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SEPTEMBER 2022

Cosmic Triplets

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SMASH and Nu

This year, the DART mission will make humanity's first perceptible impact on the motion of a celestial body. The result might help us someday avert our potential annihilation by asteroid.

For all its destructiveness, smashing stuff together tells us a great deal about the universe. Colliding suspended balls demonstrated conservation of momentum and energy in the 17th century and led to every 1980s executive's favorite desk decoration, Newton's cradle. Atom smashers like the Large Hadron Collider have revealed the tiniest constituents of reality. And observing two distant black holes violently merge has offered us a new window into extreme gravity at work in the cosmos.

Our exploration of the solar system has been no different. Sending multi-million-dollar probes into fatal nose-dives has a rich past. After the USSR's Luna 2 made history with the first impact on another world in 1959, the NASA Ranger 7–9 probes followed, smashing into the Moon's surface in 1964 and 1965 in order to take detailed images that would inform the design of Apollo. More recently, NASA's Deep Impact shot a projectile into Comet Tempel 1 at the end of its primary mission in 2005, revealing surprising details about the comet's composition.

Most impactor missions in the last couple of decades have been designed to expose the makeup of the body into which they collide. But the latest project has a different aim. NASA's Double Asteroid Redirection Test (DART) mission is traveling to Dimorphos, a companion moonlet of asteroid 65803 Didymos, in order to bump it off course in its orbit.

NASA is not doing this because the binary asteroid is a threat to us: "It's always good to state clearly that we are not in danger — we are not doing this because we have to. It's a test," emphasizes DART program scientist Tom Statler (NASA). Moreover, the change won't push the asteroids onto a dangerous path toward Earth — Dimorphos won't leave its orbit around Didymos, and the asteroids will continue on their current trajectory around the Sun.

Instead, scientists hope that DART will show us whether crashing a probe into an asteroid actually changes its motion, knowledge we must have in case we ever need to nudge an asteroid away from Earth to avert annihilation.

Don't Look Up

Planetary defense against asteroid impacts can be boiled down to two tasks: finding threats and removing them. Responsibility for the former rests on the International Astronomical Union's Minor Planet Center (MPC) and the Jet Propulsion Laboratory's Center for Near-Earth Object Studies (CNEOS).

The MPC is the internationally recognized clearinghouse for small-body position measurements, including near-Earth objects. Data fed into the MPC come from observatories around the world and include valuable contributions from amateur astronomers. CNEOS in turn plugs MPC data into its recently updated Sentry-II impact-monitoring system, which continuously performs long-term analyses of the

◀ **INCOMING** The DART spacecraft will slam into Didymos' moon, Dimorphos, in an attempt to change the size of the moon's orbit around the larger asteroid.

NASA / JHU APL

The Hazard by the Numbers

Asteroid Size	4 meters	25 meters	140 meters	1 kilometer	10 kilometers
Impact Frequency	~1 per year	~1 per 100 years	~1 per 20,000 years	~1 per 500,000 years	~1 per 100–200 million years
Effects	Bright flash, no ground damage, possible meteorites	Airburst explosion, could cause widespread injuries if over populated area	Crater 1 to 2 km wide, deadly over metro or state-size areas, mass casualties	10-km-wide crater, global devastation, possible civilization collapse	100-km-wide crater, global devastation, mass extinctions
Est. Number of Objects	~500 million	~5 million	~25,000	~900	4
% Discovered	<0.1%	0.4%	39%	>95%	100%

▲ **NEAR-EARTH OBJECTS** Scientists have found nearly all of the nearby asteroids that could cause global devastation, but they have a far more incomplete tally of smaller, regionally dangerous objects. A given object's effect depends on many factors, including composition, speed, and incoming angle, not just its size.

orbits of potentially hazardous objects.

Up to now, results from CNEOS have been comforting. There's virtually no chance a known hazardous object will impact Earth in the next 100 years. Even 101955 Bennu, one of the most likely asteroids to hit Earth, only has a 1-in-1,800 chance of a future collision over the next three centuries.

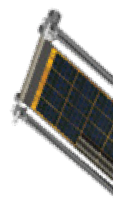
But this doesn't mean we should sit back and relax. There are still unknown objects flying through the solar system that could suddenly pose a threat to Earth at any given moment. At the time of writing, observers had discovered 28,539 near-Earth asteroids. Of these, 10,030 appear to be at least 140 meters (460 ft) wide, and 881 are thought to be more than 1 kilometer wide. Objects of these sizes would have impacts ranging from significant regional damage to worldwide extinction if they hit Earth. (For a gauge of what "significant regional damage" means, think the devastation of an entire U.S. state.)

According to NASA, only about 40% of asteroids larger than 140 meters have been found. And to add to the uncertainty, only about 2,000 of these objects have been properly characterized by the only instrument suitable for the task: NEOWISE, an old, partially broken down, and repurposed space-based infrared telescope.

Amy Mainzer (University of Arizona) is principal investigator on both NEOWISE and its purpose-built successor, NEO Surveyor, scheduled to launch in 2026. With Surveyor, she says, our knowledge of near-Earth objects (NEOs) will expand dramatically; over its lifespan, the space telescope could add a few hundred thousand objects to our roster.

Of these, there is no telling if any will be racing towards Earth in the near future. But if one does, Surveyor's infrared data should enable scientists to accurately estimate its size and probable shape and, when combined with visible-light observations, the object's albedo and hints of its composition. Having that knowledge well in advance of any potential asteroid rendezvous with Earth is essential to planetary defense. "We really want to try to give people time, because that's the best weapon in this business," says Mainzer.

But time is not the only weapon humanity would need. There's little point in finding and characterizing threats if we have no way of removing them. This is why DART is on a collision course with Dimorphos now — so that scientists can test mitigation measures, just in case they have to use them.



DARTing into Didymos

Since its launch on November 24, 2021, DART has raced through space to reach the Didymos system. Didymos and Dimorphos are approximately 780 meters and 160 meters wide, respectively. They take 770 days to orbit the Sun at a distance that varies from 1.0 to 2.3 astronomical units (a.u.), and they orbit each other at a distance of about 1 kilometer. They will make their "close" approach to Earth on October 4, 2022, at 10.7 million km — nearly 30 times farther away than the Moon.

Sometime between September 26th and October 1st, just before the asteroid's perigee, the 550-kilogram spacecraft will zoom towards Dimorphos at 6.7 kilometers per second (15,000 mph). As the moonlet comes around from the backside of Didymos on its 11.92-hour orbit, DART will collide with it head-on.

TERRI DUBÉ / S&T, SOURCE: NASA

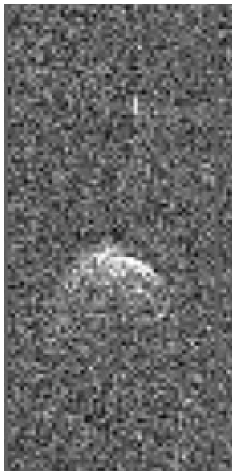
DART will have two witnesses to this manufactured cosmic event: the impactor's own high-resolution imager, named Didymos Reconnaissance and Asteroid Camera for Optical navigation (DRACO), and a small Italian CubeSat called the Light Italian CubeSat for Imaging of Asteroids (LICIACube) that will piggyback the DART spacecraft.

DRACO performs two roles, supporting the autonomous guidance system to ensure DART hits its target and providing essential data for the analysis and interpretation of the results. It will snap images of Didymos and Dimorphos on approach to measure their size and shape, as well as images of Dimorphos' surface in order to characterize the impact site just before the probe's annihilation.

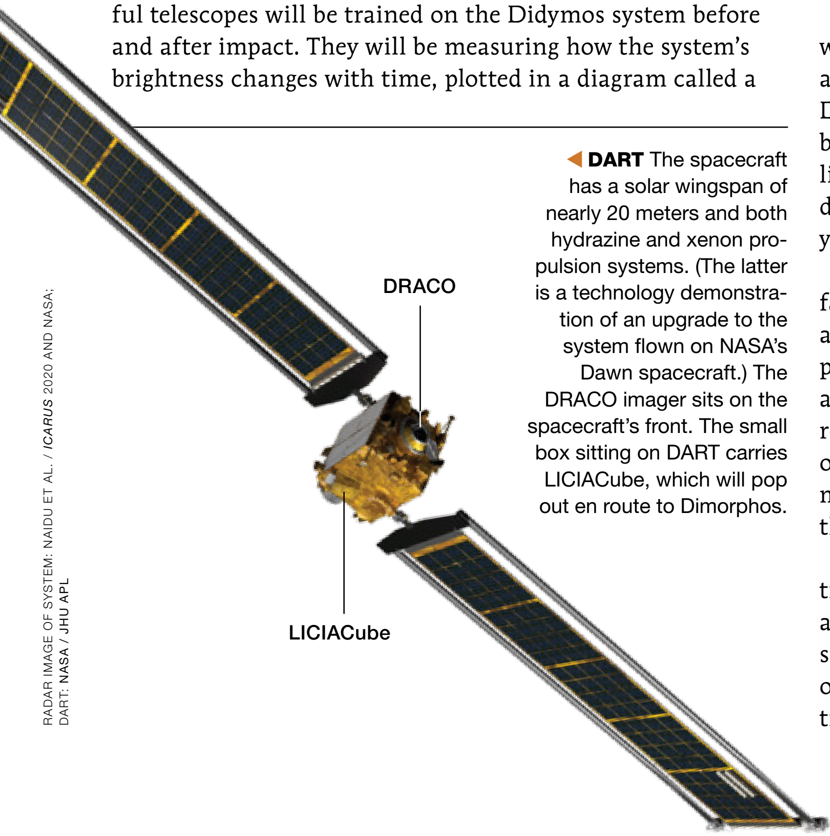
Meanwhile, LICIACube will have detached from DART 10 days prior to impact and altered its trajectory to lag just under 3 minutes behind the main spacecraft, so as to fly safely past the target. As the CubeSat sweeps past the Didymos system, just 55 km away at its closest approach, its two optical cameras — dubbed LICIACube Unit Key Explorer (LUKE) and LICIACube Explorer Imaging for Asteroid (LEIA) — will witness the impact itself, the initial ejecta plume and beginnings of the impact crater, and finally the backside of both Didymos and Dimorphos as it speeds away. With no way to slow down, the sole survivor of the DART impact will continue travelling through the celestial abyss, doomed to purposelessly circle the Sun.

But back on Earth, the DART team's excitement will only now be reaching its zenith. Some of the world's most powerful telescopes will be trained on the Didymos system before and after impact. They will be measuring how the system's brightness changes with time, plotted in a diagram called a *light curve*. Dips in the light curve indicate when the smaller moonlet passes in front of (or is hidden behind) Didymos from Earth's point of view, giving a precise gauge of the orbital period.

"When we see the binary orbit start going off schedule in the data, that's when we know we have, in fact, changed the motion of a celestial body in space for the first time," says Statler. "That's the goosebumps moment for me." With initial estimates of how much DART changed Dimorphos' orbit expected around two weeks after impact, the NASA mission will be complete.



◀ **DIDYMOS SYSTEM** Captured by the Arecibo Observatory in 2003, these radar images are the best views we have of Didymos and its moon, Dimorphos.



◀ **DART** The spacecraft has a solar wingspan of nearly 20 meters and both hydrazine and xenon propulsion systems. (The latter is a technology demonstration of an upgrade to the system flown on NASA's Dawn spacecraft.) The DRACO imager sits on the spacecraft's front. The small box sitting on DART carries LICIACube, which will pop out en route to Dimorphos.

RADAR IMAGE OF SYSTEM: NAIDU ET AL. / *ICARUS* 2020 AND NASA; DART: NASA / JHU APL

Uncertain Beta

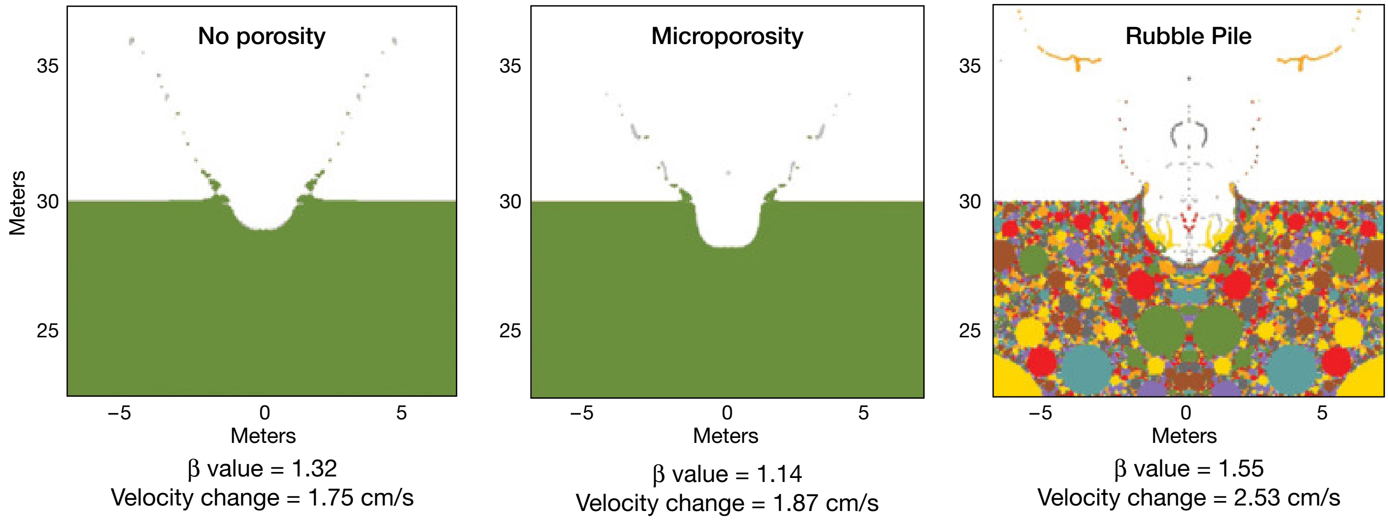
The collision should slow the moonlet down and kick it into a slightly lower orbit with a shorter period. Although the deflection will be declared a success if DART shoves Dimorphos' orbit off schedule by the minimum amount deemed detectable from Earth — a measly 73 seconds — Statler is more optimistic: "We're expecting a change in period in the vicinity of 10-ish minutes," equivalent to bringing the asteroids' nearest approach 22 meters closer. "But this is why we have to do the test, because we don't know."

Uncertainty can be boiled down to a single figure, *beta* (β). Beta is a number that compares the momentum of Dimorphos before and after the collision. More specifically, it is a measure of how much additional momentum *beyond* what's carried by the spacecraft itself is transferred to the asteroid.

If beta equals 1, DART will have a perfect *inelastic collision* with Dimorphos, adding all of DART's momentum to the asteroid. But what mission scientists are hoping for is that DART's momentum gets a boost from a huge plume of ejecta blasted off the surface. "It works like an extra, instantaneous little rocket engine that pushes the asteroid in the other direction," explains Statler. "By having this ejecta help you, you get beta greater than 1."

But calculating beta is no simple task. It consists of many factors linked to the properties of both the impactor and asteroid in question. And right now, most of Dimorphos' properties are completely unknown. Is it shaped like a potato, a donut, a die, or some other wacky configuration? Is it solid rock? Basalt? Is it porous or dense, cracked or solid, strong or weak, tough or brittle? What happens if the probe hits the moonlet at a different location or angle than simulated? All these factors play a part in determining the beta value.

Depending on the best guesses physicists choose, simulations suggest the beta of the DART collision could range from a little extra push (β = 1.5) to a huge shove (β = 5), Statler says. And this is a problem. If ever we need to deflect an asteroid from Earth's path, we will require more precise simulations, to tell us if our efforts are likely to succeed or fail.



▲ **BETA** An asteroid's porosity affects how it responds to being hit by a projectile, as shown in these simulated collisions. As microporosity increases, β decreases but the imparted velocity increases, because the asteroid is less massive and thus easier to deflect. However, a rubble-pile asteroid forms a larger crater and far more ejecta, increasing both β and the change in velocity. These snapshots are for 5 milliseconds after the impact.

Europe Follows Up

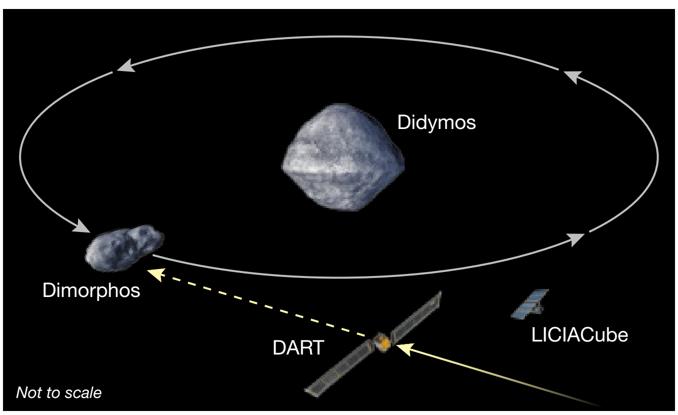
DRACO's head-on view, LICIACube's sweeping perspective, and distant observations from Earth will bring most of the unknowns in calculating beta into focus. But some will remain a little hazy. This is why, long after Dimorphos' dust settles, the moonlet will receive another visitor.

The European Space Agency's Hera is scheduled to arrive at the Didymos system in December 2026. Like a crime scene investigator, Hera will be tooled up with various instruments to pick apart precisely what happened when DART smashed into Dimorphos. "We want a fully documented impact experiment," explains Hera principal investigator Patrick Michel (Côte d'Azur Observatory, France). "DART will provide the initial conditions, but we need two other things: the outcome of the impact and the physical properties of the target."

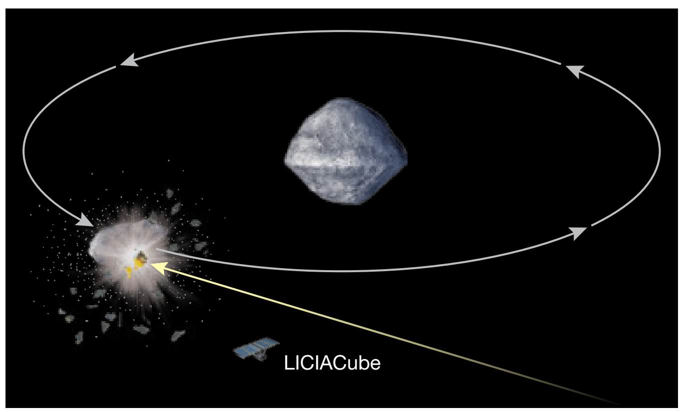
One key property that the investigation will uncover is Dimorphos' mass. DART will measure this indirectly, using DRACO and LICIACube imaging to constrain the asteroid's shape and volume and assuming an appropriate density. Hera will take a more accurate mass measurement by determining the "wobble" the moonlet causes in Didymos' position, relative to the system's common center of gravity. This should lead to a value with an uncertainty of less than 10%.

Hera will also map the shape of DART's impact crater in detail, which has a bearing on the accuracy of impact simulations as well. After DART's obliteration, LICIACube will only witness the immediate impact aftermath from close range. From previous experience, this might not be long enough to see the full extent of DART's effect.

NASA's OSIRIS-REX spacecraft touched down on asteroid Bennu on October 20, 2020. The mission team was hoping to collect at least 60 grams of material from the surface in a "touch-and-go" maneuver. But the spacecraft's grabber penetrated much deeper into the asteroid than anticipated, scoop-



1. DART and LICIACube bear down on Dimorphos in late 2022.



2. DART hits Dimorphos, creating a blast of debris that helps slow the moonlet down.

BETA EXAMPLES: ANGELA STICKLE / JOHNS HOPKINS APL; MISSION STEPS: GREGG DINDERMAN / S&T, SOURCE: NASA / JHU APL ing up at least 10 times as much. Digging into Bennu was more like dipping a hand in water than penetrating solid rock. “This material just doesn’t seem to dissipate energy,” explains Statler. “It’s friction-free. It’s strength-free. It doesn’t cohere.”

This should perhaps have been less surprising than it was. When a 2-kilogram copper impactor from JAXA’s Hayabusa 2 crashed into asteroid Ryugu at 2 km/s more than a year earlier, over 8 minutes passed before the crater finished forming. “You would think this would all just settle down and stop within a few seconds, because you surely lose a lot of energy just in the friction,” explains Statler. “But instead, these little bits of rock kept pushing on each other little piece even when it got down to less than walking speed motion — it’s just totally counterintuitive.”

15%

Fraction of near-Earth asteroids that are binaries

Both Bennu and Ryugu are rubble-pile asteroids consisting of a hodge-podge of large rocks and gravel, held together by the asteroid’s weak gravity rather than material strength. If Dimorphos turns out to be similar, reconstructing DART’s collision becomes a challenge for theorists. Researchers traditionally base impact simulations on known shock physics and verify them through laboratory-based experiments here on Earth. The codes are not built to handle this liquid-like, friction-free material moving in slow motion, Michel explains.

As a result, experts have been developing simulations that incorporate granular physics, accounting for the strange, cohesionless material encountered on Bennu and Ryugu. “It becomes very complex code, and therefore we need to make sure we do it correctly, which is why DART and Hera are so important,” he says.

With the real-world data that DART and Hera will offer, physicists should finally have everything they need to confirm the impact’s beta value and reproduce exactly what happened on Dimorphos. And if they can simulate the DART impact accurately, then they can apply the same physics in simulations of other asteroids and impacts, taking a lot of the guesswork out of planning a real deflection mission.

What If . . . ?

A concern on many people’s minds is that Dimorphos will follow Bennu and Ryugu’s lead and throw a curveball. What if DART’s crash produces a beta value models cannot explain? In this case, asteroid impact science will need to go back to the drawing board. “As a scientist, I would like to be surprised by DART,” says Statler. “As a planetary defender, I really don’t.”

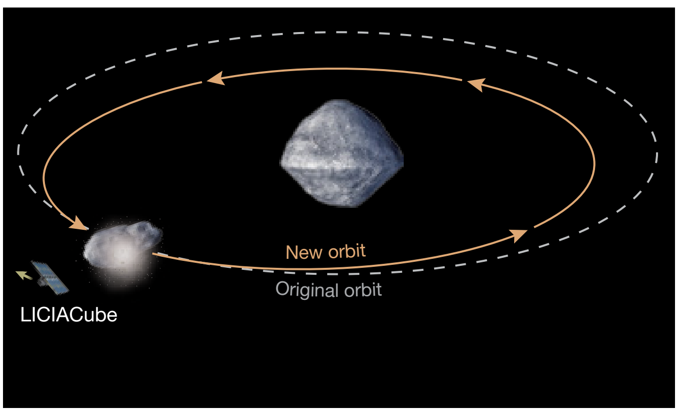
Another worry is that the DART impact simply won’t provide enough data. Crashing into Dimorphos represents just one real-world data point to verify a vast range of impact scenarios. How can one test validate an entire field of research?

In reality, it can’t. All DART and Hera can really do is tell us whether physicists’ current understanding and simulations are heading in the right direction. We’ll need more missions to other asteroids before any planetary defender can say with confidence that we could successfully deflect a dangerous asteroid headed for Earth.

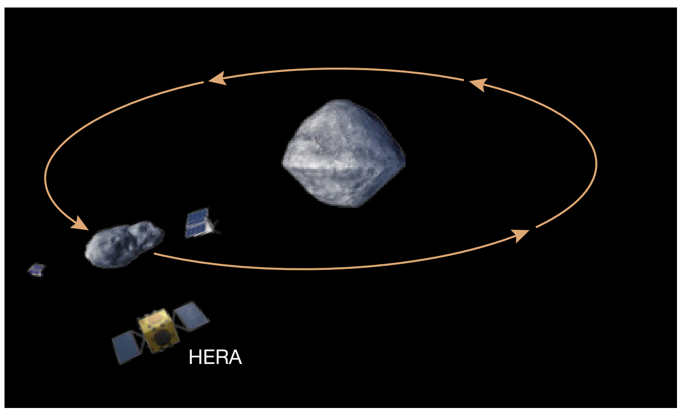
Some people might see DART and Hera, and planetary defense more generally, as a frivolous waste of money when the chances of a large asteroid impacting Earth in the near future are vanishingly small. But recent world events have taught us that low-probability situations can and do have huge, global consequences — and preparedness is key to mitigating their impact. Michel feels it would be foolish to put off planning for the worst: “We have the means and time to prepare for what’s necessary to offer security for future generations,” he says. As the proverb goes: “Failing to plan is planning to fail.”

■ **BENJAMIN SKUSE** is a science writer based in Somerset, United Kingdom.

Explore Sentry’s list of potential hazardous objects: cneos.jpl.nasa.gov/sentry. Find a list of observable asteroids and comets (hazardous or not) at https://is.gd/ssd_observe.



3. A few minutes later, LICIACube flies safely by, observing the wreckage. The smack robs Dimorphos of orbital energy, slightly shrinking its circuit around Didymos (size change and elongation exaggerated for clarity).



4. In 2026, Hera and its two tagalong CubeSats arrive to investigate.