Architecture for Mitigating Short-Term Warning Cosmic Threats: READI Project

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Abstract— Earth is being constantly bombarded by a large variety of celestial bodies and has been since its formation 4.5 billion years ago. Among those bodies, mainly asteroids and comets, there are those that have the potential to create large scale destruction upon impact. The only extinction-level impact recorded to date was 65 million years ago, during the era of dinosaurs. The probability of another extinction-level, or even city-killer, impact may be negligible, but the consequences can be severe for the biosphere and for our species. Therefore it is highly imperative for us to be prepared for such a devastating impact in the near future, especially since humanity is at the threshold of wielding technologies that allow us to do so. Majority of scientists, engineers, and policymakers have focused on long-term strategies and warning periods for Earth orbit crossing Near-Earth Objects (NEOs), and have suggested methods and policies to tackle such problems. However, less attention has been paid to short warning period NEO threats. Such NEOs test current technological and international cooperation capabilities in protecting ourselves, and can create unpredictable devastation ranging from local to global scale. The most recent example is the Chelyabinsk incident in Russia. This event has provided a wakeup call for space agencies and governments around the world towards establishing a Planetary Defense Program.

The Roadmap for EArth Defense Initiative (READI) is a project by a team of international, intercultural, and interdisciplinary participants of the International Space University's Space Studies Program 2015 hosted by Ohio University, Athens, OH proposing a roadmap for space agencies, governments, and the general public to tackle NEOs with a short warning before impact.

Taking READI as a baseline, this paper presents a technical description of methodologies proposed for detection and impact mitigation of a medium-sized comet (up to 800m across) with a short-warning period of two years on a collision course with Earth. The hypothetical comet is on a highly-inclined orbit having a high probability for Earth impact after its perihelion. For detection, we propose a space-based infrared detection system consisting of two satellites located at the Earth-Moon Lagrange points L1 and L2 coupled with space observatories, like the James Webb telescope and the Centennial telescope. These telescopes are supported by ground-based telescopes, like the Arecibo and Green Bank telescope, in the search for NEOs. Upon detection, the comet is tracked constantly using space- and ground-based telescopes. The deflection system is two-pronged, firstly involving the use of a high energy Directed Energy Laser Terminals (DELT) placed at Sun-Earth Lagrange points L4 and L5 so as to initiate and increase the ablation rate of the comet and deviate it from its collision trajectory, and secondly by the Hypervelocity Comet Intercept Vehicle (HCIV), a space-borne system combining a kinetic impactor with a thermonuclear device. The policy and international collaboration aspects to implement these methods are also outlined in the paper. The techniques mentioned could also be applied to mitigate medium-to-large sized asteroids (up to 2km across).

Keywords: Planetary Defense, Earth Protection, Comets, Asteroids, NEO, PHO, Short-Term Warning, ISU, SSP15.

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1. INTRODUCTION

Earth is known as the cradle of life and protects its inhabitants from external threats. Despite a thick atmosphere and a magnetosphere, it cannot protect against all hazards, in particular significant cosmic hazards. The potential dangers associated with high energy impacts from NEOs pose a real threat to life on Earth. One of the major extinction events known as the K-T extinction occurred 65 million years ago, when a large comet struck the Earth causing a mega tsunami forming a crater in what is now the Yucatan Peninsula in

Mexico [2]. There are numerous other smaller impacts that have not been reported or documented, but occur more frequently. Events like Tunguska in 1908 [1, 2, 3] and Chelyabinsk in 2013 demonstrate that consequences from impacts of such threats are more drastic than the public usually believes. Although the Chelyabinsk incident obtained temporary international attention, it failed to effectively stimulate space agencies, governments, policy makers and the public to action.

Current technologies have reached the point where it is plausible for humans to take a proactive role in defending Earth. As such, it is critical for humanity to conduct studies and develop the necessary technologies to protect our planet. It is also essential to ensure that people are educated on the threat so they can make informed decisions. Governments and non-governmental groups need to collaborate much more, and must accept that impacts will occur in the future and be ready to mitigate the threat or respond to the resulting devastation. Any Planetary Defense program will require a huge effort, time, and support to be successful, and it demands increased global attention.

Planetary Defense was one of the team projects participants worked on at International Space University-Space Studies Program, 2015. The combined effort of 34 participants from 17 different countries was an Earth protection proposal called Roadmap for Earth Defense Initiative (READI). READI identifies five elements of Planetary Defense and discusses in depth potential solutions for each [1]. The elements covered are:

- Detection: The detection of NEOs and Long Period Comets (LPCs) is the first fundamental step in preventing hazardous objects from impacting Earth. After detection, the tracking phase becomes the most important, since a precise orbital determination is fundamental for implementing a successful defense strategy. This is pursued through professional ground and space-based telescopes that observe the sky in the visible and infrared bands.

- Deflection: We selected innovative, but feasible technical ideas inspired by an extensive literature review of existing concepts. These mainly revolve around the use of thermonuclear devices, and Directed Energy Systems (DES). The need for highly redundant and robust mitigation architecture led the group to also investigate ground-based solutions that would act as a last line of defense. We emphasized the need to overcome numerous political and economic hurdles to increase the Technology Readiness Level (TRL) of the proposed solutions. Even though further analyses are required to assess the technical feasibility of the proposed scenarios, we highlight the main needs in order to increase the chances of success in such missions.

- Global Collaboration: The most important challenge is the establishment of new norms and a legal basis for action in the case of an imminent impact threat. The second challenge would be the creation of an advisory body that would oversee the implementation of a Planetary Defense Program and provide advice to the United Nations Security Council (UNSC). We recommend taking immediate action in these areas because establishing international consensus could be a lengthy process, and that time is needed for the internalization of our newly proposed norms as a moral obligation.

- Outreach and Education: READI aimed to increase interest in Planetary Defense among children and students. Targeting this demographic provides access to future active members of society, and will likely involve their parents indirectly. We considered an educational campaign as being twofold. First, it brings the threat of cosmic impacts to the general public in a way that provides scientifically accurate information to decrease the risk of misunderstanding and opposition when actions are needed. Second, it contributes to the Science, Technology, Engineering, Arts and Mathematics (STEAM) movement by bringing science and engineering education to the youth through the arts, which could in return lead to new creative and innovative approaches to Planetary Defense.

- Evacuation and Recovery: According to the threat characteristics, asteroid and comet impact responses will differ from typical disaster response techniques. With most asteroid or comet threats, the timely identification of the point of impact seriously affects the successful implementation of evacuation and shelter allocation. The best scenario for saving as many citizens as possible is to start evacuation days prior to the impact. To minimize loss of life and ecosystems, disaster preparations must be developed at different scales, and global collaboration will be useful in the case of large city-killer threats. New techniques for shelter design and remote sensing are also required to assist with recovery efforts. Our investigation of evacuation and recovery shows that this is a critical element of Planetary Defense that does not get enough focus yet, in order to see significant improvements.

2. TECHNICAL BACKGROUND

NEOs are asteroids or comets that orbit the Sun with a closest distance to it (perihelion) of 1.3 Astronomical Unit (AU) or less [3], while LPCs are comets with periods greater than 200 years. Asteroids and comets are thought to be relatively unchanged remnants of the primordial phase of the Solar System formation that were not accreted onto planets about 4.6 billion years ago.

Most asteroids are rocky bodies, with a minority composed of metal, principally nickel and iron. These celestial objects range from very small sizes (some less than meters across) to hundreds of kilometers in diameter. They generally orbit the Sun in a region between Mars and Jupiter. Asteroids, classified as NEOs, can be found in four types of orbits: the Atiras and Amors orbits come close to Earth but never cross its orbit, while the Atens and the Apollos have Earth-crossing trajectories and have a higher chance of impacting our planet.

Comets on the other hand are made of ice, rock, and organic compounds, and are often only a few kilometers or less in size. They mainly exist in the outer Solar System, in the Kuiper Belt and the Oort Cloud. Oort Cloud comets can enter into an orbital course around the Sun with any inclination with respect to Earth's orbital plane due to the Oort Cloud being spherical. These are called LPCs because they orbit the Sun in elliptical trajectories with orbital period ranging from 200 years to several million years. The short-period comets that exist in the Kuiper Belt periodically approach the Sun in orbits with periods of under 200 years with inclinations generally close to Earth's orbital plane [4] and they are included within the NEO category if they fulfill the perihelion criterion.

Figure 1 shows the number of expected Near-Earth Asteroids (NEAs) and their estimated impact interval vs. their diameter, the expected impact energy, and their absolute magnitude (brightness). The red solid line represents the number of detected objects as of 2014.
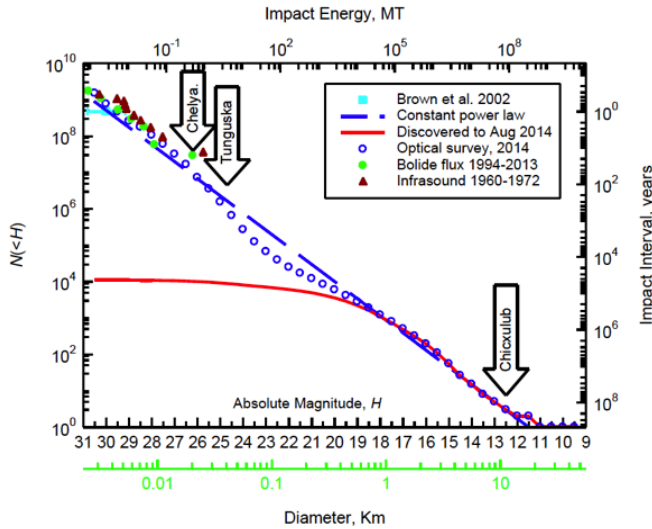
Figure 1. Near Earth Asteroids (NEA) Impact Interval vs. Diameter and Impact Energy [27]

Almost all of the biggest objects, greater than 1km in diameter, have already been discovered. An impact from any of these objects could create a global extinction event [5], but none of those detected currently threaten Earth, and their estimated probability between impacts is in the millions of years. On the other hand, objects smaller than 20m in diameter may disintegrate in the atmosphere and create no damage on the ground, but impact Earth at least once a

century. The most threatening asteroids are those between 20m and about 800m in diameter. The extremes of this range have either very high impact intervals or very low impact energies, but the objects in between are mostly undetected, which means they can impact Earth with little to no notice, and they can destroy a city or even devastate a whole region [1]. Comets are expected to have a similar mathematical distribution according to size [6] but have much lower impact rates [7]. The same reasoning as for asteroids can be applied to them regarding size and threat, but LPCs present an added challenge: they rarely come into the inner Solar System, and spend very little time there compared to the rest of their orbit, making their approaches to Earth essentially unpredictable. They also have higher velocities relative to Earth and therefore deliver more energy on impact. These two reasons make it necessary to be prepared for comets of larger sizes than asteroids.

3. PROBLEM STATEMENT

From the engineering aspect of Planetary Defense, current technologies need further development. Moreover, to effectively detect and mitigate asteroid and comet threats, we must increase TRL and Operational Readiness Levels (ORL) of current technologies. The human side of the Planetary Defense problem also presents an incredibly complex challenge. Therefore, it is critical to frame the context of our approach to Planetary Defense by bounding the problem and making it manageable. We used a specific set of elements as the foundation for our analysis to enable us to develop solutions for a limited range of problems, rather than a broader perspective of Planetary Defense. The most important bounding factor to our focus is that we are looking at a short-warning threat. We constrained ourselves to two years from the time of detection until impact.

We chose to look at solutions that address threats within a determined range in size because of the limits to our current technological and operational capabilities. As mentioned earlier, asteroids between 20m and 800m in diameter are the most threatening to Earth, but regarding comets it is important to be prepared to deal with bigger sizes. Comets come with much higher velocities relative to Earth due to their highly elliptical trajectories spend little time in the inner Solar System where they are visible before they pass near or potentially collide with Earth. Even if an impact from a bigger object is highly unlikely, the limited warning time and high energy motivated us to ensure that our solutions mitigate comets up to 2km. Our solutions deal with both asteroids and comets, since they represent similar threats to the planet, so our final bounding factor of our scope ranges from 20m to 2km in diameter.

4. DETECTION

As Potentially Hazardous Objects (PHOs) are results of cosmic activities, they are different in size, velocity and composition. Those parameters are unknown before or at the

initial stage of detection. Cosmic trajectories have many parameters and these parameters are very important to all mitigation strategies and in particular for deflection. However, there are still uncertainties in these parameters due to the lack of the detection capabilities. Hence, more efforts are needed to be implemented in order to increase the capability of the early detection of NEOs.

Comet Trajectory

We selected a comet with a realistic size of 800m across on an impact trajectory with the Earth. The comet has the following orbital parameters [21]:

- Inclination: 174 degrees to J2000 ecliptic
- Semi-major axis: 34.24 AU
- Eccentricity: 0.992
- Perihelion: 0.27 AU
- Aphelion: 68.15 AU
- Period: 200 years

PHO tracking is very important for any Planetary Defense program. For comets, tracking is crucial because they exhibit increased activity near perihelion. Even after the comet has passed through perihelion, it is possible that the comet fragments. In the case of asteroids, tracking continues to improve our knowledge of the object's orbit. Figure 2 shows the initial trajectory of the comet using MATLAB. Further simulations have been done using Systems Tool Kit (STK) using the above orbital parameters.
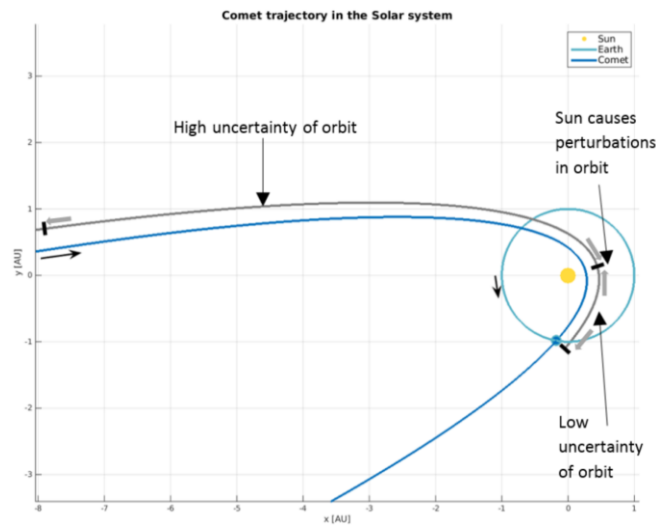

Figure 2. Comet path on an impact trajectory with the Earth

5. DEFLECTION

There are many proposed solutions for cosmic threats in the literature however none of them reached the point where they are feasible and cost-effective to be implemented as mitigation strategies for cosmic threats. NASA, ESA and independent researchers have proposed different options to deflect cosmic threats that include using lasers to cause ablation, nuclear explosives, gravity tractors, and even painting asteroids and comets.

The authors reviewed and analyzed the different proposed solution techniques, looked at the most promising methods and ranked them based on their feasibility (technical, cost-effective and ethical) for a given PHO, the warning time (time from detection to impact) and the required development time of the chosen technology. Three development periods have been chosen that are up to 2 years, 2-10 years and more than 10 years. Development time up to 2 years was taken as a worst case scenario because it is a very short time to design, develop and launch the solution to deflect a PHO in, compared to time period more than 10 years which is considered to be the best case scenario as it provides enough time to test the proposed system in space and improve the TRL. Table 1 presents a tradeoff of deflection techniques along with grades from 0 to 10 to give an indication of the feasibility level or a performance map for a comet or an asteroid that might impact Earth in the near future, taking into account development time. The higher the grade the more feasible it is deflect certain PHOs [20, 23].

**Table 1. Table presenting all the major Deflection Strategies**

GRADE /10	Distance Action							Contact Action						Combination					
	Active				Passive			Active				Passive							
Threat	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
20-40m	4	7	4	2	6	4	5	5	5	7	7	3	1	3	0	6	4	6	5
40-100m	3	8	3	1	4	4	4	2	0	4	6	1	0	4	0	7	5	7	2
100-140m	2	9	0	0	2	2	2	0	0	1	5	0	0	5	3	6	5	8	1
140-200m	1	9	0	0	1	1	1	0	0	0	2	0	0	6	4	4	3	9	0
500m	0	6	0	0	0	0	0	0	0	0	1	0	0	4	5	2	1	9	0
>1km	0	4	0	0	0	0	0	0	0	0	0	0	0	4	5	1	0	9	0
Comet	0	4	0	0	0	0	0	0	0	0	0	0	0	3	2	0	0	9	0
Grade /70	10	47	7	3	13	11	12	7	5	12	21	4	1	29	19	26	18	57	8

A	**Painting**
B	**Nuclear deflection**
C	**Laser ablation**
D	**Ion Beam deflection**
E	**Solar concentrator**
F	**Gravity Tractor**
G	**Sun Shade**
H	**Robotic Arm**
I	**Net**
J	**Lander Chemical Thruster**
K	**Kinetic**
L	**Solar Sail**
M	**Electrical Sail**
N	**Asteroid mining (send spacecraft)**
O	**Asteroid mining (send humans)**
P	**Swiss army knife swarm spacecraft (Gravity tractor + Painting + Solar concentrator)**
Q	**Multi-landers solution (type Rosetta-Philae) + Explosive**
R	**Orion-like solution (Nuclear bombs + spacecraft (umbrella) that lands on the target to increase the efficiency)**
S	**Combination (Robotic Arm + Net)**

Directed Energy Systems (DES):

After reviewing the above deflection methods, we suggest the use of the Directed Energy Systems (DES) as sustainable mitigation architecture. The DES can be used as a contactless tool to deflect comets and asteroids as it uses high-power pulsed laser beams to heat up the object and increase its surface temperature thereby vaporizing the surface. The DES technique requires relatively long-time interactions thus early detection of the cosmic threat is essential. DES are currently applied for military purposes therefore the technology exists but has not reached the readiness level for PHO deflection [9, 25, 26, 28]. Techniques can be used to amplify the laser power and produce a very high-power laser beam which is essential to raise its surface temperature to the evaporation temperature, Figure 3. The evaporated material from the target generates thrusts that delivers delta-V and eventually change its trajectory. Any change in the orbital velocity of an object in space leads to a new orbit configuration. Over long-period of interaction, the delta-V on the target will deflect the object away from its original orbit and thus the intersection of the PHO with the Earth's orbit no longer occurs.
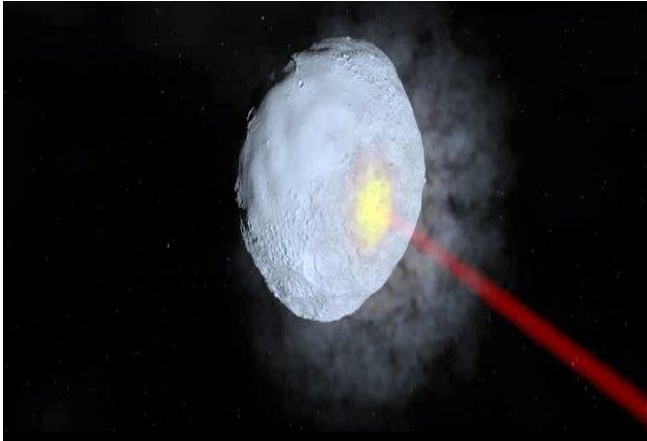

Figure 3. Visualization of laser beam. The plume density is exaggerated to show ejecta

Deflection or mitigation of an Earth collision-bound comet is a highly complex engineering problem. Various techniques have been discussed in the literature for NEOs having a longer warning time of more than 5 years. As mentioned, the object under study has a short warning period of 2 years and there is little in the literature to provide adequate solutions for such objects. We propose a 2-layered solution involving lasers, kinetic impactors and thermonuclear devices.

Comets, being icy bodies, are particularly vulnerable to DES ablation. Current research in lasers have increased the efficiency to more than 80% and have proven their resilience to be used for deflecting comets and asteroids in laboratory conditions. Highly focused beams of energy can be used for increasing the ablation rate and controlling the spin rate of comets. Laser systems can be placed at critical points between the Sun-Earth systems and using Lagrange point 4 (L4) and Lagrange point 5 (L5) Sun-Earth Langrage points for the same was decided. If building and operating large

heliocentric orbital structures are found untenable both from technology or policy considerations, we propose using the Moon as a platform for testing and evolving a DES capability.

STK software was used to simulate and analyze the comet trajectory and Earth's orbit as seen in Figure 4. The comet trajectory is shown in dark blue and Earth's orbit in yellow. Figure 2 and Figure 4 show that the chosen comet has a trajectory that intersects with the Earth's orbit indicating high probability of an impact. The two laser beams from L4 and L5 are shown in red.
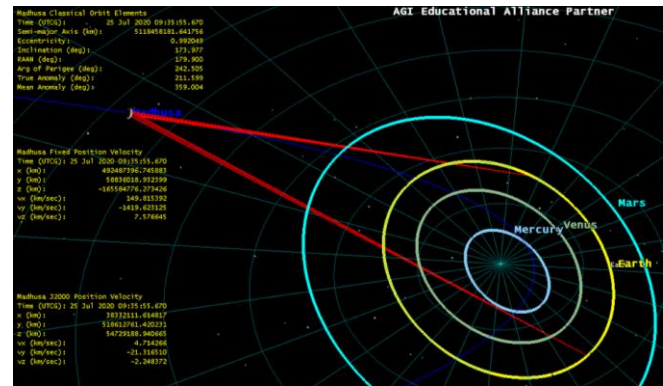
Figure 4. STK illustration for the comet (dark blue), Mercury, Venus, Earth and Mars orbits. Two laser beams (red) interacting with the comet from L4 and L5

Hypervelocity Comet Impactor Vehicle (HCIV):

The HCIV launch vehicle is part of the space deflection system, together with the DELT. The purpose of the HCIV is to disrupt and deflect the comet from its original orbit, by means of the modification of the momentum of the body. This is achieved by the transmission of the energy generated by the thermonuclear device that is integrated within the vehicle. The vehicle consists of two spacecraft: a fore body called the Leader Impactor (LIMPACT), and an aft body called the Thermonuclear Energy Device (TED), Figure 5. The HCIV is created under a restricted combination of safety and affordability. Advertised as HCIV, the concerns from the public-domain based on its thermonuclear device are reduced. By using a combination of kinetic impact, followed by detonation of a thermonuclear device inside a newly made crater, the HCIV only needs 12% of the explosive yield otherwise required to shatter a similar comet with a stand-off nuclear. At the same time, it directs as much energy as possible into the asteroid to pulverize it into fragments, not just to break it up. After launch from Earth, the payload located on the LIMPACT spacecraft detects the comet, while the sensors on-board continue acquiring data through optical and IR cameras located on the LIMPACT spacecraft. By this, optimal impact locations on the surface of the comet are targeted. The TED is protected by a broad range of safety features and arm/fire protections in order to prevent its detonation, even if the spacecraft itself should be terminated by mission failure. At approximately 500m from the target, the LIMPACT spacecraft separates from the TED.
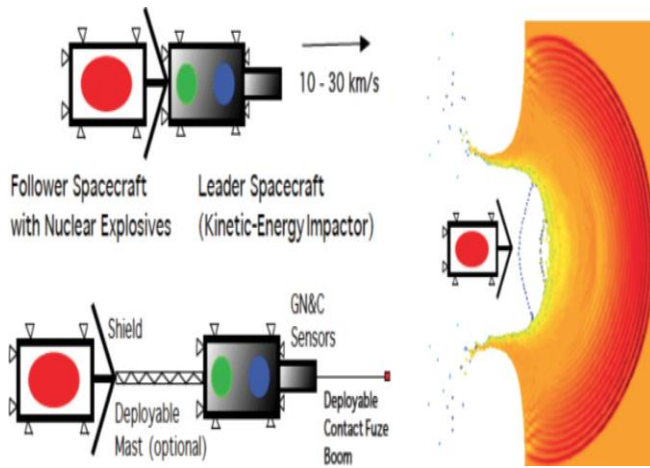
Figure 5. Architecture for a vehicle including a thermonuclear device evaporating the subsurface layers [24, 28]

The bus designed for the vehicle, and therefore the one being used by the LIMPACT and the TED is using 100V, with on-board power up to 20kW. The embedded application for navigation of the flight on-board software (DART) is in charge of the autonomous navigation. DART is also in charge of a myriad other tasks, such as maintaining the power balance, to point its arrays at the sun for solar energy collection, and to point the spacecraft antennas back to Earth for data transmission, Figure 6.
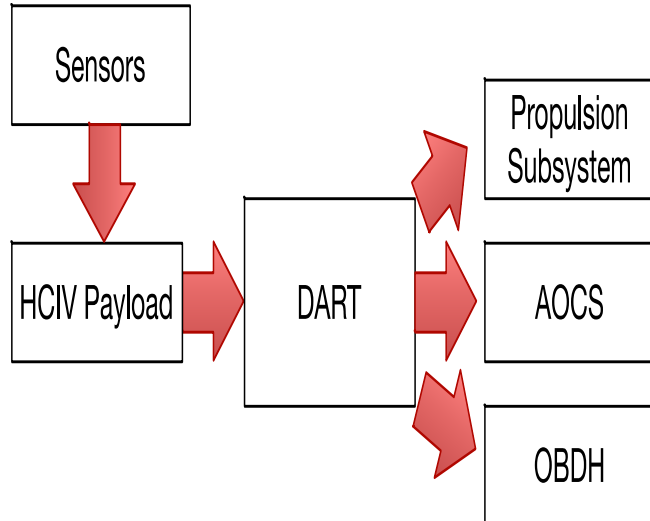
Figure 6. Flow chart indicating the command flow of on-board bus for autonomous navigation

Multiple launchers can be used for the HCIV mission carrying the TED, which is foreseen to include a thermonuclear payload of approximately 500kg.

Leader Impactor (LIMPACT):

The Leader Impactor (LIMPACT) spacecraft delivers a payload of inert mass onto a trajectory to impact the comet with a relative impact velocity of 25–30 km/s. Before the impact, 500m away from the comet surface, the spacecraft

separates from the TED for the engagement phase. Travelling at ~30km/s, it delivers kinetic energy to the comet to generate a shallow crater thereby exposing the inner sub-surface of the comet. The impactor contained the main telemetry, tracking and ranging subsystem (TT&R) of the HCIV system, and processed the main set of housekeeping data of the mission by its on-board data handling subsystem (OBDH). The dissipation of the impactor's kinetic energy on impact explosively craters the surface, ejecting asteroid material into space. The LIMPACT delivers 238 GJ (energy corresponding to 940 tons of TNT) of kinetic energy to excavate the crater, which is generated by the combination of the mass of the Impactor (530kg dry-mass approximately) and its velocity when it impacts (~30km/s).

$$E = {}^1\!/_2\, mv^2$$

Thermonuclear Energy Device (TED):

The Thermonuclear Energy Device (TED) spacecraft includes the thermonuclear equipment that will be detonated once close to the crater generated on the comet's surface by the LIMPACT. The concave surface area of the crater increases the absorption of the released energy and maximizes the ground shock coupling and disruption of the target. Its main payload consists of a three-stage (fission-fusion-fission) jacket thermonuclear payload. Each TED is capable of delivering a 1MT blast, with a mass of approximately 500kg. The desired Δv is aligned with, or opposite to, the velocity of the comet, such that the entire effect goes toward altering the semi-major axis and period of the asteroid's orbit, thus avoiding bolide collision with Earth. NASA Nuclear Interceptor is an example for this deflection technique, Figure 7.
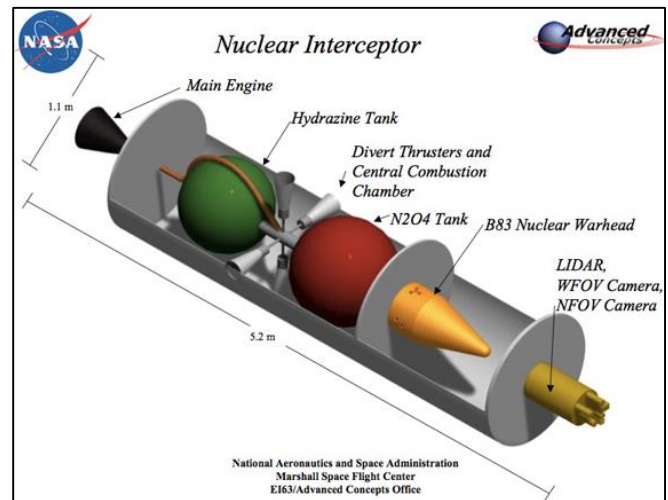
Figure 7. NASA Nuclear Interceptor Concept [19]

We assume an average comet density of 0.6g/cm3 and estimate the total mass to roughly match comets of known mass such as comet 1P/Halley and 67P/Churyumov-Gerasimenko, which is being studied in great detail by the Rosetta and Philae spacecraft.

The energy released upon impact is based on an energy distribution and coupling mode with respect to the comet material characteristic models and given as (in MT):

$$SDE = 1000 \frac{d}{\sqrt[3]{Z}}$$

Table 2 and Figure 8 link nuclear payload weights and their potential yields. Depending on the characteristics of the target and the thermonuclear device, the explosion can have different effects on the object: fragmentation, crushing, or deviation from its initial trajectory, which is usually referred to as deflection [16]. The main solution available when designing this mission is to generate a nuclear explosion below the surface of the object.

Table 2. Link between classical nuclear payload masses and their potential yield

Mass (Ton)	Yield (MT)
0.5	1
3 to 4	10
20 to 25	100
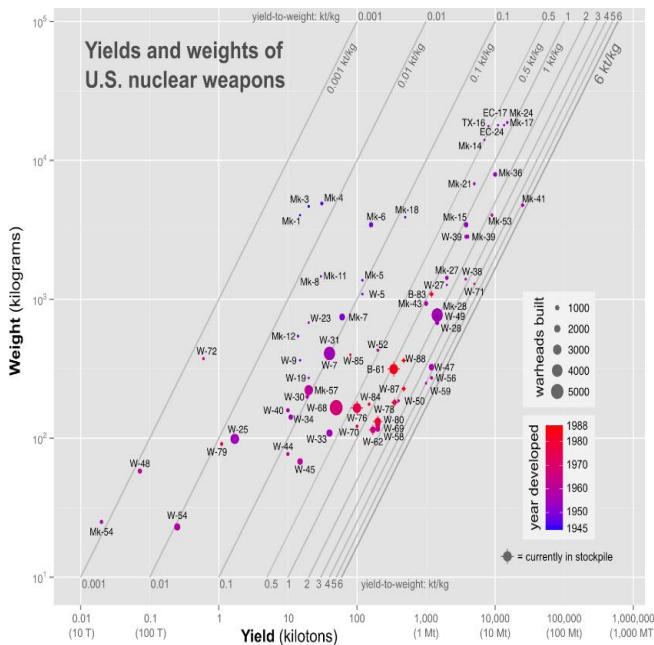
Figure 8. Yields and weights of US nuclear weapons [8]

This is the most effective solution but may only be feasible for low relative velocities as the accuracy of the trajectories is key to its success. Such an explosion may lead to a partial or total disruption of the target, Figure 9. This method requires a penetrator to allow the nuclear device to explode within the subsurface layers. An impactor requires knowledge of the composition of the object. The effect of a nuclear explosion on the comet or asteroid could be substantially increased if the nuclear device affects the inner layers below the surface of the object.
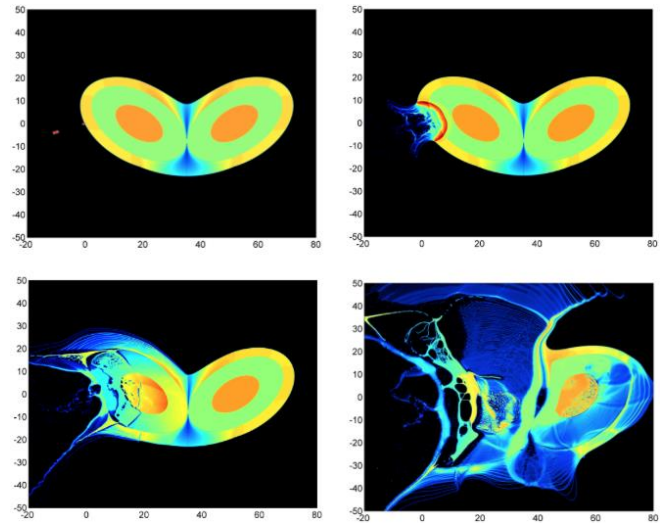
Figure 9. Sub-surface detonation simulation [29, 30, 31]

An explosion in space is inherently different from an explosion on Earth. The main differences are associated with the absence of an atmosphere, the complex shape of the object, the object's extremely weak gravity and the composition. The determination of the orbital parameters of the object is critical. At a distance of 1AU it will be necessary to determine the speed with a relative accuracy range between 10-5 and 10-4 km/s. If the object is detected at a short distance from Earth (0.1 to 0.01AU), the only possible countermeasure would be shattering it into many fragments by devices of 1 to 100MT yield, depending of the objects final composition. If the interception is carried out at a safe distance from Earth, radioactive dust fallout can be avoided.

6. POLICIES GOVERNING IMPLICATIONS OF A CELESTIAL THREAT

Policy changes do not happen overnight and they often require a posteriori triggering event, rather than a priori. In the case of a short-term celestial threat, taking responsible action would be much easier to implement if policy supporting the responsibility to defend the planet was already in place.

Because many, if not all, of the deflection techniques graded in Table 1 are considered dual use technology. Deployment of these capabilities in space would require international collaboration and support [32, 33]. The policy section in this paper describes one component of the processes that would support effective collaboration.

The creation of foreign policy and the basis for international collaboration typically takes a decade or more. For example it was more than 15 years after the Balkan conflict and more than 10 years after the Rwandan Genocide before the Millennium Report was published containing former Secretary-General Kofi Annan question "If humanitarian intervention is, indeed, an unacceptable assault on sovereignty, how should we respond to a Rwanda, to a

Srebrenica, to gross and systematic violation of human rights that offend every precept of our common humanity?" [11, 12] that triggered the creation of the Responsibility to Protect (R2P).

This report triggered the creation of a commission to respond to Kofi Annan's question, resulting UN report A/57/303 titled the "Responsibility to Protect" [15]. This report [15] outlines the core principles of R2P by stating basic principles, foundations, elements, and priorities. It goes into further detail addressing the principle of military intervention.

The three elements of the R2P describe specific responsibilities that have been embraced with its creation [15].

1. The responsibility to prevent: to address both the root causes and direct causes of internal conflict and other man-made crises putting populations at risk.

2. The responsibility to react: to respond to situations of compelling human need with appropriate measures, which may include coercive measures like sanctions and international prosecution, and in extreme cases military intervention.

3. The responsibility to rebuild: to provide, particularly after a military intervention, full assistance with recovery, reconstruction and reconciliation, addressing the causes of the harm the intervention as designed to halt or avert.

These three elements all have the potential to be applied with some modifications in scope of application to the situation presented by celestial threats.

If a short-term celestial threat presented itself today there would be numerous challenges to the global collaboration necessary to address the threat. The first of which is the lack of policy relevant to the use of the technology required to mitigate this type of threat. [9] There are two branches to the policy needed to support the mitigation of celestial threats. The first, justification of defending the Earth and its inhabitants from celestial threats. The second is the justification of taking military action necessary to do so. This paper addresses only the first branch of policy necessary as it is likely to be more readily accepted by the global political community.

The principles of the Right to Protect (R2P) were generated to address the protection of people in cases where their states don't take the necessary action to do so. In the case of a celestial threat, most states will not have the necessary capabilities to address the threat, if their state is in the path of potential impact. Not to mention that early confirmation of the exact impact site is nearly impossible. That means that to protect humankind other states will need to step in support of the less capable states in protecting their populations. Because celestial threats are highly uncommon creation of policy in this area is not considered by many people. But the

risk presented by celestial threats should not be discounted and is a case where action before imminent threat is recommended by the READI project [1]. The basis for this recommendation is the fact that, because we can act, to protect the Earth and humanity, we have the responsibility to do so. In order to help prompt action the following analysis of the Responsibility to Protect is presented.

In alignment with the first basic principle of R2P we believe that states with the technological capabilities to protect their own populations from celestial threats should have the responsibility to develop the necessary technology. Some states, such as France, Germany, the Russian Federation, Spain, the United Kingdom, and the United States are jointly working to develop technologies which might help mitigate the threat posed by asteroids [13]. If an effective solution is found, early deployment would increase the potential of successful mitigation. Deployment without the presence of an imminent threat would require the presence of policy pertaining to both the protection of humanity from celestial threats and the use of dual use technology to do so.

In alignment with the second basic principle of R2P the capable states should also be prepared to act on behalf of less capable states. The potential of a short-warning celestial threat is prudent to be prepared for, to act before the threat is confirmed due to the fact that deployment may require significant time and coordination because all mitigation technology to date is considered dual use. Article four of the Outer Space Treaty [17] states that "States Parties to the Treaty undertake not to place in orbit around the Earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner." Therefore this treaty would have to yield to the need to protect humanity from a celestial threat and it is desirable to discuss the distinction of weapons of mass destruction, weapons, and asteroid mitigation methods.

Similar to the R2P the presence of a celestial threat would require prevention, reaction and the ability to rebuild. The capabilities to rebuild, already exist. FEMA's National Mitigation Framework [18] supports the capability to rebuild in response to a variety of threats and these same concepts could be applied in the presence of a celestial threat.

In summary, complete preparation for mitigation of celestial threats requires a new policy approach. The basic principles of that policy could be:

- The responsibility of capable states, in cooperation with other interested states, to develop technology to mitigate celestial threats in order to defend the Earth and humanity.

- The responsibility of capable states to protect less capable states if they are threatened by imminent impact of celestial objects.

The elements in support of this policy would be:

- The responsibility to detect celestial threats

- The responsibility to react to celestial threats

- The responsibility to rebuild in the aftermath of a celestial impact

These principles and elements are presented for consideration in the discussion of policy in the domain of celestial threats, which is encouraged, due to the degree of risk presented by these threats and the fact that threat mitigation technology is being developed and the significant increase in confidence for a successful mitigation campaign if pre-threat deployment of a sturdy planetary defense architecture is commissioned.

7. FINAL REMARKS

Short warning period NEOs have not been discussed in the literature in detail and have also not attracted enough interest among space agencies and policymakers to consider it as an important threat. The Chelyabinsk incident has surely created an increase in interest of NEOs among space agencies yet more work needs to be done. The methods proposed have been built upon and validated using existing literature. The NASA ARM mission is going to test the impactor theory and work is going on to directed energy systems for planetary defense application. More work needs to be done to generate interest and develop policies that can help in proper governing of thermonuclear devices. More non-nuclear methods need to be devised for such short-warning cometary threats. The methods proposed in READI can also be extended to asteroids.

REFERENCES

[1]. *Planetary Defense team project: READI (Roadmap for EArth Defense Initiatives)*, 2015. Project Report. International Space University (ISU), Ohio, USA.

[2]. Alvarez LW, Alvarez W, Asaro F, Michel HV (1980). *"Extraterrestrial cause for the Cretaceous–Tertiary extinction"*. Science 208 (4448): 1095–1108

[3]. Napier, B. and Asher, D.*: The tunguska impact event and beyond.* Astronomy and Geophysics, 50(1)., 2009

[4]. Brown, P. G., Assink, J.D., Astiz, L., Blaauw, R., Boslough, M.B., Borovička, J., Brachet, N., Brown, D., Campbell-Brown, M., Ceranna, L., Cooke, W.,de Groot-Hedlin, C., Drob, D.P., Edwards, W., Evers, L.G., Garces, M., Gill, J., Hedlin, M., Kingery, A., Laske, G., Le Pichon, A., Mialle, P., Moser, D.E., Saffer,A., Silber, E., Smets, P., Spalding, R.E., Spurný, P., Tagliaferri, E., Uren, D., Weryk, R.J., Whitaker R., Krzeminski, Z. : *A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors*, Nature, 2013.

[5]. Chodas, P. n.d. NEO Groups. *NASA, Near Earth Object Program*, [online] Available at: <http://neo.jpl.nasa.gov/neo/groups.html> [Accessed 24 October 2015].

[6]. Dones, L., Weissman, P. R., Levison, H. F. and Duncan, M. J.: Oort Cloud Formation and Dynamics. *In Star Formation in the Interstellar Medium: In Honor of David Hollenbach*. Vol. 323, p. 371, 2004

[7]. Schulte, P., Alegret, L., Arenillas, I., Arz, J.A., Barton, P.J., Bown, P.R., Bralower, T.J., Christeson, G.L., Claeys, P., Cockell, C.S., Collins, G.S., Deutsch, A., Goldin, T.J., Goto, K., Grajales-Nishimura, J.M., Grieve, R.A.F., Gulick, S.P.S., Johnson, K.R., Kiessling, W., Koeberl, C., Kring, D.A., MacLeod, K.G., Matsui, T., Melosh, J., Montanari, A., Morgan, J. V, Neal, C.R., Nichols, D.J., Norris, R.D., Pierazzo, E., Ravizza, G., Rebolledo-Vieyra, M., Reimold, W.U., Robin, E., Salge, T., Speijer, R.P., Sweet, A.R., Urrutia-Fucugauchi, J., Vajda, V., Whalen, M.T. and Willumsen, P.S.: *The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary*. Science (New York, N.Y.), 2010

[8]. Alger, J. 2009. *From nuclear energy to the bomb: the proliferation potential of new nuclear energy programs*. Centre pour l'innovation dans la gouvernance internationale. Nuclear Energy Futures Paper No. 6.

[9]. Bible, J., Johansson I., Hughes G. B. and Lubin P. M., 2013. *Relativistic Propulsion Using Directed Energy*. Proc. of SPIE, Vol. 8876, 887605-1.

[10]. Lamy, P. L., Toth, I., Fernandez, Y. R. and Weaver, H. A: *The sizes, shapes, albedos, and colors of cometary nuclei. Comets II,* 1, pp.223-264, 2004.

[11]. Weissman, P. R.: *Terrestrial impact rates for long and short-period comets*. Geological Society of America Special Papers, 190, pp.15-24, 1982.

[12]. Balkans 1940s to 1999, 2000. *Washington Post*. [online] Available at: <https://www.washingtonpost.com/wp-srv/inatl/longterm/balkans/timeline.htm> [accessed 24

October 2015].

[13]. *A short history of the Rwanda Genocide*. About.com. [online] Available at: <http://history1900s.about.com/od/rwandangenocide/a/Rwanda-Genocide.htm> [accessed 24 October 2015]

[14]. Background Information on the Responsibility to Protect. *Outreach Programme on the Rwanda Genocide and the United Nations*. [online] Available at: <http://www.un.org/en/preventgenocide/rwanda/about/bgresponsibility.shtml> [accessed 24 October 2015].

[15]. UNGA Report by the international commission on intervention and state sovereignty. A/57/303, pp. XI; [online] <http://responsibilitytoprotect.org/ICISS%20Report.pdf > [accessed 24 October 2015].

[16]. Howley, K., Managan, R. and Wasem, J., 2014. *Blow-off momentum from melt and vapor in nuclear deflection scenarios*. Acta Astronautica, [online] 103, pp.376–381. Available at: <http://linkinghub.elsevier.com/retrieve/pii/S0094576514002215> [Accessed on 24 October 2015]

[17]. *Outer Space Treaty*, The United Nations Office of Outer Space Affairs; 1966.

[18]. *National Mitigation Framework*, 2013. Homeland Security. [online] <http://www.fema.gov/media-library/assets/documents/32209?id=7363 > [accessed 24 October 2015]

[19]. *Near Earth Object (NEO) Mitigation Options Using Exploration Technologies*, Presentation to 2007 Planetary Defense Conference, Washington, DC. [online] <http://uavarese.altervista.org/CM_ACH-2009.pdf > [accessed 24 October 2015].

[20]. Gritzner, C., Dürfeld, K., Kasper, J., and Fasoulas, S. 2006. *The asteroid and comet impact hazard: risk assessment and mitigation options*. Naturwissenschaften, 93(8), pp.361-373.

[21]. JPL, 2015. *JPL Small-Body Database Browser*, JPL, [online]. Available at: <http://ssd.jpl.nasa.gov/sbdc.cgi>. [Accessed on 20 October 2015].

[22]. Mainzer, A., Bauer, J., Grav, T., Cutri, R., Masiero, J., McMillan, R.S. and Wright, E., 2015a. *Space-Based Infrared Discovery and Characterization of Minor Planets with NEOWISE*. In Handbook of Cosmic Hazards and Planetary Defense, pp. 583-611. Springer International Publishing.

[23]. Melosh, H., Nemchinov, I.V. and Zetzer, Y. I. 1994. *Non-nuclear strategies for deflecting comets and asteroids*. In Hazards due to comets and asteroids, Vol. 1, pp.1111-1132.

[24]. Pitz, A., Kaplinger, B., Wie, B., Dearborn, D., 2012. *Preliminary Design of a Hypervelocity Nuclear Interceptor System (HNIS) for Optimal Disruption of Near-Earth Objects*. In: 22nd Spaceflight mechanics 2012, 29 January-2 February 2012, Charleston, S.C, San Diego: Univelt.

[25]. Pelton, J.N., Allahdadi, F., ed. 2015. *Handbook of Cosmic Hazards and Planetary Defense*. Switzerland: Springer International Publishing. pp.569-581.

[26]. Thangavelu, M., McVicker, J.M., 2015. *QBOLT Directed Energy System Concepts For Asteroid Threat Mitigation*; The International Academy of Astronautics Planetary Defense Conference, 13-17 April 2015, Frascati, Italy.

[27]. Lubin, P., 2015. *Directed Energy for Planetary Defense*, Core Lectures Space Studies Program 2015. International Space University, unpublished.

[28]. Wie, B., 2013. *Hypervelocity nuclear interceptors for asteroid disruption*. Acta Astronautica, [online] 90(1), pp.146–155. Available at: <http://dx.doi.org/10.1016/j.actaastro.2012.04.028>. [accessed 17 October 2015]

[29]. Kaplinger, B., Wie, B., and Dearborn, D. 2013. *"Nuclear Fragmentation/Dispersion Modeling and Simulation of Hazardous Near-Earth Objects,"* Acta Astronautica, Vol. 90, pp. 156-164.

[30]. Kaplinger, B. and Wie, B. 2012. *"GPU Accelerated 3-D Modeling and Simulation of a Blended Kinetic Impact and Nuclear Subsurface Explosion,"* IAA-PDC13-04-06, 2013 IAA Planetary Defense Conference.

[31]. Kaplinger, B., Setzer, C., Premaratne, P., Wie, B. 2013. *"GPU-Accelerated 3D Modeling and Simulation of a Blended Kinetic Impact and Nuclear Subsurface Explosion,"* AIAA-2013-4548, presented at AIAA Guidance, Navigation, and Control Conference, Boston, MA, August 19-22.

[32]. Gourdon, R., Hussein, A., Soni, A., Aliaj, B., Manuel Entrena Utrilla, C., Sisaid, I., Reinert, J., Faull, J., Bettiol, L., Schmidt, N., Nambiar, S., Dimitrov, T., and Thangavelu, M., 2015. *The International Space University Space Studies Program 2015 Planetary Defense Project*. In: 66th International Astronautical Congress 2015 (IAC 2015) "Space - The Gateway for Mankind's Future", 12-16 Oct 2015.

[33]. Burke, J., Hussein, A., Soni, A., Thangavelu, M., Schmidt, N., and Wilson, T., 2015. *Planetary defence: a duty for world defenders*. In: American Geophysical Union (AGU) Fall Meeting, 14-18 Dec 2015, San Francisco, USA.

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