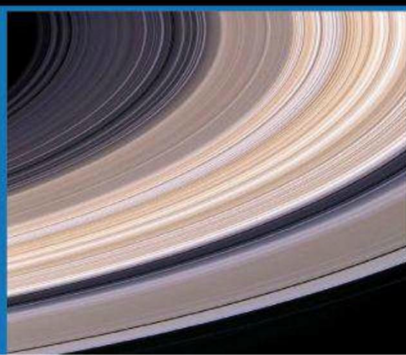
# Tour our wet

**This Pacific Ocean composite image** shows how prevalent water really is on our planet's surface. The view combines data from the Moderate Resolution Imaging Spectroradiometer on NASA's Terra satellite. NASA/Robert Simmon and Marit Jentoft-Nilsen

**Venus** has a deuterium/hydrogen ratio approximately 100 times higher than Earth, which may explain why Venus is much drier than our world. Deuterium is a heavy form of hydrogen that does not escape into space (like hydrogen does) when sunlight splits airborne water molecules into their component atoms. NASA



**The spectacular rings of Saturn** consist mostly of light-colored water-ice, although dark dust can shade those particles. The ice here contains millions of times the amount of water found on Earth. Cassini Imaging Team/SSI/JPL/ESA/NASA

# solar system

## Life-giving water covers seven-tenths of Earth's surface, but where did it come from, and where else can we find it? **by Michael Carroll**

*Day after day,*
*day after day,*
*We stuck, nor breath*
*nor motion;*
*As idle as a painted ship*
*Upon a painted ocean.*

*Water, water,*
*every where,*
*And all the boards*
*did shrink;*
*Water, water,*
*every where,*
*Nor any drop to drink.*

*— The Rime of the Ancient Mariner*
Samuel Taylor Coleridge

British poet Samuel Taylor Coleridge penned *The Rime of the Ancient Mariner* in 1798, but in some ways his poem applies to our solar system today. Modern Mariners, along with Voyagers, Vikings, Pioneers, and other probes, have mapped out a clear picture of water in our solar system. Their surveys unveil an astonishing spectrum of $H_2O$ in a variety of environments, but certainly not a drop to drink.

Instead, the precious fluid reveals its presence in the form of granite-hard ice or poison-laced brews. Although this water does not whet our whistles, it does inform us about the heritage and history of planets and moons and the possibility of life beyond our world.

### Whence came the water?

Astronomers used to think of Earth as the "water world" because salty brine, drinkable liquid, or ice blankets more than 70 percent of our planet's surface. Early observers like Percival Lowell in Flagstaff, Arizona, envisioned waterways on Mars. Others postulated carbonated seltzer-water oceans on Venus. But Earth, they believed, held the record for global seas.

Nothing could be further from the truth. Beyond the orbit of Mars, water seems bountiful. Saturn's rings contain 26 million times as much water as all of Earth's oceans combined. The average comet — and the solar system hosts a lot of them — carries several billion tons of water ice. Water also accounts for 10 percent of the asteroid belt between Mars and Jupiter.

It appears that $H_2O$ has always been abundant in the outer solar system (beyond the asteroid belt), but that's not the case for the region of the inner planets. After centuries of remote observing, half a century of space exploration, and decades of computer modeling, questions remain. Where did all the water on and near Earth come from,

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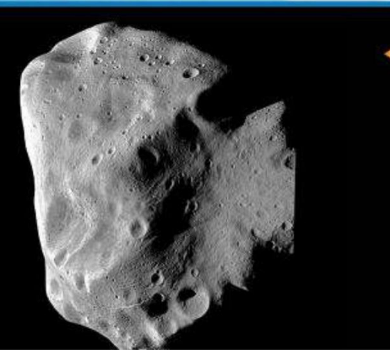
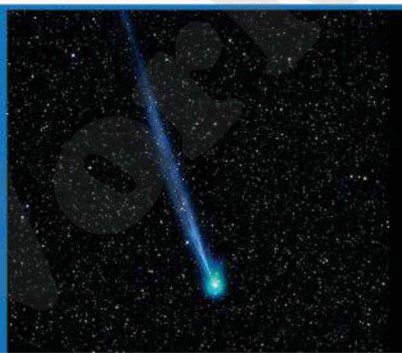
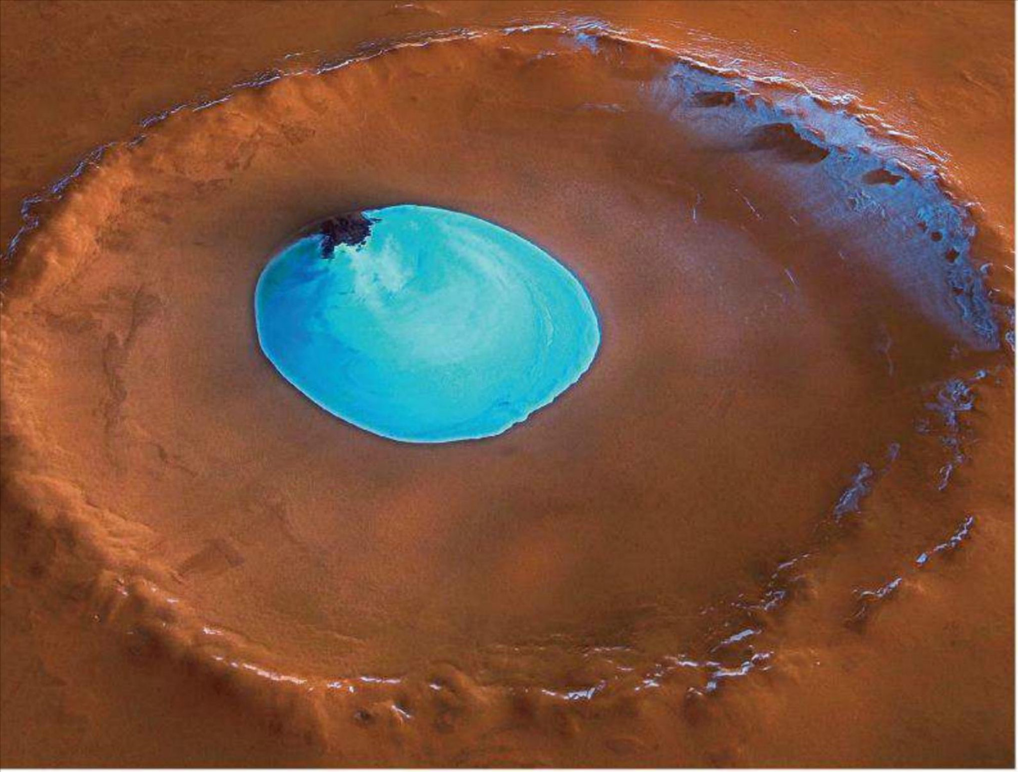


**The possibility that asteroids delivered water to Earth early in the solar system's history is a relatively new idea that not all astronomers agree with. This image shows 21 Lutetia, the second-largest asteroid yet visited by a spacecraft.** ESA



**Comet C/2009 R1 (McNaught) visited the inner solar system in 2010. Early ideas about water on Earth attributed most of it to comets. Recent studies have shown, however, that Jupiter's immense gravitational field would have prevented many more-distant objects from approaching Earth.** Gerald Rhemann



**Mars shows evidence of a watery past,** and many planetary scientists think it maintains vast quantities of $H_2O$ underground. The Red Planet does feature some frozen water on its surface. This image from the High-Resolution Stereo Camera aboard the Mars Express orbiter revealed a huge patch of water ice inside a crater near Mars' north pole. ESA/DLR/FU Berlin (G. Neukum)

and why isn't there an even distribution of it among the terrestrial worlds?

The answer lies, in large part, within our 4.6-billion-year planetary history, says astrobiologist David Grinspoon of the Museum of Nature and Science in Denver, Colorado. "There are a lot of ways the inner planets could have gotten their water. The original accretionary material may have had enough intrinsically. Then you've got the possibility of comet and asteroid fluxes."

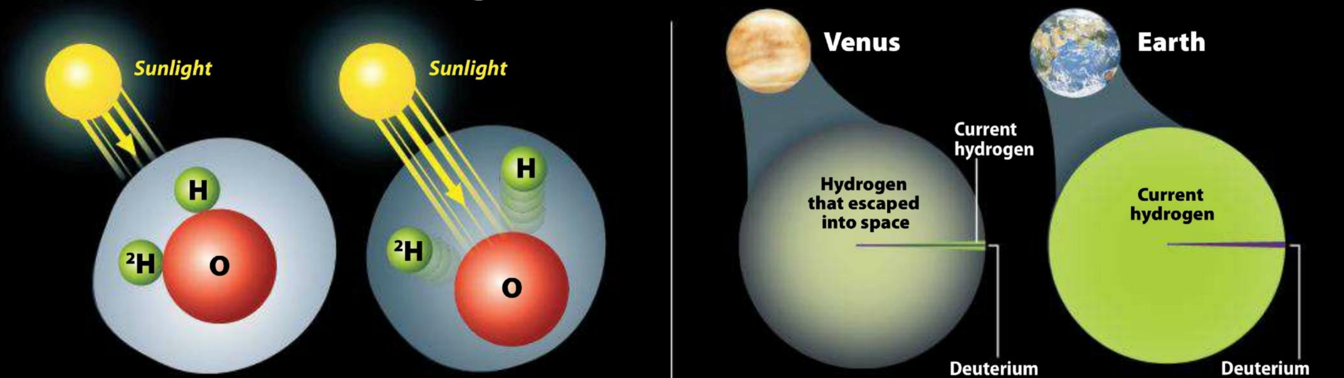
Grinspoon calls the idea of asteroid-derived water an "interesting wrinkle" in the cosmic water story. Planetary dynamicist Harold Levison has been fleshing out the idea using powerful computer simulations at the Southwest Research Institute in Boulder, Colorado. "The ideas are in flux, but the standard idea is that you get a gas and dust disk forming," says Levison.

He continues: "The dust settles toward the midplane. It turns itself into planetesimals that eat each other to form the planets. Outside of this magical boundary called the 'snow line' — the region far enough from the Sun for water to condense — there are a lot more solids than inside, so the cores of the giant planets form first. Because of the gravitational influence of Jupiter, asteroids are kicked toward the inner system, where they deliver water to the terrestrials."

This scenario suggests that the inner solar system formed within relatively dry conditions, while the outer asteroid belt contained a lot of water, with up to 10 percent in the form of hydrated minerals. Levison's models suggest that the majority of Earth's water came from the outer asteroid belt, perhaps in the form of a small number of water-rich asteroids.

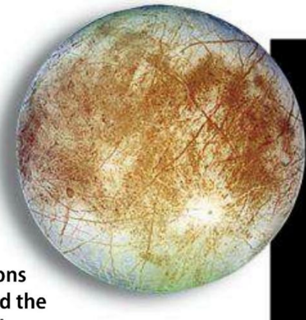
This might explain why Venus is so much drier than Earth. Both planets formed in the same region of the primordial solar cloud, but Earth has 100,000 times the water of its sister planet. Grinspoon asserts that, "If it's a small number of [asteroids that delivered water], then it makes the argument less compelling that Venus and Earth should have started out with the same amount. This way, Venus could have gotten less water than Earth. Venus could have even started out with 10

## Where did Venus' water go?

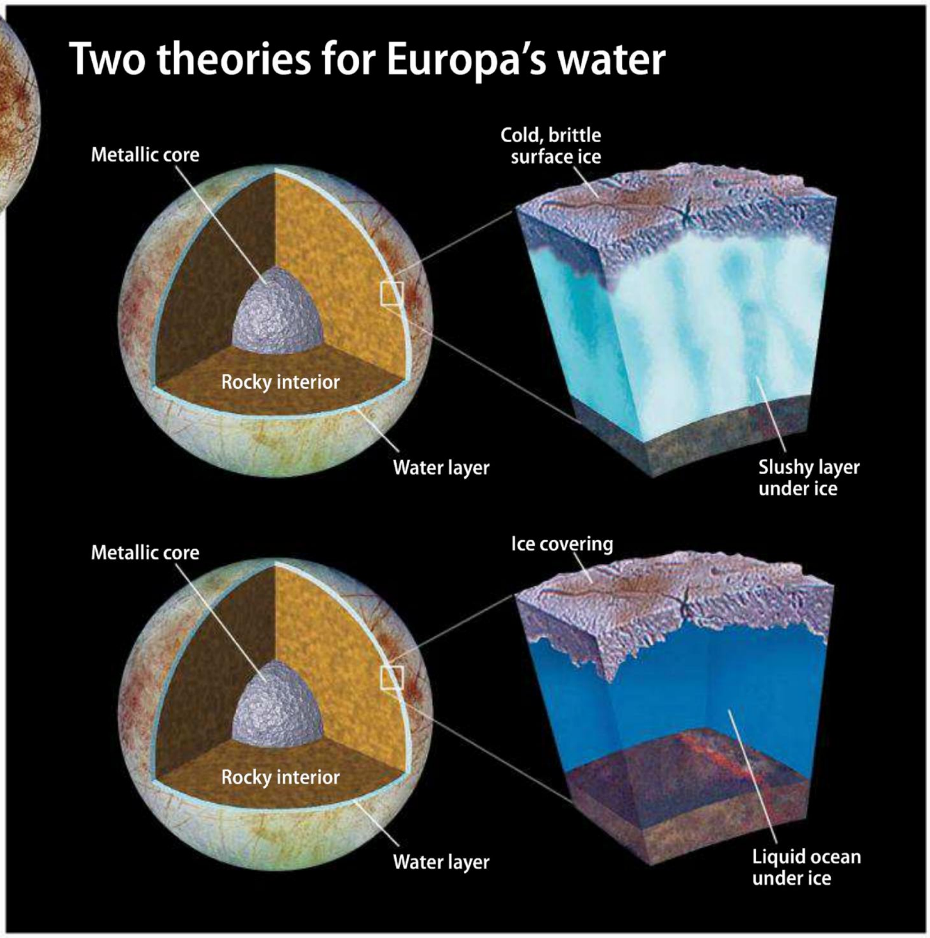



**As sunlight strikes** a molecule of semiheavy water (left), the blast of energy splits the molecule into its component atoms, oxygen (O), hydrogen (H), and deuterium ($^2H$). Because hydrogen is the lightest element, most of it will escape into space. Deuterium, however, is about twice as heavy, and planets the size of Venus and Earth can retain most of it. In regular water, approximately one molecule in 3,200 is semiheavy water. *Astronomy*: Roen Kelly

**Venus and Earth** may have started with similar amounts of water in their atmospheres. This comparison shows that the current amount of deuterium (heavy hydrogen) in the atmospheres of the two planets is similar. But the hydrogen remaining in Earth's air (mainly combined with oxygen as water molecules) is 100 times greater than on our sister world. And Venus has only 1⁄100,000 the amount of water that our planet retains. *Astronomy*: Roen Kelly



**Beneath the icy surface** of Jupiter's moon Europa, astronomers think there lies a layer of either slushy ice (far right, top) or liquid water kept warm by gravitational interactions with its host planet and the other large moons of that system. If the surface ice is between 6 and 18.5 miles (10 and 30 kilometers) thick, then Europa's liquid ocean would be approximately 60 miles (100km) deep and hold twice the water contained in all of Earth's oceans. NASA/Illustrations by *Astronomy*: Roen Kelly




times the water of Earth. That's how ignorant we are at this point."

But all is not well with the current models of planetary formation. The most widely accepted scenario of solar system evolution describes all of the planets forming in the outer regions of the asteroid belt. Gravitational interactions with Jupiter then kicked newly formed planets out of the belt. But if planetary embryos developed within the asteroid belt, Levison warns, "You would expect to see gaps. You don't. [The asteroid belt is] amazingly smooth. That screams for the idea that the asteroid belt never had a lot of mass. If so, then all the water on Earth couldn't have come from there." Recent research suggests that if the asteroid belt were massive enough to supply all of Earth's oceans, the asteroid Vesta would be far more battered than the Dawn spacecraft has revealed it to be.

The inner solar system is also hiding water at the poles of Mercury and the Moon. Water cannot exist for long in a vacuum unless it is covered by dirt, and it certainly cannot survive solar radiation in an airless void. But several deep craters on both Mercury and Luna never experience sunlight. Radar shows the signature of water on both these small worlds, and the LCROSS spacecraft excavated evidence of lunar water when it smashed into the Moon's south pole.

## The clue that remains

One indicator of just how much water a planet used to have — and thus how much it might have lost — comes from the ratio of deuterium to hydrogen in its atmosphere. Deuterium is a heavy form of hydrogen whose nucleus contains a neutron in addition to a proton. When solar energy splits water into hydrogen and oxygen, the lighter hydrogen escapes to space, leaving the oxygen behind to combine with other elements. But something else is stranded in the air: deuterium. Its level remains nearly constant while the lighter hydrogen atoms escape to space. The amount of deuterium left behind provides an excellent gauge for lost hydrogen and, by inference, lost water.

In 1978, NASA's Pioneer Venus orbiter recorded high deuterium levels in the venusian atmosphere. "The deuterium to hydrogen ratio on Venus is dramatically higher than on Earth," says Grinspoon, "roughly 100 times higher, which reflects a lot of hydrogen escaping." Grinspoon and other researchers believe that this loss equates to water escaping because water is the dominant hydrogen-containing molecule in the inner solar system. The ratio of deuterium to hydrogen (d/h) provides a clue that Venus' history is the story of lost water.

Did Venus, in fact, ever have an Earth-like ocean? Grinspoon is cautious. "Clearly, Venus was formed wetter than it is today, and there's been a lot of water loss," he says. "Now, whether there's been a full ocean of water loss and Venus formed as wet as Earth, that's something we don't know yet."

Atmospheric scientists have developed various scenarios by which planetary dehydration can occur. Models of a runaway greenhouse effect posit that Venus could have lost up to a full ocean's worth of water. But there are kinds of water loss that do not leave the "isotopic signature" of d/h ratios.

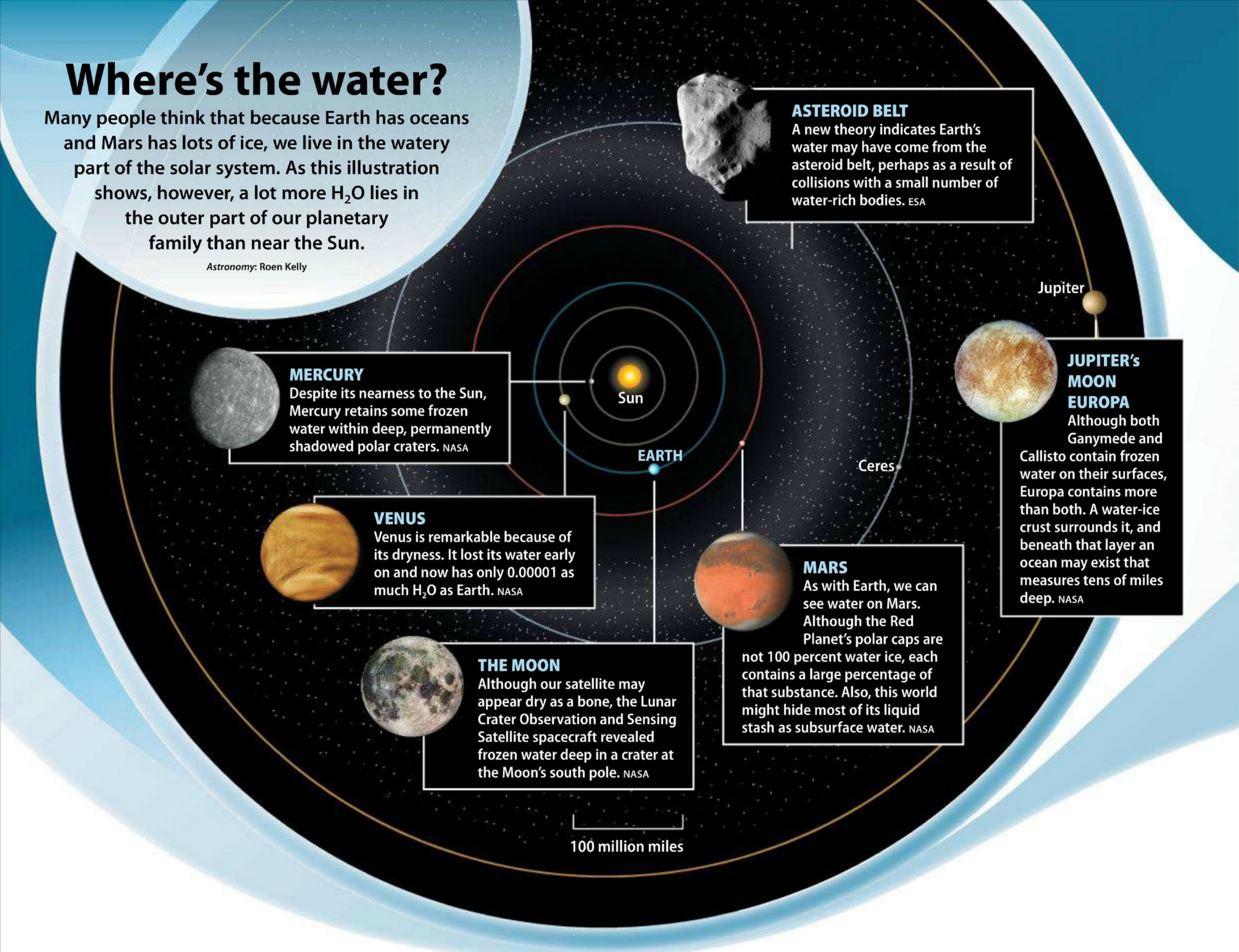
Venus could have lost most of its water in what experts call hydrodynamic escape. In this process, a flow of expanding gas and water drift away from the planet gradually as the atmosphere develops. Hydrodynamic escape would not leave a d/h fingerprint. In addition, a number of "loss processes" do not depend on heat — processes operating

Because of the gravitational influence of **JUPITER**, **ASTEROIDS** are kicked toward the inner system, where they deliver **WATER** to the terrestrials.

# Where's the water?

**Many people think that because Earth has oceans and Mars has lots of ice, we live in the watery part of the solar system. As this illustration shows, however, a lot more $H_2O$ lies in the outer part of our planetary family than near the Sun.**

*Astronomy*: Roen Kelly




even today. For example, Venus' abundant sulfur particles attract oxygen atoms from water, freeing the hydrogen to escape.

The multitude of possible venusian pasts and how much water it had leaves scientists scratching their brainy scalps. "Do we see enough to prove to us that Venus had Earth's ocean-amounts of water?" asks Grinspoon. "Absolutely not. The challenge of Venus is that it's so hard to get direct evidence. We have not explored Venus nearly as thoroughly as we have Mars, for example, because it's a lot harder to explore."

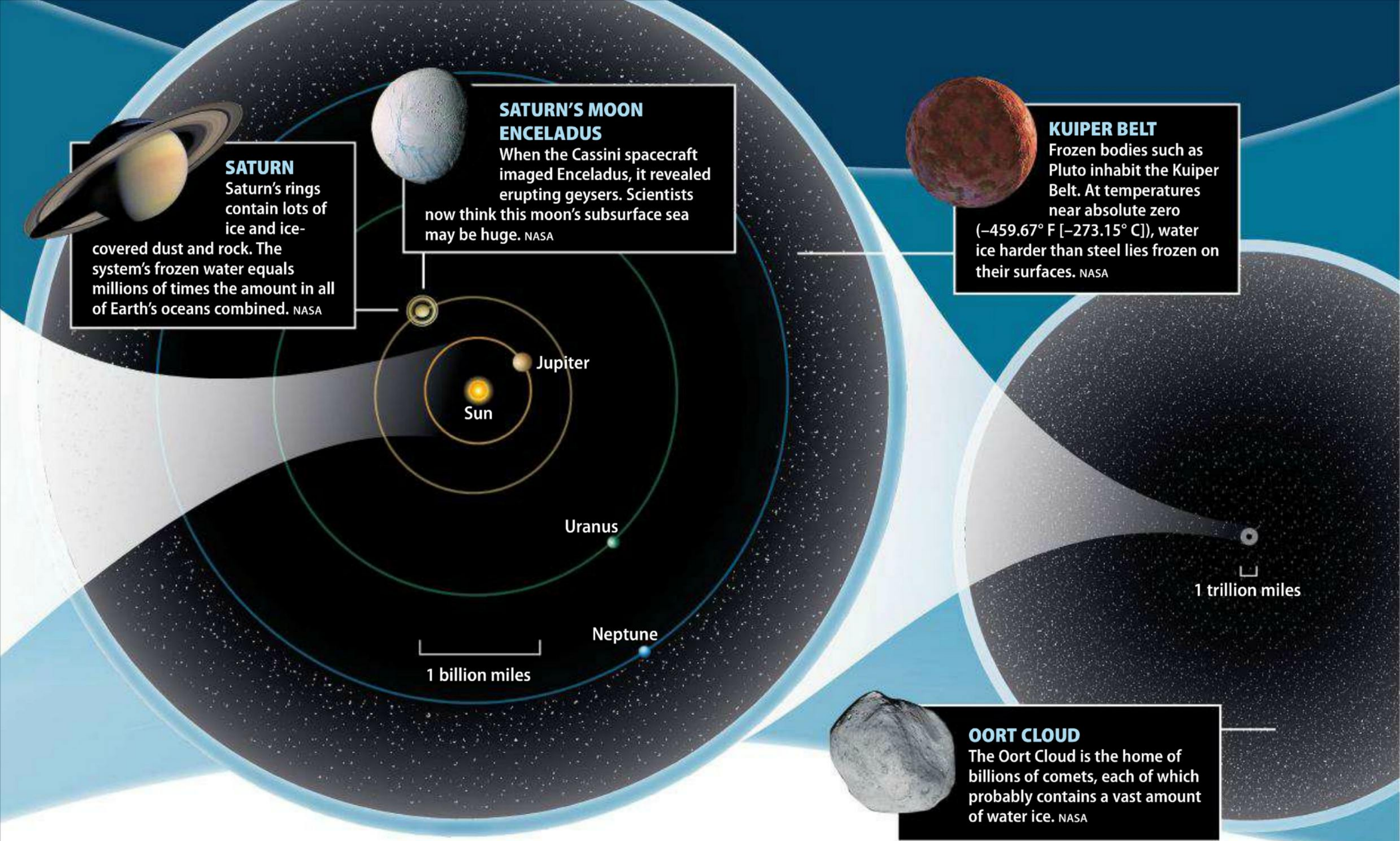
Still, Grinspoon suspects that Venus was once swathed in global oceans. "In my view, the most likely scenario is that Venus started out with a similar water inventory to Earth, and then lost it," he says. "Venus' water vapor in the air is equivalent to what is in Earth's atmosphere, but there's no huge, condensed reservoir on its surface. The d/h ratio tells us that Venus had at least 100 times as much water as it does now."

But the terrestrial planet water story doesn't end at Venus. Closer to that water-giving asteroid belt lies Mars, and it's a place we know more about.

The story of martian moisture ebbs and flows like the tide. Despite astronomers' knowledge of the polar ice caps, early robotic explorers returned images of desiccated craterscapes and vast deserts. Only later did the Mariners and other probes reveal networks of dry river valleys, many trending north toward great basins, which may well have contained shallow seas. The Opportunity and Spirit rovers studied rocky records of brine that perhaps suggest long-standing saltwater lakes eons ago. Even today, spacecraft hint at great quantities of frozen subsurface water.

Mars lost its water primarily because of two factors. The first is that the planet simply doesn't have enough gravity to hold on to as much atmosphere as its larger siblings. The second factor concerns large impacts by asteroids and comets that blasted its atmosphere into space. Because of its low gravity, Mars was much more vulnerable to such impact blow-off than Earth or Venus, although it happened on them, too.

For some time, scientists believed that a large amount of **EARTH'S WATER** came from **COMETS** from the outer solar system.





**Ganymede,** another satellite of Jupiter, is the solar system's largest moon. Half of its surface — the younger, brighter terrain of Harpagia Sulcus (right) — is ice-rich, and the other portion — ancient, dark Nicholson Regio (left) — is rocky with lots of impact craters and fracture zones. NASA/JPL/DLR


**Jupiter's Callisto** is similar to Ganymede: equal parts rock and ice. The impact structure shown in this image is Asgard. The bright crater at the top is Burr. The ice excavated by younger craters contrasts sharply with the darker, redder coatings on Callisto's older surfaces. NASA/JPL/LPL/Univ. of Arizona

## Frosty frontiers

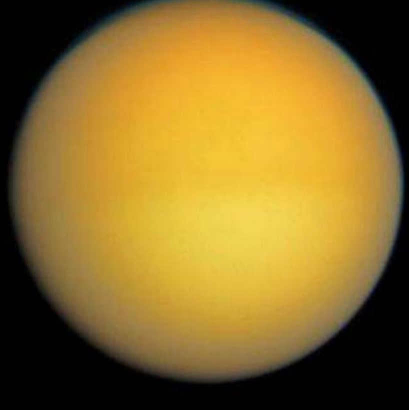
Beyond the asteroid belt's snow line, where comets are plentiful and water freezes to the consistency of stone, water may have remained at levels similar to current ones. Nevertheless, mystery saturates this soggy story even that far out.

For some time, scientists believed that a large amount of Earth's water came from comets from the outer solar system. But today, researchers doubt this model because the gravity of Jupiter acts as a significant barrier to more-distant objects falling sunward. "It's got the biggest baseball bat in the solar system," says Levison. "It's hard for that stuff to get past it into the inner solar system." Additionally, the majority of comets have d/h ratios quite different from Earth's, while the d/h ratio coming from the asteroids resembles earthly water.

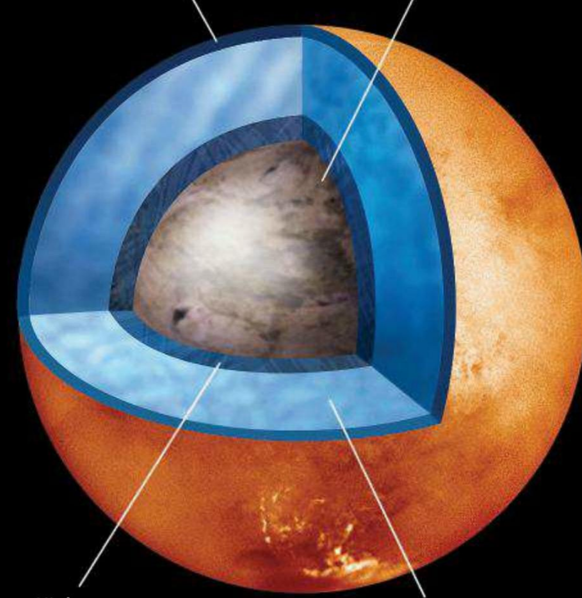
While the atmospheres of Jupiter and Saturn, and the cores of Uranus and Neptune, contain $H_2O$, the ancient waters of the outer worlds also have settled into a variety of icy moons. Within their cryogenic mantles, these natural satellites may have mystery oceans ranging from subsurface lakes

## Inside Titan

Titan's interior structure remains a mystery. But planetary scientist Giuseppe Mitri of NASA's Jet Propulsion Laboratory has developed a theoretical model of Titan's interior that describes one possibility. In Mitri's model, Titan has a warm rocky core surrounded by a layer of compressed ice about 1.4 times denser than common ice. (The compressed layer formed as Titan was cooling and contracting in the early solar system.) An ocean of water and ammonia underlies Titan's frozen outer crust.



**Titan** **is Saturn's largest moon and the only satellite in our solar system with a thick atmosphere.** NASA/Illustration: *Astronomy*: Jay Smith




to vast seas. A gravitational cotillion between satellites and their planets called orbital resonance warms the ice in these moons. When the relationship is just right, the gravity of the two bodies heats both interiors. Many of the moons in the outer solar system endure such resonances.

The poster child for extraterrestrial oceans — and perhaps extraterrestrial life — is Jupiter's moon Europa. Slightly smaller than Earth's Moon, a water-ice crust swaths Europa. That crust is not completely frozen, however. Beneath the surface lies an ocean perhaps 60 miles (100 kilometers) deep. "To understand the processes that have formed and shaped the solar system, water is very key," says Senior Research Scientist Robert Pappalardo of NASA's Jet Propulsion Laboratory. "It's the most common volatile. To understand whether the ingredients for life are or were present, that's in large part a search for water and the history of water."

Europa may not be a snorkeler's paradise, however. Its waters probably contain brines and chemistry that are less Pacific and more battery acid. Pappalardo and his colleagues get clues from the surface. "At Europa, infrared spectroscopy tells us that there are hydrated minerals, which means there's probably salt that may come from the ocean," he says. "There's sodium and potassium that's got to relate to those ocean contaminants. We see peroxides from radiation hitting the ice, and sulfur dioxide."

While nearby Io is devoid of water, dried by eons of volcanic activity, the other two large moons of Jupiter have plenty of moisture. Planet-sized Ganymede and Callisto feature thick ice crusts overlaying rocky cores. Studies of their magnetic fields imply the existence of oceans buried deep under the ices. Dark organic material blankets their surfaces, probably deposited in a steady rain from the jovian environment.

"On Europa, we've not observed the dark organics that we've seen on Ganymede and Callisto," Pappalardo says. "But what we *don't* see on Europa is what's interesting. It has none of these organics. On Europa, what wasn't destroyed by radiation was incorporated into the ocean. There's been a rain of organic materials over time, and Europa cleans them off into the interior." These organics combine with the strange brew simmering beneath Europa's ice sheet, adding to the promise of life on this moon.

Farther out, water also dominates the moons of Saturn, Uranus, and Neptune. One of them, Saturn's moon Enceladus, has

**Iapetus has a dark hemisphere that reflects only 4 percent of the light that hits it and a bright ice-covered half that reflects nearly all the light striking it. This image from NASA's Cassini orbiter revealed the first glimpse of the bright trailing hemisphere of this moon of Saturn.** NASA/JPL/SSI

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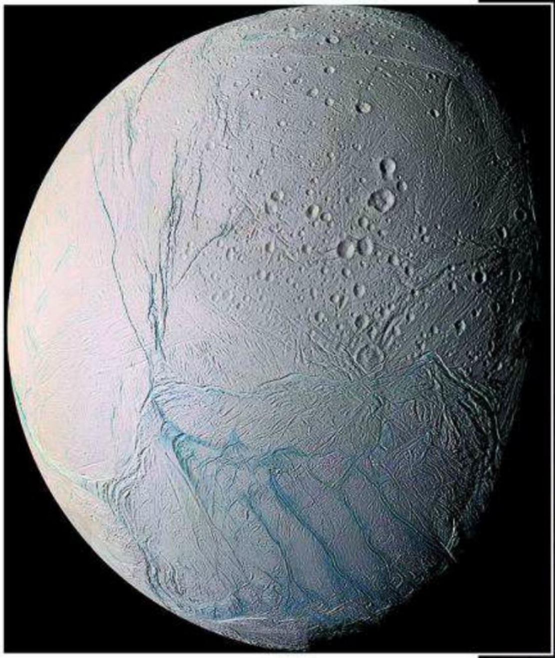
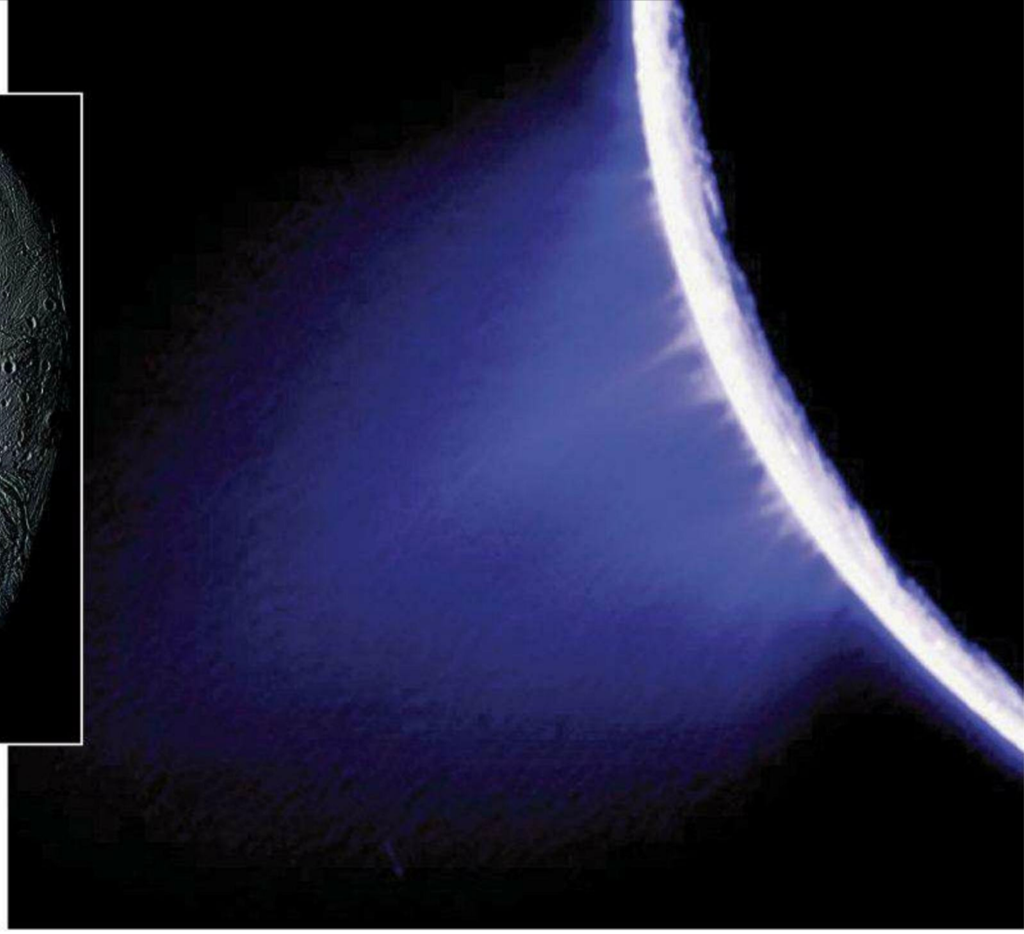
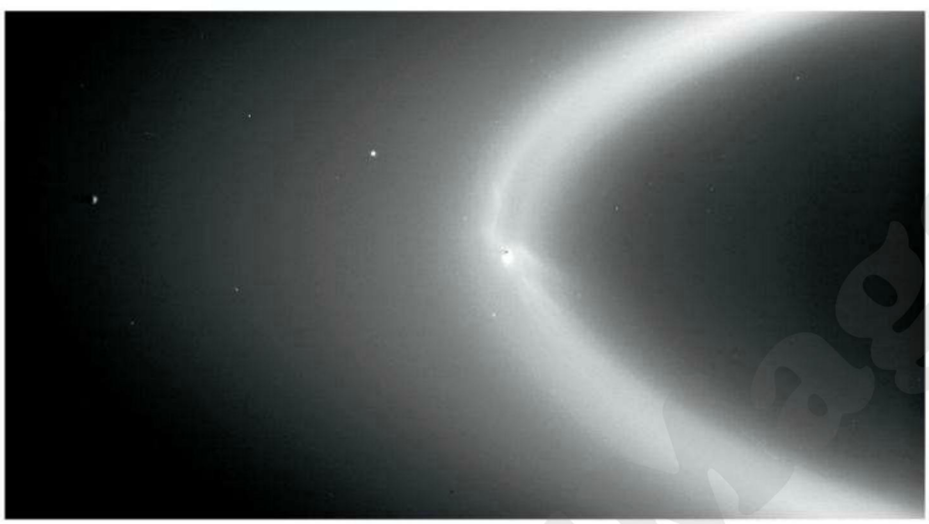


**The celebrated "tiger stripes"** of Enceladus adorn this color-enhanced portrait taken by NASA's Cassini orbiter. The stripes mark fractures in the moon's icy crust where plumes of warm material erupt to elevations of 100 miles (160 kilometers) or more. NASA/JPL/SSI



**Cassini imaging scientists** enhanced this color snapshot of Enceladus' edge to highlight individual jets spewing ice particles, water vapor, and organic compounds into space. The scientists identified eight individual jets feeding a larger plume. NASA/JPL/SSI



**Microscopic ice particles** spewing from the surface of Enceladus fill Saturn's E ring. The moon is visible as the bright white spot amid the fog of ring particles. NASA/JPL/SSI

the most obvious evidence of subsurface water: erupting geysers. Theorists first thought shallow lakes might be at the root of the geysers, but some now believe that Enceladus' waters run deeper.

"At Enceladus, we're seeing salt in the plumes from the dust detector aboard the Cassini spacecraft," says Pappalardo.

Some researchers believe that geologic forces deep within the moon are spraying an interior sea out into space as plumes containing salt. To get the salt into the plumes, experts argue, interaction must occur between the substantial water below and the surrounding minerals. Saturn's largest moon, Titan, has an abundance of water, too, but its $H_2O$ resides in its landscape as rock-hard ice.

The larger icy moons orbiting Uranus and Neptune record past geologic catastrophes. Across their cratered landscapes spreads evidence of earlier faulting and bizarre surface flows. At Uranus, Miranda stands as a prime example to Pappalardo. "Miranda shows evidence of past activity, and it's about the same size as Enceladus. The uranian system wouldn't have long-term resonances like those at the saturnian or jovian systems, where the satellites get locked into resonance, but because they are small moons, they may have passed through resonances and been active for a short amount of time and then died out."

Neptune's largest moon, Triton, is probably a captured Kuiper Belt object that underwent intense heating during capture. It may still have liquid water within it. Vast amounts of water orbit the Sun within the Kuiper Belt, and beyond it circle the comets of the Oort Cloud.

Indeed, with few exceptions, it seems wherever astronomers look in our solar system — from the hot terrestrial worlds to the outer fringes bordering interstellar space — water is plentiful. And there's no reason to think that we are unique in this respect. Water surely exists in planetary systems throughout the universe. And if there's water, can life be far behind?