Water and Space

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I am convinced that He does not play dice.
ALBERT EINSTEIN

God not only plays dice, he also sometimes throws the dice where they cannot be seen.
STEPHEN HAWKING

In a book about water on Earth, it is perhaps unusual to describe the search for water in outer space. When we think of water, we think of the blood of all life on Earth. Space, on the other hand, is a vast, unimaginably empty vacuum, dotted with stars and inherently inimical to life on Earth. Why would we look for water in outer space?

What would it mean to find extraterrestrial water? In learning about water in space, can we perhaps learn something about our own water? Water itself is a fascinating thing, not just because of its importance to life here, but because of where it can take us. Water in space is a necessary precursor to humans in space. And if we find water in space, we begin to wonder what else we might find out there, including life.

Surprisingly, we have found water, a simple unmistakable molecule, to be widely distributed in space. Earth's moon, the driest of bodies, may have frozen water at the poles. Mars, with its red sands and carbon-dioxide atmosphere, has water frozen in ice caps and may have subterranean ice. Several moons of Jupiter, circling their forbidding gas giant, may have large quantities of ice. Europa, in particular, looks promising as a source of liquid water, kept from freezing by the heat of its volcanic core. We have even found traces of water in far stellar clouds and galaxies.

The Origin of the Earth's Water

Scientists have asked for years how water came to this world. Many Earth scientists argue that water vapor from volcanic eruptions collected on the surface. Many space scientists have argued that water, and the complex carbon-based molecules necessary to produce life, arrived here in a mix of comets and meteors.

Cosmic Snowballs

The first volume of *The World's Water* discussed Dr. Louis Frank's novel theory that cosmic snowballs augmented terrestrial water supply (Gleick 1998). First hypothesized in 1986, Frank proposed that small comets, the size of a house or even smaller and made of pure water, strike the earth's atmosphere 20 times per minute. They do not show up as typical meteors with a fiery tail because they are made of uncompacted snow rather than rock. As a result, they are not cohesive enough to strike the earth's surface; they vaporize thousands of kilometers above the atmosphere (Kerr 1988).

Frank faced ridicule from his colleagues for this novel, and apparently counterintuitive, idea, until eleven years later, when some observations from NASA's POLAR satellite's Visible Imaging System appeared to support his hypothesis. The satellite's sensors showed what could be water from comets breaking up at high altitude, between 960 and 24,000 kilometers above the planetary surface. The suspected trail of one such cosmic snowball vaporizing over the Atlantic Ocean and Western Europe at an altitude of 8,000 to 24,000 kilometers is seen below (Figure 1). As it descends, wind disperses it; the water vapor condenses in the atmosphere and falls to Earth as precipitation (Broad 1997a). More recently, Frank and his coauthors published a new paper reporting the results of a ground-based telescope survey, which they suggest also provides supporting visual evidence for such cosmic snowballs (Frank and Sigwarth 2001). This celestial precipitation is thought to add approximately 2 to 3 centimeters of water over the entire surface of the planet every 20,000 years (Kluger 1997). If such a process has continued throughout Earth's history, as Frank hypothesizes, the water accumulation would be enough to fill all the earth's oceans (Frank et al. 1986). This hypothesis is still highly controversial, and the ultimate origin of Earth's water is unresolved.

Water-Bearing Meteorites

Snowball comets are not the only way water has arrived on Earth from space. Space scientists have uncovered the existence of liquid water older than solar system contained in two meteorites that fell to Earth in 1998, one in Monahans, Texas, and one in Zag, Morocco (Zolensky et al. 1999). Thanks to an alert group of children playing nearby, the Monahans meteorite made it to NASA's Johnson Space Center a record 46 hours after it landed. This allowed scientists there to examine the meteorite before the water it contained evaporated. They saw what appeared to be bubbles of liquid in blue-purple crystals inside the meteorite (Figures 2 and 3). Further testing indicated the presence of saltwater inside crystals that were 4.6 billion years old (Cowen 1999).

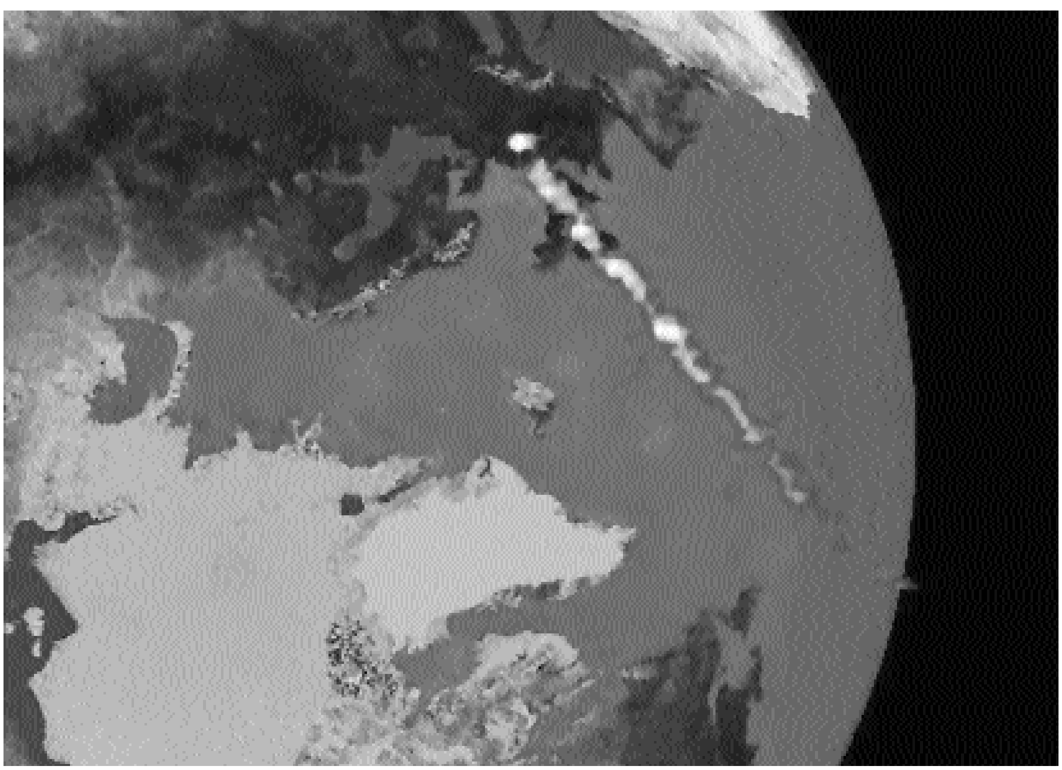

FIGURE WB.1 A water comet vaporizing in high atmosphere.
Source: L. Frank, U. Iowa

The Zag meteorite, which fell in a remote part of Morocco that same year, also contains water droplets inside blue-purple salt crystals. As in the Monahans meteorite, the salt crystals are tinged blue-purple by the cosmic radiation to which it was exposed

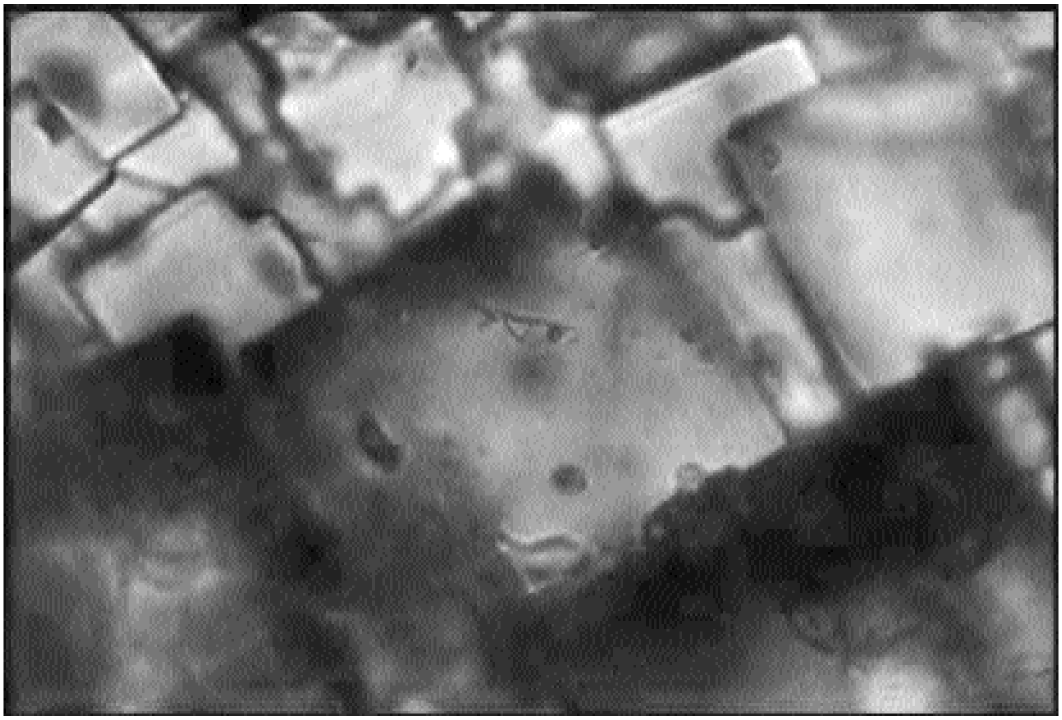

Figure WB.2 Monahans halite crystals.
Source: NASA JPL

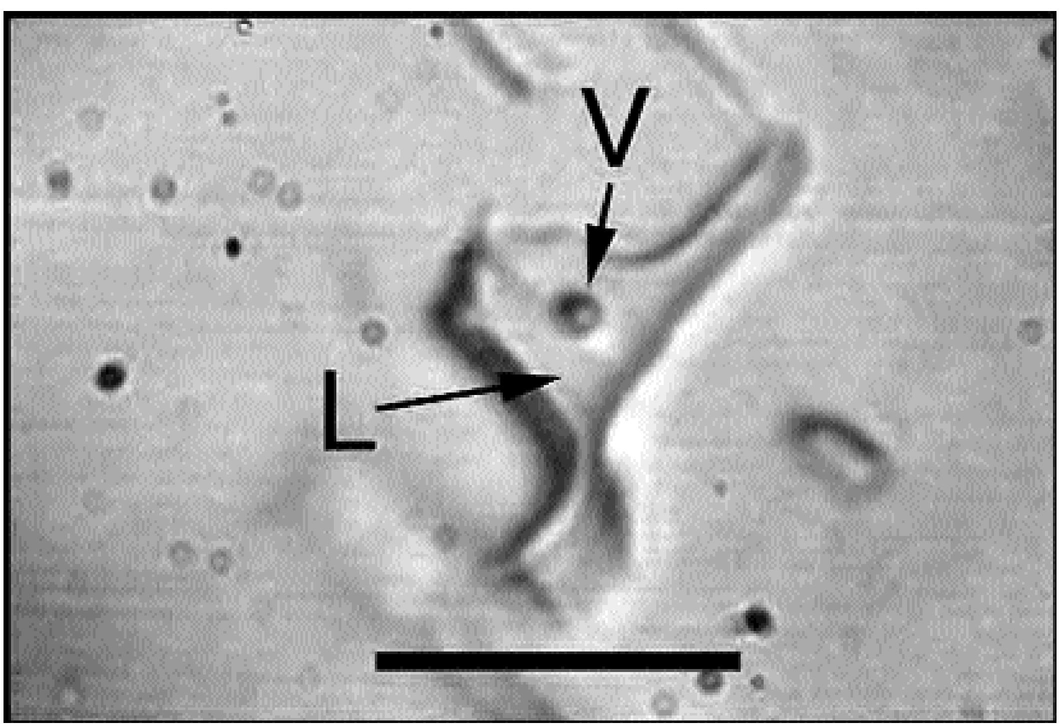

Figure WB.3 V = Water bubble 15 microns across (one-quarter the width of a human hair).
Source: NASA JSC

before falling to Earth. Preliminary dating of the Zag meteorite by scientists from the University of Manchester showed that the water had formed within 100 million years after the formation of the solar system, around 4.5 billion years ago. A subsequent analysis of the proportion of xenon and iodine isotopes contained in the rock showed that it and the water it contains were formed within 2 million years of the birth of the solar system (Whitby et al. 2000), making it even older than previously thought.

The fact that meteorites can contain primordial water is exciting because it has far-reaching implications for theories on the origin of life. Water is one of the essential compounds of life, and its existence outside Earth would suggest that there are other places where conditions could be favorable for the development of life.

The Moon

The search for extraterrestrial water focused early on the Moon. Efforts to find water on the Moon underlie a significant opportunity for human exploration of space. If the Moon or other celestial body has water, it could provide critical resources for human use. NASA has undertaken a series of missions to search for water on the Moon. In 1994, radar measurements from *Clementine,* a Defense Department satellite launched

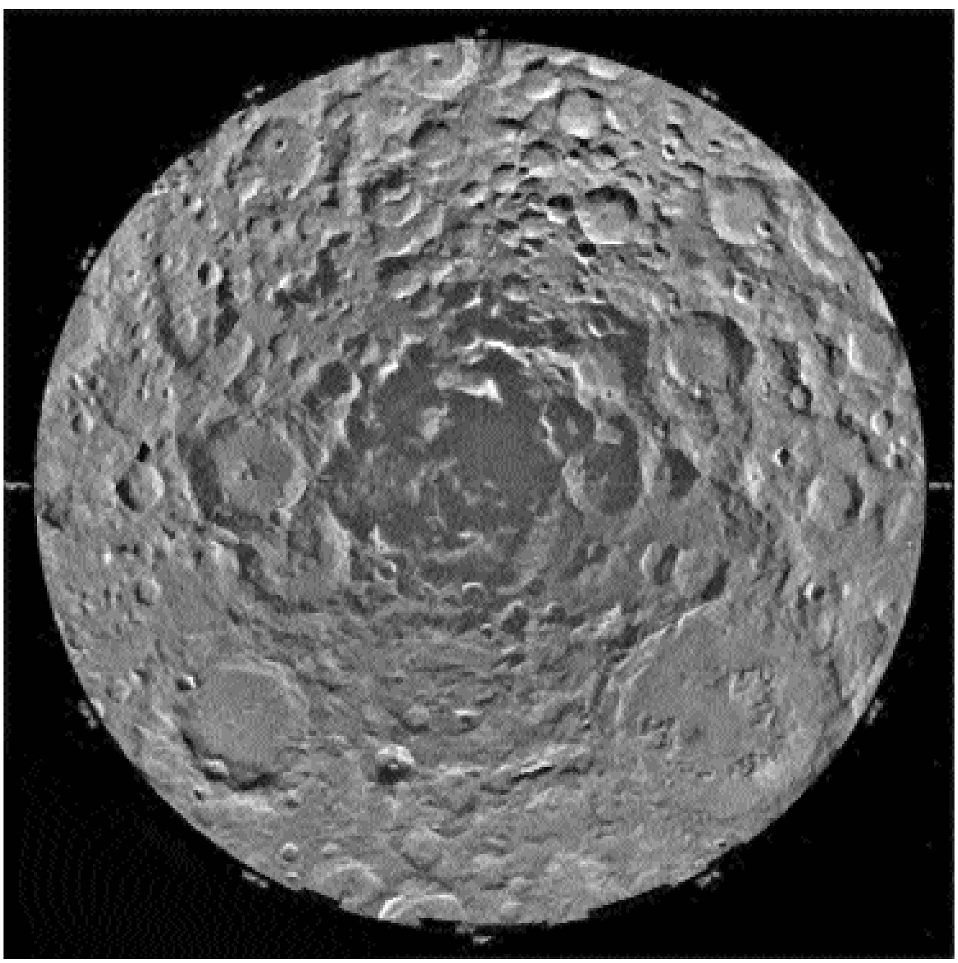

FIGURE WB.4 Lunar South Pole.
Source: NASA

to test space and missile technology, suggested the presence of permanently frozen ice at the shaded areas of the lunar poles (Figure 4), possibly deposited when water-rich comets and meteorites struck the surface (Wilford 1998).

The possibility of water on the Moon intrigued scientists, and on January 6, 1998, NASA launched the *Lunar Prospector,* designed to map the Moon's surface composition and its gravity and magnetic fields (Binder et al. 1998). Its neutron spectrometer (NS) (see Sidebar 1) scanned for hydrogen and oxygen at the Moon's north and south poles, and from its findings, NASA inferred the existence of water. Two months later, they announced the existence of anywhere from 11 to 330 million tons of frozen water mixed in with the lunar soil (Hall 1998).

In an unusual attempt to confirm this finding, NASA crashed the 160-kilogram *Lunar Prospector* on July 31, 1998, into a crater at the Moon's south pole in an effort to kick up ice-bearing rock and dust. Earth-bound observers of the crash used sensitive spectrometers to search for the ultraviolet emissions of hydroxyl (OH) molecules, the expected signature of water (NASA 1999). The crash of the *Lunar Prospector* did not yield any observable water signature, although scientists and astronomers pointed out that the chances of positive detection were judged to be less than 10 percent. To date, NASA still considers open the question of whether frozen water exists in usable quantities on the Moon.

In situ water could yield oxygen for a breathable atmosphere and hydrogen for rocket fuel, making water not only biologically necessary but also economically desirable. Currently, spacecraft must carry with them all the fuel needed for the

Box WB.1 Neutron Spectrometer

An NS searches for water ice by detecting the element hydrogen. Since water molecules contain atoms of hydrogen and oxygen, hydrogen is a good marker for water. If lunar water is present in usable quantities, the amount of hydrogen locked up in water molecules will dwarf the amount that may be present for any other reason. Even if only 0.5 percent of the surface material at a given location is water, Lunar Prospector is capable of finding it.

Because it flies 100 kilometers above the Moon's surface, the NS does not detect hydrogen directly. Instead, it looked for what scientists call "cool" neutrons—neutrons that have bounced off a hydrogen atom somewhere on the lunar surface. The only effective way to slow down a speeding neutron is to have it collide with something approximately its own size, such as a hydrogen atom. If the Moon's crust contains a lot of hydrogen at a certain location, any neutron that bounces around in the crust before heading out to space will cool off rapidly. When Lunar Prospector flew over such a crater, the NS could detect a surge in the number of cool ("thermal") neutrons, and a dropoff in the number of warm ("epithermal") neutrons. Soil containing ice, for instance, should yield more cool neutrons and fewer warm neutrons than soil devoid of ice. Because the spacecraft carrying the NS passed over the lunar poles every orbit, the NS produced the most accurate data precisely where the water is thought to be.

outbound and return trips. Such off-world sources of fuel would make space travel much more productive by allowing spacecraft to expand the payload weight. In addition, launching rockets from the Moon rather than Earth would extend the range of future missions. The Moon's gravity is a fraction of Earth's, and the escape velocity—the speed that a spaceship has to reach to escape its gravitational pull—is a mere 2.38 kilometers (1.4 miles) per second, compared to Earth's 11.2 km (about 7 miles) per second.

Mars

NASA's search for extraterrestrial water has not been limited to just the Moon. Mars may once have been a very wet place. Recent astronomical research from a number of institutions has uncovered what appears to be evidence of various forms of water on Mars, in the past and perhaps presently. However, Mars, like the Moon, is cold and dry. Since the average surface temperature on Mars is -81 degrees Fahrenheit and the atmospheric pressure is only one-sixth that of Earth, the existence of liquid water becomes more than problematic. Even if some internal heat source warmed up the planet enough to permit any surface ice to melt, the atmosphere is so thin that the ice would change directly to water vapor (NASA Astrobiology Institute 2001).

Since the early Viking flyby missions of the 1960s, pictures of the Martian surface have shown evidence of the movement of water. There is evidence of permafrost activity on the surface, indicating a "youthful" phase of water-related activity. In addition, integrated networks of channels and tributaries (Figure 5) cross the surface in what appear to be complex drainage and erosion patterns formed by surface water activity (Baker 2001).

Recent photographs and high-resolution laser topography data of Mars sent back by the *Mars Global Surveyor* show large plains in the northern hemisphere that appear at one time to have been oceans (Figure 6). What could be at least two concurrent northern ocean beds have been determined, and supporting characteristics such as shoreline erosion, meteorite ejecta properties, and the interaction of outflow channels and the ocean bed have been identified near the surface of the northern lowlands (Head et al. 1999). In addition, topographic and free-air gravity models have shown that these large, flat northern lowlands contain large buried channels that are consistent with the northward transport of water and sediment (Zuber et al. 2000). Some scientists have recently described evidence that the ridged areas that appear to be shorelines may have been caused by tectonic activity (Withers and Neumann 2001,

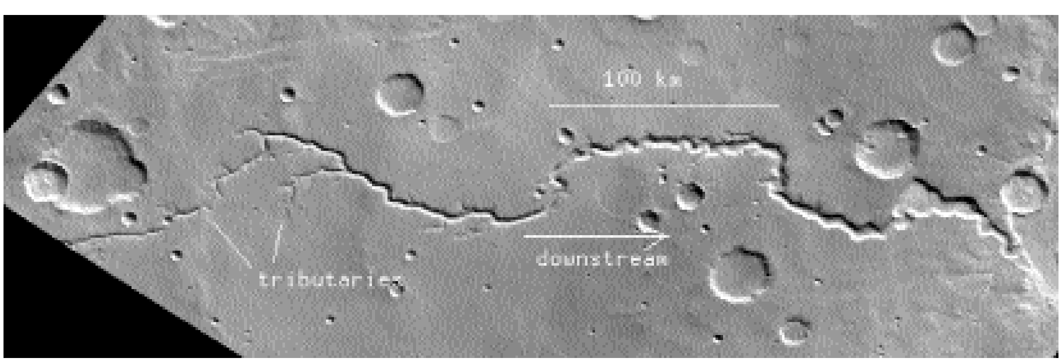

FIGURE WB. 5 Nirgal Vallis.
Source: Malin Space Science Systems

Lloyd 2001). Since the evidence is contradictory, the debate continues as to what caused these features.

These possible northern oceans are not the only features on Mars that may indicate water. Findings from the *Mars Orbital Camera* (MOC) have revealed pictures of what look like flood gullies very near the surface, where liquid water may burst forth from underground for a brief flash flood before evaporating. Since the temperature and atmospheric pressure conditions on the Martian surface make the existence of liquid fresh water almost impossible, scientists have hypothesized that any liquid water underground must be saltwater. Since saltwater freezes at temperatures significantly lower than that of fresh water, this expands the regions on Mars where ice melting could occur and increases the total time such conditions might exist for liquid water (NASA 2000). However, an alternative explanation posed by Australian geoscientist Nick Hoffman for these features involves a much colder Mars, where its carbon dioxide atmosphere could have condensed into layers of CO_2 ice covering the planet. Pressure from these ice layers would have allowed a layer of liquid CO_2 to form underneath, as liquid water forms under glaciers here on Earth. This liquid CO_2 would bubble to the surface and vaporize explosively in "pyroclastic flows," and the resulting gas, mixed with dust and rocky debris, could mimic the movement of water and carve the same sorts of channels and gullies. Hoffman came to this conclusion when he noticed a lack of calcium carbonate in the rocks on the Martian surface, a geologic byproduct formed when liquid water absorbs carbon dioxide out of the atmosphere (Davidson 2001).

Water may exist on Mars to this day. Research by Nadine Barlow, director of the University of Central Florida's Robinson Observatory, has uncovered what appears to be an Arizona-sized underground ice reservoir. Located in the Solis Planum region, the ice could

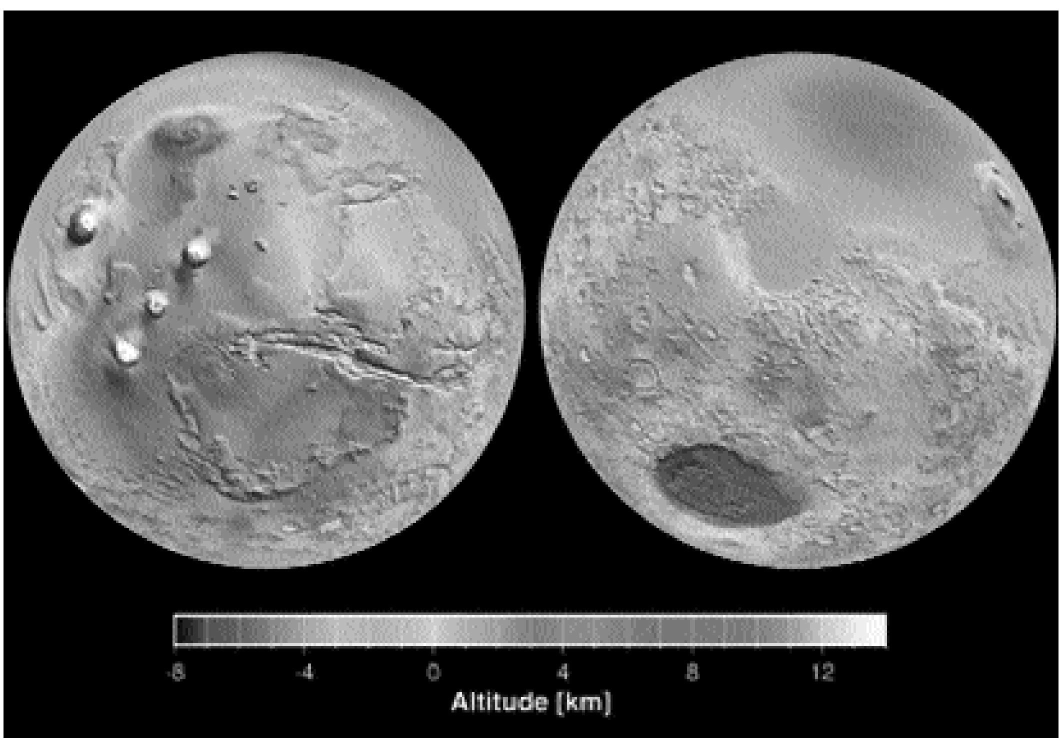

FIGURE WB.6 Global Mars (false color image).
Source: NASA

start just 200 meters from the Martian surface, making it an ideal water-mining area for future manned landings. Barlow hypothesizes that water has gathered in that spot because of volcanic activity tilting the water table into the low-lying region (David 2000).

While all this physical evidence shows signs of past (and possibly present) oceans on Mars, a recent analysis of the interior of a 1.2-billion-year-old Martian meteorite may give researchers a glimpse into the chemical content of these oceans. The Nahkla meteorite, which landed in El-Nahkla, Egypt, in 1911, showed residue from what is believed to be salts from brine. Researchers at Arizona State University examined the interior of the meteorite and found ionic chloride and sodium. Since these elements are predominant in Earth's oceans, scientists have interpreted a chemical similarity between oceans on Earth and an early Martian ocean (Hathaway 2000).

Being There

All the evidence described above has been gathered long-distance, via satellites and cameras. In order to confirm the existence of water on Mars, we must go there, in person or robotically. NASA has planned missions to search for evidence of water on the Martian surface. In April of 2001, NASA launched *Odyssey,* the latest Mars mission designed to search for water, with the goal of determining if life ever existed there. *Odyssey* successfully arrived in Mars orbit in fall 2001 equipped with an array of infrared, visible-light, and gamma-ray spectrometers, and in March 2002, NASA scientists announced findings of a significant hydrogen signature near the Martian equator (Britt 2002).

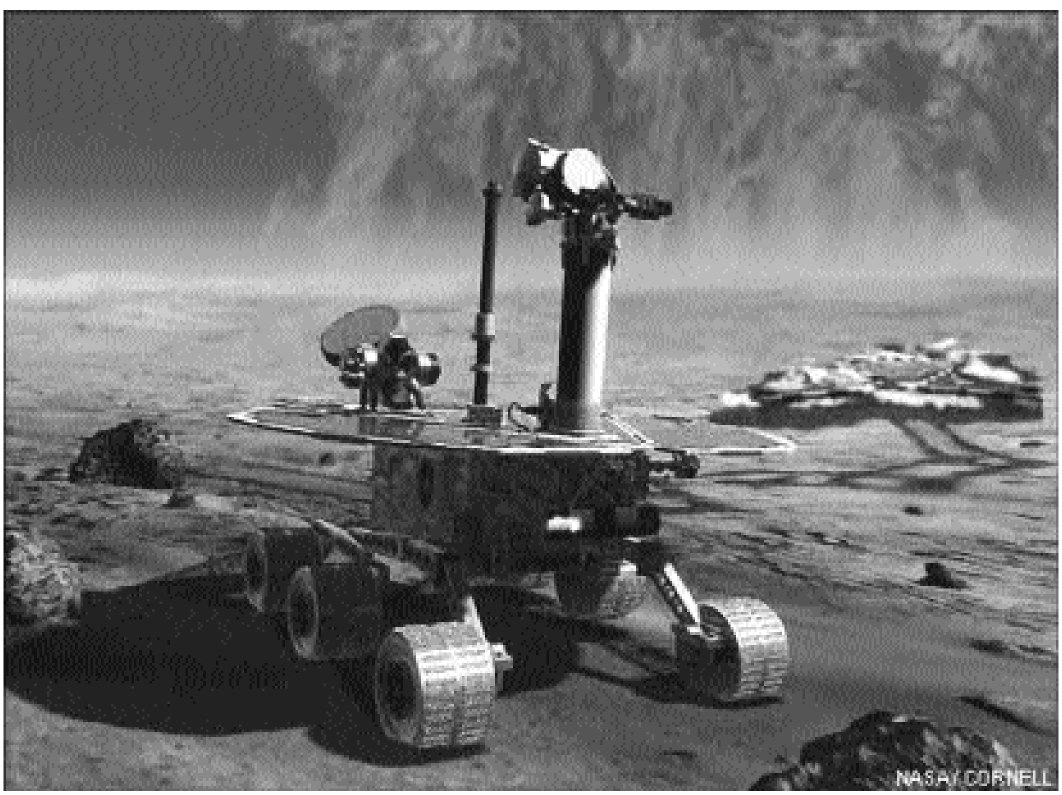

FIGURE WB.7 Mars Water-Sniffing Rover.
Source: NASA artist's rendition

NASA's Mars exploration plans also include the 2003 launch of a water-sniffing rover (Figure 7) similar to the extremely successful *Pathfinder*. The rover would carry among its six instruments a color camera and a detector to search for evidence of liquid water

Finding water in any form on Mars could provide the same benefits as finding water on the Moon: oxygen and hydrogen could be produced for breathing and fuel. In addition, water itself will be necessary for human colonization and possible terraforming of Mars, though the latter may take hundreds if not thousands of years (Bonsor n.d.).

Jupiter's Moons

Early radar observations of Jupiter's moon Europa detected a layer of water up to 160 kilometers deep covering the surface, but it was unknown if the water was frozen or liquid (Perlman 1999). In 1999, however, detailed photographs from NASA's *Galileo* spacecraft, orbiting Jupiter since 1995, clearly showed an ice surface with a network of unusual cracks and fissures (Figure 8) (Wilford 1999). Gregory Hoppa and other space scientists from the University of Arizona have theorized that these scalloped cracks were caused when the ever-changing tidal stress from Jupiter exceeded the tensile strength of the ice. As Europa moves around Jupiter in its irregular orbit, Jupiter's gravitational pull causes subsurface tides on Europa to flex and crack the ice shell. Hoppa and his colleagues modeled the stress fractures and concluded that for these sorts of cracks to appear the ice crust must sit on top of a liquid layer deep enough to account for significant tidal amplitude (Hoppa et al. 1999). However, the photographic evidence was not sufficient to determine if liquid water currently exists on Europa, only that it likely existed at some point in the past.

Further physical evidence for a liquid-water layer existing on Europa at present was detected in the late 1990s by *Galileo*'s magnetometer. Magnetometers function by detecting changes in magnetic fields over time. *Galileo* made close passes in 1996 and again in 1998, and from these magnetic readings, Margaret Kivelson and fellow researchers from UCLA have presented strong evidence that Europa currently has a global, spherical conducting layer just under the surface. Although this layer might be some other conductive material like graphite (Weinstock 2000), salty water is the most likely explanation, in light of the geologic and photographic evidence previously found

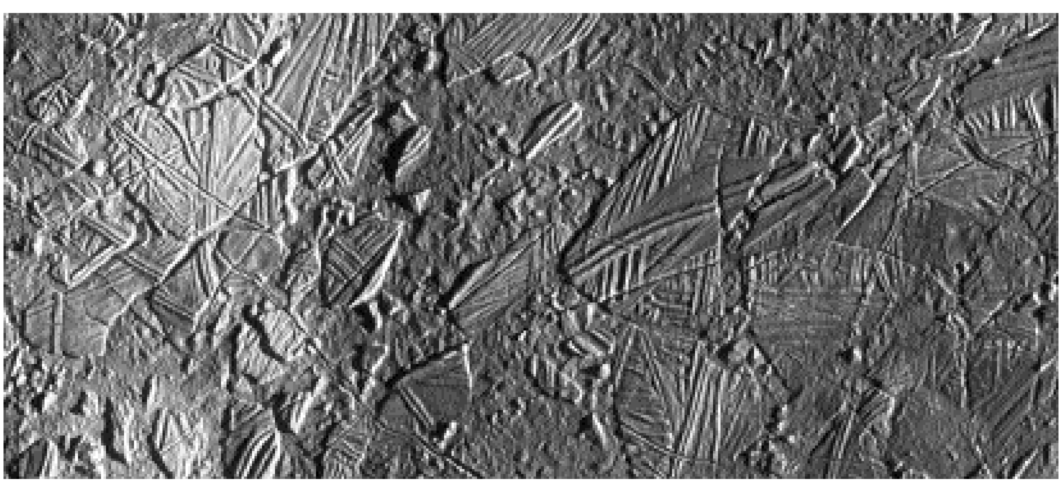

Figure WB.8 The surface of Europa.
Source: NASA JPL

(Kivelson et al. 2000). NASA hopes to answer this question definitively when it launches the *Europa Orbiter* in 2003, a spacecraft with ice-penetrating radar. Liquid water on Europa would be a major find and would give rise to the same speculations surrounding human use of the Moon and Mars (see Sidebar 2).

Two other Jovian satellites, Ganymede and Callisto, may also have liquid water, though not as near the surface as Europa. Infrared measurements from *Galileo*'s near-infrared mapping spectrometer identified hydrated minerals on the moon's surface, and researchers hypothesize that Ganymede may have a subsurface layer of briny fluid like Europa's (McCord et al. 2001). In addition, magnetometer readings from *Galileo* flybys of Callisto indicated that this moon may also have a layer of melted salty water deep below its surface. However, unlike Europa, Callisto's surface is heavily cratered, indicating that the watery layer is much farther below (NASA 2001).

The existence of water on Europa or other Jovian moons raises again the question of extraterrestrial life. We know that Earth's least hospitable environments can support life in various forms. The liquid-water ocean on Europa could also not support life if other conditions permit. Researchers have considered the biochemical conditions necessary for life, or at least life as we know it, and most concluded that it is not the lack of water that makes Europan life problematic, but rather the lack of a chemically appropriate energy source. Some scientists have concluded that conditions on Europa change too quickly to sustain evolution of life beyond single-celled bacteria (Gaidos et al. 1999), though even this would, of course, be a remarkable finding.

Water Beyond Our Solar System

Water has also been found to exist in space beyond our own solar system. Hydrogen, originally produced in the Big Bang, is found everywhere in the universe. Oxygen is made in stars and dispersed out into the universe in events such as supernova explo-

Box WB.2 The Artemis Society

The relative closeness of the Europan subterranean ocean to the surface has given rise to some peculiar plans. The Artemis Society, a private venture dedicated to developing a permanent, self-supporting human colony on Earth's moon, has also formulated a plan to put human colonists on Europa. No such plans are possible without the presence of water. However, a colony poses more than logistical problems. Europa is right in the middle of Jupiter's deadly radiation belt, and humans on the surface would not survive more than ten minutes. However, Peter Kokh, the author of the Artemis plan, assumes that the engineering challenges inherent in radiation shielding will have been solved by the time humans are ready to mount a manned expedition to Europa. A manned mission would erect a surface hangar made of ice and would then deploy a submersible vehicle to tunnel under the surface ice and into the global ocean below (Kohk et al. 1997). NASA is skeptical, although several technical details envisioned by the Artemis Society have later shown up in NASA plans (Lipper 2001).

sions. The two elements mix in star-forming clouds and form large amounts of water (Figure 9). The molecules of water leave the clouds and end up in many different places: comets, planets, and the centers of galaxies. When stars age, more oxygen is made available to the cosmic water factory. Various efforts have been made to search for water outside of our solar system.

Interstellar Clouds

The Submillimeter Wave Astronomy Satellite (SWAS), operated by the Harvard-Smithsonian Center for Astrophysics, is a NASA Small Explorer project designed to study the chemical composition of interstellar gas clouds. SWAS was launched into low Earth orbit on December 5, 1998. Its primary objective is to look for the spectral emission lines of water, isotopic water, molecular oxygen, neutral carbon, and isotopic carbon monoxide in a variety of galactic star-forming regions. The results from SWAS observations will help determine if these elements and compounds are the dominant coolants of molecular clouds during their collapse to form stars and planets (Melnick et al. 2000). If true, this raises the interesting possibility that water is or was part of every star and planet in the galaxy.

On July 11, 2001, SWAS scientists announced their findings of water around a distant star, IRC+10216. More commonly known as CW Leonis, this star is located 500 light-years from Earth in the constellation Leo. The SWAS team found that it is a red giant star, vaporizing a belt of water ice comets surrounding its system and depositing large

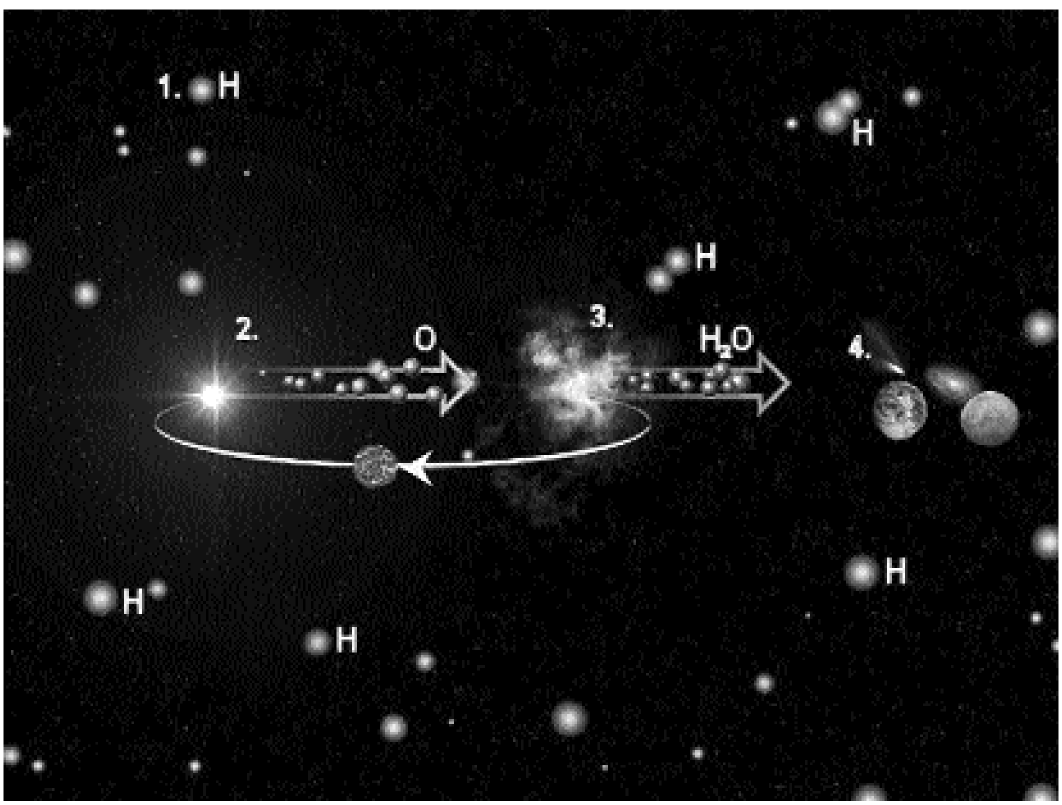

FIGURE WB.9 How water is made in space.
Source: European Space Agency

amounts of water vapor into the surrounding space (Vedantam 2001, Melnick et al. 2001). Our solar system has a similar set of comets, called the Kuiper Belt. Located beyond the orbit of Neptune, the Kuiper Belt contains many billions of icy objects, of which Pluto is the largest currently known. Most Kuiper Belt objects orbit the Sun quietly and unobserved, except very occasionally when one of them is deflected onto an elliptical orbit. As a comet comes close to the Sun, it heats up and starts to vaporize, yielding the fireball and tail that we recognize. Giant stars like CW Leonis have grown roughly 10,000 times more luminous than the Sun and are now so powerful that they vaporize comets even at the distance of the Kuiper Belt (see Sidebar 3).

SWAS is not the only low-orbit craft designed to look for extraterrestrial water in our galaxy. Using the European Space Agency's Infrared Space Observatory (ISO), Spanish and Italian astronomers have found water in the cold, dark areas of the galaxy: stellar clouds and the interstellar medium (Moneti et al. 2001). Previously, scientists assumed that the water-forming process would most likely be sustained only in warm stellar clouds such as the Orion Nebula, where astronomers found enough water vapor being produced to fill the earth's oceans every 24 minutes (Harwit et al. 1998). In this process, however, the water is heated to 200 degrees Fahrenheit or more (Roylance 1998). ISO's observations found substantial water vapor and ice in quiescent regions of the galaxy where the mean temperature is just 10 degrees above absolute zero. Astronomers estimate that there are millions of these cold clouds in the galaxy, containing as much water as the active, star-forming regions, and that by colliding and sticking together, they may form planets and comets (Recer 2001).

Water on the Other Side of the Universe

Water has even been detected outside of our own galaxy. In 1994, radio astronomers from the University of Maryland and the Max Planck Institut für Radioastronomie announced the discovery of water signatures in five active galaxies, the farthest of which, Markarian 1, is 200 million light years away (Braatz et al. 1994, Dawson, pers. comm. 2001). Specifically, these water signatures are called H2O "megamasers," or photon-emitting water-vapor clouds at the center of active galaxies. A maser is the microwave analogue of a laser; naturally occurring masers are frequently found in

Box WB.3 Could This Happen Here?

SWAS scientists point out that the process going on in IRC+10216 will be our fate eventually. In several billion years, our Sun will expand into a red giant star, and its power output will increase 5,000-fold. A wave of water vaporization will spread outward through the solar system, starting with Earth's oceans and extending into the Kuiper Belt, well beyond the orbit of Neptune. Icy bodies as large as Pluto will be vaporized, leaving nothing but a hot cinder of rock. From Earth, we are able to detect water vapor from similar events elsewhere in the galaxy.

Source: SWAS Press Release

dense clouds of gas in our own galaxy, where molecules such as water amplify the radiation from stars. Very powerful masers (megamasers) are observed in other galaxies, where dense clouds of molecular material orbit the black hole at the galactic center and amplify the intense radiation from its vicinity. Since 1994, at least 15 other H_2O megamasers have been discovered using a technique called Very Long Baseline Interferometry (VLBI; see Sidebar 4).

Water-vapor megamasers are useful to radio astronomers in two ways. By examining the orbital motions of megamasers, astronomers can calculate an absolute geometric distance between galaxies, making extragalactic measurements more accurate than they have ever been (Herrnstein et al. 1999). NASA and the National Radio Astronomy Observatory are currently planning a project called ARISE (Advanced Radio Interferometry between Space and Earth) to measure the distances to galactic centers containing these water-vapor megamasers. Also, emissions from water-vapor megamasers give astronomers detailed evidence of the structure and dynamics of active galaxies, furthering the study of black holes thought to be at the center of these galaxies (Ishihara et al. 2001).

Conclusion

Why do we care if there is water in deep space, or even on Europa? It's not likely that humans will have access to this water for hundreds of years, if ever. Its existence will certainly not provide relief to drought-stricken areas, supplement human consumption, or increase aquatic streamflows here on Earth, and huge physical and engineering challenges must be overcome before such water can be of use for human space exploration.

We care because the presence of accessible water greatly improves the chances of successful human exploration of space. Water is heavy to transport, but needed for the health and physical well-being of the explorers. If future manned NASA missions had to carry all the water the crew would need even to Mars and back, the cost of such a journey would be prohibitive. If such a mission had to carry its own water to Europa and back, current size limitations of spacecraft might make such a mission physically impossible. However, if water could be found and utilized *in situ,* suddenly the whole possibility of sending humans into space enters the tantalizing realm of possibility. The presence of water also offers a source of fuel for future missions, further reducing the resources that must be provided from Earth.

Box WB.4 Very Long Baseline Interferometry (VLBI)

Interferometry is a type of data gathering in which one image is made from the results of several different telescopes. The farther apart the telescopes are (the longer the baseline), the more detailed the picture. Current VLBI baselines are limited by the size of the earth, but an orbiting radio telescope, such as the ARISE project, combined with Earth-bound telescopes can increase the size of the baseline to four times the size of Earth!

Source: NASA JPL

Finally, we also care because where there is water, in any form, there *might* be life. Theoretical considerations suggest that prebiotic chemical evolution could lead to the development of self-replicating life, and we have already seen that water and other organic chemical molecules, like formaldehyde and benzene, exist in space. Because the known conditions under which life has actually arisen are limited to Earth, most exobiologists think that liquid water is necessary for life (Carr et al. 1995), or at least where water exists we know that a fundamental precursor to life is present. Thus, the past or present existence of liquid water anywhere in the universe gives us a kind of roadmap to discovering extraterrestrial organisms, whether one-celled or complex. Water has certainly defined our human past and now may point the way toward our human future.

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