies have tied lunar infrastructure, asteroid mining, and fuel through directed-energy to potential planetary defense infrastructure, opening new sectors in the long term to incentivize short term investments in planetary defense-supportive services. Investment here may also produce an international market for planetary defense, whether new arrivals wish to save on R&D by purchasing existing assets or if nations in need contract the U.S. as a service provider with the equipment and experience to successfully defend where they cannot. The infrastructure needed to support planetary defense, from lifters to rapid response mechanisms to situational awareness assets, may also support national security interests, keeping decision-makers better appraised in one more dimension of their jurisdiction. Likewise, with the vulnerability of critical orbital infrastructure in ever-greater focus, providing a means of rapid asset replacement through on-call lifters may help fill the gap and justify a standing defensive capacity.

3.2 Transparency and Predictability

Ultimately, the main purpose of this paper is to help inform both domestic and international bodies of beneficial opportunities to pursue greater planetary defense efforts by promoting a greater understanding of current conditions and providing a foundational assessment of how future efforts are may proceed. For the first aspect, greater understanding of the actual hazard may allow policymakers to bypass the reductionist conclusions of averages-based risk analysis. Likewise, overcoming the potential shortcomings of heuristic policymaking requires accurate appraisal of the available options so that policymakers can still determine which from a range of imperfect options is at least the best available. Comprehension of current options will likewise allow these same figures to choose which to support later and how to help address any political obstacles to long-term gains from within their own occupational sphere. Informed governments are also necessary for alleviating concerns of resource wastefulness, uncooperative behavior (free-riding), and ulterior motives which might dissuade broader or deeper collaboration. The recent Planetary Defense Gateway may valuably assist with these various informational needs, providing a unified database for common reference and equal assessment of requirements and capabilities [74].

Concurrently, predictability assists with the long-term viability of planetary defense efforts, particularly in terms of trans-administration survivability. Identifying short-term gains draws initial supporters, but only long-term benefits can retain their support throughout the project’s lifetime. The CARDINAL framework can promote predictability, serving as a programmatic structure purpose-built to help design an achievable mission, with a focus on reducing prospective social costs which might be incurred in the event of an emergency without ex ante planning [75]. The same heuristic policymaking which forces planetary defense to compete with projects offering immediate results will remain in effect even after program expansion begins, requiring policy elements which assure policymakers that investment into planetary defense will outweigh the benefits of redirecting resources towards some future alternative policy.

When securing international partners, evidentiary assessment of long-term needs can help avoid inaccurate expectations, or in the case of dual-use techniques, assuage fears of project misuse. For historical precedent, NASA-ESA cooperation on Spacelab demonstrates the consequences of low-predictability, as ESA undertook the brunt of the effort with the expectation of numerous upcoming purchases by

NASA, but in the end sold only one unit for NASA use alongside a donated companion [32]. This incident prompted far stronger preconditions for future cooperation, including a better assessment of expectations, requirements, and adaptability. In the next decade, one can, in no small part, attribute the success of the International Space Station to the parallel studies conducted by all governmental and corporate partners, which all allowed for a clear delineation of responsibilities and contingencies for the project’s timeline and has held for decades since.

3.3 Legitimacy

Any successful planetary defense effort will require domestic and international acceptance, both to secure material backing and to prevent potential obstacles or limiting factors which reduce mission options. Most concerns here focus on methodology, with the acceptability of certain mitigation options, dual-use and particularly nuclear devices, in question. Previous evaluation predicts that the deployment of technologies with military applications would invoke opposition and curtail testing opportunities and mitigation options [58, 80]. Therefore, to provide policymakers with the greatest freedom of implementation, any policy proposal may incorporate legitimizing components that either ease mission justification or limit grounds for opposition.

Drawing from precedent here, planners may replicate the legalization procedure used to overcome ambiguity and concerns over jurisdiction and utilization of the International Space Station. The partners overseeing the station make use of the 1998 Intergovernmental Agreement, balancing legitimizing mechanisms without restricting participants to the point where they seek to withdraw from collaboration [29]. In this style, planetary defense may achieve legalization-based legitimacy through incorporation of obligation, precision, and delegation clauses, particularly in the event of international cooperation. These factors institutionalize the effort and further allow invaluable cooperation without reliance on more coercive enforcement mechanisms [3].

Obligation, referring to the degree of constraint placed on participant conduct by procedural guidelines, can reduce the reliance on ambiguous norms of cooperation [29]. Some theorists posit that planetary defense will function best within an atmosphere of cosmopolitanism [73, 81], claiming that the normative approach can transcend the interstate dimension of planetary defense and allow action as a united front and immune against opposition. However, achieving the laudable goals therein will likely be a difficult and uncertain process, in line with concerns with about the critical theory approach used in the aforementioned proposal [55]. As such, legal delineation may help assure compliance until such time as cosmopolitan norms proliferate and render the guidelines unnecessary.

Precision of policy and agreements concerning implementation increases their predictability, reducing the likelihood of misinterpretation. Careful delineation of activities likewise facilitates better project management as “hard law” foundations can lower inter-partner transaction costs, improve risk management, increase project transparency, limit strategic political behavior, and promote obligation enforcement by private actors [2]. Replicative planetary defense agreements would therefore critically rely on preemptive planning, as ad hoc coalitions or agreements leave less room to prevent ambiguity and no chance to enjoy the benefits provided by a precise institutionalized cooperative framework.

Delegation involves the degree in which a third party is allowed to arbitrate or legislate new regulations with some degree of independence from the participating partners. As the ISS case demonstrates, delegation to oversight boards eases consensus-based decision-making, dispute settlement, and accounting for contemporary or unexpected problems [29]. As such, planetary defense efforts may also benefit from some degree of delegation, enjoying the aforementioned benefits while deflecting accusations of subordination to the interests of any single participant. Utilizing delegation does require consideration of some principal-agent relational mechanics, as participant states may seek to pressure the delegated body to conform to their interests, potentially undercutting the benefits of delegation. As such, states may consider predetermining functions and constraining the delegated body via precision/obligation to secure its position as a consistent support for all participants.

3.4 Cost-Efficiency Optimization

In addition to selecting options that are intrinsically simpler to develop, attention should be paid to opportunities to further reduce the expenses of planetary defense, continuously diffusing distributional concerns and opening avenues for interest groups to become invested in the program as well. Much in line with the goal of framing planetary defense as conducive to space commercialization, the program itself may benefit greatly from chances to directly limit expenditures and thereby secure the immediate viability and long-term survivability of the program.

One such opportunity for limiting expenditures of a high-efficiency planetary defense mission could involve a system of lifter cycling. With launch availability playing a vital role in determining the ultimate effectiveness of any mitigation method, allowing policymakers to launch as early as they are willing could limit the ultimate cost of the deflection campaign. Maintaining purpose-built infrastructure for a planetary defense mission, potentially for decades, could incur undesirable expenses, requiring a means of which to perhaps recoup certain expenditures. Such an opportunity may be to explore equipment and management processes which allow alternative use for the lifter vehicle. Project leaders could maintain a planetary defense-dedicated lifter vehicle until a replacement becomes available, allowing a private actor to purchase use of the original for their own launch. The defending agency can enjoy greater launch flexibility at a more reasonable cost while private partners can perhaps enjoy the benefits of guaranteed ability to launch on schedule and the reduced cost of buying a “used” lifter from the defending agency.

Alternative precedent may be found in the Civil Reserve Air Fleet (CRAF), which reserves the right to requisition assets from commercial airlines in the event of a national emergency. The program emerged in the wake of the 1948 Berlin airlift, noting the logistical difficulties of an ad hoc campaign [14]. In this vein, a replicative program could evade delays and obstacles to availability. A RAND assessment of the CRAF has specifically noted the similarity to “nonmilitary space systems”, observing that to “…contend with the problem of providing an appropriate mix of incentives for participation, both must overcome or cope with design incompatibilities between commercial and military systems, and both must balance the need to maintain a high state of readiness and responsiveness with the need to maintain high participation" [22]. Using the same study's reasoning, assured government contracts may incentivize participation by emerging lifter providers, with the ~$600 million figure from 1990 suggesting comparable expenditure parallels to launch costs in a mitigation campaign. In terms of design compatibilities, R&D is needed well in advance of a campaign to design mitigation methods as compatible with the vehicle intended to ferry them. Lastly, prior agreement and procedural planning is important to securing adequate response time for asset conscription, particularly considering the scheduling sensitivities of planetary defense. While not the focus of the current paper, a "Civil Reserve Space Fleet" could prove invaluable to both planetary defense and other contemporary national security and commercial applications, and therefore warrants further exploration.

3.5 Policy Structural Compartmentalization ("Salami-Slicing Tactics")

Incrementalistic strategies may play a useful role within easing the policy acceptance stage. Accounting for the possibility of a risk-adverse administration unwilling to commit comprehensive funding, or alternatively one seeking more immediate opportunities to claim successes, obligates planners to perhaps offer planetary defense advancements in staged formats. Where some means of threat mitigation, or infrastructure to augment their mission, may be too expensive for policymakers to adopt wholesale, proponents may seek to secure investment in the early steps for a specific approach. This process can help facilitate a positive feedback loop, where inexpensive support for the beginnings of a specific option provides evidence of easier gains, produces feedback, and increases the perception that the approach has perhaps "matured" enough for investment in a similar subsequent stage. This is why we currently consider a phased model towards comprehensive planetary defense, starting with the more acceptable steps to catalyze or ease the process toward the subsequent phases.

3.6 Multilateralism

A planetary defense mission, whether singular or ongoing, could benefit greatly from international cooperation. Some collaborative activities do exist but are currently limited to situational awareness and observational coordination. However, greater effort towards long-term planning could expand development and management opportunities and provide additional cost-efficiency benefits. Multilateralism therefore fits within both the politics and policy streams, allowing for distinct opportunities to enhance many planetary defense methods in the eyes of policymakers.

Numerous large-scale joint space projects have succeeded despite domestic controversy and opposition and can now inform any attempt to replicate their great successes in making possible what programs might have been prohibitively or burdensomely expensive otherwise. The best examples emerge from the international efforts to create a reusable Space Transport System (STS), known colloquially as the Space Shuttle, and the subsequent transformation of the proposal for a long-term transit point for a Mars mission into the contemporary International Space Station. Both programs allowed NASA to outsource significant development costs to major allies, with a norm of ~11% of the program's budget from the European Space Agency alone [46], and to take advantage of their ever-increasing specialized expertise as well. In order to access international partnerships, NASA needed to address major concerns over dual-use capabilities and sensitive tech transfer considerations. The Department of Defense remained concerned by projects that risked proliferating advantageous technology, even to allies, and delayed both programs in addition to their international aspects until ultimately both opted to pursue purely civil functions with the option of military access at a later point. Contemporarily bypassing these considerations in favor of the "civil-first" approach may preempt domestic obstacles to multinational collaboration early on, maintaining focus on opportunities for mutual gain instead of reasons not to try.

To maximize the possible gains, prospective participants may need to be aware of the project's parameters and needs as early as possible. American-dictated designs have long become unacceptable, with any major partner unwilling to replicate the lopsided results of the Spacelab program. Instead, what allowed STS and ISS to succeed was the offer for major international and corporate partners to conduct parallel studies, though mutually insulated to allow for maximum breadth of innovation and to avoid cross-contamination [46]. What emerged was a cohesive effort with a clear understanding of each partner's capabilities and expectations, all before true R&D or any formal agreement had been implemented. Altogether this comprehensive foundation allowed U.S. policymakers to comfortably advocate their decades-long programs (which cost >$340 billion altogether to present, some of which was funded concurrently) with the continuous support of the international community until the 1998 Intergovernmental Agreement could solidify the partnership through the present day [18, 42, 83].

For the purposes of internationalized planetary defense, regardless of which mitigation option is eventually selected, involving potential cooperators in the R&D process early can provide a more accurate assessment of room to collaborate and prevent points of contention from arising and undermining the joint effort.

4.0 The Foundation for Defense

4.1 Phase 1: Baseline Mitigation Capacity (BMC)

The first step in achieving any meaningful risk-reduction against NEOs may lay in preparing for the scenarios which are dangerous enough to warrant an immediate response, while also requiring the least amount of effort to achieve. The former point simply refers to the need to prepare for short-warning hazards which leave the least room for policymakers to gradually scale-up preparation and instead require some standing capacity to address. At the very least, a defensive actor must guard against NEOs which arrive before any more comprehensive apparatus exists to protect the Earth. Likewise, considering the possibility that the first incoming threat we face may not facilitate the use of more "slow-push/pull" methods, the first defensive technologies may need to retain the capability to mitigate a threat discovered relatively late into its journey toward interception.

The latter clause is another critical point of focus, as a mitigation method which may prove desirably effective for planetary defense but requires significant research and development may not be available in time for a short-warning deployment, obligating us to consider methods which may become available sooner rather than later. In parallel, minimizing the deviation from existing capabilities may ease support-building and resource acquisition, as policymakers would need to reallocate less funds to the program and supporters may expect to see tangible results earlier than they might for another mitigation technology.

As such, the primary emergent options for a BMC consist of either kinetic impactors, nuclear explosive devices, or some combination. While all these approaches are well within the scope of contemporary capabilities, there are distinct advantages, drawbacks, and conditional characteristics which may affect their desirability as first-stage defensive assets.

Kinetic Impactors

Kinetic impactors are a relatively well-understood threat mitigation option, drawing on long-observed astrophysical mechanics which major projects such as Deep Impact and the upcoming DART mission continue to demonstrate. The method itself consists of a guided projectile which imparts kinetic force during impact onto the incoming object in order to shift its velocity enough to miss undesired points of impact [71]. There are strong technical and political advantages to opting for this approach as a first option, and its prospects likely increase in coming years as well. First, the relative familiarity of the mechanics reduces the amount of prospective R&D required to bring this option to mission-ready status [5]. In service of a technology-readiness designation, upcoming (DART) and hypothetical demonstrations should facilitate greater predictability for planning use of this procedure and contribute to a greater degree of mission assurance. Second, unlike certain other proposals for mitigation, kinetic impactors serve no inherent military purpose that is not already available, such as Anti-Satellite missiles (ASATs).
As such, the technology would possibly suffer less international opposition and help prevent political obstacles to international collaboration. In parallel, there is concern that military innovations could advance on the backing of planetary defense [36]. Preventing such advancements may avoid an arms race, but may stifle military backing for a civil application. Kinetic impactors can straddle the middle ground, fulfilling a planetary defense role without promoting new military applications or sending threatening signals to other actors, suggesting noteworthy political feasibility for kinetic deflection on a unilateral and multilateral bases.

Cost plays an important role within considerations of kinetic impactors. A 2010 Study, using the ESA-proposed Don Quijote as its model, set the joint observation/mitigation mission cost at up to $1.9 billion [77]. While not an unachievable cost, the likely requirement for redundancies and the value of reducing costs in general suggests a need for careful cost-effectiveness optimization. In a statistical-tech feasibility assessment, analysts determined that a one-ton kinetic deflector could efficiently support small and medium size/range planetary defense needs, such as airburst/local-level threats, albeit requiring observational support and early launches for peak effectiveness and upward scaling for larger threats [69]. With the Falcon 9 Full Thrust capable of carrying a 4,020 kg (8,860 lb. or ~4 tons) payload to an interplanetary trajectory, potentially of the scale of a planetary defense mission, for $50-62 million, launching a one-ton deflector with redundancies appears not only achievable, but also relatively cost effective [13]. For comparison, an individual F-35 Lightning II fighter jet of any configuration in use costs $20-60 million more than a single launch for a deflection mission (of the aforementioned scope) and 2,443 of the aircraft are expected to be sold over the next 17 years [63, 66]. The combined technological readiness and relative cost-efficiency, as well as existing support infrastructure, such as compatible lifters, makes the kinetic impact-based deflector a reasonable option for the first phase of planetary defense.

The disadvantages of kinetic deflection are primarily technical and temporal, a byproduct of the method's comparatively lower force imparted when compared to its explosive alternatives. This deficiency can be a liability in comparison to explosive options, whose greater force allows them to be effective against larger NEOs. However, ongoing research may help compensate for this, with a recent framework proposing deflection of an Apophis-sized (or comparable scale) object through kinetic impactors assisted by redirected collected asteroids, though these efforts remain immature and would require R&D regardless [45]. Kinetic impactors also suffer from a sharp reduction in effectiveness when used against specific classes of NEOs with lesser structural integrity, such as a rubble pile, limiting their applicability when compared to the more "one-size-fits-all" usage of explosive options [5]. Similarly, the applicability of these impactors may drop dramatically as the NEO approaches its Earth-interception point, considering the low chances of policymakers agreeing to an early launch due to trajectory uncertainty [25]. Compounded by the overall uncertainty involved in a deflection campaign, any kinetic-based mitigation mission would likely require multiple launches to comfortably assure a successful threat mitigation. This degree of redundancy would entail significant expenses which must be addressed if the policymakers hope to utilize the design and other advantages of this approach.

From the policy standpoint, if policymakers choose kinetic impactors as their preferred route to BMC, any proposal can play to the method's strengths as an achievable and acceptable foundation, particularly in light of its historically demonstrated feasibility. Within the politics stream, kinetic impactors currently lack a distinct public following or formal advocacy group to pressure policymakers, but the method has generally achieved acceptance within the policy community. This is not to say that other methods are not strongly endorsed; but simply that within the inter-policy competitive pool only kinetic impactors have attained enough support for proof-of-concept demonstrations within the target environment. A particularly important aspect of these demonstration missions has been their trans-administration survivability, with Deep Impact surviving R&D during the Clinton Administration to complete its mission during the subsequent Bush Administration, and DART beginning development in the Obama Administration, receiving approval from the Trump Administration, and possibly set to launch in 2021 [16, 44]. As such, policymakers may invest in kinetic impactors with some reduced vulnerability to administrative turnover.

The primary challenges remain accruement of public/interest group pressures and compensation for the redundancy requirements of this method. For the first issue, a possible solution lies in increasing awareness of the viability of this method within the considerations of planetary defense. The scheduled 2022 DART impact will provide the first opportunity in over a decade to highlight the effectiveness of kinetic impactors and, as a focusing event, may accrue enough attention to help open a policy window for meaningful advancement of this method, depending on the outcome. As such, proponents must prepare to make full use of the results to request support for the next step while the success is fresh in the minds of the public and policymakers. It the test were to fail, this would provide important insight into the dependability of the specific approach and may encourage alternate mitigation paths. Serving a parallel informational and mission-design role for the public, planners, and policymakers, the Jet Propulsion Laboratory's NEO Deflection App is currently functional and may invaluably assist with mission planning, as well as showcasing the conditions for methodological viability [57]. The app is also set to incorporate NEO orbital trajectory and physical characteristic uncertainties in a coming update, allowing for accurate assessment of the needs of a planned kinetic deflection. Together, these projects make kinetic deflection one of the more transparent and predictable methods for both overseers and the interactive public.

To accommodate public concerns, planners may seek to offset expenditures toward redundancy, either through R&D oriented to reduce costs or through cost-efficiency programs such as lifter cycling. Meeting these challenges might benefit from the support of policy entrepreneurs, both in media, to assist with greater informational accessibility to couple the policy and politics streams, and in government, in order to overcome opposition to redundancy expenses. Incorporation of redundancies may itself entice support or entrepreneurs, as redundant launches may expand the market for lifter vehicles, spurring both support from prospective providers and catalyzing development of cheaper and reusable lifters. Kinetic Impactors are not only a mitigation option but also an opportunity to shape the future of American access to space on the foundation of an achievable and acceptable defensive platform.

Explosive Devices (Standoff Method before Surface Detonation)

Explosive devices, particularly those utilizing nuclear technology, offer a comparable degree of technological feasibility to kinetic impactors and can, in fact, work in concert with them to provide additional imparted force at the moment of NEO interception. Tangentially, this methodology resembles that of kinetic impactors in that force is imposed on the incoming NEO to redirect its trajectory, but in this case the force imposed comes from the material vaporized by the high-energy reaction of the explosion, either from the expanding wave from a standoff device or from a surface (subsurface) detonation. The designs for explosive (including nuclear) guided missiles have enjoyed over a half-century of improvement and optimization, suggesting greater cost-efficiency through less R&D funding [5]. Concurrently, the existing inventory of such technology for military needs guarantees a supply and bypasses much of the concerns with supporting a standing capacity, thus supporting trans-administration program survivability. In terms of planning, the NEO Deflection App update will also integrate the standoff nuclear explosive method, allowing for precise mission needs assessment and mission-specific feasibility comparison to the already-included kinetic option.

Nuclear explosives offer wide utility for BMC, capable of deflecting or destroying all but the largest of NEO. Deployment of this method may provide breathing room for planetary defense efforts, guaranteeing protection until long-term options can replace them. However, this same opportunity has several major obstacles to deployment. First and foremost, the 1963 Partial/Limited Nuclear Test Ban Treaty and 1967 Outer Space Treaty explicitly disallow any testing of nuclear explosives in space and the deployment of weapons of mass destruction in space, respectively. The United States is a signatory to both these and other agreements (e.g., the pre-application 1996 Comprehensive Test Ban Treaty) which may affect the acceptance of nuclear deployment [37]. Separate comprehensive analyses for the legal prospects of nuclear-based mitigation both concluded that multilateralist approaches would best fit deployment here, with assent from the United Nations Security Council serving as a precedented and accepted justification [37, 41]. They also note that ideally such negotiation should conclude before a real-world scenario, lest participants risk in-crisis efficiency loss or political obstructionism. Further limiting application or even the viability of proposed use, nuclear devices have never been field tested against a NEO (a product of the aforementioned international agreements and general opposition amongst policymakers to the militarization of space) prompting concerns of improper disruption of a NEO which might insufficiently remove the hazard, or worse, fragment it into multiple impactors [70].

However, the very same capabilities which allow nuclear mitigation tactics to protect against a large range of possible threats even relatively late into the NEO's interception route could also incur a moral hazard. The term stems conceptually from economics, whereby actors who are insured willingly take greater risks than they might if uninsured. In the nuclear mitigation sense, this dynamic may manifest as a reduced willingness to invest in less controversial or more appropriate planetary defense technologies due to the broad protections provided early on. The moral hazard effect is most acutely felt when a secondary party undertakes the burden of insuring the risk-taking actor to its own detriment. From an international perspective, there is therefore a risk of an ex-ante moral hazard, as the outcome variable (the need for a threat mitigation mission) is unpredictable, which may dissuade participation by partners who could otherwise contribute vital elements to a collective effort.

Should policymakers opt for the nuclear approach, there may be steep requirements to achieve broader acceptance beyond government. In terms of the politics stream, it may be difficult to achieve strong public approval or legitimacy, sans a means of last resort, leaving pressure to emerge from within the community of expertise. Relevant policy entrepreneurs would consist of subject-matter experts from the Departments of Defense and Energy, for their experience with the method, as well as from the Department of State. The first two groups can successfully promote the methodology to policymakers, while the last group are critical to assuage militarization concerns of partners and prospective international opposition. Likewise, the legalization of this methodology requires negotiation to pursue a consensus toward exclusive use in planetary defense circumstances, clearly falling within the jurisdiction of foreign policy if policymakers seek to avoid unilateral treaty withdrawals and risk triggering an arms race.

Policy entrepreneurs may legitimize this method through reframing the technology from a military weapon to a utilitarian asset. In support, NASA has considered framing the attribution of nuclear technology to civil needs as a net-demilitarization policy as fissile material is removed from the pool available for military inventory [5]. In terms of public acceptance, past media is already credited with imbuing the public with an unrealistic perception the effectiveness of cinematographic techniques such as nuclear explosives. Informative media, such as the upcoming IMAX film *Asteroid Impact*, can assist with filling the gap, clarifying the prospective nuclear role, as well as reintroducing planetary defense into the public discourse [28]. However, the legitimization of nuclear technology in space poses a normative risk as well, as implementation for planetary defense purposes may undermine the nuclear taboo [79]. Likewise, use for civil designs may provide justification for less cooperative parties to deploy similar technology on the grounds of planetary defense. As such, proponents of this approach may need to balance its effectiveness against the significant opposition and consequences the approach could incur. Proper management may ease this step, notably with respect to proposals to maintain an orbiting explosive available for rapid deployment or orbit the Earth for speed/orbit change before reaching escape velocity. Such proposals are recognized to likely aggravate political anxieties [21] but are not so advantageous as to necessitate inclusion regardless [41], and may perhaps be left aside in favor of terrestrial deployment. However, the existing military capacity of both nuclear weapons and ICBM technology suggests that repurposing R&D can be initiated at a later point; a desirable option considering NASA’s 2004 appraisal predicted a longer R&D cycle for nuclear deflection than for purely kinetic methods [5]. As such, the option may alternatively prove useful even if rejected as a first option, serving as a supplementary safety net instead of a go-to path.

Analysis has also posited the capacity for utilization of nuclear devices in conjunction with kinetic impactors to magnify the initial force expressed [10]. One possible scenario may be to pursue kinetic deflection, ascribe solely research to the nuclear deflection method, and then pursue true implementation in the event of an emergency, where opposition will be most limited, public opinion/pressure will be most supportive, and the policy window is most viable. In any case, whether a Phase 1 application or later addition, international coordination is critical here, as one of the first steps towards making full use of a recognized effective method is to secure broad understanding and consent to its use. This process may be aided by a specific administration or periodic atmosphere of cooperation and/or multilateralism, as to promote transparency and predictability, with respect to both intentions and cultivation of mutual trust. Any R&D effort is likely wasted if testing or deploying the product remains prohibited, obligating proponents of this option to seek domestic approval to explore international willingness to provide a limited exemption for use, precluding reliance on negotiations at the time of emergency or the unfavorable uncertainty of negotiations at the time of emergency.

5.0 Continuations

5.1 Phase 2: Filling Gaps and Building Bridges

Phase 2 options exist to fulfill what needs the first round of planetary defense assets cannot. A key factor in planning for Phase 1 methods involves providing options for which later methods will augment or eventually replace the original mitigation method(s). Kinetic impactors may require a more specialized counterpart to handle NEO threats for which it is not ideal. For example, while the kinetic deflector cannot mitigate low-structural-integrity threats such as rubble piles, a gravity tractor suffers no such disadvantage, highlighting its potential as a supporting asset or successor. However, in the event of nuclear mitigation deployment, the Phase 1 option would already capably mitigate low-integrity threats, perhaps offering planners and policymakers the opportunity to opt for Phase 2 options which serve a secondary purpose, such as direct motive force options, or simply reduce cost and controversy. As such, it is critical to chart the latter stages of planetary defense in order to optimize the first as well.

This second phase is characterized by “slow push/pull” methods which can redirect NEO over time, from several years to decades, offering a form of predictability that may be absent from impulsive designs. If actors are concerned about the possibility of strategic redirection of the NEO into a political adversary, a slow method that facilitates tracking of the trajectory shift may limit potential misunderstandings which might arise over the use of a method capable of redirection at once. These methods may be costly to develop and maintain, and indeed require investment into complex capabilities such as sustained positioning for the gravity tractor and attachment for direct motive force. Phase 2 methods may eventually support commercial ventures, especially through precise and controlled redirection of the NEO to a utilitarian position, but like Phase 1 mostly lack inherent market application. Overall, Phase 2 is a bridge, enhancing Phase 1 and preparing capabilities which may prove useful during Phase 3.

Gravity Tractor

The gravity tractor is another relatively well-understood design and could therefore offer policymakers a cost-effective alternative to compensate for imperfections in Phase 1 methods. In this mission design, a spacecraft would maintain a close distance to the threat to gradually allow the natural attractive forces between them to draw the NEO off-course. Furthermore, the gravity tractor is capable of mitigating NEOs of varying mass/composition, scale, or shape/structure, and can do so with relatively little R&D, with the technology well-simulated and deemed a high-readiness technology among the “slow-pull” techniques [5]. Such a method offers significant political advantages, requiring neither the expensive redundancy of kinetic impactors nor the legal-normative disruption of nuclear or other explosive designs.

The primary limitation of the gravity tractor which prevents its placement as a Phase 1 option is its slow rate of deflection which makes this approach unfeasible when protecting against short-warning or particularly large hazards. Instead, the gravity tractor offers a reasonable expansion to the baseline mitigation capacity, neutralizing threats at reduced cost and minimized provocation while expanding the portfolio of redirectable NEOs to complex bodies like rubble piles. Technically, the preexistence of a Phase 1 mitigation option may compensate for partial or complete mission failure of a gravity tractor, assuaging fears of accidental redirection enough for the international community to consent to its use.

The incremental format for redirection also has the capacity to pose a strong political obstacle in the absence of a comprehensive preexisting international cooperative framework. As recognized even by the project’s most ardent proponents, the gradual nature of this method leaves the possibility of unintended redirection into another impact site on the Earth [52]. By design or intra-campaign mission failure, a gravity tractor may only save the original target while dooming another, though careful planning may yet compensate for this discrepancy by political or technical means. It may also become necessary to formalize an agreement for the maintenance of participation across the campaign, thus preventing participants from withdrawing once their territory is no longer threatened. In the political sense, users of this approach will likely require a multilateralist approach to policy acceptance, as a unitary mitigation mission may spark opposition even if the mitigator is functional and the sponsor's intentions are pure. If concerned by the previously mentioned concerns born of incremental redirection, policymakers can instead reframe the gravity tractor's gradual redirection. Instead of a burden the danger of incomplete redirection may serve as a catalyst for active participation and continued compliance by any country along the projected corridor of possible impacts, as well as their own capable affiliates.

Planning ahead for utilization of this option after policymakers select a Phase 1 design, planners can incorporate the policy advantages offered by gravity tractors. Their methodology may facilitate international cooperation, lacking sensitive or militarized components. Likewise, the gravity tractor offers great predictability, due to its well-understood and incrementally-measurable progression, Lastly, recalling the politics stream, this design already enjoys a following of active and prospective policy entrepreneurs among the B612 organization. These experts have already, under NASA contract, conducted feasibility studies on the Gravity Tractor method and may continue to serve as a valuable supportive asset. Additionally, required entrepreneurs will include the standard domestic supporters, but may benefit greatly from pursuing international support early on, if not first, as to prompt the beginnings of an multilateralist consensus which may ease domestic support building in turn.

Direct Motive Force

The Direct Motive Force method utilizes either a standard chemical rocket to briefly push or pull the NEO, or alternatively an impulsive high-energy rocket to apply force for a longer time period. Mechanically, there is some disparity between these methods, with chemical rockets serving as a shorter R&D option due to the use of familiar technology while impulse high-energy vehicles would require greater development but produce far greater change in the NEO's velocity. Likewise, impulse versions may rely on experimental technologies (Nuclear Propulsion, VASIMR), reducing applicability as a near-term asset but offering policymakers a guaranteed application for the development of new advanced propulsion systems. In terms of deployment, its reduced capability against rotating NEOs greatly constricts the prospects for this method.

Practically, this method would require many of the same political and procedural measures as the gravity tractor, with its likely strong acceptability and legitimacy balanced against the risk of partial mission failure or hostile controlled redirection. However, the need for physical contact with the NEO, whether pressing or pulling the target, reduces feasibility until sufficient research confirms several factors. Research suggests greater attention is needed both on target characteristics (requiring further understanding of generalized NEO surface structure [5] and likely an observation in advance for specific target topographies) as well as techniques for effectively intercepting and coupling the target and mitigator for the duration of force application. Proponents of this path to defense may therefore invest in similar political measures as with the Gravity Tractor, building international ties toward consensus, while investing in improved propulsion technologies domestically so that planetary defense applications may emerge as efficiency rises.

5.2 Phase 3: Long-term Projections and Commercialization

Phase 3's designs are likely decades away from implementation on the scale where planetary defense applications are possible. Like Phase 2, they are characterized by very gradual trajectory redirections but also differ due to the significant research or infrastructure requirements for field application. These methods are unlikely to pass on the grounds of planetary defense alone, rather instead offering additional justifiable capabilities which may tangentially support or fulfill planetary defense obligations. Falling under the purview of long-term planners, supporters for these designs can frame their pursuit within national space priorities and couple research toward the underlying technologies to applications as they become apparent, opening a future policy window.

Such long-term mitigation options will likely rely not on purpose-built assets, but rather on the conscription of existing assets as American and international space infrastructure develops and expands. The advantage here instead lies in avoiding maintenance costs of purpose-built defensive assets, as well as taking full advantage of opportunities for commercialization. Here, instead of seeking commercial applications for planetary defense assets to reduce costs and build support, commercial assets can instead maintain some planetary defense capability as a lesser-priority function that remains on call. The advantage of this phase is that planetary defense can become part of a self-sustained program and recoup costs continuously instead of continuous one-way investment. Herein applies the utility of the Civil Reserve Air Fleet template, delegating maintenance and training to external parties while ensuring access when needed. Therefore, policymakers may consider approaching these methods with both R&D and preliminary access agreements, either investing in the establishment of a service-provider or pursuing arrangements with existing private actors.

Mass Driver

The Mass Driver method, which consists of digging into and then ejecting parts of a NEO in order to shift its course, is too slow a process to serve as a Phase 1 option. Also, like Direct Motive Force, mass drivers would lose much of their effectiveness in deflecting a rotating NEO. Likewise, the method would likely require greater R&D than Phase 2 options as there exists little precedent for asteroid mining beyond minimal sampling (OSIRIS-REx and Hayabusa) and therefore requires extensive design and testing for a platform with the flexibility to mine. In addition to the general political acceptability of this non-military method, asteroid mining is a field of emerging interest to private commercial ventures and government proponents. Therefore, mass drivers offer an excellent opportunity for stream coupling, tying the policy stream to the political stream by offering prospective investors and government funding sources an appealing opportunity to achieve security and profit together. Where developing a mass-driver specifically to mitigate might dissuade policymakers who doubt its usability compared to simpler options, the business opportunity may instead drive the necessary research. While Phase 1 options defend throughout development and Phase 2 until the necessary infrastructure proliferates, mass drivers can enter the emerging space market and join a later PD effort at their own pace, perhaps refunding some degree of the mission through extracted materials.

Solar Sail

The Solar Sail is another developing methodology which benefits from a limited degree of feedback from comparable projects, primarily from the 2010 JAXA IKAROS, NASA NanoSail-D, and Planetary Society LightSail projects which cumulatively reinforced the technological foundation for use as a propulsion system, though the only test beyond LEO was IKAROS. The proposed technique would attach to the NEO and use the increased sensitivity to solar radiation pressure provided by the sail to incrementally shift the trajectory. The notable benefits of this methodology are its international political feasibility, due to lack of military application, and significant opportunity for non-planetary defense uses, based on the system's origins as a propulsion system. The foremost constraint of this method is that its use, even after considerable R&D, would be limited to only smaller NEOs, barring significant lead time and the deployment of a highly-vulnerable and very large solar sail [5]. This setback extends to both a vulnerability to damage from particulate matter surrounding the target as well as much-reduced efficiency against fragmented objects, increasing odds of mission failure while limiting uses. As such, implementation of this method will likely focus on non-planetary defense programs to which it is better-suited until such time as its proliferation makes conscription for small-scale mitigation campaigns possible. Alternatively, the upcoming NEAScout asteroid detection mission will, through its use of solar sail technology, demonstrate the viability of solar sails, not as a mitigation technique, but rather as a low-cost asteroid reconnaissance asset [38, 54]. As an observational resource, solar sail-based technology has the capacity for extended use to analyze multiple objects, with one proposal positing five NEO rendezvous missions over a decade utilizing near-term technologies [64]. Even then, assessment has revealed that significant R&D is required within the "sail geometry, membrane materials, sail packaging, and sailcraft attitude control" sectors before the technology becomes viable for priority missions [78].

Proponents of this method may seek to frame solar sail R&D as conducive to both planetary defense and to larger U.S. space policy. In addition to its role as a potential mitigation mechanism, solar sails can serve as a means of primary propulsion in conjunction with other planetary defense methods like the gravity tractor [82]. Alternatively, development of solar sail technology can support other mid/long-term national priorities such as Mars explorations [26]. In support of prioritizing planetary defense applications, the NEAScout mission should serve as valuable feedback for the problem stream, setting the basis for the design of an observational craft to aid in NEO characterization and mitigation tracking and assessment efforts.

5.3 "Exotic Designs"

Certain designs may become viable in the farther long-term and may even offer efficient or cost-effective means of planetary defense but entail steep requirements which prevent their implementation for foreseeable planning sessions. For example, one exotic design involves painting an oncoming NEO so that its albedo/solar radiation reflectivity increases, slightly influencing the orbit through the Yarkovsky effect [35]. Such a method may save on costs of more complex methodologies and proponents have also posited other albedo-based methods utilizing mirrors or similar means, but the comparative vulnerability and slowness of this overall design remains a significant limiting factor. Alternative designs exist as well, such as “Ion-beam Sheparding”, involving on-site projected plasma, redirecting the object without need for contact but still requiring propulsion towards interception and maintenance of accurate proximity to the NEO [17]. Again, this method requires significant R&D to improve ion-propulsion technology and may yet serve as a viable Phase 3 design but is simply far too less efficient than even some Phase 1 options for use as a purpose-built design. Overall, all exotic designs may be best left to tangential research, benefitting from advances in other planetary defense means. Policymakers may seek to avoid splitting funding away from more immediately usable paths, highlighting the likely difficulty of aligning the policy stream.

5.4 The Variable-Phase Option: Directed Energy

Directed Energy serves as a variable-phase option, not solely due to any technical variations, but rather due to questions of legality and normative considerations. The actual method involves ablation of the NEO, redirecting the target by vaporizing the surface layer [71]. The technology is scalable [50] and may function from alternate locations on ground, air, and space [51, 59]. A directed energy platform may also support existing planetary defense methods instead of serving as the sole mitigator itself. In the event of a NEO threat that is too imminent to deflect slowly via ablation or Phase 2 methods, a directed energy platform may enhance, through propulsion, an interception utilizing Phase 1 kinetic/nuclear/both methods [15]. Technically, therefore, policymakers may select a directed energy platform during Phase 1 as a support platform or later even as an independent mitigation method.

High-powered laser technology exists and has undergone considerable development, though much has been oriented towards military applications such as ballistic missile interception [43]. As such, the technology is inherently dual-use, and although no formal treaty bans the deployment of arms not deemed weapons of mass destruction, past executive, congressional, and international administrations have cautiously limited the weaponization of space (not to be confused with militarization of non-weaponized assets) [58, 60, 87]. While proponents may seek to reframe directed energy as a peaceful tool, it is also clearly within the (inter)national interest to avoid inadvertently triggering an arms race in space. Therefore, implementation of directed energy-based mitigation likely rests on the degree of international agreement or multilateralist tendencies of users. These factors seemingly indicate technology may be better reserved until such time as such consensus exists around its use or else space militarization from other sources precludes directed energy as a trigger. However, proponents may consider several factors which may support a feasible directed energy utilization.

There are major non-military and non-planetary defense applications for a directed energy platform, with a broadly researched proposal offering space debris management, communications, launch/orbit change/interplanetary transit propellants, and energy provision at up to one-fourth of total U.S. consumption (100 of 400 GWe) [48, 49, 51]. With such significant benefits available, directed energy suggests a strong fit for the no-regrets approach, serving valuable and peaceful purposes before, after, and in the absence of a planetary defense deployment. Making these benefits available internationally may outweigh their dual-use concerns. Some proposals using directed-energy consider international-scale infrastructure to operate the platform [20]. Compartmentalizing components has historically prevented defection from international asset-sharing partnerships, such as the International Space Station, and may legitimize the method while also preventing its abuse by opportunists [73].

Certain proposed formats for this method involve secondary assets far from readiness and incurring their own uncertainties. Such proposals include the use of mirrors to concentrate the directed energy onto a target as small/far as an oncoming NEO [20] or the construction of a lunar moon base to aim all projections solely toward space targets [72]. Such assets may involve significant expenses, suffer their own vulnerabilities, and may even be considered moot investments if the policymakers cannot overcome the controversy of the underlying application. However, these components may yet function within the context of a Phase 2-3 application. Secondary components may justify the directed energy approach on the grounds that their secondary functions will justify the costs of development. Alternatively, the secondary components may be the end goal into and of themselves, with directed energy instead serving as an on-call capability which they might fulfill during emergencies before reverting to research or productive purposes.

6.0 Future Directions

This study offers a foundation for method selection and decision-making towards programmatic design for planetary defense. However, there remain several further questions to answer and opportunities to explore. Many advantageous routes to comprehensive defense may benefit greatly from international cooperation, but there remain factors to consider in addition to the groundwork conditions considered here. In particular, the 2019 Pew Research survey has invaluably showcased the latent public support base for planetary defense within the United States. A similar study conducted either internationally or within prospective partner states could shed light on the degree of complementary interest elsewhere and verify the viability of promoting international cooperation via public demand. Furthermore, for our purposes, domestic, foreign, and international surveys could benefit from more questions focused on public perception of planetary defense specifically, instead of relative to other possible space priorities, allowing planners to gauge interest and support for specific methods or the multilateral approach. This information is an essential insight, as a potentially global problem may extend the national mood of the politics stream to an “international mood” that decides the availability or efficiency of certain options.

In the interest of limiting vulnerabilities that might dissuade attempts at cooperation, the risk of political opportunism merits greater attention. While international agreements may greatly limit state concerns and prevent misunderstandings through information transparency, there could remain incentives to take advantage of the situation or abuse planetary defense assets. Planners have offered certain generalized policies to limit such exposure here, but for thorough risk management, they may also identify specific paths to opportunism stemming from either mitigation methodology and/or circumstances during the crisis. Once identified, we may incorporate further issue-specific mechanisms to dissuade defection, building on previous proposals and the preliminary measures offered in this paper.

Domestically, a topic which may require greater investment is the concept of induced policy windows for planetary defense. A common theme across this paper is that waiting for natural circumstances to justify investment into improving our capabilities may limit options during a planetary defense campaign. We identified feedback-providing missions like DART, public outreach events such as Asteroid Day, and accessible informative programs including the *Asteroid Impact* film as existing means of improving the policy window through focusing events, but planners can also identify further opportunities to bring about opportunities for progress. Such opportunities may emerge from high up as well-situated policy entrepreneurs lend their support towards bringing about a practical window, or from below as grassroots efforts coalesce the resources of many to open a window together. Once advances on the scale of IAWN and SMPAG are possible without a Chelyabinsk-scale event as their trigger, we can perhaps more effectively manage the development of our planetary defense capabilities.

7.0 Conclusion

Planetary Defense is a statistically inevitable hazard; the question is not if we have to deal with the threat, but when. Research points to the utility of maintaining availability and readiness of defensive infrastructure in advance of the crisis, obligating proponents to consider the benefits and requirements achieving this capability. The conditions for advancing planetary defense are not only technical but also political, with projects posing considerable challenges due to the lack of perceived need for prioritization along with an atmosphere of heuristic policymaking and interstate competition in which proposals for progress must survive. The multiple streams approach provides a framework through which to predict the viability of certain methods of planetary defense, as well as strategies through which to promote useful designs which might otherwise go opposed and unused. In favor of the selection of a starting point from which to attain security and a platform for additional advancements, we considered a range of proposed options and identify both first phase options for threat-mitigation infrastructural development, as well as several conditional considerations which must factor into the policymaker’s eventual selection.

Policymakers may consider preparing to take advantage of the possible incoming policy windows through which to advance planetary defense and provide a modicum of security from which to build. First comes the insertion of planetary defense into the public consciousness. Entrepreneurs should align the political stream of public pressure by raising awareness of the hazard (perhaps assisted by the public release of an upcoming IMAX feature film). This opportunity will also allow planners to gauge the reaction and provide a modern and accurate assessment of the national mood, thus demonstrating the political foundation for progress. Then, this process should repeat and extend to promoting and measuring government interest (assisted upon arrival of the DART mission scheduled for 2022). A successful technical demonstration will provide an opening unparalleled in immediacy to reinforce topical awareness and end the misperception of planetary defense as an impossible investment. Together, these two intervals present the sole assured windows for planetary defense and may provide further chances to emphasize the prospects for planetary defense to catalyze space infrastructural advancement and the capability of a demonstrated methodology to jump-start this process.

The importance of public image to both method selection and a real-world threat mitigation campaign should not be underestimated. Beyond questions of technological feasibility, progress toward meaningful planetary defense cannot progress without broader support that can in turn promote deeper support. The most favorable conditions for planetary defense, from increased funding to multilateral cooperation, rely on far greater public pressure or executive investment than exists contemporarily. As such, just as proponents seek to maximize awareness of the great need for planetary defense and the many benefits its various approaches may offer, planners may minimize the vulnerabilities to criticism by avoiding large-scale and long-term investments that are difficult to advocate to legislators and the public so early into this endeavor. This proposal offers the option of an incremental approach, pursuing a series of tangible goals that meet policymakers' goals and keep the project flexible in its response to techno-political developments which may arise throughout the process. Our phased options, starting with a foundational option and attaining room for subsequent augmentations, may help transcend consideration of mitigation options as self-contained proposals. Such advocacy leaves room for opposition on the grounds of ambiguity, with respect to capability achievement, and denies opportunities for proposals to stand together where they might fail on their own. By considering the realistic first options we can achieve both sustained security and a foundation for the type of expansions envisioned by visionary planners and idealists. In favor of this path, we depict these potential projects as interconnected segments of an evolving planetary defense mission, which itself is part of the progressive position of humanity in space.

For all options, policy advocates and entrepreneurs may strategically amplify favorable policies that risk inattention behind solely-technological assessments. Domestically, one such potential approach lies in coupling the compatibility of planetary defense with American and international commercial and security goals set forth in the last decade's space policy and legislation. Cumulatively, this means that policies that advance space safety, coordination, cooperation, and commercialization are the more likely to not only attain a foundation for support, but also grow into a truly self-sustaining space program. Defense efforts will benefit if they escape the perception of planetary defense as a risky money-sink and transform the project into a supplementary measure towards the stated goal of advancing the position of humanity in space. We may pursue this approach through incorporation of the economic, infrastructural, and technological byproducts into planetary defense proposals, advancing towards the society-shaping projects to which planetary defense can contribute.

The beginnings of a planetary defense initiative are already in place, ready to catalyze progress towards a range of national and/or multilateral means of protection against NEOs. However, proceeding to the next stage requires careful consideration of the policy conditions needed in addition to the required technological components. During this critical stage, advocates of planetary defense may prepare to both set the strongest foundation to draw support and take advantage of developments as they occur, attaining the optimal readiness for the arrival of incoming policy windows and aligning the streams as needed to help remedy one of the most dangerous yet solvable issues in our history.

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