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Defending Earth against Asteroids

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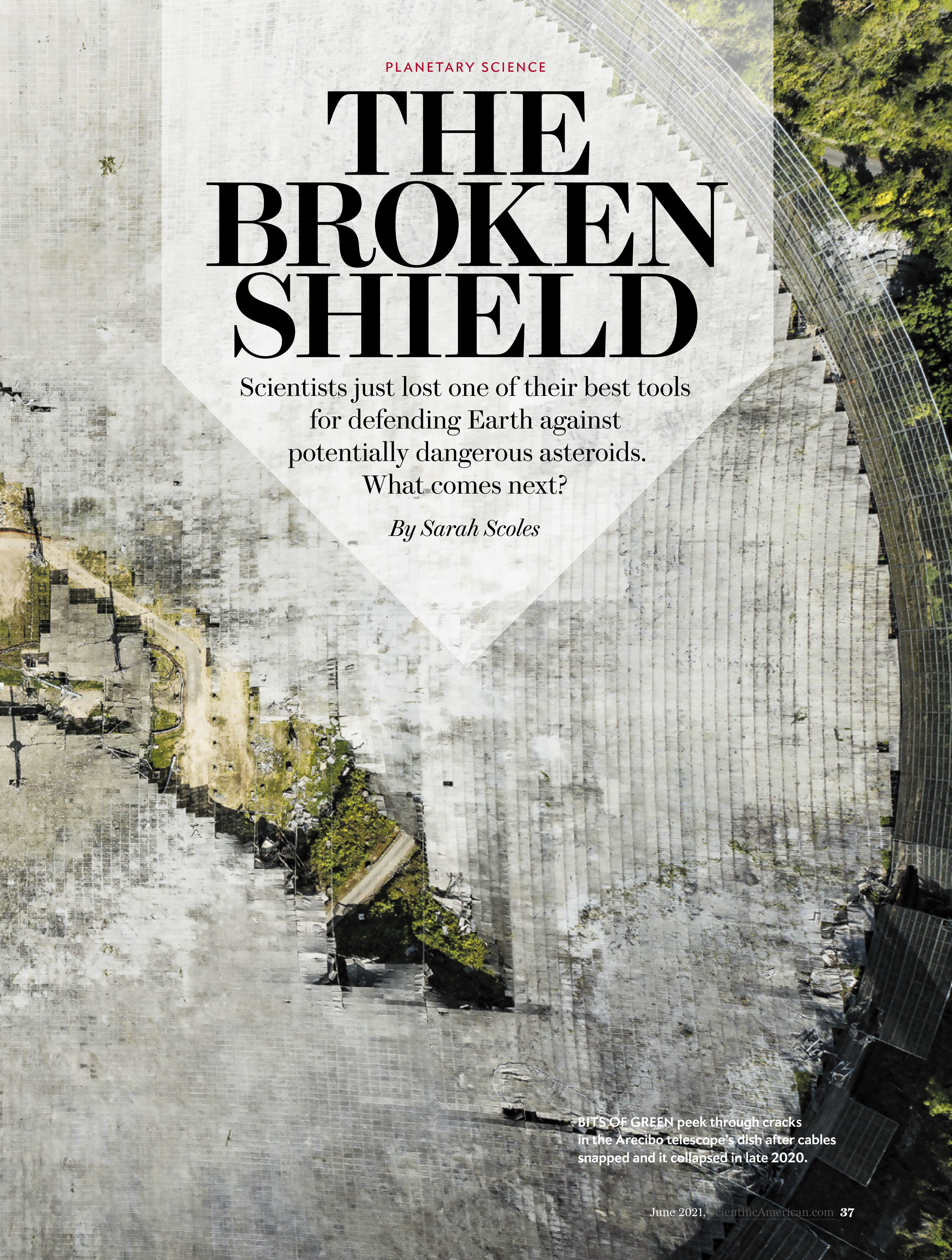
PLANETARY SCIENCE

THE BROKEN SHIELD

Scientists just lost one of their best tools for defending Earth against potentially dangerous asteroids. What comes next?

By Sarah Scoles



BITS OF GREEN peek through cracks in the Arecibo telescope's dish after cables snapped and it collapsed in late 2020.

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IN THE FIRST FEW SECONDS OF VIDEO TAKEN AT THE ARECIBO RADIO TELESCOPE ON December 1, 2020, everything looks normal. Sure, support cables had broken the previous August and November, damaging the 300-meter-wide dish. And *sure,* the National Science Foundation was already planning to decommission Arecibo, an instrument that began scanning the sky in 1963. So things weren't great for the telescope. But it was at least still there.

That changed just before 8 A.M. when, as if on command, a bit of dust puffed out from a support pillar. That was, it turns out, a cable beginning to snap off. Left with extra load, other cables began to break, too. Soon the massive equipment platform, once suspended over the bowl-shaped observatory, began to tip. After an agonizing swing downward, the platform crashed. More cables snapped, and debris flew around like in a demolition. At the end of the footage, giant holes were visible in the iconic telescope, and dust rose all around. Arecibo, at least as scientists knew it, was gone.

When Edgard Rivera-Valentín, a staff scientist at the Lunar and Planetary Institute and formerly part of the planetary radar group at Arecibo, clicked on the video, they could stomach only a few seconds. It took them days to get through the full two minutes. "When everything went down, it was—I use the word 'tragedy,'" says Rivera-Valentín, a native of Puerto Rico.

Arecibo had a long and storied legacy of scientific discovery, studying space weather, searching for extraterrestrials, timing pulsars, mapping neutral hydrogen gas. But it also had an unconventional claim to fame: It boasted the world's most powerful, sensitive and active planetary radar system. That radar could peer through Venus's thick atmosphere and map the dusty Martian surface, but it also helped protect Earth from asteroids. The data showed scientists those rocks in detail, revealed whether they might present a threat, and helped humans figure out what they could reasonably do if an asteroid was heading our way. "One of the neat things about doing radar is that you're actively defending the entire Earth," Rivera-Valentín says. "So if anyone asks you, 'Why should I care?,' it's like, 'I'm going to make sure that asteroid doesn't come for you.'"

Arecibo's radar efforts fell under the umbrella of "planetary defense": the attempt to identify and prevent potential collisions between asteroids (and comets) and this planet, which, ideally, we would like to keep intact.

On any given day the likelihood is low that a space rock will devastatingly smash into Earth. But the consequences of such a catastrophe would be severe. And our solar system's history—planets pocked with craters, crashes on other planets in recent memory, huge objects hurtling through Earth's atmosphere and captured on dashcams—demonstrates the statistical truth that events unlikely to happen on any given day do happen, given enough days. That's why NASA has an entire office dedicated to the problem; why a slew of astronomical facilities gather preventive data; and why an upcoming space mission will demonstrate what earthlings can do if a space rock does come knocking.

But is it enough? With Arecibo and its radar out of commission, our planetary defense arsenal comes up short. The U.S. and other nations are assessing the risk, brainstorming new ways to stay ahead of the threat and formulating plans for what might come next.

COUNTING SPACE ROCKS

PLANETARY DEFENSE has been plagued by a "giggle factor." After all, apocalypse by asteroid seems the stuff of feature films, not serious science. But officials started to pay more attention soon after a comet called Shoemaker-Levy headed straight for Jupiter in 1994. Linda Billings, a consultant for NASA's planetary defense communications efforts, remembers when the two collided. On July 21, 1994—a few days into a series of impacts—she went to an

PRECEDING PAGES: CAVAN IMAGES *Alamy Stock Photo*

ALEX ALISHEVSKIKH (HTTPS://PHOTOS.CYBERBOREAN.ORG/FEATURED/2013-CHELYABINSK-METEOR-TRAIL)

ON THE MORNING of February 15, 2013, an asteroid the size of a house entered Earth's atmosphere and exploded over Chelyabinsk, Russia. The event was a reminder of the potential perils of rocks falling from space.

open house at the Naval Observatory in Washington, D.C., where sky watchers could spy on Jupiter. On the lawn outside, amateur astronomers trained their own instruments on the scarred planet. Jupiter's gravity had shredded the comet into pieces, which streamed into the planet's swirling atmosphere, reaching 40,000 degrees Celsius and sending 3,000-kilometer-high plumes of material shooting into space. "We had solid evidence that impacts occur," Billings says, understatedly.

Soon after, U.S. Air Force officials published two reports, *SpaceCast 2020* and *Air Force 2025,* on what the military could or should do to mitigate the threat of space rocks in the coming decades. Space impacts were a national security problem. The first report, meant to figure out how the U.S. could maintain the "high ground" in space, coined the term "planetary defense." The second had much the same goal, and both described asteroid detection and mitigation, the word for efforts to dispense with a threat if one arises—by, for instance, deflecting an asteroid by slamming into it with a spacecraft or exploding a nuclear weapon nearby.

Back then, scientists now well known for their planetary protection work were part of the air force—people such as Lindley Johnson, now program executive of NASA's Planetary Defense Coordination Office (and an author of the relevant part of *SpaceCast*), and Pete Worden, former director of NASA's Ames Research Center. They and their colleagues warned about the risk of civilization turning into a crater. But especially after 9/11, the issue did not receive as much attention as many would have liked. Johnson retired from active duty in 2003. "NASA said, 'Come on over. We've got a job for you,'" he says. One of his duties was to run NASA's Near-Earth Object Observations program. Today, in large part a result of Johnson's efforts, that has mushroomed into an entire Planetary Defense Coordination Office, where he is the boss. "An unwarned impact would be the biggest natural disaster we've ever seen, quite frankly," Johnson says. His office hopes to make any hypothetical impact an avoidable one.

To that end, NASA's office runs asteroid data-gathering programs, relying in part on wide-field optical and infrared telescopes that can see a broad expanse of the sky. Observatories run by the University of Arizona and the University of Hawaii have worked with Johnson's office to adapt their existing telescopes into sentries. The group also repurposed the space-based Wide Area Infrared Survey Explorer (WISE) into NEOWISE (Near-Earth Object WISE) in the years after it was initially decommissioned in 2011. NEOWISE recently completed its 14th all-sky survey and is working on its 15th.

Meanwhile M.I.T. Lincoln Laboratory's Lincoln Near-Earth Asteroid Research (LINEAR) software is currently installed on an air force asset called the Space Surveillance Telescope (SST) in Australia. The software makes this military observatory the world's most productive asteroid-hunting instrument, by some metrics. It has discovered 142 previously unknown near-Earth objects, four potentially hazardous objects and eight new comets.

That's great but not as good as Congress would like. The official mandate these days is to discover 90 percent of the objects that are 140 meters or larger—the size at which a boom would result in "a pretty bad day anywhere," according to Johnson. There are an estimated 25,000 such baddies. "We are getting close, and maybe by the end of the year we'll have found 10,000 of those," he says. That is 40 percent completion for 20 years of effort. Overall, scientists have discovered more than 25,000 near-Earth asteroids of any size, and around 19,000 of those caught on camera are bigger than 30 meters.

REPLACING ARECIBO

GLOBALLY, 30 SPACE ORGANIZATIONS—based everywhere from Latvia to Colombia, from China to Israel, and involving dedicated amateurs, national space agencies and individual observatories—participate in the International Asteroid Warning Network. The group, formed at the recommendation of the United Nations, coordinates observation and response efforts across our vulnerable planet. Since 2016 it has logged more than 300 close approaches, when asteroids were projected to come within one lunar distance—the average distance between Earth and the moon—of the globe's center. It has also coordinated three campaigns to practice "the observing resources and characterization capabilities that may be applied to a near-Earth object on a reasonably short timescale."

That is useful because the work is not finished when close-calling objects are discovered. Ground-based optical and infrared telescopes in places such as Hawaii, New Mexico and Arizona make follow-up observations to learn more about the objects than the fact of their existence. Planetary radar, too, typically plays a role in refining the orbits of newly discovered asteroids and projecting their paths into the future—mapping out where those objects will go in the years to come and whether they might intersect with Earth. Radar also helps to discern asteroids' shape, composition and trajectory.

Radar observations such as Arecibo's work like this: If you blast powerful radio waves toward the object, they bounce back, changed by the object's spin, motion, shape and size, as well as by any moons the asteroid might have. The time they take to holler back also reveals the object's precise distance from Earth. With all that information, you can refine its orbit and predict where it will be far into the future and whether that "where" includes Iowa. You can also learn about its properties—useful if you must knock it off course. Is it dense? Porous? Round? Peanutty? "When we record the echo that comes back, if it's different in any way from what we transmitted, we know that was due to the properties of the target, in this case, the asteroid," says Patrick Taylor, a senior staff scientist at the Lunar and Planetary Institute and former group lead for Arecibo's radar program.

Getting a radar observation is like taking a picture of the asteroid from the safety of the ground. "That is kind of like a flyby of a spacecraft at a tiny fraction of the cost," says Ellen Howell of the University of Arizona. "We get pictures of them as individual rocks, not just points of light." Which is significant, because as planetary scientists are fond of saying, if you've seen one asteroid, you've seen one asteroid. With the loss of Arecibo, Howell says, "that capability is now severely diminished." This ability to take observations of the present, predict the future and then *change* the future is what could set us apart from the poor saps of the past, who just had to take whatever knocks space sent their way. "Dinosaurs didn't have a space program," Rivera-Valentín says. "But we do."

Arecibo was not the only planetary radar in the U.S. There is one left—the Goldstone Solar System Radar in California—but it can detect less than half the near-Earth asteroids that Arecibo could. And even if Goldstone were the perfect instrument, stuff happens, and if it is down—as it was for around 18 months of maintenance just before Arecibo collapsed—this planet will have to fly through space without seeing as much as it previously did. "Losing Arecibo is going to make people think more about what that next-generation step will be," Taylor says. "Whatever that is, I don't know."

Scientists have ideas. Some would like to build Arecibo 2.0, synthesizing a number of smaller dishes in the same island spot to work together as one larger dish, thereby restoring radar capabilities. At Green Bank Observatory in West Virginia, scientists just did their own demo with defense contractor Raytheon, beaming a radar signal to the moon and receiving the bounce-back at antennas spread throughout the U.S. in the Very Long Baseline Array, which is operated from New Mexico. They hope this will pave the way for a setup with more oomph that could do asteroid work. "The Green Bank proposal for upgrade sounds terrific to me," Billings says. "But it's not yet funded."

And even if it were, Michael Nolan of the University of Arizona doubts that Green Bank could replace Arecibo's capabilities. Transmitting from one spot and picking up in another is a data-intensive approach, and doing both from Green Bank has its own issues. "I don't see any of the things I've seen so far being the workhorse system," he says. Arecibo's hypothetical replacement does not have funding either, for instance.

And the question of what to do is only the first hurdle. There is also the larger issue of who should do it. Some experts argue that the burden is too much for the scientific community to bear alone. Perhaps, they say, the task should fall to an organization with extensive experience in long-term planning and, more important, stable funding. In other words, the Department of Defense—specifically, its newly minted Space Force.

STOPPING ASTEROIDS

THE SPACE FORCE, a new branch of the military that largely deals with satellites and their safety and security, aims to track objects large and small, from here to the moon, as international and commercial activity—satellites, spacecraft, orbital manufacturing systems, pay-as-you-go trips—ramps up. That general effort is called space situational awareness, and it is usually carried out by optical instruments and long-range radar. While that radar is monitor-

How to Deflect an Asteroid

What if scientists discover a large space rock heading toward Earth? Humanity has several options to try to move the body off course, although none have been tested. Some, such as using a nuclear weapon on the incoming rock, bring their own risks—for instance, the possibility that debris from the explosion could still reach our planet.

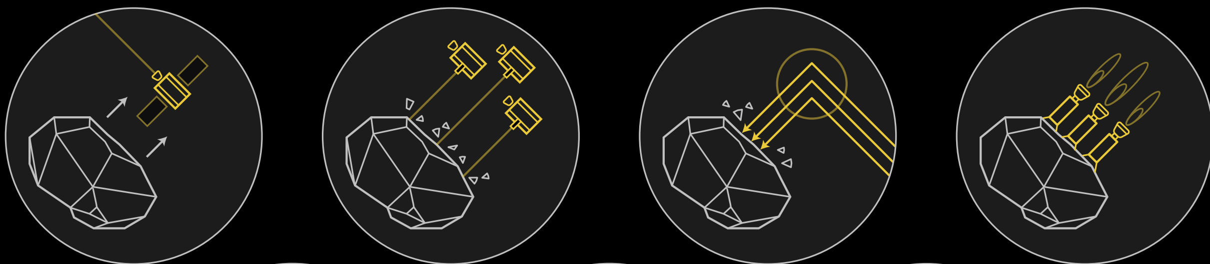
POSSIBLE DEFLECTION METHODS

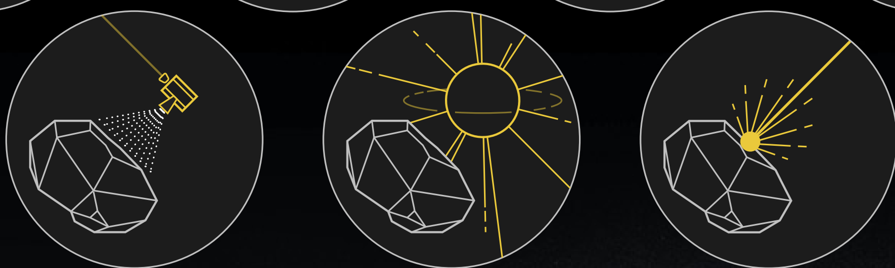
Fly a heavy spacecraft near the rock to act as a "gravity tractor," influencing the rock's direction over decades.

Shoot lasers from small spacecraft to vaporize material, which flies off the surface and creates a push in the opposite direction.

Shine a mirror to redirect sunlight, causing the rock to shed material, which gives it a nudge.

If the asteroid is solid enough, land equipment on the surface to propel it with rockets.





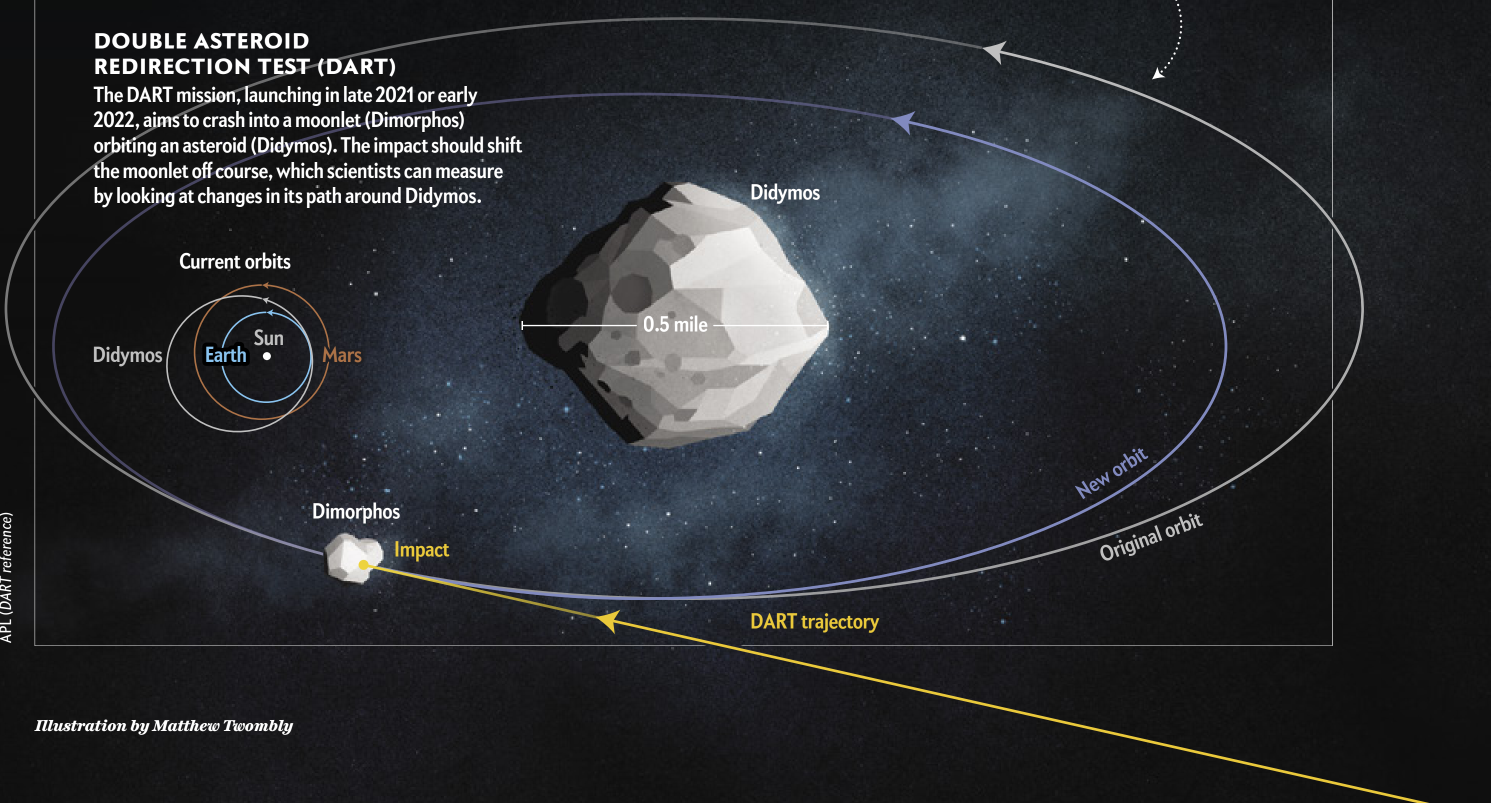
Paint it to alter its thermal properties so that sunlight will change its direction.

Detonate a nuclear weapon near an object, transferring energy and pushing it off course.

Slam an asteroid with a spacecraft before it slams into Earth. Scientist hope to test this method with DART.

DOUBLE ASTEROID REDIRECTION TEST (DART)

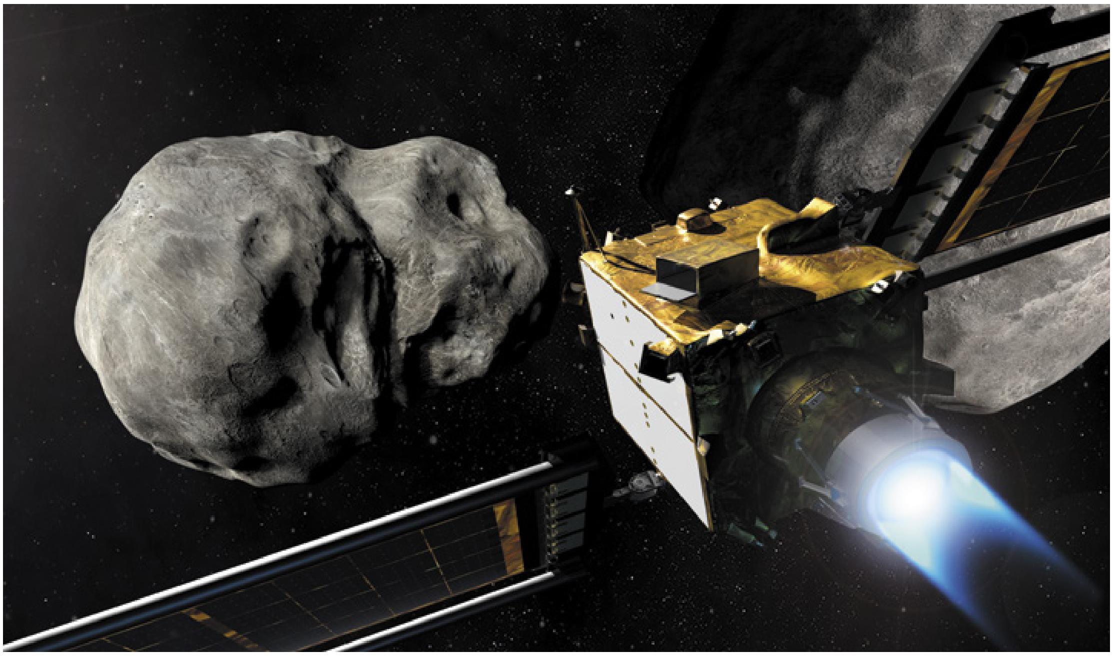
The DART mission, launching in late 2021 or early 2022, aims to crash into a moonlet (Dimorphos) orbiting an asteroid (Didymos). The impact should shift the moonlet off course, which scientists can measure by looking at changes in its path around Didymos.



SOURCE: NASA, JOHNS HOPKINS APL (*DART reference*)

Illustration by Matthew Twombly

DUE TO LAUNCH this year or next, the Double Asteroid Redirection Test (DART) will try to alter the course of a space rock by slamming into it.



NASA, JOHNS HOPKINS APL

ing the activity in orbit, it could also detect asteroids that happen to be zooming through space in the same direction as (but, it is hoped, much farther out than) a satellite. NASA and Space Force officials have been talking about collaborating on such a win-win system. "It is beyond just brainstorming, but we have not settled on a particular concept yet," says Johnson, noting that the discussions are ongoing. In 2020 the two organizations signed a memorandum of understanding, agreeing to work together on certain things—including both planetary defense and space situational awareness. The Space Force referred questions about the collaboration back to NASA.

Some, though, want to expand the idea of military involvement. Peter Garretson, a senior fellow at the American Foreign Policy Council and former director of Air University's Space Horizons Research Task Force, would like to see the military lead planetary defense efforts, particularly mitigation. "NASA is principally a science and exploration agency. In my view, this is clearly a defense mission," Garretson says. "You're not deflecting the asteroid for science."

And actually *no* federal organization is specifically tasked with deflecting asteroids. But people are working on it anyway. One agency steeped in the effort is the Department of Energy—you know, the one with the nukes. At Los Alamos National Laboratory, Cathy Plesko does asteroid mitigation research. She got into planetary defense by studying impact craters on Mars using computer models. "But how do you *stop* making a crater?" she wondered. One day a senior astrophysicist at the lab said he thought the same sorts of code she used to model the craters could be used to model asteroid mitigation: They would show how an asteroid would react if something impacted it—rather than if it impacted something. This was the very stoppage she was wondering about.

She began studying the problem, but the lab's efforts weren't extensive—until February 2013. That month a 20-meter-wide asteroid screamed through the atmosphere and exploded nearly 30 kilometers above Chelyabinsk Oblast in Russia with the force of around 450 kilotons of TNT, injuring 1,600 people. As with Shoemaker-Levy, officials opened their eyes wider. Plesko's team spooled up and, together with NASA, started scrambling to understand what physics problems they needed to solve to respond if something bigger and badder came along. That work begins with revealing what asteroids are made of, a surprisingly hard problem to which radar provides the best Earth-based solution. "Are they rubble piles? Are they kind of mud balls? Are they chunks of iron?" Plesko asks. "There's a lot of variety." That variety makes simulations difficult. If you are modeling a plane on a computer, you know exactly how dense it is and how it is shaped. "We don't have those specifications for asteroids and comets," she says. "That's something we have to figure out."

Today Plesko examines the plethora of possibilities to whisk different kinds of asteroids away from the globe. One option is called a gravity tractor. You fly as heavy a spacecraft as you can muster as close to a space rock as you can sidle. "Your spacecraft can sort of lure the asteroid or the comet off its original course over time," she says. But it requires decades of luring, and the technology, she estimates, will not be ready for a century or so.

Some scientists have looked at using lasers attached to small spacecraft to heat up material and vaporize it, throwing it off the surface and thus—every action resulting in another equal and opposite—pushing the asteroid in the other direction. More bluntly, one could also slam an asteroid with a spacecraft before it slams into Earth. Alternatively: Shine a mirror at it, focusing solar rays, until it sheds material. Move it with rockets. Paint it to change its thermal properties and thus its orbit. Plesko, being at the Department of Energy, also studies the boomier menu choice: a "nuclear standoff burst." That means detonating a nuclear weapon close to a near-Earth object, transferring energy and throwing off some material. That deflects the rock just like the other techniques, only more, you know, emphatically. But studies on exploding bombs on or below the surface of an asteroid suggest that they might break up into smaller pieces that present their own problems. Either way, this option gets complicated quickly given the nature of nuclear bombs and the international ban on placing weapons of mass destruction in space. A country could use "prepping for asteroids" as an excuse for nuclear proliferation; furthermore, an asteroid is a global threat, but a single country would be using its own arsenal to fight it. "No one takes that lightly," Plesko says.

Every two years the global community stages a Dungeons-and-Dragons-style role-playing game, in which agencies act out their response to a fictional planetary defense scenario. Information about the "impact scenario" gets posted online ahead of time, with more revealed each day in PowerPoint-style briefings. In 2019, ahead of their arrival at the conference, participants knew a rock between 100 and 300 meters across had a 1 percent change of hitting Earth eight years in the future. By day three they knew it was 260 meters long and 140 meters wide, dead set on a straight course to Denver.

While the group developed a mission to deflect the problem object, a broken-off piece 60 meters across nonetheless set a course for Manhattan. The role players switched to disaster-dealing mode, looking at how to evacuate, what to do about chemical factories and nuclear plants, and what the economic fallout would look like. The gamers returned to the tabletop this year (via videoconference) to investigate an asteroid that could come calling in just six months. The entire exercise "gives a reality check on how long it takes to do things," Plesko says. It's not like in Hollywood, she adds, which goes more like, "An asteroid is discovered; let's launch the thing." Still, responding in a meaningful way is something humans can accomplish, even if more slowly than on-screen.

A TEST RUN

SOON AN AUDACIOUS MISSION will test our ability to move mountains in space. Due to launch in late 2021 or early 2022, DART—the Double Asteroid Redirection Test—will aim to demonstrate that we can change an asteroid's path like that of a wayward teen. Andrew Rivkin, one of the mission's investigation team leads, started studying asteroids for the fundamental science—the "origins of the solar system" stuff. "No matter what you're trying to answer, it kind of comes back to asteroids somehow," he says. Plus, he adds, you can buy pieces of them on eBay.

Or you can build a spacecraft to shove one around, as Rivkin is now doing. DART will travel to the Didymos system, which has a large asteroid called Didymos and a small moon called Dimorphos. Then the spacecraft will slam into the moon, changing its orbit around its bigger sibling and thus the bigger sibling's motion around the sun. The 610-kilogram spacecraft will hit the 4.8-billion-kilogram ("small") Dimorphos at a speed of 6.58 kilometers per second, changing (scientists think) its orbital period by about 10 minutes. Because Dimorphos itself is the size of an asteroid that could endanger cities, scientists hope to see how well they can transfer momentum from a spacecraft to a space rock. It is the medium-sized mitigation option, midway between "you nuke it, or you hide in the basement," as Rivkin frames it. It is also preventing an impact by making an impact. The general technique would work in single-asteroid systems, too—you can slam a spacecraft into a loner—but scientists have a good reason for choosing a double system for this test: it is simple to measure how much you changed a moon's orbit because you can just watch it pass in front of the larger asteroid in real time.

Scientists will get their first view of the system—as a single pixel—about a month before the smashup in 2022. "That one pixel is what we're trying to guide toward," says Elena Adams, the mission systems engineer. An hour before arrival, they will glimpse the moon and begin navigating toward it. "And then *bam,* we lose all contact, which is good," Adams says. It means things have gone boom. ("Somebody pays you to do that, right?" Adams exults. "You get to destroy a $250-million spacecraft!")

The team hopes that the Goldstone radar, as well as space telescopes, will also watch the show. "We hoped Arecibo would," Rivkin says sadly. The data gathered, then and after the fact, will be fed into future models that scientists such as Plesko use to determine how to respond to an actual asteroid threat. "Programs like DART, they're insurance in case we do find something," Rivkin says. People pay for fire insurance and flood insurance; they check their basements for radon. "We are hoping and expecting that the radon test won't find any radon and the house is not going to catch fire or flood, but we are kind of doing our due diligence."

Although Rivkin is glad people no longer think of planetary defense as a joke and instead can fathom the utility of cosmic insurance, he cautions against space rock anxiety. "If people are being kept up at night by asteroids, hopefully it's thinking about all the cool science," he says. It is that science, in fact—figuring out how to detect, track, project and characterize these lonesome travelers—that enables the whole of planetary defense. And planetary defense, in turn, enables humans to wrest some control from the cosmos. "This is the first time as a species we have the opportunity to prevent a natural disaster," Plesko says. "We can't stop a hurricane or prevent earthquakes. We can't just go superglue the San Andreas Fault shut." But stopping a planet killer? "If we needed to," she says, "I really do believe we could do this." SA

FROM OUR ARCHIVES

Stop the Killer Space Rocks. Edward T. Lu; December 2011.

scientificamerican.com/magazine/sa