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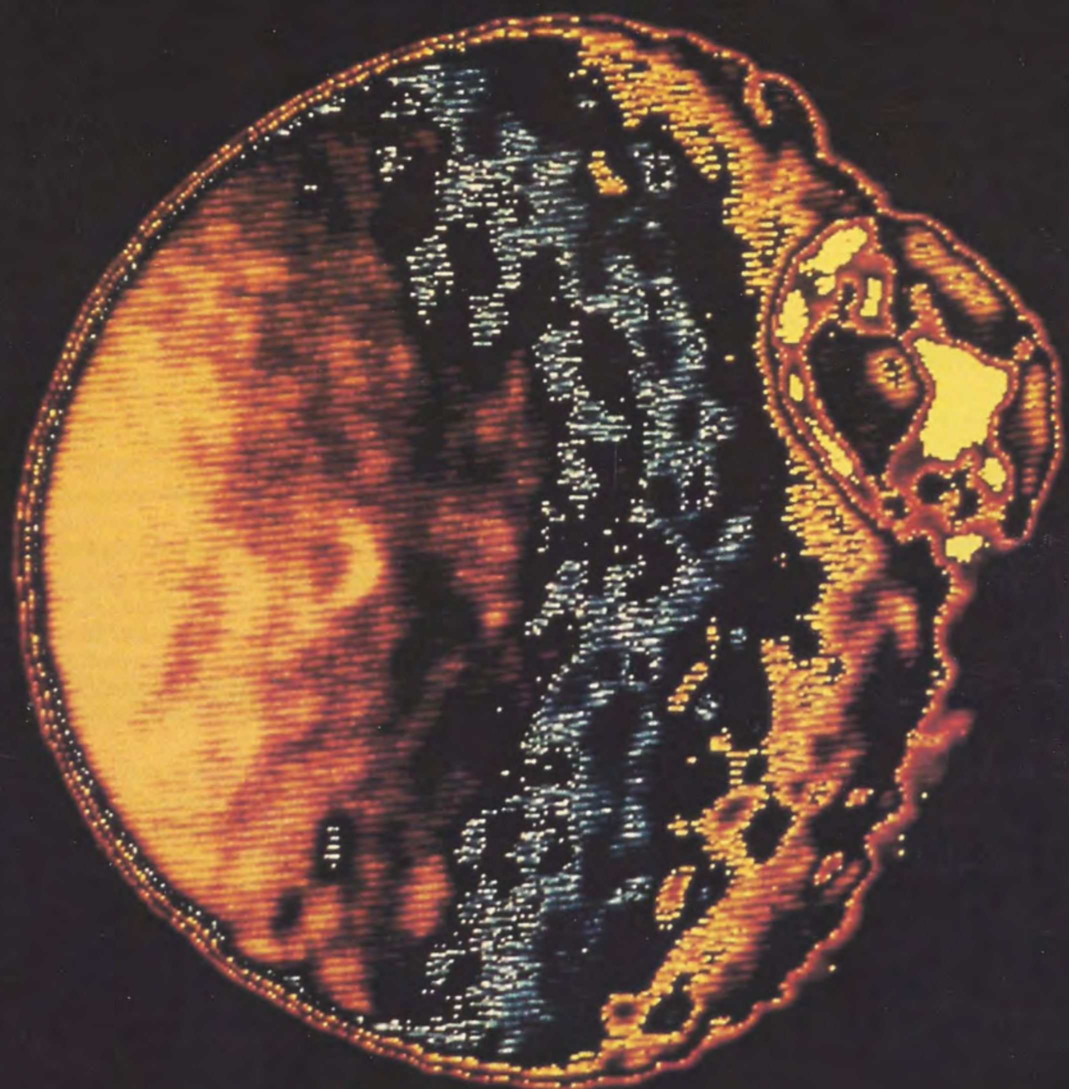

Planetary Catastrophes

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COVER: Sometime in the distant past, an asteroid or comet struck Saturn's moon Mimas with nearly enough force to break the satellite into pieces, leaving a giant crater over 100 kilometers across. Another wayward asteroid or comet may have struck Earth 65 million years ago, causing the extinction of the dinosaurs. This computerized image of Mimas accentuates the crater, appearing here in relief against the darkened limb of the satellite. ***Image courtesy of Alan Ames, I.M.A.G.E.S. Computer Graphics System, Columbia College, Hollywood***

Letter to the Editor

TOWARD THE EXPLORATION OF EXTRA-SOLAR PLANETARY SYSTEMS

The possibility of an epic odyssey some time in the future to visit a nearby star with planets is now an intriguing topic at NASA's Jet Propulsion Laboratory in Pasadena, California. The electronic picture of the young star Beta Pictoris made by astronomers Bradford Smith and Richard Terrile is the first ever to show a protoplanetary disk around a star. [*See the November/December 1984* Planetary Report.] This disk is believed to be associated with planet formation and may be the debris from an already existing system of planets around Beta Pictoris. It stirs the imagination to envisage an opportunity to at last see planets from their infancy, and to travel to them.

Artificial intelligence would guide an interstellar spacecraft moving at approximately one-tenth the speed of light for the generation-long journey to a nearby star. A journey to Epsilon Eridani, which might also have a protoplanetary disk, would take only about 100 years. Such an interstellar ship would be propelled away from our solar system by nuclear means to rendezvous with the star. This interstellar spacecraft would be far from silent even during its voyage. It would be a busy astronomical observatory returning information about stars and sampling space from an entirely new perspective. Soon after it leaves our solar system, the interstellar spacecraft will give us our first view of our own system as seen from the outside. The images of our 4.5 billion year old planetary system will be fainter than the relatively younger and more dusty disk of Beta Pictoris at a comparable distance.

By these comparative studies we will begin to learn much about solar system evolution, and find out whether stellar planetary systems are the exception or the norm. After crossing the great gulf between stars, close-up images would find the individual planets and show the nature of their surfaces. Will a "blue-water" world like Earth be found, orbiting at just the right distance from the star? The images would be sent back on the beam of a laser at the culmination of the long interstellar voyage, to be seen by the descendants of we who sent the spacecraft on its journey.

Before such a journey could be undertaken, however, several advances in technology are necessary. Currently the technology for interstellar travel is not available, but we are in the process of acquiring it. Progress must be made in the fields of propulsion, artificial intelligence and communication. To solve problems in these fields we need to examine a combination of micro spacecraft with a small launchable mass, use of planetary and stellar gravity assist, and very advanced modes of propulsion to escape from the solar system and then accelerate toward a flyby of other stars. For spacecraft propulsion we need to examine nuclear, electric and other exotic propulsion systems. Highly efficient optical communication is another challenge, as is producing micro components that will perform flawlessly for a century or more. We also need to design an intelligent observing system.

But what we need most of all is imagination and vision.

Meticulous observations using ground-based and Earth orbiting telescopes are the foundation for an epic spacecraft mission such as a visit to a star. The objectives are not only to select the most advantageous protoplanetary system for the mission, but also to define the questions which can only be answered by a visit to the vicinity of another stellar system.

DR. LEW ALLEN, JR., *Director, Jet Propulsion Laboratory, Pasadena, California*

[After this letter was submitted, Donald McCarthy, Jr., Frank Low and Ronald Probst announced their discovery of a possible planet orbiting the star Van Biesbroeck 8.]

by Owen B. Toon

PLANETS and PERILS

A luxurious organic cloth, wonderfully complex and intertwined, covers the surface of our planet, but none other in our solar system. Many local disasters, such as hurricanes, tornados and earthquakes, rend this covering in a human lifetime, but these tears are soon mended. So it is easy to believe that Earth is a placid planet, successfully designed to ensure that billions of years of uninterrupted evolution would eventually produce humans. This view, referred to as uniformitarianism, has represented the mainstream of geological thinking for over a century. It holds that the slow, subtle processes we observe acting today, such as erosion, mountain building, continental drift and evolution through survival of the fittest, are responsible for virtually all changes that have ever occurred on our planet.

Recent studies of our planetary neighbors and of Earth itself, however, reveal that life on Earth has not had such an easy time of it. Uniformitarianism accounts for much of Earth's history, but the opposing viewpoint— catastrophism — also explains much of that history. We have found evidence of great terrestrial catastrophes that have repeatedly threatened total extinction of the biota. Furthermore, the inhospitable environments of our neighboring planets indicate that Earth could have developed in other ways than it did — and ended up a hostile and forbidding place.

Stenonychosaurus inequalis ***(rear), one of the last dinosaurs, may also have been one of the most intelligent, perhaps as smart as a modern armadillo or opossum. Its large brain, stereoscopic vision, opposable fingers and bipedal stance suggest to Dale Russell of the National Museum of Natural Science, Ottawa, that one of its descendants could have been this hypothetical intelligent being (front). If it weren't for the asteroid collision that might have killed the dinosaurs, such creatures might now rule Earth.***

Models by D.A. Russell and R. Sequin

Mass Extinctions

At least five times during the past 600 million years a large fraction of the species on our planet has suddenly become extinct. The last time this happened, 65 million years ago, more than 50 percent of all species identified in the fossil record abruptly ceased to exist. Among the victims were the dinosaurs, and among the survivors were the mammals. Were it not for this catastrophe, dinosaurs' descendants, rather than us mammals, might now be embarked upon the exploration of our solar system. Presumably their views on geology would be decidedly uniformitarian.

The cause of this most recent mass extinction has been debated for a long time. A few scientists pointed out years ago that collisions with comets or asteroids occur frequently and should be considered as a possible cause of extinctions. The pockmarked faces of the Moon and Mars reveal that devastating impacts do occur, and Earth itself bears many sizeable craters. But those ideas were ignored, swept up onto a great heap with other seemingly bizarre explanations. Proof in science rests not with a plausible theory, but with conclusive data. Such data were produced a few years ago by a group of scientists from the University of California at Berkeley led by Nobel-prize-winning physicist Luis Alvarez and his son, Walter. They found the remains of the meteorite that killed the dinosaurs! It was not a single rock, but a thin sheet of crushed meteorite and pulverized soil hurled up from the impact site to cover our planet worldwide. This debris can be found in an easily visible, readily touched layer anywhere that rocks of the proper age are exposed.

Darkness and Cold

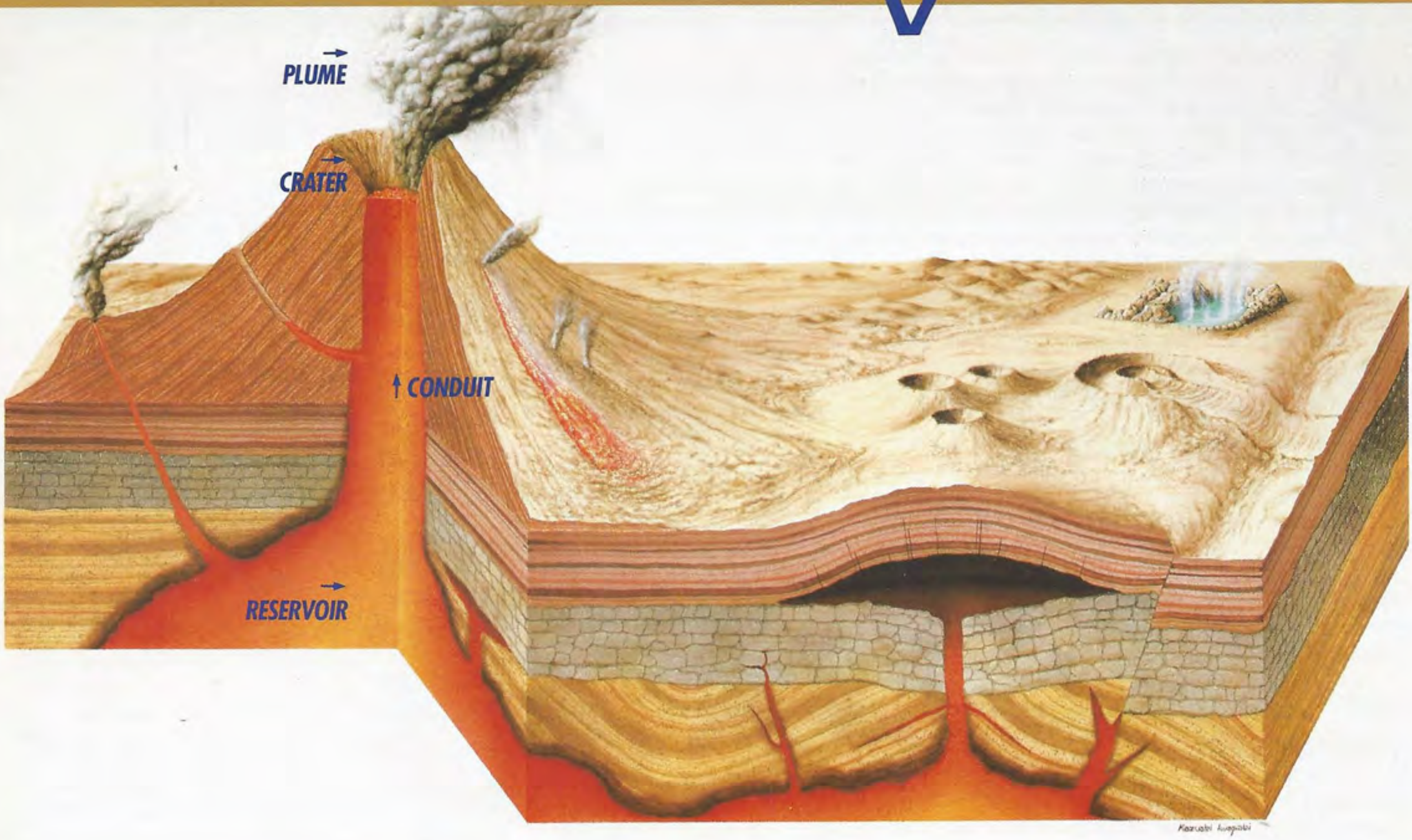
When this cloud of debris was in the atmosphere, it blotted out the Sun, inducing darkness and cold temperatures for many months. Toxic vapors may also have built up in our atmosphere. The food chain collapsed under the strain, plants died back, and mass starvation followed. Precisely which effects were most lethal is still uncertain, but a large fraction of the biota quickly died off, followed by the survivors' slow recovery in a greatly altered ecological setting.

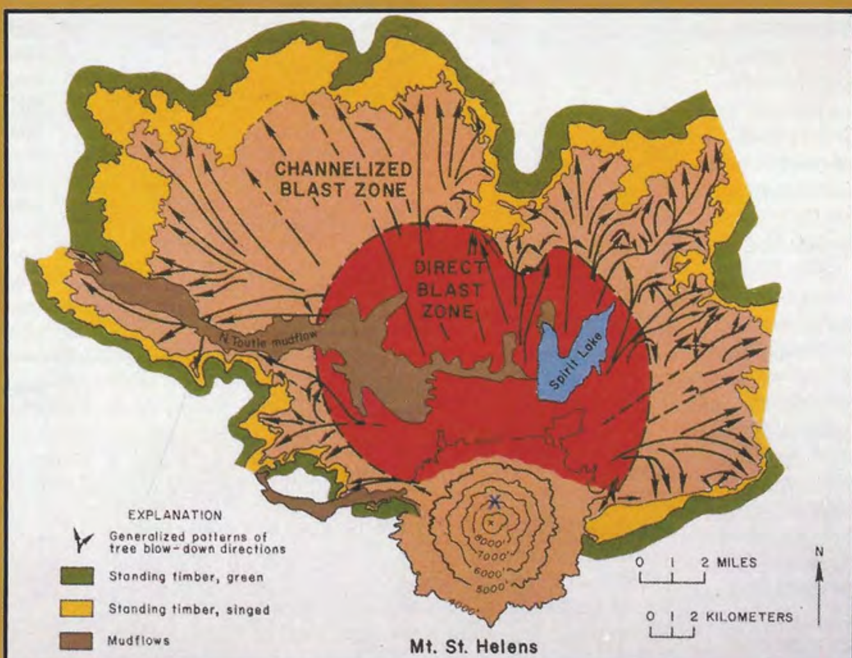
The discovery of the dinosaur-killing meteorite has triggered a rush to determine if other major extinction events were triggered by asteroid impacts, along with a search for other evidence of catastrophes. We know that several large asteroids are now in orbits that could eventually cause them to hit Earth. Moreover, the great cloud of millions of comets lying outside Pluto's orbit may be disturbed occasionally by a passing star or by other galactic phenomena, triggering a shotgun blast of comets aimed at the inner solar system. We need to better understand our planetary system to predict these possible events and to devise ways to protect ourselves from them.

The fossil record shows that life on Earth narrowly survived this planetary pinball game. An element of luck has been involved. Collisions haven't happened too often, and their direct effects have not been so extensive or so long-lasting that living organisms were unable to wait them out. Earth has been lucky in other ways. Planetary explorations

(continued on page 22)

VOLCANOS





TOP: Many parts of the subsurface world of volcanos are illustrated in this painting of a stratovolcano and its peripheral craters, lava flows and geothermal features. Hot magma rises from a supply region at great depths into a reservoir centered under the mountain. From there the magma rises through the main conduit into a crater. As the magma rises, expanding gases separate it into a mixture of liquid droplets and hot gases which is erupted from the volcano into the plume. *Painting: Kazuaki Iwasaki* ***LEFT: This map shows the pattern of devastation caused by the lateral blast at Mount St. Helens on May 18, 1980. The arrows indicate the direction of flow as shown by the directions of fallen trees. Note how the fallen trees show that the flow, initially directed north at the vent, diverged to the east and west.*** *Map: S.W. Kieffer, United States Geological Survey* ***ABOVE: This eruption column developed after the lateral blast at Mount St. Helens on May 18, 1980. Note the typical vertical plinian eruption column.*** *Photo: David Frank, United States Geological Survey*

AND ATMOSPHERES

Catastrophic Influences on Planets

by Susan Werner Kieffer

For a rare and brief instant in geologic time, we can imagine that the sulfurous, chromatic surface of Io lies quiet. Perhaps stars glisten brilliantly through the tenuous night sky. Here and there, thick icy fogs enshroud fumaroles where sulfur dioxide leaks from the underworld. Suddenly, a fissure splits the surface and billowing clouds of sulfurous gases and ice hurl orange and black ash into the atmosphere. Minute by minute, the intensity of the eruption builds; stars begin disappearing from the night sky. The rising plume inhales the nearby atmosphere, mixing it with the exhalations from the volcano. Particles of sulfur, sulfur dioxide snow and ash rise to 300 kilometers, later raining down across the planet a thousand kilometers away.

An area the size of Alaska is rapidly engulfed by the products of the erupting volcano. Under the veil of plume ejecta, dense clouds of gas and ash roll across the land, their particles mixing with ash falling from the sky; lava flows rush in torrents down the slopes. Pele, the Hawaiian goddess, is playing with Loki, Marduk and other gods and goddesses of volcanism on Io. Time and time again, they repaint the land with different sulfurous colors. Their paint brushes are lava flows, ash hurricanes and ash falls; their paint pots are reservoirs of molten sulfur, sulfur dioxide and silicate that exist in the ground and atmosphere of Io.

The mythical figures of volcanism play and paint until the excess heat in the planet is gone. Then, almost suddenly, they retire into the underworld, having sculpted anew the surface, refreshed the atmosphere, and cooled the tempers of the fiery interior. All is quiet...briefly.

Volcanos and Atmospheres

Large volcanic eruptions are so common on Io that they hardly can be called catastrophes. But on Earth, even much smaller events so perturb the delicate balances of life, land and weather that we do call them catastrophes. For example, El Chichón, a small, remote volcano in Mexico, awakened in 1982. Ash flows rolled down its flanks and gullies, destroying villages and annihilating a tropical forest and its life. Ash and sulfurous droplets, propelled into the stratosphere by the towering column of gas emitted from El Chichón, circulated around Earth, reducing ever so slightly the warming effect of the Sun and causing a mildly cooler winter. El Chichón was giving us a gentle reminder that Io is not the only planet on which volcanic activity affects the atmosphere.

The historic record suggests that sometimes this reminder has been more severe. Often the most visible catastrophe from an eruption is the blanket of ash deposited from the volcanic plume, but ash is only part of the problem. In 1783, a 25-kilometer-long fissure split the ground in Iceland. For eight months lava oozed out over Earth's surface at Laki; there were few of the fireworks and towering ash clouds that El Chichón displayed. Yet the continuous injection of sulfurous droplets from that eruption into the lower atmosphere dramatically altered the weather for several years: Red sunsets, atmospheric hazes and fogs, and cold winters were observed worldwide. Most of the livestock, and one-fourth of the people of Iceland, died from famine and starvation as a result of the weather change caused by the volcanic eruption.

Do volcanic eruptions influence long-term climatic patterns as well as day-to-day weather? Benjamin Franklin first suggested that the answer to this question was "yes." Scientists now realize that if the eruption of the 12 cubic kilometers of basalt at Laki over eight months could alter the climate for several winters, other much larger eruptions might have had even greater effects. The whole of northern and western India surrounding Bombay, an area of over 250,000 square kilometers, is covered by basalt flows, some reaching over three kilometers in thickness. About twenty million years ago over 130,000 square kilometers of Washington and Oregon were buried by thousands of cubic kilometers of basalt.

We will never know for certain the magnitude of the effects of these eruptions on the atmosphere, on life on the planet, and on glaciers and oceans. But after a century of controversy, we are beginning to believe that the effect of volcanos on Earth's atmosphere can indeed be catastrophic.

Atmospheres and Volcanos

We are also learning that planetary atmospheres affect the type of devastation wrought by volcanos because the atmospheres provide the "back-pressure" against which volcanic gases work when they enter the atmosphere. Volcanic gases originate in regions of a planet where pressures are a few hundred to a few thousand times greater than the atmospheric pressure at the surface of Earth. If high-pressure volcanic gases were suddenly exposed to the atmosphere, violent eruptions would blast hot gases and rock up, down and sideways — much as a water balloon exploding on a sidewalk has little directionality in selection of its victims.

But terrestrial volcanos commonly vent their gases unidirectionally — most often vertically into the towering eruption columns that we call *plinian*, after Pliny the Younger's classic description of the eruption column from the 79 AD eruption of Vesuvius. That extremely violent eruption destroyed much of the ancient volcano and buried the Roman cities of Pompeii and Herculaneum under millions of tons of ash.

Why do many of the gases released from terrestrial volcanos rush into these towering vertical columns instead of spreading out around the volcano? As magma (a mixture of melted rock and hot gases) rises from depth through a volcanic system toward Earth's surface, the pressure, density and temperature of the gases all decrease in response to the ascent. Energy that was stored in compression is used to overcome friction and gravity as the material rises, and to accelerate the material into the lower-pressure environment. Quantitative models of these processes indicate that the pressure on a magma can drop hundreds or thousands of times as the magma accelerates from its reservoir through the conduit to the vent where it enters the atmosphere (see diagram at left). If there is any excess pressure left in the gas when it reaches the vent, lateral expansion in a small crater (less than 50 meters deep) relieves this pressure.

In a typical eruption then, volcanic gases are at about atmospheric pressure when they enter the atmosphere, and they simply flow from the volcano under the impetus of their own momentum — upward into a plume or, sometimes, laterally into a flow. Thus, although the scale is vastly different, the flow of gases in a plinian eruption is much like the flow of water from a fire hose, gas from an automobile exhaust pipe, or air through an orchestral flute.

Catastrophic Eruptions

Plumes *do* sometimes emerge into our atmosphere with a pressure higher than atmospheric. When this happens, the effects can be truly catastrophic. On May 18, 1980, gas and rock stored at more than 100 times atmospheric pressure in the north flank of Mount St. Helens were suddenly exposed to the atmosphere when the overlying rocks fractured and slid into the drainage of the North Fork of the Toutle River. Because the magma was stored so high in the volcano, pressure on the buried gases and hot rock could not be reduced by the normal processes that occur during ascent of magma through the crust. Instead, the depressurization happened as the flow accelerated across the land. (A similar decompression, although from lower pressure, occurs at the end of a rifle barrel, a geothermal bore or a rocket engine. The effect of varying atmospheric back-pressure can be seen as rockets ascend through the atmosphere: Their trailing plumes become more and more flared because the atmosphere becomes more tenuous and less able to confine the high-pressure gases.)

When the opening through which high pressure gases are released is large, the distance required for decompression of the gases is also large: The gases in the Mount St. Helens lateral blast remained at pressures greater than atmospheric for several kilometers, and over this distance obtained velocities over 100 meters per second. In this region, the forest was blown from the land, soil was stripped down to bedrock, and no life survived.

Because the vent through which the material within Mount St. Helens had to escape opened to the north, the blast was initially directed northward. However, because the gases in this material were at higher pressure than atmospheric, they expanded to both the east and west (as well as upward), and material was spread over the whole sector north of the volcano rather than being restricted to a narrow zone directly in line with the actual vent (see map). The back-pressure of the terrestrial atmosphere, however, kept the blast confined to the northern sector of the volcano, and much of the southern flank was spared the direct effect of the blast (although it was devastated by later ash flows).

***Voyager 1* photographed eruptions of the ionian volcanos Prometheus (top) and Loki (above). Compare the symmetric, umbrella shape of Prometheus with the more irregular shape of Loki. The volcanos of Io are named after gods and goddesses of volcanism on Earth.** Images: JPL/NASA

Dramatic Io

If different ratios of magmatic and atmospheric gas pressures on Earth produce plumes of such different shapes, we might expect quite dramatic effects on Io, where atmospheric pressure is ten million times less than on Earth. If the volcanic conduits on Io were narrow and constricted, when the volcanic gases emerged they would be at much higher pressures than Io's atmosphere. The plumes on Io would look like giant rocket engines or geothermal wells; they would flare outward near the ground, and be diffuse and irregular in structure because of internal shock waves. Loki may, at times, have had such a configuration (see photo).

However, such flaring near the vent of a constricted volcanic conduit would rapidly erode the ground, and a crater would form over the conduit. The high-pressure gases would expand laterally from the conduit into the crater, reducing the plume pressure by many orders of magnitude. Gas could enter the crater at a pressure of tens to hundreds of bars and be decompressed to a millionth of a bar before leaving the crater, if the crater were a kilometer deep. (One bar equals Earth's atmospheric pressure at sea level.)

The trajectories of the volcanic gases and particles are altered by divergence into the crater, and thus, when the gases and particles reach the surface, they are launched obliquely into the atmosphere and follow trajectories that produce the characteristic umbrella shapes of the ionian plumes, rather than the vertical columns of terrestrial plinian eruptions. The plume of Prometheus (see photo) is a good example of such a structure.

What would have happened if Mount St. Helens had erupted on another planet? On Io, Mars or the Moon, atmospheric pressure could not have prevented devastation around the whole mountain. In contrast, on Venus, where atmospheric pressure is nearly 100 times that of Earth, the spread of the blast would have been much less than here on Earth. In fact, we can hypothesize that eruptions on Venus would resemble terrestrial eruptions deep in the ocean, where the pressure of the overlying water suppresses the expansion of volatiles and produces nonexplosive effusions instead of high-velocity plinian eruptions or violent lateral blasts. This comparison illustrates the dramatic effect that planetary atmospheric pressure has on the nature of the catastrophes wrought by volcanos.

Planetary Lessons

We of the 1980's are the privileged first generation of volcanologists who have been able to study active volcanos on two planets. On Earth, truly large, catastrophic volcanic eruptions are infrequent. However, because of the finite probability that an eruption of the size that created Long Valley in California, or the calderas in Yellowstone National Park, will occur within the span of human existence, it is important that we try to understand the behavior of such volcanos — particularly that we try to learn what activity might precede such a catastrophic event.

Perhaps some answers will come to us through studies of the large-scale events on Io. The lessons already learned from planetary volcanology have been numerous: Volcanos are a major safety valve by which planets dissipate their excess heat; atmospheric pressure plays an important role in shaping volcanic plumes; volcanos, in turn, play a major role in determining the composition of the atmosphere, climate and weather. The future holds promise of many more lessons as we await the portrait that Pele is creating for us on Io.

Susan W. Kieffer is a volcanologist with the Branch of Igneous and Geothermal Processes, US Geological Survey, in Flagstaff, Arizona. She studies geysers, the Mount St. Helens volcano, and volcanism on Io.

A Talk With Eugene Shoemaker

What killed the dinosaurs? ***This question has long intrigued scientist and layman alike. Those glamorous reptiles ruled Earth for some 300 million years, and then suddenly disappeared. Numerous hypotheses have been advanced: Rising temperatures overheated their testicles, causing sterility; the recently evolved mammals ate dinosaur eggs, destroying the succeeding generations; newly developed flowering plants gave them hayfever, and they sneezed to death. While many of these ideas were interesting, none was testable, and the debate raged on.***

Then, in 1980, Luis and Walter Alvarez, Frank Asaro and Helen Michel proposed a new, testable hypothesis: An asteroid had collided with Earth, and this catastrophe had killed the dinosaurs. Earth's history is divided into eons, eras, periods, epochs and ages, based primarily on fossil types found in sedimentary rocks. The boundary between the Cretaceous and Tertiary Periods marks the end of the dinosaurs' reign on Earth. At precisely that boundary, Walter Alvarez found a very interesting piece of rock that may have unlocked the puzzle of the dinosaurs' disappearance.

In this interview with our editor, Dr. Eugene Shoemaker of the United States Geological Survey tells the story of the asteroid and the dinosaurs for readers of The Planetary Report. Dr. Shoemaker is one of the premier planetary scientists, a leading expert on asteroids, comets and craters. He is contributing his considerable expertise to the question of an asteroid impact with Earth at the time of the Cretaceous-Tertiary boundary.

Charlene Anderson: *Why have some scientists come to believe that an asteroid hit Earth at the time of the Cretaceous-Tertiary extinctions?*

Eugene Shoemaker: The discovery of the evidence leading to that view was serendipitous. Walter Alvarez, a geologist from the University of California at Berkeley, has for many years studied the geologic structure and tectonics of the central Apennine region of Italy. He became interested in the precise dating of sedimentary beds whose ages span part of the Cretaceous and Tertiary Periods. He worked with Italian paleontologists and geologists from Princeton on a beautiful sequence of exposed sedimentary layers along a road cut near the medieval village of Gubbio.

Walter's father, Luis Alvarez, a Nobel-Prize-winning physicist, is also on the faculty at Berkeley. Luis Alvarez was in charge of a seminar at the Lawrence Berkeley Laboratory, and he invited Walter to talk about the work he had been doing at Gubbio. It happened that Walter had a small specimen in his pocket, a piece of rock with a one-centimeter-thick clay layer sandwiched between two limestone layers. The clay layer marked the precise boundary of the Cretaceous and Tertiary Periods, determined by microscopic fossils. He remarked to the seminar that this clay layer marked a point in geologic time when there had been a major extinction of living species.

This enormously intrigued Luis. To paraphrase, he said that was the dangedest thing he'd ever heard of. He began to wonder what could have happened to produce that catastrophe in the biosphere. His interest focused on the clay layer.

The first question was "How much time does that clay layer represent?" Maybe there was some mechanism that shut off the formation of limestone while the clay was being deposited. The limestone at Gubbio is made up of the skeletal debris of microscopic organisms, the phytoplankton and zooplankton (drifting plants and animals) that live in the surface layers of the oceans. If you wiped them all out, you would stop limestone production. If it were turned off for a long period of time, clay carried to the ocean by streams and by wind might have been slowly deposited to form the one-centimeter layer.

There was a rather neat way to determine the length of time represented by the clay layer that the people at the Lawrence Berkeley Laboratory could bring some special expertise to. Extraterrestrial particles steadily fall onto Earth, from sporadic meteors, shower meteors and zodiacal dust, and they contribute to the ocean floor sediments. You can recognize the signature of the cosmic infall by trace elements that are relatively abundant in meteorites but severely depleted in Earth's crust.

Now the siderophile elements — the "iron lovers" such as gold and platinum — are enormously depleted in Earth's crust compared with their normal abundance in the solar system. As Earth's iron core formed, they were extracted into the iron down there. So the siderophiles are down deep in a region we don't get to see — that's why some of them are so valuable. The normal abundance of these noble metals in meteorites is about 10,000 times greater than normal Earth-crust abundances. So these noble metals are nice tracers for cosmic material. And of all the noble metals, the one that is easiest to measure in small concentrations is the element iridium, one of the platinum group.

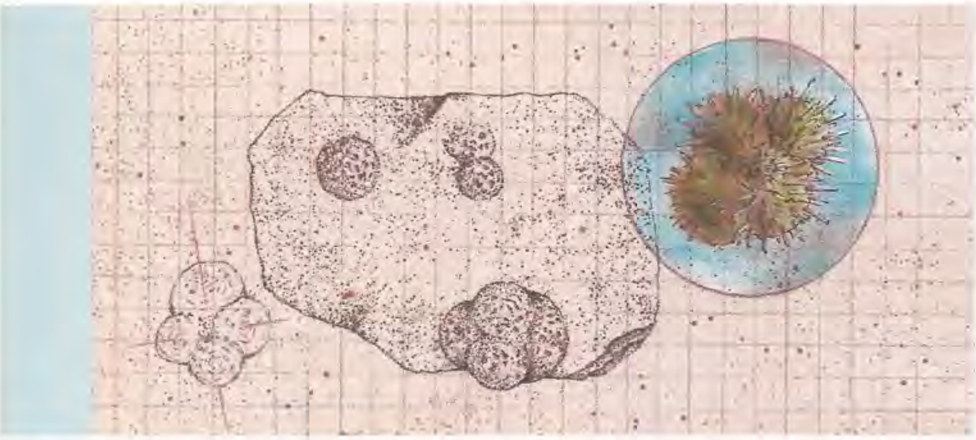
Luis and Walter, along with two radiochemists at the Lawrence Berkeley Laboratory, Frank Asaro and Helen Michel, decided "Let's measure the iridium content in the Gubbio clay boundary. This will tell us how much cosmic material fell into the ocean while the clay was being deposited, and will give us a measure of the time it took the clay to form, since we know the infall rate for more recent geologic time."

Well, they found vastly more iridium than they expected. That meant either there was a big interval of time missing in the sedimentary record, or there had been some unusual source of iridium. The former possibility could be eliminated because they knew, from the fossil record, that a nearly complete sequence of strata was present at Gubbio. The clear implication was that there was some unusual source of iridium.

CA: *What were the possible sources?*

ES: One of the hypotheses for the extinction of the dinosaurs, put forward many years earlier, was that there had been a supernova explosion in the neighborhood of Earth. That could indeed yield a flux of iridium and other noble metals onto Earth. But if that were the source, one would expect that there would be isotopic differences between noble metals from a supernova and those from the solar system. The Berkeley group made a quick check of the isotopic composition of one of the noble metals extracted from the clay layer and found that it looked like solar system material. Besides, it is unlikely that a supernova could occur close enough. So the supernova possibility could be eliminated.

That left one really attractive alternative: instead of the normal flux of cosmic material, a big slug of it might have come in all at once from one big object. And this was the hypothesis that the Alvarezes, Asaro and Michel unveiled at a national meeting of the American Association for the Advancement of Science in San Francisco, and published in a 1980 paper in *Science*. They described the iridium enrichment at three localities in Italy, Denmark and New Zealand, and their hypothesis that it was due to the impact of a substantial extraterrestrial body.



Many types of planktonic foraminifera (above), all of the ammonites (far right) and the dinosaurs (below) became extinct 65 million years ago at the boundary of the Cretaceous and Tertiary Periods.

Illustrations: S.A. Smith

The newspapers picked up the story immediately, saying that a meteorite or an asteroid had caused the extinction of the dinosaurs. Of course, the Alvarez team was not talking about the dinosaurs directly; they were talking about the extinction observed in the microscopic marine organisms, the phytoplankton and zooplankton, and also the extinction of some of the larger marine organisms. Ammonites, for example, suddenly disappeared precisely at this clay layer. I have personally picked out ammonites from immediately beneath the boundary clay layer at Stevens Klint in Denmark, and that's the last of the ammonites. But it's also true that, in correlating continental deposits with marine deposits, vertebrate paleontologists have long used the extinction of the dinosaurs to mark the end of the Cretaceous. Walter Alvarez knew this quite well, and it was mentioned at the AAAS meeting. So it was reported in the newspapers that an asteroid caused the extinction of the dinosaurs.

CA: *How would an asteroid impact have affected Earth and caused the extinctions?*

ES: The Alvarez team offered an hypothesis that the clay layer represented high-velocity ejecta from the crater formed by the asteroid impact. They imagined that an enormous amount of material was injected into the atmosphere and carried worldwide by atmospheric circulation. They noted that if this amount of fine particles, represented by one centimeter of clay, were carried up into the atmosphere it would make the atmosphere opaque to sunlight. Therefore, it would have been dark at Earth's surface for a substantial period of time, perhaps a year. This would have suppressed photosynthesis and essentially stopped the food chain at its base. Animals would have died of starvation. We have jocularly come to call this particular model the "darkness at noon" hypothesis.

It's apparent, however, that this is only one of many possible effects. There were some difficulties with the original hypothesis. For example, how could that much material be distributed globally by normal atmospheric circulation? Solid particles would fall out too fast, and the clay layer ought to be thickest near the source. Later work by Eric Jones and others at the Los Alamos National Laboratory suggested that, when you make a giant crater, you get a huge fireball. If the fireball were big enough, it would burst right out of the top of the atmosphere. The particles entrained in the expanding fireball would be distributed around Earth on ballistic trajectories.

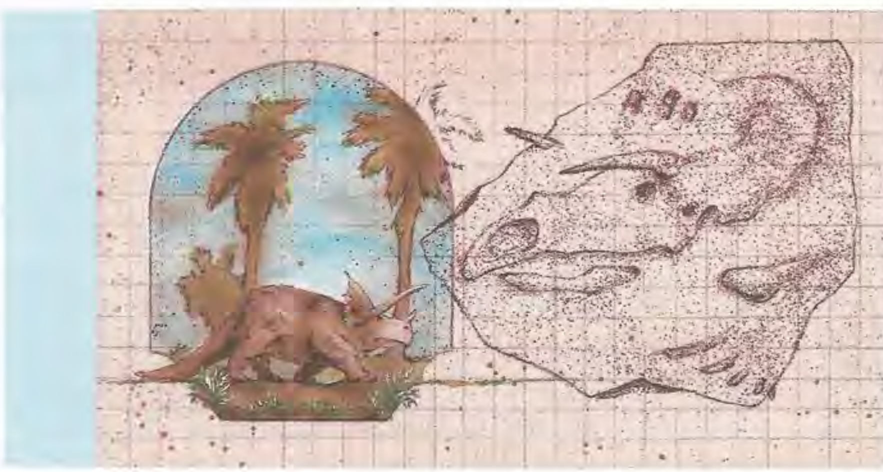
Other people, such as Brian Toon and his colleagues at Ames Research Center, have made a special study of dust-settling times. Their best estimates suggest that most of the dust would have settled out in only a few months. Now, there is a problem, even if the dust were up for only a few months, in the survival of some microscopic organisms. There have been some interesting experiments carried out by David Milne, among others, that show the atmosphere has to clear fairly quickly or you will have a problem explaining the survivors.

CA: *How dark would it have been after the impact?*

ES: In the first few hours, it would be totally black on the surface of Earth — except for lightning bugs or whatever else makes their own light. If it stayed dark very long, it would get very cold.

There are several other possible consequences to this event. One, pointed out by Cesare Emiliani, Eric Kraus and myself, was that if the impact occurred in the ocean — and I think that there is good circumstantial evidence that it did — it would inject a large amount of water vapor into the atmosphere. The amount of water vapor would be so large that the atmosphere could not hold it all, and most of it would promptly precipitate out. But it would saturate the stratosphere, which is normally very dry, so that even after the atmosphere had cleared there would be an unusual water vapor content in the stratosphere.

This would produce a partial barrier to infrared radiation emitted from Earth's surface. Several positive feed-



back mechanisms would enhance this effect. An infrared barrier introduced in the upper atmosphere would make the troposphere warmer. It would warm the ocean surface, making the troposphere more humid, thereby increasing the greenhouse effect. That would release carbon dioxide from the ocean surface as it warms up, further enhancing the greenhouse effect. This might raise the average temperature ten or more degrees Celsius, above a level at which many organisms could survive. We suggested that this effect could last much longer than the dust, and many life forms could have been killed by hyperthermia.

Another suggestion was made by Kenneth Hsu: The atmosphere might have been contaminated by poisonous components of the impacting body. He was thinking of a comet that would have poisoned Earth with cyanide. I think he has since thought better of that idea, because the cyanide would decompose with the shock of impact.

John Lewis, then at MIT and now at the University of Arizona, and his colleagues pointed out another thing: The fireball would make an enormous quantity of nitrogen oxides (NOx) which promptly oxidize to NO_2. That would have made the original acid rain.

Impact of a large body (about 10 kilometers in diameter) could certainly cause an environmental catastrophe. First there is darkness at noon. When the atmosphere clears, there could be a prolonged thermal pulse. The atmosphere could have been contaminated with poisonous trace metals. And there is acid rain. On top of all this was a major extinction of species at the end of the Cretaceous, so the ecological balance was dramatically changed.

It's very interesting that the whole business of nuclear winter (*see pages 20-21*) has since been proposed. It was stimulated, at least in part, by recognition of the Cretaceous-Tertiary event. Some scientists began to wonder what would happen if you put smoke and dust into the atmosphere as a result of nuclear war. In particular, people became concerned about the effects of optically active particles, such as you find in smoke. There are some significant differences between a nuclear winter, which would depend primarily on smoke particles, and an impact winter, which would depend on rock particles. But there is a close relationship between predicted atmospheric effects of a nuclear war and an impact catastrophe.

CA: *Have iridium anomalies been found at the boundaries of any other eras?*

ES: There are about half a dozen other extinction events of a magnitude comparable to the Cretaceous-Tertiary event. We have an abundant fossil record for about the last 600 million years, and there have been big extinction events about once every 100 million years, on average. The granddaddy of all recognized extinctions is at the Permian-Triassic boundary (245 million years ago) at which time more than half the living families became extinct; this means that at the genus level the effect was immense, and at the species level, extinction was extraordinary.

People have searched for a noble metal anomaly at the Permian-Triassic boundary. The difficulty is that sea level was very low at that time, so there are very few places on Earth where we have a continuous record of deposition. One region where the boundary appears to be continuous is in China. Very early in the game, the Alvarez group, working with Chinese colleagues, got samples of a clay layer at the Permian-Triassic boundary and found nothing.

Carl Orth of the Los Alamos National Laboratory has carefully examined the Ordovician-Silurian boundary (435 million years ago) and the Cambrian-Ordovician boundary (500 million years ago), both well-known extinction boundaries. So far, he's had negative results.

Philip Playford has been working on ancient reefs and rocks of Devonian age in the Canning Basin of Western Australia. He took samples from the Frasnian-Famennian boundary (365 million years ago), which corresponds to one of the great extinctions. Orth and his team analyzed these rocks and found a spectacular noble metal anomaly. But this situation is a little sticky: There is no clay layer, and the anomaly is found in limestones with fossils of an iron-precipitating cyanobacterium, or blue-green alga, known as *Frutexites.*

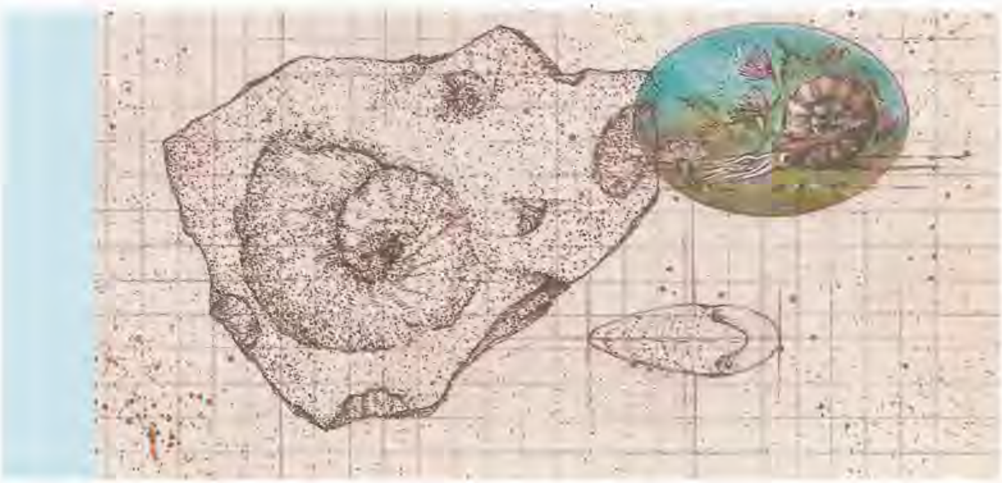
CA: *So the bacteria could have concentrated the noble metals into the rock?*

ES: If you take the rock apart, you find little branching structures called stromatolites, built by the cyanobacteria. If you compare the stromatolites with the surrounding matrix of limestone, you find that the noble metals are concentrated in the fossil stromatolites.

So the question is, is this phenomenon simply a biological concentration of these elements from seawater, or was there an anomalous source for the noble metals? There's no doubt that the *Frutexites* concentrated these elements. It's remarkable that *Frutexites* is found in only one place in the Devonian section, essentially at or very close to the Frasnian-Famennian boundary. All of these things together lead me, as a bystander, to suspect that these associations are not just funny coincidence, but that there is a causal connection between the mass extinction, the occurence of *Frutexites* and the noble metal anomaly. This may be the signature of an impact event. I would say that, at the present time, the search for evidence of large-body impacts associated with extinctions comparable that of the Cretaceous-Teriary boundary has been unsuccessful, with one possible exception.

Another obvious place to look for an iridium anomaly is in a layer of deep ocean sediments of very late Eocene age that contain microtektites (Microtektites are small bits of glass, found in sediments, and possibly associated with meteorite impacts.) Late Eocene microtektites have been traced around the world by a man named Billy Glass — quite a name for a person who studies glass, which is what these microtektites are. Glass was able to trace a late Eocene microtektite horizon in deep sea cores from the Gulf of Mexico and the Caribbean across the Pacific and into the Indian Ocean. He once thought that this event was precisely at the Eocene-Oligocene boundary (37 million years ago), but more detailed work has shown that the event is a little earlier in the Eocene.

Microtektites have since been found in the Atlantic Ocean by Gerta Keller, working on sediments with abundant fossils of little beasties called foraminifera. This discovery showed that the late Eocene microtektites are globally distributed. We know from other evidence that microtektites are signatures of major impact events. So you might expect that there would be an iridium ano-



maly associated with them, and indeed there is. It now appears that there is more than one microtektite horizon in the very late Eocene, and work is being done to find out if there are noble metal anomalies associated with different microtektite horizons.

CA: *Is there a periodicity to these impact events?*

ES: That has been the hot new topic for 1984, and it came out of a very careful piece of work by David Raup and Jack Sepkoski at the University of Chicago. They analyzed the record of extinctions of families of organisms over the last quarter billion years. They concluded that there have been about twelve mass extinctions during this time which seem to have recurred with a period of about 26 million years.

Now, if you accept that the extinctions are periodic, the next question is: "What in the world could cause such periodicity?" If you look at the record of determined ages of impact craters on Earth, many appear to coincide roughly with the mass extinctions identified by Raup and Sepkoki. So, there is some reason to think that there is a connection between surges in the impact rate and mass extinctions.

A number of people have now entered the fray. Some astronomers said, "One way you could get a periodic surge in the impact rate is if the Sun had a companion star." One team of scientists went so far as to offer a name for this star: Nemesis. But there are some severe difficulties with this hypothesis because of the large orbit required to account for the very long orbital period of 26 million years. At the farthest point in its orbit, this companion would be almost as far away as Proxima Centauri, our Sun's nearest known stellar neighbor. It would be so weakly bound to the Sun that small perturbations from passing objects could cause it to drift away. I have carried out calculations with my colleague Ruth Wolfe, and found that there is less than one chance in a thousand that the postulated companion star, jocularly called the "Death Star," has a long enough lifetime and an orbit stable enough and eccentric enough to do what it is advertised to do.

CA: *Such a star might not affect the asteroids, but couldn't it affect the comets out in the far reaches of the solar system?*

ES: What we are talking about now is the comet cloud surrounding the Sun. In 1950, Jan Oort showed that, if you traced the trajectories of these very-long-period comets back before their encounters with planets, you can find the region from which these comets are coming. The comets in this region can be shown to be uniformly distributed around the Sun in an enormous halo that has since been called the Oort Cloud.

Many people have thought that there might be an even more massive reservoir of comets inside that halo. My own work with Ruth Wolfe has shown that, if comets originated as planetesimals (small clumps of solar system material) of the planets Uranus and Neptune, and I think they did, then there should be a massive inner reservoir of comets, and the Oort Cloud is its outer edge. Rare close encounters with passing stars would perturb the inner reservoir and produce showers of comets in the inner solar system.

Now the question is: "Are there periodic comet showers?" If the showers are only caused by passing stars, it's difficult to see how this could be anything other than random occurrences. But if we look at the apparent clustering of impact crater ages over the last 150 million years — not the quarter billion years analyzed by Raup and Sepkoski — there does seem to be an association of crater ages with the times of mass extinctions. However, the period I get is 33 million years, not 26 million.

That is an interesting number, which turns out to be the best estimate of the period for the Sun's crossings of the galactic plane. (The galactic plane is an imaginary plane drawn through the flattened disk of the galaxy, where most of its matter is concentrated.) As pointed out in a very important paper by Rampino and Stothers, this could be the clock that has controlled the apparent periodicity in mass extinctions. One then asks: "During crossings of the galactic plane, what could stimulate periodic comet showers?" It can't be stars; they're not sufficiently concentrated near the galactic plane. I think it could only be small interstellar clouds of gas.

CA: *When can we expect the next comet shower?*

ES: I claim that we may be in a very weak comet shower now. We are in a period when we are probably seeing a larger than average comet flux. The Sun has just passed through the galactic plane in the past million years. If we start counting at the present and go backwards, 33 million years puts us pretty close to, but not precisely, at the late Eocene extinction peak of Raup and Sepkoski. If we go back 33 million years more, it puts us almost right bang on the Cretaceous-Tertiary boundary. Moving further backwards, the next galactic plane crossing puts us back to the mass extinction at the Cenomanian-Turonian boundary (91 million years ago). There seem to have been two significant extinctions rather closely spaced about that time. A modest search has been made for an iridium anomaly at this boundary, so far without success. But there are some crater ages fairly close to that time.

I think we are seeing two effects from comet showers. First, there is the incoming flux of long-period comets from the comet cloud. Second, there is an enhancement in Earth-crossing asteroids, which are probably mostly extinct comets. A few comets stray into long-lived orbits and decay into asteroids. This spreads the effect of the comet showers out over time. The surge in the impact rate is spread out over some 10 million years, or a substantial fraction of the 33-million-year cycle.

CA: *One paleontologist told me he thought this asteroid hypothesis was "a lot of hooey" at first, but he has now changed his mind.*

ES: It's interesting to see what has happened in the last four years since the Alvarez team's paper was published. When they first heard the hypothesis, most of my colleagues reacted with scorn. But as they became aware of the facts of the case, many gradually warmed to the idea. There has been a steady conversion to the impact camp.

You must remember that many paleontologists, particularly those who studied the Cretaceous-Tertiary boundary, had their own pet hypotheses, which they are not likely to abandon until the evidence is overwhelming. They will be convinced only if we can document many different large impact events and show that they are related to mass extinctions. I believe that we are going to find other good cases. This is a brand-new field of inquiry and will take a lot of hard work.

On the other hand, I have to say that if, after that hard work, the Cretaceous-Tertiary impact turns out to be a unique event, the importance of impacts to the phenomenon of extinction will not be as great as some of us now think.

Impacts could turn out to be a minor part of the story of evolution, or they could be a driving force in speciation (the evolution of new species). There is a more-or-less steady background rate of extinction, and a background rate of speciation. Then there are surges of speciation following mass extinctions. No one is suggesting that the background rate is related to impact; that would be a silly point of view. What we are talking about is whether major impact events — global catastrophes — may have been major drivers of evolution.

No one has understood mass extinctions up to now. It may well be that we are onto the key. If mass extinction rates turn out to be truly periodic, as I suspect they will, then we suddenly have a very interesting and powerful approach to understanding evolution. □

News & Reviews

by Clark R. Chapman

There are two major weekly science magazines in the English language. *Science* is published by the American Association for the Advancement of Science and is available in many public libraries. Also widely available is the British magazine, *Nature*. Unlike the popular science magazines that I usually discuss in this column, these two publications are written for scientists and others interested in up-to-date technical information about scientific developments. But both magazines are more accessible to the layperson than are most technical journals. Since they cover the full breadth of science, from sociology to biology, from technology to physics, the technical articles are edited to be understood by readers from many different disciplines. While the reports are not free of jargon, there are at least editorial attempts to *define* the jargon. Both magazines also carry popularly written perspectives on various research topics of current interest. And they carry book reviews and news about the politics of science.

The technical articles are never long and they frequently report major scientific discoveries. Instead of waiting in the editorial and publication queues of specialty journals, most of which delay publication for a year or more, articles can be published in *Science* or *Nature* within several weeks, if they are deemed to be sufficiently important. Therefore many scientists, including astronomers and planetary geologists, submit their most important reports to these rapid-publication magazines, and you can follow developments in your local library. Earth-shaking discoveries are rare in science, however, so many of the reports in *Science* and *Nature* simply describe another brick on the wall in the construction of new scientific paradigms. Some planetary science articles in recent issues of *Science* and *Nature* are examples of such methodical progress, albeit on topics of great interest.

This picture provides the latest news about Halley's Comet, which was doing fine somewhere out there. It appeared in the sky near Betelgeuse (the red star in Orion), when I observed it on Halloween using a CCD (charge-coupled device) camera attached to the 88-inch telescope on Mauna Kea, Hawaii. Three exposures are superimposed; the three faint dots in a row, labelled "Halley," show the comet's motion. Fainter than 20th magnitude, Halley still requires a large telescope to be seen. This will change by late this year, when the comet will become visible with the unaided eye.

Triton and Pluto

In the September 27th issue of *Nature*, William McKinnon discusses the origins of Neptune's large moon, Triton, and of the planet Pluto. Recall that Pluto is an unusual planet in an elongated orbit that actually crosses inside the orbit of Neptune. Considering the size of its large nearby moon, Charon, Pluto is most properly considered as a small double-planet. Triton is larger than Pluto (about the size of our own Moon) and is particularly remarkable because it orbits Neptune in a *retrograde* sense – clockwise when viewed from the north, opposite to the direction in which the planets revolve about the Sun and in which most other planetary satellites orbit their primaries.

Nearly half-a-century ago, the British astrophysicist R.A. Lyttleton proposed that the peculiar orbits of Triton and Pluto could be due to the same cause: dual formation in orbit around Neptune, followed by a close gravitational encounter between the two, which ejected Pluto into an independent orbit about the Sun and "flipped" Triton's orbit. McKinnon assembled some of the more recent ideas about Pluto and Triton, made a few calculations, and concludes that Lyttleton's ideas won't work. He proposes, instead, that Triton was captured as a satellite of Neptune from a once independent orbit. Shortly after capture, the tidal interactions between Neptune and Triton would have produced a "spectacular" melting event on Triton, according to McKinnon, which might explain the unique surface of that satellite. (It is thought that much of Triton's surface may be immersed in an ocean of liquid nitrogen.)

Ionian Volcanism

A team of scientists from the University of Hawaii and the Jet Propulsion Laboratory has been using NASA's Infrared Telescope Facility atop Mauna Kea to map the distribution of "hot spots" on Jupiter's weird moon, Io. Since the original theoretical predictions of energetic volcanism on Io, published in *Science* in 1979, and following *Voyager's* two brief visitations that same year, all follow-up work on Io's remarkable sulfur-volcanism has had to be done with ground-based telescopes.

Torrence Johnson and his Hawaii/JPL colleagues conclude that most of the thermal energy output from Io is coming from a very few hot spots on Io, perhaps only two. Indeed, a single feature called Loki may be responsible for *most* of the ionian infrared emission. This is an important result because, under earlier assumptions, the thermal emission near Loki was typical of most provinces on Io, rather than unique. It had been calculated that Io was radiating more heat than is theoretically possible by the heating mechanism proposed in 1979, just before *Voyager* confirmed the volcanic activity on Io. Now we begin to see that Io's volcanic activity may be spotty, in both space and time, and averaged over centuries or millennia it could well be less than the immense radiance of Loki today.

Another article in the October 12th *Science* is the latest contribution by the Alvarezes and their collaborators (see pages 7-10). They offer further proof that the clay layer at the Cretaceous-Tertiary boundary is due to chemical alteration of impact-generated glass, distributed worldwide during the catastrophic event 65 million years ago.

Clark R. Chapman is a research scientist at the Planetary Science Institute, a division of Science Applications International Corporation.

Greenhouses

Climatic Change Continuously Hab Zone Around the

by James F.

Should Earth's climate warm up, the polar ice caps could melt, flooding low-lying cities like London (above). Should it become colder, glaciers could expand outward from the poles, engulfing productive habitats (right).

Paintings: David Hardy (above), Chesley Bonestell (right).

Earth is a nearly ideal ho as we know it. Over most face, temperatures are and liquid water, the elixir of abundant. Our neighbors in system are not so fortunate. V ing 25 percent closer to the Su than an oven (460 degrees C while Mars, 50 percent farth Sun, is colder than an icebo grees Celsius). Neither Venu now has any liquid water, alth planets may have possessed la tities of liquid water in the pas theories suggest that Venus its present hot, dry state as a r runaway greenhouse effect, gravitated toward the opposi extreme: runaway glaciation. tunately, has managed to do these catastrophes. Was Eart lucky to have remained habit throughout its history, or we complicated processes invol writers on this subject did n any fundamental problem in a temperate climate. Earth, t sumed, just happened to have the proper distance from the ceive a favorable amount of s tion. But this static concept challenged in recent years as have learned more about ste planetary evolution.

The Changing Sun

The problem of evolutionary was studied closely by Carl S George Mullen of Cornell Un They pointed out that the Sun ably increased in luminosity b 25 to 30 percent since the sola formed, about 4.5 billion yea The increase has been cause slow conversion of hydrogen helium, an inevitable conseq

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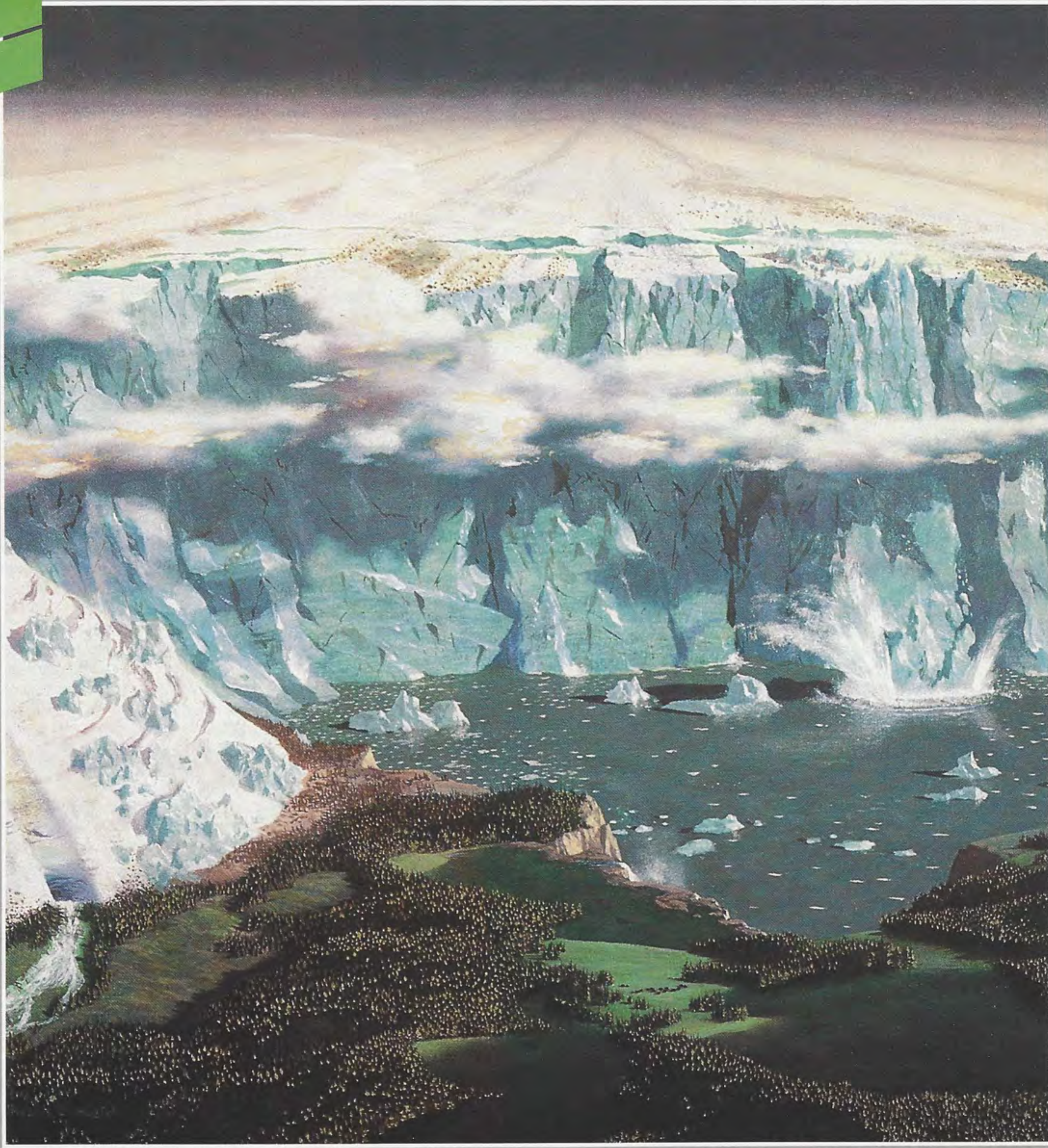


the thermonuclear combustion process that powers stars. As its helium accumulated, the Sun's density increased, leading to higher pressures and temperatures in its core. The higher core temperatures, in turn, cause fusion reactions to proceed more rapidly, so that the Sun now produces energy at a faster rate.

If solar luminosity has indeed increased, it follows that, all other things being equal, Earth should have been much colder in the past. In fact, Sagan and Mullen showed that the oceans would have been completely frozen over, forming a global glacier, prior to 2.2 billion years ago if its atmospheric composition was the same as at present. The geologic record tells us, however, that liquid water has been present on Earth's surface for at least the last 3.8 billion years. This apparent contradiction has come to be known as the "faint young Sun paradox."

An Atmospheric Greenhouse

Speculation about planetary habitability has also been influenced by the discovery of the extremely hot surface temperature of Venus. Venus maintains this hothouse even though it absorbs significantly less solar energy than Earth. The solar flux is 1.9 times higher at Venus' orbit, but the thick sulfuric acid clouds reflect nearly 80 percent of this energy back into space. The amount of solar energy that actually heats the planet is about the same as that available at the orbit of Mars.

The large greenhouse effect of its dense carbon dioxide atmosphere causes Venus' high surface temperature. Its atmosphere contains about 200,000 times as much carbon dioxide as does Earth's. In fact, Venus' carbon dioxide weighs 90 times as much as Earth's entire atmosphere, and has roughly the same weight as all the carbonate rocks on Earth. Most of Earth's carbon dioxide is trapped in these rocks by liquid water, which greatly aids the formation of carbonate minerals.

Venus probably once possessed large amounts of water, perhaps even oceans, but lost it because of a "runaway greenhouse effect." In this condition, the atmosphere grew so hot that the oceans boiled off; their water vapor was dissociated by sunlight into hydrogen and oxygen, and the hydrogen escaped to space. Earth would almost certainly have suffered a similar fate had it formed somewhat closer to the Sun.

A Frozen Wasteland

Networks of channels cover parts of Mars' surface, evidence that this cold, barren planet once possessed large quantities of liquid water. There is, as yet, no consensus on how much water must have once flowed across Mars to create these channels. But estimates indicate that the planet once had enough water to form a layer 10 to 100 meters deep over its entire surface.

So where is Mars' water now? The equivalent of about 0.1 meter of that water is frozen out in the polar caps. Another 2.5 meters or more has probably been lost by photodissociation in the atmosphere; the water molecule breaks into hydrogen and oxygen, and the hydrogen escapes to space. However, most of Mars' water is still there, tied up in a deep layer of permafrost that covers much of the planet's surface. The rest has gone into hydrated minerals. The surface temperature is too low to permit liquid water to exist, so Mars water must be bound up in this manner.

Our planet thus appears poised between two possible climatic catastrophes: runaway glaciation and runaway greenhouse. Because neither of these catastrophes ever occurred here on Earth, space scientist Michael Hart was led to suggest that we live in the Sun's "continuously habitable zone," defined as that region of space in which planetary surface temperatures are never too hot nor too cold to support life.

The Habitable Zone

How wide is this continuously habitable zone? Hart's own projections were extremely pessimistic. By using a computer model which predicted changes in both atmospheric composition and surface temperature, he concluded that the zone extended only from about five percent, or 7.5 million kilometers, inside Earth's orbit to one percent, or 1.5 million kilometers, farther out. Most of Hart's simulated evolutionary sequences ended in one climatic catastrophe or another, leading Hart and others to speculate that Earth may have been exceedingly lucky, and that the chances of finding another habitable planet around any other star were remote.

Hart's analysis, however, was oversimplified. In particular, it did not take into account feedback mechanisms that may have helped to stabilize Earth's surface temperature. One such mechanism leads to the "Gaia hypothesis" proposed by Jim Lovelock and Lynn Margulis. They suggested that Earth's climate has been actively modulated by the biota through the effect of vegetation on the amount of sunlight that the planet reflects back to space and through biological control of the concentrations of greenhouse gases, such as carbon dioxide, methane and nitrous oxide. But the Gaia hypothesis has yet to suggest any practical mechanism by which the biota have actually regulated climate. Also, since different life forms prefer greatly different climates, it is hard to imagine why they should act in concert to maintain the global surface temperature at its present value. Consequently, researchers have been searching for purely physical processes that might have stabilized Earth's climate.

Carbon Dioxide Key

Much of this attention is now focused on atmospheric carbon dioxide. Carbon dioxide has attracted considerable interest in the past decade because of the concern that humans, by burning fossil fuels, may alter Earth's climate. If present trends continue, atmospheric carbon dioxide concentrations may double by the end of the next century, causing a global temperature rise of two to four degrees Celsius. Such a temperature increase may seem insignificant compared to the catastrophic changes caused by a runaway greenhouse or runaway glaciation, but it would nonetheless be large enough to shift precipitation patterns and raise sea level by several meters. This would be enough to flood low-lying port cities, such as London, New York or Tokyo.

We have discovered, however, that there is also a large natural variability in atmospheric carbon dioxide. Chemical analyses of air bubbles trapped in ice cores from Greenland and Antarctica indicate that carbon dioxide levels rose abruptly from 0.02 to 0.028 percent (compared to 0.034 percent today) at the close of the last Ice Age, some 10,000 years ago. On longer timescales, we now have indirect evidence that carbon dioxide concentrations could have been four to six times higher 100 million years ago, when dinosaurs roamed Earth. Eric Barron of the National Center for Atmospheric Research has calculated that the warm climate of that period can be explained only if one assumes enhanced concentrations of some atmospheric greenhouse gas, most likely carbon dioxide.

Geochemical Models

Barron's conclusion is supported by geochemical models developed by Robert Berner of Yale University and his coworkers Anthony Lasaga and Robert Garrels. Over millions of years, the carbon dioxide in the atmosphere and oceans is controlled by interconversions between carbonate and silicate rocks. Carbon dioxide is lost when silicate minerals combine with carbon dioxide dissolved in rainwater as it weathers continental rocks.

The carbon dioxide is carried down rivers as bicarbonate ions and is deposited on the ocean floor as calcium carbonate (limestone). The spreading seafloor then carries these sediments down into Earth's interior, where heat and pressure convert the calcium carbonate back into calcium silicate. Gaseous carbon dioxide released in this process eventually bubbles back to the surface through volcanos.

Berner and his coworkers argue that the strength of this volcanic or metamorphic source of carbon dioxide should be linked to the rate of seafloor spreading, which was much faster 100 million years ago. Their calculations indicate that there was four to six times more carbon dioxide in that ancient atmosphere than there is today.

We can apply this same reasoning to much longer timescales — billions of years — where it may provide a natural solution to the faint young Sun paradox. Increased radioactive heat release in the interior of primitive Earth should have led to faster mountain building and seafloor spreading, and so to an increased metamorphic source for carbon dioxide. Earth at that time had fewer exposed continental rocks, and so less silicate rocks to remove carbon dioxide through weathering.

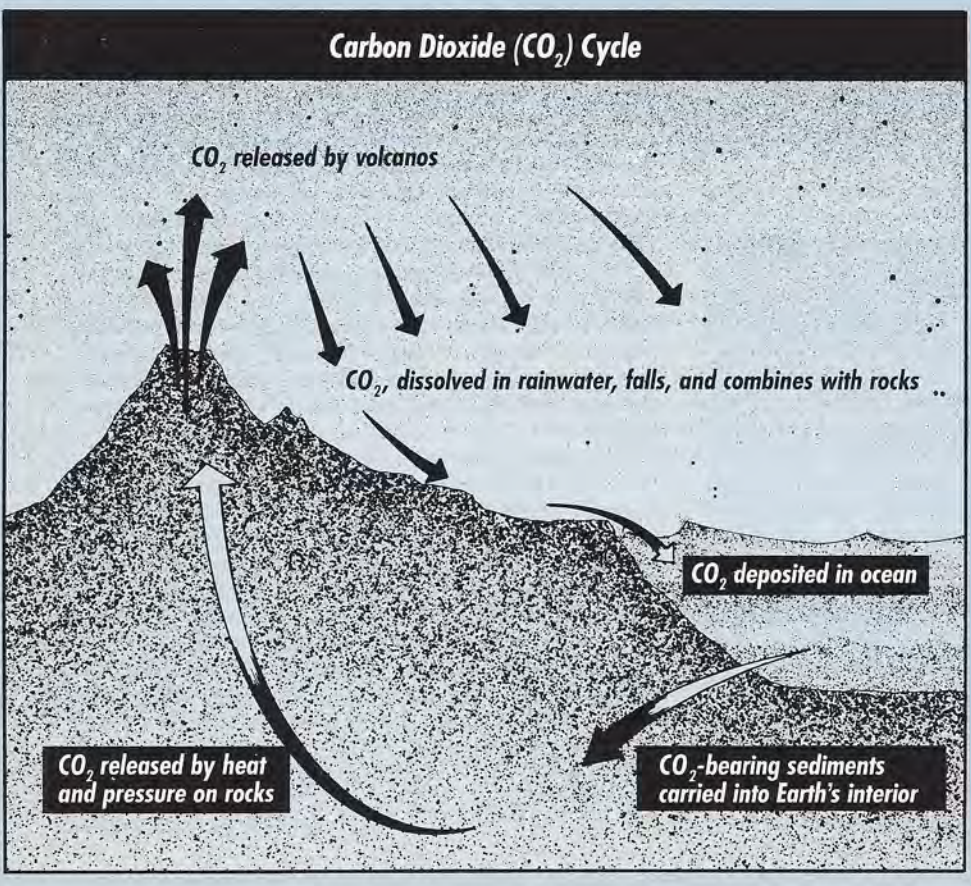
An additional, "quasi-Gaian" factor would have favored high carbon dioxide levels: the absence of land plants, which evolved only 480 million years ago. Land plants pump up soil carbon dioxide concentrations to 30 to 50 times the atmospheric value; hence their absence on the early continents means that atmospheric carbon dioxide levels must have then been higher to keep the rock cycle in balance. During Earth's early history, the atmosphere may have held 100 to 1000 times more carbon dioxide.

Self-Regulating Climate

The carbon dioxide climate-buffering mechanism is also self-regulating. As surface temperatures fall, rainfall and silicate weathering also decrease, so carbon dioxide accumulates in the atmosphere. This surplus carbon dioxide causes greenhouse warming, which offsets the original temperature drop. The converse happens when surface temperatures become too warm: Rainfall and weathering increase, and atmospheric carbon dioxide begins to decline.

If Earth had ever become cold enough for the oceans to freeze over, this negative feedback process would have taken over. The deposition of carbonate sediments would have ceased, and carbon dioxide would have accumulated in the atmosphere as it was released from volcanos. The volcanic release rate is large enough that ice could have covered Earth for only a few tens of millions of years before the carbon dioxide greenhouse effect returned the oceans to their liquid state.

The implications of this carbon dioxide/climate story are encouraging to those who believe that life might exist in other planetary systems. The outermost boundary of the continuously habitable zone for an Earthlike planet may well lie at — or beyond — the orbit of Mars. A planet orbiting farther from its central star ought to compensate for the reduction in solar heating by storing more carbon dioxide in its atmosphere.



Cold Mars

Mars itself is too cold for most terrestrial life — not because it is too far from the Sun, but because it is too small. Mars' internal heat engine ran down early in its history; without active volcanos it has no effective way of recycling carbon dioxide back into its atmosphere. Furthermore, Mars' gravity is so weak that it loses carbon, oxygen and nitrogen compounds to space. (Earth, by contrast, loses only the lightest elements, hydrogen and helium.) The channels on Mars provide evidence of a warmer, wetter climate earlier in its history. Had Mars been Earth-sized, this more equable climate might very well have lasted to the present day.

At the opposite end of the climatic spectrum, we still don't know how much closer to the Sun Earth might have formed without triggering a runaway greenhouse effect. Recent calculations by Richard Lindzen and coworkers at Harvard University, and by James Pollack, Thomas Ackerman and me at NASA's Ames Research Center, have shown that the surface temperature in a warm, moist atmosphere responds very slowly to increases in solar flux. The calculations are not sufficiently refined to provide a reliable estimate for the inner boundary of the continuously habitable zone. They do suggest, however, that Venus could have possessed liquid oceans early in its history, when solar luminosity was lower. Life may have evolved on Venus, only to be wiped out as surface temperatures skyrocketed. Radar on orbiting spacecraft may ultimately reveal the remnants of ancient rivers, lakes and oceans, evidence of a drastically changed world.

Other Planetary Systems?

A wide continuously habitable zone around our own Sun does not necessarily imply that all planetary systems should contain habitable planets. Stars that are more massive than the Sun emit more of their energy as biologically harmful ultraviolet radiation; this might make even their more distant planets unhealthy places to live. The continuously habitable zones around smaller stars would be closer in. But planets within these zones could have their rotations slowed to a halt by tidal drag, which could also be climatically disastrous. Even stars otherwise similar to our Sun might not have Earth-sized planets in habitable orbits, or they might lack planets entirely. There are so many stars in our galaxy, however, that the chances are good that other habitable planets exist. The question then becomes: Are any inhabited?

James F. Kasting is a space scientist at NASA Ames Research Center, Moffett Field, California. Atmospheric evolution on Earth and the terrestrial planets is his major research interest.

Precessing Worlds

Planetary Spin and Climatic Stability

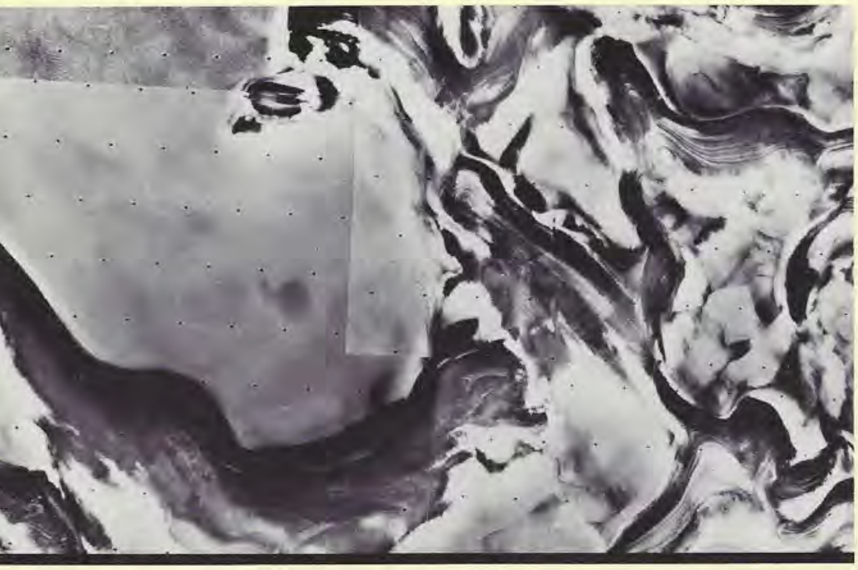
by William R. Ward

The greening landscape of spring, the butterflies in summer, the vibrant colors of fall, the freezing pond in winter – all are manifestations of the tilt of Earth's spin axis. As Earth moves in its orbit, first one hemisphere is tilted toward the Sun, causing summer, then is tilted away, bringing on winter. If our planet's spin axis were perpendicular to its orbital plane, instead of being tilted 23.5 degrees, there would be no seasons. Although climate would still vary greatly with latitude, local weather would be limited to daily fluctuations or storms only a few days long. Earth's yearly revolution about the Sun would no longer be a pacemaker of weather and climate.

Many of Earth's animals and plants have evolved complex life cycles adapted to the seasons. Migration is a common response among animals: Birds fly south in winter, whales cross oceans to feed and breed. Other animals alter their activities: Bears hibernate in winter, salmon spawn in spring or fall. Some even change their appearance: Snowshoe rabbits turn white in winter, deer shed their antlers yearly. Even more apparent are the seasonal changes of plant life, from the falling leaves of deciduous trees in autumn to the myriad cycles of flower, fruit and seed production repeated each year.

The land, too, is imprinted with the annual signature of seasons. The heating and cooling of the ground, together with wet and dry cycles that produce ice in winter and drought in summer, are powerful local erosional mechanisms. Seasonal changes also cause erosion over large areas, as when the melting snow pack causes springtime flooding.

Earth is not alone in experiencing seasons. Mars has a



Changes in Mars' climate, due to its varying tilt and precessing orbit, may be recorded in the layered terrain near its poles. Image: JPL/NASA

similar axial tilt, termed the planet's *obliquity*, of 25 degrees. As far as we know, Mars has no life forms to respond to its seasons. However, the major constituent of its atmosphere, carbon dioxide, can precipitate seasonally as dry ice at its winter pole. Annual changes in Mars' atmosphere-polar cap system have been quite evident in both Earth-based and spacecraft observations. About 25 percent of the tenuous martian atmosphere may disappear into the seasonal ice caps that alternate between the north and south poles over the 1.88 Earth-years it takes Mars to orbit the Sun. Still other important weather phenomena, such as global dust storms, are seasonally controlled.

But just how stable is a planet's tilt? Have the orientations of Earth's and Mars' spin axes changed over time? Will they change in the future? We have found that the tilts of both planets are oscillating. Earth's tilt oscillates slightly, with an amplitude of about two degrees, centered on its present value. Mars' obliquity changes much more, as shown in **Figure 1** showing the past 10 million years. There are epochs during which the tilt may swing by 20 degrees in only 60,000 years. Such periods are separated by relatively quiescent times every 1.2 million years. This latter behavior is a direct consequence of the changing orbital inclination of Mars, also shown in **Figure 1** for comparison.

One agent of change for Earth are the tides raised by the Moon, and to a lesser extent, the Sun. These forces deform Earth as it rotates, dissipating its energy, and slowing the planet's spin. As a result, the days are getting longer by two milliseconds per century, and the tilt is increasing. At the same time, the Moon is receding from us. These changes are slow: The Moon, now about 400,000 kilometers away, will take about 1.5 billion years to drift out another 40,000 kilometers; meanwhile, calculations indicate the Earth's tilt will increase by about three degrees. (The lunar tidal pull is now about twice that of the Sun, but it was much greater in the past when the Moon was closer.) Mars, on the other hand, has only two tiny moons, Phobos and Deimos, both too small to significantly alter that planet's spin. Being farther away from Mars than it is from Earth, the Sun has much less effect on Mars.

Why, then, does Mars' tilt change so dramatically? Planets are not perfect spheres, but bulge out at their equators due to their spin. The Sun tugs on this bulge; these tugs are like the forces acting on a spinning top. If a rotating top is perpendicular to the ground, it simply spins about its axis. But if the top is tilted, gravity pulls on it, and its axis begins to move, tracing out the surface of a cone. This motion is called *precession*. Planets precess for exactly the same reason. For Earth, this motion takes about 26,000 years to complete one cycle; for Mars the precessional time scale is about 175,000 years. We see the evidence of this motion as a shift in the North Pole's position relative to the stars. Navigators would quickly be lost if carried a few thousand years into the past or future because the star now marking the North Pole would appear to have moved.

The planets also pull upon each other, so that their orbits about the Sun undergo similar precessions. If we imagine the orbits as physical ellipses, they would appear to "wobble" slowly around the Sun. The time scales for complete precessional cycles for both Earth's and Mars' orbits are fairly well defined at about 70,000 years.

The overall behavior of a planet's tilt depends on the relative time scales of the spin axis and orbit precessions. **Figure 2** illustrates the combined effect of these two motions. If the spin axis precesses more quickly, its path will "track" the more slowly changing orientation of the orbit. In this case, the tilt will change little in spite of the orbit plane motion. This is Earth's current situation. If, however, the orbit precession is quicker, the spin axis cannot track the orbit pole well, and the tilt can oscillate greatly. This is Mars' current situation.

FIGURE 1

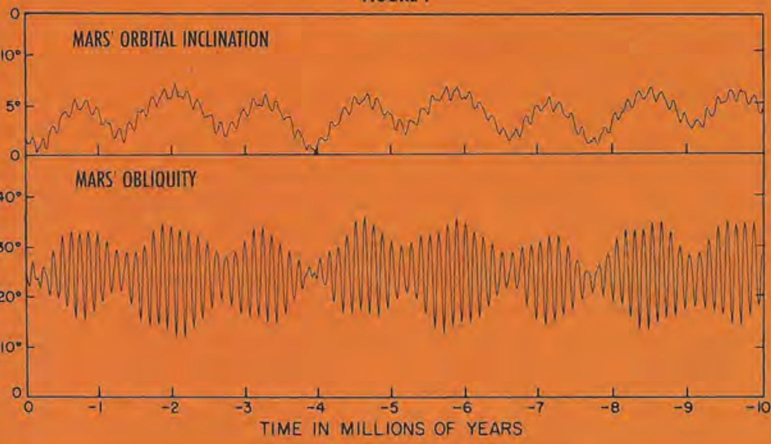


FIGURE 2

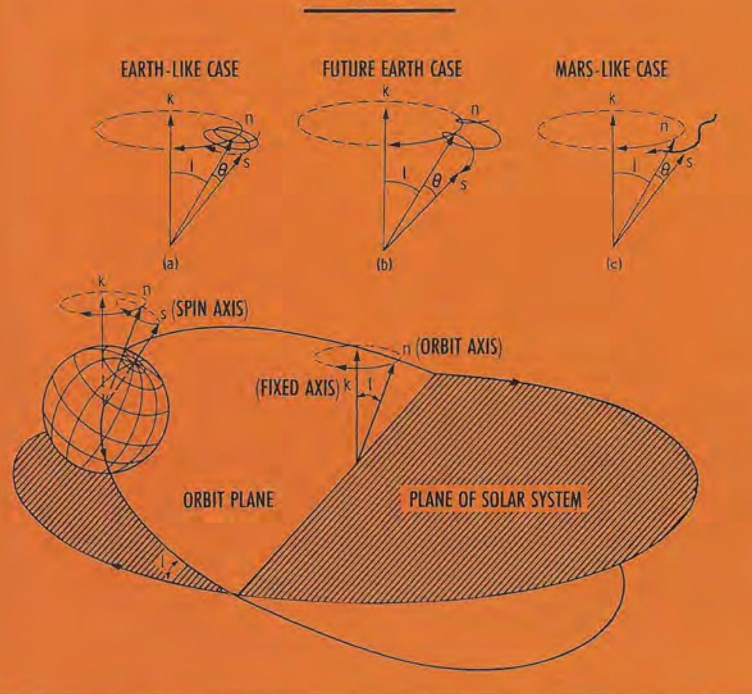


Figure 1. The inclination and obliquity (tilt) of Mars have changed greatly over the past 10 million years. The obliquity undergoes short-term (120,000 year) oscillations as a result of combined spin axis and orbit plane precessions. The longer term (1.3 million year) modulation is a consequence of changes in the orbital inclination. **Figure 2.** This shows a schematic representation of orbit plane and spin axis motions. As the orbit precesses, it maintains inclination, **I**, between its axis, **n**, and a fixed perpendicular, **k**, to the plane of the solar system. At the same time, the spin axis, **s**, attempts to circle the orbit axis. If the spin axis is faster, it can track the moving orbit axis inset (a). This is the current case for Earth, with only small changes in the obliquity, **θ**, resulting. If the spin axis and orbit axis precess at comparable rates, the tracking becomes more difficult and large tilt oscillations occur, as in (b). Earth will approach this case as the Moon recedes in its orbit due to tides. If the orbit axis moves faster than the spin axis, the tracking breaks down, as in (c). This is the case for Mars. (Note: For sake of illustration, **I**, is shown as larger than **θ**, while in the actual applications discussed, **θ**, is the larger angle. However, this does not alter the interpretation.)

The large changes in Mars' tilt cause great variations in the average amount of sunlight falling on a given location. At the poles, the value changes by a factor of two between extremes in Mars' tilt. When Mars has the least tilt, the Sun's rays strike the polar regions very obliquely and they receive little solar energy. The atmospheric pressure drops by 90 percent as the carbon dioxide is frozen into the polar caps. With its atmosphere nearly gone, dust storms and the erosional action of the wind is greatly diminished. The polar regions of Mars may preserve a clear record of such changes in the ice and dust deposits called *layered terrain* that were discovered by spacecraft reconnaissance.

By contrast, Earth's tilt oscillates very little. Nevertheless, the timing of terrestrial ice ages seems to be correlated with changes in Earth's orbit, indicating that even these small variations can produce important changes in Earth's climate. Clearly, changes of the magnitude experienced by Mars would be of tremendous importance were they to occur on Earth. This suggests some important questions: Just how fortunate is our present spin axis stability? Is this situation likely to persist?

A closer examination of Earth's motion leads to the somewhat surprising conclusion that the presence of our Moon accounts for the different behaviors of Earth and Mars. If the Moon were not there, Earth's spin axis precession would take much longer (some 81,000 years), and Earth tracking of its moving orbit pole would be less complete. As a result, Earth would be executing tilt oscillations larger than Mars'!

It may be misleading, however, to claim that we owe our dynamic, and hence climatic, stability to the Moon. During its lifetime, the Moon has slowed Earth's spin considerably. Had the Moon never existed, Earth's day would probably have been shorter. Indeed, tracing the Earth-Moon system back into the past reveals that Earth's tilt was more stable then than it is now.

The real legacy of the Moon is that its tides will someday drive Earth to tilt changes similar to Mars'. As the Moon continues to recede from Earth, the strength of its tidal pull diminishes. At the same time, both solar and lunar tides slow Earth's rotation. Both effects lengthen the spin axis precessional period. This period will become comparable to the 70,000-year orbit precession by the time the Moon has drifted out another 50,000 kilometers. Earth's motion will then be quite complicated, and our planet may be tilted by as much as 60 degrees! It's hard to even imagine the possible effects on Earth's sensitive climate.

But the Moon's orbit is changing slowly, so these events are still 1.5 to 2 billion years away. However, that is less than half the age of the Earth-Moon system, suggesting that, had certain parameters such as lunar mass, or Earth's initial rotation rate, been slightly different, these extreme tilt oscillations would have been experienced long ago. Apparently, past changes in our planet — perhaps continental drift — have prolonged the tidal evolution of the Earth-Moon system.

We have Mars to show us how dramatically the tilts of planets can vary. Clearly, the climatic consequences on Earth would be profound if its tilt were to become as great as Mars'. At Earth's greatest tilt, the Arctic Circle would extend down to about 30 degrees, the latitude of Cairo and New Orleans. Earth's climate would change radically over the hundred thousand to million years of the tilt's oscillation period. These intervals are short compared to the time scales of biological evolution. Under less fortunate timing, such severe oscillations of climate might have impeded (or just possibly, accelerated) the development of the complex life forms that inhabit Earth today.

William R. Ward is a Senior Research Scientist specializing in solar system dynamics at the Jet Propulsion Laboratory in Pasadena. He is also manager of the Planetology and Oceanography Section of the Earth and Space Sciences Division.

World Watch

Europe and the United States Propose Joint Space Ventures

by H. Fechtig

In April 1984, 110 scientists from Western Europe met with 20 scientists from the United States at the European Planetary Science Symposium in Germany. The purpose of the symposium was to discuss a joint US-European space program for planetary exploration.

The possibility of US-European cooperation in space has been under study for several years. In Europe, the Space Science Committee of the European Science Foundation (ESF) under its chairman, Professor Johannes Geiss of Switzerland, sought to coordinate European planetary scientists and strengthen overall European efforts in space science.

Interested space scientists had met in 1980 to discuss mutual problems, document European activities in planetary science, and develop a strategy for future cooperative efforts. The meeting resulted in the ESF report, "Planetary Physics in Europe."

On the basis of that report, Professor Geiss and Professor Thomas Donahue, chairman of the Space Science Board of the US National Academy of Sciences (NAS), decided to study a US-European planetary exploration program. A joint working group of ESF and NAS was then formed to identify and justify missions to planets and primitive bodies (asteroids and comets). From the joint working group, three study teams were established to specifically address the terrestrial planets, the outer planets and the primitive bodies.

Problems to Consider

The joint working group had to take into account the very different situations of planetary research in the US and Europe. NASA has always had a strong and exciting planetary program, while the European Space Agency (ESA) has had no planetary program at all. However, individual European scientists have had many opportunities to cooperate with NASA and other US colleagues. But recently, ESA decided to send a flyby spacecraft to Halley's Comet, giving us in Europe our first opportunity for a planetary science program.

Another difficult problem is the modest ESA budget, which cannot be compared with NASA's budget. This means that the European contribution to joint missions should not exceed $200 million. Exciting new missions to the planets are expensive, particularly missions following the first exploratory spacecraft.

A third constraint to a cooperative effort was that NASA has recently established its own planetary space program, following the recommendations of the Solar System Exploration Committee (SSEC). The joint working group's decision was to propose three supplementary missions to the SSEC program. Following general guidelines, these missions would:

- ☐ deal with scientific questions of the highest priority,
- ☐ involve a broad cross-section of scientific disciplines,
- ☐ be technologically challenging.

Proposed Missions

The joint working group presented its specific proposals to the interested European community at the European Planetary Science Symposium last April. The three proposed missions are listed here in their recommended launch sequence, without priority:

- ☐ Titan Probe and Saturn Orbiter Mission,
- ☐ Multiple Asteroid Orbiter with Solar Electric Propulsion,
- ☐ Mars Surface Rover Mission.

The Saturn-Titan project would be the first extended mission to Saturn following the exploratory *Voyager* flybys. The Saturn Orbiter would orbit that planet and its giant moon, Titan. Its task would be to examine the structure of the planet's atmosphere, its magnetic field and magnetosphere, its ring system and satellites. A probe would be released from the spacecraft to penetrate Titan's atmosphere down to its surface. It would study the composition and structure of the moon's atmosphere, with its clouds, aerosols, lightning and wind. Learning about the nature and composition of Titan's surface would be another important goal. The Saturn Orbiter would be a NASA *Mariner Mark II* spacecraft; the Titan probe would be designed and built in Europe.

Investigating Asteroids

The Multiple Asteroid Mission would be the first dedicated mission to the asteroids, those numerous small bodies orbiting the Sun between Mars and Jupiter. The asteroids appear to be made of several different types of material, reflecting their different origins and histories. The asteroids have been divided into classes based on their composition, and this mission would rendezvous with one representative asteroid of each class. Four to six asteroids would be thoroughly investigated during the mission.

The spacecraft would orbit the asteroids to explore their composition, structure, surfaces and other features. To perform such a multi-rendezvous mission, it will be necessary to use a new type of rocket propulsion. Instead of chemical propulsion, this spacecraft will be electrically powered. The propellant will be mercury or xenon; the atoms of these elements will be ionized and then electrically accelerated up to exhaust velocities of 30 to 50 kilometers per second. These electric engines can operate for several months and therefore can perform complicated trajectories that would be impossible to do ballistically using chemical propulsion.

Exploring Mars

The Mars Rover Mission to softly land two or three robot rovers on Mars is challenging both scientifically and technologically. The rovers would be movable stations capable of covering a few thousand kilometers of martian surface over the one- or two-year duration of their mission. During that time, it would be possible to globally explore the planet Mars and determine its chemical, isotopic and mineralogical composition, and perhaps even determine the age and structure of the body itself. Working with an orbiter, the rovers could study the martian atmosphere. Such rovers could also collect soil samples that could be picked up and returned to Earth by a later mission.

As a next step, NASA and ESA have established joint scientific study teams to pursue these proposals. We should all support this hopeful beginning for a substantial planetary science program involving both Europe and the United States.

Hugo Fechtig is a Director at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany, and a Distinguished Visiting Scientist at the Jet Propulsion Laboratory in Pasadena. He is an active experimenter in space research.

SOCIETY-NOTES

NEW MILLENNIUM COMMITTEE SCHOLARSHIPS

Today's high school students will be spending most of their adult lives in the 21st century. Therefore it is with special pleasure that The New Millennium Committee of The Planetary Society announces a scholarship fund for students planning to pursue careers in space and planetary science.

To be eligible for a scholarship, the student must be a member of the Society, or the child or nominee of a paid member, and in the senior year of high school.

Awards will be made on the basis of: SAT or ACT scores, scholastic achievement, letters of recommendation, accomplishments that demonstrate leadership and creativity, a written essay, and plans for a career in space science.

Deadline for completed applications is April 1, 1985. To obtain an application form, write or call The Planetary Society, Dept. ED, 110 S. Euclid Ave., Pasadena, CA 91010. Phone (818)793-5100.

The New Millennium Committee established the scholarship fund at a meeting following its successful art auction held in Houston, Texas. Chairman of the committee, David Brown, stated "The education of young people, especially in the areas of space science and exploration, is one of the most vital legacies our generation can leave to those who will shape the next millennium."

HANS MARK REJOINS BOARD

Dr. Hans Mark, physicist and space scientist, has rejoined the Planetary Society's Board of Advisors. Last summer, Dr. Mark left his post as Deputy Administrator of NASA to become Chancellor of the University of Texas System. He had resigned from the Board of Advisors when he assumed the NASA post in 1981. During his distinguished career, Dr. Mark has served as Director of NASA's Ames Research Center and as Secretary of the Air Force under President Carter.

Society Executive Director Dr. Louis Friedman commented, "It is with great pleasure that the Officers and Directors of The Planetary Society welcome Dr. Mark back on our Board of Advisors. His rich experience as a scientist, and as a leader of the US space program, will help greatly in our efforts to advocate new missions to explore the solar system."

SPACE CALENDAR

Space Calendar, a weekly newsletter published by Space Age Review, provides an excellent service for professionals in the aerospace community. It gives information about the space program (mainly the "manned" program), and announces meetings, conferences and other events. A synopsis of recent results from various space programs is given in every issue.

The Planetary Society is now joining with *Space Calendar* to improve communication about space exploration. As part of the cooperative effort, Planetary Society members may subscribe to the weekly six-to-eight-page newsletter for $39 for the first year, a $20 reduction. The two-year subscription rate for Society members is $79 — a one-time offer. For information, write to Space Age Publishing Company, Department PS, 3210 Scott Blvd., Santa Clara, CA 95054.

ON TO AMPHITRITE

We were pleased to learn that JPL project management recommended, and NASA has decided, to modify the 1986 Galileo mission trajectory to include an historic flyby of the asteroid Amphitrite (see the September/October 1984 *Planetary Report*). The Society had urged that NASA take advantage of the newly discovered opportunity for the first close flyby of an asteroid — even though it would involve extra cost and effort. Dr. Sagan wrote NASA Administrator James Beggs in July to support the asteroid flyby. In the public interest, the Society presented the case for new exploration to project and science leaders whose recommendations were influential in securing a favorable decision. Many other components of the planetary science community worked very hard on the Amphitrite project.

COOPERATION RESOLUTION SIGNED

Following hearings on Senator Spark Matsunaga's (D-Hawaii) joint resolution to renew the agreement on US-USSR cooperation in space science and exploration (see the November/December 1984 *Planetary Report*), the US Congress unanimously passed the resolution and President Reagan signed it. Society President Carl Sagan and Executive Director Louis Friedman had testified at the hearing, and the Society had submitted a statement citing its policy on international cooperation and its efforts to bring the two countries together for joint space initiatives.

The quick passage of the Congressional resolution was a surprise since the idea of cooperative initiatives, as an alternative to space weapons competition, had been considered controversial. However, the positive aspects of new space initiatives turned out to be a unifying theme in Congress.

The Society recently set up a special fund to promote cooperative initiatives. Members donating $35 or more to the International Space Cooperation Fund are receiving the internal Society report on the recent meeting of Soviet and American scientists, hosted by the Society in Graz, Austria.

MEMBERS — GET MEMBERS

Many exciting things are happening at The Planetary Society. The above Notes mention a few recent successes. Especially important is the international cooperation initiative for new steps in space exploration, which will lead to a renewed effort for manned flight into the solar system. Project META, the multi-channel extraterrestrial assay, an expansion of our Project Sentinel, is now under construction and will begin operation in 1985.

But the strength of the Society is in its members. Starting this year, membership recruitment campaigns will be organized at local levels, as well as nationally. Individual Society members now have an opportunity to provide the leadership necessary to help us grow further. If you want to help, write us at The Planetary Society, Membership Recruitment, 110 S. Euclid Ave., Pasadena, CA 91101.

Intelligence and Catas

The Cosmic Quarantine Hypothesis

by Steven Soter

Why haven't we discovered any extraterrestrial civilizations? If, as many astronomers suspect, our Milky Way Galaxy contains a large number of civilizations far more advanced than our own, why haven't we found any signs of them? To paraphrase a remark made by physicist Enrico Fermi in the 1940's, if the extraterrestrials are so clever, then where are they? The question is not a trivial one. The answer, I believe, will take us to the very heart of the crisis now confronting our own global civilization.

But, first, let us pose Fermi's question in its contemporary form. Our galaxy probably contains more than 100 billion planets. Given the abundant distribution of the necessary chemical building blocks and suitable energy sources, we may reasonably estimate that life might have independently arisen on more than 0.1 percent of those planets during the ten-billion-year history of our galaxy.

And given the powerful evolutionary advantages of intelligence, some fraction of the life-bearing planets will have produced technical civilizations. Even if we take that fraction to be only 0.01 percent, more than 10,000 technical civilizations may have independently arisen during the vast age of our galaxy.

But suppose that even just one of them possessed a strong drive to establish colonies on the planets of neighboring stars, and succeeded in this endeavor. Some of those colonies could, in turn, reproduce by sending out their own colonies, and so on for generations. It is easy to calculate that Earth, and the entire galaxy, should have been swamped by a wave of colonization in only about 100 million years. Why, then, have we seen no signs of extraterrestrials? Is something wrong with the argument?

One might object that very few, if any, civilizations would be motivated to undertake such an enormously expensive project as interstellar colonization. Perhaps. But it seems far more likely that many emergent civilizations will be directed onto such a course by their biologically derived tendencies for exponential growth and territoriality. And it only takes one of them to cross the point of no return. Once the single step between a parent world and a neighboring solar system has been mastered, what remains to stop the colonizing process before it fills up the galaxy?

Chain Reaction

Exponential reproduction coupled with the diffusion of offspring leads to a chain reaction that spreads like a wave. The process would resemble the overrunning of territory by a newly introduced species on Earth. Recall, for example, the settlement of continents and islands by the human beings who evolved in Africa. Or consider how a new viral disease can colonize the human population.

Similarly, once released into the galaxy, alien colonizers could spread among the stars. Over millions of years, they and their machines would probably evolve into many new forms as they diverged into space. But as long as the "gene" for colonization remained strong, whether encoded genetically, electronically or culturally, the colonies would continue to propagate to every favorable planet in the galaxy. Why, then, have no aliens landed on our planet? And even if the colonizers, for some unknown reason, avoided Earth, why have astronomers observed no traces of their existence in the nearby galactic environment? That is Fermi's question in its up-to-date form.

Two very different types of answers have been offered. The first, the Uniqueness Hypothesis, is argued most forcefully by Frank Tipler of Tulane University. He assumes that the evolution of technically advanced civilizations is likely to result in the large-scale colonization of the galaxy. If this has not been observed, it is simply due to the absence of any civilization in the galaxy technically more advanced than ours. If any interstellar colonization is to be done, our descendants will do it. Tipler concludes that extraterrestrials do not exist.

But that answer is too Earth-centered, according to Carl Sagan of Cornell University and William Newman of the University of California at Los Angeles. They offer another solution, which I call the Cosmic Quarantine Hypothesis. It is based on the idea that any civilization with a highly aggressive drive for colonization and exploitation is almost certain to self-destruct long before it can acquire the powerful technology needed for interstellar travel.

Cosmic Quarantine

The Cosmic Quarantine Hypothesis allows for the existence of many advanced civilizations, but recognizes that all of them must pass through a natural selection filter that strictly eliminates, by war, exhaustion of resources or other self-inflicted catastrophes, all those candidates lacking enough wisdom to control their expansive and aggressive impulses. Thus the only civilizations able to survive while possessing the technical potential to swarm over the galaxy are precisely those with no desire to do so. Instead, they have found far better things to do than we may be able to imagine.

Such a cosmic quarantine effect would constitute a permanent, self-activated barrier, preventing undesirables from overrunning and despoiling the galactic neighborhood. Even if it failed to operate in every case, there might still be a powerful backup mechanism to suppress any outbreak of an interstellar plague of colonists: The most advanced civilizations in the galaxy, having no interest in the aggressive exploitation of other worlds, would be strongly motivated to "nip in the bud" any later emerging civilizations that showed signs of launching a campaign of galactic imperialism.

The danger posed by the possibly lethal infection of exponentially reproducing aliens bent on conquering the galaxy would be far too serious to

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ignore. Recent human history suggests how a self-activated cosmic quarantine effect might operate. Our modern technical civilization, however impressive, is still weighed down with the prehistoric baggage of aggressive and expansive behavior patterns. If we do not change our course, this terrible contradiction will almost certainly lead to a self-inflicted catastrophe: nuclear war, exhaustion of resources, environmental collapse or some combination of these. It has probably happened many times before in the history of the galaxy.

I must emphasize that we have not yet even come close to inventing the kind of technology needed for interstellar colonization; it is still too difficult a problem because the stars are so far apart. But the physics of inducing an explosive nuclear chain reaction is relatively easy. That unfortunate fact of nature, combined with our fondness for primitive and obsolete ways of thinking, has allowed us to acquire an extremely efficient means for self-destruction, and for activating the cosmic quarantine effect. There is no doubt that we possess this capability.

Loose in the Biosphere

Nuclear radiation is of the sort normally encountered in exploding stars, but if we are ever foolish enough to let the weapons out of their cages, the radiation will be set loose within the confines of a delicate biosphere. The global nuclear arsenal presently amounts to some 15,000 megatons, the explosive equivalent of one million Hiroshima bombs. That is, if one Hiroshima were destroyed every second, nearly twelve days would be needed to use up the arsenal. In any realistic nuclear war scenario, thousands of these bombs will explode, converting military bases and government command centers into radioactive mushroom clouds, and turning cities into scorched rubble and billowing plumes of smoke and toxic chemicals.

More than a hundred million human beings would be killed outright in the target nations, mostly from the compounded effects of blast, burns and prompt radioactive fallout. Within a few weeks, the soot and radioactive dust would have spread out from the targets to cover the northern hemisphere and, to a lesser extent, the southern hemisphere. As much as 90 percent of the sunlight striking Earth would be unable to reach the surface.

A group of planetary scientists, who observed a similar phenomenon connected with martian dust storms, calculated that this loss of sunlight would in turn cause average surface temperatures in continental interiors to fall by more than 10 degrees Celsius, and perhaps by as much as 35 degrees Celsius, for several months. They call this effect "nuclear winter." To judge the severity of such an effect, compare it with the last Ice Age, when the average global surface temperature was only about five degrees Celsius lower than its present value.

We have long understood that the massive and simultaneous destruction of major industrialized cities and the radioactive poisoning of the global environment could cause the collapse of civilization. Added to this is now the prospect of nuclear winter, which could wipe out most of the survivors, raising the possibility of human extinction.

Learning the Lessons

I believe that, even if we were to do our worst, the human race would probably survive, although reduced to a few scattered bands subsisting at a primitive level in a hostile environment. After a few thousand years or so, their descendants might even revive and rebuild a powerful technical civilization. But if they had not learned any lessons from the nuclear catastrophe, they would be doomed to repeat the cycle. The fundamental incompatibility between aggressive behavior and the possession of powerful technology might knock them back down again, before they could reach for the galaxy.

The cosmic quarantine barrier can be surmounted only by a civilization that adopts and strongly enforces ethical standards compatible with its material power, that always chooses rational thinking over brute force to solve disputes, and that always chooses long-term self-interest over short-term self-interest. That is the intelligence test facing our present civilization.

During the first hours of a nuclear war, smoke plumes begin to rise from the east coast of the United States (left). Several weeks later, Earth is enshrouded in the smoke and dust produced by massive fires and mushroom clouds (above). The radioactive cloud has now spread to the southern hemisphere, blocking sunlight from reaching the surface, and producing nuclear winter. Paintings: Jon Lomberg

Natural catastrophes have threatened life on Earth before. Some 65 million years ago, an asteroid may have collided with our planet and caused the mass extinction of the dinosaurs and many other life forms. The dinosaurs had no warning of the cosmic missile on its collision course with Earth, and in any case, they couldn't have done anything about it. Unlike them, we have had ample and repeated warning, by the wisest members of our human tribe, of a danger of comparable magnitude. And unlike the dinosaurs, we have the power to avert the looming threat because it is entirely of our own making. Nuclear war is by no means inevitable. Perhaps, faced with the prospect of such an unprecedented self-inflicted catastrophe, we humans will choose to break free from the dead hand of the past and change our course.

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(PLANETS AND PERILS/continued from page 3)

have revealed unexpected events upon other planets which, if they had occurred on Earth, would have been truly devastating. Today's Earth might have been a much different place.

Lurking Catastrophes

Our new view of the solar system reveals potential catastrophes lurking in many places. The ground upon which we stand has been torn apart in the past by tremendous volcanic blasts that dwarf the 1980 Mount St. Helens eruption. A volcanic crater 100 miles in circumference forms what is now Yellowstone National Park in Wyoming. When it erupted, dense layers of volcanic ash fell as far away as California and Louisiana. On Jupiter's satellite Io, volcanos erupt so frequently that the entire moon is continually bathed in their debris. The orbits of the planets, instead of being steady and repetitive, can oscillate dramatically. The poles of Mars, for example, bob toward and away from the Sun like some crazy top, causing periodic ice ages that suck away more than 90 percent of the atmosphere to form gleaming polar caps of dry ice. Earth's ice ages are partly due to very similar — but much smaller — oscillations in its orbit. Only a bit of luck involving the position of our Moon saves us from the wild swings exhibited by Mars. Our two nearest neighbors also show us that Earth has been fortunate to have maintained a stable climate throughout its entire history. Venus has suffered a runaway greenhouse effect; Mars, runaway glaciation. Earth, fortunately, avoided these life-threatening fates.

Agent of Catastrophe

Life itself may be an agent of catastrophe. As we examine the factors controlling the destinies of intelligent life in the universe, we find that one of the foremost threats is mass suicide through nuclear war. Unfortunately, we have definite evidence that nuclear war is possible in our solar system. Planetary scientists have recently discovered new phenomena which indicate that such a war might present a hazard to the continued existence of human life on Earth.

In this special issue of *The Planetary Report*, a group of scientists discusses new discoveries about these and other planetary catastrophes. There is excitement surrounding this forbidding topic, partly because these discoveries are so recent, but more importantly, because of the fresh insight they provide about our place in the universe. When we had only Earth to study, our existence seemed inevitable. But now we see better what might have been, and what could eventually be. New, fundamental questions arise: Will we annihilate ourselves? Will the delicate balance of natural forces that stabilizes our environment be maintained indefinitely, and can it be accidentally upset by human interference? What will happen when catastrophic natural events, such as giant asteroid impacts or massive volcanic eruptions, happen again as they have throughout geologic history? Does life in the universe have a less secure abode and fewer places to persist than we thought? These questions are posed here along with our best current thinking on the subject, but definitive answers await future space exploration and an improved understanding of the planets.

Owen B. Toon is a Research Scientist at NASA Ames Research Center, Moffett Field, California. He studies climates of the planets, including Earth's, and is one of the originators of the nuclear winter theory.

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