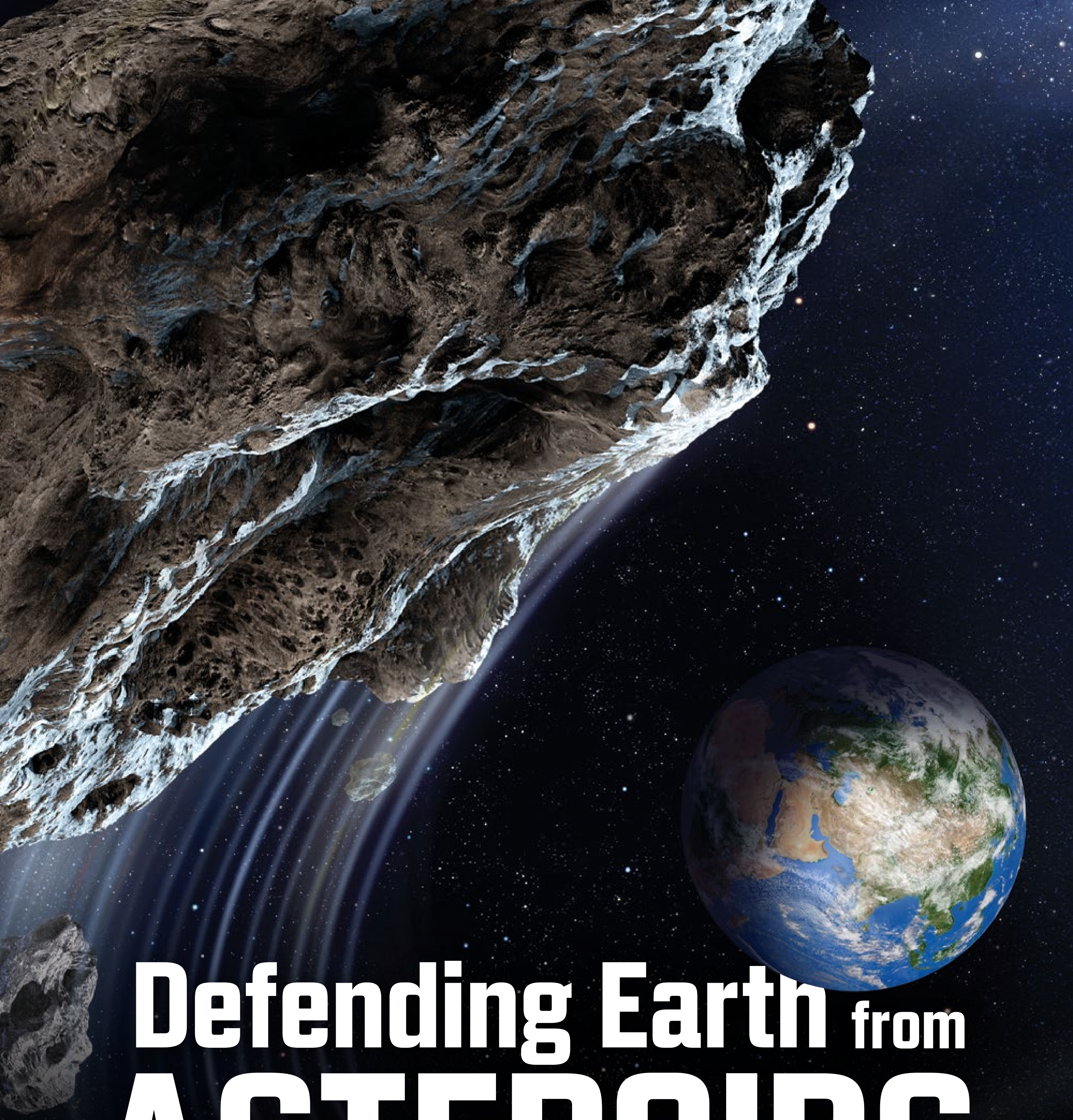

Defending Earth from ASTEROIDS

ASTRONOMY: ROEN KELLY

SCIENCE FOR THE CURIOUS
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EVERYTHING WORTH KNOWING

Asteroids

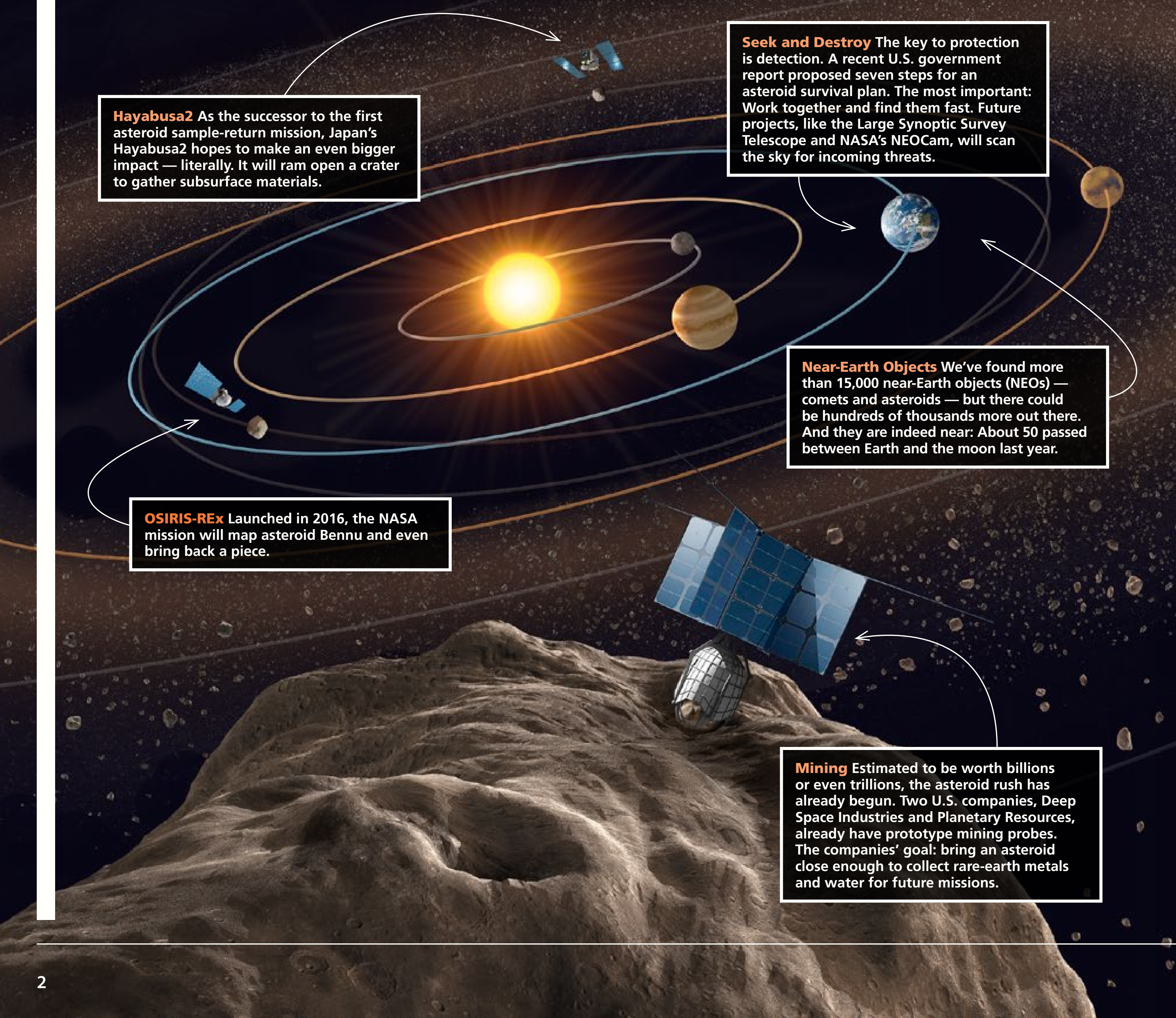
World killers. Life builders. And they could be worth trillions.

BY NATHANIEL SCHARPING ILLUSTRATION BY **ROEN KELLY**

Our early solar system was a wild place. Dust grains grew into pebbles, and pebbles became world-building planetesimals. These rocks spun around and bumped into each other in a chaotic dance that left a trail of debris in its wake. The remnants of these festivities remain strewn about our cosmic backyard. Many rocky and metallic bodies now orbit in what's called the Main Asteroid Belt, between Mars and Jupiter.

More than just leftovers, asteroids offer clues to the earliest days of our solar system, as well as the promise of valuable minerals and precious resources.

Assuming they don't kill us first.



Trojans Two separate groups of asteroids, known as the Trojans, are ensnared by Jupiter's gravity. Their numbers could rival that of the Main Belt asteroids.

Lucy Mission NASA's Lucy spacecraft is set to swing by six of Jupiter's Trojans beginning around 2025 to get an up-close view of this still-mysterious group of ancient asteroids.

Main Belt Chill out, Han Solo. Although the Main Belt is populated by millions of asteroids, the odds of hitting one are tiny. They're separated by at least twice the Earth-moon distance on average.

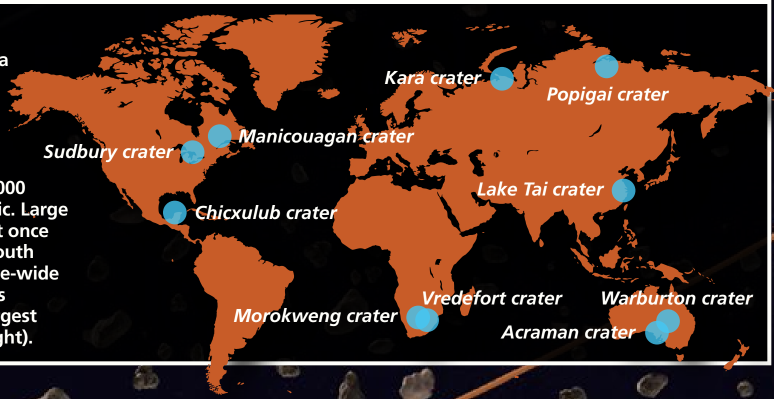
Ceres NASA's Dawn spacecraft recently brought the largest asteroid into view. It's an active world with evidence of ice volcanoes and an ancient ocean.

Psyche Mission Scientists think the all-metal asteroid Psyche was once the core of a protoplanet. A NASA mission of the same name will visit the 150-mile-wide nickel-iron body in 2030 to find out.

Panspermia Life might have a cosmic origin. We know some precursor molecules came to Earth from space because amino acids are found in meteorites — fallen space rocks. But some scientists believe life might have started on Mars and traveled to Earth after impacts.

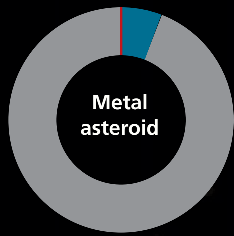
IMPACTS

Small rocks can make a big bang: The 2013 Chelyabinsk meteor was 65 feet across, but the shock wave shattered enough glass to injure over 1,000 people. But don't panic. Large impacts happen about once every million years. South Africa's nearly 200-mile-wide Vredefort crater places first among Earth's largest confirmed impacts (right).

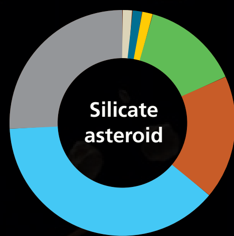


COMPOSITION

Silicate and metal asteroids are somewhat uncommon space rocks — most others are mainly carbon. But rare metals, a tiny slice of the compositions below, make them lucrative mining targets.



Iron	91%
Nickel	8.5%
Cobalt	0.06%



Oxygen	36%
Iron	26%
Silicon	18%
Magnesium	14%
Aluminum	1.5%
Nickel	1.4%
Calcium	1.3%

SPACECRAFT, CLOCKWISE FROM BOTTOM LEFT: BRYAN VERSTEEG/DEEP SPACE INDUSTRIES; NASA; JAXA; NASA (3). MAP BY EKLER/SHUTTERSTOCK

Imagine the science and the safety we could achieve by finding space rocks like Chelyabinsk before they enter our atmosphere. **by Mark Boslough**

In search of DEATH PLUNGE ASTEROIDS

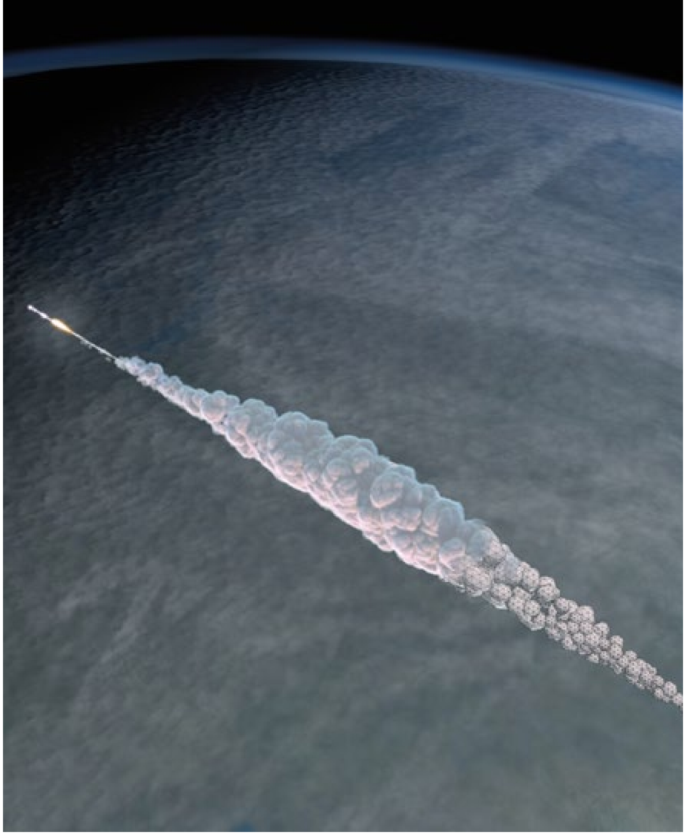
The 2013 meteor that exploded over Chelyabinsk in Russia was captured in images only by those fortunate enough to be looking up at the right moment. Imagine what we could have seen with advanced warning. MARAT AKHMETALEYEV

In an alternate world with a more advanced asteroid search campaign, astronomers could have prepared all night for the big impact. OSHIN D. ZAKARIAN

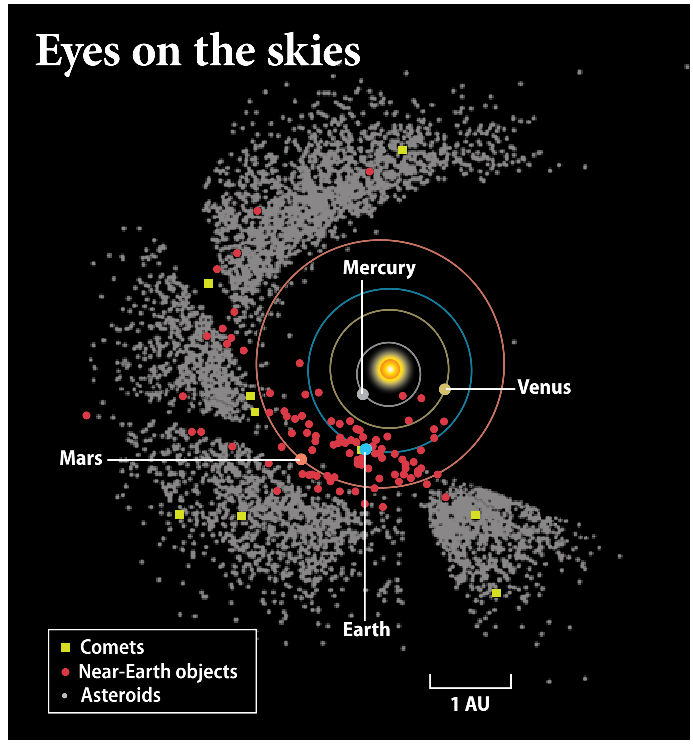
MUCH TO THE DELIGHT of scientists and technicians, the frigid sky over the snow-covered Siberian fields and villages remained clear as dawn approached. The February stars put on a dazzling show as they revolved about Polaris, higher in the sky than many of the foreign visitors were used to seeing it. The frequency of sporadic meteors increased as the night grew long, as if providing a warm-up act.

Charter flights were already in the air, filled with business tycoons and celebrities, and rumor even had it that Russian President Vladimir Putin was on one. The planes could be seen in all directions except in the special airspace dedicated to cooperative research flights by the Russian Federal Space Agency, the European Space Agency, and NASA, and in the restricted airspace directly beneath the asteroid's projected path. In order to keep light pollution from interfering with the observations, the nearby city of Chelyabinsk was in blackout. Everyone waited at the ready for the meteor event of the century.

This is a fictional account of what might have happened February 15, 2013, if we had been a decade further along in our efforts toward asteroid discovery and planetary defense. An array of powerful space-based infrared survey telescopes (such as the proposed NEOCam or Sentinel Mission), combined with dedicated ground-based telescopes (such as ATLAS and LSST, both



The meteor explosion pictured here is the result of a 3-D simulation by the author. By modeling such events, he and colleagues can compare them to past and future airburst observations in order to learn more about both their progenitor asteroids and the power they bring with them into Earth's atmosphere. M. BOSLOUGH/B. CARVEY/A. CARVEY



ASTRONOMY: ROEN KELLY, AFTER NASA/JPL-CALTECH

In NEOWISE's first six months, it discovered dozens of new near-Earth objects and observed many more. Each gray dot represents an asteroid, most of which orbit in the main belt between Mars and Jupiter. Yellow squares represent comets, while red circles indicate near-Earth objects that orbit within 1.3 astronomical units (1 AU is the average Earth-Sun distance).

currently under construction) might have been able to warn us of the 65-foot-wide (20 meters) asteroid that exploded over Russia, causing damage and alarm. We have pieced together the asteroid's story from recovered fragments and serendipitous dashboard-camera footage. But imagine instead how the events near Chelyabinsk might have unfolded if an advanced detection system had already been in place.

Getting ready

In that fictional world, by the time the southeastern sky began to glow with faint hints of light, scientists had been up all night calibrating and testing their equipment. The weeks of planning meant they had time to spare, and they spent it photographing the stars, drinking coffee or tea, fidgeting, and (except for the North Americans) smoking cigarettes. High-definition cameras, telescopes, radiometers, radar dishes, spectrometers, and optical pyrometers all pointed at a spot above the eastern horizon. The instruments were mounted on gimbals so they could rapidly slew at just the right rate to track the fireball. Even with advanced warnings, there would be no second chance.

Researchers already had deployed arrays of seismometers, geophones, microphones, infrasound detectors, microbarographs, anemometers, and dust collectors. Now, just before sunrise, they launched drones and balloons to get precise readings of atmospheric conditions and to record the characteristics of the blast wave in three dimensions.

It wasn't just the scientists who were recording. Production company film crews were on the scene, including multiple IMAX cameras on the ground and in the air. This would be the best-documented natural event in history because it was the best ever predicted.

Since its discovery a month earlier by two new space-based infrared telescopes, designed and launched for just this purpose, the asteroid had swept close enough to be observed by ground-based optical telescopes. In the last few days, radio telescopes at Goldstone and Arecibo were able to join the effort, and last night even amateurs made sightings. Its reflectance spectrum suggested that it was an ordinary chondrite, rocky and unevolved. Radio telescopes estimated that it was between 17 and 20 meters in diameter.

There was still a lot of uncertainty about its mass because no one knew whether the asteroid was a single rock or a porous rubble pile. But it couldn't be much more than 12,000 tons even if it were fully dense. Meticulous observations had characterized the asteroid's orbit so precisely that scientists were predicting the time of impact to the nearest second, the location to the nearest kilometer, and the entry speed to be exactly 12 miles (19 kilometers) per second. It would almost certainly explode in the atmosphere, and simple physics determined the energy of the explosion: about a half megaton of TNT.

Despite being 30 times bigger than the explosion that destroyed Hiroshima, that estimate had come as a great relief to the residents of Chelyabinsk. A month earlier, a much bigger explosion had not been ruled out, and there had been contingency plans to evacuate the city's million residents. A half-megaton explosion high in the sky can be powerful enough to blow out windows and do damage, but officials determined "shelter in place" and the Cold War "duck and cover" drill sufficient to protect city residents 25 miles (40km) to the north. On the other hand, more local villages were still at risk from falling meteorites, which could be fatal, and residents were advised to leave the area.

Mark Boslough *is a principal member of the technical staff at Sandia National Labs with a focus on national security applications.*

The show begins

About 15 minutes before sunrise, powerful radar started receiving reflections from over the horizon while the asteroid was still thousands of kilometers above the Pacific Ocean. Twelve minutes later, it had traversed China and Kazakhstan. A few minutes after that, the Russians fired an array of smoke tracer sounding rockets, like fireworks, into the sky along both sides of the asteroid's trajectory, to measure the shock wave like in the good old days of Cold War atmospheric nuclear testing. As the asteroid approached the border into Russia, still more than a hundred kilometers up, sensitive infrared detectors and radiometers locked onto it.

As the clock ticked, events accelerated. The asteroid was coming in hot — 19 km/s is 42,000 mph, or Mach 56. It was moving mostly sideways, descending only 1 kilometer for every 3 kilometers of horizontal flight. That was lucky for everyone. The scientists had more time to gather data, the tourists had a longer show, and the locals were spared the damage that a steeper entry angle would have inflicted by carrying the energy downward toward the villages.

The asteroid rammed into the air faster than the molecules could get out of its way. Like a snowplow, it scooped them up, compressed them, and carried them along as a high-temperature plasma that pushed a shock wave ahead of it and then wrapped around it in a pencil-thin wake. After a few seconds, the asteroid descended into air that was thick enough to be opaque when compressed, and hot plasma grew bright enough to see with the human eye.

Scientists whooped as their trackers started tracking and their high-speed cameras started whirring. Cheers went up from the open fields in Chelyabinsk, where spectators watched at safe distances from window glass and anything that could fall. Movie stars in private jets clinked their champagne glasses together. Villagers who refused to evacuate hugged one another and hoped that a meteorite would fall near them, but not on them.

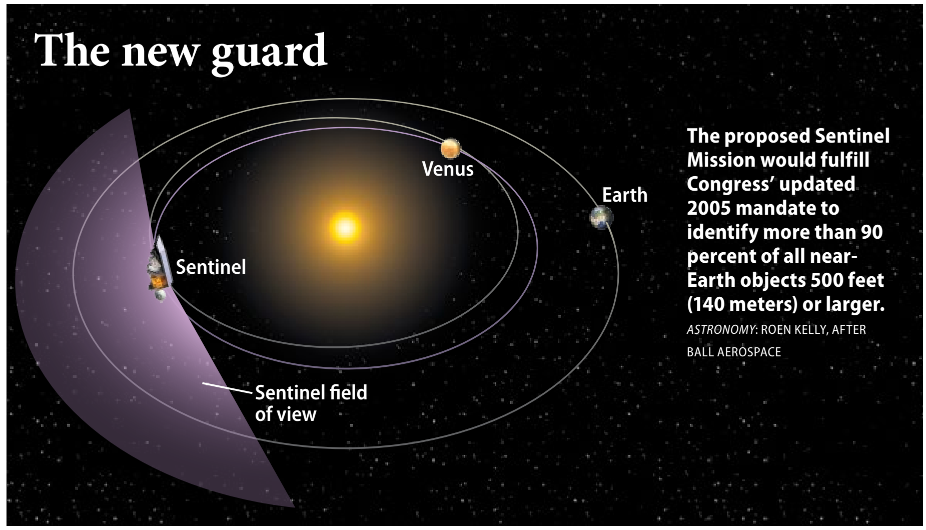
But the show had just started. For the next 10 seconds, the asteroid grew much brighter as it forced its way through the air, compressing it into an ever hotter and denser plug of ionized gas. The asteroid's core was as yet undisturbed, the pressure in the thin upper atmosphere too small to deform or break solid rock. But the heat of entry penetrated the surface of the rock, removing material that was immediately vaporized and swept away into the wake.

As the excitement continued, the asteroid reached a critical altitude at which pressure from the air finally exceeded its strength, and the core began to fracture. This led to a mutually reinforcing cascade of processes: The fragmentation meant exponentially increased surface area and therefore exponentially increased drag forces, and the increased drag forces caused further fragmentation. When the fragments became small enough, they vaporized entirely, kinetic energy converting to explosive energy in the spectacular climax of the asteroid's death plunge.

Even as the tremendous explosion lit up the sky, a small fragment that looked like a mere spark popped out and continued downrange to the west. Infrared and radar trackers were able to follow it for several more seconds. They calculated its impact point before it even touched the ground.

Before the explosion had finished fading from sight, the charter flights and private jets were already turning to flee the scene. They were not supersonic and could not outrun the blast wave, but the farther they got, the weaker it would be. The first to feel the blast were observers near the villages at ground zero, directly beneath the main explosion. It only took about a minute. Ground arrays provided a precise pattern of surface effects, which would be invaluable for estimating risk and planning for future events. Another minute later, the blast reached Chelyabinsk. It did limited damage because most residents and businesses had heeded warnings and boarded up their windows, saving up to 1 billion rubles ($33 million) in potential damages.

Within only a few more minutes, a helicopter landed next to a hole in the ice of the frozen Lake Chebarkul, the location pinpointed by tracking data of that small spark, actually the largest remaining piece of the meteorite. Arrays of acoustic sensors had located many of the other large meteorites that fell on solid ground, and meteorite collectors — both professional and amateur — raced to their locations. Laboratories were at the ready to measure short-lived radioisotopes, and the analysis work proceeded swiftly, according to careful plan.



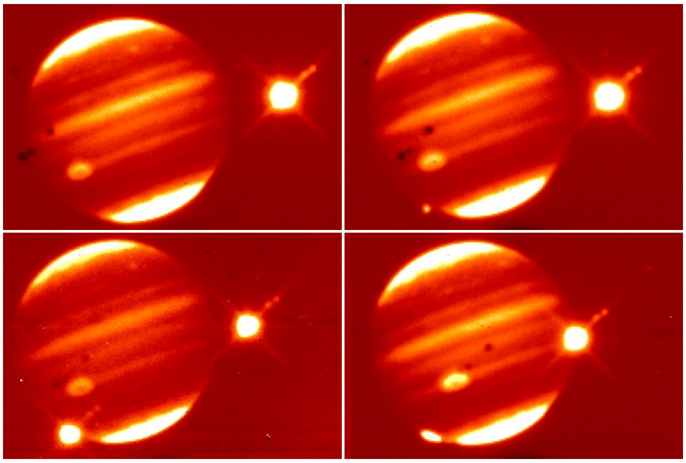
The proposed Sentinel Mission would fulfill Congress' updated 2005 mandate to identify more than 90 percent of all near-Earth objects 500 feet (140 meters) or larger. *ASTRONOMY*: ROEN KELLY, AFTER BALL AEROSPACE

While some fragments from the Chelyabinsk meteor were recovered quickly, others took months to locate and retrieve, partially due to incomplete information regarding the unexpected meteor and its trajectory. DIDIER DESCOUENS

Back to reality

The description in this story of the Chelyabinsk asteroid itself is scientifically accurate to the best of my knowledge. Whereas the rest of the tale — the media coverage, the scientific preparedness — is science fiction, there is really no fundamental reason why the story could not have unfolded much as I have described.

To make this possible for future impacts, we need to continue to pursue the goal of finding as many near-Earth objects (NEOs) as possible, especially those on their final approach to Earth that could arrive with little or no warning, like Chelyabinsk. I like to call these "death plunge" objects because they are already



This sequence of near-infrared images shows the first fragment of Comet Shoemaker-Levy 9 impacting Jupiter. The bright object to the right is the moon Io, while the region at lower left center is the Great Red Spot. The impact point on Jupiter's southeastern limb first flares to brightness in the second image and rivals Io at its brightest point in the third image. The fourth image, taken roughly 20 minutes after impact, shows the fireball already fading from sight. CALAR ALTO OBSERVING TEAM

The Tunguska event in 1908 ranks among the most powerful explosions in recorded history. Luckily, the meteor exploded in the air over a remote region in Siberia. LEONID KULIK EXPEDITION

falling to their demise when they are discovered. They are not going to go around their orbit again, and there is no time to deflect them. Fortunately, most will likely be much smaller than Chelyabinsk. In most cases, they will be so small that they are no threat at all, but merely an opportunity for science and tourism.

Jupiter test-bed

My idea of death plunge science was inspired by the events surrounding Comet Shoemaker-Levy 9 (SL9) in 1994, which was the first death plunge object to be discovered before impact. Luckily, it had taken aim at Jupiter, not Earth. I was fortunate to be a member of the team that used the mightiest computer on Earth at the time to make predictions about the comet's exciting final act.

Carolyn Shoemaker, one of SL9's discoverers, first described the comet March 25, 1993. "I don't know what this is," she said. "It looks like … like a squashed comet." It looked that way because it was no longer one comet, but had broken into about 20 fragments. It was in orbit around Jupiter and had passed so close that tidal stress from the planet had torn it apart.

By the time it was discovered, it was in its final two-year orbit around the planet, too late for any hypothetical jovians to attempt a deflection mission. Within months, scientists determined that the fragments would collide in July 1994, and further observations refined the trajectory and predicted specific impact locations and times. With no cities or lives at stake, researchers could focus on scientific observations.

IN DEFENSE OF EARTH by Rusty Schweickart

Asteroids are multidimensional space attractions with facets that appeal to scientists, explorers, entrepreneurs, and the wider public. And among all these groups, much of the discussion of late comes from the crowd (of which I am a part) concerned with public safety — protection from asteroid impacts, or planetary defense.

Most of our focus has been on the long-term potential for impact prediction and deflection. This challenging but achievable capability depends on using powerful telescopes to find asteroids in space, calculate their future locations, and change their arrival time slightly if they are on a path that would intersect with Earth. We can literally prevent future impacts.

But more recently we discovered that even a set of small telescopes, like the Asteroid Terrestrial-impact Last Alert System (ATLAS), can see asteroids when they're very close and about to hit. This first happened in October 2008 when a Catalina Sky Survey telescope picked up a small asteroid in the evening sky that actually hit Earth 19 hours later! Discovering it even that close to impact allowed NASA's Near-Earth Object (NEO) Program to analyze its trajectory and predict precisely when and where it would hit.

It quickly became evident that a short-term (or last minute) warning system for asteroid impacts was possible. Planetary defense suddenly had two strategies: long-term prediction and prevention, and short-term civil defense. "Duck and cover" re-entered the lexicon — or, with just a few hours' of warning, evacuation.

Interestingly, this short-term strategy to avoid impact threats to life (albeit not to property) suddenly put NEO programs on the radars not only of the civil defense systems of the world, but also of the general public. Unlike the long-term impact prevention aspect of planetary defense, where the public is a largely unwitting beneficiary, here the public is an active participant in evacuation and preparation. In fact, success depends on the public responding rationally to a threat completely outside their experience.

Who warns them? How are they warned? Duck and cover or evacuate? How does the identification of a moving spot in a small telescope's field of view get out as news to real people in time to save lives? These questions and many more will be addressed as part of Asteroid Day on June 30, an event whose goal is to familiarize the public with this unfamiliar threat and how to respond (see www.asteroidday.org).

It is truly amazing that with inexpensive technology available right now, we can prevent almost all of the potential loss of life from asteroid impacts, both long- and short-term. We are not dinosaurs, nor part of the 70 percent of life that was wiped out with them 66 million years ago. We have the tools and can act instead of merely observe. We can do this.

Rusty Schweickart *is a former Apollo 9 lunar module pilot and founded the Association of Space Explorers and the B612 Foundation, which focuses on planetary defense.* NASA (EARTH IMAGE)

The timing of the discovery was perfect because a convergence of developments in 1994 enabled planetary scientists to take full advantage. The Hubble Space Telescope had just been serviced and was now operating as originally designed, producing exceptionally high-quality images. Sandia Labs in New Mexico had recently installed the most powerful computer in the world and had just developed a parallel version of a nuclear weapons-related code that enabled us to model the impact event at high enough resolution to make useful predictions. In science, prediction is everything, especially when there is disagreement — which there was.

Two members of our modeling team were experimentalists by training, and we began to think of the impact of SL9 as a giant experiment in the sky that would either provide validation for our computer models or show us where we had gone wrong. This was an experiment larger than any you could ever carry out in a lab on Earth — or want to.

Considering the lack of human design for this experiment, it was brilliantly formulated. For one thing, a good researcher does a series of experiments with a range of parameters, and that's what we had with about 20 fragments of various sizes. The event also contained elements that even the cleverest experimentalist might not have thought to include. At the time of the orbital calculations, everyone was disappointed that the impact sites would be on Jupiter's far side. But it was not a total loss. The fragments would hit just over the southeastern limb. Jupiter's phase would be slightly less than full at the time of impact, with a dark strip between the eastern limb and the dawn terminator. The comet fragments would pass into the shadow of Jupiter before going below the limb, and any debris or ejecta coming back up would rise over the limb into darkness before being illuminated by the Sun. These would potentially be discrete events.

As it turned out, our simulations showed that sufficiently large fragments would produce fireballs, or plumes of incandescent hot gas, that would rise above the limb and be bright enough to be seen from Earth. As they kept rising, they would emerge into sunlight, at which point they would scatter light from condensed particles. We advised the Hubble Imaging Team to set up an observational sequence for Jupiter's limb. The imaging program included the first fragment as well as a few of the brighter (and presumably larger) pieces. The Hubble images beautifully confirmed our model predictions for plume-forming impacts on Jupiter. But what about Earth?

The Catalina Sky Survey is the result of a 1998 congressional directive to find and characterize at least 90 percent of the near-Earth objects 0.6 mile (1 kilometer) or larger. NASA declared this goal achieved, but the hunt is still on for medium-sized asteroids. CATALINA SKY SURVEY, UNIVERSITY OF ARIZONA

Searching closer to home

We quickly realized that the properties of Jupiter's atmosphere that led to the formation of the giant plumes were not unique to that planet. The same physics should control the aftermath of an airburst on Earth. We began to run similar models for Earth impacts and showed that high plumes form as the result of impacts the size of the one that exploded over Siberia in 1908: the Tunguska event.

Our model seemed consistent with the sketchy historical observations, but we didn't have a "validation experiment" this time. We were now doing historical science, which is subject to interpretation, difficult to quantify, and easy to dismiss. That's not very satisfying for a physicist. When we wrote up our work in a 1997 paper, we pointed out that sources of data for airbursts on Earth included U.S. government sensors, infrasound detectors, and seismic data, all operating in what is essentially "open shutter" mode. If something happened in a fortuitous location, it would be recorded, but no observational campaign existed.

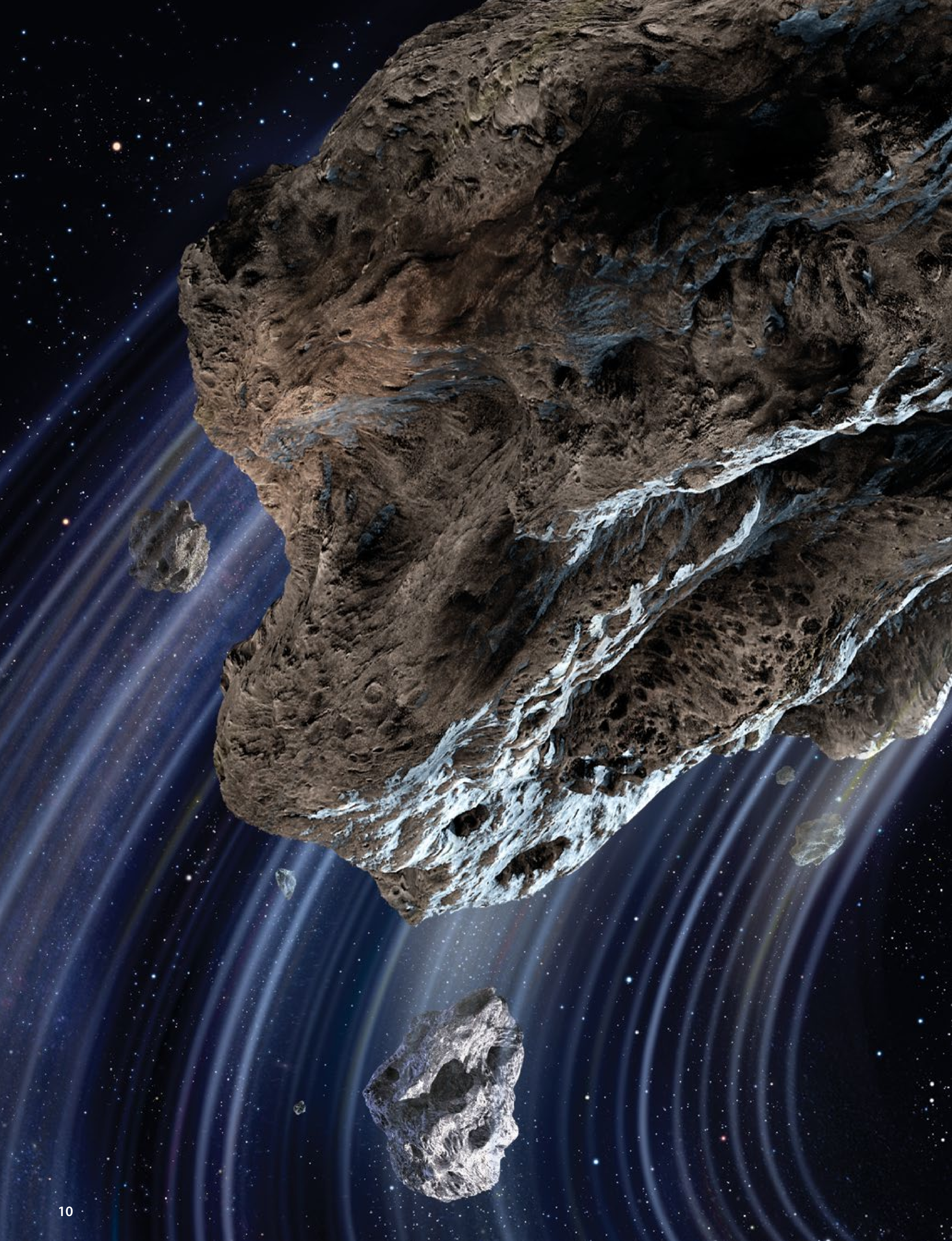
We suggested a methodical search for asteroids of the size that generate the airbursts we theorized and proposed a ground-based survey system capable of providing short advance notice of a 100-kiloton-range impact, so that we could characterize an approaching object before it struck. We explained that this would enable validation of our predictions, as well as provide immensely better data on impact events.

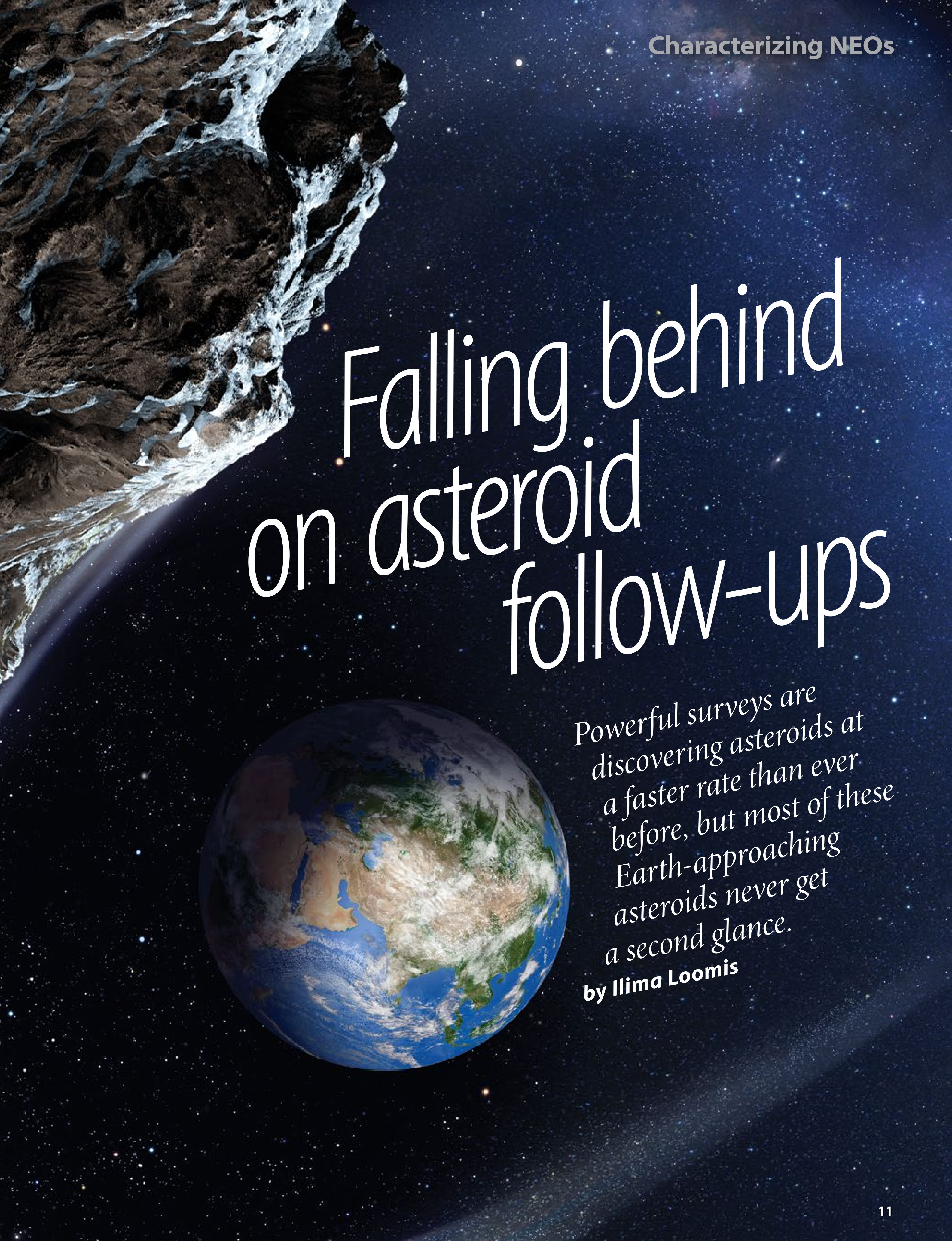
Technology has advanced greatly in the past two decades, and while current surveys such as NEOWISE, Pan-STARRS, and the Catalina Sky Survey are making steady progress in cataloging devastation-range near-Earth objects, there is no reason that the threshold for discovery cannot be lowered to a few kilotons — events that happen several times every year. Most events would not be as spectacular or conveniently located as Chelyabinsk, but the creation of a comprehensive death plunge observational campaign would provide rapid benefits to both science and planetary defense. It also would supply a constant flow of meteorites from objects that had been observed in space, at a fraction of the cost of an asteroid sample return mission.

Economic benefits also raise the appeal of such a campaign. Excited tourists might be willing to spend a significant amount of money to see a rare cosmic spectacle and help collect meteorites on the ground. Perhaps the allure of adventure and the increasingly high value of meteorites would be incentive enough for deep-pocketed investors to help scientists, humanity, and themselves — all at the same time.

Technologically, there is no better time than now to create an international partnership among governments and private financiers to pay for infrared space telescopes and ground-based observatories to search for incoming asteroids. If that happens, it will just be a matter of time before tickets go on sale for the next death plunge event!

EXPLORE MORE DETAILS ABOUT CHELYABINSK'S 2013 DEATH PLUNGE METEOR AT **www.Astronomy.com/toc.**





Falling behind on asteroid follow-ups

Powerful surveys are discovering asteroids at a faster rate than ever before, but most of these Earth-approaching asteroids never get a second glance.

by Ilima Loomis

NASA's Infrared Telescope Facility on Hawaii's Mauna Kea can help scientists characterize asteroids from its perch high above the Pacific Ocean. ERNIE MASTROIANNI

It didn't take long for Vishnu Reddy to significantly lower the price tag of the so-called "trillion-dollar asteroid." This giant space rock loaded with precious metals made headlines last July, but all it took was a quick peek with NASA's Infrared Telescope Facility (IRTF) on Mauna Kea to show it was just a run-of-the-mill, ordinary chondrite.

"It turned out to be completely bogus," Reddy, an associate research scientist at the Planetary Science Institute, said hours after observing the asteroid in August. "It's not made of platinum, like the press release claimed."

The lure of space mining is just one reason why many asteroid researchers are itching to get a closer look at the objects zooming past Earth. But not many asteroids get the same treatment as that faux-platinum behemoth. In fact, even though astronomers are now finding more space rocks than ever before, most are never studied further.

"We can't keep up," says José Luis Galache, acting deputy director of the Minor Planet Center at the Harvard-Smithsonian Center for Astrophysics, "not because it's impossible, but because there are no dedicated programs to characterize [near-Earth asteroids], unlike how there are dedicated programs to look for them."

Astronomers have cataloged more than 12,000 asteroids orbiting close to Earth, but only about 1,000 have been characterized — studied to determine their composition, size, shape, rotation speed, and other data. Of the more than 1,000 new asteroids discovered every year, less than 10 percent are ever characterized. At the current rate of follow-up, it would take another 100 years to do so for just the known population of objects, according to a paper Galache co-authored last year in the journal *Planetary and Space Science*.

Planetary defense is one big reason to study more asteroids. Astronomers already have found the vast majority of large asteroids, but smaller objects — those with diameters less than 0.6 mile (1 kilometer) — remain a significant blind spot. Powerful sky surveys like Pan-STARRS, the Panoramic Survey Telescope and Rapid Response System, are on a mission to discover such asteroids that could strike Earth. This fast-moving behemoth on Hawaii's Haleakalā volcano uses the world's largest digital camera to catalog near-Earth asteroids as small as 1,000 feet (300 meters) wide. However, even Pan-STARRS doesn't reveal much information about the kind of threats those objects actually pose. Knowing whether an Earth-threatening asteroid is likely to be solid rock or a pile of rubble would make a big difference in how governments and civil defense agencies prepare, says Reddy.

Planetary defense is one big reason to study more asteroids.

"It helps us better know our adversary, for lack of a better word," he adds. "If something is going to impact us, we want to know as much as possible about this object."

Studying asteroids that pass by Earth can also reveal tantalizing clues about how the solar system formed. These objects give scientists a close-up look at the building blocks of the solar system, notes planetary astronomer Andy Rivkin of the Johns Hopkins University Applied Physics Laboratory. They allow scientists to study objects smaller than they can see in the main asteroid belt between Mars and Jupiter.

"Each one is a piece of this bigger puzzle," Rivkin says. "They're the leftovers from the formation of the inner planets, and because they haven't experienced wind, erosion, water, or volcanoes, they're all pretty much as they were."

Ilima Loomis *is a freelance writer based in Hawaii. She tweets about science and the Aloha State from @iloomis.*

ARTWORK PREVIOUS TWO PAGES *ASTRONOMY*: ROEN KELLY

The fragments of Comet Shoemaker-Levy 9 stretch a distance three times that between Earth and the Moon, as the space rocks progress on their collision course with Jupiter in this 1994 Hubble Space Telescope image. NASA/ESA/H. WEAVER AND E. SMITH (STScI)

Space exploration is another reason to push for better asteroid characterization. Knowing whether an object is likely to contain water or precious minerals would help private companies select targets for mining. And scientific missions to redirect or place a rover on asteroids might want to avoid trying to land on fast spinners, for example. "For all these things, you want to know a little bit more than just the orbit of the asteroid," Reddy says.

A widening gap

So why are so few asteroids ever investigated? Part of the reason is simply that it's easier to spot new asteroids than to study them in depth. "Doing characterization takes a lot more effort," Reddy says. In the same way, "it's easier to count a group of people than to find out about each person's genetic history or research their heritage."

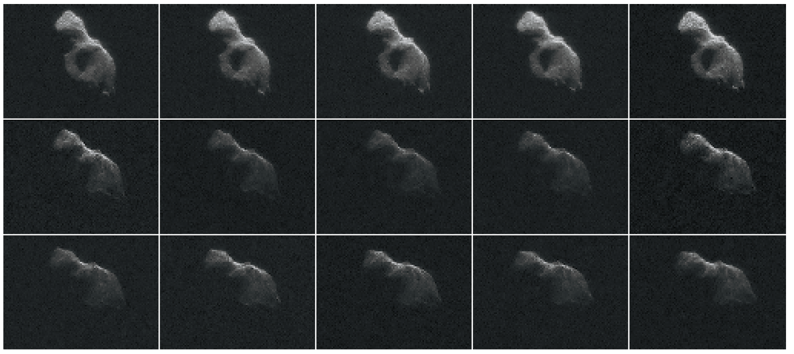
But the gap between discovery and characterization is getting wider. Not only are survey telescopes now cataloging more new asteroids than ever before, says Martin Elvis, an astrophysicist at the Harvard-Smithsonian Center for Astrophysics, "they're going fainter, and they're also finding smaller objects."

Many of those smaller objects become visible only when they are close to Earth, often within days of their closest approach. That means there's a small window to observe them, typically around two weeks, before they move away again and become too faint. Large asteroids that were once astronomers' main target tend to make a return trip past Earth after a year or two, giving scientists a second look. But the smaller objects now being found either get lost altogether or are too faint to see on their return trip. "You either get it the first time, or not at all," says Elvis.

Characterizing 100 near-Earth objects (NEOs) a year used to be enough to satisfy scientists, but that's no longer the case now that surveys are discovering as many as 1,400 new objects a year, Elvis says.

"It's like going from artisanal production to industrial," he says. "They're finding objects at such a rate — and they disappear so quickly, and don't come back for a long time — that we've got to up our game and keep up with discovery."

Finally, there's the matter of policy. While NASA received a congressional mandate in 2005 to identify 90 percent of large NEOs by 2020, no similar mission exists to perform follow-up observations.



Earth-based radar tracked asteroid 2014 HQ_{124} as it passed within 776,000 miles (1.25 million kilometers) of our planet June 8, 2014. The images revealed a rapidly rotating and peanut-shaped space rock — a binary trait shared by as many as one in six asteroids. NASA/JPL-CALTECH/ARECIBO OBSERVATORY/USRA/NSF

Galache says dedicating a telescope to that mission full time — or preferably one each in the Northern and Southern hemispheres — is what's needed to keep up with discovery. "There are several telescopes that perform a few nights of characterization a month, but that's not enough," he says. "The funding agencies just don't see this as a priority."

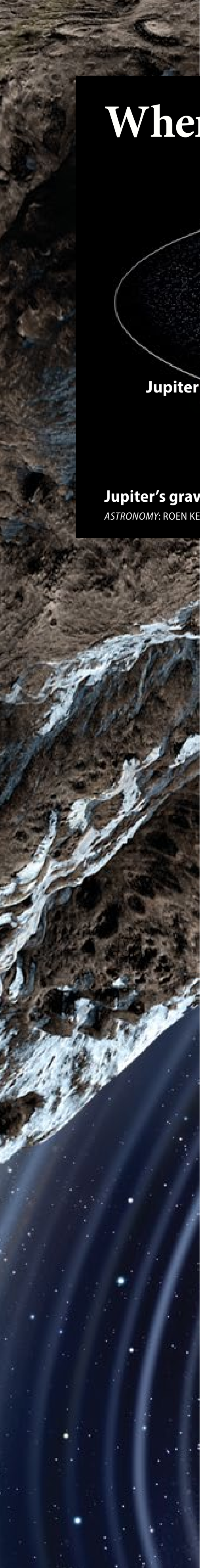
From a planetary defense point of view, Galache says he understands why NASA's focus has been on discovery.

"They feel as long as they're discovering as many as possible, if we do find one that's dangerous, resources will come in to study that one in depth, and that will be enough," he says.

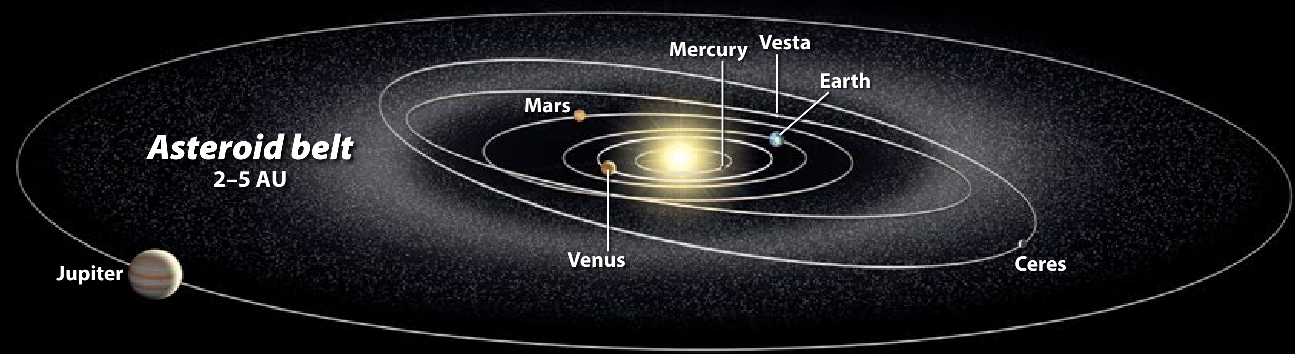
But with surveys now spotting smaller, closer objects than ever before, there may not always be time to perform a full characterization on an asteroid found to be heading toward Earth, Rivkin notes. Getting a statistical sample of NEOs could provide critical information to help the planet prepare for impact on short notice, he says.

Galache is quick to note he's not arguing for 100 percent characterization, but he says he'd be happy if researchers could sample 2,000 to 3,000 large asteroids and several hundred smaller asteroids. "In order to say something scientifically about the distribution of compositions at various sizes and within a range of orbits, we do need a larger sample than we have now," he says.

There's a particular need to better understand smaller objects, says Cristina Thomas, a planetary astronomer at NASA's Goddard Space Flight Center employed by the Planetary Science Institute and Universities Space Research Association. Some of the work now being done has revealed that small asteroids differ from the population of larger bodies in important ways, including composition and rotation speed.



Where do NEOs come from?



Jupiter's gravity bumps rocks from the asteroid belt, setting them on paths that can cross Earth's orbit and create so-called near-Earth asteroids.
ASTRONOMY: ROEN KELLY

AMATEUR EYES ON THE SKY

As the asteroid community struggles to step up characterization efforts, some researchers are getting an assist from amateur astronomers.

Asteroid researcher Vishnu Reddy of the Planetary Science Institute has partnered with a network of dedicated amateurs to make light-curve observations that help to determine asteroid rotation speed.

"They're simply invaluable," he says. "They can make good observations, and they have all the telescope time they want because it's their own personal telescope."

Bruce Gary, a retired Jet Propulsion Laboratory (JPL) scientist and consultant and an amateur astronomer, got involved after Reddy spoke to his astronomy club in Arizona. He was excited to take on the challenge.

"He said, 'Can you do near-Earth asteroids? We want to characterize as many as possible,'" Gary recalls. "The goal was to do several a month." On a typical observing night, Gary would check a list of near-Earth objects maintained by JPL and find out which ones were passing close to Earth that evening, and would select a likely target based on Reddy's parameters. Around sunset, he'd open the domed observatory in his backyard and get his telescope ready.

After making his calibrations, he'd settle in for a night of observing, repointing his telescope every half-hour to track the asteroid, and shooting 200 to 300 images on a good night.

"The next morning I'd wake up, filled with anticipation. Could this be a binary? Could it be a fast rotator? Because those are rare, everybody wants to catch a fast rotator," Gary says.

He observed 28 asteroids for Reddy over nine months before moving on to other interests in June 2015.

Gary says he enjoyed working on the project. "It's like going out on the beach looking for shells. You never know what you're going to stumble across," he says. — *I. L.*

"We certainly don't need spectra or light curves of every NEO — that would be excessive," she says. "For the largest objects in the population, I think we kind of have a handle on what's going on. But I think we're really not very good at understanding the objects that are less than a couple of kilometers [across]."

The explosion of the Chelyabinsk meteorite over Russia in 2013, which caused tens of millions of dollars in damage and injured more than 1,500 people, was a wake-up call that more study of small objects was needed, Galache adds. "What this showed is that even something as small as 17 meters [56 feet] across can be dangerous," he says. "You can't just ignore it."

"Even something as small as 17 meters [56 feet] across can be dangerous. You can't just ignore it."

Rapid response

One program working to help close the characterization gap is the Mission Accessible Near-Earth Object Survey (MANOS). The project is designed to make "rapid response" follow-up observations of newly discovered near-Earth asteroids, with observing time on 4-meter and larger telescopes.

"We're using some of the largest telescopes in the world to study this population," says principal investigator Nick Moskovitz, an astronomer at Lowell Observatory in Flagstaff, Arizona.

Of the approximately 100 new NEOs discovered by survey telescopes each month, MANOS follows up on about 10 percent of them, gathering spectra and light curves to determine size, composition, rotation speed, and other information. Moskovitz expects to complete observations of several hundred asteroids by the end of the project.

MANOS started in 2013 with observing time awarded by the National Optical Astronomy Observatory, and it went on to get funding time from NASA and the National Science Foundation, as well as observing time on other telescopes,

This six-image mosaic of asteroid Eros was captured by NASA's NEAR Shoemaker mission in 2000. For scale, the crater at the top of the image is 3.3 miles (5.3 kilometers) wide. NASA/JPL/JHUAPL

NASA's IRTF is part of an asteroid-observing network. Their research shows meteorites and large near-Earth objects come from distinct populations. HARUN MEHMEDINOVIC/WWW.SKYGLOWPROJECT.COM

including Gemini, NASA's IRTF, Lowell's Discovery Channel Telescope, and others.

"We're slowly growing, slowly adding telescopes to our network," Moskovitz says, adding that the program's results to date have helped his team of about 20 scientists leverage more funds and observing time.

"Because we're studying a population that hasn't been studied much before, we're continuing to find new and interesting things," he says.

Those surprises include more asteroids with rotational periods faster than what scientists had predicted. MANOS recently identified the fastest-spinning asteroid yet, a 20-meter object with a rotational period of just 16 seconds. "We're finding some that are very, very fast," says Thomas, who's also a co-investigator on MANOS.

Knowing the rotation speed of an asteroid provides important clues about its composition, notes Moskovitz. A fast spinner is likely to have a solid, dense interior because centrifugal force would pull apart a clump of boulders or rubble. "That's one of the holy grails in understanding asteroids — what are their internal properties," he says.

MANOS' research is also raising some intriguing questions about where meteorites come from. Scientists had long believed that most came from small asteroids because meteorites recovered on Earth are compositionally different from the large-NEO population. But Moskovitz says based on recent studies of small NEOs, that doesn't seem to be the case.

"We're finding that their composition looks nothing like the meteorite population," he says.

Galache and Reddy say MANOS has yielded important results and is a big step toward a more coordinated effort. It approaches the characterization problem systematically rather than leaving follow-up to individual scientists looking at a handful of objects at a time.

"It's the only project that has attempted to do rapid follow-up of newly discovered asteroids, with the sole purpose of characterization," Galache says. "Unfortunately, the count is still quite small."

Moskovitz agrees. "Yes, we have a lot of resources. Yes, we're building a nice statistical sample," he says. "But there's still 90 percent of the population that isn't being studied, and not much is being done about it."

Scientists still know relatively little about the makeup of most small asteroids, like the one that exploded over Chelyabinsk, Russia, in 2013. These chondrite fragments (shown actual size) were found in a field between two nearby small villages. DIDIER DESCOUENS/WIKIMEDIA COMMONS

With so much potential benefit to commercial mining operations, is private funding for asteroid characterization on the horizon? Galache, Reddy, and Moskovitz all say they've been informally approached by wannabe space mining companies, but haven't seen them demonstrate any serious interest in getting involved for the time being.

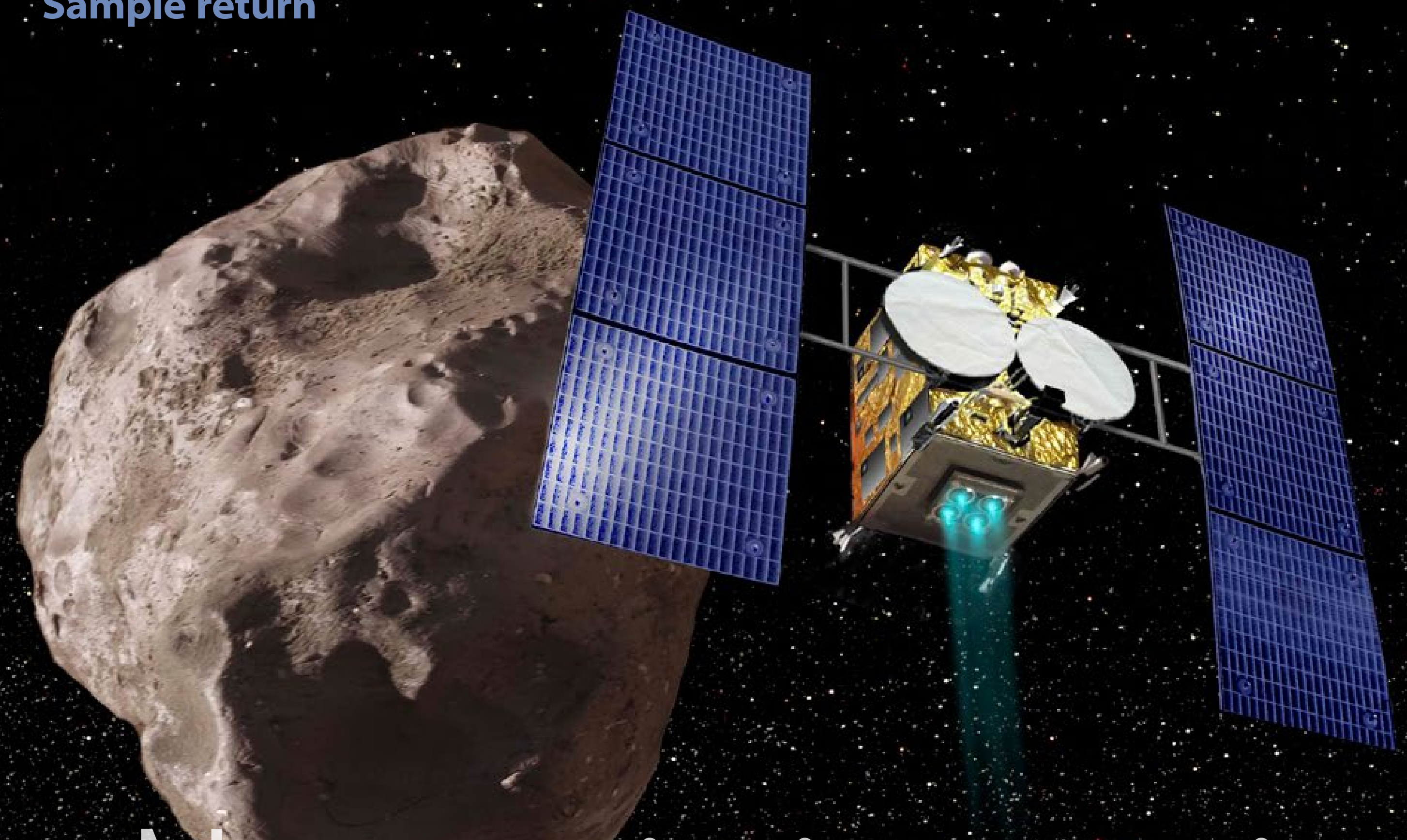
"There haven't been any offers of money," Galache says. "There have certainly been conversations about [characterization], but at the moment, they're not in the position to start prospecting. So I think they consider this as something they need to do a bit further down the line."

So far, most of the firms that have contacted Moskovitz seem to be working toward doing their research in-house, he says. "It's still early for many of these companies," he says.

Meanwhile, 2013's Chelyabinsk meteorite has rekindled interest in asteroid research in general, and scientists like Galache and Thomas hope some of that attention and funding will find their way past discovery and trickle down to characterization.

"I'm sad people got hurt — don't get me wrong — but for us, it was a big 'wow,' moment," Thomas says. "We were all completely floored that we didn't see it coming, and then all of a sudden, everyone was like, 'Oh my God, we need you so much.' It really put the attention back on us."

She predicts the event will be a key talking point for asteroid scientists explaining the importance of their work for years to come. "You can only make so many *Armageddon* references," she says, "before people don't know what you're talking about anymore."



New missions mine

When Rosetta landed on a comet, the world held its breath. Now, scientists are about to attempt an even more ambitious mission — twice.

by Elizabeth Tasker

ON Friday, February 15, 2013, everybody was staring up at the sky. They were waiting for the record-breaking close approach of asteroid 367943 Duende. This 100-foot-wide (30 meters) space rock was due to pass our planet at a distance of only 17,000 miles (28,000 kilometers), sweeping inside the ring of geostationary weather and communications satellites that keep pace above the equator. Then, while the world stared in one direction, a second asteroid shot in from behind and exploded above Chelyabinsk, Russia.

Pieces of the surprise asteroid fell to Earth to become meteorites. It was a sizable 65 feet (20m) in diameter, and its fireball explosion lit up the morning sky brighter than the Sun. Buildings in six neighboring cities were damaged and about 1,500 people sustained injuries needing hospital treatment. The shock left everyone asking one question: How could scientists know about Duende but have missed the approach of the Chelyabinsk asteroid?

Two missions, one goal

The answer goes far beyond one rogue asteroid, demanding that we understand intimately the composition and movement of distant, dark, orbiting rocks. Two space agencies are setting out to tackle the problem. This September, NASA will launch its Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx) spacecraft to the asteroids. It is a journey that runs hot on the heels of the Japanese Aerospace Exploration Agency's (JAXA) asteroid mission, Hayabusa2. Both spacecraft are due to intercept their targets in 2018, with plans to touch down and gather rocks

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Elizabeth Tasker *is an astronomer at Hokkaido University in Japan, building stars and planets in her computer. She is on Twitter: @girlandkat.*

ILLUSTRATION BY *ASTRONOMY*: RON MILLER, AFTER NASA (OSIRIS-REx), AKIHIRO IKESHITA (HAYABUSA2) from the asteroid surfaces. These handfuls of pebbles will be incredibly precious because humans have retrieved pristine samples from only two surfaces beyond our planet: the Moon, using the full power of the Apollo program, and asteroid 25143 Itokawa, in a daring mission by Hayabusa2's predecessor. And it is these pebbles that should shed light on the difficult problem of tracking asteroids.

OSIRIS-REx and Hayabusa2 are heading for asteroids that orbit the Sun close to Earth. This classifies the two mission targets as near-Earth objects (NEOs). Hayabusa2 is heading for an asteroid named 162173 Ryugu, a rock a little over half a mile (1km) across whose orbit does not pose any threat to our planet. The target for OSIRIS-REx is the asteroid 101955 Bennu, about half Ryugu's size but with a more risky future.

Most asteroids reside in the asteroid belt, a band of rocks that orbits the Sun between Mars and Jupiter. Asteroids may leave this desirably distant location to approach Earth after collisions that scatter the rocks into different orbits. Their new routes through the solar system depend on gravitational tugs from the Sun and planets and the mysteriously tricky effect of sunlight.

When sunlight strikes an asteroid, its surface absorbs the Sun's energy and re-emits it as heat. There is a delay between these two events while the rock warms, during which time the asteroid rotates. This motion causes it to emit the heat in a different direction than when it absorbed the energy. The result is like catching a ball and throwing it to a person standing to your right. The small recoil from catching and throwing push in different directions, and you feel a force. For light particles called photons, this is called the Yarkovsky effect.

While the Yarkovsky effect also pushes on Earth, the force is too tiny to make any difference to our motion. Even on an asteroid the effect is not large, but over time it can change the asteroid's trajectory enough to make it a real problem.

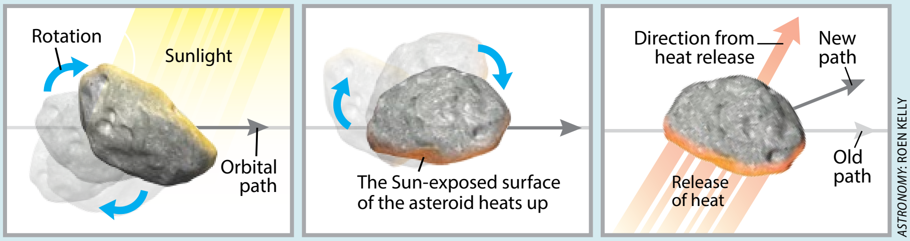
The direction and strength of the Yarkovsky sunlight push depend on the type of rock and its shape. Different materials have different heating and cooling rates, and surface topography may place part of an asteroid permanently in shadow. This is the crux of why asteroid motion is so hard to predict: Scientists do not know enough about asteroid composition to accurately calculate the Yarkovsky force.

Bennu is currently orbiting the Sun between Venus and Mars on a path that brings it close to Earth every six years.

Two spacecraft from two nations — Hayabusa2 from Japan (left) and OSIRIS-REx from the United States (below) — will make their way to small, dark, moving asteroid targets. But the most audacious part of the missions comes when they attempt to return bits of their asteroids home to Earth.

asteroid secrets

Asteroid motion is tough to predict



The Yarkovsky effect describes how light can change an object's path by pushing it in one direction when the object absorbs light, and in another when the object later emits the energy as heat.

Japanese Aerospace Exploration Agency scientists successfully test Hayabusa2's Small Carry-on Impactor. They plan to use it to blow a 33-foot (10 meters) crater in asteroid Ryugu to collect samples from its interior. JAXA/NIHONKOHI

While the asteroid is not in immediate danger of hitting our planet, there is a 1 in 2,500 chance that it will strike Earth in the late 22nd century. This is one of the highest probabilities of any known asteroid.

Scientists cannot be more precise about Bennu's fate without knowing more about the force from the Yarkovsky effect. It is one thing to predict Bennu's motion a few years out, but decades of cumulative Yarkovsky effects will make its position less certain 200 years in the future. A major goal for OSIRIS-REx is to record Bennu's motion accurately enough to measure sunlight's push. This will both constrain Bennu's future path and make vital improvements to the predictions for other NEOs.

The beginnings of life

Yet the threat of an Armageddon impact from an unknown asteroid is only half of the reason for these twin missions. Examinations of meteorites have revealed that many once contained water, leaving them packed with organic molecules. These finds open the door to the intriguing possibility that life on Earth may have come from space.

Exactly how life began on Earth remains unknown. In most formation theories for our solar system, Earth's building blocks were dry grains too warm to contain the amounts of water the planet boasts today. The young desert Earth then gained its oceans from the arrival of ice-laden meteroids. It is possible that this water delivery also contained the first organic molecules. To prove this theory, scientists need to find a similar icy rock while it is still in space, uncontaminated by the now-biologically active Earth.

There are two main reservoirs for meteoroids that are siblings to the ones that hit early Earth. The first are the comets that originate from beyond Neptune. Consisting mainly of ice, comets grow their distinctive tail as they travel toward the heat of the Sun. But measurements of the vapor surrounding comet nuclei suggest they were not our water delivery service.

Most cometary water contains too much deuterium, a heavy version (with a neutron) of the hydrogen atom (no neutron) that bonds with oxygen to make a water molecule. In December 2014, based on its studies of Comet 67P/Churyumov-Gerasimenko, the European Space Agency's Rosetta team concluded it was unlikely our oceans came from the comet population.

The second option is asteroids. Ground-based observations of Ryugu suggested the asteroid might contain water-rich minerals that must have formed in wet conditions. While Ryugu is too small to support liquid water, water in its parent asteroid may have left it full of organic molecules.

The same may also be true of Bennu. Both asteroids are carbonaceous chondrites, a class that formed in the early days of the solar system and has remained nearly unchanged during the past 4.5 billion years. This makes them kin to the meteorites that struck early Earth. It is therefore a good bet that any molecule found on these bodies would have also been delivered to our planet in its past.

Touching the asteroids

OSIRIS-REx and Hayabusa2 will arrive at their respective targets in 2018. Then they will begin intensive 1.5-year analyses of their asteroids, exploring their structure from the largest scales down to surface grains smaller than a millimeter. Yet the most daring moments will be when the two spacecraft touch down on the asteroid surfaces.

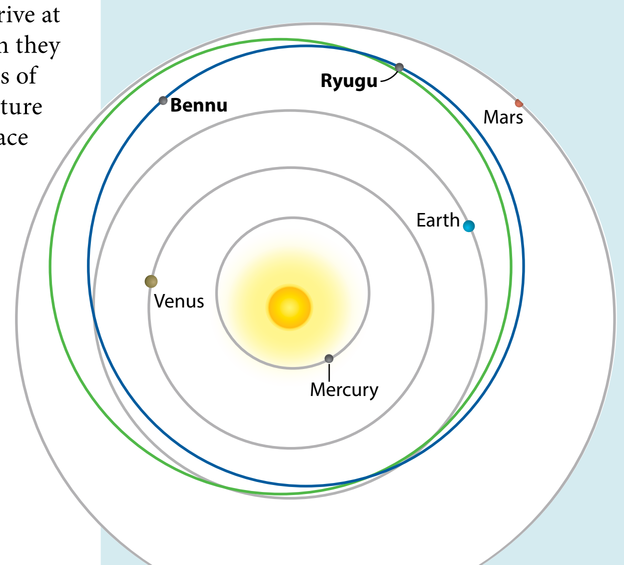
When Rosetta visited Comet 67P, it dispatched the Philae lander to the surface to make a one-way trip, which went awry when the probe bounced repeatedly, landing on its side in a dark shadow. But in order to return asteroid samples to Earth, OSIRIS-REx and Hayabusa2 must land the main spacecraft to gather material and then safely take off back into space. The small surface area of the asteroids, their weak gravity, and the unknown surface composition make this a dangerous endeavor, and failure could cost a mission its whole spacecraft. However, this mammoth task has been undertaken successfully once before.

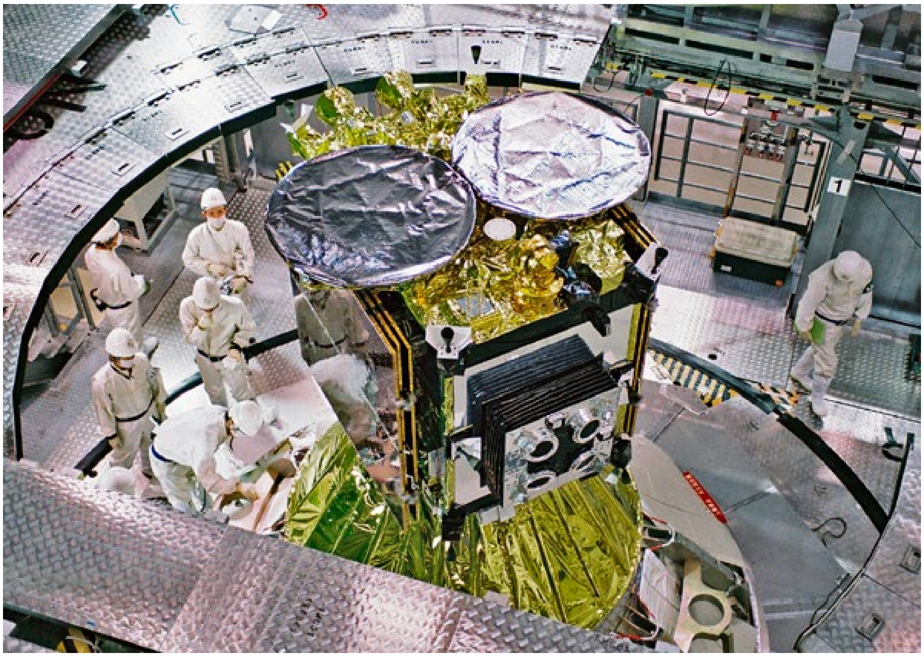
As its name implies, Hayabusa2 has a predecessor. The first Hayabusa spacecraft returned to Earth in June 2010, bringing with it samples from asteroid Itokawa.

Like the Rosetta mission, Hayabusa did not have an easy time landing in the low-gravity environment of such a small rock. The spacecraft was designed to make only a brief touchdown on the asteroid's surface, but a malfunction caused it to bounce just as Philae did a decade later. When Hayabusa

Crossing paths

Ryugu and Bennu have Earth-crossing orbits, but Bennu's has a much higher chance of impacting Earth in a few centuries. *ASTRONOMY*: ROEN KELLY





Scientists work on the nearly complete Hayabusa2 spacecraft prior to its launch. JAXA

Hayabusa2 launched December 3, 2014, and is already well on its way toward asteroid Ryugu and set to arrive in 2018. JAXA

fell back to the asteroid's surface, it stayed there for half an hour, exposing itself to temperatures far beyond its design specification.

Despite this, Hayabusa survived to make a second successful landing attempt. It returned to Earth to bring back the first grains from an asteroid. Unlike Ryugu and Bennu, Itokawa has changed greatly since its formation and contains no signs of water or organic molecules. What it did provide was a resource on how sunlight can weather an asteroid's surface — information that will be key to understanding the observations from OSIRIS-REx and Hayabusa2. Its return also highlighted the importance of such sample retrieval missions.

"The images of these tiny grains appeared and were instantly recognizable to petrologists," says Harold Connolly, the mission sample scientist for OSIRIS-REx, as he describes the presentation of the results from Hayabusa. "It was a fixed moment in time for me."

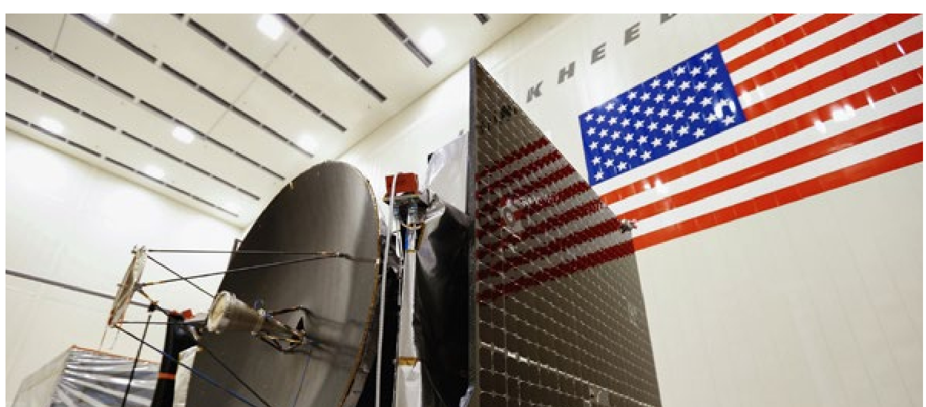
It was a discovery that never would have been as obvious from an analysis performed remotely in space. Connolly realized that to understand our planet's past and future, he had to return to the asteroids.

The mechanism for collecting these vital grains is different between the two current missions. OSIRIS-REx will touch down at the end of its mission in 2019. When it lowers onto Bennu's surface, an extended mechanical arm will release a strong jet of nitrogen gas. As the jet hits the surface, loose rocks and grains will be stirred up and collected in the sample chamber at the end of the arm. "Our collector is a lot like a vacuum cleaner or Hoover," explains Connolly. "It will sweep up rock particles on the surface of Bennu using an inert gas." This inert gas will not contaminate or change the samples scientists need for their studies.

To check that this system will work in the vicinity of the asteroid, NASA scientists tested the equipment back on Earth in the so-called "vomit comet." Named for its effect on the stomach of human passengers, the airplane mimics the low-gravity environment of space through regular dips in its flight.

The cleaning job will yield a sizable haul of rocks for OSIRIS-REx — between 2 ounces and 4 pounds (60 grams to 2 kilograms) of differently sized particles. The plan is to perform this challenging landing only once, but OSIRIS-REx is equipped to try three times if there are any problems.

Hayabusa2 has a different game plan. The spacecraft intends to land not just once, but three times on Ryugu. By gathering material at different sites, Hayabusa2 will sample any variation in the asteroid's composition. It is a schedule that increases the risk to the spacecraft, but then, Japan has done this before.



OSIRIS-REx displays its high-gain antenna and solar arrays before engineers move it from construction to environmental testing in October 2015. LOCKHEED MARTIN CORP.

Hayabusa2 will shoot an explosive charge into asteroid Ryugu and then flee to the space rock's far side to avoid damage when it blows. The spacecraft will return to sweep up the pulverized material churned up from deep inside the asteroid's bulk. AKIHIRO IKESHITA

WHAT'S IN A NAME?

Bennu

In 2013, the Planetary Society held a naming contest for the asteroid 1999 RQ_{36}. The winner was 9-year-old Mike Puzio, who submitted the name Bennu, an Egyptian deity depicted as a heron in mythology and associated with the god Osiris. In addition to the mythological pairing, Puzio also thought the spacecraft resembled a bird in flight, and the asteroid itself an egg.

Ryugu

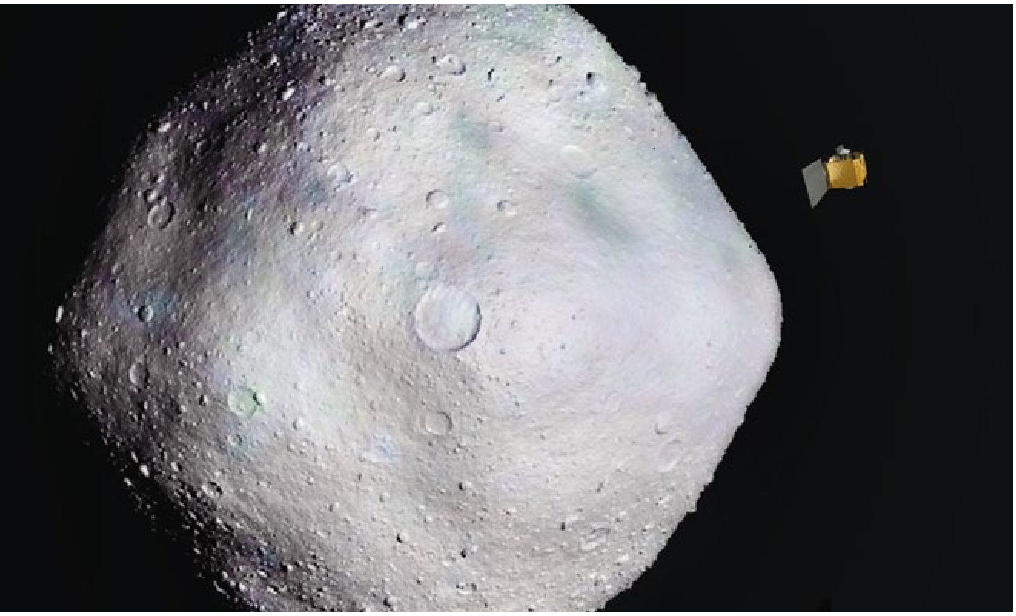
The Japanese space agency renamed its target from 1999 JU_3 to Ryugu in 2015, also based on public submissions. In Japanese folklore, the hero Taro Urashima retrieves a treasure chest from a dragon-guarded castle named Ryugu at the bottom of the sea. Likewise, astronomers count on Hayabusa2 to bring back treasures that will inform them about Earth's oceans. — **Korey Haynes**

To stir up the surface material for collection, Hayabusa2 will fire a bullet into the asteroid as it touches down for its first two landings. At least one of these locations will be at the site of the observed water-rich minerals, while the second will be selected after Hayabusa2 has scouted the asteroid from above.

On the third landing, the spacecraft plans to gather material from deeper inside Ryugu's belly. For that, a larger explosion is needed. Hayabusa2 is carrying a "Small Carry-on Impactor" containing 10 pounds (4.5kg) of explosives. When it hits the asteroid, the resulting blast will carve a crater up to 33 feet (10m) across. To protect itself from the explosion, Hayabusa2 will duck behind the asteroid, dispatching a camera to monitor the result in its stead. Then the spacecraft will make its final collection from the freshly exposed rock.

While Hayabusa2 cannot linger on the surface, it will leave behind a lander packed with three rovers. These robotic explorers will examine Ryugu's surface in greater detail and test the challenges of motion in a low-gravity environment.

Hayabusa2 is aiming for a smaller sample yield than OSIRIS-REx, with a minimum weight of 100 milligrams. Small though this sounds, the first Hayabusa mission revealed an enormous amount of information about the asteroid, Itokawa, with roughly 10,000 times less material. A tenth of a gram is sufficient for all the analysis the mission needs to complete, although the team's best-case scenario will see several grams returned to Earth.



NASA scientists overlaid simulated craters and topography on real radar images of asteroid Bennu, with an artist's depiction of OSIRIS-REx in flight next to it. Genuine high-resolution images will not arrive until shortly before the spacecraft itself does in 2018. NASA/JPL/GOLDSTONE/GSFC/UA/MIKE NOLAN (ARECIBO OBSERVATORY)/BOB GASKELL (PLANETARY SCIENCE INSTITUTE)

Samples from the three sites will be stored separately inside Hayabusa2's container, which will be completely sealed to prevent contamination from terrestrial molecules upon return to Earth. Hayabusa2 is due to land in the Australian outback at the end of 2020, while OSIRIS-REx will land in the Utah desert in 2023. When the containers are cracked open, the science teams will be looking into time capsules from the earliest days of our solar system.

Teamwork

Having independent data from two asteroids greatly reduces the possibility that the collected sample is not typical of the objects. This allows for scientists to draw much bigger deductions from the data. "Samples from two asteroids more than doubles their worth," states Connolly.

Because of this, NASA and JAXA officially joined the OSIRIS-REx and Hayabusa2 missions with a "Memorandum of Understanding." The two teams will share expertise and exchange a fraction of the samples from each mission. JAXA will send 10 percent of the Hayabusa2 samples from Ryugu to NASA, which in turn will send half a percent of the OSIRIS-REx Bennu sample to JAXA. The difference in the figures reflects OSIRIS-REx's larger sample size, and the fact that JAXA will make use of NASA's Deep Space Network of communication antennas to track Hayabusa2 on its journey.

Hayabusa2's first landing on Ryugu will come a year before OSIRIS-REx touches down on Bennu. Both teams will be glued to the data so that they can prepare for any surprises in their future landings. In return, the OSIRIS-REx team is sharing its software to construct three-dimensional models of asteroids to assist Hayabusa2 in its navigation.

Both agencies strongly support this collaboration, as revealed in a meeting between the director general of the Institute of Space and Astronautical Sciences at JAXA, Saku Tsuneta, and OSIRIS-REx's principal investigator, Dante Lauretta, in October 2014. "For a center director to reach out and discuss a particular science expedition is unprecedented," says Connolly, who was also at the meeting.

Connolly has been working extensively with his sample collection counterpart on the Hayabusa2 mission, Shogo Tachibana. The two agree that the collaboration is rewarding but not always easy.

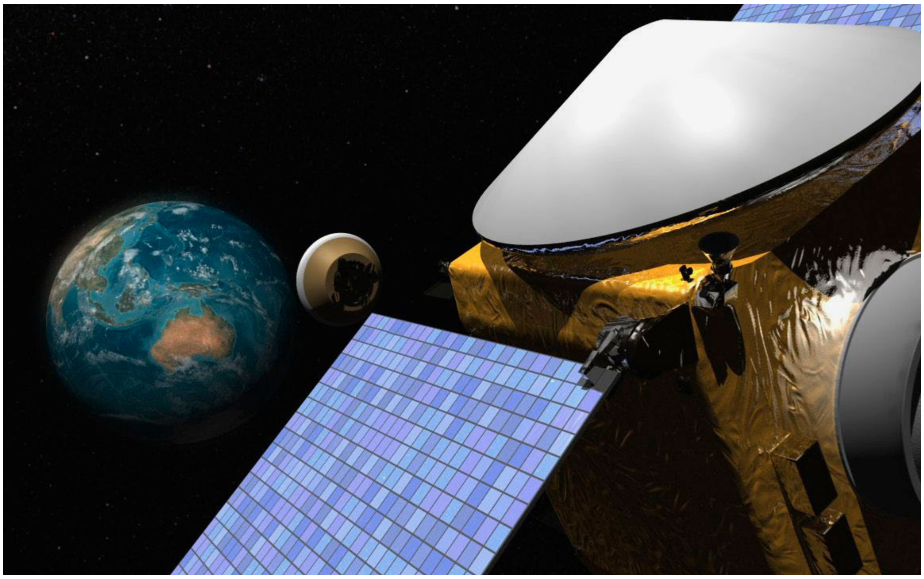
The differences in size between the two space agencies has raised questions about the balance of power. Japan initially voiced concerns that a collaboration with NASA would result in the larger agency dominating both asteroid missions. But Japan's expertise in asteroid missions and meteorite science balances the scale. "In asteroid research, we can make this an even collaboration between us," Tachibana states.

But JAXA's smaller size contributes other more subtle factors to the work culture as well. "Japan is used to working alone," explains Tachibana. "We operate more as a family than a corporate business, where everyone's role is implicitly understood. But a company the size of NASA requires detailed contracts for all aspects of the research."

Such cultural differences don't exist only within the mission teams. Connolly describes his experience during a visit to Japan when a bartender found out that Tachibana was a member of the Hayabusa2 mission. "This guy went down on one knee to shake Shogo's hand," he says. "That would never happen in America! There is a huge difference in perception."

Yet despite these mismatches in size and recognition, NASA and JAXA are taking similar steps to reach beyond the scientific community. Both organizations held public naming competitions for their asteroid targets. Additionally, the OSIRIS-REx team is organizing a citizen science project to help identify NEOs. Project "Target Asteroids!" asks amateur astronomers to send in images of asteroids to increase researchers' knowledge of these poorly understood objects. The two missions keep their websites busy with animated videos, interviews with project scientists, and mission updates. Much of JAXA's outreach takes place in Japanese, of course, but they also run an English Twitter feed and share news on the mission website in both languages.

Even with all the differences international collaborations can bring, there is no doubt in the minds of the OSIRIS-REx and Hayabusa2 teams of the worth of this partnership. The samples OSIRIS-REx and Hayabusa2 will bring home contain the history not of a single country, but of all life on Earth, and keys to its future as well. Both groups want to ensure the best expertise is waiting to receive it.

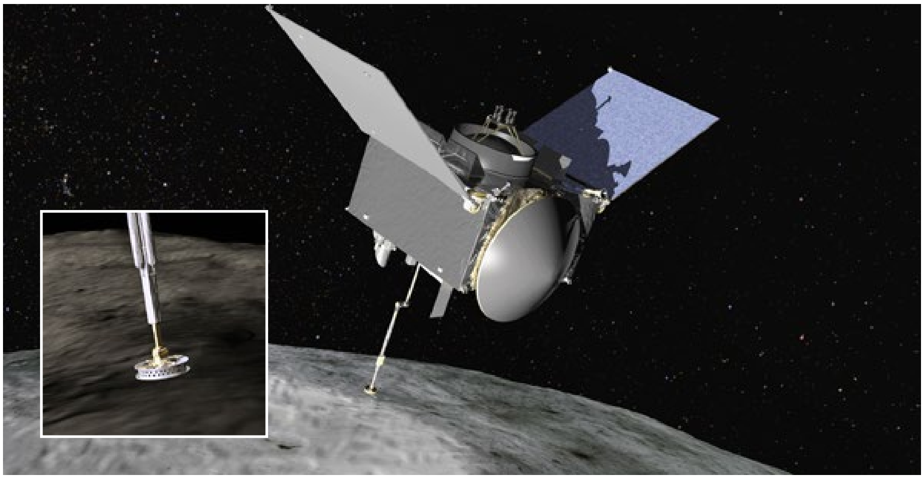


NASA GODDARD SPACE FLIGHT CENTER

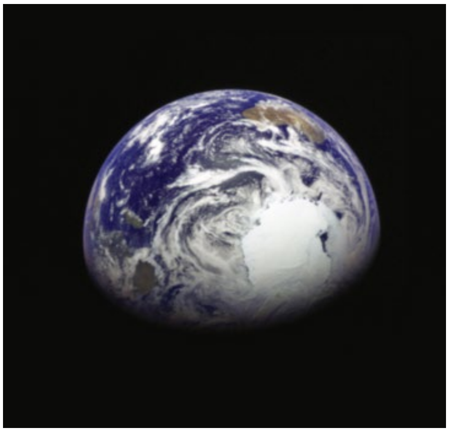
An artist envisions OSIRIS-REx releasing its Sample Return Capsule when it returns to Earth. It should land in the Utah desert in 2023.

AKIHIRO IKESHITA

Hayabusa2 will return its samples in 2020, when they plummet to the Australian outback.



OSIRIS-REx will reach out its sample collector like a vacuum cleaner extension (inset) to gather samples from asteroid Bennu's surface, possibly retrieving up to a few pounds. NASA GODDARD SPACE FLIGHT CENTER



JAXA

Exactly a year after its launch on December 3, 2014, Hayabusa2 performed an Earth flyby on its way to asteroid Ryugu, capturing this image at a distance of 340,000 kilometers (211,000 miles).