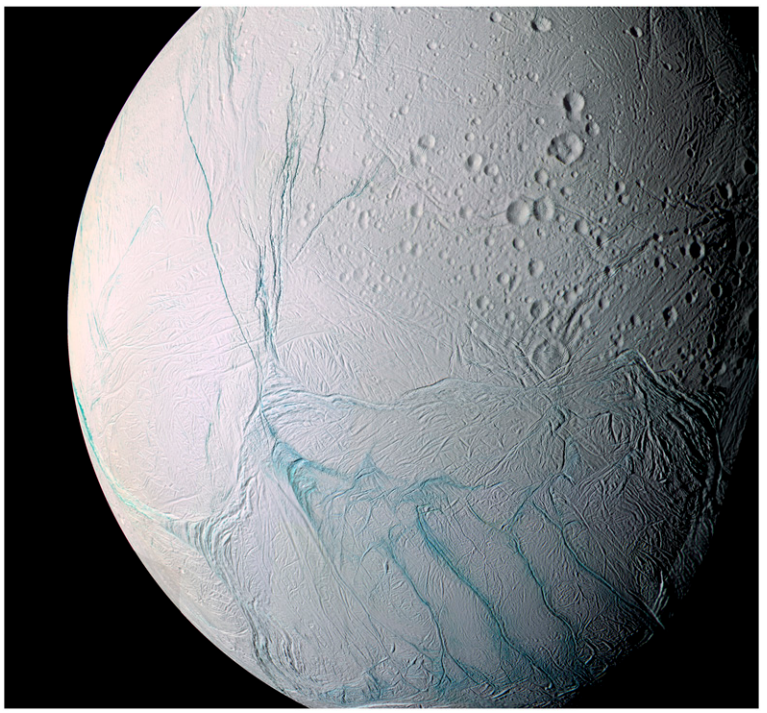
cy ocean worlds offer chances to find life

Adam Mann, *Science Writer*

Sometime in the early 2030s, a washing machine-sized robot could be carefully descending toward the icy crust of Jupiter s moon Europa. Armed with cameras, a spectrometer, a microscope, and a scoop, the vehicle would be lowered from a UFO-like sky crane similar to the one that delivered the Curiosity rover to Mars. As the robot nears the frozen ground, its autonomous navigation system may have to take evasive action. "Maybe the surface is nice and flat and smooth," says Curt Niebur, a program scientist at the National Aeronautics and Space Administration (NASA) headquarters in Washington, DC. "But maybe it s covered in penitentes, which are literally six-foot-tall ice spikes."

The probe s mission is a familiar one: to find signs of life beyond Earth. But its target for this investigation, a moon s ocean, has only recently gained popularity.

Europa is thought to have a vast liquid water ocean beneath its frozen crust, a potentially perfect place to find extraterrestrial organisms. The Jovian moon is merely one of many similar locations. In recent decades, exploratory spacecraft have revealed that our solar system is chock full of icy ocean worlds. Along with Europa, there are Saturn s moons, the geyser-spewing Enceladus, and the methane-filled Titan. Then there s Neptune s cryovolcanic Triton and the distant dwarf planet Pluto, just to name a few. "You throw a stone, and you find another ocean world," says planetary scientist Francis Nimmo of the University of California, Santa Cruz. "They re all over the place."



Saturn s moon Enceladus, shown here via a mosaic of images collected by the Cassini spacecraft in 2005, is one of many moons with oceans that could harbor signs of life. Image courtesy of NASA/JPL/Space Science Institute.

The moons of Jupiter, Saturn, Uranus, and Neptune are built largely from frozen water, which becomes hard a rock at the frigid temperatures far from the sun. Even small amounts of internal heat can turn that ice to liquid. Beneath their protective icy shells, these worlds might collectively hold 100-fold the volume of Earth s oceans, calculates geologist Kevin Hand of NASA s Jet Propulsion Laboratory (JPL) in Pasadena, California.

Scientists have yet to understand these strange ice balls surface processes or internal compositions entirely, and NASA and other space agencies are interested in further investigating their secrets. Last year, NASA started putting together an Ocean Worlds program; the earliest targets will be Europa, Enceladus, and Titan, which have the best evidence for liquids on or near their surfaces. Within a couple of decades, these places might tell us if life is widespread in our solar system, and perhaps elsewhere.

"We know that physics works beyond Earth; we know that chemistry works beyond Earth. We know that geology works," says Hand. "But we have yet to determine whether or not biology works beyond Earth. These liquid water environments in our cosmic backyard present the opportunity to answer that question."

Ice on Top

Our knowledge of icy ocean worlds came about gradually. Back in the 1960s, some scientists argued that the outer solar system satellites would be nothing more than dusty gray worlds not too different from our own moon. But several researchers pointed out that a number of outer solar system bodies contained enough ice and rock—which would be studded with radioactive elements—that the heat from decay could melt their interiors, leading to large pockets of liquid water topped with a frozen crust (1).

When Voyager 1 and 2 swept past Jupiter in 1979, they beamed back startling images. Rather than an inert dust ball, the moon Io turned out to be the most volcanically active body in the solar system, whereas its

www pnas org/cgi/doi/10 1073/pnas 1703361114

nearby sister Europa had a surface of broken chaotic terrain similar to tectonic plates. "Once the Voyager probes saw that these moons had few craters and huge cracks on them, it gave us a clue that they weren t just places of boring rock and ice," says atmospheric, oceanic, and space scientist Catherine Walker, also of the JPL. "They were floating laboratories of geology."

The full scope of oceanic incidence in the solar system became clearer when the Galileo mission arrived at Jupiter in 1995. The spacecraft measured odd anomalies in Jupiter s magnetosphere near the moons Callisto and Europa (2). Because Jupiter s magnetic axis is tilted relative to its poles, its moons experience a periodic magnetic oscillation as the giant planet rotates. Basic electromagnetic theory states that a changing magnetic field will induce a current in a conductive material, generating a secondary, weaker magnetic field. Galileo was seeing this induced magnetic field at Europa and Callisto, suggesting their interiors were made from some electrically conductive material. The most likely culprit? Seawater.

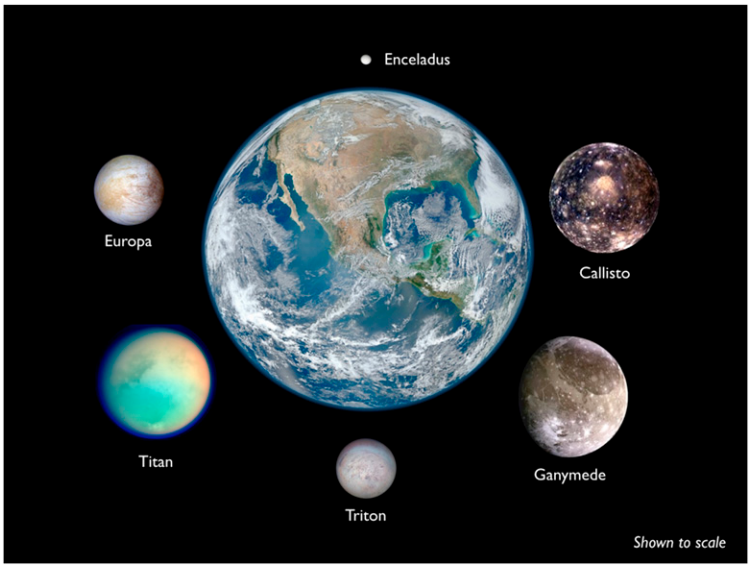
"That result was surprising because Callisto had this heavily cratered surface and looked as if it had never done anything interesting in its life," says planetary scientist David Stevenson of the California Institute of Technology in Pasadena. "It was the ugly stepsister and, look, it had an ocean."

By the time the Cassini spacecraft reached Saturn in 2004, researchers were ready to hunt for ice-capped ocean moons. Although Titan s methane lakes and thick nitrogen atmosphere initially drew the most interest, tiny Enceladus soon stole the show. Cassini s cameras spotted the source of a faint and unique Saturnian ring—incredible plumes of water ice, silica, and ammonia that were shooting hundreds of kilometers from Enceladus surface (3).

The tally of frozen ocean worlds continues to grow. The same magnetic effect pointing to salty water on Europa and Callisto suggests that Jupiter s moon Ganymede possesses an interior liquid layer (4). When it flew past Pluto in 2015, the New Horizons spacecraft spotted a smooth 1,000-kilometer-wide plain thought to house an underground ocean (5). Surface features on Pluto s moon Charon hint that it, too, once had liquid water, a characteristic that the dwarf planet Ceres, the largest member of the asteroid belt, seems to share (6). When prompted, planetary scientists throw out a half-dozen other worlds that might be worth investigating, including Saturn s moons Mimas, Dione, and Tethys, and Uranus moons Ariel, Umbriel, and Miranda.

Feeling the Heat

How can all these bodies, so far from the sun, sustain liquid water in their interiors? In addition to radioactive decay, many moons in the solar system are heated by gravitational effects known as tidal forces. Worlds like Io, Europa, and Enceladus follow eccentric orbits around their parent planet, which causes varying gravitational stress on the small bodies, alternatively squeezing and relaxing their crusts and driving



Researchers hope to explore the oceans of Neptune s moon Triton; Saturn s moons Enceladus and Titan; and Jupiter s moons Europa, Callisto, and Ganymede seen here to scale with Earth). Image courtesy of Kevin P. Hand/JPL/NASA.

phenomena such as Enceladus powerful plumes. Even without tidal effects, natural antifreezes like ammonia, found on many icy worlds, can drive down water s freezing point to 100 °C.

In learning about these icy ocean worlds, researchers have come to realize just how alien they are. Models often use analogies with rock and magma, but the parallels are far from perfect. Solid rock, for instance, is denser than molten magma "but with ice and water it s the opposite," says planetary scientist Kate Craft of Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland. "And we say when ice gets so cold, it acts like rock. But really does it at the microscale?"

"Once the Voyager probes saw that these moons had few craters and huge cracks on them, it gave us a clue that they weren t just places of boring rock and ice."
—Catherine Walker

Scientists are therefore itching to revisit these bodies. The European Space Agency intends to launch the Jupiter Icy Moons Explorer in 2022 to investigate Ganymede, Callisto, and Europa. NASA is working on a Europa-centric mission that could also launch that year and conduct multiple close flybys of the icy moon. The spacecraft will sniff Europa s thin atmosphere, map the ice shell s thickness, image the surface at high resolution, and possibly sample some faint putative plumes. The mission will determine if the frozen world contains the organic chemistry, liquid water, and energy sources necessary for life as we know it.

A follow-up lander would try to answer the much harder question of whether living organisms exist on Europa. NASA is still deciding if and how it wants to

take that next step. A preliminary study released in February 2017 (7) suggested sending such a probe 2 years after the multiple flyby spacecraft launches, giving the earlier mission enough time to assess Europa s habitability.

Although Europa is getting the most attention at the moment, another world beckons. "Enceladus is the only place in the solar system that checks all the boxes," says planetary scientist Carolyn Porco of the Space Science Institute in Boulder, Colorado. "We know it s got an ocean, it s got organic material, and we even think there s evidence for hydrothermal activity on the sea floor."

Rather than try to determine habitability, an Enceladus mission could go straight to searching for evidence of extant organisms. The icy moon even offers up free ocean samples via its geysers, which a spacecraft could easily fly through. A proposed mission called the Enceladus Life Finder (ELF) could use mass spectrometers to look for amino acids in the water plumes. Living creatures on Earth require complex amino acids in ratios that wouldn t be expected from abiotic processes. Finding such a pattern would be a giveaway for life. A European spacecraft proposal called Explorer of Enceladus and Titan would focus on these questions for both Enceladus and the methane-filled Titan.

ELF is competing for funding under NASA s New Frontiers program, and a decision is expected around 2019. The mission could be of historic importance, says planetary scientist Jonathan Lunine of Cornell University in Ithaca, New York, who heads up the proposal. Were it to find evidence for extraterrestrial organisms, researchers could be fairly certain that the Enceladus biosphere experienced its own, independent genesis, because there s little chance of an exchange of material with the Earth over geologic time. "It would tell us," he says, "that life is a common outcome of cosmic evolution."

Lewis J (1971) Satellites of the outer planets: Their physical and chemical nature. *Icarus* 15(2):174–185.

2 Khurana KK, et al. (1998) Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto. *Nature* 395(6704):777–780.

3 Porco CC, et al. (2006) Cassini observes the active south pole of Enceladus. *Science* 311(5766):1393–1401.

4 Sohl F, et al. (2002) Implications from Galileo observations on the interior structure and chemistry of the Galilean satellites. *Icarus* 157(1):104–119.

5 Nimmo F, et al.; New Horizons Geology, Geophysics Imaging Theme Team (2016) Reorientation of Sputnik Planitia implies a subsurface ocean on Pluto. *Nature* 540(7631):94–96.

6 McCord T, Sotin C (2005) Ceres: Evolution and current state. *J eophys Res Planets* 110(E5):2156–2202.

7 Hand K, et al. (2017) Europa Lander Study 2016 Report: Europa Lander Mission, JPL D-97667 (NASA, Washington, DC). Available at solarsystem.nasa.gov/docs/Europa_Lander_SDT_Report_2016.pdf. Accessed February 18, 2017.