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The threat from cosmic flotsam

Mark Boslough

A power-law distribution of asteroid impacts on Earth spans 13 orders of magnitude in energy. The risk is dominated by low-probability but high-consequence events.

Since its birth 4.5 billion years ago, our home planet has been flying through a sea of debris. The Sun formed when the dense inner part of a nebular disk collapsed and lit itself up by nuclear fusion. Over the following millions of years, most of the solid pieces remaining were pulled together by gravity and conglomerated into planets. As the growing worlds gobbled up more mass, their gravitational influence increased, until most of the original source material was depleted. The leftover bits of solid matter eventually became what we know as comets and asteroids.

The solar system evolved into a reasonably stable configuration, but it never fully settled down. Some objects were big enough to trap their own radioactive heat, and they developed planet-like structures with metallic cores, mantles, and crusts. Eventually, some of those planetesimals slammed into one another and broke up, and the impacts created all sizes of asteroids with different compositions. Over the eons, asteroids continued evolving, with their orbits ever changing through near encounters with planets. Like Earth-bound geology, the evolution has been a slow, never-ending process.

Gravitational encounters, impacts, and other forces have led to a distribution of orbits. The main asteroid belt lies between Mars and Jupiter, but not all asteroids reside there. Many have ended up in the inner solar system and have orbits that cross or pass close to Earth's. They are called near-Earth objects (NEOs), and depending on their paths and locations, some may pose an impact risk.

Cosmic violence shapes the distribution

The ongoing grinding, smashing, and breaking of asteroids have also resulted in an emergent phenomenon: a power-law size distribution. Clark Chapman and David Morrison, in their 1989 book *Cosmic Catastrophes*, described the nonuniformity of asteroid sizes as an inherent property of the 3D universe. The chances of collisional fragmentation of a given asteroid depend on how large it is. When a big asteroid breaks up, the total surface area of material increases, and the more numerous fragments have a higher total chance of being involved in other collisions, which would cause them to break up into even smaller pieces.

Figure 1 shows the size distribution of near-Earth asteroids. The biggest ones, shown on the right-hand side of the graph, collide with Earth every few hundred million years on average. A smaller one, about 10 km in di-

ameter, formed the Chicxulub impact crater when it wiped out the dinosaurs 66 million years ago and changed our planet forever. The probability of a similar impact catastrophe in a given year is about one in a hundred million, the reciprocal of the mean impact interval. That's greater than the odds of winning a Powerball jackpot.

At the other end of the spectrum are objects a few meters in diameter, which US government sensors observe exploding in the atmosphere as fireballs, also called bolides, several times every year. They are frequent but inconsequential in terms of risk—the most likely victim being a person, car, or house.

On the continuum of asteroid size, a threshold exists in which the explosions are as big as nuclear detonations and close enough to Earth's surface to kill people and destroy infrastructure. They are low-altitude airbursts, like the simulated example shown in figure 2, and are rare on the time scale of human lives. The meteor that fell over Chelyabinsk Oblast, Russia, in 2013 was about 20 m in diameter. It released about

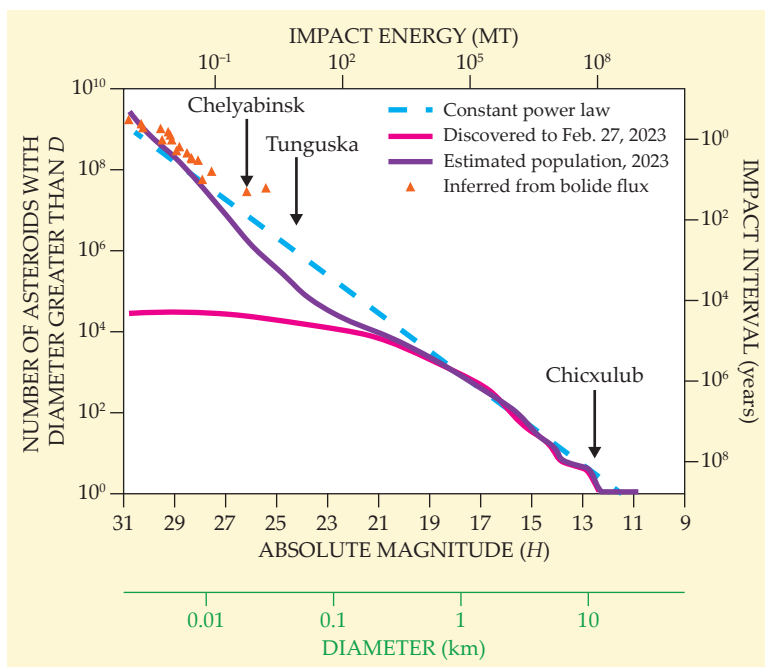


FIGURE 1. NEAR-EARTH ASTEROID size–frequency distribution is shown in units of asteroid diameter D and absolute magnitude H , a measure of intrinsic brightness. Smaller asteroids are dimmer and the hardest to discover, so their discovered fraction gets smaller as the size decreases, resulting in a flattening of the magenta curve. (Courtesy of Alan Harris.)

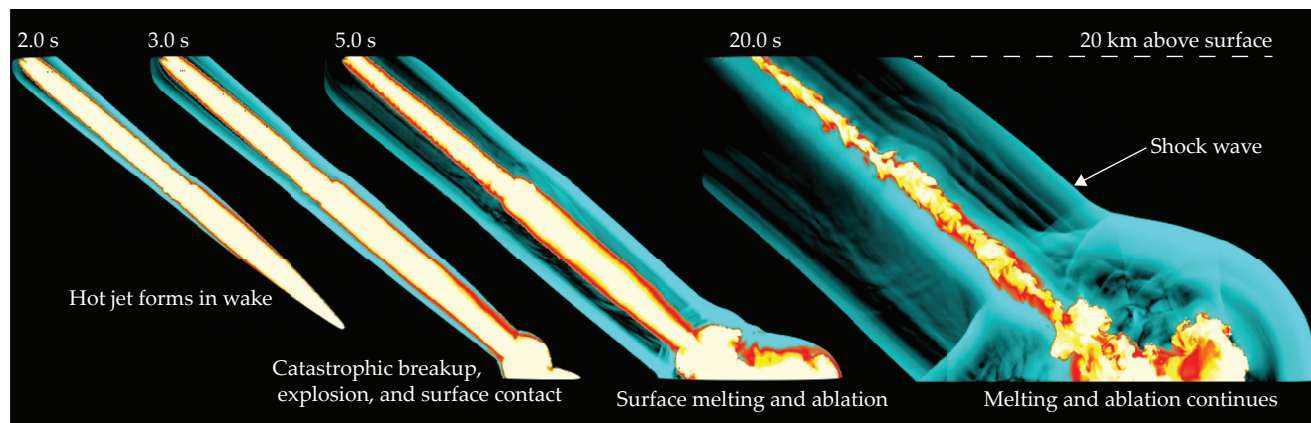


FIGURE 2. A SIMULATION. A 100 m asteroid enters Earth's atmosphere at a 35° elevation angle and traveling 14.2 km/s. It has a 30 megaton kinetic yield and is shown passing beyond a point 20 km above Earth. In my numerical simulations, each frame is one in a sequence, a few seconds apart. (The time in each one is the number of seconds since the asteroid passed the 20 km point.) In the second frame, the airburst occurs 2 km above ground. The resulting vapor jet keeps descending in subsequent frames until it reaches the surface.

a half megaton of explosive energy and injured more than a thousand people (see my article with David Kring, *PHYSICS TODAY*, September 2014, page 32). Airbursts of that size happen once every 50 years on average.

The 1908 explosion in Russia known as the Tunguska event is probably an order of magnitude more energetic (and likely several megatons), but that estimate is uncertain because the event happened at a time and location for which observational and instrumental data are sparse. The best data come from the physical evidence left on the ground, where trees were blown down over an area spanning more than 2000 square km—the size of a large metropolitan area. We can expect events of that size to happen with a mean interval of about 500 years.

Distribution shapes the risk

The first attempt at a quantitative probabilistic NEO risk assessment was published in 1994 by Chapman and Morrison. Their estimates of airburst damage were based on nuclear weapons' effects and scaling laws. But that method breaks down for larger asteroids because such global effects as climate change come into play. Chapman and Morrison extrapolated their estimates up to a global-catastrophe-threshold asteroid size between 0.5 and 3 km in diameter, above which they assumed a quarter of the world's population would die. That estimate provided a crude framework for deciding how to begin reducing the danger.

By integrating their risk curve, Chapman and Morrison estimated a few thousand fatalities per year. That result is counterintuitive because there is no direct evidence that anyone has ever been killed by an asteroid. The risk is dominated by low-probability, high-consequence events. Fatal impacts are rare but expected to kill many people when they happen.

The best way to reduce the risk is to prevent large impacts. Preventing a catastrophic impact requires finding all the NEOs above the global catastrophe threshold, so a survey program was established by a 1998 NASA directive to discover 90% of NEOs greater than 1 km in diameter. Fortunately, there are only about 1000 NEOs of that size. Because they are the biggest and brightest in the sky, they are also the easiest to discover.

Eliminating catastrophic risk with surveys uses the same principle as looking both ways before crossing the street. Situational awareness doesn't by itself change the probability of impact. An NEO will either collide with Earth on some speci-

fied time interval or it won't. Observation creates the opportunity to take preventive action to mitigate the risk if something is discovered to be on a collision course.

The method of choice for planetary defense is to deflect an asteroid from its collision course by sending a spacecraft to collide with it and changing its velocity. That option is available only if the asteroid is discovered well in advance, because there must be sufficient time for the asteroid to drift away from where it would otherwise be at the time it crosses Earth's path.

Astronomical surveys may have reduced our assessment of the likelihood of a global- or continental-scale catastrophe by an order of magnitude, to an estimate of about 100 fatalities per year. Recent advances in hydrocode models, however, suggest that severe airburst effects, which also accompany crater-forming impacts, may have much more severe consequences than we had imagined and that the global catastrophe threshold might be triggered by smaller asteroids than we had thought. So the probability-based reduction in catastrophic risk may have been partially offset by an understanding-based lowering of the catastrophe threshold.

As the risk from larger asteroids shrinks, the relative hazard shifts to small impacts or airbursts that are much more frequent and difficult to avoid. Barring the discovery of a large NEO on a collision course, mitigation methods will shift from deflecting the asteroid to evacuating people from the impact zone, an activity that the Federal Emergency Management Agency and NASA are practicing with exercises involving simulated strikes. A new space-based IR telescope, the *Near-Earth Object Surveyor*, will be an essential tool for reducing the remaining risk and providing early warning.

Additional resources

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