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 search of DEATH PLUNGE ASTEROIDS

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

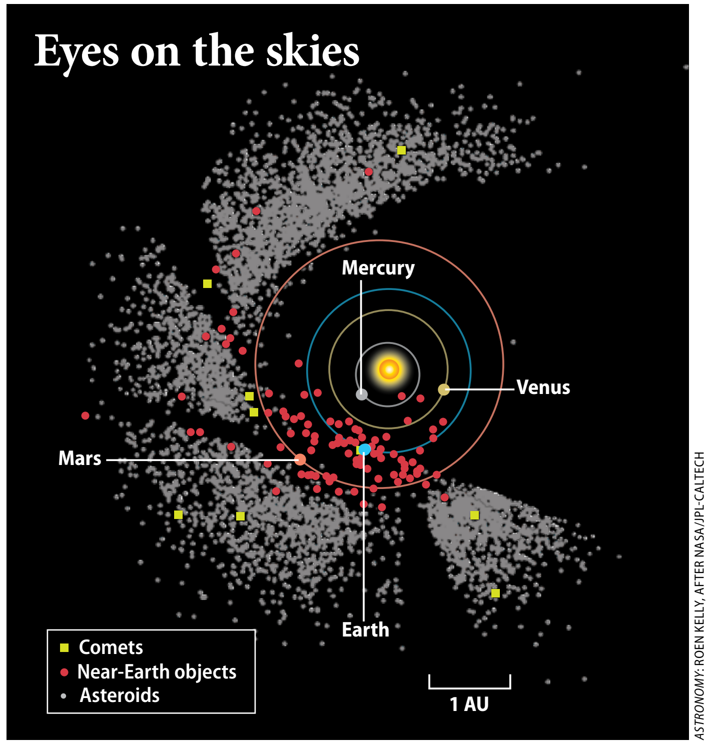
In an alternate world with a more advanced asteroid search campaign, astronomers could have prepared all night for the big impact. OSHIN D. ZAKARIAN

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



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.

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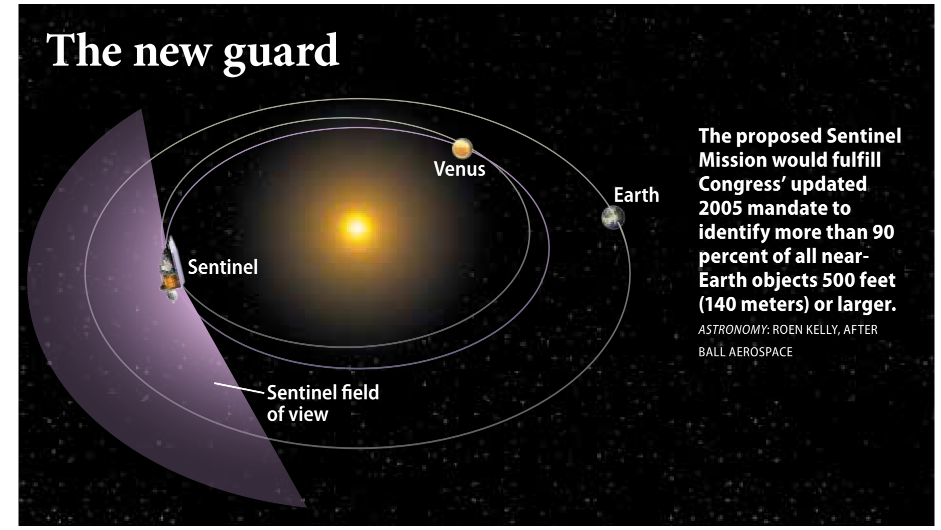
The show begins

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.



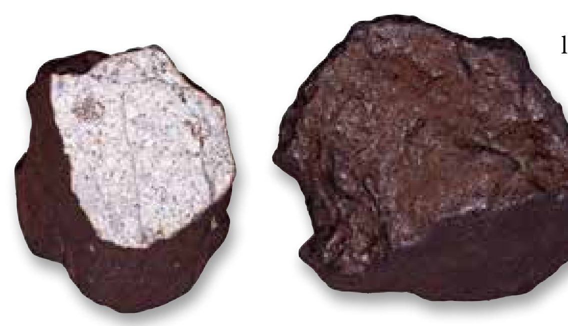
But the show had just started. For the next 10 seconds, the asteroid grew much brighter as it forced its way through the air, compressing it into an ever hotter and denser plug of ionized gas. The asteroid's core was as yet undisturbed, the pressure in the thin upper atmosphere too small to deform or 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.

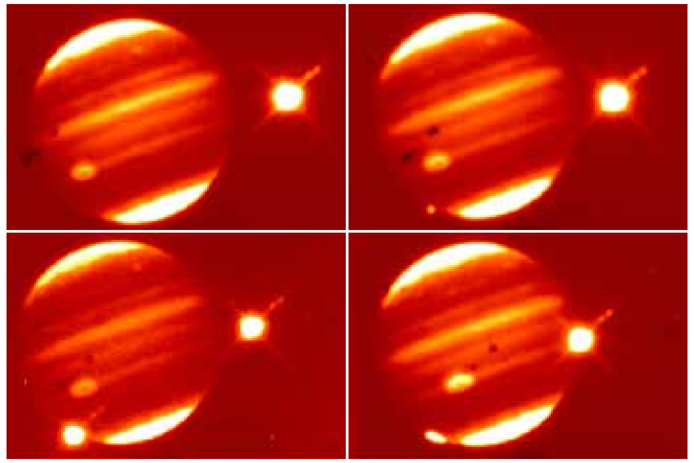


While some fragments from the Chelyabinsk meteor were recovered quickly, others took months to locate and retrieve, partially due to incomplete information regarding the unexpected meteor and its trajectory. DIDIER DESCOUENS

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

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)

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.

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.**