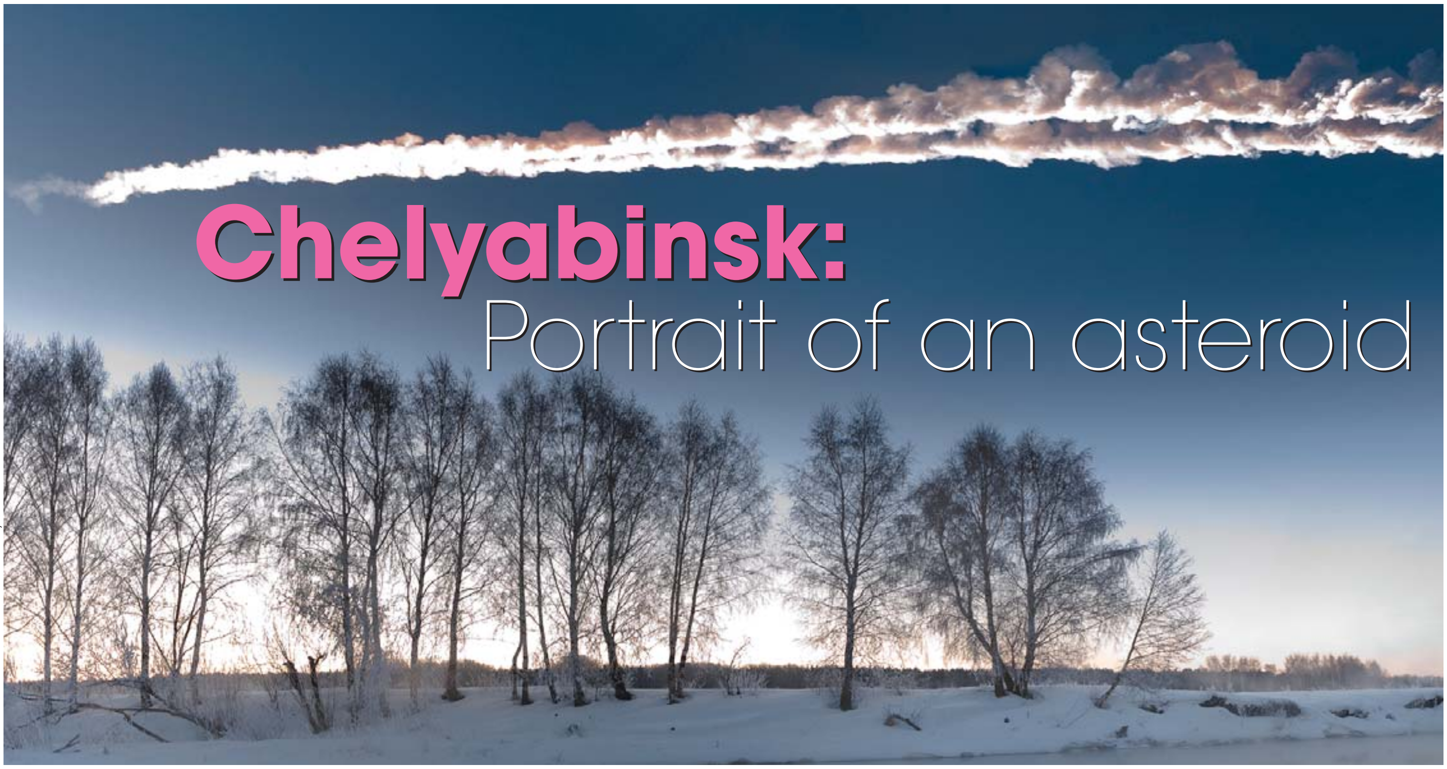

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Chelyabinsk: Portrait of an asteroid

Video and audio from hundreds of smartphones and dashboard cameras combined with seismic, acoustic, and satellite measurements provide the first precise documentation of a 10 000-ton asteroid explosion.

On 15 February 2013, 100 km above the snow-covered Russia–Kazakhstan border, a 4.5-billion-year-old relic of the solar system pierced Earth's atmosphere and began a fiery descent toward the surface. Moving in excess of 19 km/s (faster than Mach 60), it crossed over the glaciated and kettle-rich plains of Kurgan and Chelyabinsk Oblasts, trailed a pair of smoky, iridescent plumes, and repeatedly shed debris before abruptly decelerating and exploding in a final half-megaton detonation a little more than 15 seconds later.

The asteroid passed about 40 km south of the Chelyabinsk city center. It blasted residents with a shock wave from the explosion above the countryside and hammered them with repeated sonic booms from trailing fragments. A few rocky remnants continued to move westward, the smallest on paths that were altered by the wind as they fell; the largest landed 30 km farther in Lake Chebarkul at the foot of the Ural Mountains. The event was the most dramatic near-Earth asteroid airburst since the 1908 Tunguska impact blast in Siberia.

Source of the debris

The speed of whatever collides with Earth's atmosphere depends on its orbit, which in turn depends on its source. The impactor's entry at 19 km/s means that it came from the asteroid belt between Mars and Jupiter, not from a ballistically launched missile, whose speed is less than 11.2 km/s; a short-period comet, with an average speed of 35 km/s; or a long-period comet with an average speed of 55 km/s. As investigators began retracing the path of the meteor that blazed across the sky, their reconstructed orbit bore out that provenance.

The altitude of the blast suggested the object was relatively small and weak. In the past, showers of meteorites have been produced by so-called brecciated, or fragmented, asteroids, and it was likely that Chelyabinsk's was made of such material. A quick assessment of the energy of the airburst, when factored together with the observed velocity and assumed density of the impacting material, suggested an object about 20 m in diameter. Although all of those parameters have been refined with additional analyses,[1–3] 20 m remains a good round-number estimate for its size.

The meteorite shown in figure 1 and many others were collected by local residents within days of the airburst. The debris is generally light colored, intensely fragmented, and crosscut with veins of jet-black material. The black material experienced high-pressure shock and was partly melted—evidence of a preexisting collisional history on a small planetary body, which is often called a planetesimal or the parent body of the meteorite. The juxtaposition of highly shocked and less shocked (light-colored) material is a hallmark of impact-cratering processes on asteroids, planetesimals, and any other solid-surface planetary body.

The Chelyabinsk meteorites range in size from

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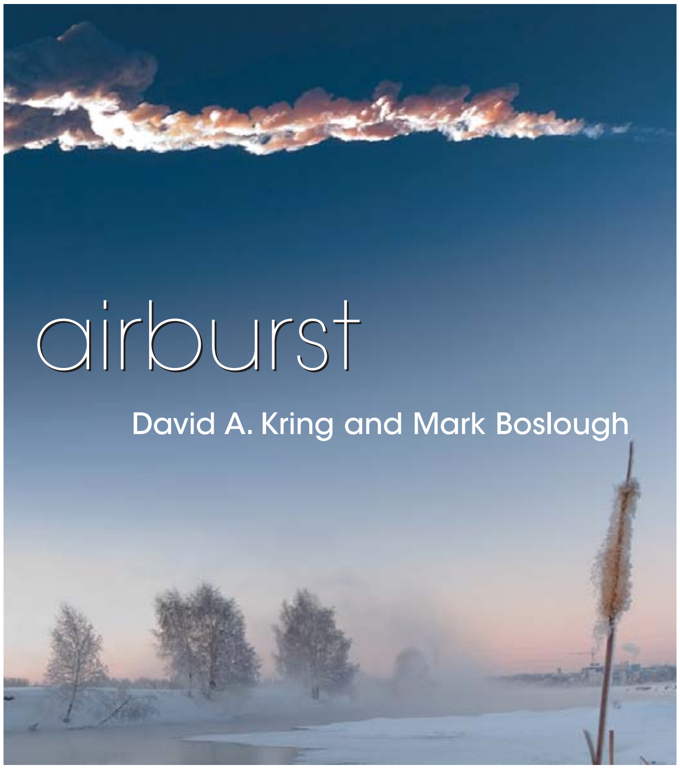

airburst

David A. Kring and Mark Boslough

dust particles to a 1.5-m boulder. Chemical and petrologic analyses indicate the meteorites are in a class called ordinary chondrites, the most common types of meteoritic material to hit Earth. Ordinary chondrites are composed mostly of stone (mixtures of silicate and oxide minerals), but they also contain small amounts of iron, nickel metal, and sulfides. There are three groups of ordinary chondrites, each with slightly different chemistry: H chondrites, which are high in iron; L chondrites, which are low in iron; and LL chondrites, which contain low total iron and low metal. Ordinary chondrites represent different planetesimals that once existed between the orbits of Mars and Jupiter.

Ancient worlds

Those planetesimals have a remarkable history. They are called chondritic bodies because they contain chondrules, millimeter-size spherules that formed in the solar nebula—the disk of dust and gas that surrounded the proto-Sun 4.56 billion years ago. The spherules have the same textures as igneous rocks, indicating they were once molten droplets of silicate, metal, and sulfide material produced by intense, high-temperature nebular storms before they cooled and accreted to form small planetary bodies.

The compositions of minerals in the meteorites—the silicates olivine and pyroxene and the metal alloy kamacite—can be used to determine the specific planetary source of the Chelyabinsk samples. Those analyses indicate the meteorites are related to the LL chondrites. The group is not uncommon: Some 40 000 ordinary chondrites populate meteoriticists' collections and nearly 6000 of them have LL-chondrite affinities. In addition, in 2010 the Japan Aerospace Exploration Agency returned samples from the Itokawa near-Earth asteroid and showed that it, too, has LL-chondrite affinities. Pictured in figure 2, the Itokawa asteroid is 540 m long and contains many boulders similar in size to the Chelyabinsk asteroid. Both objects, however, are small compared with the original LL-chondrite parent body, which is estimated to have been at least 100 km in diameter. (It is also generally assumed that all LL-chondritic materials come from the same parent body, though the possibility of multiple parent bodies cannot yet be dismissed.)

The interior of that parent did not get hot enough to melt, but the deeper material was nonetheless altered by the heat given off from radioactively decaying isotopes like short-lived aluminum-26. The degree of thermal metamorphism that affected the chondrules in the Chelyabinsk samples suggests what became the asteroid was initially buried several kilometers beneath the surface of the LL-chondrite parent.

Collisional evolution

Numerous studies have shown that the parent had an extensive collisional history over the past 4.5 billion years.[4] The collisions heated and, in some cases, melted portions of the parent, which reset the radiometric ages in those areas. Several meteoritic samples were affected by one or more impact events about 4.20–4.35 billion years ago that reset their ages. Two additional meteorites have impact ages of 3.9 billion years, which corresponds to a period of collisional history first recognized among samples collected by Apollo astronauts on the Moon. That period of bombardment was initially called the lunar cataclysm, but we now understand that the bombardment affected the entire inner solar system.

There is a dearth of impact ages among LL chondrites over the next 2 billion years, and only a few ages are indicative of impact events during the past billion years. In general, the collision rate has decreased as the solar system has aged and material has been swept up by the larger planets. Small but abrupt increases in the impact flux may occur, however, following the catastrophic breakup of a minor planet or large asteroid. That type of event appears to have occurred as recently as 500 million years ago when an L-chondrite parent body broke up and produced a large number of meteorites that found their way to Earth shortly thereafter.

The Chelyabinsk samples fill in other details about the collisional evolution of the LL-chondrite parent body. According to uranium–lead and lead–lead isotopic analyses of the black shock-melted material, the sample was affected by an impact event about 30 million years after the solar nebula formed,[5] after 115 million–125 million years,[3,6] or both. Thus Chelyabinsk provides evidence of collisions affecting the LL chondrite at the same time the proto-Earth was still accreting and before the Earth–Moon system had formed (see the article by Robin Canup in Physics Today, April 2004, page 56). The argon–argon isotopic system was also reset, but by a much younger event that occurred only 29 million years ago.[7] Analyses of other cosmogenic radionuclides indicate that the surface of the Chelyabinsk asteroid was exposed to cosmic radiation about 1.2 million years ago,[8] which suggests yet another collision or fragmentation event. Based on the dynamical lifetimes of debris that size, Chelyabinsk probably entered a gravitational resonance in the

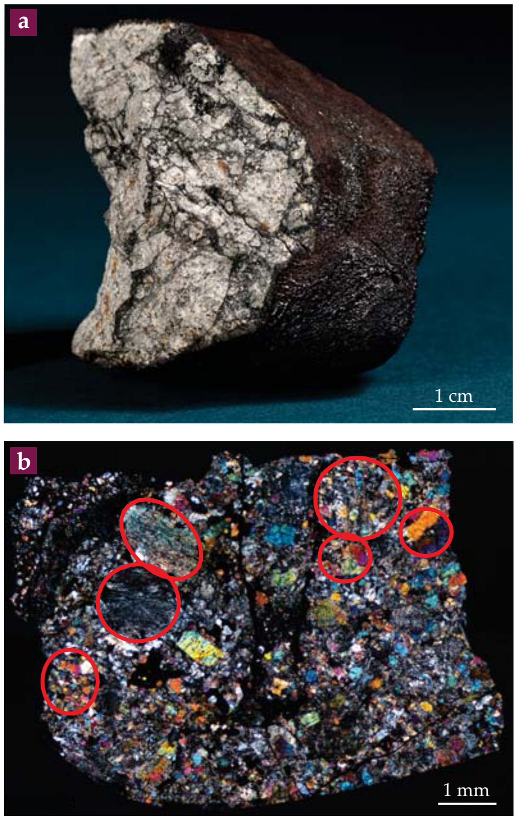

Figure 1. The Chelyabinsk asteroid was a fragmented, metal-poor rock heavily damaged during its history wandering the solar system. **(a)** One of its meteorites has been broken open to show its fragmented interior on the left side and the dark-colored crust on the right side. The crust was produced when the surface was melted as it passed through the atmosphere. (Image courtesy of Svend Buhl/Meteorite Recon.) **(b)** A microscopic view of the interior of the meteorite. A few chondrules—molten droplets that crystallized in the solar nebula—are circled among various mineral grains. Black shock veins (the two near-vertical lines) penetrate the center of the sample and are also evidence of prior melting. (Courtesy of Amy L. Fagan.)

main asteroid belt between the last two events. That increased its orbital eccentricity and put it into the Earth-crossing orbit that led to its final fate.

The strength of near-Earth asteroids appears to be limited by structural flaws,[9,10] such as the fractures and material contrasts produced by the repeated collisions that Chelyabinsk underwent. Observations of other falling meteorites indicate that fragmental asteroids tend to produce meteorite showers. Not surprisingly, the surviving samples of the Chelyabinsk asteroid are intensely fragmented and crosscut with impact melt veins generated by older collisional events. The Chelyabinsk near-Earth asteroid came with built-in weaknesses.

Entry, deceleration, and breakup

The Chelyabinsk asteroid first felt the presence of Earth's atmosphere when it was thousands of kilometers above the Pacific Ocean. For the next dozen minutes, the 10 000-ton rock fell swiftly, silently, and unseen, passing at a shallow angle through the rarefied exosphere where the molecular mean free path is much greater than the 20-m diameter of the rock. Collisions with molecules did nothing to slow the gravitational acceleration as it descended over China and Kazakhstan. When it crossed over the border into Russia at 3:20:20 UT and was 100 km above the ground, 99.99997% of the atmosphere was still beneath it.

Because the asteroid was moving much faster than air molecules could get out of its way, the molecules began to pile up into a compressed layer of high-temperature plasma pushing a shock wave forward. Atmospheric density increases exponentially with depth, so as the asteroid plunged, the plasma layer thickened and its optical opacity rapidly increased. About one second later, at 95 km above the surface, it became bright enough to be seen from the ground. That was the first warning that something big was about to happen.

For the better part of 10 seconds, the asteroid pushed through the air as a rigid body, moving at a shallow angle—about 17° from the horizon—and descending 1 km for every 3 km of horizontal flight. At that altitude, the air density is so low that the dynamic pressure, even at 19 km/s, is too small to deform or break a rock—even one as weak and damaged as Chelyabinsk. Like the fastest supersonic jet (but 20 times as fast), the asteroid generated a bow shock that wrapped around it into a conical shape. The cone was very slender, blunt at the front end, and more like a cylinder surrounding the wake. The bow shock was invisible from the ground, but the meteor got steadily brighter as the plasma layer continued to thicken. The ionized air also radiated energy backward toward the asteroid, which absorbed it in a thin layer that vaporized and was swept away by the flow into the trailing wake.

At about 45 km above Earth's surface, the nature of the entry began to change. The dynamic pressure built up to 0.7 MPa—not enough to slow the asteroid but enough to exceed its strength. Within a couple more seconds, below 40 km, pressure on the now-fracturing asteroid increased past 1 MPa, breaking it into a number of large fragments. As the pressure grew exponentially, the process cascaded and formed ever-smaller fragments that rapidly increased the total surface-to-volume ratio. As fragments in the dense collection ablated, the hot gas between them began to build up.

The pressure buildup, in turn, caused an outward expansion that further increased the surface area on which the rising aerodynamic drag could act. The only possible result of such a chain reaction is a massive explosion from the abrupt conversion of the asteroid's kinetic energy into heat and pressure. Even as that massive explosion was under way, with half the original kinetic energy lost, one relatively unbroken main fragment, trailed by about 20 boulders, continued downrange, with a barely measurable loss of speed as it descended below 29 km.

The cascading breakup continued as the mass

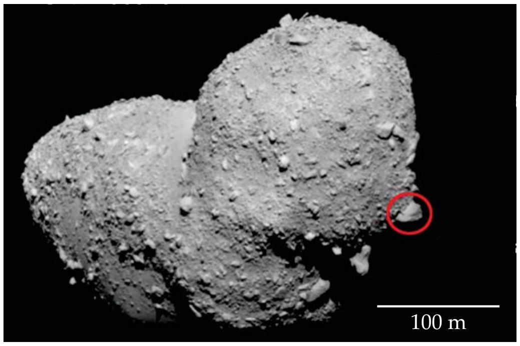

Figure 2. The Itokawa near-Earth asteroid is 540 m long and compositionally related to the Chelyabinsk asteroid. Both are assumed to come from the same LL-chondrite parent body that was originally 100 km or more in diameter. Boulders on Itokawa, such as the one circled, are similar in size to the 20-m-diameter Chelyabinsk. Many other objects like Chelyabinsk and Itokawa are thought to occupy near-Earth orbits. (Photograph courtesy of the Japan Aerospace Exploration Agency.)

and energy of the remaining fragments were spent in the deeper, denser parts of the atmosphere until only one prominently visible piece remained to pop out, like a spark from the front of the explosion. That piece was visible until it slowed too much to generate a plasma, stopped ablating, and blinked out. It continued to fall as a ballistic missile in "dark flight" at terminal velocity until it punched a hole in the ice of the frozen Lake Chebarkul. The 1.5-m-wide boulder dredged up from the muddy lake bottom eight months later was the largest Chelyabinsk meteorite found.

Much of the evidence for the fragmentation cascade and the determination of altitude comes from the dramatic audio portions of recordings of the event. At some locations, the main blast is heard, followed by a long sequence of weaker booms, each generated by its own fragment or fragmentation event.

Bow shock or explosion?

Two processes can generate strong air shocks: the passage of a supersonic body and the detonation of an explosive charge. The first process is normally associated with a high-speed jet that generates a conical bow shock along the flight path. When the wave intersects the ground, a sonic boom moves underneath the aircraft. Under textbook conditions, the intensity of the boom is constant along the ground track and decays laterally, which gives the appearance of cylindrical symmetry.

An explosion, on the other hand, is a point source. A purely explosive airburst, like the detonation of a bomb, radiates energy in all directions; it generates a spherical air shock with a peak pressure on the ground directly below and decays radially.

An asteroid airburst does not fit neatly into either category. At the beginning of its flight, the asteroid acts more like the supersonic aircraft, and at the end it acts more like an explosion. In Chelyabinsk, the energy deposition that led to the explosion took place in stages and was spread out over a long distance because of the shallow entry angle. Energy was deposited at linear densities greater than 1 kiloton per kilometer and rose to a peak value of 80 kt/km; most of the energy deposition occurred at altitudes from about 38 km down to about 23 km. It took about 4 seconds for that to happen, during which the asteroid left a 50-km-long wake of hot, expanding air and ablation products.

That slug of energetic material carried much of the original momentum of the asteroid and continued to push its way downrange as it exploded—still moving much faster than a fighter jet. Because of the long distance over which energy was deposited, the geographic pattern of the shock intensity, inferred from observed damage, looked more like an inclined cylindrical bow shock than a spherical explosion.

One might assume that a rare event like this can be generalized. But not all asteroids enter at such a shallow angle, and not all asteroids break up in stages over a long distance. There is no reason to think that a steeply entering asteroid could not break up and deposit most of its energy over a much smaller distance and yield a shock pattern on the ground that looks more like a point-source explosion. In fact, the appearance of the tree-fall pattern at Tunguska in 1908 indicates a more abrupt explosion.

Damage on the ground

Much of our understanding of airburst damage, including the concept of an "optimum height of burst" for which damage from a point-source explosion is maximized, comes from the literature on nuclear weapons effects. The damage is estimated by the area on the ground that experiences an overpressure above some threshold value. A lower-altitude source concentrates its energy into a smaller area but falls off more rapidly at a distance. The blast from a higher-altitude source diverges more before it reaches the ground. It may affect a larger area but is weaker.

The Chelyabinsk airburst caused damage out to 120 km from the supersonic path.[3] In the city of Chelyabinsk, glass was shattered and broken in more than 3600 apartment and commercial buildings

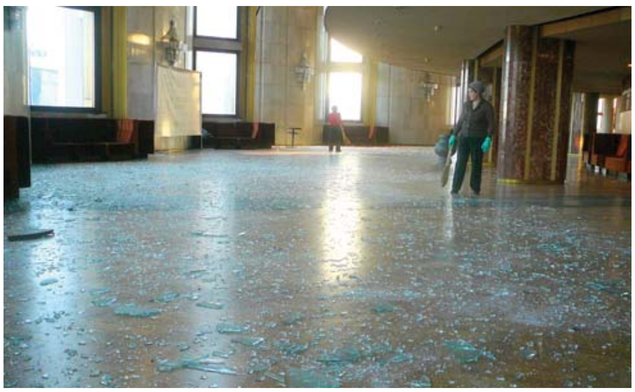

Figure 3. The airburst damaged buildings throughout Chelyabinsk, shattering windows and, in one case, causing the wall of a zinc factory to collapse. This photograph was taken inside the glass-strewn lobby of the local drama theater. (Photo by Nikita Plekhanov.)

(see figure 3), people were blown off their feet, and well over 1000 injuries were reported. Based on pre-Chelyabinsk scaling, blast damage over an area from 100 km^2 to 1000 km^2 is expected for a half-megaton explosive event.

The damage could have been far worse for two main reasons: The explosion occurred well above its optimum height of burst, and it was not a point-source but a "line-source" explosion. For some combination of entry angle and strength, an asteroid can effectively deliver its energy at its optimum height of burst. Fortunately, that did not happen in Chelyabinsk.

Plumes and double trails

The 1994 impact of comet Shoemaker–Levy 9 on Jupiter yielded enormous insight on hypervelocity-airburst physics and has informed much of what we understand about the threat from space. For example, the phenomenon of ballistic plumes, predicted just prior to impact,[11] was observed for the first time. Large parcels of air and comet debris were ejected above the cloud tops to an altitude of 3000 km before smashing back into Jupiter's atmosphere. When the comet entered it broke up and was ablated by much the same process observed in the Chelyabinsk event, but it approached at the much steeper angle of 45°. Its wake was more vertical and better aligned with the atmospheric density gradient, so the expanding linear explosion was boosted backward along the same path into a suborbital trajectory. Numerical modeling suggests that smaller airbursts on Earth, such as the one at Tunguska, should launch similar ballistic plumes to altitudes greater than a few hundred kilometers.[12] Such airbursts would thus pose a risk to satellites.

Because the Chelyabinsk asteroid arrived on a shallow-angle trajectory, such a plume did not form. However, one of the most stunning and unexpected sights was the splitting of the wake into bilateral, contrarotating vortices containing asteroid vapor that condensed and made them visible, separated by a thin band of clear air with spots of blue sky. Preliminary models suggest that the splitting was driven by buoyancy. Immediately after entry, the wake approximated a very hot cylinder of expanding gas. The center of the cylinder rose faster than the edges, which caused both sides of the rising parcel to rotate outward in a way analogous to the toroidal vortex surrounding the buoyant fireball in a nuclear explosion. The photograph on page 32 illustrates the phenomenon seconds after the asteroid passed overhead, and figure 4 outlines the trails' time evolution.

Impact airbursts versus impact craters

The Chelyabinsk airburst was roughly two orders of magnitude more energetic than the approximately 10-kt Sikhote-Alin asteroid event of 1947 and roughly an order of magnitude less energetic than the 3- to 15-MT Tunguska blast of 1908. The considerable uncertainty in estimates of the energy of those and other relatively small impact events makes it difficult to quantify future hazards. For that reason, the Chelyabinsk impact event is incredibly important: It produced the first high-precision values for the energy of a blast—see the box on this page—and the ground damage it caused.

Fortunately, Earth's atmosphere screens most objects from reaching the surface with cosmic velocities. Some objects are large enough and strong enough, however, to penetrate deeply into the atmosphere before exploding in an airburst or reaching Earth's surface to produce a crater.

Although stony near-Earth asteroids dominate the impact flux, nearly all of the smallest craters on Earth were produced by iron asteroids. Small stony asteroids, like Chelyabinsk, preferentially produce airbursts before reaching the ground. Small iron asteroids, however, survive atmospheric passage and cause explosions at the surface that excavate impact craters. The most famous is the 49 000-year-old Barringer meteorite crater in northern Arizona. That breathtaking impact site was produced by a roughly 30-m-diameter iron asteroid, remnants of which are known as the Canyon Diablo meteorites.

Although the Barringer crater's 1.2-km diameter is relatively small compared with some of Earth's largest, such as the dinosaur-killing Chicxulub impact crater, 180 km in diameter, the kinetic energy of Barringer's impact is sufficient to destroy a modern city.[13] The pressure pulse and airblast can be devastating. The blast was immediately lethal for human-sized animals within 6 km of it. Those within 10–12 km suffered severe lung damage from the pressure pulse alone. Winds in excess of 1500 km/h were produced within the inner 6-km-diameter zone and still exceeded 100 km/h at radial distances of 20 km.

Mitigating the impact hazard

With Chelyabinsk, scientists can, for the first time, link the damage from an impact event to a well-determined impact energy in order to assess the future hazards of asteroids to lives and property. Using methods of quantitative risk assessment, one can estimate the range of probabilities of various events and the consequences of those events. Asteroid impacts represent a classic low-probability, high-consequence risk: very unlikely but potentially catastrophic.[14] Moreover, the greatest contributor to long-term risk is from the most improbable but

Kinetic energy of the Chelyabinsk event

Most of the kinetic energy released during the collision of the Chelyabinsk asteroid with Earth was produced during its midair explosion. To estimate the size of the explosion and thus the kinetic energy, researchers used four sources:[2] the energy of infrasonic airwaves from the International Monitoring System of the Comprehensive Nuclear-Test-Ban Treaty (see the article by Matthias Auer and Mark Prior on page 39 in this issue of PHYSICS TODAY); the energy of Rayleigh "ground roll" seismic waves generated when the airburst shock wave hit Earth's surface; the energy of radiated light derived from more than 400 video camera and smartphone images; and radiated energy measured by US government satellites.

The total energy yield determined by those sources ranged from the explosive equivalent of 200–990 kilotons of TNT, where 1 kt = 4.184×10^{12} joules. The best impact-energy estimate in that range is 500 ± 100 kt, which is about 25 times the yield of Trinity, the first atomic explosion.

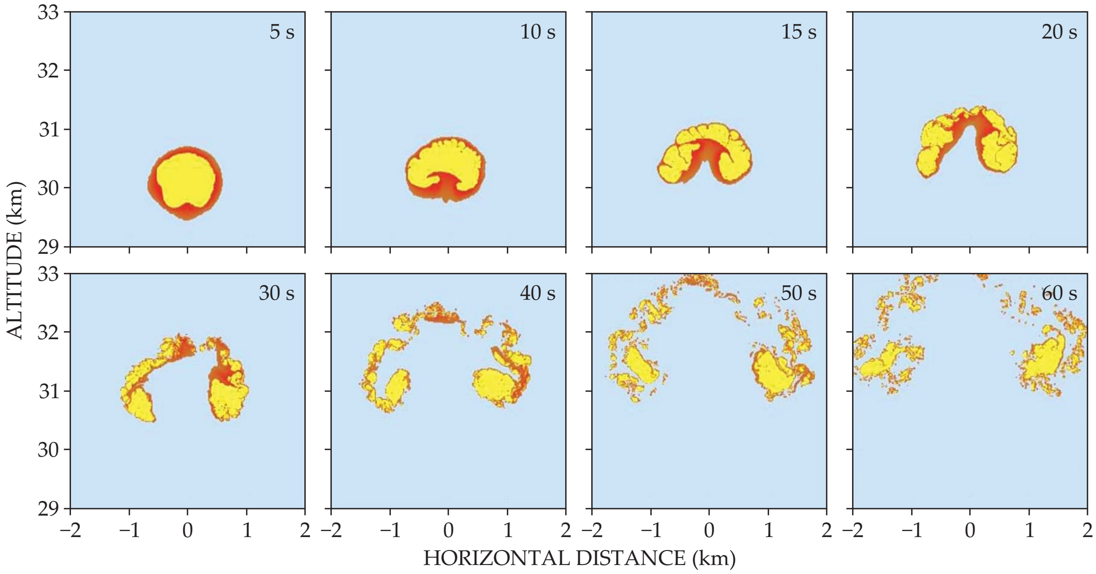

Figure 4. This computational simulation of the evolution of the asteroid's atmospheric wake was adapted from code developed at Sandia National Laboratories for modeling nuclear explosions. The simplified two-dimensional model assumes that energy is deposited in a horizontal cylinder of air, which expands, rises buoyantly, and separates into two contrarotating vortices by a mechanism similar to that which forms a toroidal vortex in the mushroom cloud from a nuclear airburst. Each panel is a cross-sectional slice at the same location along the meteor's path, for different times since the energy was deposited. Temperatures range from several hundred kelvin (red) to a few thousand kelvin (yellow). (For a movie of the simulation, see the online version of this article.)

largest impacts, which can lead to civilization collapse or even human extinction. Fortunately, the largest are also the easiest to discover, and about 90% of nearby objects greater than 1 km in diameter have been cataloged. And because none are on a collision course, the assessed risk from large asteroids has dropped since the survey began by more than an order of magnitude.

The remaining risk comes from smaller, crater-forming impacts and airbursts. Most of the objects in that size range remain undiscovered, and the impact community's assessment of the airburst risk has increased for two reasons. First, the vast majority of asteroids enter the atmosphere at steeper angles than Chelyabinsk and do more damage on the ground than nuclear explosions of the same energy;[15] our understanding of the risk assessment has progressively increased since the original assessments of the early 1990s. Second, the occurrence of the Chelyabinsk event and other, remotely detected airbursts over the last few decades has caused some scientists to question astronomically based estimates of the frequency of large airbursts. According to some studies, that frequency may be underestimated by as much as an order of magnitude.[2]

The impact community's asteroid risk mitigation strategy has consisted of three parts: Understand the impact process through experiments, field studies of craters, laboratory analyses of meteorites, and computer modeling; survey, track, and characterize asteroids in Earth-crossing orbits; and develop the means to deflect an asteroid, if one is found with sufficient warning on a collision course.

As a small object that approached Earth from the Sun, Chelyabinsk struck our planet with no prior warning. The desire for some warning about future events, particularly if they are more energetic, implies a fourth component to the strategy—that scientists develop the tools required to evaluate the consequences of an unavoidable impact and develop rapid communication protocols with the appropriate civil authorities. They would be the ones having to make some difficult decisions.

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