Collisions with Comets and Asteroids

The chances of a celestial body colliding with the earth are small, but the consequences would be catastrophic

by Tom Gehrels

Are we going to be hit by an asteroid? Planetary scientists are divided on how worrisome the danger is. Some refuse to take it seriously; others believe the risk of dying from such an impact might even be greater than the risk of dying in an airplane crash. After years of studying the problem, I have become convinced that the danger is real. Although a major impact is unlikely, the energies released could be so horrendous that our fragile society would be obliterated.

Early in our planet's history, asteroids and comets made life possible by accreting into the earth and then by bringing water to the newborn planet. And they have already destroyed, at least once, an advanced form of that life. The dinosaurs were killed by such an impact, making way for the age of the mammals. Now for the first time, creatures have evolved to a point where they can wrest control of their fate from the heavenly bodies, but humans must come to grips with the danger.

Some four and a half billion years ago, the solar system formed out of a swirling cloud of gas and dust. Initially the planetesimals—coarse collections of rocky materials—coagulated, merging with one another to create planets. Because of the energy released by the colliding rocks, the earth began as a molten globe, so hot that the volatile substances—water, carbon dioxide, ammonia, methane and other gases—boiled off. As the material of the inner solar nebula was mopped up by the growing planets, the bombardment of the earth slowed. The glowing planet cooled, and a crust solidified. Only then did water—the life-giving fluid that covers three quarters of the earth's surface—return, borne on cold comets arriving from the solar system's distant reaches. Fossil records show that simple life-forms started evolving almost right away.

Comets and asteroids are, in fact, leftover planetesimals. Most asteroids inhabit the vast belt between the orbits of Mars and Jupiter. Being quite close to the sun, they were formed hot; as on the early earth, the high temperatures vaporized the lighter substances, such as water, leaving mostly silica, carbon and metals. (Only recently have astronomers found some rare asteroids that contain crystalline water embedded in rocks.)

Comets, on the other hand, hover at the outer edges of the solar system. As the solar system was formed, a good deal of matter was thrown outward, beyond the orbits of Uranus and Neptune. Coalescing far from the sun, the comets were born cold, at temperatures as low as –260 degrees Celsius. They retained their volatile materials, the gas, ice and snow. Sometimes called dirty snowballs, these objects are usually tenuous aggregates of carbon and other light elements.

Fiery Visitors

In 1950 Jan H. Oort, professor of astronomy at Leiden University in the Netherlands, was teaching a class that I was allowed to attend as an undergraduate. While reviewing astronomical calculations for his students, Oort noted that a number of known comets reach their farthest point from the sun—called the aphelion—at a great distance. He went on to formulate the idea that a cloud of comets exists as a diffuse spherical shell at about 50,000 or more astronomical units. (One astronomical unit is the distance from the earth to the sun.) This distant cloud, containing perhaps some 10^{13} objects, envelops the solar system.

The Oort cloud reaches a fifth of the distance to the nearest star, Alpha Centauri. Inhabitants of this shell are thus loosely bound to the sun and readily disturbed by events beyond the solar system. If the sun passes by another star or a massive molecular cloud, some of these cometary orbits are jarred. The planetesimal might then swing into a narrow elliptical orbit that brings it toward the inner solar system. As it nears the sun, the heat vaporizes its volatile materials, which spew forth as if from a geyser. In ancient cultures, this celestial spectacle was sometimes an ominous event.

Some visitors from the Oort cloud are never seen again; others have periods that get shorter with each successive pass. The best known of these comets are those that return regularly, such as Halley's, with a period of 76 years. The chance that such a comet will collide with the earth is exceedingly small, because it comes by so infrequently. But the patterns of their orbits suggest that in the next millennia, comet Halley or Swift-Tuttle (with a period of 130 years) will sometimes swing by too close for comfort.

In 1951 Gerard P. Kuiper, then at Yerkes Observatory of the University of Chicago, surmised that another belt of comets exists, just beyond Neptune's orbit, much nearer than the Oort cloud. Working at the University of Hawaii, David C. Jewitt and Jane Luu discovered the first of these objects in 1992 after a persistent search; by now some 31 bodies belonging to the Kuiper belt have been found. In fact, Pluto, with its unusually elliptical orbit, is now considered to be the largest of these objects; Clyde Tombaugh, who discovered Pluto in 1930, calls it the "King of the Kuiper belt."

Comets belonging to the Kuiper belt are not directly disturbed by rival stars. Instead they can stray close to Neptune, which may either help stabilize them or, conversely, throw them out of orbit. (An as yet unknown 10th planet may also be stirring the comets' path, but the evidence for its existence is inconclusive.) The comets may then come very close to the sun. Although those from the Kuiper belt tend to have shorter periods than those from the Oort cloud, both types of comets can be captured in tight orbits around the sun. It is therefore impossible to tell where a particular comet—such as Tempel-Tuttle, which sweeps by at 72 kilometers per second every 33 years—originated from.

Some comets are bound into small orbits and have short periods, on the order of 10 years. These comets pose more of a concern than the ones that come by only every century or so. A collision with such a short-period comet might occur once in some three million years.

However infrequent a cometary collision might be, the consequences would be calamitous. The orbits of comets are often steeply inclined to the earth's; oc-

F. GOHIER *Explorer*

METEOR CRATER in northern Arizona, a depression 1.2 kilometers in diameter, was carved out by an asteroid that struck the earth 50,000 years ago. The asteroid was only 30 meters wide but, being metallic, was strong enough to penetrate the atmosphere without disintegrating. The earth collides with an object of this size or larger once in a century.

casionally, a comet is even going in the opposite direction. Thus, comets typically pass the earth with a high relative velocity. For example, Swift-Tuttle, which is about 25 kilometers across, flies by at 60 kilometers per second. It would impact with cataclysmic effect.

Unless it runs into something, a comet probably remains active, emitting gases and dust for some 500 passages by the sun. Eventually, the volatile materials are used up, and the comet fades away as a dead object, indistinguishable from an asteroid. Up to half of the nearest asteroids might in fact be dead, short-period comets.

Falling Rocks

Indeed, most of the danger to the earth comes from asteroids. Like comets, asteroids have solar orbits that are normally circular and stable. But there are so many of them in the asteroid belt that they can collide with one another.

The debris from such collisions can end up in unstable orbits that resonate with the orbit of Jupiter. By virtue of its immense mass, Jupiter competes with the sun for control of the motions of these fragments, especially if an asteroid's orbit "beats," or resonates, with that of the giant planet. So, for instance, if the asteroid goes around the sun thrice in the same time that Jupiter orbits once, the planet's gravitational influence on the rock is greatly enhanced. Just as a child on a swing flies ever higher if someone pushes her each time the swing returns, Jupiter's rhythmic nudges ultimately cause the asteroid to veer out of its original orbit into an increasingly eccentric one.

The asteroid may either leave the solar system or move in toward the terrestrial, rocky planets. Eventually, such vagrants collide with Mars, the earth-moon system, Venus, Mercury or even the sun. A major fragment enters the inner solar system once in roughly 10 million years and survives for about as long.

To estimate the chances of such a rock hitting the earth, the asteroids have first to be sorted according to size. The smallest ones we can observe, which are less than a few tens of meters across, rarely make it through the earth's atmosphere; friction with air generates enough heat to vaporize them. The asteroids that are roughly 100 meters and larger in diameter do pose a threat. There are 100,000 or so of these that penetrate the inner solar system deeper than the orbit of Mars. They are called near-earth asteroids.

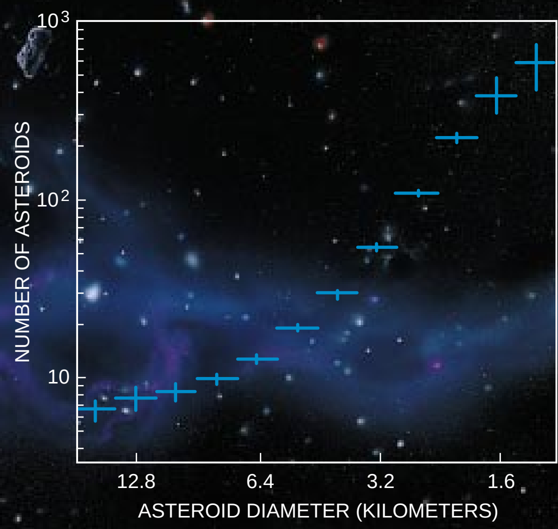
In 1908 one such object, a loose conglomerate of silicates about 60 meters wide, entered the atmosphere and burst apart above the Tunguska Valley in Siberia. The explosion was heard as far away as London. Although the fragments did not leave a crater, the area below the explosion is still marked by burnt trees laid out in a region roughly 50 kilometers across. The identity of the Tunguska object inspired a lot of nonsensical speculation for decades, and some highly imaginative suggestions were made, including that it was a mini–black hole or an alien spacecraft. Scientists, however, have always understood that it was a comet or asteroid.

Events such as the Tunguska explosion may occur once a century, and it is most likely that they would occur over the oceans or remote land areas. But they would be devastating if they happened near a populated area. If one exploded over London, for instance, not only the city but also its suburbs would be laid waste.

Of the smaller asteroids, the few metallic ones are tough enough to penetrate the atmosphere and carve out a crater. The 1.2-kilometer-wide Meteor Crater in northern Arizona is an example; it came from a metallic asteroid about 30 meters in diameter that fell some 50,000 years ago.

The Threat from Asteroids

The asteroid belt, home of most asteroids, lies between the orbits of Mars and Jupiter. The chart (*below*), put together from Spacewatch observations, shows that smaller asteroids, produced by fragmentation of the larger ones, are more numerous.The rocks normally remain in circular, stable orbits, but collisions, along with the gravitational influence of Jupiter, can throw them into narrow, unstable orbits. Then the asteroids may enter the inner solar system, where they pose a threat to the earth.



ALFRED T. KAMAJIAN (*illustration*); JOHNNY JOHNSON (*graph*)
ROBERT JEDICKE *University of Arizona*

An even greater peril is posed by the 1,000 or 2,000 medium near-earth asteroids that are roughly one kilometer and larger in size. One of these asteroids is thought to collide with the earth once in about 300,000 years. Note that this estimate is only a statistical average. Such a collision can happen at any time—a year from now, in 20 years or not in a million years.

Frightful Darkness

The energies liberated by an impact with such an object would be tremendous. The kinetic energy can be calculated from $1/2\ mv^2$, where m is the mass of the object, and v is the incoming velocity. Assuming a density of about three grams per cubic centimeter, as known from meteorites, and an average velocity of 20 kilometers per second, a one-kilometer-wide object would strike with a shock equivalent to tens of billions of tons of TNT—millions of times the energy released at Hiroshima in 1945.

Granted, asteroids do not emit the nuclear radiation that caused the particular horrors of Hiroshima. Still, an explosion of millions of Hiroshimas would do more than destroy a few cities or some countries. The earth's atmosphere would be globally disrupted, creating the equivalent of a nuclear winter. Large clouds of dust would explode into the atmosphere to obscure the sun, leading to prolonged darkness, subzero temperatures and violent windstorms.

Even more dangerous are the largest near-earth asteroids, which are about 10 kilometers in diameter. Fortunately, there are only a few such threatening objects, perhaps just 10. (Even more fortunately, they happen to be mere fragments of the objects in the asteroid belt, which can be as large as 1,000 kilometers across.) An asteroid of this size collides with the earth only once in 100 million years or so.

One such event is evident in the fossil record. The impact of a celestial object marks the end of the Cretaceous geologic period and the beginning of the Tertiary, 65 million years ago. After years of searching, the crater from that event—a depression about 170 kilometers in diameter—has been identified in the Yucatán Peninsula of Mexico. Although the crater cannot be directly seen, it has fortuitously been identified by drillings for oil and in images taken from the space shuttle *Endeavour*. The depression resulted from the explosive impact of an object perhaps 10 to 20 kilometers in diameter.

Studies of the effects of that explosion paint a frightening picture. An enormous fireball ejected rocks and steam into the atmosphere, jarred the earth's crust and triggered earthquakes and tsunamis around the globe. Vast clouds of dust, from the earth and the asteroid, erupted into the stratosphere and beyond. There ensued total darkness, which lasted for months.

Acid rain began to fall, and slowly the dust settled, creating a layer of sediment a few centimeters thick over the earth's surface. Below this thin sheet we see evidence of dinosaurs. Above it they are missing, as are three fourths of the other species. The darkness following the explosion must have initially plunged the atmosphere into a freeze.

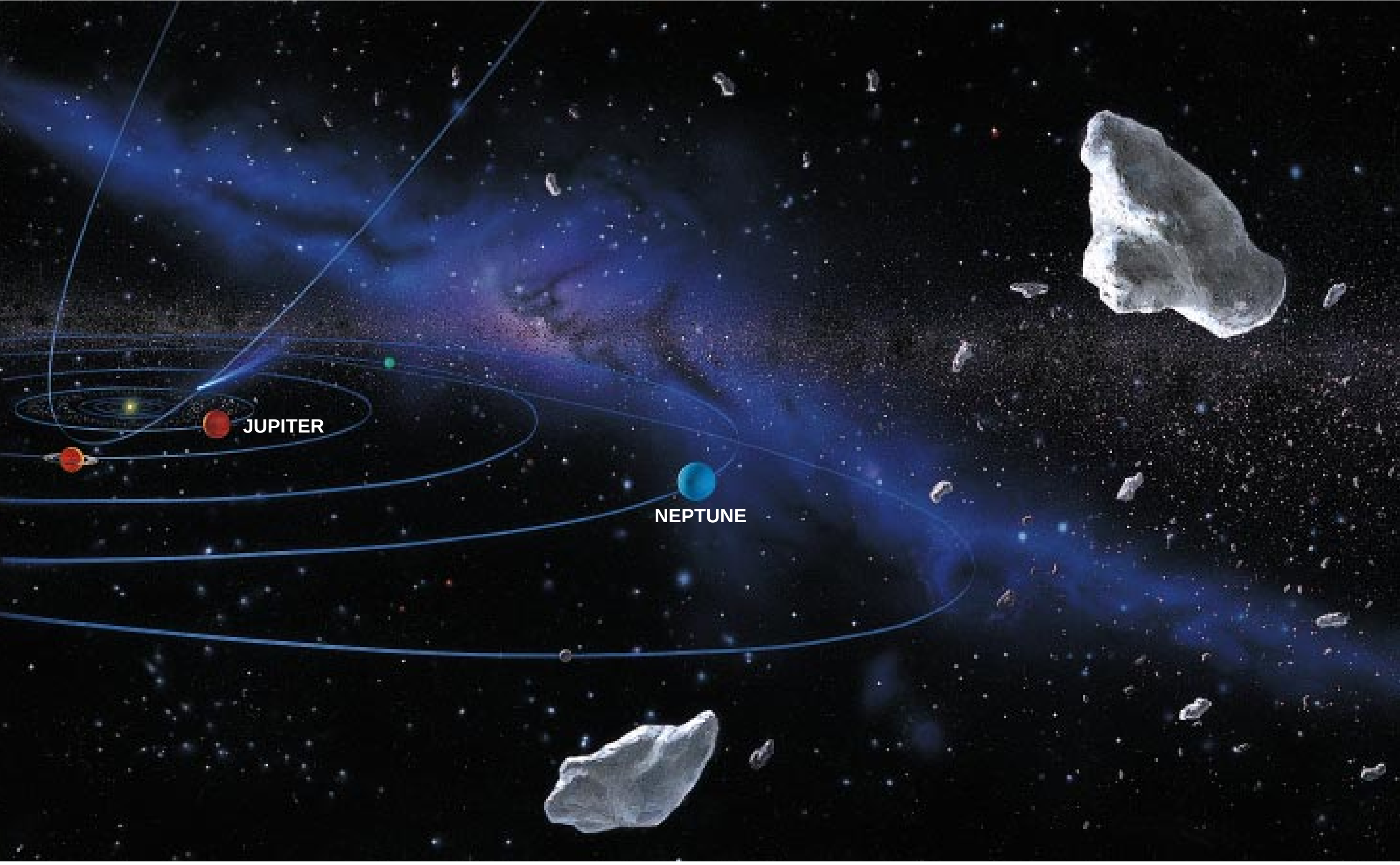
Over many centuries, the reverse effect—a slow greenhouse warming, by as much as 15 degrees Celsius—had an equally devastating outcome. The asteroid had struck the earth in a vulnerable place, slicing into a rare region with a deep layer of limestone. (Less than 2 percent of the earth's crust has so much limestone; Australia's Great Barrier Reef is an example.) The explosion ejected the carbon dioxide from the limestone into the atmosphere, where, along with other gases, it helped to trap the earth's heat. Jan Smit of the Free University, Amsterdam, has proposed that the severe warming, rather than the initial freeze, killed the dinosaurs—there is some evidence that they died off slowly.

Spacewatch

So—are we going to be hit? To begin with, the answer lies in the domain of planetary astronomy. The dangerous objects have to be located, as soon as possible, to diminish the chances of our unexpected demise. Furthermore, they have to be tracked on the succeeding nights, weeks, months and even years so that their orbits can be accurately extrapolated into the future.

In the early 1970s a 0.46-meter photographic camera at the Palomar Observatory in southern California was dedicated to the search for near-earth objects. Eleanor Helin of the Jet Propulsion Laboratory in Pasadena, Calif., led one of the teams of astronomers, and Eugene M. and Carolyn S. Shoemaker of the U.S. Geological Survey led the other. The scientists photographed the same large areas of the sky at half-hour intervals. As asteroids orbit the sun, they move with respect to the background stars. If near to the earth, the asteroid is seen to travel relatively fast; the motion is easily recognized from the multiple exposures.

Since the pioneering efforts at Palo-

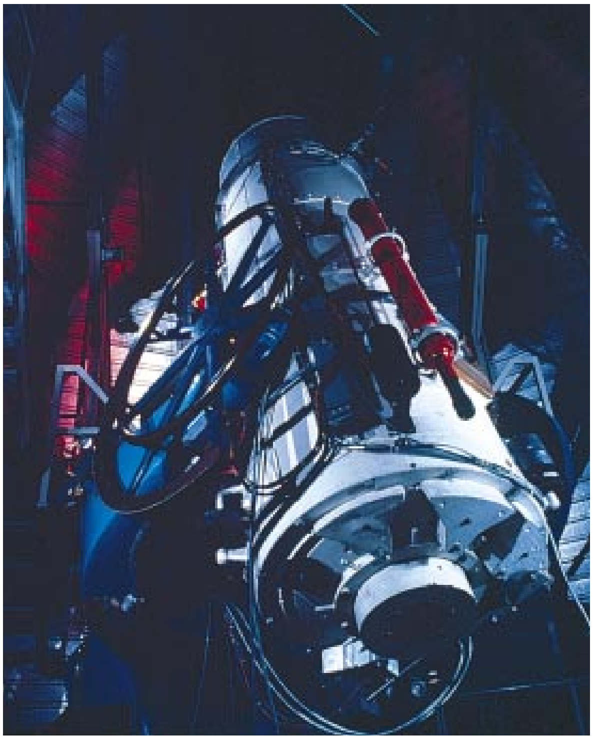


mar, other observers have become interested in near-earth asteroids. At Siding Spring in the mountains of eastern Australia, a dedicated group of scientists uses a 1.2-meter photographic camera to hunt for these rocks. In 1994 observers in California and Australia, with their photographic methods, jointly discovered 16 near-earth asteroids. (At the end of that year, the Palomar project closed as more modern techniques were developed elsewhere.)

About 15 years ago Robert S. McMillan, also at the University of Arizona, and I began to realize that at this rate, it would take more than a century to map the 1,000 or more asteroids that are larger than one kilometer across. By taking advantage of electronic detection devices and fast computers, the rate of finding asteroids could be greatly increased. Spacewatch, a project dedicated to the study of comets and asteroids, was born in Tucson. A 0.9-meter telescope at the University of Arizona's Steward Observatory on Kitt Peak, 70 kilometers west of Tucson, is now dedicated to Spacewatch. Robert Jedicke, James V. Scotti, several students and I, all from Tucson, use this facility regularly for finding comets and asteroids. McMillan, Marcus L. Perry, Toni L. Moore and others, also from Tucson, use it for finding planets around other stars.

Instead of photographic plates, our electronic light detectors are charge-coupled devices, or CCDs. These are finely divided arrays of semiconductor picture elements, or pixels. When light hits a pixel, its energy causes positive and negative electrical charges to separate. The electrons from all the pixels provide an image of the light pattern at the focal plane of the telescope. A computer then compares images of the same patch of sky scanned at different times, marking the objects that have moved.

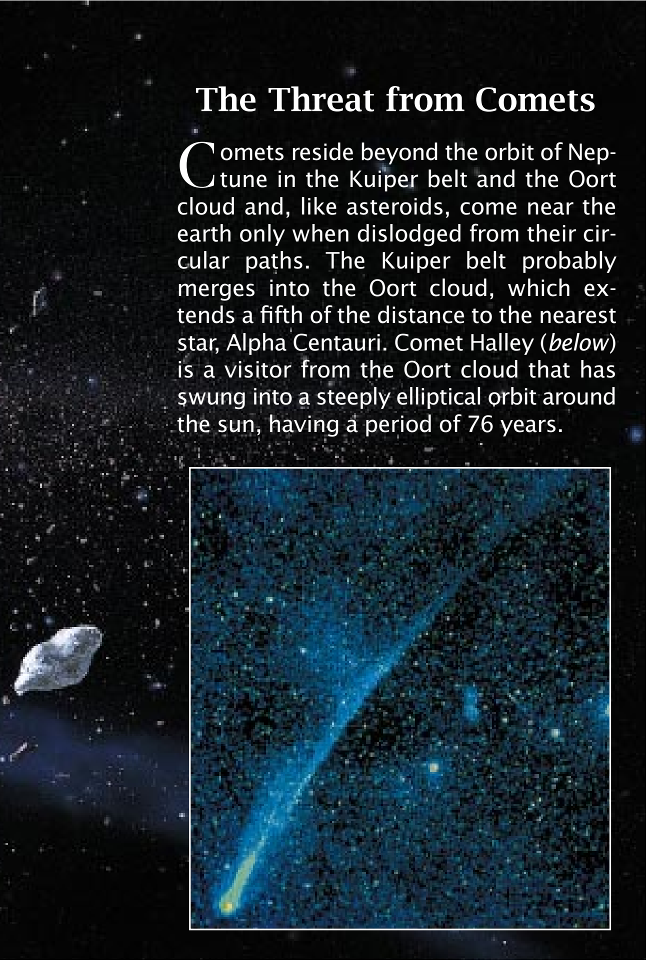
In this manner, Spacewatch observers may find as many as 600 asteroids a night. Most of these are in the asteroid belt; only occasionally does an object move against the star field so fast that it must be close to the earth. (Similarly, an airplane high above in the sky seems to move slower than one coming in low for a landing.) In 1994 Scotti found an asteroid that


UNIVERSITY OF ARIZONA

SPACEWATCH telescope on top of Kitt Peak in southern Arizona is dedicated to searching for comets and asteroids.

The Threat from Comets

Comets reside beyond the orbit of Neptune in the Kuiper belt and the Oort cloud and, like asteroids, come near the earth only when dislodged from their circular paths. The Kuiper belt probably merges into the Oort cloud, which extends a fifth of the distance to the nearest star, Alpha Centauri. Comet Halley (*below*) is a visitor from the Oort cloud that has swung into a steeply elliptical orbit around the sun, having a period of 76 years.



ALFRED T. KAMAJIAN (*illustration*); ROYAL GREENWICH OBSERVATORY *Science Photo Library/Photo Researchers, Inc.* (*photograph*)

passed within 105,000 kilometers of the earth. Also in that year, Spacewatch reported 77,000 precise measurements of comet and asteroid positions. One gratifying aspect of Spacewatch is that it has private and corporate supporters (currently 235) in addition to the U.S. Air Force Office of Scientific Research, the National Aeronautics and Space Administration, the Clementine space program, the National Science Foundation and other governmental organizations.

Spacewatch has discovered an abundance of small asteroids, those in the range of tens of meters. The numbers of these objects exceed predictions by a factor of 40, but we do not as yet understand their origins. These asteroids we call the Arjunas, after the legendary Indian prince who was enjoined to persist on his charted course. Military reconnaissance satellites have since also observed the Arjunas. The data, once routinely discarded but now stored and declassified, show the continuous showering of the planet by small asteroids. Because of the atmosphere, these rocks burn up with little consequence, even though similar ones scar the airless moon.

The next step for Spacewatch is to install our new telescope, which was built with an existing 1.8-meter mirror, so that we can find fainter and more distant objects. This state-of-the-art instrument, the largest in the field of asteroid observation, should serve generations of explorers to come. Meanwhile, at Côte d'Azur Observatory in southern France, Alain Maury is about to bring a telescope into operation with an electronic detection system. Duncan Steel and his colleagues in Australia are switching to electronics as well, although this project has funding problems perhaps more severe than ours. Next to join the electronic age might be Lowell Observatory near Flagstaff, Ariz., under the supervision of Edward Bowell. The U.S. Air Force is also planning to use one of its one-meter telescopes to this end; Helin and her associates already use the one on Maui in Hawaii. And amateur astronomers are coming on-line with electronic detectors on their telescopes.

If there is an asteroid out there with our name on it, we should know by about the year 2008.

Deflecting an Asteroid

And what if we find a large object headed our way? If we have only five years' notice, we can say good-bye to one another and regret that we did not start surveying earlier. If we have 10 years or so, our chances are still slim. If we have 50 years' notice or more, a spacecraft could deploy a rocket that would explode near the asteroid. Perhaps the most powerful intercontinental ballistic missiles could blast a small object out of the way. (That, incidentally, would also be a good means of getting rid of these relics from the cold war.)

It seems likely, however, that we will have more than 100 years to prepare. Given that much time, a modest chemical explosion near an asteroid might be enough to deflect it. The explosion will need to change the asteroid's trajectory by only a small amount so that by the time the asteroid reaches the earth's vicinity, it will have deviated from its original course enough to bypass the planet.

Present technology for aiming and guiding rockets is close to miraculous. I once overheard two scientists arguing about why *Pioneer 11* had arrived 20 seconds late at Saturn—after a journey of six years. But the detonation will have to be carefully designed. If the asteroid is made of loosely aggregated material, it might disintegrate when shaken by an explosion. The pieces could rain down on the earth, causing even greater damage than the intact asteroid, as hunters who use buckshot know. A "standoff" explosion, at some distance from the surface, may be the most effective in that case. Earth-based radar, telescopes and possibly space missions will be needed to determine the composition of an asteroid and how it might break up.

Further into the future, laser or microwave devices might become suitable. Gentler alternatives, such as solar sails and reflectors planted on the asteroid's surface—to harness the sun's radiation in pushing the asteroid off course—have also been suggested. A few scientists are studying the feasibility of nuclear devices to deflect very massive asteroids that show up at short notice.

Comets and asteroids remind me of Shiva, the Hindu deity who destroys and re-creates. These celestial bodies allowed life to be born, but they also killed our predecessors, the dinosaurs. Now for the first time, the earth's inhabitants have acquired the ability to envision their own extinction—and the power to stop this cycle of destruction and creation.

The Author

TOM GEHRELS was inspired to study celestial objects upon attending a class given by Jan Oort in the Netherlands, who surmised the existence of a distant shell of comets now called the Oort cloud. Gehrels is professor of planetary sciences at the University of Arizona at Tucson, a Sarabhai Professor at the Physical Research Laboratory in India and principal investigator of the Spacewatch program at Kitt Peak, Ariz., where he hunts for comets and asteroids.

Further Reading

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