Planetary Defense: How to Become Armed and Ready

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NASA's Near Earth Object (NEO) observation program has been finding and tracking NEOs for about a quarter of a century uncovering about 40% of the 100,000 objects expected. Today it has been determined that a collision of a very large NEO with the Earth would be a rare but life altering occurrence. The near miss of comet Siding Spring to Mars moving at a phenomenal 56 km/s and at a size of half a kilometer should be humanities wakeup call. This comet came out of the Oort Cloud at an inclination of 129º to the ecliptic and was first spotted only 22 months before its near miss of Mars. It was a complete surprise to scientists worldwide. The close flyby of the comet caused Mars to be nearly engulfed by the comet's coma and dust tail, leading to significant but short-lived changes in the Martian atmosphere. Had this comet hit the Earth, based on our current unprepared state, it would have been impossible to stop a significant extinction event. The recent detection of three interstellar comets presents another low probability but high impact danger. It is now clear that Earth impacts from Oort Cloud comets and interstellar objects are a type of "Black Swan" event which are extremely rare, unpredictable events that have massive, wide-ranging consequences. Planetary defense techniques have become more mature for Earth bound asteroids while cometary "Black Swan" threats have been largely ignored to date. This paper proposes to mitigate this problem by implementing a quick reaction kinetic impactor system using the Space Launch System (SLS) to provide the largest impactor mass with the greatest possible velocity in space ready to go. This requires the SLS launch of the large impactor mass to be placed into cislunar space such that the payload can quickly reach an incoming comet at any inclination by using the Earth or Moon as the appropriate gravity assist or to newly discovered incoming asteroids approaching from unfavorable orbital paths, such as directions close to the Sun.

I. Nomenclature

AU = Astronomical Unit, C3 = Twice the injection energy/unit mass (km^2/cm^2), DART = Double Asteroid Redirection Test, EML2 = Earth-Moon Lagrange point 2, EUS = Exploration Upper Stage, KI = kinetic impactor, LEO = Low Earth Orbit, NASA = National Aeronautics & Space Administration, NEOs = Near Earth Objects, NGIMS = Neutral Gas and Ion Mass Spectrometer, PHO = Potentially Hazardous Objects, RCS = reaction-control system, SHLLV =

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Super Heavy Lift Launch Vehicle, SLS = Space Launch System, ΔV = Change in velocity (a deep space maneuver),
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II. Introduction

Near Earth Objects (NEOs) have impacted the Earth throughout its history, profoundly altering the course of life on our planet. NASA's NEO observation program has identified nearly ~40,000 NEOs out of the expected ~100,000 population. The NEOs that cross our orbit or fly by within 20 million miles are referred to as potentially hazardous objects (PHO) and they come in sizes from 10's of meters to several kilometers. NASA is currently tracking ~2160 PHOs with ~160 that are 1 km and larger. Table 1 provides an overview of the predicted impact occurrence with NEO size and the total expected number of NEOs. In addition, the percent currently discovered is also given. This table illustrates that significant discoveries have been made of the largest NEOs, the remaining ones to be discovered are much smaller but still significant in size (from 140 m up to1 km) that would produce regional damage. We must anticipate that a new detection of a NEO, that would cause regional damage, may yet to be discovered.

Table 1: NEO hazards by size and occurrence.

Size (m)	Damage	Occurrence	Expected Number	Discovery
50	Local to regional effects, airburst, may leave small impact crater	1 per 1000 years	~120,000	12%
140	km-scale crater or airburst, deadly over cities, mass casualties	1 per 20,000 years	~25,000	43%
1000	10 km crater, country devastation-potential global scale	~1 per 700,000 years	~900	95%
10,000	100 km crater, global devastation with mass extinctions	~1 per 100 million years	~4	~100%

Although today the large-sized NEO's that would impact the Earth are expected to be extremely rare, the consequences are so devastating that the U.S. Government has decided to be prepared. In January 2016, NASA created the Planetary Defense Office to find and catalog all NEOs, develop and execute mitigation strategies by conducting simulations, and to execute test missions to defend the Earth against hazardous NEOs. Recently, a new goal has been issued in the National Preparedness Strategy for NEO hazards and planetary defense report [1]. Goal 3 stated that NASA should develop technologies for NEO reconnaissance, deflection, and disruption missions.

In the National Academy of Sciences 2010 report [2], *Defending Planet Earth*, several mitigation strategies were delineated. These strategies included: civil defense and evacuation for small (~50 m) newly discovered NEOs or when there is not enough time for a defensive response, kinetic impactor (KI) which utilize spacecraft to collide with the object, thereby transferring momentum to alter its trajectory, gravity tractor which positions a spacecraft close to a NEO and using gravitational attraction between the object and spacecraft to gradually pull it into a safer orbit, and finally nuclear deflection which employs a nuclear explosion near the NEO giving a significant push to alter its trajectory to miss the Earth. It is important to note that the nuclear deflection technique was recommended for larger NEOs or those discovered with insufficient time for other methods to be employed but this still requires the development and execution of a delivery system which will take years to realize since it is currently only a concept.

The origin of most objects that compose NEOs were originally from the asteroid belt that have been pushed inward through gravitational resonances, largely from the planet Jupiter. This will continue to happen over time. Among the NEOs that NASA is keeping track of, only a few are comets. These comets come from large reservoirs of short period comets with an orbital period of less than 200 years that reside largely in the equatorial plane and whose orbits are greatly affected by the giant planets, and Jupiter in particular. These comets return to the inner solar system regularly allowing NASA to predict their orbital motion.

It is important to note that there is another large reservoir of comets with periods of millions of years that reside at great distances (~2,000 to 100,000 Astronomical Unit or AU) from the sun in the Oort cloud. The sudden appearance of Oort Cloud comets may pose the greatest immediate threat to life on planet Earth. Although asteroid impacts occur approximately 100 times more frequently than comet impacts, the energy delivered by a comet impact can exceed that of a typical asteroid by over 100-fold, making their potential destructiveness nearly equivalent. The goal of this paper is to discuss our greatest impact threats from Oort Cloud comets and undiscovered destructive NEOs with short warning times and how to become armed and ready to defend the planet as soon as the threat of impact has been determined.

III. Defending the Planet

For small NEOs (~50 m) with short warning time (10s of hours to a few days) civil defense processes should be used. For medium sized NEOs (<140 m) with longer lead warning times the KI technique is preferred and for very large NEOs (>140 m) KI gravity tractor or nuclear options should be considered based on warning time. The KI technique is all about moving the entire NEO, keeping it intact, while completely missing the Earth as it flies by.

Late detection of a NEO on a collision course with Earth presents substantial challenges with any of the above known strategies. Since a gravity tractor could take as much as a decade or more and a nuclear explosive device will encounter significant challenges with the approval process relative to current international laws and treaties then the KI technique must be the preferred option as the mitigation method. Effective execution of any deflection mitigation strategies typically demands significant advance warning, often measured in years or even decades, to properly design, develop, launch, and guide a spacecraft capable of altering the asteroid's orbit. When the discovery of an impending impact is delayed, the available reaction time is significantly shortened, restricting mission planning and limiting opportunities for effective intervention.

In cases of late detection, the asteroid would have already approached close enough that a greater change in its velocity would be required to divert it from an Earth collision path. This necessity translates into more energy-intensive maneuvers, potentially requiring multiple KI missions or an impactor spacecraft of greater mass and complexity. Furthermore, late discovery severely constrains possible launch windows and available interception trajectories, forcing missions into more demanding, risky, and expensive approaches.

Additionally, the shortened preparation time greatly reduces the ability to design robust backup options or contingency plans. Consequently, a single mission failure or less-than-ideal performance in achieving the required orbital deflection could leave Earth with little or no time to deploy alternative mitigation strategies. For these reasons, a KI mission, with as large a mass as possible should be designed, developed and launched into a staging orbit that would be a quick reaction capability that could be sent, based on its associated planetary launch window, within a matter of days to its intended target. This new mitigation strategy should be considered seriously and implemented as soon as possible for reasons discussed below.

IV. NASA's Kinetic Impactor Test

The NASA Double Asteroid Redirection Test (DART) mission was the first-ever demonstration of a planetary defense technology aimed at altering the trajectory of an asteroid through kinetic impact [3]. Launched on November 24, 2021, the DART spacecraft targeted Dimorphos, the small 170 m moonlet orbiting the larger asteroid Didymos which was 780 m in diameter. On September 26, 2022, DART intentionally collided with Dimorphos at a speed of approximately 6.1 km/s, successfully shortening its orbital period around Didymos by about 32 minutes, significantly more than NASA's initial goal of just 73 seconds. DART was only 580 kg in mass at impact and took 11 years to develop from the initial concept to launch due to yearly funding constraints. A normal planetary mission would require about 5 to 6 years of development time.

The DART mission was designed to test humanity's capability to redirect potentially hazardous asteroids away from Earth. Observations from ground-based telescopes and spacecraft (such as the Italian LICIACube cubesat) confirmed the mission's success, providing crucial data to refine asteroid deflection strategies. DART's results are being analyzed and incorporated into planning future planetary defense missions. Since the DART impact of Dimorphos resulted in a much larger change in its orbital period than planned, the kinetic impactor may be an effective deflection mitigation technique to NEOs and comets as large as ~1 km.

V. Comets Pose the Greatest Threat

Planetary defense techniques have become more mature for Earth bound asteroids while cometary threats have been largely ignored to date. The origin of the objects that compose NEOs are not only from the asteroid belt but also from the large reservoirs of comets. Comets in the NEO database typically have orbital periods of less than 200 years. These comets are often associated with the Kuiper Belt, a region of icy bodies beyond Neptune. A larger, more distant reservoir of comets is the Oort Cloud [4].

The Oort Cloud is a vast, spherical reservoir of icy bodies that surrounds the solar system at great distances and is believed to be the source of long-period comets as illustrated in Fig1. It is hypothesized to extend from roughly 2,000 AU to 100,000 AU from the Sun. This cloud of comets is divided into two regions: a spherical outer Oort Cloud, believed to be isotopically distributed around the Sun, and a flattened inner Oort Cloud, which lies closer to the Sun and may be a more disk-like structure around the ecliptic plane. Objects in the Oort Cloud are thought to be remnants from the solar system formation ~4.6 billion years ago and gravitationally scattered by the giant planets during the system's early formative period (within the first billion years). These icy bodies are generally inactive, but when one is perturbed by a passing star or galactic tidal force, it may fall into the inner solar system. Such comets often have highly elliptical, randomly inclined orbits and can take thousands to millions of years to complete a single orbit. Although their composition may be largely volatiles their cold environment has made them completely frozen and as hard as granite.

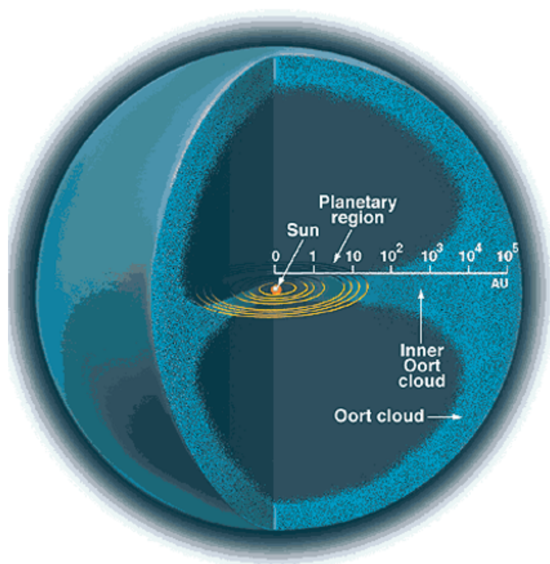

Fig. 1. An illustration of the Oort Cloud comet reservoir.

Table 2 provides a compilation of high inclination comets, primarily from the Oort Cloud, that approached the Sun between 2011 and 2025 derived from the Jet Propulsion Laboratory Small Body Database. Such extreme inclinations are a hallmark of comets arriving from the Oort Cloud. The variety in orbital inclination underlines that these comets are not confined to the plane of the solar system, in contrast to most planets and short-period comets that lie closer to the ecliptic plane. Each inclination value in the table is rounded to the nearest whole degree and referenced from the comet's orbital data around the time of its perihelion. The inclinations illustrate the diverse orientations of Oort Cloud comets. In addition, most of the comets in Table 2 are on the order of ~1 km in size however there are some that are significantly larger. All these comets have eccentricities that are less then one, meaning they orbit the sun allowing them to be distinguished from the interstellar comets on hyperbolic orbits with eccentricities greater than one (see Section VIII).

Table 2: High inclination comets.

Comet Designation	Closest Approach	Detection to Perihelion (time)	Orbital Inclination (°)	Size (diameter)
C/2011 W3	16-Dec-11	~3 weeks	134°	~1 km
C/2011 L4	10-Mar-13	1 yrs 9 months	84°	~1–2 km
C/2012 S1	28-Nov-13	1 yrs 2 months	62°	~1 km
C/2013 R1	22-Dec-13	~3½ months	64°	~1–2 km
C/2013 A1	25-Oct-14	1 yrs 10 months	129°	~0.5 km
C/2014 Q2	30-Jan-15	~5½ months	80°	~5–6 km
C/2013 US10	15-Nov-15	~2 yrs	149°	~2–4 km
C/2016 R2	9-May-18	1 yrs 8 months	58°	~2–5 km
C/2010 U3	1-Feb-19	~8 yrs 3 months	56°	~few km
C/2020 F8	27-May-20	~2 months	111°	~1 km
C/2020 F3	3-Jul-20	~3 months	129°	~5 km
C/2021 A1	3-Jan-22	1 yrs	133°	~1 km
C/2017 K2	19-Dec-22	5 yrs 7 months	88°	~18–20 km
C/2022 E3	12-Jan-23	~10 months	109°	~1–2 km
C/2014 UN271	23-Jan-31	~16 yrs 3 months	95°	~137 km

As shown in Table 2, on the average, only one Oort Cloud comet comes into the inner solar system per year. This rate is expected to continue making the appearance of these comets rare but not extremely rare. The low rate of inward moving Oort Cloud comets may be enhanced due to a previous close stellar passage which would have gravitationally pushed many Oort Cloud comets inward at once. Since the actual dynamics of the Oort Cloud is not well understood, the total number of comets on their way to the inner solar system is largely unknown. In addition, as shown in Table 2, a third of these comets were discovered within a few months prior to perihelion. Another third within two years and only three with more than five years of warning. Therefore, the sudden, but constant appearance of Oort Cloud comets, along with only months to a few years of warning, poses the greatest immediate threat to life on planet Earth.

VI. A Comet Surprise

Robert McNaught discovered an Oort Cloud comet (designated C/2013 A1) on January 3, 2013, at the Siding Spring Observatory in Australia and therefore named the comet, Siding Spring [5]. Some 22 months later, on October 19, 2014, the comet traveling at ~56 km/s relative to Mars streaked by the planet, at an angle of 129° to the ecliptic and at a range of 83,900 miles (135,000 km) a distance close enough for Mars to be engulfed by the comet's coma (the gas and dust cloud around the nucleus). The orientation of the C/2013 A1 inner and outer comas during the flyby are shown in Fig. 2.

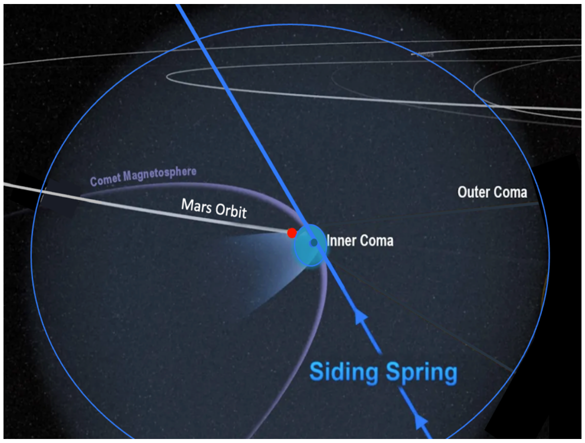

Fig.2. Illustration of C/2013 A1 engulfing Mars with its inner and outer coma of dust and gas.

Siding Spring was a 500 m Oort Cloud comet coming from an enormous distance and had been traveling toward the inner solar system for more than a million years and yet the flyby of Mars event was a complete surprise to space scientists worldwide. The event allowed scientists to obtain an unprecedented view of how a planet with an atmosphere interacts with a glancing blow from a relatively small Oort Cloud comet.

VII. The Effect of Comet C/2013 AI on Mars

As the comet's outer coma and tail swept by Mars, an estimated 1,000–2,000 kg of cometary dust (rich in magnesium, silicon, calcium, potassium, etc.) were deposited into Mars' upper atmosphere. These high-speed dust particles (moving ~56 km/s relative to Mars) were vaporized at high altitude, producing what was likely an intense meteor shower in the Martian sky. Spacecraft observations confirmed that the infalling dust created a temporary, but extremely strong, layer of ionized plasma in Mars' ionosphere [6]. The sudden injection of meteoric material dramatically enhanced electron densities high above Mars while also heating its upper atmosphere.

Orbiter instruments detected metal species in Mars' upper atmosphere that had never been observed there before and MAVEN recorded intense ultraviolet emissions from magnesium and iron ions high in the atmosphere immediately after the dust influx [7]. These emissions were so strong that they dominated Mars' ultraviolet spectrum for several hours, a response more intense than any meteor storm known on Earth. MAVEN's Neutral Gas and Ion Mass Spectrometer (NGIMS) directly sampled the comet's vaporized dust and identified eight different metal ions, including Na, Mg, K, Fe, and others. This was the first in-situ measurement of the composition of dust from an Oort Cloud comet, yielding valuable data on the primordial materials in Siding Spring. The influx of dust and metals were short-lived, lasting for a Martian day or two, and then it relaxed back to normal.

Beyond chemical effects, Comet Siding Spring's flyby also disturbed Mars' magnetic field environment. The comet carried a powerful intrinsic magnetic field generated by plasma in its coma, and during the encounter this field overwhelmed Mars' weak magnetic bubble flooding the atmosphere with charged particles from the comet's coma. The comet's passage caused a temporary surge in the escape of Mars' upper atmosphere gases into space. These atmospheric stripping effects were analogous to the passage by Mars of a massive coronal mass ejection.

The close passage of Siding Spring posed a potential hazard to spacecraft orbiting Mars, so mission teams took careful steps to protect their probes. In 2014 there were five active orbiters at Mars (NASA's MAVEN, MRO, and Odyssey; ESA's Mars Express; and ISRO's Mars Orbiter Mission), all of which had to face the oncoming comet debris. Approximately 90 minutes after the comet's closest approach, Mars would travel through the densest part of Siding Spring's dust tail. Space agencies predicted that while the risk was relatively low, high-velocity dust particles could damage spacecraft instruments or solar arrays if struck. To mitigate this risk, all three NASA orbiters were positioned on the far side of Mars, using the planet itself as a shield against the comet's debris. In addition to orbital repositioning, several of the spacecraft instruments were powered down during the comet's approach to prevent electrical or mechanical damage from the anticipated dust hits. The precautionary measures proved very effective. NASA confirmed that all three of its Mars orbiters survived the comet flyby unharmed, with no damage from comet dust [8].

Despite the spectacular atmospheric fireworks, Comet Siding Spring did not have any direct impact on Mars' surface. The comet's solid nucleus missed Mars by a wide margin (about one-third the Earth–Moon distance), so there was no collision. Only a minimal defection in the comet's trajectory, due to the mass of Mars was observed due to the very large speed of the comet (56 km/s). The shower of dust particles burned up in the upper atmosphere and no large fragments were reported to reach the ground. Had the comet hit the planet Mars, a very different story would have emerged. These results require that we need to be armed and ready on a very short notice to react to an incoming Oort cloud Comet whose trajectory includes the Earth.

VIII. Interstellar Visitors

The very recent discovery of interstellar objects passing through our solar system on hyperbolic trajectories has opened an entirely new window onto the material and processes shaping planetary systems across the galaxy but also presents the potential danger that may exit if they impacted Earth [9]. The sequence of detections was 1I/'Oumuamua in 2017, 2I/Borisov in 2019, and 3I/ATLAS in 2025. These objects act like comets and reveal a surprising diversity among bodies that have been created in distant stellar environments and set adrift into interstellar space by some unknown mechanisms. Together, these visitors provide the first direct evidence that fragments from other solar systems routinely pass through our own, each carrying chemical, structural, and dynamical clues about their origins, and like the Oort Cloud comets, present a new danger that must be considered. It is important to recognize that the first interstellar objects discovery, ‘Oumuamua, is largely based on the recent major improvements in the detection of NEOs since it is understood that undetected interstellar visitors moving through our solar system must have been occurring for billions of years.

Table 3: Orbital characteristics of the recently discovered interstellar visitors.

Object	Inclination	Perihelion Distance	Perihelion Velocity	Orbital Direction	Size (km)	Relation to the Ecliptic Plane
Oumuamua	~122.7°	~0.255 AU	~87.7 km/s	Retrograde	0.2	Approached from far above the ecliptic, crossed near perihelion, departed above.
2I/Borisov	~44°	~2.0 AU	~43.9 km/s	Prograde	~0.4 - 1	Entered above the ecliptic, departed below the ecliptic.
3I/ATLAS	~175°	~1.36 AU	~68 km/s	Retrograde	~0.4-5.6	Approached from slightly above the ecliptic with a close flyby of Mars.

Key orbital characteristics of the interstellar objects is given in Table 3, and they are much like the Oort Cloud comets except for higher velocities. These fast-moving objects, approaching from random directions, make gravitation interactions with the Earth extremely unlikely except when they are on an impact trajectory. Due to the nature of comets, the actual size is difficult to determine. Given the volume of space at 1 AU, the chance of Earth and an interstellar object occupying the same tiny collision point at the same moment is extremely small, but it is not zero.

IX. Black Swan Events

A future Oort Cloud comet or interstellar object impact on the Earth would represent the very definition of a Black Swan event since it has an occurrence that is extremely unlikely, difficult to predict well in advance, but capable of producing catastrophic consequences, and often rationalized only in hindsight [10]. History is littered with Black Swan events. Consider what has happened in the last 35 years alone. The 2008 Global Financial Crisis demonstrated how hidden vulnerabilities in housing and banking cascaded into a worldwide recession few anticipated. The September 11 attacks revealed an unexpected mode of terrorism that transformed international security and geopolitics. The COVID-19 pandemic showed how a novel virus could rapidly disrupt economies, healthcare systems, and daily life on a global scale. Similarly, the collapse of the Soviet Union was a startling geopolitical upheaval that ended the Cold War far sooner than most analysts predicted. The Fukushima nuclear disaster highlighted how compounding natural hazards could overwhelm even advanced technological safeguards. The dot-com crash exposed the fragility of speculative markets built on untested internet-era business models. Even, the discovery of ‘Oumuamua, the first known interstellar object to pass through the Solar System, surprised planetary astronomers and its discovery has expanded our thinking about planetary defense and the frequency of interstellar visitors. Together, these events underscore how low-probability, high-impact occurrences should redefine assumptions, policies, and scientific understanding, often only fully appreciated after the fact. Therefore, the approach we must take for adequate planetary defense is to consider that, to understand a phenomenon, we must take into account the extreme examples.

Although known interstellar objects and Oort Cloud comets have passed harmlessly through the Solar System, their unexpected arrivals demonstrated that such bodies can approach rapidly, on hyperbolic trajectories, and often with very limited warning. Nearly all will miss Earth by vast distances, but the small probability of a direct impact cannot be assumed to be zero. Because interstellar objects travel at unusually high velocities, far faster than typical asteroids or short period comets, any collision would release significantly greater kinetic energy, amplifying damage even for modest-sized bodies. The rarity of these visitors also means we have little statistical knowledge of their size distribution or structural properties, making risk assessment inherently uncertain. If a future interstellar object were on an impact path, humanity might discover it only months, or even weeks, before arrival, leaving minimal time for mitigation. Our current capability for planetary defense is in its infancy and therefore fragile to these extreme impact events. Thus, while the probability is extraordinarily low, the impact of a fast-moving, little-understood interstellar object would have the characteristics of a true Black Swan event, a surprising, high-impact event, recognized clearly only after it occurs when the immediate habitability of Earth comes into question. We need to avoid this outcome at all costs and can only do this through the advanced planning and execution of a mission.

X. Proposed Mitigation Strategy

The strategy proposed in this paper is to leverage the initial plan and existing international relationships identified in the April 2023 National Preparedness Strategy for Near-Earth Object Hazards and Planetary Defense [11] and relevant technologies available to provide initial capability as soon as possible. The proposed approach includes utilizing existing and planned world-wide NEO detection capabilities for an initial space-based intercept capability. This capability would consist of a viable, large mass KI mission in cislunar space ready to go. Also, in case this mission is not adequate, and after the assessment of the 1st mission, be ready to launch either another kinetic impactor or nuclear payload to complete the deflection. This pre-positioned KI mission capability presents several advantages: 1) Enables rapid and decisive initial response utilizing the maximal payload capacity provided by a Super Heavy Lift Launch Vehicle (SHLLV) such as SLS. 2) Allows adaptive follow-up missions, whether additional kinetic impactors or nuclear payloads, based on early mission assessments, if possible. 3) Offers the flexibility to respond to both Black Swan cometary and asteroidal threats, as well as potential interstellar objects, thereby enhancing Earth's planetary defense readiness.

The proposed KI mission requires a staging point that minimizes departure energy while maximizing responsiveness. The Earth-Moon Lagrange point 2 (EML2), as shown in Figure 3, is a particularly attractive location for such an interceptor system. Because a spacecraft in halo orbit around EML2 is gravitationally balanced relative to Earth and the Moon, it requires very low ΔV to depart the system and quickly maneuver onto an intercept trajectory. For this reason, EML2 is adopted as the baseline node for this mission concept.

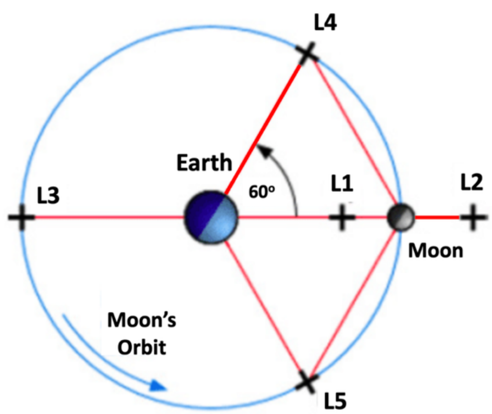

Fig.3. Location of the Earth-Moon Lagrange points. The KI mission would be located at L2.

NASA's Space Launch System (SLS) provides substantial mass-to-EML2 capability. With its high-energy injection to a translunar trajectory ($C3 \approx -1$), the Exploration Upper Stage (EUS) can deliver roughly 40 metric tons to EML2 after conducting a modest lunar-swing-by maneuver of approximately 310 m/s. This means that, in the baseline scenario, no additional dedicated transfer stage is required merely to place the interceptor stack at EML2. However, mission planners may still elect to include a specialized transfer or propulsion module for flexibility, increased station-keeping capability, or for tailoring the interceptor architecture to specific threat scenarios.

Once at EML2, the stored interceptor system would rely on space-storable bipropellant engines, solid-motor kick stages, or a hybrid combination. These propulsion options maximize long-term readiness, crucial for a system that could remain quiescent for years before being activated. When a hazardous long-period comet or interstellar object is detected on a threatening inbound trajectory, the interceptor departs EML2 on a rapid intercept trajectory designed to achieve high closing velocity with the minimum practical warning time.

Three general trajectory classes should be considered:

1. Minimal transfer-time trajectory
    - Shortest time-of-flight
    - Highest ΔV demand
    - Lower payload mass at intercept
    - Appropriate for extremely short warning times
2. Propellant-efficient trajectory
    - Reduced ΔV
    - Maximizes mass delivered to the target
    - Longer trip time
    - Useful when earlier detection provides adequate lead time
3. Hybrid/compromise trajectory
    - Balances time-critical response with delivered mass
    - Likely the mission default for most threat scenarios

To streamline system integration and ensure resilience in deep-space environments, the in-space transfer stages may reuse hardened avionics from the SLS/EUS, including flight computers, guidance sensors, and communication hardware. These components are already designed to withstand radiation-induced upsets, making them well-suited for long-duration storage at EML2 and for operations beyond low Earth orbit.

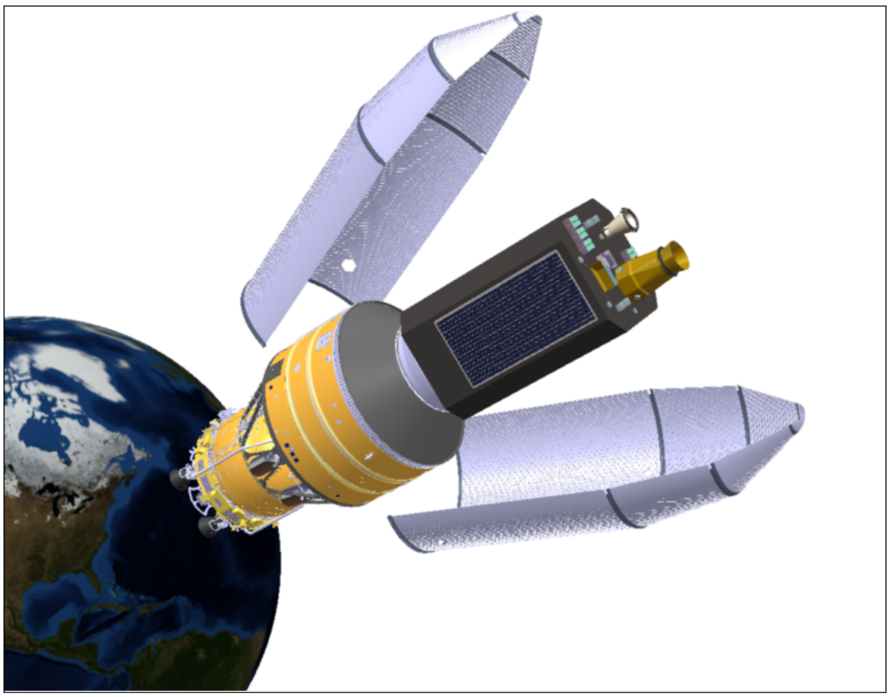

Fig.4. SLS has the capacity of launching the KI with a 40 mt impact mass.

Fig. 4 provides an illustration of the KI mission showing similar instrumentation as the DART system [3] previously discussed. High resolution imaging will be needed to provide the operational navigation for target acquisition. During the terminal phase of the mission, closing on the high-velocity target, the interceptor will rely on its reaction-control system (RCS) for precise navigation. The final "aim-point maneuver," executed shortly before impact, provides the last trajectory refinement required to ensure the interceptor strikes the object at maximum effective momentum-transfer geometry.

XI. Discussion

Recognizing that studying mitigation strategies, such as discussed here, is just the start of a longer sustainable process of planetary defense, the new Planetary Decadal [12] recommended that NASA should develop a rapid-response reconnaissance flyby mission designed to gather the key data necessary to better prepare for a short-warning-time destructive NEO. The data collected would include the mass of the object, its internal structure, and strength (to determine disruption threshold), and precise orbit etc. Once these and other NEO characteristics are understood, realistic kinetic intercept trajectories and spacecraft impactor momentum can be calculated giving an impactor mission with the greatest miss distance, without disrupting the structure of the NEO. The maximum spacecraft mass that can be launched on this intercept trajectory with the largest impact speed gives the maximum NEO size that can be deflected.

As pointed out in this paper, there is a class of objects, such as Oort Cloud comets, interstellar objects, and newly found destructive NEOs, in which the time consuming information collection approach briefly described above cannot be implemented in a timely manner. This necessitates that an alternate quick reaction capability be implemented. A previous study by Nuth et al. [13], calls for readiness measures with stored interceptors to handle a sudden comet threat. The authors require that an interceptor might carry either nuclear explosives or kinetic impactor mass and be ready to launch when a long-period comet is detected inbound. Unfortunately, this approach may be too late, since the longer it takes to launch the mission the more orbital deflection is needed. This also becomes problematic if the mission does not adequately move the comet on the first try.

Addressing this vulnerability, this paper proposes a new planetary defense strategy which involves establishing a rapid-response KI mission. Utilizing NASA's Space Launch System, this strategy entails placing a substantial impactor mass into cislunar space, strategically positioned for swift deployment. This approach ensures rapid reaction capability against Oort Cloud comets, interstellar objects, or asteroids approaching from difficult observational angles, such as near the Sun, using Earth or lunar gravity assists to obtain interception paths. Moreover, this strategy includes contingency planning. If the initial KI mission proves insufficient and time permits, a follow-up kinetic impactor or, if necessary, a nuclear payload should be deployed, informed by data from the results of the initial KI mission. The strategic placement of the KI system in cislunar space is essential for the earliest response possible, effectively evaluating initial mitigation efforts and facilitating informed secondary actions.

XII. Conclusion

Interstellar objects and Oort Cloud comets could, like the recently observed Comet C/2013 A1 Siding Spring, pose significant collision risks to terrestrial planets with very limited advance notice. Comets, with their immense speeds, unpredictable outgassing, and icy makeup pose a formidable challenge distinct from asteroids, and therefore we must tailor our deflection strategies accordingly. Similarly, certain asteroids approaching from unfavorable orbital paths, such as directions close to the Sun, can also result in very brief warning intervals. However, developing, building, testing, and launching a highly reliable interceptor spacecraft generally requires about five to six years, which significantly exceeds the short reaction times available for addressing these threats. The very short warning times dictate that our first attempt at an orbit deflection should be using the kinetic impactor technique, which should be already in orbit, preferably at a lunar Lagrange point, with the largest mass, to then be targeted at the comet or asteroid at the earliest possible moment.

It is time we take advantage of the SLS launch capabilities [14] that can enable unique robotic missions that can be designed to protect Earth from the threat of a catastrophic impact from threatening objects. The SLS provides the spacecraft impactor mass of about 40 mt, at the greatest speed possible, and therefore should be part of NASA's overall assets to be used to defend the planet Earth from the newly found destructive NEOs, interstellar objects, and Oort Cloud comets. If we ignore these as potential impactors due to their very low impact probability, we do so at our own peril.

XI. References

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