The PLANETARY REPORT

Volume XV Number 2 March/April 1995

Clues to Catastrophe

On the Cover:

Craters are not the only traces that asteroids and comets leave on Earth. A thin layer of iridium-rich clay found outside Gubbio, Italy, was the first recognized evidence that some large near-Earth object had once obliterated itself by colliding with the planet. (The layer is seen here as the greenish gray-to-red segment between the white limestone below and the pinkish tan limestone above.) While rare on the surface of Earth, iridium is plentiful in asteroids and comets, and one of these struck the planet 65 million years ago, leaving its signature in this clay layer. It also left a mark by wiping out the dinosaurs. Evidence such as this warns us that danger from the skies is real and should not be ignored.

Photograph: Frank Asaro

From The Editor

We've been publishing *The Planetary Report* for 15 years now, and we're still seeking ways to make it better serve the members of The Planetary Society.

Over the years we've dropped columns, added others and changed things around as inspiration struck. The first purpose of a magazine is to be read, and we try to craft our columns to be accessible. At the same time, we strive to fulfill the Society's goal of bringing the results of planetary exploration to as wide an audience as possible. Those results are sometimes a bit arcane and difficult to convey, but we do our best to lay everything out plainly without oversimplifying the content.

In this issue we're launching our latest effort, a column called Basics of Spaceflight. Dave Doody, who shared his experiences on the *Magellan* mission in our March/April 1994 issue, cowrote a training manual for new employees at the Jet Propulsion Laboratory. He's offered to adapt that material into a primer for our readers, revealing just how the seeming miracles of discovery are accomplished. We hope you find it illuminating and useful. If not, let me know what you think of the idea.

—Charlene M. Anderson

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Plate tectonics is and has been the dominant process shaping the face of Earth. So dominant is it here that it seemed natural to assume that it would play a major role on other worlds. But that does not seem to be the case, as we discuss in this column.

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Members' **Dialogue**

Preserving Other Worlds

I was doubly proud to be a Planetary Society member when I read our July/August 1994 *Planetary Report* on planetary protection. While some advocates of planetary exploration talk of the commercial benefits of "space exploration," as if other worlds were just more real estate to carve up, it's good to know that The Planetary Society has the foresight to consider preserving the integrity of those worlds.

Based on population projections and the possibility of catastrophic collisions between Earth and other planetary bodies, I expect that extraterrestrial mining and colonizing, even terraforming, will become increasingly important as the centuries roll by. It will be wise to be mindful of our impact as we expand our frontiers. Maintaining other worlds as close to their natural state as possible will be of ongoing importance to science. A scarcely noticed feature on a distant moon today could deepen our understanding of solar system formation tomorrow.

Before we begin tampering, I hope planetary exploration will be conducted relatively noninvasively (not precluding Mars rovers and such), with the aim of enhancing our understanding and appreciation of our solar system heritage. Protecting all worlds from forward and back contamination by any possible life-forms is a major step in this direction.

—MARGE CURRIE,
Boulder, Colorado

The Moon belongs to no one. Not its rocks, its minerals or its features. *Look* at the picture on page 28 of the July/August 1994 issue where the mining machine is processing rock and leaving behind it a trail of desolation. Do we really need energy so badly as to destroy our most inspiring neighbor?

When we have finished our mining activities, the Moon will no longer be the poetic inspiration for humankind it has always been. It will be a large eyesore from which we cannot hide. If anybody believes that a little mining can't hurt anything, then he or she hasn't been paying attention to what we have already done to Earth.

It is not acceptable to burn down the rain forest. We, as a planetary community, are taking a long time to come to that realization. It is not acceptable to mine the Moon, period. There must be some other path than one that is so destructive we dare not look back at the damage we have done.

—D. DOWNS,
Los Gatos, California

NASA's Future

Your November/December 1994 issue was one of the most spectacular ever. The coverage of the comet crash was superb, and I found Daniel Goldin's article to be very interesting.

While I agree that NASA must change, and that missions to determine the presence of life-supporting worlds around other suns are valuable goals, and I look forward to the results of missions to the Sun and Pluto, I firmly believe that NASA's ultimate goal should be the *permanent* return of humans to space, perhaps starting with a base on the Moon and then a mission to Mars. This will give the generation in which it happens a way to look back, to the *Apollo* missions that made it possible, and a way to look to the future with the greatest achievement of humankind firmly established.

Too many young people today claim that they have nothing to look forward to. That's why there are so many gangs that have no compassion for human life. It's worthless to them because they see no future. They see no greatness.

Discovering a life-supporting world in another star system would be a great scientific achievement. But it would still be remote, impersonal and ultimately meaningless to most people. Arriving on Mars would be a good bit closer to home. And it would show our young people what science, and what humans, can accomplish.

—THOMAS WHEELER,
Tucson, Arizona

The fundamental problem facing NASA is justifying the expenses involved in space exploration. For me there is only one reason to explore space and that is to guarantee the survival of the human species. As long as we have all of our eggs on one planet, there is always the risk of sudden extinction (ask any dinosaur—and they didn't have 50,000 nuclear devices scattered around the globe). I think the best long-term goal for NASA is to build a self-sustaining colony on the Moon or Mars.

—WES BURGER,
East Warren, Michigan

Oops!

In your November/December Questions and Answers column, Robert L. Forward seems to have lost over 22 trillion miles, or at least one decimal point position. He states, "The nearest star system, Alpha Centauri, is 4.3 light-years, or 4 trillion kilometers (2.5 trillion miles) away."

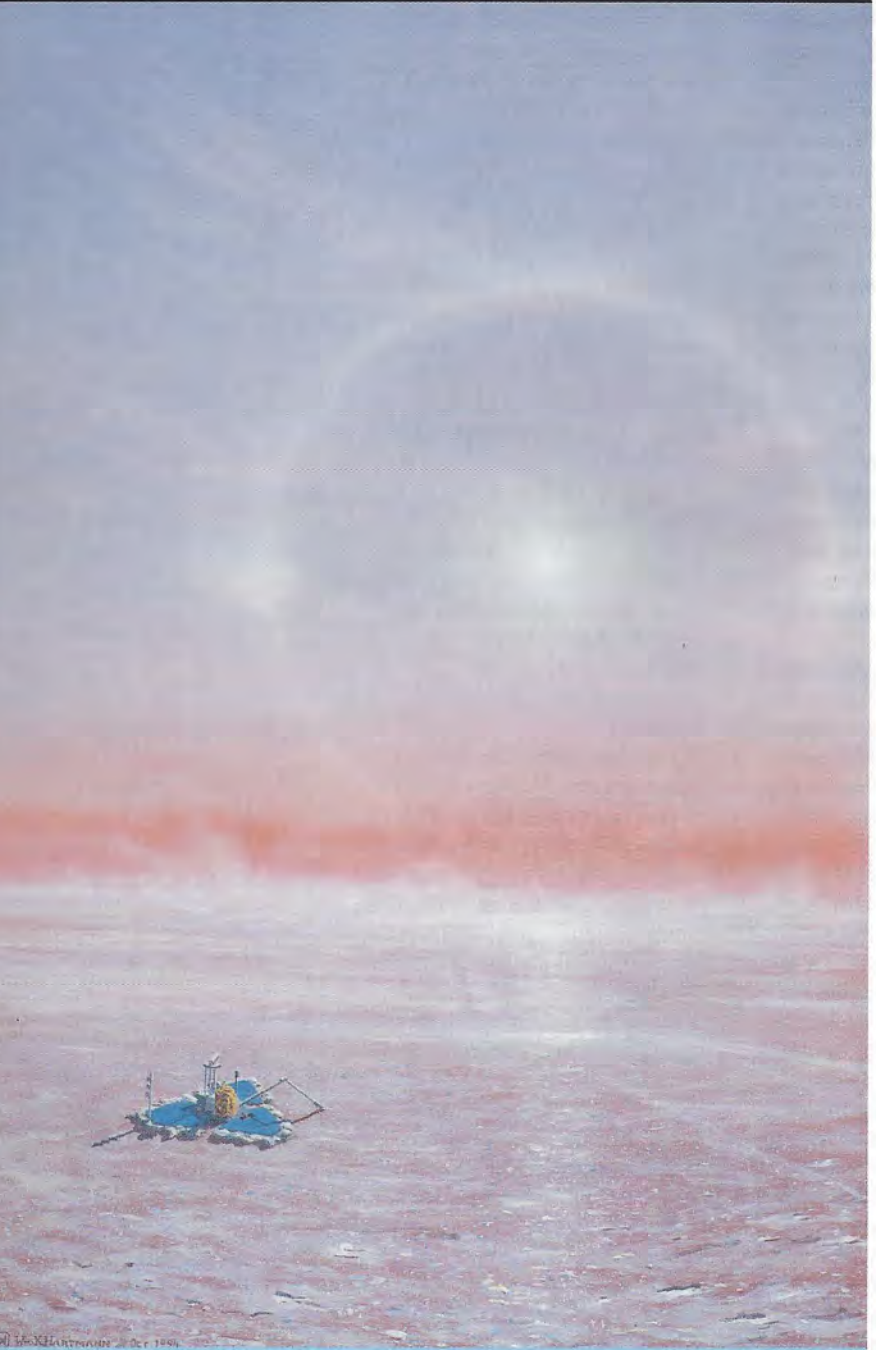
According to my calculations, the speed of light (approximately 186,000 miles per second), configures to about 5.8 trillion miles per light-year. This puts Alpha Centauri's distance at about 25 trillion miles from Earth.

—PETER SQUARINI,
Lauderhill, Florida

Please send your letters to Members' Dialogue, The Planetary Society, 65 North Catalina Ave., Pasadena, CA 91106-2301.

The Planetary Exploration Survey: What Society Members Think About Planetary Protection

by Donald MacGregor and Paul Slovic



There are hopes and plans to send many spacecraft to Mars' surface in the next decade, and each one will have to meet certain criteria to help ensure that it does not carry terrestrial invaders to the martian environment. Among the spacecraft could be the proposed Mars Polar Pathfinder. Painting: William K. Hartmann

The July/August 1994 special issue of *The Planetary Report* covered the topic of planetary protection, a matter that must be confronted as space scientists and engineers plan new missions to Mars and other planets in our solar system. We asked Society members to share their views on many aspects of the topic by completing a survey questionnaire included in that issue.

More than 4,300 Society members from countries around the world responded. That so many of you were willing to share your opinions with us was both gratifying and exciting. As we promised, here's a breakdown of members' responses to the survey.

Value of Space Exploration and Scientific Research

The vast majority (95%) felt that space exploration is essential to the future of our society, and most (85%) said they were familiar with NASA's plans to conduct missions to the surface of Mars. Not surprisingly, the majority saw space exploration as having high benefits in terms of scientific knowledge and human fulfillment; fewer people saw high benefits in economic and military areas (see Figure 1).

In general, Society members strongly supported other large-scale scientific research, and held highly positive views about the benefits of the superconducting supercollider, mapping the human genome and continuing the search for extraterrestrial intelligence (see Figure 2).

Potential for Life on Other Planets

The possibility of life on other planets is one of the most intriguing aspects of space exploration. While people who responded to the survey were either skeptical or uncertain that intelligent extraterrestrial life will be discovered within a decade or so, most were confident that intelligent life does exist on other planets in the universe. Fewer agreed that some form of life exists either on other planets in our solar system or on Mars in particular (see Figure 3).

Risks of Interplanetary Contamination

The need for planetary protection arises because of the possibility that Earth or another planet (or both) could be contaminated by the exchange of biological materials as the result of space missions. While

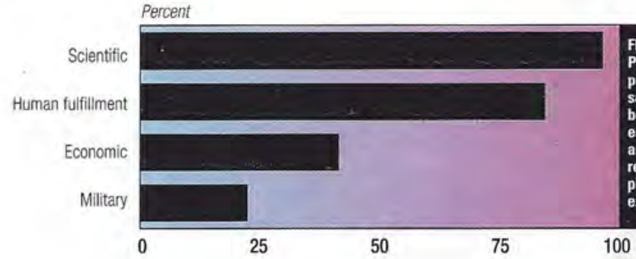


FIGURE 1: Percentage of people who said that high benefits in each of these areas could result from planetary exploration.

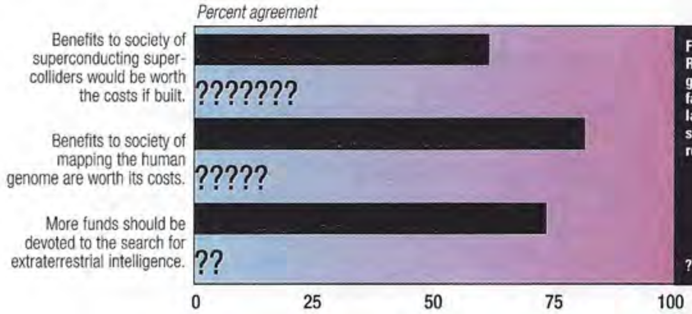


FIGURE 2: Respondents generally favored large-scale scientific research.

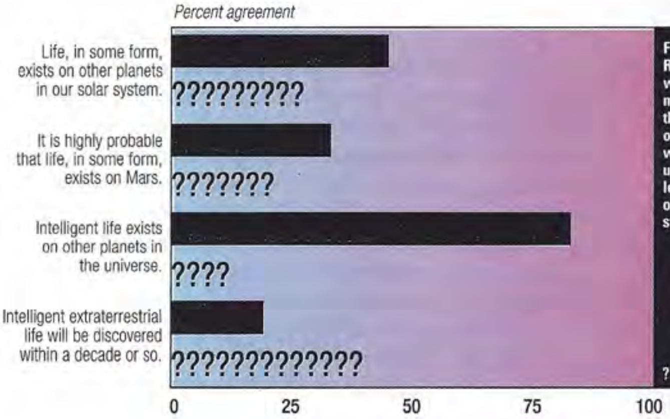


FIGURE 3: Respondents were optimistic about the existence of life elsewhere in the universe, but less so in our own solar system.

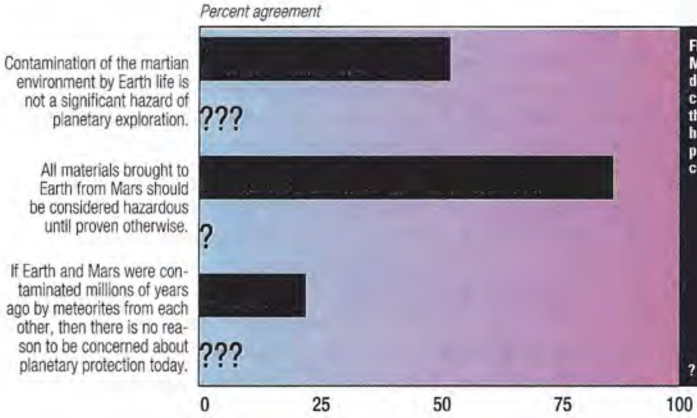


FIGURE 4: Most respondents were cautious about the potential hazards of planetary contamination.

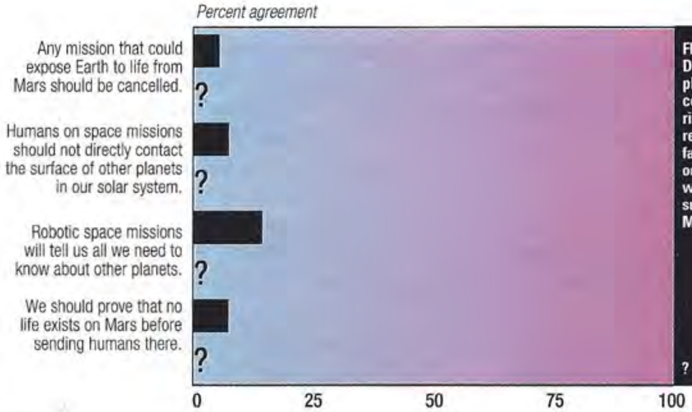


FIGURE 5: Despite planetary contamination risks, few respondents favored limited or no contact with the surface of Mars.

a slight majority of respondents thought that the contamination of the martian environment by Earth life is not a significant hazard, an overwhelming majority indicated that materials brought to Earth *from* Mars should be considered hazardous until proven otherwise.

One article in the special issue discussed a theory that Earth and Mars were contaminated millions of years ago by meteorites from each other (see "Swapping Rocks: Exchange of Surface Material Among the Planets," by H. Jay Melosh), suggesting that there may be no need for concern about planetary protection today. However, most respondents disagreed that concern was unnecessary even if such contamination actually did occur millions of years ago (see Figure 4).

Despite these views about the potential hazard of biological materials from Mars, there was a high level of support for future Mars missions. Very few respondents agreed that possible exposure of Earth to life from Mars was reason to cancel a Mars mission. Also, few agreed that humans on space missions should not directly contact the surface of other planets, or that robotic space missions will tell us all we need to know about other planets. Likewise, very few agreed that we should prove that no life exists on Mars before sending humans there (see Figure 5).

While planetary protection is intended to guard against inadvertent introduction of life either onto our planet or onto another planet, an important goal of space exploration is to study life elsewhere in the universe, if it exists. To do so may involve taking samples of life and returning them to Earth. Few respondents agreed that life on Mars, if it exists in any form, should be left there undisturbed. Even fewer agreed that it is morally wrong to bring life back to Earth from another planet or to introduce life from Earth onto another planet (see Figure 6).

Survival and Adaptability of Life

Whether life on Mars, if it exists, would survive on Earth and whether life from Earth would survive on Mars are important questions in the development of measures for planetary protection. Of all the items in the survey, those relating to the survival and adaptability of life received the highest percentages of "don't know" responses, indicating a high degree of uncertainty about these topics.

Among those respondents who did offer opinions, however, few agreed that the environment on Mars is too harsh to sustain any life from Earth. Likewise, few thought that life that evolved in the rich natural environment of Earth would not be fit enough to survive on Mars. Conversely, life on Mars was viewed as more fragile if brought to Earth.

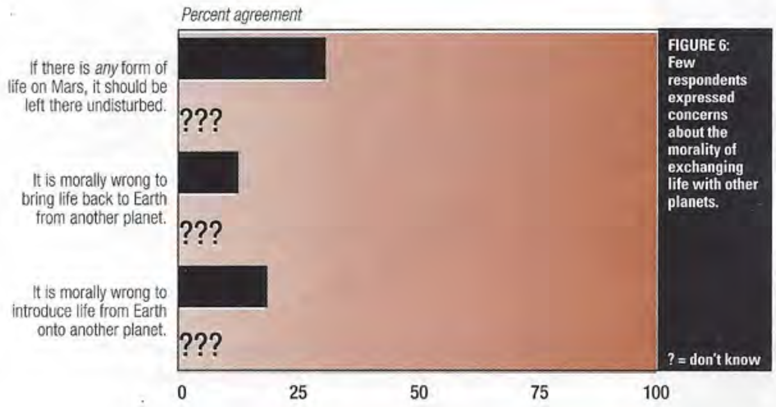


FIGURE 6: Few respondents expressed concerns about the morality of exchanging life with other planets.

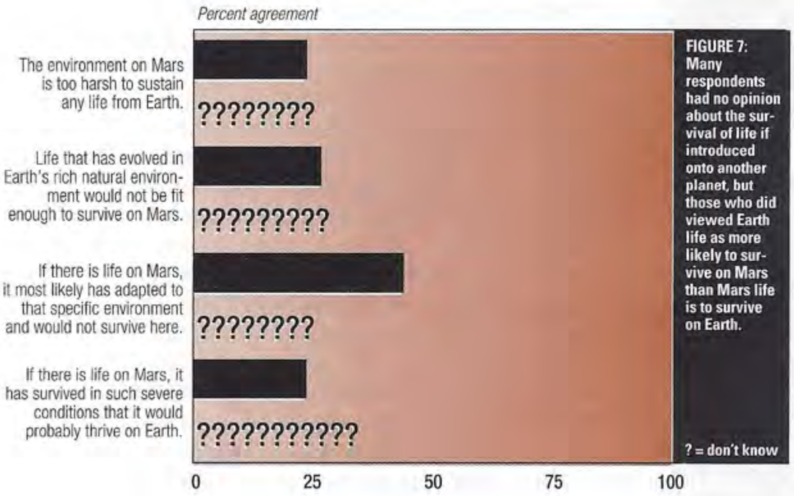


FIGURE 7: Many respondents had no opinion about the survival of life if introduced onto another planet, but those who did viewed Earth life as more likely to survive on Mars than Mars life is to survive on Earth.

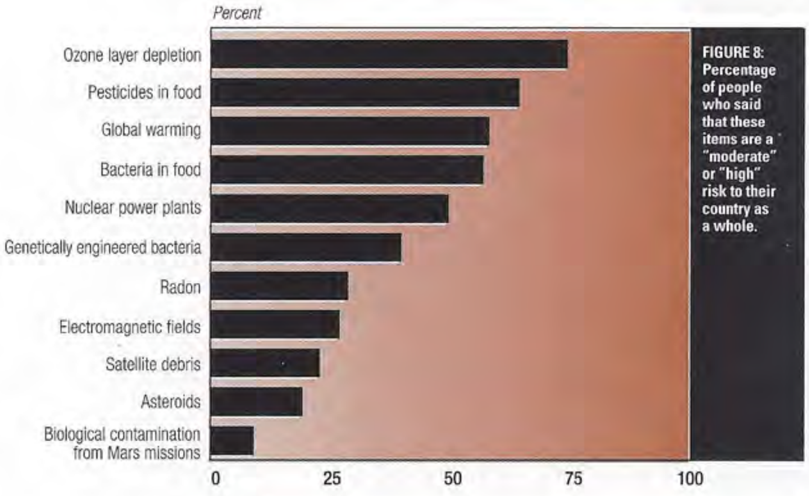


FIGURE 8: Percentage of people who said that these items are a "moderate" or "high" risk to their country as a whole.

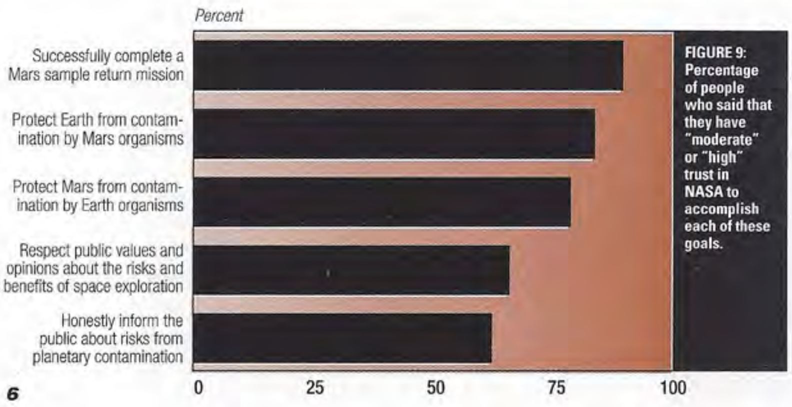


FIGURE 9: Percentage of people who said that they have "moderate" or "high" trust in NASA to accomplish each of these goals.

A majority of the respondents giving opinions about the ability of martian life to survive on Earth agreed that if there is life on Mars, it most likely has adapted to that specific environment and would not survive on Earth. Less than half (34%) agreed that it has survived in such severe conditions that it would probably thrive on Earth. Overall, respondents had an asymmetric view about the survival and adaptability of life—life from Earth was seen as more likely to survive on Mars than life from Mars was to survive on Earth (see Figure 7).

Rating the Risks

The potential contamination of Earth and Mars as part of space missions is just one among many risks faced by people on Earth. To put the risks of interplanetary contamination in a larger risk context, respondents were asked to rate the risks to their country from a number of different sources.

The highest perceived risk was ozone layer depletion, followed by global warming and food contamination (from pesticides and bacteria). Biological contamination from Mars missions was rated as the lowest risk, along with asteroids and satellite debris (see Figure 8). This does not mean, however, that these risks are of little or no concern to people. Indeed, at least half of the respondents indicated some level of risk for all of the items they rated, including those that ranked lowest.

Trust in NASA

In general, respondents had a high level of trust in NASA to successfully carry out a Mars sample return mission and to protect both Earth and Mars from interplanetary contamination. However, respondents were somewhat less trusting in NASA to respect public values and opinions about the risks and benefits of space exploration and to honestly inform the public about planetary exploration risks.

Though the percentage of respondents indicating "moderate" or "high" trust was over 50% for all items, the skepticism often voiced about the trustworthiness of government was echoed in these results as well (Figure 9).

To Sum Up

Overall, survey respondents were very optimistic about space exploration but cautious about the potential hazards of planetary contamination. As plans for future Mars missions move forward, public attitudes about managing the risks of space exploration will play an important role in the formulation of space policy. Your responses to this survey are a key to the development of a successful relationship between the public and organizations like NASA. Thank you for your contributions.

Donald MacGregor and Paul Slovic are senior research associates at Decision Research in Eugene, Oregon. Both are psychologists who specialize in the study of public attitudes about technological hazards.

World Watch

by Louis D. Friedman

Columbus, Ohio—Ohio State University's "Big Ear," one of a very few radio telescopes in the world dedicated to the Search for Extraterrestrial Intelligence, is in danger of being abandoned. The 10-year lease is up, and the person who owns the property wants the telescope torn down to make the land available for development.

The university's administration has given no support to the facility—which admittedly does not bring in any money to the university. It is strictly a center for observation and research.

The Planetary Society is asking concerned members to write letters supporting "Big Ear" to E. Gordon Gee, president of the university, at the following address: 190 North Oval Mall, Ohio State University, Columbus, OH 43210; telephone, (614) 292-2424; fax, (614) 292-1231.

Washington, DC—On February 6, 1995, NASA Administrator Daniel Goldin presented the proposed budget for NASA for the next five fiscal years (1996–2000). It specifies cuts of over $1 billion over that time. Compared to 1995's proposed budget, the drop in the projected total over the 1996–2000 period is 5 percent; compared to 1994's, it is 18 percent; and compared to 1993's, 36 percent. (The 1993 budget predicted that the NASA budget in the year 2000 would be approximately $22 billion.) Space science would drop from its current $2 billion level to less than $1.6 billion in about 1999.

Obviously, cuts this severe will profoundly affect the space agency. In presenting the budget, Goldin stated, "We hope to make all of the cuts through restructuring. If our analysis shows we can't, then and only then will we cancel programs." Restructuring means that NASA employment will drastically decrease and many operations will be reduced or cut out. There is also political pressure to move operations out of the federal government into private or contractor institutions.

The implication of Goldin's statement is that, if the plans drawn up in the next few months do not provide the requisite cuts, mission projects and other programs in the agency will be canceled or severely cut back.

The president's budget still shows all approved missions in place. These include *Cassini;* Mars Surveyor; the Discovery program; the Space Infrared Telescope Facility (SIRTF); the Lewis and Clark advanced technology spacecraft; and the New Millennium spacecraft, a new generation of smaller and lower-cost spacecraft for the next century. Cooperation with Europe will continue on *Rosetta* for a comet rendezvous to be launched in 2003.

Washington, DC—Congress has begun work on the NASA budget for fiscal 1996,which begins in October 1995. It is a new Congress, with long-time minority members now assuming chairmanships of key committees. Because of pressures being applied by both Republicans and Democrats as a result of proposed spending cuts—including those being ordered to finance a proposed "middle-class" tax cut—and defense increases, we can expect existing NASA programs to be targeted for cuts.

The following is a list of key leaders of the congressional committees concerned with the NASA program:

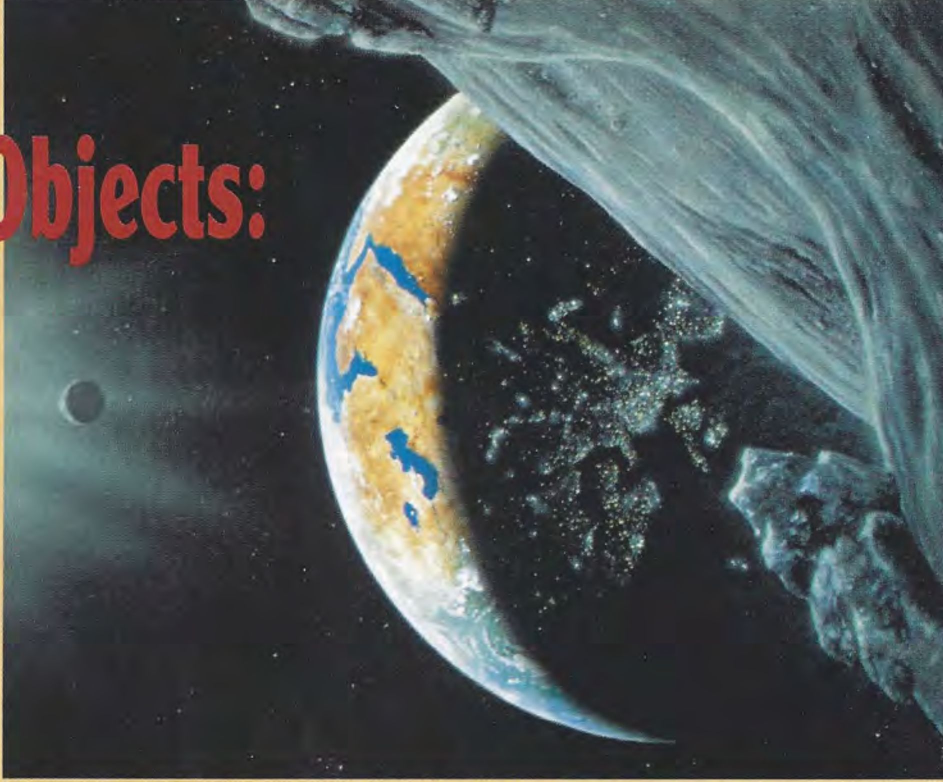
- Senate Committee on Commerce, Science and Transportation—chairman, Larry Pressler, South Dakota; ranking minority member, Ernest Hollings, South Carolina
- Subcommittee on Science, Technology and Space—chairman, Conrad Burns, Montana; ranking minority member, Jay Rockefeller, West Virginia
- Senate Committee on Appropriations—chairman, Mark Hatfield, Oregon; ranking minority member, Robert Byrd, West Virginia
- Subcommittee on VA, HUD and Independent Agencies—chairman, Christopher Bond, Missouri; ranking minority member, Barbara Mikulski, Maryland
- House Committee on Science, Space and Technology—chairman, Robert Walker, Pennsylvania; ranking minority member, George Brown, California
- Subcommittee on Space and Aeronautics—chairman, Jim Sensenbrenner, Wisconsin; ranking minority member, Ralph Hall, Texas
- House Committee on Appropriations—chairman, Robert Livingston, Louisiana; ranking minority member, David Obey, Wisconsin
- Subcommittee on HUD, NASA, Veterans Affairs—chairman, Jerry Lewis, California; ranking minority member, Louis Stokes, Ohio

The course of the budget through Congress will be followed on The Planetary Society Home Page and on our GEnie roundtable.

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

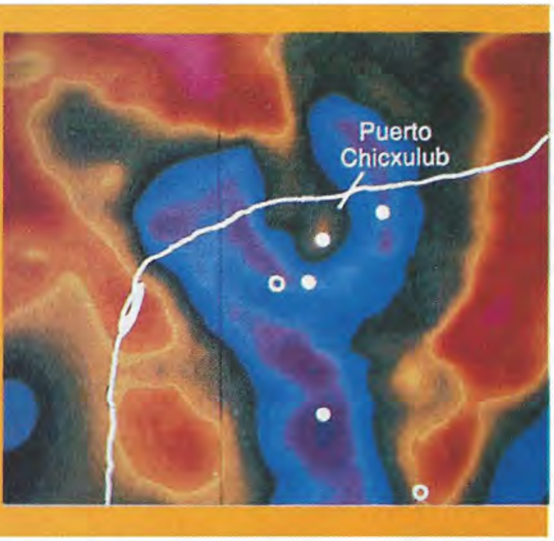
Near-Earth Objects: FRIENDS OR FOES?

by Richard P. Binzel



An asteroid passes perilously close to Earth, with the lights of Europe glowing obliviously below. Painting: Michael Carroll

Nature could hardly have paired a more odd-looking couple. The Moon's jagged and cratered surface contrasts sharply with Earth's fluid oceans and comparatively smooth continents. Returned samples from the United States' *Apollo* and Russia's *Luna* programs proved to us that the Moon has an ancient surface, one that has retained a record of cosmic bombardment over the age of the solar system. Earth, however, with its water, weather, erosion and tectonic activity, has long since erased any ancient record of cosmic impacts.



The circular structure of a buried impact crater becomes visible in this gravity map of the Yucatán peninsula centered near Puerto Chicxulub. The ringed structure is over 150 kilometers (95 miles) across, with an age that coincides with the end of the Cretaceous period—and the dinosaurs—65 million years ago. Map courtesy of Adriana Ocampo

Given that no impact craters were recognized as such on Earth until the 1960s and that cratering was thought to be an ancient phenomenon, it is easy to understand our modern-era sense of security and insulation from cosmic collisions on Earth. However, that complacency has been eroding over the past decade in the wake of both geological and astronomical discoveries. The first news to rock our cradle was the now widely accepted geological discovery published in 1980 by Luis and Walter Alvarez and their colleagues that the impact of a large extraterrestrial body coincided with a mass extinction of life at the end of the Cretaceous period 65 million years ago. A clay layer marking the boundary between the Cretaceous and Tertiary periods is rich with iridium and other trace elements that are relatively common in meteorites but generally rare in Earth's crust. This layer is found worldwide, suggesting that dust injected into the atmosphere by the impact was distributed globally. With the help of atmospheric models, we can speculate that the impact caused a global climate disaster leading to the extinction of 75 percent of the species then on Earth, including the dinosaurs.

Can we comfort ourselves by assuming that the impact that sealed the dinosaurs' fate was a complete cosmic fluke? Recent astronomical discoveries indicate that it would be shortsighted to do so—there is no shortage of objects in Earth-crossing orbits whose impact would pack a wallop capable of initiating instant global climate change. These discoveries have come about through dedicated search programs operated independently by Eugene Shoemaker and Eleanor Helin at Palomar Observatory in California, and by Tom Gehrels at the Steward Observatory in Arizona. Planetary Society members have shared in the success of these discoveries through the Society's sponsorship of Helin's program.

Perhaps the final blow to our notion of a serene cosmos was delivered by the great crash of comet Shoemaker-Levy 9 into Jupiter in July of last year. This planetary impact, perhaps the most remarkable single event ever observed in astronomical history, vividly demonstrated to us all that planetary impacts can and do occur in the solar system today. An examination of the recent lunar cratering record from your own backyard (see sidebar, page 11) reveals the expected frequency of very large impacts on Earth. Such events may be exceedingly rare, but they do occur nonetheless.

With our sense of security shattered, our rational next step is to quantify the hazard posed by cosmic impacts and place it in context with other hazards faced by our civilization (see Table 1, next page). Clark R. Chapman (of the Planetary Science Institute in Tucson, Arizona), a regular contributor to *The Planetary Report,* and David Morrison (of NASA's Ames Research Center in Moffet Field, California) have led the effort toward making an assessment. These researchers have found that the problem is multifaceted, and the viewpoints to be considered include the scientific, sociological and public policy sides of the issue.

On the scientific side, we must assess the relative hazard posed by more frequent small impacts compared with the much rarer, but more devastating, large impacts. On the sociological side, we must understand how such low-probability but high-consequence disasters are perceived. And finally, on the public policy side, we must evaluate what course of action, if any, is most prudent for the international community to pursue.

Global Versus Local

Scientifically, it is useful to divide the impact hazard into two types of events: those having local consequences and those having global consequences. On the low end of the local scale is the fall of meteorites that seem to have a propensity for conking cars (for example, the October 9, 1992, fall in Peekskill, New York, that demolished an old Chevrolet) but are not known to have caused any serious human injuries in modern times. Progenitors for such meteorite falls are probably bodies only a few meters across. Bodies 50 meters (about 160 feet) across having modest strengths are likely to strike the ground intact, creating a crater and a local explosion. The 1908 airburst over the Tunguska River in Siberia was probably due to the atmospheric entry of a comet or weak asteroid about 50 meters across.

Had the Tunguska blast, which leveled 1,000 square kilometers (400 square miles) of forest, occurred over a populated area, the result would have been a devastating disaster with a death toll equivalent to or exceeding such other natural disasters as floods, hurricanes and tsunamis. A Tunguska-like event probably occurs somewhere on Earth's surface once every three centuries. Estimating that only 10 percent of Earth's surface is lightly or densely populated, a threat to humans from such an impact is likely to occur once every 3,000 years.

What distinguishes a "local" impact event from a "global" one are the responses of Earth's ecosystem and society. While the occurrence of a Tunguska-like or larger event over a major city would be an unprecedented human disaster, the consequences to the worldwide ecosystem and climate would be minimal. Assuming that the cosmic impact is not misinterpreted as a hostile nuclear attack set in motion by a real or imagined enemy, the remaining civilizations of the world would presumably remain stable and would be able to supply aid and comfort to the afflicted area.

Although Earth's face is relatively free from pockmarks caused by extraterrestrial impacts, the face of the Moon is a different story. While our planet's surface is continuously reworked by erosion and plate tectonics, its companion retains the scars of over 4 billion years of collisional history. The Moon's face is a nightly reminder that we do indeed live in a cosmic shooting gallery.

Photograph of Earth: NASA
Image of the Moon: JPL/NASA

In contrast, a global event is one where the impact fallout (dust lofted into the stratosphere, smoke from possible wildfires and so on) causes a global climate change sufficient to disrupt worldwide agriculture and threaten mass starvation. For a global event, all citizens of the world are endangered, regardless of whether the impact occurs in an inhabited or uninhabited part of our planet.

Most estimates suggest that an impacting stony asteroid about 1.5 kilometers (1 mile) across or larger marks the threshold energy for causing a globally devastating event. However, there is much uncertainty associated with making this size estimate, and realistic guesses fall between 0.5 and 5.0 kilometers (0.3 and 3 miles). One part of the uncertainty is the lack of knowledge about how our planet's ecosystem and our society would respond to the sudden and severe stress wrought by an impact. Another area of uncertainty arises from variations in the nature of potential impactors.

TABLE 1

Chances of Dying From Selected Causes (US)

Cause of Death	Chances
Motor vehicle accident	1 in 100
Murder	1 in 300
Fire	1 in 800
Firearms accident	1 in 2,500
Asteroid/comet impact (lower limit)	**1 in 3,000**
Electrocution	1 in 5,000
ASTEROID/COMET IMPACT	**1 in 20,000**
Passenger aircraft crash	1 in 20,000
Flood	1 in 30,000
Tornado	1 in 60,000
Venomous bite or sting	1 in 100,000
Asteroid/comet impact (upper limit)	**1 in 250,000**
Fireworks accident	1 in 1 million
Food poisoning by botulism	1 in 3 million
Drinking water with EPA limit of TCE*	1 in 10 million

Source: Reprinted from Clark Chapman and David Morrison, Nature, Vol. 367, page 39 (1994).
*EPA, Environmental Protection Agency; TCE, trichloroethylene.

For example, asteroids in near-Earth space typically encounter our planet with velocities of about 20 kilometers (12 miles) per second. Comets, however, encounter Earth with much higher velocities, typically 30 to 60 kilometers (19 to 37 miles) per second. Because the damaging effects are dependent upon the kinetic energy of the impact (equal to 1/2 mv^2, where m is the mass of the projectile and v is its velocity), a comet smaller than 1 kilometer (0.6 mile) across could pack a punch with sufficient energy to initiate a global climate disaster.

Given their greater numbers in near-Earth space, asteroids probably account for 75 percent of the total hazard. Comets comprise the other 25 percent. From the recent lunar cratering record, from the record of more than a hundred now identified terrestrial craters and from our preliminary reconnaissance of near-Earth space, we can estimate that the impact of a 1.5-kilometer asteroid (or equally energetic comet) probably occurs on Earth once every 500,000 years on average. (For more about comets and asteroids, see the November/December 1991 issue of *The Planetary Report.*)

Perception of Risk

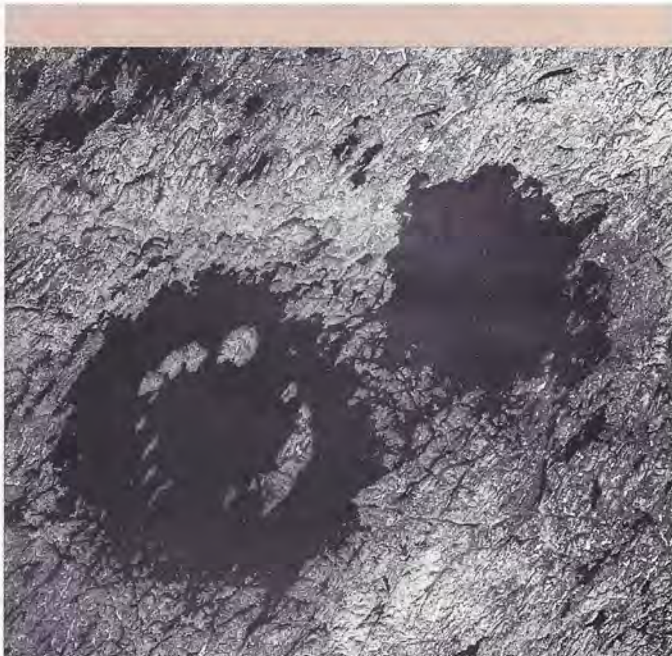
From a sociological standpoint, it is important to consider whether the hazard due to cosmic impacts is worth worrying about at all! Cosmic impacts fall into the category of events that are extremely rare but are of high consequence when they do occur. An airliner crash is an example of an infrequent but high-consequence event that seems to grab international attention. Motor vehicle accidents, on the other hand, kill 200 times more people in an average year, yet these frequent events, with lesser consequences per event, garner comparatively less public attention.

Thus it would seem that we, as a society, are attuned to low-probability but high-consequence events. However, extremely low probability events such as cosmic impacts are beyond our personal and even historical experience, requiring that we take a long-term view in evaluating the hazard and relating it to everyday life.

One way to examine the cosmic impact hazard is to compare the long-term threat to you as an individual posed by the two categories of collisions: the local Tunguska-like events and the larger, global-consequence events. Tunguska-like events occur on average once every 300 years and are likely to directly result in your death only if you happen to be within the approximately 1,000-square-kilometer region of devastation. Given the surface area of Earth, it is fortunate that there is only a 1 in 500,000 chance that you would be at the right patch of the planet at the wrong (!) time.

Thus, in any given year there is only a 1 in 150 million chance that you will die from a Tunguska-like impact. Over a human lifetime, which we round up to an even 100 years for simplicity, it would seem there is only a 1 in 1.5 million chance that a Tunguska-like impact will result in your untimely death. A 1 in 1 million chance may be small enough that most people would give it little practical concern.

What about the comparative hazard from much less frequent global-scale impacts? If we assume that such events occur only once every 500,000 years but are so devastating to the climate that the ultimate result is the death of one-quarter of the world's population, this translates to an annual chance of 1 in 2 million that you will die from a large cosmic impact even if you happen to be far removed from the impact site. Integrated over a century, our simple metric for a human lifetime, the chance becomes 1 in 20,000 that a large cosmic impact will be the cause of your death. Such a probability is in the realm that most people consider to be a practical concern.



What to Do?

If we do find the hazard from cosmic impacts to be a matter of concern, what can we as members of The Planetary Society do about it? The first step, I believe, is to advocate gaining more knowledge. Currently, we have discovered probably only 20 percent of the near-Earth asteroid and short-period comet population having body sizes of 1.5 kilometers or larger, whose impacts could have global consequences. For smaller asteroids and comets, our knowledge of the population is correspondingly less complete.

A first order of business, it would seem, would be to expand current survey programs so as to obtain as complete as possible a census of the population of near-Earth objects. Such an expanded survey program was proposed in 1992 by a NASA working group chaired by David Morrison. This group, working in response to a request by the US Congress, proposed initiating a "Spaceguard" survey consisting of a set of six dedicated ground-based telescopes distributed internationally. Although no official action was taken toward implementing the plan, the issue appears to remain open within Congress, as another working group, chaired by Eugene Shoemaker, has been given the task of making further recommendations.

Once an expanded survey effort is under way, it will become possible to know with confidence whether there are at present any near-Earth objects with hazardous trajectories. By the nature of the survey and the population itself, we will gain our most complete census of the largest objects first. As the survey continues over one to two decades, the limit of completeness will progress toward smaller and smaller sizes.

Thus, it is providential that a straightforward survey strategy will address the greatest hazard (largest objects) first and evolve to evaluate more thoroughly the lesser hazard as time progresses. Through such a stepwise increase in our knowledge, we can prudently evaluate what approach should be taken to mitigate any possible hazard. For any asteroid or short-period comet actually found to be in a menacing orbit, chances are quite high that we will have decades of advance warning before a hazardous encounter would occur. For such objects, it would not seem necessary to have an active mitigation system (likely involving nuclear explosives) sitting by, ready to launch on a moment's notice. The expenditure necessary for such a system, at this time, does not appear to be commensurate with the threat.

Long-period comets (those coming in from the outer solar system), however, would likely be detected only a few months before they reached the vicinity of Earth. Through a Spaceguard-like survey evaluation of the proportion of long-period comets crossing Earth's orbit, we can make a rational assessment of the hazard posed by these objects.

An additional area of knowledge that we can advocate gaining access to is the military surveillance satellite data on small-scale impacts into Earth's atmosphere. Meteoroids with energies equivalent to the Hiroshima bomb strike the atmosphere annually. Fortunately, the US Department of Defense has begun to release information on selected recent events. However, a fuller disclosure of the signatures and frequencies of these types of events would help reduce the risk that such a natural event, occurring over an area of political tension, would trigger a martial and possibly nuclear response.

Finally, it is vital to evaluate whether near-Earth objects really are our foes, or our friends. Over the next three centuries, there is a 1 in 10 chance that a Tunguska-like impact will result in some human casualties and a 1 in 1,600 chance for a larger, global-scale impact. A Spaceguard survey, however, is certain to find in near-Earth orbits several thousand nonthreatening objects that are more accessible than the Moon in terms of rocket propulsion. Over the next three centuries (and hopefully sooner), these objects can provide intermediate mission destinations as we prepare for long-duration human flights to Mars. As we begin to utilize space, the metals and volatiles (chiefly water) we find in these objects may become vital space resources. Thus, in taking a long view of only a few centuries, it is most likely that we will know the near-Earth objects as our friends. The lesson for us now is to keep in mind that all friends need respect.

Richard P. Binzel is an associate professor of planetary science at the Massachusetts Institute of Technology. He was the principal editor for Asteroids II, *the primary reference book for the field, which was published in 1989.*

Radar images of the asteroid Toutatis and* Galileo *images of Ida and its moon, Dactyl, have shown that double asteroids are common. The Clearwater Lakes in Canada, shown here, are further evidence that some of the bodies that could collide with Earth travel in pairs.

Photograph: Lunar and Planetary Institute

Yes, Do Try This at Home

David Morrison, a noted author and director of the Space Science Division at NASA's Ames Research Center in California, has proposed the following experiment you can try at home. The purpose of the experiment is to estimate how often large impacts occur on Earth by counting large craters on the Moon.

Here's how it works: Use binoculars or a small telescope to count the number of craters larger than 50 kilometers across that can be seen in the lunar maria ("seas") on the near side of the Moon. (There are five: Copernicus, Aristoteles, Bullialdus, Eratosthenes and Aristillus.) Given the *Apollo* and *Luna* data that the lunar maria are 3.5 billion years old, an impact of a 5-kilometer or larger object to form such craters must occur in the lunar maria, on average, once every 700 million years. To find out how often such bodies must strike Earth, it is only necessary to know that the total surface area of Earth is about 70 times larger than our "counting area" in the lunar maria.

Thus, on average, we can expect one such impact to occur on Earth every 10 million years. Because the lunar maria record also shows there are about a hundred craters larger than about 15 kilometers across, bodies inferred to be about 1.5 kilometers across must strike Earth and the Moon about 20 times more frequently. Thus a 1.5-kilometer body strikes Earth, on average, about once every 500,000 years. —*RPB*

THE CRASH ON JUPITER: LOOKING

by Paul Weissman

What really happened when the fragments of comet Shoemaker-Levy 9 slammed into Jupiter last July? At the first two post-impact scientific gatherings—the Hypervelocity Impact Symposium in Santa Fe, New Mexico (October 17 to 19, 1994), and the meeting of the American Astronomical Society's Division for Planetary Sciences in Bethesda, Maryland (October 31 to November 4, 1994)—it was clear that observers and theorists were overwhelmed by the task of explaining the complex sequence of events that we saw each time a cometary fragment dove into the atmosphere at 60 kilometers per second (about 130,000 miles per hour). Answers are beginning to emerge. But they are dwarfed by the many more questions being raised.

Some of the most important questions are the same as before the impacts occurred: How big were the cometary fragments, and how deep did they penetrate into the jovian atmosphere? Other questions are entirely new: How did Earth-based astronomers see "around the corner" and actually observe the impact events on the nightside of Jupiter, as seems to have occurred? What was the composition of the huge dark plumes of debris thrown out of the impact sites, forming clouds larger than Earth in the jovian stratosphere?

Flashes and Fireballs

The key to answering many of these questions may be new data returned from the *Galileo* spacecraft, which had the only direct view of the cometary impacts on the nightside of the giant planet. *Galileo* was still about 1.6 astronomical units (about 240 million kilometers or 150 million miles) away from Jupiter when its instruments recorded the impact events last July. Because of the spacecraft's damaged high-gain antenna, data have trickled back to Earth at a mere 10 bits per second since then.

Included in that trickle was a joint observation of the impact of Shoemaker-Levy 9's G fragment, one of the largest, by *Galileo*'s near-infrared mapping spectrometer, photopolarimeter–radiometer and ultraviolet spectrometer. Robert Carlson and Terry Martin of the Jet Propulsion Laboratory and Wayne Pryor of the University of Colorado reported that the instruments observed a 7,500-degree Kelvin (13,000-degree Fahrenheit) fireball perhaps 10 kilometers (6 miles) in diameter appearing at the top of the jovian clouds. The infrared data at wavelengths of 2.3 and 3.5 micrometers show the fireball growing at about 2 to 3 kilometers per second (4,500 to 6,700 miles per hour) over more than a minute, cooling slowly at the same time so that energy was conserved. The photopolarimeter data for the same event show the fireball fading out sooner—after about 30 seconds—because the instrument was observing at a shorter wavelength, 0.945 micrometer, where the cooling fireball disappeared more quickly.

Galileo's photopolarimeter observed the same profile for the H and L events, both large impact events, and a very similar profile was reported for the K event, another of the larger events, by the *Galileo* CCD (charge-coupled device) camera team's Clark Chapman (Planetary Science Institute).

Observing the K event at 0.882 micrometer, the camera saw a bright flash that lasted about 5 seconds, faded and then brightened again in about 10 seconds, remaining visible for 30 seconds longer. For one of the smaller impact events, N, the camera again saw a bright flash that lasted about 5 seconds, but that flash was followed by a much dimmer fireball lasting only about 10 seconds. A similar 5-second initial flash was seen for the W event, and a faint, glowing cloud of material for another 15 seconds.

Interpreting the Data

The *Galileo* investigators believe that the first 5-second flash seen for each impact was the comet fragment entering the atmosphere and beginning to burn up like a meteor or bolide. As each fragment plunged into the atmosphere, shedding energy and material along its path, it superheated a column of jovian air. This column exploded instantly and created the intense fireball seen by the *Galileo* instruments for the next 15 to 60 seconds. Curiously, all seven (G, H, K, L, N, Q1 and W) bolide entry flashes seen thus far had about the same brightness (within a factor of 2), whereas the magnitude and

FOR ANSWERS IN THE IMPACTS

Almost two months after the fragments of comet Shoemaker-Levy 9 collided with Jupiter, the planet's atmosphere still bore the scars. In this infrared image, debris from the impact appears red (as do the polar hazes), indicating it is very high in the atmosphere. Blue areas are the deepest, and clouds of intermediate height, such as the Great (normally) Red Spot, are white. The small aerosol particles produced in the impacts can remain in the atmosphere for months, as they do on Earth in the aftermath of volcanic eruptions.

Image: Keith Noll, taken from the NASA Infrared Telescope Facility

duration of the fireballs appeared to reflect the relative sizes of the impactors. More *Galileo* data on the G, R and W impacts are currently undergoing analysis at JPL.

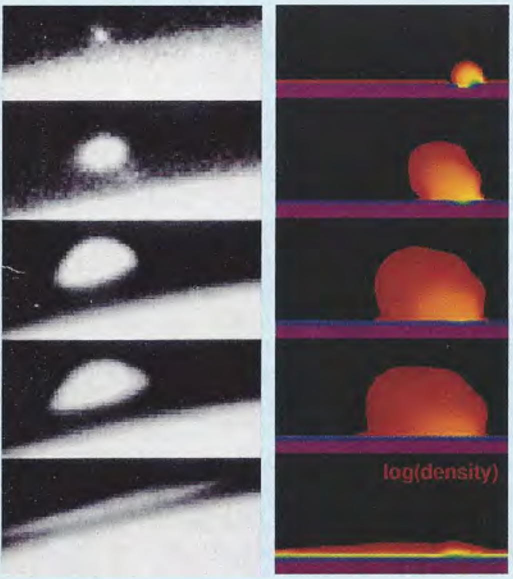
Although there are still discrepancies in the timing of events, it now appears that the combined bolide/fireball events seen by *Galileo* correspond to the first of two precursor flashes that ground-based infrared observers often saw before each impact site rotated into view from Earth. But how did ground-based observers see these events from behind the planet?

One speculation is that the flash was reflected off either a dust trail behind each comet fragment or a cloud of high-altitude debris deposited by dust that preceded each fragment into Jupiter's atmosphere. Alternatively, observers may have been seeing the beginning of the fragment's glowing, meteor-like interaction with the thin upper atmosphere.

The second precursor flash seen by Earth-based observers is believed to have been the plume of high-speed ejecta from the impact, rising into sunlight above Jupiter's limb. Hubble Space Telescope (HST) images show the development of the plume very nicely over a period of about 20 minutes for four of the impacts (A, E, G and W). Emerging at velocities of 10 to 15 kilometers per second (about 20,000 to 30,000 miles per hour), the ballistic ejecta forming the plumes fell back on the upper stratosphere of Jupiter, heating a huge area of the atmosphere—typically about the diameter of Earth, or more. As they rotated into view from Earth, these enormous hot, dark clouds of debris produced the immense infrared brightenings seen by the ground-based observers. In the final data returned from *Galileo*, the near-infrared mapping spectrometer saw the heating caused by the fallback of impact debris for both the G and R impacts, starting about 6 minutes after each impact. The time delay between impact and fallback means that the ejecta from the initial explosion had a velocity of at least 4.1 kilometers per second (9,200 miles per hour).

But what made up these gigantic clouds, easily visible from Earth, even with amateur telescopes? Presumably, each comet fragment was vaporized in the impact and its constituent molecules were dissociated (broken apart), as was a considerable amount of jovian atmosphere along the explosion path. Large amounts of sulfur compounds, carbon monoxide and water were observed in the plumes.

For one impact site, Gordon Bjoraker (of NASA Goddard Space Flight Center) and colleagues observing with NASA's Kuiper Airborne Observatory reported a quantity of water equivalent to a sphere of ice 1 kilometer (0.6 mile) in diameter. The amount of sulfur was so great that it must have come from a jovian source, presumably the clouds of ammonium hydrosulfide in the atmosphere. But where the carbon, oxygen and hydrogen came from was much less clear. Bjoraker believes that the high temperature of the water in the plumes indicates that the source was the cometary fragments themselves. In addition, emission lines from various metals were observed, and these would almost certainly need to be from the comet fragments.



A series of Hubble Space Telescope (HST) images of the fragment G impact is here compared with a computational simulation from Sandia National Laboratories. The HST sequence on the left shows the fireball and debris plume over 18 minutes, and the corresponding times of the simulation appear on the right. The match between observations and simulation will help scientists understand what happened on Jupiter.

Images: Mark Boslough, Sandia National Laboratories

The confusing chemistry even led some observers to suggest that Shoemaker-Levy 9 might have been an asteroid. However, that idea is refuted by the persistent coma (the fuzzy cometary atmosphere) that the comet fragments displayed from their discovery right up until hours before the impacts. In addition, a cometary origin for Shoemaker-Levy 9 is far more probable based on orbital statistics.

Still, detailed modeling of the chemistry of the fireballs will be needed to unravel the spectroscopic evidence. An aid to solving that problem will be the measurements of jovian atmospheric composition and structure to be made by the *Galileo* atmospheric entry probe when it plunges into Jupiter on December 7, 1995.

Supercomputer Modeling

An interesting fact, found from HST images, is that the impact plumes all appeared to be the same height, about 3,300 kilometers (2,000 miles), regardless of the size of the impactor that generated them. This point, reported by Heidi Hammel of the Massachusetts Institute of Technology, greatly confounds the impact modelers who have tried to use the heights of the plumes to estimate the diameter of the impacting comet fragments. It appears that plume height is not a very meaningful discriminator.

There are some points that the modelers, who used supercomputers to simulate the complex physics of the impact events, do agree on. The simple concept of a cometary fragment entering the jovian atmosphere as a meteor and then exploding in a sudden, suicidal point explosion is not correct. As noted previously, when each comet fragment entered the jovian atmosphere it shed material and energy along a column of superheated gases that it drilled in the atmosphere. This entire column exploded, somewhat like a line charge of explosives, but with varying effects because of the irregular pattern of the energy deposition and the increasing atmospheric density as the comet fragment plunged through the atmosphere. Most theorists also agree that the comet fragments appear to have deposited a large amount of energy high in the atmosphere, above the jovian cloud decks.

Here the consensus stops. Modelers Kevin Zahnle of NASA Ames Research Center and Mordecai-Mark Mac Low of the University of Chicago believe that the comet fragments deposited energy high up because they were small, only 0.5 to 1.0 kilometer (0.3 to 0.6 mile) in diameter, with a density of 0.5 to 1.0 gram per cubic centimeter. Zahnle and Mac Low's model predicts that the comet penetrated the ammonia and ammonium hydrosulfide clouds on Jupiter but did not reach the water clouds lower in the atmosphere. The cometary debris was then ejected back up the column in a high-speed jet that formed the huge debris clouds visible from Earth.

This model explains the large amounts of sulfur but lack of jovian water observed in the ejecta plumes (though, as noted earlier, the source of the water in the plumes is not clear). The model also agrees with predictions of the size of the impactor fragments based on modeling of the tidal disruption of the original comet when it passed inside Jupiter's Roche limit (the distance from the planet within which an object held together only by its own gravity would be torn to pieces by the planet's gravity) in July of 1992.

At the other end of the modeling spectrum are simulations by Mark Boslough and David Crawford of Sandia National Laboratories, who find that the impactors had to be large, up to 3 kilometers (about 2 miles) in diameter, to account for the substantial energy deposition at altitude. Boslough and Crawford find that the larger comet fragments must have plunged deeper into the jovian atmosphere, well below the water clouds, but at that altitude the atmospheric pressure contained the explosion and prevented it from expanding back up the superheated column. In effect, Jupiter's atmosphere swallowed up most of the energy of the explosion, and most of the cometary material and jovian cloud material remained at depth where they were invisible to Earth-based observers. Boslough and Crawford's supercomputer model uses a more complete, 3-D simulation, compared to Zahnle and Mac Low's 2-D simulation, so the physics should be more complete. However, they fail to explain why HST saw large amounts of sulfur in the impact plumes.

Yet another model, by Toshiko Takata and Thomas Ahrens of the California Institute of Technology, finds an intermediate impactor size, 2.1 kilometers (1.3 miles) in diameter, for the largest events. Like the other models, this one predicts huge plumes emerging from the impact sites. Using a 3-D simulation, Takata and Ahrens also find the comet fragment penetrating deep into the atmosphere, below the water clouds. However, in their model both the jovian and cometary water failed to rise high enough in the atmosphere to be observed, and remained obscured by the plumes.

Putting It All Together

It may be possible to reconcile the different modeling results with a relatively small impactor if each comet fragment was a "rubble pile" of smaller icy conglomerate subfragments. Tidal forces would have caused the rubble pile to begin to disperse as it again passed inside Jupiter's Roche limit, though there would not have been enough time for the fragments to spread very far. However, there might have just been enough to give a large effective cross section, resulting in considerable energy deposition at high altitudes. For now, it is not clear if this actually occurred.

The form and structure of the debris clouds may also be a clue to how deep the impactors penetrated, and thus to how large they were. Each impactor created a central dark cloud of debris where it struck Jupiter, but only the largest impactors created broad, dark clouds of ballistic ejecta out to distances of 6,000 to 8,000 kilometers (roughly 4,000 to 5,000 miles) from the impact sites. Since all the impactors appeared to generate equally high plumes, why were the ejecta from only the largest impacts visible? Mordecai-Mark Mac Low speculates that only the largest impactors dredged up sulfur compounds from the jovian ammonium hydrosulfide cloud deck, and it was the various sulfur compounds that made the debris clouds easily visible.

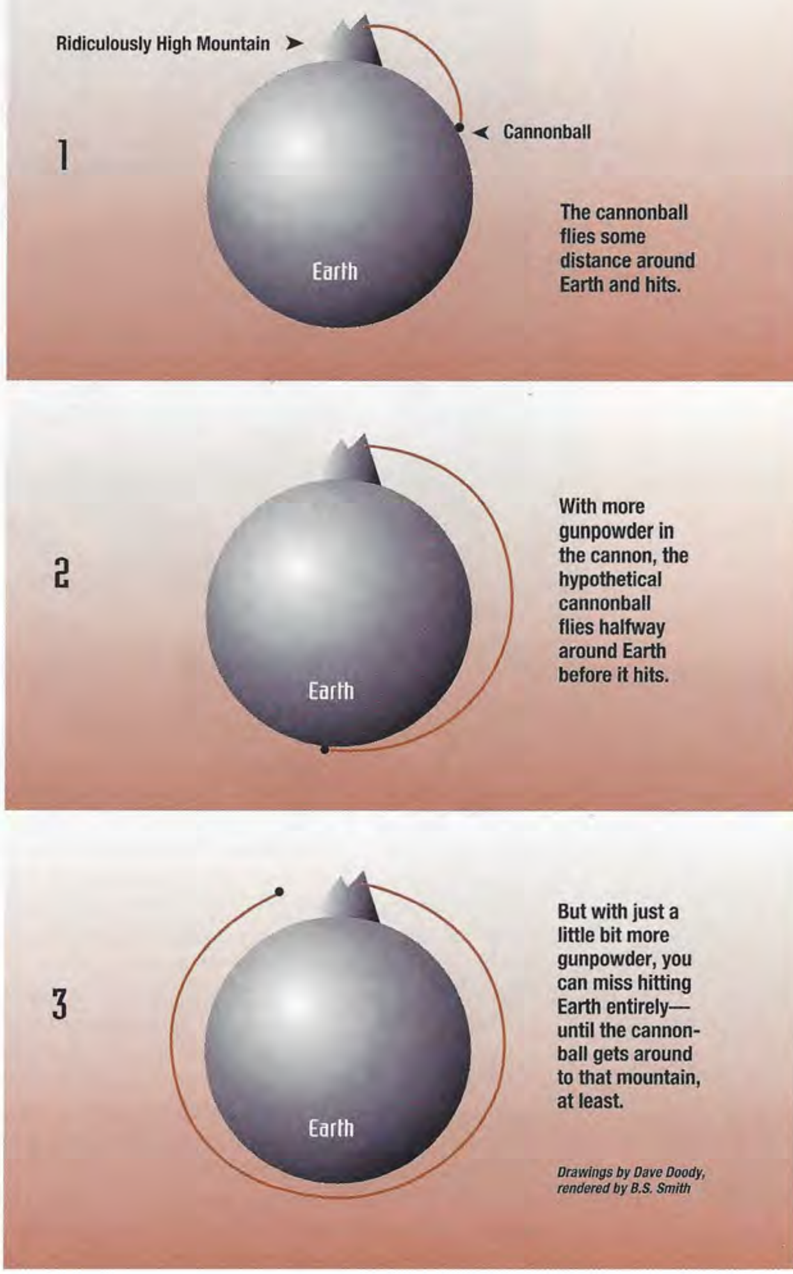
Additional meetings on the Shoemaker-Levy 9 impacts have been planned—for Europe this winter, and afterward, in May, there will be a four-day conference at the Space Telescope Science Institute in Baltimore. By that time, comparison and coordination of the multitude of observational data sets, advanced modeling efforts and the remaining *Galileo* data may come together to provide answers to the many questions that have been raised so far.

Paul Weissman is a research scientist in the Earth and Space Sciences Division of the Jet Propulsion Laboratory in Pasadena. This article was adapted from an article that appeared in the December 1, 1994, issue of Nature.

Basics of Spaceflight: Getting There

by Dave Doody

Figure 1



The cannonball flies some distance around Earth and hits.

With more gunpowder in the cannon, the hypothetical cannonball flies halfway around Earth before it hits.

But with just a little bit more gunpowder, you can miss hitting Earth entirely—until the cannonball gets around to that mountain, at least.

Drawings by Dave Doody, rendered by B.S. Smith

What is involved in flying a spacecraft to Venus, or Mars, or other planets? Do you just point the rocket at Mars and launch? Exactly how did *Voyager* use "gravity assist" to travel to Neptune? Doesn't gravity just slow you down again when you fly past a planet? How do you communicate with a robot in orbit at Venus or in the depths of the outer solar system? How do you measure its path and speed, and tell it where to go? What is a robotic spacecraft like? What's a geostationary orbit? A Sun-synchronous orbit?

This article is the first in a series that will discuss these subjects, and more. The material has been adapted from *Basics of Space Flight,* a training manual I coauthored with George Stephan that is in use at the Jet Propulsion Laboratory. An electronic, interactive version of the original training manual, by the way, is available to anyone who is familiar with the World Wide Web on the electronic information highway. Using Mosaic (or equivalent World Wide Web machine), the URL (Uniform Resource Locator) is http://oel-www/basics/bsf.htm. Or, select the manual from Online Tours on JPL's Home Page, which has the following URL: http://www.jpl.nasa.gov.

We'll begin by taking a look at some of the basic orbital mechanics involved in flying a spacecraft to a nearby planet: Venus or Mars. As you undoubtedly suspect, you don't just point the rocket at Mars and light the fuse. We'll consider first of all the process of orbiting a spacecraft around Earth. Then we'll consider what's involved in the trips to Venus and Mars.

First, Earth Orbit

The drawings in Figure 1 simplify the physics of orbiting Earth. We see Earth with a huge, tall mountain rising from it. The mountain, as Isaac Newton first envisioned, has a cannon at its summit. When the cannon is fired, the cannonball follows its ballistic arc, falling as a result of Earth's gravity, and it hits Earth some distance away from the mountain. If we put more gunpowder in the cannon, the next time it's fired the cannonball goes halfway around the planet before it hits the ground! With still more gunpowder, the cannonball goes so far that it just never touches down at all. It falls completely around Earth. It has achieved orbit.

If you were riding along with the cannonball, you would feel as if you were falling. The condition is called free fall. You'd find yourself falling at the same rate as the cannonball, which would appear to be floating there (falling) beside you. You'd just never hit the ground. Notice that the cannonball has not escaped Earth's gravity, which is very much present—it is causing the mass to fall. It just happens to be balanced out by the speed provided by the cannon. (A side thought: If someone tells you things are weightless in space because there's no gravity there, just remember what's causing the cannonball to fall in the first place.)

In the third drawing in this figure, you'll see that part of the orbit comes closer to Earth's surface than the rest of it does. This is called the periapsis of the orbit. It also has various other names, depending on which body is being

Our knowledge of how bodies travel through space has taken us from Earth, to the Moon, and beyond.

Painting: David Hardy

orbited. For example, it is called perigee at Earth, perijove at Jupiter, periselene or perilune in lunar orbit, and perihelion if you're orbiting the Sun. In the drawing, the mountain represents the highest point in the orbit. That's called apoapsis (apogee, apojove, aposelene, apolune, aphelion). Oh, by the way, you'd better get away from that mountain (Mount Apoapsis). The cannonball will return soon. The time it takes, called the orbit period, depends on altitude. At space shuttle altitudes, say 200 kilometers (about 120 miles), it's 90 minutes.

The cannonball provides us with a pretty good analogy. It makes it clear that to get a spacecraft into orbit, you need to raise it up (the mountain) to a high enough altitude so that Earth's atmosphere isn't going to slow it down too much. You have to accelerate it until it is going so fast that as it falls, it just falls completely around the planet.

In practical terms, you don't generally want to be less than about 150 kilometers (93 miles) above the surface of Earth. At that altitude, the atmosphere is so thin that it doesn't present much frictional drag to slow you down. You need your rocket (or cannon) to speed the spacecraft up to the neighborhood of 30,000 kilometers (about 19,000 miles) per hour. Once you've done that, your spacecraft will continue falling around Earth. No more propulsion is necessary, except for occasional minor adjustments. These very same mechanical concepts apply whether you're talking about orbiting Earth, the Moon, the Sun, or anything. Only the terms and numbers are different.

A speed of 30,000 kilometers per hour is tremendously high in human terms. Today's rockets can, of course, achieve this kind of speed, but it comes at a great price. Their technology is complicated, and their success rate is not the 100 percent we might wish for. So we need all the help we can get. Fortunately, Earth is rotating on its axis, and we can use that fact to advantage.

In Figure 1, the mountain is positioned at what appears to be Earth's north pole. But if we transport our rocket to a site close to the equator for launching, we can cheat a little. Earth's surface is traveling pretty fast there. Consider that a spot on the equator goes around once every 24 hours, covering about 40,000 kilometers (roughly 25,000 miles). That's 1,600 kilometers (about 1,000 miles) per hour we don't have to ask the rocket to provide, as long as we launch it toward the direction Earth's surface is moving: east. A good many rocket launches do take place from sites at low latitudes, such as Cape Canaveral and French Guiana.

The cannonball analogy is good, too, for talking about changes you can make to an orbit. Looking at the third drawing in Figure 1, imagine that the cannon has still more gunpowder in it, sending the cannonball out a little faster. With this extra speed, the cannonball will miss Earth's surface by a greater margin. We could say the periapsis altitude has been raised by increasing the spacecraft's speed slightly at apoapsis.

This concept is very basic to spaceflight. Increase the orbital speed when you're at apoapsis, and you'll raise the orbit's periapsis altitude. Similarly, with slightly less gunpowder—less speed, that is—the cannonball will come closer to Earth at periapsis. So: decrease the speed when you're at apoapsis, and you'll lower the periapsis altitude.

Likewise, if you increase speed when you're at periapsis, this will cause the apoapsis altitude to increase. Decelerating at periapsis will lower the apoapsis. (The last is what *Magellan* did in Venus orbit when it was aerobraking. See the March/April 1994 issue of *The Planetary Report.*)

This works up to a point. If you decrease the speed too much, of course, you'll hit the planet. And, if you increase the speed enough, you'll leave the planet behind completely. That speed is called the escape velocity, and it depends on how great the planet's gravity is. At Earth, the escape velocity is in the neighborhood of 40,000 kilometers per hour. For comparison, the escape velocity from Jupiter is over 200,000 kilometers (about 120,000 miles) per hour.

Extending the Orbit to Venus and Mars

When you woke up this morning, you were in orbit! The whole Earth, of course, is orbiting the Sun, speeding around at just over 100,000 kilometers (60,000 miles) per hour. For our purpose here, let's pretend that Earth orbits the Sun in a perfect circle. That's not too far-fetched, since our solar orbit varies from actually being a circle by a small percentage. We'll say our distance in orbit is 1 AU (astronomical unit), about 150 million kilometers (93 million miles) from the Sun. Venus' orbit is closer to the Sun than Earth's is.

Let's call Venus' orbit a circular one having a distance from the Sun of 0.72 AU. So when we think about sending a spacecraft from Earth to Venus, we should think in terms of adjusting its current solar orbit so that 1 AU, where the spacecraft is at the beginning of the flight, is the aphelion of its orbit, and the destination, 0.72 AU, would be the perihelion of its new orbit. It boils down to wanting to reduce the perihelion of the spacecraft's existing solar orbit.

How do we accomplish that? Remember, we just have to slow down the spacecraft when it is at aphelion: right here, in the vicinity of Earth, where it's going just over 100,000 kilometers per hour around the Sun at 1 AU. We need to slow it down from that a bit. The part we won't be discussing here is how to figure out exactly how much of a difference in speed is necessary. Keep in mind that to get there, the major thrust is required only at the beginning of a flight, to establish the desired orbit. For the rest of the orbit, the spacecraft is simply coasting in free fall, in solar orbit.

Look at the diagram in Figure 2. Notice the direction Earth is moving in as it goes around the Sun at over 100,000 kilometers per hour. In its new orbit, known as a Hohmann transfer orbit, the spacecraft will be going in the same direction around the Sun as Earth is, but it will be going just a little bit slower than Earth, causing it to drop in a little bit toward the Sun. The section of the spacecraft's new orbit that reaches from Earth to the destination is known as its trajectory.

Now we'll look a bit more closely at the launch process, getting the spacecraft up away from Earth in such a way that it will be slowing down a bit in its solar orbit. To cause the spacecraft to go a bit slower than Earth in its solar orbit, we'll want to have the rocket go in the direction opposite Earth's orbital direction.

When the rocket has finished expending its fuel a few minutes after liftoff, the spacecraft will still have a large portion of the 100,000 kilometers per hour it started out with going around the Sun. But not all of it. So it will lag behind Earth in orbit around the Sun, even though it will be traveling in generally the same direction as Earth is.

Again, since the speeds being dealt with are so very great, our meager rocket will need all the help it can get. So we'll launch the spacecraft at just the right moment of the day when the launchpad is swinging around (as Earth rotates on its axis) toward the same direction we want the rocket to go. Figure 3 shows how the launchpad is moving with Earth.

For our example, to illustrate the concept, we'll pretend that the launch process doesn't take much time at all. This might not be the case in an actual launch, though, where some important spacecraft activities, or other considerations, might require us to "park" it in Earth orbit for some amount of time.

Referring to the diagram, then, we would want to launch as the site is moving in the direction of the arrow. The Sun will be coming overhead as viewed from the site. Clearly, the time of day for launch is important in that it controls the amount of energy available from Earth's rotation. The day of year is chosen carefully on the basis of knowledge of the planets' positions and orbital motion, so that the destination planet will be in the necessary position in its orbit when the spacecraft arrives at perihelion.

The process of launching a spacecraft to Mars, whose orbit is farther away from the Sun than Earth's is, is much the same. A Hohmann transfer orbit is used, but this time Earth's position represents perihelion, and the destination at Mars is the aphelion of the spacecraft's new solar orbit. (See Figure 4.) The spacecraft must be accelerated, adding speed in the same direction as Earth's orbital motion, in order to raise the aphelion to the desired distance to reach Mars. The time of day for launch, per our diagram in Figure 3, would need to be chosen for best advantage. In the simple example, this would place it on the opposite side of Earth from where the X is shown in Figure 3.

Figure 2

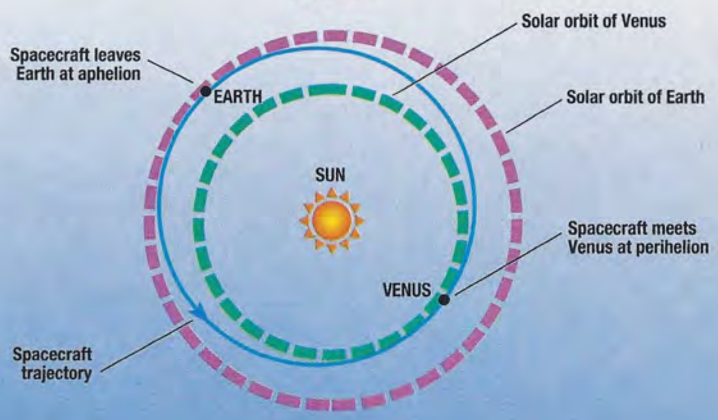


Figure 3

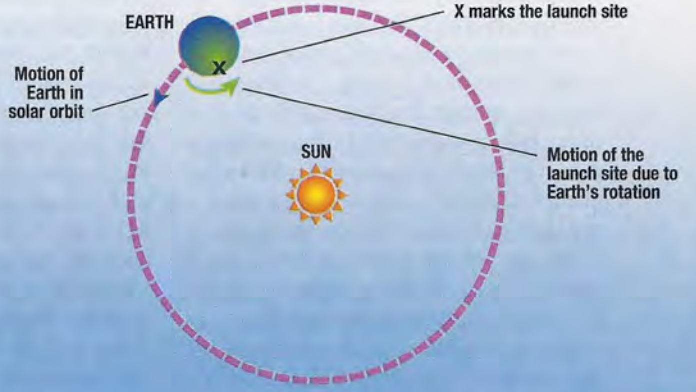
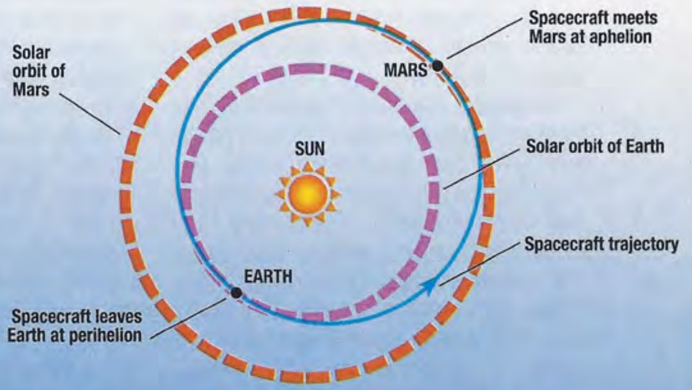


Figure 4



All views are looking down on Earth's north pole. Not drawn to scale.

Drawings by Dave Doody, rendered by B.S. Smith

In the next article in the series, we'll talk about a wonderful technique, gravity assist, that enables us to obtain that free ride to distant places in the solar system.

Dave Doody is a member of the Jet Propulsion Laboratory's Mission Operations Section. He is currently working on the Cassini *project, which will launch a spacecraft to Saturn in 1997.*

News and Reviews

by Clark R. Chapman

Science often advances by great leaps and bounds, as one way of looking at nature is superseded by a radically new perspective. In 1962, Thomas Kuhn defined the nature of such "paradigm shifts" in his classic book, *The Structure of Scientific Revolutions.* Within the next four years, one of the greatest paradigm shifts in the history of science occurred. A static view of our planet's geology was suddenly replaced by the acceptance of continental drift and the framework of plate tectonics.

One geologist-turned-scientific-historian who has tried to understand the plate tectonics revolution is William Glen. He published a monograph on that topic in 1982, just as yet another revolution in the earth sciences began to unfold—the controversy over whether the Cretaceous/Tertiary (K/T) boundary was due to a giant impact. Glen was luckily able to chronicle the K/T revolution from its start.

A recently published book, edited by Glen, summarizes this "work in progress" (*The Mass-Extinction Debates: How Science Works in a Crisis*, Stanford University Press, 1994, available in hardcover and paperback editions). The volume contains two chapters by Glen (one a précis of a longer, not yet completed book), interviews with two prominent paleontologists (William Clemens and Stephen Jay Gould), a panel discussion organized by Glen during a 1991 science historians' meeting, and nine chapters by other participants in, and watchers of, the controversy.

Readers of *The Planetary Report* have long been familiar with spacecraft photos of cratered planetary surfaces and with research on asteroids and comets, which clutter interplanetary space. To us, it seems a little strange that many paleontologists and geologists still deny that—to put it starkly—an asteroid killed off the dinosaurs. The idea was a natural. And now it has been proved by the straightforward march of science and testing of predictions. Right? Not really.

The idea of Luis and Walter Alvarez and their Berkeley collaborators was that the iridium-rich rock layer they found near Gubbio, Italy, marked a global deposit of extraterrestrial material. They theorized that it was laid down 65 million years ago, when asteroid-rich ejecta from a huge, billion-megaton impact rained back down around the world. It coincided with the supposedly sudden demise of the dinosaurs and most marine species then alive, as well as with lesser extinctions of plants and land animals. They hypothesized that a stratospheric ejecta cloud darkened the Sun, resulting in the great killing.

Soon the iridium-rich layer was found at dozens, then hundreds, of sites around the globe, confirming the first Alvarez prediction. Later, impact-shocked quartz and microtektites were found in the boundary layer, just as expected. Then the search was on for the 100- to 200-mile-wide impact scar. A 65-million-year-old crater might well have been subducted and destroyed by now, but luckily it was not. The Chicxulub crater on Mexico's Yucatán peninsula beautifully fills the bill: Not only is it the largest crater yet identified on Earth, but it is precisely 65 million years old, and the chemistry of the rocks in which it was formed agrees with that of the K/T boundary layer.

How can the debate continue? Glen's book helps us understand the very different world of paleontology. Several contributors to the book, including William Clemens, who worked at Berkeley alongside the Alvarezes as they developed their theory, remain skeptical of the role of impacts in shaping the K/T mass extinction. John Briggs' chapter ends with the shocking statement that "there is no evidence that global mass extinctions ever took place." The training and methods of paleontologists—necessitated by the nature of their subject—formed an intellectual gulf making it virtually impossible for them to deal with the Alvarez proposal, which came literally from outer space.

The lay reader will be amazed by how many supposedly expert opinions were formed with inadequate knowledge of relevant facts. Few scientists have read more than a handful of the important papers published during the course of the debates, and many learned what they thought they knew just like lay readers did, from *The New York Times* and other mass media.

Glen's purpose is to treat the sociology of science. But his book also provides the best available (and most balanced) summary of how the science unfolded and what we actually know about the K/T boundary holocaust and its causes. Inevitably, *The Mass-Extinction Debates* is already somewhat dated, with some of its contributions written as long ago as 1991. Glen's own chapters summarize research through mid-1993, including the discovery of comet Shoemaker-Levy 9.

Physicists, astronomers and planetary geologists tossed a bomb into the world of paleontology. William Glen provides us with multifaceted insights into the resulting intellectual explosions.

Clark R. Chapman is a senior scientist at the Planetary Science Institute (Tucson, Arizona), which became a division of the San Juan Capistrano Research Institute in February 1995.

Society News

Looking at Asteroids and Other Near-Earth Objects

Comet Shoemaker-Levy 9's collision with Jupiter made many people wonder if a similar crash could occur on Earth. With this in mind, The Planetary Society is joining the Explorers' Club and the United Nations Office for Outer Space Affairs to hold an international conference on near-Earth objects.

On April 24 through 26 in New York City, the conference will focus on comet Shoemaker-Levy 9, on the asteroid impact that marked the end of the Cretaceous period (and the dinosaurs) and on methods of detecting near-Earth objects.

The Planetary Society will present a public event on April 25 at the Museum of Natural History's Hayden Planetarium. For information, contact me at Society headquarters, 65 North Catalina Avenue, Pasadena, CA 91106-2301; phone, (818) 793-5100; e-mail, TPS.sl@genie.geis.com.
—Susan Lendroth, Events and Communications Manager

Society Launches New Asteroid Telescope

The Planetary Society is providing seed funding for a new optical telescope array that will dramatically increase the ability to search for objects that come close to Earth. The nine-telescope array is based on an innovative small CCD (charge-coupled device) camera designed by Lawrence Livermore National Laboratory (LLNL) to optically image areas of the sky where gamma-ray bursts are observed.

Such bursts are seen only once every week or two, and so most of the time the array would be available for other applications. Hye-Sook Park of LLNL suggested to planetary scientist Eugene Shoemaker that the array be used to search for near-Earth comets and asteroids. Shoemaker told The Planetary Society of the idea.

A University of Michigan group under Carl Akerlof proposed building the array. While grants from the National Science Foundation and the university were pending, the group needed immediate funding to keep the project alive. The Society stepped in and paid half the funding for the first telescope, in the hope of seeing it make observations by the end of 1995.

Shoemaker and Observatory Director Ted Bowell will install the camera, and eventually the full array, at the Lowell Observatory in Flagstaff, Arizona.
—Louis D. Friedman, Executive Director

Getting On Line With The Planetary Society

TPS123: That's your special code for getting connected to The Planetary Society Roundtable, where you can download images of the planets, post messages about NASA and international missions, read the latest news about spacecraft and exploration and glance at the most recent issue of *The Planetary Report.*

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—Michael Haggerty,
Information Services Manager

Society Takes Large Steps to Mars

The Planetary Society will commemorate the 20th anniversary of the *Apollo-Soyuz* mission, as we did the 10th anniversary, with a major "Steps to Mars" symposium. But this anniversary event is also scheduled to celebrate the rendezvous and docking of a US space shuttle and the Russian *Mir* (slated for some time between June 10 and 17). In July 1995, the Society will join the American Astronautical Society and the Association of Space Explorers to celebrate these space milestones.

The symposium plans include a commemoration of the *Apollo-Soyuz* and shuttle-*Mir* programs with crew members from both missions. For more information, contact me at Society headquarters. *—SL*

Millennium Approaches

The revitalization of the New Millennium Committee has brought renewed excitement to Society programs. The group expanded from its original 12 members in 1982 to 68 members in September 1994 to 148 members in January 1995.

The Planetary Society thanks this group of leaders and would like to mention especially founding members George Awad, Sandra Bentley, Polly Brooks, Emanuel Cashell, Abe Gomel, Alford Karayusuf, Norman Kinsey, Sidney Newman, Steven Spielberg and David Steinbuhler, and Leadership Council members John De Biase, Eugene Cloud, Hildegard Flesch and Kenneth Norris. The Society also extends special gratitude to the first two chairmen, founding members David Brown and Richard Weisman.
—Diana Marquez,
Director of Development

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Questions and Answers

Are there any other planets in our solar system that exhibit plate tectonics? If not, why is Earth unique in this aspect?
—Doug Burden,
Lacombe, Alberta, Canada

The tectonic evolution of planets in our solar system is a fundamental concern of planetary geology. Thus far, none of the planets we have explored has a recognizable system of plate tectonics like that on Earth.

A planet's size is one of the key factors that shape its tectonic evolution. Small planets, such as Mercury, Mars and Earth's Moon, have large ratios of surface area to volume. As a result, they cooled very quickly in their evolution and developed thick lithospheres that were unable to break apart into separate, mobile plates. None of these bodies shows any evidence of plate tectonics. Tectonic faults and other features on these "one-plate" bodies are related to processes such as global cooling and contraction and impact cratering.

As recently revealed by the *Magellan* mission to Venus, tectonic style may also be related to subtle variations in mantle composition. We think that Venus is similar in composition to Earth because it formed in the same general region of the solar system and has a similar density. As a result, it probably has a similar abundance of elements like uranium, thorium and potassium, which produce a large amount of heat in Earth's interior. Unlike Mercury and Mars, Venus is also similar in size to Earth and, like our planet, probably has not cooled to the extent that these smaller bodies have. Thus, many scientists believe Venus has an amount of internal heat similar to Earth's. Because of these similarities, some scientists expected Venus to have plate tectonics. However, they found no global system of plate boundaries in the *Magellan* radar data.

This is something of a puzzle, not only because Earth and Venus are so similar in size and bulk composition, but also because Venus does have orogenic belts (that is, mountains like the Rockies or Himalayas on Earth) that have formed by crustal folding and faulting. On Earth, these processes are driven by plate motions. On Venus, there are no plates.

The answer to this puzzle may be linked to a missing asthenosphere. On Earth, the asthenosphere is a weak region of the upper mantle over which glide the rigid plates. It is known as

The* Magellan *(far right) and* Venera *(right) images here show part of Venus' Maxwell Montes region. The mountains in these images bear a strong resemblance to Earth's Appalachians (bottom). Spacecraft images such as these help scientists piece together the complex puzzle of what shaped the face of our planet, as well as those of our neighbors.

Images: (far right) JPL/NASA; (right) Space Research Institute, Russia; (bottom) Nicholas Short, Bloomsburg State College, Pennsylvania "the low-viscosity zone" because minerals at these depths and temperatures are near their melting points and may even be partially molten. As a result, the asthenosphere decouples lithospheric plate motions on Earth from convection patterns deeper in the mantle. The gravity data that *Magellan* gathered reveal a very strong correlation between areas of high elevation and regions of strong gravity on Venus. This indicates that, in contrast to Earth, convection patterns deep in the planet's mantle may be directly coupled to the lithosphere to produce mountain belts and other tectonic features (see the January/February 1995 issue of *The Planetary Report*).

Why Venus should lack an asthenosphere isn't fully understood, but it may be related to slight differences in mantle composition, especially the amount of water. The water in Earth's mantle lowers the melting temperature of mantle rocks, producing the asthenosphere. It may be that without substantial amounts of water in its upper mantle, Venus was unable to form an asthenosphere, and without it there can be no plate tectonics as we know it on Earth.

On Earth, plate tectonics is responsible for the vast majority of heat loss from the mantle. If Venus has a similar amount of internal heat, but no plate tectonics, how does it vent this heat? One possibility is that the crust and mantle completely overturn on Venus in a global catastrophic event every 500 million years or so. Some scientists have likened this to episodic plate tectonics. Although Earth-like plate tectonics may not be active on Venus now, there is a possibility that plate tectonics (or something similar) was active in the past and will resume again at some point in the future. The mechanism and even the evidence for such an episodic system of plate tectonics are matters of great scientific debate among Venus researchers.

What about the other bodies in the solar system? Pluto and most of the asteroids and satellites of the outer gas giants are probably too small for plate tectonics, as discussed earlier for the smaller inner planets. And we've seen no global system of plate boundaries on any of the satellites that the *Voyager* spacecraft visited. The icy surface of Ganymede, Jupiter's largest moon, is dissected by extensive fractures that may represent incipient plate boundaries. However, these "plates" have moved only slightly relative to one another, and there appear to have been no large-scale collisions or relative motions between adjacent plates.

Could Titan possess some icy variation of plate tectonics? Currently, we have no information on the tectonics of Saturn's largest moon. The *Cassini* mission will use radar to probe beneath Titan's atmosphere, in much the same way that *Magellan* unveiled the surface of Venus.

When the *Cassini* data arrive, planetary geologists will have yet another clue in piecing together the puzzle of the development of plate tectonics on Earth and the tectonic evolution of other bodies in the solar system.

—KARI MAGEE,
Resource Center Manager

Factinos

Atomic sodium is a useful tracer of the Moon's tenuous atmosphere because of its high efficiency in scattering sunlight at certain wavelengths. In this image, the greatest quantities of sodium appear as magenta and red, while blue represents the lowest values.

Image: McDonald Observatory, Boston University/Center for Space Physics

The only atmosphere that our Moon can call its own is a thin exhalation of gases from the surface. But researchers from Boston University have produced the first detailed picture (at left) of the sodium gas that surrounds the Moon, showing that it extends unexpectedly large distances—as far as five times the lunar radius.

In a July 1993 issue of *Science*, graduate student Brian Flynn and professor Michael Mendillo described results of observations, conducted at the McDonald Observatory in Texas in 1991, in which they mapped the distribution of sodium gas with latitude and radial distance from the Moon. Sodium atoms are easy to detect because they reflect sunlight very efficiently, even in small quantities. To capture the light coming from those sodium atoms, Flynn and Mendillo used a telescope with a black shield at the center of the lens system to block the bright light coming from the Moon itself.

Sodium gas is not the major component of the Moon's atmosphere; it is just the easiest to detect. As such it is called a tracer of all the other gases that may be present.
—from Boston University

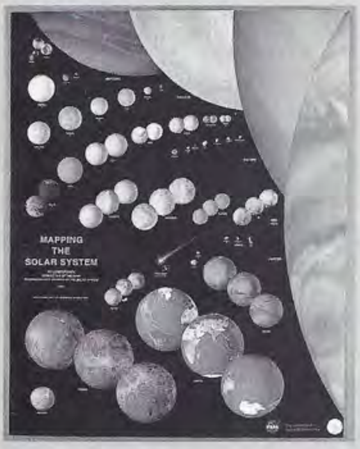
A set of 60 Hubble Space Telescope images, taken in the 15-month period before the telescope's repair, reveals that Pluto's moon Charon moves in a slightly elliptical path around the planet. That puzzled a team of scientists studying the images, because Pluto's gravitational embrace rapidly changes an elliptical orbit into a perfectly circular one.

David J. Tholen of the University of Hawaii in Honolulu and Marc W. Buie and Lawrence H. Wasserman of Arizona's Lowell Observatory say that the simplest way to account for Charon's slightly oval path is to assume that an object slammed into Pluto or its moon sometime in the past 10 million years.

Tholen says that such a collision must have been powerful enough to throw Charon slightly off its orbit and recent enough that gravity wouldn't have restored the circular path yet. He speculates that some of the darker regions on Pluto may stem from such a collision and that a flyby mission to the planet could find out for sure.
—from Ron Cowen in *Science News*

Three years of data from NASA's Upper Atmospheric Research Satellite (UARS) have provided conclusive evidence that human-made chlorine, which results from the breakdown of chlorofluorocarbons (CFCs) in the stratosphere, is the cause of the Antarctic ozone hole. The satellite's instruments found CFCs in the stratosphere. The UARS global data also found worldwide buildup of stratospheric fluorine gases corresponding to the breakdown of CFCs, according to NASA.

The UARS data have ended recent debate that natural causes might be sources of stratospheric chlorine. Mark Schoeberl, UARS project scientist, says, "Detection of stratospheric fluorine gases, which are not natural, eliminates the possibility that chlorine from volcanic eruptions or some other natural source is responsible for the ozone hole."
—from NASA



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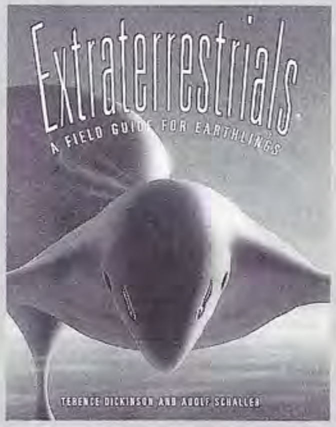

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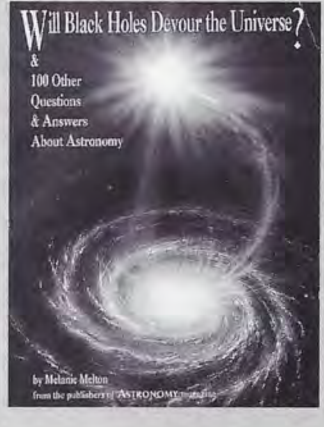

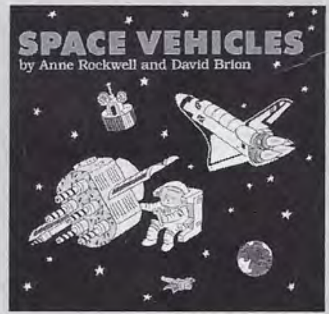

Space Vehicles
By Anne Rockwell and David Brion.
For the littlest folk who cuddle on your lap while you watch TV, we suggest this book. It is a very simple explanation of rockets, probes, satellites, modules, rovers and shuttles, even a future space station, and features whimsical illustrations, in paint-box colors, of kittens as the astro-cats that maneuver these contraptions through space. 22 pages (hard cover). 2 lb.
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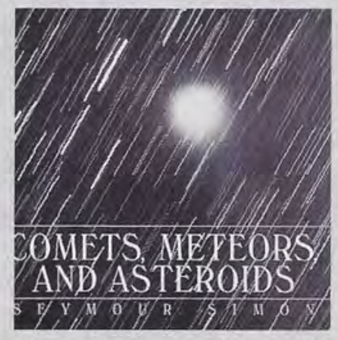

Comets, Meteors, and Asteroids
By Seymour Simon. Written for kids in middle school, this splendidly illustrated account includes a description of the Oort cloud, as well as close-ups of meteorites from Antarctica, and an asteroid named Gaspra photographed in space by the *Galileo* spacecraft in 1991. 28 pages (hard cover). 2 lb. **#015 $12.00**

Jupiter in July 1994 is the setting for "Impact Site of Fragment G." Just moments after the explosion of comet Shoemaker-Levy 9's G fragment, a mushroom cloud forms above the planet's cloudscape, eventually growing to the size of Earth. Shock waves ripple out in concentric rings for thousands of kilometers. Two of Jupiter's moons are visible in the distance.

Michael Carroll is a space artist who lives and works in Littleton, Colorado. His work can be seen in Carl Sagan's latest book, *Pale Blue Dot*, as well as Arthur C. Clarke's upcoming book, *Snows of Olympus*.

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