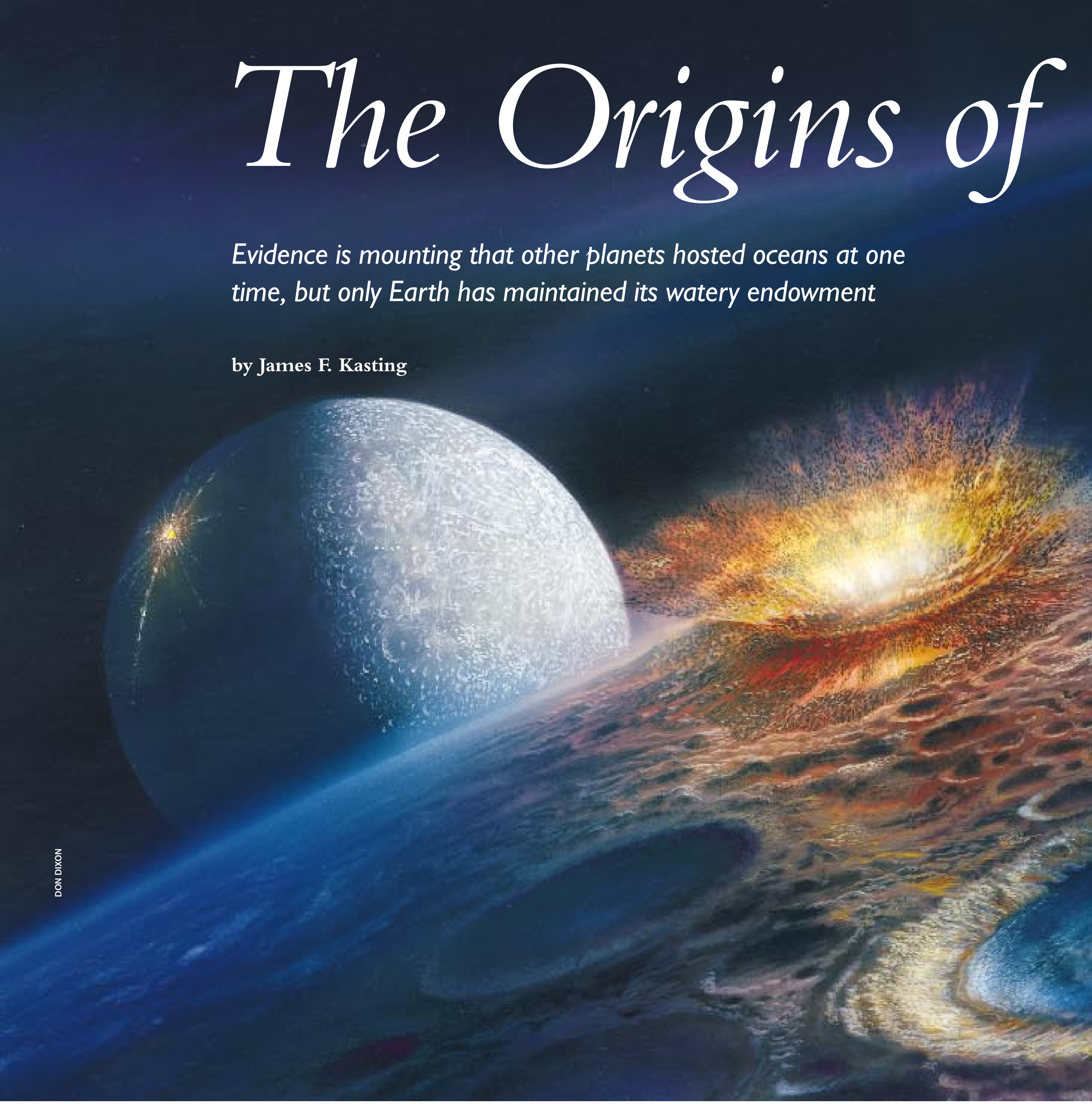
# The Origins of

*Evidence is mounting that other planets hosted oceans at one time, but only Earth has maintained its watery endowment*

**by James F. Kasting**



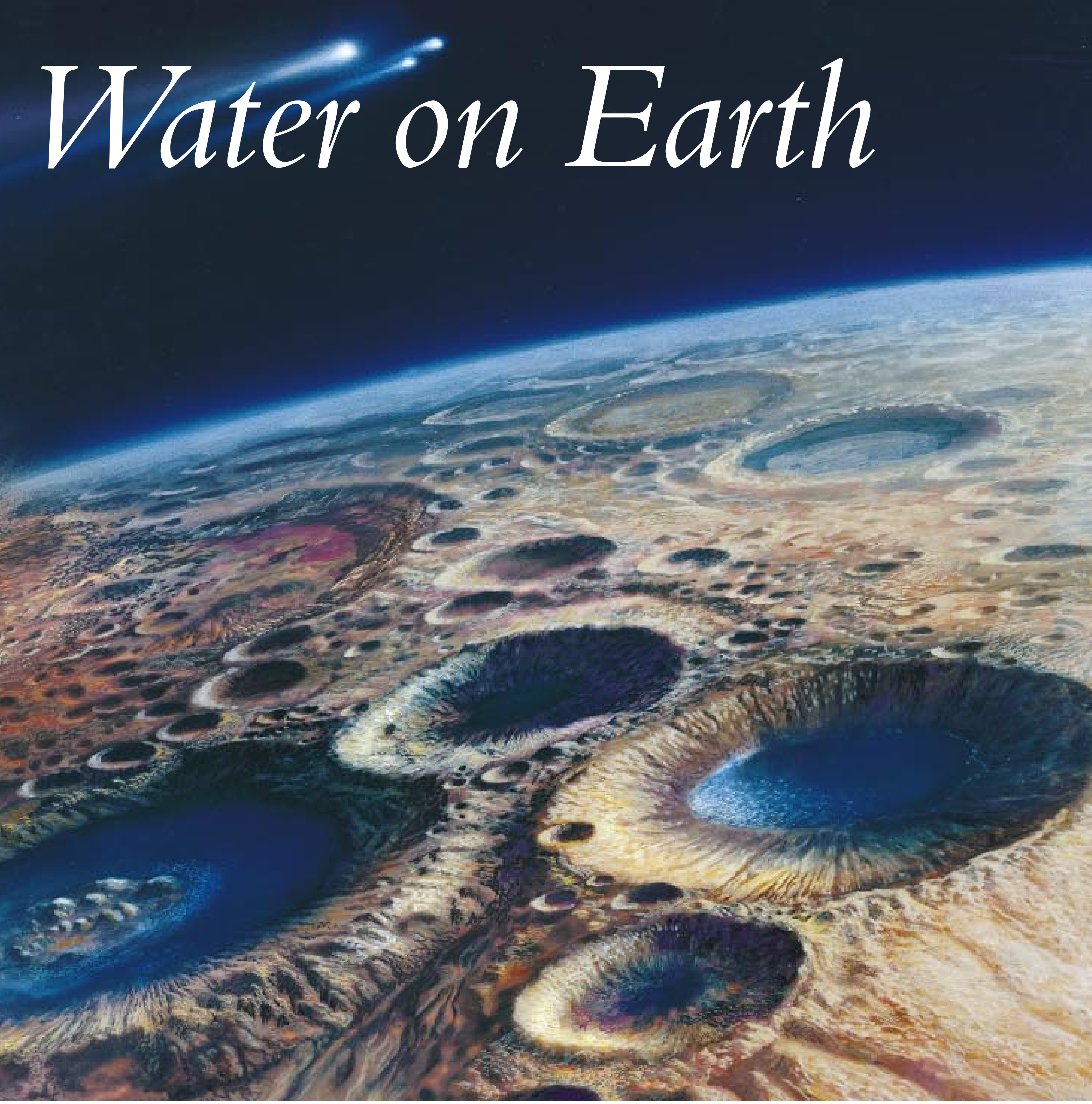
DON DIXON

ICE-LADEN COMET crashes into a primitive Earth, which is accumulating its secondary atmosphere (the original having been lost in the catastrophic impact that formed the moon). Earth appears moonlike, but its higher gravity allows it to retain most of the water vapor liberated by such impacts, unlike the newly formed moon in the background. A cooler sun illuminates three additional comets hurtling toward Earth, where they will also give up their water to the planet's steamy, nascent seas.

Of all the planets in the solar system, why is Earth the only one fit for life? Simple: because Earth has a surface that supports liquid water, the magic elixir required by all living things. Some scientists speculate that forms of life that do not require water might exist elsewhere in the universe. But I would guess not. The long molecular chains and complex branching structures of carbon make this element the ideal chemical backbone for life, and water is the ideal solvent in which carbon-based chemistry can proceed.

Given this special connection between water and life, many investigators

# Water on Earth



have lately focused their attention on one of Jupiter's moons, Europa. Astronomers believe this small world may possess an ocean of liquid water underneath its globe-encircling crust of ice. Researchers at the National Aeronautics and Space Administration are making plans to measure the thickness of ice on Europa using radar and, eventually, to drill through that layer should it prove thin enough.

The environment of Europa differs dramatically from conditions on Earth, so there is no reason to suppose that life must have evolved there. But the very existence of water on Europa provides sufficient motivation for sending a spacecraft to search for extraterrestrial organisms. Even if that probing finds nothing alive, the effort may help answer a question closer to home: Where did water on Earth come from?

## Water from Heaven

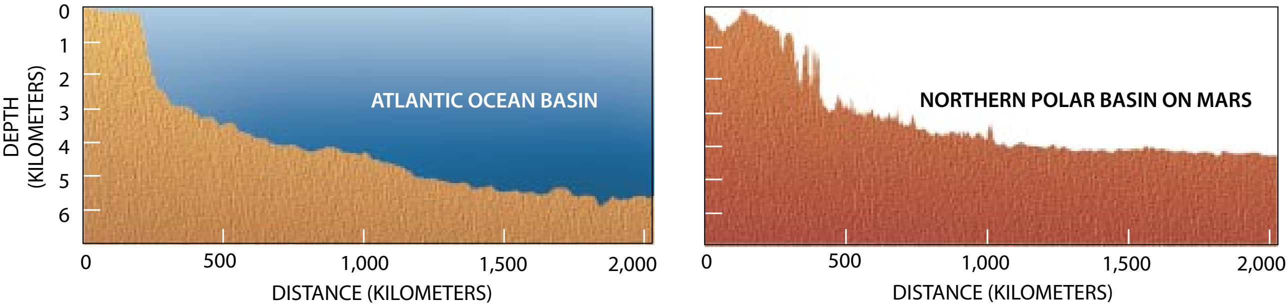
Creation of the modern oceans required two obvious ingredients: water and a container in which to hold it. The ocean basins owe their origins, as well as their present configuration, to plate tectonics. This heat-driven convection churns the mantle of Earth—the region between the crust and core—and results in

BARRAGE OF COMETS nears an end as a late-arriving body hits at the horizon, sending shocks through the planet and stirring up this primordial sea.

the separation of two kinds of material near the surface. Lighter, less dense granitic rock makes up the continents, which float like sponges in the bath over denser, heavier basalt, which forms the ocean basins.

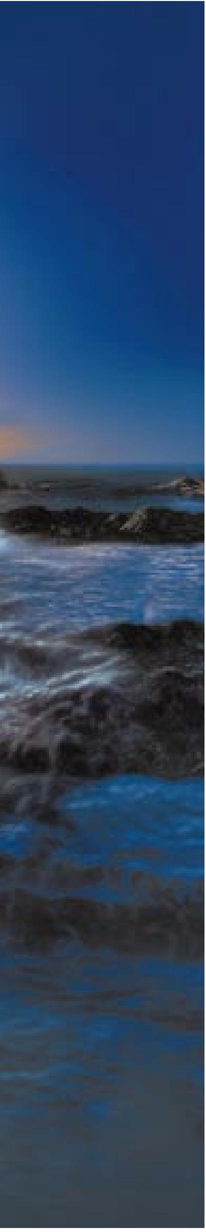
Scientists cannot determine with certainty exactly when these depressions filled or from where the water came, because there is no geologic record of the formative years of Earth. Dating of meteorites shows that the solar system is about 4.6 billion years old, and Earth appears to be approximately the same age. Yet the oldest sedimentary rocks—those that formed by processes requiring liquid water—are only about 3.9 billion years old. This observation proves that at least some water was present on the surface of Earth by that time. But earlier conditions remain something of a mystery.

Kevin J. Zahnle, an astronomer at the NASA Ames Research Center, suggests that the primordial Earth was like a bucket. In his view, water was added, not with a ladle



DAVID SCHNEIDER

TOPOGRAPHIC MAPPING of Mars has recently revealed remarkable similarities to the ocean basins on Earth. For example, the western Atlantic near Rio de Janeiro (*left*) presents a similar profile to that of the northern polar basin on Mars (*right*).



DON DIXON

but with a firehose. He proposes that icy clumps of material collided with Earth during the initial formation of the planet, injecting huge quantities of water into the atmosphere in the form of steam.

Much of this water was lost back into space. Some of the steam immediately streamed skyward through holes in the atmosphere blasted open by these icy planetesimals themselves. Many of the water molecules ($H_2O$) were split apart by ultraviolet radiation from the sun. Hydrogen produced in this way most likely escaped into space, and the oxygen left behind would have become bound to minerals in the crust. But enough of the initial steam in the atmosphere survived and condensed to form sizable oceans when the planet eventually cooled.

No one knows how much water rained down on the planet at the time. But suppose the bombarding planetesimals resembled the most abundant type of meteorites (called ordinary chondrites), which contains about 0.1 percent water by weight. An Earth composed entirely of this kind of rubble would therefore have started with 0.1 percent water—at least four times the amount now held in the oceans. So three quarters of this water has since disappeared. Perhaps half an ocean of the moisture became trapped within minerals of the mantle. Water may also have taken up residence in Earth's dense iron core, which contains some relatively light elements, including, most probably, hydrogen.

So the initial influx of meteoric material probably endowed Earth with more than enough water for the oceans. Indeed, that bombardment lasted a long time: the analysis of the impact craters on the moon, combined with the known age of moon rocks, indicates that large bodies continued to strike the moon—and, by implication, Earth—until about 3.8 billion years ago. The latter part of this interval, starting about 4.5 billion years ago, is called, naturally enough, the heavy bombardment period.

One of the unsolved mysteries of planetary science is exactly where these hefty bodies came from. They may have originated in the asteroid belt, which is located between the orbits of Mars and Jupiter. The rocky masses in the outer parts of the belt may contain up to 20 percent water. Alternatively, if the late-arriving bodies came from beyond the orbit of Jupiter, they would have resembled another water-bearing candidate—comets.

Comets are often described as dirty, cosmic snowballs: half ice, half dust. Christopher F. Chyba, a planetary scientist at the University of Arizona, estimates that if only 25 percent of the bodies that hit Earth during the heavy bombardment period were comets, they could have accounted for all the water in the modern oceans. This theory is attractive because it explains the extended period of heavy bombardment: bodies originating in the outer solar system would have taken longer to be swept up by planets, and so the volley of impacts on Earth would have stretched over billions of years.

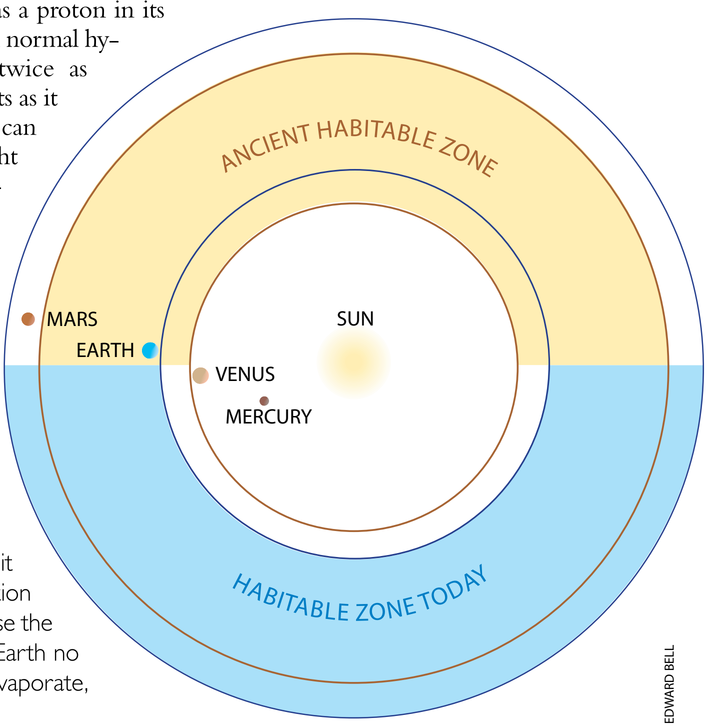
This widely accepted theory of an ancient, cometary firehose has recently hit a major snag. Astronomers have found that three comets—Halley, Hyakutake and Hale-Bopp—have a high percentage of deuterium, a form of hydrogen that contains a neutron as well as a proton in its nucleus. Compared with normal hydrogen, deuterium is twice as abundant in these comets as it is in seawater. One can imagine the oceans might now contain proportionately more deuterium than the cometary ices from which they formed, because normal hydrogen, being lighter, might escape the tug of gravity more easily and be lost to space. But it is difficult to see how the oceans could contain proportionately less deuterium. If these three comets are representative of those that struck here in the past, then most of the water on Earth must have come from elsewhere.

A recent, controversial idea based on new observations from satellites suggests that about 20 small (house-size) comets bombard Earth each minute. This rate, which is fast enough to fill the entire ocean over the lifetime of Earth, implies that the ocean is still growing. This much debated theory, championed by Louis A. Frank of the University of Iowa, raises many unanswered questions, among them: Why do the objects not show up on radar? Why do they break up at high altitude? And the deuterium paradox remains, unless these "cometesimals" contain less deuterium than their larger cousins.

## The Habitable Zone

Whatever the source, plenty of water fell to Earth early in its life. But simply adding water to an evolving planet does not ensure the development of a persistent ocean. Venus was probably also wet when it formed, but its surface is completely parched today.

How that drying came about is easy to understand: sunshine on Venus must have once been intense enough to create a warm, moist lower atmosphere and to support an appreciable amount of water in the upper atmosphere as well. As a re-



EDWARD BELL

HABITABLE ZONE, where liquid water can exist on the surface of a planet, now ranges from just inside the orbit of Earth to beyond the orbit of Mars (*blue*). This zone has migrated slowly outward from its position when the planets first formed (*yellow*), about 4.6 billion years ago, because the sun has gradually brightened over time. In another billion years, when Earth no longer resides within this expanding zone, the water in the oceans will evaporate, leaving the world as dry and lifeless as Venus is today.

sult, water on the surface of Venus evaporated and traveled high into the sky, where ultraviolet light broke the molecules of $H_2O$ apart and allowed hydrogen to escape into space. Thus, this key component of water on Venus took a one-way route: up and out [see "How Climate Evolved on the Terrestrial Planets," by James F. Kasting, Owen B. Toon and James B. Pollack; SCIENTIFIC AMERICAN, February 1988].

This sunshine-induced exodus implies that there is a critical inner boundary to the habitable zone around the sun, which lies beyond the orbit of Venus. Conversely, if a planet does not receive enough sunlight, its oceans may freeze by a process called runaway glaciation. Suppose Earth somehow slipped slightly farther from the sun. As the solar rays faded, the climate would get colder and the polar ice caps would expand. Because snow and ice reflect more sunlight back to space, the climate would become colder still. This vicious cycle could explain in part why Mars, which occupies the next orbit out from Earth, is frozen today.

The actual story of Mars is probably more complicated. Pictures taken from the Mariner and Viking probes—and from the Global Surveyor spacecraft now orbiting the Red Planet—show that older parts of the Martian surface are laced with channels carved by liquid water [see "Global Climatic Change on Mars," by Jeffrey S. Kargel and Robert G. Strom; SCIENTIFIC AMERICAN, November 1996]. Recent measurements from the laser altimeter on board the Global Surveyor indicate that the vast northern plains of Mars are exceptionally flat. The only correspondingly smooth surfaces on Earth lie on the seafloor, far from the midocean ridges. Thus, many scientists are now even more confident that Mars once had an ocean. Mars, it would seem, orbits within a potentially habitable zone around the sun. But somehow, aeons ago, it plunged into its current chilly state.

## A Once Faint Sun

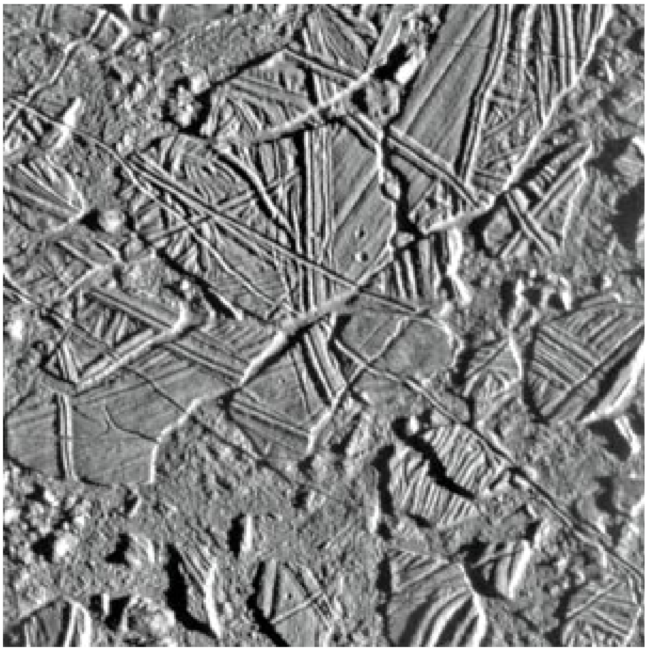
Understanding that dramatic change on Mars may help explain nagging questions about the ancient oceans of Earth. Theories of solar evolution predict that when the sun first became stable, it was 30 percent dimmer than it is now. The smaller solar output would have caused the oceans to be completely frozen before about two billion years ago. But the geologic record tells a different tale: liquid water and life were both present as early as 3.8 billion years ago. The disparity between this prediction and fossil evidence has been termed the faint young sun paradox.

The paradox disappears only when one recognizes that the composition of the atmosphere has changed considerably over time. The early atmosphere probably contained much more carbon dioxide than at present and perhaps more methane. Both these gases enhance the greenhouse effect because they absorb infrared radiation; their presence could have kept the early Earth warm, despite less heat coming from the sun.

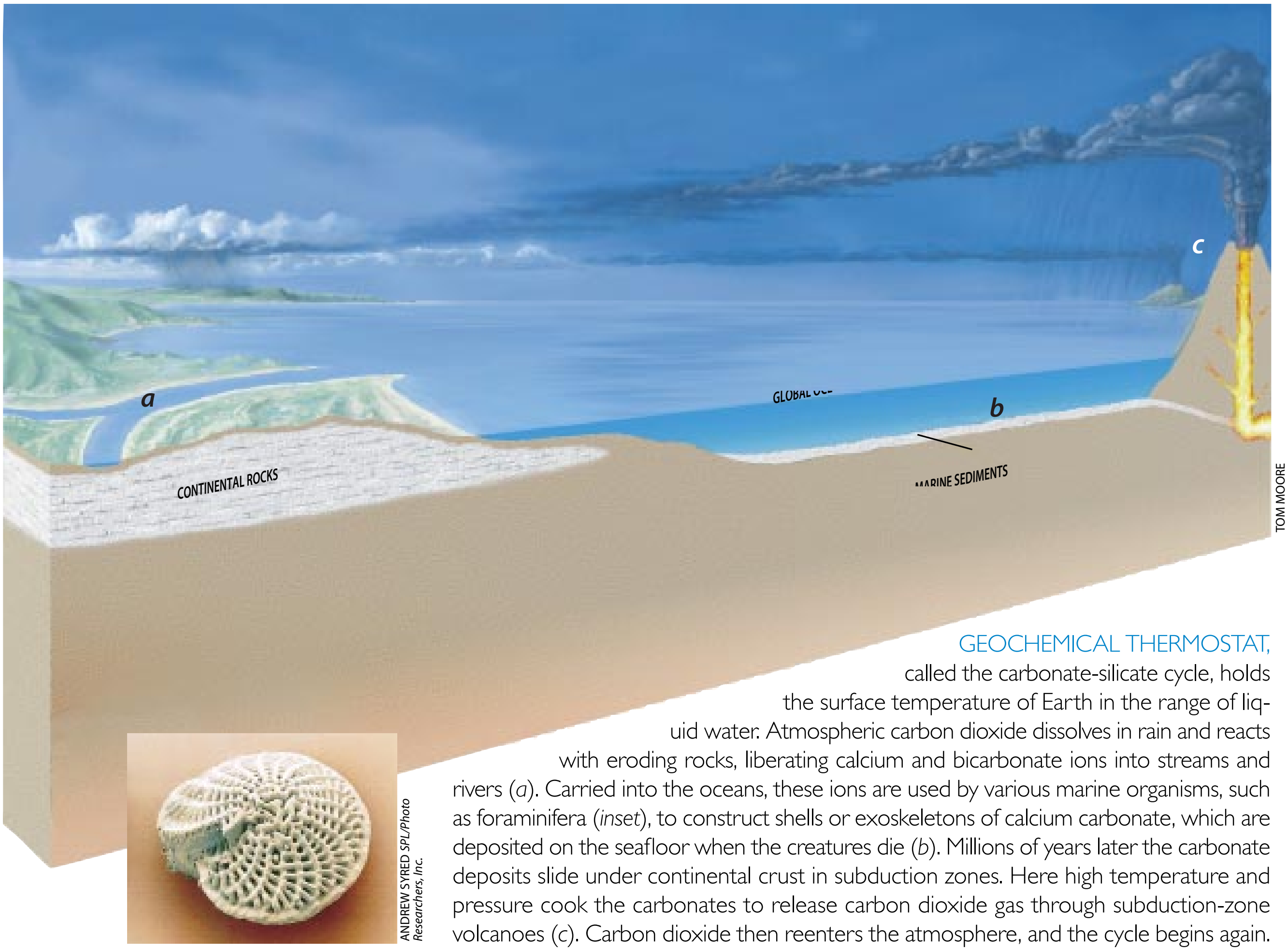
The greenhouse phenomenon also helps to keep Earth's climate in a dynamic equilibrium through a process called the carbonate-silicate cycle. Volcanoes continually belch carbon dioxide into the atmosphere. But silicate minerals on the continents absorb much of this gas as they erode from crustal rocks and wash out to sea. The carbon dioxide then sinks to the bottom of the ocean in the form of solid calcium carbonate. Over millions of years, plate tectonics drives this carbonate down into the upper mantle, where it reacts chemically and is spewed out as carbon dioxide again through volcanoes.

If Earth had ever suffered a global glaciation, silicate rocks, for the most part, would have stopped eroding. But volcanic carbon dioxide would have continued to accumulate in the atmosphere until the greenhouse effect became large enough to melt the ice. And eventually the warmed oceans would have released enough moisture to bring on heavy rains and to speed erosion, in the process pulling carbon dioxide out of the atmosphere and out of minerals. Thus, Earth has a built-in therm-


GALEN ROWELL *Mountain Light*


NASA/JET PROPULSION LABORATORY

ICY BLOCKS cover the Weddell Sea off Antarctica (*left*); similarly shaped blocks blanket the surface of Europa, a moon of Jupiter (*right*). This resemblance, and the lack of craters on Europa, suggests that liquid water exists below the frozen surface of that body.



TOM MOORE

ANDREW SYRED *SPL/Photo Researchers, Inc.*

GEOCHEMICAL THERMOSTAT, called the carbonate-silicate cycle, holds the surface temperature of Earth in the range of liquid water. Atmospheric carbon dioxide dissolves in rain and reacts with eroding rocks, liberating calcium and bicarbonate ions into streams and rivers (*a*). Carried into the oceans, these ions are used by various marine organisms, such as foraminifera (*inset*), to construct shells or exoskeletons of calcium carbonate, which are deposited on the seafloor when the creatures die (*b*). Millions of years later the carbonate deposits slide under continental crust in subduction zones. Here high temperature and pressure cook the carbonates to release carbon dioxide gas through subduction-zone volcanoes (*c*). Carbon dioxide then reenters the atmosphere, and the cycle begins again.

ostat that automatically maintains its surface temperature within the range of liquid water.

The same mechanism may have operated on Mars. Although the planet is now volcanically inactive, it once had many eruptions and could have maintained a vigorous carbonate-silicate cycle. If Mars has sufficient stores of carbon—one question that NASA scientists hope to answer with the Global Surveyor—it could also have had a dense shroud of carbon dioxide at one time. Clouds of carbon dioxide ice, which scatter infrared radiation, and perhaps a small amount of methane would have generated enough greenhouse heating to maintain liquid water on the surface.

Mars is freeze-dried today, not because it is too far from the sun but because it is a small planet and therefore cooled off comparatively quickly. Consequently, it was unable to sustain the volcanism necessary to maintain balmy temperatures. Over the aeons since Mars chilled, the water ice that remained probably mixed with dust and is now trapped in the uppermost few kilometers of the Martian crust.

The conditions on Earth that formed and maintain the oceans—an orbit in the habitable zone, plate tectonics creating ocean basins, volcanism driving a carbonate-silicate cycle and a stratified atmosphere that prevents loss of water or hydrogen—are unique among the planets in our solar system. But other planets are known to orbit other stars, and the odds are good that similar conditions may prevail, creating other brilliantly blue worlds, with oceans much like ours. SA

### *The Author*

JAMES F. KASTING received his bachelor's degree in chemistry and physics from Harvard University. He went on to graduate studies in physics and atmospheric science at the University of Michigan, where he obtained a doctorate in 1979. Kasting worked at the National Center for Atmospheric Research and for the National Aeronautics and Space Administration Ames Research Center before joining Pennsylvania State University, where he now teaches in the departments of geosciences and of meteorology. Kasting's research focuses on the evolution of habitable planets around the sun and other stars.

### *Further Reading*

How Climate Evolved on the Terrestrial Planets. James F. Kasting, Owen B. Toon and James B. Pollack in *Scientific American,* Vol. 258, No. 2, pages 90–97; February 1988.

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Possible Cometary Origin of Heavy Noble Gases in the Atmospheres of Venus, Earth and Mars. T. Owen, A. Bar-Nun, and I. Kleinfeld in *Nature,* Vol. 358, pages 43–46; July 2, 1992.