Voyage to the Planets
Lecture 6:
Jupiter
and its moons

Presented by

Dr Helen Johnston
School of Physics

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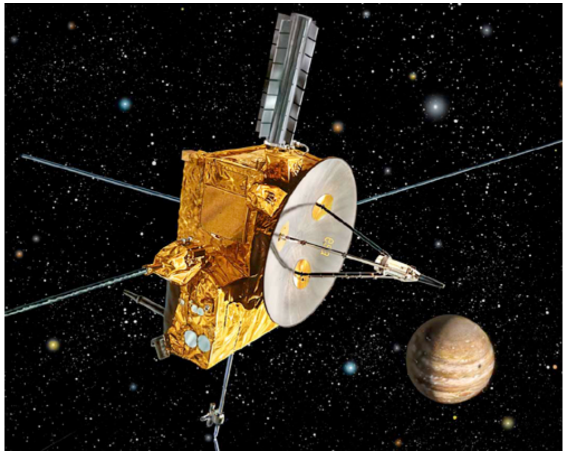
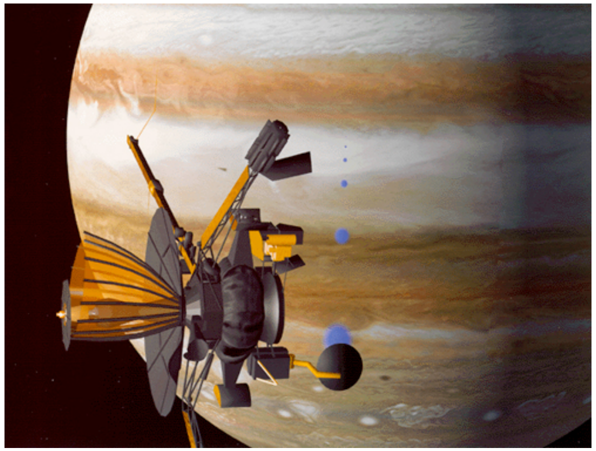
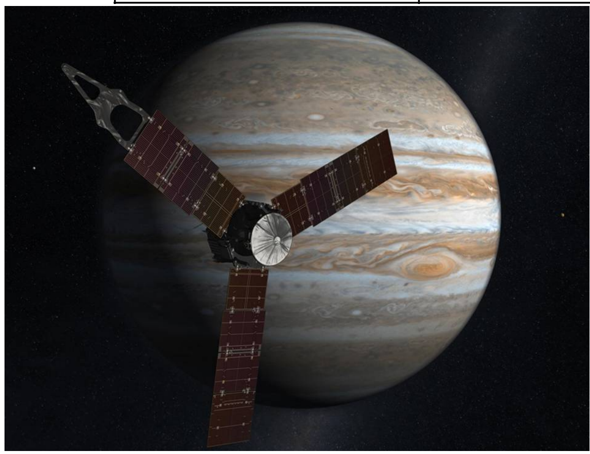
THE UNIVERSITY OF SYDNEY

There have been six spacecraft which performed flybys of Jupiter, and two orbiting spacecraft. *Galileo* orbited Jupiter for eight years. *Juno* was launched in 2011 and is currently in orbit around Jupiter.

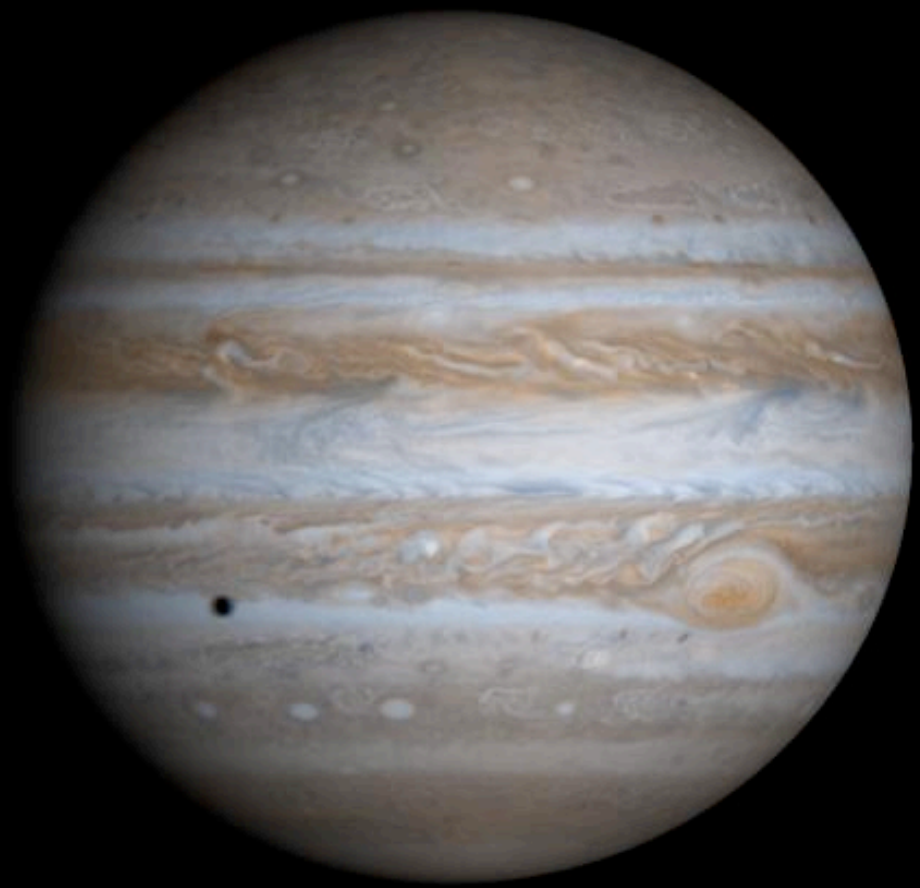
Pioneer 10	1973	Flyby
Pioneer 11	1974	Flyby
Voyager 1	1979	Flyby
Voyager 2	1979	Flyby
Galileo	1995–2003	Orbiter and probe
Cassini	2000	Flyby
New Horizons	2007	Flyby
Juno	2016–	Polar orbiter







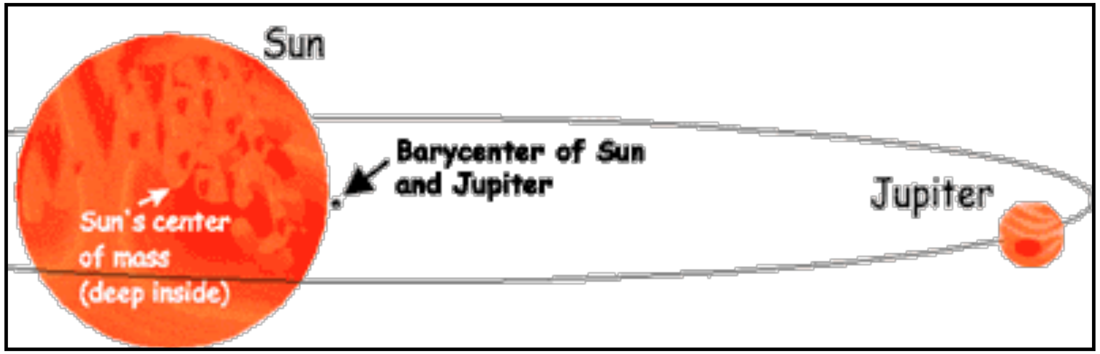
Jupiter



Basic data

	Jupiter	Jupiter/Earth
Mass	1899×10^{24} kg	317.83
Radius	71,492 km	11.21
Mean density	1.326 g/cm^3	0.24
Gravity (eq., 1 bar)	24.79 m/s^2	2.53
Semi-major axis	778.57×10^6 km	5.204
Period	4332.589 d	11.862
Orbital inclination	1.304°	-
Orbital eccentricity	0.0489	2.928
Axial tilt	3.1°	0.133
Rotation period	9.9250 h	0.415

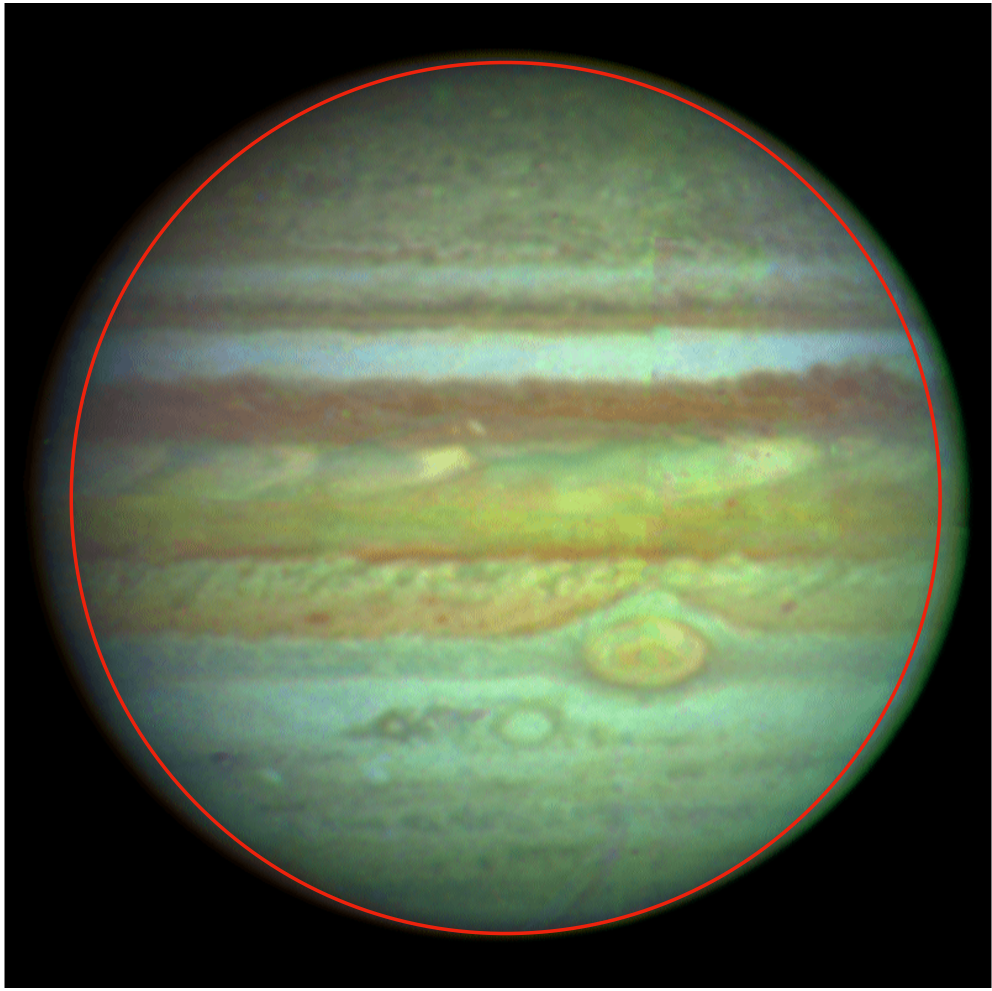
Jupiter is the most massive of the planets, 2.5 times the mass of the other planets combined. It is the only planet whose barycentre with the Sun actually lies above the Sun's surface (1.068 solar radii from the Sun's centre).



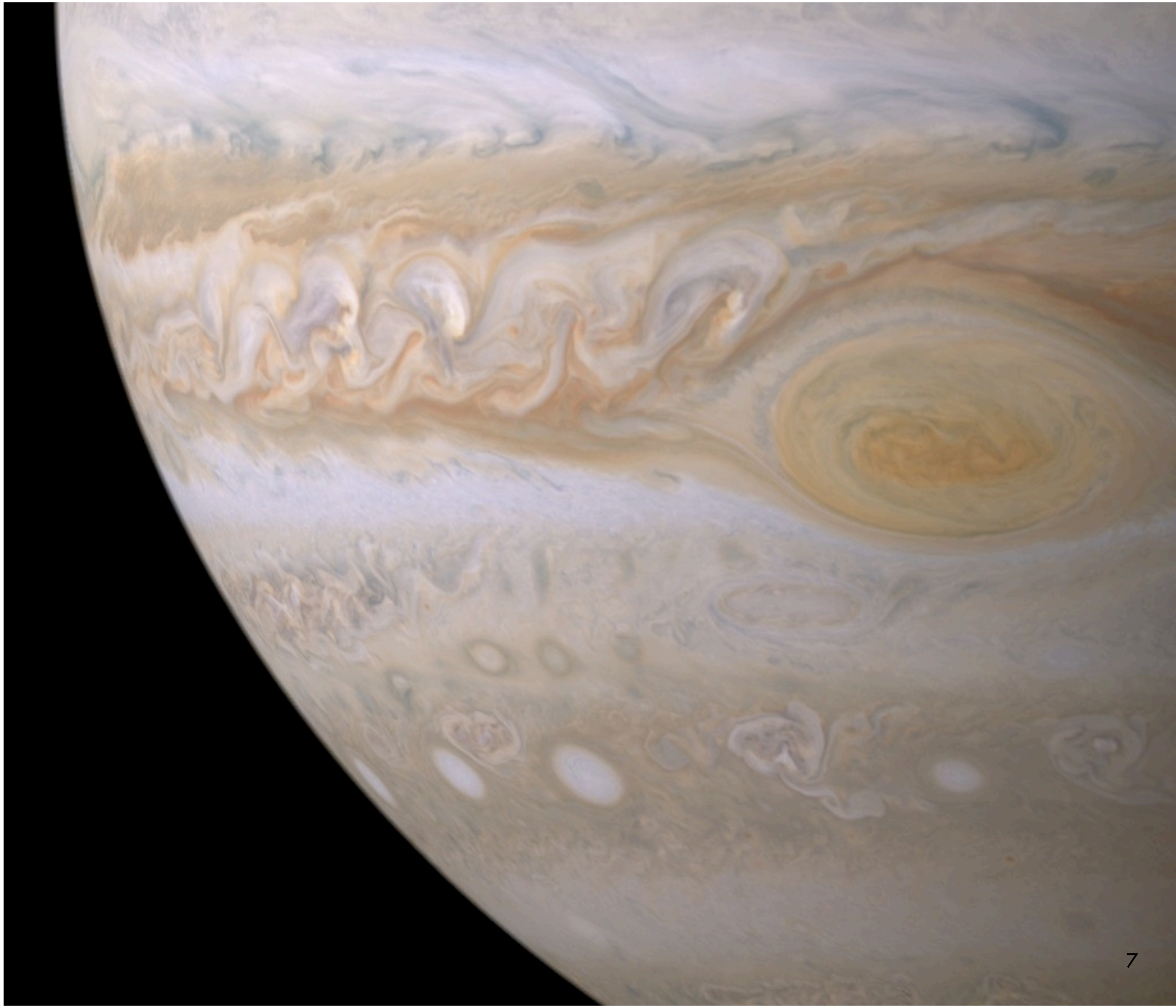
True colour picture of Jupiter, taken by Cassini on its way to Saturn during closest approach. The smallest features visible are only 60 km across.

Jupiter exhibits *differential rotation* – the rotational period depends on latitude, with the equatorial zones rotating a little faster (9h 50m period) than the higher latitudes (9h 55m period). This must mean that Jupiter's visible surface is not solid but is fluid: a *gas giant*.

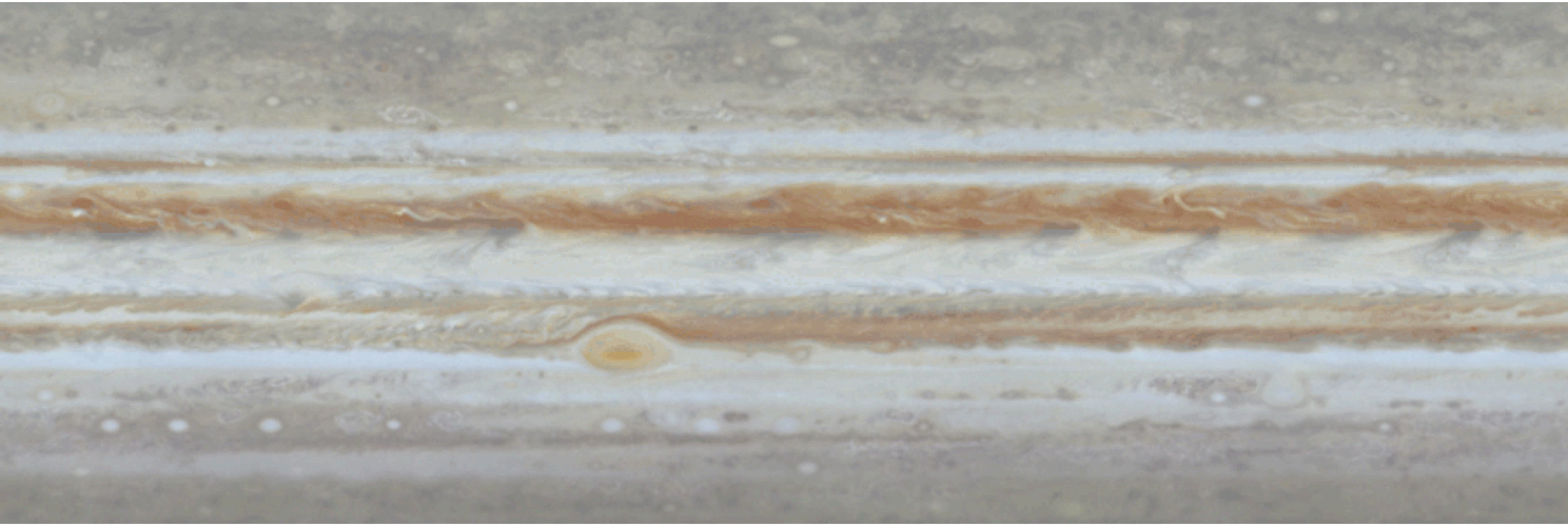
Such a rapid rotation produces a noticeable bulge at the equator: Jupiter’s equatorial radius (71,500 km) exceeds its polar radius (66,900 km) by about 6.5%.



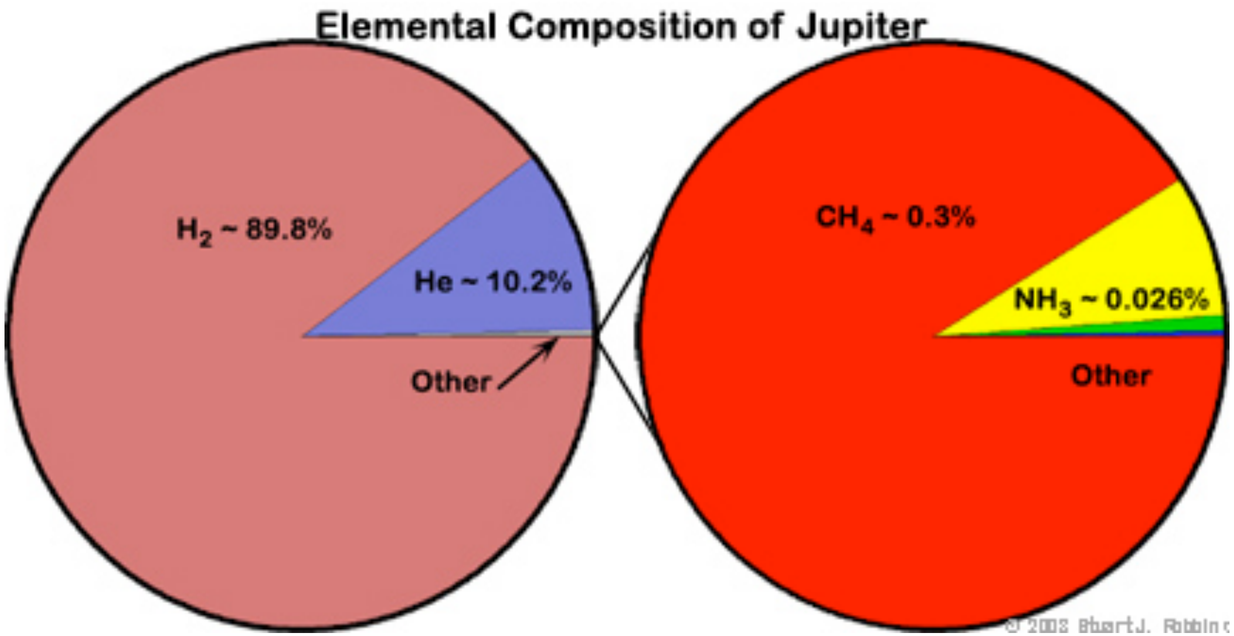
Everything visible on the planet is a cloud. The parallel reddish-brown and white bands, the white ovals, and the large Great Red Spot persist over many years despite the intense turbulence visible in the atmosphere. The details of the cloud patterns change over hours or days.



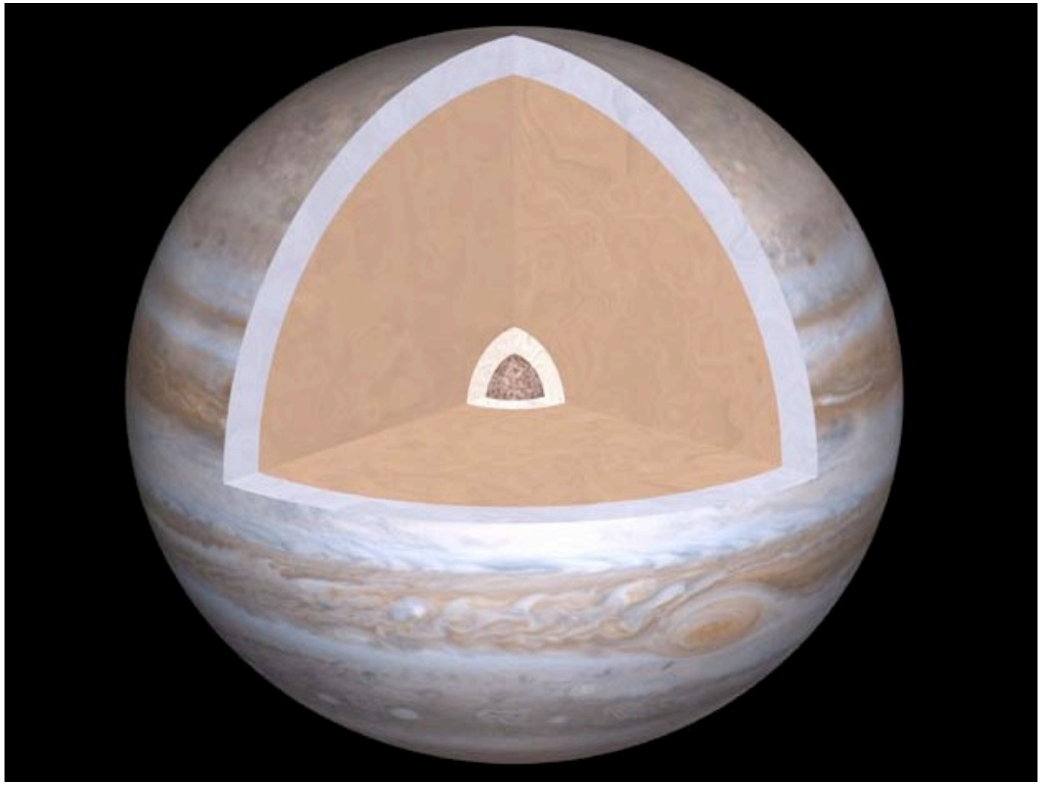
Like the other gas giants, Jupiter does not have solid surface. Its gaseous material simply gets denser with depth. What we see when looking at these planets is the tops of clouds high in their atmospheres (slightly above the 1 atmosphere level).



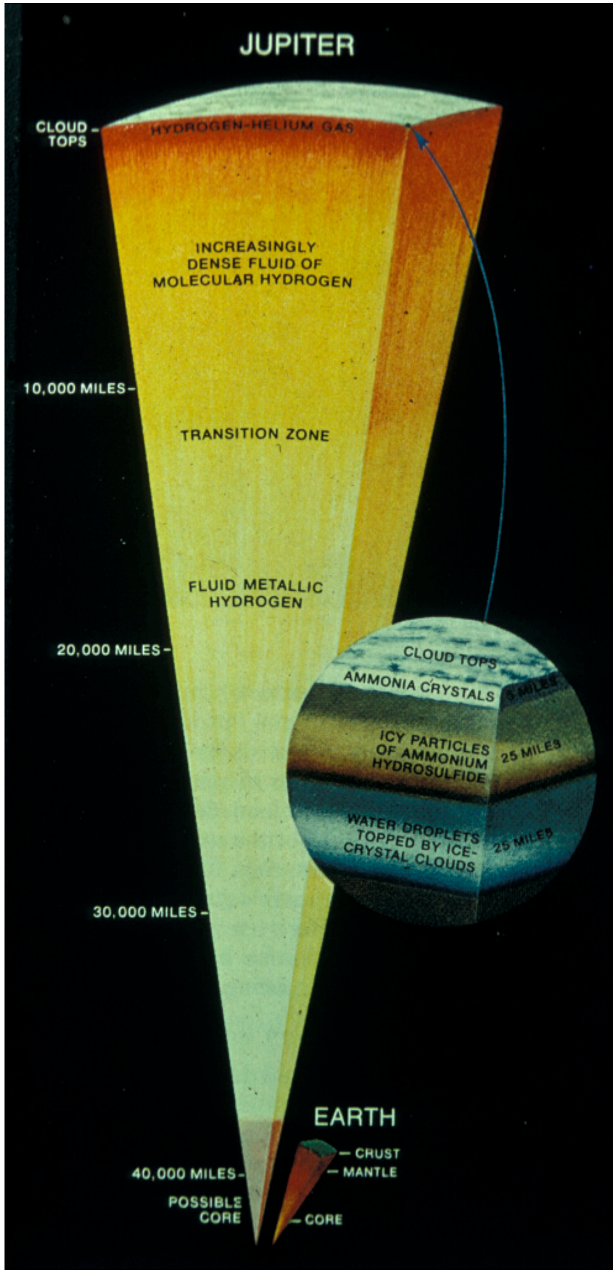
Jupiter consists of 90% hydrogen, 10% helium, very similar to the composition of the Sun, with trace amounts of methane, water, ammonia, and hydrogen sulphide. The colours in the clouds arise from various minor constituents of the atmosphere, probably sulphur and phosphorus, and possibly even sophisticated compounds including simple amino acids.



The mean density of Jupiter is 1326 kg/m^3, less than a quarter the density of Earth, which implies the atmosphere must be very deep, possibly the entire planet. Jupiter probably contains a rocky core, about 10–15 Earth masses.



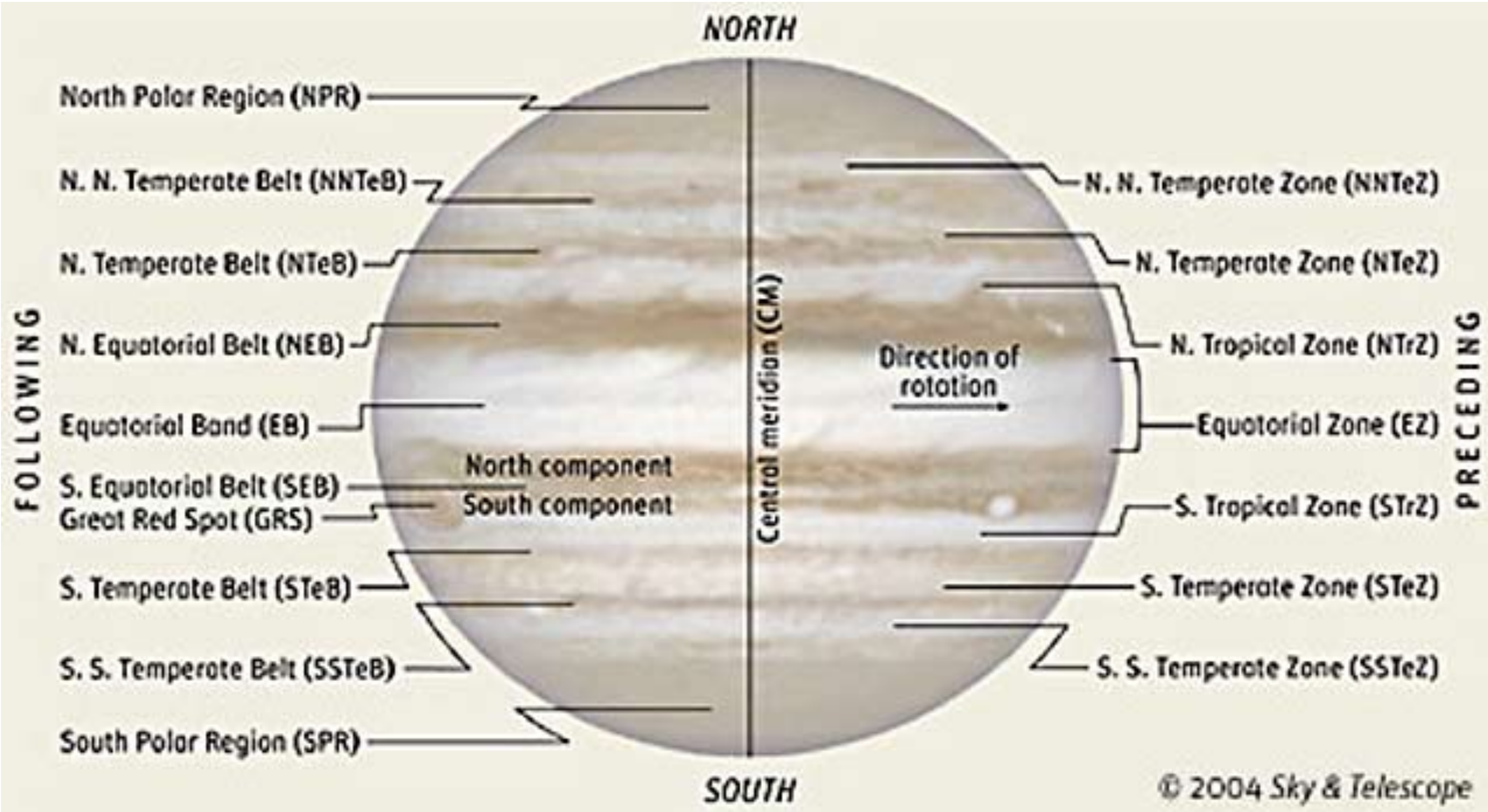
The core is surrounded by *metallic hydrogen*, where the electrons have been ionised, at a pressure of 1,000,000 bar. Surrounding this is liquid hydrogen, which is surrounded by gaseous molecular hydrogen. There are no clear boundaries between these various phases.



Jupiter's atmospheric circulation is not primarily driven by the Sun. Jupiter's centre still has residual heat from its formation 4.6 billion years ago, which means that it heats the atmosphere from below. Jupiter radiates about twice as much heat as it receives from the Sun.

The large size of Jupiter combined with its rapid rotation means that the atmosphere at the equator travels at 48,000 km/h.

The winds on Jupiter are confined in wide bands of latitude: these are easily visible on the globe. The light coloured stripes are called *zones*, the dark ones *belts*. The thin narrow dark stripes which separate the regions are known as *bands*.



These bands and belts change significantly from year to year. Some features appear and disappear, others change colour or shape.

2009

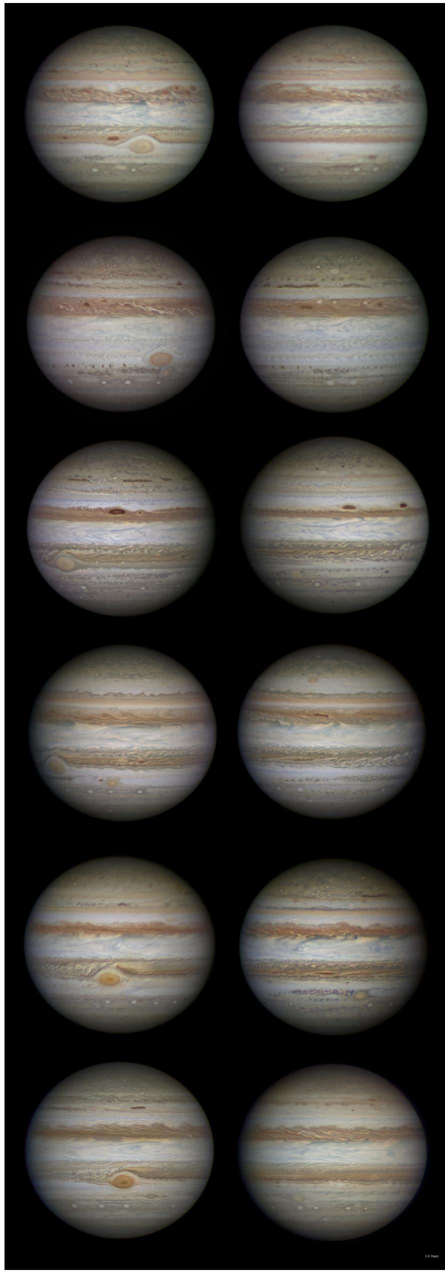
2010

2011

2012

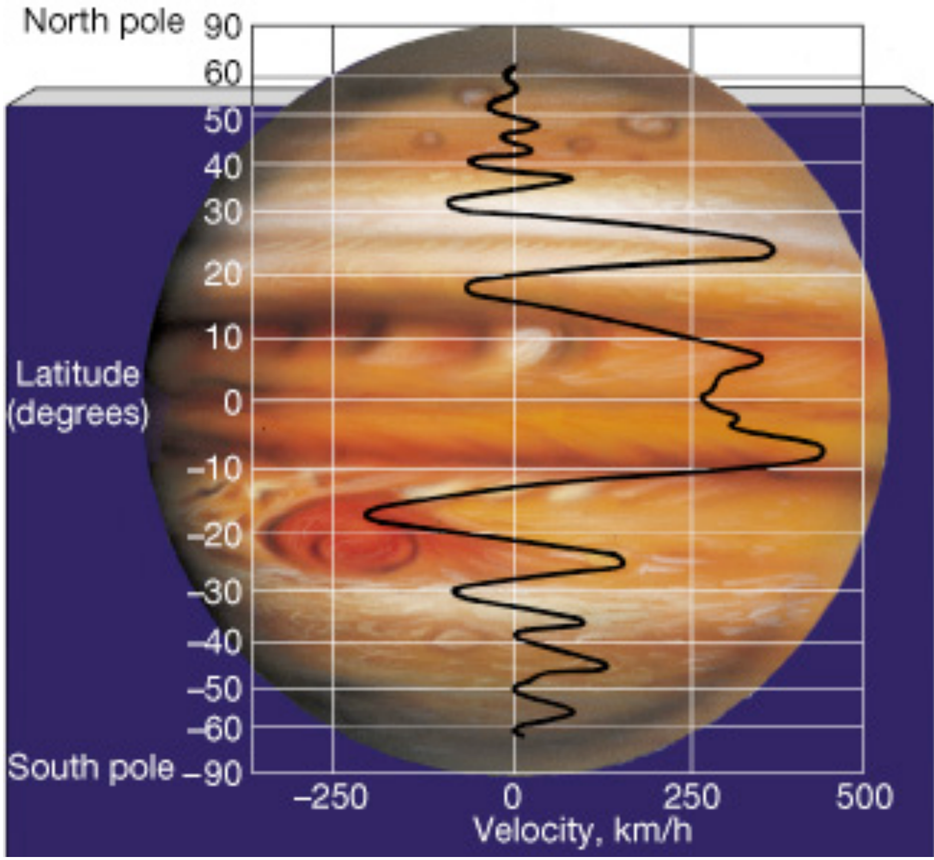
2013

2015



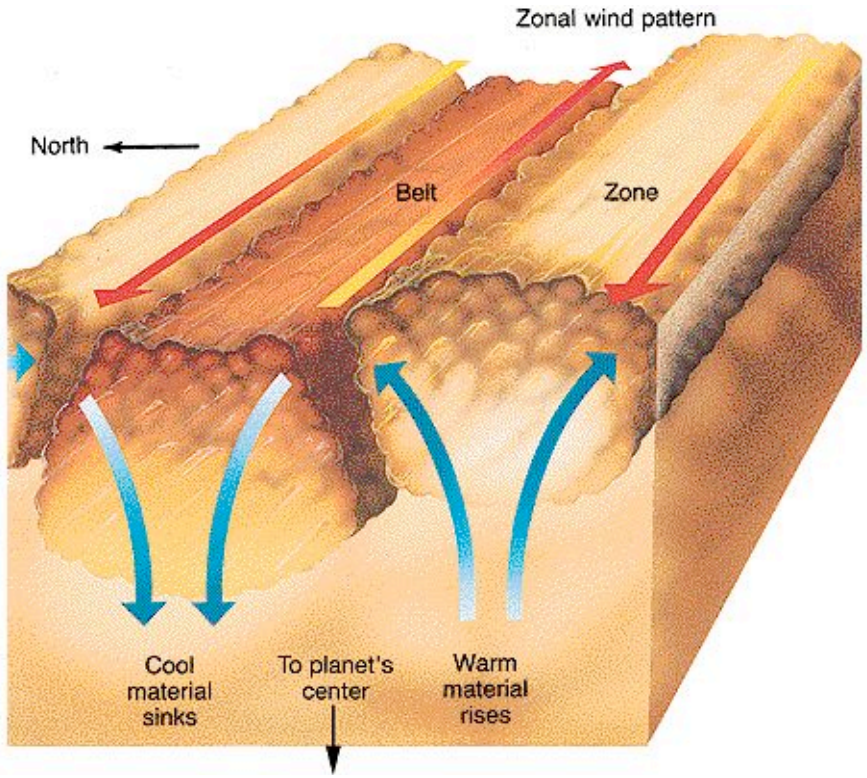
Photos of Jupiter by amateur astronomer Damian Peach

The equatorial regions of the atmosphere rotate faster than the planet, with an average flow speed of some 85 m/s, or about 300 km/h, in the easterly direction. Further away from the equator, there are alternating streams of westward and eastward flow, with the speed diminishing toward the poles.

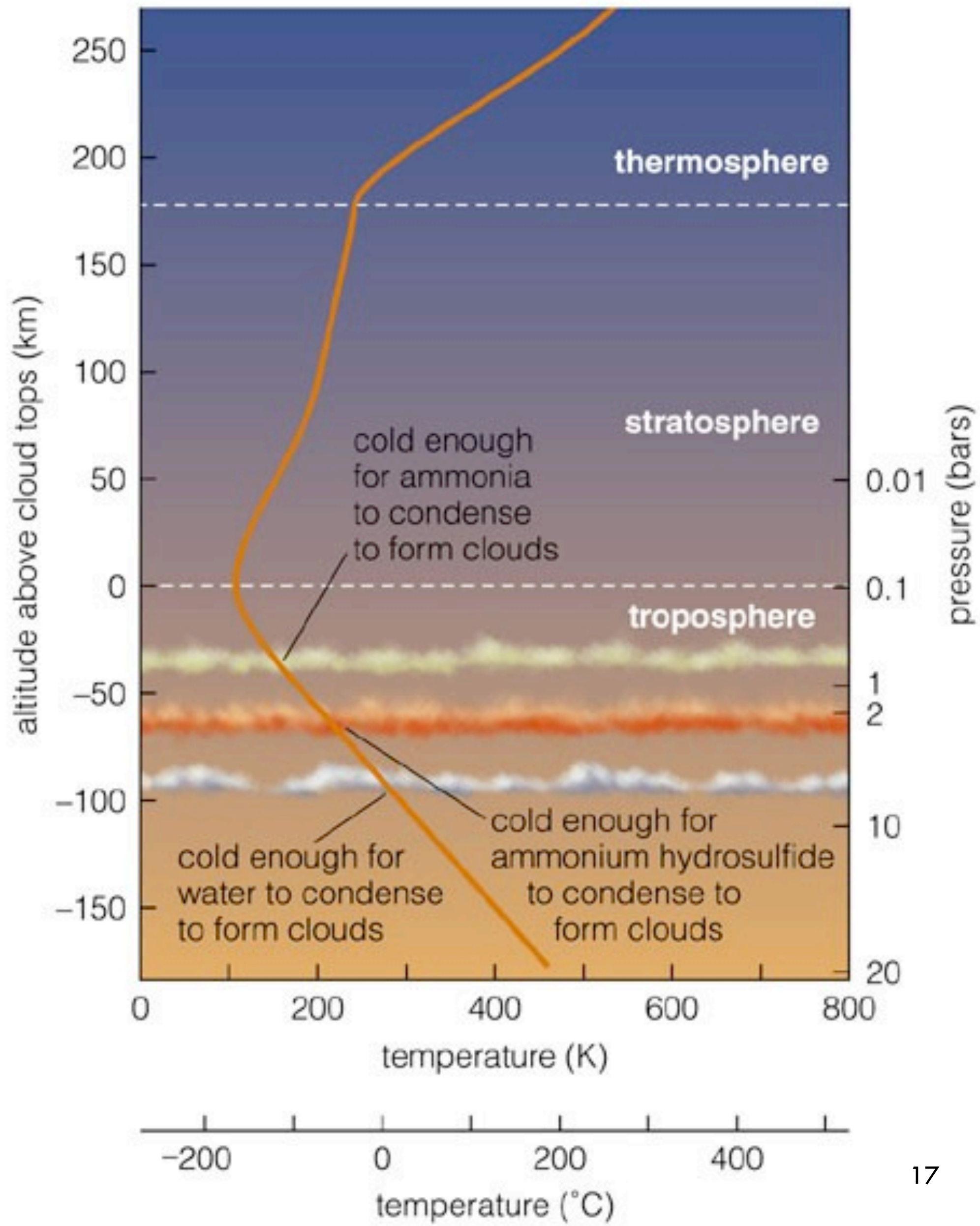


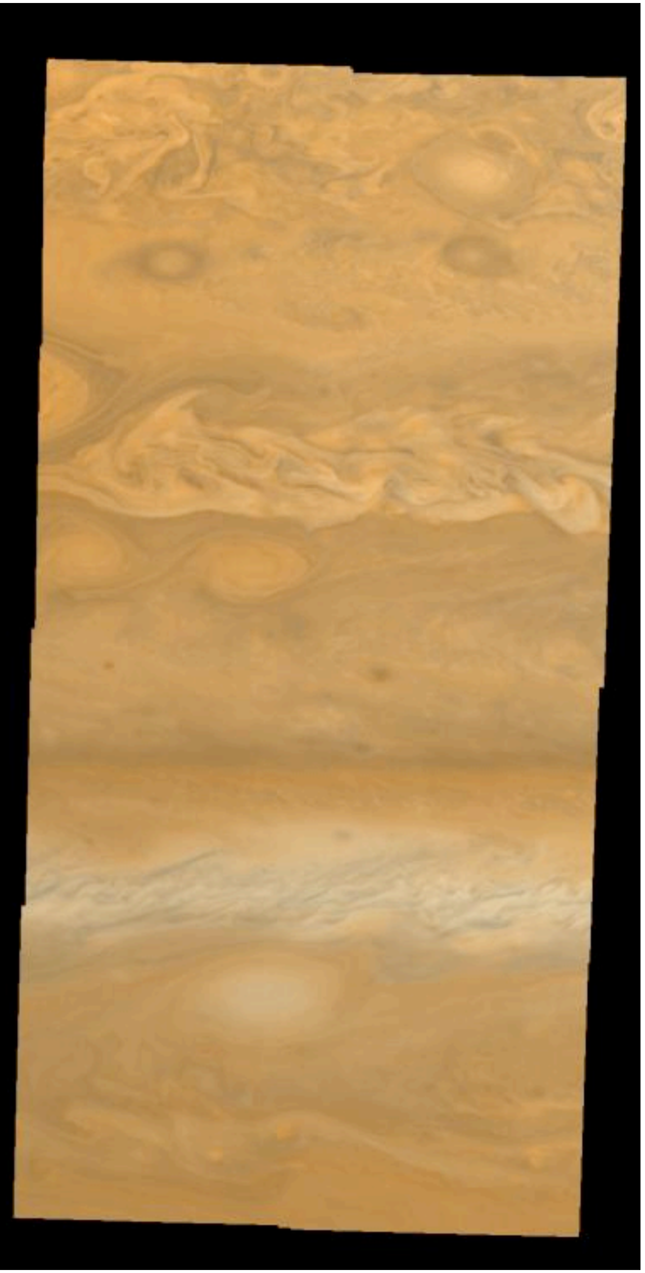
Wind speed measured relative to Jupiter's internal rotation. Changes in wind direction are associated with the atmospheric band structure.

The bright zones represent material rising, the dark belts material sinking. Jupiter's rapid rotation is responsible for it having so many more circulation cells than Earth's atmosphere.



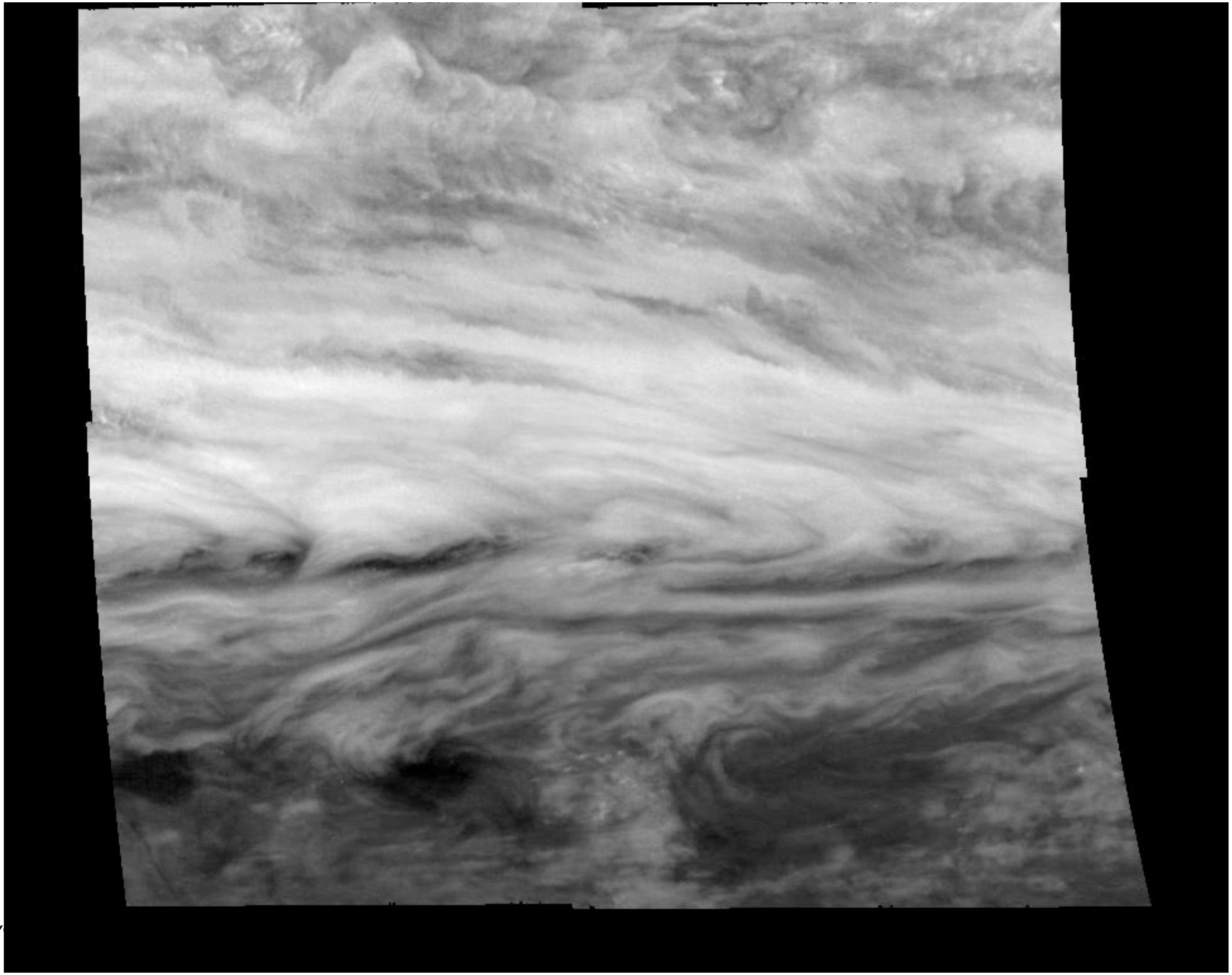
The colours of the clouds correlate with the temperature: cool clouds (about –140° C) are predominantly white, intermediate temperature (about –40° C) brown, while the warm clouds (about 0° C) are so deep that Rayleigh scattering makes them appear blue.



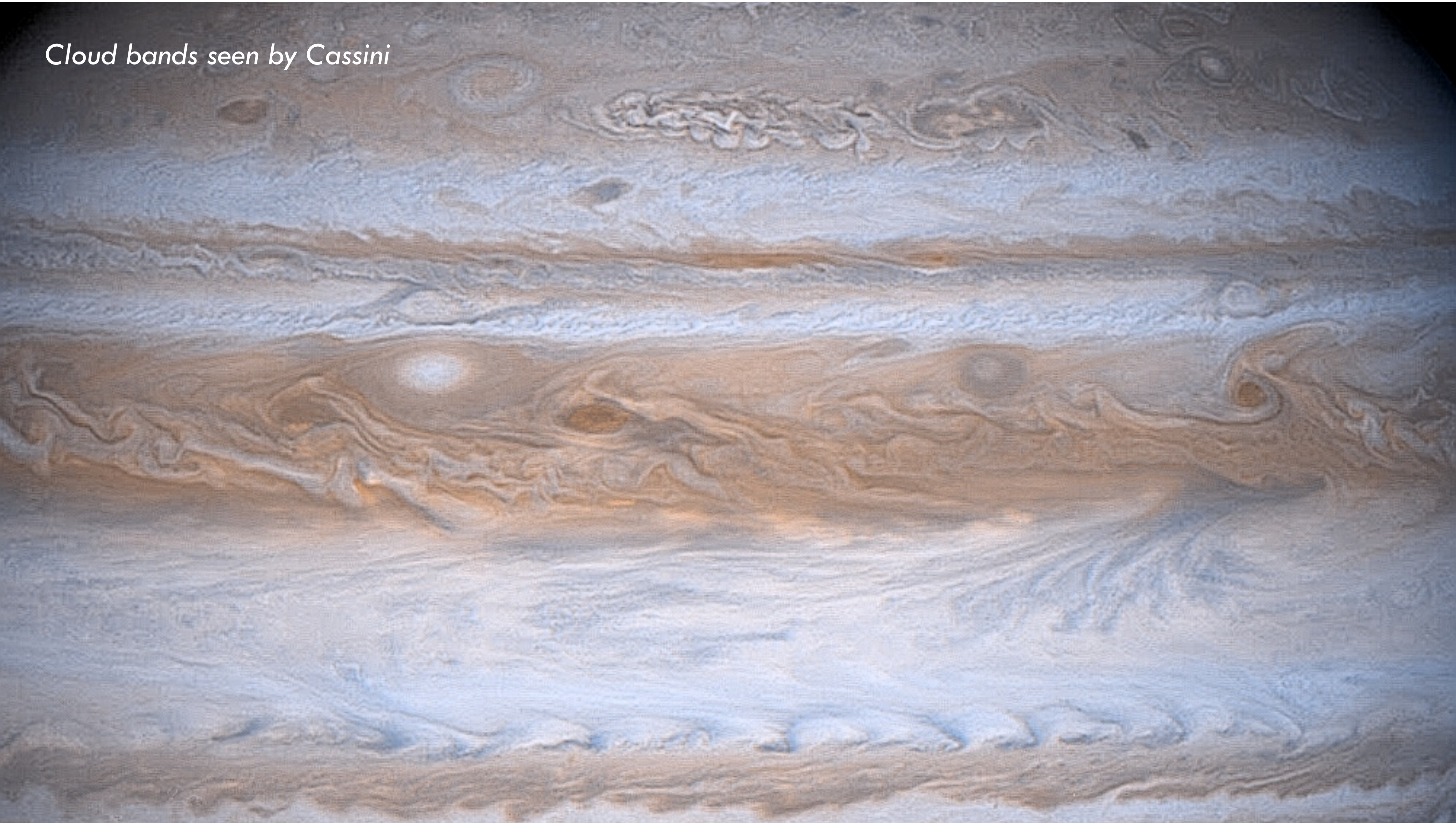


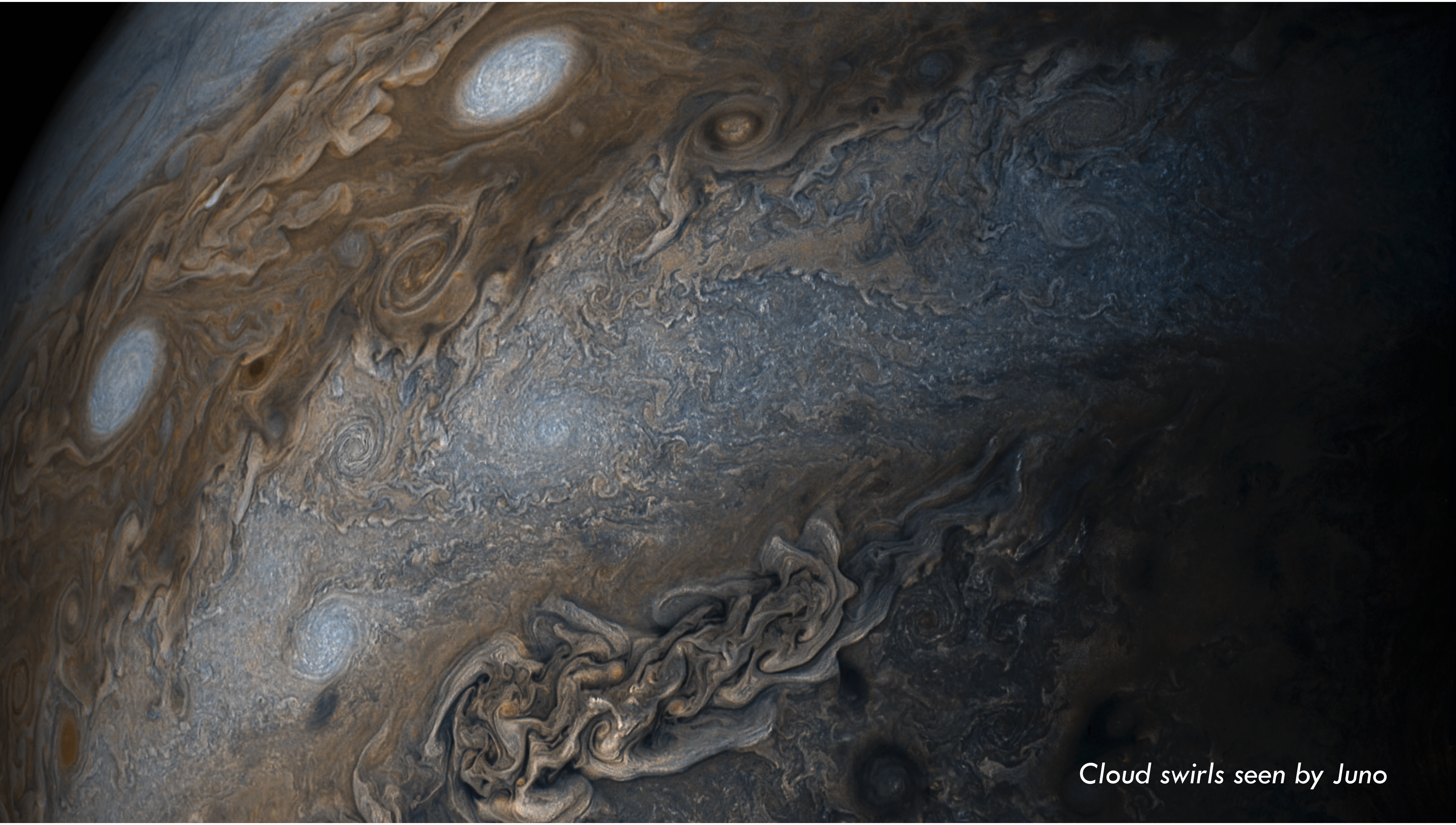
Winds in adjacent bands blow in opposite directions, and turbulence builds up at the interface.

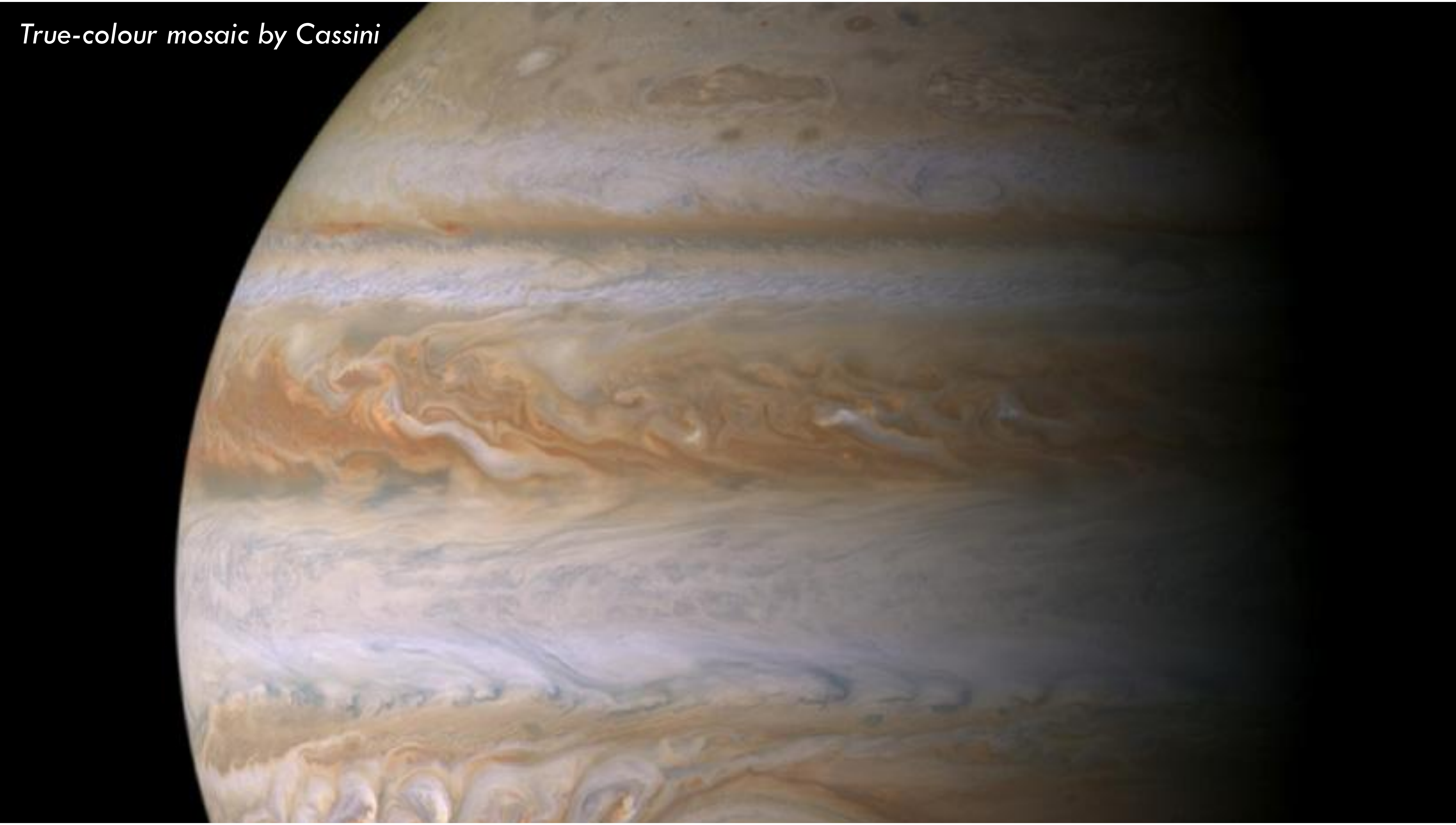
True colour (left) and false colour infrared (right) images of part of the northern hemisphere, taken by Galileo.



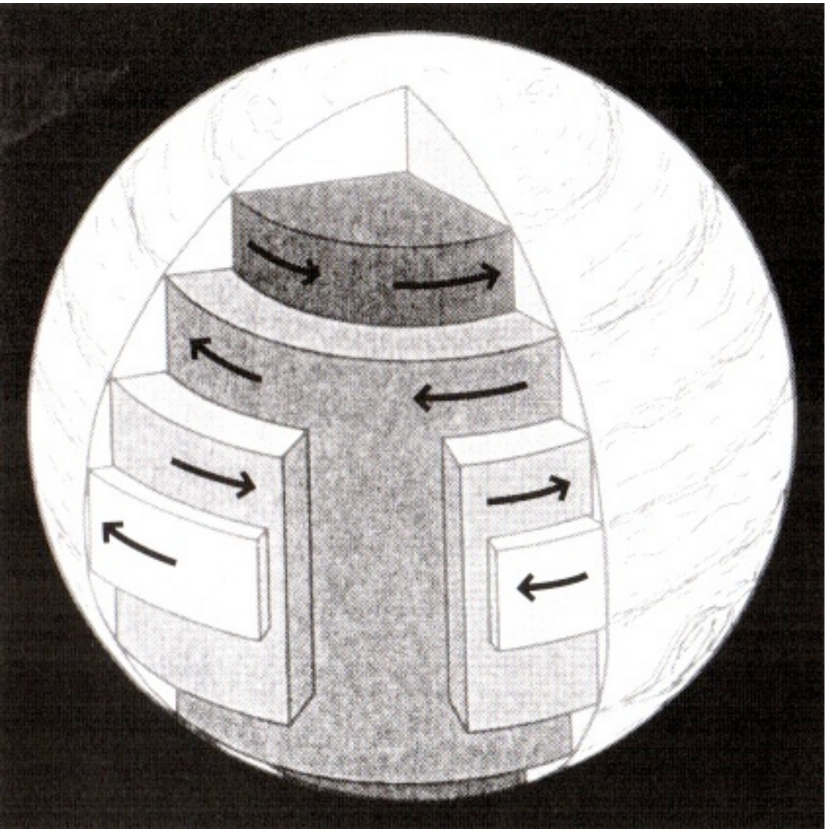
A belt-zone boundary near the equator.


Cloud bands seen by Cassini

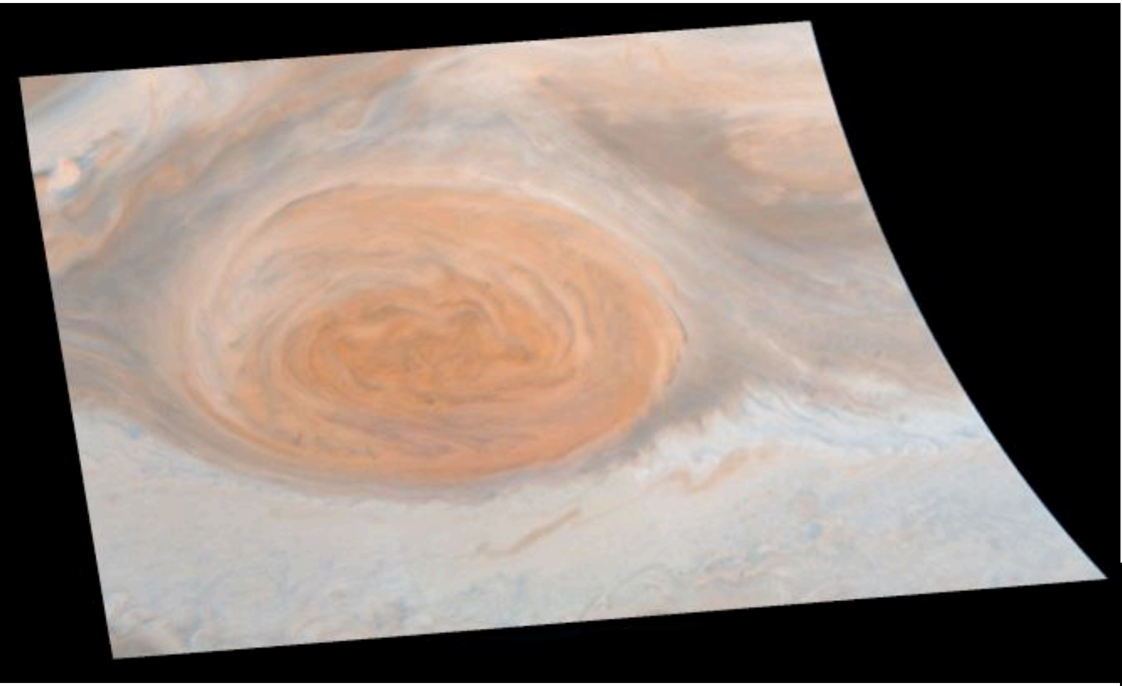

Cloud swirls seen by Juno


True-colour mosaic by Cassini

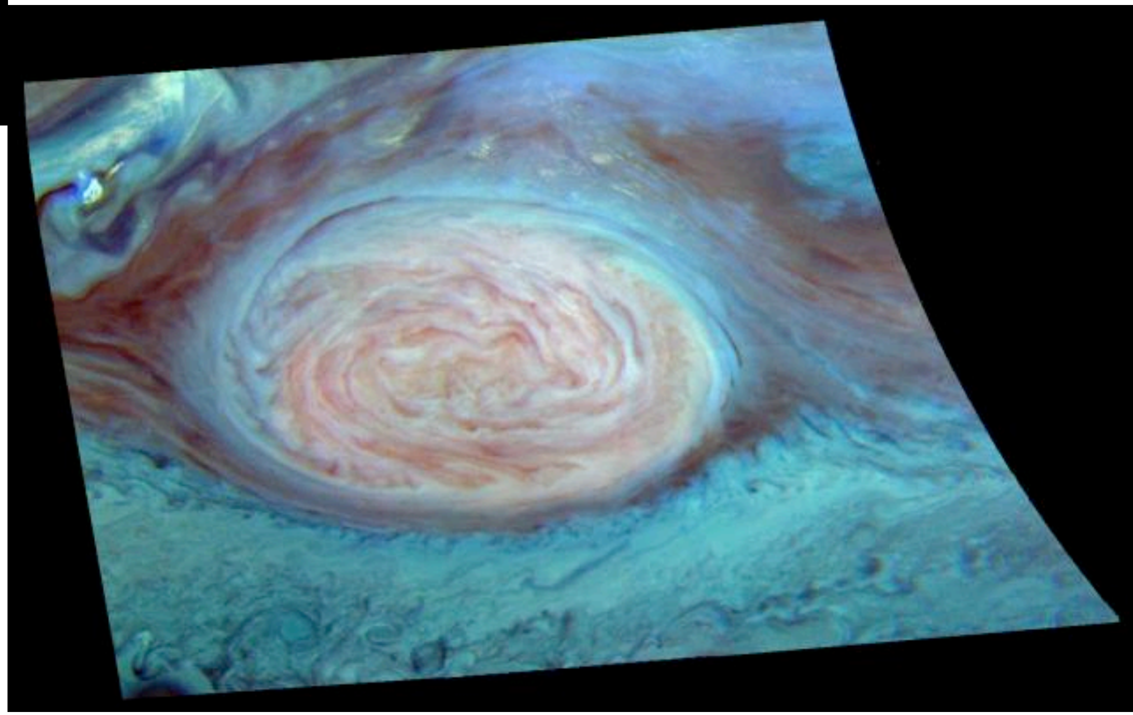
The depth to which the winds extend is not clear. They might be restricted to a thin weather layer, like on Earth; or they may extend deep into the atmosphere. One suggestion is that the interior might rotate as a series of concentric cylinders, each rotating at its own speed.

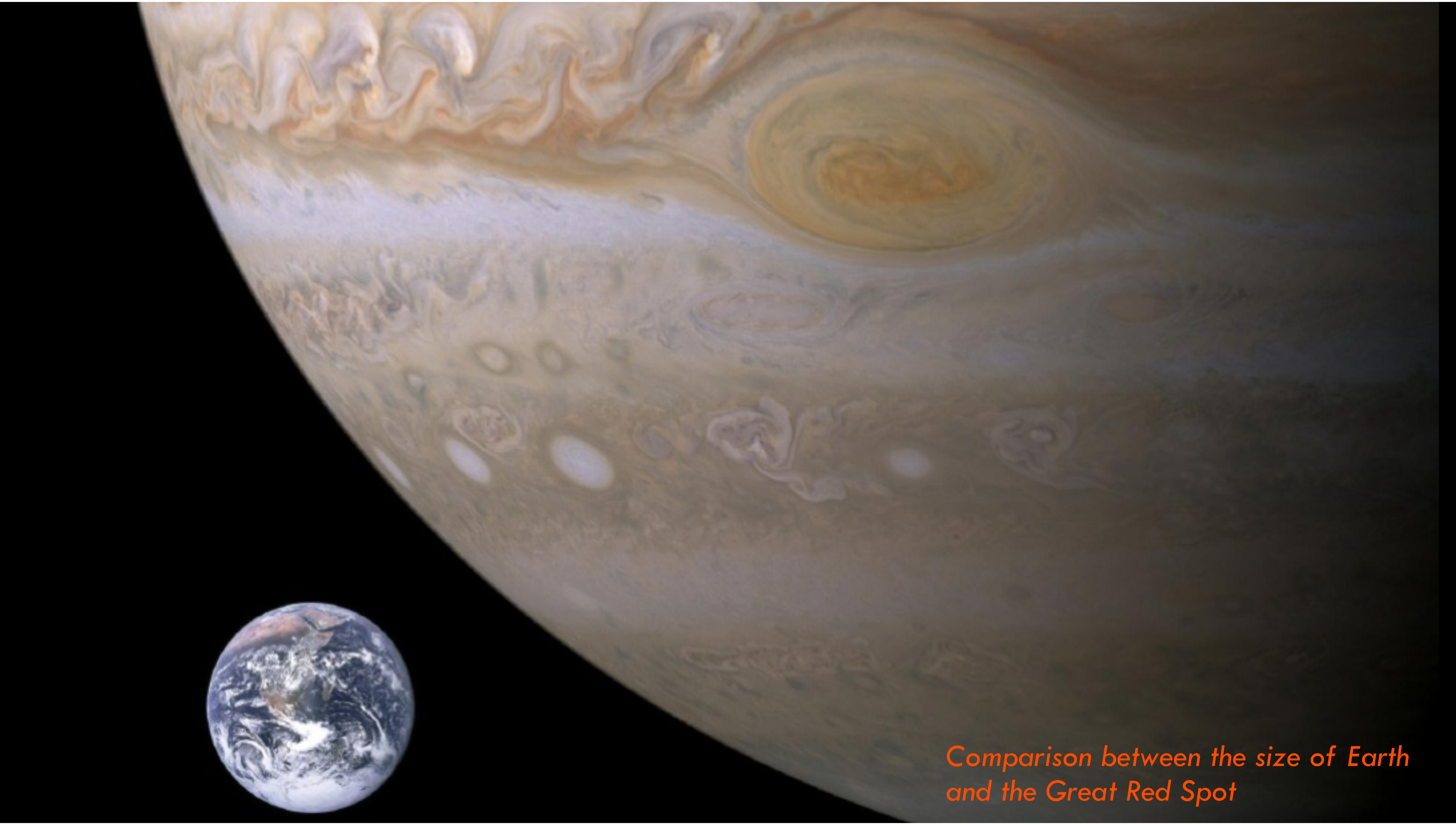


Galileo measured an increase of wind speed with depth, indicating that internal heat is the driving force for the winds.

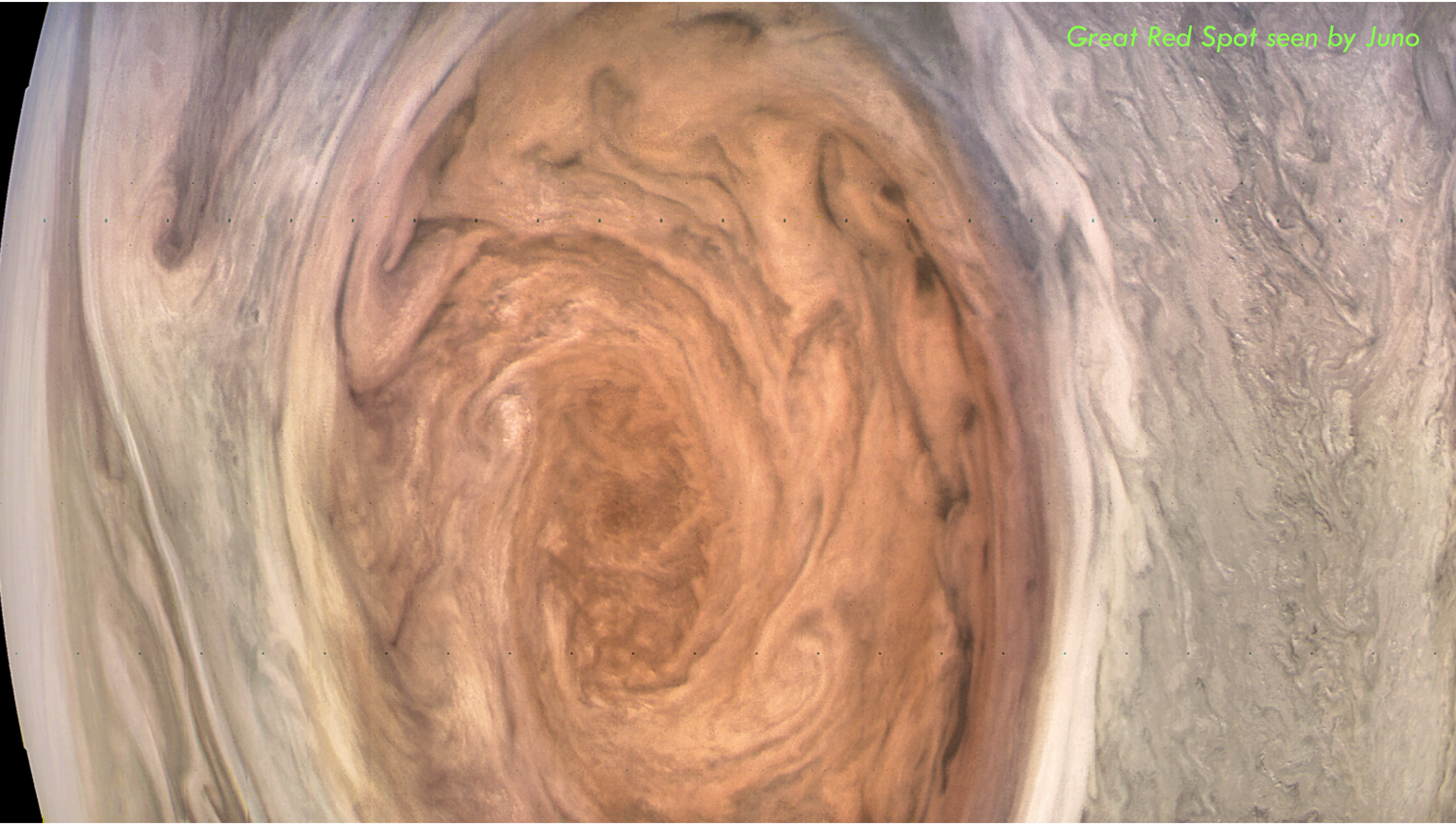


The regular bands are sometimes disturbed by giant storms. The most famous of these is the *Great Red Spot*, which has persisted for at least 350 years, since its discovery by Robert Hooke in 1664.

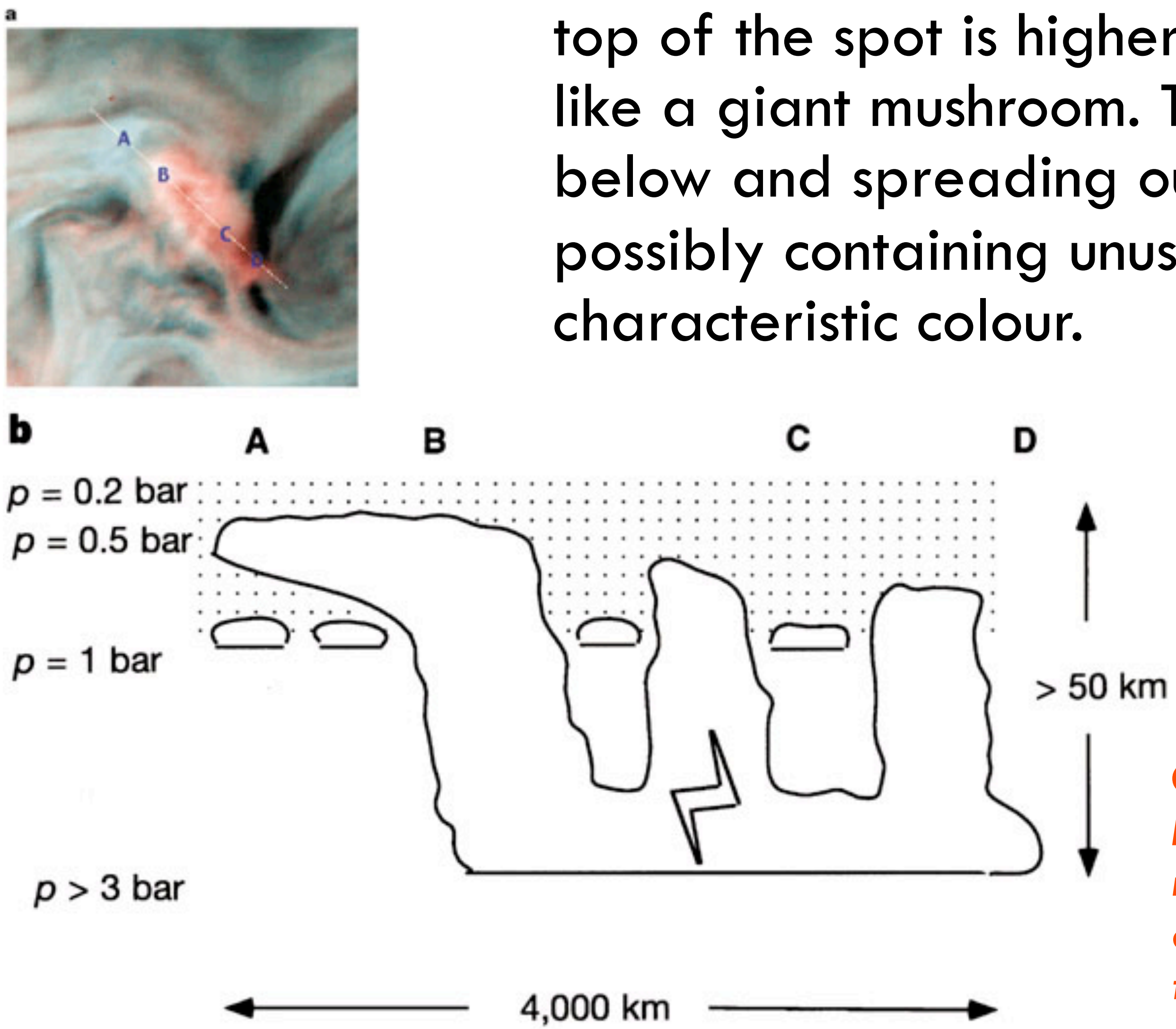




Comparison between the size of Earth and the Great Red Spot

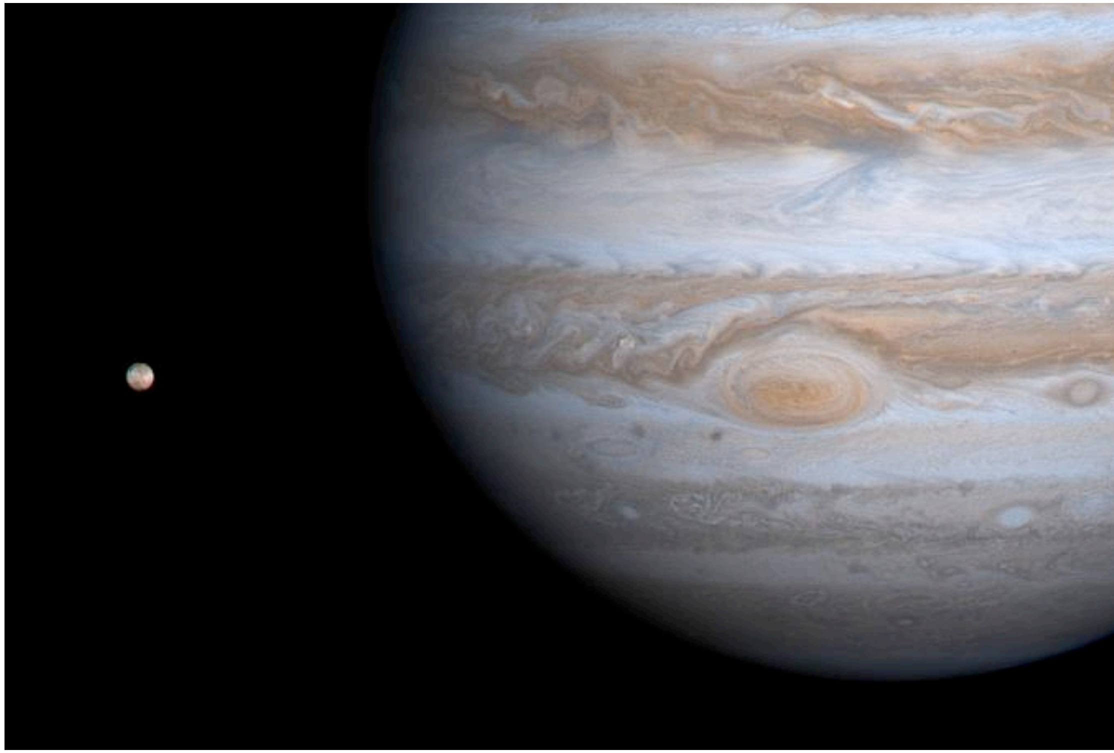

Great Red Spot seen by Juno

The temperature of the GRS is low, implying that the top of the spot is higher than the surrounding clouds, like a giant mushroom. This implies air is rising from below and spreading out over the troposphere, possibly containing unusual chemicals which give it its characteristic colour.

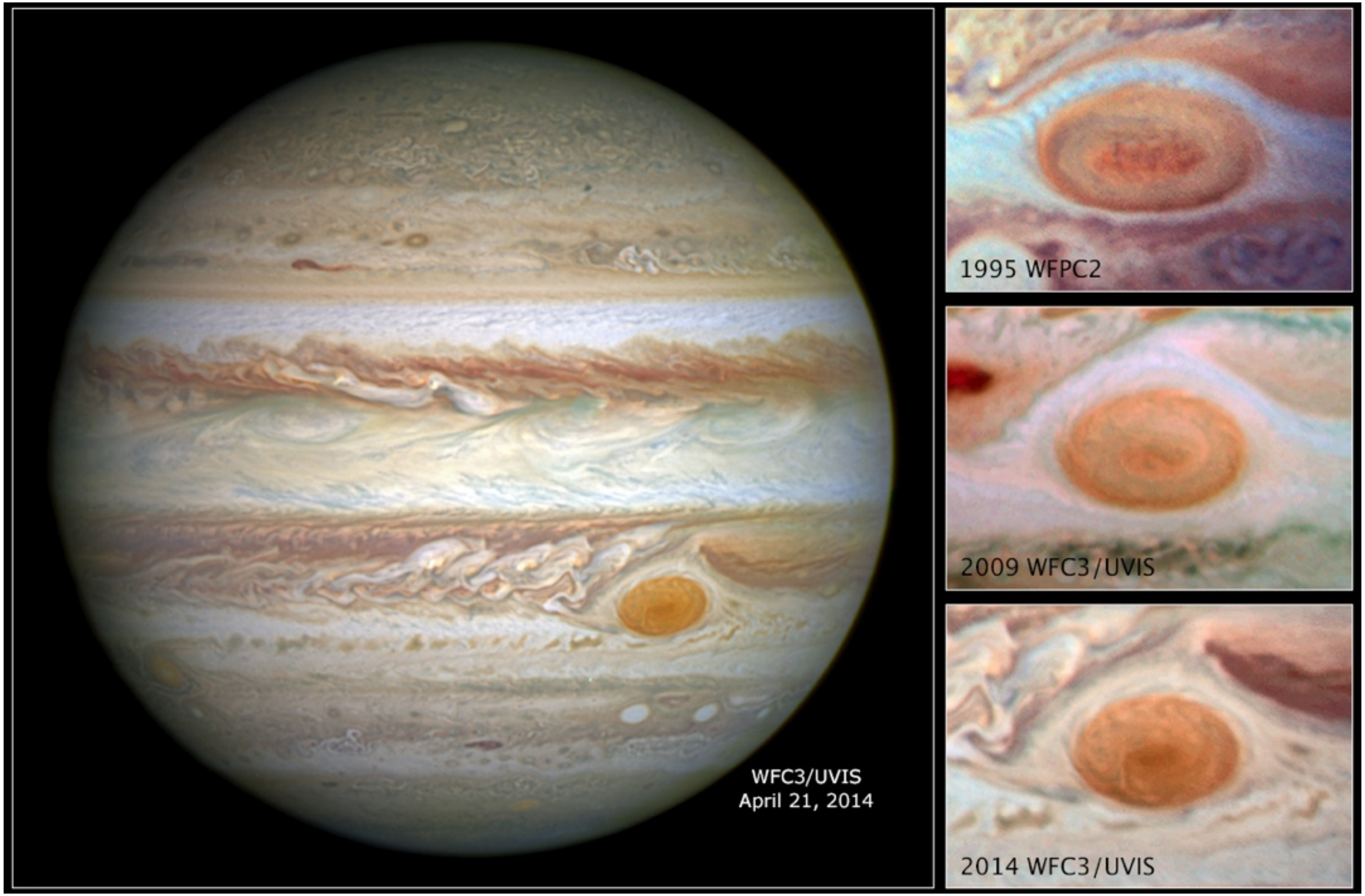


Galileo image of a storm in the South Equatorial Belt, together with a sketch of the inferred cloud heights. The top of the storm clouds stand 25 km or so above the rest of the cloud layer.

Jupiter and Io from Cassini



It is not clear why the Great Red Spot has lasted so long, as usually a vortex will dissipate quite rapidly. Recent computer simulations suggest that the vertical motion of the gas is the key to its longevity. As the vortex loses energy, the vertical air flow transports hot gas from above and cold gas from below toward the centre of the vortex, restoring its energy.

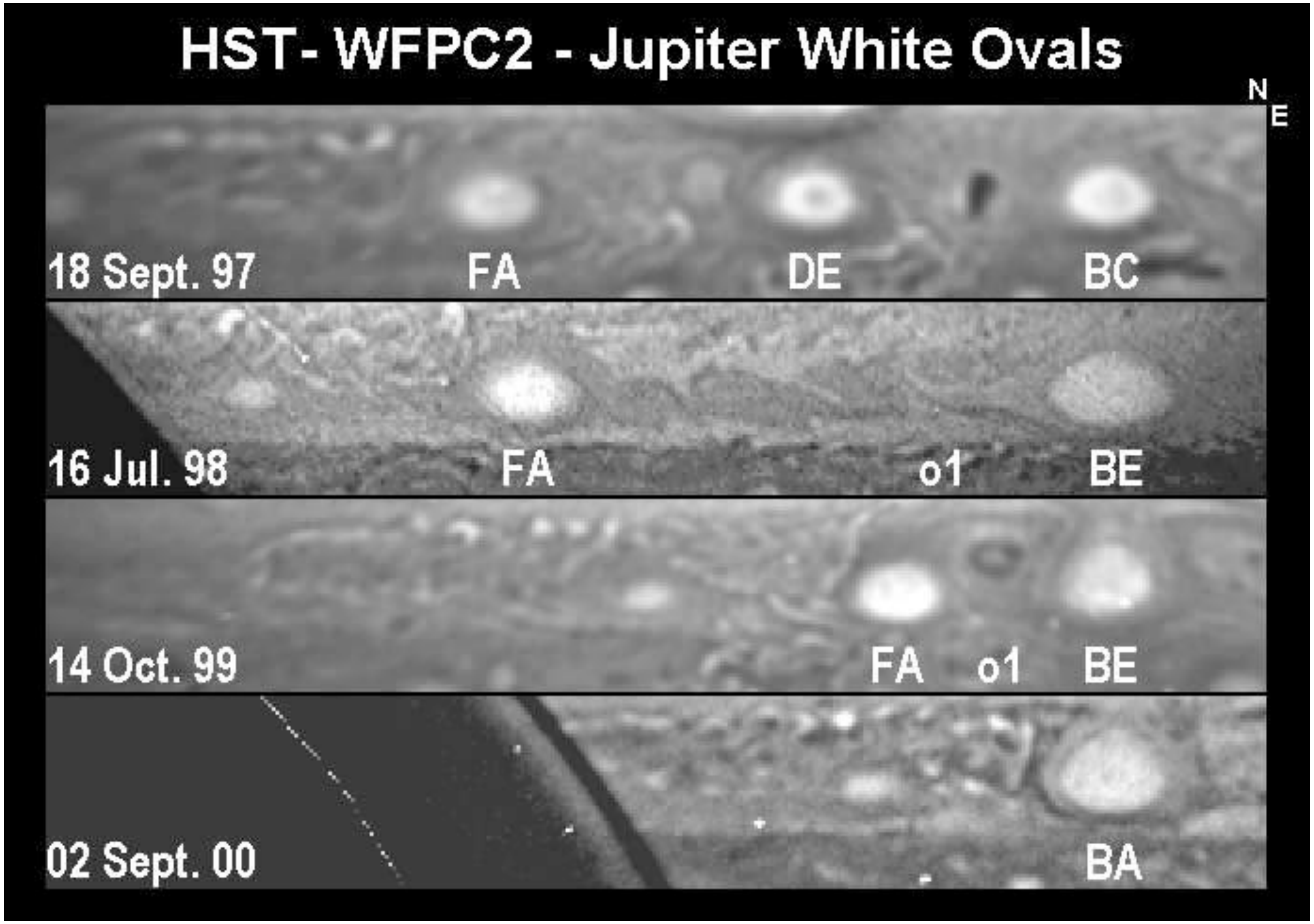


Recent Hubble observations show the Great Red Spot has shrunk significantly in recent years.

There are other permanent or semi-permanent features of the Jovian clouds: *white ovals*, *brown barges*, *white anvils*. The white ovals are anticyclones, since they rotate anticlockwise, and their cloud tops are high in the atmosphere. They are typically the size of the Earth.

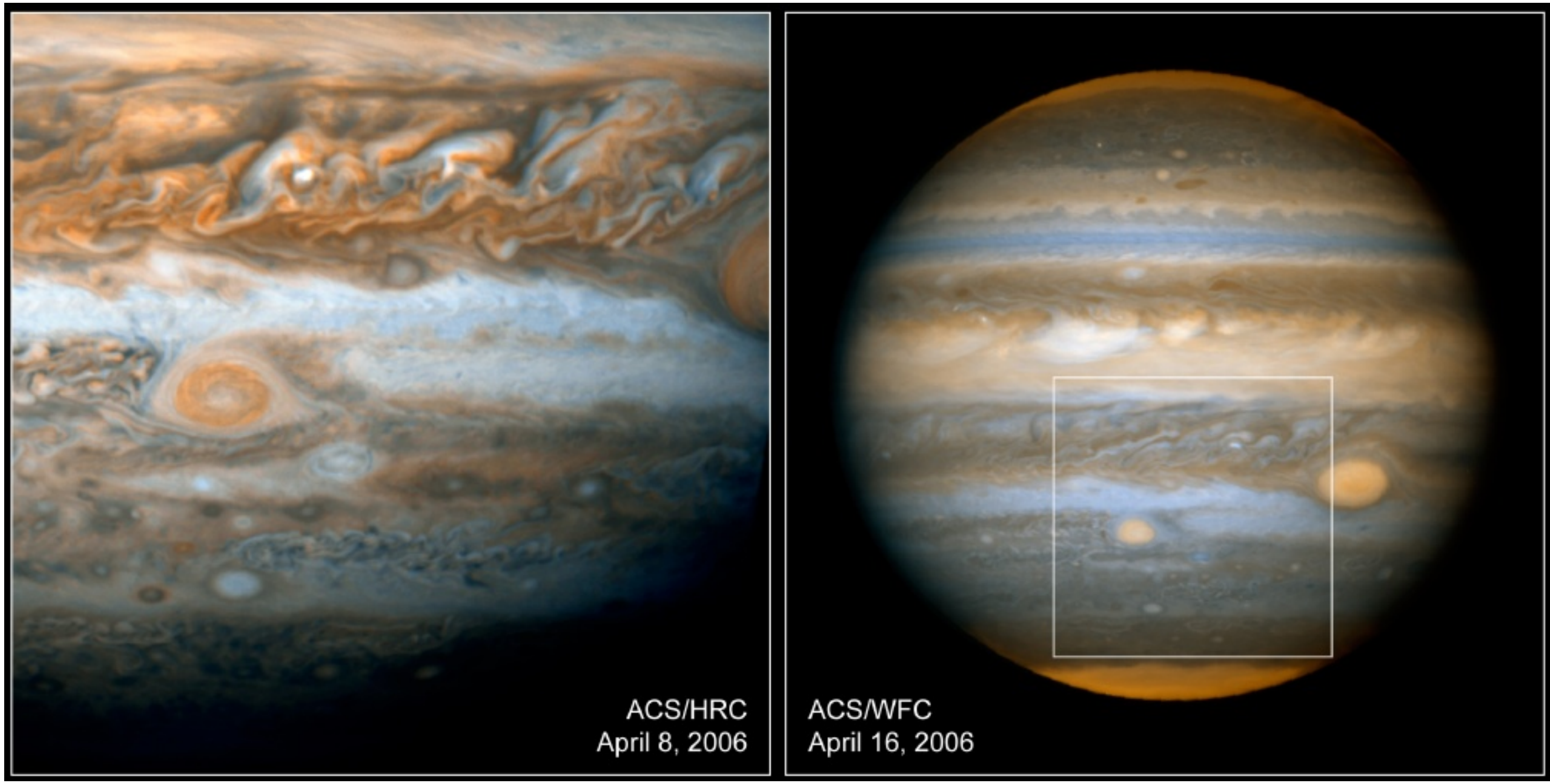
White oval seen by Juno

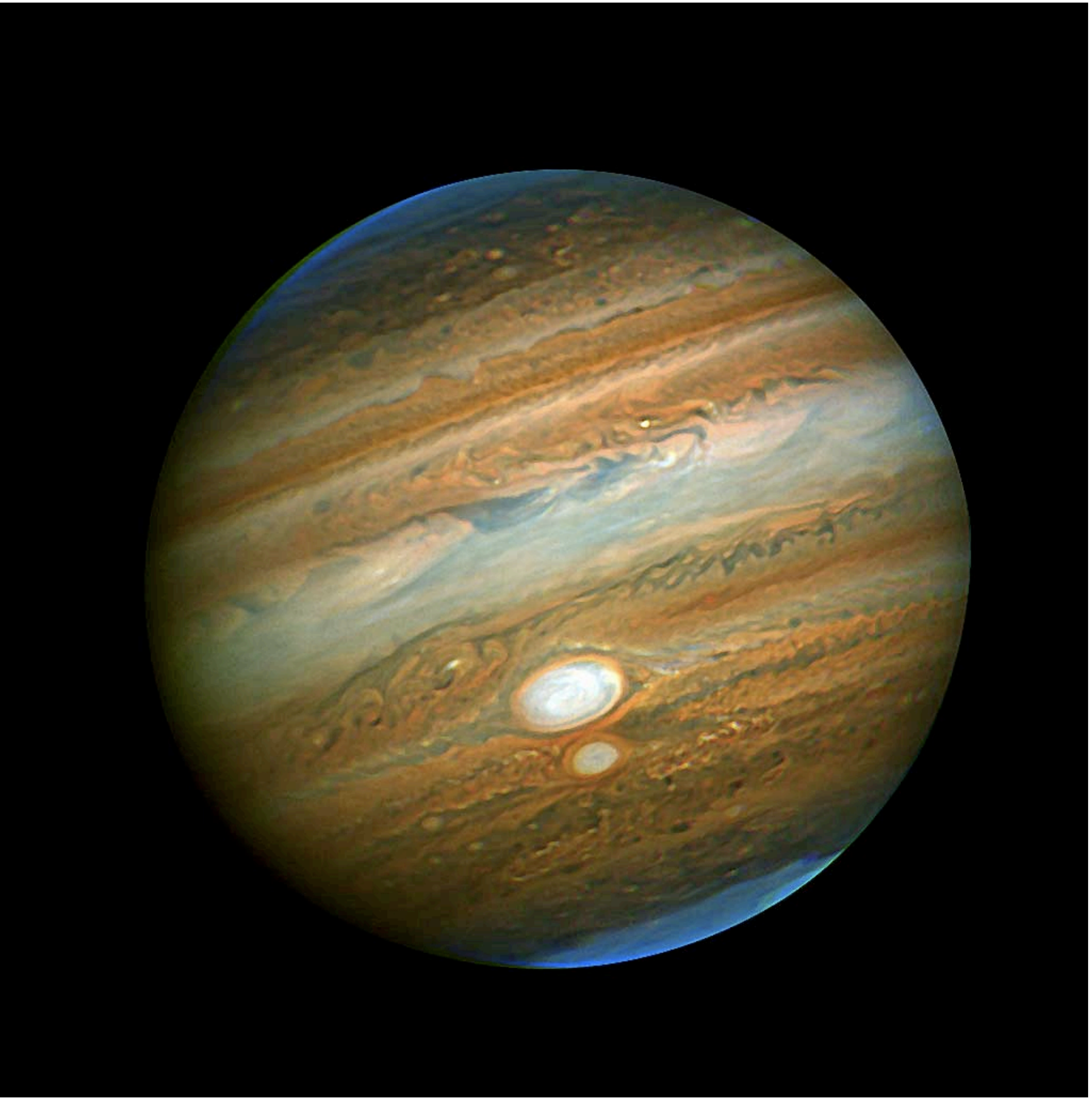
Hubble captured this sequence of images, showing the merger of white oval storms which had coexisted for about 60 years.



By February 2006, the merged spot had turned red, and is now about half the size of the original Great Red Spot, similar in diameter to Earth.

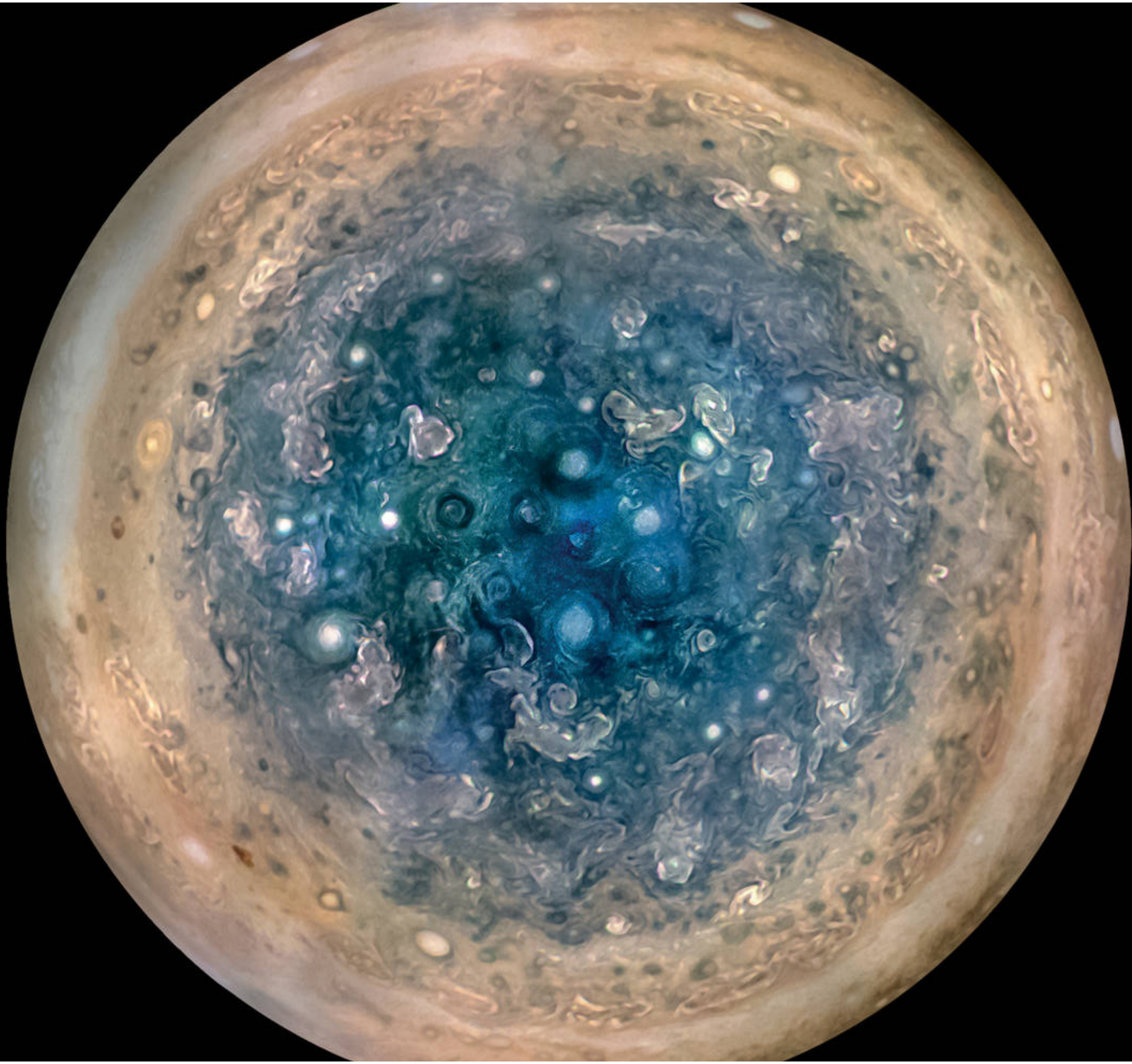
The wind speeds in the storm have also increased to about 600 km/h, which is probably related to the colour change. Possibly as it grew, it began pulling material from deeper in the atmosphere.





In July 2006 the Great Red Spot and the Little Red Spot brushed past each other, with no apparent effect.

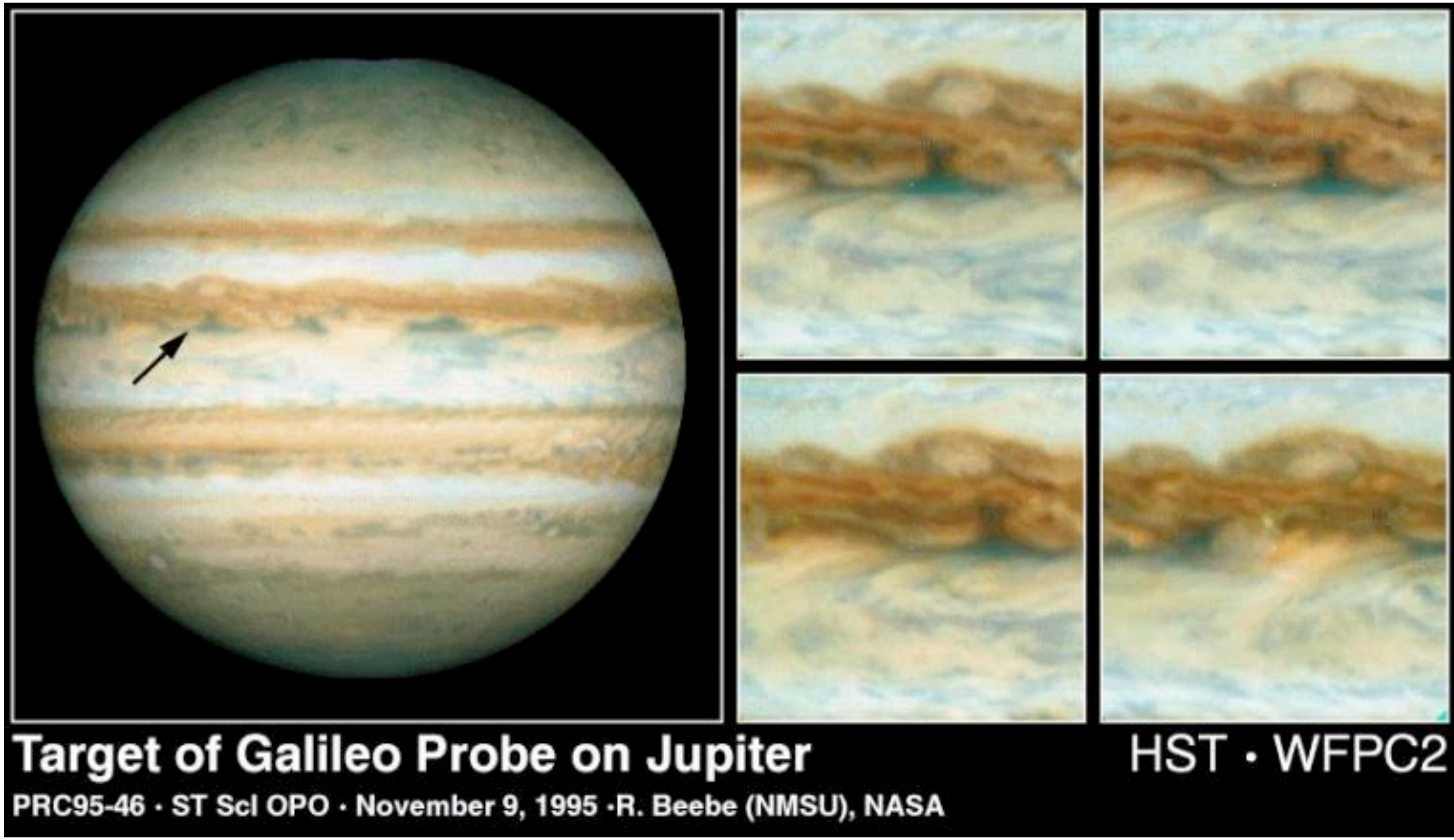
Infrared image from Gemini

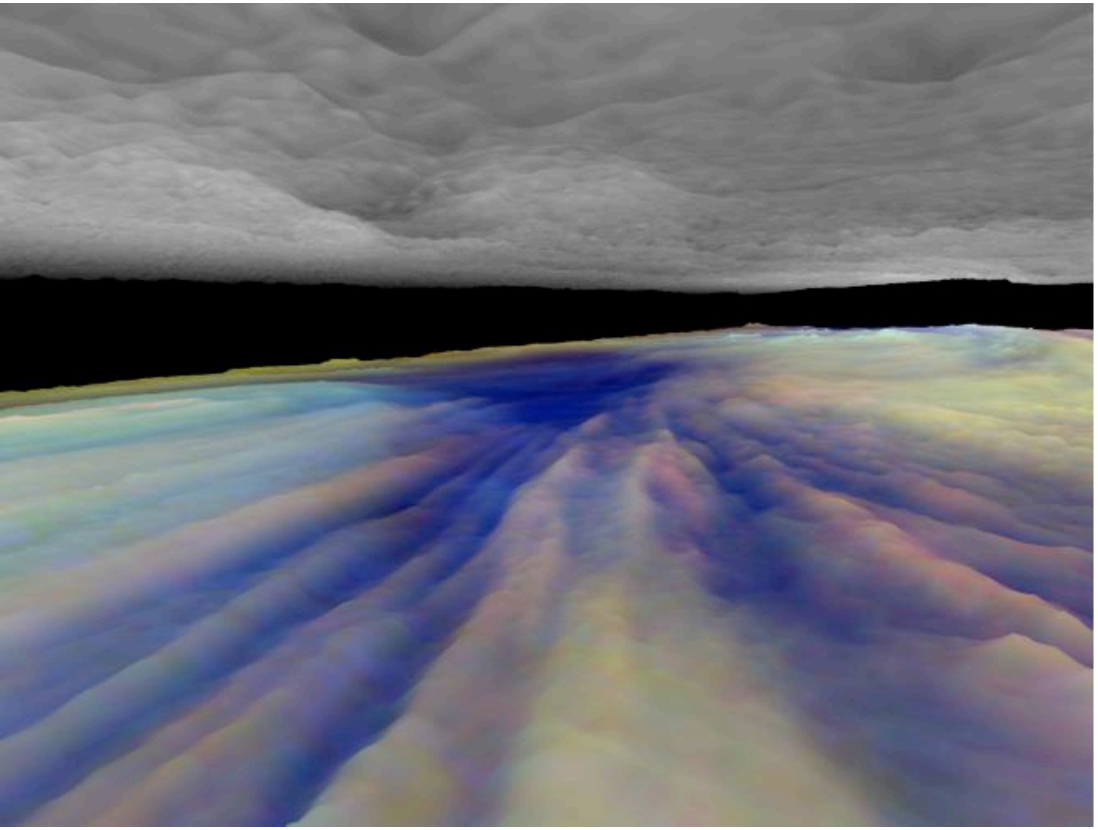


Cyclones at Jupiter's south pole, from Juno

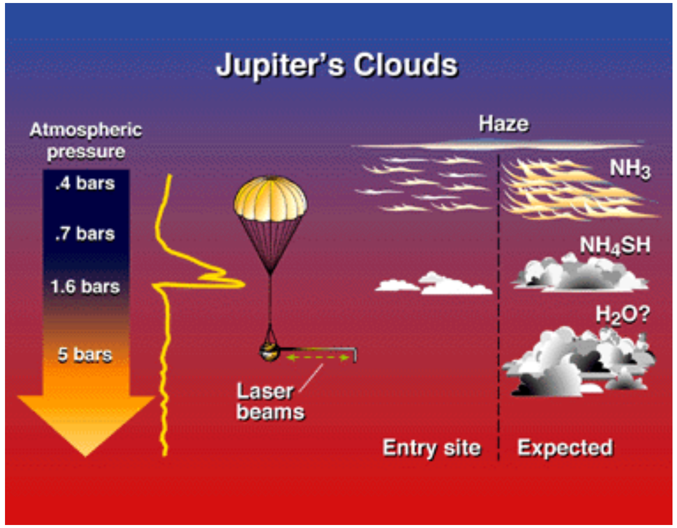
The *Galileo* probe dropped into Jupiter's atmosphere on the boundary between the Equatorial Band and the darker North Equatorial Belt.

Much to everyone's surprise, the probe did not detect the predicted three-layer cloud structure as it fell: in fact, it measured almost no clouds at all!





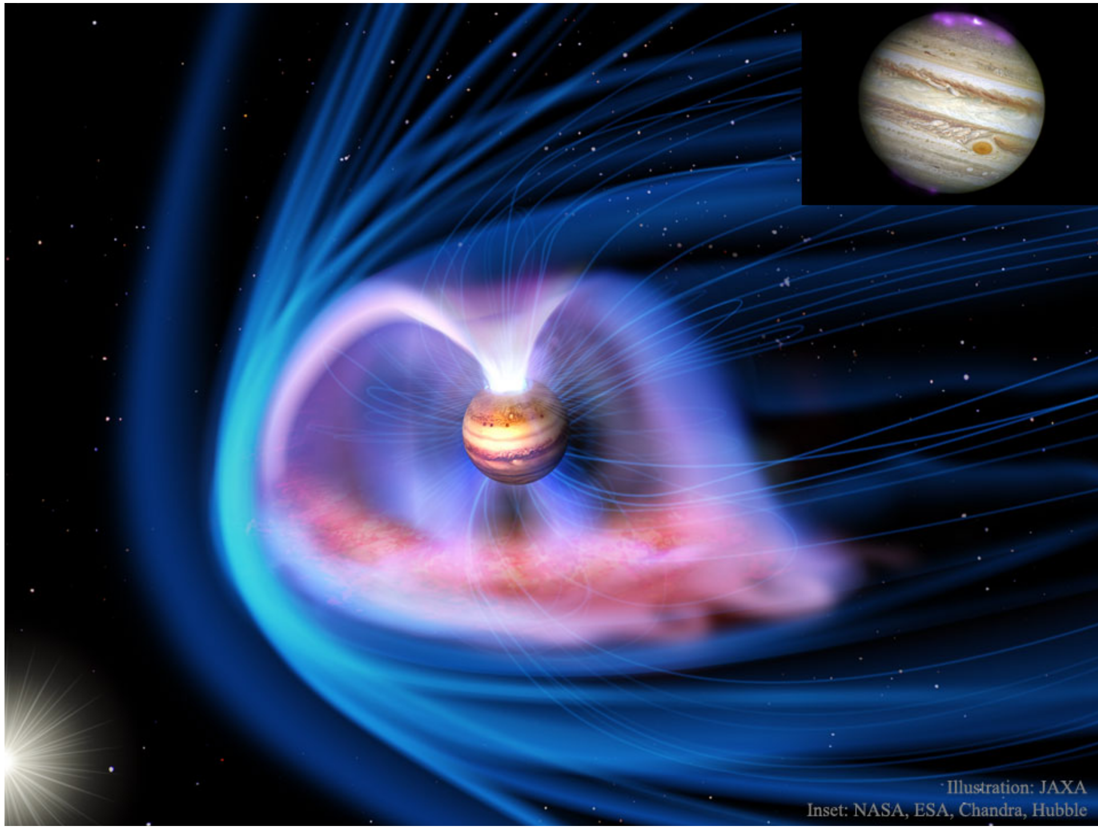
(left) Visualisation of Jupiter's atmosphere, looking between the cloud deck. The clear hotspot where the Galileo probe fell appears as a dark blue feature. (below) What the probe found, compared with what was expected.



It appears that the probe had the bad luck to fall into a hole in the clouds of Jupiter, one of the very few areas where the clouds were so thin as to be almost invisible. The probe entry site appears to be one of the clearest and driest on the planet.

Jupiter has a powerful magnetic field, 10 times stronger at its cloud tops than Earth’s. The Jovian magnetic field's "north" magnetic pole is at the planet’s geographic south pole, with the axis tilted 11° from the rotation axis. The magnetosphere extends more than 650 million km – past the orbit of Saturn, making it the largest “object” in the solar system. Jupiter's moons therefore lie within its magnetosphere, with major effects on Io, as we will see.

Jupiter’s magnetic field produces intense auroras, thousands of times brighter than any auroral display on Earth.



Jupiter's magnetic field creates a hazardous radiation environment for spacecraft. *Pioneer* found the radiation levels to be ten times stronger than predicted, leading to fears the probe would not survive. It lost most of its images of Io due to spurious commands.

Voyager was redesigned to cope with the massive radiation levels, but was still affected. The spacecraft clocks had several malfunctions, and some of the highest-resolution images of Io and Ganymede were seriously degraded.

Galileo successfully survived, but still had a few glitches, including the total loss of data from three of the orbits.

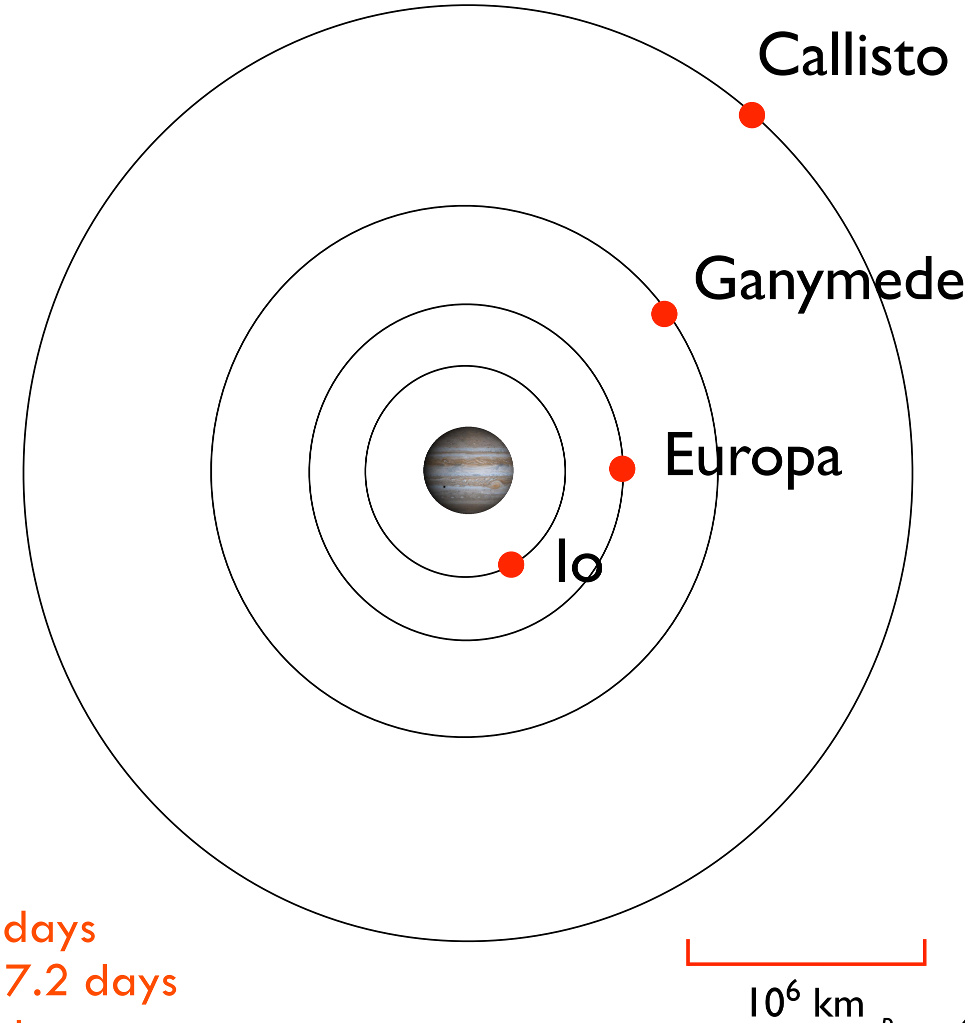
The Jovian moons

Jupiter has (at least) 67 known satellites. The largest four were discovered by Galileo, and bear his name.

There are also four small satellites inside Io's orbit – Metis, Adrastea, Amalthea and Thebe; together these eight are the *regular satellites*.

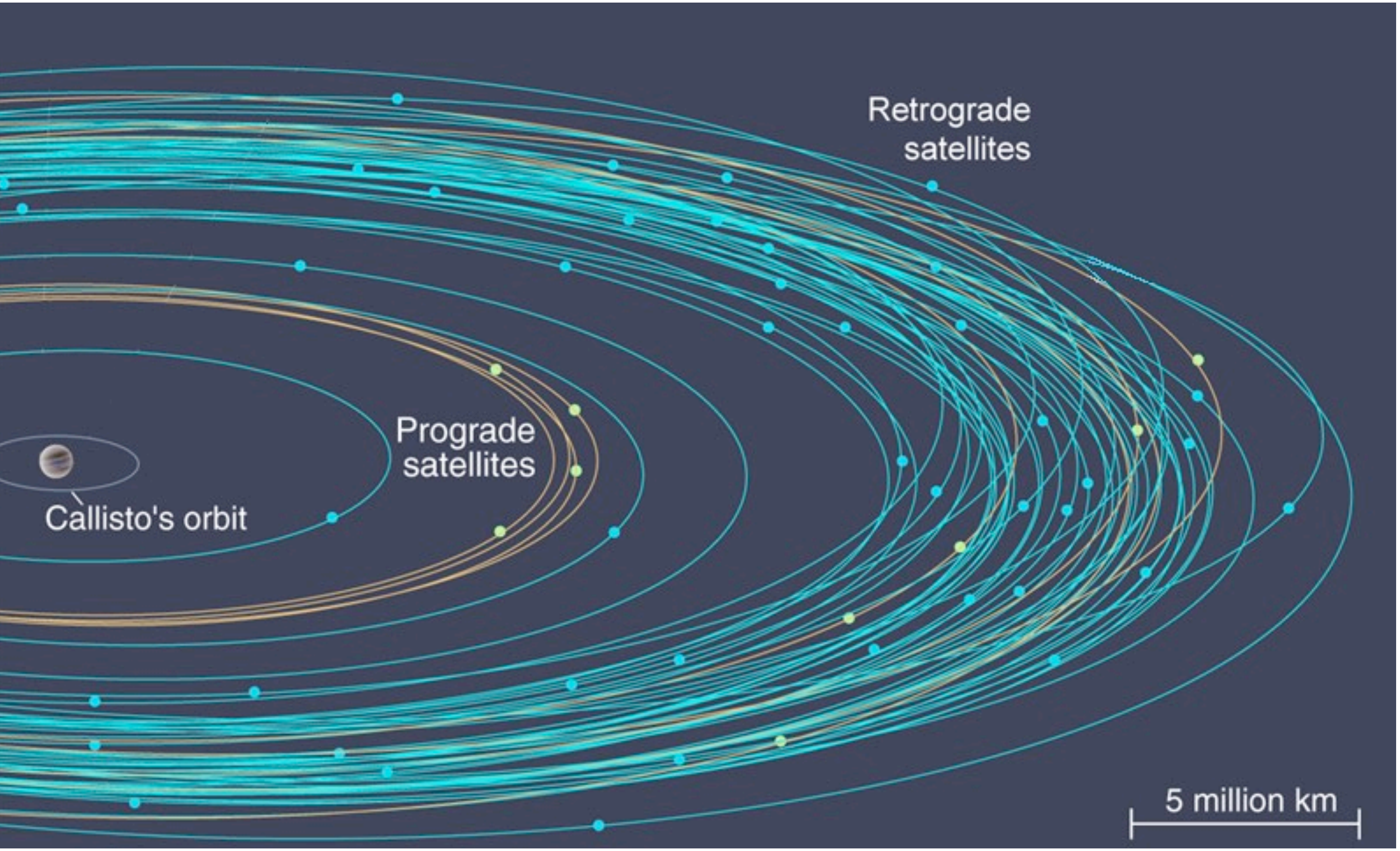
Europa and Callisto in front of Jupiter, taken by Cassini.

Io, Europa and Ganymede are locked together in a 1:2:4 orbital resonance, and their orbits evolve together. In a few hundred million years, Callisto will be locked in too, orbiting at exactly twice the period of Ganymede (eight times the period of Io).

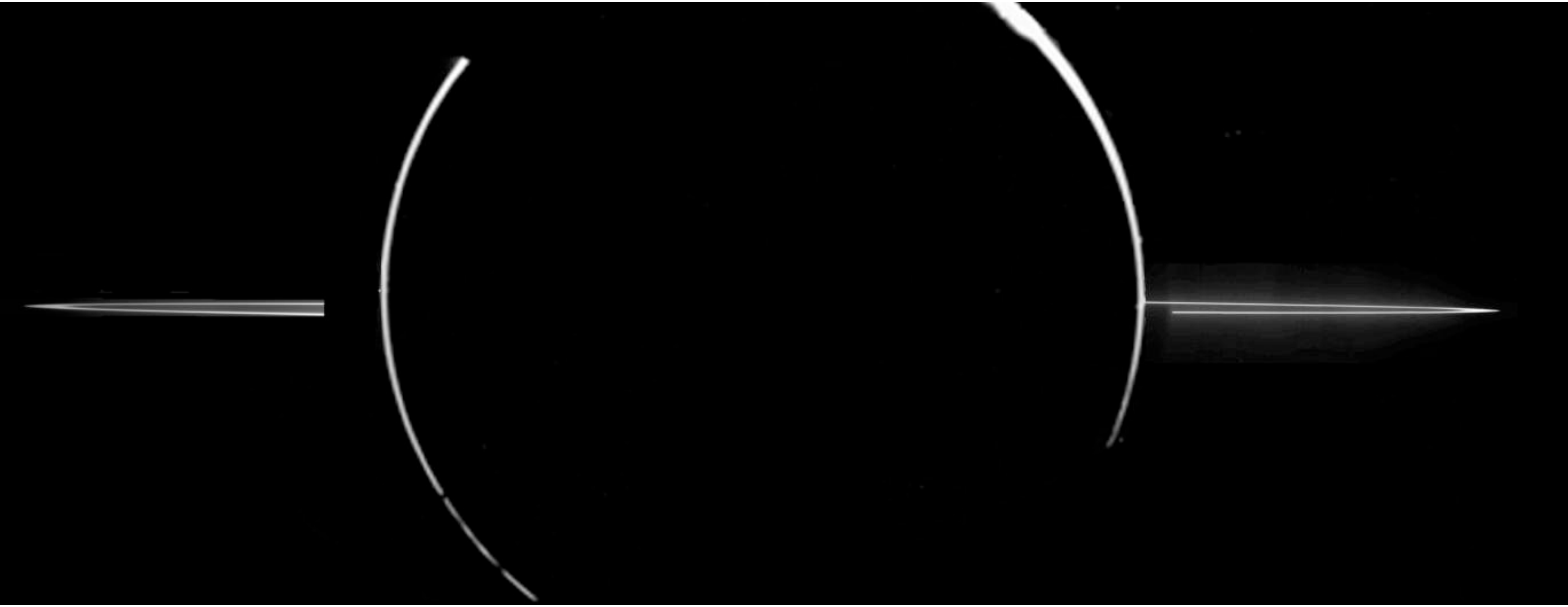


Io: 1.8 days
Europa: 3.6 days
Ganymede: 7.2 days
Callisto: 17 days

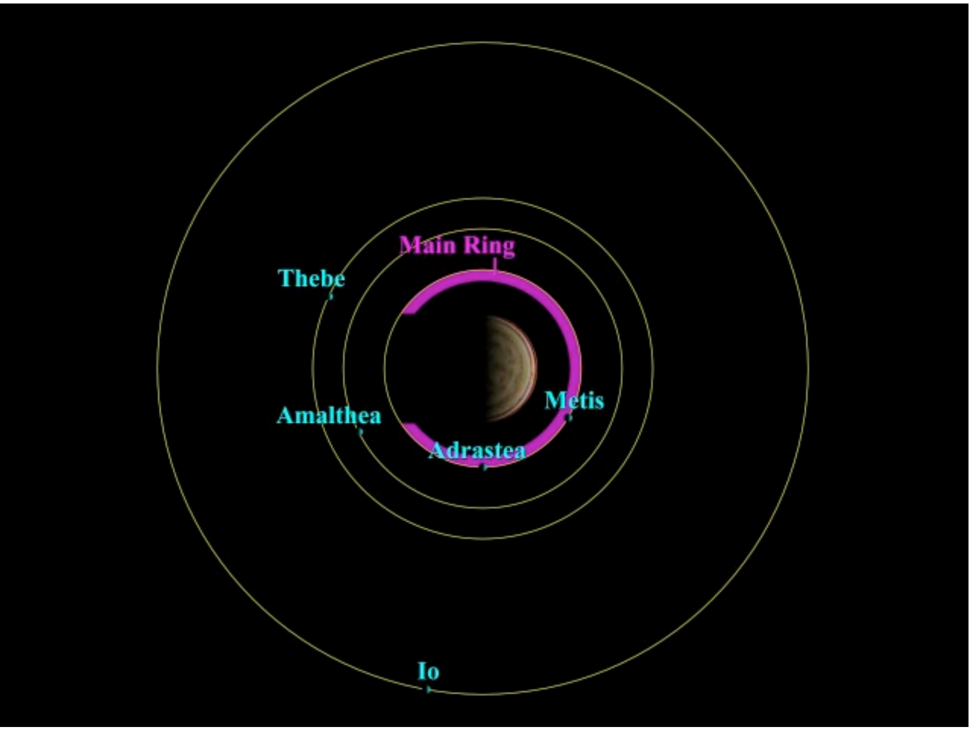
Then outside Callisto’s orbit is a whole swarm of tiny satellites, all irregular, and most in retrograde orbits.

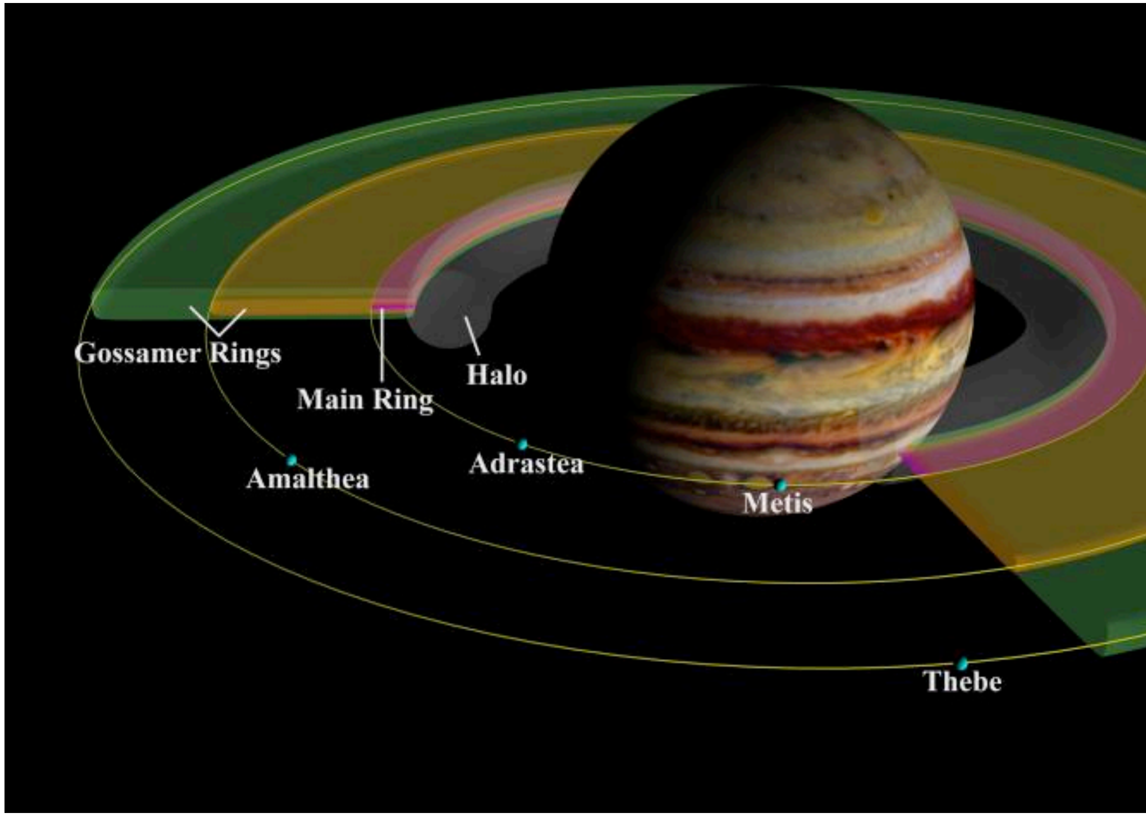


Jupiter also has a system of rings. The main ring is about 6500 km wide, and less than 10 km thick.



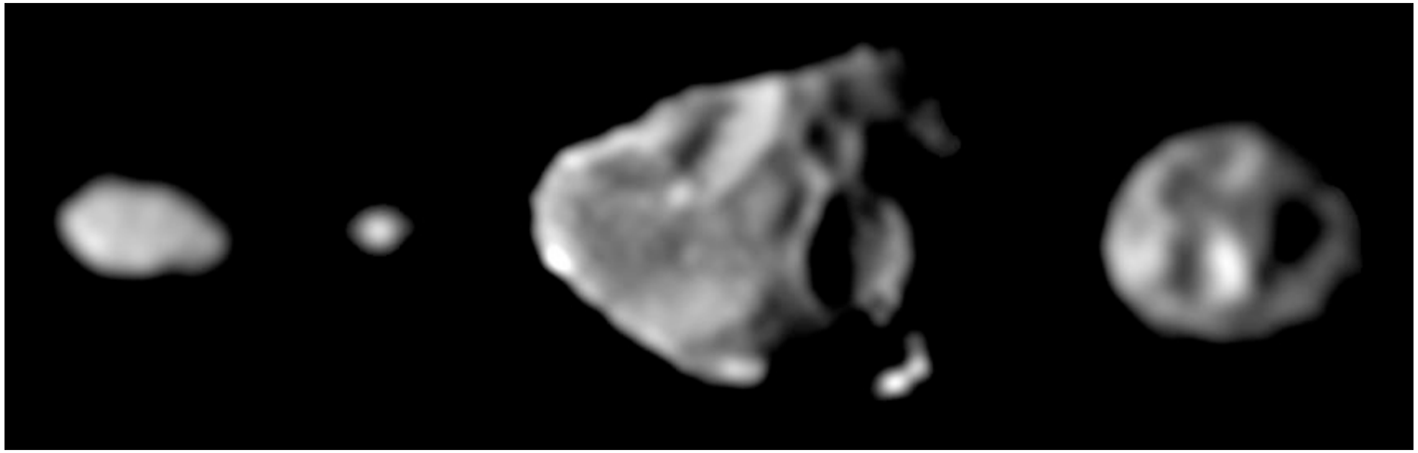
The *main ring* is composed of fine particles knocked off Adrastea and Metis. Impacts by small meteoroids into these small, low-gravity satellites feed material into the rings. There is an inner ring called the *halo*, and a third, outer ring called the *gossamer ring*. This actually consists of two rings, which are microscopic debris from the tiny moons Amalthea and Thebe.





The two tiniest moons, *Metis* (longest dimension is approximately 60 km) and *Adrastea* (20 km), are embedded in the rings. *Amalthea* (247 km) and *Thebe* (116 km) act as "shepherd moons" to confine the rings.

From left to right, in order of increasing distance from Jupiter: Metis, Adrastea, Amalthea, and Thebe.



Amalthea is the reddest object in the solar system, probably due to sulphur from Io. Amalthea's density is about the same as water, and since it is unlikely to be composed of ice, it is most likely porous with lots of empty space.

The Galilean satellites


Ganymede
5262 km
Titan
5150 km
Mercury
4880 km
Callisto
4806 km
Io
3642 km
Moon
3476 km
Europa
3138 km
Triton
2706 km
Pluto
2300 km
Titania
1580 km

The four Galilean satellites are worlds in their own right; in many ways, they make up a planetary system in miniature.

	Callisto	Ganymede	Europa	Io	Moon
Diameter (km)	4821	5262	3122	3643	3475
Mass (10^{21} kg)	107.6	148.2	48	89.3	73.5
Density (g/cm^3)	1.83	1.94	3.01	3.53	3.34
Gravity (g)	0.126	0.146	0.134	0.184	0.163
Rotation period (h)	400.5	171.7	85.2	42.5	655.7
Orbital distance (10^3 km)	1883	1070	671	422	384
Orbital period (d)	16.7	7.2	3.6	1.8	27.3
Orbital eccentricity	0.007	0.0015	0.0101	0.004	0.055

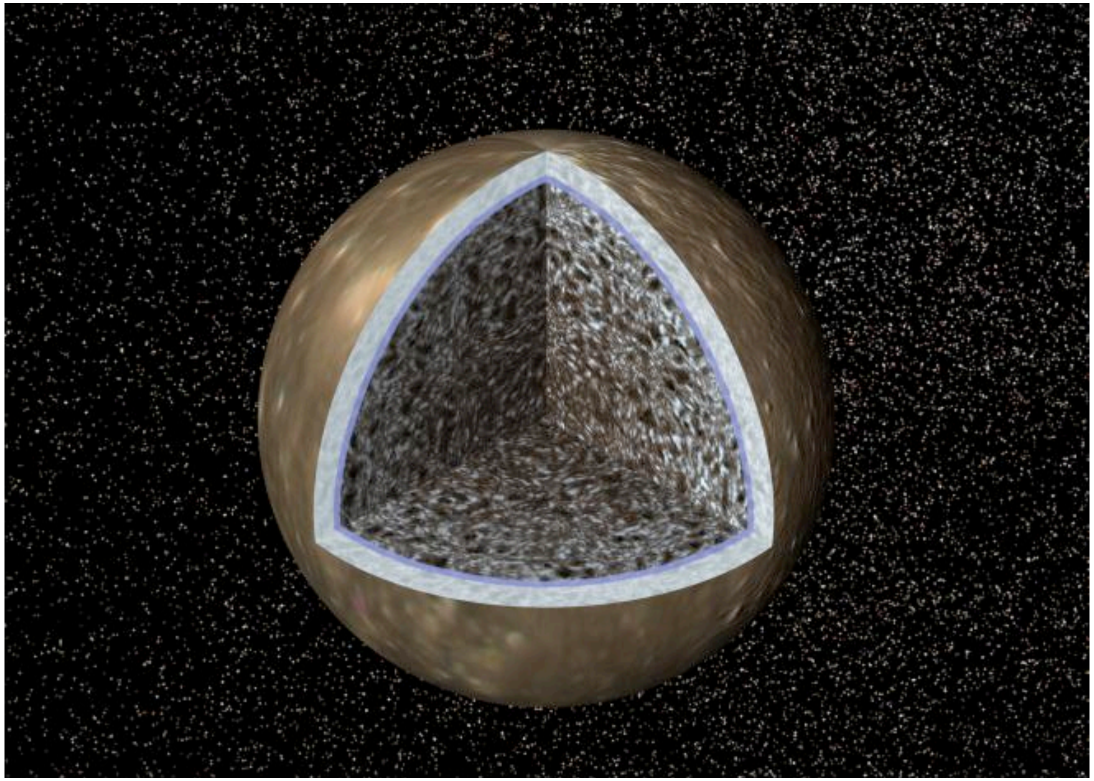
All of them are rotationally locked to Jupiter (so they always show the same face to the planet), and the closer moons are significantly denser than the outer moons.

Callisto

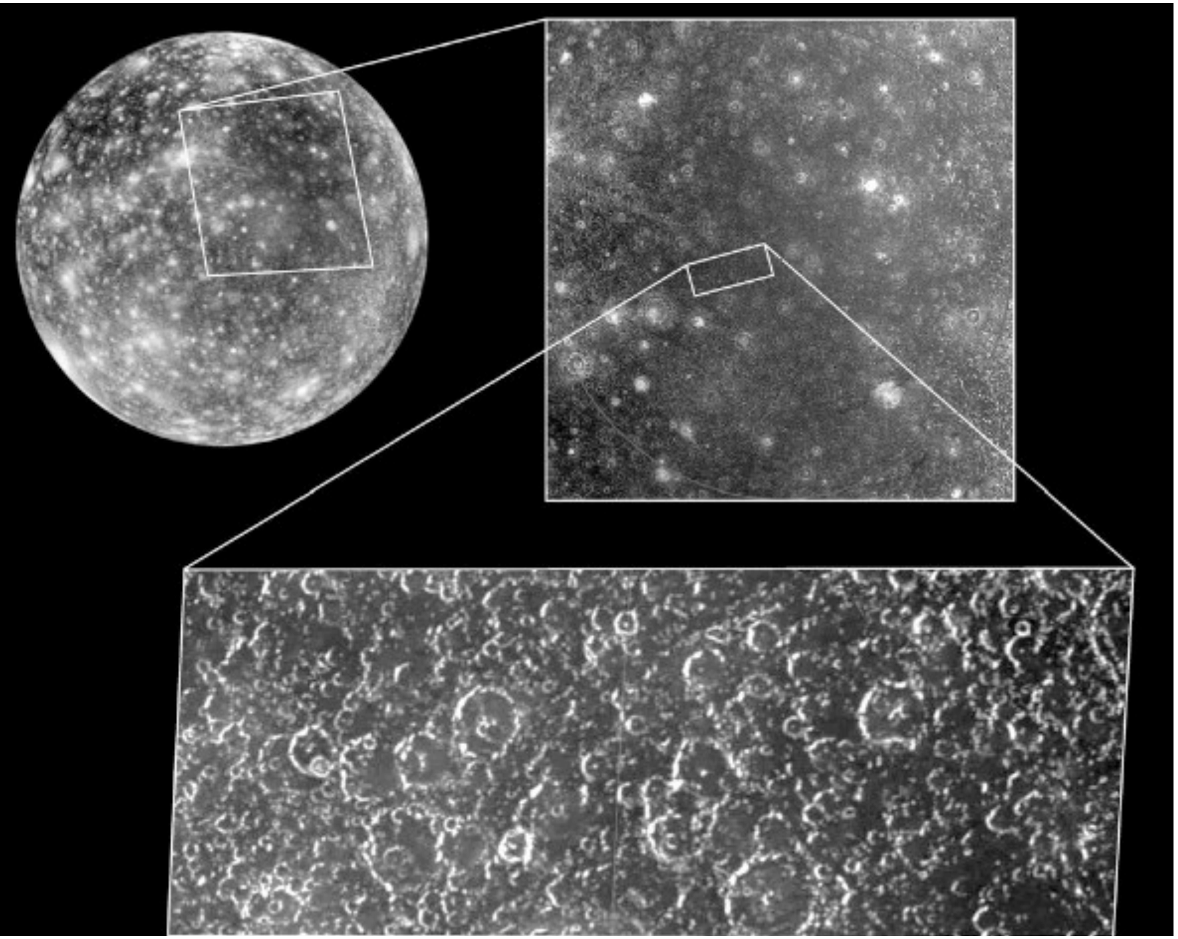
– a dead world

Callisto is the second largest and least dense of the Galilean satellites. It is almost the same size as Mercury, but only a third of its mass. This means it must consist of a mixture of rock and ice; gravity measurements by *Galileo* indicate its interior is mostly undifferentiated.

Callisto's surface lies on top of an ice layer about 200 km thick. There may be a subsurface briny ocean at least 10 km in depth below that.



Callisto's surface is the darkest of Jupiter's moons, though still twice as bright as Earth's moon. It is the most heavily cratered object in the Solar System.

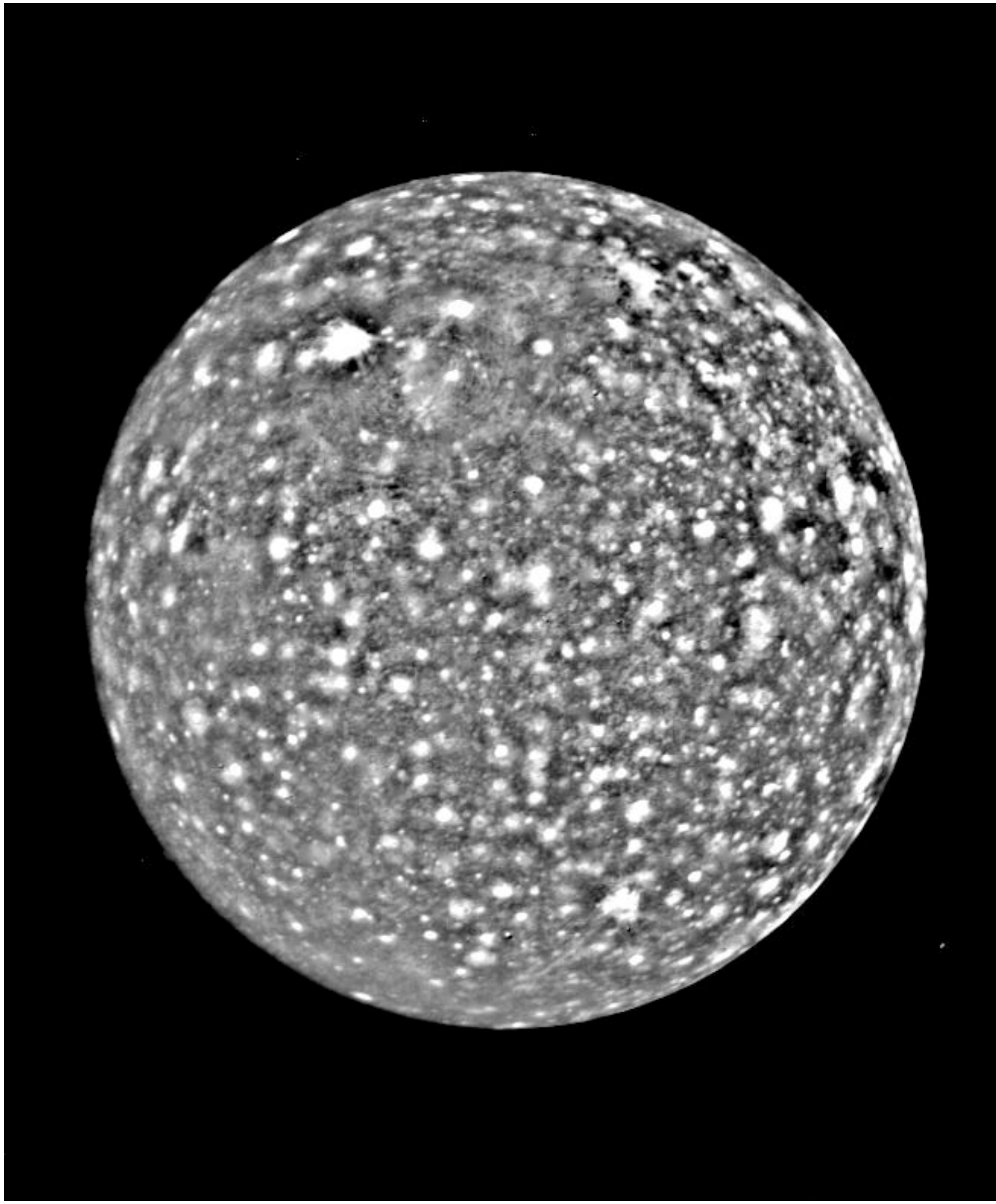


Callisto's surface is dominated by impact craters in all shapes and sizes. Crater counts indicate that the age of the surface is 4 billion years old.

Heavily cratered region of Callisto, imaged by Galileo. This region is opposite to the Valhalla basin, but shows no "weird terrain", adding to the likelihood that Callisto has a subsurface ocean.

In fact, Callisto is the only body greater than 1000 km in diameter in the solar system that has shown no signs of undergoing any extensive resurfacing. With a surface age of about 4 billion years, Callisto has the oldest landscape in the solar system.

The younger craters are bright, indicating the impacts are excavating ice-rich material.

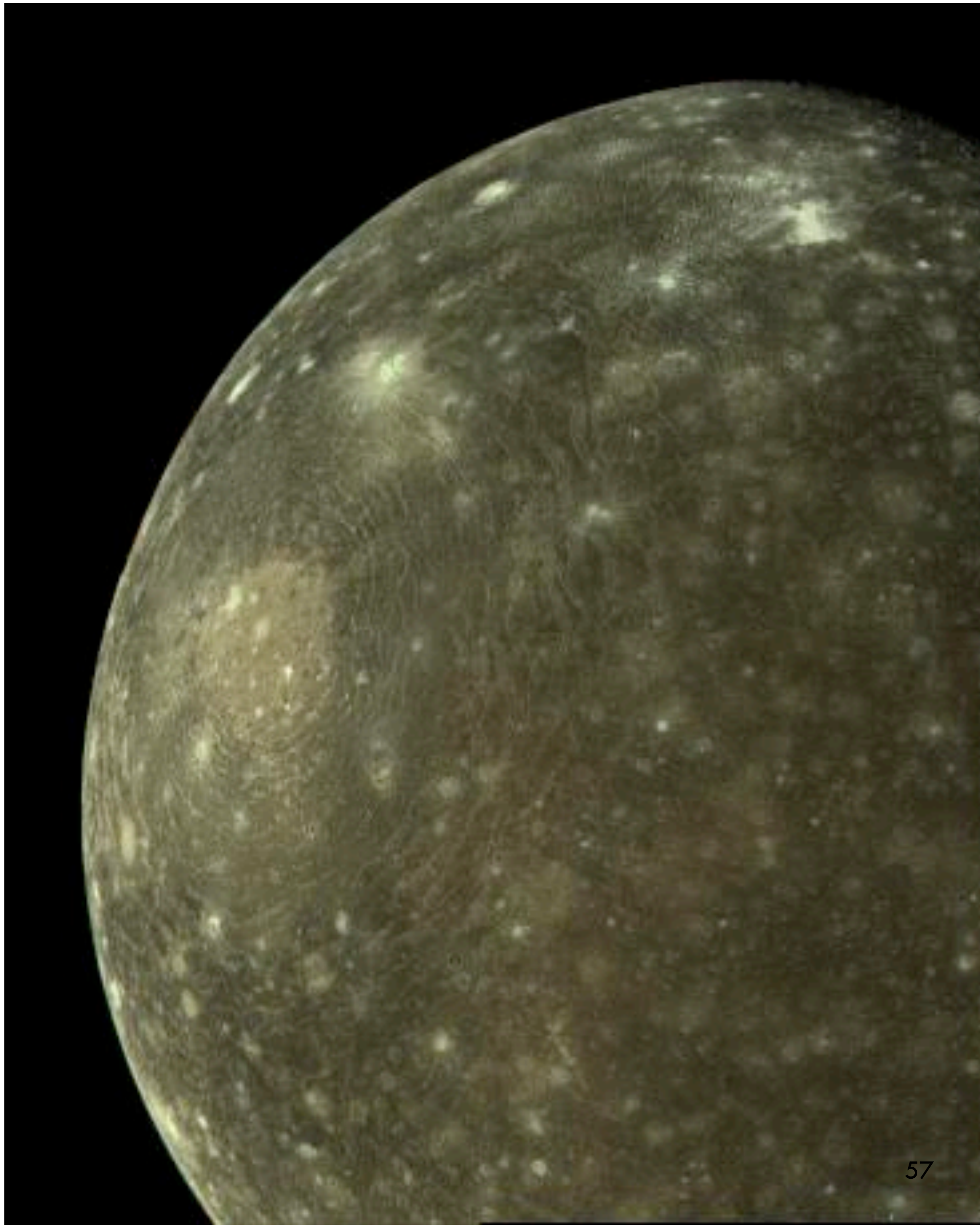


Mosaic of images taken by Voyager 2.

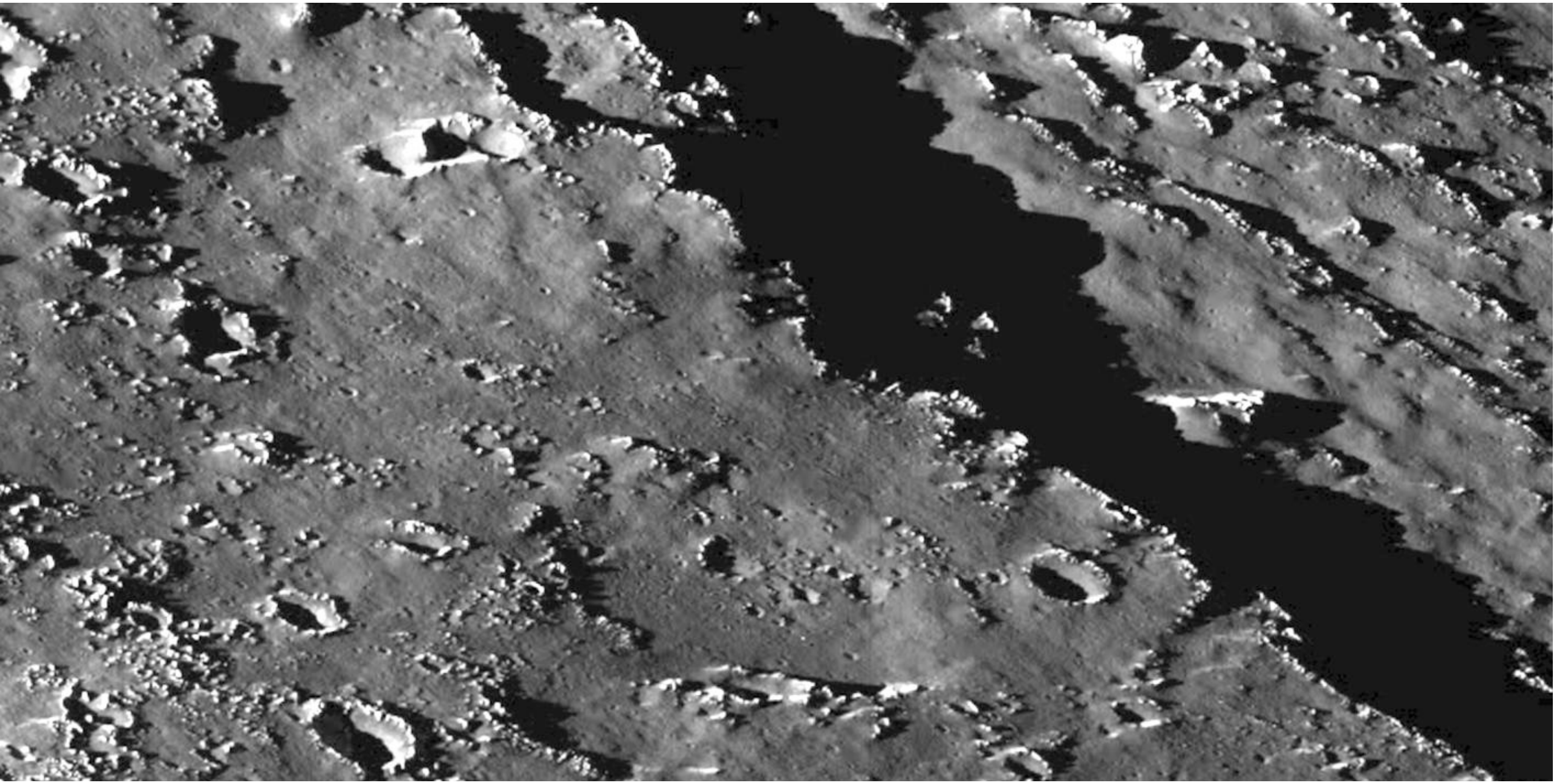
The largest impact structure is called *Valhalla*: it is a multi-ring basin nearly 4000 km in diameter, the largest in the Solar System.

There is no longer a central crater, just a bright central region which is 600 km in diameter.

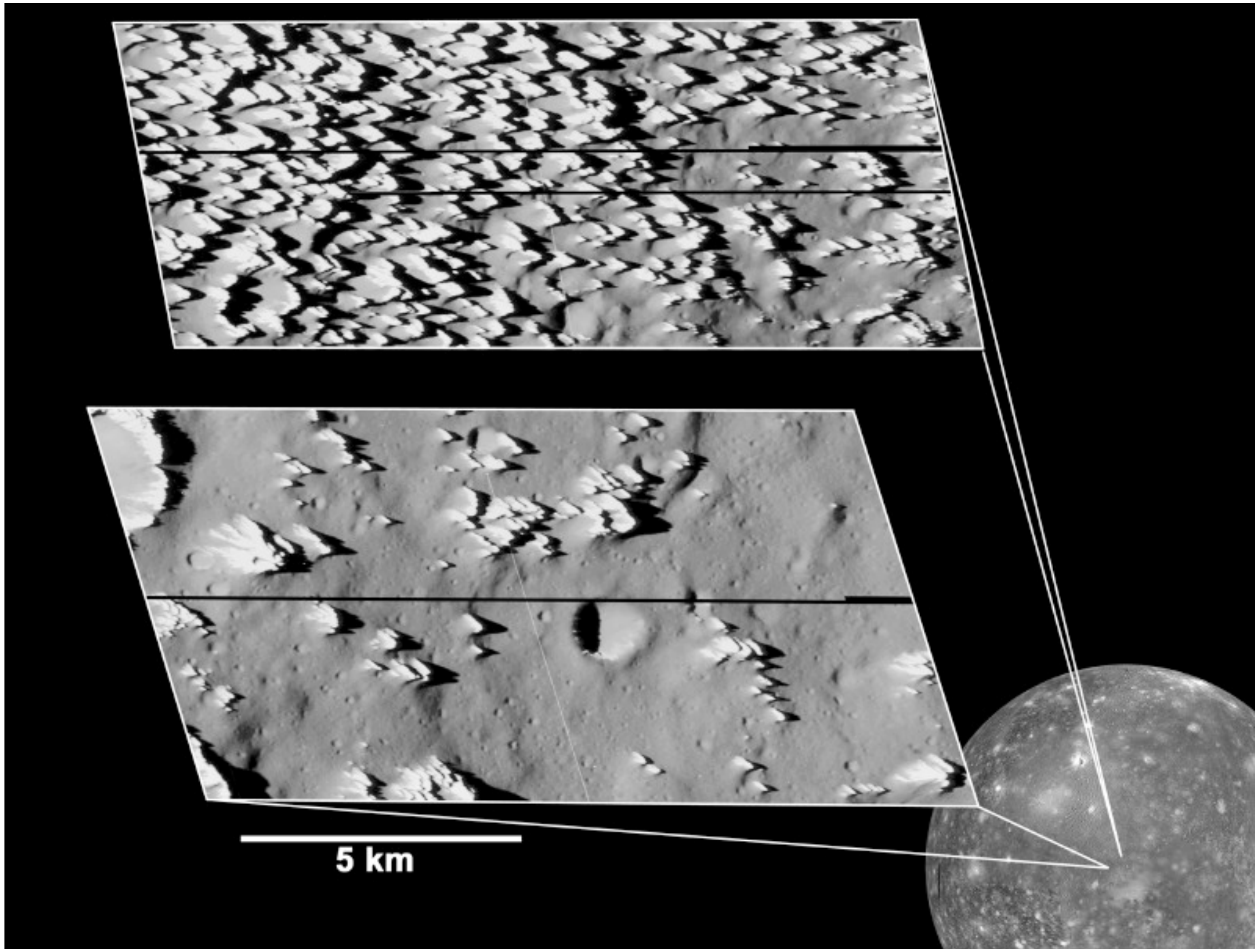
These "ghost craters" have been called *palimpsests*, and are seen on other Jovian moons. They were probably formed when the crust was still warm, as the crust relaxed under its own weight.



Callisto has very little vertical relief: there are no mountains higher than a kilometre or so. There are scarps in the Valhalla region, several hundred metres high.



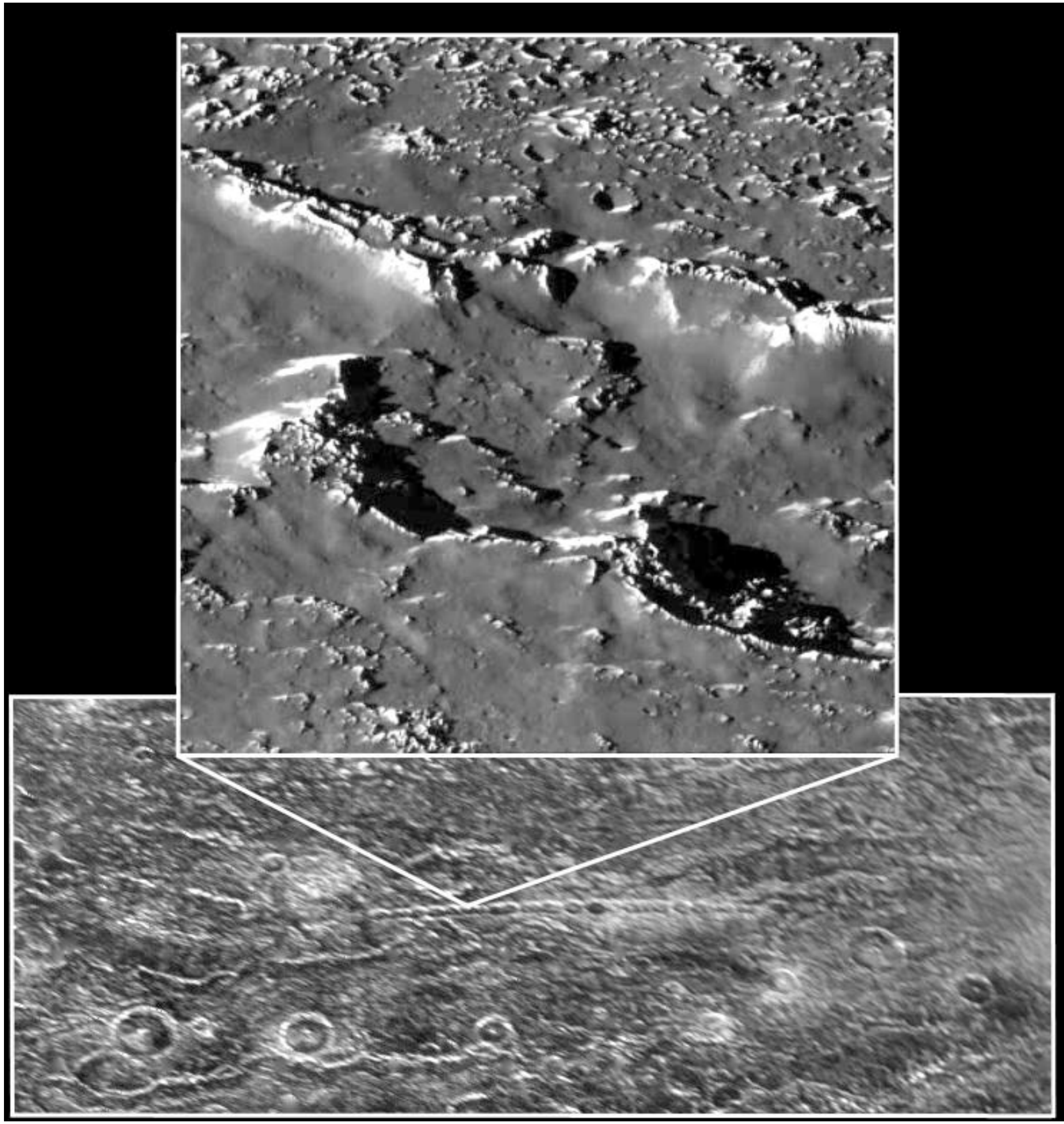
Galileo saw knobby peaks, with icy spires 80–100m high, which may consist of material thrown outward from an ancient impact.



Icy spires in a region south of Asgard. Objects as small as 3m can be discerned in this image.

Callisto contains at least ten crater chains. The largest is Gipul Catena, consisting of 12 craters spread over 620 km. The largest crater is 40 km in diameter.

The mystery of the origin of these chains was solved when we saw Comet Shoemaker-Levy 9 split into pieces and collide with Jupiter.

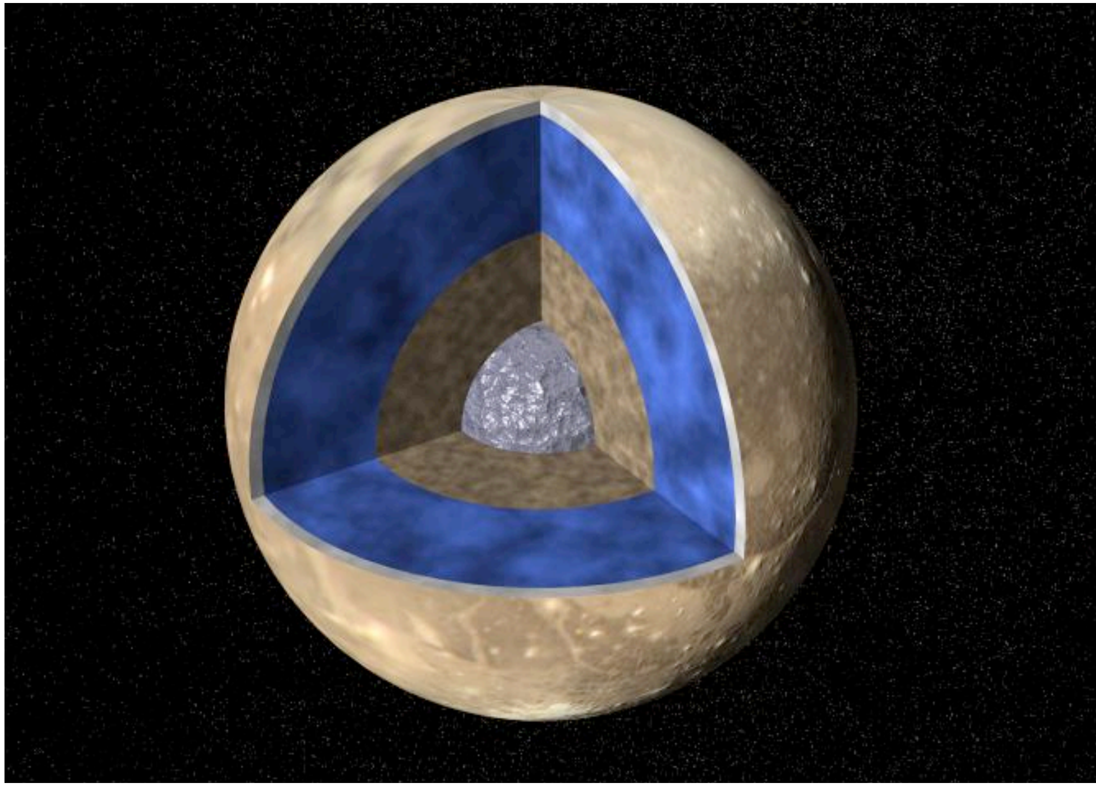


Ganymede

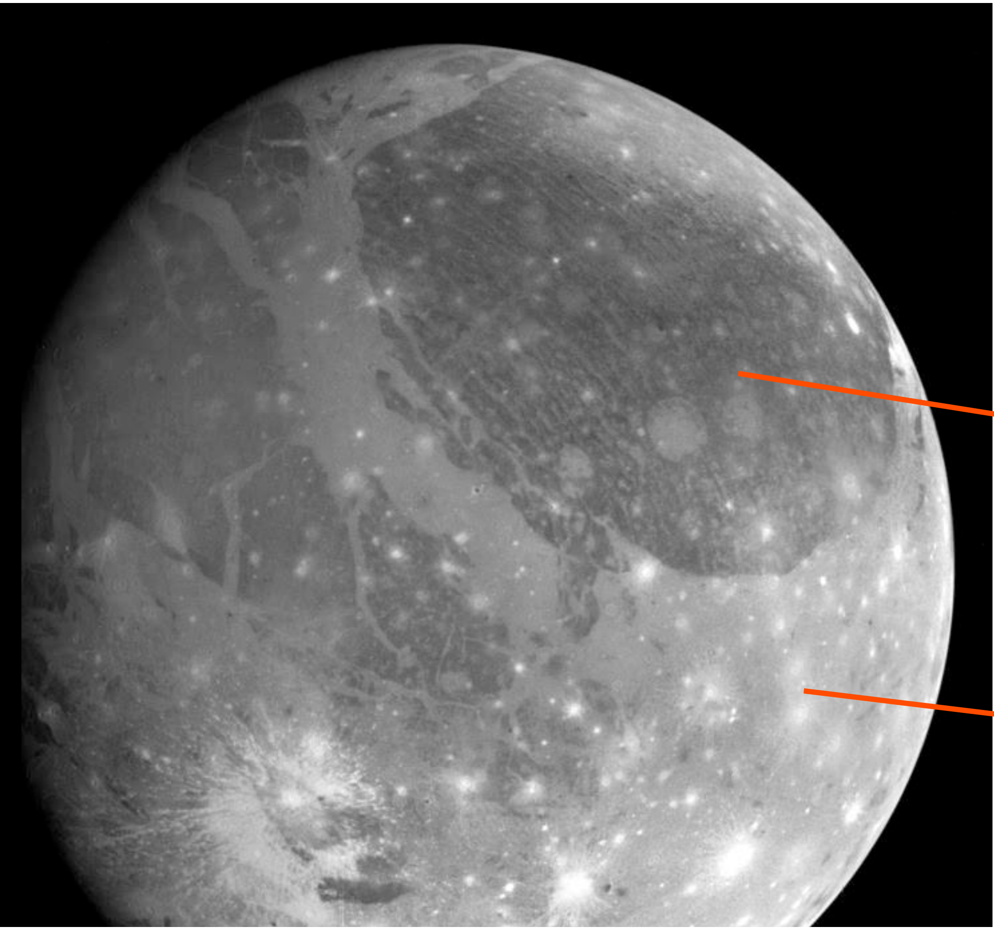
– the largest moon

Ganymede is the largest satellite in the solar system. It is larger in diameter than Mercury but only about half its mass. Measurements by Galileo indicate that Ganymede has a rocky outer core about the size of Earth's moon, with a metallic inner core which is the source of the moon's magnetic field. The mantle is a mixture of ice and silicates, with an icy crust.

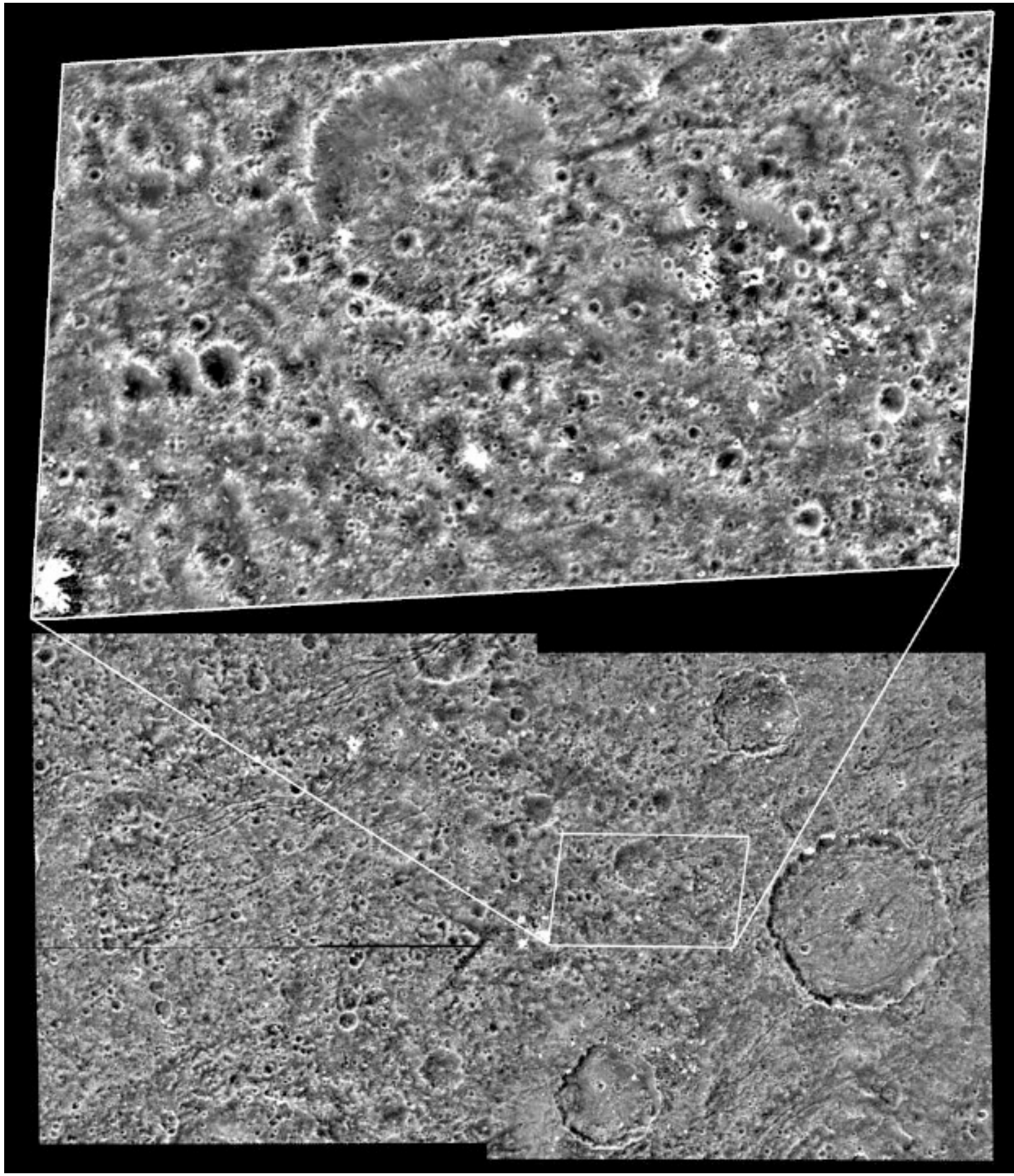
Ganymede is not much bigger than Callisto, so why is it fully differentiated with a tectonic history, in contrast to Callisto?



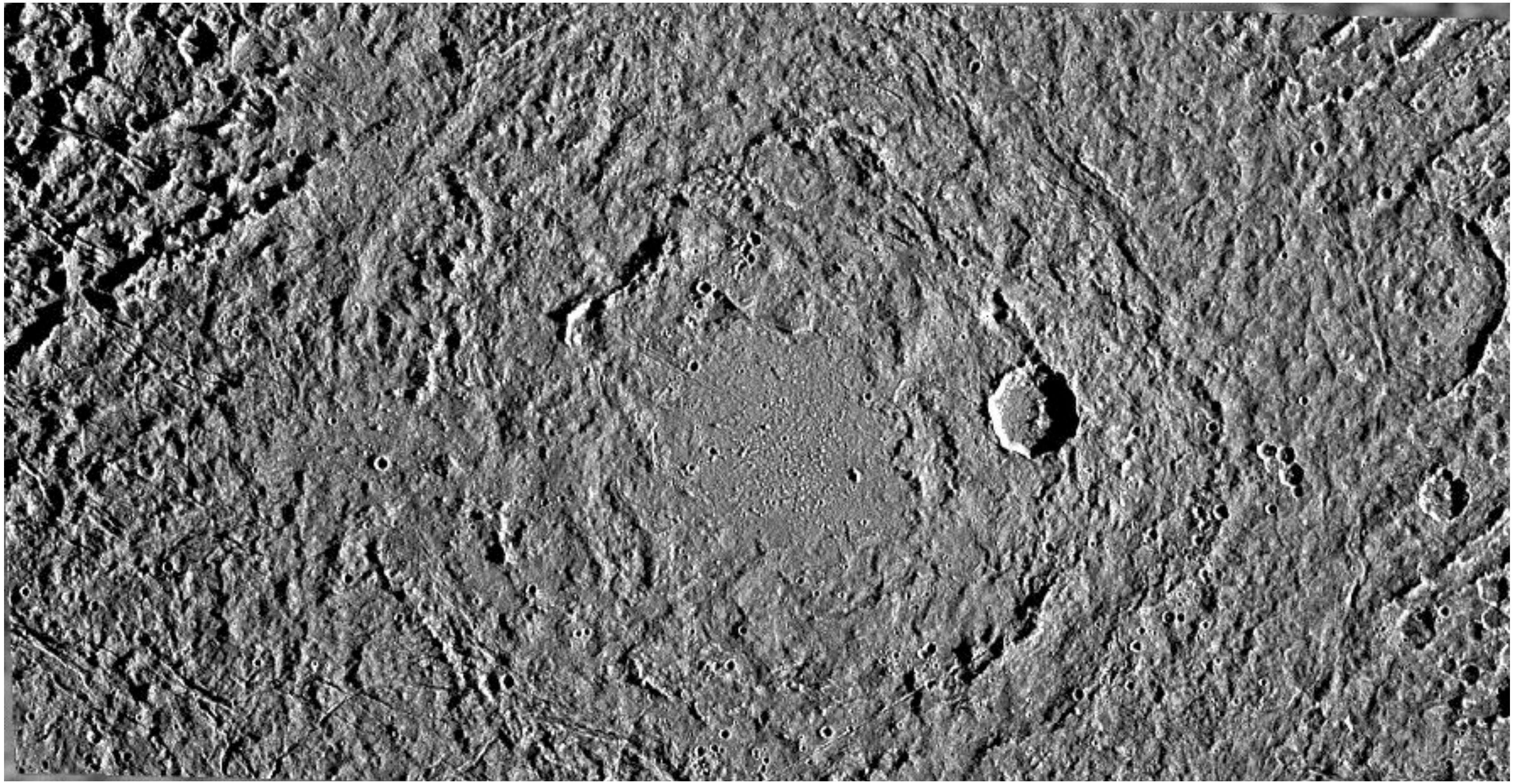
Ganymede’s surface shows the satellite has a complex geological history. Ganymede's surface is a mixture of two types of terrain. 40% of the surface of Ganymede is covered by highly cratered dark regions, and the remaining 60% is covered by a light grooved terrain which forms intricate patterns across Ganymede.



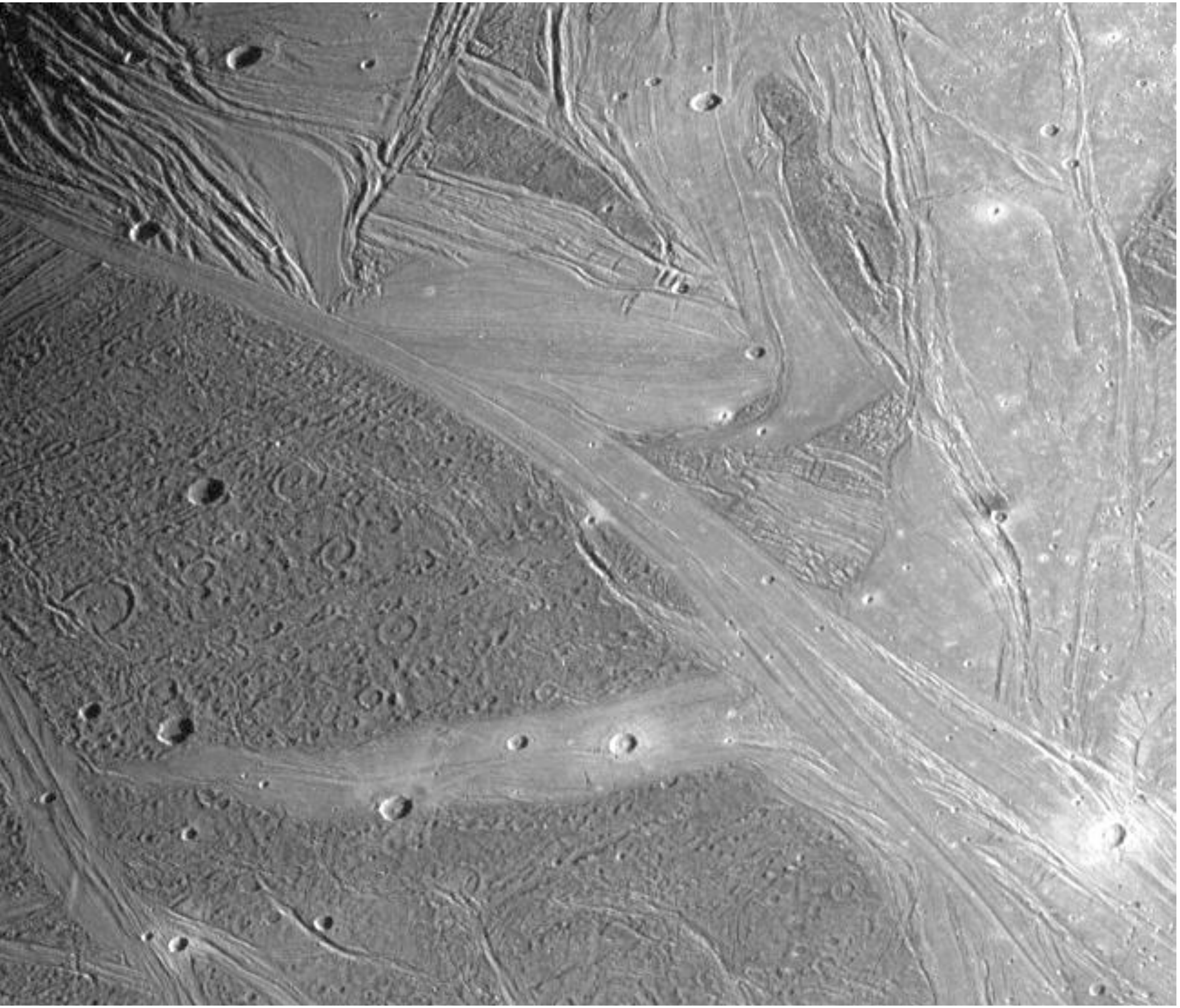
The dark terrain is dominated by craters, just like the highlands on the Moon and Mars. However, the craters are nearly all flat, lacking raised rims and central peaks, probably because of Ganymede's relatively weak icy crust.



There are few large craters on Ganymede; instead, there are ancient pale ghosts of craters, 100–350 km in diameter, which have lost all vertical relief. Like the features on Callisto, they are called *palimpsests*.

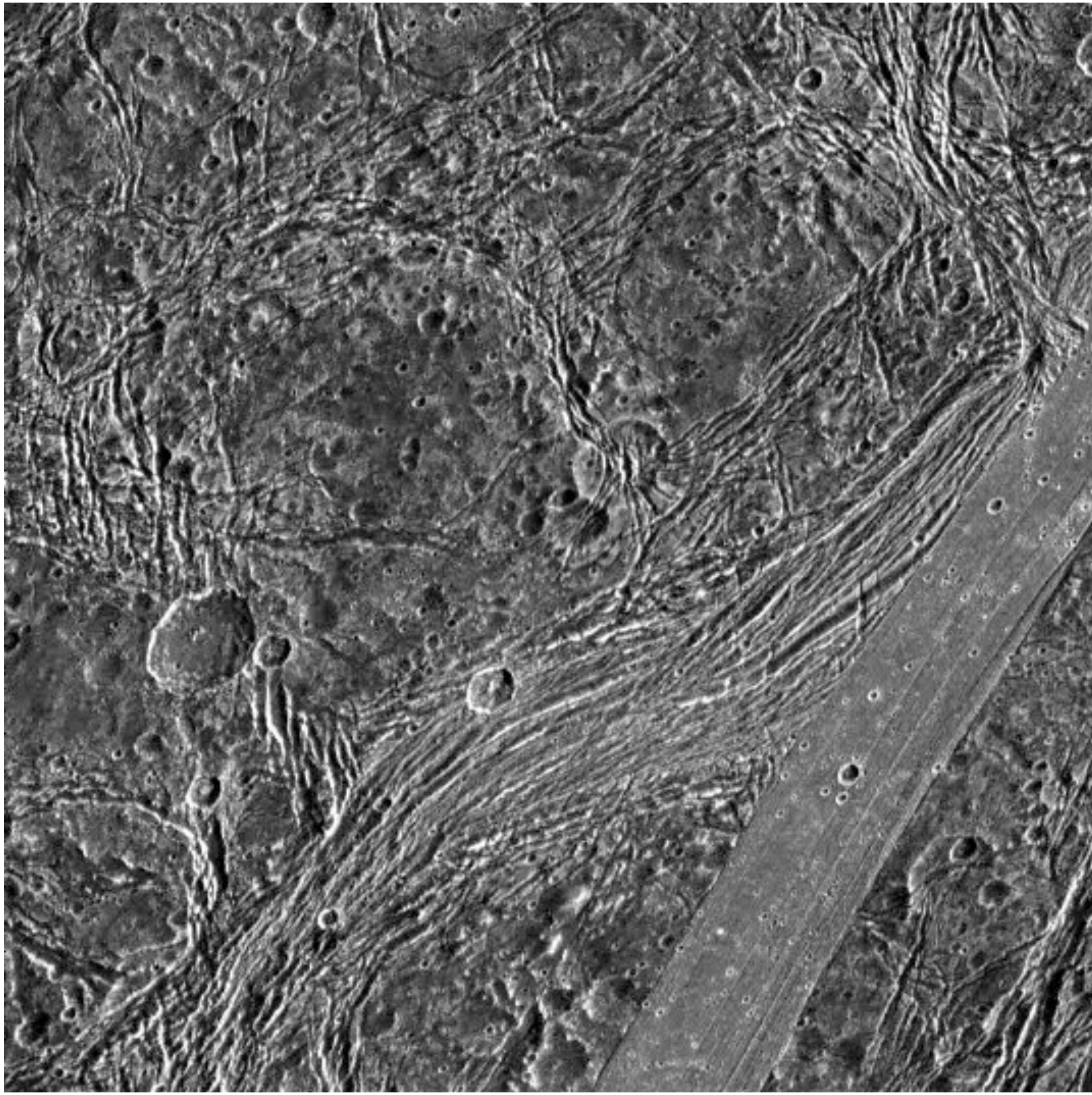


The palimpsest Buto Facula, from Galileo



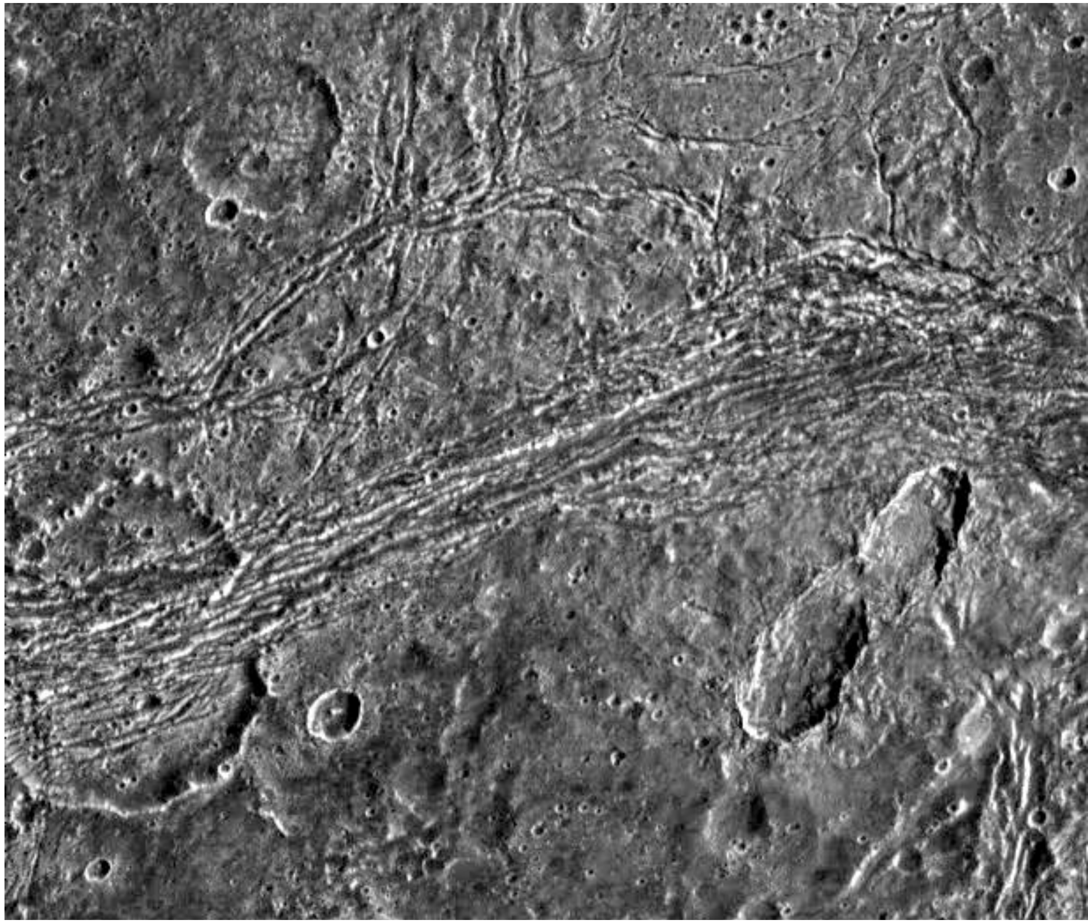
The bright terrain is clearly younger than the dark terrain. In some places it appears relatively smooth, but in others it is highly grooved and ridged.

The bright regions are probably formed by fresh material (water?) being extruded onto the surface after tensional faulting of the crust. This extension also produced fractures in the surrounding dark terrain, some of which are focused around old craters.



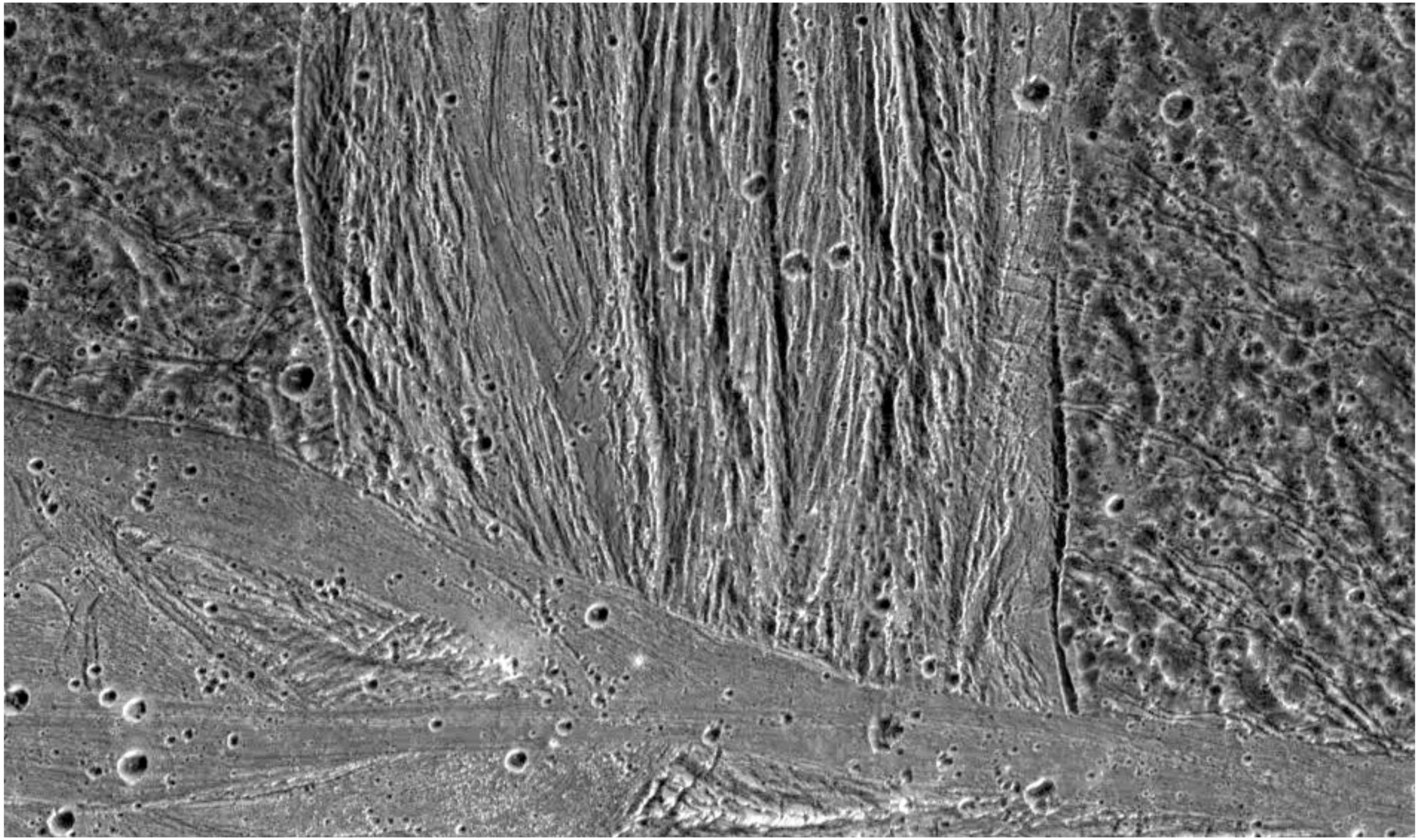
Galileo view of Nicholson Regio, showing heavily fractured dark terrain and a lane of smooth bright terrain.

Some craters overlie the fracturing, while others craters have been torn apart by tectonic forces. In this image, a lane of ridges and grooves cuts through the crater and distorts its originally circular shape. This implies the cratering and fracturing were happening at the same time.

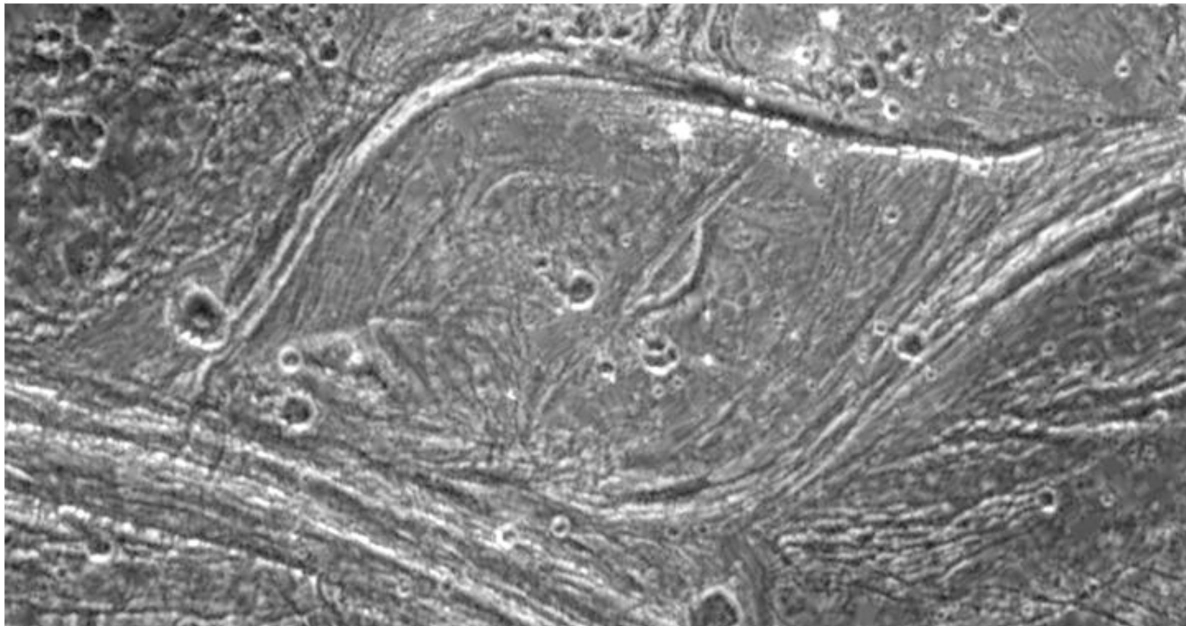


Galileo image of the dark terrain of Nicholson Regio.

Belts of bright terrain overlap each other, showing that the events that created them were complex and took place over a period of time.



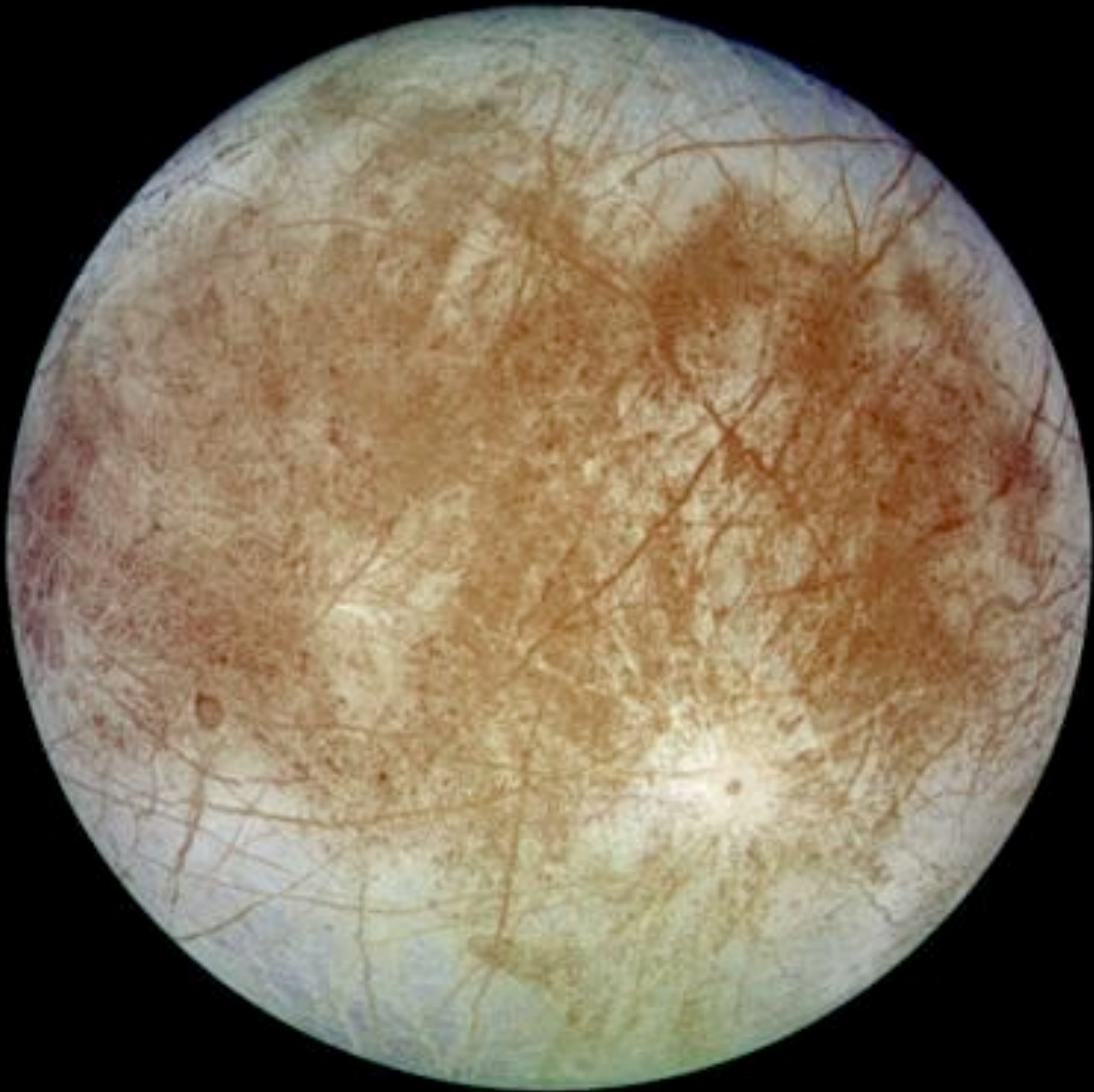
These features must be tectonic in nature. Many pieces of dark terrain have straight boundaries, so some kind of tectonic action involving stress that causes breaks along long straight lines is probably involved. Ganymede's crust appears to be divided into separate plates which, like Earth's tectonic plates, are able to move independently and interact along fracture zones. Ganymede would thus be the first world other than Earth to show tectonic processes.



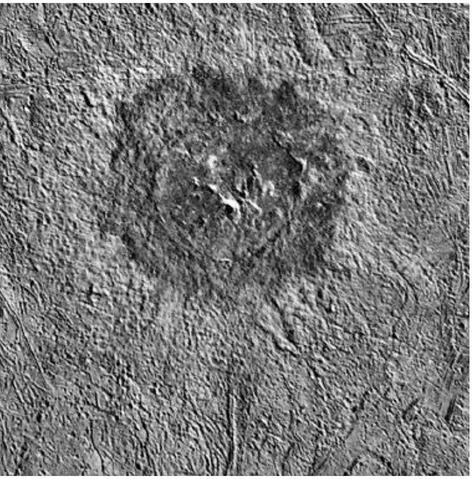
Galileo image of a region of ancient dark terrain known as Marius Regio.

Europa

– *ice moon*



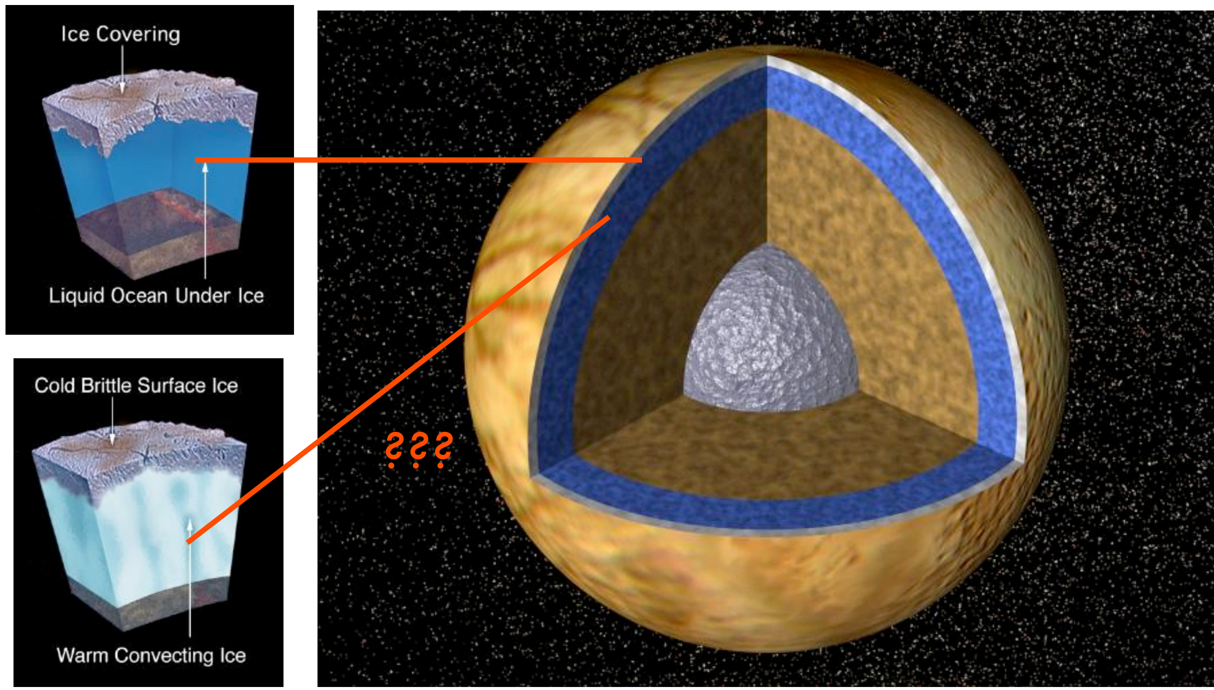
Europa is the smoothest object in the Solar System. It has virtually no vertical relief and a very high albedo. There are very few craters on Europa, with only three craters larger than 5 km in diameter. This would seem to indicate a young and active surface; based on estimates of the frequency of cometary bombardment Europa probably endures, Europa's surface must be no more than 30 million years old.

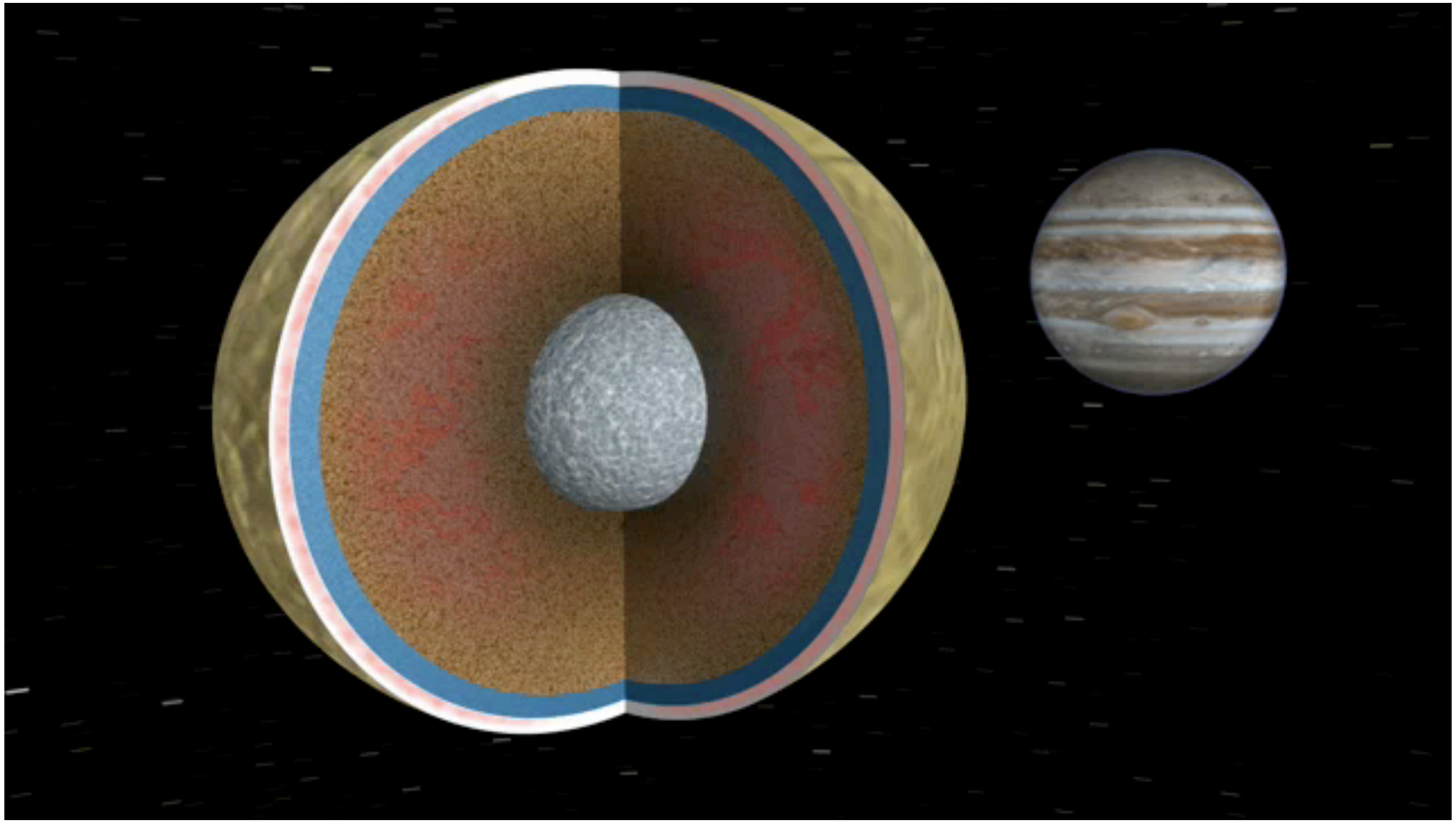


(right) Voyager view of Europa; (left) Pwyll crater, 26 km in diameter.

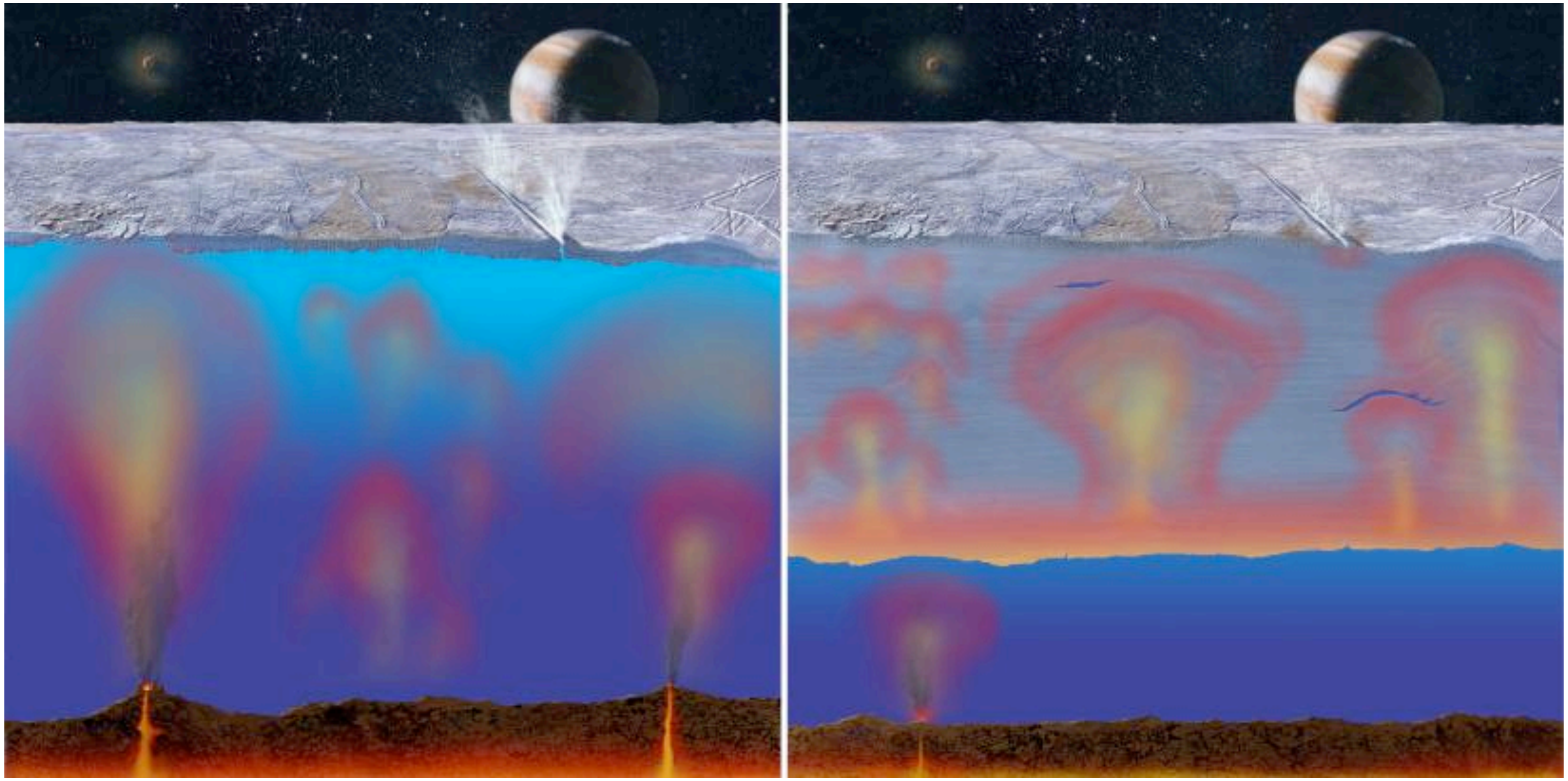

Europa rising, seen by New Horizons

Europa is about the size of our Moon, and density measurements suggest it consists of a rocky core surrounded by an ice and water crust between 10 and 100 km thick; there could also be a metal core. It is not clear whether the subsurface layer is warm convecting ice or liquid water. If a 100 km deep ocean existed below a 15 km thick ice crust, it would be 10 times deeper than any ocean on Earth and would contain twice as much water as Earth's oceans and rivers combined.



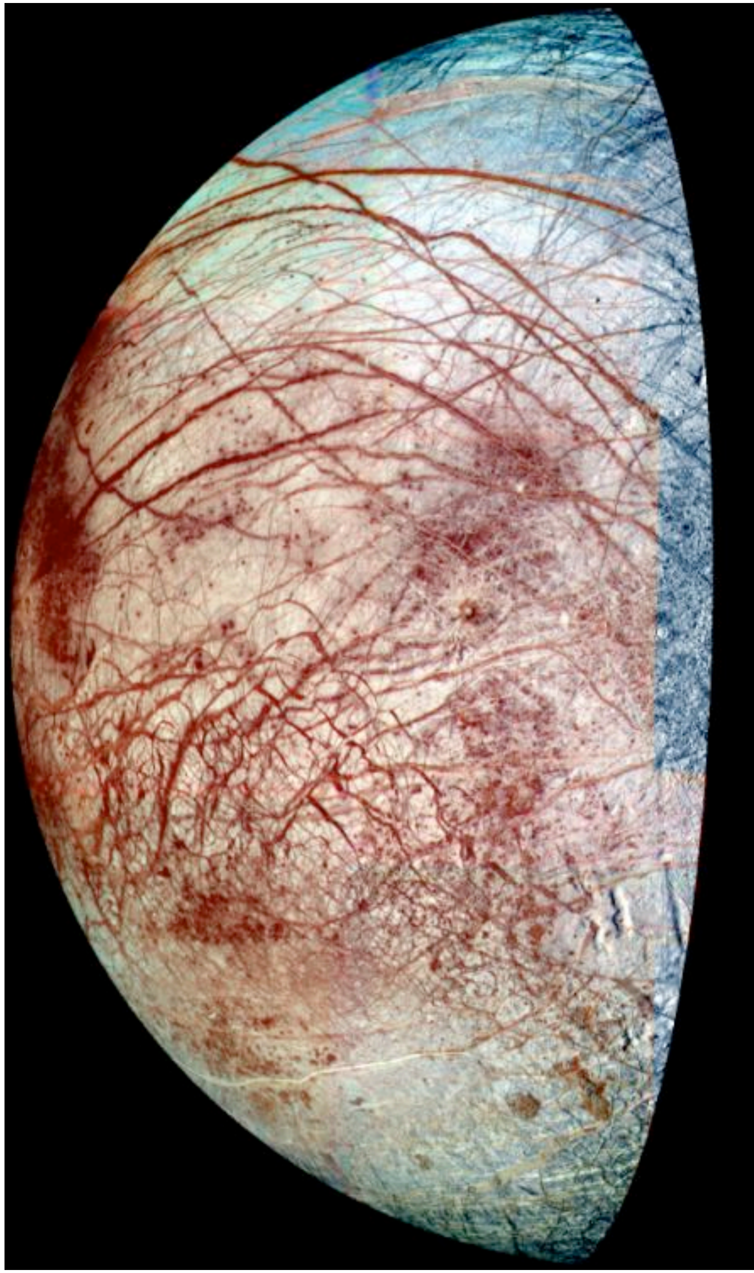


Europa's orbit is eccentric, which means as it travels around Jupiter, Jupiter raises large tides. This tidal kneading causes frictional heating within Europa, which is what keeps Europa's ocean liquid

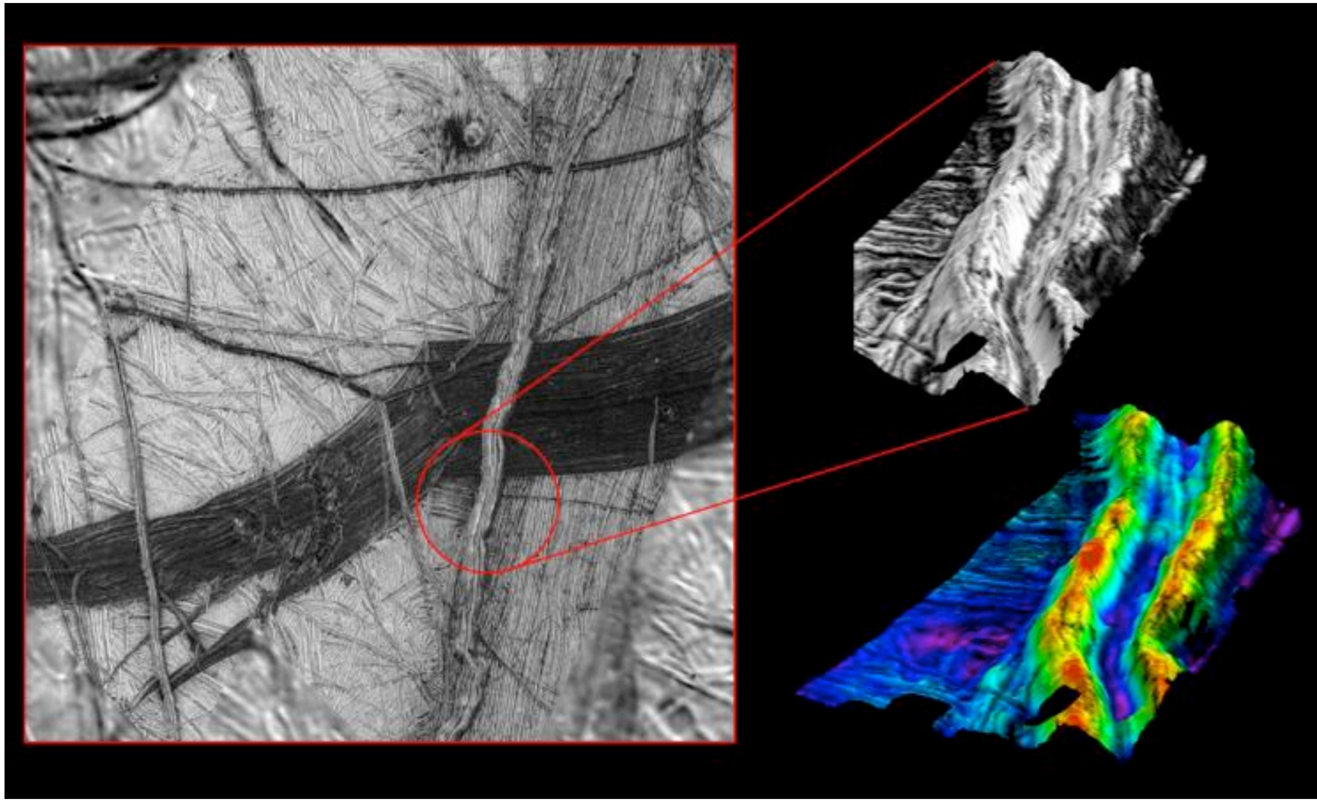


One important question is how thick the ice is. If it is thin (~10 km), then the ice can melt directly and there can be contact between the sub-surface ocean and the surface. If the ice is thick (~100 km), then heat must be transferred by slowly convecting ice.

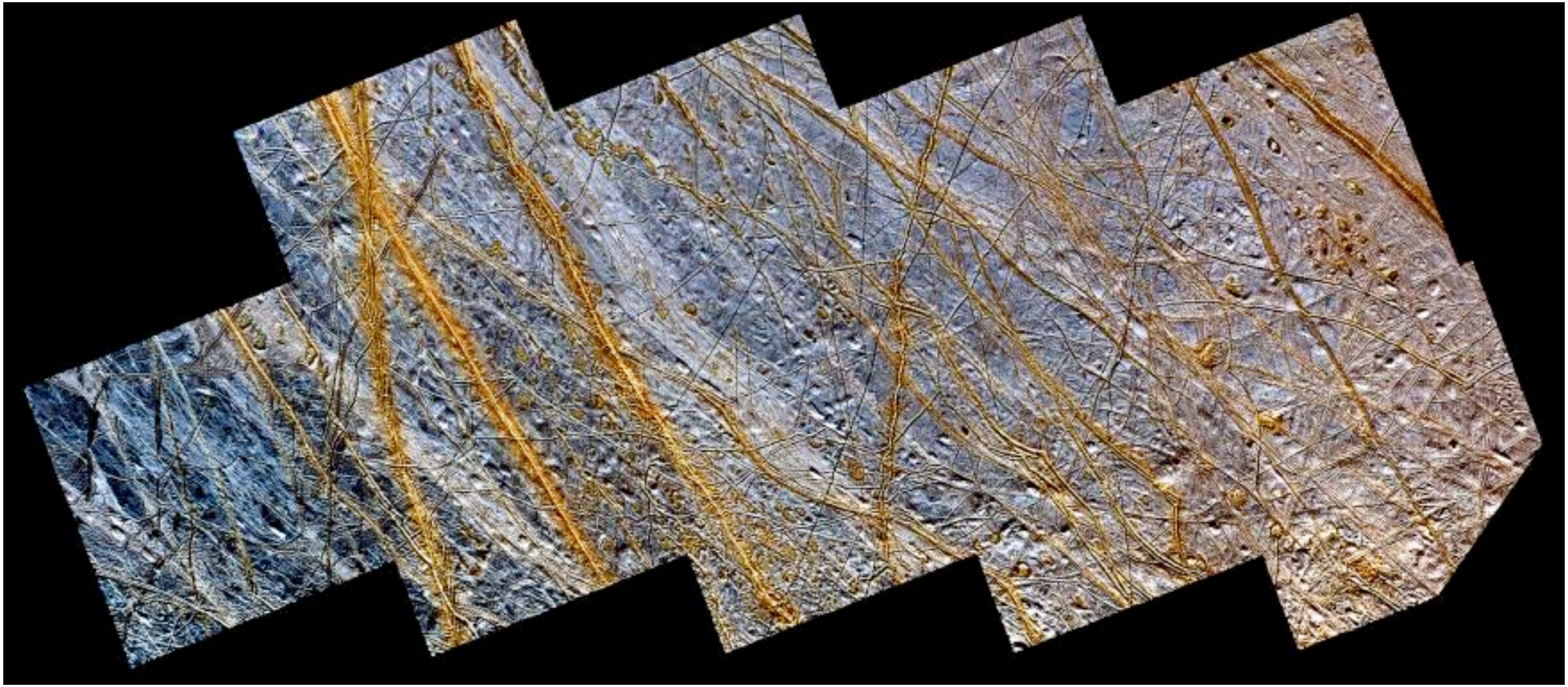
Europa’s surface is covered with dark bands, which stretch for thousands of kilometres, and are typically 20–40 km wide. They may have originated in an episode of global expansion, where the crust fractured and the fractures filled with water which froze quickly. The red material is a non-ice contaminant and could be salts brought up from a possible ocean beneath Europa's frozen surface.



A close-up view of some of these stripes reveals criss-crossing features. The younger pale stripe is actually a double ridge with a deep intervening trough, probably showing where the crust has pulled apart and allowed dark material from beneath the surface to well up and fill the cracks. The ridges are about 300 m high, and the valley is about 1.5 km wide.

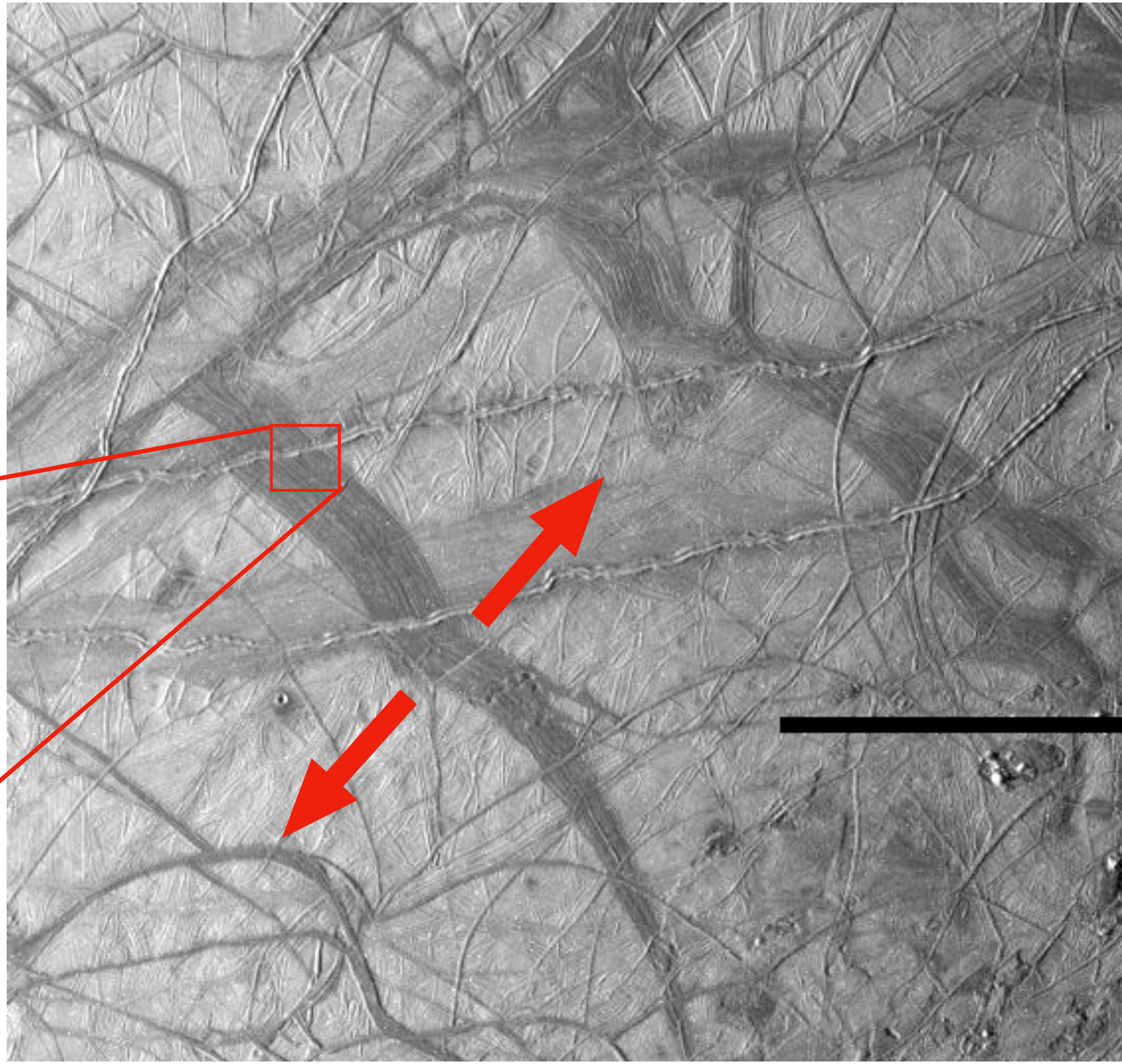


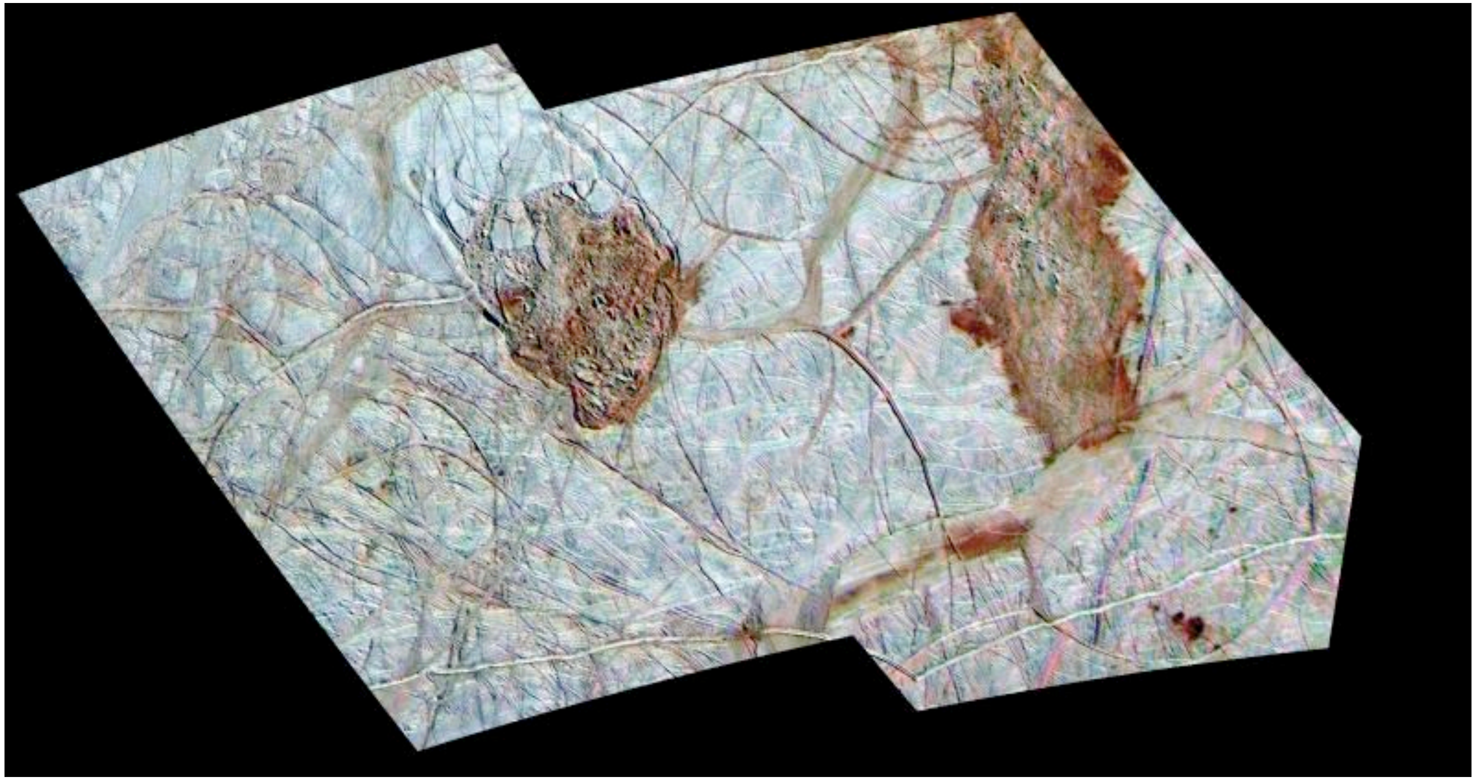
On Earth, volcanic fissure eruptions occur when magma flows through a long crack, often caused by plate movement. These fissures usually clog up with in a few hours, confining the eruption to discrete vents along the fissure. On Europa, the long ridges suggest that eruption continued along the whole length of the fissure.



A region in the northern hemisphere showing brown, linear (double) ridges criss-crossing over a geologically older, smoother surface, bluish in tone. The blue surface is composed of almost pure water ice. Dark spots, several kilometres in diameter, are distributed over the surface. The concentration of minerals along the bands suggests they were dispersed from fissure eruptions.

Dark wedges show regions which have pulled apart, like tectonic plates. Cutting across these are more double ridges, which must be younger.

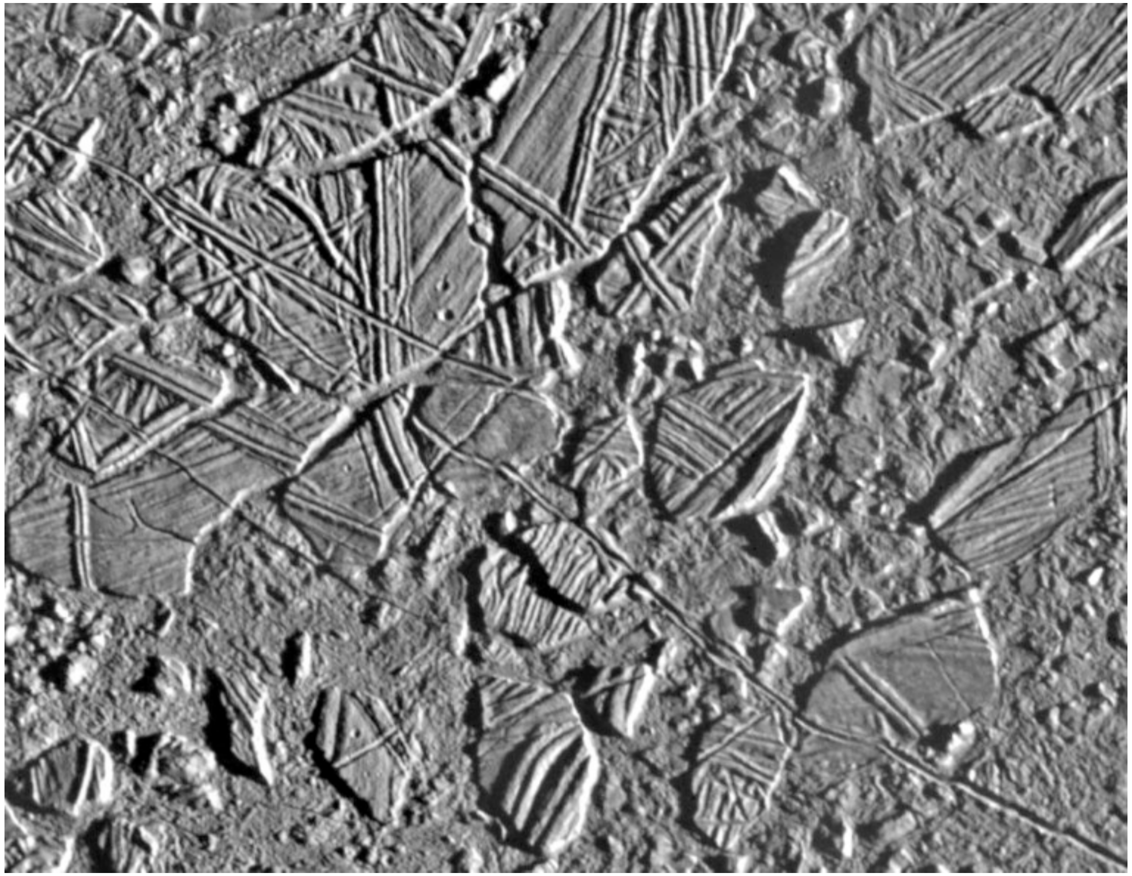


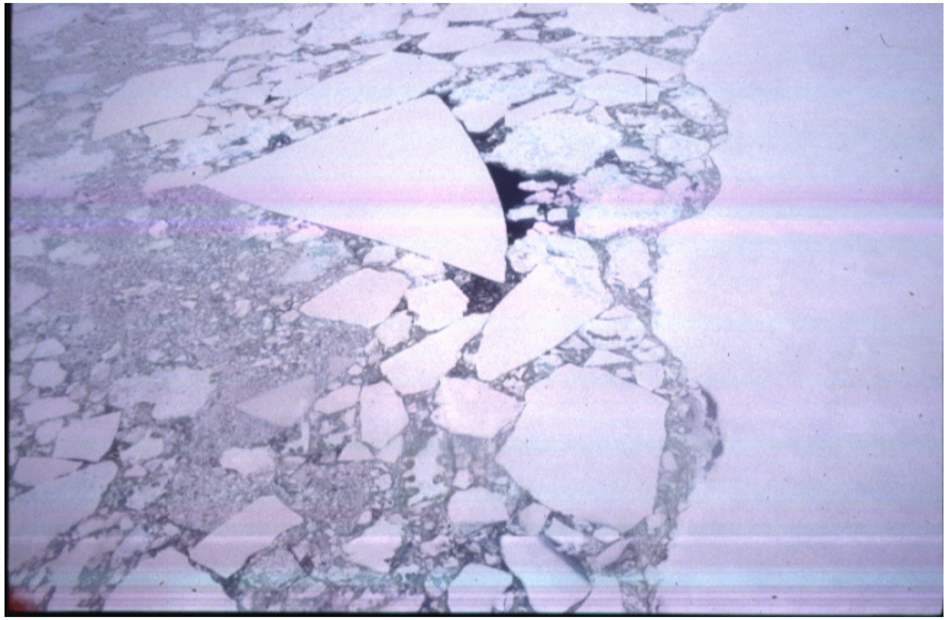


Galileo mosaic of Thera (left) and Thrace; Thera is about 70 km wide by 85 km high and appears to lie slightly below the level of the surrounding plains.

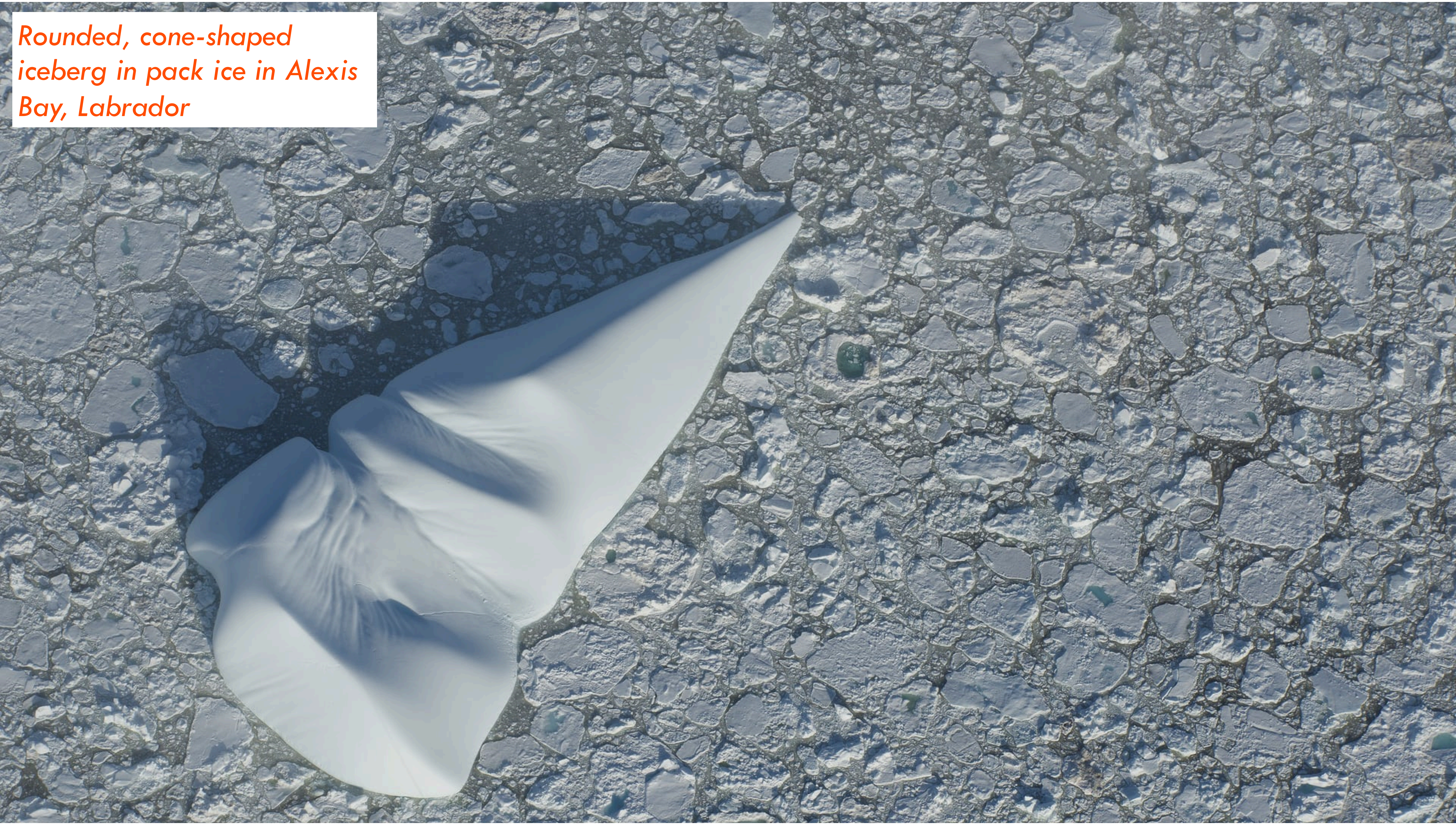
Thera and *Thrace* are two dark, reddish regions of peculiar terrain that disrupt the older icy ridged plains. The regions are rich in magnesium sulfate. They may represent regions on Europa where the icy crust has completely melted through from below, to allow material from an ocean below to well up.

The Conamara Chaos is a region of bright terrain which has broken into a multitude of irregular fragments 1–10 km across, whose edges are cliffs 100–200m high. This is the clearest evidence for a subsurface ocean, topped by an ice crust only a few kilometres thick.



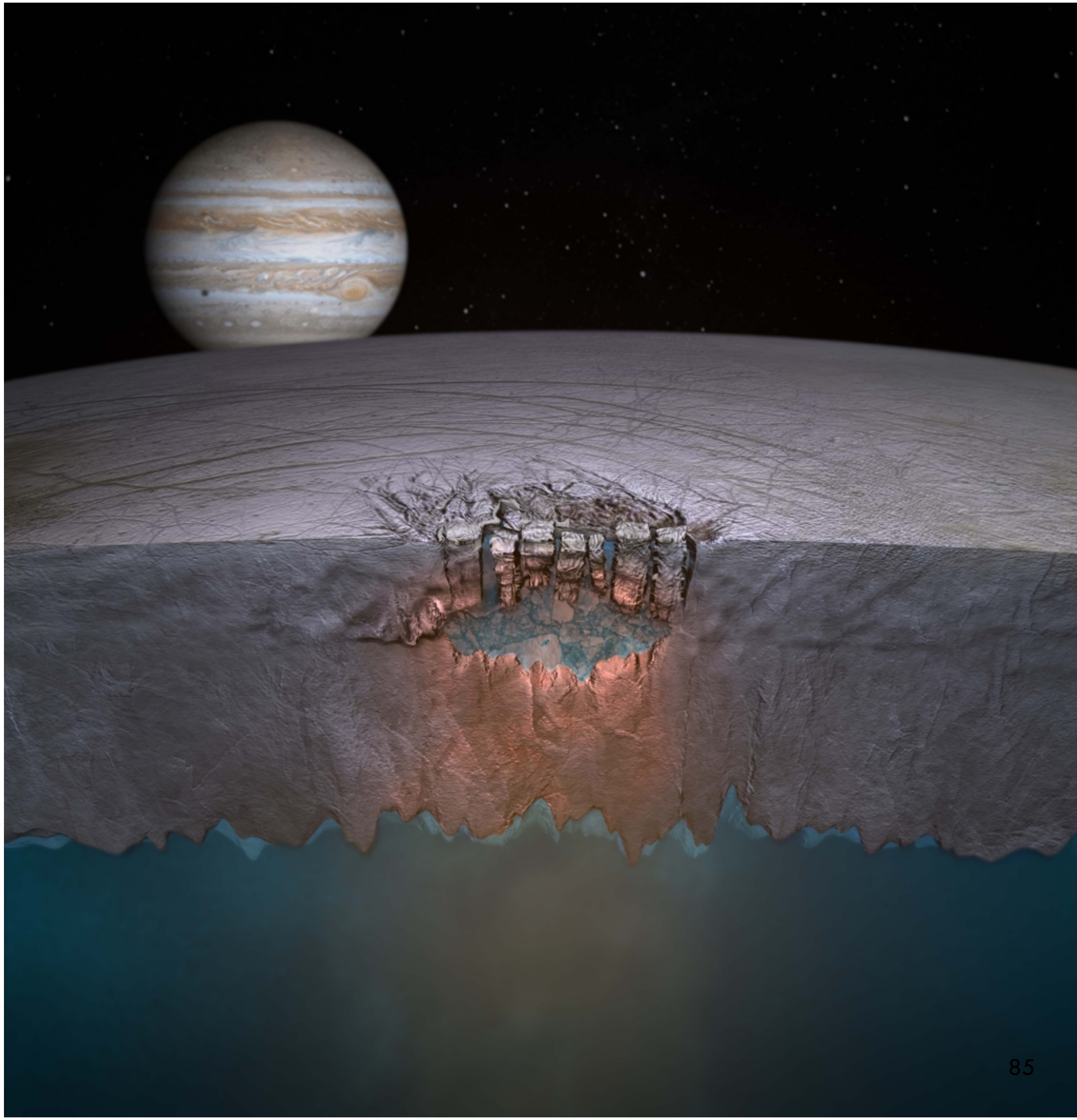


Crustal plates ranging up to 13 kilometers across, which have been broken apart and "rafted" into new positions, looking very like pack ice on Earth (above).

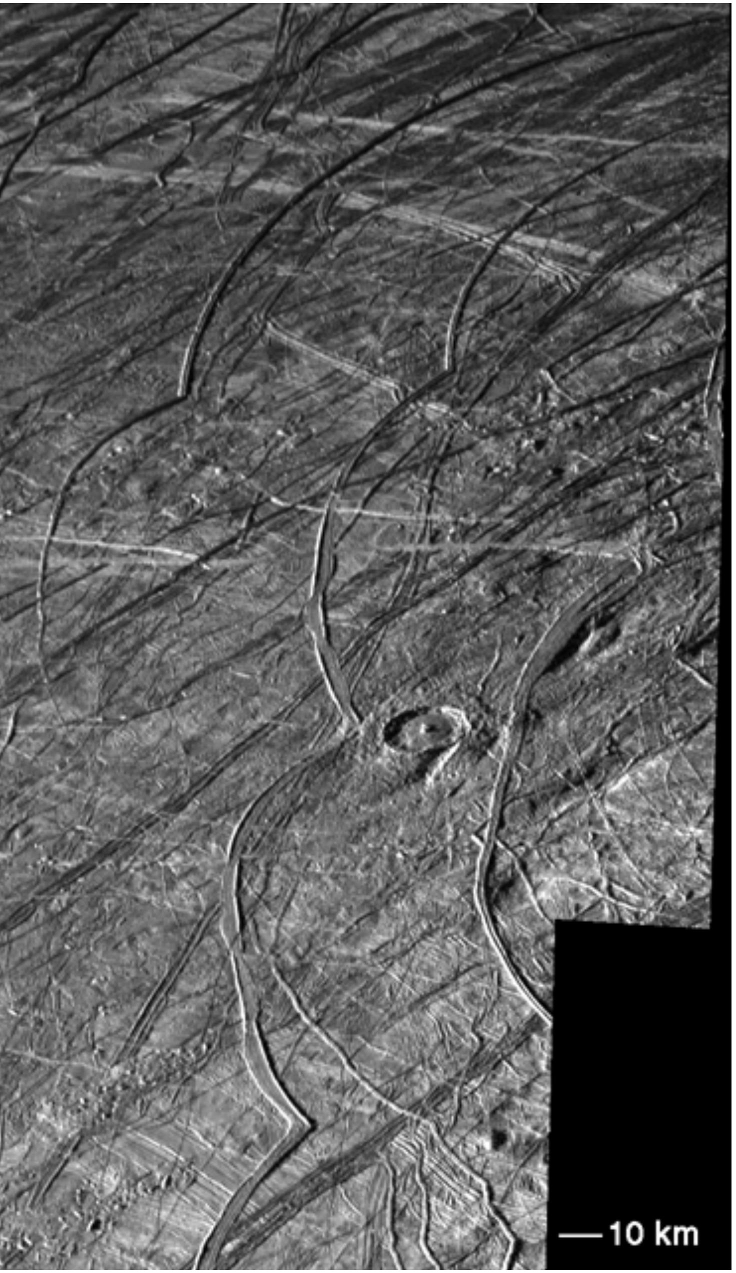


Rounded, cone-shaped iceberg in pack ice in Alexis Bay, Labrador

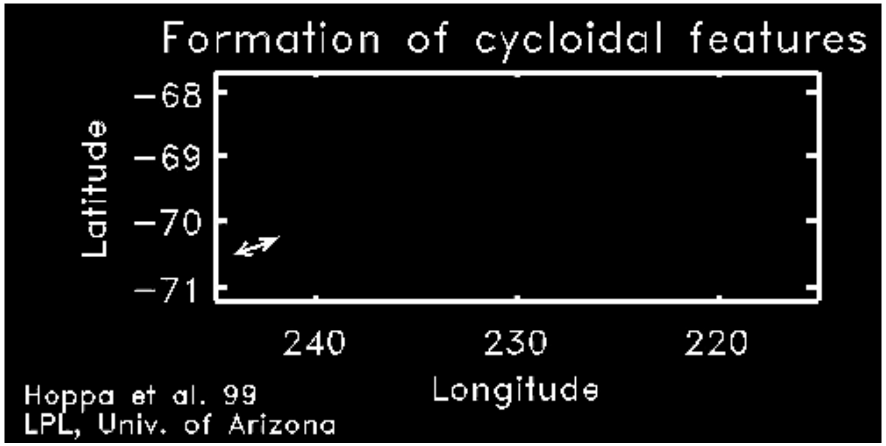
A recent paper suggests that this “chaos terrain” indicates the presence of a sub-surface lake. The authors suggest this means Europa is currently active, so if Juno gets a close look at Europa, the region might look very different.



Model for the chaos terrain, with warm water seeping up and causing the surface to break into jumbles of icebergs.



Europa has a series of distinctive *cycloidal ridges*: long arc structures that cut across other terrain. These are cracks in the icy surface, which propagate in an arc because of the changing tidal stress from Jupiter during the day. This will only happen if there is a global ocean beneath the ice.



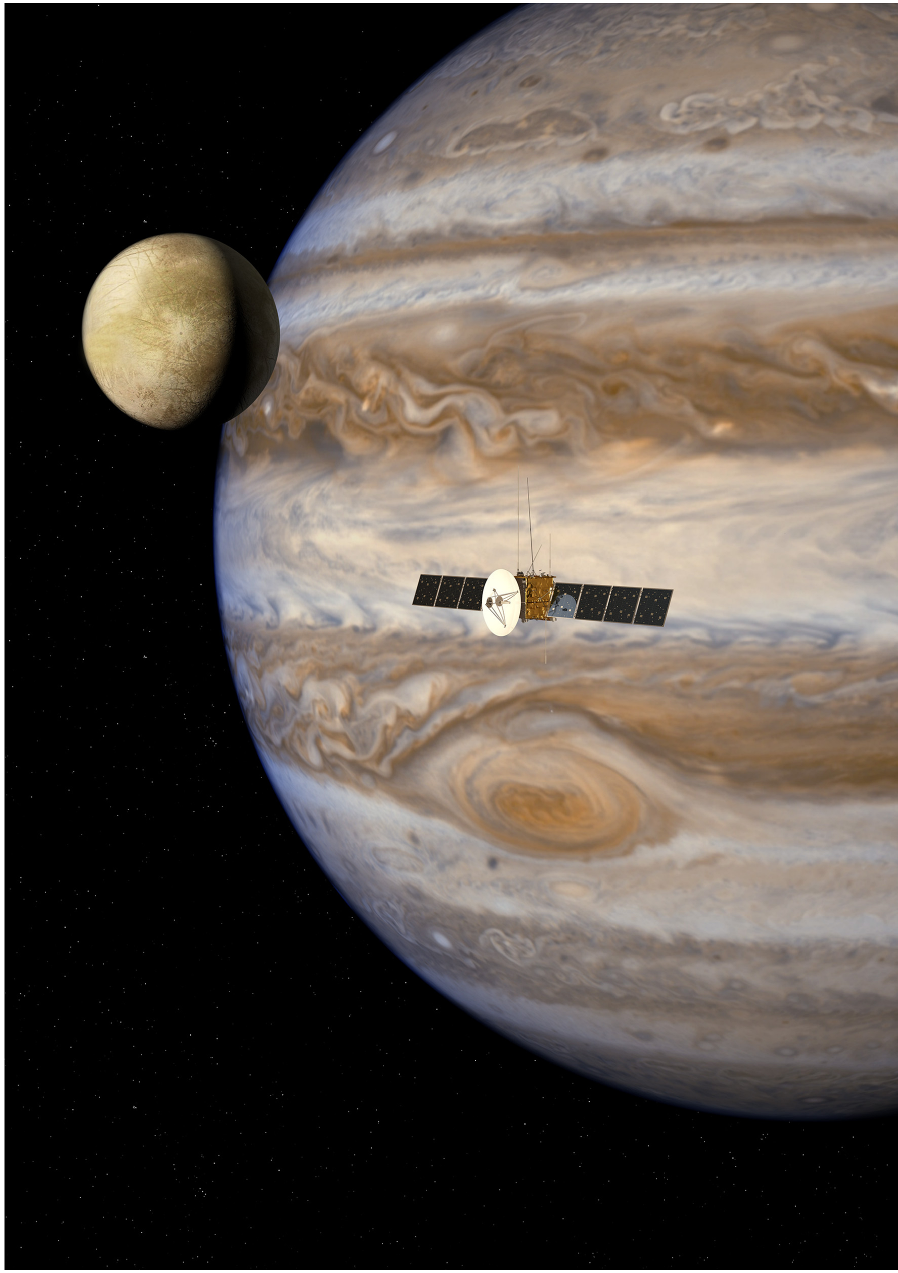
Is Europa still active? The ages of the youngest surfaces seem to be anywhere between a few million and a hundred million years old.

We also have no idea how long it took to form the features we see. The spreading could be slow like on Earth's sea floor (cm per year), in which case the double ridges would take 50,000 years to form; or they could form in hours, if they form like a Hawaiian erupting fissure.

It seems likely that if Europa has been active as recently as a few million years ago, it probably still is.

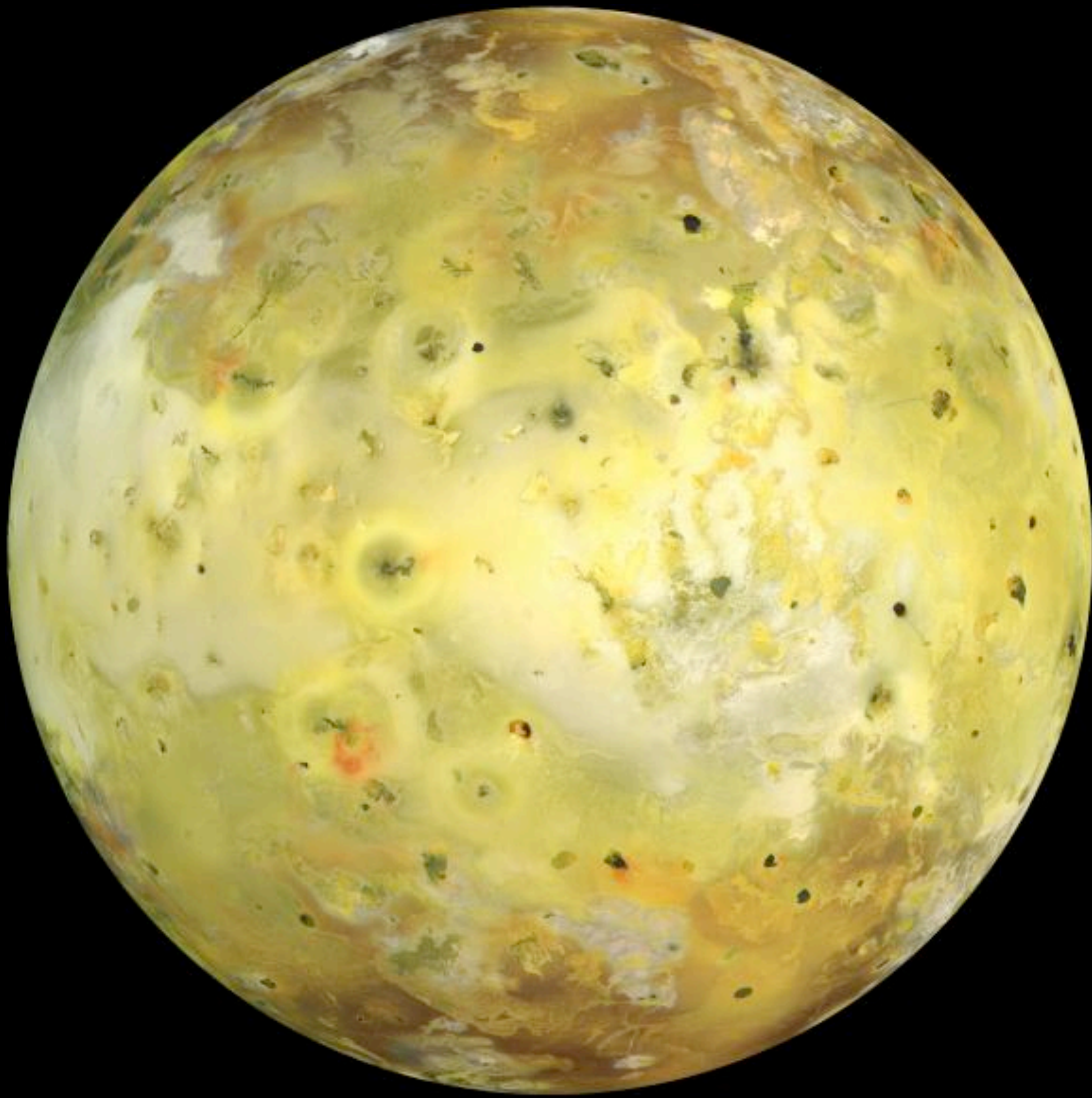
Two missions to Europa are currently planned. The European Space Agency is planning a large-scale Jupiter mission, called the *Jupiter Icy Moon Explorer* mission (JUICE). It is scheduled for launch in 2022, for arrival at Jupiter in 2030.

NASA plans a mission called the *Europa Multiple-Flyby Mission*. It is also scheduled for launch in 2022, for arrival at Jupiter in 2030, where it will perform 45 flybys of Europa.



Io

– world of volcanoes



Io is the most volcanically active body in the Solar System. The activity arises because of the resonance with the other Galilean satellites. Tidal interactions force Io's orbit to be slightly eccentric (e = 0.004). Although Io is tidally locked to Jupiter, the eccentricity means that Io's surface flexes up and down by 100m each orbit, which generates enough heat to melt most of the interior.

An exaggerated rendition of Io's terrible tides.

Plumes over Pillan Patera and Prometheus, taken by Galileo.

Melting of Io by Tidal Dissipation

Abstract. *The dissipation of tidal energy in Jupiter's satellite Io is likely to have melted a major fraction of the mass. Consequences of a largely molten interior may be evident in pictures of Io's surface returned by Voyager I.*

The free eccentricity of Io's orbit is approximately .00001 (*1*). If this eccentricity accounted for all of the variation in the Jupiter-Io separation, the dissipation of energy from tides raised on Io by Jupiter would be negligibly small (*2*), since Io is synchronously rotating. But the resonant structure of the Galilean satellite leads to forced eccentricities that are considerably larger than the free values. Although still modest by most standards, these forced eccentricities coupled with the enormous tides induced by Jupiter lead to magnitudes of tidal dissipation that are certainly important and may completely dominate the thermal history of the innermost satellite Io. We will first establish values of the forced eccentricities and later substitute these into an expression for the total tidal dissipation.

The Galilean satellites are numbered in the conventional manner with 1 to 4 corresponding respectively to Io, Europa, Ganymede, and Callisto. Let λ_i, n_i $(=d\lambda_i/dt)$, and $\tilde{\omega}_i$ denote the mean longitude, mean orbital motion, and longitude of the perijove. The relation $n_1 - 3n_2 + 2n_3 = 0$ is satisfied exactly within observational error such that $\lambda_1 - 3\lambda_2 + 2\lambda_3 = 180°$ with no observed libration amplitude. This is the well-known Laplace relation and is often called simply the libration. In addition, the mean motions of 1 and 2 and, separately, of 2 and 3 are nearly in the ratio 2:1

$$n_1 - 2n_2 = n_2 - 2n_3 = 0.^\circ 739507/\text{day} \quad (1)$$

compared to $n_2 = 101.^\circ 375/\text{day}$. The nearness of the two sets of mean motions to the 2:1 commensurability suggests that some of the resonance variables $\lambda_1 - 2\lambda_2 + \tilde{\omega}_1$, $\lambda_1 - 2\lambda_2 + \tilde{\omega}_2$, $\lambda_2 - 2\lambda_3 + \tilde{\omega}_2$, and $\lambda_2 - 2\lambda_3 + \tilde{\omega}_3$ may be librating about constant values. A periodic solution of the equations of motion with these resonance variables having constant values was used by de Sitter (*3*) as a first approximation in his theory of the Galilean satellites. Sinclair (*4*) has rederived the complete periodic solution and shown that in fact the first three of the four resonance variables are librating with small amplitude—the first and third about 0° and the second about 180°. This means that conjunctions of 1 and 2 occur when 1 is near its perijove and 2 is near its apojove; conjunctions of 2 and 3 oc-

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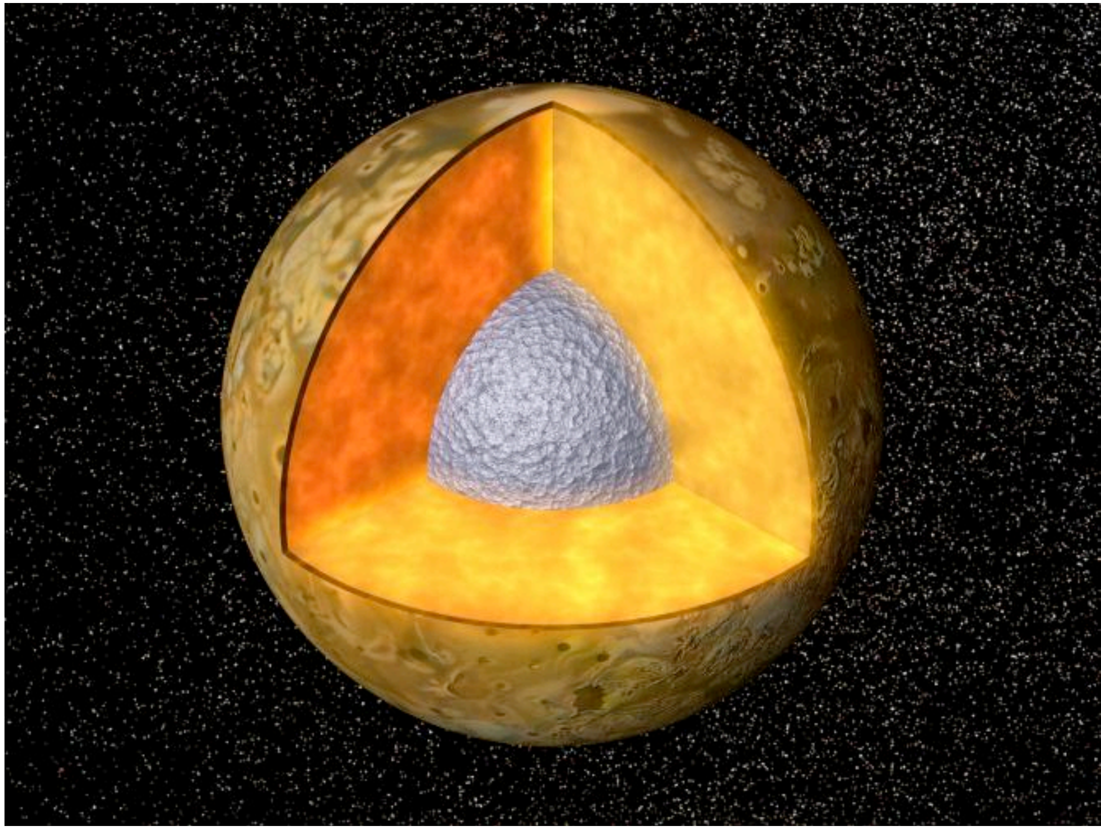
Paper published by Stanton Peale et al., one week before Voyager 1 encountered Jupiter in 1979

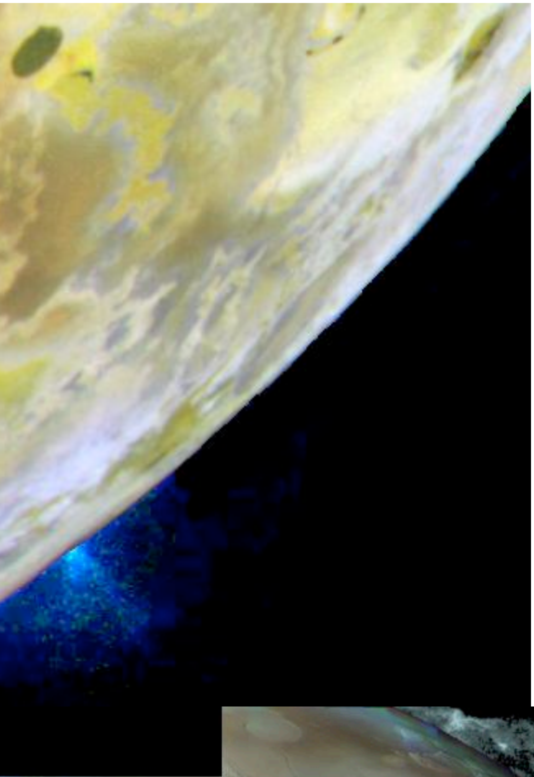
Io is so dense that its interior must be rocky, with little or no ice content. Gravity data from Galileo's close flyby show that it has a dense core, probably iron mixed with sulphur. Surrounding the core is a silicate mantle, covered by a crust, at least partly sulphur, about 50 km thick.

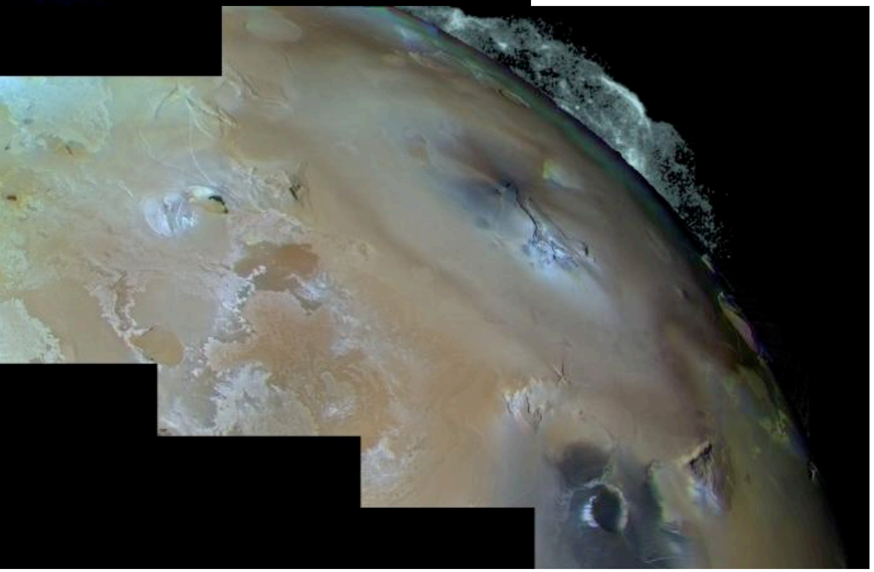


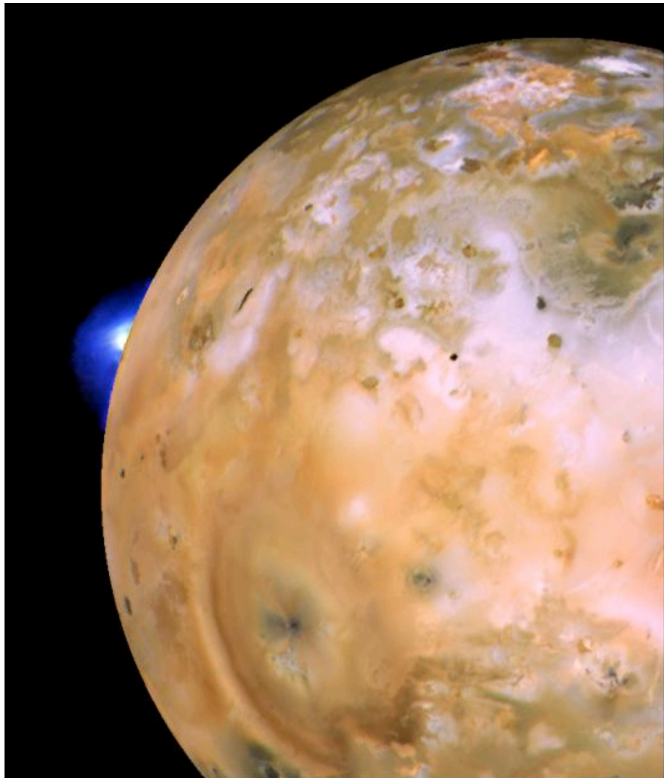
There are no impact craters on Io. The surface of Io must be younger than a millions years old, and is continually being resurfaced by volcanic activity.

Instead, Io has an amazing variety of terrains: deep calderas, lakes of molten sulphur, mountains, lava flows hundreds of kilometres long, and volcanic vents. Sulphur and its compounds take on a wide range of colours which are responsible for Io's variegated appearance.

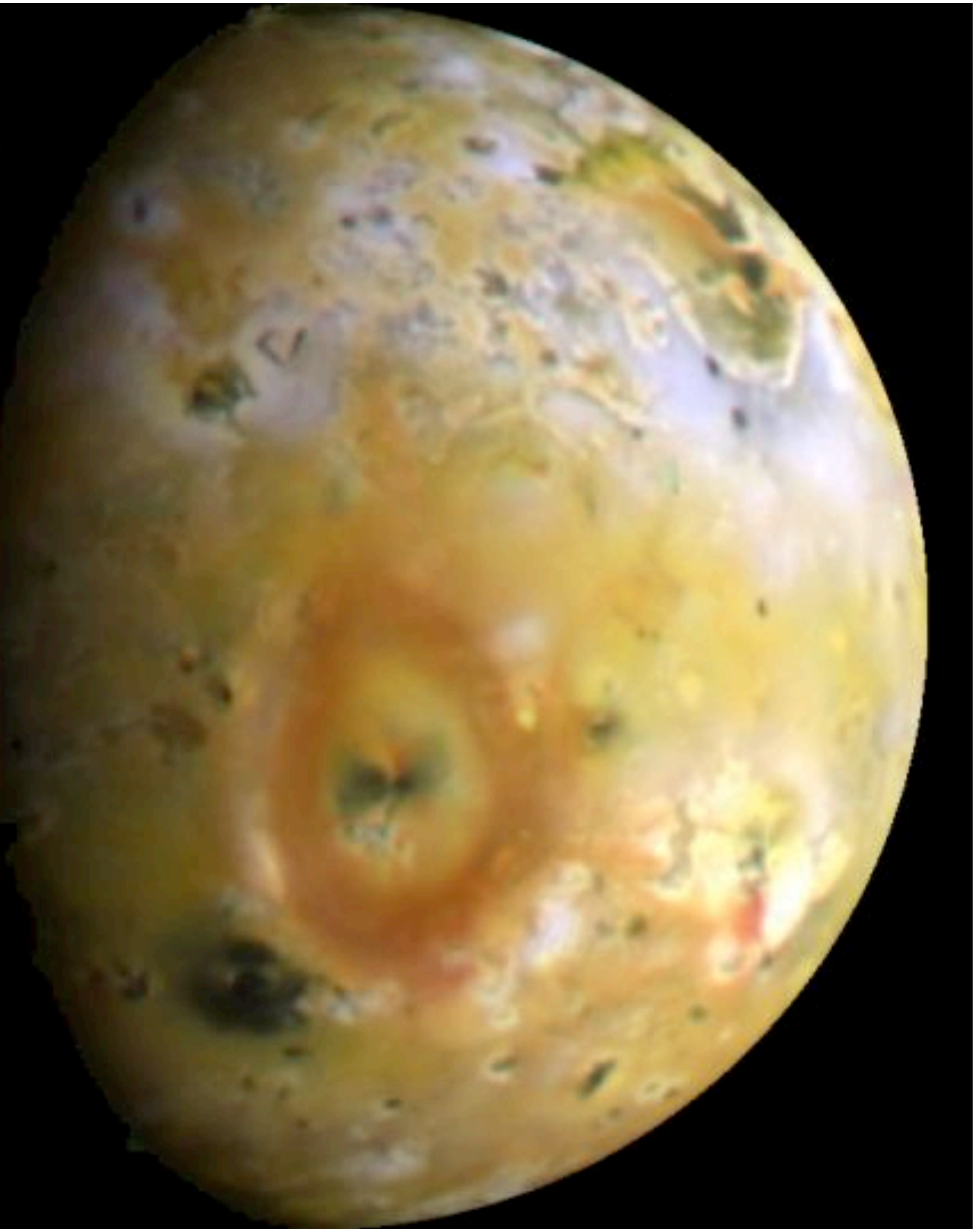
Io is convulsed with continuous volcanic activity. *Voyager 1* observed eight eruptions simultaneously; several months later, *Voyager 2* found six of the eight volcanoes were still active. We now know of at least 120 active volcanoes on Io. The longest-lived volcano, Prometheus, has been seen in every suitable *Voyager* and *Galileo* image.







Eruptions over Io. Clockwise from top left: Masubi (Galileo), Loki (Voyager 1), and Pele (Galileo).



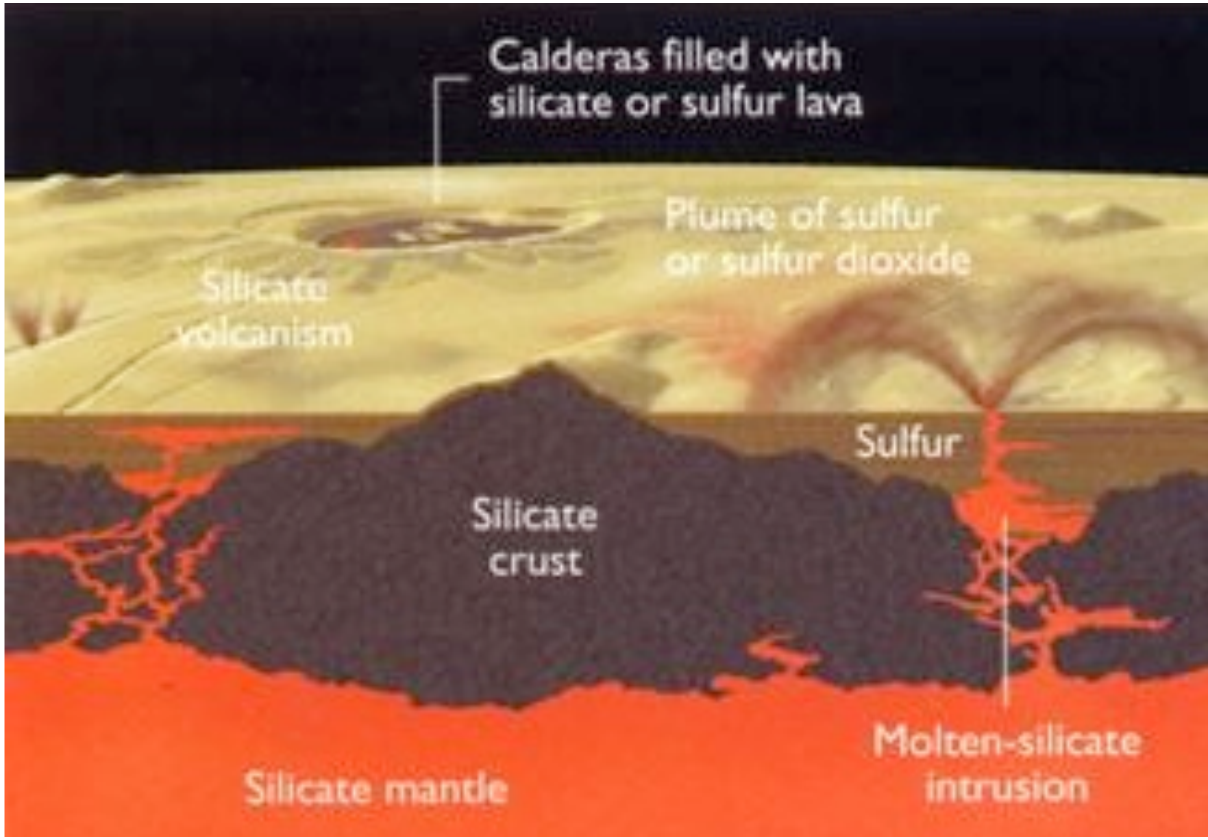
The eruptions seen on Io appear to be continuous explosive ejections of gas (probably sulphur dioxide) and fine particles. The plumes reach heights of up to 100 km above the surface, before the gas and dust return to the surface, leaving ring-like deposits typically 200–300 km in diameter.

Galileo image of Pele.

The lava itself is too hot to be molten sulphur, so must be molten silicates. Some of the hottest spots on Io may reach temperatures as high as 2000 K.

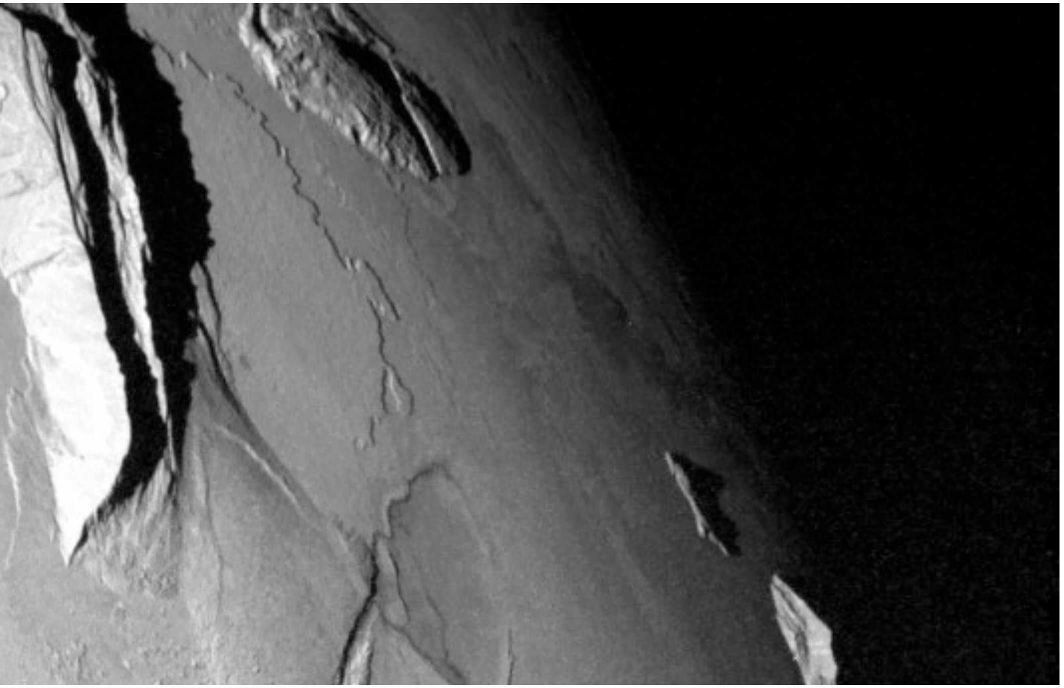
An active eruption at Tvashtar Catena, caught in action in November 1999 by Galileo. The false colour image shows the newly erupted hot lava as yellow-white because of infrared emission. The picture is about 250 km across.

This suggests that many eruptions do involve molten silicates (i.e. lava), but some may be primarily molten sulphur. The sulphur on Io's surface could be a thin coating, or it could form relatively thick deposits in localized areas.



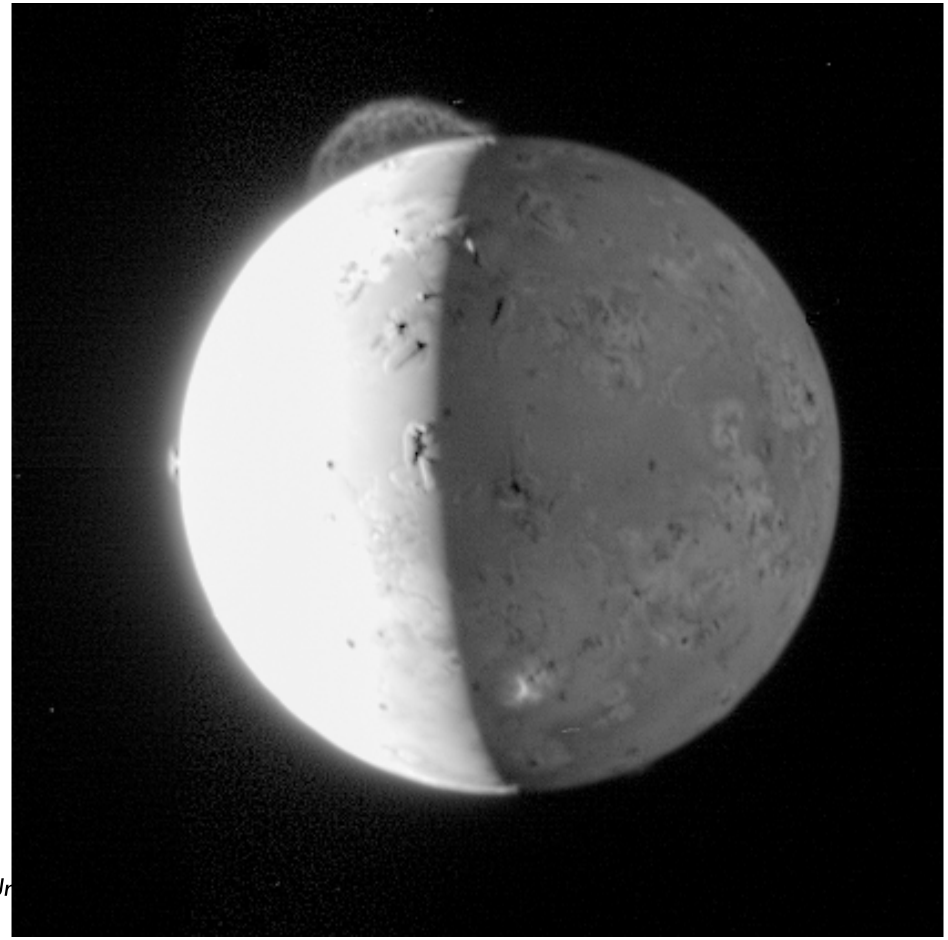
Schematic depiction of the major phenomena found on Io.

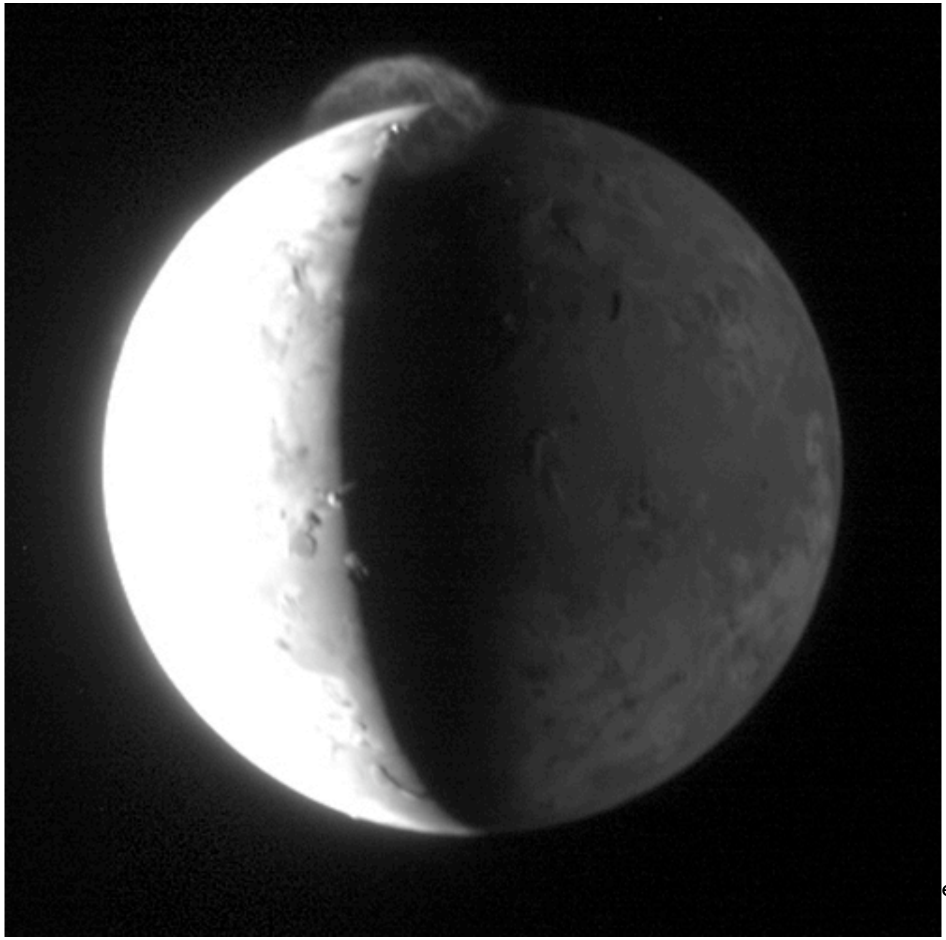
Io also has mountains which appear not to be volcanic in origin; the tallest is 16.8 km high. They are formed by faulting of the crust, with some sections being tilted upwards. The high surface temperatures means the rock is soft, so older mountains collapse and deteriorate.



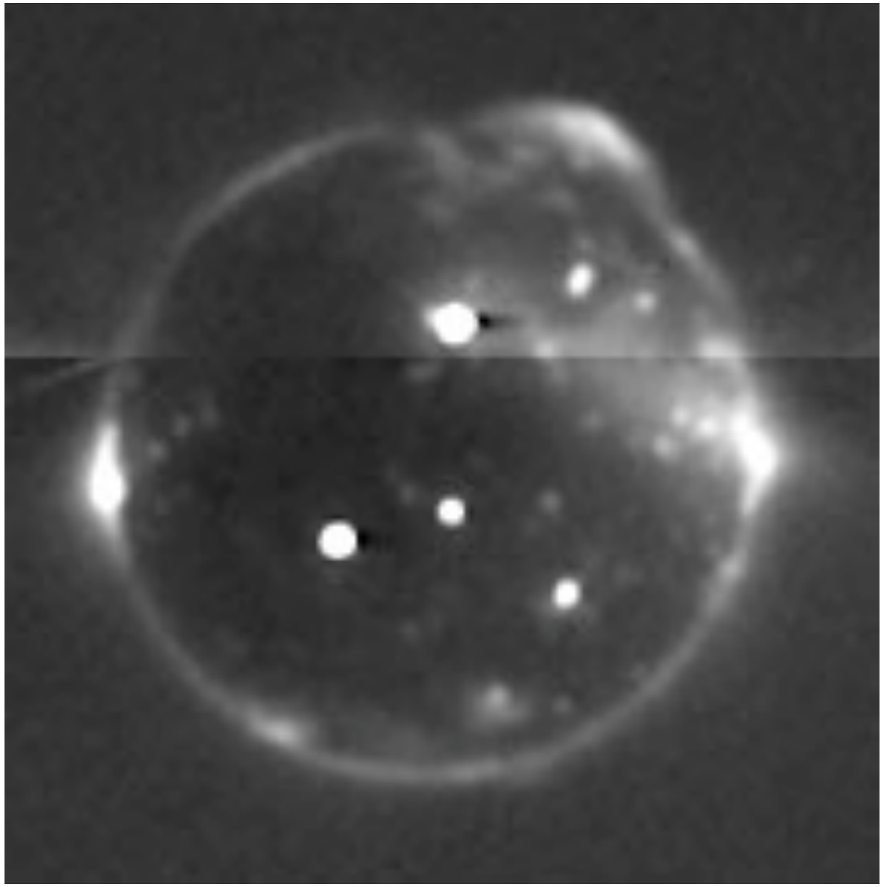
Mountains on Io: Tohil Mons (above) and Mongibello Mons (left). An older mountain with more subdued topography can be seen near the top centre of this image.

New Horizons, on its way to Pluto, saw plumes from two volcanos: Prometheus and Tvashtar. The plume from Tvashtar is rising 330 km from the surface.

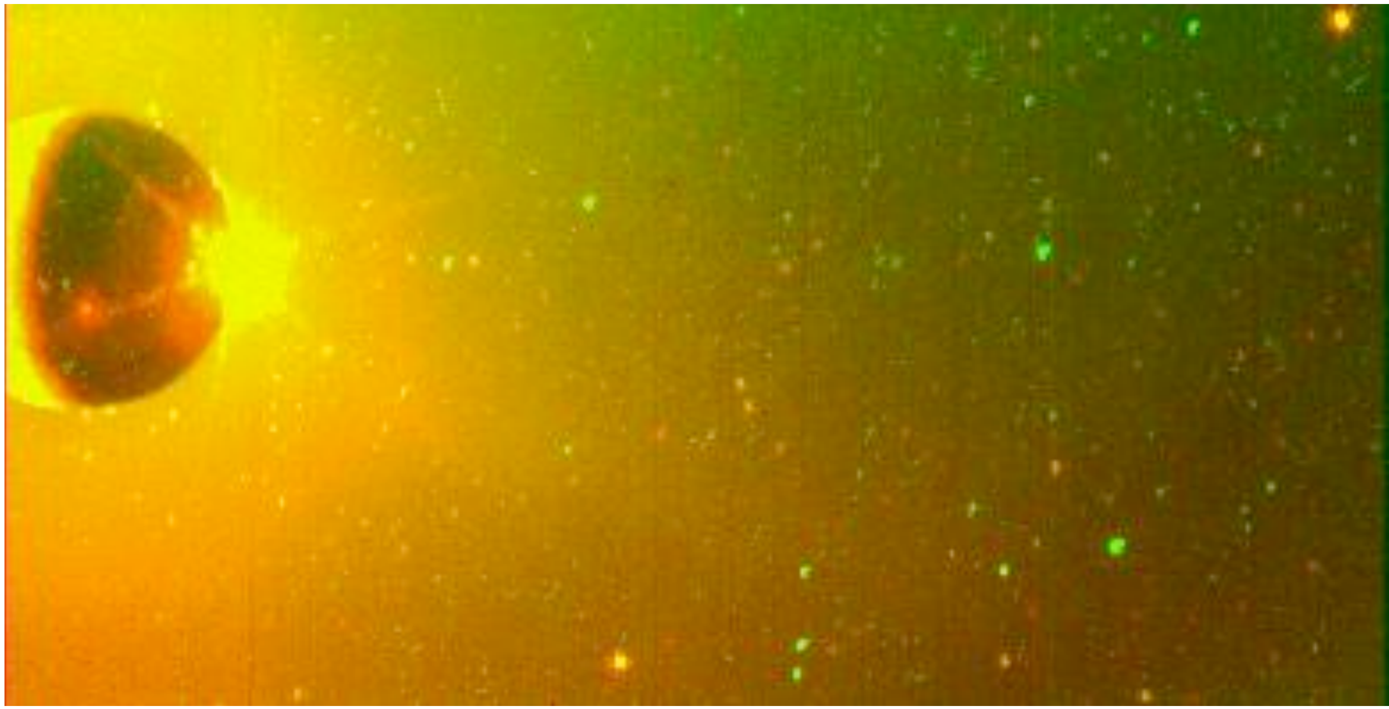




With its infrared camera, it saw several more active volcanoes.

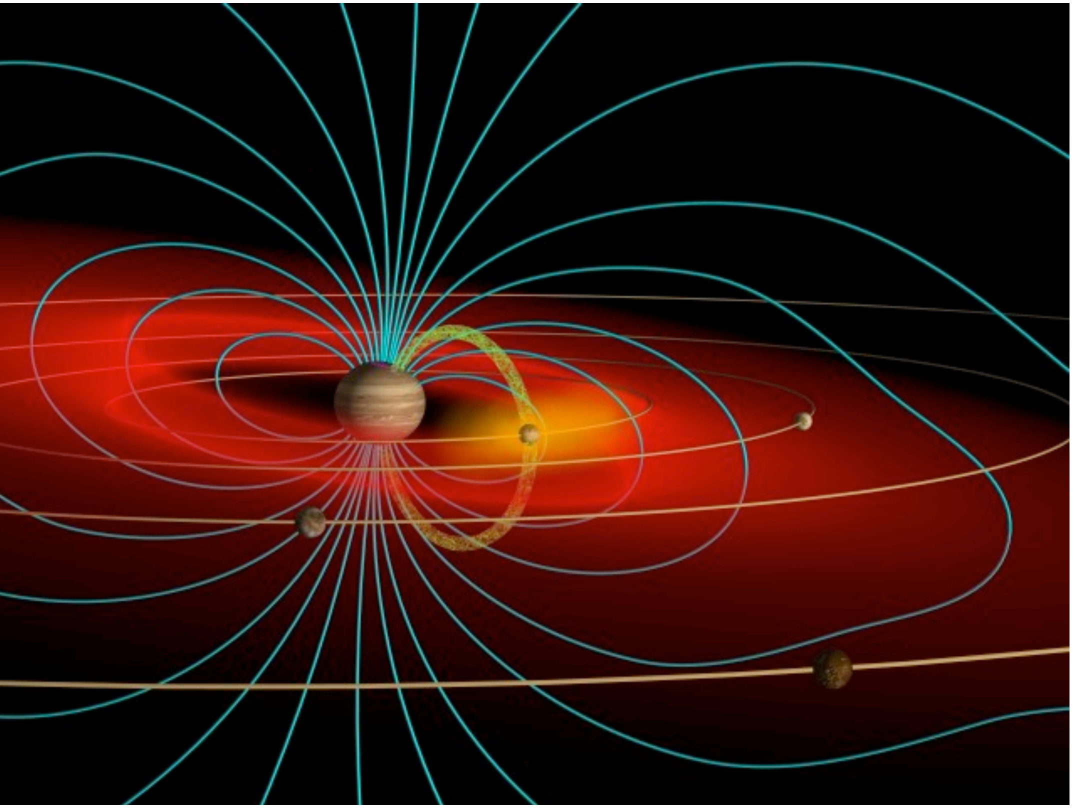


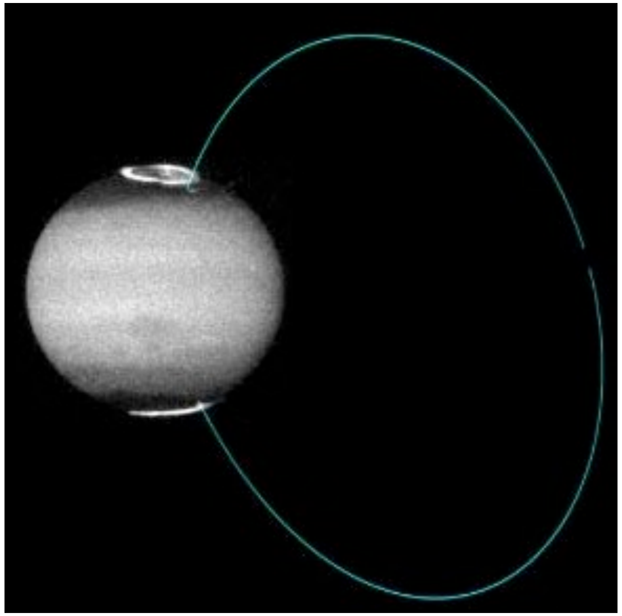
Io is surrounded by a cloud of sodium, potassium and oxygen (shown in yellow). In addition, Io's volcanoes continually expel large amounts of material into space. This material becomes ionised in Jupiter's magnetic field and forms a doughnut-shaped track around Io's orbit called the *Io Plasma Torus*.



Yellow haze of sodium surrounding Io; gas from two active volcanoes can also be seen.

As Io moves around its orbit in the strong magnetic field of Jupiter and through this plasma torus, a huge electrical current (1 million amps) is set up between Io and Jupiter in a cylinder of highly concentrated magnetic flux called the Io Flux Tube. It produces bursts of radio waves, as well as aurorae on Jupiter from the flux tube footprints.



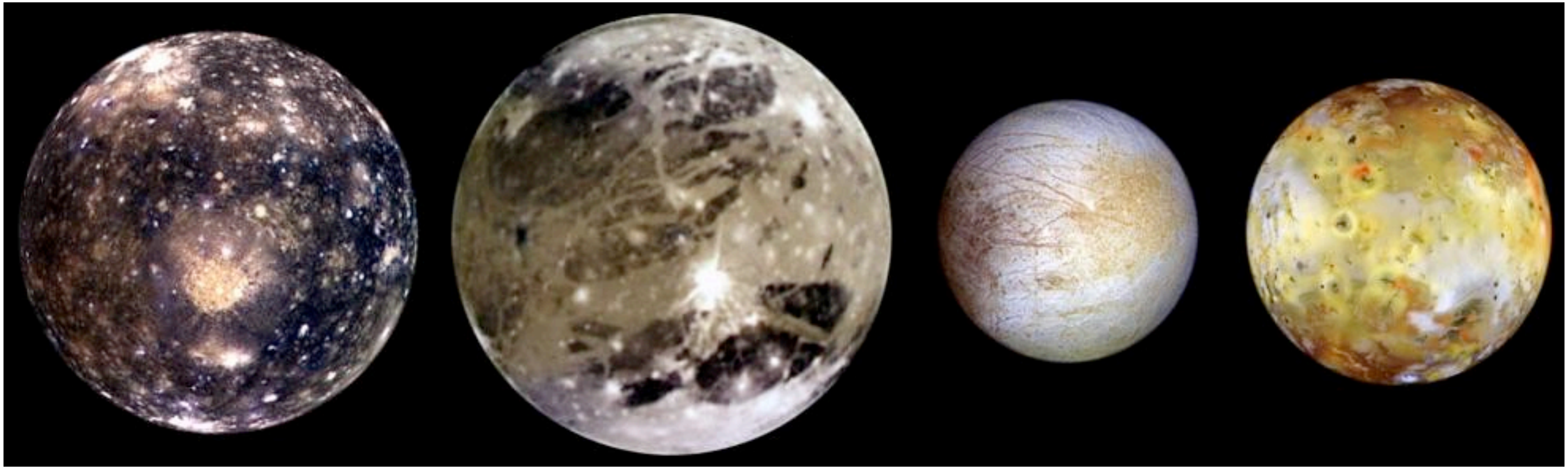


(left) Sketch of the Jovian magnetosphere, showing the sodium cloud and torus. (above) HST ultraviolet image showing a bright auroral spot where the Io flux tube intersects Jupiter's atmosphere.

"There's one lesson we learned from *Voyager*: Nature is much more inventive than our imaginations"

– Ed Stone, Voyager Project Scientist

The moons of Jupiter form a fascinating system of their own. Each is unique, but we can see some patterns.



closer to Jupiter →

denser →

rockier →

more active →


Next week
... we'll look at Saturn
– the real Lord of the Rings

Further reading

I had trouble finding a really good book about Jupiter and the Galileo mission.

- "**The Worlds of Galileo: The inside story of NASA's mission to Jupiter**" by Michael Hanlon (St Martin's Press, 2001) is not bad, but I found it a bit pedestrian, lacking the real excitement that some of the other books on the planets manage to convey.
- I stumbled across a very interesting book: "**Satellites of the Outer Planets: Worlds in their own right**" by David Rothery (Oxford UP, 1999). As the title implies, it looks at the satellites of all the outer planets together, looking at similar moons together, like the geologically active ones (Io, Europa, Triton) versus the "dead worlds" like Callisto or Umbriel. It's based on the Voyager missions, though in the second edition he's updated the book to include results from Galileo (I guess we'll have to wait for the third edition before he talks about the results from Cassini!). It's reasonably technical, but a wonderful book, and very helpful for seeing the patterns in the satellites which not many other books bring out.
- "**Unmasking Europa: the search for life on Jupiter's ocean moon**" by Richard Greenberg (Springer, 2008) is a book all about Europa, and in particular about the "thin ice" model. I found it an intensely irritating book: the tag-line on the back cover says "A close look at Europa, and how big science gets done", but a lot of the book comes across as a long whinge. Nonetheless, he's got lots of fascinating (and persuasive!) information, as well as lots of detailed images.
- A complete up-to-date list of all of Jupiter's satellites can be found at Scott Sheppard's "The Jupiter Satellite Page", http://www.dtm.ciw.edu/sheppard/satellites/
- There's a very good explanation of how tidal heating works for Io at "The Astro 150 Tidal Heating Tutorial", http://tobyrsmith.github.io/Astro150/Tutorials/TidalHeat/

- The Juno mission web page is at http://missionjuno.swri.edu/. The rather more pedestrian NASA page on the mission is at http://www.nasa.gov/mission_pages/juno/
- Emily Lakdawalla has an interesting discussion of the effects of radiation on the Pioneer and Voyager missions at http://www.planetary.org/blogs/emily-lakdawalla/2009/1871.html, as well as some musings on how many "what ifs" there are in planetary exploration!

Sources for images used:

- Jupiter title image: Cassini composite, with the shadow of Europa, PIA02873, from NASA Planetary Photo Journal, http://photojournal.jpl.nasa.gov/catalog/PIA02873
- Spacecraft images: from NASA Solar System Exploration: Spacecraft images http://solarsystem.nasa.gov/multimedia/gallery.cfm?Category=Spacecraft
- Jupiter barycentre: from NASA Space Place: What's a barycenter? http://spaceplace.nasa.gov/en/kids/barycntr.shtml
- All images of Jupiter and its moons are from the NASA Planetary Photo Journal, unless otherwise indicated. http://photojournal.jpl.nasa.gov/target/Jupiter
- Jupiter rotation movie: from Cassini images, PIA02863, from NASA Planetary Photo Journal, http://photojournal.jpl.nasa.gov/catalog/PIA02863
- Jupiter's composition: from Journey through the Galaxy: Jupiter, http://home.cwru.edu/~sjr16/advanced/jupiter.html
- Jupiter's interior: from Views of the Solar System by Calvin Hamilton, http://www.solarviews.com/cap/jup/jupint.htm
- Interior: from Lawrence Rudnick AST1001 http://webusers.astro.umn.edu/~larry/CLASS/AST1001/jupsat/Jupiter+Saturn.html
- Names of atmospheric features: from Sky and Telescope: A Jupiter Observing Guide, http://skyandtelescope.com/observing/objects/planets/article_174_1.asp
- Jupiter's changing face 2009–2015: from http://www.planetary.org/blogs/emily-lakdawalla/2015/jupiters-changing-face-2015.html
- Jupiter atmosphere structure; and Belts and zones: from Atmospheres of Jupiter and Saturn, http://zebu.uoregon.edu/~imamura/121/lecture-13/jupiter_atmosphere.html
- Jupiter's northern hemisphere in true and false colour: https://photojournal.jpl.nasa.gov/catalog/PIA00892 and https://photojournal.jpl.nasa.gov/catalog/PIA00893
- Jupiter's clouds from Cassini: from https://apod.nasa.gov/apod/ap050911.html
- Jupiter's bands of clouds from Juno: from https://www.missionjuno.swri.edu/news/jupiters-bands-of-clouds
- Storm and cloud heights: from Gierasch et al. 2000 "Observation of moist convection in Jupiter's atmosphere", Nature 403, p. 628.
- Pacific storm: photo by Santiago Borja, from National Geographic Nature Photographer of the Year 2016
  http://photography.nationalgeographic.com/nature-photographer-of-the-year-2016/gallery/winners-all/7
- Earth/Great Red Spot comparison: Wikipedia – Great Red Spot http://en.wikipedia.org/wiki/Great_Red_Spot
- Jupiter from Cassini: PIA 02852 http://photojournal.jpl.nasa.gov/catalog/PIA02852.
- Great Red Spot from Juno: http://www.planetary.org/multimedia/space-images/jupiter/jupiters-great-red-spot-from-juno-gill.html
- Shrinking Great Red Spot: STSci release STScI-2014-24 http://hubblesite.org/newscenter/archive/releases/2014/24/
- Motion of white ovals: from Galileo images, PIA01231, http://photojournal.jpl.nasa.gov/catalog/PIA01231
- Little Red Spot: Hubble Site News Release 2006-19 http://hubblesite.org/newscenter/archive/releases/2006/19/
- Red Spot Jr from Gemini: Gemini release 20 July 2006 http://www.gemini.edu/index.php?option=content&task=view&id=196
- Jupiter's south pole: from https://www.nasa.gov/press-release/a-whole-new-jupiter-first-science-results-from-nasa-s-juno-mission
- Jupiter's magnetosphere: from https://apod.nasa.gov/apod/ap160406.html
- Montage of Jupiter's moons: from "Views of the Solar System" by Calvin Hamilton, http://www.solarviews.com/cap/jup/jupsystm.htm
- Europa and Callisto in front of Jupiter from Cassini: from APOD http://apod.nasa.gov/apod/ap010102.html
- Satellite orbits: from The Jupiter Satellite Page by Scott Sheppard, http://www.dtm.ciw.edu/sheppard/satellites/
- Jupiter's rings from Galileo: from APOD http://apod.nasa.gov/apod/ap080106.html
- Jupiter's ring components: http://photojournal.jpl.nasa.gov/catalog/PIA01627
- Ring-shepherding satellites: http://photojournal.jpl.nasa.gov/catalog/PIA01624

- The Galilean moons; from Views of the Solar System by Calvin Hamilton, http://www.solarviews.com/cap/jup/jupmoon.htm
- Callisto cutaway: http://photojournal.jpl.nasa.gov/catalog/PIA01478
- Vallhalla antipode: http://photojournal.jpl.nasa.gov/catalog/PIA02593
- Callisto from Voyager: http://photojournal.jpl.nasa.gov/catalog/PIA02253
- Callisto from Voyager 1 showing Valhalla: http://photojournal.jpl.nasa.gov/catalog/PIA00080
- Scarps: http://photojournal.jpl.nasa.gov/catalog/PIA00561 and spires http://photojournal.jpl.nasa.gov/catalog/PIA03455
- Crater chain on Callisto: from NEO program: Images of impact crater chains on Calliso, http://neo.jpl.nasa.gov/images/callisto.html
- Ganymede: http://photojournal.jpl.nasa.gov/catalog/PIA00716
- Ganymede cutaway: http://photojournal.jpl.nasa.gov/catalog/PIA00519
- Ganymede terrain: http://photojournal.jpl.nasa.gov/catalog/PIA00706
- Dark terrain craters: http://photojournal.jpl.nasa.gov/catalog/PIA02571
- Palimpsest crater: http://photojournal.jpl.nasa.gov/catalog/PIA01659
- Bright terrain: http://photojournal.jpl.nasa.gov/catalog/PIA01618
- Fractures in Nicholson Regio: http://photojournal.jpl.nasa.gov/catalog/PIA01613
- Overlapping belts http://photojournal.jpl.nasa.gov/catalog/PIA01615
- Tectonic features in Marius Regio: http://photojournal.jpl.nasa.gov/catalog/PIA01091
- Europa: http://photojournal.jpl.nasa.gov/catalog/PIA00502
- Europa from Voyager: http://photojournal.jpl.nasa.gov/catalog/PIA01970. Pwyll crater: http://photojournal.jpl.nasa.gov/catalog/PIA01661
- Europa rising: New Horizons mission photos http://pluto.jhuapl.edu/gallery/missionPhotos/pages/050107/050107_01.html
- Subsurface structure: http://photojournal.jpl.nasa.gov/catalog/PIA01669
- Tides on Europa: Planetary Photojournal http://photojournal.jpl.nasa.gov/catalog/PIA10149
- Thick or thin ice: Planetary Photojournal http://photojournal.jpl.nasa.gov/catalog/PIA10131
- Red linear features: http://photojournal.jpl.nasa.gov/catalog/PIA10149
- Double ridges: http://photojournal.jpl.nasa.gov/catalog/PIA01664
- Fissure eruptions: from USGS Photo glossary: fissure eruptions, http://volcanoes.usgs.gov/Products/Pglossary/FissureEruption_examps.html; and Howstuffworks: How volcanoes work, http://science.howstuffworks.com/volcano4.htm
- Brown ridges: http://photojournal.jpl.nasa.gov/catalog/PIA01641
- Thera and Thrace: http://photojournal.jpl.nasa.gov/catalog/PIA02099
- Conamara Chaos: http://photojournal.jpl.nasa.gov/catalog/PIA01403. Terrestrial ice floes: from Sea Ice by Nico Gray, http://www.ma.man.ac.uk/~ngray/Seaice/Seaice.html
- Pack ice in Labrador: from “Extreme ice on Canada's east coast”, https://www.theguardian.com/environment/gallery/2017/jul/04/extreme-ice-on-canada-east-coast-in-pictures
- Sub-surface lake: from http://www.jsg.utexas.edu/news/2011/11/scientists-find-evidence-for-great-lake-on-europa/
- Cycloid features: from Hoppa et al. 1999, images at http://pirlwww.lpl.arizona.edu/~hoppa/science.html
- Artist’s impression of JUICE at Jupiter: http://www.planetary.org/multimedia/space-images/spacecraft/juice-at-jupiter.html

- Io: http://photojournal.jpl.nasa.gov/catalog/PIA02308
- Plumes over Pilan Patera: http://photojournal.jpl.nasa.gov/catalog/PIA01081
- Io interior: http://photojournal.jpl.nasa.gov/catalog/PIA01129
- Rotating Io: from Astronomy 161: The Solar System – The Moon Io, http://csep10.phys.utk.edu/astr161/lect/jovian_moons/io.html
- Masubi: http://photojournal.jpl.nasa.gov/catalog/PIA02502; Loki http://photojournal.jpl.nasa.gov/catalog/PIA00010; Pele http://photojournal.jpl.nasa.gov/catalog/PIA00323
- Pele hemisphere http://photojournal.jpl.nasa.gov/catalog/PIA00718
- Eruption at Tvashtar Catena: http://photojournal.jpl.nasa.gov/catalog/PIA02550
- Volcanism on Io: Robert Nowack EAS 105–The Planets, lecture 17 http://web.ics.purdue.edu/~nowack/geos105/lect17-dir/lecture17.htm
- Mountains on Io: http://photojournal.jpl.nasa.gov/catalog/PIA03600 and http://photojournal.jpl.nasa.gov/catalog/PIA03886
- New Horizons images of Io: from New Horizons mission photos https://www.nasa.gov/mission_pages/newhorizons/news/jupiter_images.html
- Io sodium cloud: http://photojournal.jpl.nasa.gov/catalog/PIA01111
- Io sulfur torus: from John Spencer's Astronomical Visualizations, http://www.boulder.swri.edu/~spencer/digipics.html
- Cassini's Millennium image of Io in front of Jupiter: http://apod.nasa.gov/apod/ap020706.html
- The Galilean satellites: http://photojournal.jpl.nasa.gov/catalog/PIA01400