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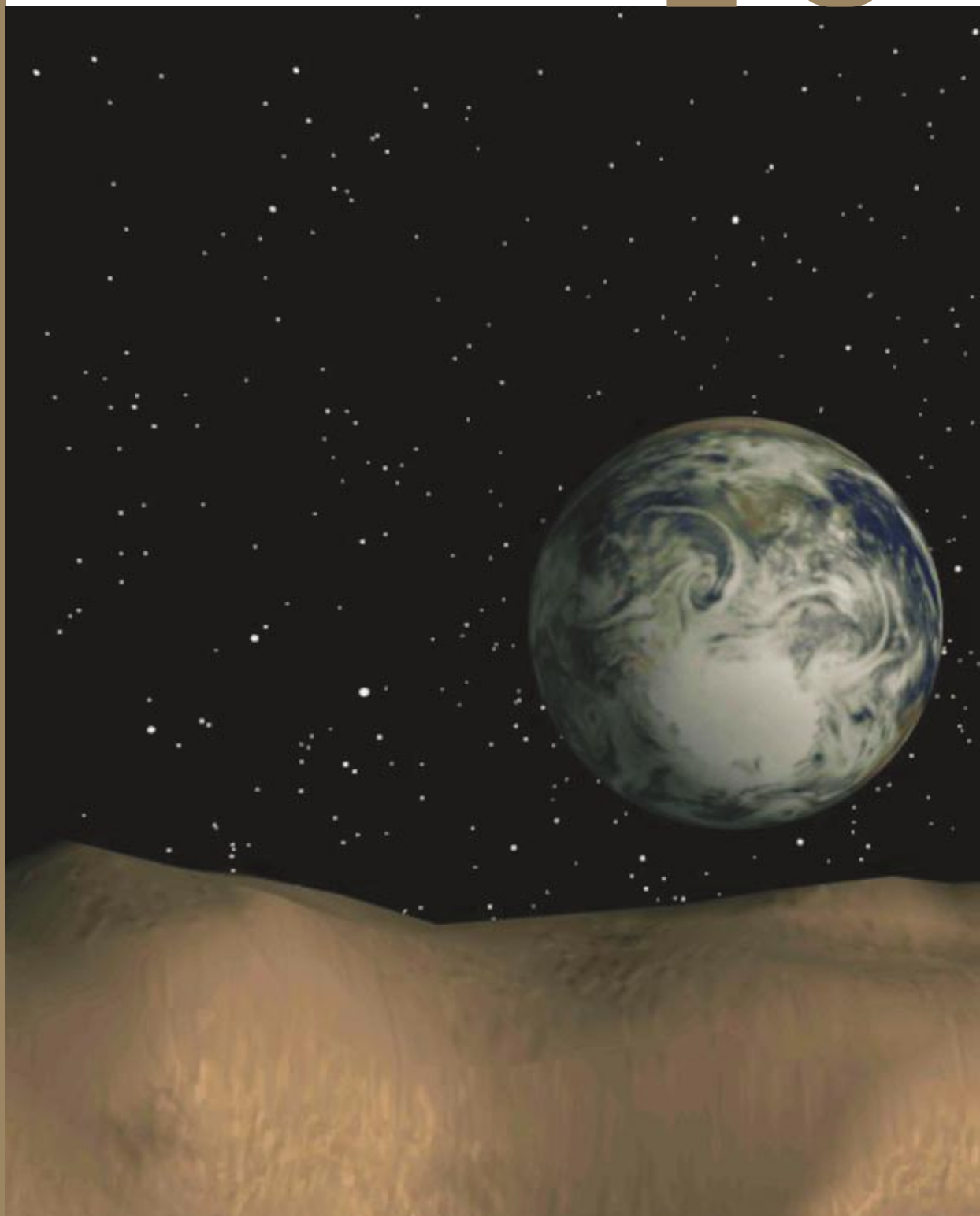
IN THIS ISSUE



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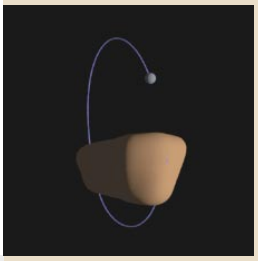

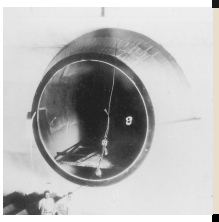

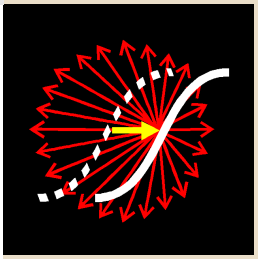

On the cover: In 2004, an asteroid named Toutatis will whiz by Earth at a distance of four lunar orbits. If you were vacationing on Toutatis then, this is what you'd see. Earthbound radar astronomers are taking close looks at a number of Earth-approaching asteroids, as you'll see on page 14.

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We live amid a swarm of small worlds whose existence was unsuspected a century ago.

Radar Observations of Earth-Approaching Asteroids

by Steven J. Ostro

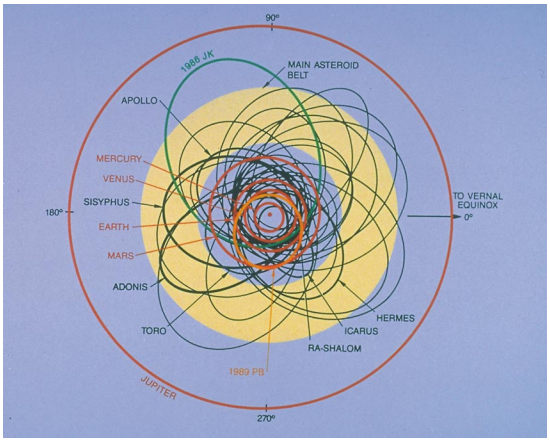
As part of their opposition to the Comprehensive Test Ban treaty, the Chinese have declared that they would like to hold on to their nuclear weapons just in case they have to blow up an approaching asteroid. Are they playing politics? Or are they acting out of a societal memory of a day in the year 1490 when, according to records from the Ming dynasty, stones fell from the sky and killed thousands of people? Are killer asteroids finally getting some respect?

We call these objects Earth-crossing asteroids. The main asteroid belt lies between Mars and Jupiter, but the Earth-crossers travel in orbits that cross that of our own planet and occasionally collide with Earth itself. At that point they become meteors, and, if they don't burn up in the atmosphere on the way down, meteorites. The first Earth-crosser was discovered in 1918 by Max Wolf in Heidelberg, Germany. We now know of a few hundred, most of which have been discovered during the past decade. By looking at the size distribution of craters on the moon, we think we know what the undiscovered population of these bodies looks like. (The cratering record also shows that the impact rate hasn't changed dramatically over the last 3 billion years, which implies that as Earth-crossers hit us and are thus removed from circulation, the pool is replenished at an equal rate, presumably mostly from the main belt.) We believe that there are about 2,000 Earth-crossers at least as large as a kilometer, which turns out to be an important size. Two thousand is a lot—if you drove far from Los Angeles on a perfectly clear, moonless night, you could see about 2,000 stars with your naked eyes. The number of smaller Earth-crossers is much larger—there are some 100,000 waiting to be discovered that are larger than the Rose Bowl, and about 70 or 80 million larger than a typical tract house. We live amid a swarm of small worlds whose existence was unsuspected a century ago, and whose abundances have been realized only during the past few decades.

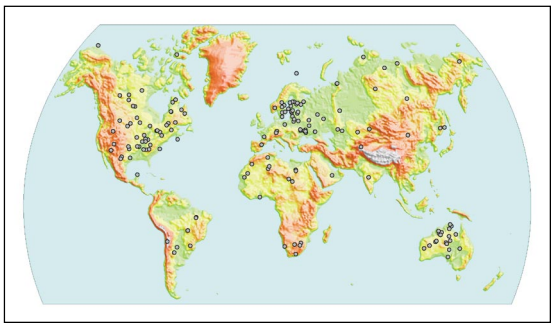
The 70-meter Goldstone antenna is part of the Jet Propulsion Laboratory's Deep Space Network, which also includes sites near Madrid, Spain, and Canberra, Australia. The three locations are approximately 120 degrees apart, so a spacecraft is always within view of one of them. When the Goldstone antenna isn't busy talking to spacecraft, it's also used for radar astronomy. Caltech manages JPL for NASA.

These are scientifically very precious stones—more so than diamonds!—and taking samples of them, unaltered by a fiery passage through our atmosphere, would tell us a great deal about the evolution of our solar system. In particular, one type of asteroid—the carbonaceous chondrites—formed by condensation 4.5 billion years ago when the solar system did, and they're made out of the same stuff that went on to form the sun, the planets, and us. They're called "carbonaceous" because up to 6 percent of their weight is complex organic compounds, including amino acids and nitrogenous bases, which are the building blocks of proteins, DNA, and RNA. At the other extreme, some asteroids come from planetary bodies that had already condensed, but later melted from the heat of radioactive elements decaying within them. Then, as they cooled, the denser stuff sank and the lighter stuff floated, creating a core-mantle-crust structure just like Earth's. Some time later, they were blown to smithereens in violent collisions with other large asteroids. The fragments from the crust and mantle are now stony asteroids, while the fragments from the core are metallic ones. These objects are actually samples of the insides of small planets, from which we can decipher their histories.

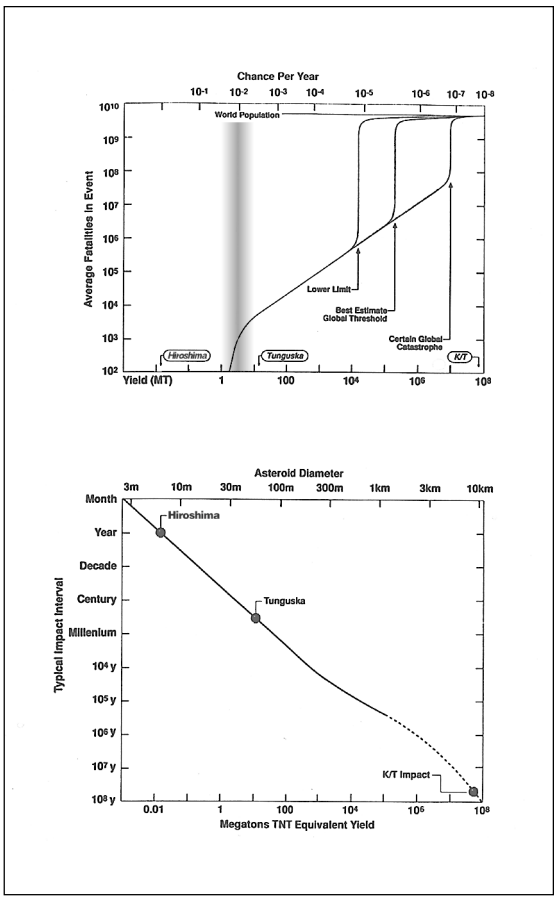
As well as being scientifically valuable, these rocks are potentially a minable resource. The metallic ones are solid hunks of nickel-iron alloy that contain 10 parts per million of platinum and one part per million of gold. And many of them are unbelievably easy to get to. We dream of colonizing the solar system, but the cost of a space mission, regardless of whether there are people on board or just robots, depends on how much orbital velocity change you have to introduce to get from Earth to your destination and back. Since Earth-crossing asteroids come so close, a properly timed launch could essentially just step over to them. For economic reasons alone, these are the objects we're going to colonize first, after the moon.



Left: The orbits of 33 Earth-crossing asteroids. The main asteroid belt is shaded yellow. Right: Every now and then, an Earth-crosser becomes an Earth-hitter. Each of the 156 dots on this map marks an impact crater. Many more, obscured by vegetation and erosion, wait to be discovered. Map courtesy of R. A. F. Grieve, Geological Survey of Canada.



An asteroid hits at about 20 kilometers per second—a velocity well beyond human experience.



The damage an Earth-crosser does when it hits us depends on its energy release, which in turn depends on its size, both of which are plotted logarithmically on the horizontal axes. "Size" is only roughly equivalent to diameter, as many of these objects have irregular (or unknown) shapes. The penetration threshold (shaded) is really more of a transition zone than a sharp threshold. The K/T impact is widely believed to have killed the dinosaurs. After Chapman and Morrison, 1994.

But even if we never go to these objects, eventually it is inevitable—absolutely inevitable—that they will come to us. The surface of the moon is covered with craters made by asteroid and comet hits. The surface of the Earth doesn't have as many craters, even though it has suffered the same violent history, only because ours is an active planet. Plate tectonics, volcanism, weather, erosion, and so forth have erased the record of long-ago collisions. But we're still finding the scars, as the little dots on the above map of the world show.

When an asteroid hits the Earth, the damage it does depends on how big it is, as shown in the diagram at left. An asteroid hits at about 20 kilometers per second—a velocity well beyond human experience—and all its kinetic energy is released upon impact. The amount of kinetic energy depends upon the asteroid's mass, and hence its size. We measure the energy release in megatons, where one megaton (4.2×10^{15} joules) is the energy equivalent of detonating a million tons of TNT all at once. The atomic bomb dropped on Hiroshima was a mere 15 kilotons, a number so tiny that it's way over on the left of the diagram. As we move across the diagram from left to right, at first the objects are too small even to make it through the atmosphere. These meteors do no damage—their energy release just powers a light show. But soon the penetration threshold is crossed; slightly larger ones deposit most of their kinetic energy on or near the planet's surface and devastate larger and larger areas. Should the impact leave a crater, it will be 10–20 times the asteroid's size. Then, at a diameter of about a kilometer, we cross a global threshold. It no longer matters where an object hits—it will kick so much dust up into the upper atmosphere that the sun will be blotted out worldwide for several years, making agriculture impossible and leading to the starvation of roughly a quarter of the people on the planet. This is a civilization-ending asteroid. At much higher energies—10-kilometer

Kilometer-sized, civilization-ending impacts happen on average once every 100,000 years, so the probability that we face one during the next century is roughly one in a thousand.

objects—we cross another threshold where the devastation is so horrendous that most of the life on Earth is eliminated. The most popular mass-extinction event was 65 million years ago, of course, when not just the dinosaurs but some 75 percent of the species on the planet were wiped out, but there are other such events in the paleontological record.

So how often do these collisions happen? The very, very low-energy events—the Hiroshimas—happen maybe once a year. But you hardly ever hear about them, because they leave no trace on the ground and they generally occur over unpopulated areas or the ocean, where their fireworks go unappreciated. Impacts like the Tunguska event, which happened in Siberia in 1908 and released 15 megatons of energy but left no crater, happen once every several centuries. The Tunguska asteroid was about 60 meters across, and it released as much energy as a magnitude 8 earthquake. This is at the low end, in terms of the number of people who could be killed by an asteroid impact. As we approach the global threshold, we suddenly get to the point—because the effects *are* global—where the number of fatalities skyrockets. And, finally, mass-extinction events are very rare—once every 100 million years, on average.

Kilometer-sized, civilization-ending impacts happen on average once every 100,000 years, so the probability that we face one during the next century is roughly one in a thousand. Those odds are extremely low—however, the consequences are extremely horrible. That fact alone suggests that it's worth finding all the kilometer-sized objects and determining their orbits, just in case we're unlucky.

This would be very easy to do. Asteroids are discovered with wide-field cameras that take time-exposures of the sky. The camera pivots to follow the stars, so that they appear as points in the image. But asteroids, which are moving with respect to the stars, show up as streaks. There are several ongoing asteroid searches, but they haven't got the resources to be exhaustive. For less than $5 million a year over a 10-year period, we could find more than 90 percent of the kilometer- and larger-sized asteroids. It seems to us very cost-effective risk reduction—very good insurance—logical in the same way that life insurance, or fire insurance, or car insurance is logical. NASA's annual budget is $14 billion a year, so we're completely perplexed as to why NASA does "not recommend this program…." If you feel that such a program would be sensible, tell your congressperson.

If we did find a threatening object, what would we do? With current technology, if we had enough warning, we could set off a nuclear warhead near the asteroid, nudging its orbit so that it would miss the Earth. However, until we discover such an object, most of us feel that developing a deflection system would be too costly to warrant our actually doing so; also, if we had a standby deflection system and actually started to experiment with orbit modifications, the system might be accidentally used or even intentionally *mis*used to deflect a harmless asteroid into a collision course with Earth—an idea that is very popular with some people who write comic books or design video games. With somewhat more-advanced technology, we could travel out to the asteroid and attach a solar sail or some sort of rocket engine to push it away from us. Everything would depend on how much warning we might have. The odds are that we would have enormous warning—maybe centuries—but not if we don't start looking.

Coincidentally, on May 19, 1996, an asteroid designated 1996JA1, which had been discovered only three days earlier, passed within a hair's breadth of Earth—only slightly outside the orbit of the moon. Less than a week later, on May 25, asteroid 1996JG (discovered on May 8) whizzed by us at eight times the distance to the moon. Both bodies are only a few hundred meters across, so they could not have produced global catastrophes had they hit us. But if they had landed in the ocean (71 percent of Earth's surface is ocean), they might have raised tsunamis that could have wiped out the coastlines of the adjacent continents. Up to 1 percent of the global population would have been killed by such an impact.

Those two asteroids missed us this time, but where are they going to be in the future? Unfortunately, with just optical measurements, it's hard to predict a newly discovered asteroid's orbit for, say, the next century. What matters is the uncertainty. It's one thing to say an asteroid is going to pass one lunar distance from Earth, but quite another to say that the asteroid is going to come within one lunar distance plus or minus 21 lunar distances. That's very uncomfortable. But if we use radar observations, there's very little uncertainty left. Donald Yeomans, Paul Chodas, and

Photo by David Parker, 1997/Science Photo Library

We can get 10-meter resolution, which is about the length of a school bus, and we can measure velocities of one-tenth of a millimeter per second, which is the speed of the tip of the minute hand on a kitchen clock.

The radio dish at Arecibo was carved out of a natural "punch bowl," or sinkhole, in the limestone karst region of northwestern Puerto Rico. The telescope is aimed by moving the antenna feed system, which hangs from rails on a support structure that is itself suspended over the dish from three towers. The telescope can see a cone of sky 40 degrees in diameter and centered on the zenith. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation.

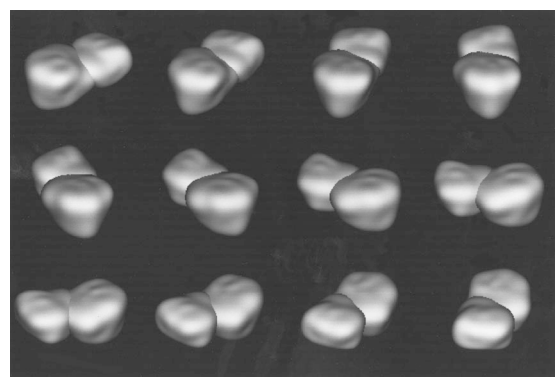
Jon Giorgini of JPL's Solar System Dynamics Group can use our radar data to work up an orbit that's good for 100 years or more. We would immediately know whether we're safe or not.

We study these asteroids with either of two very large antennas. One is the 70-meter Goldstone antenna, about a three-hour drive from Pasadena. Goldstone is part of the Jet Propulsion Laboratory's Deep Space Network, so the antenna is used primarily for talking to spacecraft, but up to 4 percent of its time is devoted to radar astronomy. The other is the largest radio telescope in the world, the 305-meter (1,000-foot) Arecibo telescope in Puerto Rico. The two instruments are complementary. The Arecibo telescope is not fully steerable (Goldstone is), but it's 30 times more sensitive. But it also has been used for radar only 4 percent of the time.

When we bounce a radar pulse off an asteroid, we measure the time it takes the echo to return, which tells us how far away the asteroid is, and the echo's Doppler shift, which tells us how fast the asteroid is moving. (Objects moving toward us compress the echo to higher frequencies; receding objects stretch it out to lower ones.) For an asteroid about 20 lunar distances from Earth, we can get 10-meter resolution, which is about the length of a school bus, and we can measure velocities of one-tenth of a millimeter per second, which is the speed of the tip of the minute hand on a kitchen clock. That's why radar is so powerful in refining orbits.

But wait—there's more! Asteroids appear only as points of light in even the best telescope photo—they're just too darn small. But radar can pick out surface features. A Caltech grad who's now at Washington State University, R. Scott Hudson [BS '85, PhD '91], developed a technique to generate a three-dimensional model of an asteroid from a sequence of radar observations, and from this model we can make images that look like photographs. We tried this for the first time with an asteroid named Castalia, using data we got from Arecibo within two weeks of the asteroid's discovery (by JPL's Eleanor Helin at Caltech's Palomar Observatory) in August 1989. (Castalia was named for a nymph who, while fleeing the amorous attentions of the god Apollo, dived headlong into Mount Parnassus. Instead of making a crater, she left the spring that bears her name.)

Because Castalia was quite close to Earth at the time—a mere 11 lunar distances away—this was also the first-ever set of delay-Doppler data with sufficient echo strength and resolution to reconstruct a shape. (We have since done this with objects at greater distances.) The resolution is pretty poor, but the important finding is that Castalia is a double asteroid—a contact-binary



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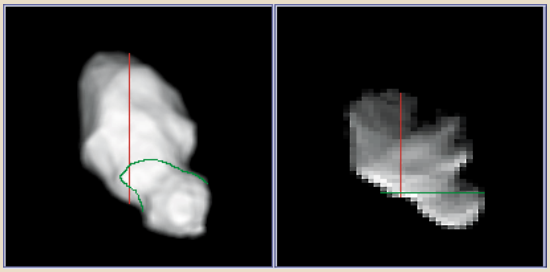
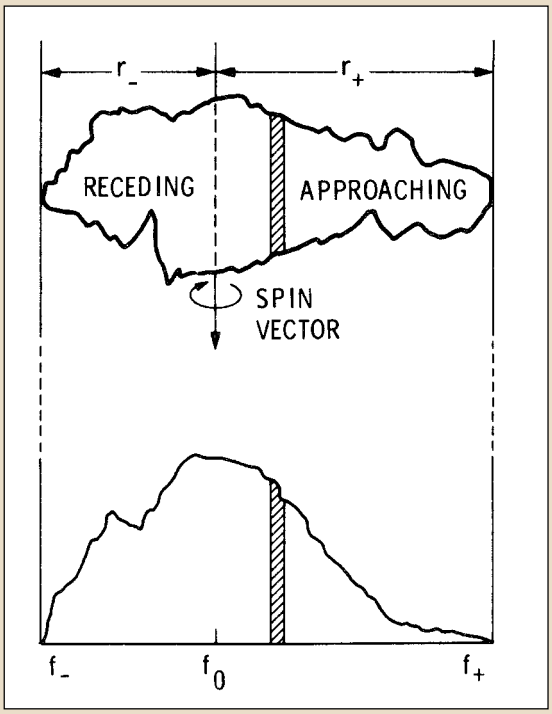
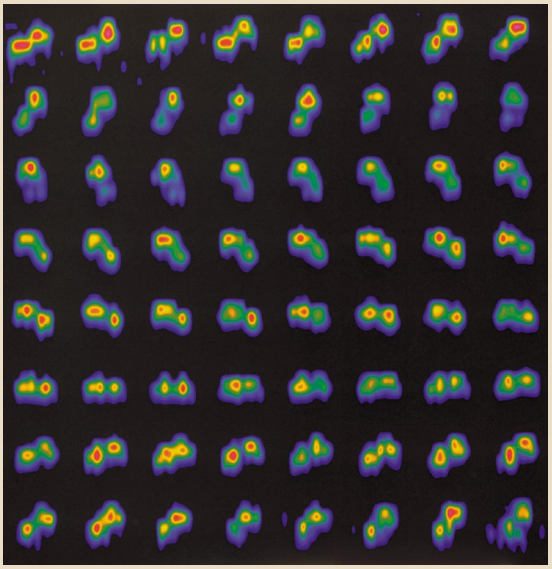
Castalia as modeled by the Hudson inversion looks rather like two biscuits that sat too close together in the oven and fused. The lobes are roughly 0.8 and 0.9 kilometers in diameter; at 100 meters or more deep, the cleft between them could swallow a 27-story building. The dimples on the model might be craters. The asteroid is seen rotating through 220 degrees in 20-degree increments.

"Seeing" Shapes with Radar





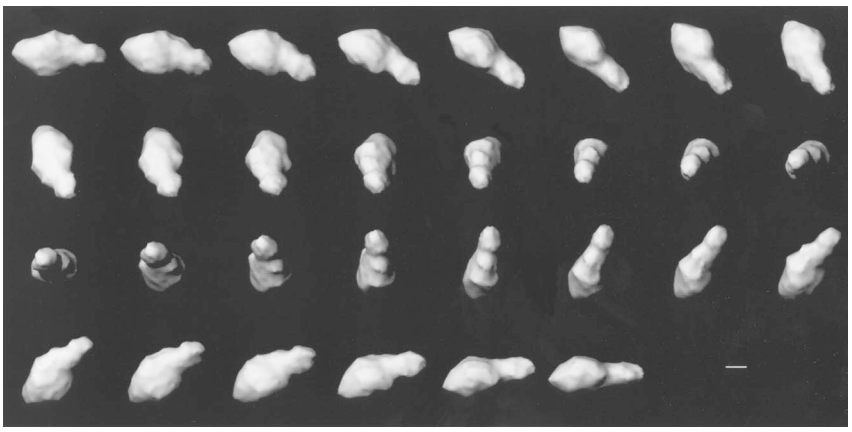


Above: A radar image of an asteroid (right) doesn't look exactly like a 3-D reconstruction of the real thing (left). Radar slices up the asteroid by the length of time it takes a reflected pulse to return—the green line traces out such a slice.

Center: The echoes from a slice through a rotating asteroid are shifted to both sides of the center-of-mass frequency (f_0) by the Doppler effect. The signal's strength at any frequency is proportional to the asteroid's area in that slice, as shown by the shaded bar. The red lines in the previous picture are the three-dimensional equivalent of this shaded bar.

Bottom: This delay-Doppler "movie" of Castalia consists of 64 images made over 2.5 hours. The images read from left to right, top to bottom. The colors from blue to red represent increasing intensity.

A camera, in essence, holds a sheet of glass perpendicular to the camera's line of sight and maps where every ray of light from the scene you're looking at passes through the glass. Radar imaging works in a fundamentally different way. When an asteroid reflects a radar pulse, the pulse returns to the receiver smeared out over time. The part reflected off the nearest tip of the asteroid makes a shorter round trip than the part bouncing off the farthest tip, and so returns to the receiver first. By chopping up the echo into slices of time as thin as 10^{-7} seconds and measuring the echo's strength in each slice, we can assemble a set of cross sections through the asteroid that tell us something about its shape—the more powerful the echo, the more of the asteroid there is in that slice. However, this doesn't say anything about how that surface area is distributed. But if the asteroid is also rotating, the Doppler effect will shift the echoes from the side of the slice that is turning toward Earth to proportionately higher frequencies, depending on how far away the reflecting point is from the rotational axis's projection in the plane of the slice. (Similarly, the side turning away from Earth will shift the echo to lower frequencies.) Thus, a radar image plots the echo's brightness versus its delay time on the vertical axis and brightness versus frequency on the horizontal axis to generate what's called a delay-Doppler image. In effect, the asteroid has been sliced along two perpendicular planes like a potato being sliced into French fries. And that's one reason why these plots don't look exactly like the asteroid—each point in the image contains the reflection from both ends of each French fry. A point may even contain more than two reflections, if that particular French fry passes through the side walls of a crater, or a cleft on the asteroid's surface! It takes a mathematical analysis, using Scott Hudson's techniques, of a sequence of delay-Doppler images to resolve the ambiguities and reconstruct the asteroid's actual shape. □



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Toutatis as seen at six-hour intervals over the week beginning at 10:00 a.m. Pasadena time on December 3, 1992. Although the long axis has essentially returned to its original orientation by the end of the sequence, the asteroid's orientation around that axis is not the same—the lobe that was pointing downward in the first image is now sticking out toward us. The scale bar in the lower right corner is one kilometer long. Data are from Goldstone and Arecibo.

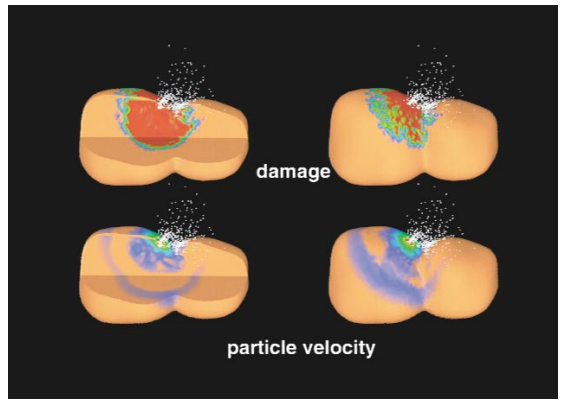
asteroid, the first ever seen. Such a thing could form only if the two lobes mated at a very gentle relative velocity, so that they didn't pulverize each other. Perhaps it formed out of the wreckage of a much larger asteroid. If two shards went sailing out along a common trajectory close enough to each other, they might stay gravitationally bound. The two lobes could even be physically touching each other, but in no way "cemented" together. The discovery that contact binaries exist has implications for interpreting the cratering record elsewhere in the solar system, and also for defending ourselves from such objects. If we blew up a nuclear bomb closer to one lobe than the other, we would shatter the nearer lobe but leave the other one completely intact and the asteroid's course unaltered.

Thre years after the Castalia observations, in December 1992, we did a three-week-long experiment on another object, called Toutatis. Toutatis, by the way, is one of the most accessible asteroids. Its orbital plane is almost identical to Earth's; it's an excellent candidate to collide with us sometime during the next several million years. In fact, that's how it got its name. Its discoverers, Christian Pollas, Alain Maury, and their colleagues at the Côte d'Azur Observatory, are fans of the Astérix and Obelix comics. Those ancient Gauls swear by the god Toutatis, and the only thing they fear is that someday the sky will fall on their heads. Toutatis won't quite fall on our heads in the year 2004, but it will miss us by a mere four lunar distances, coming close enough to be visible through binoculars. At that point, Earth will be as large in Toutatis's sky as the moon is as seen from the Earth.

Above left are stills from our three-dimensional model of Toutatis. It's a much higher-resolution model than the one of Castalia, and represents an even stranger world. From some orientations it looks like a single object. From others, it looks like it has two parts. From still others, it looks like it has three. Geologically, we're at a loss to explain this—we know that collisions were involved, but we don't know exactly how. But the strangest aspect of Toutatis is its rotation. It doesn't spin around a single axis, but tumbles in a manner radically unlike anything else in the solar system that we know of. Toutatis rotates around its long axis once every 5.41 days. Meanwhile, this axis is precessing around a direction fixed in space—Toutatis's angular-momentum vector—once every 7.35 days. These are non-commensurate numbers, which means that Toutatis's orientation in space never repeats. There is no truly periodic pattern. How it got into this rotation, we don't know. It had to be a collision, but we don't know what kind of collision. We do know that it would be a spectacular experience to land on Toutatis and watch the sky. Imagine trying to navigate by using the stars—the "Pole Star" would change daily! Earth

Naming an Asteroid

When an (optical!) astronomer discovers an object, the sighting is reported to the Minor Planet Center at Harvard, which gives it a provisional designation (e.g., 1989 AC). Many astronomers may then observe the asteroid, making the measurements needed to refine the orbit. When Brian Marsden of the Minor Planet Center considers the orbit secure, he gives the asteroid a number (e.g., 4179) and then the discoverer(s) can name it (e.g., Toutatis). Marsden considers an orbit secure when the object is seen again, on a subsequent approach to Earth, in the location and at the time predicted by that orbit. In some cases, the object proves to be one that had been seen earlier, but then had been lost before enough observations could be made to pin down its orbit. Marsden then decides which "discovery" counts, i.e., who gets naming rights. In Toutatis's case, 1989 AC proved to be 1934 CT, which had been seen twice by Eugene Delporte in Uccle, Belgium in 1934; the discovery belongs to the 1989 discoverers, whose data permitted the orbit to be traced backward through half a century. □



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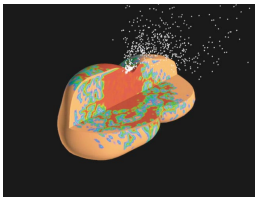
Geographos, as seen from above. The central bright square marks the north pole, and Geographos is spinning clockwise in the plane of the page. The radius of curvature of the knobs on either tip of the asteroid is only a few hundred meters; then beyond the gentle concavity that defines the knob, the trailing edges are nearly linear for a kilometer. The tick marks along the picture's right edge are one kilometer apart. The data were taken at Goldstone in August, 1994.

Above: A 6,000-ton rock hitting Castalia at the comparatively gentle velocity of five kilometers per second has 20 percent more force than the Hiroshima bomb. In this set of exterior and cutaway views at one-tenth of a second after impact, the top row shows damage ranging from minor (blue) to pulverization (red). The red fingers are actually hairline fissures—given infinite computing power, you'd eventually see these fractures opening up and pieces coming apart near the impact zone. The bottom row shows particle velocity (on a logarithmic scale where blue is 0.1, green is 1.0, and red is 20 centimeters per second) as the pressure wave propagates through the interior. Castalia is assumed to be a homogenous, basaltic body. Below: Although the crater itself takes much longer to form, the impact fragmentation is all over in three-tenths of a second. The impact severely damages Castalia, but does not blow it apart or appreciably alter its trajectory.

has a fixed north star—fixed on the time scale of someone reading this, at any rate—because Earth's rotational axis precesses only once every 26,000 years, but Toutatis's rotation and precession rates are comparable to each other.

At left is Geographos, which is about 5.1 kilometers long by 1.8 kilometers wide. It was discovered in 1951 by Albert Wilson [MS '42, PhD '47] and Rudolph Minkowski as part of the Palomar Observatory Sky Survey, which photographed the entire Northern Hemisphere sky over several years. The survey was sponsored by the National Geographic Society, hence the asteroid's name. We don't have a 3-D model of this one yet, but the radar images, processed by Keith Rosema [BS '89] at JPL, are good enough for us to see some unusual features. Geographos is paramecium-shaped—the most elongated body yet discovered. But to my eye the strangest of its features are the knobs on each end. Their leading edges (with respect to Geographos's rotation) are convex and their trailing edges are slightly concave, giving Geographos's ends a sort of pinwheel look. How did these form? And how can they survive, given the constant bombardment they must undergo from other asteroids? Perhaps it has to do with the asteroid's low gravity, long shape, and rapid, five-hour rotation. The centrifugal force at Geographos's tips might be just about equal to its gravitational pull, and the asteroid is almost able to fling the material off. When we finish the 3-D modeling, we can do computational experiments to test hypotheses about how these protuberances formed.

Once we have three-dimensional models, we can use them as targets in physically realistic computer simulations of impacts. Collisions are terribly important, and we need to understand their effects if we are to learn how asteroids evolve. Erik Asphaug of NASA/Ames has run such simulations, based on our model of Castalia's shape and rock properties derived from laboratory



experiments. In the frames from an animation by JPL's Eric De Jong and Shigeru Suzuki (above), an eight-meter, 6,000-ton rock (a small asteroid) crashes into Castalia. A spray of particles is ejected, and a shock consisting of a compressional wave followed by a smaller extensional wave (not shown) rips through the body. Exactly what happens depends on both Castalia's physical properties and its collisional history, because every impact affects the asteroid's integrity and the way it responds to impact stress. Even this relatively small cratering event causes widespread internal

It could bring a whole new dimension to parenting. If your child's been bad, instead of "Go to your room!" you could say, "OK, you go into orbit for a while."

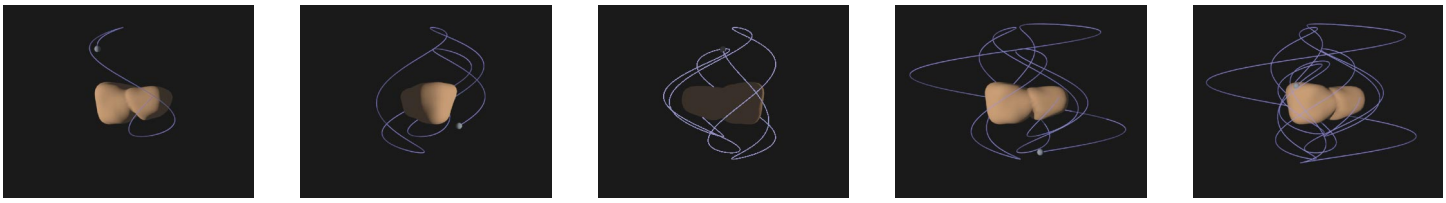
fracturing. Escape velocity on Castalia is about one meter per second, but most of the rock we pulverized in this simulation attained velocities of only a few centimeters per second and so remains gravitationally bound together. It's quite different from what we're used to on Earth, where the self-gravity between, say, the pieces of a broken saucer is negligible.

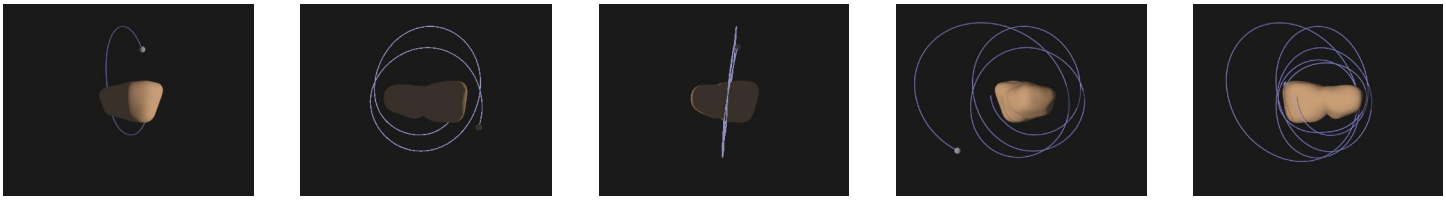
We want to understand the effects of collisions not just to make sense of the physical properties we observe—to connect what we've learned from meteorite samples with what we can learn about asteroidal composition through ground-based telescopes—but also to look ahead to the day when we might have to nuke one of these objects in self-defense. What this and other simulations have taught us is that it might be much easier to turn an asteroid into a flying rubble pile than to alter its trajectory by more than one or two centimeters per second. To make matters worse, loosely consolidated bodies don't propagate stress waves well. A nearby nuclear detonation would basically be "soaked up" by such an asteroid, shattering it into finer pieces instead of pushing it off course. This is a problem, because the overwhelming odds are that any asteroid that could threaten Earth has itself been hit at some time in the past by something larger than eight meters in diameter, and therefore is probably already fragmented.

We also want to understand the dynamics of orbits that are very close to small, irregularly shaped, rotating asteroids. Some ejecta will be thrown off too slowly to escape from the asteroid. Daniel Scheeres of JPL has found that the geometry of return orbits—orbits that eventually return to the asteroid's surface, or the equivalent of a ballistic trajectory on Earth—is very peculiar. The top row of illustrations below shows what you would see if you were standing on Castalia and weren't aware that the asteroid was rotating—what we call a Castalia-fixed frame of reference—and you threw up a rock that left a trail. It wanders all over the sky and, depending on where you stood, which way you were facing, and how hard you threw the rock, you'd get a completely different orbit. This is a realm of geometric complexity that we never appreciated before. If you stood off from Castalia and watched it rotate beneath you—a star-fixed reference frame—the orbit would now be almost planar, but the trajectory would still go through a bunch of strange gyrations in space before returning to the asteroid. And finally, of course, if you threw the rock a little too hard, it could whirl around Castalia for several passes before escaping and going into orbit around the sun.

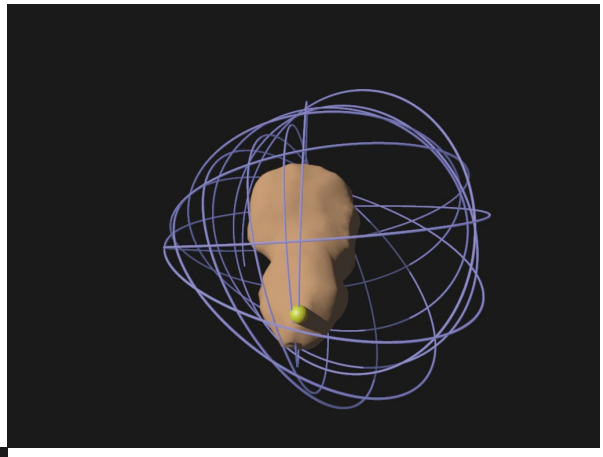
These calculations also apply to human and spacecraft operations in the vicinity of a small asteroid. Imagine what it would be like to play baseball on Castalia—you'd have to have a lot of patience and do a lot of practicing. If you went

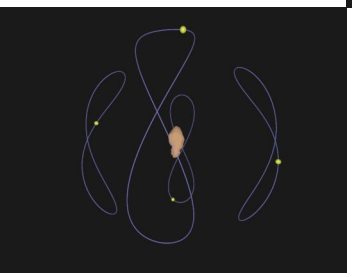
PICTURE CREDITS:
14, 16 – JPL; 19 – Steven Ostro; 21-23 – Eric De Jong & Shigeru Suzuki





A return orbit around Castalia, seen simultaneously in a Castalia-fixed reference frame (above) and a star-fixed reference frame (below). Although the reference frame is fixed in each set of images, the point of view sometimes moves in order to highlight some aspect—the planar nature of the orbit in the star-fixed reference frame, for example. The entire orbit takes 16.9 hours to complete.





Above, right: This return orbit around Toutatis, shown in a star-fixed frame of reference, takes 2.9 days to complete.

Above: This family of four "geosynchronous" orbits—in which a satellite appears to hang at a fixed point in the heavens, as seen from the orbited body's surface—instead trace out figure-eights in the sky over Toutatis. From a star-fixed point of view, the four satellites would be spaced 90 degrees apart in a roughly circular orbit around Toutatis.

out for a walk, and were feeling in good spirits and jumped up, you might go into an orbit that would take you around the asteroid for days! If you were too light on your feet, or unlucky, you might never come back. And parents like to toss their little kids up into the air and say "Wheeee!" They'd have to be really careful about that on Castalia. But it could bring a whole new dimension to parenting. If your child's been bad, instead of "Go to your room!" you could say, "OK, you go into orbit for a while."

As I mentioned before, Toutatis has a weird, tumbling rotation like a football during a botched pass. Consequently, orbits around Toutatis are very different from orbits around Castalia. On Castalia, in a star-fixed frame, the return orbit I showed you had a strange shape, but at least stayed nearly planar. Not so on Toutatis, where return orbits can form cocoons around it. There are some orbits that circle hundreds of times before eventually making it back to the surface. Above is a star-fixed view of a shorter return orbit.

Surprisingly, it is possible to have periodic orbits around Toutatis. In a star-fixed frame, you would see a satellite in one of the simplest of these orbits moving along a nearly elliptical path, just like it would around Earth. But if you were standing on Toutatis, you'd see something completely different. For example, a satellite in what would be a geosynchronous orbit around Earth would trace a giant figure-eight over the surface of Toutatis. And some orbits close to rotating asteroids are highly unstable, which is of concern to the NASA engineers flying the NEAR (Near-Earth Asteroid Rendezvous) spacecraft toward Eros, a large Mars-crossing asteroid. If they pick the wrong orbit, NEAR will collide with Eros or escape from it. NEAR was launched on February 17, 1996, and should rendezvous with Eros in late January or early February 1999.

We're approaching the turn of the millennium. I think it would be wonderful to have an event deserving of that moment in history, such as sending a human being to an Earth-crossing asteroid and really beginning the manned exploration of the solar system. Of course, such an undertaking would be very expensive and isn't likely to happen by that time. Meanwhile, we'll continue exploring with radar. And if we could fund a serious optical search for these objects, we'd start discovering them in huge numbers, and eventually we'd get to the point where almost once a week—certainly once a month—we could have an encounter via radar with a new Earth-crossing asteroid. We could put it on our World Wide Web site (http://echo.jpl.nasa.gov/), so that anybody with a computer could witness the first radar imaging of the object and see the radar movies and eventually the three-dimensional models. With a three-dimensional model, you could make virtual visits to the asteroid, putting yourself into orbit around it and trying to land on it. People love to explore strange, exotic places—if you could call your travel agent and book a cruise to Castalia or Toutatis tomorrow, I'm sure it would sell out. In a few years, with high-definition TV and high-resolution computer models, you could almost vacation there. You could walk around, play a little catch, even hit golf balls into orbit. Our models are the first step toward that experience, and it's going to be how most of us will explore these worlds. Sooner or later the survival of human civilization will depend on how intimately we know these near neighbors of ours, but in the meantime, it would be possible to make a first-time encounter with a fantastic new world part of the regular experience of everybody on the planet who's connected to the Internet. That's my personal millennial vision. □

Steven J. Ostro earned a BS in ceramic science and an AB in liberal arts from Rutgers in 1969. He went on to Cornell for a master's degree in engineering physics in 1974, and earned a PhD from MIT in planetary sciences in 1978. He then returned to Cornell, joining the astronomy department as an assistant professor. He arrived at JPL in 1984, where he now holds the title of senior research scientist, is the Goldstone Solar-System Radar project scientist, is a member of the science team for the Titan radar-mapping experiment on the Cassini mission to Saturn, and, in his spare time, teaches a graduate course at Caltech. The leading authority on the radar properties of asteroids, the satellites of Mars and Jupiter, and Saturn's rings, Ostro has been a "regular" at Arecibo and Goldstone for two decades, and he and his colleagues have bagged 80 near-earth and main-belt asteroids. He was also one of seven astronomers to play key roles in three NASA workshops on detecting and intercepting Earth-crossing asteroids.

This article is adapted from a Seminar Day talk given in May 1996.