

# HOW LIFE SURVIVED

The Sun was barely two-thirds as bright in its youth as it is today. So how did Earth's surface stay warm enough for liquid water to exist and life to emerge?

by **Bruce Dorminey**

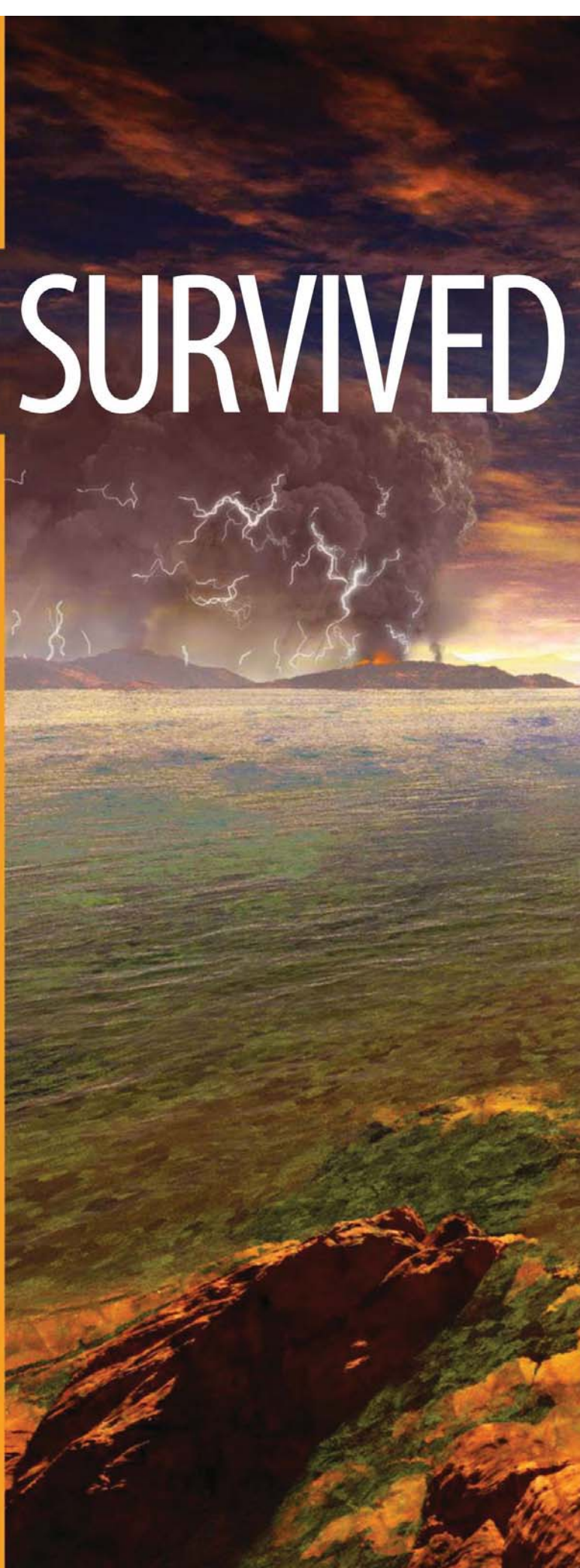
**M**ore than 3.5 billion years ago, not long after our young Earth morphed from a hot molten state into a solid planet and only primitive cyanobacteria drifted in our oceans, the Sun was some 30 percent fainter than it is today. That's no surprise. Models of stellar evolution clearly show that during their hydrogen-burning main sequence lives, Sun-like stars grow steadily more luminous, adding a bit less than 10 percent to their brightness every billion years. The surprise is that in the presence of such a faint Sun, Earth would have had liquid water at all.

By all accounts, our planet's surface should have been frozen solid for the first 2 billion of its 4.5-billion-year history. But the geologic record from the Archean Eon, which dates from 3.8 to 2.5 billion years ago, contains more than enough evidence that liquid water and clement conditions existed at the surface — and primitive life gained a strong foothold. Some researchers estimate that Earth's oceans at this time may have had temperatures above 130° Fahrenheit (55° Celsius). That's roughly halfway to the boiling point of water under current atmospheric conditions.

Scientists have labeled this conundrum the "faint young Sun paradox." But some investigators can't even agree on the proper terminology. "It's not a paradox — that's hyperbole," says planetary scientist David Stevenson of the California Institute of Technology. "It's something less than a paradox. It's a puzzle." Whatever it is, it has plagued astrophysicists and geoscientists

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Frequent contributor **Bruce Dorminey** is a science journalist and author of *Distant Wanderers: the Search for Planets Beyond the Solar System* (Springer, 2001).



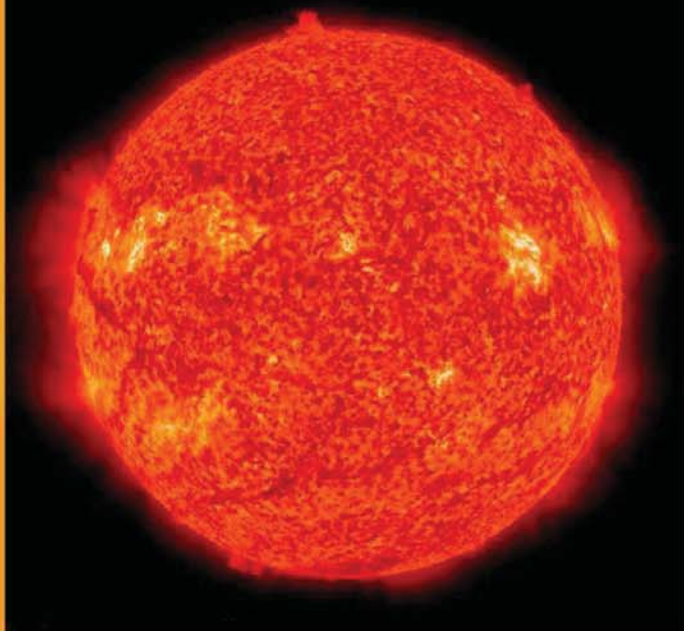




# A COOL EARLY SUN

Some 3.8 billion years ago, liquid water and primitive life existed on Earth's surface despite a Sun that radiated far less energy than it does today. RON MILLER FOR ASTRONOMY





The Sun is a roiling ball of hot gas, but it once was only some 70 percent as bright as it is today. NASA/SDO/AIA



Why wasn't Earth frozen solid when the Sun was much less luminous in its early days?

alike since 1972, when Carl Sagan and George Mullen of Cornell University first examined the problem.

In the four decades since, scientists have proposed all manner of solutions. Some suggest that the Sun had more mass and thus shone brighter in its early history. Others propose that our young planet had a thicker atmosphere rich in greenhouse gases or a lower albedo (reflectivity) caused by a lack of cloud cover and a dearth of continental land mass.

## Is the Sun at fault?

Most astronomers think the Sun began its life on the main sequence with essentially the same mass it has today. "Predictions from the standard model of solar evolution have not changed appreciably in 30 years," says James Kasting, a planetary scientist at Pennsylvania State University.

Astronomer David Soderblom at the Space Telescope Science Institute in Baltimore concurs. "The assumption that the Sun's

mass has changed only marginally over its life is based on the fact that the present-day solar mass loss through the solar wind is tiny," he says. "But we cannot measure such mass loss for other stars, [so] we've had to assume that mass loss is negligible at all ages."

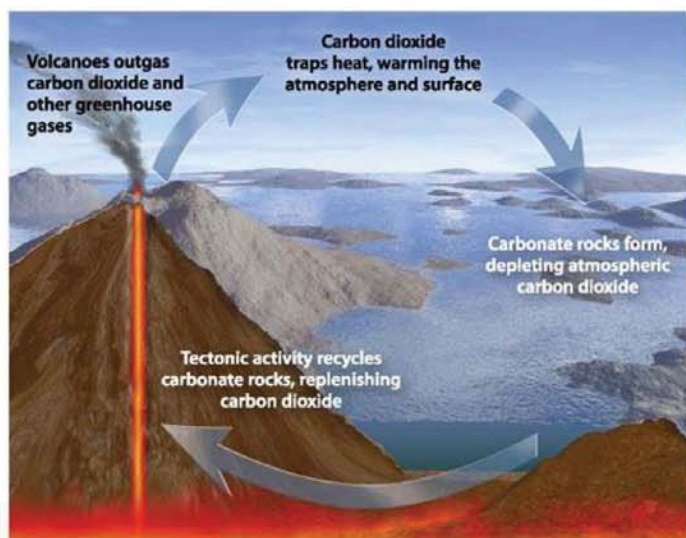
Soderblom notes that some researchers think the faint young Sun problem simply would go away if the early Sun were only 3 to 5 percent more massive than it is today. But he adds that even this much extra mass is hard to reconcile with the current Sun because it likely would leave some observable evidence, such as a higher helium abundance in the core.

Travis Metcalfe at the Space Science Institute in Boulder, Colorado, is one of several stellar astrophysicists who don't believe the Sun's mass has stayed constant since its formation. They think the most promising solution to the faint young Sun problem is that our star was born slightly larger and brighter. They say the star we see today is the result of billions of years of slow mass loss.

"If the Sun was born 5 percent more massive than it is today and slowly lost that excess over the last 4 billion years, you'd still get the same present-day solar structure," says Metcalfe. Therefore, there remains "wiggle room" of at least 5 percent for just how massive our young Sun might have been.

## Up in the air

Stevenson thinks the solution to the puzzle lies closer to home. He says that for this issue, at least, scientists understand the Sun — the problem lies with knowledge of our planet. A growing consensus of astrophysicists and earth scientists agrees. These researchers believe that significantly different conditions in Earth's early atmosphere compared with today offer the best solution. The most likely culprits: a mixture of greenhouse gases that warmed our planet



Scientists think the greenhouse effect contributed to early Earth's warmth. Volcanoes erupted carbon dioxide and other gases, which trapped heat radiating from the planet. Recycled rocks kept the process going. MICHAEL CARROLL





Scientists suspect that a large atmospheric greenhouse effect, a lower albedo, or a more massive Sun kept our entire planet from resembling Antarctica. GUILLAUME DARGAUD

sufficiently despite the young Sun's reduced radiation, or a lower albedo that helped the atmosphere retain more of the Sun's energy.

Many scientists argue that larger quantities of gases such as carbon dioxide, methane, and ethane could have done the trick. Such molecules let sunlight at visible wavelengths pass through unimpeded. The planet's surface absorbed this energy and re-radiated it in the infrared part of the spectrum. The gases then absorbed this longer-wavelength light, warming the young Earth significantly.

"You have to crank up the greenhouse gases to allow the planet to stay clement," says planetary scientist Joseph Kirschvink of Caltech. Theorists tend to focus solely on carbon dioxide as the greenhouse gas of preference, he adds, even though methane traps heat more efficiently and has turned up in fluid inclusions — liquids trapped inside crystals — in Australian rocks dating to 3.5 billion years ago.

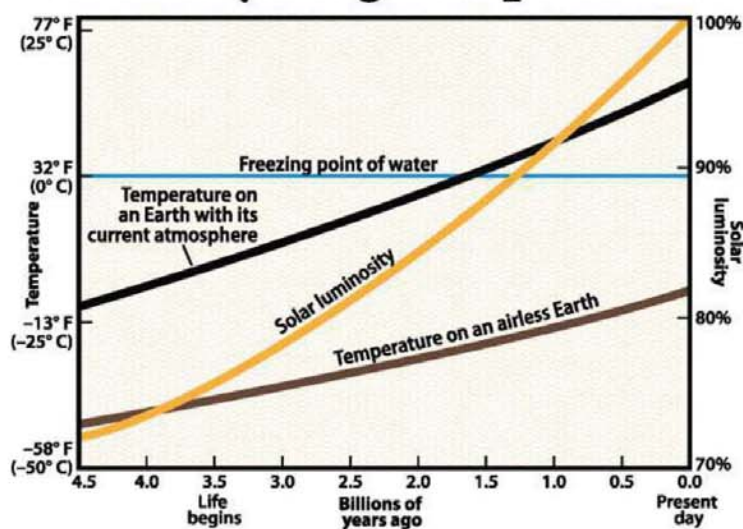
"[Theorists] get into difficulty by saying Earth has to be warm and there may not have been enough greenhouse gases," says Kirschvink. He contends that the greenhouse effect can solve the problem, but he also thinks researchers remain "sufficiently ignorant" about the whole affair and that there's no need to try to pin the solution on a single silver-bullet molecule.

Matthew Johnson, an atmospheric chemist at the University of Copenhagen in Denmark, suggests a different molecule played the key role. He argues that carbonyl sulfide is a superior greenhouse gas to carbon dioxide for warming the young Earth. That's because it absorbs the infrared radiation emitted by our planet better and does so over a broader range of wavelengths.

## On a clear day

The second major difference between Earth's early and current atmosphere is the change in cloud cover. Many researchers think large droplets dominated the clouds of the Archean, and theorists argue that such clouds would not have lingered as long as those

## The faint young Sun paradox



The Sun grows more luminous as its internal structure and composition change over billions of years. The problem: Even with an atmosphere like the current one, Earth's surface temperature should have been far below the freezing point of water for more than half its history. ASTRONOMY: ROEN KELLY

today do. Because most clouds reflect incoming sunlight back into space, the relative lack of cloud cover would have lowered Earth's albedo and let in more solar radiation, warming our planet.

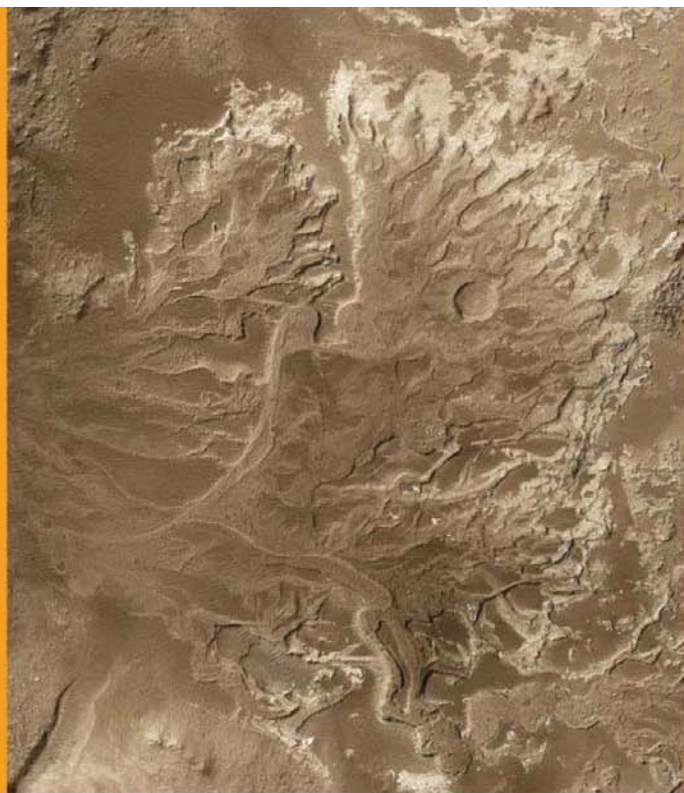
The large droplets were caused primarily by bigger condensation nuclei. These nuclei, upon which water vapor condensed, may have been composed of dimethyl sulfide, a biological byproduct of eukaryotes. And these microorganisms, which have distinct nuclei and cellular membrane structures, likely arose during the second half of the Archean. Thus, the emergence of life may have contributed to a more clement Earth.

It doesn't take something as complex as life, however, to reduce Earth's cloud cover. Friction between the oceans and the crust induced by tides has significantly slowed our planet's rotation rate

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Although it lies much farther from the Sun, Mars also was warm enough in its early history to support liquid water. This fossilized delta at Eberswalde Crater clearly shows past water flow across the martian surface. NASA/JPL/MSSS

since the Moon formed 4.5 billion years ago when a Mars-sized object collided with the proto-Earth. Days during the Archean may have been as short as 14 hours. And computer models show that as Earth's rotation speeds up, cloud cover goes down.

While Earth was spinning faster, so was the Sun. Observations of young Sun-like stars show that despite their lower luminosities, they rotate more quickly and generate more activity than our Sun. According to Nir Shaviv, an astrophysicist at Hebrew University of Jerusalem, a more active Sun would have produced a stronger stream of charged subatomic particles known as the solar wind. And these particles, in turn, would diminish the number of "cosmic rays" that reach Earth from beyond the solar system.

Shaviv contends that fewer cosmic rays would mean fewer ions in the young Earth's atmosphere, resulting in less cloud cover. Still, Johnson says the link between cosmic rays and cloud cover remains controversial, even in the modern atmosphere.

Another factor affecting our planet's albedo is the relative amount of land and water. Geologists think that continents likely covered as little as 3 percent of Earth's surface during the Archean, just one-tenth of what they do now. The expansive dark waters would have lowered the planet's albedo and thus intensified the warming effects of incoming solar radiation.

## Under pressure

But some researchers think clouds and albedos are extraneous to a more significant finding about the Archean — the eon may have had a substantially higher atmospheric pressure than previously believed. And the chief contributor to this increased pressure is the atmosphere's most abundant constituent: molecular nitrogen.

"We now have [nearly] 80 percent nitrogen in the atmosphere," says Colin Goldblatt, a geoscientist at the University of Victoria in British Columbia. "But Earth's early atmosphere would have been some 90 percent nitrogen." Much of this excess nitrogen eventually found its way into Earth's crust and mantle. Some bacteria convert

atmospheric nitrogen into a form that plants can use. This nitrogen gets incorporated into organic matter, which then gets buried and eventually can reach the mantle.

Although nitrogen is not a greenhouse gas in itself, Goldblatt explains that greater amounts of this molecule in the atmosphere increase the pressure, and this makes existing greenhouse gases more effective in absorbing heat radiated from Earth's surface. Kasting adds that larger pressures also make collisions more likely, allowing molecular hydrogen to act as a greenhouse gas and boosting the efficiency of carbon dioxide.

## Blue waters for a Red Planet

Earth isn't the only planet that managed to overcome a faint young Sun. Although Mars is cold and dry today, ample geological evidence shows that the Red Planet was much warmer and wetter in the distant past. And this occurred despite the fact that Mars lies more than 50 percent farther from the Sun and receives less than half the solar radiation that our planet does.

"It took a lot of water to form Mars' valley networks," says Kasting. These systems consist of channels that typically measure 0.6 to 6 miles (1 to 10 kilometers) wide and a few hundred feet (100 to 200 meters) deep. The valley networks have well-developed tributary systems that look remarkably similar to river systems on Earth.

Although an impact with a large comet or asteroid could have raised global temperatures on Mars enough to allow water to flow on the surface temporarily, Kasting says this scenario doesn't fly for some martian features.

"[The impact hypothesis] fails to generate enough water to carve the larger valleys seen on Mars," he says. "It doesn't just fail by a small amount — it fails spectacularly. This can be demonstrated either by simple analogy to features like the Grand Canyon on Earth or by detailed hydrologic analysis."

Kasting and his colleagues have developed new climate models for Mars that show warm average surface temperatures were possible across the globe as far back as 3.8 billion years ago, when the Sun's luminosity was only 75 percent of what it is today. The



This 2.1-billion-year-old banded iron formation consists of distinct layers of sedimentary rock laid down in seawater. Such rocks are among the best evidence that liquid water existed on Earth's surface billions of years ago.

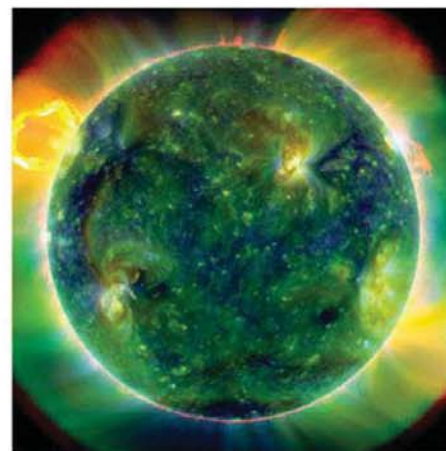
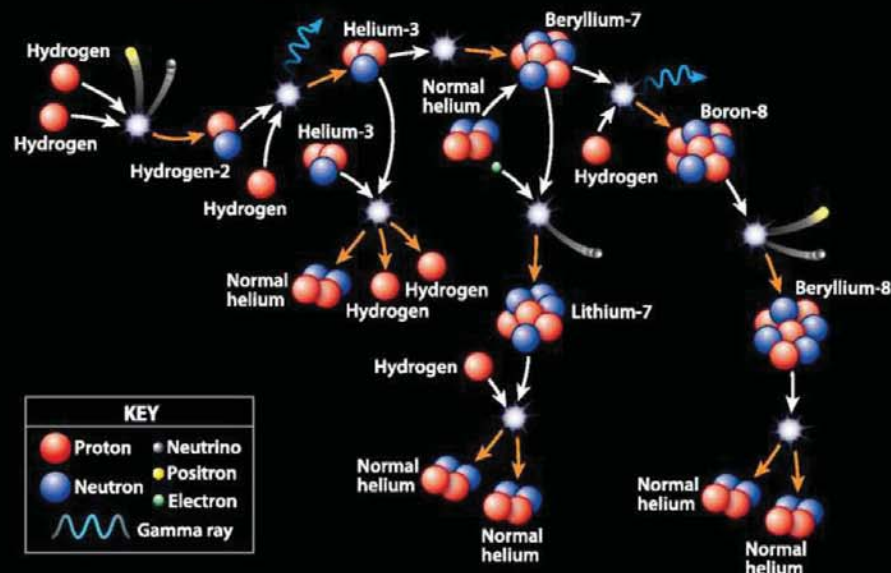
ANDRÉ KARWATH



Black smokers on Earth's seafloor (this one lies near the Galapagos Islands) suggest that life could have remained vibrant even during episodes when thick layers of ice may have covered Earth's surface. UCSB/UNIVERSITY OF SOUTH CAROLINA/NOAA/WHOI



# A changing Sun



The Sun generates energy by converting hydrogen into helium through the so-called proton-proton chain (left). The reaction rate rises as the number of particles in our star's core falls, and that number has been decreasing as the conversion process continues. The result: Today's Sun (above) generates more energy than before, so it is more luminous.  
ASTRONOMY: ROEN KELLY (ILLUSTRATION); NASA/SDO/AIA (PHOTO)

models use a combination of greenhouse gases — including carbon dioxide, hydrogen, methane, and nitrogen — and require a relatively dense atmosphere having at least twice Earth's current atmospheric pressure to get these clement conditions.

Some researchers contend that impacts or interactions with the solar wind would have stripped away a dense martian atmosphere quickly. Still, Kasting says the valley networks we now see on Mars' ancient heavily cratered terrain argue otherwise.

## Toward a solution

So when will planetary scientists finally resolve the faint young Sun paradox? For geophysicists, "It comes down to the geologic record," says Goldblatt. "The further back in time, the fewer rocks are available. But researchers are learning to get more and more out of the rocks that do exist." He says the geologic record preserves the state of Earth's surface fairly well dating back to about 3.5 billion years ago. Although evidence suggests widespread glaciation existed 2.9 and 2.4 billion years ago, there was little in between. Goldblatt thinks the only good explanation is a stronger greenhouse effect during the Archean.

Much of the geologic evidence for water on Earth's surface comes from sedimentary rocks up to 3.8 billion years old. For example, banded iron formations, which consist of alternating thin layers of iron oxides and iron-poor rocks, formed in seawater. Free oxygen produced by blue-green algae combined with dissolved iron to create the iron-rich layers; the opposing layers accumulated during periods when the algae died off from an excess of free oxygen.

Other signs of liquid water include so-called pillow lavas, created when molten lava pushes forth from the ocean floor, and ripple marks in the sediments themselves caused by wave action in Earth's ancient oceans.

Despite the evidence for liquid water, Stevenson says there's nothing in the geologic record that excludes the possibility of significant ice cover at times during this early epoch. He also notes that there's nothing in our understanding of how life originated that requires Earth's entire surface to be warm and void of ice. Some scientists believe that life arose around hydrothermal vents deep under the sea, where surface conditions wouldn't matter.

Planetary scientists can point to an array of greenhouse gases, a lower planetary albedo, or some combination of the two as reasons why Earth remained warm despite a faint young Sun. Darrell Strobel at Johns Hopkins University in Baltimore says that in the broadest sense, geologists seem to think the issue has been solved, whereas astronomers and astrophysicists believe it's still an open

**"The climate models . . . are primitive, and whenever something doesn't work out, [theorists] introduce clouds." — Darrell Strobel, JHU**

question. "The climate models used for Earth's early climate are primitive, and whenever something doesn't work out, like magic, [theorists] introduce clouds," says Strobel. "You can solve the problem with ad hoc assumptions, but whether you have the right solution is another question."

Yale University astrophysicist Sarbani Basu thinks the final answer to this decades-long faint Sun conundrum may have to wait awhile. She believes astronomers first need to compare what we know about the young Sun with how quickly stars in the early stages of their lives lose mass — and precise observations of youthful Sun-like stars are still in their infancy.

Despite the progress scientists have made trying to resolve this issue during the past 40 years, it seems likely that the faint early Sun and its interaction with our own young planet will remain a paradox — or at least a good puzzle — for the foreseeable future. ☛



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