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Pieces of the Sky

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COVER: We glimpse the ancient past through rocks that have survived their fall through Earth's atmosphere. Some of these meteorites, a type called carbonaceous chondrites, contain material virtually unaltered since the formation of our solar system. In this sample from the Allende meteorite, which fell in 1969, the 0.5-millimeter spherical chondrules appear in a dark, carbon-rich matrix. Some carbonaceous chondrites contain complex organic molecules, including amino acids, the building blocks of carbon-based life.
Photograph: John L. Berkley

FROM THE EDITOR

Near-Earth asteroids are small bodies with great potential—for both good and harm—and they are now the focus of a major Planetary Society program. From June 30 to July 3, 1991, the Society cosponsored, with NASA, the International Conference on Near-Earth Asteroids at the San Juan Capistrano Research Institute in Southern California.

The conference was attended by nearly every professional astronomer searching for near-Earth asteroids, engineers planning spacecraft missions to them, and scientists seeking to understand them. More than 40 percent of the participants came from outside the United States. Nightly television news shows, newspapers, magazines and radio brought the once-arcane topic of asteroids into homes around the world.

To say we are pleased with this result would be to understate our sense of accomplishment. So, to share this conference with members who were unable to attend, we have put together this special issue of *The Planetary Report*.

The conference organizer, Clark R. Chapman, considered publishing a volume of scientific proceedings. Instead, he decided to present the results to Society members as a series of articles summarizing the conference.

Page 3—Members' Dialogue—Several Planetary Society projects have been triggered by suggestions from members. Two members have ideas to share, and another catches a mistake.

Page 4—Killer Rocks and the Celestial Police—To study or to visit near-Earth asteroids, we first have to find them. The search began in the 19th century and continues today, yet we've found only about 1 percent of the estimated population.

Page 8—Asteroids and Comets in Near-Earth Space—Meteorites provide convenient samples we can study in the laboratory, and telescopes enable us to study asteroids and their close relatives, comets, in their native environment. Although we have learned much, we have many questions to answer before we understand their role in the evolution of the solar system.

Page 12—It's a Small, Small World—They are tiny targets, but their orbits bring them tantalizingly close to Earth. The asteroids' size and proximity make them attractive targets for spacecraft exploration. The authors explain how they plan trips to asteroids.

Page 16—The Sky *Is* Falling—Whether or not an asteroid or comet killed off the dinosaurs (as many scientists believe), the inevitable collisions between Earth and its neighbors have affected our planet's environment. Are they hazards to us now? Quite possibly, as we see here.

Page 20—Prospecting the Future—As a nonprofit organization funded almost entirely by our members' donations, The Planetary Society must pick its programs very carefully. Near-Earth asteroids are now the focus of a major program, and here we tell you why.

Page 23—World Watch—We report or the effect of the space station on NASA's budget, the state of *Galileo*'s antenna, and tests of the Mars Rover.

Page 24—An Executive Report to Members: The State of The Planetary Society—Economic recession and political problems have affected our programs, but our Executive Director reports that The Planetary Society has never been in better shape.

Page 26—News & Reviews—Our columnist has recently returned from a conference on asteroid hazards held in St. Petersburg, Russia. He reports here to our members.

Page 27—Society Notes—New appointments, programs and a call for help fill this column on Society activities.

Page 28—Questions & Answers—Can *Magellan* detect volcanic eruptions on Venus? Why don't moons have moons? Could a comet pass through a gas planet? A distinguished group of scientists addresses your questions.

—*Charlene M. Anderson*

Members' Dialogue

As administrators of a membership organization, The Planetary Society's Directors and staff care about and are influenced by our members' opinions, suggestions and ideas about the future of the space program and of our Society. We encourage members to write us and create a dialogue on topics such as a space station, a lunar outpost, the exploration of Mars and the search for extraterrestrial life.

Send your letters to: Members' Dialogue, The Planetary Society, 65 N. Catalina Avenue, Pasadena, CA 91106.

The week after I received and read "What Now With the Soviets?" by Louis Friedman [see the July/August 1991 *Planetary Report*], the Soviet Union weathered an attempted coup and then ceased to exist. Obviously and unfortunately, these events, coupled with Mr. Gorbachev's recent statement that the Soviet space program is temporarily on hold, have rendered many of the article's assumptions obsolete.

However, Dr. Friedman made what may be a prophetic statement when he wrote, "It will be a long time before Americans will fly in orbit for periods of over a month—unless they fly on *Mir*." Now the Soviets have put most of their space industry up for sale to the West, leading to the possibility that the United States could, in fact, purchase *Mir* [see News Briefs]. I encourage the exploration of this possibility. Although *Mir* will come to the end of its operational life within a few years, and with our government floundering on the form and funding of a $30 billion space station *Freedom*, to purchase *Mir* for a projected $800 million may not only add resources to our space program, but inject desperately needed funds into a Soviet economy on the brink of collapse.

Also, let me congratulate the Society for its new status as a nongovernmental organization associated with the Economic and Social Council of the United Nations. This status is even more important when the UN's heightened role in recent world affairs is considered.

I've just become a member again after a one-year hiatus. My only question to myself is, why did I ever let myself leave?
—GARY LAI, *Binghamton, New York*

So far, the Soviets working on the Mars '94 *and* Mars '96 *projects assure us that they are going ahead on schedule. As for* Mir, *US astronauts are scheduled to fly on* Mir *as a result of the last Bush-Gorbachev summit. —Louis D. Friedman, Executive Director*

When I received the July/August 1991 issue of *The Planetary Report*, I got the distinct impression that the picture of Meteor Crater on the cover was backward. I wonder how many other people picked this up?
—DONALD RATHBUN, *El Paso, Texas*

The photo was inadvertently flopped during the production process. —Editor

I was delighted to see that the European Space Agency was able to provide us with a "new perspective" on Eclipse 1991 [see the September/October 1991 *Planetary Report*]; it's the sort of international cooperation that The Planetary Society is already making great strides in promoting.

But looking at those pictures saddened me also, for I was reminded that we in Europe are denied a great deal when it comes to sharing the bounty of American space exploration. In particular, European taxpayers who fund vast amounts of cooperative space ventures are unable to tune in to the educational programming of NASA Select television—the world's only "space channel." Most planetary mission reporting and shuttle flight coverage relates to projects that have a deep European involvement. The US State Department operates a transatlantic satellite TV transponder that is inoperative most of the day, and the opportunities for reaching a vast new audience are breathtaking.

Might I suggest that this is a matter which could be pursued by The Planetary Society on behalf of its many European members—East and West. As a professional broadcaster with links throughout the continent, I would be happy to draw up any projections you might need about likely usage of the signal by cable and broadcast companies. From my contacts, and knowing the passion for space in Europe, I am certain NASA Select would be a big success, in promoting space science and in furthering the State Department's own more complex aims!
—LEO ENRIGHT, *Dublin, Ireland*

NEWS BRIEFS

The lucky few who have seen "this fragile Earth, our island home," from space have all been struck by the disappearance, from that wondrous vantage point, of political borders. From out there, the whole Earth is the only Earth you see. And no one who has felt the romance and the implicit hope of all can quite suppress a sigh at the thought that the internal borders of the Soviet Union, once barely visible even from down here, have started to count for so much up there.

The Soviet Union is breaking apart as the travel-weary cosmonauts orbit high above it; still, for all that, the Earth itself may be knitting together.

Safe home, brothers. Let's hope that one day we can look back on this—on *all* this—and laugh.
—from the *Los Angeles Times*

This country's troubled space program is not helped by the prospect of $1.4 billion going down the drain because of an 80-thousandths-of-an-inch glitch [on *Galileo*'s stuck antenna]. But oddly, the fix-it operations now under way also illustrate the allure of space exploration. If the engineers succeed in making this minute correction by remote control on a spacecraft soaring out beyond the ether somewhere, who is going to say that's not astounding?
—from the *Sacramento Bee*

Soviet space officials have told the White House that their cash-hungry civilian space program may collapse unless it makes large sales to the West. Almost everything, they said, is on the table, even space station *Mir*, now orbiting Earth.

White House officials are reported to be unsure of how much credence to give the new offer, given the swift pace of political change in the Soviet Union. So far they have not responded. Any decision to buy a piece of the Soviet space program would require high-level federal approval and would be done only after careful study.
—from William J. Broad in *The New York Times*

Killer Rocks and

The Search for

by Donald K. Yeomans

The realization that comets and asteroids might pose a danger to Earth does not belong to the late 20th century. This 19th-century cartoon from France shows an extremely dramatic outcome of a cometary collision.

Illustration courtesy of Donald K. Yeomans

On January 1, 1801, the Italian monk and astronomer Giuseppe Piazzi was only dimly aware that it was the first day of the nineteenth century. Rather, he was quietly celebrating something else: his discovery of a new planet in the constellation of Taurus the Bull.

While checking the stellar positions given in a new star catalogue, Piazzi found an object that was not in the catalogue, an object that appeared to be moving from night to night. Because it lacked the diffuse appearance of a comet, Piazzi dared to hope that "it might be something better than a comet." What he had discovered was Ceres, the first of the bodies we call asteroids, and the largest.

Fourteen weeks earlier, the Hungarian-born astronomer Baron Franz Xaver von Zach had called together several prominent astronomers to solicit their support in forming a search party. Zach reasoned that the nearly circular planetary orbits should be arranged with their distances from the Sun increasing in an orderly fashion. There was, however, an unacceptable gap between the paths of Mars and Jupiter.

Zach's own search efforts had failed to find a planet within this region, but he hoped that a coordinated international search would be more successful. His search party was dubbed the "celestial police." Before Zach could get word of the search to Piazzi, the latter had found what was apparently the missing planet. The search was over—or so it seemed, until another little world was located the next year and still another in 1804. By the end of the nineteenth century, nearly 500 asteroids had been discovered, most of them in Zach's gap between Mars and Jupiter, what is now termed the main asteroid belt.

The asteroid discovery rate accelerated. Some astronomers who were trying to observe faint stars were irritated by the asteroids' often unexpected appearance in the star fields; one German astronomer derisively referred to the asteroids as the "vermin of the skies."

Not all the asteroids discovered in the nineteenth century were in the main asteroid belt. In 1873, asteroid 132 Aethra was discovered; its orbital path brought it inside the orbit of Mars. Twenty-five years later asteroid 433 Eros was found —it not only passed within the orbit of Mars but approached the orbit of Earth. Eros was the first of the near-Earth asteroids to be discovered.

In 1932, the discovery of asteroids 1221 Amor and 1862 Apollo laid the basis for the classification system we now use to describe two types of near-Earth asteroids, the Amor and Apollo objects. Amors cross Mars' orbit and come closest to the Sun just outside Earth's orbit. Apollos cross the orbits of both Mars and Earth. The orbits of the third group of near-Earth asteroids are smaller than that of Earth, but their paths are more eccentric and they travel just outside Earth's orbit when they are farthest from the Sun. These asteroids are termed Atens, after the prototype, 2062 Aten, discovered by Eleanor "Glo" Helin in 1976.

It is obvious that Earth runs its course about the Sun in a swarm of asteroids. Sooner or later, our planet will be struck by one of them. Recent media accounts have likened Earth to a target in the solar system shooting gallery, with near-Earth asteroids described as "killer rocks."

Searching for Suspects

Today, efficient search programs are in place and astronomers are discovering near-Earth asteroids at the extraordinary rate of about two per month. In 1973, astronomers Glo Helin and Gene Shoemaker initiated the Planet-Crossing Asteroid Survey, a search program designed to find Earth-approaching asteroids and comets. In 1980, Gene's wife, Carolyn, joined the search, and two years later Mom and Pop Shoemaker, as Gene jokingly refers to the team, began a separate search for close-approaching objects. Helin's team and the Shoemakers use the same Schmidt telescope at Palomar Mountain Observatory in Southern California.

These two search teams cover vast regions of dark sky during the one week per month that each group is allotted on the telescope. With its 18-inch (45-centimeter) aperture and 8.5-degree field of view, the Palomar Schmidt telescope is well suited for the task. The wider the searchers can cast their net, the more chance they will have of pulling in a new catch.

The success of their programs also depends upon how faint an object they can catch in their photographic nets and the efficiency of their procedures. Using precise, well-

the Celestial Police

Near-Earth Asteroids

Even the most idyllic vacation is in danger of being disrupted by a near-Earth asteroid, as recorded by an alert photographer in Grand Teton National Park. On August 10, 1972, an object estimated at 80 meters (about 260 feet) in diameter and weighing 1 million metric tons narrowly missed colliding with Earth's surface, although it burned in our atmosphere for 101 seconds over 915 miles as it traveled at 33,000 miles per hour.

Photograph: James M. Baker, courtesy of Dennis Milon

choreographed movements, one person exposes a film at the telescope while the other prepares for the next exposure. Often a third team member simultaneously inspects a previously developed exposure to detect new near-Earth objects.

Telescopic searches are usually conducted during periods of new Moon, when light from the faint asteroids is not washed out by moonlight. The search is centered at opposition—that is, the telescope is pointed in the direction in the night sky opposite the Sun, which is then on the other side of Earth. Since the object is facing the Sun directly, with its entire hemisphere illuminated, it appears at its brightest.

Astronomers program the telescope to track on the stars as Earth's rotation carries them across the night sky. A closely approaching asteroid will appear to move in a different direction than do the background stars, and with a different velocity. In the few minutes it takes to expose the photographic film, an asteroid forms an elongated image on the film, while the stars appear as points of light.

The searchers must somehow distinguish the near-Earth suspect from the vastly more numerous main-belt asteroids. The person working the telescope takes two exposures 45 minutes apart. Because at the time of discovery near-Earth objects generally appear to be moving faster than, and in a different direction from, the main-belt objects, the direction of their motions, together with the elongation of their photographic images, usually gives them away.

Larger asteroids tend to appear brighter than smaller objects at the same distance, and the closer an asteroid is to Earth, the faster it is moving and the more elongated its image will appear. By carefully examining the two films,

Naming an Asteroid

When it is found, an asteroid is given a temporary designation consisting of the year of discovery and two letters. The first letter indicates the half month of discovery, while the second gives the order of discovery. For example, the asteroid 1991BA was the first asteroid (A) discovered in the second half of January (B) in 1991.

Once we know an object's orbital path well enough, the temporary designation is replaced by a permanent number. Then its discoverer is given the privilege of naming it.

This year Glo Helin allowed Planetary Society members to suggest names for her discovery, 1982DB, one of the best candidates known for a spacecraft mission. From the hundreds of names submitted, she selected "Nereus," suggested by Robert M. Cutler of Potomac, Maryland.

Nereus joins nearly 5,000 named asteroids, with appellations relating to such diverse entities as Greek and Roman gods (1 Vesta, 1221 Amor, 1682 Apollo), an airline (2138 Swissair), a restaurant (2038 Bistro) and the Beatles (4147 Lennon, 4148 McCartney, 4149 Harrison and 4150 Starr).

With so many names to work with, ample opportunities arise for unabashed silliness. For example, by combining the names of the numbered asteroids 904, 673, 449, 848 and 1136, one gets Rockerfellia Edda Hamburga Inna Mercedes. Asteroids 3651, 1485 and 1589 give a result with special meaning for Planetary Society members: Friedman Isa Fanatica. —DKY

an astronomer can determine the direction of the asteroid's apparent motion in the sky.

Tracking New Discoveries

As soon as the searchers spot a near-Earth asteroid, they quickly send word out to other observers before it is lost. New suspects move fast, and the light of the Moon will soon interfere, so follow-up must be done at once. Telephones, astronomical telegrams and computer "e-mail" services all relay the position of the object at the time of its discovery. A loose network of observers around the world makes follow-up position measurements so that the object's orbit can be computed accurately. With that done, astronomers can predict its future positions with some confidence.

Discoveries are usually made with short-focus, wide-field telescopes, but the follow-up observers—knowing the object's location in the sky—can look more intensively at smaller areas using long-focus instruments that have narrow fields of view. With this equipment they can measure with extreme accuracy the object's position against the background stars over several days. The follow-up observers can also take advantage of charge-coupled devices (CCDs)—electronic detectors that are several times more sensitive than photographic equipment in capturing images of weak light sources.

During the dark of the Moon, many astronomers remain on call, waiting for news of a discovery so they can act quickly before the object is lost. Among the most successful of these observers are Rob McNaught at Siding Spring, Australia; Ted Bowell at Lowell Observatory, Arizona; Richard McCrosky at Oak Ridge, Massachusetts; and Jeremy Tatum and David Balam in Victoria, British Columbia. Helin and her team from the Jet Propulsion Laboratory (JPL) also follow up recent discoveries, both their own and those of others.

Since near-Earth asteroids are usually found when they are close to Earth, it's possible for radar astronomers to observe them soon after discovery. Using positions taken optically to find their target, these researchers can almost immediately and very impressively refine the object's orbit.

Steve Ostro of JPL has had great success using two radar dishes, the giant 300-meter (1,000-foot) antenna at Arecibo, Puerto Rico, and the 70-meter (230-foot) antenna in California's Mojave Desert.

It takes skill, hard work, perseverance—and a little luck—to find an asteroid as it passes by Earth. In this discovery image of Apollo asteroid 1991TB1, the asteroid appears as a short, smeared feature against a background of fixed stars. 1991TB1 was discovered on October 9, 1991, during the Planet-Crossing Asteroid Survey led by Eleanor Helin and partly supported by The Planetary Society. PCAS team member Perry Rose found the object with the help of Ken Lawrence.
Photograph: JPL/NASA

When word goes out that a new asteroid has been discovered, Ostro often shuttles between both places to observe the visitor from two sites before it moves beyond the radar's reach.

Checking the Record

During the follow-up procedure, astronomers often try to find the new asteroid in images that have been taken before the discovery. As soon as a preliminary orbit is determined, they try to match its predicted position in the past with an enormous file of asteroid and comet observations. They often find "prediscovery" observations that had been erroneously assigned to other asteroids or comets.

If prediscovery data are found, astronomers can calculate a far more accurate orbit than is possible with only the discovery and immediate follow-up observations. They can predict with accuracy the object's past and future motions. At this point, the object is said to be secure, and its provisional designation can be replaced with a permanent number and name. (See box on page 6.) Some of the celestial detectives involved in securing asteroids' orbits by using prediscovery observations are Brian Marsden, Conrad Bardwell and Gareth Williams at the Center for Minor Planets in Cambridge, Massachusetts; Rob McNaught; Ted Bowell; and Syuichi Nakano in Japan.

Once its orbit is secure, observers using telescopes can glean information on the asteroid's physical characteristics from the properties of its reflected light and radar signals. Researchers can estimate its reflectivity and rotation period, as well as its size, shape and mass. If an asteroid were found to be on a trajectory that would cause it to collide with Earth, an estimate of its mass would be vital in deciding if the resulting disaster would be of regional concern, or perhaps global in its consequences.

An Early Warning System

Earth's closest call—that we know about—occurred this year, on January 18, when asteroid 1991BA passed well within the orbit of the Moon. There have undoubtedly been closer encounters, but we haven't had the technology to detect them until recently.

Asteroid 1991BA, only about 10 meters (30 feet) in diameter, was detected with the new Spacewatch Telescope on Kitt Peak near Tucson, Arizona. Tom Gehrels and Robert McMillan began the Spacewatch program in 1983, and it may herald the future of near-Earth asteroid search efforts.

The Spacewatch system uses a CCD operating in a semiautomatic search mode. A chosen star field is allowed to drift through the telescope's field of view, and a half hour later, the same field is scanned again. The detector automatically compares the two scans and electronically subtracts the first from the second. Since the stars haven't changed their positions, they are removed in the subtraction process. Gehrels wryly refers to these *stars* as "vermin of the skies"! Objects that have moved occupy different positions on the two scans, so they remain after the subtraction is complete. The observers note the remaining objects and make follow-up observations.

An astronomer's calendar is marked by meteor showers, which occur on the same days every year as Earth passes through clouds of cosmic debris—perhaps dust left behind as comets passed by. This meteor from the mid-August Perseid shower was photographed in the 1920s with a Kodak Brownie camera.

Photograph courtesy of Dennis Milon

Although the Spacewatch system is a clever use of a CCD in a semiautomatic mode, the relatively small size of current CCDs precludes their use in searching the large swaths of sky now scanned with photographic techniques. However, as larger and larger CCD arrays are developed, the detection of asteroids by automated systems like Spacewatch may become the preferred technique.

We've only recently realized that Earth—and those who live upon it—is orbiting through a swarm of asteroids. Simply to ensure our survival, we need to identify and track any objects that pose a threat. Researchers estimate that there are more than 10,000 objects large enough—0.5 to 5 kilometers (0.3 to 3 miles) in diameter—to cause serious terrestrial consequences.

Of this population, we've discovered and charted about 1 percent, and none of these are now on collision courses with Earth. But what of the remaining 99 percent?

To find all the objects that might endanger us, we must continue to search the skies. And we must begin new, more comprehensive programs. The vagaries of weather and the fleeting nature of close approaches ensure that a network made up of only a few telescopes will overlook a lot of suspects. We need telescopes searching for near-Earth asteroids from both hemispheres, scattered around the world at a variety of longitudes.

The gravity of the threat—as well as the potential scientific return—affects all nations of Earth. If we are ever to institute a successful asteroid early warning system, we must undertake a worldwide campaign of discovery and follow-up—spearheaded by a new, international organization of celestial police.

2956 Yeomans tracks asteroids and comets at the Jet Propulsion Laboratory. His book Comets: A Chronological History of Observation, Science, Myth, and Folklore *has recently been published by John Wiley & Sons.*

Asteroids and Comets

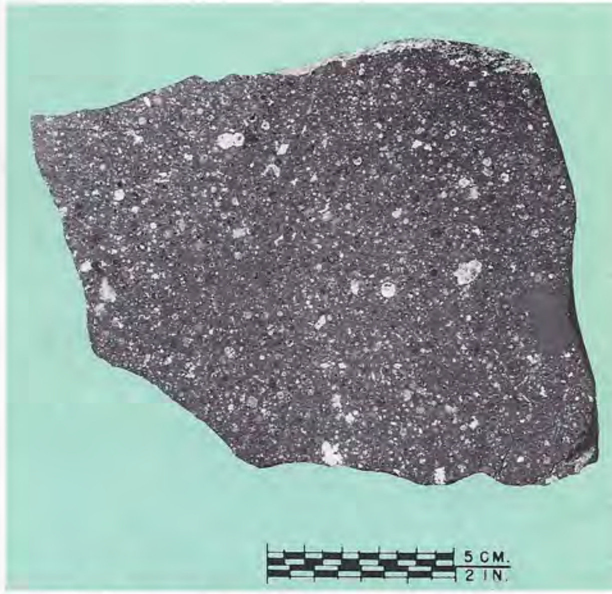
In Near-Earth Space

by Richard P. Binzel

Picture yourself outdoors on a crisp autumn evening, enjoying a star-filled sky. Toward the west, a bright comet with a long tail dangles above the horizon. As you turn to go inside, the flash of a streaking meteor catches your eye. Inside by the fireplace, you pick up your just-arrived copy of *The Planetary Report* and read about the latest near-Earth asteroid discoveries.

At first glance it might seem that comets, meteors and asteroids are distinct and unrelated members of the solar system. But we are learning more about them, and it is becoming evident that these bodies may be intimately linked. Understanding the links is one of the key goals of planetary science, and the focus of intensifying inquiry.

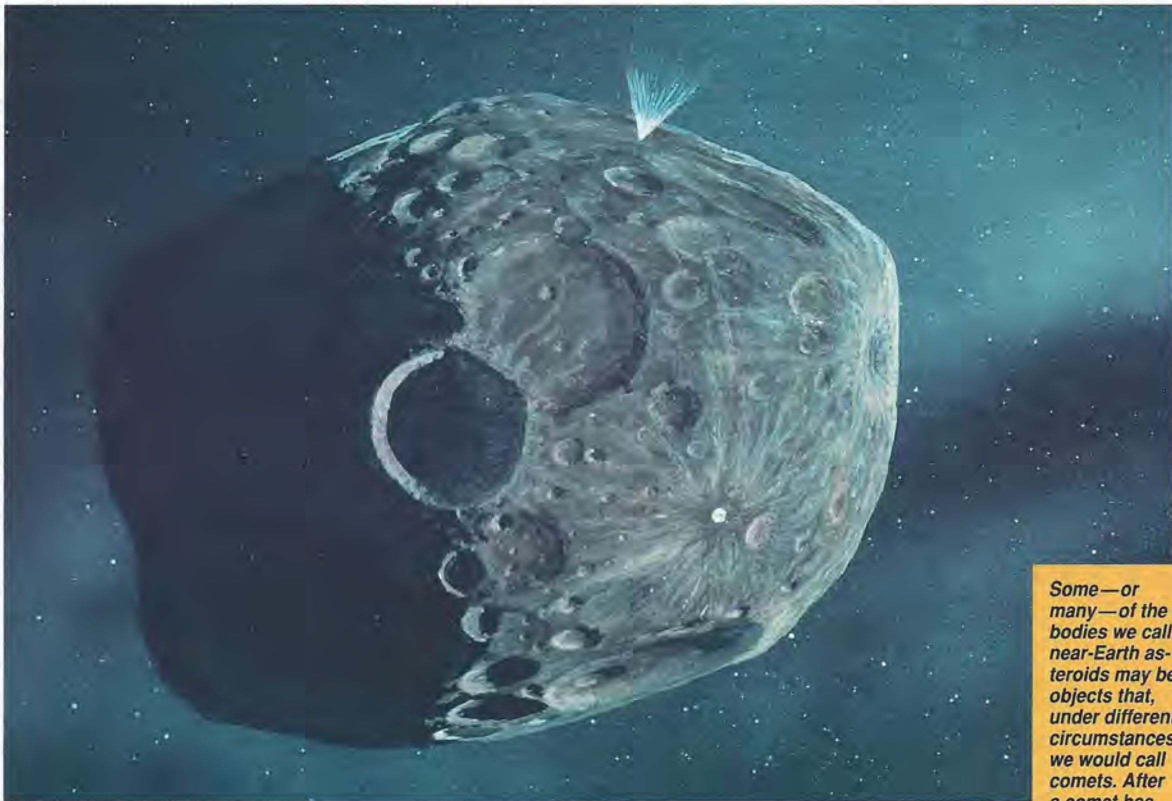
This burgeoning scientific interest in the small bodies of our solar system coincides with a heightened awareness of them for other reasons—the impact hazard to Earth; their accessibil-



ABOVE: This cross-section of a piece of the Allende meteorite reveals the round blobs called chondrules that characterize the type of meteorite called a chondrite. Scientists prize such samples from space, for these meteorites may contain samples of the primordial solar system. Chondrules may be composed of pristine material that has not been geologically processed into another form by heat, pressure or chemical interaction.

LEFT: Meteorites range from rocks the size of a room to particles the size of a dust mote. This bit of the multi-ton Allende meteorite, which fell on February 8, 1969, was a little larger than a pair of sunglasses, photographed next to it. The cactus paddles scattered on the ground were victims of the meteorite's fall.

Photographs courtesy of the Smithsonian Institution ity, which makes them attractive destinations for testing human capabilities in deep space; and their potential as sources of raw materials for future missions. Thus, a confluence of important research and technology motivations puts us on the threshold of a new era in the exploration of asteroids and comets.



Some—or many—of the bodies we call near-Earth asteroids may be objects that, under different circumstances, we would call comets. After a comet has made several passes through the inner solar system, it may become encrusted by a layer of insulating dust, which prevents it from forming a characteristic coma and tail. Still, small jets may occasionally break out.

Painting: William K. Hartmann

What They Are and Where They're Found

Near-Earth objects include asteroids and comets whose orbits about the Sun periodically bring them close to the orbit of our own planet. If the object displays a coma (a "head") or a tail of dust and gas when viewed through a telescope, it is classified as a comet. If it does not, it is classified as an asteroid.

Objects displaying cometary properties are categorized according to orbital period as long-period or short-period comets, with the latter having orbital periods of less than 200 years. Some members of both groups have orbits that cross Earth's. There are about 200 known short-period comets, representing a small fraction of the total population. Although most of these have orbits that carry them well above and below the plane of Earth's orbit, about 30 have low enough inclinations to make them accessible from Earth using modest rocket propulsion systems. (See "It's a Small, Small World" on pages 12-15.) Objects in this category include Giacobini-Zinner, the first comet to be visited by a spacecraft, and Encke, perhaps the most carefully studied comet after Halley. These comets' nuclei, which are about 10 kilometers (6 miles) in diameter, are reservoirs of volatile ices and dust and may store material virtually unaltered since our solar system formed. As a comet approaches the Sun, solar radiation releases gas and dust from the frozen body. A stream of ionized particles flowing out from the Sun, called the solar wind, blows this gas and dust away from the nucleus, creating the distinctive cometary tail.

Near-Earth asteroids (NEAs) are categorized according to their orbits as Amors, Apollos or Atens. (See box on page 11.) About 200 have been discovered. Estimates range from 5,000 to 10,000 objects larger than 0.5 kilometer (0.3 mile) in diameter, suggesting that we have so far detected only about 2 percent of the total population. The largest one we know of is 1036 Ganymed (not to be confused with Jupiter's moon Ganymede), which is 40 kilometers (25 miles) in diameter. The smallest is 1991BA, only 10 meters (about 30 feet) in diameter, noteworthy because it passed within 170,000 kilometers (about 100,000 miles) of Earth —half the distance to the Moon—in January 1991.

Asteroids and comets are the larger bodies in a range of objects that pass close by or collide with Earth. The "shooting stars," visible as they streak across the sky at night, are evidence of dust-sized bodies burning up as they enter Earth's atmosphere. They demonstrate that the continuum of bodies permeating our neighborhood extends down to extremely small objects. Fortunately, most incoming meteoroid-class objects are so small that they burn up in the atmosphere.

Bodies larger than about 10 meters in diameter are able to survive their atmospheric passage and fall as meteorites to Earth's surface. Thus meteorites provide us with vital laboratory samples from objects in near-Earth space. With aircraft such as NASA's converted U-2 spy plane, we can collect extremely fine interplanetary dust particles at extremely high altitudes. These flights have yielded samples that are broadly expanding our knowledge of the chemistry of the solar system.

Applying the scientific method to understand the population of near-Earth objects leads us to frame a few key questions that must be answered before we can fully unravel their mysteries.

Where Do They Come From?

The scarred face of the Moon tells us that small objects that stray into near-Earth space often collide with the local planet-sized bodies. Dynamical studies of their orbits suggest that gravitational interactions with Earth and other planets often fling the small objects out of the inner solar system. Given these continual and efficient removal processes, the population we see today must be continually resupplied from somewhere. Any small bodies that remained in the inner solar system right after the formation of the planets would have been depleted long ago. One or more still-active processes must add new objects to the inner solar system at about the same rate at which they are removed.

The attempt to unravel these processes may seem like an exercise in supply-side economics, but we must grapple with them in order to reconstruct the evolution of the terrestrial planets. Consider the immense impact basins and nearly innumerable craters on the airless surfaces of the Moon and Mercury. Both Mars and Venus (even with its thick atmosphere) show an abundance of impact craters. On our own planet, oceans plus relentless tectonic and weathering processes have mostly obscured the impact record.

Cometary visitors appear to be supplied from the Oort cloud, a deduced reservoir of primordial solar system material encircling the Sun more than 10,000 AU away. (An AU, or astronomical unit, is equal to the average distance from Earth to the Sun.) A second source may be closer—a disk of comets orbiting the Sun just a few times more distant than Pluto's orbit. Although all objects that enter the inner solar system initially have long orbital periods, some are perturbed into short-period orbits through gravitational interactions with Jupiter and the other planets.

The population of near-Earth asteroids, on the other hand, may be replenished from the main asteroid belt between Mars and Jupiter. We've tracked the orbits of nearly 20,000 objects through this region, and there are many more to be discovered. A process called chaotic dynamics may be responsible for removing objects from the asteroid belt and placing them on trajectories that bring them near Earth. (For a discussion of the new mathematical field of chaos, see the May/June 1989 *Planetary Report*.)

Suspect supply areas in the asteroid belt include the famous Kirkwood gaps, regions within the main belt where the population of asteroids has been severely depleted. These gaps were first noted in 1867 by the American astronomer Daniel Kirkwood, and they correspond exactly to positions of average motion resonances with Jupiter. At these locations, the orbital period of an asteroid is an exact integer ratio of Jupiter's—for instance, at the 3:1 resonance an asteroid completes exactly three revolutions in the time it takes Jupiter to complete one. Notable gaps appear at the locations of the 3:1, 5:2, 7:3 and 2:1 resonances.

Objects orbiting in a 3:1 resonance with Jupiter would be placed in the Kirkwood gap some 2.5 AU from the Sun. There the giant planet's gravity would perturb their orbits so that they would eventually cross the orbit of Mars. Then that planet's gravity would speed their delivery to the inner solar system.

Apart from the calculations that support this hypothesis, observational evidence shows that many NEAs reach aphelia (their most distant point from the Sun) within the asteroid belt. Spectral observations also support this hypothesis, showing that these NEAs are similar in composition to main-belt asteroids.

A second hypothesis for the resupply of NEAs is that they are derived from dormant or extinct comets that no longer display their distinctive tails as they approach the Sun. This leads us to our second key question.

The terrestrial neighborhood on June 30, 1991—the first day of the near-Earth asteroid conference cosponsored by The Planetary Society. The first chart shows the orbits and positions of Mercury, Venus, Earth and Mars. The second shows the orbits of the 50 largest known Apollo asteroids. The third gives an idea of how crowded our neighborhood is. *Charts: Richard P. Binzel*

How Are Asteroids and Comets Related?

The end stages of a comet's life are poorly understood. According to one scenario, in repeated passes through the warm inner solar system, an inert mantle forms over the nucleus. This layer of dust seals off and insulates the easily evaporated volatile ices within the interior. With the gases and dust that form a comet's coma and tail effectively trapped, it would look like an asteroid. In fact, because we classify a headless and tailless body as an asteroid, even if its orbit resembles those of known comets, the population of objects colloquially called near-Earth asteroids probably includes many dormant comets. Increasingly precise, and extensive, observations are providing evidence that some catalogued asteroids, such as 1566 Icarus, 2201 Oljato and 3200 Phaethon, may have originally been comets.

At least one of these catalogued asteroids, 3200 Phaethon, is associated with the Geminid meteor stream. This trail of dust particles is the source of the shooting stars that shower down through the night sky each year around December 14. Such meteor streams were assumed to be the tracks of dust left by active comets as they crossed Earth's orbit. That 3200 Phaethon has left such a track suggests that it was once a comet.

The confusion with comets was compounded by the discovery that the orbits of some asteroidal near-Earth objects do not follow strict gravitational laws. In other words, something besides gravity has disturbed their orbits. Intermittent jets caused by outgassing—perhaps as heated gases manage to break through a dormant comet's insulating crust—could slightly modify their orbits, just as small thruster rockets can change a spacecraft's trajectory. Such nongravitational forces have long been known to affect the orbits of active comets.

Now that we've established the relationship between active comets, meteor showers and at least one comet/asteroid, we can move on to the next question.

How Do Meteorites Fit In?

The dynamical processes that deliver asteroids from the main belt to the inner solar system can also work on much smaller objects, including those that fall to Earth as meteorites. Analyses of the trajectories of these bodies on their collision courses with Earth have shown that several were traveling in orbits that extended out into the asteroid belt.

The convenient delivery of meteorites to Earth has enabled us to get our hands on objects that had their origins in other parts of the solar system. We can then take them into the laboratory and analyze them. Using telescopic spectroscopy, we can remotely analyze passing asteroids to investigate their mineralogy. Our interpretations of asteroid surfaces are intimately tied to our direct measurements of meteorites. Both kinds of measurements are vital to our studies of solar system chemistry. However, the pieces of the puzzle do not fit together neatly, as the observed asteroids and meteorites appear to represent partly mismatched sets.

The greatest discrepancy is that the most common meteorite type (ordinary chondrites, stony objects containing BB-sized silicate globes) has no spectrally observed analogue among comet nuclei or asteroids in the main belt. Scientists have long debated whether the most common (spectral class S, assemblages of iron, nickel and silicates) asteroids are the parent bodies of these most common meteorites. Although they are made of the same minerals and metals, the proportions of the mixes are difficult to determine. Their spectra have led some researchers to believe that S-type asteroids are more metal-rich and are more closely related to the stony-iron meteorites, objects that have undergone substantial heating, than they are to ordinary chondrites, relatively primitive bodies that have undergone little heating.

Neither do comets match the ordinary chondrites. Comets probably contain material that is even more primordial. Perhaps this paradox between what we find on Earth (the meteorites) and what we observe in space (asteroids and comets) results from some unknown form of "space weathering." Solar radiation or micrometeoroid impacts might alter the upper few microns of a near-Earth object's surface enough to affect the spectral characteristics.

We are fortunate that near-Earth objects, the bodies that may provide the missing links between meteorites, comets and main-belt asteroids, include the most easily accessible targets in the solar system. As the last major class of objects to be investigated by spacecraft, we can expect them to yield vital new details of the processes that shaped our solar system. When we can answer these questions, we will be better able to explore, assess the hazards and even exploit these bodies that share the inner solar system with us.

Richard P. Binzel is an associate professor of planetary science at the Massachusetts Institute of Technology. He is the recipient of the 1991 Harold C. Urey Prize awarded by the Division for Planetary Science of the American Astronomical Society for outstanding achievement by a young scientist.

Some Useful Terms

Amors — Asteroidal objects that cross the orbit of Mars and approach the orbit of Earth. About 10 percent of the Amors have orbits that evolve into Earth-crossing orbits over short timescales—hundreds or thousands of years.

Apollos — Asteroidal objects that cross Earth's orbit. This family is composed of some of the closest planetary objects to Earth. A few known examples come closer even than the Moon.

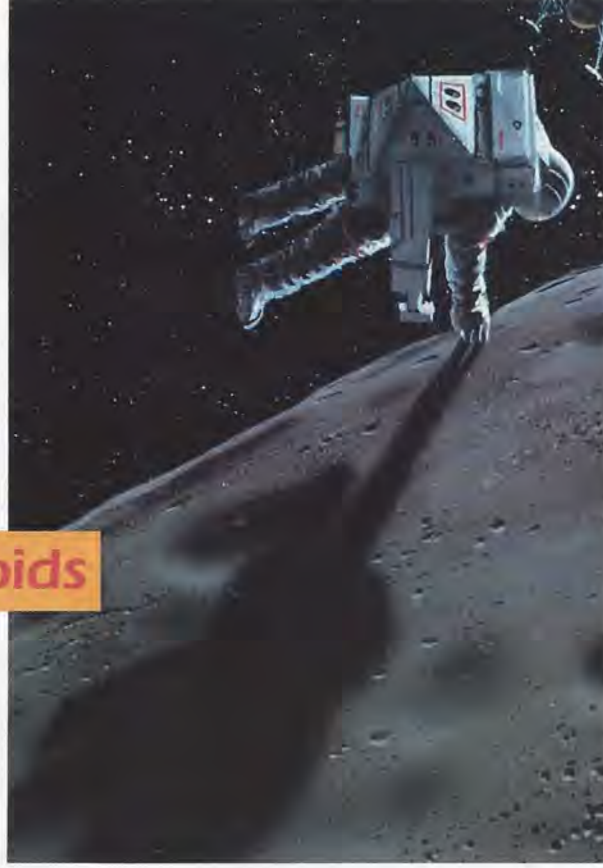
Atens — Asteroidal objects with orbits that lie primarily inside Earth's orbit. However, at their farthest point from the Sun, Aten asteroids may cross Earth's orbit.

Meteor — A flash of light visible as an object passes through Earth's atmosphere and burns as a result of frictional heating.

Meteorite — A natural object of extraterrestrial origin that survives passage through Earth's atmosphere.

Meteoroid — A natural object in interplanetary space, smaller than about 10 meters (30 feet) in diameter. A larger object would be an asteroid.

IT'S A SMALL, SMALL WORLD



Missions to Near-Earth Asteroids

by Donald R. Davis and Alan Friedlander

After *Galileo*'s flyby of Gaspra this past October, marking the first time a main-belt asteroid has been investigated by a spacecraft from Earth, only one major class of solar system bodies remains to be visited: the near-Earth asteroids. The lack of missions to these neighbors is puzzling, since near-Earth asteroids are easier to reach—in terms of energy—than the surface of the Moon. They have much to offer us, both as repositories of solar system history and as storehouses of precious resources. If we are serious about someday sending a human expedition to Mars, then near-Earth asteroids (NEAs in scientific jargon) would be excellent practice targets.

We might speculate that these asteroids have been overlooked because of their relative obscurity when compared to other solar system objects. The Moon dominates our night sky for much of the month. Mars, Jupiter, Venus and Saturn are brilliant objects, both to the naked eye and through small telescopes. Comets produce some of the most spectacular shows ever seen from Earth.

Even in the largest telescopes, asteroids remain unresolved points of light. Powerful radars are beginning to produce crude images of large-scale features, and meteorites provide small samples from the charred remains that survive passage through our atmosphere. But we really know very little about these small but potentially valuable objects. To learn more, we must go visit them.

Why Go?

We can quickly recount the justifications for a spacecraft mission. NEAs are a diverse population of objects, containing both very primitive material, unchanged from the earliest eras of solar system history, and bodies that have been heated to different temperatures, producing "cooked" mineral assemblages. By exploring them, we can sample different evolutionary paths for early planetesimals.

We can also sample objects from different regions of space. Most NEAs are probably fragments of larger main-belt asteroids, which circle the Sun between the orbits of Mars and Jupiter. Catastrophic collisions among these asteroids inject fragments into certain orbits that are "resonant" with Jupiter's. For example, in a 3:1 resonant orbit, every three times an asteroid travels around the Sun, it and Jupiter are in the same relative positions. This amplifies Jupiter's great gravitational effect, which can sling the asteroid onto an orbit that crosses Earth's orbit.

Other NEAs may be extinct comets that, over many passages around the Sun, have blown off the gas and dust that produce their characteristic tails. These dormant bodies continue to orbit the Sun and, if visited by a spacecraft, could tell us much about the outer solar system where they were born billions of years ago.

NEAs are also promising sources of materials that might be used as humanity expands into the space frontier. The most precious of these is water, which we know exists on active comets and in many main-belt asteroids. We assume it is also available on their near-Earth relatives. Some NEAs have nickel and iron in abundance, and they may also contain very high grade ores for precious metals, such as gold and platinum. For spacefarers, however, these bodies may be even more valuable in a more straightforward way: as bulk shielding for spacecraft or orbiting stations, to protect them from energetic particles ejected by solar storms.

The Space Exploration Initiative (SEI) proposed by President Bush plans to establish a lunar base early in the 21st century and to land humans on Mars by the year 2019, the 50th anniversary of *Apollo 11*'s landing on the Moon. However, sending people to the Red Planet may be too giant a leap to follow directly from the lunar base phase of SEI. A more prudent course might be to gain deep-space experience with intermediate missions to near-Earth asteroids. It

Near-Earth asteroids are very attractive targets for exploratory missions—both with robotic craft and with humans. An asteroid's small size and low gravity would make it an easy object to approach. A spacecraft would not need powerful retrorockets to rendezvous or to land, and a space-suited human could gently drift to its surface.

Painting: Ron Miller

may even be possible to skip the Moon entirely and proceed directly from asteroid missions to a martian mission. Such missions are currently being considered as the SEI architecture is being shaped.

Precursor missions to NEAs could provide experience with long flights, the significant time needed to communicate with mission control, and the steps required to return the voyagers to the friendly environs of our planet. Just as the *Apollo 8* mission that orbited the Moon tested both the hardware and the procedures that were used in the *Apollo 11* landing, so a human mission to a near-Earth asteroid could test those needed for a Mars mission.

Such an asteroid mission would, of course, have a scientific bonus. The astronauts could be more than just experimental subjects for the collection of biological data in spacecraft snugly orbiting Earth or the Moon. They could be trained scientists investigating the geology of NEAs close up and in person.

Types of Missions

Scientists would like to collect data from a variety of different NEAs. A fragment of a main-belt asteroid would tell a different story than would the husk of a degassed comet. Our exploration of NEAs will probably follow the traditional hierarchical approach, beginning with robotic flybys and moving to rendezvous missions, then progressing to sample returns and human missions.

Multi-asteroid flyby missions would be important and quick first looks at NEAs. They could give us information on several different asteroids in a cost-effective way. Such missions to main-belt asteroids have been examined in previous studies, and mission analysts at the Jet Propulsion Laboratory, Science Applications International Corporation and Johns Hopkins University's Applied Physics Laboratory have identified similar opportunities for NEAs.

The most important step in our reconnaissance will involve rendezvous missions where a spacecraft will fly "in formation" with an asteroid, using remote sensing techniques to conduct a global survey. We can expect to use several types of instruments, including imaging systems to show us what the asteroid looks like, laser altimeters to map its topography, and infrared and gamma-ray spectrometers to tell us what it's made of.

Sample-return missions would allow us to conduct a host of complex analyses on bits of NEAs, which we could then compare with analyses of meteorites. We could determine the precise ages and histories of specific asteroids, which would improve our understanding of their evolution. We could also conserve the samples, saving them for later researchers who may ask questions we've not yet conceived.

The ultimate mission would, of course, consist of sending trained and experienced field geologists to NEAs. Astronaut-scientists could prepare geologic maps, excavate subsurface samples from several locations, survey the potential resources and carry out other activities. Remotely controlled robots, guided by scientists on Earth, might be able to accomplish these tasks, but it is also possible that they could best—and perhaps uniquely—be done by humans.

The Critical Step: Orbital Analysis

Near-Earth asteroids make up a population of small bodies ranging from less than a kilometer to some 40 kilometers (25 miles) in diameter. Their orbits approach or cross that of Earth. A useful definition of an NEA is an object whose perihelion distance (its closest approach to the Sun) is less than 1.3 AU (an AU, or astronomical unit, is the average distance from Earth to the Sun, about 150 million kilometers or 93 million miles).

Within this definition we find a diverse group of orbits. Some are almost circular, while others are extremely elliptical; some are nearly parallel to Earth's orbital plane, while others are highly tilted. Orbit sizes are quite variable, with a few lying mostly inside Earth's orbit. Most NEAs, however, swing out to the main asteroid belt between Mars and Jupiter.

The NEAs we know of—about 180 objects—are only a sample of the much larger true population that has been predicted by Eugene Shoemaker and other researchers. Current estimates of this population are $1,700 \pm 800$ NEAs larger than 1 kilometer in diameter, and $5,700 \pm 2,600$ if the diameter is reduced to 0.5 kilometer. These large numbers suggest that there are many potential targets for spacecraft missions.

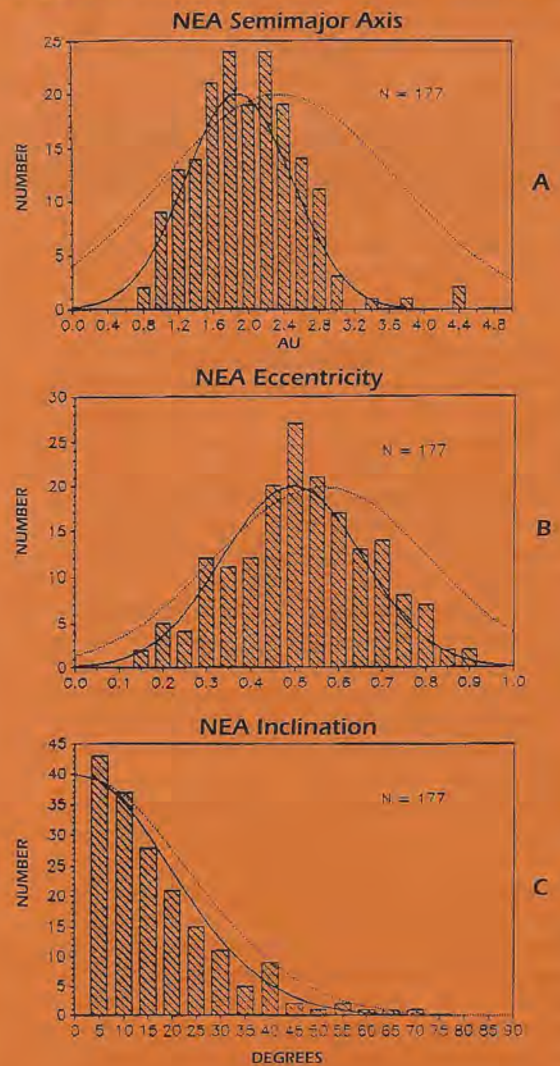
To determine the requirements for a mission to a known asteroid, we work with certain orbital elements—primarily the size, shape and inclination of the orbit. We also use this information to estimate mission requirements for yet undiscovered NEAs.

Figure 1 (on page 14) shows the distributions of these orbital elements for 177 of the known NEAs. **Graph A** describes the semimajor axis as a standard measure of the elliptical orbit's size. (A major axis is defined by a line drawn within the ellipse through its two foci; the semimajor axis is half of that, and we use this as the standard measure of an orbit's size. For an object in a solar orbit, the Sun sits at one focus of the ellipse. The other focus—located equidistant from the center of the ellipse—is empty.) **Graph B** displays the eccentricity parameter, which measures the deviation from circularity, and **Graph C** shows the inclination as the degree of orbital tilt relative to Earth's plane of motion around the Sun. The solid lines in these graphs are our representations of the observed data.

However, the orbits of NEAs that we have observed provide a somewhat biased sample. This is because those asteroids whose paths bring them close to Earth, or that pass by slowly, are more likely to be discovered by our telescopic searches. The dotted lines in Figure 1 represent a more accurate estimate of the true distributions of NEA orbits, corrected for the foregoing biases as best we can.

Although there are other orbital elements that determine

Figure 1: Distributions of Orbital Elements



the spacecraft requirements to reach an asteroid, the three we have described here are the most important. As a general rule, the best NEA mission candidates have orbits of low inclination and eccentricity, with semimajor axes not too far removed from 1 AU.

Mission Design

We begin designing a mission by determining the best trajectory, or path, to our target asteroid. At the most basic level, trajectory characteristics are measured by two performance parameters: (1) the total velocity change, ΔV, imparted to the spacecraft in all maneuvers starting from low Earth orbit departure through final target encounter, and (2) the flight time. (The Greek letter delta, Δ, is the mathematical symbol for difference, or change.)

The separate components of total ΔV (in kilometers per second, km/s), together with information about the launch vehicle and the spacecraft systems, then allow us to determine launch vehicle capability and how much propellant the spacecraft will need to carry to reach its target. Flight time is important in mission design because it sets requirements on spacecraft reliability and operations, and determines how quickly the mission science and exploration objectives will be achieved. Although shorter flight times are generally desired, this parameter is inevitably related to the ΔV requirements: We can get to a target asteroid more quickly with bigger ΔV's. But larger ΔV's require bigger, more expensive rockets. Thus trade-offs must be made to find the best overall trajectory. Both ΔV and flight time are strongly linked to the orbital elements of the target asteroid.

When dealing with a large population of potential targets, it is useful to first conduct a statistical analysis of the ΔV requirements. To do this we use simplified analytical formulas to calculate ΔV for known or specified target orbital elements. Actual trajectory calculations can then be made later for the reduced set of good performance targets.

Another useful approach involves using the simplified formulas and statistically sampling the distribution of orbital elements. We've done this for rendezvous missions to the estimated true population of NEAs described earlier. Our results show, for example, that 0.9 percent of the target population (or 47 of 5,000 asteroids) could be reached in a favorable launch opportunity for a total ΔV of less than 5 kilometers per second, 5.1 percent for less than 6 kilometers per second and 14.2 percent for less than 7 kilometers per second.

This is very encouraging, given the fact that the discovery rate of NEAs has been increasing dramatically in recent years with the dedicated search efforts led by Eleanor Helin, Eugene Shoemaker, Tom Gehrels and others. One may ask how the asteroid rendezvous ΔV requirements compare to those for other mission targets. A ΔV of about 6 kilometers per second is needed to land on the Moon, while Mars landing requirements range from 4 to 9 kilometers per second, depending largely on whether aerocapture or rockets are also used at Mars, as well as on the trip time. So a sizable number of NEAs are easier to reach than the Moon.

In **Table 1** (below) we have summarized the performance data of actual target trajectories for a wide variety of flyby, rendezvous and round-trip missions. The flyby missions are easily within the capability of a *Delta 2* launch vehicle, and many could possibly use smaller vehicles such as the *Pegasus* and *Taurus*. Assuming use of these small, inexpensive launchers, Carl Sauer of JPL has found 349 launch opportunities to 104 different asteroid flyby targets in the years between 1995 and 2006. Paul Penzo at JPL has found 36 launch opportunities between 1995 and 2000 for double target flyby missions.

Table 1: NEA Mission Performance Data

Mission Type	Total ΔV (km/s)	Flight Time (days)
Single Flyby	3.20 – 3.47	85 – 451
Dual Flyby	3.30 – 3.92	164 – 1,734
Rendezvous	4.21 – 8.00	120 – 1,096
Round-trip	5.58 – 10.00	363 – 1,502

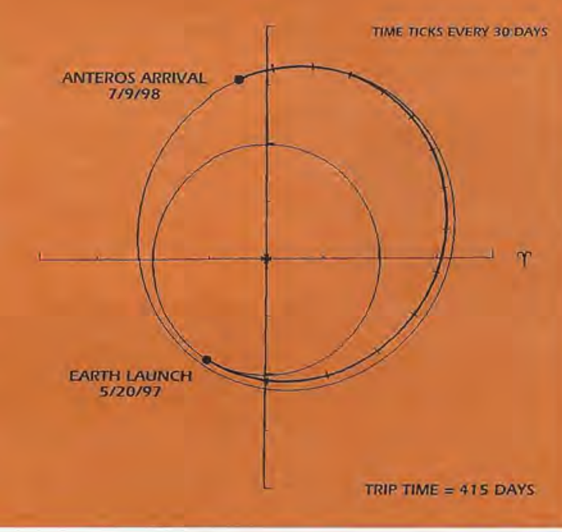
Rendezvous missions are more demanding of performance and would require the launch capability of a *Delta 2* or *Atlas 2AS* vehicle. The rendezvous cases summarized in the table represent 145 mission opportunities to 31 known NEAs with launch dates between 1997 and 2010. One example of a very good mission candidate is the asteroid 1943

Anteros. **Figure 2** (below) illustrates the 415-day trajectory for a mission launched in 1997. The total ΔV is 5.4 kilometers per second. Both the United States and Japan are studying this possibility.

Round-trip missions are particularly fascinating, for these have application to more advanced robotic sample return as well as to human exploration flights. With total ΔV limited to 10 kilometers per second and trip times between 1 and 4 years, we found 56 mission opportunities to 13 known NEA targets. These cases assume direct atmospheric entry at Earth return in order to avoid the additional ΔV for propulsive capture to orbit.

Among the round-trip examples is a mission to the asteroid 1991JW, which was discovered in May 1991 by Eleanor Helin and Ken Lawrence during the Planet-Crossing Asteroid Survey supported by members of The Planetary Society. 1991JW is currently the most accessible known target for quick round-trips appropriate for human spaceflight. The trajectory profile for a one-year mission launched in 2009 is shown in **Figure 3** (right). The total ΔV for this mission is only 5.9 kilometers per second.

Figure 2: 1997 Launch Opportunity for Anteros Rendezvous



Proposed Missions

The continuing discovery of more near-Earth asteroids and our discovery of easy trajectories to reach them have increased interest in asteroid missions. Several nations are now considering missions to NEAs.

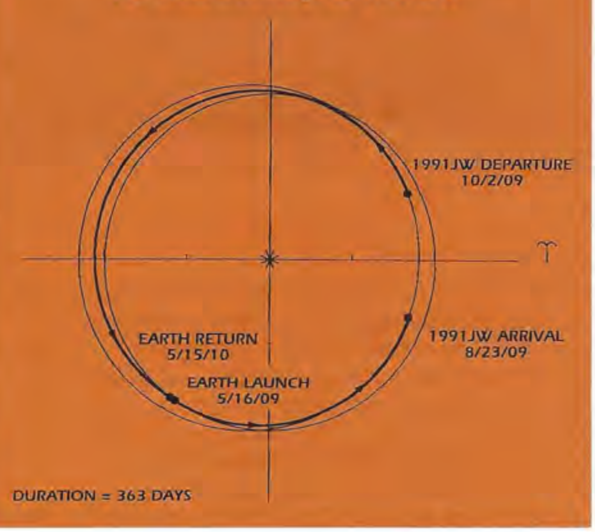
In the United States, NASA is undertaking a new Discovery program of small missions designed to cost less than $150 million each. A rendezvous with an NEA may receive a "new start" as early as 1994. Dramatic advances in reducing spacecraft weight and costs have been accomplished as part of the Strategic Defense Initiative, and this new technology could be used to develop inexpensive spacecraft that could fly by several NEAs for quick first looks.

Japan's Institute of Space and Astronautical Sciences has proposed a rendezvous with the asteroid 1943 Anteros for a 1997 launch. This mission would consist of a five-month orbital mapping and reconnaissance phase, followed by a descent and hovering phase lasting another five months.

The Italian Space Agency (ASI) and the community of asteroid scientists have proposed a slow flyby mission named *Piazzi*, after the Italian astronomer who discovered the first asteroid. This mission would be an intermediate step between a flyby and a rendezvous mission. Instead of whizzing by at several kilometers per second, it would slowly fly by at about 100 meters per second. This low encounter speed would increase the time for scientific measurements, enable accurate determination of the asteroid's mass, and make it easier to point instruments at the target. The *Piazzi*-class missions could very well become real as part of an Italian national program or as a small-body mission by the European Space Agency.

The growing interest in near-Earth asteroids, coupled with their accessibility and the increasing technical prowess evidenced by several nations, augurs well for the robotic exploration of NEAs in the 1990s. Perhaps humans will visit them not too long afterward.

Figure 3: 2009 Launch Opportunity for a Round-trip to 1991JW



The diversity of types of NEAs means that there will be rich rewards from these missions. We will not be able to understand their population from just one or two missions, unless each one visits several asteroids. We will need to plan a series of missions to the various types of bodies. Given this requirement, exploration of NEAs would be ideal for international projects. We could find economies of scale in spacecraft production, launches and spacecraft operations, yielding a wealth of data at a low unit cost.

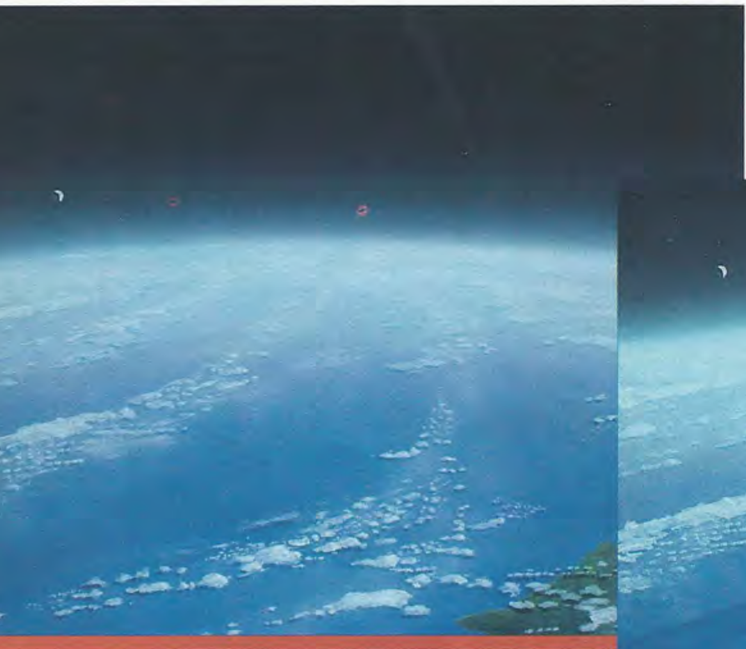
In these times of budgetary crises, cooperation among nations gives us an opportunity to enhance the productivity of space exploration. Indeed, it may be the only way to accomplish significant exploration of NEAs in this decade.

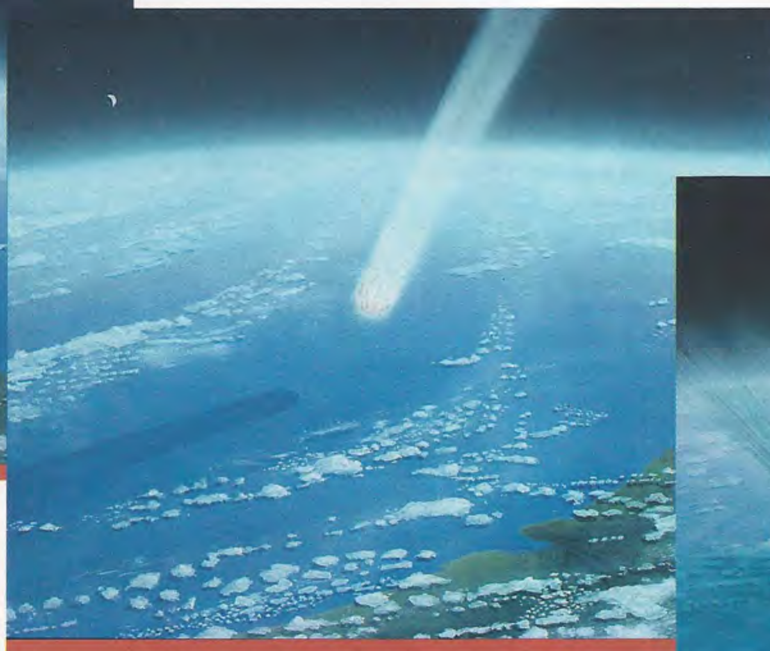
Donald R. Davis is a senior scientist at SAIC's Planetary Science Institute in Tucson, Arizona. Alan Friedlander is a senior research engineer with SAIC's Advanced Planning and Analysis Division in Chicago, Illinois.

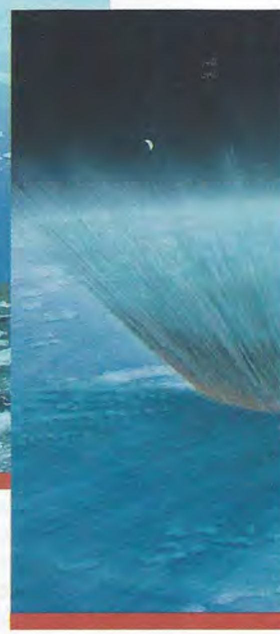
The Sky Is Falling:

The Hazard of Near-Earth Asteroids

by John Pike







For 140 million years, the dinosaurs dominated life on Earth. Then, within an instant of geologic time, every one of these awesome creatures disappeared. Something happened 65 million years ago, something so devastating it wiped out most types of organisms on Earth. The identity of the culprit responsible is one of the great mysteries of science.

Since the early 1980s, researchers have been hot on the trail of a likely suspect: a near-Earth asteroid or comet, some 10 kilometers (6 miles) in diameter. Many threads of evidence, gathered from around the world, converge at the same time—65 million years ago—and the same place—the Caribbean basin—for the collision of such an object with Earth.

The exact means of death—global cooling and darkening by a dense dust cloud, poisoning by toxic gases, decimation by acid rain—has not been determined. Still, there is enough physical evidence to convince a growing number of scientists that the murderer of the dinosaurs came from outer space.

And there is a small but real possibility that a similar fate may someday befall the human race.

Identifying the Suspects

We know that bits of space debris fall to Earth every day. Any night, from a dark location, you can spot several meteors as they streak across the sky. These flashes are caused by objects no larger than motes of dust, and few are large enough to survive passage through Earth's atmosphere. The charred remains of the larger objects fall as meteorites. These are uncommon rocks, but not exceedingly rare; most well-stocked rock shops offer these pieces of the sky at modest prices.

A much smaller, but not negligible, number of objects are large enough that a collision with Earth could disrupt life everywhere on the planet. An asteroid even a tenth of the size of the dinosaur-decimator might be able to disrupt agriculture globally. The resulting political and social disorder would surely rank such an event as the greatest catastrophe in human history, easily exceeding the Black Death of the Middle Ages.

Planetary scientists estimate that in Earth's immediate neighborhood there are now 1,000 to 2,000 objects having diameters greater than 1 kilometer (0.6

BELOW, LEFT TO RIGHT:

***ONE MINUTE TO IMPACT:** On a calm morning 65 million years ago, a few streams of clouds drift across the sea near present-day Mexico.*

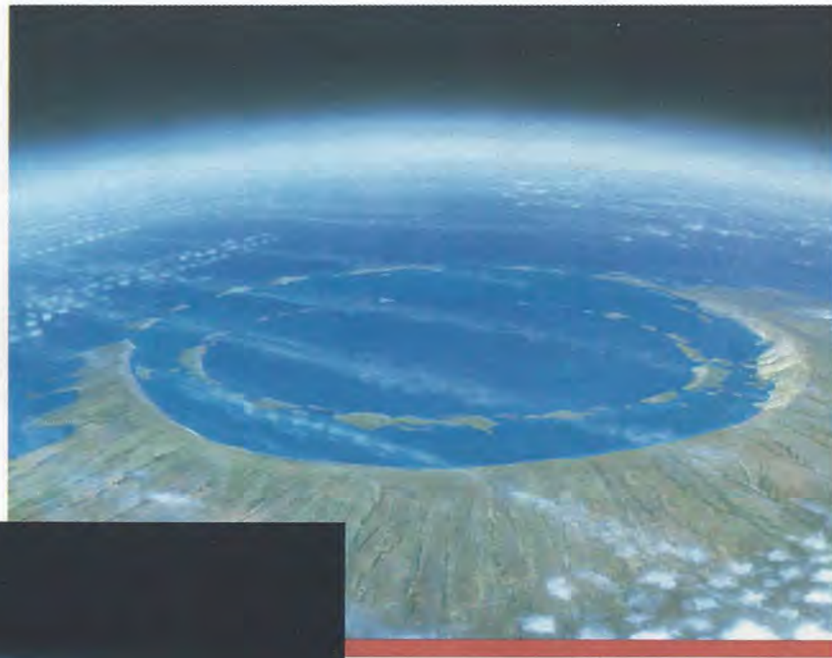
***TWO SECONDS TO IMPACT:** A giant fireball breaks the calm and streaks toward the surface at 20 kilometers per second.*

***ONE MINUTE AFTER IMPACT:** The asteroid has struck. Vaporized water and pulverized rock are blasted into the atmosphere and beyond.*

***ONE MONTH AFTER IMPACT:** A layer of dust and smoke completely obscures Earth's surface.*

***ONE THOUSAND YEARS AFTER IMPACT:** The atmosphere has cleared. A multi-ringed crater remains as evidence of the asteroid's impact. On Earth, the food chain has been totally disrupted and effects propagate through the biosphere as various species become extinct.*

Paintings: William K. Hartmann, from the forthcoming book, The History of Earth



mile). We've tracked only about 100 of these objects. The evidence displayed in the cratering record on Earth and the nearby Moon suggests that the interval between impacts is only hundreds of thousands to a few million years for such objects.

There are even more objects that are smaller and therefore harder to find. Estimates vary for the number of Earth-crossing objects having diameters greater than 50 meters, covering a range from several hundred thousand to a few million. The expected impact interval here is somewhere between many decades to a few centuries.

The Tunguska Impact

These smaller objects may not threaten civilization as we know it, but their local impact could be devastating. We have a recent example of what something only about 50 meters in diameter can do. In 1908, an object that was probably an icy piece of a comet exploded over the Tunguska region of Siberia. The blast flattened 2,000 square kilometers of (fortunately) uninhabited forest. The object itself does not appear to have survived its fall, and it left no crater.

If a Tunguska-class object were to strike a typical rural portion of the United States today, nearly 70,000 people could be killed, and property damage could exceed $4 billion. If such an object were to strike an urban area, perhaps 300,000 people (or more, depending on the city) could be killed, and property damage could exceed $280 billion.

The fact that the Tunguska object appears to have been a fragment of a comet adds a twist to our story. When we characterize our suspect impactors, it's easy to stereotype them as solid, asteroidal bodies. But we really do not understand the makeup of the near-Earth object population, and some researchers estimate that 10 to 50 percent of them are actually the husks of extinct comets.

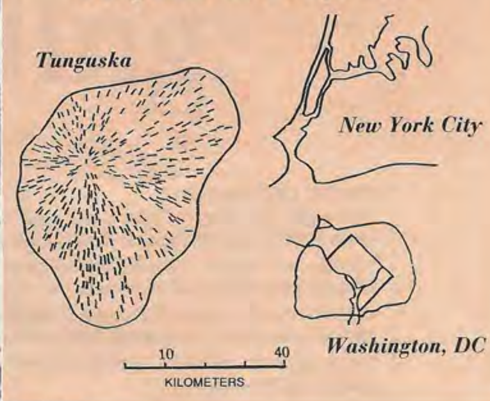
An Episodic Threat

These comets have a sinister characteristic: As they pass close to the Sun, they may fragment into many potentially dangerous pieces, multiplying the chances of collision. With a swarm of comets locked in a periodic orbit in

On June 30, 1908, at 7:40 AM, something (probably a piece of a comet) exploded in the sky over Siberia. It flattened 2,000 square kilometers of forest in the Tunguska region. If a similar event were to occur over a populated area today, hundreds of thousands of people would be killed, and damage would be measured in hundreds of billions of dollars.

Photograph courtesy of the Smithsonian Institution

Tunguska in Perspective



Earth's neighborhood, we could be faced with a threat that repeats episodically.

There is some evidence that the catastrophic event that marks the boundary between the Cretaceous and Tertiary periods—and the end of the dinosaurs—was not one impact but two or three. There is more than one sizable crater of the proper age. Moreover, a look at the recent cratering record on Earth discloses that there were three or four impacts about 10,000 years ago, and three smaller ones some 6,000 years ago.

These clusters suggest that, unlike other natural disasters that occur on a continual basis, the impact threat may be episodic—the result of the fragmentation of a comet. It is possible that Tunguska heralded a period of above-average impact risk, and that similar events could be more frequent than we might expect. Some researchers have associated the Tunguska fragment with comet Encke, which orbits the Sun every 3.3 years.

Coming to Terms With Disaster

Just in recorded history, tens of millions of people have perished in natural disasters—fires, famines, epidemics, storms, volcanoes and earthquakes. Multitudes still die each year in less developed countries. In contrast, there is not a single recorded instance of a person being killed by a meteorite impact. While the total killed is one measure of disaster, this standard may say more about demographic geography than about relative hazard, since a cyclone in heavily populated Bangladesh can kill many more people than can a comet impact in relatively uninhabited Siberia.

Infrequent natural disasters tend to be ignored. In California, the awareness of the earthquake hazard is much higher than it is in southern Missouri. Californians frequently feel small quakes, and they have experienced several larger quakes in recent years. In contrast, the last major earthquakes in Missouri were the New Madrid shocks of 1812, and there have been no significant temblors since. But the risk of a catastrophic quake, causing tens of billions of dollars of damage and killing tens of thousands of people, is higher in Missouri than in California. Missourians, in general, are not as prepared for quakes as are Californians. This tendency to ignore infrequent natural hazards is also seen in public attitudes toward volcanoes and hurricanes.

Still, more people are giving attention to the impact hazard. Part of this may be because impacts, unlike most other natural hazards, are not location specific. Volcanic eruptions are highly visible and earthquake zones are well established. Hurricanes, cyclones and tornadoes only threaten certain areas. But impacts can occur anywhere.

Watching the Skies

In recent years, many people have put forth proposals to help safeguard Earth from impact. These range from attempts to better characterize the Earth-crossing population to plans to divert potentially threatening objects. Hundreds of millions of dollars would be required for the first, and certainly much greater amounts for the second. This is a very high cost, but quite possibly a prudent insurance investment.

To evaluate the investment, we must first define the nature of the threat. We can ignore the smaller objects that disintegrate in Earth's atmosphere many times each year—although some produce energy yields equivalent to several kilotons. Large objects, over a kilometer in diameter, could produce global effects, so we would have to divert them, and this would require the greatest investment. Let's begin our evaluation with intermediate objects, ranging in diameter from several dozen to a few hundred meters.

These objects could cause local damage over thousands of square kilometers. With good tracking data, we could pinpoint the place of impact and, with adequate warning, evacuate the threatened population. Based on experience evacuating coastal populations and analyses for civil defense, we'd need a minimum of 24 hours warning. Do we have the technology to give us such a warning?

The large missile-launch detection systems of the United States and the Soviet Union, and the radars that track geosynchronous satellites 35,000 kilometers up, could track an incoming object 50 meters wide at ranges of 20,000 and 750,000 kilometers, respectively—if we knew in advance the trajectory the object was traveling. The giant 300-meter Arecibo radio telescope in Puerto Rico, used as a radar, could track such an object at over 5 million kilometers. As sensitive as these systems are, however, they are not yet powerful enough to detect an unknown incoming object.

The NASA Near-Earth Object Detection Workshop recently considered how we might search for intermediate-sized incoming objects. The members concluded that no practical systems exist or can be easily contemplated that would provide the desired warning.

Perhaps fortunately, there is a relatively inexpensive detection system we could build for the most dangerous objects: asteroids or comets over a kilometer in diameter, which could cause global catastrophes. For them we would need a network of ground-based telescopes, which could identify and track them many years, if not decades, before impact. This network would require an initial investment of less than a hundred million dollars, and a fraction of that cost as yearly operating expenses.

Planning for the Worst

Once we've found an incoming asteroid, what can we do to prevent its impact? For a large object, we could send out a probe armed with a nuclear device and try to divert its path—toward an ocean, if not away from Earth entirely. Studies dating back to the 1960s have suggested that high-yield hydrogen bombs could do the job, although there is a risk that a nuclear explosion would merely shatter the object and compound the threat. Existing launch vehicles, such as the American *Titan 4* or the Russian *Energia*, would be up to the task.

If we had years of warning, we could send a probe to characterize the object and minimize the risk. Perhaps some advanced propulsion system could be attached to the object to nudge it gently onto another, less-lethal trajectory. For smaller objects with less warning, the interceptors might have to fly out to their target and hope for the best.

To obtain this capability, we would have to invest several billion dollars over and above the cost of the detection systems. If we had to, in a crash program working around the clock, we could probably create the hardware in less than a year.

At present, we are spending only a few hundred thousand dollars a year on discovering and studying the Earth-crossing population. A prudent first step would be to construct that dedicated network of ground-based telescopes to identify all objects with diameters larger than 1 kilometer—that is, those objects that could lead to global catastrophe, and for which evacuation would be pointless.

Another step would be to embark upon intensive studies to determine the relationship between the size of an impacting object and the consequences of impact. What size object could wipe out civilization? What is the minimum size of an object that we must divert, no matter the cost?

As we better understand the hazard of these larger objects, we also need to plan how to evacuate populations threatened by smaller objects. What is the smallest object that would pose a significant threat? What is the largest object for which evacuation rather than diversion is the appropriate response? Given the property damage possible from an urban impact, it might be prudent to divert even a small object if it threatened an urban area.

Whatever the program, it will not be cheap. But an investment of tens of millions of dollars each year might be prudent in light of the hundreds of thousands of lives that could be saved.

We've only recently identified our prime suspect in the death of the dinosaurs. We have much more investigation and analysis to do to ensure that we have truly identified the culprit, and to avoid the same fate ourselves.

With luck, an event like this will never occur. But the statistics suggest that it will happen. Some researchers have estimated an individual's chance of being killed by an asteroid impact at 1 in 6,000—about the same chance as being killed by an earthquake. Large asteroids may not strike as often as earthquakes do, but if a large one hits, it could kill many more people than an earthquake could.

Painting: Paul DiMare

John Pike is the Director of the Space Policy Project of the Federation of American Scientists.

Prospecting the Future

The Planetary Society Asteroid Program

by Charlene M. Anderson and Louis D. Friedman

The Planetary Society has built a worldwide reputation for taking seriously what some consider to be dreams: sending humans to explore Mars, for example, or searching for extraterrestrial civilizations. Yet we have made perhaps our most tangible contributions in projects involving some of the smallest things in our solar system: the minor planets, or asteroids. Since 1982 we have supported Eleanor "Glo" Helin's extremely fruitful search for near-Earth objects, we have sponsored projects to measure their orbits with extreme accuracy and we have commissioned scientific reports on human missions to asteroids.

Why, you might ask, in a solar system filled with large planets waiting to be explored, have we devoted so much of our time and resources to such small bodies? These minor planets—perhaps best visualized as flying mountains in orbit about the Sun—may have an importance to the human future out of proportion to their size. They could be excellent practice targets for human planetary missions. They could provide raw materials for a spacefaring civilization. Like all members of our solar system family, they have a story to tell about our shared past. But, most important, they are the only solar system bodies that could have a direct impact on civilization on Earth.

Past, present and future—asteroids have roles to play in them all.

Let's start with the past. Modern theories of the formation of our solar system begin with a tenuous cloud of molecular gas collapsing into a swirling disk. At the center of the disk, a star starts to form. Orbiting around this protostar, the molecules collide and stick together, eventually forming clumps of frozen gas and rocks in a process called accretion.

Over hundreds of millions of years, some of these clumps grow into planets. The collisions continue, leaving multitudinous scars of their existence on the faces of Mercury, Earth's Moon and the outer planets' satellites. On entering the atmospheres of the largest planets, the clumps disappear, but contribute their gases to the giant atmospheres. On the smaller, terrestrial planets, internal processes rework their surfaces and erase traces of this early bombardment.

Remnants of the Past

Scientists have deduced this scenario by examining the solar system as it exists today. But from Earth's surface, there are only a limited number of clues to collect. We have meteorites, and some of them are remnants of the early solar system. Some of the rocky clumps from that primordial time have survived to orbit the Sun as asteroids. Those clumps richer in ices are the comets. To test this hypothesis of solar system formation, we must study the asteroids and comets.

On a more parochial level, these small bodies may

Approaching Antarctica, but not yet on a collision course, an asteroid passes close by our planet. Near-Earth asteroids' proximity makes them attractive targets for spacecraft missions, but it also makes them dangers to life as we know it. Recognizing the promise and the peril of these objects, The Planetary Society has made near-Earth asteroids the focus of a major program. Painting: Michael Carroll

have played major roles in the evolution of life on Earth. There is some evidence (see the January/February 1990 *Planetary Report*) that the atmosphere that today supports life on Earth is secondary. That is, much of the primary atmosphere that formed as gases escaped from the condensing planet was eventually lost to space. The oxygen- and water-rich layer that surrounds Earth today, as well as minerals and organics, may have been delivered by volatile-rich comets and asteroids, which gave up their frozen gases as they were destroyed by impact.

Scientists seeking to understand the origin of life on Earth have begun to consider another possibility: that in the first billion years or so of our planet's existence, life may have begun several times, only to be wiped out each time by extraterrestrial bombardment. The violent impacts would have raised enough dust to block out the sunlight that nascent life needed to survive. Only when most of these minor planets had been swept up by collisions with the larger ones would the rate of impact have slowed enough for life to survive. This "impact sterilization" hypothesis is relatively new and will require more study of comets and asteroids before it can be proven or disproven.

Asteroids and comets may have meddled further in the evolution of terrestrial life: The impact of a 10-kilometer-sized object may have wiped out the dinosaurs and most other species. (See page 16; also the January/February 1985 *Planetary Report*.) In the aftermath, the mammalian class rose to dominance.

By piecing together these bits of scientific evidence, we come to the conclusion that, as human beings, we may owe our very existence to asteroids and comets. They may be small bodies on solar-system scales, but their importance to our present lives could not be greater.

And they may have a similar role in our future. Our telescopic searches have revealed that near-Earth space is still inhabited by asteroids and comets. It is inevitable that one will again strike Earth, with results painful to contemplate. The only question is, "When?" The search programs now supported in part by The Planetary Society may in time detect an object on a collision course. Someday soon, Earth's inhabitants may have the technology to deflect it. Until then, our searches could provide a warning and give civilization time to prepare.

In the distant future, humans may move out into the solar system and, eventually, evolve into a spacefaring species. The process may be similar to that by which the American West was settled. First, explorers will trek across the wilderness, mapping the terrain as did Lewis and Clark, or scouting for readily available resources, as did the mountain men. Then the prospectors will come, searching for hidden, but more valuable, resources. They will be followed by the builders of infrastructure, like the railroad barons. For all these types, asteroids will be important territories to explore.

The Planetary Society is not so much interested in the possibilities of the far future as we are in the exploratory ventures that can be accomplished within our lifetimes. We aspire to be Lewises and Clarks, not railroad barons. Asteroids may well be our first stop in the reconnaissance of the solar system.

Our initial reason for supporting Glo Helin's program in 1982 was to find the best candidates for spacecraft missions. Our support was almost immediately rewarded when she found 1982DB (now numbered asteroid 4660; see the January/February 1991 *Planetary Report*), until this year the most accessible solar system body known. A few months ago, she and her team found 1991JW, which now holds that title. We cannot ask for better results than that!

Visions of 2010

Then, in our role as advocates for planetary missions, we began to investigate just how asteroid missions might be accomplished. In the July/August 1983 issue of *The Planetary Report*, Society Executive Director Louis Friedman and President Carl Sagan published their early thoughts on the possibilities. Two years later, in our March/April 1985 issue, they published their "Visions of 2010" on a human mission to an asteroid, based on a Society-commissioned study by Science Applications International Corporation (SAIC).

The SAIC report detailed a two-year mission to 1982DB that could be accomplished for about $20 billion —a relatively quick and cheap proposal for a human expedition into space. A three-person crew would leave Earth orbit on January 5, 2000, reach their target on October 12, 2001, and return home on January 13, 2002. They would travel in a dumbbell-shaped spacecraft that would rotate about its center to provide artificial gravity.

The spacecraft would hover above 1982DB for 30 days, providing ample time for reconnaissance. (A 1-kilometer-diameter asteroid would have a surface area approximately equal to New York City's Central Park.) Before completing their mission, they would deploy seven experiment packages.

They would also have time for some interesting athletic events. Even a large asteroid 10 kilometers in diameter would have a gravity only 0.1 percent that of Earth. In the asteroidal high jump, an astronaut could clear a bar about 1 kilometer high. In the shot put, one could heave the thing into an independent orbit about the Sun.

Such a mission would be valuable in and of itself, teaching us much about asteroids and all the scientific topics we've detailed above. We quickly realized that it could also serve as an important precursor for human missions to Mars. Thus our interests in asteroids for their own sake dovetailed with our advocacy of Mars missions, and our interest intensified.

We renewed our support for Glo Helin's Planet-Crossing Asteroid Survey (PCAS), which she conducts primarily from the Palomar Mountain Observatory. We collaborate in this support with NASA and the World Space Foundation. Glo and her team have steadily increased their discovery rate, and they are now finding new objects on the average of once a month.

We learned that the follow-up to the discovery process is almost as important as the discovery itself. To determine the precise orbit of an object, we must have measurements from several locations. Without this precision, an observer may not be able to find an asteroid again. And without knowing exactly where an object is in the solar system, we would never be able to land a spacecraft on it!

To encourage these follow-up observations, in 1987 we funded the astrometry program of Jeremy Tatum and David Balam at the University of Victoria, British Columbia. (See the September/October 1991 *Planetary Report.*) In the last year, the National Geographic Society joined us in recognizing the value of this work and has become a cosponsor of the program.

Earlier this year, The Planetary Society cosponsored with NASA a major international conference on near-Earth asteroids held at the San Juan Capistrano Institute in California. Since asteroids have the potential to affect the entire Earth, we hoped to bring together scientists from around the world to build an international community to discover and study them. We were delighted that over 40 percent of the attendees came from countries other than the United States.

Enthusiastic for Asteroids

At the conference we heard papers on new asteroid discovery programs, research on the nature of these bodies and their role in the evolution of life on Earth, as well as the possibilities for missions of exploration. The enthusiasm of the researchers was infectious, and we came away with renewed determination to pursue the Society's asteroid program.

We have instituted an Asteroid Discovery and Exploration Fund to support our new initiatives. At the conference, we identified several directions that the Society's asteroid program might take:

- Extending the network of observers around the world to increase the discovery rate.
- Investigating and disseminating new methods to detect near-Earth asteroids, including the developing technology of charge-coupled devices (CCDs).
- Complementing NASA's asteroid program.
- Advocating government support for observation programs.
- Developing new concepts for microspacecraft missions to asteroids.

As we prepare this article, four leading asteroid researchers are attending a conference in St. Petersburg, Russia, on the danger of asteroid impacts—with Planetary Society support. Glo Helin is, of course, one of them, as is Clark R. Chapman, our faithful News & Reviews columnist, who in his professional life is a leading asteroid scientist. We have also been able to help Tom Gehrels of the University of Arizona, whose Spacewatch camera, using CCDs, is pioneering a new method of asteroid discovery. Alain Maury of the Observatoire de la Côte d'Azur in France completes the Planetary Society contingent.

The Planetary Society has committed itself to promoting, supporting and enabling programs to discover near-Earth asteroids and to illuminate their role in humanity's future.

Charlene M. Anderson is Director of Publications for The Planetary Society and Society Director Louis D. Friedman is a member of NASA's Near-Earth Object Detection Workshop.

World Watch

by Louis D. Friedman

WASHINGTON—The long, divisive and debilitating process of determining NASA's budget for 1992 is over. Economic problems in the United States forced Congress to make a stark choice: Cancel space station *Freedom* or scale back NASA's scientific and exploratory missions.

The Bush administration and NASA's top management chose the space station over science and exploration, and Congress followed their lead. The Appropriations Committees in both the House of Representatives and the Senate had reduced the administration's budget request for NASA by 10 percent, forcing the choice.

In an extraordinary display of unity, many government advisory groups and national scientific organizations have stressed that *Freedom* will do very little either for science or for exploration, but their testimony has had almost no influence on the executive and legislative branches.

Planned planetary, astronomy and life science missions have been canceled, curtailed and delayed. These are some of the casualties:

• Comet Rendezvous Asteroid Flyby (CRAF) and *Cassini*: The 36 percent reduction to this budget makes it impossible to launch either spacecraft as planned. NASA and the Jet Propulsion Laboratory are developing a new plan that will delay the launches at least two years—which will probably require an eventual budget increase of at least 25 percent. With NASA's budget likely to be squeezed even more next year, it is probable that CRAF will eventually be canceled.

• Advanced X-Ray Astrophysical Facility (AXAF): The budget for the proposed orbiting telescope was cut 28 percent and the project delayed one year. This delay will increase its budget for 1993, and additional delays are possible.

• Space Infrared Telescope Facility (SIRTF): All funding for this project—given highest priority among all astronomy programs for the 1990s by the National Research Council—was cut. It may be proposed again next year.

• Orbital Solar Laboratory: All funding for this project was eliminated.

• Lifesat: This proposed biomedical research program using small satellites was terminated.

• Space Exploration Initiative: No program related to the human exploration of the Moon or Mars was funded. This means that NASA has no budget to study Mars missions beyond the 1992 launch of *Mars Observer*, and no funds available for possible lunar missions. There are no funds to prepare for long-duration spaceflight.

Two NASA advisory groups, the Committee on the Future of the US Space Program and the Synthesis Group on America's Space Exploration Initiative, had both strongly urged that the United States develop a new heavy-lift launch vehicle for human planetary exploration. However, this advice was ignored during the budget process. Funds for this National Launch System were nearly deleted. No new launch system will now be possible before 2002.

And this is the good news—according to most congressional staff members who worked on the budget. Next year's allocation for NASA will be even tighter.

PASADENA—*Galileo*'s antenna is still stuck. Three of the ribs in the umbrella-like device are refusing to move, preventing the antenna from unfurling and assuming the parabolic shape it will need to communicate with Earth. Mission controllers have been trying various maneuvers to unstick the ribs, and the latest attempt in August failed.

They will try again in December, when *Galileo* will reach the coldest point this year on its trajectory to Jupiter. Engineers hope that the cold will cause the antenna's central column to shrink slightly and thus allow the ribs to slip into their open position.

On October 29, *Galileo* flew close by the main-belt asteroid Gaspra and gathered data that were stored on board for later transmission to Earth. The spacecraft can communicate with Earth using its small, low-gain antennas, but the data can be transmitted only slowly.

At Jupiter, *Galileo* will deploy a probe into the planet's atmosphere and then embark on a loop-the-loop trajectory past the large moons Io, Europa, Ganymede and Callisto. The low-gain antennas will be able to handle the data from the probe. But each image of the moons will be composed of millions of bits of data, requiring a powerful antenna to transmit the planned 50,000 to 100,000 images to Earth. If the large, high-gain antenna cannot be unfurled, most of the images will be impossible to return.

Fortunately, *Galileo* will not reach its target until 1995, giving the resourceful JPL team a few more years to try different solutions. If temperature changes don't help, they may try firing the spacecraft's thrusters to shake the ribs loose.

A small communications satellite to orbit Jupiter and relay *Galileo*'s signals to Earth has been mentioned, but NASA is seeking less expensive, more reliable alternatives.

KAMCHATKA—Sometimes history catches up with you. In the July/August *Planetary Report* I published "What Now With the Soviets?" about the future of the Soviet space program. Then, on August 18, while I was in the air, flying to Kamchatka to participate in field tests of the Soviet Mars Rover, the coup leaders tried to seize control in Moscow. Three days later, the coup was over.

I am happy to report that the coup had no effect whatsoever on the rover tests, except to provide a little extra excitement. Our primary reason for going to Kamchatka was to orient the Society team as to the capabilities and requirements of the Soviet rover program so that we can prepare for more advanced tests in the Mojave Desert next spring.

We now have a good idea of the mobility characteristics, control system requirements and operational sequences for the rover. We have begun planning the Mojave tests and will keep you informed of our progress.

Executive Director Louis D. Friedman spent a year in Washington, DC, during the late 1970s working on the staff of the US Senate.

The State of The

by Louis D. Friedman

As we near the close of 1991—a watershed year for many, many reasons—I want to present a report to our members on the state of The Planetary Society. Political upheavals and economic concerns have changed the priorities of the spacefaring nations. More mundane factors, such as postage increases, have made it harder for nonprofit organizations to survive.

But, despite many negative factors, I believe that The Planetary Society has never been in better shape.

We are deeply disappointed that Earth's space programs have made no progress toward the goal of landing humans on Mars. In the United States, President Bush's Space Exploration Initiative, enunciated two years ago on the 20th anniversary of the *Apollo 11* landing on the Moon, seems to have died. At best it is moribund, without political support, program accomplishments or funding from Congress.

The Officers of The Planetary Society argued against building space station *Freedom* as it is now designed, yet Congress funded it—to the detriment of space science and exploration. It appears that NASA will build its orbiting station, but to accommodate it the agency risks delaying or canceling other programs, such as the Comet Rendezvous Asteroid Flyby, the *Cassini* mission to the Saturn system, a lunar polar orbiter and missions to the surface of Mars, as well as astronomy and life science missions.

We are now ready and able to grasp the opportunities appearing as the economic and political situation improves.

In Russia and the other formerly Soviet republics involved, work is continuing on the now-split *Mars '94* and *'96* missions. However, as we have reported, the mission plan has been cut back and the spacecraft that will carry the Mars Rover and the Mars Balloon equipped with our SNAKE guide-rope has been delayed to 1996. Mars missions beyond 1996 are not yet on the agenda of the new republics.

Overriding our concerns for the Mars missions is, of course, the great uncertainty about the future of what was the Soviet Union. We are hopeful. While we wait to learn what the new governments' attitudes toward space exploration will be, we are striving to open new contacts there.

In the smaller realm of The Planetary Society itself, our membership numbers have decreased by about 10 percent. This is primarily because we halted our direct-mail solicitation campaigns during the recession and the war in the Persian Gulf. Other membership organizations have experienced similar or far greater drops in their numbers, attributed to the economic hard times and uncertainty.

Somewhat ironically, our decision to put mail solicitations on hold has been extremely good for the Society's financial health. Those organizations that mailed into the teeth of the recession have been badly hurt. Our decision to wait and accept a modest drop in membership numbers has ensured that we are now ready and able to grasp the opportunities appearing as the economic and political situation improves.

But with our membership down, the Space Exploration Initiative eviscerated, space station *Freedom* gobbling up space science and exploration projects, uncertainty about the Soviet space program, and a lingering recession, you might ask, how can I say that the state of The Planetary Society has never been better?

I have been impressed by the internal strength of the organization, the loyalty of our members and their commitment to our programs. External factors, such as changing government policies, wars, recessions and misguided space policies, do affect us. But where we have control—the Mars Balloon and Rover, Project META, our Asteroid Discovery Project and other programs—things are going extremely well. And the promise of things to come is even brighter.

We are all gratified by the depth of support for our programs that our members have demonstrated again and again. This is the greatest testimony to the health of our organization. The renewal rate has risen to an all-time high, with our longtime members renewing at a rate of over 80 percent. Planetary Society members are committed for the long haul.

The most memorable—for me—example of this commitment was the astounding response to our appeal for funds to test the Mars Rover. You gave us a solid mandate for a risky project with great potential. Imagine, a group of private individuals, independent of government or industry, raised enough money to become a key player on an international mission to explore Mars.

With your support, not only are we part of the *Mars '96* rover program, but we are helping to develop rover technology in the United States and around the world. Next year a large contingent of Soviet scientists and engineers will come to California to demonstrate robotic devices and test their readiness for Mars. The Society is putting together an international team to wrestle with the problems of navigation and control on an alien and relatively unknown world.

We are also advancing an innovative microrover concept for martian exploration 10 years earlier than called for in the plans of government space programs. The microrover is based on the robotic "insects" developed at the Massachusetts Institute of Technology. The technology is now being furthered by a university-private sector partnership, with some technical interest (but little money) from NASA. The Planetary Society has proposed that the microrovers be considered for the *Mars '96* mission as mechanical scouts and sampling hands for the rover.

But the Mars Rover project is not the first instance of

Planetary Society

private citizens playing a role in a planetary mission. That distinction belongs to the Mars Balloon project. The Society-designed SNAKE guide-rope is a critical part of the balloon system. After proving the concept, we were officially engaged as part of the project team by the Centre National d'Études Spatiales (CNES), the French space agency. CNES is now partly funding our engineering program.

Our Project META, the Megachannel ExtraTerrestrial Assay developed by Harvard University professor Paul Horowitz, remains the most comprehensive and advanced search for extraterrestrial intelligence on this planet. META has operated continuously for the six years since Society Director Steven Spielberg provided the seed money for its construction.

Our members have supported our SETI projects since "Suitcase SETI" in 1981. You've enabled us to duplicate META for the Southern Hemisphere and get it operating in Argentina. Our multichannel spectrum analyzers are now operating at Harvard's Oak Ridge Observatory in Massachusetts and at the Argentine Institute for Radio Astronomy outside Buenos Aires. We've not yet found an unambiguous signal from another technological civilization, but we have learned a lot about how to search and how to deal with radio interference.

NASA's $100 million SETI project will come on-line in 1992 and will conduct occasional, very comprehensive searches of the radio spectrum. NASA's program will complement, not compete with, our own. At The Planetary Society, we are preparing to jump to 100 million channels with Project BETA, with an ultimate goal of building a 6-billion-channel receiver.

Our asteroid program has continued to flourish. In the first nine months of this year, Eleanor "Glo" Helin and her team in the Palomar Planet-Crossing Asteroid Survey have discovered two comets and seven near-Earth asteroids. That's a discovery rate of one new object per month! We have supported Glo's program since 1982, and, considering her continuing productivity, we will be funding her for some time to come.

We've also provided funds for Jeremy Tatum and David Balam's astrometry program at the University of Victoria, British Columbia. As Dr. Tatum reported in our September/October 1991 issue, astrometry may not be as glamorous as other branches of astronomy, but their asteroid work is extremely important if we are to locate orbits precisely in preparation for missions of exploration.

When I am depressed about NASA's lack of vitality and about the struggles of other space programs, I find renewed hope in the success of The Planetary Society's projects and in our members' steadfast support. The Society may never conduct the big space missions we so earnestly advocate, but we are pushing for them and contributing to their eventual accomplishment. And we have demonstrated very vividly that private citizens can make a difference—even in a venture as grand as the exploration of the planets.

Space projects are, by their very nature, future-oriented. We intend The Planetary Society to be a beacon of hope for the future. Thus our efforts to improve science education are a logical part of the Society's activities. We have developed, under Carl Sagan's leadership, a partnership with the National Science Teachers Association in a major new program to reform the science curriculum in the United States.

We have also recently embarked on a project to involve students directly in planetary exploration. We hope to give them a chance to learn science by doing it—in a laboratory called Mars. In cooperation with NASA and the Jet Propulsion Laboratory, we are developing a *Mars Observer* Student Interaction Project. We hope to provide students with data from the orbiting spacecraft, encourage them to analyze the data, and make it possible for them to test their hypotheses with the help of the *Mars Observer* team.

Our "Together to Mars" Student Contest, funded by a grant from H. Dudley Wright, has attracted considerable attention around the world. We've received some 900 entries from more than 30 countries. We are impressed by the geographic diversity represented by the entries—from Nigeria to Argentina to the Soviet Far East. And the age range also is impressive: One of the American finalists is a 14-year-old student!

We have demonstrated very vividly that private citizens can make a difference—even in a venture as grand as the exploration of the planets.

We are looking forward to 1992 with a lot on our plate. 1992 will be the International Space Year, and we are planning to celebrate! The launch of *Mars Observer* will capture the exploratory spirit embodied by Columbus as he set sail for a new world, and we're working on some exciting programs centered around launch activities. At the end of the summer, we plan to hold a Rover Expo in Washington, DC. This will coincide with the World Space Congress being held there at that time.

And so, I am pleased to report that The Planetary Society has never been stronger. Our organization is very healthy, active and growing once again. We have an array of ambitious projects before us. Just consider the intellectual scope of a search for alien civilizations or the technological challenge of sending robots to land on Mars. And we are continually seeking out new projects where we can and will contribute to the exploration of the solar system.

Louis D. Friedman is Executive Director of The Planetary Society.

News & Reviews

by Clark R. Chapman

There is new public awareness of an old idea—the potential threat to civilization of an asteroid impact onto our planet. There are many fictional accounts of a celestial Armageddon. In 1949, lunar expert Ralph Baldwin warned of a possible asteroidal impact explosion that "would, anywhere on Earth, be a horrifying thing, almost inconceivable in its monstrosity."

A decade ago, a NASA workshop concluded that, with large uncertainties, there is one chance in 300,000 of a civilization-destroying impact occurring *each year*. If you have a 50-year future life expectancy, that is one chance in 6,000 that your epitaph will say that you died when an asteroid struck Earth and killed billions of people.

Such an ecological disaster that sends society back into the Dark Ages would *not* render our species extinct, like the catastrophe that killed the dinosaurs 65 million years ago. But the fragile economic and social structure of modern society might not withstand the stress of a year with no crops anywhere, which would result from the impact of a mile-wide asteroid. Such a million-megaton explosion would inject enough dust into the stratosphere (hundreds of times as much stuff as injected by the Pinatubo volcano, causing this summer's beautiful sunsets worldwide) so that sunlight would be blocked around the globe, bringing about mass starvation.

Two years ago, Dave Morrison and I described the 1981 study in our book *Cosmic Catastrophes*. After Morrison gave a speech about it to congressional staffers, Congress directed NASA to study the hazard. Then I was asked—by NASA and by The Planetary Society—to organize the International Conference on Near-Earth Asteroids, held in San Juan Capistrano, California, last July. Since then, there has been much public concern (and some skepticism) about the hazard.

A NASA committee chaired by Morrison studied how to detect the hazardous projectiles. It concluded that a 20-year international telescopic survey, using a network of six new, large telescopes, could inventory nearly all of the objects that would threaten civilization. We already know how many potentially threatening objects there are—1,000 to 2,000—but more than 90 percent of them remain unknown today, and one could strike anytime.

In January 1992, another congressionally mandated committee will investigate what to do if a threatening object is unexpectedly found to be on a collision course. Smaller impacts, like the 15-megaton blast over an uninhabited part of Siberia in 1908, occur much more frequently than civilization-destroying ones. Such an impact in a metropolitan area could kill millions of people, like the greatest natural catastrophes in history (floods and earthquakes). But strategies for protecting ourselves from these more numerous, smaller projectiles, which are much more difficult to detect, are likely to be extremely expensive.

I have just returned from an asteroid hazard meeting in St. Petersburg, Russia, organized by Andrei Sokolsky, the Director of the Institute for Theoretical Astronomy of the Soviet Academy of Sciences. Given the dire economic problems facing this far-northern metropolis during the coming winter, it may seem ironic that representatives of 38 scientific and technological organizations from throughout Russia and the other republics would consider the long-shot threat of an asteroid impact. But Russia has been ground zero for some of the biggest meteorite falls in history; there is nothing abstract about this hazard. Also, cross-disciplinary, USSR-wide, international programs are needed to sustain scientific research following the breakup of the Soviet Academy of Sciences.

In the United States, I have encountered cynicism about why the asteroid hazard has suddenly made national television just when NASA-funded scientific research programs are being cut back and the Star Wars military programs have lost their *raison d'être* because of the end of the Cold War. Certainly, some of my colleagues' astronomical research could benefit from more telescopes. But the cost of a couple of hundred million dollars to prove once and for all that our civilization is *not* threatened (or to warn us of an impending holocaust in the very unlikely event that an incoming object is found) represents a rational option for society in allocating precious resources.

I think that it is my responsibility as a scientist to inform the public about this hazard and about approaches to addressing it. But I do *not* think it is my place to advocate such a program. Given the widely disparate views individuals have about the seriousness of this hazard, once they are informed about it—just as divergent as opinions about nuclear power plant risks—it will be a close call for the politicians to decide whether to proceed.

However, I am more cynical, myself, about the vastly more expensive, Star Wars–based defensive "shields" that have been talked about, which conceivably could protect us from the regional (not global) catastrophes caused by smaller projectiles. I would rather that the superpower military establishments protect us from a celestial threat than renew dangerous conflicts between nations. But the billions of dollars that whet their appetites about this abstract hazard could be directed more appropriately toward dangers and suffering that are with us now.

Clark R. Chapman was part of a five-person US delegation to the St. Petersburg meeting in October. The Planetary Society provided partial support for four of the delegates.

SOCIETY Notes

GOODBYE AND HELLO TO A VALUED FRIEND

James D. Burke, who has served as Technical Editor for *The Planetary Report* since its inception, recently retired from the Jet Propulsion Laboratory after 42 years of dedicated work. Being quick on our feet, the Society staff immediately took advantage of this and offered Jim a new home base at our headquarters, where he now enjoys the title of Technical Consultant to The Planetary Society.

Jim's career is filled with achievements. He served as manager of the *Ranger* project, the first United States mission to the Moon, and as the manager of advanced engineering technical studies at JPL. In his spare time, he worked on the human-powered *Gossamer Condor* and *Albatross* and the *Solar Challenger* aircraft.

Jim is perhaps best known to Society members as co-inventor of the SNAKE guiderope for the Mars Balloon, which is scheduled to fly on the Soviet *Mars '96* mission.

We've already put Jim to work planning the test program for the Mars Rover, scheduled for the Mojave Desert next spring. His enthusiasm, energy and creativity will be great assets for The Planetary Society.
—Louis D. Friedman, Executive Director

ASTEROID CONTEST WINNER

Our January/February 1991 issue presented you with an unusual contest—an opportunity to help Eleanor "Glo" Helin name near-Earth asteroid 1982DB. We're pleased to announce that a name was indeed selected from the suggestions made by Planetary Society members.

The winning entry is "Nereus," submitted by Robert M. Cutler of Potomac, Maryland. Nereus is one of the oldest of the Greek gods, a benevolent sea-deity gifted with the power of prophecy. Mr. Cutler points out that his choice is uniquely appropriate for an asteroid with an orbit so close to Earth, as Nereus sounds very much like the words "near us."

For his winning contest entry, Mr. Cutler has won an all-expenses-paid trip to a future conference of his choice.
—Charlene M. Anderson, Director of Publications

HELP WITH THE ROVER TEST

Next May we will be testing the Soviet *Mars '96* rover in the Mojave Desert. This ambitious project will involve the coordination of many people and support equipment at remote test sites.

We will need two passenger vans, a recreational vehicle or trailer for use as an office/control station (housing video and computer equipment plus operators) and an enclosed cargo truck for moving equipment. We'll also need two video monitors, VCRs (or combined units), camcorders, plus an IBM-compatible PC with printer and plotter.

If you are able to lend any of these items to the Society, we would greatly appreciate it. We would, of course, insure the equipment while we are using it. Please contact us at the address below, if you are able to help. *—LDF*

DON'T FORGET SOCIETY DAY IN BOSTON

We would like to remind members that the Society will be holding its second Planetary Society Day on March 27, 1992, at the National Science Teachers Association's national convention in Boston. Featured speakers will include renowned physicist Philip Morrison on the question, "What About the Big Bang?" and planetary scientist Richard P. Binzel, who will discuss "Asteroids: The Next Frontier."

Planetary Society presentations will range from the current state of the Soviet space program to our programs in the Search for Extraterrestrial Intelligence. Society members will enjoy the same discounted convention rates as members of NSTA.

For more information on registration and housing, please write to me at the Society's offices, or call 1-800-WOW-MARS. Please be sure to give your name and address and tell us that you are requesting NSTA information. *—Susan Lendroth, Manager of Events and Communications*

SOCIETY LAUNCHES NEW PHONE LINE

Do you have friends or colleagues who would like to know more about The Planetary Society? Tell them about 1-800-WOW-MARS, our 24-hour information line.

Interested parties within the continental US can call anytime, day or night, and leave their name and address. Within 48 hours we'll be mailing them information on The Planetary Society and membership benefits.

We do want to emphasize that 1-800-WOW-MARS is for prospective members and NSTA information only. Current Society members and parties outside the US should address their questions to our headquarters office at (818) 793-5100.
—Lu Coffing, Financial Manager

EVENTS CALENDAR AVAILABLE

The Society's Volunteer Network organizes a great variety of events every year. If you would like to receive a copy of the network events calendar, please write to me at the Society's offices.
—Carlos J. Populus, Volunteer Coordinator

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Questions & Answers

Can* Magellan*'s radar system be used as a microwave radiometer to detect active volcanoes and volcanic vents on Venus from their heat?
—Bruce Moomaw, Cameron Park, California

Magellan's radar system *is* being used as a radiometer, although its primary purpose is to penetrate Venus' thick clouds to permit the mapping of the surface. Two different modes of operation are involved. To map the surface, the radar system is "active"—it provides its own radio illumination of the surface and records the reflected signal. That is, it shines its own bursts of energy at the planet and catches the reflections. The wavelength of the radar is 12.6 centimeters.

When the radar system is used as a radiometer to detect and measure radiant energy, however, it simply listens *between* radar bursts for microwave energy radiated from the surface of the planet.

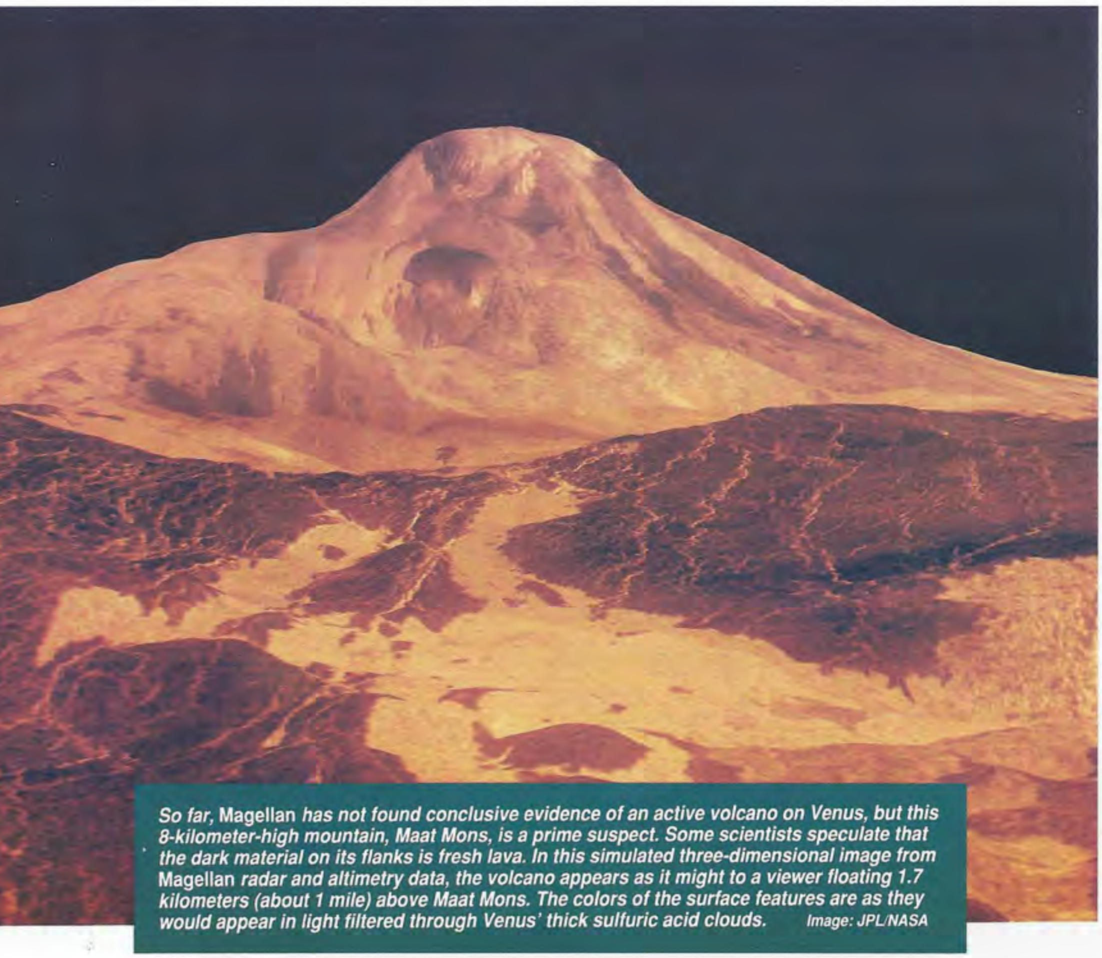
All matter with a temperature above absolute zero radiates electromagnetic energy, the wavelength and strength of which depend on the temperature. *Magellan*'s radar helps us estimate the planet's surface temperature by measuring the so-called microwave brightness temperature, which is determined by how well the surface radiates or absorbs energy.

While Venus' surface temperature is well known to average 460 degrees Celsius (860 degrees Fahrenheit), the atmospheric temperature varies with elevation, just as it does on Earth—the higher you go into the mountains, the cooler the air becomes. Unless there is some anomaly like a volcanic eruption, the microwave brightness temperature tells us how well the surface radiates heat.

We've already seen some differences in surface temperature on Venus, though most of these have been instances of areas cooler than their surroundings. This is because some types of materials apparently radiate heat much better than the average surface. Generally, we've seen this effect at higher elevations, such as on Maxwell Montes, the highest mountain on Venus.

Halfway into *Magellan*'s mission, we found a high-temperature anomaly—more than 100 degrees Celsius higher than expected. But it turned out that the Sun, Venus' surface and the spacecraft were all in just the right positions to give us a direct reflection of the Sun off the planet's surface.

Magellan's radar is sensitive enough to detect a temperature difference of about 1 degree Celsius. Basaltic lavas on Venus would erupt at temperatures about 700 to 800 degrees hotter than the surface, but they would cool in hours to days. Many of the lava flows we've seen in



So far, Magellan has not found conclusive evidence of an active volcano on Venus, but this 8-kilometer-high mountain, Maat Mons, is a prime suspect. Some scientists speculate that the dark material on its flanks is fresh lava. In this simulated three-dimensional image from Magellan radar and altimetry data, the volcano appears as it might to a viewer floating 1.7 kilometers (about 1 mile) above Maat Mons. The colors of the surface features are as they would appear in light filtered through Venus' thick sulfuric acid clouds. Image: JPL/NASA the *Magellan* images cover hundreds of square kilometers, and when the spacecraft acts as a radiometer, it looks at an area a few hundred square kilometers in size. Thus, if we happened to take data over an eruption that occurred within the past few days, it would show up as a thermal anomaly.

Volcanic vents would be harder to detect, since they are much smaller, and their thermal effect would be smeared over the entire antenna beam width; that is, *Magellan*'s radar looks at the average temperature of its viewing area, not at any one spot.

Whether we could "see" a volcanic eruption would depend on how big the volcanic vent or eruption was and whether it was active and still hot at the time of measurement.

—R. STEPHEN SAUNDERS, *Jet Propulsion Laboratory*

Why don't any of the satellites of planets in our solar system have little satellites of their own? Is there some principle of orbital mechanics that renders such a situation impossible or unstable over the long term?

—Bruce Hallock, Austin, Texas

To set matter in motion around a central body—a star, a planet or a satellite—the central body must be spinning and have a magnetic field capable of transferring momentum to the electrically charged building material surrounding it. From this material, secondary bodies, such as planets, satellites or satellites of satellites, might form.

As a consequence, only those planets that spin reasonably fast and have (or possibly have had) a sufficiently strong magnetic field have well-developed satellite systems around them. This is the case with Jupiter, Saturn and Uranus. Mercury and Venus spin very slowly and have weak magnetic fields, and therefore, as expected, no satellites. Mars has a weak magnetic field, which may have been stronger in the past, and its satellite system is rudimentary—in fact, its moons may actually be captured asteroids.

Neptune and Earth are interesting cases—their major satellites are abnormally large and are probably planetoids captured from solar orbits or formed by some other unusual process. In the process of capture, they could have spiraled in toward the planet, sweeping up its original orderly system of much smaller satellites. Such an origin has been proposed for Neptune's large moon Triton, leaving distant Nereid as the sole survivor.

A similar origin has been proposed for our Moon. The late heavy bombardment of the lunar surface 3.8 billion years ago would mark the sweeping up of Earth's original collection of perhaps 6 to 10 small satellites. Another current theory is that our Moon formed as a result of a collision between Earth and a large, Mars-sized body.

In contrast to the planets, none of the satellites appear to have enough mass and spin to develop a magnetic field that could have induced secondary satellites. We think that the magnetic fields of stars and planets are due to the motion of conducting molten matter in the interior, creating a self-amplifying dynamo.

—GUSTAF ARRHENIUS, *University of California at San Diego*

What would happen if a comet hit one of the gas planets? Would it pass right through?

—Pete Purviss, Creve Coeur, Illinois

No comet could pass through a gas giant planet. The force of the gas molecules striking the comet would slow it down and break it up. The cometary fragments would either vaporize or fall like rocks to the planet's center.

The deepest a comet could survive intact is the point at which it has swept out a mass of atmosphere equal to its own mass. This critical depth (pressure) is proportional to the density of the comet and its diameter. For example, an icy comet 1 kilometer in diameter might survive to a pressure of 100 bars (100 times Earth's sea-level pressure). It would still barely penetrate the planet, surviving to a depth within only 0.5 percent of a gas giant's surface. The central pressures of such a giant are so great that they are measured in megabars, or *millions* of bars.

—ANDREW P. INGERSOLL, *California Institute of Technology*

FACTINOS

Astronomers at the University of Arizona in Tucson have discovered that Pele, the largest volcano on Jupiter's moon Io, has come back to life. This volcano was the most powerful of eight that were erupting on Io when *Voyager 1* serendipitously photographed them in March 1979. Four months later, however, *Voyager 2* detected no activity on Pele, and scientists classified it as "short-lived."

But the volcano has been caught erupting again, this time by Brian A. McLeod, Donald W. McCarthy, Jr., and Jonathan D. Freeman, who used a ground-based telescope to photograph Io. Besides Earth, Io is the only other solar system body that is known to be volcanically active.

—from the University of Arizona

A strange brightening of Halley's Comet earlier this year may have been caused by a shock wave initiated by a solar flare, researchers say. In February, the inert comet sprouted a shiny dust cloud about 290,000 kilometers (180,000 miles) across and flared up to be hundreds of times brighter than expected. Scientists could only guess why.

But Devrie Intriligator of the Carmel Research Center in Santa Monica, California, and Murray Dryer of the National Oceanic and Atmospheric Administration in Boulder, Colorado, suggest that a solar flare may have created a shock wave that traveled through space and hit the comet. The impact may have been strong enough to crack the icy crust of the comet's potato-shaped nucleus, letting dust escape to produce the huge cloud.

—from the *Los Angeles Times*

In July, British astronomers announced the discovery of a planet orbiting a pulsar—the dense, spinning remnant of an exploded star (see Factinos in the September/October *Planetary Report*). Now astrophysicists Douglas Lin, Peter Bodenheimer and Stan Woosley from the University of California at Santa Cruz have published, in *Nature*, a model for the birth of the planet they call "Phoenix."

They suggest that a disk of gaseous debris began to orbit the pulsar after a tiny bit of material "bounced back" from the supernova explosion. Over time, the debris condensed into dust-sized grains, then boulders, then asteroid-sized objects, and finally into a single planet.

"No one had ever predicted this type of planet," says Woosley. "This is basically a scenario—a plan for how things might have worked without violating physics."

—from the University of California at Santa Cruz

The Solar System in Pictures and Books

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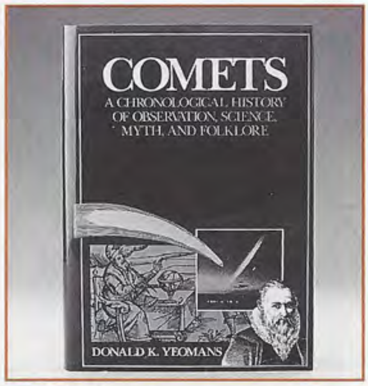

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FIRST CLOSE-UP OF AN ASTEROID—*Looping its way through the solar system,* Galileo *took advantage of its circuitous route to Jupiter to capture this image of asteroid 951 Gaspra as the spacecraft traversed the main asteroid belt. This is the first time scientists have been able to get a close look at an asteroid in space. Before this encounter, their views were limited to streaks of light on photographic plates or blob-like forms reconstructed from radar data.*

Sunlight illuminates a pockmarked portion of Gaspra about 16 by 12 kilometers (10 by 7.5 miles) across. The entire asteroid is estimated to be about 20 by 12 kilometers (12.5 by 7.5 miles) across. Its faceted appearance recalls a catastrophic history; Gaspra was probably once part of a larger planetoid now broken into many, many bits. Craters are further evidence of its violent past; the largest one clearly visible is about 1.5 kilometers (5,000 feet) across, while the smallest visible are about 300 meters (1,000 feet) across.

With its main antenna still only partly unfurled, the spacecraft returned this image to Earth using a small, low-gain antenna, which transmits its information slowly. Most of the data Galileo *gathered during the Gaspra encounter will be transmitted next November when the spacecraft prepares to once again swing by Earth, although it is possible that the best picture (with three times better detail) will be dribbled back as early as next spring.*

Image: JPL/NASA

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