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PLANETARY DEFENSE AGAINST ASTEROID STRIKES: RISKS, OPTIONS, AND COSTS

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Foreword

The potentially severe consequences of an impact by a near Earth object (NEO) require proactive planning. This paper addresses a hypothetical asteroid impact and options for launching a mission to deflect or destroy it. The decision to launch such a mission must consider not only the nature of the threat and the odds of success, but the possibility of inadvertently shifting risk from one location to another. Decisions made today regarding mitigation capability can considerably reduce the future NEO hazard and help ensure national and international safety.

Introduction

Significant asteroid impacts are indeed far between, which has led to a perceived lack of urgency. Although a damaging event tomorrow is unlikely, should one occur, it would change life locally, regionally, and beyond. Both likelihood and magnitude determine risk. Deciding how to respond to a particular NEO risk depends on the physical and temporal parameters of the object as well as the state of preparation, locally and globally. A process that begins well in advance of an impact will greatly assist and inform real-time decisions. The likelihood of impact, the impact corridor, the extent of possible damage, the existing mitigation capacity, the resources needed to develop or extend such capacity, the size of the mitigation campaign, the global coordination necessary, and the information different groups will need to fulfill their respective tasks are all factors a decision-maker will need to know at the onset of a threat.

The basic outline for handling an asteroid threat, with steps for decision-makers, was put in place as far back as the early 2000s.[1,2,3] What the authors wish to bring to the discussion is a new perspective from within the decision-making process aimed at improving the chances of success of a planetary defense mission while limiting the overall cost.

A Multinational Challenge

Figure 1 depicts a typical deflection mission scenario in which a spacecraft is launched and intercepts the asteroid to nudge it off course and avert impact with Earth. Within the United States, there are two primary schools of thought on how to undertake such a mission.[4] One option would be for the United States to deal with the threat on its own—which would not be unrealistic, considering the country's technological advantages. A second option would be for an international agency to coordinate the response. A notable concern is that sharing technology with foreign states could allow exploitation and misuse in a fashion that goes against national interests. The challenge, then, is to establish such an agency without compromising the advantages of any one nation. Such an approach, if successful, could counterbalance possible risks through strict compartmentalization of state-specific components. Contributions in nonthreatening areas, such as logistics and funding, can potentially serve as the necessary support where unwanted dissemination of information is a risk.

In addressing asteroid threats, the first step is recognition and analysis. Communities at risk will need to raise awareness within their respective borders and coordinate local preparations and cooperative actions. This is especially important for any threat whose potential

A Crash Course In NEOs

MILLIONS of rocky or metallic bodies orbit the sun, primarily in a belt between Mars and Jupiter known as the asteroid belt. Ejected fragments from collisions in this belt are the predominant source of Earth-approaching asteroids. Comets originate from the outer region of the solar system, but occasionally have elliptical orbits that bring them closer to the sun, potentially crossing Earth's orbit. Together, asteroids and comets that pass within 45 million kilometers (km) of Earth's orbit are classified as Near Earth Objects (NEOs); some collide with our planet.[5]

The most recent noteworthy event occurred on Feb. 15, 2013. A small 18-meter object performed a shallow entry into the atmosphere and exploded 23 km above the city of Chelyabinsk, Russia, with the force of 30 atomic bombs, blowing out windows, destroying buildings, and injuring more than 1,000 people. Had the object entered at a steeper angle, the damage on the ground would still be local but more severe. Recent research suggests that Chelyabinsk-type events occur every 30 to 40 years, with a greater likelihood of impact over the ocean than over populated areas.[6]

In the morning of June 30, 1908, a space rock 30–40 meters across entered the atmosphere over Siberia, Russia, and detonated in the sky, producing a fireball and releasing energy equivalent to about 185 Hiroshima bombs.[7] About 2,000 km^2 of remote forest consisting of 80 million trees were on their sides, lying burnt in a radial pattern away from the blast's epicenter. Such an explosion would badly damage Washington, DC, and New York City, whose metropolitan land areas are 3,400 and 9,000 km^2, respectively.[8]

The probability of larger objects striking Earth is extremely remote, but the consequences could be severe. In a close call on Oct. 31, 2015, a 600-meter asteroid (2015 TB145) passed at about 1.3 times the distance from Earth to the moon (480,000 km) with a speed of 126,000 km/hr.[9] If this object had struck Earth, the effects at a distance of 100 km from impact would include 7.5 Richter Scale seismic effects, third-degree burns for exposed individuals, and the collapse of multistory buildings.[10] An ocean impact 100 km offshore would generate tsunami waves 18 to 37 meters high, arriving roughly 17 minutes after impact.

impact location runs through nations incapable of mounting significant deflection or destruction efforts. This remains a likely condition, considering that only 10 of the 193 United Nations members have developed the capacity to launch satellites into space.[11,12] Only five nations (the United States, Russia, India, Japan, and China) and one international organization (the European Space Agency) have the capability to conduct interplanetary launches. Thus, nearly 190 member countries remain entirely incapable of self-defense. For these countries, international cooperation is essential.

One effective early-phase measure the international community could undertake is to ensure that the crisis is not handled in a segregated fashion. Spreading the effort among a number of willing contributors can limit the cost and risk. The cost of building a kinetic impactor spacecraft is dependent on how much mass needs to be delivered. Launch vehicle costs range from roughly $270 million to $450 million for commercially available launch service providers, so a deflection campaign comes at a steep cost of about $1 billion per launch.[13] Implementing a policy of planetary defense as a global effort allows the application of technological, economic, intellectual, and political resources of many nations. A unified international front that passively monitors threats on a continuing basis and that can be mobilized to handle active threats upon detection could greatly enhance flexibility in handling a greater variety of NEO threats.

Present-day predictions of future scenarios are invariably inaccurate due to the magnitude of variables involved.[14] Therefore, a notable option for the international community is to take various proactive measures to enhance planetary defense capabilities. These

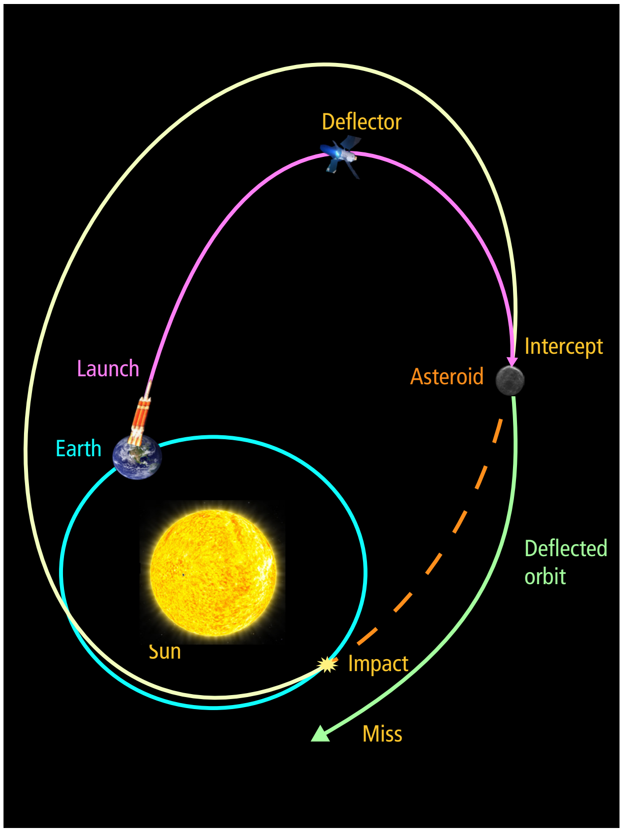

Figure 1: Notional asteroid deflection mission. A NEO with the potential to hit Earth would swing by many times before striking, possibly allowing several opportunities to counter the threat.

include funding research and development of observatory infrastructure to enhance threat-detection capacity (which is already underway) as well as improving launch vehicles and payloads to optimize capability of deflection. Any minimization of reaction time, development of new technology, and construction of necessary infrastructure is invaluable in planetary defense. Having a deflection and delivery system in place at the onset of a threat could lower the response period, and therefore the overall risk. Because certainty of impact is low at the beginning of threat detection and analysis, the preexistence of necessary infrastructure provides greater maneuverability throughout the preparation. Advance planning increases options, readies physical components, limits supplementary construction time, and establishes political ties to help maximize efficiency.

Creating a unified nonpolitical organization specifically aimed at global protection from NEOs could greatly decrease the amount of bureaucracy and differences among separate measures set in place by individual nations. In a crisis where the potential cost is so high and the time for action so limited, unity and coherence in response is not only desirable but essential. Coordinated communication and action could help reduce misinterpretation and prevent a general state of panic at the onset of the crisis when uncertainty is high and misinformation prevails.

There are, however, factors that should be considered for an effective membership to form. Many countries currently lacking space-capable infrastructure are unable to afford such institutions. The NEO threat does not distinguish between political boundaries, so these nations remain at risk, and would benefit from membership. To compensate spacefaring nations for the additional burden of protection, these countries could still provide materials, funds, facilities, and specialists to the proposed agency.

Belonging to such a collection of nations could benefit nonspacefaring member states by advancing their technological capabilities, allowing greater future contribution to exoatmospheric endeavors and creating practical technologies. Past orbital experiments have produced now-commonplace discoveries such as freeze-dried food, solar cells, and temper foam.[15] Future research in the field of planetary defense could likewise produce useful advances in aerospace equipment and other related technologies. With the rise of private interest in extraterrestrial resources, participation in planetary defense could open numerous states to greater economic development and contribute to global stability.

Domestic organizations, both governmental and private, could also contribute. The Air Force has traditionally fulfilled the role of aerospace defense for the United States, and could fill a niche role in the American component. The Air Force already maintains advanced orbital assets and retains invaluable experience and equipment in this field.[16] The military could stand to further improve those resources through the knowledge gained from developing an effective NEO impact prevention capability.

Implementing a Deflection Mission

Experimental missions involving asteroids include the recently canceled Asteroid Redirect Mission (ARM)[17] and Asteroid Retrieval Robotic Mission (ARRM),[18] intended to capture a boulder from a distant asteroid and bring it to a stable orbit around the moon. Similarly notable is the proposal of a joint NASA-ESA mission, the Asteroid Impact and Deflection Assessment (AIDA),[19] which would attempt to deflect the moon of an asteroid via high-energy kinetic impact. These missions would demonstrate key elements of planetary defense methodology, including the ability to reach and manipulate asteroids.[20] Survey data from an ARM/ARRM mission would provide much needed information on the characteristics of threatening bodies.[21] An ARM/ARRM mission or a future variant could serve as a precursor to a real NEO deflection effort and demonstrate the capabilities of available assets and identify necessary improvements. The fact remains that no asteroid redirection mission has ever been undertaken; as such, missions such as ARM/ARRM are the only way to assess and advance the capability needed to execute one with precision. Likewise, the proposed AIDA mission could prove invaluable in improving and testing a deflection capability.

The kinetic deflector remains one of the simplest, most affordable, and technologically available proposed methods of asteroid deflection,[22] and would be tested in depth by an AIDA mission. Alternatively, survey and postmission data from a successful NEO deflection would assist in any future ARM/ARRM or AIDA mission or comparable project. Therefore, the goals of these programs, while distinct, complement each other. Without predecessor missions, ARM/ARRM and AIDA missions depend on each other for practical physical data. Thus, a certain synergy could arise in which the benefits of planetary defense efforts are maximized to justify the inevitable costs and complications. To make up for the distinct difference in funding between national space programs and other budgetary priorities—a condition that exists among all spacefaring nations—the objectives of planetary defense could be tied to those of comparable and related projects to build widespread support.

Involving private enterprises in planetary defense could also boost commercial expansion in space. Private-sector investment in interplanetary endeavors is needed to further advance technologies and operations applicable to NEO mitigation and, in turn, greatly improve global security. Private enterprises have reason to invest in these endeavors, both as a measure to safeguard their own corporate infrastructure and as an opportunity to pursue government funding and contracts. The growth of companies such as SpaceX demonstrates the possibility of creating an atmosphere for financial success within the aerospace community. Advances in reusable rocketry (such as the Falcon 9 launch vehicle) have shown that private companies can make influential steps to make the future of space investments far more feasible financially and materially. Securing the assistance of such private investors, in combination with government resources, would both further the efforts of the planetary defense program itself and support the growth of public interest and investment in space.

Simulated NEO Impact Scenario Decisions

The International Academy of Astronautics 2017 Planetary Defense Conference (PDC17) brought together experts on what is known about asteroids and comets that might impact the planet, the consequences of such an impact, how such a threat might be mitigated, and the political factors that could affect a decision to take action. Conference attendees participated in a realistic exercise designed to illustrate how an asteroid threat might evolve and explored the decision-making and disaster mitigation and response challenges. The exercise was based on a fictional asteroid projected to strike Earth in 10 years.[23] The orbit for the central point of the risk corridor was loaded into the NASA/JPL NEO Deflection App, an online tool that allows users to study the velocity change required to deflect an object away from Earth as a function of time.[24]

Involving private enterprises in planetary defense could also boost commercial expansion in space.…

The NEO Deflection App showed three launch opportunities over the decade: immediately upon discovery, and afterward every approximately 1200–1300 days. At the point immediately following discovery, an asteroid at the low to mid ranges of size and density could be deflected with a single Atlas V vehicle (see Table 1). The benefit of such a mission would be questionable, as the projected impact probability at this time is only one in a hundred at best. In any case, the United States does not maintain planetary defense rockets on alert status, nor

Table 1: Minimum Launch Effort Needed to Deflect a PDC17-Type Asteroid of Varying Size and Composition

Asteroid Composition Launch Period	Porous Rock (100 m)	Porous Rock (250 m)	Dense Rock (100 m)	Dense Rock (250 m)	Iron (100 m)	Iron (250 m)
Early Launch Opportunity (3750 days until Earth impact, 100 days from launch to intercept)	1 Atlas V	1 Atlas V	1 Atlas V	2 Atlas V or 1 Delta IV	1 Atlas V	5 Atlas V or 3 Delta IV
Middle Launch Opportunity (2450 days until Earth impact, 375 days from launch to intercept)	1 Atlas V	2 Atlas V or 1 Delta IV	1 Atlas V	3 Atlas V or 2 Delta IV	1 Atlas V	7 Atlas V or 5 Delta IV or 1 SLS
Late Launch Opportunity (1250 days until Earth impact, 200 days from launch to intercept)	1 Atlas V	3 Atlas V or 2 Delta IV	1 Atlas V	5 Atlas V or 3 Delta IV or 1 SLS	1 Atlas V	15 Atlas V or 10 Delta IV or 2 SLS

This table presents the main parameters for the PDC17 asteroid threat, as well as the minimum launch vehicle requirements. Object density is lowest for porous rock and highest for iron. The launch opportunity describes the number of days until Earth impact/days from Earth launch until NEO interception within the early, middle, and late launch windows. Foreign launchers, Falcon Heavy, and other experimental models are not shown; values for the Falcon Heavy and Delta IV Heavy, as modeled in the NEO Deflection App, serve as comparable heavy-lifters and can be considered interchangeable for the purposes of this physical model.

does it have a stock of kinetic delivery devices; consequently, responding immediately upon discovery would not be possible. The second launch period, standing at approximately 7.5 years from projected impact, would require greater effort to deflect the approaching object to a statistically adequate miss. The task could be accomplished with either two Atlas V vehicles or a single Delta IV. Here, the cost of deflection rises dramatically, possibly even doubling. Finally, at approximately four years before impact, there is a launch window in which the asteroid is particularly close to impact, and therefore requires heavy deflection to reach adequate orbital shift for a miss. Specifically, the options here would be three Atlas V vehicles, two Delta IV launches, or a NASA SLS lifter (the SLS is still in the R&D stage, and as such, remains a hypothetical option).

Simplified, an asteroid threat of this type gives a spectrum of options with pros and cons. Earlier launches are the least expensive, but most likely to be wasted on nonthreats; later launches are more expensive, but allow greater time to prepare and to verify the need. In a scenario when launch periods are more limited, possibly to a single time close to discovery, the first launch period may be the only deflection option. In this case, the lack of a constantly available interceptor ready at a launch facility would be a notable weakness. If lifter rockets and standard kinetic deflection vehicles (once an accepted design is manufactured) can be put into limited production, then rapid assembly and early launch can remain a viable option, unlike in the PDC17 case.

In most actual NEO threats, impact probability will be negligible after additional measurements are made. In such cases, the need for deflection can possibly vanish after the interceptor has already launched. To avert at least some of this waste, deflection devices could be designed with secondary objectives that could be activated in the event of an aborted deflection. These could include finding and characterizing unknown NEOs and identifying opportunities for space mining, scientific study, and commerce. Also, instead of multipurpose deflectors, dedicated reconnaissance probes could be launched during this early launch period to provide data needed to improve subsequent launches, or even to disprove the need for further launches at all.

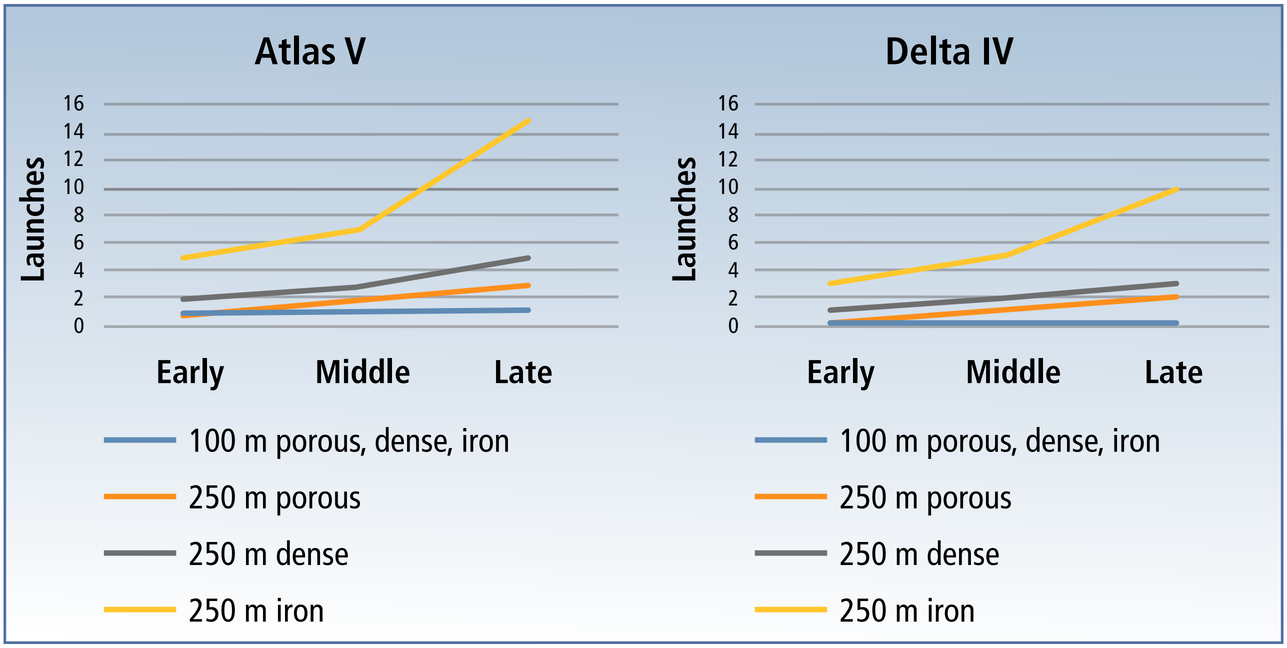

Figure 2: Minimum launch requirements needed to deflect an asteroid of varying size and composition, as modeled by the NEO Deflection App.

Within the parameters of the PDC17 scenario, the technology and equipment required to successfully launch a device to deflect an approaching object exists and includes models that have been both tested and used on numerous missions (with the exception of the SLS). Therefore, such a mission could be undertaken by the United States alone. However, the cost of deflecting larger and denser objects highlights the need to consider alternatives (see Figure 2). While technically feasible, the cost of up to 15 Atlas V or 10 Delta IV lifters might not be politically or economically feasible for one nation. The PDC17 scenario presented multiple opportunities for international cooperation. The projected impact corridor ran primarily along the northern hemisphere and included multiple national capitals, including Copenhagen, Beijing, and Tokyo as well as populated regions in the United Kingdom, western Russia, and East Asia. All these nations faced the risk of an asteroid impact that could cause a thermal-kinetic explosion in the multi-megaton range. Thus, in the exercise, securing their support was relatively simple, and provided greater flexibility in deflection options. Of course, if such ties had been in place before detection, then the analysis and deflection effort could have begun immediately, rather than waiting until such ties could be established.

The European Space Agency, Roscosmos State Corporation of Russia, the Japanese Aerospace Exploration Agency, and the Chinese National Space Agency all maintain launch capability, allowing them to provide vehicles for deflection devices or similar resources as probability of impact rises. Governments and militaries around the world dedicate significant funds to maintain programs that detect and defend against human-produced threats. Since an inbound asteroid could cause as much damage as a nuclear weapon, a similar amount of support could be dedicated to handling a NEO threat. The argument that the early low-probability of interception makes such investment unviable may be countered by the fact that the United States already takes steps to protect against low-probability crises, human-based or otherwise, through agencies such as FEMA and the CDC, though natural disasters and pandemics are not common. Since agencies already exist to handle low-probability/high-consequence threats, similar protective measures could be considered, possibly with the designation of NEOs as a hazard comparable to those within the jurisdiction of existing agencies.

Recognizing that the first launch period comes with risk of waste and that the third launch period may require either great expense or international cooperation, if the United States wanted to handle the PDC17 crisis single-handedly, the best approach may be to conduct necessary research on the NEO and prepare a lifter and a kinetic delivery vehicle for the second launch period. Atlas V, Delta IV, and Falcon 9 launches are commonplace, and the technology used in kinetic deflection is achievable with today's standards. Therefore, a purely American undertaking in deflecting PDC17 in the second launch period would be possible. However, since the United States is not under direct threat in the PDC17 scenario, and since no clear jurisdiction exists for such a situation, the legality of American involvement is unclear. Instead, to avoid political complications, the United States could declare that protection of the threatened nations is within its national interests and offer its significant resources in conducting a joint operation. This could be done in coordination with the UN-endorsed Space Mission Planning Advisory Group and the International Asteroid Warning Network, which are independent bodies of the world's national space agencies.[25] U.S. investment in mitigating a threat to primarily Eurasian nations may imply an investment in all asteroid threats, and could set the perception that the United States will take the lead on all planetary defense missions, or will support international cooperation on NEO threats worldwide. By doing so, an approach based on altruism can be established, and possibly promote similar attitudes internationally.

International association does not, however, change the situational physical/technological requirements. It does, instead, make a launch during the second period more affordable, and perhaps even more importantly, raises the third period as a realistic option. Through international support, the burden of developing and maintaining equipment such as the SLS and comparable lifters can be spread among multiple participants. Delta IV and comparable heavy lifters remain in use, or are in development by other spacefaring nations, and, along with U.S. development of kinetic deflectors, can be mobilized more quickly and with greater effectiveness.

Conclusion

Typical NEO threats have high initial orbital uncertainty and low impact likelihood that rises over time and eventually drops as additional measurements are made. Decisions on what actions to take, or not, must be made at the onset of the threat when uncertainty is high, considering the potentially severe consequences that rare impactors may inflict.

The PDC17 scenario illustrates the steps that can be taken to deflect a typical NEO. Analytic probes or kinetic deflectors can be launched at the intervals highlighted, and experimental designs can be further developed for possible late-scenario use—but the real decision involves the procedural execution of these steps. The United States could unilaterally deflect the scenario's NEO with modern technology, but it could also pursue international and unified responses to both this example danger and potential real ones in the future. By developing measures to strengthen international cooperation on handling the fictional PDC17 asteroid, the groundwork can be laid for a real version in the near future for use in real situations.

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