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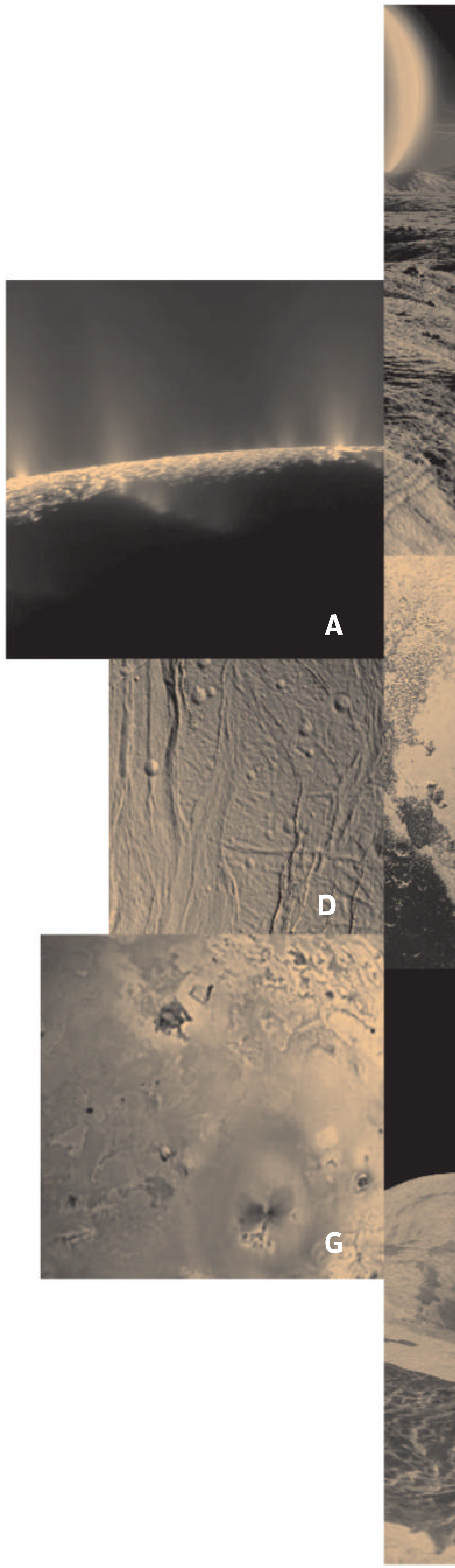
Alien volcanoes

Bizarre volcanoes erupt on many planets and moons in our solar system. **Natalie Starkey** takes a tour to investigate what they mean for life beyond Earth



ONE OF the most exciting moments of my life was when I stood on the summit of Kilauea volcano in Hawaii looking out over its crater. I was several kilometres from the edge, but I could see orange liquid bubbling and sputtering inside. I was awed by the extraordinary power inside this planet of ours – capable of turning rock to liquid.

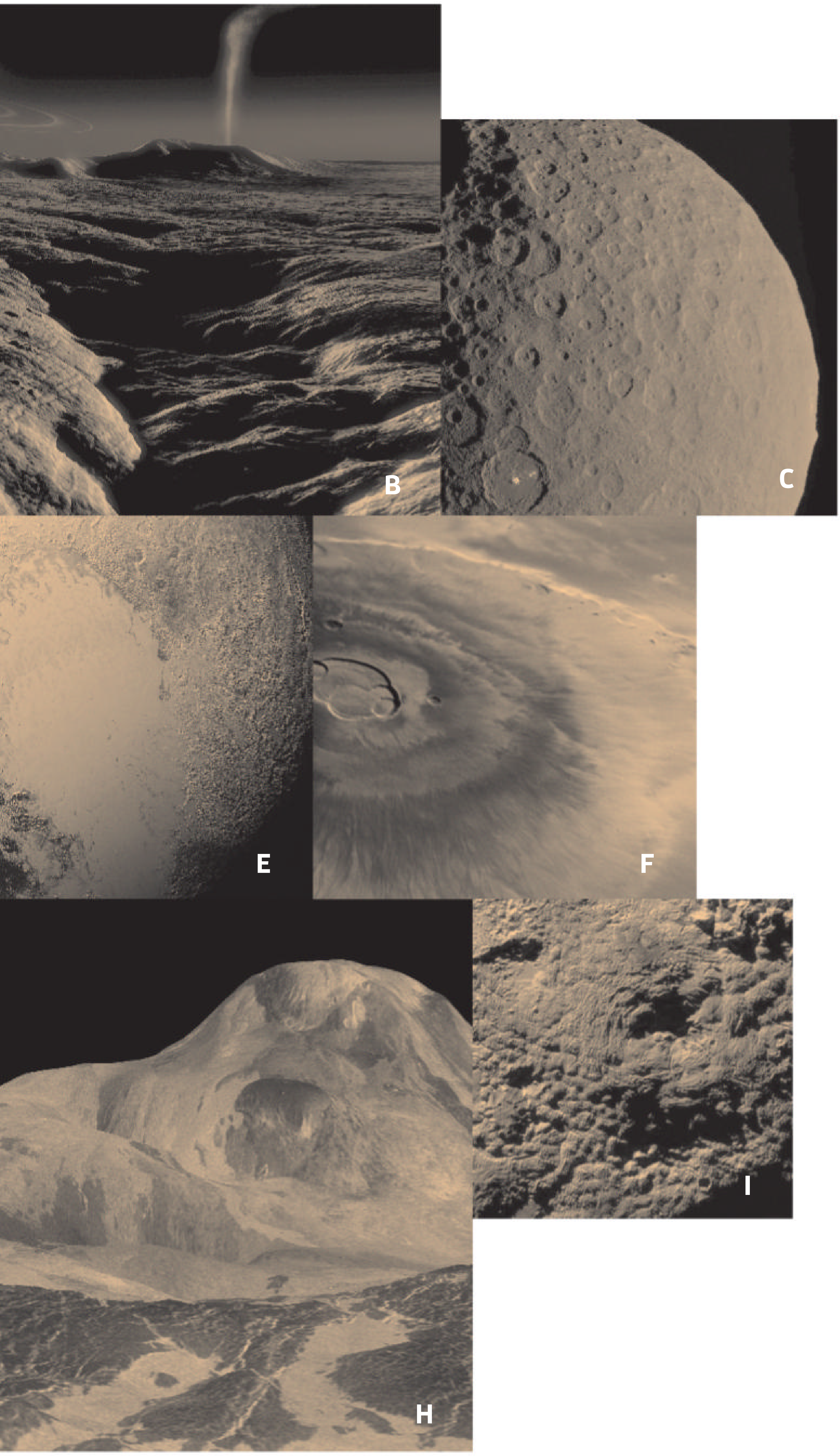
Kilauea is just one of many impressive volcanoes. About 60 have erupted on Earth this year alone. Before we had the ability to explore beyond Earth, many assumed that this planet was where it stopped; that you could never stand atop an active volcano on another world in this solar system because they just weren't out there. The rest of our solar system seemed geologically dead.

We now know that is far from true, and have evidence that volcanism exists beyond Earth in strange forms and in the most unexpected places. There are plumes spurting into space around Saturn and ice volcanoes on Pluto. Even lumps of rock in the asteroid belt produce their own unusual brand of lava. Finding these fascinating features – and how they came to exist – gives us a window into the innards of the solar system's most mysterious worlds.

There is more at stake than extreme geology. There is a consensus that a source of energy is required to kickstart the chemistry essential for life and, on Earth, a prime candidate for that is volcanic activity, particularly at the bottom of the ocean. So, if volcanoes are common across the cosmos, does that mean life could be too?

We typically think of a volcano as an opening in Earth's crust where hot liquid rock, or magma, bubbles upwards. Explosive eruptions can blow the magma into tiny fragments, forming clouds of volcanic ash. And magma can ooze onto the surface – at which point we call it lava.

On our planet, volcanoes often form at the boundaries between tectonic plates. They can also appear in the middle of them, where tall natural chimneys called mantle plumes are thought to carry magma to the surface. The heat that keeps all this going



A Plumes on Enceladus
B Geysers on Triton
C Volcanic craters on Ceres
D The icy crust of Enceladus
E Pluto's rugged surface
F Olympus Mons, an extinct volcano on Mars
G Volcanoes on Io
H Maat Mons, a volcano on Venus
I Wright Mons, an ice volcano on Pluto

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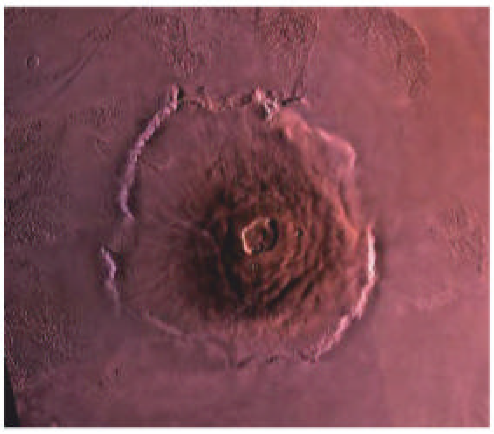
comes from radioactive elements that were locked away inside Earth as it formed some 4.5 billion years ago.

The other rocky planets, Mercury, Venus and Mars, formed at the same time and in roughly the same place as Earth and so also had a radioactive heat source inside. However, Mars is about 15 per cent the volume of Earth and Mercury is smaller still, so almost all the warmth has radiated away from these planets. Their surfaces are covered in the relics of ancient volcanism but now stand quiet. Only Venus, just a shade smaller than Earth, still has active volcanoes.

Beyond Mars comes the frost line where temperatures drop and the solar system is starkly different. The planets out here were formed mainly from what planetary scientists call ices – grains of substances that would normally be liquids or gases on Earth, like water, ammonia and carbon dioxide. It is so cold in this region that these compounds are solids, even in the low pressure of space. You wouldn't expect volcanoes on such chilly worlds. ›

Exotic eruptions

The solar system is home to many volcanoes and strange blasts. Here are some of the biggest beyond Earth



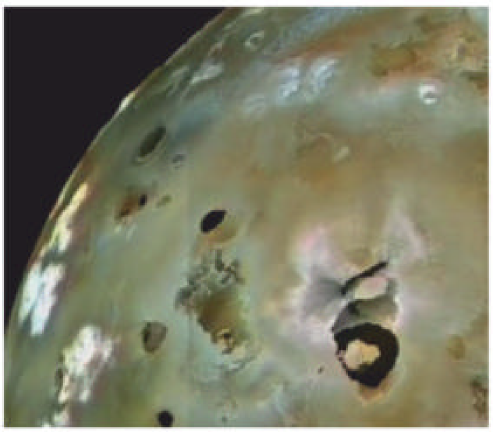
NASA/JPL/USGS

OLYMPUS MONS

MARS

Size: 25 km high

At about 2.5 times the height of Mount Everest above sea level, this is the solar system's highest volcano. It probably formed as a tall chimney of magma rose up from the planet's core. It last erupted 25 million years ago.



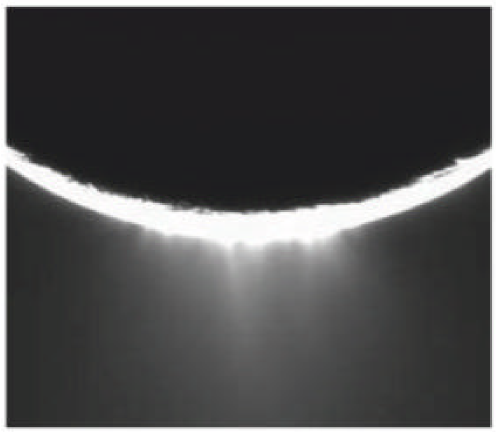
NASA/JPL/USGS

LOKI PATERA

IO

Size: 200 km wide

This is a horseshoe-shaped lava lake on the solar system's most volcanically active object. It seems continuously active, bubbling away on the surface of this moon of Jupiter since it was spotted in 1979.



NASA/JPL/SPACE SCIENCE INSTITUTE

PLUMES

ENCELADUS

Size: Extending into space

Several plumes of water and ice spurt from Enceladus's south pole. Grains of ice then drift away to form one of the rings of Saturn, the planet this moon orbits. The plumes also contain salts and organic compounds.

At least, that was the prevailing view in 1979 as the Voyager 1 spacecraft approached Jupiter. But when it reached the planet's innermost moon Io, which is only slightly bigger than Earth's moon, it snapped pictures of volcanic plumes 100 kilometres high. Io's shiny yellow surface is pockmarked with more than 400 volcanoes and their eruptions glow blue. The biggest, Loki Patera, isn't immediately recognisable as a volcano. It is a 200-kilometre-wide depression, part-filled with a horseshoe-shaped lake of bubbling lava. We don't see Loki explode, but the lava lakes periodically warm up and cool.

What is driving this activity on such a small, freezing world? Just a few days before Voyager 1 arrived at Io, scientists published a hypothesis, predicting that Io is continually squeezed and warmed by the force of gravity. Io orbits Jupiter in a such a way that it gets pulled in different directions at intervals by the giant planet and some of its other moons. "Io is caught in a tug of war," says Rosaly Lopes at NASA's Jet Propulsion Laboratory in Pasadena. This tidal heating squeezes Io like fingers warming up a squash ball.

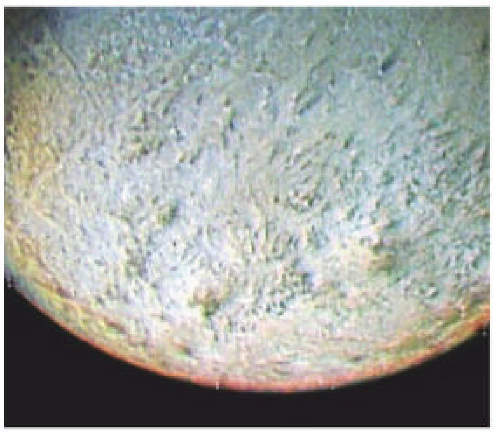
Yet Io is an outlier. It seems to have formed closer to its parent planet than many of the other moons beyond the frost line. In this colder part of the solar system, most moons are made principally of ices with smaller rocky cores. Surely they would be devoid of volcanic activity?

Voyager 1 and its sister probe Voyager 2 approached Saturn and its satellites in the early 1980s and soon swooped past one moon, Enceladus, which is just 500 kilometres across. It was expected that, like Earth's moon, Encedalus would be covered in craters caused by comet and asteroid impacts. But that wasn't the case. Voyager 2 revealed this world's surface to be bright white, with smooth areas.

> "Io's shiny yellow surface is pockmarked with more than 400 volcanoes and their eruptions glow blue"

We had to wait a quarter of a century to find out why. When the Cassini spacecraft looked closer at Enceladus in 2005, it became clear this moon was pumping plumes of water into space. "It was a jump-out-of-your-seat moment to see water coming out from such a tiny object that everybody thought was boring and dead," says Nozair Khawaja at the Free University of Berlin. It turns out that these plumes come from a salty, liquid water ocean hidden below Enceladus's icy surface. The pristine smooth areas are a result of the snow raining down from these plumes.

The subsurface ocean is kept warm by the same mechanism that melts Io's insides, tidal heating caused by the gravitational tug of nearby bodies. These forces also open and close fissures on Enceladus's crust allowing the plumes of water to shoot out.



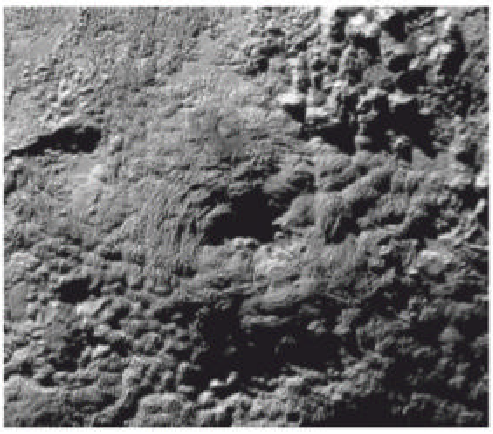
NASA/JPL

LEVIATHAN PATERA

TRITON

Size: 80 km wide

On Neptune's largest moon, a crater sits within a 2000-kilometre-wide volcanic dome. This is the second largest volcano in the solar system by area – and is connected to currently inactive cryolava lakes.



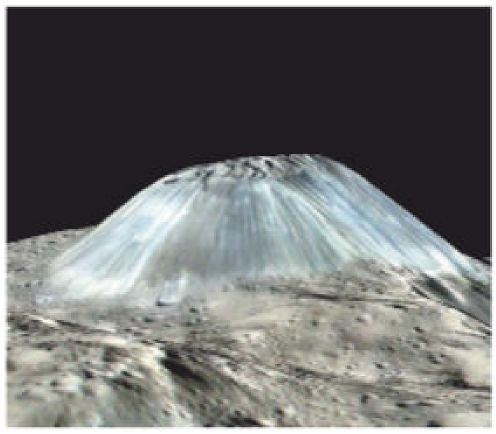
NASA/APL/SOUTHWEST RESEARCH INSTITUTE

WRIGHT MONS

PLUTO

Size: 150 km wide, 4 km high

This low, wide mountain has an obvious depression at its summit and its sides are streaked with red material. It is probably a volcano that once erupted a slurry of water ice spiked with ammonia.



NASA/JPL-CALTECH/UCLA/MPS/DLR/IDA/SPL

AHUNA MONS

CERES

Size: 4 km high

The largest mud-and-brine volcano on the dwarf planet Ceres in the asteroid belt. This is volcanism in slow motion: the last eruption on Ceres was 200 million years ago and the next isn't expected for millions more.

When Cassini flew right through these plumes, it revealed that they contained mineral grains, sodium salts and complex carbon-based molecules. All of this indicated that there must be a rocky floor at the bottom of Enceladus's hidden ocean – much like the sea floor on Earth, with its underwater hydrothermal vents that are a popular candidate for where life got started. "If we're looking for life elsewhere, we would like to see liquid water, organic molecules and an energy source that can trigger reactions. All these criteria are present at Enceladus," says Khawaja. "The chances are there for life."

There is impressive activity at even colder reaches of the solar system. The only time we have visited Neptune and its moons was a Voyager mission in 1989. That far out, the sun is a dot of light and everything should be frozen solid. The surface of Triton, Neptune's largest moon, is a frigid -235°C. Yet Voyager 2 saw geyser-like plumes erupting, throwing material 8 kilometres above the surface. "To find activity so far away in such a cold place was just remarkable," says Candice Hansen at the US-based Planetary Science Institute. "What is the energy source?"

One possible explanation is related to a layer of dark material below Triton's translucent nitrogen ice caps. These areas are expected to absorb the small amount of sunlight that reaches this part of the solar system, creating a kind of underground greenhouse effect that warms the subsurface ice. This causes nitrogen gas to build up, becoming pressurised to the point of explosion.

Rethinking volcanoes

Findings like this are forcing scientists to reassess what makes a volcano a volcano. The geology on Enceladus is referred to as cryovolcanism because it involves similar processes to those on Earth, but with materials that can flow at far lower temperatures. In the case of Triton's geysers, however, that term doesn't easily fit because the explosions may not be fuelled by internal heat – it is a form of explosive geology unlike anything seen elsewhere.

The geysers weren't all that Voyager 2 spotted on Triton. It also pictured an 80-kilometre-wide crater called Leviathan Patera with two enormous depressions nearby that are thought to have once been frozen lava lakes. Elsewhere, Triton's surface is smooth, probably thanks to the eruption of icy lavas. These features suggest that there must be warmth within Triton. It may come from tidal heating as well as radioactive decay within its rocky core – we still aren't sure.

More recently, probes have voyaged even further, all the way to the dwarf planet Pluto. If you had a craft that could travel at the speed of light, it might get from Earth to Neptune in about 4 hours 15 minutes. Pluto's distance from us varies but it would usually take more than an extra hour to get there – it is a distant and deeply mysterious place.

When NASA's New Horizons probe flew past it in 2015, we had little idea what to expect. The craft revealed that Pluto's crust is made of ice so hard that it acts like rock, allowing for a wondrous variety of ice geology. There are mountains and smooth, crater-free plains, including a heart-shaped area known as Tombaugh Regio. There are even dunes made of frozen methane. But one thing immediately screamed volcano. ›

A lava fountain erupts spectacularly on the slopes of Kilauea volcano in Hawaii

DOUGLAS PEEBLES/GETTY IMAGES

"Some of the mountains, such as Wright Mons, looked strange – they have a hole in them," says Carly Howett at the Southwest Research Institute in Boulder, Colorado. "On Earth, mountains with a hole are typically volcanoes." These features were geological flags telling us that Pluto is an active world, with the strong possibility that it contains a liquid ocean below the surface that fuels its cryovolcanoes.

You might wonder how water can flow at such extremely low temperatures. It turns out that it is probably down to a splash of ammonia. Just 5 per cent of it in water ice can lower its viscosity by a factor of 100,000, turning solid ice into a slurry that flows like liquid rock.

Even so, Pluto must have some heat to fuel its activity. But the explanations that served us before are out. This distant world has several moons, but none is big enough to provide significant tidal heating. And the dwarf planet itself is tiny, with a volume less than 1 per cent of Earth's. This means that the heat from any radioactive elements within ought to have dissipated long ago.

Our best explanation is that Pluto's icy crust includes a layer of planetary bubble wrap. This could be a substance called clathrate hydrate, which is composed of tiny molecular cages that trap methane gas inside them. The layer of gas is a poor thermal conductor and so locks heat inside the planet.

As we explore the solar system, we see wild and wonderful volcanism almost everywhere we look. What does this mean for the chances of life beyond Earth? Well, we know life needs a world with internal energy to support chemical processes. Having volcanoes doesn't mean a planet will have life. But they are a sign that a world is geologically alive, which boosts the chances of it supporting the right conditions for life.

That is particularly relevant when we look at the hundreds of rocky planets that we have discovered orbiting other stars. Take the exoplanet 55 Cancri e, which is expected to be molten in places, a sure sign of an energy-filled interior. Then there are the moons that could be orbiting larger exoplanets. These are hard to spot because they are so small and distant, but one exoplanet called WASP-49 b is thought to have an Io-like rocky moon that is erupting into space. Finds like this hint that there are probably many volcanically active worlds out there where life might have had the spark it needed to get going.

However, one of the biggest volcanic mysteries is closer to home. In 2015, NASA's Dawn spacecraft went into orbit around the dwarf planet Ceres, the largest known asteroid in our solar system, beaming back pictures of a mountain called Ahuna Mons. It had bright streaks running down its sides that looked suspiciously like lava. It seemed that even this mini world – its diameter is only as long as Britain – has a cryovolcano.

"Volcanoes are a sign that a planet is geologically alive, which boosts the chances of it supporting the right conditions for life"

We now know it has dozens of them, which, according to a growing body of evidence, may all be fed by an underground ocean. When active, these volcanoes collectively splurge out an average of 10,000 cubic metres of muddy brine a year. "At -40°C you already have liquid brine and possibly mud flowing upwards to build mountains," says Ottaviano Ruesch at the University of Münster in Germany. As yet, we have no idea what could be powering these eruptions. It just goes to show that, when it comes to volcanoes, the solar system can still spring a surprise or two. ∎

Natalie Starkey is a science writer based in Cambridgeshire, UK. Her book *Fire and Ice: The volcanoes of the solar system* is out in 2021