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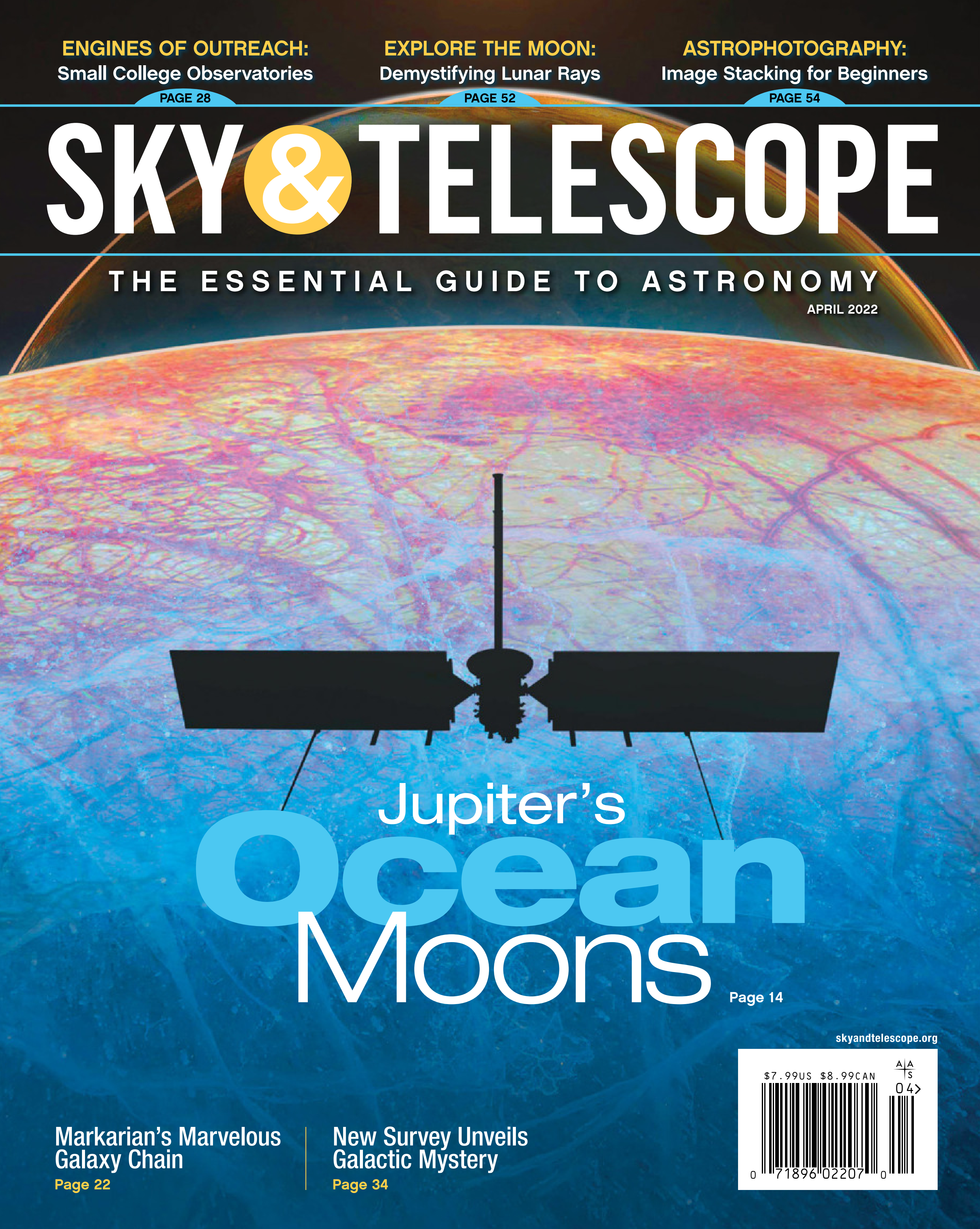
APRIL 2022



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 by Benjamin Skuse

WHAT LIES BENEATH THE ICE? The Europa Clipper spacecraft will explore Europa's icy geology, as well as look for leaks from its subsurface ocean.

NASA / JPL-CALTECH

Ocean Underworlds

Two missions launching soon will take a close look at some of our best bets for finding alien life in the solar system — Jupiter's icy moons.

Ask any amateur astronomer and they will likely tell you that of all the planets in the solar system, Jupiter holds a special place in their heart. But for me and many others, the gas giant itself plays second fiddle to the Galilean moons merrily dancing around it. Even when viewing them through wobbly binoculars for the umpteenth time, there's still a giddy rush of joy in seeing energy and movement in the sky as the moons change position, in having the ability to track the moons' orbits, and in knowing I'm viewing the same scene and following the first steps that helped Galileo Galilei more than 400 years ago come to the conclusion that the universe doesn't revolve around us.

For showing that worlds can orbit other bodies, not just Earth, the Galilean moons — Io, Europa, Ganymede, and Callisto — played a key role in humanity's realization that our tiny rock is just a small part of something much, much bigger. But this might not be the only profound truth they harbor. Though all their surfaces seem harsh and barren, Jupiter's four large moons might just offer hope of finding other life in the solar system.

During their 1979 Jupiter flybys, NASA's twin Voyager spacecraft swept past the Galilean satellites, snapping pictures that revealed hugely diverse worlds, from the bristling volcanic activity of Io to the dead cratered surface of Callisto. But it was the images of Europa that would lead scientists to wonder about potential alien life. Europa's terrain was riddled with wide, brown, crack-like streaks — the first visible hint that something might be going on below the surface.

Twenty-seven years later, NASA's Galileo mission began taking measurements of Jupiter's magnetosphere near Callisto and Europa. After analyzing the data, scientists found something startling. The periodic planetary magnetic field felt by the moons due to Jupiter's rotation was inducing weaker magnetic fields at Europa and Callisto. The only way this could happen was if the moons contained a huge amount of conductive material, and the best match to the data was liquid salt water. With gravity measurements from Europa backing up the magnetic field results, scientists tentatively concluded that Europa and Callisto — and later, Ganymede as well — likely host ocean underworlds beneath their protective icy shells.

The Key Ingredients

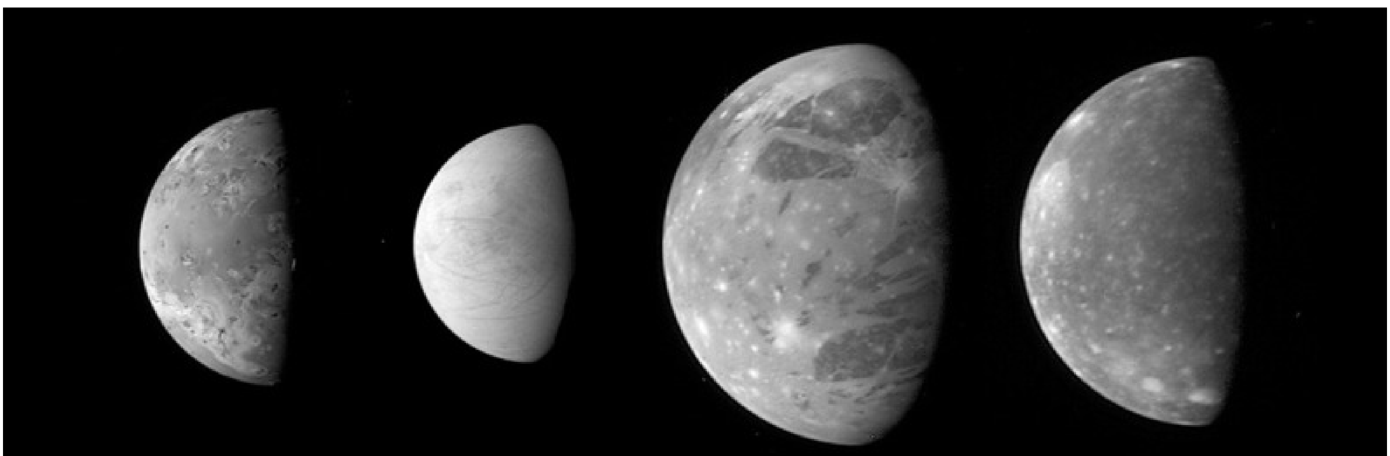
Why this discovery was important is simple: no water, no life (at least, as we know it). Among other key properties, water is essential because it is an amazing solvent. More substances dissolve in water than in any other liquid, meaning it enables important nutrients to pass into a cell and toxic substances such as waste products to be shuttled out.

Given water's key life-giving role, Io — the closest moon to Jupiter and the most volcanically active body in the entire solar system — represents the longest shot among the Galilean moons for hosting extant life. Blasted by radiation from Jupiter, any liquid water that might have existed on Io in the distant past was stripped from the surface long ago; only places such as the moon's subsurface lava tubes might still host a habitable environment.

Discarding Io (and Jupiter itself, plus the 75 other smaller Jovian moons) leaves just three hopes for finding life in the Jovian system: Europa, Ganymede, and Callisto. All three are thought to have an abundance of liquid water beneath their icy shells. How do we whittle down the contenders to give us the best chance of finding life?

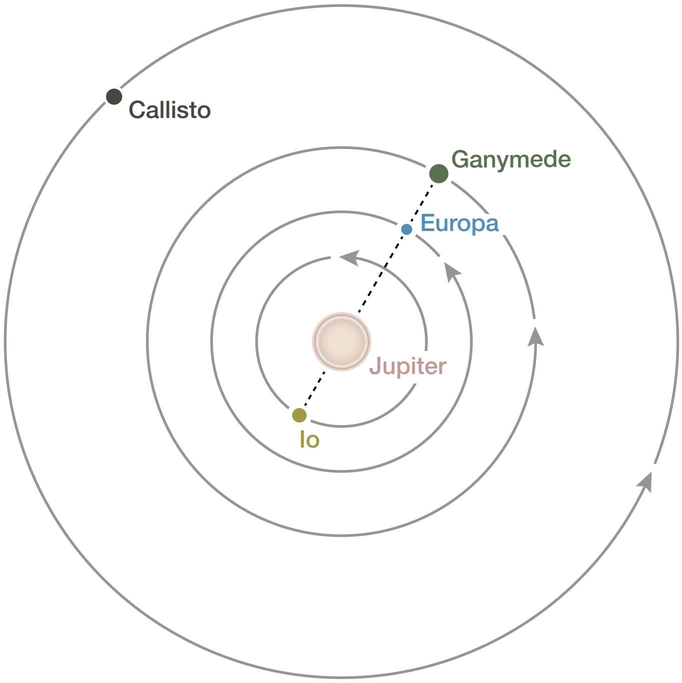
To answer this question, we need to get to the nub of what is absolutely essential to life here on Earth. And when we do, the list is surprisingly short. Given enough time, life appears to only need water, a source of energy, and a handful of essential elements.

On our world, most life ultimately takes its energy from the Sun, which is not an option on a distant ocean world covered by a thick layer of ice. But some *extremophiles* are known to harvest their energy from hydrothermal vents deep underwater (*S&T:* Jan. 2020, p. 34). Some scientists even think life on Earth originated around such vents. With a

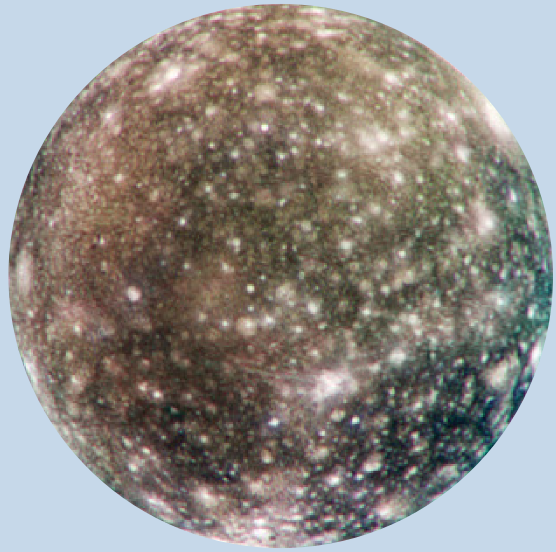


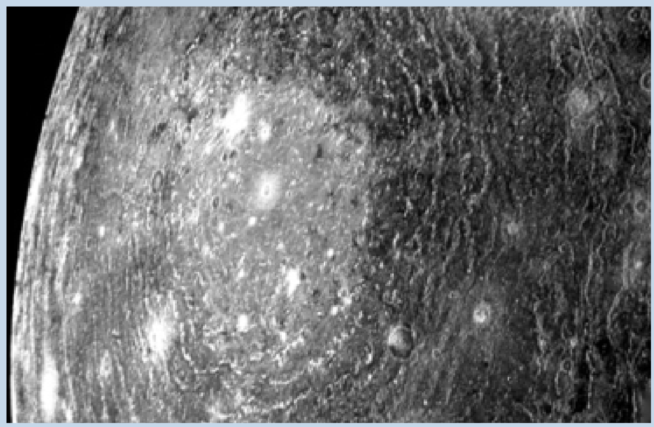
ALL IN THE FAMILY The Pluto-bound New Horizons spacecraft took these images of the Galilean satellites during its 2007 flyby. The images are scaled to the moons' relative sizes and placed in order of distance from Jupiter, left to right: Io, Europa, Ganymede, and Callisto.

NASA / JHU APL / SWRI



▲ **RESONANCE** The Galilean moons orbit Jupiter closely, and the three inner satellites travel in resonant orbits: For every orbit Ganymede completes, Europa completes two and Io four. When Europa and Ganymede are closest to each other, Io is always on the opposite side of Jupiter.





▲ **CALLISTO** *Top:* This color image from the Galileo spacecraft shows bright impact scars on the dark surface of Jupiter's most distant Galilean moon.

▲ **BIG SMACK** *Bottom:* Voyager 1 snapped this image of a 300-km-wide impact basin on Callisto in 1979. The multiple rings that surround the basin indicate that the surface is less dense and stiff than, say, the crust of the Moon.

suitable energy source to heat their cores, these moons too could host vents teeming with life.

In terms of essential elements, there are six that make up 98% of most life here on Earth: carbon (C), hydrogen (H), nitrogen (N), oxygen (O), phosphorus (P), and sulfur (S), or CHNOPS for short (pronounced "schnapps," like the liqueur). If the icy Galilean moons show signatures of these elements and have a way to produce energy, it's a fair bet they could host life.

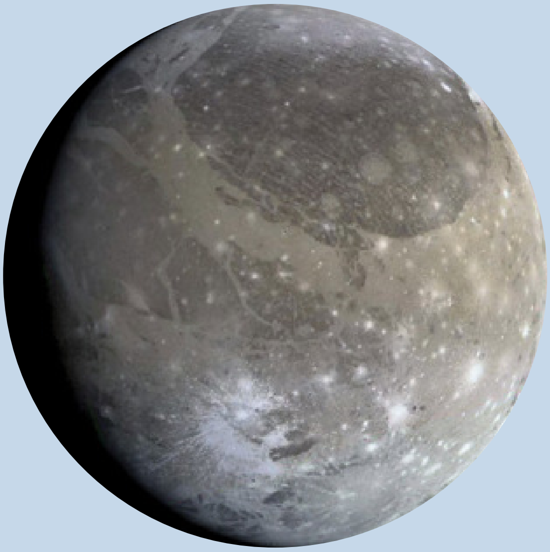
Callisto: The Dead Surface

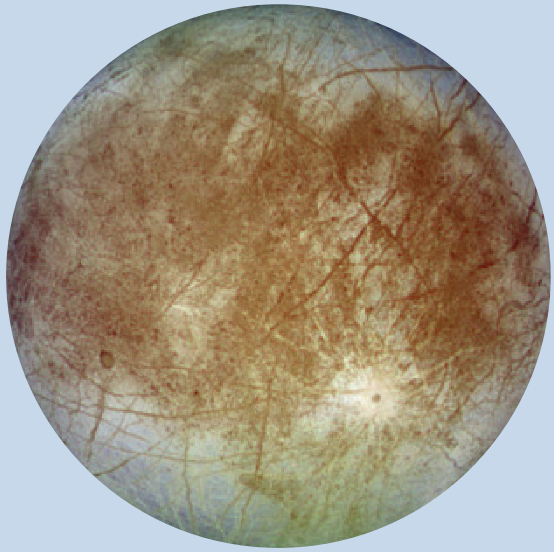
When we assess what we know about each of the three icy Galilean moons, Callisto stands out as a rank outsider in the "potential for life" pecking order. Its rocky, icy surface is the oldest and most heavily cratered in the entire solar system, with no large mountains and no evidence of volcanic or tectonic activity.

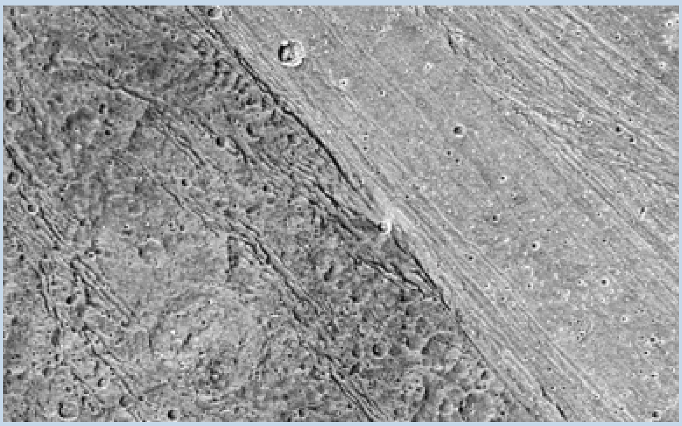
In large part, Callisto's dead appearance stems from a lack of energy. Just as the Moon's gravitational tug creates ocean tides here on Earth, the Galilean satellites experience tidal forces from Jupiter. In their slightly elliptical orbits, these moons are pulled by time-varying gravitational forces that stretch and squeeze them as they move closer and farther away from their host planet, like pinching a tennis ball from the top and bottom with one hand and then from the sides with the other repeatedly. This constant bulging in different directions causes friction, which creates internal heat.

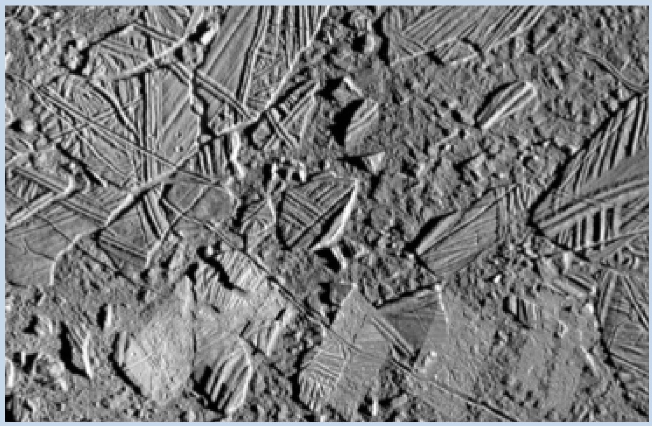
Io, Europa, and Ganymede gain an extra energy boost from their huge gravitational influence on one another, due to being in *resonant orbits* around Jupiter. Ganymede's 7.2-day orbit is two times Europa's 3.6-day orbit, which in turn is twice Io's 1.8-day orbit. This synchronization reinforces Jupiter's gravitational tug, creating much bigger tidal effects. Being the farthest from Jupiter and not being part of the resonant gang means Callisto experiences little tidal heating. As a result, the case for Callisto's ocean receiving enough energy to support life is weaker.

What's more, Callisto might not even have a subsurface ocean. "We can interpret Callisto's gravity [measurements] to be consistent with an ocean," says planetary scientist Wil-









▲ **GANYMEDE** *Top:* This color composite shows Jupiter's largest moon as seen by the Galileo spacecraft. Ganymede has a complex surface, its darker, heavily cratered regions striated by lighter, more pristine regions that might be due to past cryovolcanism.

▲ **TERRAIN BOUNDARY** *Bottom:* The ancient, dark terrain of Nicholson Regio (left) lies alongside the smoother Harpagia Sulcus. Perhaps the bright regions have been smoothed by tectonic processes?

▲ **EUROPA** *Top:* This Galileo image shows the smallest of Jupiter's ocean moons in approximately natural color. The myriad lines are fractures in the crust, some stretching more than 3,000 km long.

▲ **CHAOS** *Bottom:* In several places on Europa, ice appears to have broken up, shifted, and even tipped over in a surrounding liquid or slush that then refroze as a solid but brittle surface. This mosaic shows the Conamara Chaos region.

liam McKinnon (Washington University). "But it also could simply have a core that is sufficiently lumpy that it gives the very weak gravity signal that Galileo saw." And perhaps the magnetic measurements come from the moon's ionosphere, mimicking a conductive subsurface ocean, he adds. "We simply don't know."

Despite these doubts, Callisto is not completely ruled out. It hosts a rich store of essential elements, revealed by carbon dioxide, hydrogen, and oxygen detected in its thin atmosphere. In addition, its putative dark ocean could be heated to some extent by the decay of radioactive elements in the moon's core. "I think it's very mysterious," says planetary scientist Olivier Witasse (European Space Agency). "This moon, which seems to be dead from the geological point of view, could be interesting in terms of habitability."

Ganymede: The In-Betweener

Witasse is the project scientist of ESA's Jupiter Icy Moons Explorer (JUICE) mission, which will launch in 2022 and travel for almost seven and a half years to reach the Jovian system. JUICE will peer over Callisto and Europa, as well as Jupiter itself. But the mission's main goal is to interrogate the habitability of Ganymede from above.

Bigger than Mercury, Ganymede is the largest moon in the solar system. Its surface has a split personality. Darker regions are heavily cratered like Callisto, suggesting they have not changed in billions of years. Lighter regions look geologically younger, like Europa, with puzzling geology and fewer craters. Scientists have proposed many explanations for these lighter regions' features. For instance, McKinnon and his colleagues have suggested that liquid water flooded rifts in the surface and subsequently froze over, relandscaping Ganymede. Others have touted the idea that these regions stem from tectonic activity. These and other explanations point to Ganymede's subsurface ocean being internally heated at some time, though McKinnon warns: "It's not a presently active world as far as we can tell."

The most interesting aspect of Ganymede is its mysterious magnetic field. Ganymede is the only moon — and one of only three solid bodies in the solar system (alongside Mercury and Earth) — to generate its own global magnetic field. Might this field make Ganymede habitable? "It could do," says Michele Dougherty (Imperial College London), principal investigator for JUICE's J-MAG magnetometer instrument. "I mean, Earth's magnetic field protects it from the most energetic particles from the solar wind, and so it's part of what's helped make Earth habitable over a long period of time."

For Dougherty, though, Ganymede's magnetic field is more important as one of several tools to probe the subsurface ocean's habitability — for which there is a key sticking point. Given Ganymede's size, some predictions suggest that pressures might force water at the bottom of the ice-topped ocean to form another ice layer in a different phase at the seafloor, sandwiching the ocean and making it difficult for heat from the mantle to leach through in the form of potentially life-supporting hydrothermal vents. More recent predictions point to there being several liquid layers, the deepest of which may be in direct contact with the seafloor.

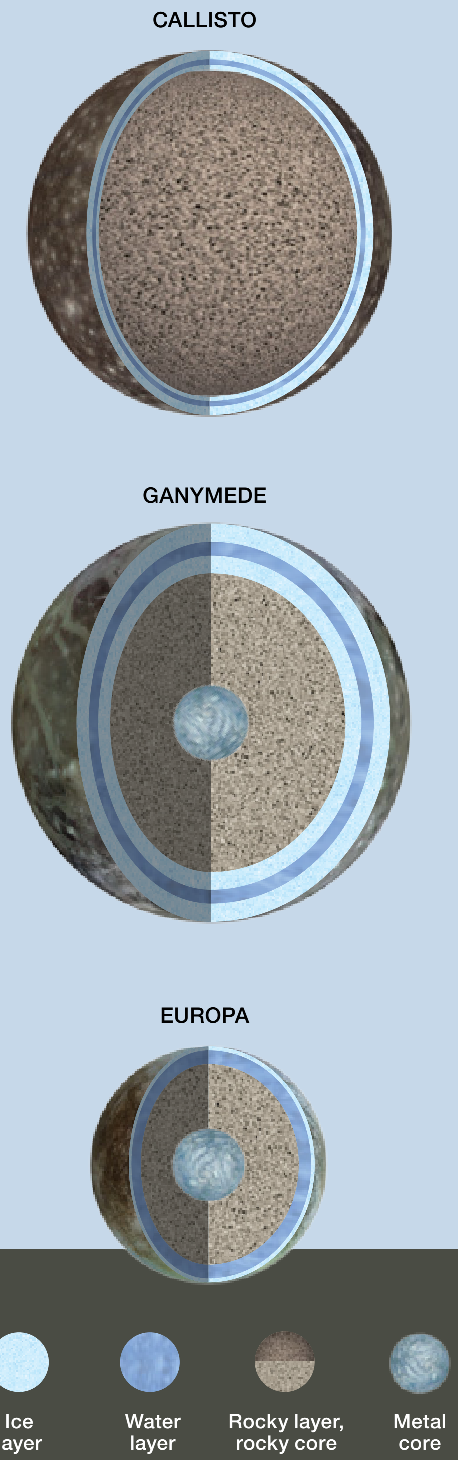
"What my instrument will do is measure the size of the currents that are flowing in the ocean," says Dougherty. Both Jupiter's daily rotation and Ganymede's monthly circuit create magnetic variations that will produce unique effects, depending on the ocean's thickness and salinity. "We're going to be able to separate out how deep the ocean is from what its salt content is."

Orbiting Ganymede for nearly a year, JUICE will also take detailed measurements of the moon's rotation rate, gravity field, and how much the surface warps due to tidal forces. Mission scientists will then compare these data with different predictions of Ganymede's composition. "We'll get the answer with JUICE," Witasse asserts.

Europa: Chaos and Geysers

If that answer is that the moon does indeed have a layer of liquid water in direct contact with the seafloor and hot mantle, Ganymede might provide one of the most fertile environments in the solar system. Yet confirming life deep

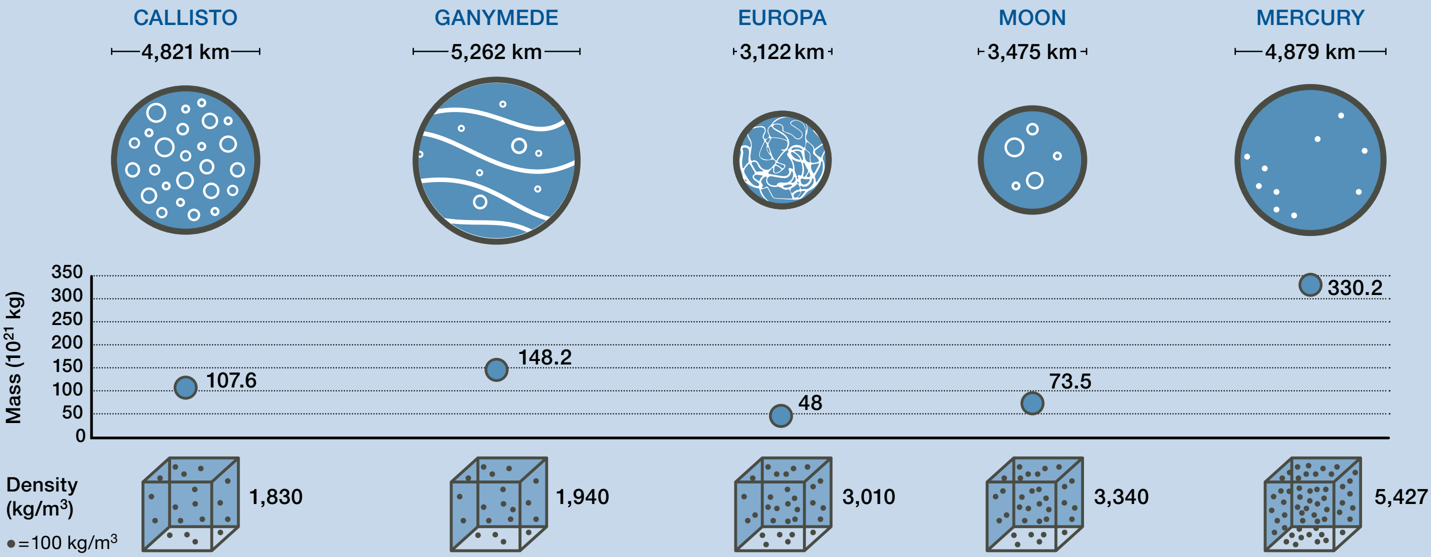
OCEAN WORLDS Jupiter's three icy Galilean moons are some of the largest satellites in the solar system and appear to have subsurface seas. If they also have energy sources (such as hydrothermal vents) and the right chemical combinations, they might be habitable.



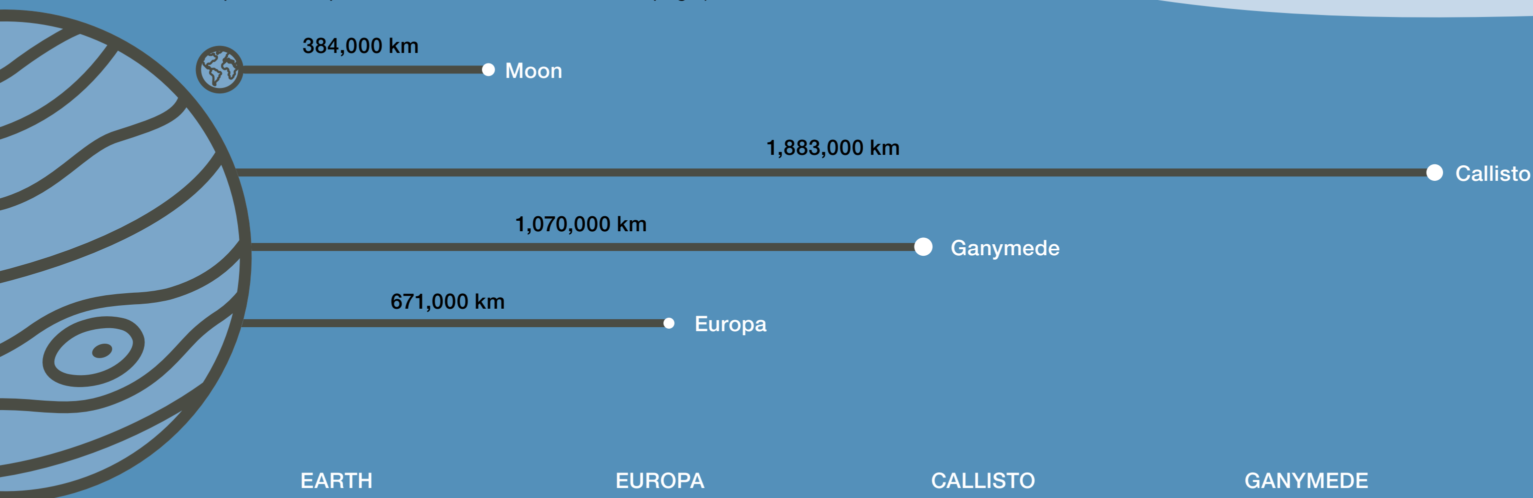
WATER LAYERS Researchers estimate that Callisto's *hydrosphere* (ice plus liquid water) makes up about 10% of the moon's radius. Ganymede's is a whopping 25%, while Europa's is 15%. Earth's oceans span less than a tenth of a percent of our planet's radius.

GREGG DINDERMAN / S&T. SOURCES: STEVEN VANCE / JPL AND DOUG ELLISON, EMILY LAKDAWALLA, BOB PAPPALARDO / CC BY 3.0

NO SMALL FRY Ganymede, the largest moon in the solar system, beats out Mercury in size, with Callisto not far behind. But both satellites are far less dense than the Iron Planet or even Earth's Moon. Europa, just smaller than the Moon, has only a slightly lower density than our satellite.

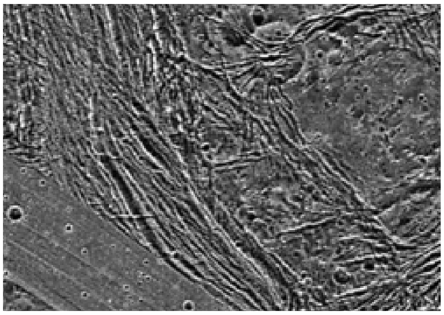
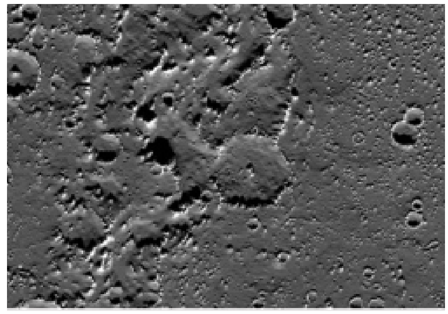


CLOSE KIN In kilometers, the Moon lies closer to Earth than the Galileans do to Jupiter. But in terms of the host planet's size, the Galileans are much closer: Ganymede lies 15 Jupiter radii away, whereas the Moon lies 60 Earth radii away. (Distances are shortened by a factor of 5 with respect to the planets' sizes, in order to fit on the page.)



HOW MUCH WATER? Estimates vary, but the Galilean oceans could easily be 25 times deeper than the average depth of Earth's seas. (Earth's deepest point is 11 km, in the western Pacific's Mariana Trench.)

INFOGRAPHIC: TERRI DUBÉ / S&T; EUROPA ICON: KAYLA VALENCIA / THE NOUN PROJECT; JUPITER ICON: VICTORULER / THE NOUN PROJECT

▲ **THREE WORLDS** The surfaces of Europa, Ganymede, and Callisto *(left to right)* show different degrees of tectonic and geologic activity, as well as cratering. An unknown dark material covers Callisto's pockmarked surface. Europa's surface looks the youngest, but just how young is it?

below layers of water and ice would be a challenge, to say the least. "In the case of Ganymede and Callisto, their ice shells appear to be very thick, quite old, and thus don't provide much of a window into the ocean below," says astrobiologist Kevin Hand (Jet Propulsion Laboratory).

This is why Hand and other scientists working on NASA's Europa Clipper are pinning their hopes on Europa. The spacecraft, which launches in the mid-2020s, will join JUICE in the Jovian system to begin its 40 to 50 close sweeps over Europa at the start of the next decade.

Europa has two key advantages for life detection over its Galilean siblings. First, it has a relatively thin ice shell — roughly tens of kilometers thick, as opposed to a hundred or more for Ganymede and Callisto — through which liquid water and biosignatures might spew. Second, evidence strongly suggests Europa's ocean is in direct contact with the seafloor. This means the deepest recesses of Europa's ocean world may be dotted with hydrothermal vents. But if not, Hand says that even water leaching through mineral-laden rocks might be enough to spark and sustain life.

And he should know. Hand took part in an expedition that sent acclaimed film director James Cameron on a record-breaking dive down to the depths of the Mariana Trench in 2012. As part of the expedition, a robotic vehicle descended to a region called Sirena Deep, where cameras captured a rocky outcrop covered in peculiar filaments. "These filaments are basically dead ringers for microbial mats," says Hand. "We think that this microbial population feeding on nutrients coming out of rocks is what then feeds a larger biosphere." The same process may have kickstarted and maintained microbes on Europa.

Further work by Hand suggests life on Europa could be more exciting than one-celled microbes. Observations and experimental evidence indicate that charged particles raining down on Europa from Jupiter's magnetic field are creating oxygen and other oxidants on the surface. Hand thinks that if these chemical modifiers are somehow delivered to the ocean below and get dissolved into the water, they could essentially power more complex organisms. "That's a big 'if,'" he says. "But I've published some numbers showing that you could get up to enough oxygen within Europa's ocean such that, not only could microbes exist, but multicellular life could also potentially survive."

Though tantalizing, all of this is moot if we cannot confirm life on Europa. Luckily, signs on the surface suggest there may be ways for Europa Clipper and JUICE to peer into the depths below. For example, an important and unique surface feature is Europa's *chaos regions*, explains planetary geophysicist Lynnae Quick (NASA), who is co-investigator on the Europa Imaging System aboard Europa Clipper. "These are areas where Europa's ice shell has broken up into plates to form humongous icebergs in an ice–slush water matrix," she says. Directly below these icebergs and slush might be Europa's subsurface ocean. In such regions, sea salts, organics, and other telltale materials could get churned up onto the surface, ready to be spied by JUICE or Europa Clipper's spectral imagers.

Another promising avenue of investigation is Europa's cryovolcanism. On Europa and other outer solar system bodies harboring dark oceans, conditions are so cold that ice can act like rock and liquid water as lava to produce frigid versions of the fiery volcanism we see on Earth (*S&T:* Aug. 2020, p. 32). Galileo images hinted that in certain regions on Europa, water seeps through the ice shell and then spreads like lava, eventually solidifying and forming smooth areas on the surface (just as McKinnon

◀ **MICROBIAL MATS** An expedition found these strange, filamentary life forms on outcrops at Sirena Deep, more than 10 km below the ocean's surface.

TERRAIN COMPARISONS: NASA / JPL / DLR; MICROBIAL MATS: K. HAND ET AL. / *DEEP SEA RESEARCH* 2020 predicted for Ganymede). And in 2013, a team led by planetary astronomer Lorenz Roth (now at KTH Royal Institute of Technology, Sweden) announced it had used Hubble data to spot potential cryovolcanic eruptions, sending plumes of water vapor roughly 200 kilometers into space. Further hints of huge plumes spewing out of different locations were reported in 2016.

Europa Clipper team members are crossing their fingers that the spacecraft spots one of these chilly eruptions. "We've seen these beautiful chaos regions, we've seen what appear to be smooth cryolava flows on Europa's surface," says Quick. "But I hope that we're actually able to catch geyser-like plumes in the act." Tempering expectations, she warns that the huge plumes reported by Roth and others might be the exception rather than the rule. "It could be that most are 20 to 30 kilometers tall," she explains. Moreover, plumes may not even originate from the Europan ocean, instead erupting from shallow pockets of briny water in the ice shell. "We're at a point where we have to plan for anything."

McKinnon, who is a member of the sounding radar teams for both JUICE and Europa Clipper — jokingly given the acronyms RIME (Radar for Icy Moons Exploration) and REASON (Radar for Europa Assessment and Sounding: Ocean to Near-surface) — is circumspect about the evidence for, and chances of, spotting plumes on Europa. However, he says that Europa Clipper offers the best hope of finding plumes if they do indeed exist. "We'll be passing really close by, and if there's any kind of even small eruptions from the surface, it will show up in the data." Better yet, if a larger geyser happens to erupt on one of the spacecraft's close approaches, Europa Clipper has instruments to "taste" the vapor as it flies through the thin spray, just as Cassini did with Enceladus' plumes (though Europa Clipper's instruments are far better equipped to analyze the kind of complex chemistry that would suggest life).

Of course, from their vantage point high above the surface, Europa Clipper and JUICE are highly unlikely to provide incontrovertible proof that life lies below the icy Galileans' surfaces. For that, we need a lander. "You've got to get down to the surface and grab a chunk of material and put that through instruments that are specifically designed to search for complex organics and various parameters that can help us assess whether or not we've actually found life itself," says Hand.

Hand — who was heavily involved in the conceptualization of Europa Clipper and is now co-investigator on the spacecraft's mass spectrometer instrument — is co-leading a pre-project team to do just that. The Europa Lander concept, if approved, will dig up samples shielded from damaging radiation about 10 centimeters beneath the surface and then analyze them in a miniature onboard laboratory to look for biosignatures.

And if signs of life are found, what then? Drill down to seek it out, of course! Already, NASA mission concepts are exploring weird and wonderful technologies to dive through the ice shell and explore the ocean underworld — including a swarm of tiny robotic fish and a larger, instrument-laden robotic snake.

Other icy worlds in the solar system — such as Saturn's moons Titan and Enceladus, Neptune's moon Triton, or even Pluto — may yet prove to offer a better chance of finding alien life in our backyard. But for now, the icy Galilean moons seem like some of our best bets. In decades to come, who knows, we may be watching in awe as a serpent robot makes first contact with a Europan squid.

■ **BENJAMIN SKUSE** is a science writer based in Somerset, United Kingdom.

FURTHER READING: For a deeper dive into the dark oceans of the solar system and beyond, read Kevin Hand's new book *Alien Oceans: The Search for Life in the Depths of Space*.

▶ **DIVING DEEP** The Sensing With Independent Micro-swimmers (SWIM) mission proposal would deploy centimeter-scale robotic fish into an icy moon's subsurface ocean. Each fish would carry its own sensing and communication systems.

NASA / JPL-CALTECH