The Future of Planetary Defense Begins with DART

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ABSTRACT

Doomsday scenarios of near-Earth objects (asteroids and comets) hitting Earth are fodder for action movies and science fiction books, but the potential for such an event cannot be dismissed as mere fiction. In 2022, the Johns Hopkins University Applied Physics Laboratory (APL) will demonstrate an important step in planetary defense, mitigating the threat of a direct hit by developing the ability to prevent an impact to Earth. DART (Double Asteroid Redirection Test) is a NASA mission managed by APL with support from several NASA centers. DART launches in 2021 and will be the first demonstration of the kinetic impactor technique to change the motion of an asteroid in space. As the first kinetic impactor far from Earth, DART will prove the ability to deflect catastrophic threats and lead to innovations in impactor/redirect technologies. This article explains DART's novelty and extrapolates how it might shape the future of planetary defense.

HAZARDS

Extraterrestrial matter falls onto Earth benignly every day as dust or meteorites. On longer timescales, large objects impact Earth and pose risks to humans. The Small Bodies Assessment Group (SBAG),[1] which NASA established in 2008 to bring together experts on small bodies throughout the Solar System, offers a few examples: In 2013, a bolide estimated to be only 20 m in diameter exploded in the atmosphere over Chelyabinsk, Russia. The airburst created a shock wave that broke windows, collapsed buildings, and injured more than 1,000 people.[2] In the Tunguska event in 1908, an object estimated to be roughly 30 m in diameter caused a larger airburst that destroyed more than 2,000 km^2 of forest.[3–5] A similarly sized airburst over a densely populated area could result in significant loss of life. As the SBAG points out,[1] fortunately most collisions with Earth involve harmless dust and the occasional meteorite—objects that are too small to threaten the planet. Larger objects do not impact Earth frequently: it is estimated that asteroids larger than 30 m in diameter collide with Earth only about once every few centuries, and those larger than 300 m in diameter impact the planet only once per 100,000 years on average. (Note, however, that these recurrence intervals are approximate. Asteroid impacts are not periodic; they can happen at any time.) While catastrophic damage could result if a large object were to impact Earth, small impactors can still cause immense damage on a local scale.[1] Figure 1 illustrates the many fireballs (i.e., small asteroids that collided with Earth) detected over the last ~30 years.

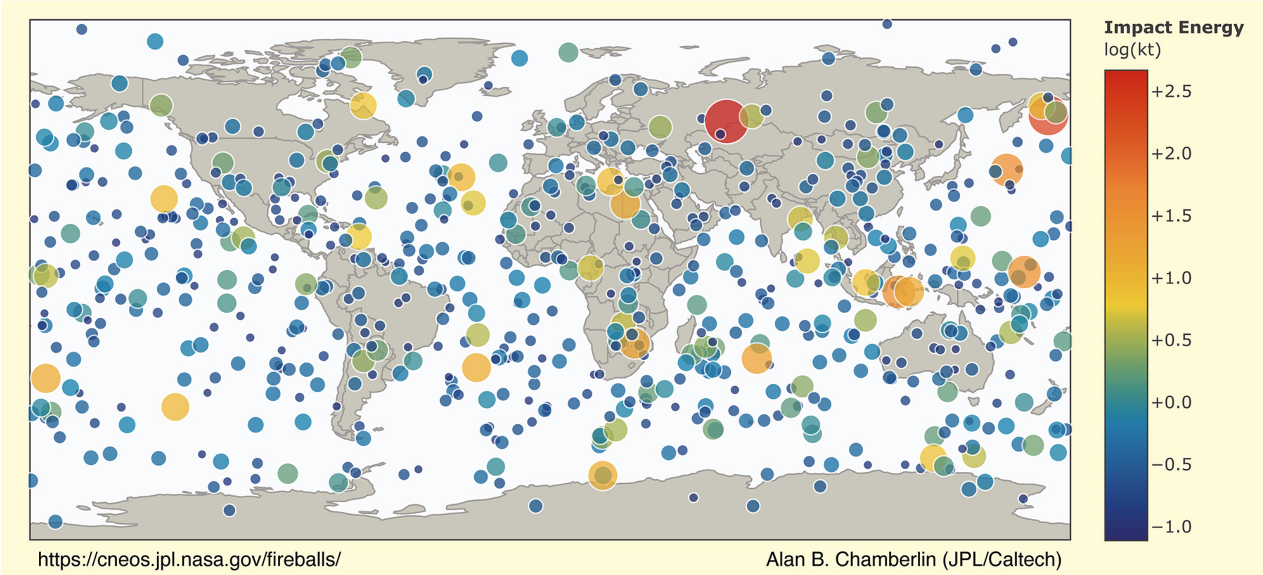

Figure 1. Fireballs (small asteroids) that hit the Earth between April 15, 1988, and January 6, 2020, as reported by US government sensors. Planetary defense is a global concern because any part of Earth could be hit by an asteroid and, depending on how big the asteroid is, the effects could be global. (Image courtesy of NASA/JPL-Caltech.)

Today, humanity is primarily concerned with smaller objects that can destroy a city or devastate a region. The impact's location (as well as its energy) is key in determining the potential damage that would occur during a near-Earth object (NEO) impact event. As Figure 2 illustrates, we are finding more and more small asteroids, a subset of which are potentially hazardous to Earth.

DEFENSE

Planetary defense encompasses the capabilities needed to detect and warn of potential impacts of asteroids or comets on Earth, and then either prevent these impacts or mitigate their possible effects. The NEO population consists of asteroids and comets, mostly asteroids, whose orbits pass within 1.3 astronomical units (AU) or 121 million miles of the Sun. A subset of the NEOs is considered to pose a greater impact hazard to Earth. These objects are the potentially hazardous objects (PHOs), defined in terms of both the proximity of their heliocentric orbits to Earth's orbit and their sizes as measured by brightness. PHOs are NEOs whose orbits take them within a distance of <0.05 AU (4.7 million miles) from Earth's orbit and whose brightness exceeds an absolute magnitude measured as H = 22, which corresponds to a minimum size of ~140 m for a typical asteroid albedo. Planetary defense is "applied planetary science" to address the NEO impact hazard.

Impact mitigation refers to the means of preventing or mitigating the damage from an NEO impact on Earth that can cause injuries, fatalities, or property damage. Impacts range in scale from those of very small NEOs

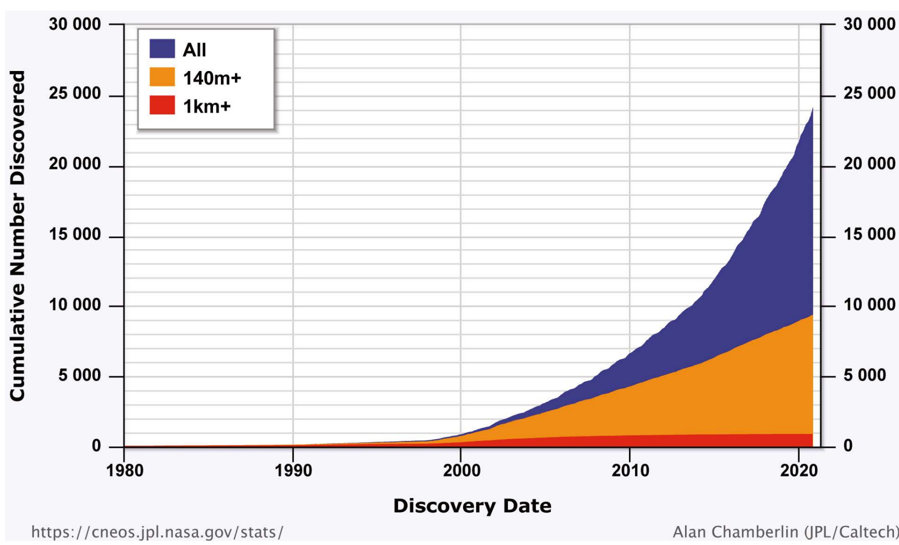

Figure 2. Near-Earth asteroids discovered. The number of small asteroids we know of continues to increase at an accelerating rate. It is not that the threat from asteroids is increasing. Rather, humanity is becoming increasingly aware of the existing threat posed by asteroids. (Image courtesy of NASA/JPL-Caltech.)

(on the order of 10 m in size) that cause minimal or no damage on the ground but are very frequent (occurring every decade) to very large impacts (NEOs ≥1 km) that are capable of causing global catastrophes or even mass extinctions but, fortunately, are much less frequent (occurring about every 500,000 years). This vast range of impact hazards already leads to a diversity of mitigation techniques, including in the first place passive civil defense—preparing a population for a natural disaster and mitigating the effects of the damage by evacuation and/or sheltering and by aiding recovery from the disaster. In events with very little warning, civil defense may be the only mitigation option available because there might be insufficient time to implement any active defense against the impact (i.e., to destroy an incoming asteroid or deflect it away from Earth).

With adequate warning (measured in years), active defense measures become feasible options to avert the impact, by deflecting or destroying the incoming object. These active mitigation techniques are broadly classified as impulsive or slow push–pull, according to whether or not the deflection or destruction is achieved by means of an impulsive event. Three active mitigation techniques have been extensively studied: kinetic impactor, nuclear explosive, and gravity tractor. Of these, the first two are impulsive and the last is a slow push–pull technique.

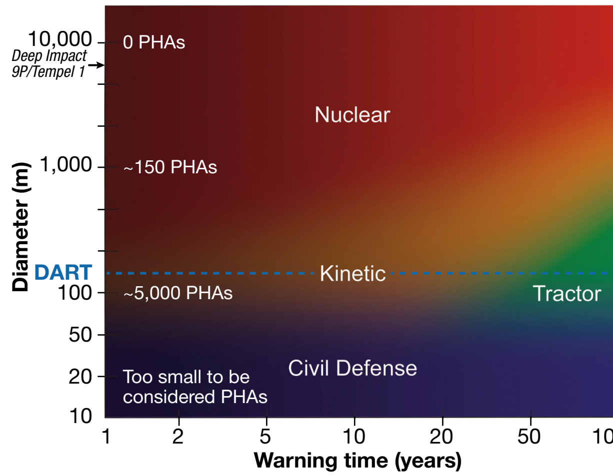

Figure 3. Mitigation techniques for potentially hazardous asteroids (PHAs). The applicability of each technique is indicated by color: civil defense in dark blue, kinetic impact in yellow, nuclear explosive in red, and gravity tractor in green. The blue dashed line indicates the size of the asteroid that will be deflected by the DART mission. The black arrow shows the size of the target impacted by the NASA Deep Impact mission, without any measurable deflection. Also indicated are estimated numbers of PHAs at each size. (Modified and republished with permission of the National Academies of Science from Ref. 6; permission conveyed through Copyright Clearance Center.)

Kinetic Impactor

The kinetic impactor technique uses a spacecraft to impact the incoming object and deflect it away from Earth by transferring momentum. The momentum transfer from a kinetic impact is influenced by production of impact ejecta, which carries away momentum, with the result that the momentum transferred to the asteroid is greater than the incident momentum of the kinetic impactor. The APL-led DART (Double Asteroid Redirection Test) mission is the first demonstration of asteroid deflection with a kinetic impactor, and it will measure this enhancement of momentum transfer by impact ejecta.

Nuclear Explosive

The nuclear explosive technique uses a spacecraft to carry a nuclear explosive device close to the asteroid and detonate it at a prescribed standoff distance and orientation relative to the asteroid to deflect and/or destroy it. This is an impulsive technique, where the momentum transfer, which causes deflection or disruption of the target, results from rapid deposition of x-ray energy, causing ablation of surface material.

Gravity Tractor

The gravity tractor technique is a slow push–pull method where a massive spacecraft is maneuvered close to the incoming asteroid, so that the gravity of the spacecraft is used to pull the asteroid and gradually implement the deflection. Since the total deflection is achieved slowly, this technique enables precise determination and control of the amount of deflection.

Figure 3 summarizes these active and passive mitigation techniques by showing the applicability of each, in terms of the scale of the threat (given as the diameter of the incoming asteroid) versus the warning time (given in years). For the smallest (the most frequent) NEO impacts, civil defense is applicable. The kinetic impactor technique is applicable for NEO impacts of bodies hundreds of meters in size, given enough warning (several years to decades). The gravity tractor technique requires many decades of warning to achieve sufficient deflection, even for 100-m targets. For the largest NEO impacts (the least frequent), the only applicable mitigation technique is nuclear explosion. For those events with the shortest warning times, only civil defense may be applicable.

DEFENDERS

The Planetary Defense Coordination Office (PDCO), established in January 2016, manages planetary defense activities for NASA and the US government. It is tasked with detecting, tracking, and characterizing PHOs and issuing warnings of possible effects of potential impacts, studying strategies and technologies for mitigating PHO impacts, and playing a leading role in coordinating US government planning for responses to impacts (see Figure 4). PDCO activities generally fall, then, into three main categories: find, warn, and mitigate. Generally robust data streams exist for warning stakeholders should a threat emerge. For these warnings to be useful, the PHO population must be surveyed and characterized, and mitigation technologies must be developed and tested.

DART is one component of the PDCO's overall strategy and the first mission to be flown by the office. The mission is a test of technologies for preventing a hazardous asteroid from impacting Earth. The design and flight of DART are activities that fall within the mitigate category of the PDCO's charter.

Figure 4. The charter of the PDCO. The DART mission is one component of the charter and the first mission being flown by PDCO. DAMIEN IWG, Detecting and Mitigating the Impact of Earth-bound Near-Earth Objects Interagency Working Group; FEMA, Federal Emergency Management Agency; IAWN, International Asteroid Warning Network; IRTF, Infrared Telescope Facility; NEOWISE, Near-Earth Object Wide-field Infrared Survey Explorer; PIERWG, Planetary Impact Emergency Response Working Group; SMPAG, Small Missions Planning Advisory Group. (Image courtesy of NASA.)

Responding to a potential asteroid impact is contingent on discovering the PHO early enough for mitigation techniques to be applied. Activities falling within the find category include surveys using both ground- and space-based telescopes to search for NEOs, determine their orbits, and measure their physical characteristics. To this end, the PDCO is increasing its mission portfolio by supporting a new space-based telescope called the Near-Earth Object Surveyor Mission (NEOSM). NEOSM will be the second mission directed by the PDCO and is designed to identify 65% of 140-m objects within 5 years of launch and 90% of 140-m threats within 10 years. NEOSM complements an array of current and planned ground-based observatories, including the Vera C. Rubin Observatory (VRO, formerly the Large Synoptic Survey Telescope, or LSST). Supported by the National Science Foundation, the VRO plans to start science operations in 2023 and eventually increase the number of known NEOs by up to a factor of 100. Nevertheless, ground-based observatories such as the VRO are obviously limited to nighttime observing, and objects on very Earth-like orbits can spend significant fractions of their time at solar elongations too small to be observed from the ground. This complement of space-based assets like NEOSM and large ground-based ones like the VRO is particularly potent for solving the NEO survey problem.

DART

DART (Figure 5) will be the first space experiment to demonstrate and measure asteroid kinetic deflection. The DART target is the binary asteroid (65803) system Didymos (Figure 6), which makes an exceptionally

Figure 5. Illustration of DART, from behind. (NASA/APL.)

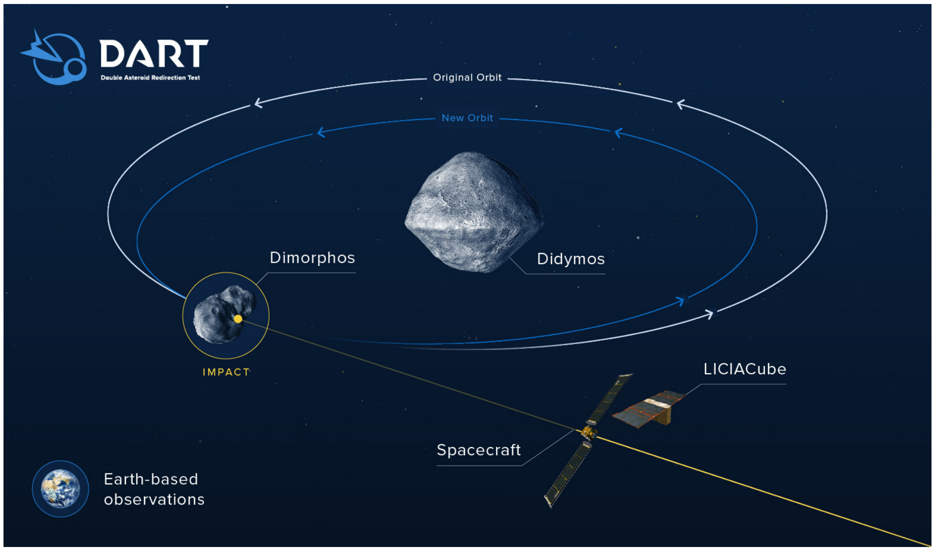

Figure 6. Schematic of the DART mission. This illustration shows the impact on the moonlet of asteroid (65803) Didymos. Post-impact observations from Earth-based optical telescopes and planetary radar would, in turn, measure the change in the moonlet's orbit about the parent body. (NASA/APL.)

close approach to Earth in October 2022. The Didymos system is favorable both for intercept and for Earth-based observing, and its secondary is a representative size of NEOs that are potentially hazardous to Earth. Table 1 shows Didymos system characteristics. The experiment requires DART to impact the secondary, the moon named Dimorphos, and alter its binary orbit period with respect to the primary, Didymos. Going to the binary system is ideal because the change in the orbit period can be measured by Earth-based telescopes without requiring a second spacecraft to rendezvous with Didymos, and because this asteroid deflection causes no appreciable impact hazard to Earth. The DART spacecraft, moving a little faster than 6 km/s, will impart an orbit period change to Dimorphos that is measurable by Earth-based observers within weeks after the impact.[7] DART is a class C mission[8] managed by APL. The DART spacecraft integration and test phase began in April 2020, preparing DART for a 2021 launch from Vandenberg Air Force Base on a SpaceX Falcon 9 rocket.

Table 1. Didymos system characteristics

Characteristic	Measurement
Primary diameter	780 m ± 78 m
Secondary diameter	163 m ± 18 m
Total system mass	$(5.278 \pm 0.54) \times 10^{11}$ kg
Component bulk density	2,100 kg m^{-3} ± 30%
Primary rotation period	2.2600 ± 0.0001 h
Component separation	1,180 +40/−20 m
Secondary orbital period	11.920 + 0.004/−0.006 h
Asteroid spectral class	S

DART will demonstrate a number of exciting new technologies as part of its mission, in addition to the kinetic impact. The DART spacecraft is the first demonstration of the NASA Evolutionary Xenon Thruster Commercial (NEXT-C) engine. The NEXT-C engine is a gridded ion propulsion system that electrically accelerates xenon to a high velocity. This engine could be used for future planetary defense missions because it provides significant flexibility in terms of trajectory design and the ability to change the trajectory late in the mission as scientists refine their predictions about the orbits of the dangerous asteroids and the best arrival geometry. To generate the necessary power for the ion propulsion system, DART relies on Roll-Out Solar Arrays (ROSA) and will be the first powered demonstration of this technology in space. The solar arrays weigh very little and thus keep the spacecraft mass low, enabling a kinetic impactor mission to potentially launch as a rideshare on short notice.

In addition, DART carries a NASA Transformational Solar Array demonstration to help characterize new concentrator arrays that deliver high-efficiency power production. DART will rely on the SMART Nav (Small-body Maneuvering Autonomous Real-Time Navigation) package to enable the impact with Dimorphos. This collection of firmware and software leverages heritage algorithms within APL's Air and Missile Defense Sector to enable the autonomous closed-loop guidance necessary to ensure the hypervelocity impact. The use of SMART Nav technology can be extended to mitigating any reasonable asteroid threat. Finally, the DART spacecraft will carry LICIACube (Light Italian CubeSat for Imaging Asteroids), a contribution from Agenzia Spaziale Italiana (ASI), which will be deployed 10 days before the DART impact on Didymos (its deployment will occur ~0.08 AU from Earth). The purpose of the CubeSat is to image the impact and ejecta and then relay the images back to Earth over the course of weeks or months after the impact.

DART's level 1 requirements are shown in Table 2. Many of the DART-1 and DART-2 requirements are met through careful mission design. After its launch in 2021, DART will perform its initial checkout operations for a few weeks before testing SMART Nav in flight and

Table 2. DART level 1 requirements

		Identification	Level 1 Requirement
Baseline	Threshold	DART-1	DART shall intercept the secondary member of binary asteroid (65803) Didymos as a kinetic impactor spacecraft during its close approach to Earth in September–October 2022.
		DART-2	DART's impact on the secondary member of the Didymos system will cause at least a 73-s change in the binary orbital period.
		DART-3	The DART project will characterize the binary orbit by ground-based observations before and after the spacecraft impact, to measure the change in the binary orbit period to within 7.3 s (1-σ).
		DART-4A	The DART project will use the velocity change imparted to the target to obtain a measure of the momentum transfer enhancement parameter referred to as Beta (β) using the best available estimate of the mass of Dimorphos.
		DART-4B	The DART project will obtain data, used in combination with ground-based observations and data from another spacecraft (if available), to constrain the location and surface characteristics of the spacecraft impact site, and to allow the estimation of the dynamical changes in the Didymos system resulting from the impact, in particular the coupling between the body rotation and the orbit.

demonstrating the NEXT-C ion engine. It will then approach the Didymos system in September–October 2022.[9] At Didymos, DART will use SMART Nav to demonstrate autonomous terminal guidance. In the final hours of the mission, SMART Nav will use images from the narrow-angle camera to determine the relative location of the target and autonomously command maneuvers to impact Dimorphos. The other three requirements (DART-3, -4A, and -4B) are met through a combination of Earth-based observations, modeling, and processing of the final images from DART's camera[10–13] and from LICIACube.[14]

Navigating the DART spacecraft to a hypervelocity impact with Dimorphos is very challenging. The trajectory must maximize deflection of the asteroid, while at the same time keeping the spacecraft close enough to Earth to enable observation of the impact and also communication capability sufficient to obtain images of the asteroid on approach. The spacecraft's 22-m^2 solar arrays (shown in Figure 7) generate the power (~3.5 kW) the NEXT-C engine requires. However, the spacecraft's narrow-angle camera must remain trained on the target asteroid, even while DART undertakes the autonomous ΔV maneuvers required to intercept the target, so this motion must be managed carefully.[12]

An additional challenge in guiding DART to the Didymos secondary is the need to switch targets late in the approach. SMART Nav must first target Didymos because the small size of Dimorphos prevents it from being seen by the narrow-angle camera until close to impact (~1 h before). The spacecraft's lighting at arrival causes shadowing of both Didymos and Dimorphos, posing a challenge to precise targeting of the impact on Dimorphos. DART streams images, basically video at 1 Hz, back to Earth in real time right up until it impacts the asteroid.[12] Demonstrating this technique, as well as solving these challenges, will pave the way for future planetary defense missions to be ready to perform the kinetic impact on a shorter timescale, if needed.

FUTURE

Because the PDCO is a new office at NASA, it is in the process of developing a full vision for the future of planetary defense and the priorities for the next decade. APL is working to help define the strategy and the innovations that might at some point help save humanity. Below we describe some of these ideas, following the PDCO's approach of find, warn, and mitigate.

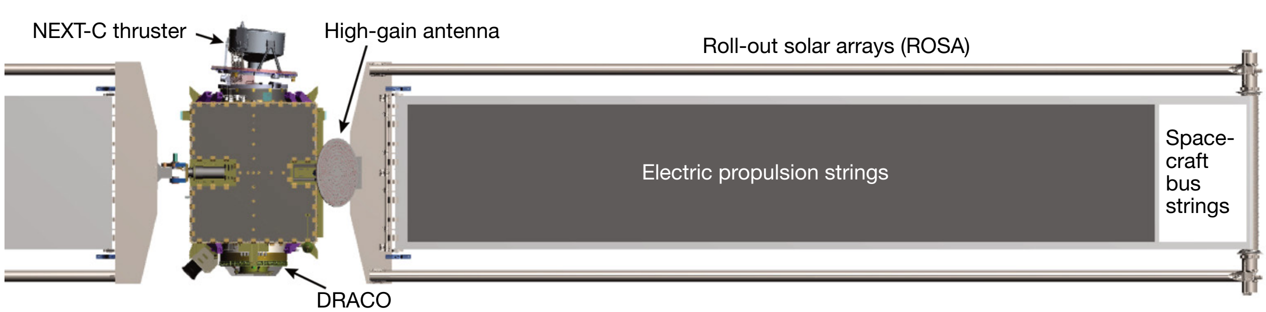

Figure 7. DART's mechanical layout. The layout is dominated by accommodation of the NEXT-C thruster and ROSA. DRACO, Didymos Reconnaissance and Asteroid Camera for OpNav.

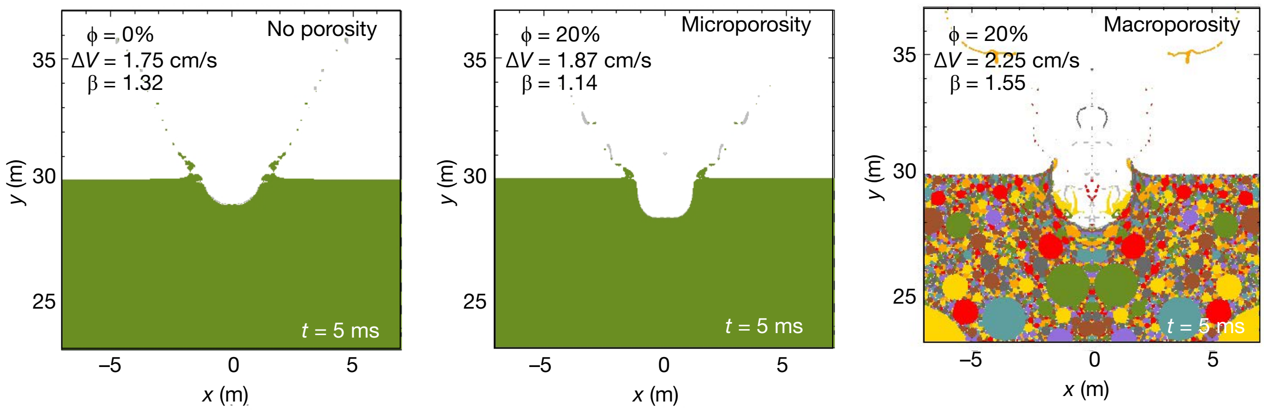

Figure 8. Effect of the target asteroid's structure and porosity on deflection from a kinetic impactor. The asteroid structure, whether made of one solid rock or a conglomeration of smaller rocks and regolith, affects the amount of deflection after the DART impact, as well as the crater shape and size created. High-fidelity impact simulations of three possible asteroid structures result in different crater shapes and orbital velocity changes. These simulations help us constrain DART's expected outcomes and plan for future planetary defense missions.

A lot of thought has been given to the space-based observation techniques for finding NEOs. Large space-based visible and infrared observatories and telescopes require substantial time and funding to develop. SmallSat constellations have been suggested as an alternative to cost-effective continuous monitoring of the skies. Unfortunately, to detect the smaller regional-scale hazards, the telescopes on these platforms need to have apertures of 20 cm or greater. These are hard to accommodate on SmallSat spacecraft and require exceptional attitude control, something not currently available on a typical SmallSat platform. Foldout optics, better infrared detectors that function well at higher temperatures, and innovative cooling systems that passively reject the heat from the SmallSats and payload are all needed to make the planetary defense SmallSats a reality.

With the rapid development of commercial space and space-based constellations for internet providers, new cameras and telescopes are being added as secondary payloads to commercial platforms in geostationary and low Earth orbits. A great example is SpaceX, which is in the process of sending up another batch of the Starlink buses for communications but is launching with unused launch vehicle capacity. Finding a way to leverage available space and unused capabilities can result in a ready-to-go available platform for rapid response to asteroid threats. In addition, over the next few years, developing new data post-processing techniques can help with tracking asteroids and better determining the orbits of these hazardous objects.

Despite our studies to date, many poorly understood aspects of NEOs affect our models of planetary defense response options. APL scientists are working to refine our understanding of asteroid material properties and interior structures by using a combination of laboratory experiments and numerical simulations. In APL's Planetary Impact Lab, researchers perform high-velocity impact experiments and track the impact dynamics with high-speed cameras, lasers, and other diagnostics. These measurements complement computational models that simulate large-scale asteroid physical responses using hundreds to thousands of computer processors. These simulations allow APL researchers to track the evolution of shock waves and the resultant material state changes and deformations that lead to craters and ejecta plumes (Figure 8). These models informed the DART design and will continue to be indispensable for planetary defense architectures going forward.

As a trusted agent, APL will continue to research, test, and apply innovative technologies to address the threat of hazardous asteroids.

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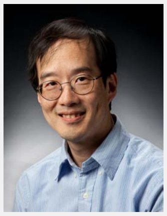

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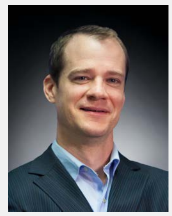

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