DEATH FROM THE SKY

It wasn't a black hole. It wasn't a UFO. It was an asteroid called Tungusta. Its explosion in 1908 points to the danger of catastrophic impacts on Earth.

By Christopher Chyba

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One summer day in 1908 a little piece of central Siberia vanished. In the midst of a powerful explosion in the atmosphere, over 2,000 square kilometers of forest were suddenly flattened. The explosion snapped trees like match-sticks and devastated wildlife. Ever since, the Tunguska explosion has fascinated scientists and the popular imagination. Long thought to be the result of a glancing blow from an asteroid or another body from the solar system, the Tunguska event is finally getting the critical analysis it deserves.

Eighty-five years after the fact, the Tunguska impact is taking on more significance because understanding it tells scientists about other impacts on Earth, past, present, and future. Will such an impact happen again? Astronomers using the Spacewatch telescope on Kitt Peak near Tucson have begun compiling a catalog of small asteroids whose orbits cross Earth's. Their findings over the past two years have been extraordinary. First, small Earth-crossers — objects smaller than 50 meters in diameter, half the size of a football field — pass close to Earth 10 to 100 times more frequently than scientists previously believed. Second, many of the small Earth-crossers have orbits similar to Earth's. Earth is slowly sweeping up these asteroids in collision after collision.

How much destructive energy do these asteroids have? Quite a bit, it turns out. One of the smallest Spacewatch objects, designated 1991 BA, measures about 10 meters or less in diameter. Yet if 1991 BA struck Earth, the resulting explosion would likely exceed the energy released by either of the atomic weapons exploded over Hiroshima and Nagasaki at the end of the Second World War, each about 20 kilotons of TNT. But we don't need to use nuclear analogies to get a sense of what such an explosion would be like. Our own century has already provided us with several examples.

Revelstoke

Early on the clear night of March 31, 1965, thousands of people in British Columbia and Alberta saw the explosion of a large meteor about 30 km up, somewhere above the town of Revelstoke, 280 km west of Calgary. Canadians heard a detonation as far as 200 km away. An Air Canada pilot reported the event from 800 km away while flying westward over Saskatchewan. Scientists recorded atmospheric pressure waves caused by the blast in Boulder, Colorado. Researchers later analyzed the recordings and found the blast had an energy of about 20 kilotons, about equal to the Nagasaki bomb in 1945.

Yet no one on the ground near Revelstoke was injured, no trees were toppled, and no crater was found. For that matter, despite searches by helicopter and plane, no one found any meteorite fragments, either.

About two weeks later, Canadians Elmer Coats and Alfred Daniels were busily snowshoeing over six feet of powder, heading north from Seymour Arm, an isolated settlement at the top of Shuswap Lake in British Columbia. The men were trapping beavers, working their way to Macpherson Lake, about 10 km away. Scientists had already combed the nearby Monashee Mountains by snowshoe and helicopter, looking without success for evidence of an explosion, and a reconnaissance plane had also turned up nothing.

Then Coats and Daniels happened onto an area of darkened snow on the surface of Macpherson Lake. Suspecting they had found something linked to the explosion, the two beaver trappers behaved just as trained scientists would. At one end of the darkened snow they could see millimeter-sized particles buried deep within the lake ice. They found two such patches of particles and dug down and recovered as much as they could of the first one. They left the other untouched to provide a pristine site for possible later research by a scientific team. When the explorers found a second, similar site about a kilometer away, they treated it the same way. Analysis of the recovered samples, which all together weighed less than one gram, revealed that the Revelstoke object was a carbonaceous chondrite, the most primitive and fragile of meteorite types known. Subsequent searches by helicopter in July and August failed to find more material. Whatever other dust had been deposited was lost as the ice and snow melted .

Had Coats and Daniels not reached the site of the meteorite fall until after the snows had melted, no trace of the Revelstoke object would ever have been found. A 20-kiloton explosion would have occurred, been witnessed by thousands, and left no visible trace. Perhaps in this case the press would even today speculate on the identity of the mysterious Revelstoke object. The supermarket tabloid headlines might read “Revelstoke! Black hole, antimatter, or UFO?”

From Revelstoke to Tunguska

The 1908 explosion over the Tunguska River in central Siberia was closer to the ground and much more powerful than Revelstoke. It released about 1,000 times more energy. Fortunately, the area was sparsely populated. A number of Tungus reindeer herders were thrown to the ground and some tents and cabins were damaged, but as far as we know, no one was killed. No crater was ever found, and no one picked up any meteorite fragments.

The atmospheric shock wave from the explosion circled Earth twice and was recorded on instruments as far away as England. The instruments used to record these pressure waves were predecessors to those used later in the century to estimate the strengths of atomic weapons tests in the atmosphere, so the data can be interpreted in an analogous way. Scientists also captured seismic readings of the ground tremors caused by the explosion. The best estimates we have for the blast energy and altitude of the Tunguska event come from these data.

However, we can also calculate the blast characteristics from the physical evidence on the ground. The explosion created a distinct pattern of treefall around Tunguska, spread over an irregularly shaped area of 40 by 45 km. Soviet expedition members later measured the orientations of some 40,000 fallen trees. All of the toppled trees pointed away from a central location that must have been directly below the point of the explosion. Interpreting the extent and orientation of the treefall pattern, scientists concluded the explosion at Tunguska likely released 10 to 20 megatons of energy somewhere around 8 km above Earth’s surface. This agrees nicely with the characteristics predicted by the atmospheric pressure and seismic records.

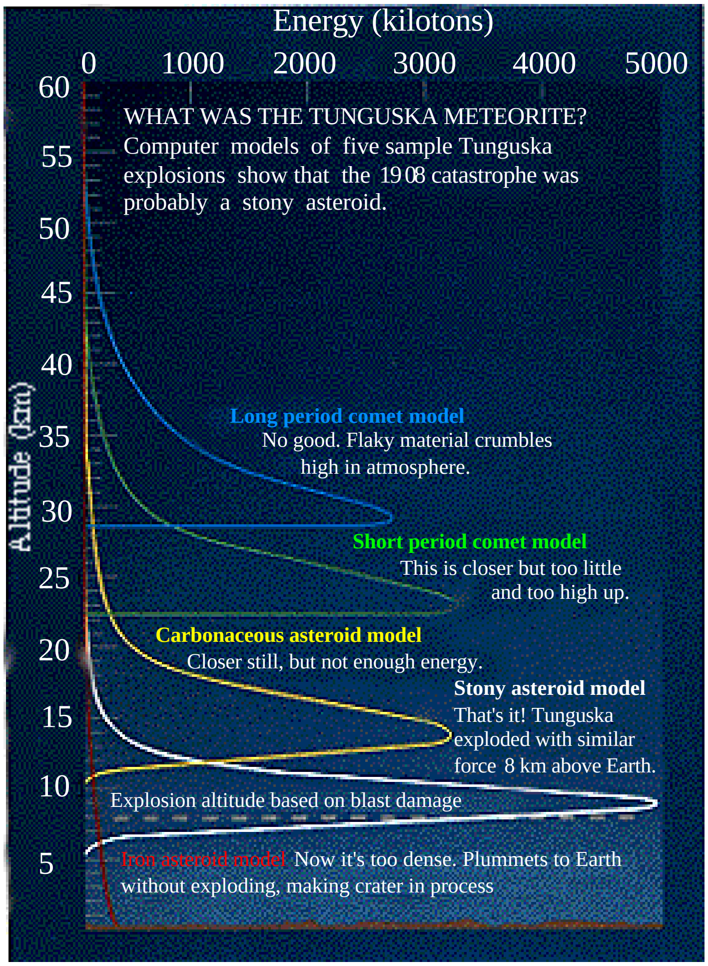
But at the time of the Tunguska event no one made a connection between the atmospheric shock waves and the Siberian explosion. No one correctly interpreted the “light nights” that followed over Western Europe during which sunlight reflected off high-altitude clouds and dust created by the explosion. Outside the local region in Siberia, the Tunguska explosion remained nearly unknown for more than a decade. In the interim, Russia was wracked by world war and revolution. Tunguska could have seemed mild by comparison.

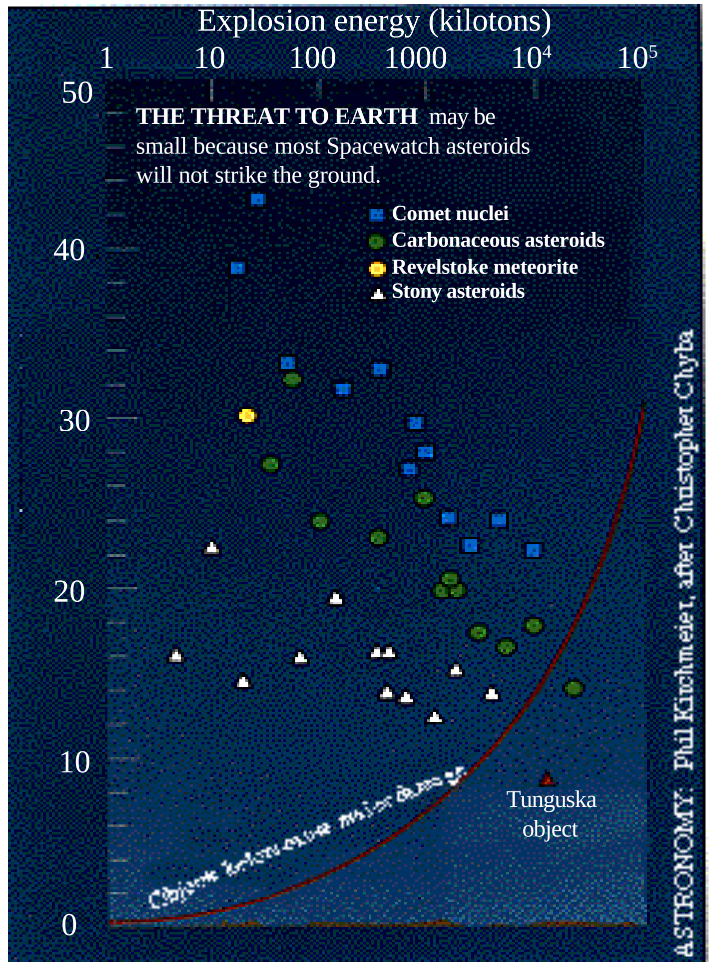
> Russia's Tunguska explosion flattened hundreds of thouands of trees and was recorded on primitive instruments as far away as England. What caused such a spontaneous blast?

“I cannot sort out my chaotic impressions.”

Leonid A. Kulik, a researcher from the Mineralogical Museum of the Russian Academy of Sciences, was the first scientist to reach the site of the Tunguska devastation. In 1921 the academy equipped the country’s first systematic meteorite expedition, led by Kulik, to investigate the sites of many supposed meteorite falls. Before leaving on the expedition Kulik by chance saw a page torn from a 1910 St. Petersburg calendar. The back of this sheet contained part of an article from a 1908 issue of Siberian Life. The article included eyewitness reports of the fall of a great meteorite somewhere near the Tunguska River. Kulik investigated and found that a number of Siberian newspapers contained stories about the fall. Some of them were embellished with fantastic details, and some contradicted others. But something impressive had happened and so in September 1921 Kulik set out by rail to the region of the Tunguska River.

Kulik’s party was ill-prepared for the extensive exploration required to find the exact location of the Tunguska





fall, which lay some 700 km north of the nearest rail line. They didn't attempt it. But Kulik did collect reports from witnesses to the event and distributed questionnaires. He convinced himself that a great explosion of some kind had taken place. Of course Kulik gathered these first reports more than 13 years after the event, and he collected additional reports throughout the twenties. On the basis of this evidence, in 1927 the Soviet Academy of Sciences authorized Kulik to lead the first expedition to the Tunguska site.

The Tunguska meteorite must have been a stony asteroid that exploded with 15 megatons of force 8 km above Earth.

In February 1927 Kulik and an assistant set out from Leningrad. By April, with the help of a Tungus guide named Il'ya Potapovich, they reached the southern boundary of the region of devastated forest. Kulik recorded the scene in his diary.

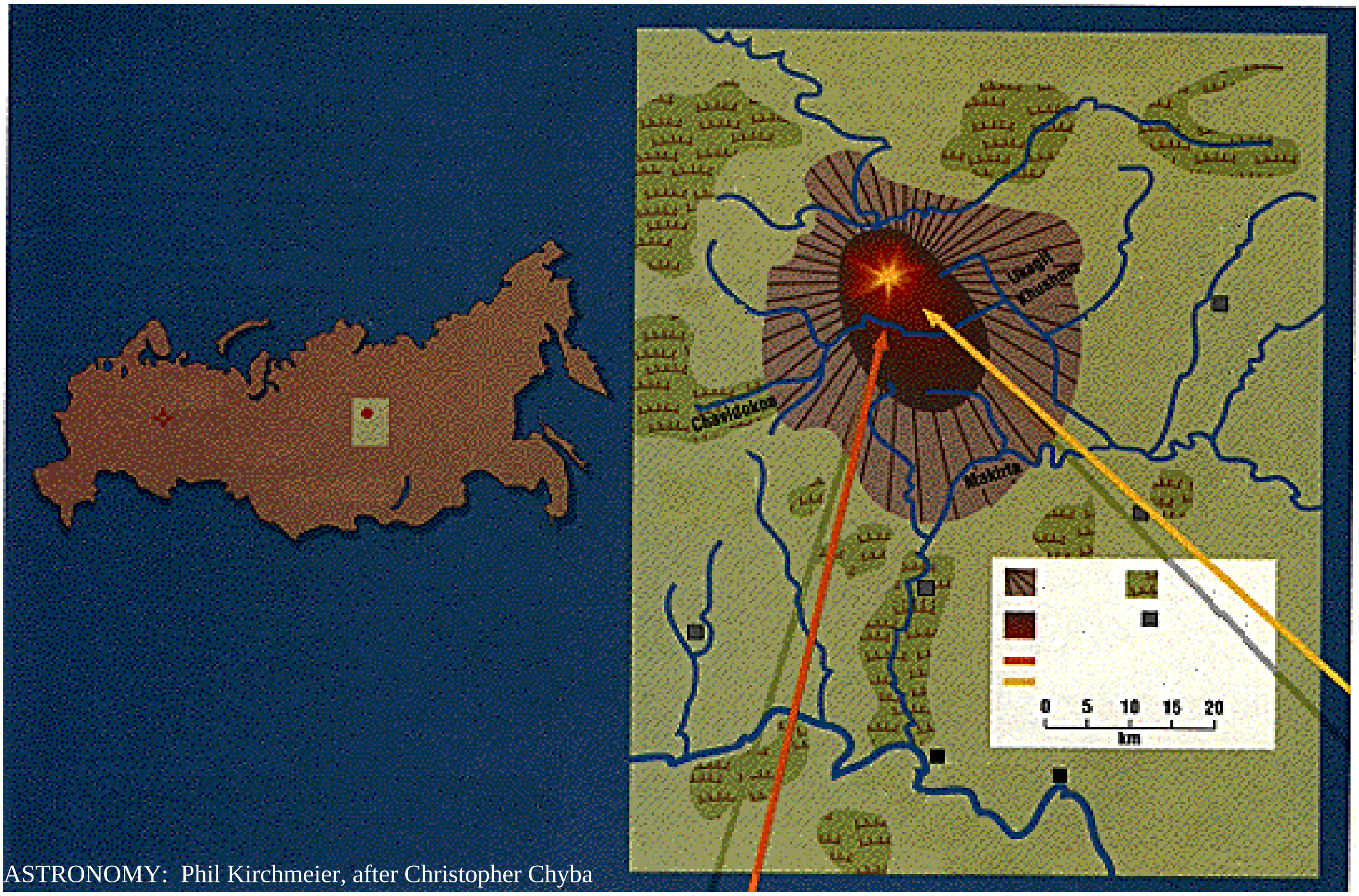
I still cannot sort out my chaotic impressions of this excursion. In the north the distant hills along the River Khushlmo are covered with a white shroud of snow half a meter thick. From our observation point no sign of forest can be seen, for everything has been devastated and burned, and around the edge of this dead area the young twenty-year-old forest growth has moved forward furiously, seeking sunshine and life. One has an uncanny feeling when one sees 20-30 inch thick giant trees snapped across like twigs, and their tops hurled many meters away to the south.

By June, Kulik had found the epicenter of the destruction. The journey through the forest wasteland had not been without peril:

In the early part of the day when the wind rose, it was very dangerous to walk through the old dead forest; twenty-year-old dead giants rotted at the roots were falling down on all sides. Some-times they fell quite close to us. As we went along we kept our eyes on the tree-tops so that, if they fell, we should have time to jump aside.

Some trees had been stripped of their branches, scorched, and killed where they stood, and many others had been uprooted or snapped clean. Kulik discovered that the trees that had been toppled or snapped all pointed away from one central area, which he named the "cauldron." The interpretation was clear. The Tunguska meteorite had exploded above this central point and the blast had blown the forest outward in all directions.

After these discoveries Kulik had little trouble getting support for subsequent expeditions. He led another in 1928 and another in 1929-30, this time wintering over at the site. Expeditions continued throughout the thirties. But despite



ASTRONOMY: Phil Kirchmeier, after Christopher Chyba

some false alarms, no craters or meteorite fragments were located. Kulik died in 1942 after being taken prisoner by the German army in World War II.

Black Hole, Antimatter, or UFO?

Kulik's on-site research leaves us with a disappointingly incomplete picture of the Tunguska event. That has troubled scientists throughout the past few decades. Not long ago, with a colleague, I gave a lecture about the Tunguska event. My colleague made the posters for our talk, secretly titling them, "Black Hole, Antimatter, or UFO?" and then put my name first. The room filled to overflowing — and my colleague failed to show up until well into the talk.

His practical joke worked because of the bizarre explanations the Tunguska event has attracted over the years. Tunguska's area of destruction is larger than the area of New York City. So much devastation and yet no crater. And if this peculiar scenario was caused by an infalling meteorite, why should the interloper explode in the atmosphere before hitting the ground?

Apart from the Loch Ness Monster and Bigfoot, virtually every scientific or pseudoscientific explanation has been tried on the Tunguska fall. What these hypotheses lack is testability. Any acceptable scientific explanation of the Tunguska explosion has to make use of phenomena that we know something about. This is so astronomers can make consistency checks and see if the explanation stands up to the tests. If it's not testable, it's not a scientific explanation. Some have suggested that a "mini" black hole collided with Earth, passed through it and left no crater. Why the black hole left no sign has never been explained.

What about antimatter? It would take only a tiny meteorite made of antimatter to produce a 20 megaton explosion. But besides the fact that astronomers have never observed any signs of antimatter meteorites, a grave objection to this hypothesis traces all the way back to 1949. In his book *The Face of the Moon*, Ralph Baldwin showed that an antimatter meteorite massive enough to penetrate as deeply into the atmosphere as the Tunguska object would generate more than ten thousand times the energy of the actual explosion.

Of course, when all else fails people call out the flying saucers. In one sense this solution to the Tunguska mystery works very well — it has to. An advocate of flying saucers can always endow the supposed alien spaceship with exactly the characteristics necessary to explain the event. Of course this isn't an explanation in the scientific sense.

Another possible explanation for the Tunguska explosion does meet the criterion of testability. Could the explosion have been caused by methane, or swamp gas? This idea can be tested. Scientists know how much energy a cubic foot of methane gas produces if it ignites with 100 percent efficiency. How much methane would have had to accumulate at the Tunguska site to have caused the explosion, assuming perfect combustion? It's a simple calculation. You would need 60 billion cubic feet of pure methane gas. Saudi Arahia produces about this much natural gas in one month. I think it strains credibility to imagine this much methane accumulating above the Tunguska swamps and then somehow generating a point-like explosion.

Enter the Asteroid

But what about Kulik's original idea, that the explosion was caused by a meteorite? Perhaps it was a small comet, or perhaps a small asteroid, but in any case some cosmic body must have exploded in the atmosphere. It's not hard to estimate how large this body must have been, from the energy it released. We know how fast typical Earth-crossing asteroids or comets are moving when they hit Earth, ahout 40 to 60 km/sec. From this, it's easy to estimate that the Tunguska object must have been about 60 meters across — a bit more than half the size of a football field. The question with the Tunguska event has always been how to convert this kinetic energy of motion into explosive energy before the object hits the ground and makes a crater.

But the Tunguska mystery goes beyond the lack of a crater. In addition, no significant pieces of the object were ever found. This objection might seem strong if not for the Revelstoke explosion. Revelstoke was a thousand times smaller than Tunguska, scientists were able to recover little more than a gram of dust at Revelstoke. If a few more months had passed nothing would have been left. So what would the chances be of finding significant amounts of Tunguska dust more than ten years after the explosion, after the snow had fallen and melted more than ten times, and the runoff had sunk into the Tunguska River? Even though the Tunguska explosion was much larger, the chances weren't good. The few submillimeter-sized metallic spheres collected by Kulik at the Tunguska site underwent analysis in the 1980s. These particles contain certain key elements in cosmic proportions, amounts characteristic of meteorites and very different from those on Earth. These spheres probably formed out of material from the object that recondensed like metallic raindrops after first being vaporized in the explosion.

Atmospheric exposions like Tunguska are ordinary events, even though we rarely witness them.

Tunguska Was Mundane

Over the past decade or so investigators have come to realize that it is not extraordinary that a chunk of rock or ice the size of a football field explodes in midair and hurtles to the ground. The Tunguska explosion is now considered typical for a small comet or asteroid entering Earth's atmosphere at a typical velocity. Despite the dramatic appearance, the Revelstoke and Tunguska explosions were anything but extraordinary — they were mundane. Many Tunguskas and Revelstokes have occurred, and many such explosions will take place in the future. From our knowledge of Tunguska and Revelstoke we can picture what this type of event must be like.

Imagine a football-field-sized asteroid in an Earth-crossing orbit. Suppose Earth happens to be in the wrong place at the wrong time and its gravity scoops up this rogue body. If the asteroid were typical, it would then enter our atmosphere with a velocity of around 15 km per second — about 34,000 miles per hour. Because the asteroid is moving so fast, the atmosphere doesn't have time to flow or be pushed out of the way. Instead, the air gets compressed and piles up in front of the body. Meanwhile, behind the asteroid, the atmosphere is a near-vacuum because the air hasn't had a chance to rush back in. An enormous pressure difference builds up across the asteroid — huge pressure in front and nearly no pressure behind — and gets bigger and bigger as the asteroid moves deeper into the atmosphere.

What happens next depends on what the asteroid is made of. If the asteroid is strong enough, say made of iron with a few cracks or lines of weakness, perhaps nothing happens until the asteroid hits the ground. An iron object with the energy of the Tunguska body produced Meteor Crater in Arizona some 50,000 years ago. Despite the enormous atmospheric pressures on this object, the Meteor Crater projectile was strong enough to withstand them.

But that's iron. What if the object is weaker? Suppose it's made of rock. In this case the pressure difference across the object will eventually exceed the object's strength. Once the rock can no longer support itself against this pressure, it will crumble and begin to "pancake." Caught in the vise of the high pressure ahead and low pressure behind (caused by its own velocity), the rock has no choice but to flatten sideways. And then, very quickly, the game is over. Once the rock begins to spread, its surface area goes up, and atmospheric drag increases, slowing the object. It spreads even more, and the density of the atmosphere all the while increases exponentially as the object nears the ground, creating more drag. These overwhelming forces together stop the fragmented object abruptly in the atmosphere, exploding it like a bomb.

Detailed computer models show that the disintegration and explosion happen in one or two tenths of a second. In the case of Tunguska, within a fraction of a second 15 megatons of kinetic energy were lost as the object stopped cold 8 km up. But energy is conserved, and those 15 megatons had to go somewhere. These 15 megatons converted into high temperatures and high pressures. The rock vaporized! A shock wave raced outward. The underlying forest was sequentially set alight, snuffed, and toppled as the heat and the shock wave raced past.

Interlopers made of different materials will in fact explode at different altitudes. The weakest ones, icy comets, explode high up in the atmosphere. Stronger objects like stony asteroids will penetrate the atmosphere more deeply before they are shattered. Iron objects may reach the surface and leave a crater. Or if they are just a little weaker they may explode just above ground.

Size also comes into play. If an asteroid or comet is too big, say bigger than a few hundred meters across, it doesn't have time to "see" the atmosphere. In effect, by the time the back end of the asteroid has had a chance to find out that the front end is meeting the atmosphere, the front end has already slammed into the ground or the ocean. For big impactors, things happen too fast for the atmosphere to play a role.

Computer modeling I've done has produced a graph showing the Tunguska explosion for four different kinds of objects (page 4, left). These include fast and slow comets and carbonaceous (fragile), stony, and iron asteroids. Each of the "candidate Tunguskas" in the graph had 15 megatons of energy to start with. Each had an explosion altitude, defined as the height where the object deposits the biggest fraction of its kinetic energy into the atmosphere. The results suggest that the Tunguska event is very well explained as the explosion of a stony asteroid, or perhaps a carbonaceous one. An iron Tunguska would have reached the surface and a cometary one would have exploded far too high. Incidentally, the computer model also predicted that a 20 kiloton carbonaceous chondrite should blow up in the atmosphere at an altitude of 30 km.

According to this picture, Tunguska goes from an exotic event demanding the invocation of UFOs or black holes to a completely normal, predictable outcome for a stony asteroid entering the atmosphere with a typical velocity. This understanding is important, for it allows us to assess the contemporary hazard posed by small asteroids and comets colliding with Earth.

The Ideas of Spacewatch

As of June 1993 the Spacewatch search at Kitt Peak has identified a dozen Earth-crossing asteroids smaller than 50 meters across, and the number is growing all the time. It's easy to calculate the explosive energies the objects would unleash if they struck Earth, as well as the odds of these collisions. For example, the Spacewatch observations indicate that Earth is struck by several objects with explosive energies in the 20 kiloton range every year. Revelstoke is an example of such a collision. As Revelstoke demonstrated, as long as these objects blow up at sufficiently high altitudes, they won't cause disasters on Earth's surface. But when does a disaster happen, and when not? How much should we be worried by the Spacewatch discoveries?

Once scientists have a model for the atmospheric explosions of small asteroids that accounts for Tunguska and Revelstoke, they can hope to predict the results of future collisions. My model shows a range of collision scenarios for Spacewatch objects (page 4, left). The vertical axis shows the altitude of the explosion for a given object's collision with Earth, and the horizontal axis shows the explosion's energy. For example, the Tunguska event, denoted by the solid triangle, was an explosion of about 15 megatons of energy at an altitude of 8 km or so. Revelstoke, the solid circle, was around 20 kilotons at an altitude of 30 km.

The other symbols — triangles, circles, and crosses — are the model's predictions of the fate of the twelve small Spacewatch objects discovered by June 1993. Astronomers don't yet know whether these objects are stony meteorites, carbonaceous meteorites, or comets, so I modeled each of the possibilities. The key point of comparison is the solid curve, the surface-hazard threshold line. This curve was derived from the results of nuclear weapons tests. Any explosion taking place above this line will not cause substantial damage on the ground: Trees will not be knocked over and frame houses will not be destroyed. Notice that Tunguska lies below this line and Revelstoke well above it. And the small Spacewatch asteroids virtually all lie above the line as well. This is good news because it says the small Spacewatch objects will explode too high and with too little energy to destroy buildings or topple forests.

Even if we are not threatened by the results of collisions with these objects, it's worth asking why we don't notice several 20 kiloton blasts in the atmosphere every year. Only a few thousand people noticed Revelstoke and saw it as little more than a bright fireball and some loud booms. What if Revelstoke had exploded during the day? Who pays attention to the distant thunder? And what if Revelstoke had exploded over the ocean?

Are these explanations sufficient? I'm not sure. But we should soon have an independent check. U.S. Department of Defense satellites designed to watch for nuclear explosions or missile launches may well be detecting these atmospheric explosions. It now seems likely, with the end of the Cold War, that in addition to watching for the threats of human enemies, some of these satellites will also soon be cataloguing atmospheric explosions from the cosmos. What we do know is that our current understanding of Tunguska and Revelstoke shows that these events are not freak "acts of God." They are normal, ordinary events in the life of a planet.

Tunguska Corrections

I want to clarify a number of errors or omissions from my article on the Tunguska meteorite explosion (December 1993). Most importantly, the modeling of the 1908 Tunguska explosion was done with my colleagues Paul Thomas of the University of Wisconsin, Eau Claire, and Kevin Zahnle, of NASA-Ames Research Center. It was not, by any stretch of imagination, work that I did alone. The editors should not have introduced the pronoun “I” without mention of my coauthors.

I later applied our model to determine the fates of the newly-discovered Spacewatch objects. We found the small Spacewatch objects pose no significant threat to Earth’s surface. We need not fear “Death from the Sky” from these objects. Yes, there’s some threat, but the threat from small asteroids and comets is not great.

The left-hand plot on page 4 contains several errors. Its horizontal scale should be in units of kilotons per km—how much energy each object delivers per kilometer of atmosphere it descends through. The labels on the curves incorrectly state why the model rules out certain objects as candidate explanations for the Tunguska event. All the candidates shown here explode with more-or-less the right energy to have been the Tunguska event. What distinguishes them is their explosion altitudes, given these energies.

Earth-crossing comets and asteroids do not typically hit Earth at 40 to 60 km/sec. Based on the statistics of the objects so far discovered, a typical Earth-crossing asteroid will strike at about 15 km/sec, and a typical short-period comet at about 25 km/sec.

Perhaps the best way to picture the “pancaking” of the object is to imagine it as trapped between the high pressure decelerationg [sic] its front face, and the high-velocity downward motion of its rear face.—Chris Chyba, Washington, D.C.

Planetary scientist Christopher Chyba wrote this article while a National Research Council Associate at the NASA Goddard Space Flight Center. He was recently named a White House Fellow.