The UN has declared 2009 the International Year of Astronomy to celebrate the 400th anniversary of Galileo Galilei's first astronomical observations with a telescope and the publication of *Astronomia Nova* by Johannes Kepler. In that connection, NPD palaeontologist Robert W Williams looks at a Saturn moon's geology.

Enceladus is the dark spot inside the bright flare at the centre of Saturn's E ring. Plumes of ice and water vapour are erupting off the moon to form this ring.
(Photo: Nasa/JPL/Space Science Institute)

Hot and cold

Saturn's little ice moon Enceladus looks very alien to terrestrial geologists. Like Earth, however, this world is crunchy on the outside and soft on the inside. A warm interior requires energy, and an unearthly source is pumping up its heat.

Saturn photographed from within its shadow. *Details of the ring system become more distinct when the Sun's illumination is from the back. Encircling the entire system is the E ring. The icy plumes of Enceladus, whose eruptions supply the ice dust of the E ring, betray the moon's position on the ring's left-hand edge. Located 1.3 billion kilometres away, just above the leftmost edge of the brighter main rings, is the pale blue dot of Earth. (Photo: Nasa/JPL/Space Science Institute)*

Water is abundant in deep space. This is partly because hydrogen is by far the commonest element in the universe. Oxygen and all other atoms heavier than hydrogen and helium (disregarding traces of lithium and beryllium) are forged in the cores of giant stars.

The entire periodic table of elements is shot into the galaxies by the explosive deaths of high-mass, short-lived stars. Gas makes up the cold, dark molecular clouds we can see with the unaided eye as a continuous shadowy intercalation stretching across the night sky along the band of the Milky Way.

Clump

Four and a half billion years ago, our solar system accreted from a gravity-collapsing clump in a dark molecular cloud in the outer disk of the Milky Way galaxy. Innumerable examples of ongoing star formation are readily observable today, so astronomers can follow the chain of events.

The cloud of star-stuff, the solar nebula, consisted of gas, ice and rock dust. Ninety-eight per cent of the mass of the cloud was hydrogen and helium gas. The remaining two per cent consisted primarily of water ice and secondly of frozen methane and ammonia. Only 0.5 per cent of the cloud was rock dust, in the form of microscopic grains the size of smoke particles.

Copious amounts of water were produced when hydrogen and oxygen combined in the frigid outer reaches of the embryonic solar nebula. Countless icy bodies took shape in the solar dust cloud through the coagulation of ice grains.

Most of these frozen clumps became comets and dwarf planets. The rest were either ingested by or formed moons of the giant outer planets – Jupiter, Saturn, Uranus and Neptune.

The ice worlds orbiting these planets are geological jewels, with a great diversity of types, and some reveal geological processes which resemble those found on Earth. These include crustal recycling and plate tectonics.

Before Galileo viewed the Tuscan sky through a small telescope in 1610, our solar system contained only eight known objects: six planets, the Sun and our own Moon.

Galileo spotted four additional objects – the largest moons of Jupiter, now called the Galilean satellites: Io, Europa, Ganymede and Callisto. Saturn's five largest moons were also discovered in the 17th century by Christiaan Huygens and Giovanni Domenico Cassini.

The frequency of new discoveries accelerated during the following centuries as optical technology improved. After 1977, practically all discoveries of additional moons were made by four robotic probes sent to the outer planets.

These included two Voyager missions in 1977, the Galileo probe to Jupiter in 1994, and the most advanced of them all, the Cassini Saturn spacecraft of 1997. Still in excellent health, Cassini is transmitting new information on Saturn and its moons even as you read this.

Dynamic

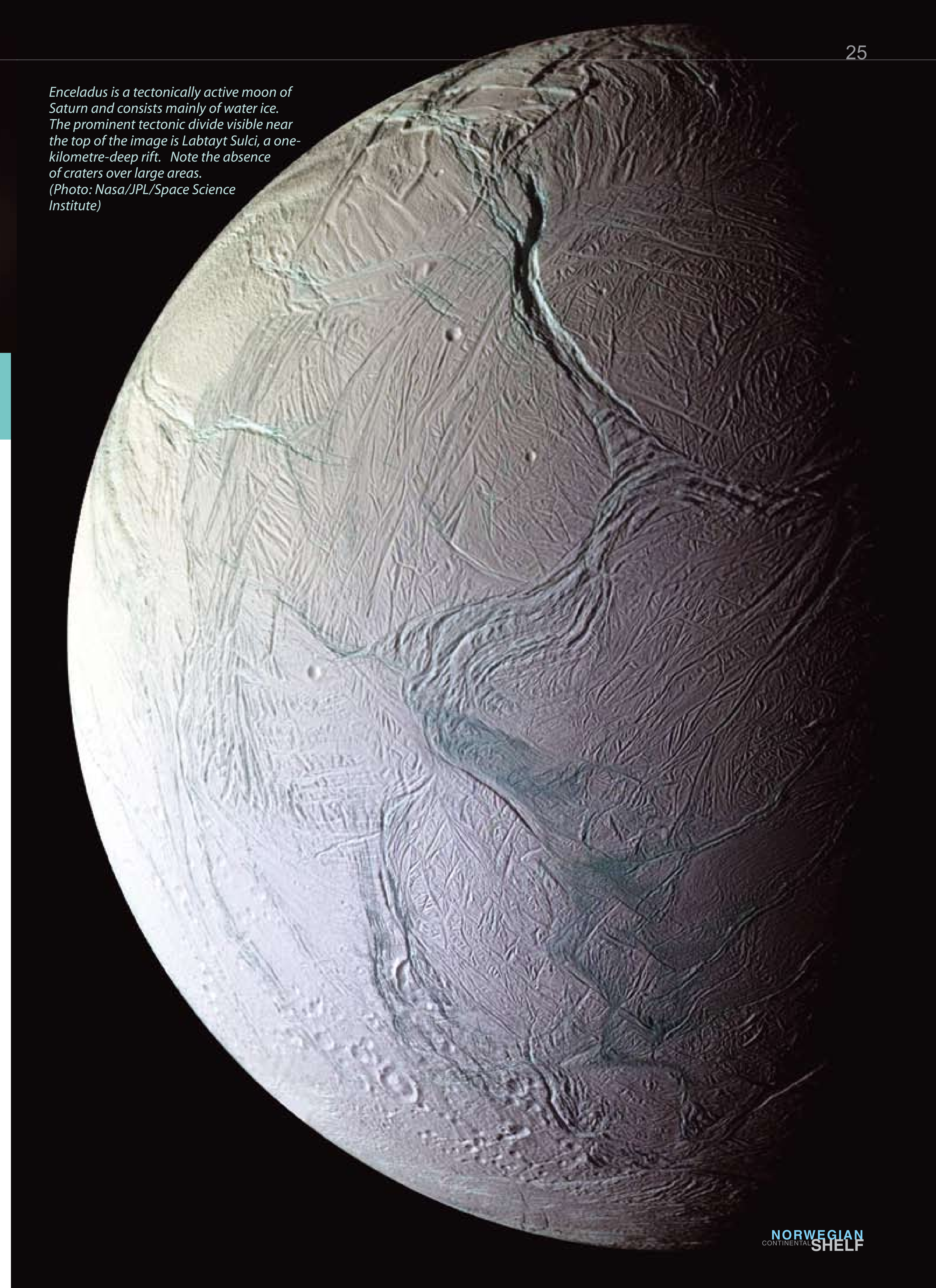
Data from Cassini proves that Enceladus is one of the most geologically dynamic bodies in the solar system. Internal heat permits geysers on this little moon to spew gossamer plumes of ice hundreds of kilometres above the surface. This creates a torus which forms one of Saturn's outermost rings, the tenuous E ring.

Cassini has shown us an extraordinary form of plate tectonics on Enceladus, where new crust is extruded from spreading ridges in only one direction – resembling an Earthly subduction zone in reverse.

Such internal heat generation is surprising given the small size of Enceladus. Measuring only 500 kilometres in diameter, it ranks as the sixth largest of Saturn's 60 moons. By comparison, our Moon has seven times the diameter, 336 times the volume and 1 000 times the mass.

In spite of its large size, however, the Moon does not generate heat from radioactive decay and is therefore geologically dead. Nothing happens there except for the occasional meteor strike. The last large lunar impact, now the Tycho crater, was 100 million years ago.

Although its interior may be as hot as 0°C, the surface of Enceladus is one of the coldest in the solar system.



Enceladus is a tectonically active moon of Saturn and consists mainly of water ice. The prominent tectonic divide visible near the top of the image is Labtayt Sulci, a one-kilometre-deep rift. Note the absence of craters over large areas. (Photo: Nasa/JPL/Space Science Institute)

Temperatures there reach -201°C at the warmest. This is because the little moon is amazingly white – whiter than fresh powder snow, in fact.

No other known object in the solar system is whiter than Enceladus. Its ice surface reflects 99 per cent of the sunlight striking it. That observation alone tells us that something is occurring on Enceladus which is consuming energy.

This is because energy is needed to keep a white surface pristine in a dusty environment like our solar system. As on Earth, vast regions on Enceladus are not pitted with impact craters. A process must be coating Enceladus with fresh ice and renewing its crust. So where is the energy coming from on this small, frigid globe?

Renewal

Hot interiors and crustal renewal are what Enceladus and Earth have in common, but that is where the similarity ends. The temperature at the Earth's core is 6 000°C, the same as the Sun's surface.

This inner core is almost the size of our moon and lies 5 000 kilometres beneath our feet. If you could see to the centre of the planet, the inner core would cover the same area of your visual field as a 35-centimetre ball held at arm's length.

It would appear 285 times brighter and feel 2 000 times warmer than the Sun because it covers 285 times the angular surface area, and has seven times the surface density of the Sun.

In the Earth's core and mantle, unstable heavy atoms decay into progressively lighter atoms, releasing energy in the process. Fortunately, the crust is not getting warmer because Earth recycles it and radiates excess heat into space at the same rate as the core and mantel produce it.

Unlike Earth, Enceladus may lack the necessary unstable atoms in its core to generate heat. Density measurements from Cassini fly-bys indicate that it may be a differentiated body with a large silicate core surrounded by a liquid water-ice mantle. In other words, the Enceladus core is made of roughly the same lightweight material based on silicon-oxygen as the Earth's crust.

Our planet's mantle is made of metal-rich, silicate-poor rock. Put simply, this means it comprises melted rock on the inside and frozen rock on the outside. By contrast, Enceladus consists of "melted" water on the inside and frozen water on the outside. In other words, it is a ball of water covered by a shell of ice, with a core of rock in the centre.

To understand Enceladus' alien energy source, we have to understand the bizarre way gravity behaves.

Stretching

Gravity stretches things. Tides on Earth are not caused by the Moon attracting the ocean, but by the Moon stretching the entire Earth. Because the oceans are more flexible than rock, they get stretched more.

In a tug of war, the rope is stretched equally in both directions, regardless of which end the winning team is pulling. The latter is simply applying a greater force on the rope in the opposite direction to the losing team. From the rope's point of view, however, the extra force exerted by the winning team would be exactly the same if the two teams were pulling in the same direction.

That explains why we have high tides simultaneously on opposite sides of Earth. The Moon's attractive force is greater on Earth's near side and weaker on the far side. The sum of these two forces stretches our planet so that it becomes an ellipsoid, like an egg, with the major axis intersecting the Moon.

Any large body in the gravitational field of another body will be pulled into an ellipsoid shape. If the bodies are rotating, rotational energy will induce friction and become converted to heat.

That is partly why Earth's rotation is slowing down. Our planet rotates 30 times faster than the Moon orbits, so its tidal bulge is always ahead of the satellite. This transfers angular momentum to the Moon, slowing Earth's rotation even more and causing the Earth-Moon gap to increase by five centimetres every year.

We humans think of gravity as an attractive force only. The reason we do not notice that we are being stretched when the Moon is overhead is because we are so small. If we were as big as Enceladus and located in Saturn's much stronger gravitational field, we would feel the stretch and we would feel the heat.

Friction

Like our Moon, Enceladus is not rotating with respect to its mother planet and always shows the same face to Saturn. Tidal friction stopped the satellite's rotation long ago, as it has done for all the large moons of the giant planets.

So Enceladus has no rotational energy to convert to heat through tidal friction. But the moon has a sibling which likes to play tug-of-war. Its name is Dione, who was the mother of love goddess Aphrodite in Greek myth.

For each orbit ice moon Dione completes around Saturn, Enceladus makes two. The orbital periods of these moons are in resonance, a stable position which orbits tend to establish.

Dione's gravity is too weak to induce notable tidal stretch on Enceladus when the two moons pass each other, but does induce eccentricity in the latter moon's orbit and makes it more elliptical.

Enceladus moves slightly closer to and slightly farther from Saturn on each orbit, which means it experiences a varying intensity of tidal stretch. In other words, it flexes like an accordion. This orbital eccentricity is maintained by consuming angular momentum from Dione.

Our solar system contains many other ice worlds. Each has a story to tell. Every planet and moon shows either a variation of Earthly mechanisms or an entirely new "alien" way of doing things. By studying other worlds, we increase geological knowledge of our own planet. ❄

The Saturnian moon Enceladus is only 505 kilometres in diameter, small enough to fit comfortably within the length of the UK . (Illustration: Nasa/JPL/Space Science Institute)

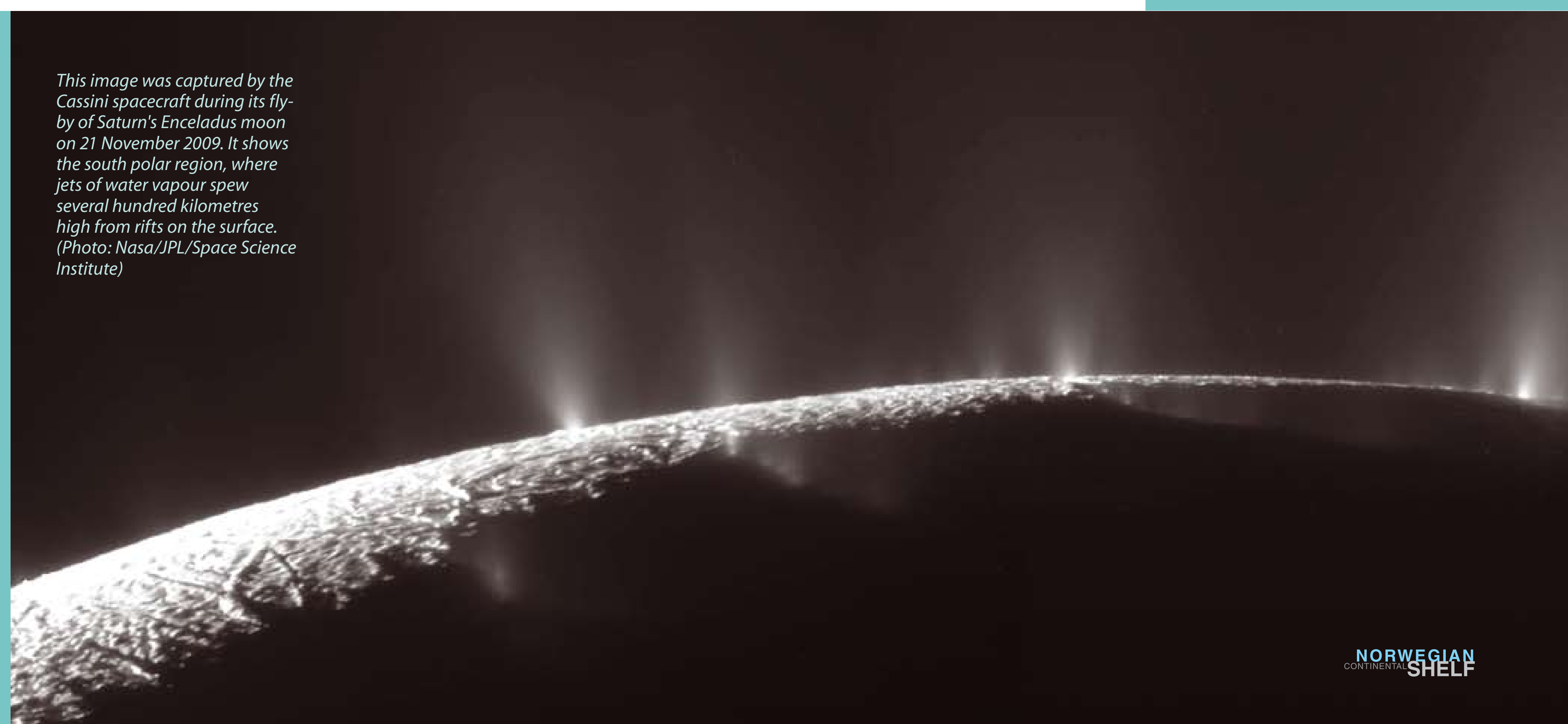
Raising the body count

Since Galileo Galilei discovered Jupiter's four largest moons in 1610, astronomers have identified more than 500 000 solar-system bodies ranging in diameter from a few metres to 51 000 kilometres. Robotic survey telescopes find thousands more each year.

Of the 500 000 objects found since 1610, only 80 are larger than 400 kilometres. Many of the latter are moons of the giant gas planets – Jupiter, Saturn, Uranus and Neptune.

They are ball-shaped because gravity squeezes icy bodies to a sphere when their diameter exceeds 400 kilometres. New surveys are turning up droves of these small round ice worlds beyond the orbit of Neptune. Called dwarf planets, Pluto is the best known.

Objects smaller than 400 kilometres are shaped like potatoes. Most orbit the Sun and are called asteroids and comets, depending on their ice content. If they orbit planets, they are known as moons regardless of their composition.



This image was captured by the Cassini spacecraft during its fly-by of Saturn's Enceladus moon on 21 November 2009. It shows the south polar region, where jets of water vapour spew several hundred kilometres high from rifts on the surface. (Photo: Nasa/JPL/Space Science Institute)