SPECIAL REPORT

2013's HISTORIC

RUSSIAN METEORITE FALL

RON MILLER FOR ASTRONOMY

The largest meteor to light up Earth's sky in more than a century exploded above Russia's Ural Mountains on February 15. Here's the inside story with pictures, analysis, and meaning. **by James Oberg**

For people in the Russian industrial city of Chelyabinsk just east of the Ural Mountains, Friday morning, February 15, started out as a typical late-winter day. Shortly after 9 A.M. local time, the Sun was hanging low above the southeastern horizon. The sky was mostly clear, streaked with high clouds and occasional airliner contrails. It was cold — around 16° Fahrenheit (–9° Celsius) — but not windy.

The tranquil dawn didn't last long. The first sign something unusual was happening came when the sky started to brighten dramatically in the direction of the rising Sun. Within seconds, that glare became blinding, and

TERMS TO PONDER

Was the sky show seen above Russia a meteor, fireball, or bolide? It was all three — and then some. Here's a guide to some of the terms used to describe such incidents.

ASTEROID — A rocky object, smaller than a planet, orbiting the Sun.

BOLIDE — An especially bright fireball that explodes in the atmosphere.

FIREBALL — A particularly bright meteor; scientists usually define it as being brighter than Venus (around magnitude –4).

METEOR — A streak of light in the sky that occurs when a solid particle (typically a meteoroid) enters Earth's atmosphere and air friction incinerates it.

METEORITE — A fragment of an asteroid or a meteoroid that survives its trip through the atmosphere and lands on Earth's surface.

METEOROID — A small rocky object, typically a fragment of an asteroid or comet less than a few feet (1 meter) across, that orbits the Sun. Meteoroids are invisible unless they encounter Earth.

Russian photographer Marat Akhmetaleyev was shooting landscape photos near his home when the fireball exploded. Although he thought at first it was a nuclear bomb, he still captured a series of dramatic images. This one shows the object's trail across the sky. MARAT AKHMETALEYEV

ASTRONOMY: ROEN KELLY

In its final minute, the impactor passed over northern China and Kazakhstan before exploding just south of Chelyabinsk, Russia. The mileage markers along the ground track indicate the object's altitude.

eyewitnesses saw it moving from left to right. In front of thousands of pairs of eyes and more cameras than you could count, stark shadows of lampposts, cars, and buildings swiveled across the pavement. A few viewers believed the ground was rotating.

As the brilliant first flare faded, the object's smoke trail across the southern sky forked into two parallel tracks. After two smaller flares, the paths then continued over the horizon to the southwest. Videos of the event lit up the Internet as surely as the blazing meteor lit up the sky.

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Impact on the ground

The excitement was only beginning. Nearly three minutes after the initial fireball appeared in the sky, a massive shock wave hit Chelyabinsk. Windows shattered, car alarms howled, and people screamed and cursed. A roof and wall at a zinc factory partially collapsed, and officials estimated that upward of 100,000 windows were destroyed. Remarkably, no one died, although approximately 1,500 people sought medical attention — most of them injured by flying glass.

The numbers associated with the spectacular fireball — or "superbolide," NASA's newly coined term — were as breathtaking as the event itself. The fireball traversed Earth's atmosphere at a shallow angle (about 7°) on a descending path traveling from east to west that passed about 12 miles (20 kilometers) south of Chelyabinsk. It exploded at an altitude of approximately 76,400 feet (23,300 meters) when it was moving at a velocity of 11.6 miles per second (18.6 km/s).

Friction with the atmosphere slowed and heated the incoming object. The body's rapid motion compressed the air in front of it, creating the shock wave that pulverized windows on the ground. The compression also heated atmospheric gases and stripped electrons from the atoms and molecules in a process called ionization. When the electrons recombined with the ionized gases, they emitted the light seen in the Russian sky. The energy caused the space rock to break up and ultimately explode when the growing pressure exceeded the object's internal strength.

The force radiated by the main fireball reached about 90 kilotons. In comparison, the atomic bomb detonated above Hiroshima in 1945 topped out at roughly 15 kilotons. The impact dumped even more energy into the upper atmosphere along the descent

RIA NOVOSTI/CAMERA PRESS/REDUX

Automobile dashcams delivered the first images of the meteor's appearance and were a godsend for scientists trying to reconstruct the object's path.

XINHUA/RIA/CORBIS

The meteor's fading smoke trail hangs in the air above Chelyabinsk, a Russian city with roughly a million residents that lies just east of the Ural Mountains.

path, although less explosively. NASA scientists estimate the total energy delivered during the entire entry at 440 kilotons.

The Chelyabinsk blast is easily the most energetic impact event witnessed since 1908, when an even larger object exploded above the Tunguska region in south-central Siberia. Researchers think the Tunguska explosion, which flattened some 770 square miles (2,000 square km) of forest, released between 3 and 5 megatons of energy.

Fragments of the Chelyabinsk impactor that reached the ground appear to be ordinary chondrite meteorites. These have typical densities of about 3.6 grams per cubic centimeter. To deliver 440 kilotons of energy, the incoming object would have needed to be 60 feet (18m) in diameter and have a mass of roughly 11,000 tons. The object unquestionably was an asteroid, albeit a small one.

A Cold War flashback

It seems almost remarkable that scientists could learn so much about the superbolide and the object that created it within just a couple of weeks. But at the moment when the fireball burst on the scene, at 9:21 A.M. local time (10:21 P.M. EST on February 14), "confusion" was the operative word. Both in the city and around the globe, the first and most important question — then, and even now in hindsight — was: Where did this object come from? The quest for information wasn't mere idle curiosity.

For the Russians in Chelyabinsk that day, the object obviously approached from the east, out of the rising Sun and from the direction of China. Some people initially panicked and thought that it might be a

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A zinc factory in Chelyabinsk lost part of its roof and wall (above) when the fireball's shock wave hit, although production continued normally. Officials estimate that the blast destroyed more than 100,000 windows (upper right); damage cleanup started right away (lower right). XINHUA/RIA/CORBIS (ABOVE); RIA NOVOSTI/CAMERA PRESS/REDUX (UPPER RIGHT); ANDREI LADYGIN/ZUMA PRESS/CORBIS (LOWER RIGHT)

nuclear attack from that country. Fortunately, those fears were short-lived.

Only one of the million humans in the target zone was prepared for the worst. Teacher Yuliya Karbysheva was with her elementary school class — 44 children in all — at School #37 in Chelyabinsk. When a flare like a second Sun bathed her east-facing classroom in blinding light, the children ran to the window. But she remembered the air-raid drills of her own childhood during the Cold War and ordered the children under their desks.

As they ducked and covered, she quickly opened the glass doors between the classrooms, another half-remembered emergency measure preached during the old drills. But as one minute passed, then another, the children's curiosity grew. She moved toward the windows to wave her antsy charges back under their desks.

It was there that the blast wave caught her, showering her with glass that inflicted severe arm cuts but nothing life-threatening. Covered with her own blood, she calmly ordered the children to get their coats and evacuate the building.

Amid all the confusion and rumors and fear of that day, Karbysheva quickly became the city's hero. Not a single child had even been scratched. One person, at least, had recognized the warning signs and taken measures to mitigate the effects.

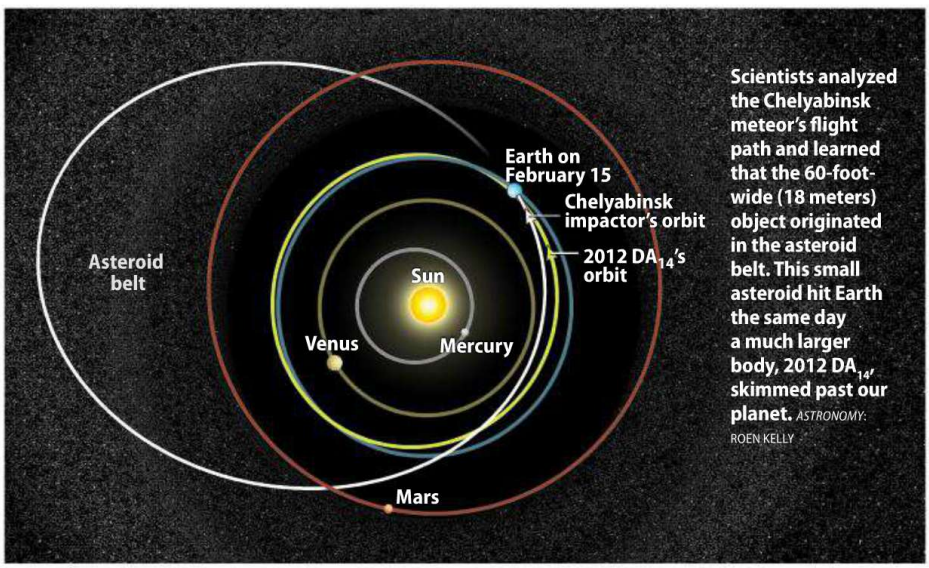
Visit from the asteroid belt

Once the initial pandemonium subsided, scientists got to work figuring out where the diminutive asteroid had originated. An underappreciated feature of Russian life facilitated the process. Many cars carry dashboard-mounted webcams — dashcams — that record a continuous loop of images. They have nothing to do with scientific studies of fireball tracking. Instead, recent years have seen increasingly corrupt traffic police as well as automobile accidents staged for insurance fraud. The dashcams provide visual records of the accidents.

Within hours of the incident, dozens of these videos appeared on the Internet. In some, the fireball flared into visibility right in the field of view. In others, the passing fireball's glare cast shadows of telephone poles onto streets. Once researchers determined a street's orientation, they could reconstruct the precise elevations and azimuths with respect to time.

Determining the object's original path through space had an urgency unusual for computational astronomy. Only 16 hours after the Chelyabinsk impact, an even bigger object would make a remarkably close flyby of Earth. Asteroid 2012 DA_{14} measures about 100 feet (30m) across and has a mass estimated at 40,000 tons.

Spanish astronomers discovered this object in February 2012 during a previous close encounter with Earth. Scientists calculated that it would pass 17,200 miles (27,700km) above Earth's surface — closer than many communications satellites orbit. But it was also so close that Earth's gravity flung it onto a new path that lies almost



Scientists analyzed the Chelyabinsk meteor's flight path and learned that the 60-foot-wide (18 meters) object originated in the asteroid belt. This small asteroid hit Earth the same day a much larger body, 2012 DA_{14}, skimmed past our planet. *ASTRONOMY:* ROEN KELLY

entirely inside our planet's orbit. Its greatest distance from the Sun dropped by 11 million miles (18 million km), and its period shortened from 368 days to 317 days.

Of immediate concern to astronomers, the general public, and emergency preparedness teams around the world was whether the Chelyabinsk fireball was associated in any way with 2012 DA_{14}. Astronomers were not aware that any debris accompanied the larger asteroid, but a relatively recent impact or fragmentation could have littered its orbit with some sizable rubble.

It seemed to defy probability that two such extremely rare events occurred so close together and were not related. Yet that's exactly what the earliest estimates of the Chelyabinsk object's orbit suggested.

Some scientists based their first guesses on a quick analysis of the dashcam videos. Others relied on the impact's happening in the Northern Hemisphere, which was out of the line of sight of DA_{14}'s approach.

More precise measurements over the next day or two confirmed these reassuring guesses. This result enormously lowered the likelihood that any other object from the same potential swarm would hit Earth during the coming days. And none ever did.

When astronomers ultimately pinpointed the Chelyabinsk fireball's pre-impact path, they found it had been a fairly typical Apollo asteroid — the largest class of asteroids whose orbits cross Earth's. The Russian object's orbit ranged from the asteroid belt inward as far as the orbit of Venus and lay close to the orbital planes of the major planets. Statistically, thousands of objects of similar size must exist.

NASA's final report, authored by Don Yeomans and Paul Chodas, two experts on near-Earth asteroids at the Jet Propulsion Laboratory, also computed the object's trajectory as it approached Earth. The impactor bore down on our planet along a path that remained within 15° of the Sun's direction. As NASA noted, Earth-based telescopes seeking to detect asteroids cannot scan regions of the sky this close to the Sun.

The hunt for fragments

People in the Chelyabinsk area certainly had to deal with the bad fortune of being hit by the biggest space impactor in a century. Yet they were lucky when it came time to search for meteorite fragments — the wintry climate provided a perfect setting.

First, a blanket of snow across the region offered an ideal backdrop on which to seek dark crumbly meteorites. Second, the weather after the event was crisp and clear, yielding perfect lighting for the search.

SERGEI ILNITSKY/CORBIS

Scientists suspect that a fragment of the incoming asteroid blasted this 26-foot-wide (8 meters) hole in frozen Chebarkul Lake, which is located about 5 miles (8 kilometers) from Chelyabinsk.

RIA NOVOSTI/CAMERA PRESS/REDUX

A researcher holds a meteorite found on the ice surrounding the gaping hole at Chebarkul Lake.

And there were plenty of searchers, few of whom were motivated by science. Within hours of the fall, "recovered meteorites" for sale flooded the Internet, and some even looked genuine. Along with the meteorites, there were the usual "meteor-wrongs" — honest misidentifications in many cases — and a collection of obvious hoaxes.

A hole in the ice at nearby Chebarkul Lake created a brief flap. Such holes can appear naturally, but researchers suspected a meteor fragment blew the hole. Officials found what were later confirmed as meteorites on the ice surrounding the hole.

Yeomans and Chodas reported that authentic fragments were silicate-rich ordinary chondrites, the type that constitutes about 80 percent of all meteorite falls. This was the last nail in the coffin to prove Chelyabinsk was unrelated to the 2012 DA_{14} flyby. Spectral observations of the larger asteroid show it has a composition similar to certain types of carbonaceous chondrite meteorites with abundant inclusions of calcium and aluminum. This is quite different from the silicate-rich ordinary chondrite meteorites from Chelyabinsk.

Now that scientists have settled what the Chelyabinsk object was not, and that its orbit placed it squarely in the group of Apollo asteroids known for more than a century, speculation has turned to what the object was in a larger sense.

It was a reminder that statistics don't lie and that Earth is not immune from impacts that can cause significant damage. It also showed that Earth-based programs seeking such objects have a long way to go. Although NASA estimates that scientists have found at least 90 percent of the potentially hazardous objects 0.6 mile (1km) in diameter or larger, they fall well short of that percentage when it comes to bodies the size of 2012 DA_{14}. And no one knows how many Chelyabinsk-sized objects lurk in our planet's vicinity.

The technology for monitoring space for potentially hazardous objects continues to improve. Still, detecting bodies approaching from the Sun's direction, like the Chelyabinsk impactor, requires telescopes far out in space. By the end of this decade, scientists expect that they will have found 90 percent of the most dangerous objects, those with diameters larger than 500 feet (150m). The Chelyabinsk fireball and the near-miss of 2012 DA_{14} seem to have strengthened the push for better warning systems. And they certainly focused public and political attention on the need to develop active countermeasures to defend our planet.

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