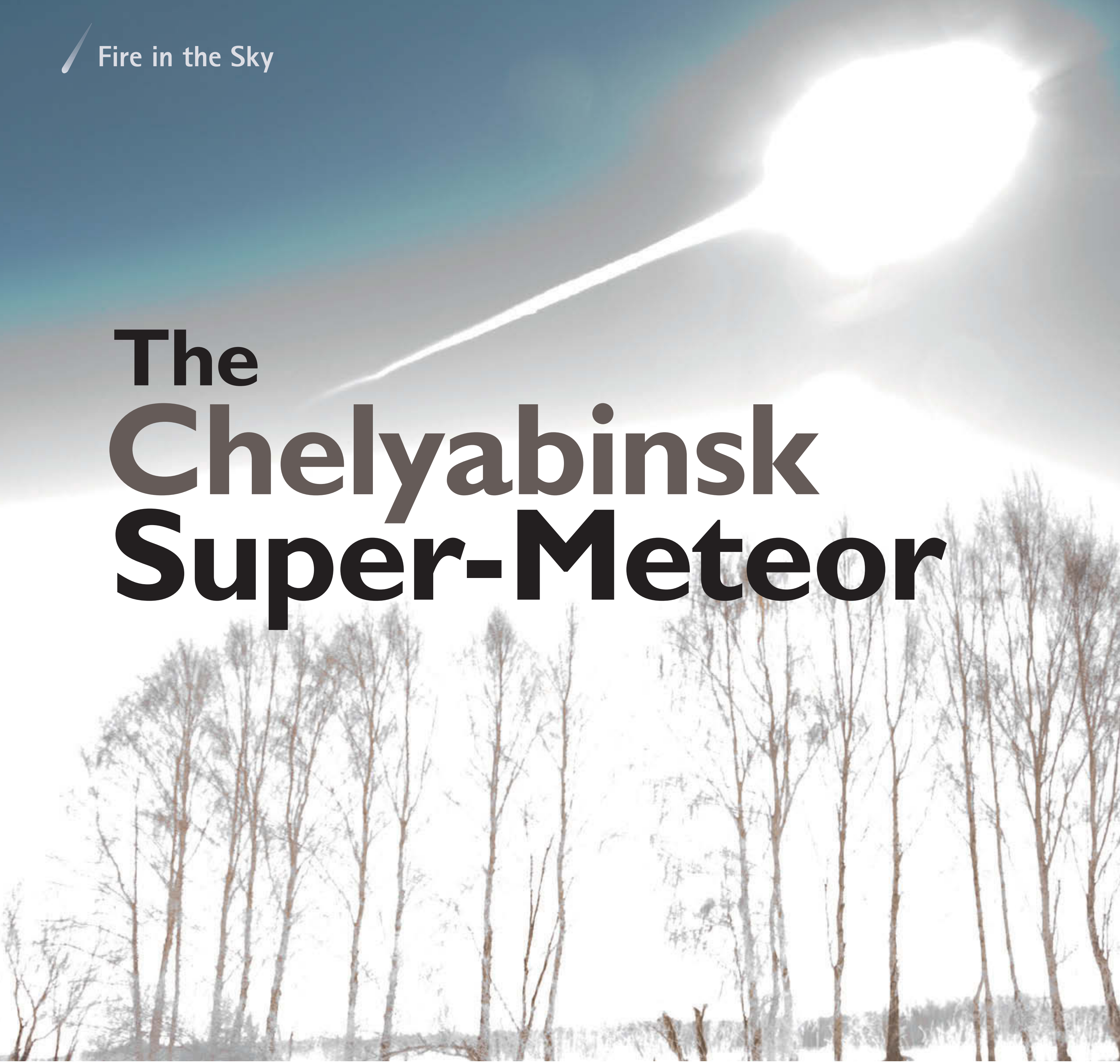


The Chelyabinsk Super-Meteor

Daniel D. Durda

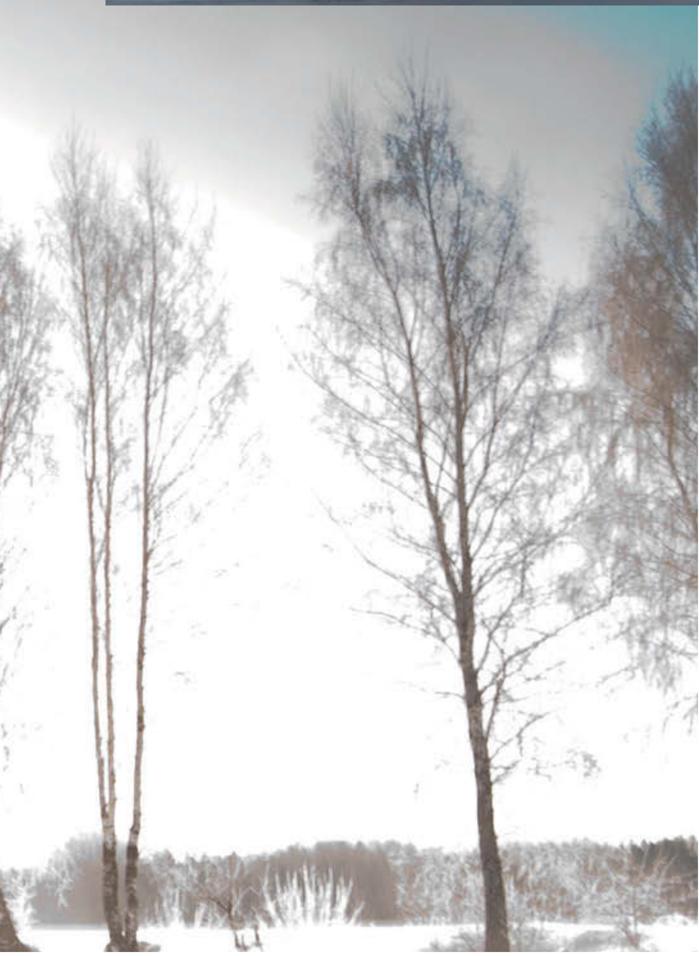
Scientists are piecing together the story of the largest asteroid impact with Earth since 1908.

On February 15, 2013, the planetary science community was geared up for a big news story: the very close approach of asteroid 2012 DA_{14}. This event would remind the world of the potential danger of asteroid impacts.

Little did we know that Mother Nature had arranged a far louder wake-up call that morning. At 9:20 a.m. local time — just 16 hours before 2012 DA_{14} swept past Earth from the south — a small, westbound asteroid blazed through the dawn twilight over the Russian city of Chel-

9:21:35

MARAT AHMETVALEEV (2)



9:20:33

yabinsk. Dozens of dashcams captured the super-bolide, thanks to its occurrence over an urban area and the proclivity of Russian drivers to record their every move in order to protect themselves from fraudulent insurance claims. Videos posted on the internet captured the brilliant fireball and thundering sonic booms. And as reports poured in of shattered windows and damaged buildings, the reality set in around the globe that a meteor event can injure hundreds of people.

EYEWITNESS TO THE EXPLOSION

Marat Ahmetvaleev

I was taking pictures in a Chelyabinsk park with my Canon 5D DSLR camera on a freezing February morning. I leaned over to change the camera angle on the tripod to take another shot when suddenly I saw a bright flash with my peripheral vision. Initially it was small. My camera was aimed almost in the same direction, but I immediately turned it toward the object to take a picture.

At about the same time I started to hear a sound that resembled white noise with a slight rustle and crackle. The sound was barely audible but lasted for the meteor's entire flight. In the first seconds my heartbeat and breathing sped up, and my hands started to shake. When the flash's brightness peaked, I felt strong heat on my face, but it lasted just a split second. I also felt a strong pain in my eyes from the intense glare.

Then, two minutes after the flash, I heard a series of explosions — the sound was clear and powerful, reminiscent of drumbeats. The first explosion was very loud, and I felt a wave of sound. I felt no physical sensations or vibrations from concrete structures or roads because I was in an area with pine trees. Immediately after, I heard a series of bomb-like sounds, and many birds flew in all directions. My heartbeat, breathing, and tremors increased from the shock of this event.

Only after the series of explosions ended did I start to return to normalcy, and I was then able to set the correct exposures and camera angles to shoot a few panoramas showing residual traces of the meteor. The surrounding scene changed. It looked like the sky was bluer and more transparent. The Sun had already risen, but its brightness was like no typical morning Sun — it looked like the Sun at its zenith.

I had a hurricane of thoughts in those first few seconds, and not in the most positive way. One of my initial thoughts was the explosion of a nuclear bomb. Then, given the insane speed of the object, I thought it was something from outer space. Immediately I began to think of the consequences for all the people and all my relatives in the city. A few minutes later I heard an ambulance and a fire alarm, which accentuated my negative thoughts. Only after I contacted my family on the phone did I begin to calm down and take more photographs.

Marat Ahmetvaleev's website is http://marateaman.livejournal.com.

RIGHT PLACE, RIGHT TIME Marat Ahmetvaleev was taking photos of the Miass River, which runs through Chelyabinsk, when a small asteroid exploded in the eastern sky. Ahmetvaleev captured the spectacle at peak brightness (*above left*) and as the train of debris dissipated over the course of 25 minutes (*above* and *pages 26 and 31*).

MARAT AHMETVALEEV

9:33:01

Characterizing the Blast

After an initial flurry of speculation, scientists needed only a day or two to sort out the basic astronomical facts. With the media and public focused on the impending close pass of 2012 DA_{14}, and with Hollywood's penchant for depicting threatening asteroids with swarms of smaller fragments, many people immediately wondered if the Russian meteor was somehow linked to 2012 DA_{14}. That suspicion was quickly erased when astronomers determined that the parent meteoroid had an eccentric orbit typical of an Apollo near-Earth-asteroid (NEA). This is wildly different from DA_{14}'s more Earth-like and inclined path.

For a few brief moments the meteor literally outshone the Sun in Chelyabinsk's dawn sky. Using models that relate a fireball's mass to its peak brightness, Peter Brown (University of Western Ontario, Canada) estimates the meteor's peak at a whopping absolute magnitude of –28 (compared to the Sun's –26.7 apparent magnitude).

Regardless of an incoming object's size, most of the energy for creating a meteor's luminous head comes from the shock-heated air surrounding it. Baked to temperatures as high as a few tens of thousands of degrees, the air becomes ionized (it turns into a plasma) and glows similar to the way a flame or lightning bolt does. The Chelyabinsk meteor impacted the atmosphere at a typical NEA speed, in this case about 18.6 km/seconds (42,000 mph). The shock formed from a meteoroid entering the atmosphere at such a hypersonic speed is truly intense. The plasma just millimeters from the meteoroid's surface radiated enough heat to vaporize the intruder's outer skin. This vaporized material was swept away by the hypersonic air flowing past, forming a trail behind the object that eyewitnesses saw as a luminous train in the sky.

Some of the first quantitative verification of the event's energy came from its infrasound signature. Since 2001, the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) has operated a global network of 45 microbarograph arrays to monitor the atmosphere for the low-frequency (less than 20 hertz) "booms" of nuclear blasts around the planet. The network is also sensitive to natural infrasound sources, such as volcanic eruptions and large bolides. The concussive atmospheric blast from Chelyabinsk was picked up by 17 CTBTO microbarograph arrays, including stations as far away as Greenland and Antarctica.

Almost immediately the infrasound data, along with the thermal infrared signature measured by space-based instruments such as those on U.S. Air Force Defense Support Program satellites, confirmed the large size. Initial reports indicated an explosive equivalent of at least 100 kilotons of TNT, and it wasn't long before the estimates climbed to a few hundred kilotons. The last meteor blast approaching this energy occurred over Sulawesi, Indonesia, on October 8, 2009; infrasound data put that bolide disruption at about 50 kilotons. The estimates of the Chel-

CHELYABINSK REGIONAL BRANCH OF RUSSIAN INTERIOR MINISTRY / AP IMAGES

IMPACT CRATER? Russian police stand near a 6-meter hole in the ice covering Lake Chebarkul, 70 km (45 miles) west of Chelyabinsk. Scientists are still investigating whether a fragment of the bolide punched through the ice to create this hole.

VIEW FROM SPACE An instrument on the European Meteosat-9 weather satellite caught the vapor trail (short white streak) of the bolide as it disintegrated.

EUMETSAT

WHAT ABOUT COMETS?

A few percent of objects that impact Earth are comets or their dormant remnants. Because comets often approach our planet on orbits that can be far more eccentric and highly inclined than those of typical asteroids, comet impact speeds tend to be significantly higher than those of asteroids. Retrograde, long-period comets can impact as fast as 72 km/second (161,000 mph), much higher than the average 17 to 20 km/second speed of most asteroids. Because of these faster average impact speeds, a comet impact will generally cause much greater damage than the impact of an asteroid of the same size.

yabinsk event have now settled in at about 440 kilotons (although this number may yet be refined) — nearly 30 times the yield of the Hiroshima atomic bomb.

This is the most energetic confirmed asteroid impact with Earth's atmosphere since the megaton-scale Siberian Tunguska airburst on June 30, 1908. We estimate that explosions roughly the size of Chelyabinsk occur about once per century, whereas Tunguska-like impacts thankfully happen only once every few centuries or so.

Blown to Bits

The fireball's brightness and the energy of the terminal explosion enabled scientists to estimate the diameter of the meteoroid prior to entry: about 17 meters (56 feet). The 11,000-metric-ton object probably experienced numerous impacts in space before its fatal encounter with Earth, so it may have already had substantial surface and internal cracks. It was catastrophically crushed to bits by the increasing dynamic pressure of a Mach 60 entry from the vacuum of space into the dense lower atmosphere (see "A Different Kind of Explosion," page 31).

The impactor's disintegration 23 km high showered fragments over hundreds of square kilometers, with some of the largest pieces estimated to weigh nearly half a ton. Rapidly braked and badly broken by the dense lower atmosphere, many of the meteorites simply fell to the ground rather than "impacting" in the manner of a large-scale cratering event. Most of the smaller fragments hit the snow-covered ground with speeds no greater than the terminal speed of an object dropped from the same high altitude, thus they remained mostly intact and left only small "entry wounds" in the snow.

Although astronomers have no formal definition for the term "impact," we have an intuitive sense that the object has to strike the ground with a significant fraction of its pre-entry speed still dominating its motion. Asteroids that are large, very dense (metallic), or both do not appreciably sense the atmosphere from a deceleration point of view; they really do "impact" the ground at speeds greater than the speed of sound and blast out craters. The biggest pieces of this Russian meteorite may

PAVEL MALTSEV (2)

ROCKS FROM SPACE Despite the extraordinary event in the sky, recovered meteorites are rather ordinary: stony chondrites with a low iron content. *Far left:* Viktor Grokhovsky of the Russian Academy of Sciences committee on meteorites is leading the recovery efforts. Hundreds of fragments collectively weighing more than 100 kg have been found.

ASTEROID ART: MICHAEL CARROLL; STADIUM PHOTO: BERNARD GAGNON / WIKIMEDIA COMMONS

SCALE MODELS Artist Michael Carroll depicts asteroid 2012 DA_{14} (left) and the Russian impactor (right) inside Heinz Field, home stadium of the Pittsburgh Steelers. Neither asteroid was imaged at high resolution, but this artwork accurately portrays their sizes. It's a good thing Earth was hit by the smaller object.

have slammed into the ground with some remnant of their original entry velocity. One of the largest chunks apparently punched a 6-meter-wide hole through the ice covering Lake Chebarkul, about 70 km west of Chelyabinsk.

The meteorites recovered so far suggest that this object was an LL5-type ordinary chondrite, among the class of stony meteorites with low iron content that are the most common to fall on Earth. A similar chondritic body four or five times larger blazed through the Siberian sky in 1908, exploding with a force of 3 to 5 megatons and leveling more than 2,000 square kilometers of taiga (**www.skypub.com/tunguska**). The Chelyabinsk event was in many respects a mini-Tunguska.

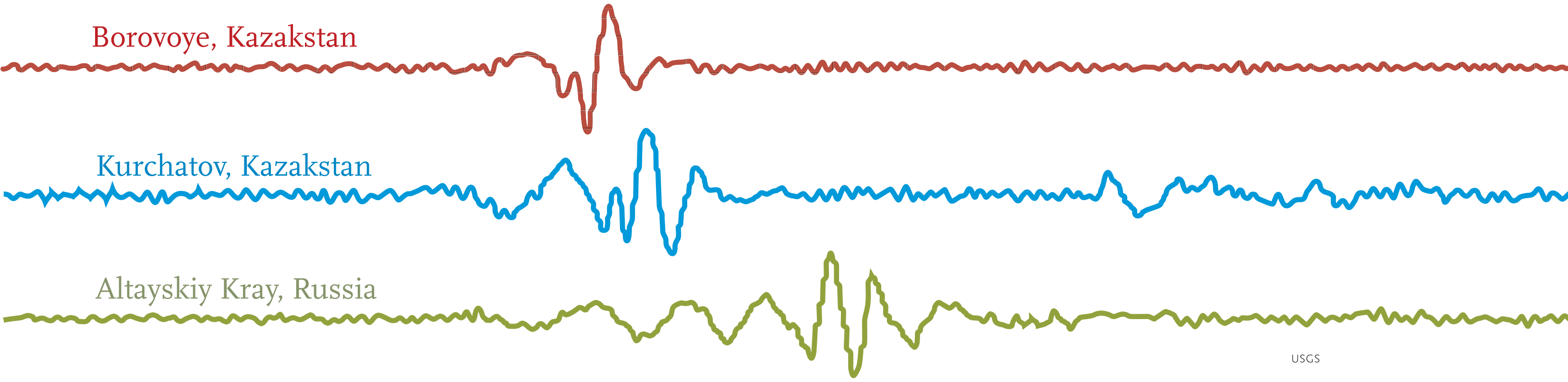
The video coverage of the bolide from many locations has enabled scientists to make a fairly robust determination of the asteroid's pre-entry orbit. By analyzing features such as the length and orientation of shadows from streetlight poles cast by the bolide, at least three different teams determined the 3-D trajectory of the terminal phases of the bolide's flight and backtracked that path into space, accounting for gravitational deflection as the asteroid approached Earth. Like several other recovered meteorites whose pre-impact orbits have been determined, this one moved along a fairly eccentric orbit with an aphelion comfortably in the middle of the main asteroid belt. Its orbital period was about 18 months.

The Human Impact

The shattered windows and collapsed walls throughout the 2,000-square-km area surrounding Chelyabinsk have provided a tangible example of the damage that even a relatively small NEA impact can cause. Had the explosion not occurred over a densely populated city of more than 1

ASTEROID OR METEOROID?

An *asteroid* is a small rocky or metal-rich object orbiting in space. A very small asteroid is often called a *meteoroid*. Although there is no formally adopted definition for the size dividing asteroids from meteoroids, for programmatic purposes NASA treats asteroids as objects detected telescopically in space before impact and meteoroids as objects that enter the atmosphere undetected. When a small object is plunging through the atmosphere, it's called a *meteor*. A piece of space rock that reaches the surface is known as a *meteorite*.



USGS

GROUND SHAKING Although the meteor exploded 23 km high, its shock wave produced ground motion equivalent to a magnitude-4.2 earthquake. These seismogram readings, in order of increasing distance, were all taken more than 620 km away.

million people, the event may have remained noteworthy only to the impact-hazard community. But the internet and airwaves were flooded with videos of the Sun-like fireball, recordings of thundering sonic booms, and images of bloodied faces due to flying glass — transforming the usually dispassionate, academic discussion of small asteroid impacts into a very real human story.

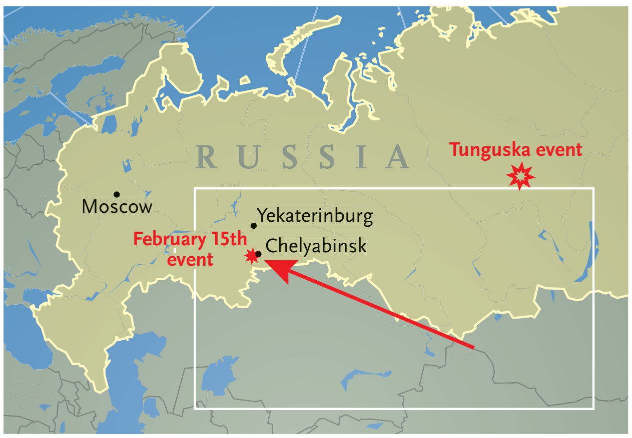
More than 1,500 people were injured and thousands more had to deal with blown-out windows in a Russian winter. Thankfully, no one was killed. In the grand scheme of things, it could have been far, far worse. If the meteoroid had penetrated the atmosphere on a steeper trajectory, instead of entering at a shallow 16° from horizontal, larger pieces might have made it to the ground intact, causing more damage, more severe injuries, and perhaps fatalities.

Some have wondered why astronomers failed to detect this object prior to impact. Interestingly, the meteoroid made its perihelion passage near the orbit of Venus just 6 weeks earlier, before approaching Earth from an apparent direction in the sky only about 20° from the Sun. Knowing the meteoroid's orbit and size, Bill Cooke (NASA/Marshall Space Flight Center) calculated that the object was

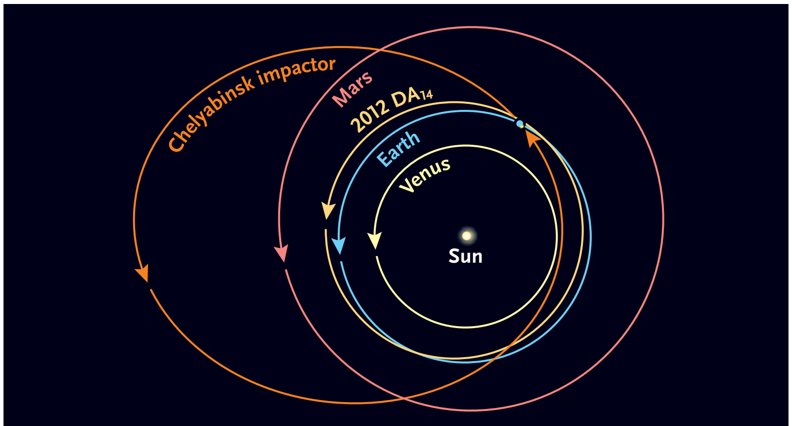
MIASS / WIKIMEDIA COMMONS

GROUND DAMAGE The shock wave from the object's rapid disintegration blew out windows and caused damage to buildings throughout the Chelyabinsk metropolitan area. Roughly 1,500 people were injured, mostly by flying glass.

GROUND ZERO These maps show the 254-km ground track of the Chelyabinsk meteor after it entered Earth's atmosphere above China's northwestern border with Mongolia. Studies of photos and videos indicate that the meteor was first seen when it was about 90 km above the ground. Its disintegration began about 11 seconds later at an altitude of 23 km (75,000 feet).

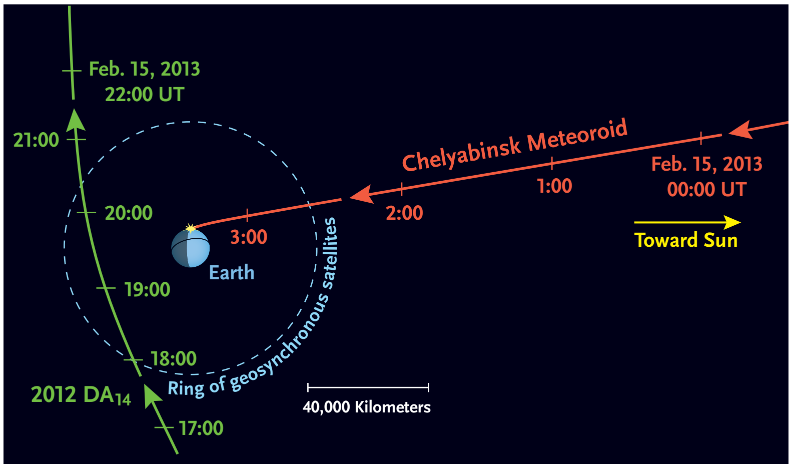


S&T: GREGG DINDERMAN (2)



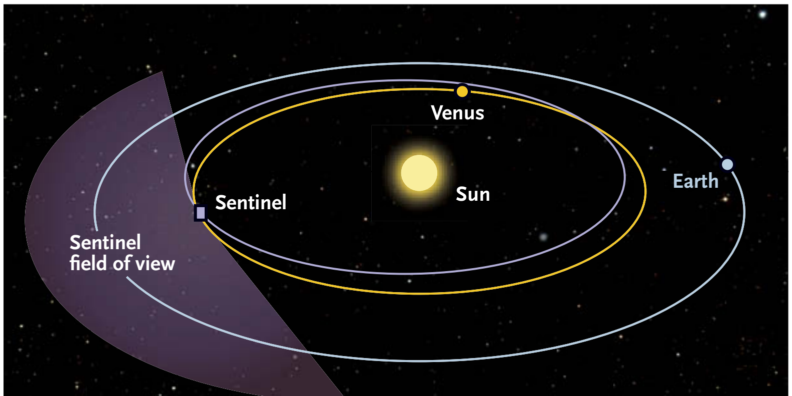
S&T: GREGG DINDERMAN

ORBITS The Chelyabinsk impactor had an eccentric orbit that carried it into the asteroid belt. Asteroid 2012 DA_{14} follows an orbit very similar to Earth's. DA_{14} will continue to have close encounters with Earth and may someday hit.



S&T: GREGG DINDERMAN

INCOMING! The Chelyabinsk impactor came from a different direction and about 16 hours earlier than 2012 DA_{14}, meaning that it was physically impossible for the two objects to be related. The Chelyabinsk meteoroid approached Earth from the direction of the Sun, which precluded any opportunity to observe it in the days prior to impact.



S&T: LEAH TISCIONE

SPACE SENTINEL Ball Aerospace and the B612 Foundation are partnering to build a privately funded wide-field infrared telescope known as Sentinel, which will be optimized to discover small asteroids in near-Earth space.

so faint that the largest asteroid survey telescopes, which can detect objects as faint as magnitude +24 under ideal dark-sky conditions, would not have seen it until just two hours before impact. But when Cooke included the fact that the meteoroid was in the daytime sky near the Sun in the days before impact, it became obvious that we never had a chance to see it coming.

What about future events of similar magnitude? Can we develop the capability to routinely detect such small objects and perhaps even have the technology in place to prevent their impact? And is it even worth the cost?

We do, of course, occasionally spot objects this size during close approaches in the course of our ongoing surveys. But those surveys are currently designed to meet the 1992 Spaceguard Survey Report goal of finding 90% of near-Earth objects larger than 1 km; they only serendipitously catch smaller objects during favorable viewing circumstances. With the Spaceguard goal now effectively achieved, we have eliminated most of the risk from global-scale, civilization-ending asteroid impact events during our lifetimes and the lifetimes of our grandchildren. We're now shifting attention to smaller potential impactors. But how do we decide how small is small enough?

To address these questions, NASA and the impact-hazard community have performed a cost/benefit analysis. How does the cost of detecting and preventing the impact of objects of a particular size match up against the cost of the damage and loss of life that would be incurred if one of those objects were to impact a populated area? Even though its impossible to assign a value to human life, scientists have done their best to weigh the tragic consequences from impacts of objects as a function of size, the frequency of such impacts, and the cost required to survey any given size of potential impactor to 90% completeness.

From these calculations, NASA's Near-Earth Object Program is focusing its efforts on finding 90% of the estimated 100,000 near-Earth objects larger than 140 meters across, using a number of ground-based telescopes either in operation now (such as those used by the Catalina Sky Survey, Spacewatch, and LINEAR) or in the development or planning stages (Pan-STARRS and LSST). Such a survey will also detect a fair number of smaller objects, but only a very small percentage of the estimated 80 million objects similar in size to the Chelyabinsk asteroid. Clearly, we have a lot of work to do.

While that search is ongoing using ground-based telescopes, several studies have concluded that a space-based wide-field infrared telescope would significantly speed things up. The nonprofit B612 Foundation and Ball Aerospace & Technologies Corporation are in the design and early development phase to build and operate just such a telescope with private funding (*S&T:* October 2012, page 13). Their Sentinel spacecraft, to be launched in 2017–18 and operated from my hometown of Boulder, Colorado, will survey near-Earth space from a Venus-like orbit around the Sun, which will significantly improve the efficiency of NEA discovery during its 6.5-year mission. Sentinel will survey 165 square degrees of sky every hour using its 5- to 10.4-micron infrared detector. Like its ground-based telescopic cousins, Sentinel will also discover many smaller NEAs down to 30 meters across, increasing the chance of cataloging some Chelyabinsk-size impactors long before their terminal approach.

Like the 1994 impact of Comet Shoemaker-Levy 9 into Jupiter's atmosphere, the Chelyabinsk event provided a particularly alarming wake-up call that we indeed live in a cosmic shooting gallery, and that asteroids, even tiny ones, pose a threat. The Russian meteor serves as a stark reminder that, behind the statistical analyses and numerical models, people going about their daily lives are the reason we're in the business of watching the skies. ✦

***Dan Durda** is a Principal Scientist at the Southwest Research Institute in Boulder, Colorado, where he studies the evolution of asteroids and the effects of their impacts on Earth. He is also a member of the B612 Foundation's Board of Directors and an accomplished artist and pilot.*

A DIFFERENT KIND OF EXPLOSION

The demise of the Chelyabinsk bolide was caused by a very rapid transformation of kinetic energy to heat and vapor. The first structural flaws to be exploited by the crushing pressure of entry caused some initial fragmentation that immediately increased the drag and pressure of the resulting pieces. This, in turn, made it easier for those pieces to break up, causing a rapid runaway disintegration.

The booms heard on the videos came from the ballistic shock of the entering object and its subsequent fragments (like an aircraft sonic boom), and the shock from the intense mass loss and vaporization associated with the terminal airburst. The fireball vapor expanded supersonically and produced an even more intense boom than the ballistic shock alone. Earth's atmosphere is quite thin and fragile compared to those of several other planets in the solar system, but it effectively shields us from impacts of house-size rocky asteroids such as this one, and even larger objects up to about 100 meters in diameter.

9:44:03

MARAT AHMETVALEEV