



Modern Astronomy: Voyage to the Planets

Lecture 6

Jupiter and its moons

University of Sydney
Centre for Continuing Education
Spring 2011

Comette family home damaged by egg-sized meteorite

Meteorite believed to be more than 4bn years old smashes through roof of home on outskirts of Paris

Kim Willsher in Paris

guardian.co.uk, Monday 10 October 2011 15.32 BST

A [larger](#) | [smaller](#)



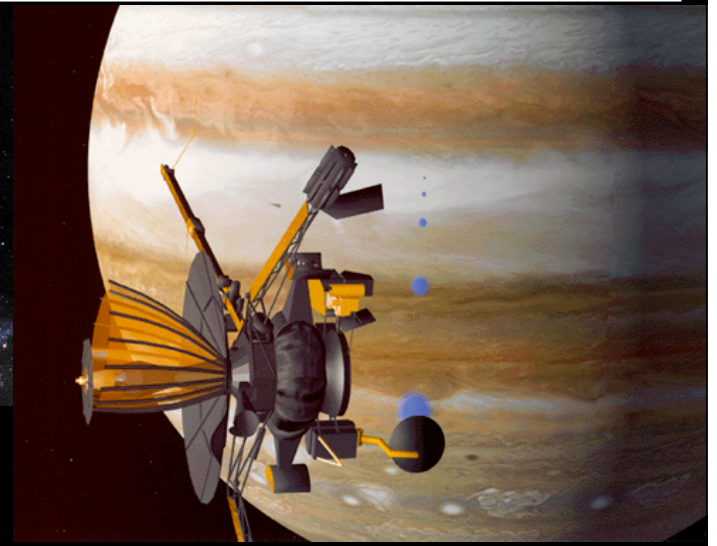
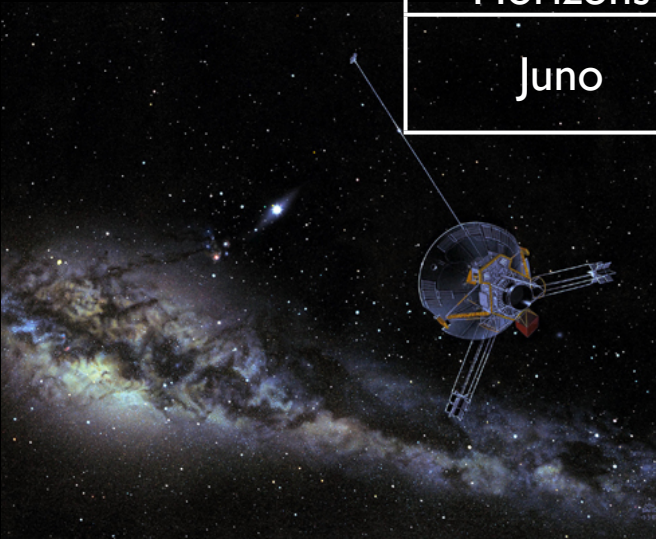
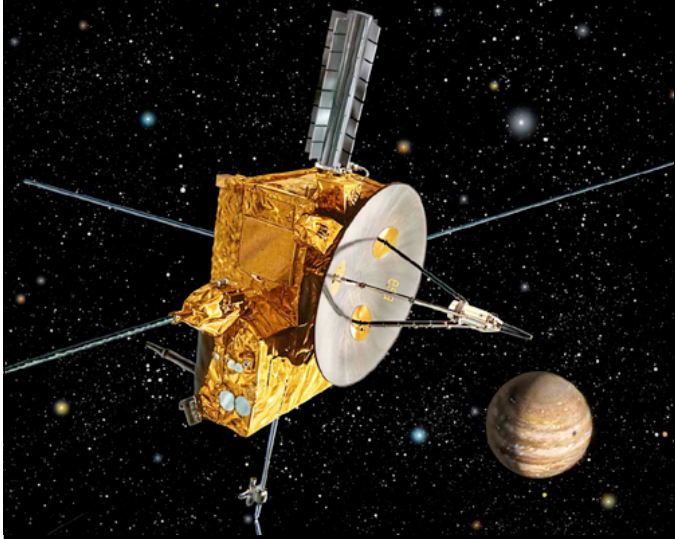
The meteorite which hit the Comette family home is thought to have come from the asteroid belt between Mars and Jupiter. Photograph: Nasa/EPA

When your name is Comette you may get used to jokes about rockets and space and planets. But French schoolboy Hugo Comette, 11, had the last laugh when of all the places, in all the countries on Earth, a piece of rock from outer space landed on his home.

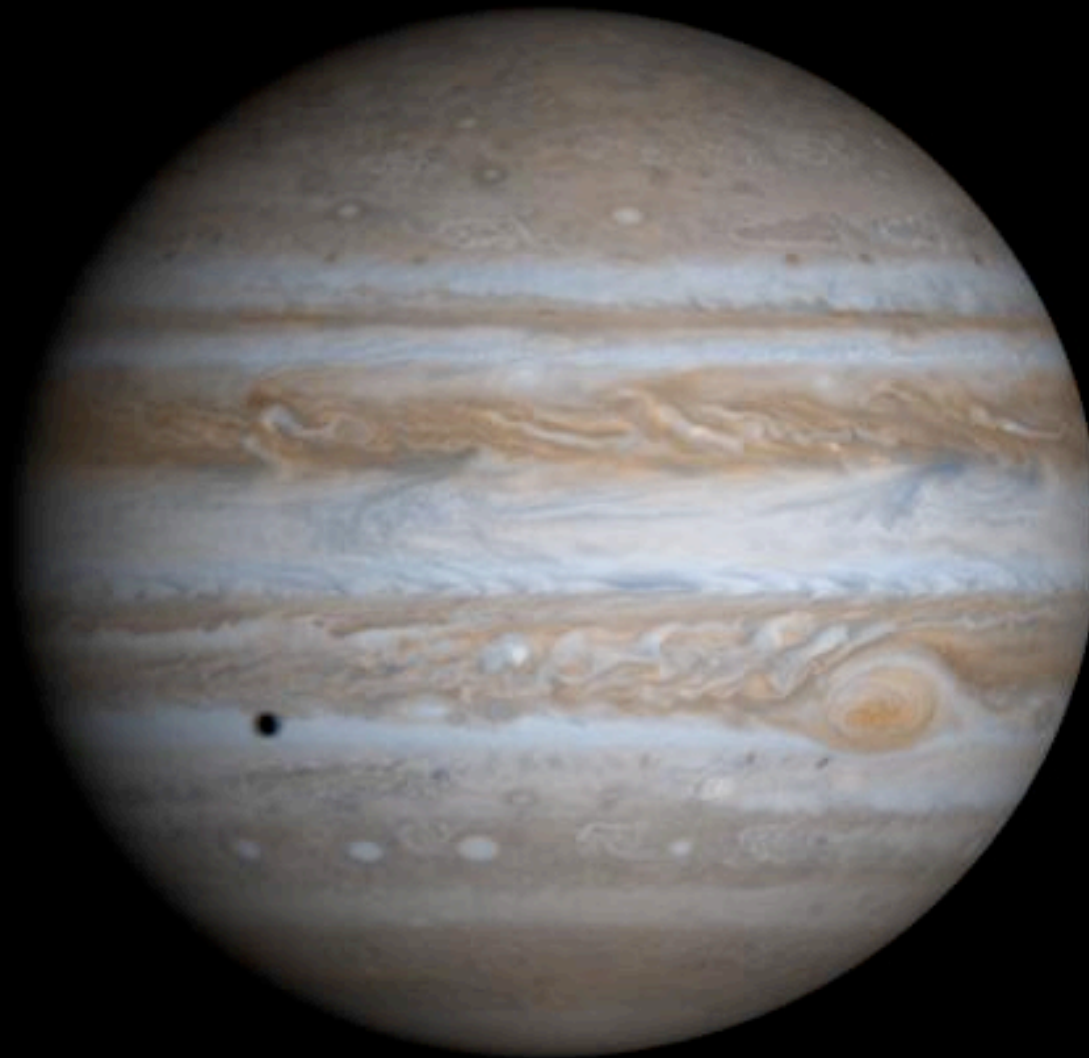
An egg-sized meteorite believed to be 4.57bn years old smashed through the roof of the Comette family home on the outskirts of Paris some time over the summer when

There have been six spacecraft which performed flybys of Jupiter, and one – *Galileo* – which orbited Jupiter for eight years. *Juno* was launched this year and will arrive in 2016.

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



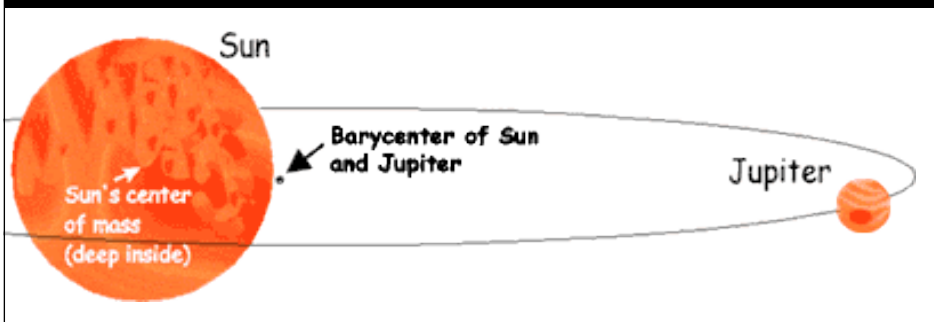
Basic facts

	Jupiter	Jupiter/Earth
Mass	$1899 \times 10^{24} \text{ kg}$	317.83
Radius	71,492 km	11.21
Mean density	1.326 g/cm^3	0.240
Gravity (eq., 1 bar)	24.79 m/s^2	2.530
Semi-major axis	$778.57 \times 10^6 \text{ km}$	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
Length of day	9.9259 h	0.414

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).



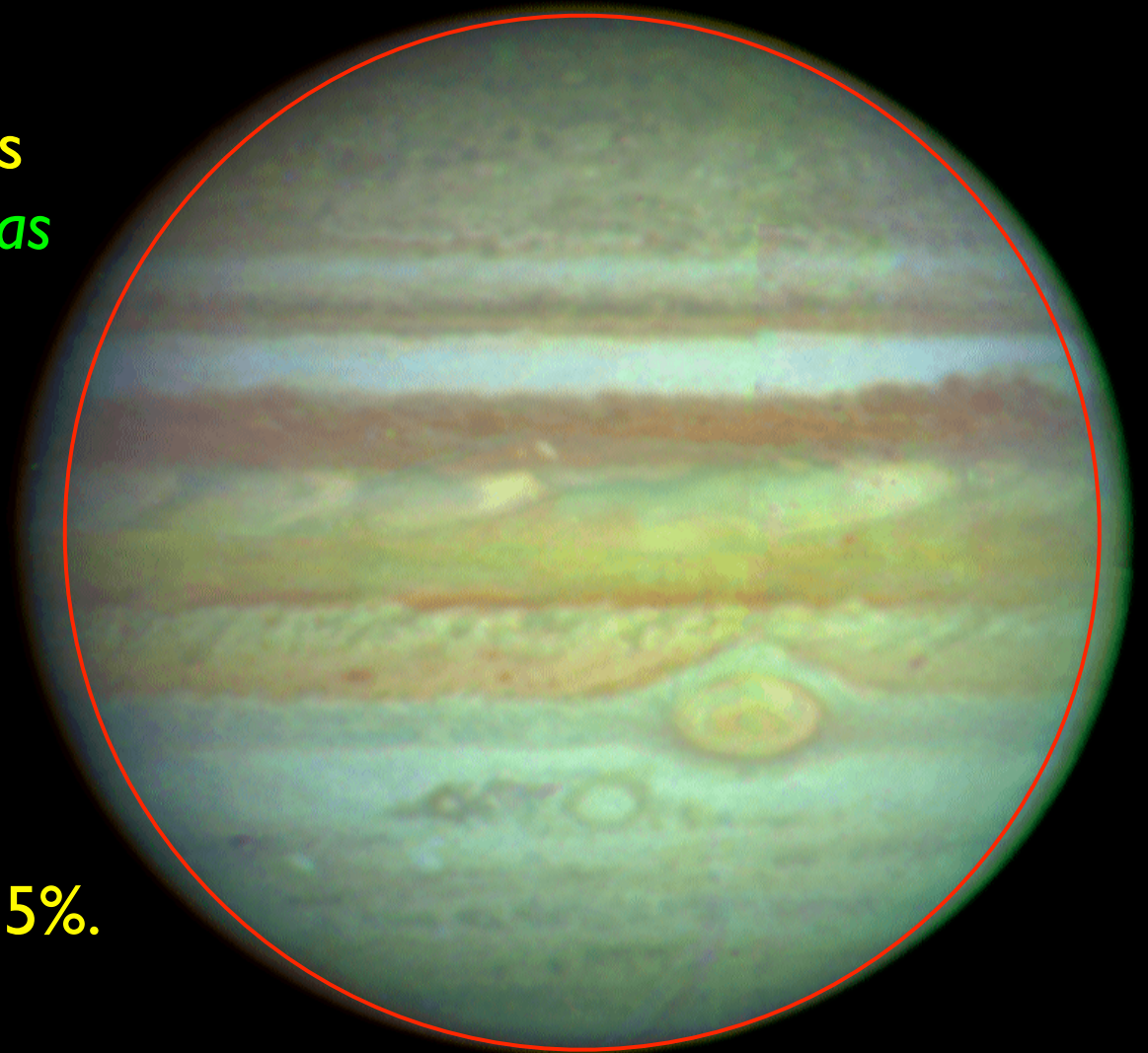
True colour picture of Jupiter, taken by Cassini on its way to Saturn during closest approach. The smallest features visible are only 60 km across.



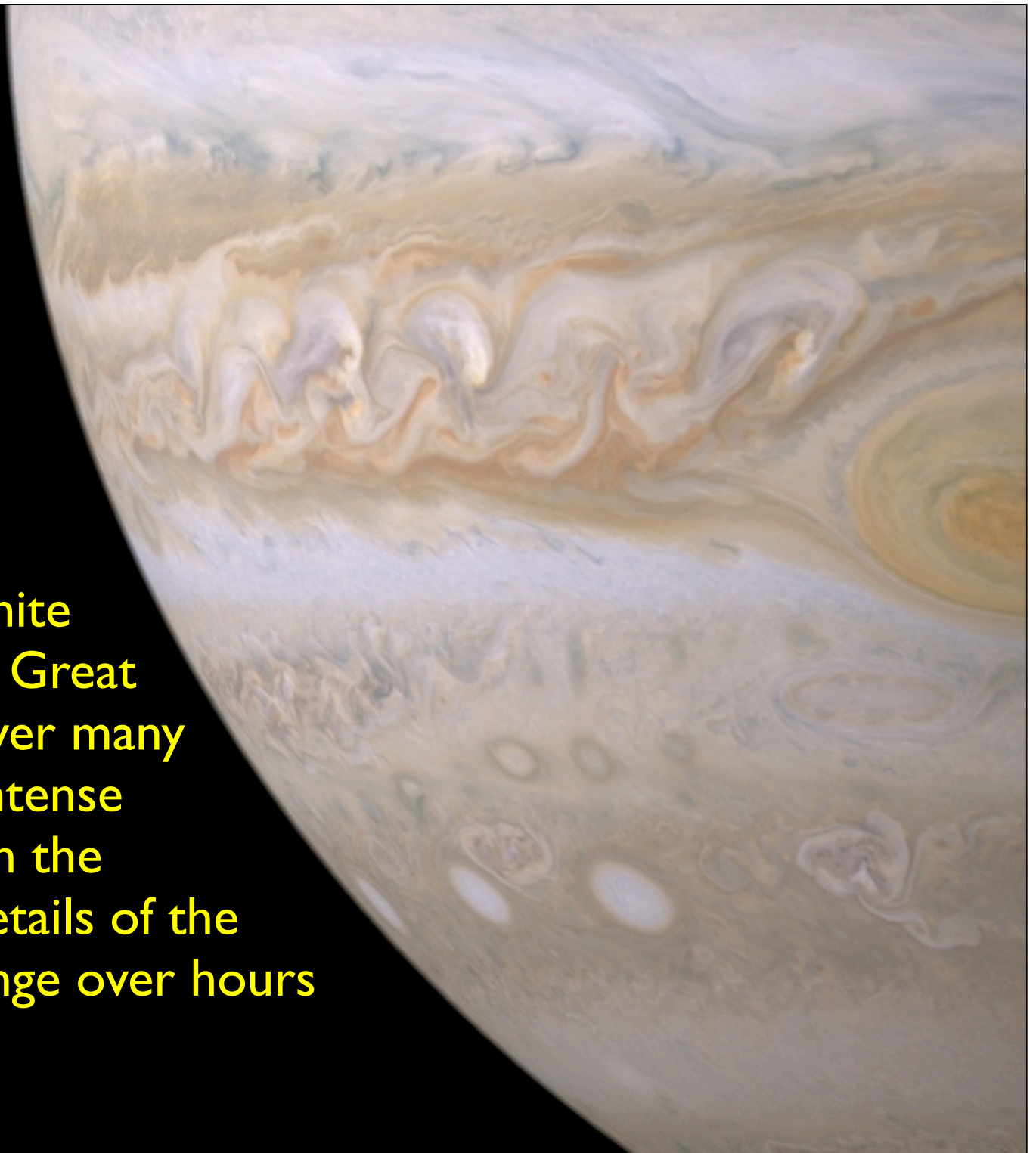
Jupiter exhibits *differential rotation* – the rotational period depends on latitude, with the equatorial zones rotating a little faster (9h 50m period) than the higher latitudes (9h 55m period).

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%.



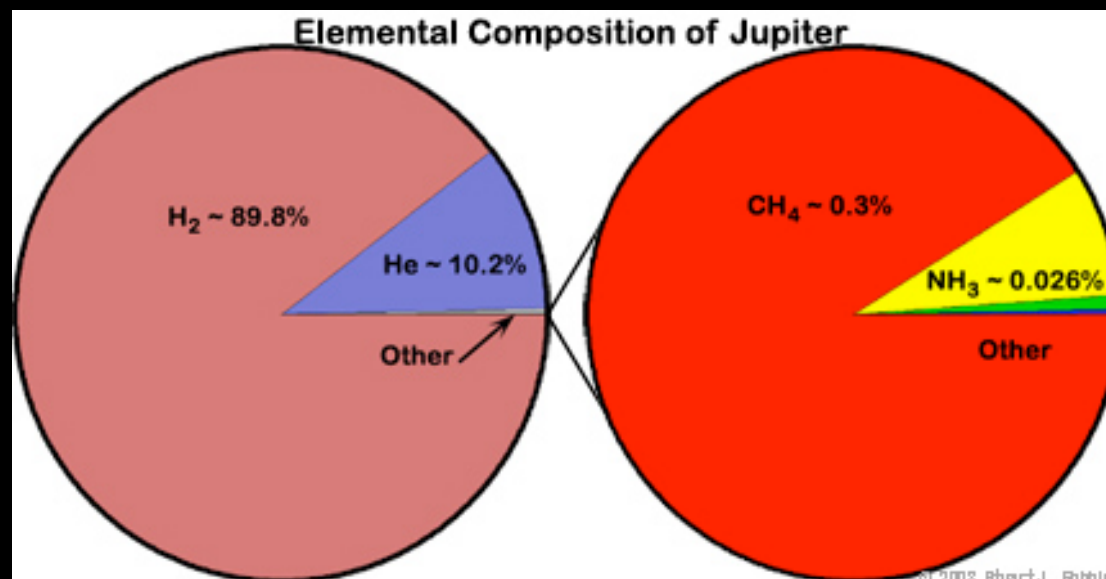
Everything visible on the planet is a cloud. The parallel reddish-brown and white bands, the white ovals, and the large Great Red Spot persist over many years despite the intense turbulence visible in the atmosphere. The details of the cloud patterns change over hours or days.



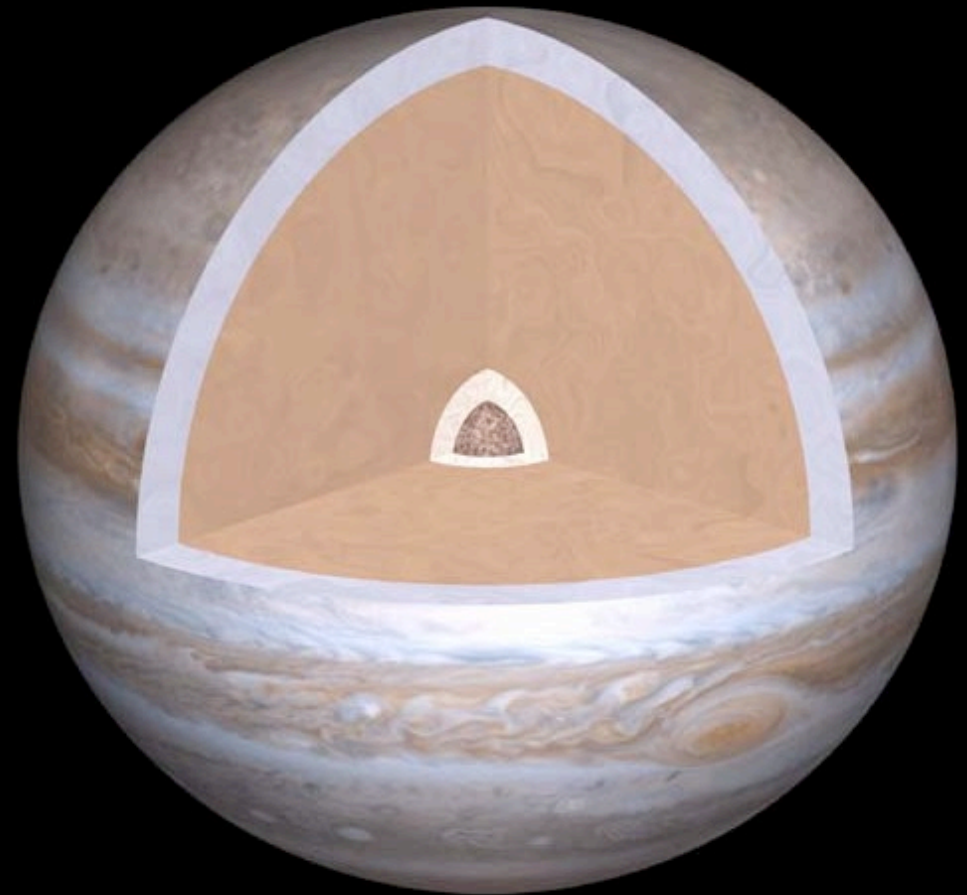
Like the other gas giants, Jupiter does not have solid surface. Its gaseous material simply gets denser with depth. What we see when looking at these planets is the tops of clouds high in their atmospheres (slightly above the 1 atmosphere level).



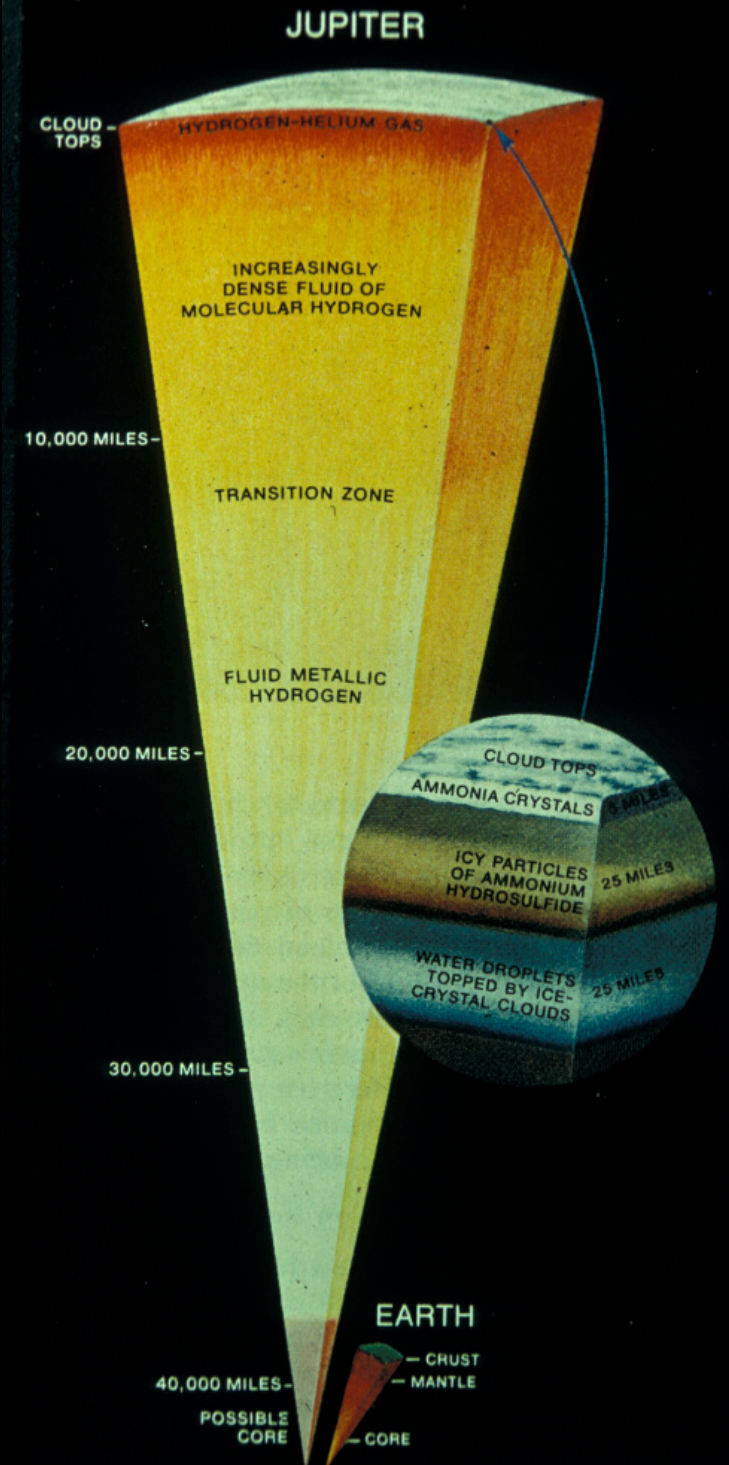
Jupiter consists of 90% hydrogen, 10% helium, very similar to the composition of the Sun, with trace amounts of methane, water, ammonia, and hydrogen sulphide. The colours in the clouds arise from various minor constituents of the atmosphere, probably sulphur and phosphorus, and possibly even sophisticated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

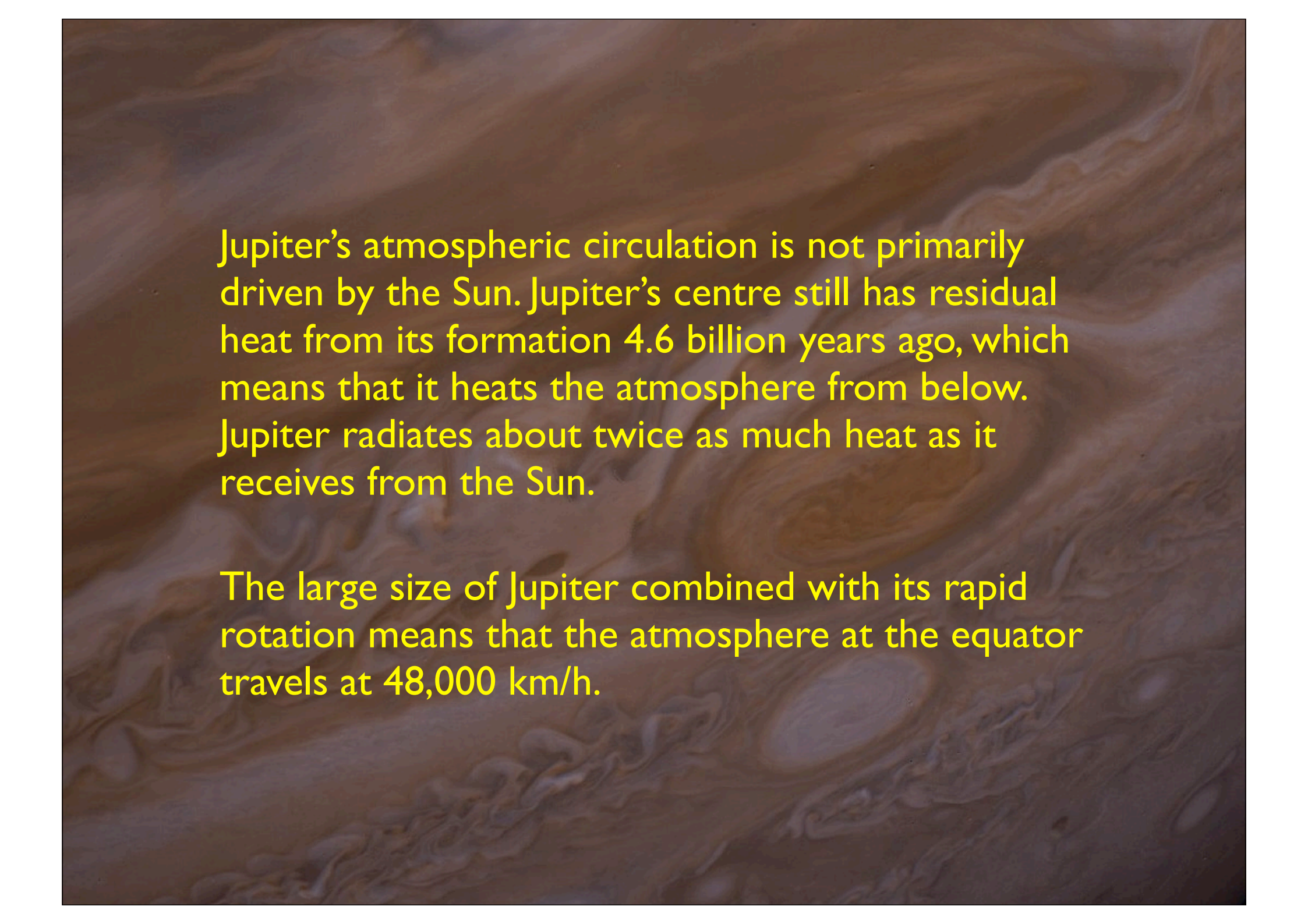


The mean density of Jupiter is 1326 kg/m^3 , less than a quarter the density of Earth, which implies the atmosphere must be very deep, possibly the entire planet. Jupiter probably contains a rocky core, about 10–15 Earth masses.



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.

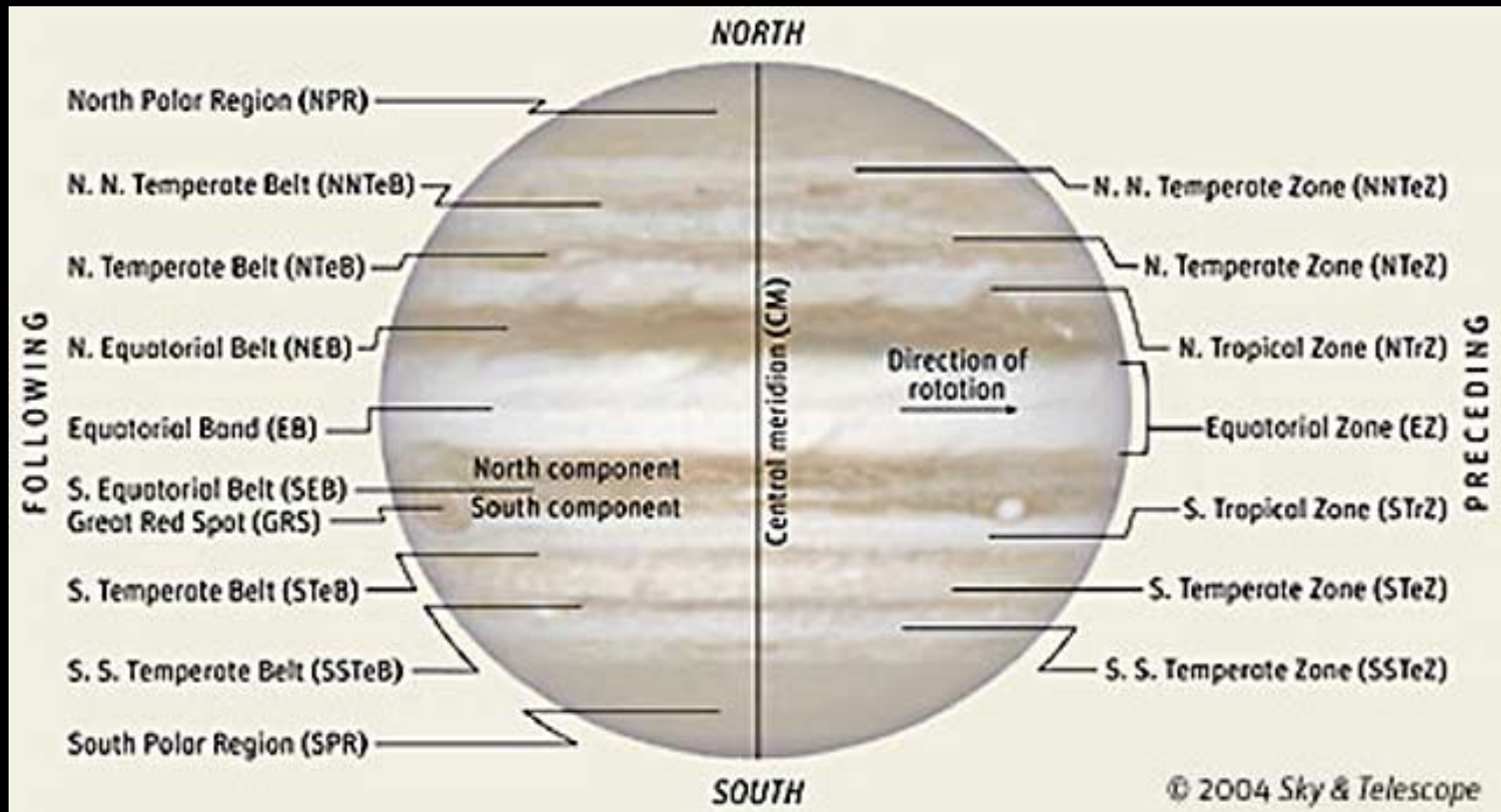




Jupiter's atmospheric circulation is not primarily driven by the Sun. Jupiter's centre still has residual heat from its formation 4.6 billion years ago, which means that it heats the atmosphere from below. Jupiter radiates about twice as much heat as it receives from the Sun.

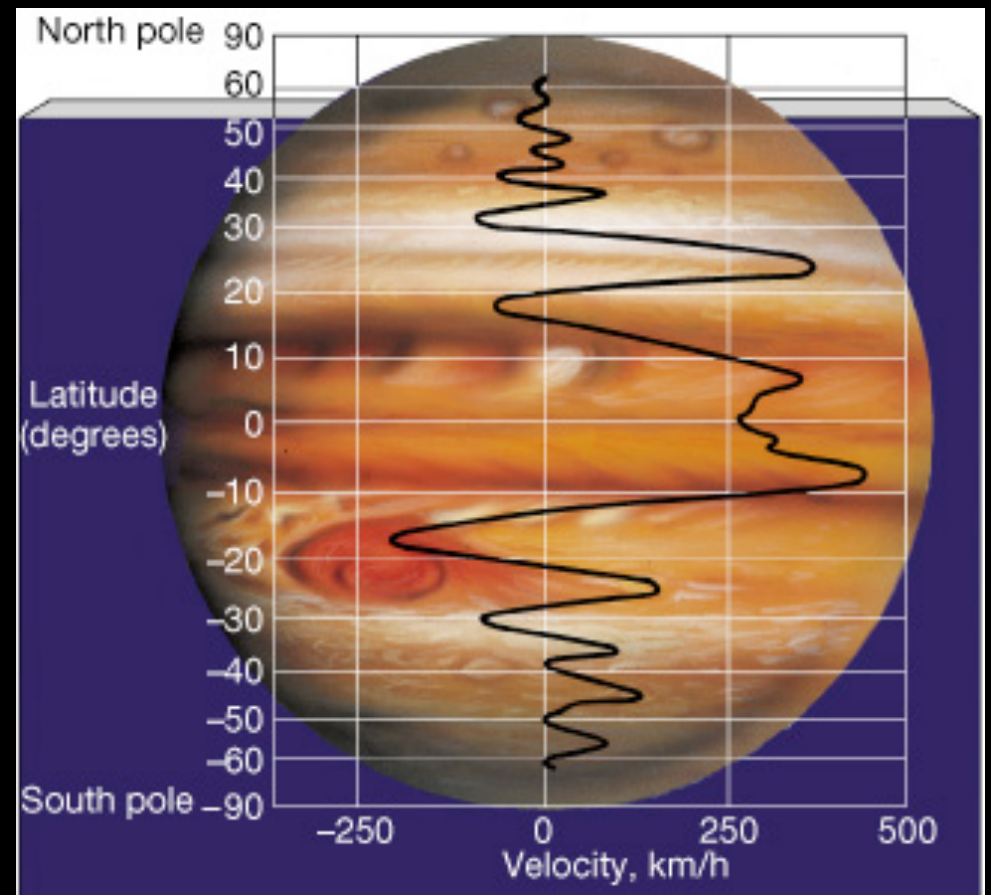
The large size of Jupiter combined with its rapid rotation means that the atmosphere at the equator travels at 48,000 km/h.

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*.

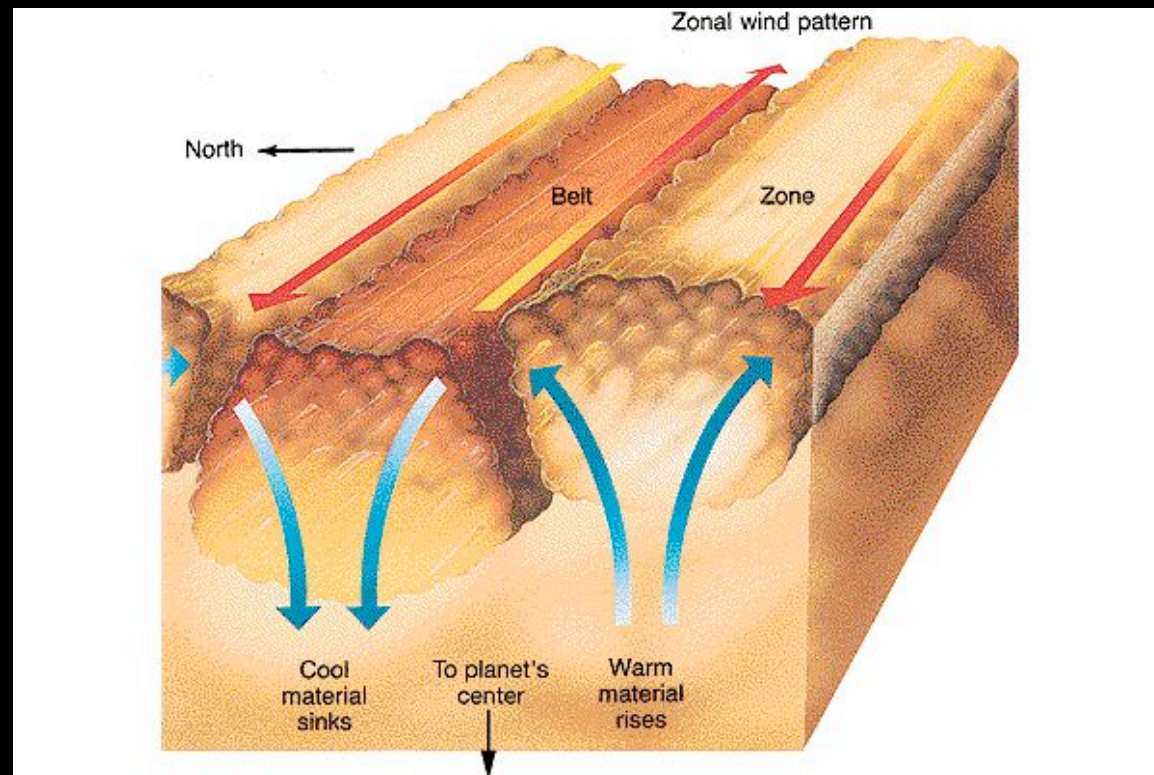


The equatorial regions of the atmosphere rotate faster than the planet, with an average flow speed of some 85 m/s, or about 300 km/h, in the easterly direction. Further away from the equator, there are alternating streams of westward and eastward flow, with the speed diminishing toward the poles.

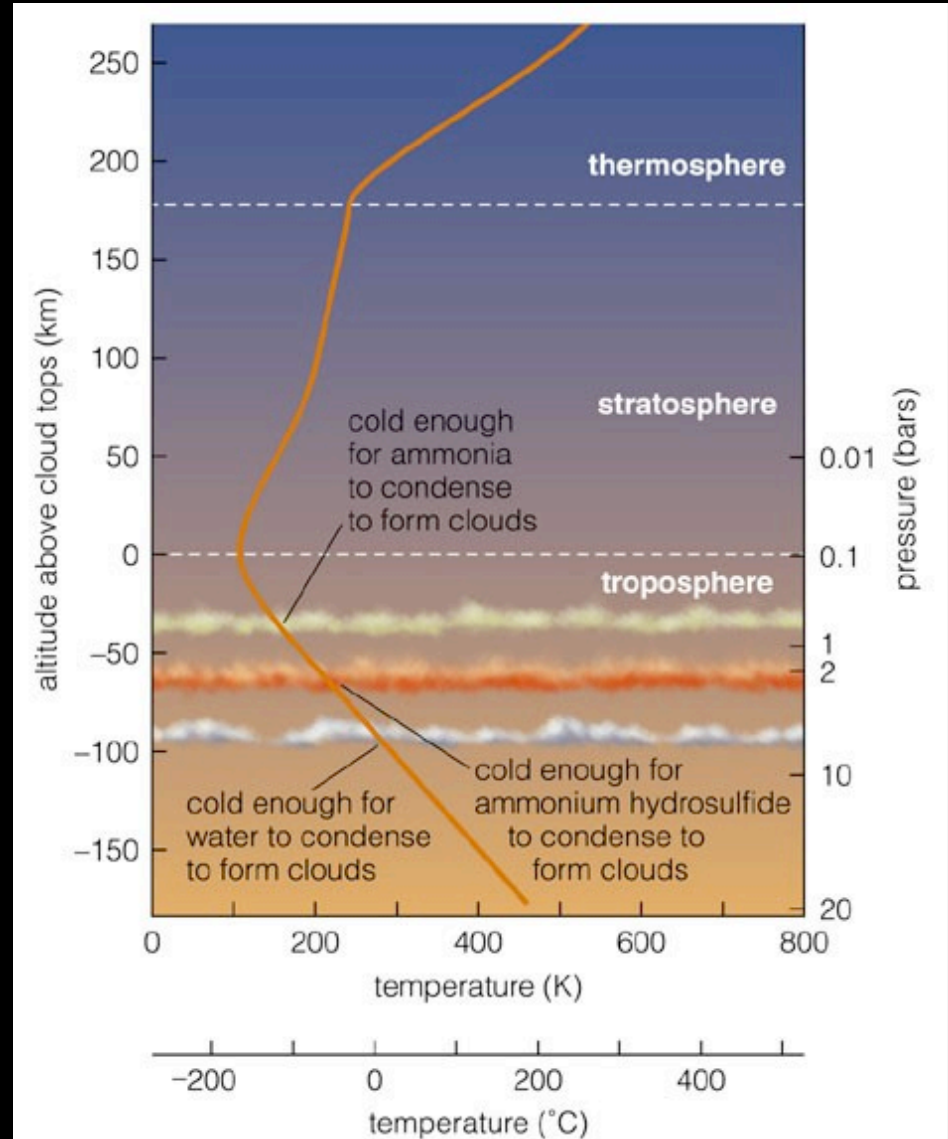
Wind speed measured relative to Jupiter's internal rotation. Changes in wind direction are associated with the atmospheric band structure.



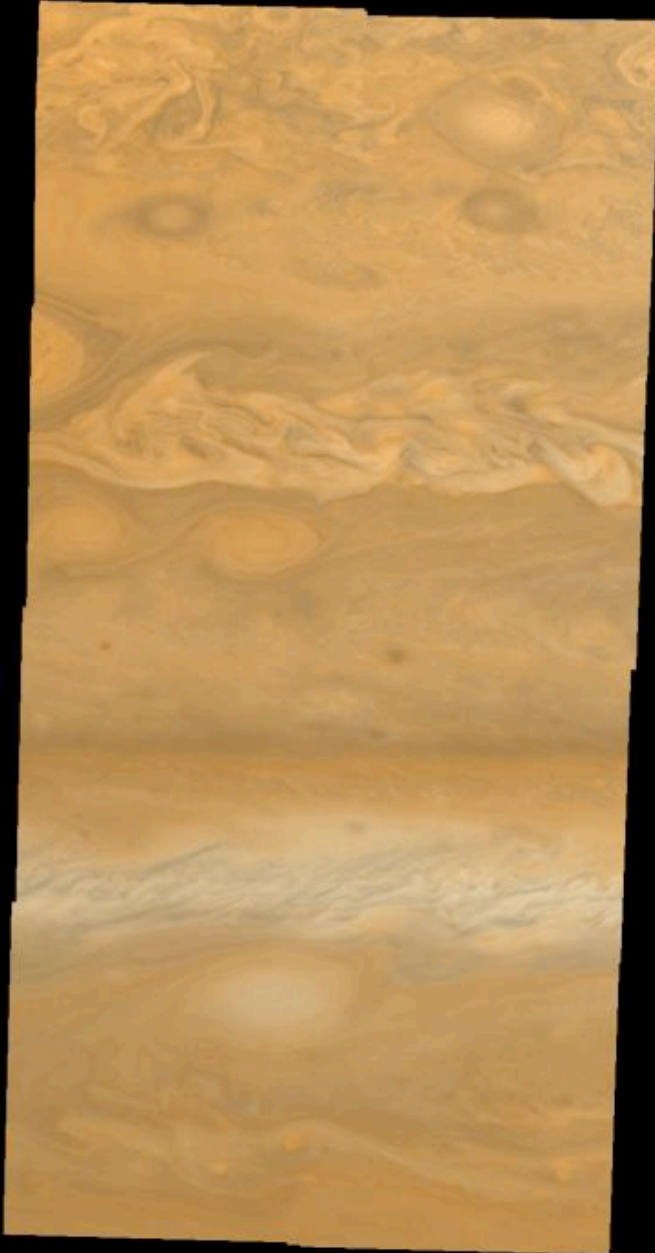
The bright zones represent material rising, the dark belts material sinking. Jupiter's rapid rotation is responsible for it having so many more circulation cells than Earth's atmosphere.



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.

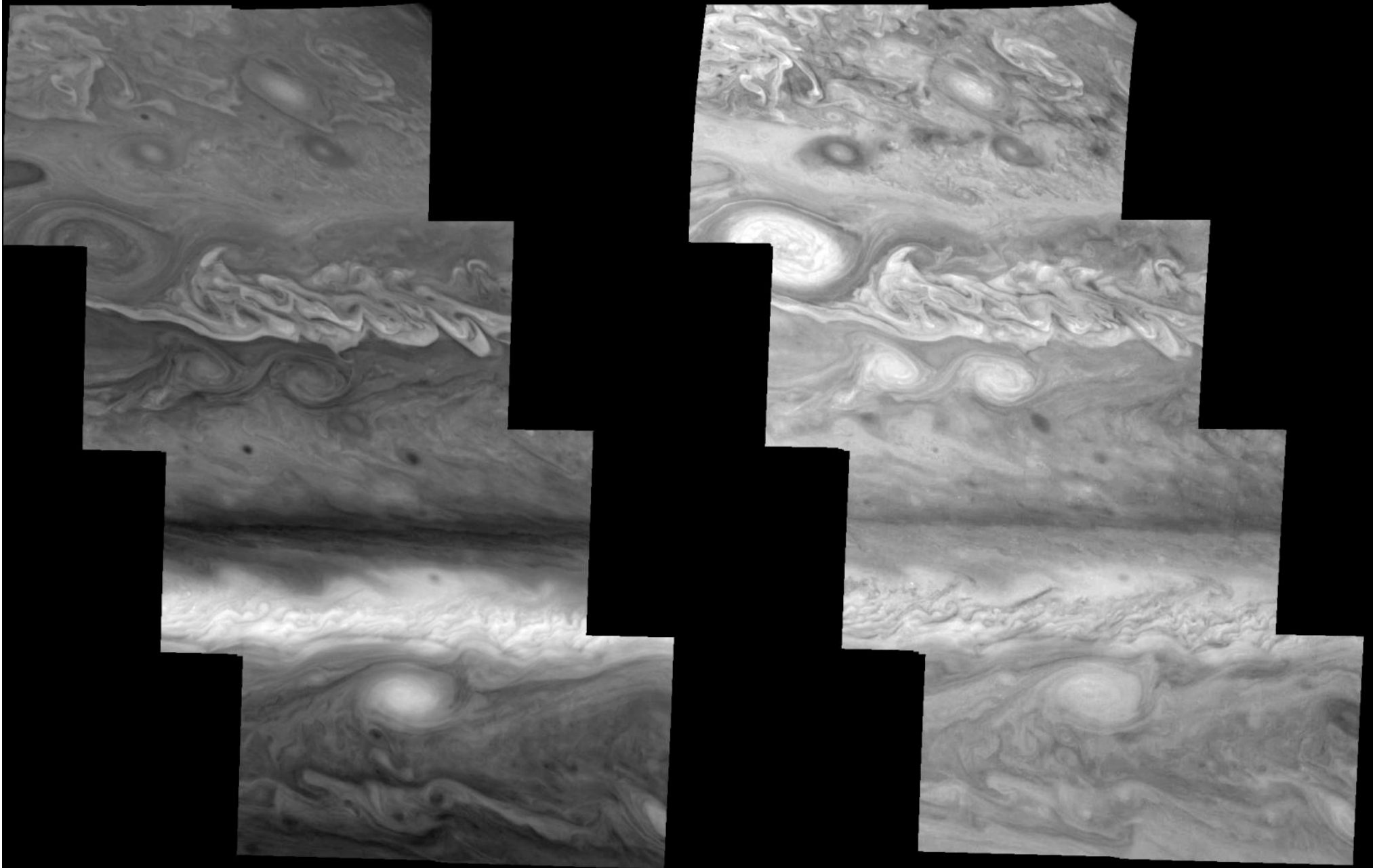


Winds in adjacent bands blow in opposite directions,
and turbulence builds up at the interface.

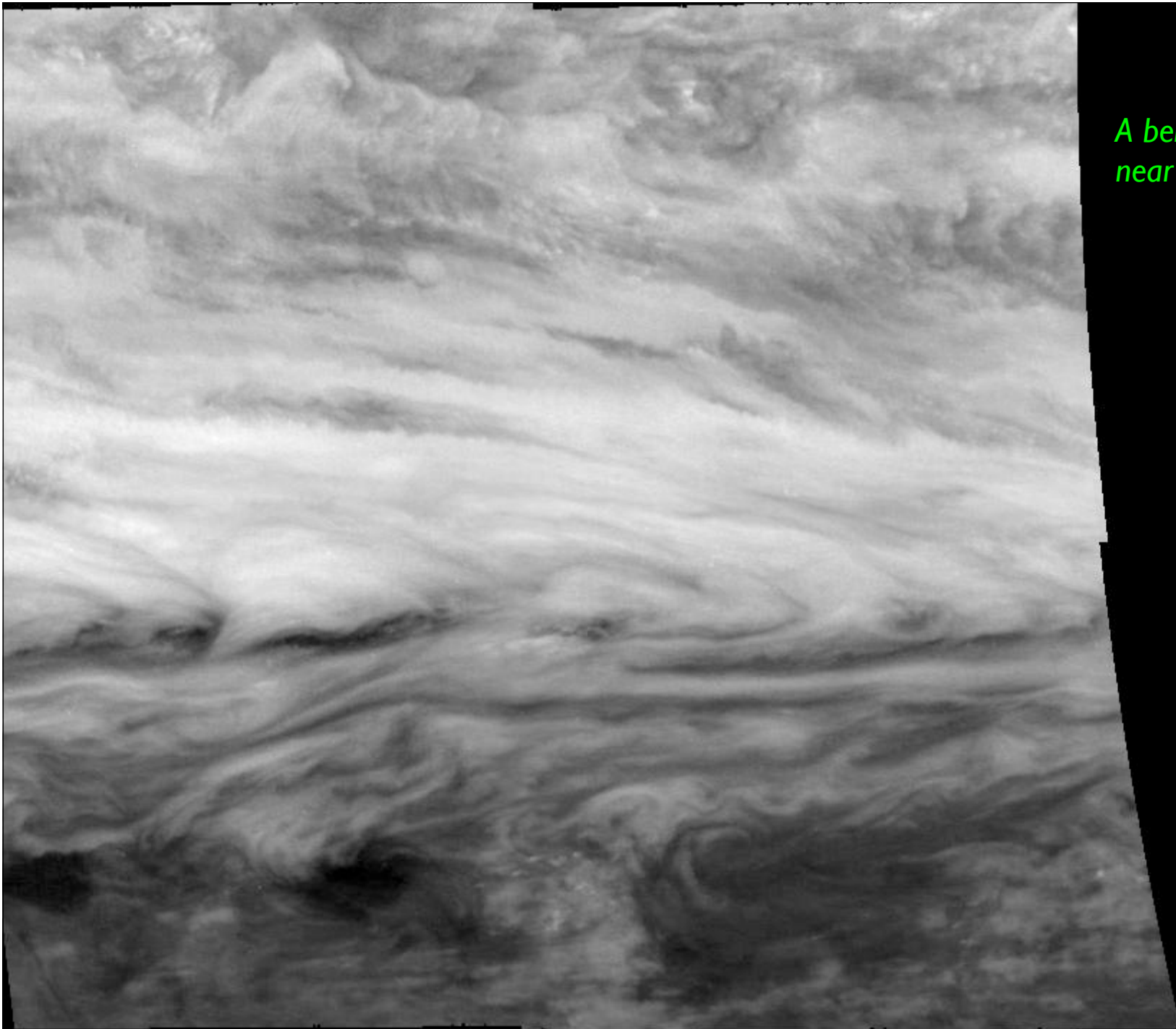


True colour (left) and false colour
infrared (right) images of part of
the northern hemisphere, taken
by Galileo.

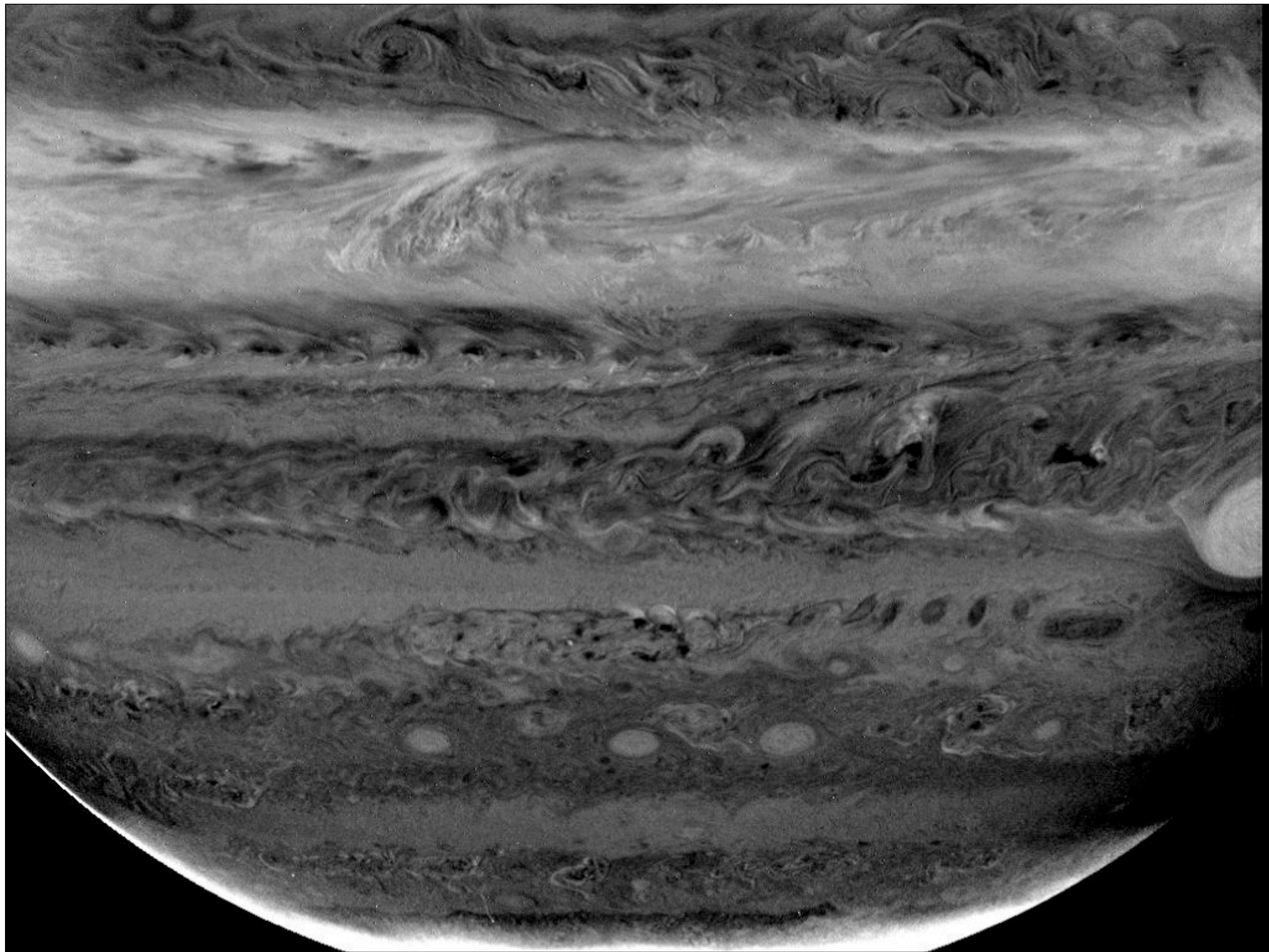




Jupiter's northern hemisphere in violet light (left) and a methane band in the near-infrared (right). The smallest resolved features are tens of kilometres in size

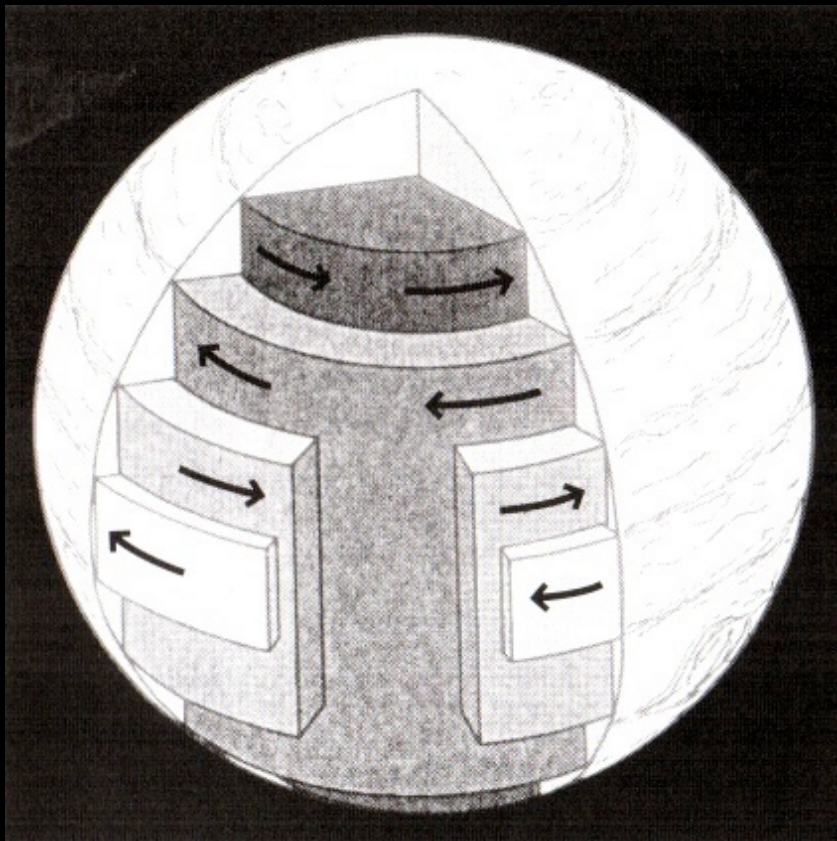


*A belt-zone boundary
near the equator.*



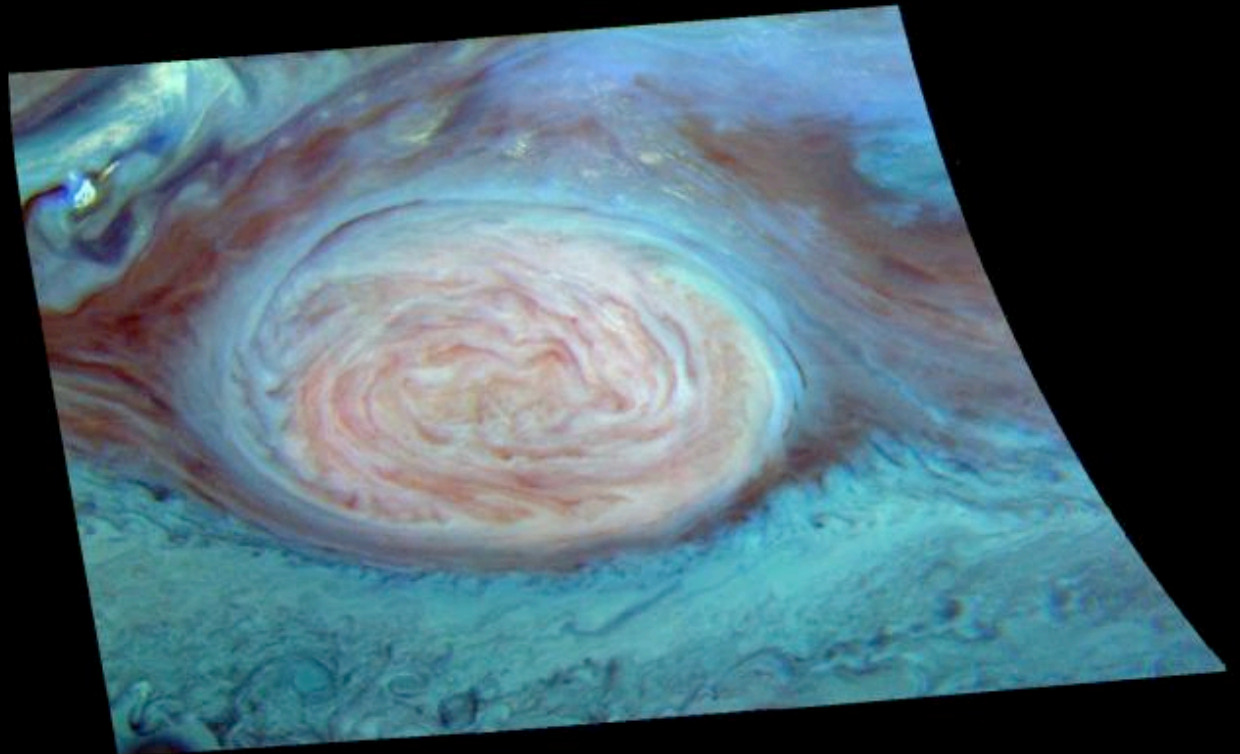
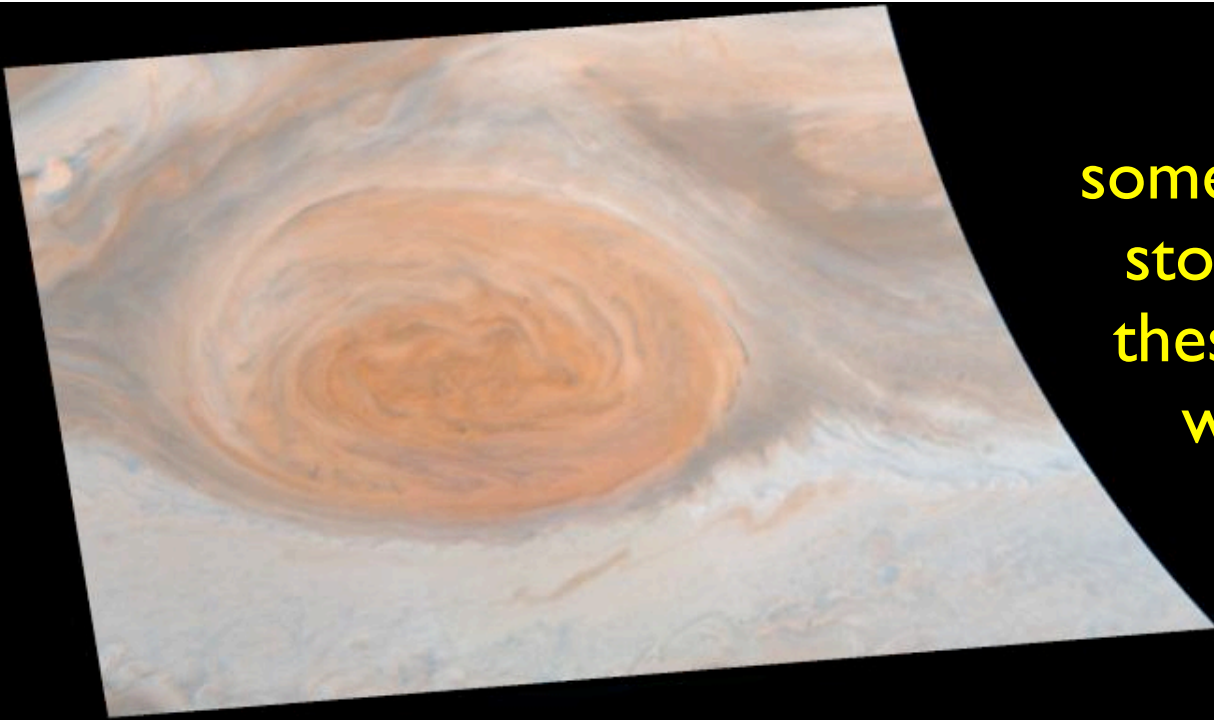


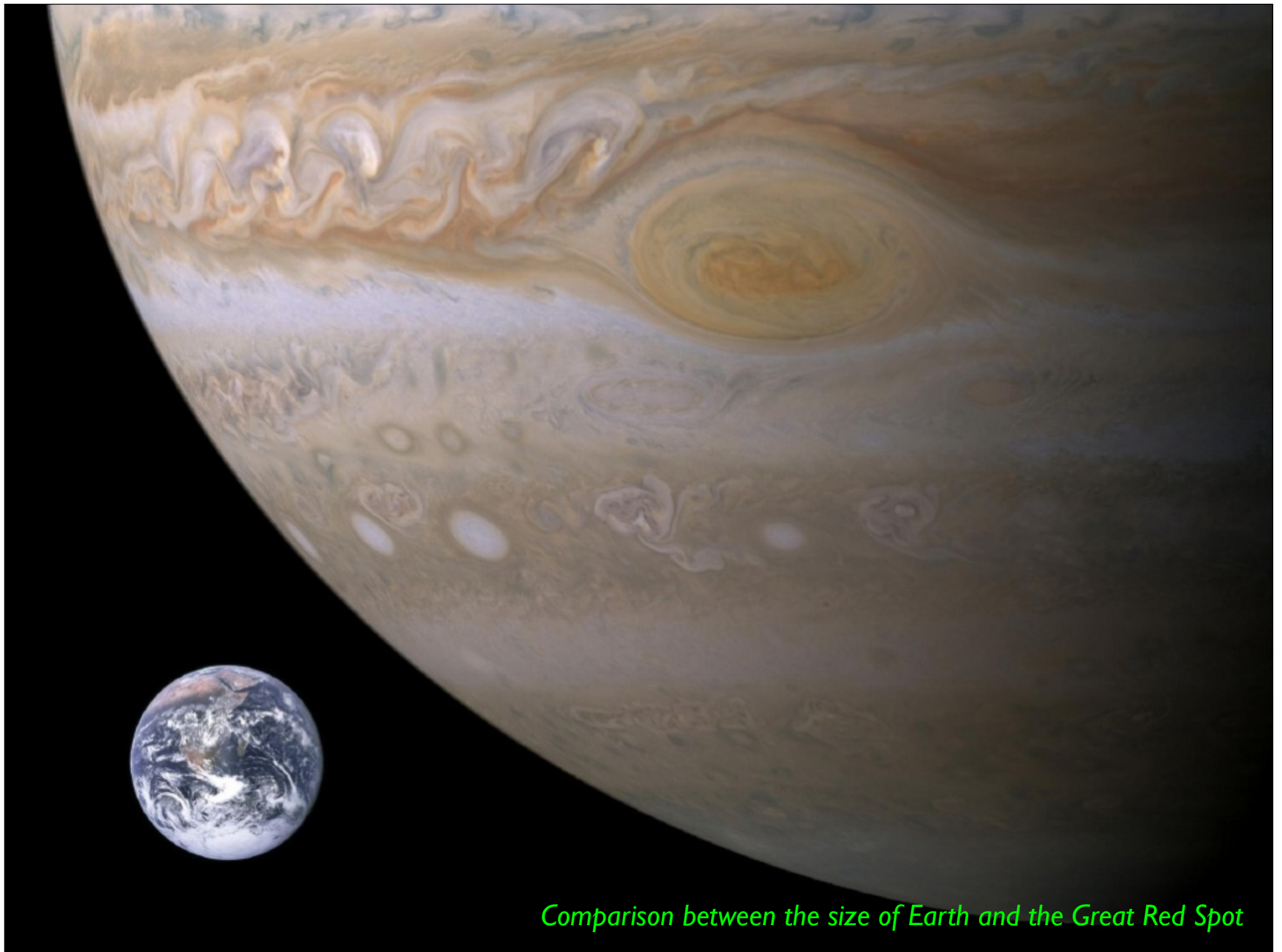
The depth to which the winds extend is not clear. They might be restricted to a thin weather layer, like on Earth; or they may extend deep into the atmosphere. One suggestion is that the interior might rotate as a series of concentric cylinders, each rotating at its own speed.



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

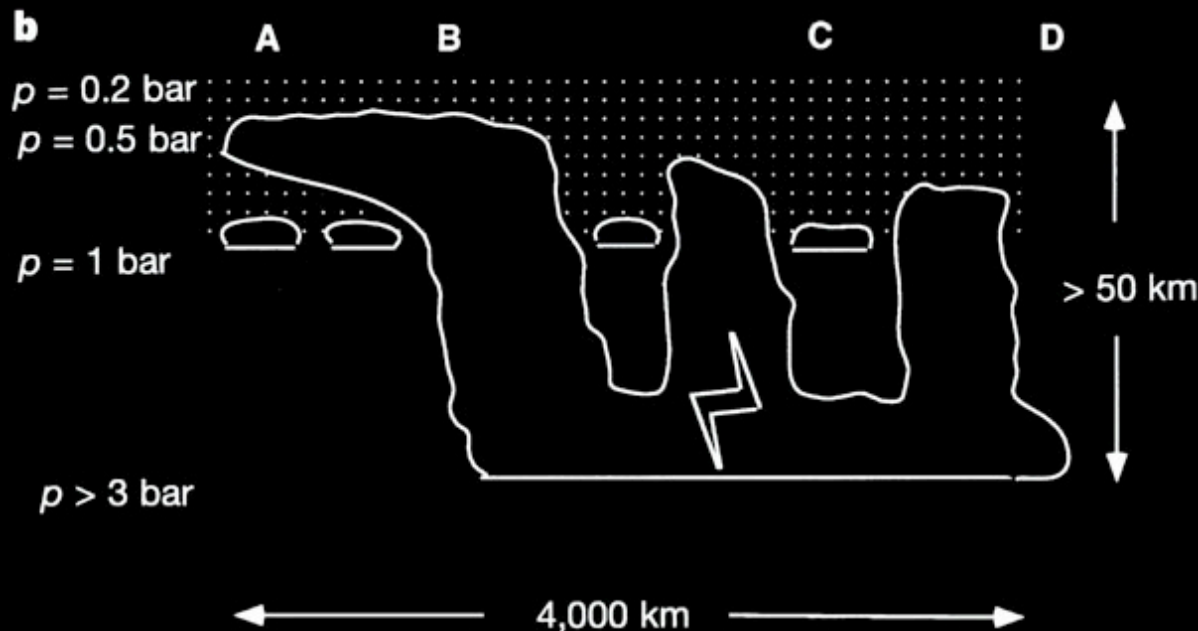
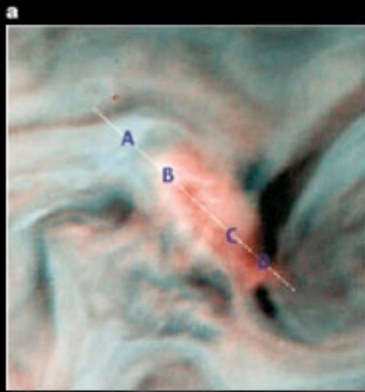
The regular bands are sometimes disturbed by giant storms. The most famous of these is the Great Red Spot, which has persisted for at least 350 years, since its discovery by Robert Hooke in 1664.





Comparison between the size of Earth and the Great Red Spot

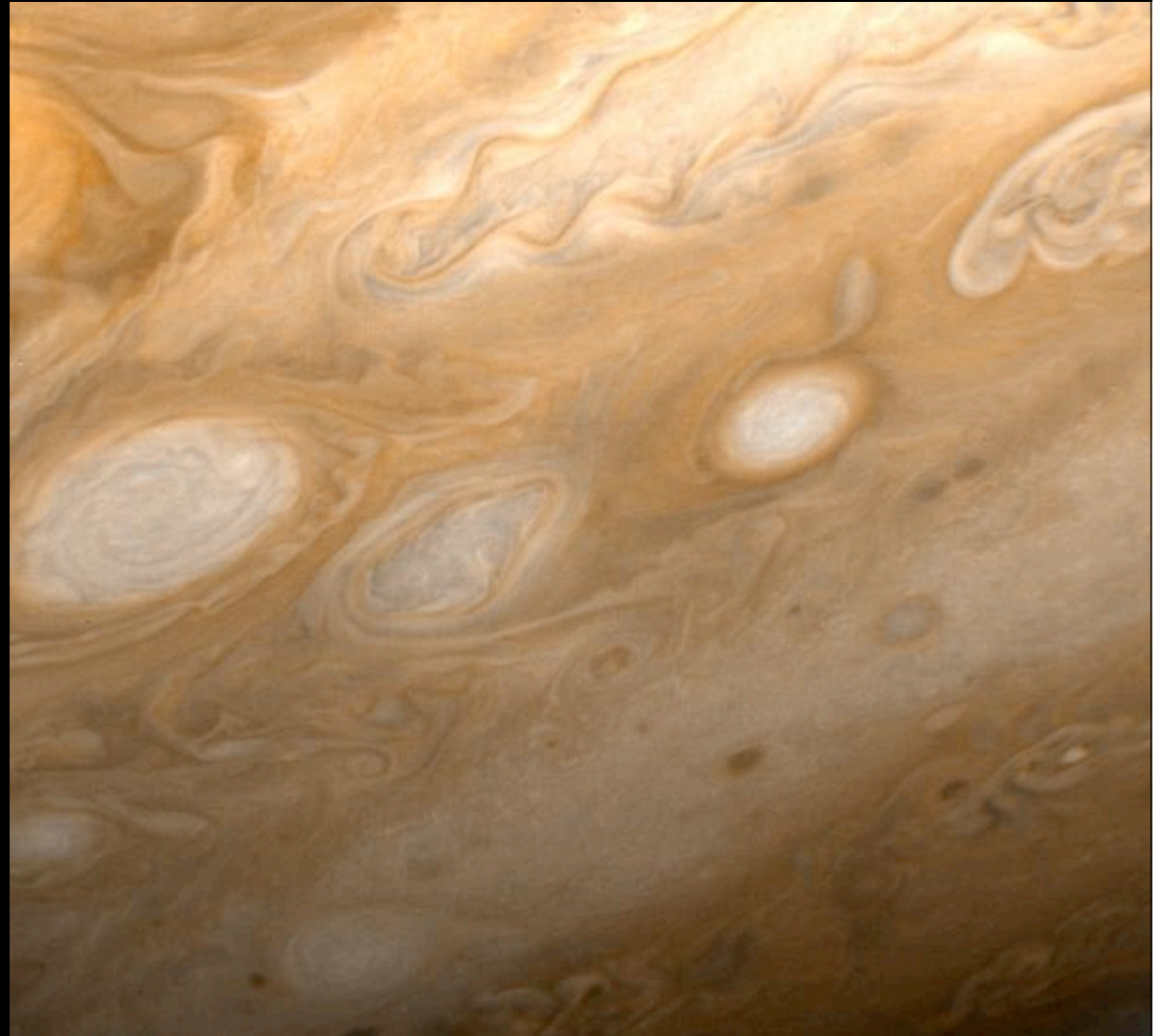
The temperature of the GRS is low, implying that the top of the spot is higher than the surrounding clouds, like a giant mushroom. This implies air is rising from below and spreading out over the troposphere, possibly containing unusual chemicals which give it its characteristic colour.



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.

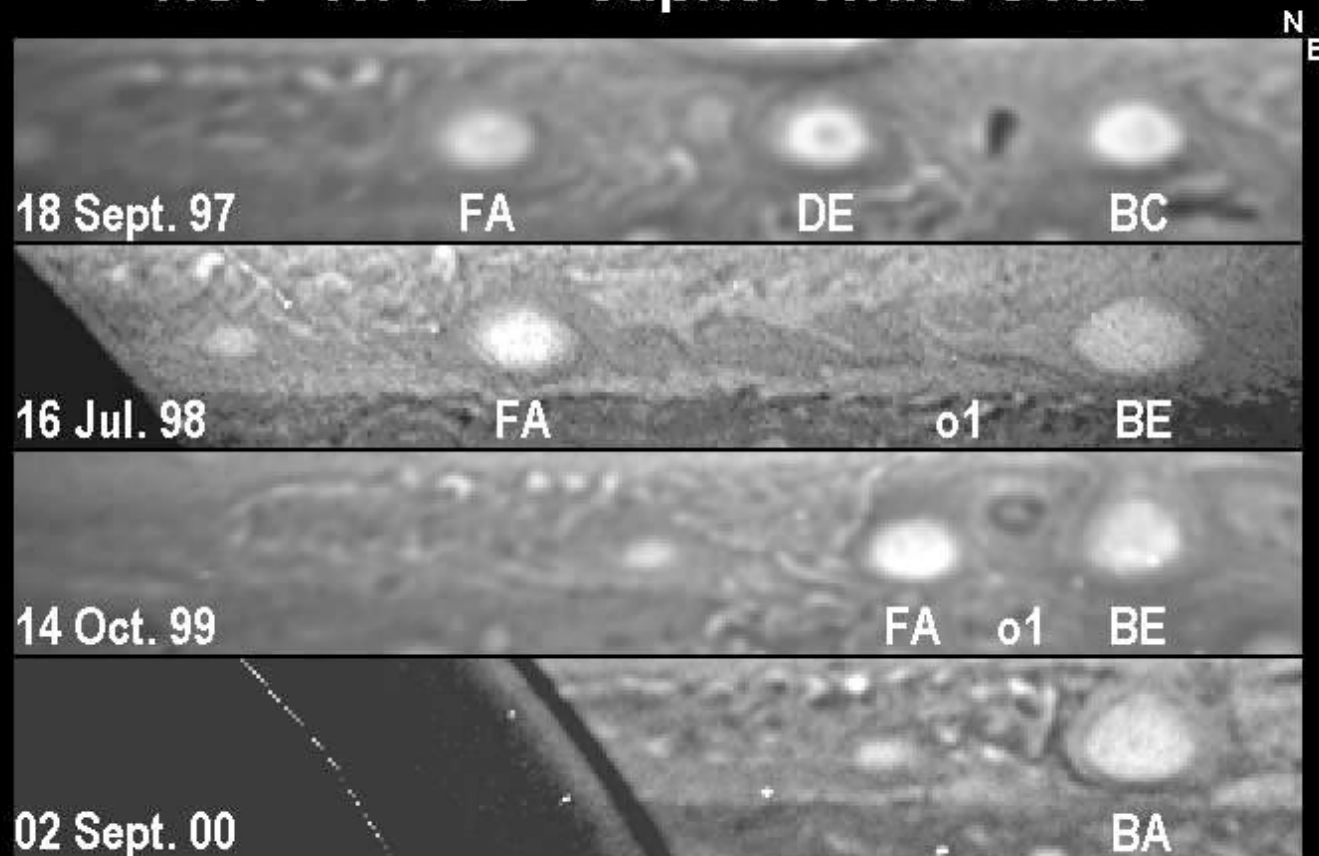


There are other permanent or semi-permanent features of the Jovian clouds: *white ovals*, *brown barges*, *white anvils*. The white ovals are anticyclones, since they rotate anticlockwise, and their cloud tops are high in the atmosphere. They are typically the size of the Earth.



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

HST- WFPC2 - Jupiter White Ovals



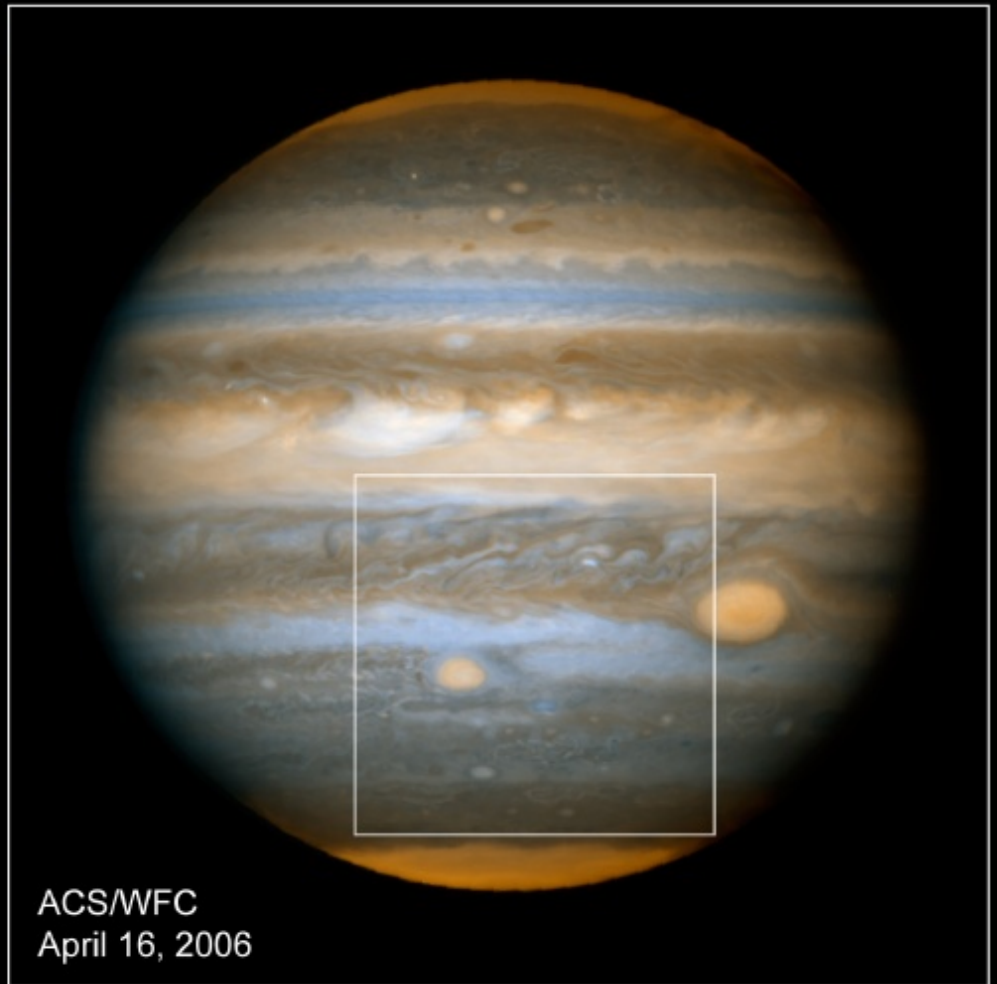
By February 2006, the merged spot had turned red, and is now about half the size of the original Great Red Spot, similar in diameter to Earth.

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.



The new spot may be related to a major climate change in Jupiter's atmosphere.

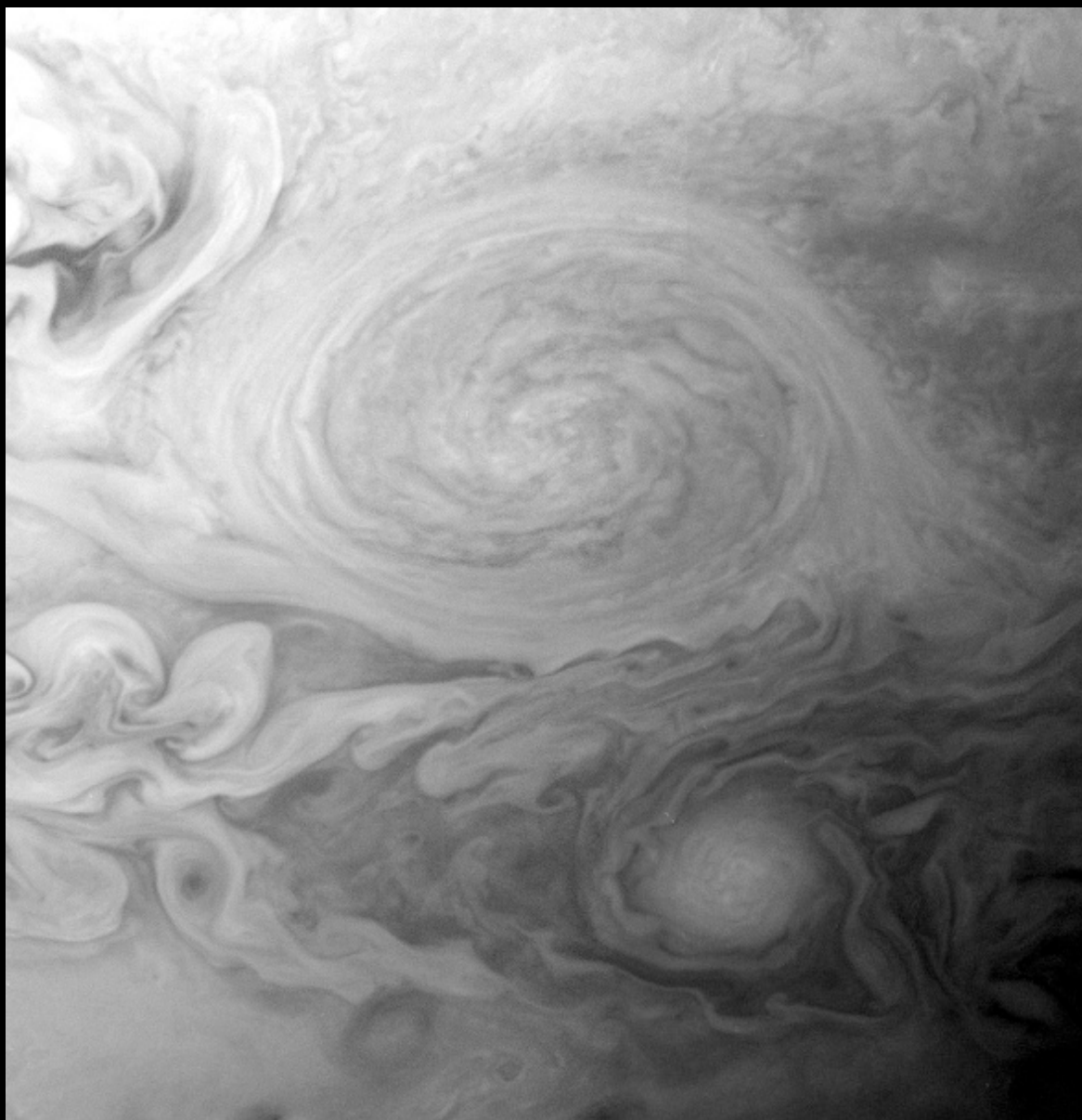


Close-up view from HST

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



Infrared image from Gemini

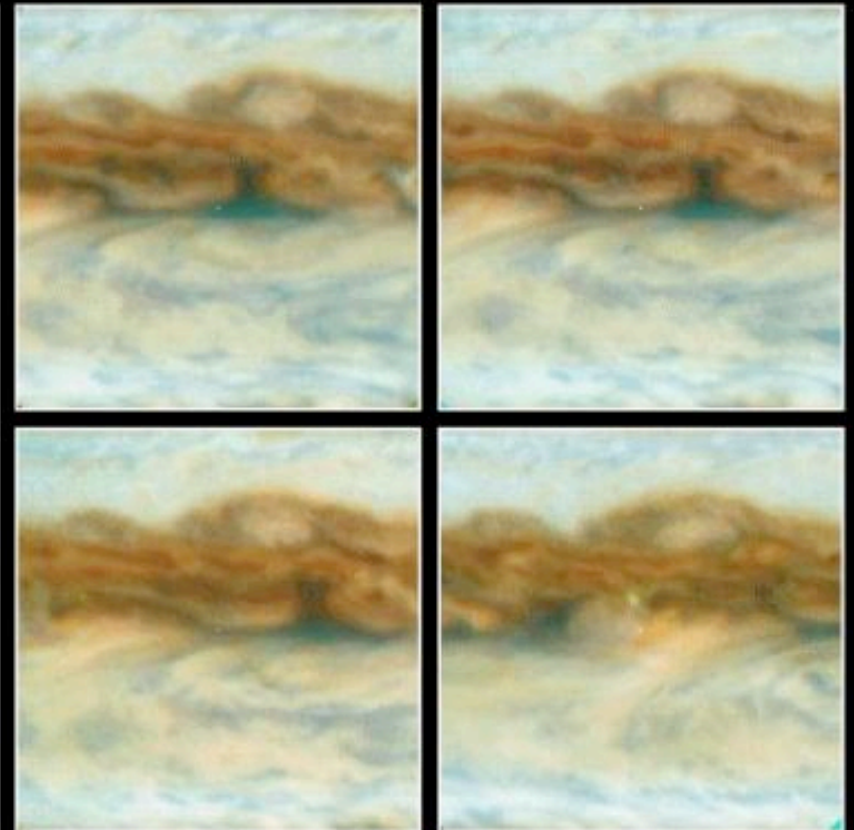


*View of the Little Red Spot from
New Horizons on 27 February
2007; the pixel scale is 15 km*

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



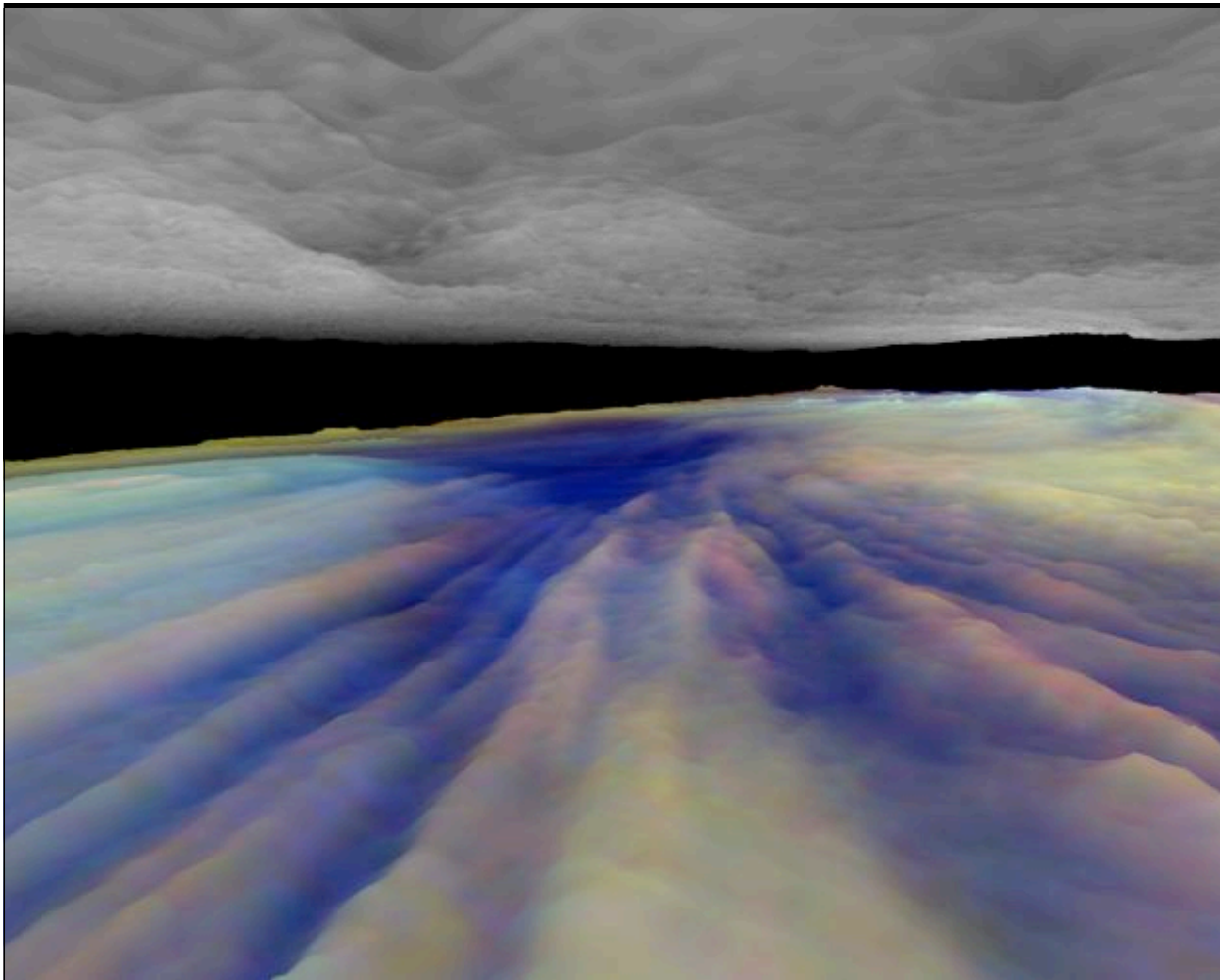
Much to everyone's surprise, the probe did not detect the predicted three-layer cloud structure as it fell: in fact, it measured almost no clouds at all!



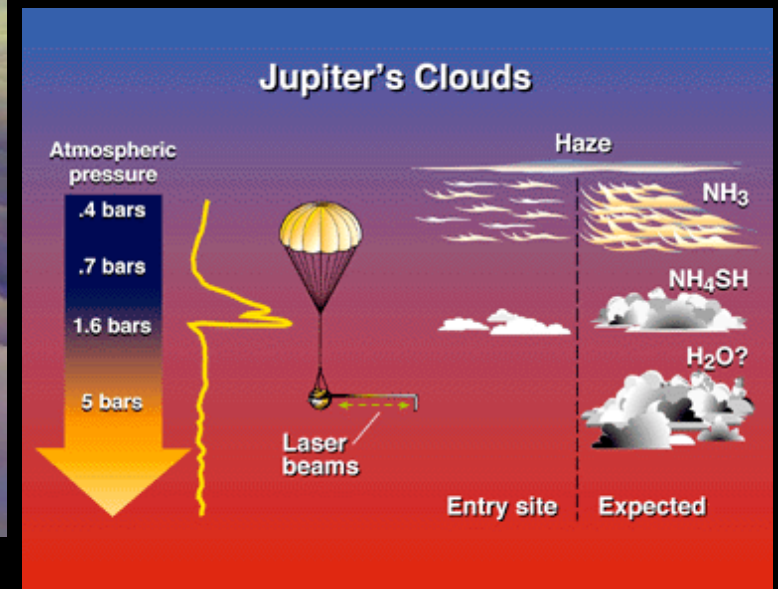
Target of Galileo Probe on Jupiter

HST • WFPC2

PRC95-46 • ST ScI OPO • November 9, 1995 • R. Beebe (NMSU), NASA



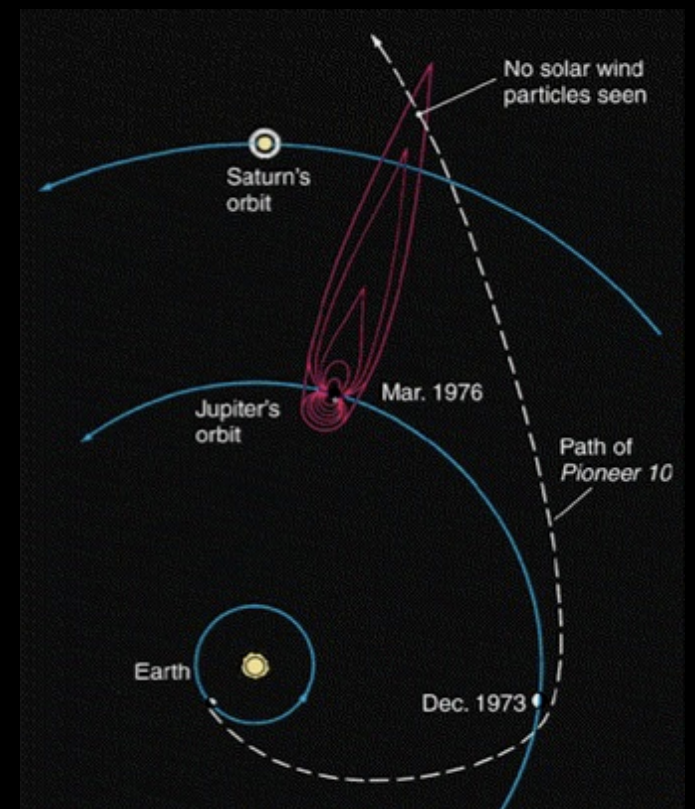
(left) Visualisation of Jupiter's atmosphere, looking between the cloud deck. The clear hotspot where the Galileo probe fell appears as a dark blue feature. (below) What the probe found, compared with what was expected.

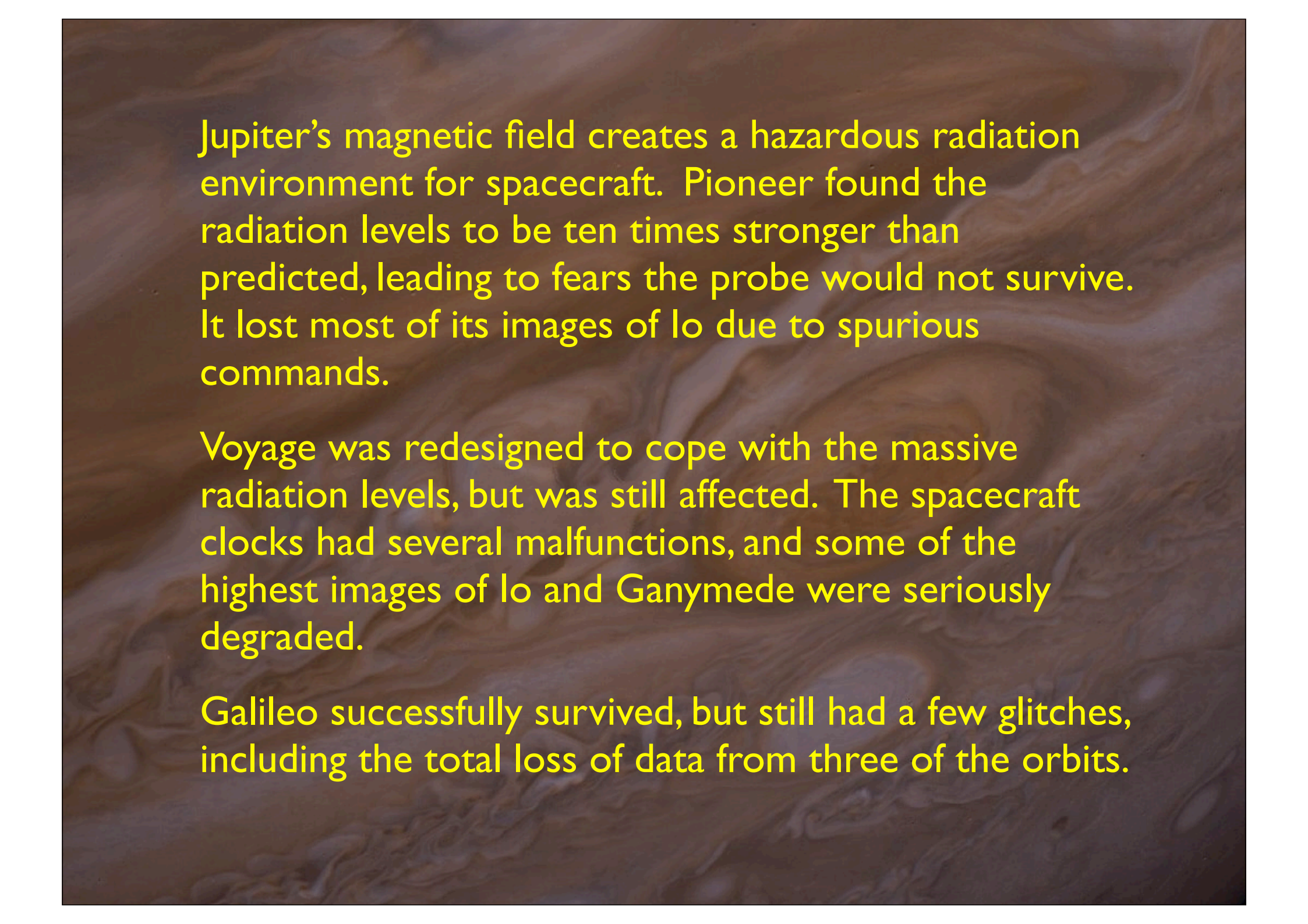


It appears that the probe had the bad luck to fall into a hole in the clouds of Jupiter, one of the very few areas where the clouds were so thin as to be almost invisible. The probe entry site appears to be one of the clearest and driest on the planet.

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.

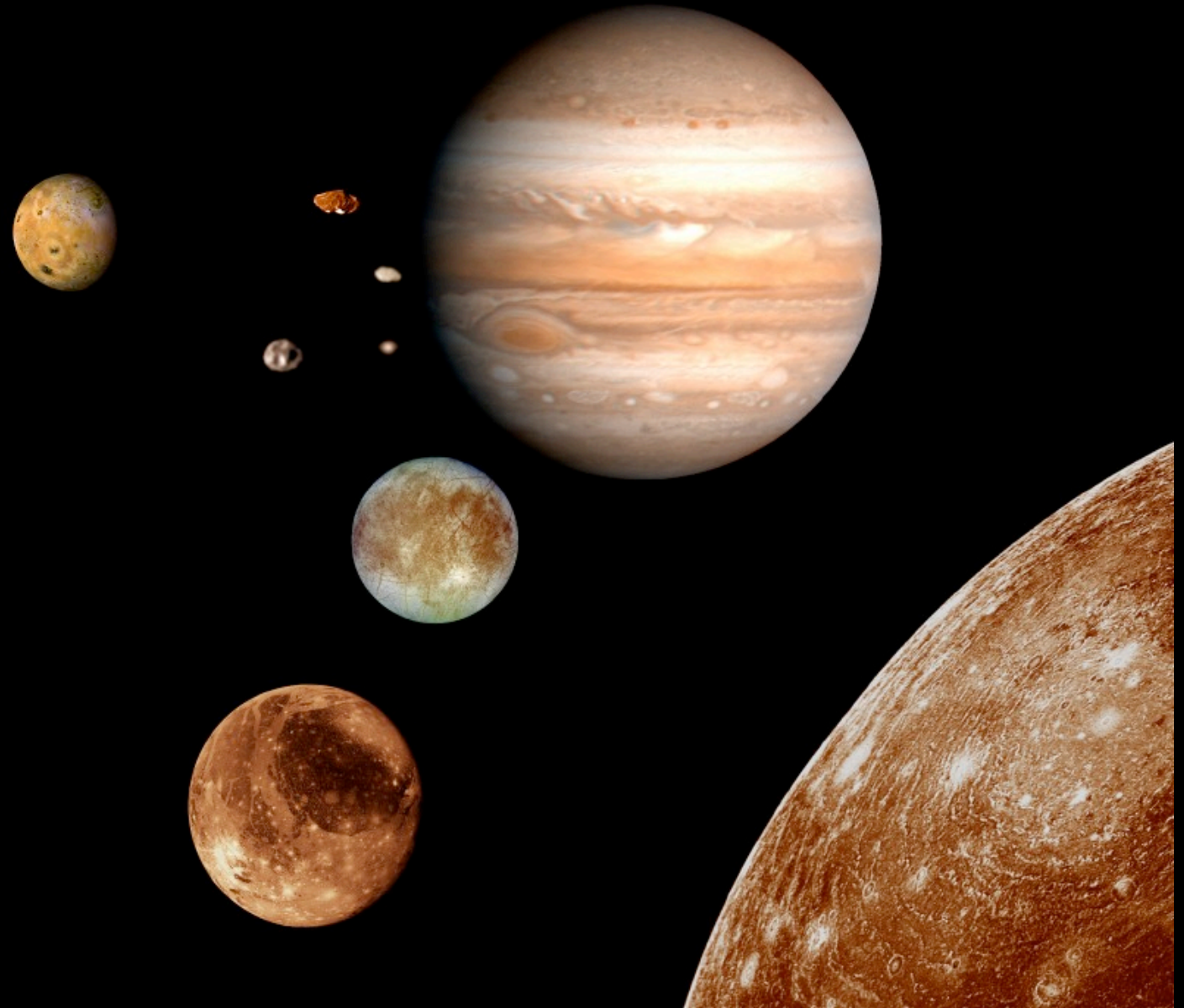
Voyage was redesigned to cope with the massive radiation levels, but was still affected. The spacecraft clocks had several malfunctions, and some of the highest images of Io and Ganymede were seriously degraded.

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

The *Juno* mission to Jupiter was launched in August 2011. It will reach Jupiter in July 2016, and will be placed in a polar orbit to study Jupiter's composition, gravity field, magnetic field, and whether the planet has a rocky core.



The Jovian moons



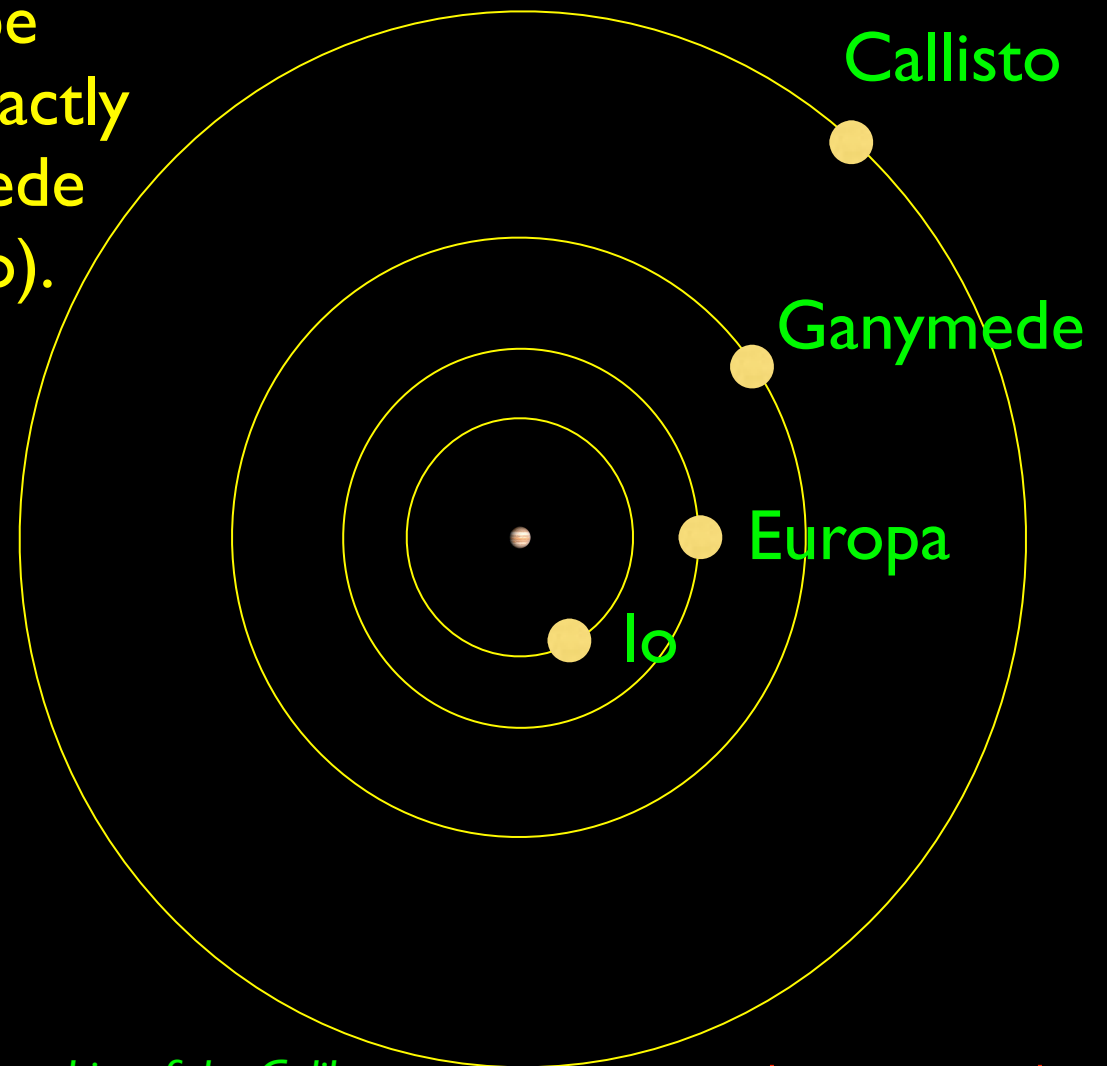
Jupiter has (at least) 63 known satellites. The largest four were discovered by Galileo, and bear his name.

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.



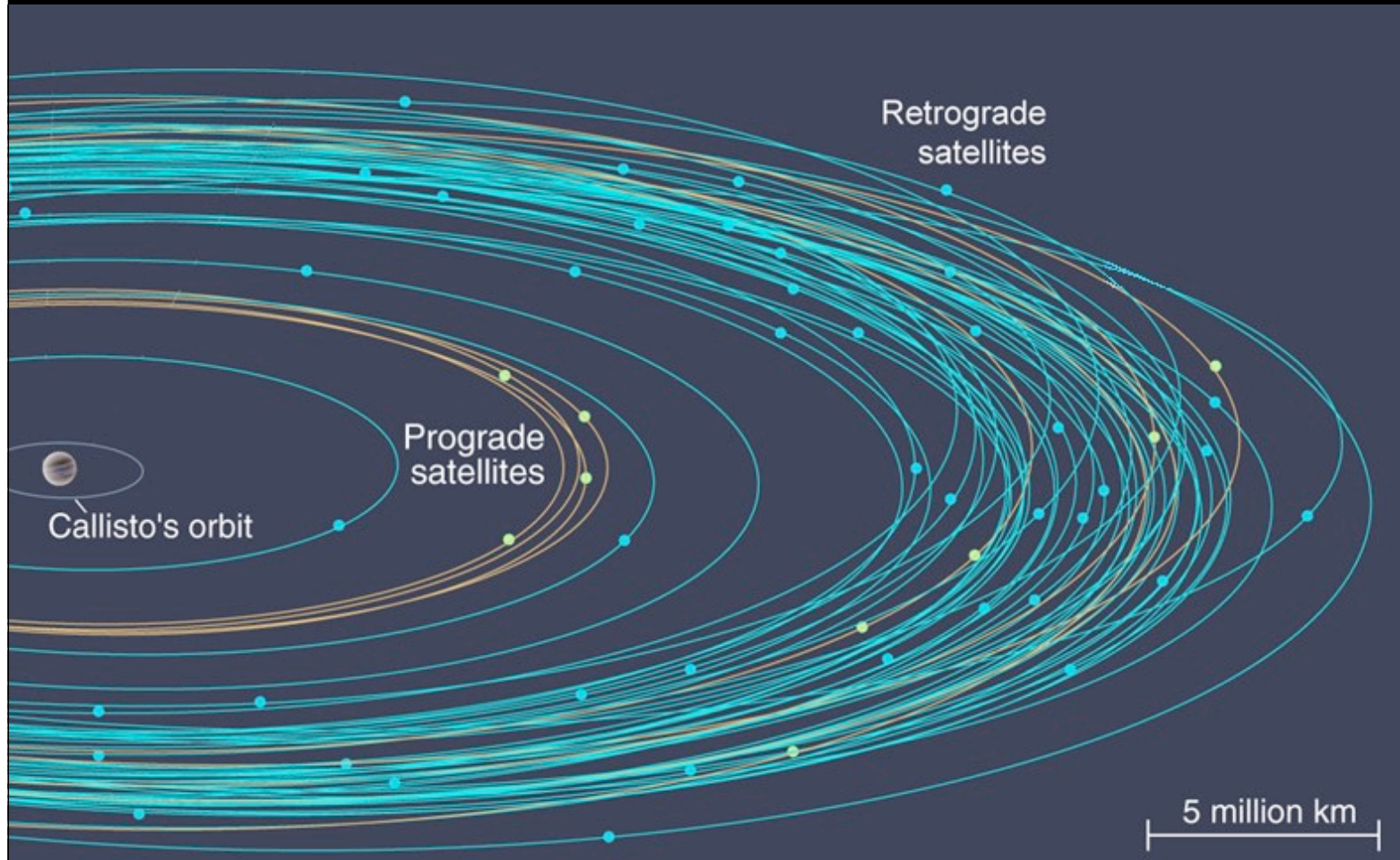
Io, Europa and Ganymede are locked together in a 1:2:4 orbital resonance, and their orbits evolve together. In a few hundred million years, Callisto will be locked in too, orbiting at exactly twice the period of Ganymede (eight times the period of Io).



The relative sizes of the orbits of the Galilean satellites. The moons are not to scale.

10⁶ km

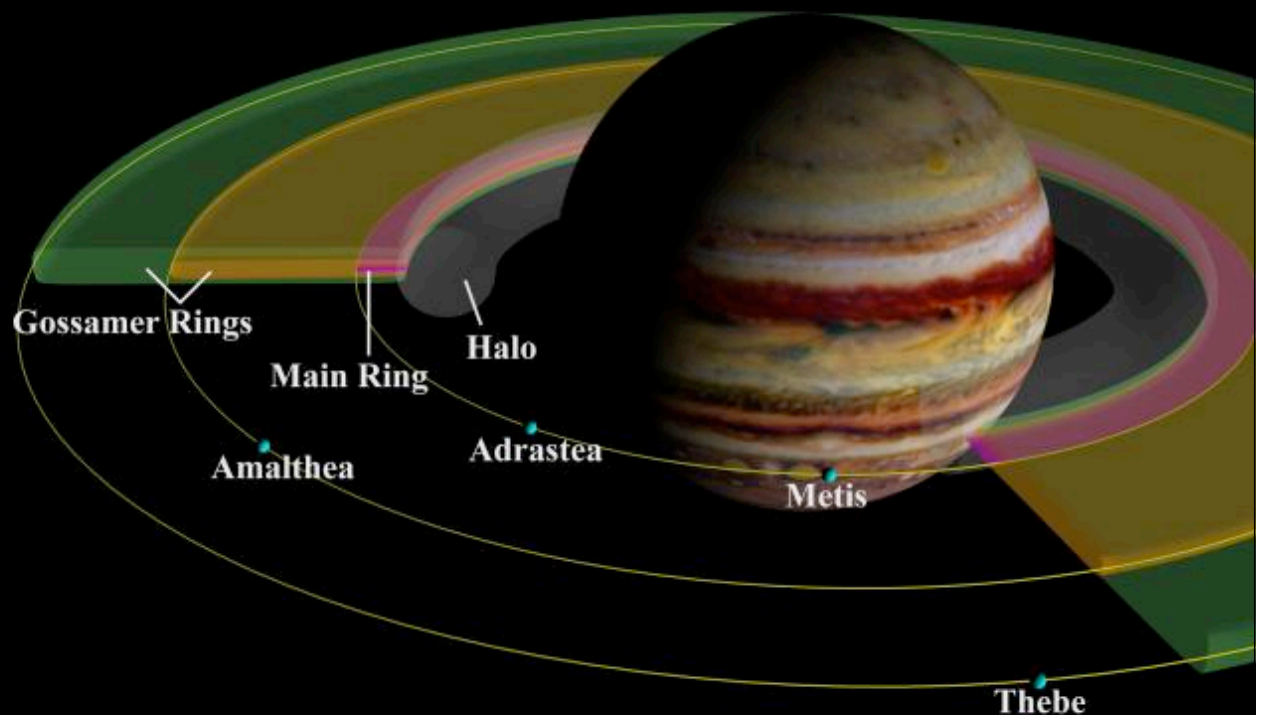
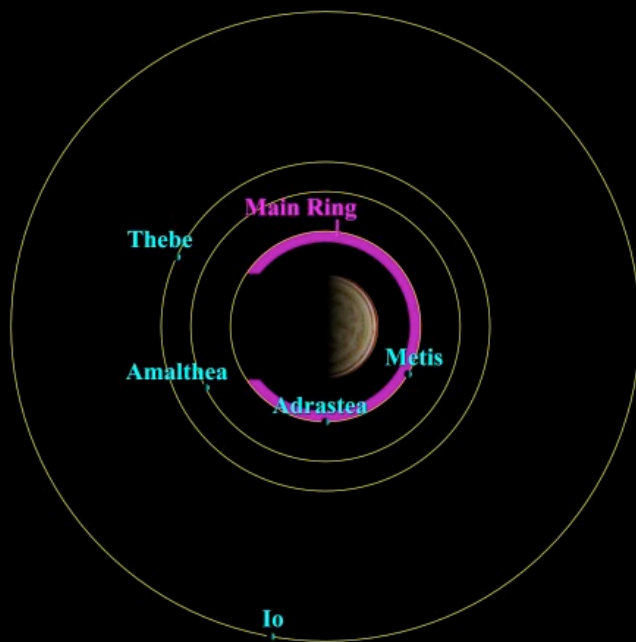
Then outside Callisto's orbit is a whole swarm of tiny satellites, all irregular, and most in retrograde orbits.



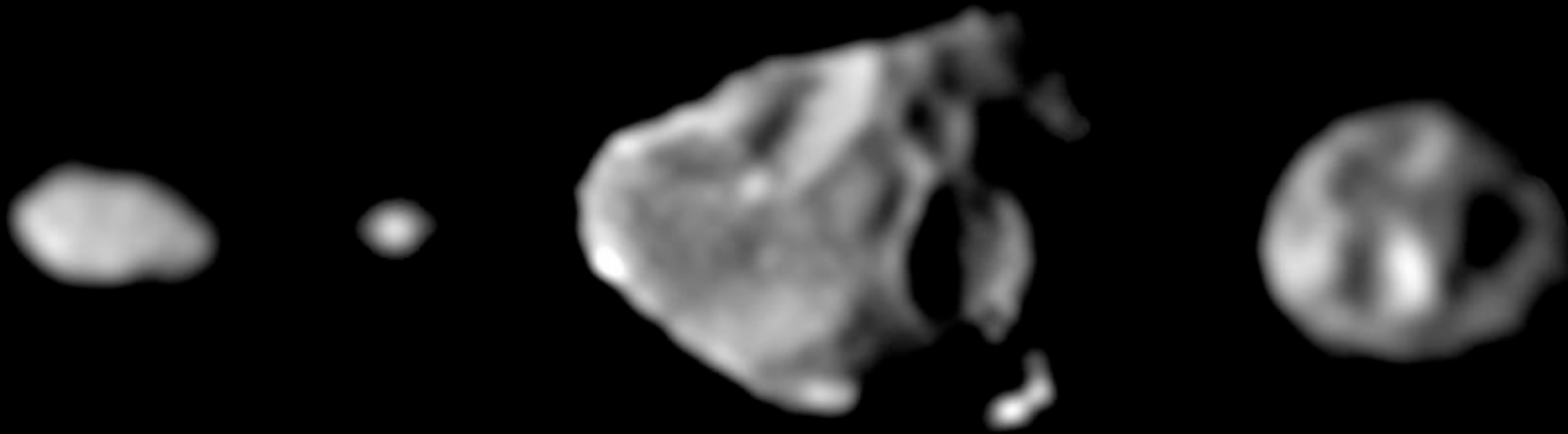
Jupiter also has a system of rings. The main ring is about 6500 km wide, and less than 10 km thick.



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 “ring-shepherding” satellites are shown in their correct relative sizes. From left to right, arranged in order of increasing distance from Jupiter, are *Metis* (longest dimension is approximately 60 km), *Adrastea* (20 km), *Amalthea* (247 km), and *Thebe* (116 km).



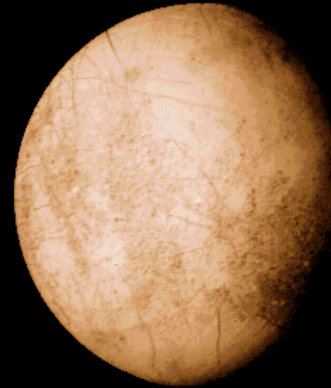
Amalthea is the reddest object in the solar system, probably due to sulphur from Io. Amalthea's density is about the same as water, and since it is unlikely to be composed of ice, it is most likely porous with lots of empty space.

The Galilean satellites

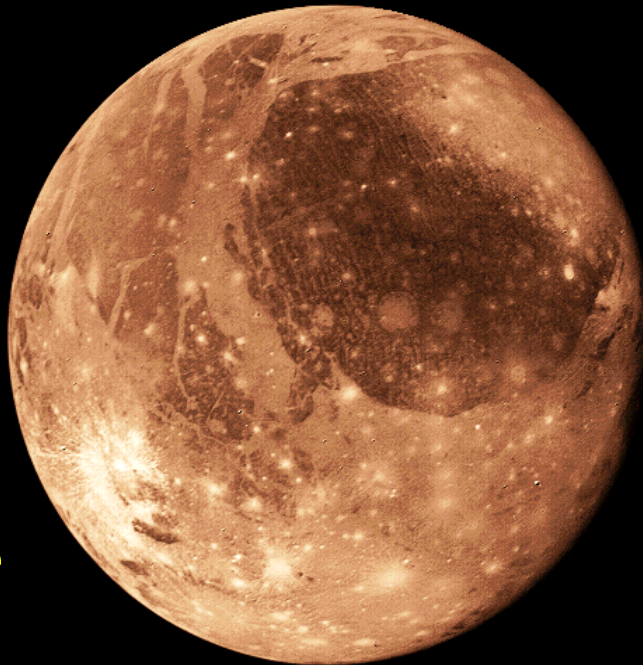
Io



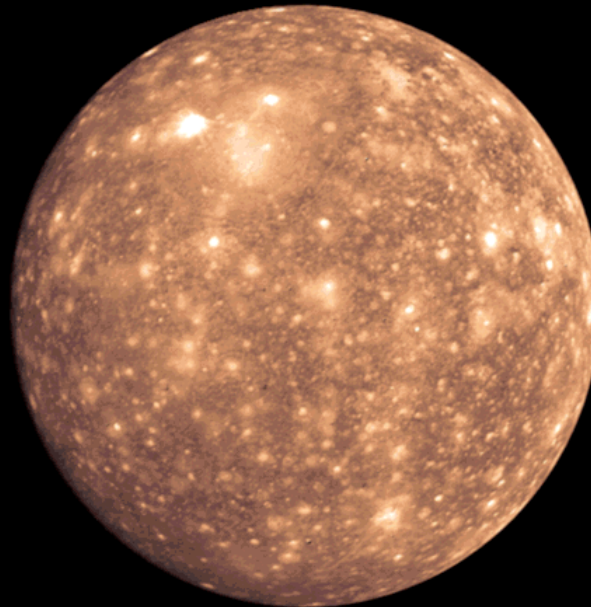
Europa



Ganymede



Callisto

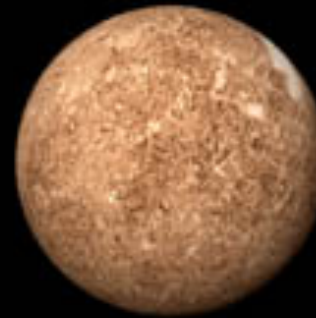




Ganymede
5262 km



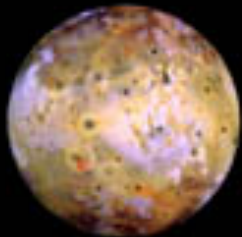
Titan
5150 km



Mercury
4880 km



Callisto
4806 km



Io
3642 km



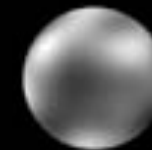
Moon
3476 km



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	48.0	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, and there is a definite trend in density as a function of distance from Jupiter.

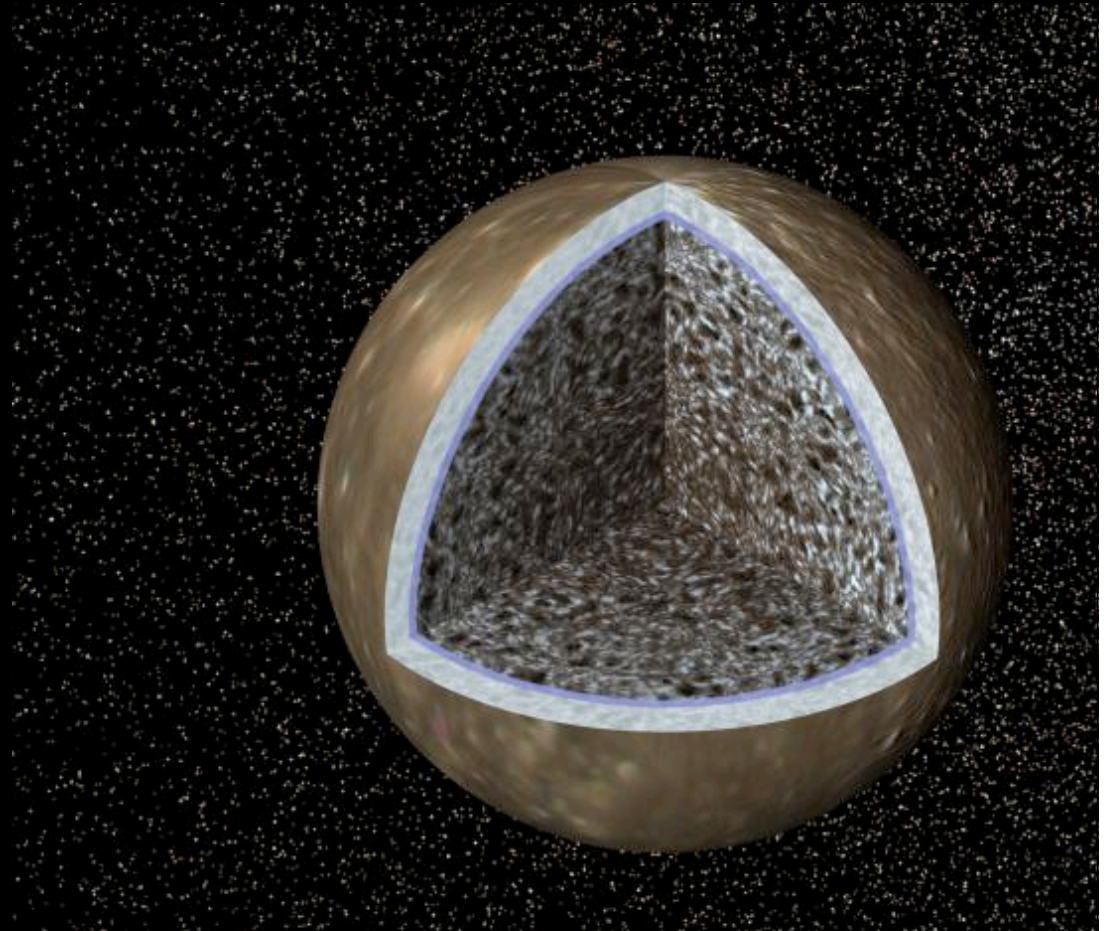


Callisto

– a dead world

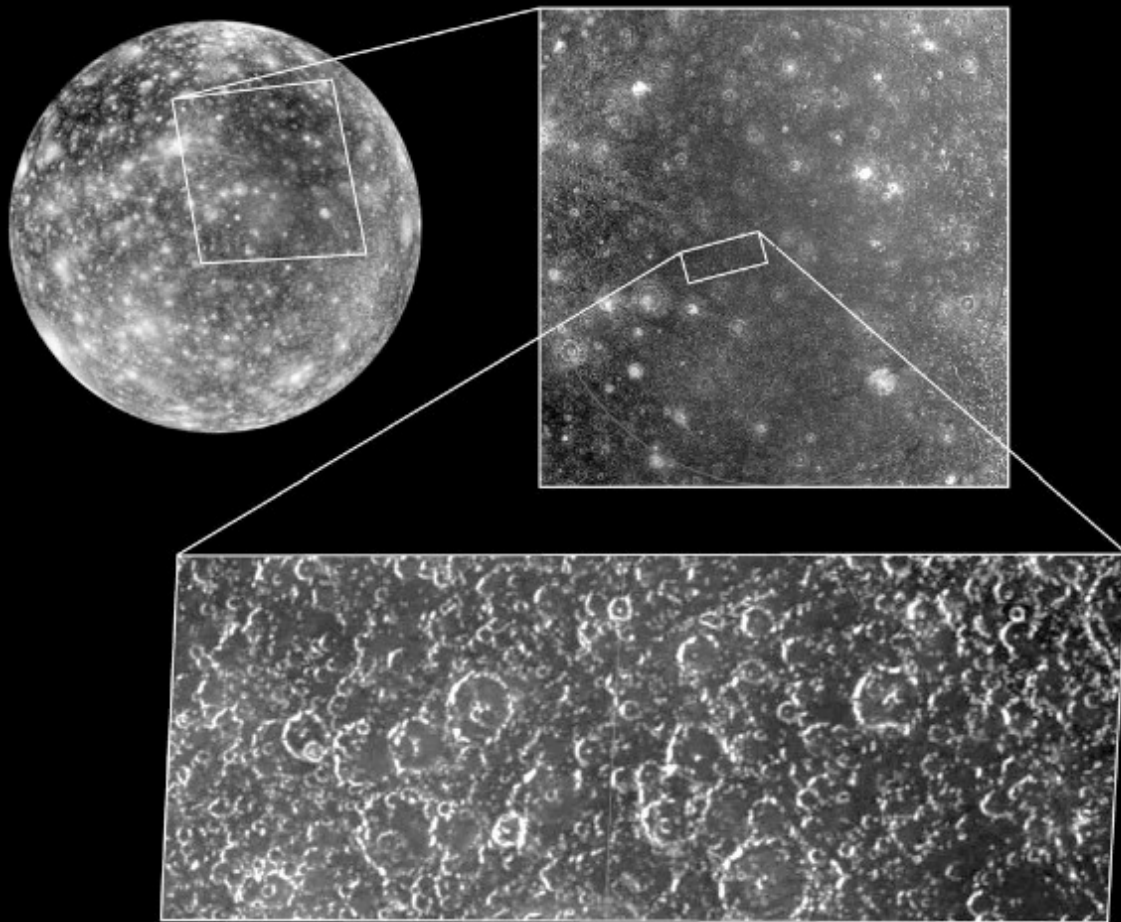
Callisto is the second largest and least dense of the Galilean satellites. It is almost the same size as Mercury, but only a third of its mass. This means it must consist of a mixture of rock and ice; gravity measurements by *Galileo* indicate its interior is mostly undifferentiated.

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.

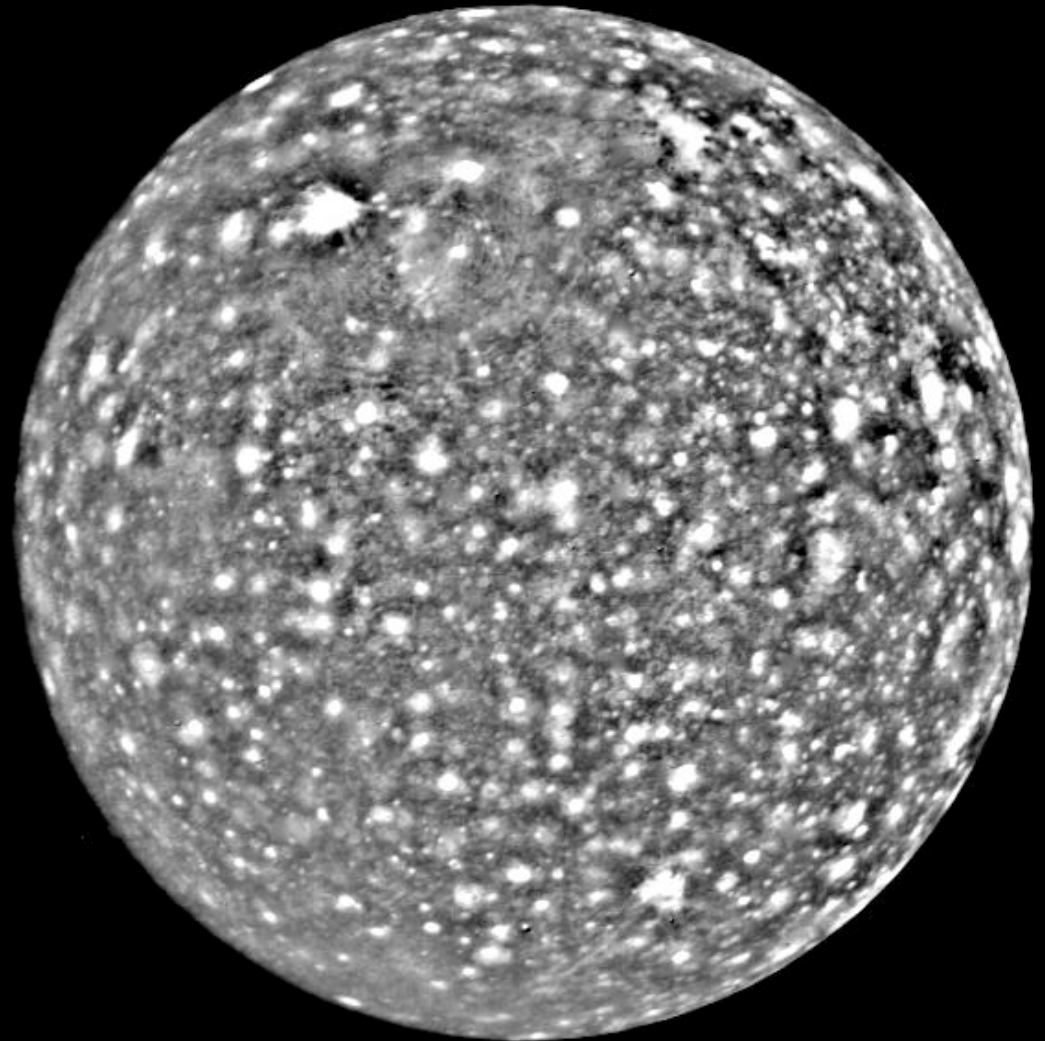
Callisto's surface is dominated by impact craters in all shapes and sizes. Crater counts indicate that the age of the surface is 4 billion years old.



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.

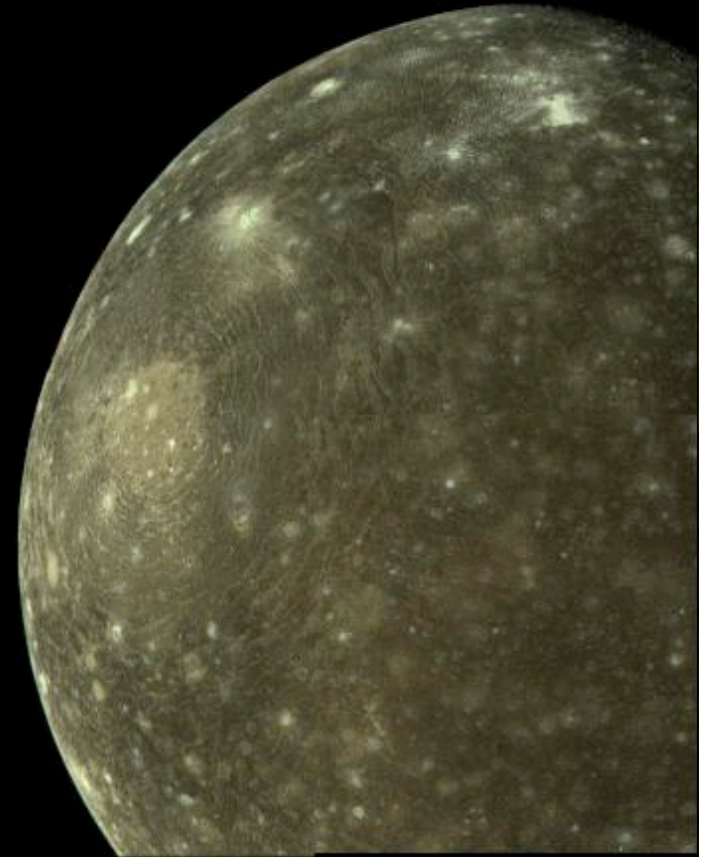


Mosaic of images taken by Voyager 2.

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 is 600 km in diameter.

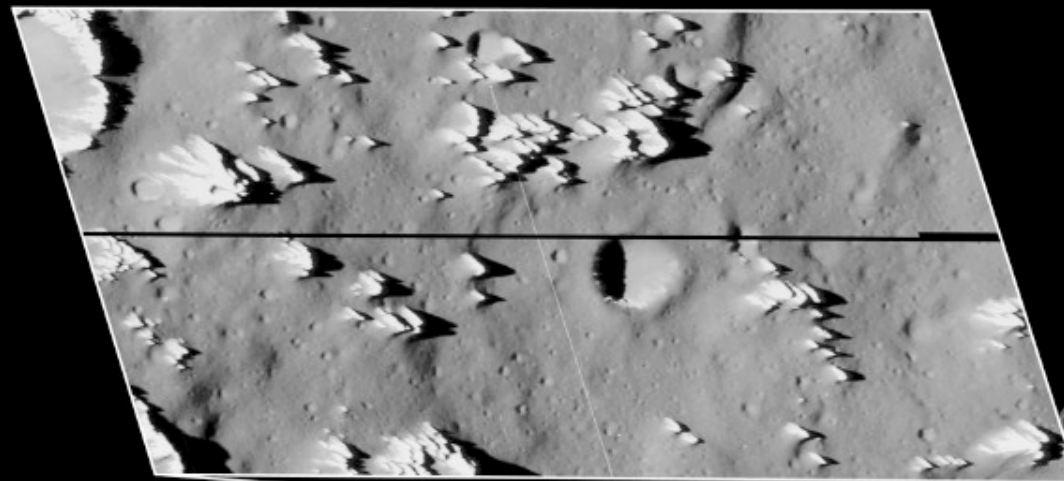
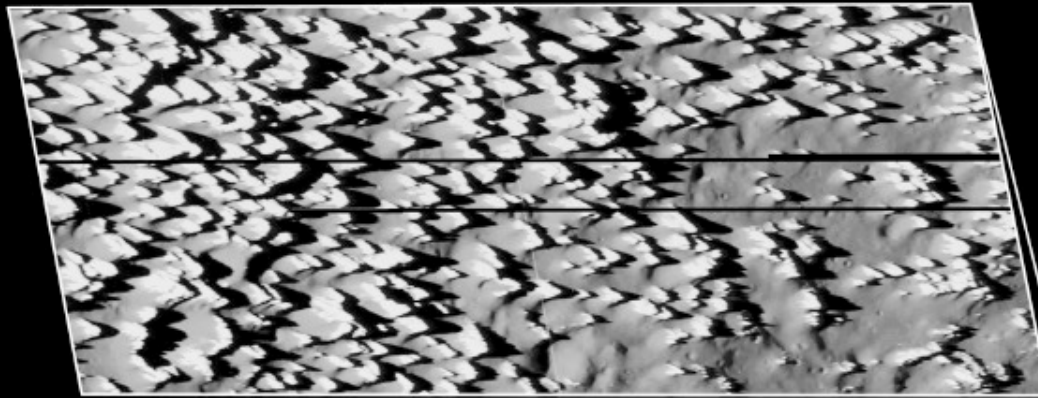
These “ghost craters” have been called *palimpsests*, and are seen on other Jovian moons. They were probably formed when the crust was still warm, as the crust relaxed under its own weight.



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.

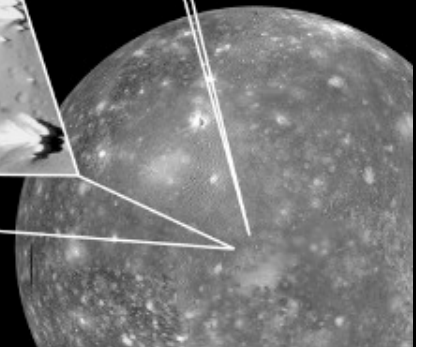


Galileo saw knobby peaks, with icy spires 80–100m high, which may consist of material thrown outward from an ancient impact.



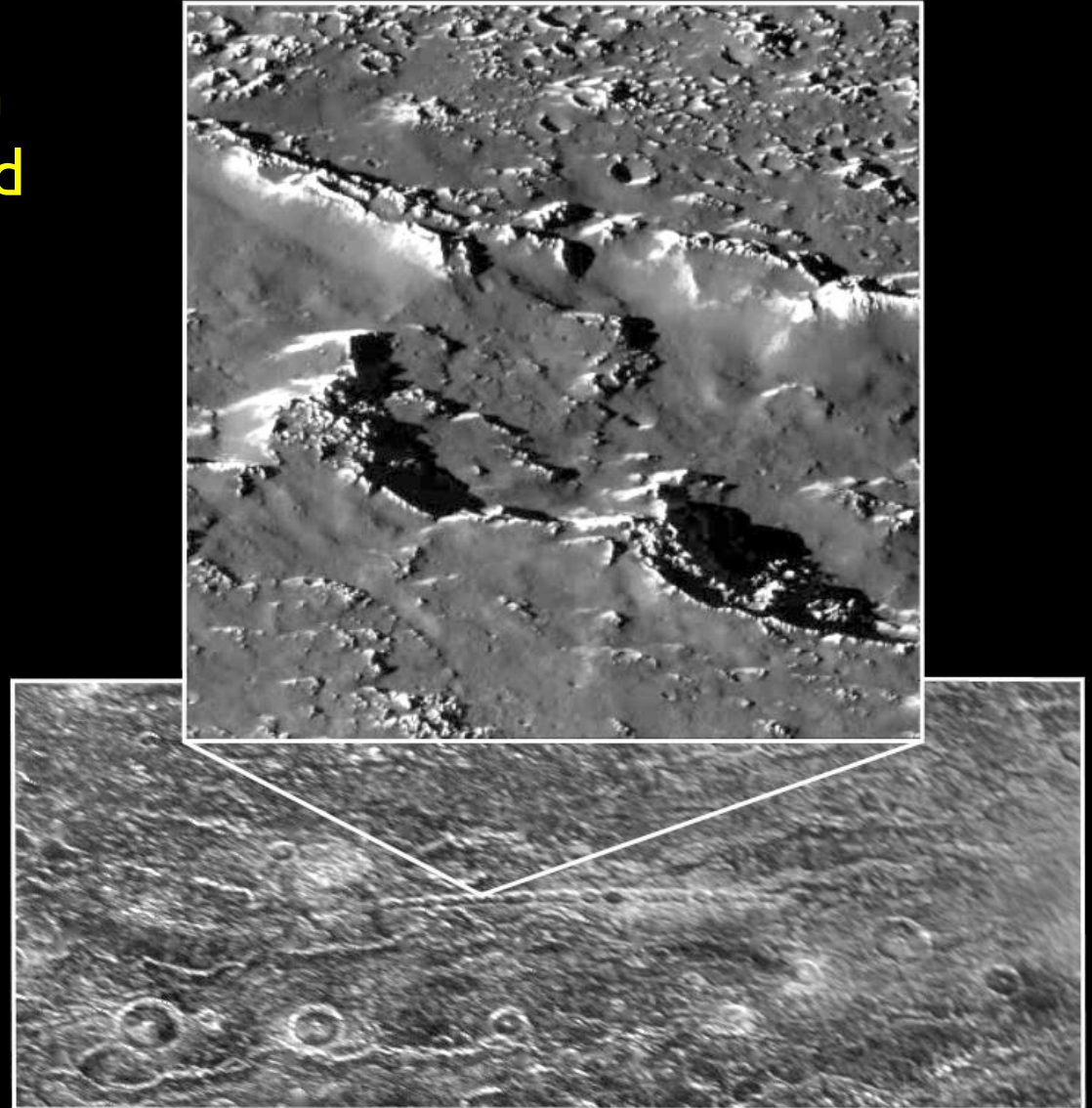
Icy spires in a region south of Asgard. Objects as small as 3m can be discerned in this image.

5 km

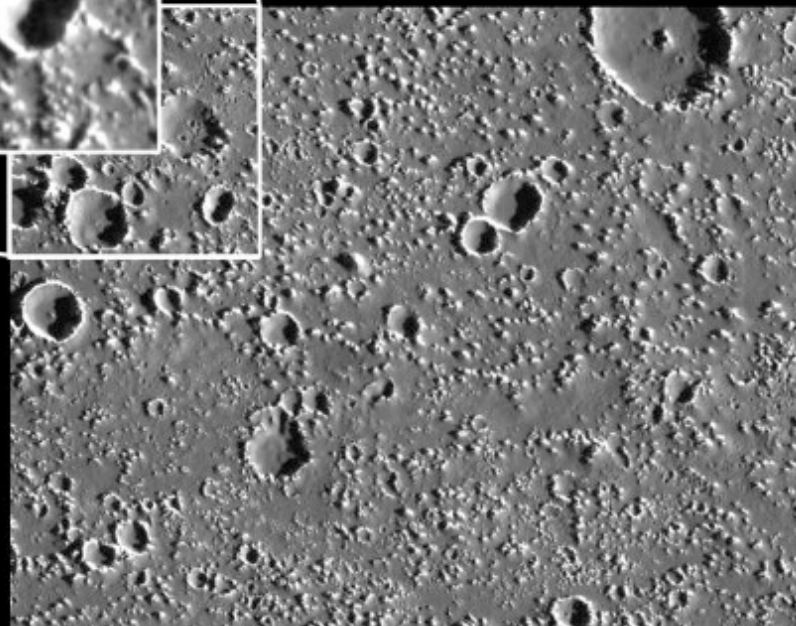
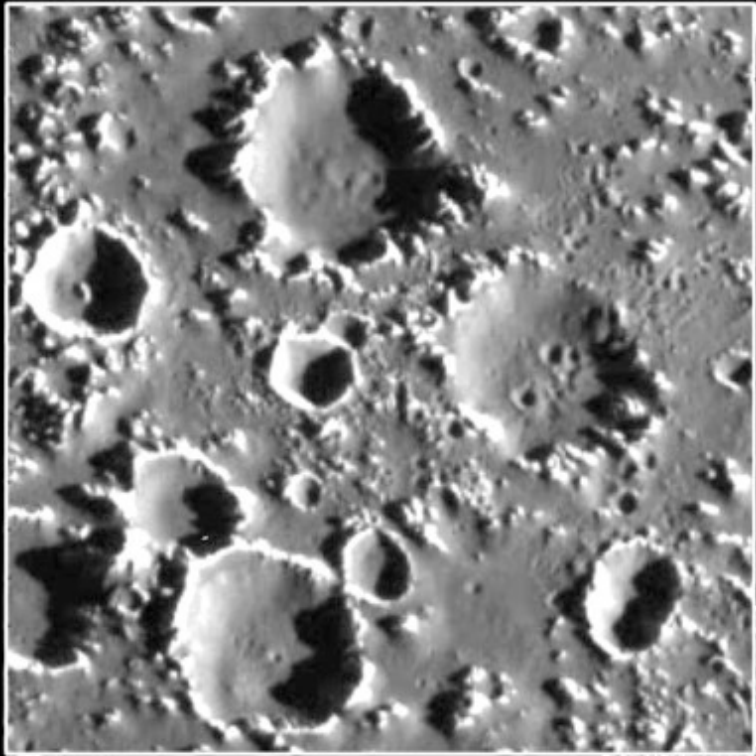


Callisto contains at least ten crater chains. The largest is Gipul Catena, consisting of 12 craters spread over 620 km. The largest crater is 40 km in diameter.

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



Galileo found very small craters called *pits* in and around some larger craters. Some these smaller craters are not entirely circular. They may be formed by some unknown surface process instead of by impacts; or they may be partially eroded secondary craters.



In a study of the possibility of human exploration of the outer solar system called *Human Outer Planets Exploration* (HOPE), NASA concluded that Callisto is the only one of Jupiter's Galilean satellites for which human exploration is feasible. The levels of ionizing radiation on Io, Europa and Ganymede are inimical to human life, and adequate protective measures have yet to be devised.

Artist's impression of a crewed mission to Callisto.



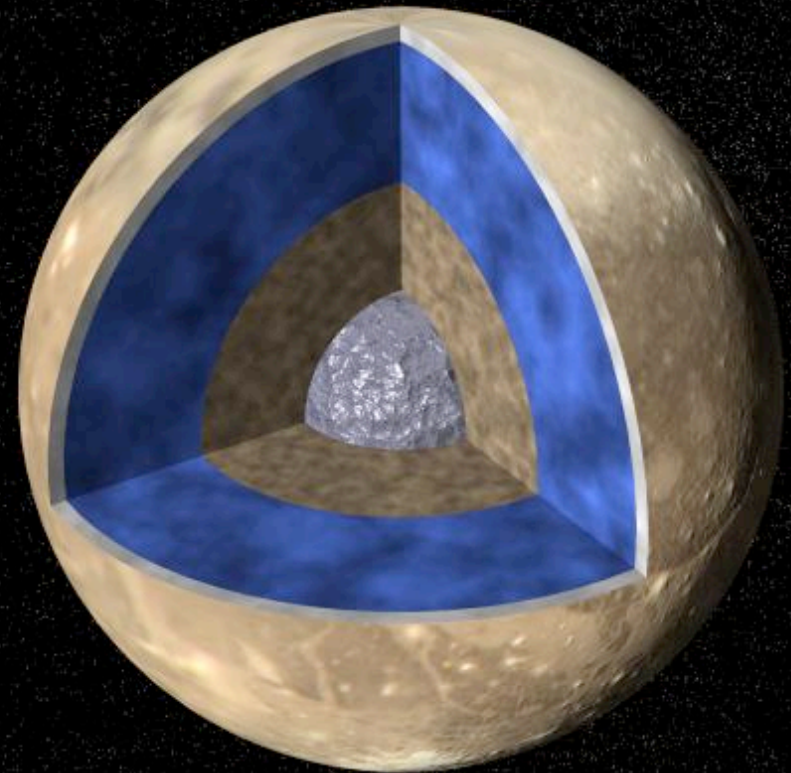


Ganymede

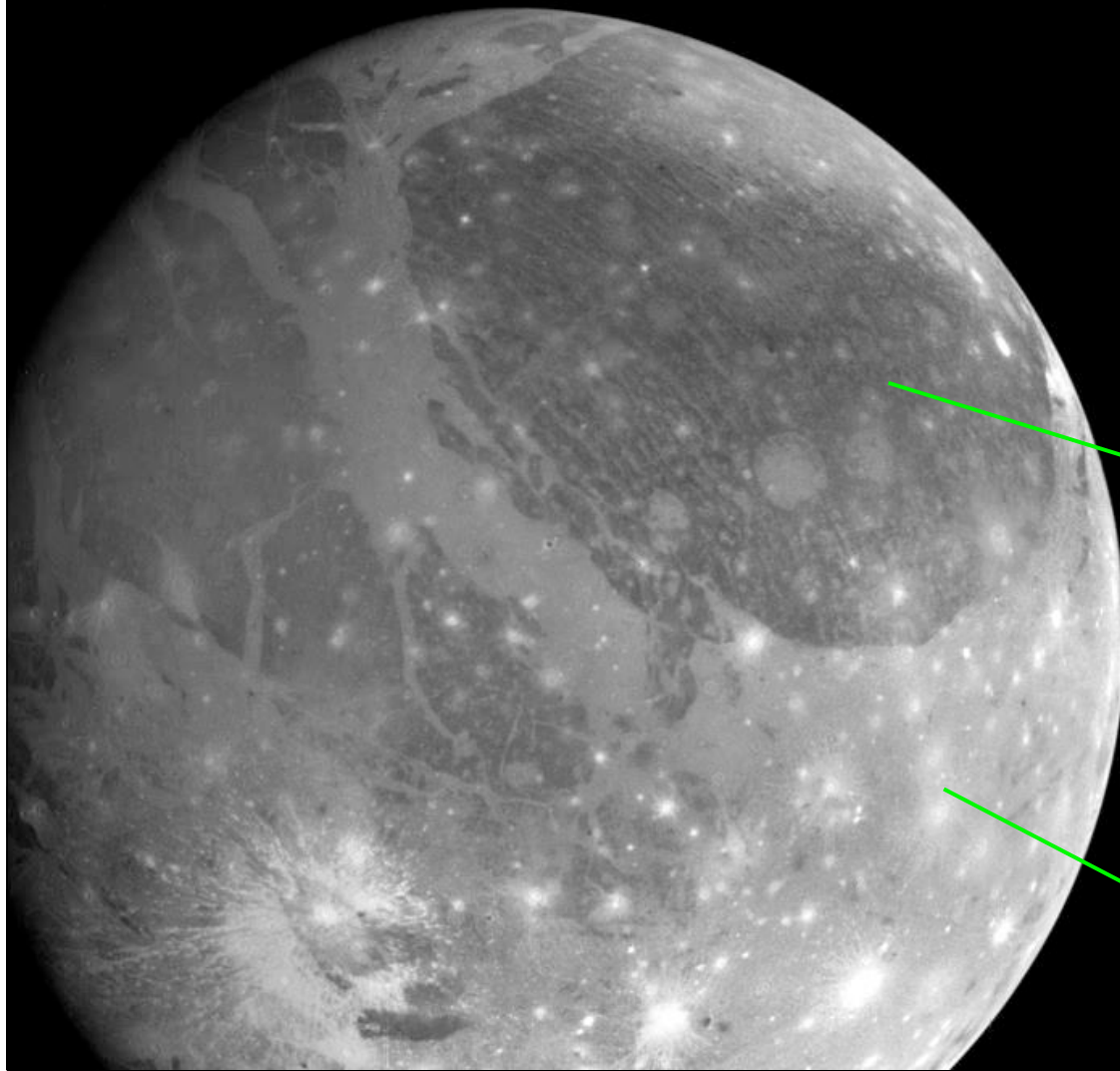
– the largest moon

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?



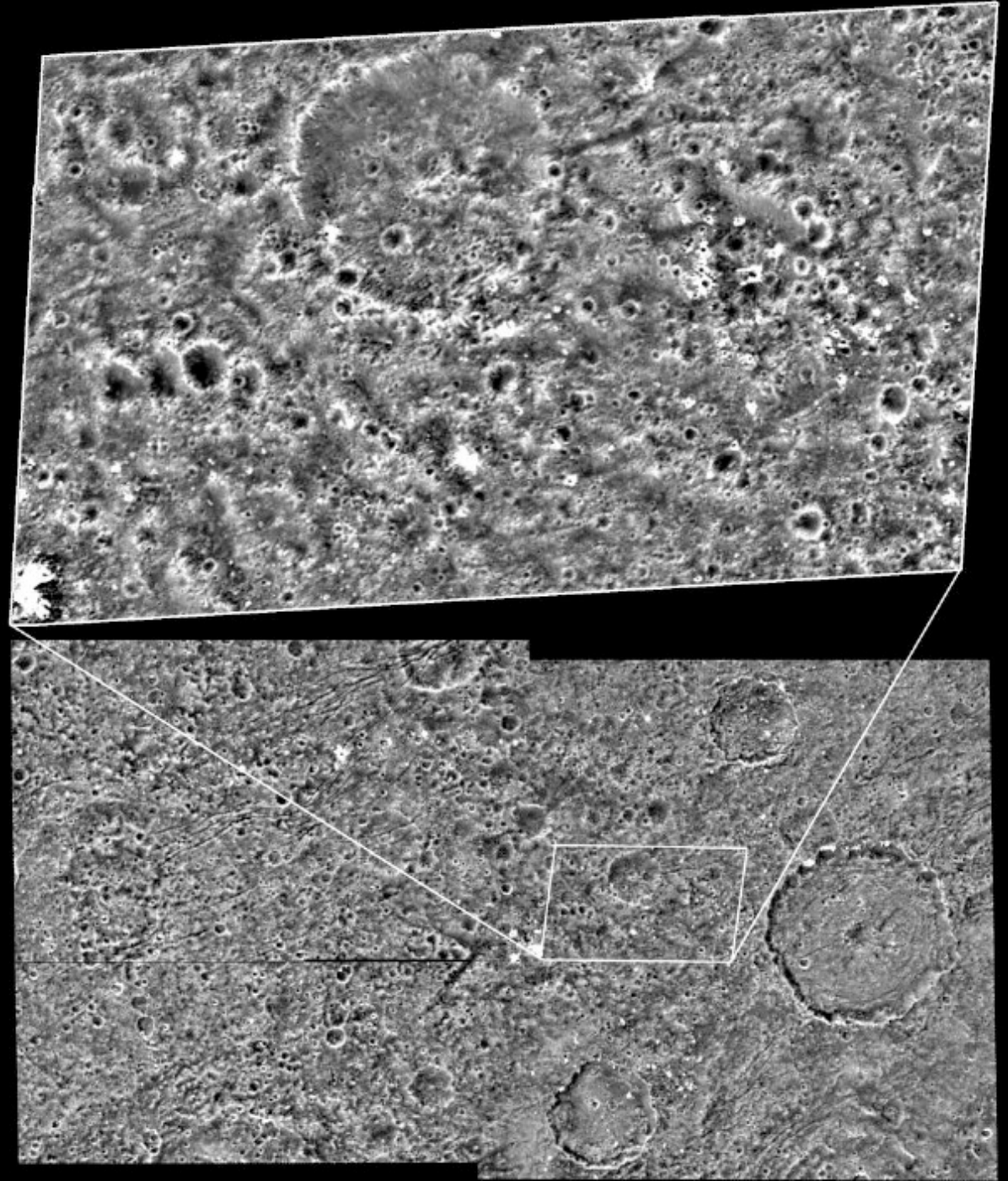
Ganymede's surface shows the satellite has a complex geological history. Ganymede's surface is a mixture of two types of terrain. 40% of the surface of Ganymede is covered by highly cratered dark regions, and the remaining 60% is covered by a light grooved terrain which forms intricate patterns across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



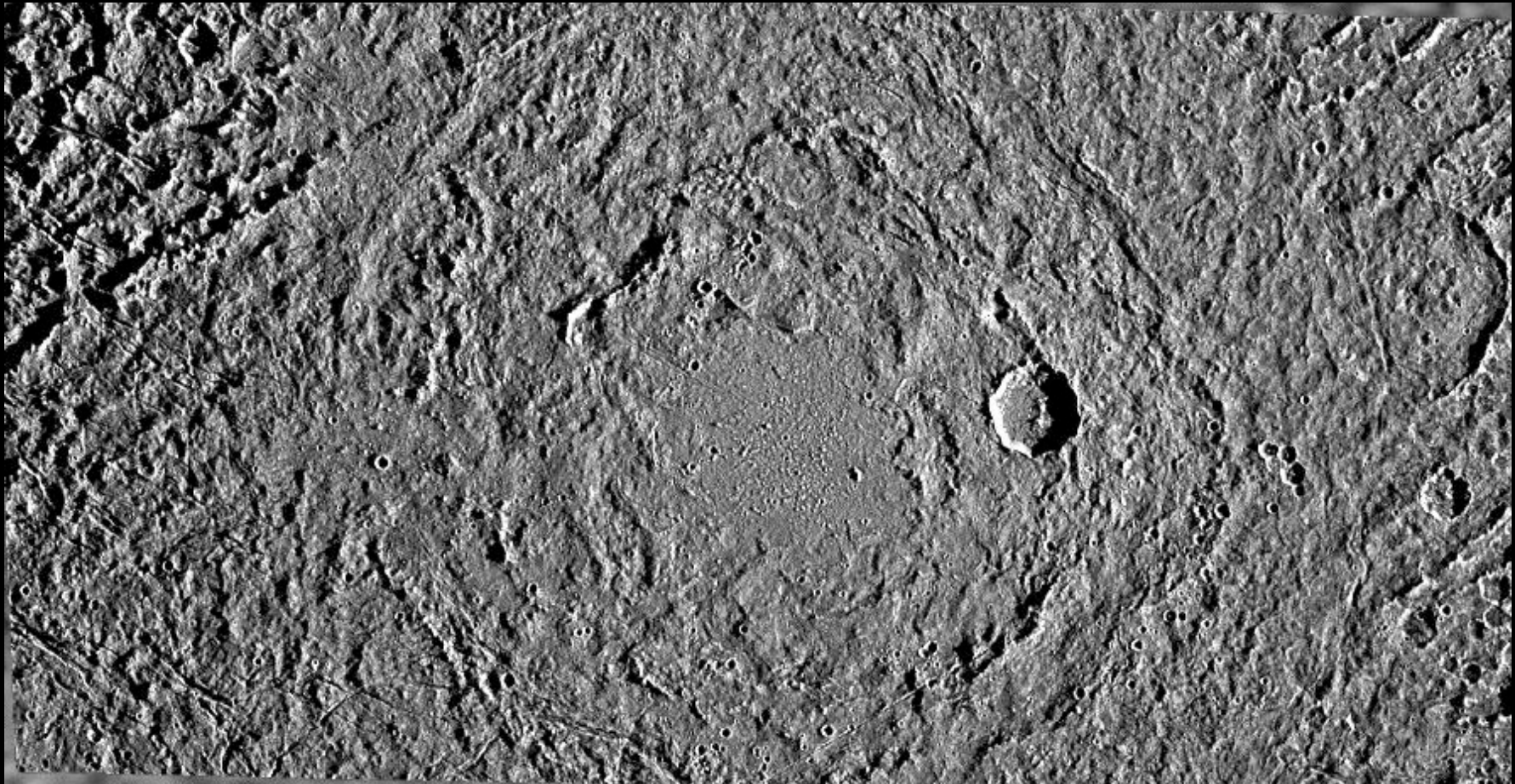
Very old, heavily cratered dark coloured surface

Slightly younger lighter terrain covered in grooves and ridges

The dark terrain is dominated by craters, just like the highlands on the Moon and Mars. However, nearly all lack raised rims and central peaks, probably due to the relatively weak nature of Ganymede's icy crust which can flow over geologic time and thereby soften the relief.



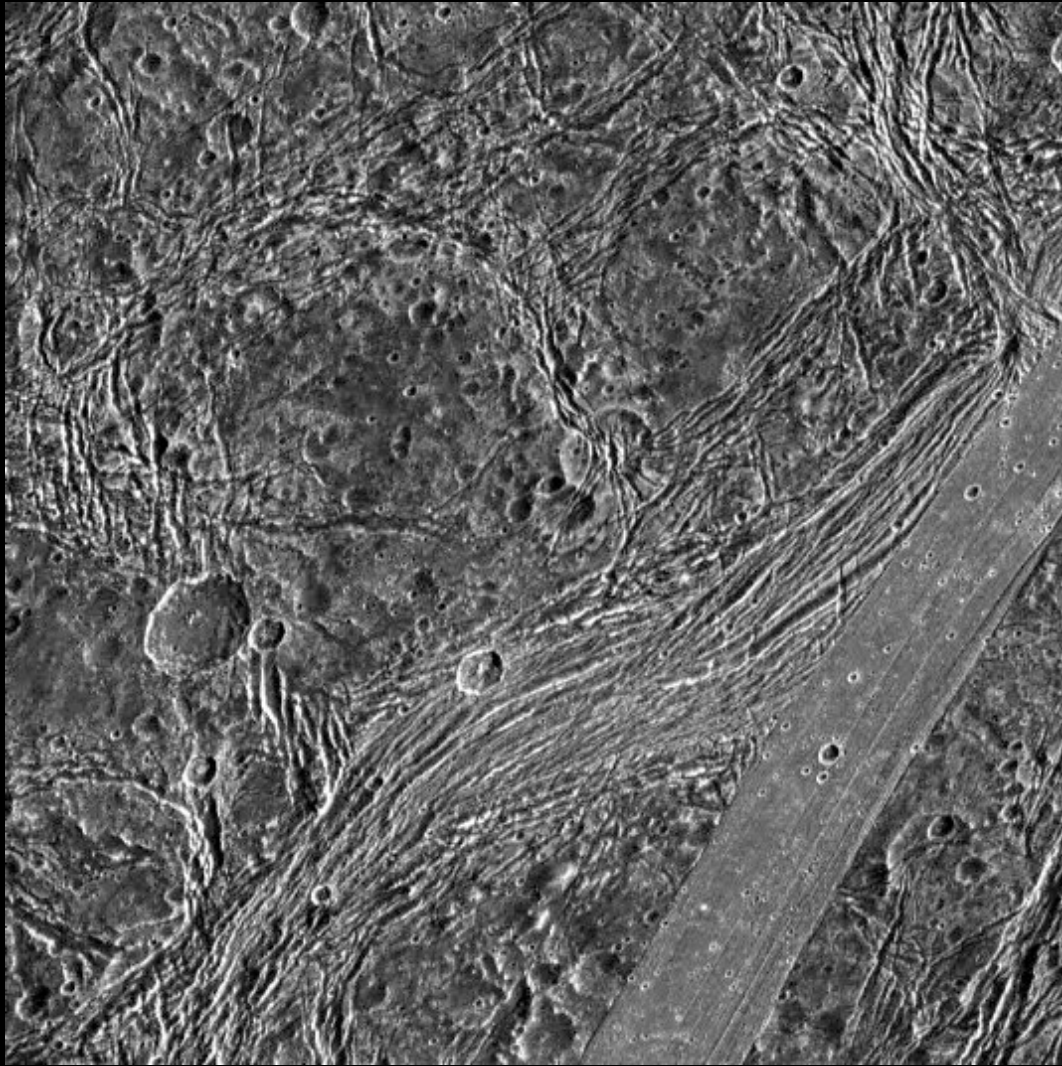
There are few large craters on Ganymede; instead, there are ancient pale ghosts of craters, 100–350 km in diameter, which have lost all vertical relief. Like the features on Callisto, they are called *palimpsests*.



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.

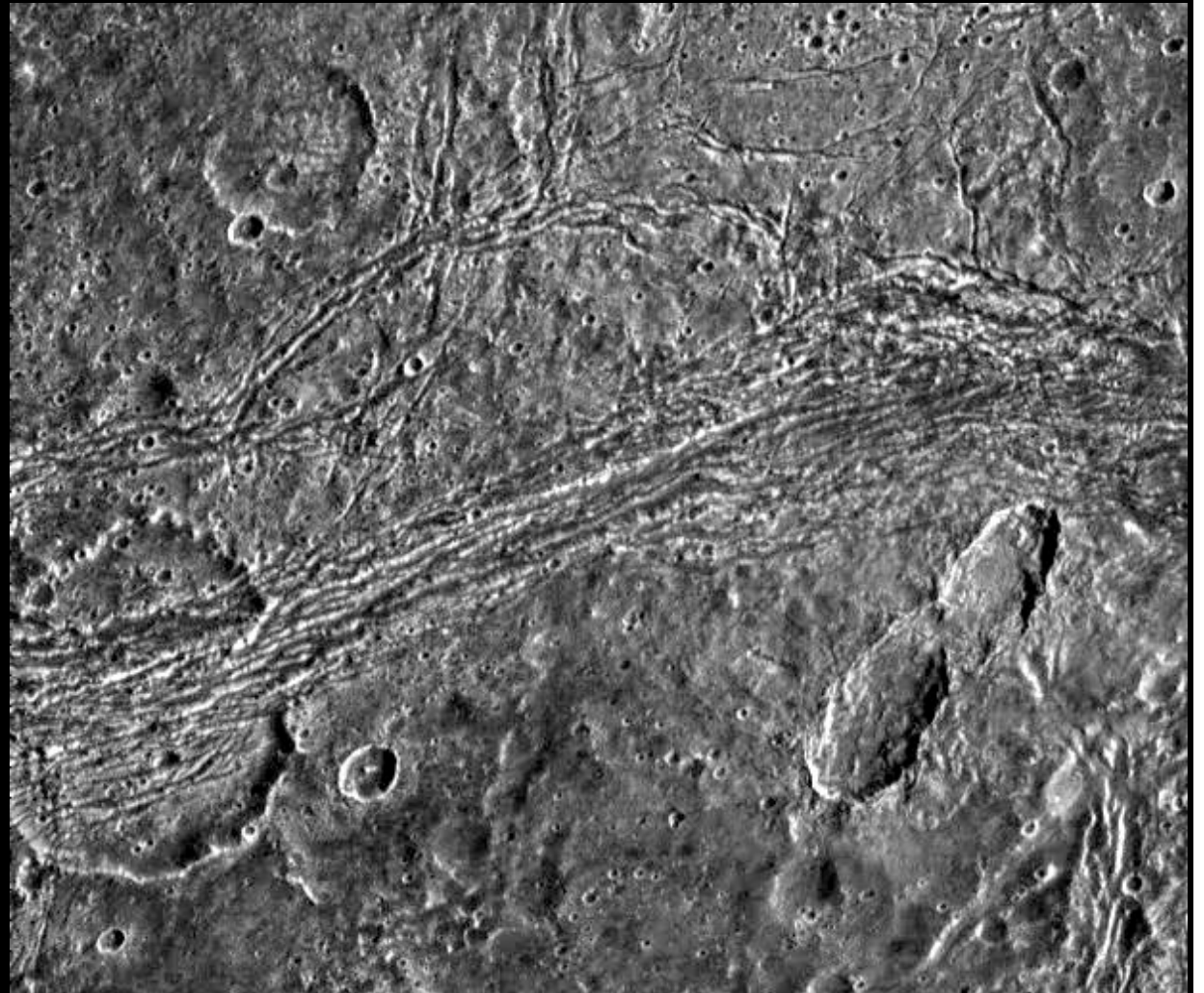


Galileo view of Nicholson Regio, showing heavily fractured dark terrain and a lane of smooth bright terrain.

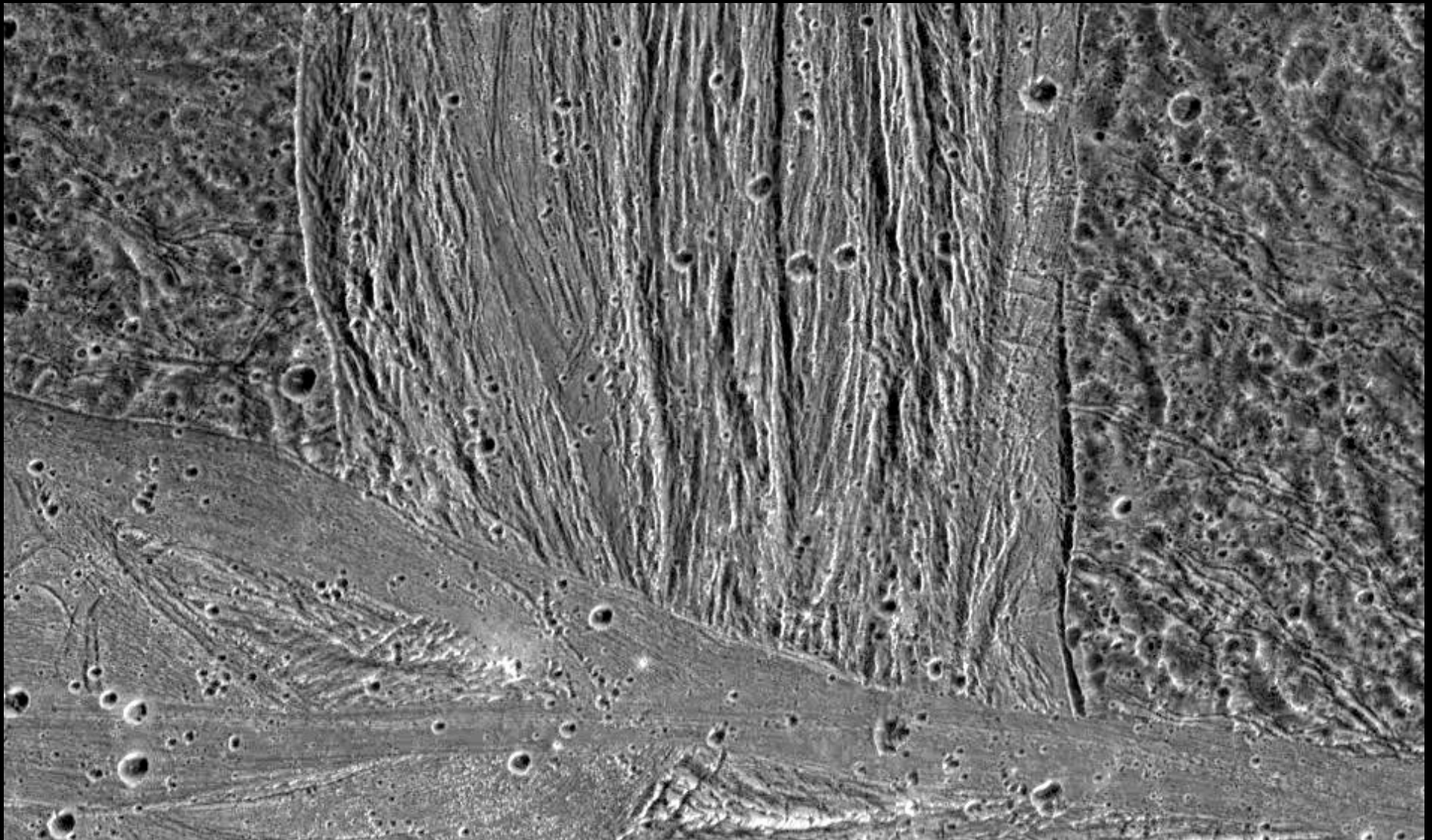
The bright regions are probably formed by fresh material (water?) being extruded onto the surface after tensional faulting of the crust. This extension also produced fractures in the surrounding dark terrain, some of which are focused around old craters.

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.



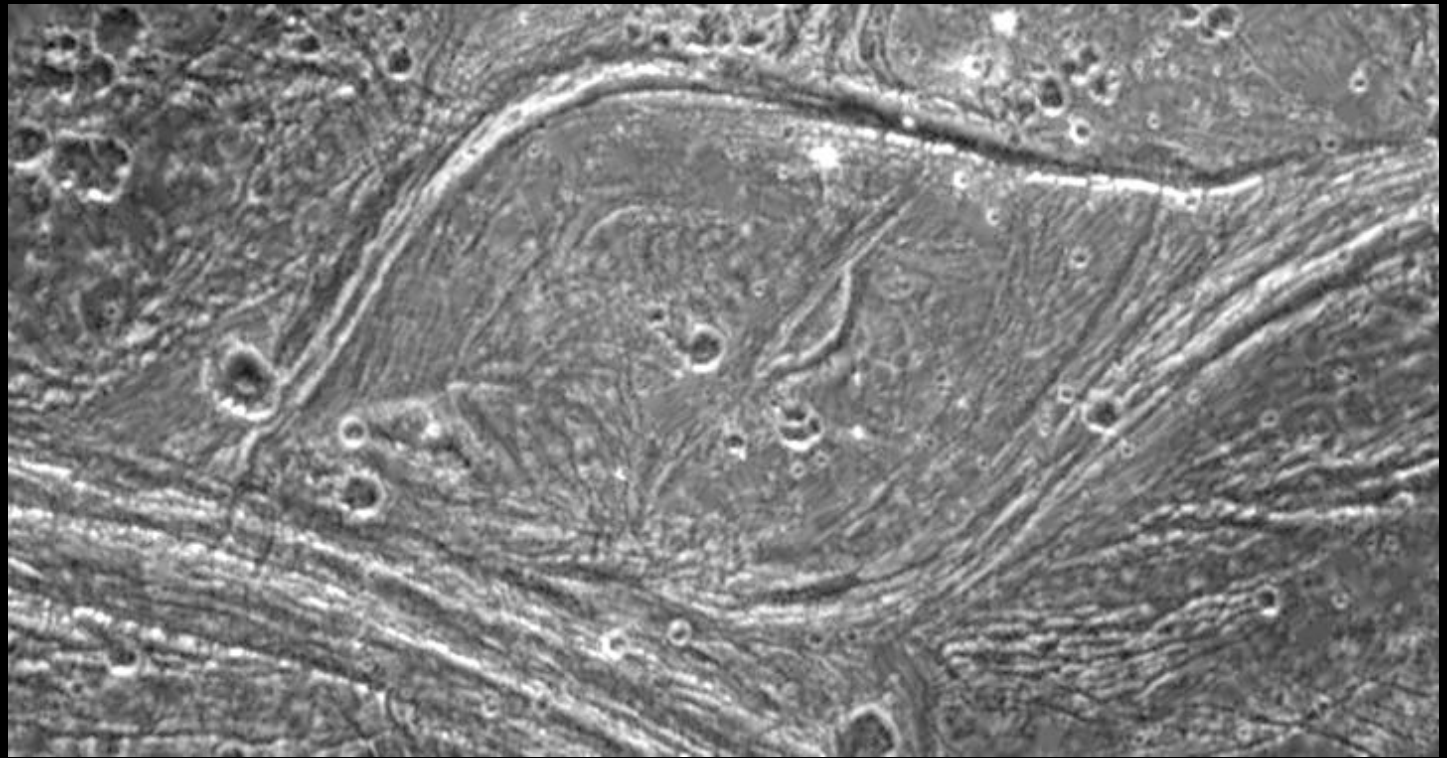
Galileo image of the dark terrain of Nicholson Regio.

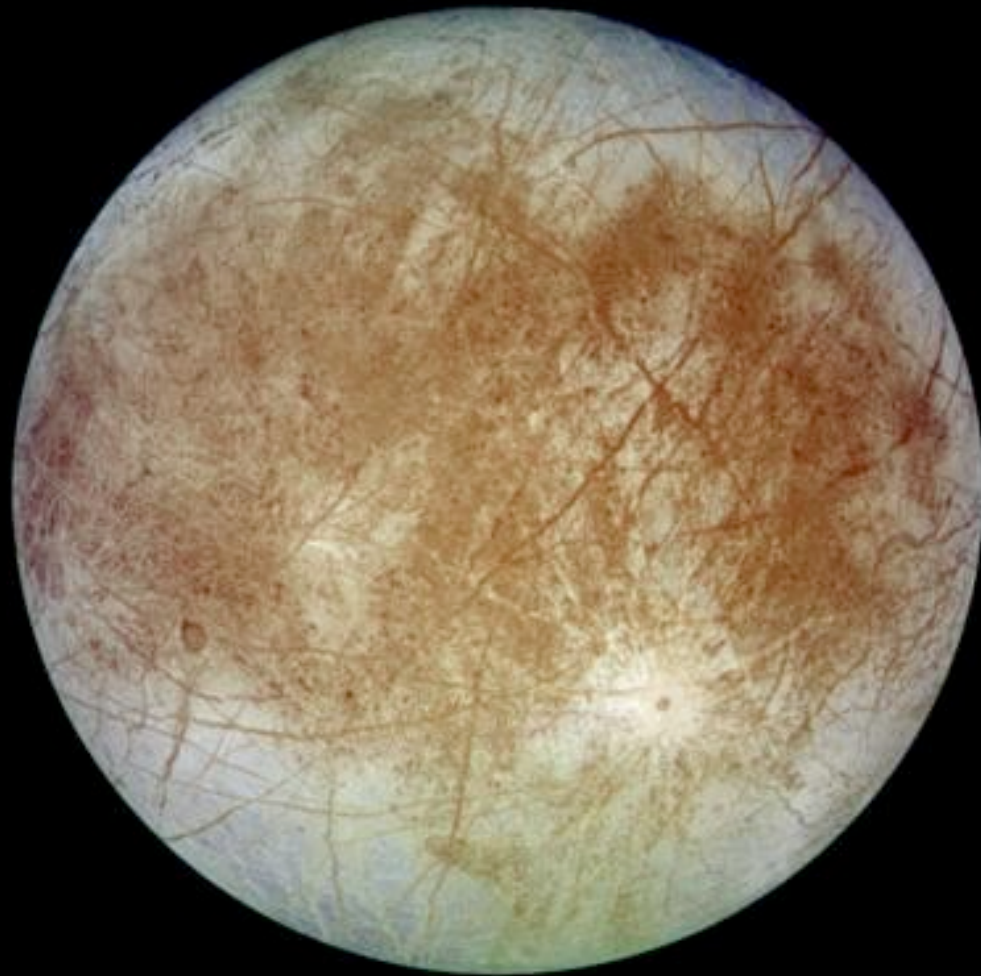


Belts of bright terrain overlap each other, showing that the events that created them were complex and took place over a period of time.

These features must be tectonic in nature. Many pieces of dark terrain have such 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.

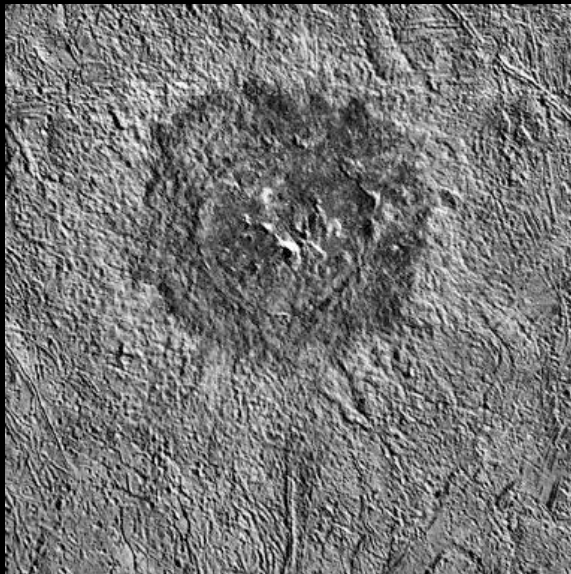




Europa

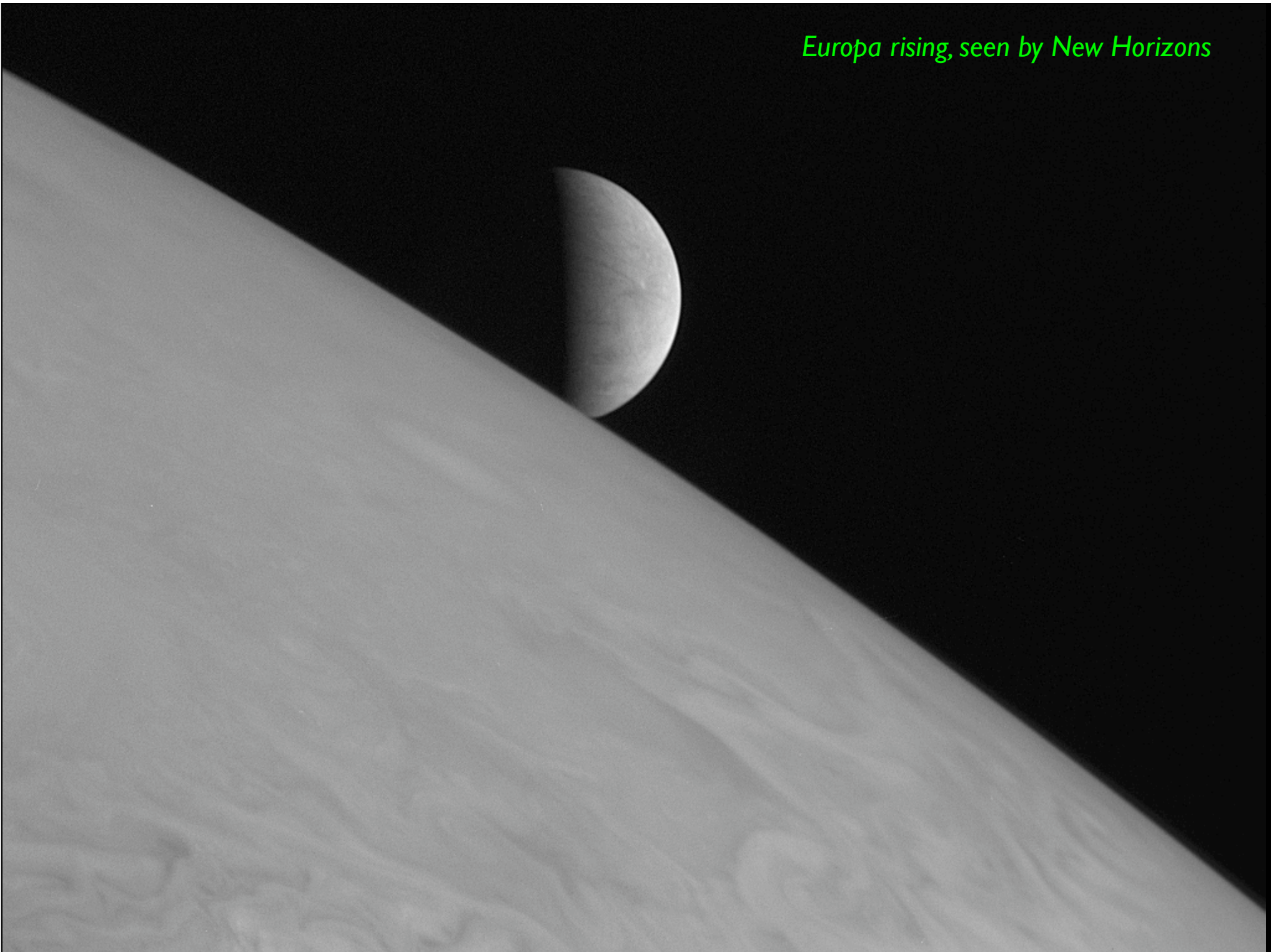
– *ice moon*

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.



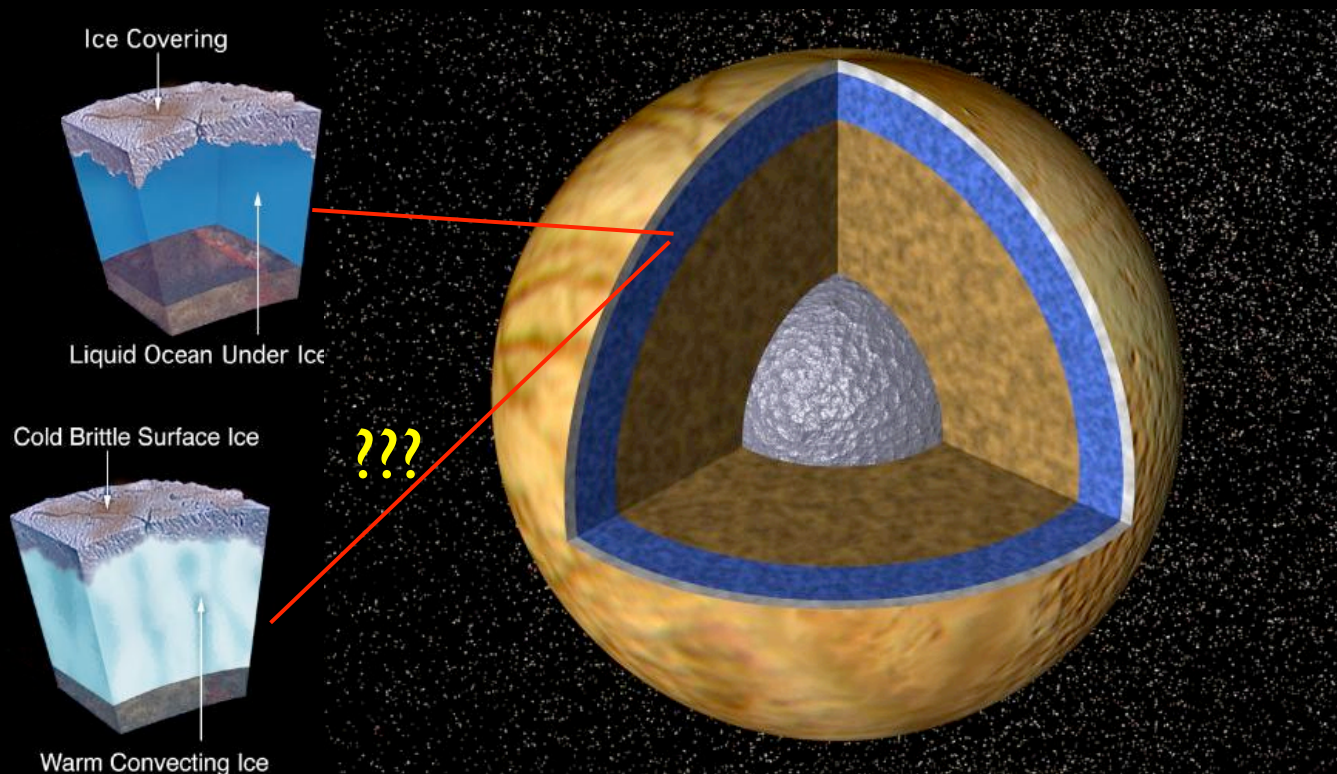
*(right) Voyager view of Europa; (left)
Pwyll crater, 26 km in diameter.*

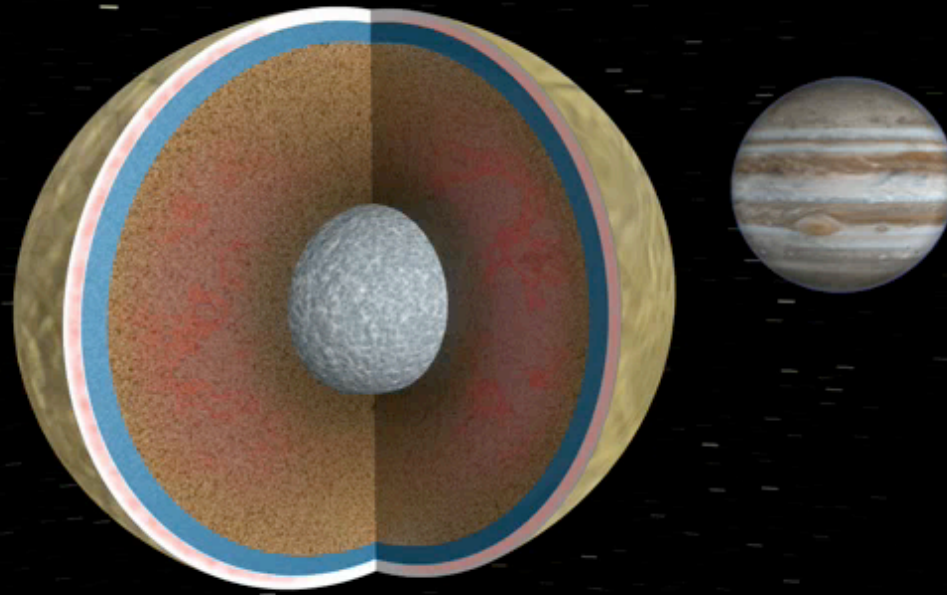
Europa rising, seen by New Horizons



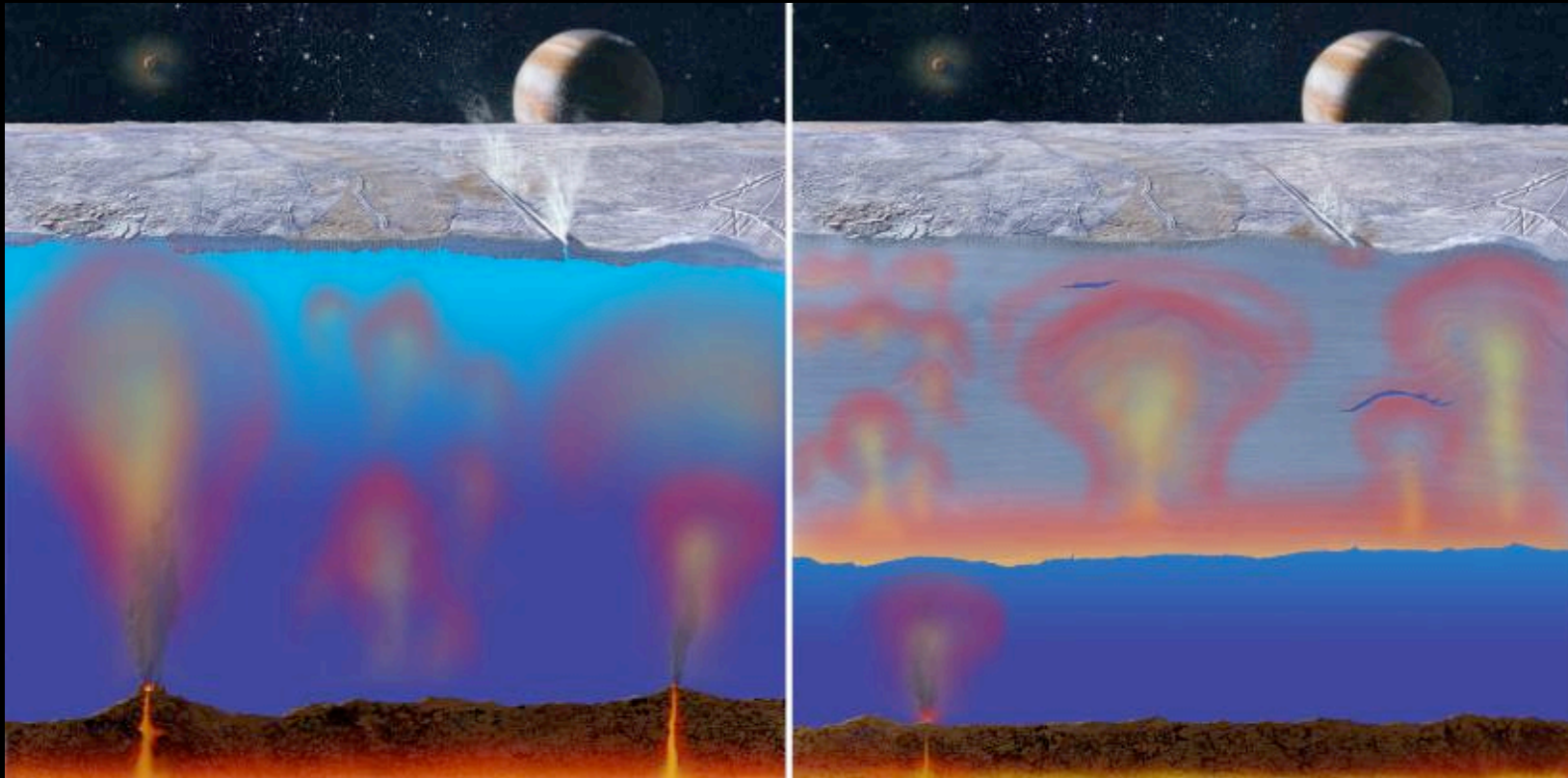
Europa is about the size of our Moon, and density measurements suggest it consists of a rocky core surrounded by an ice and water crust between 10 and 100 km thick; there could also be a metal core. It is not clear whether the subsurface layer is warm convecting ice or liquid water. If a 100 km deep 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.



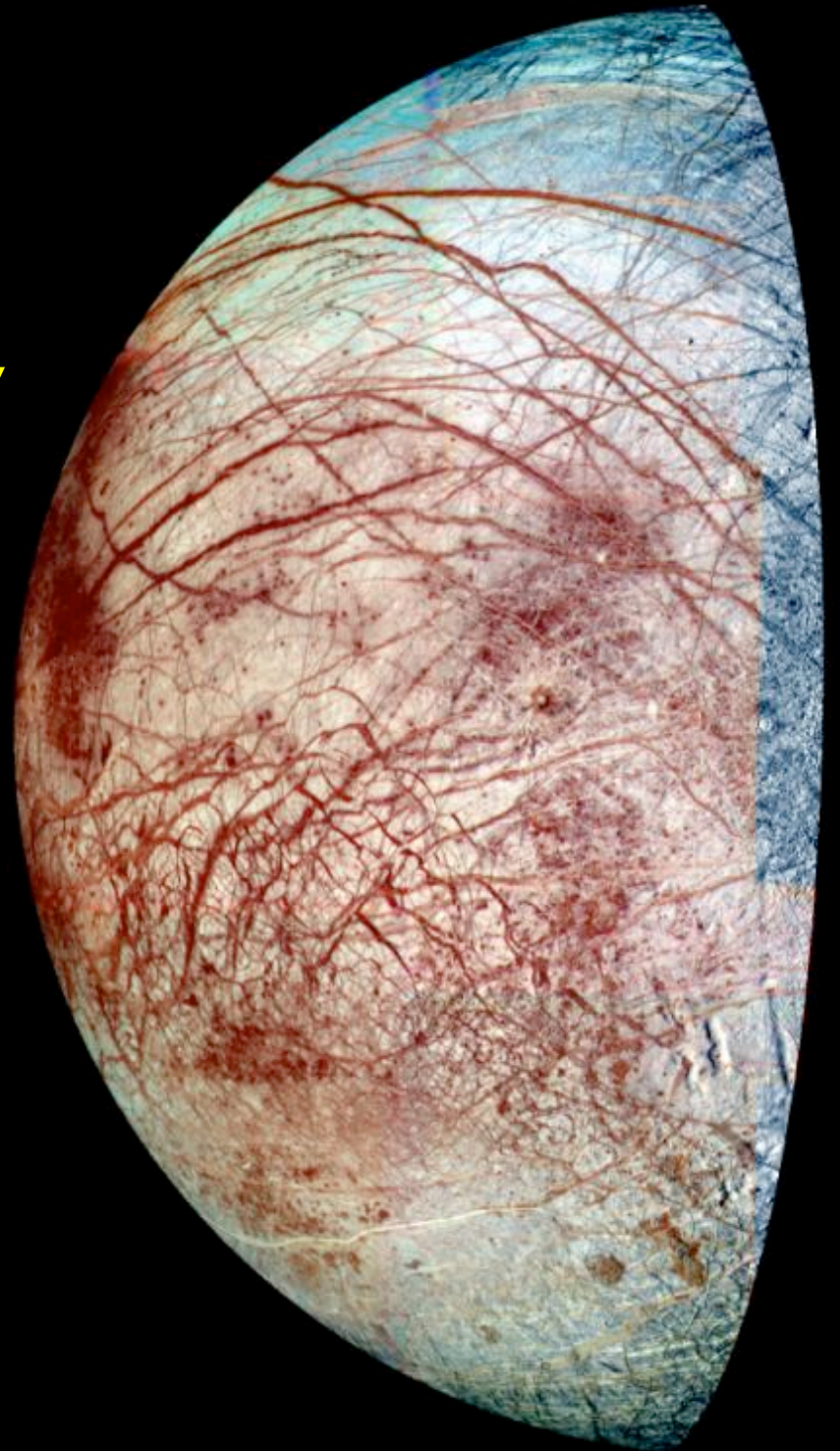


Europa's orbit is eccentric, which means as it travels around Jupiter, Jupiter raises large tides. This tidal kneading causes frictional heating within Europa, which is what keeps Europa's ocean liquid

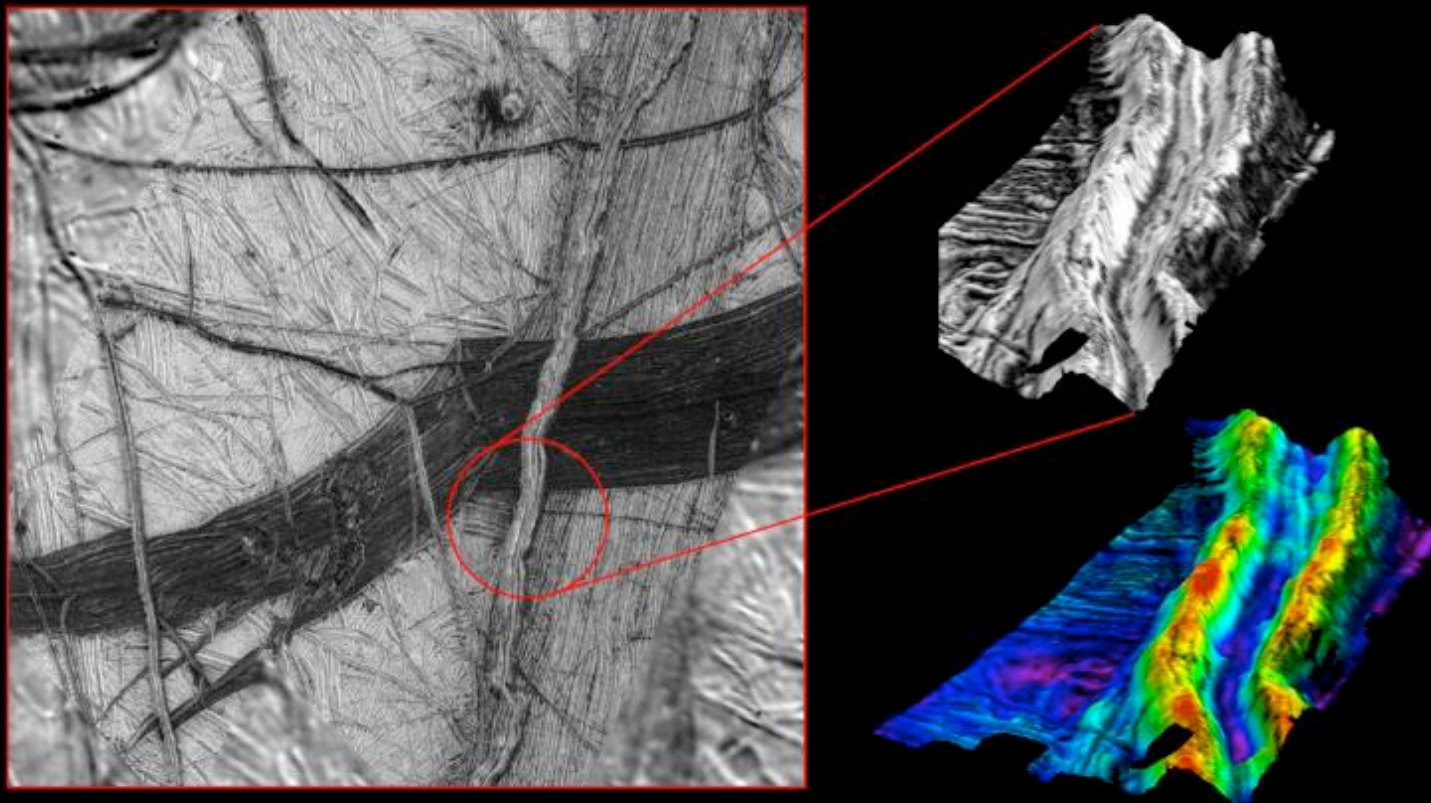


One important question is how thick the ice is. If it is thin (~ 10 km), then the ice can melt directly and there can be contact between the sub-surface ocean and the surface. If the ice is thick (~ 100 km), then heat must be transferred by slowly convecting ice.

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.

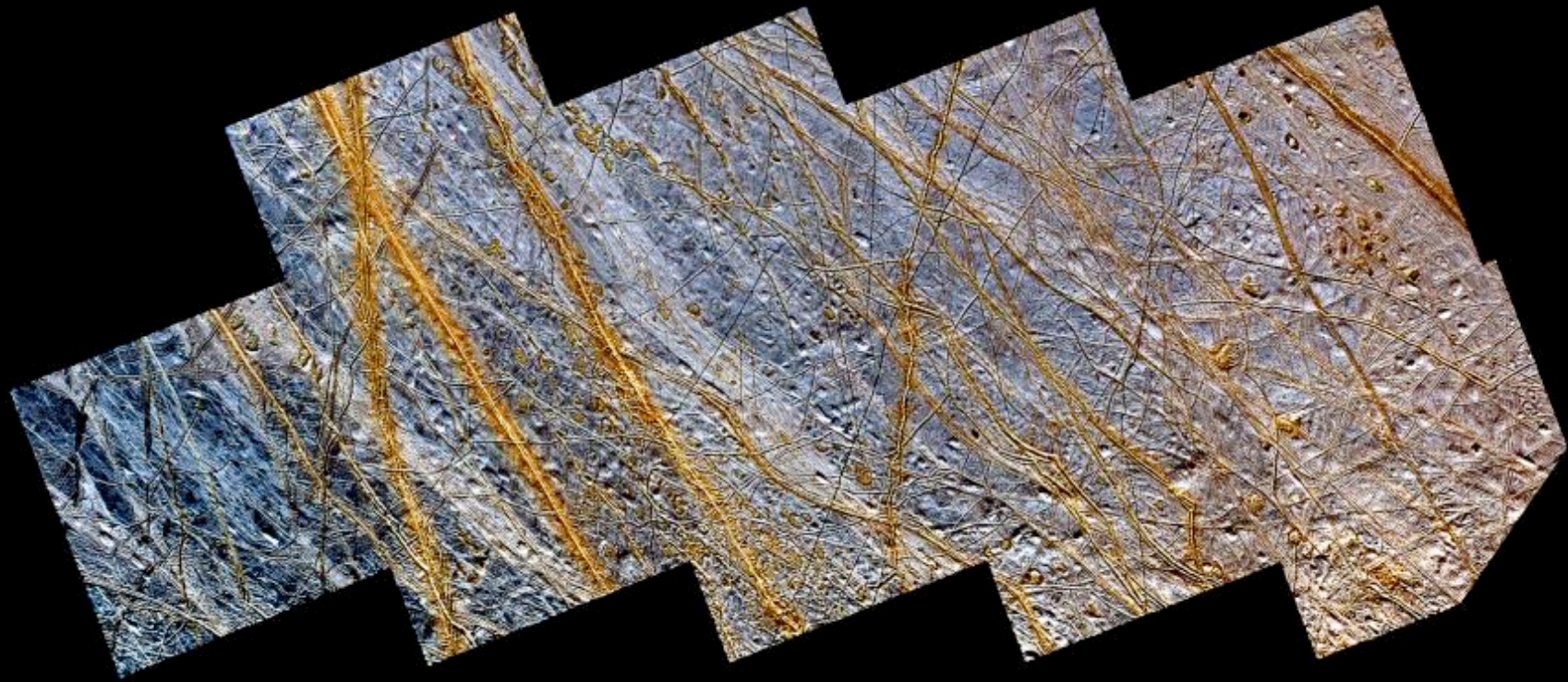


A close-up view of some of these stripes reveals criss-crossing features. The younger pale stripe is actually a double ridge with a deep intervening trough, probably showing where the crust has pulled apart and allowed dark material from beneath the surface to well up and fill the cracks. The ridges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



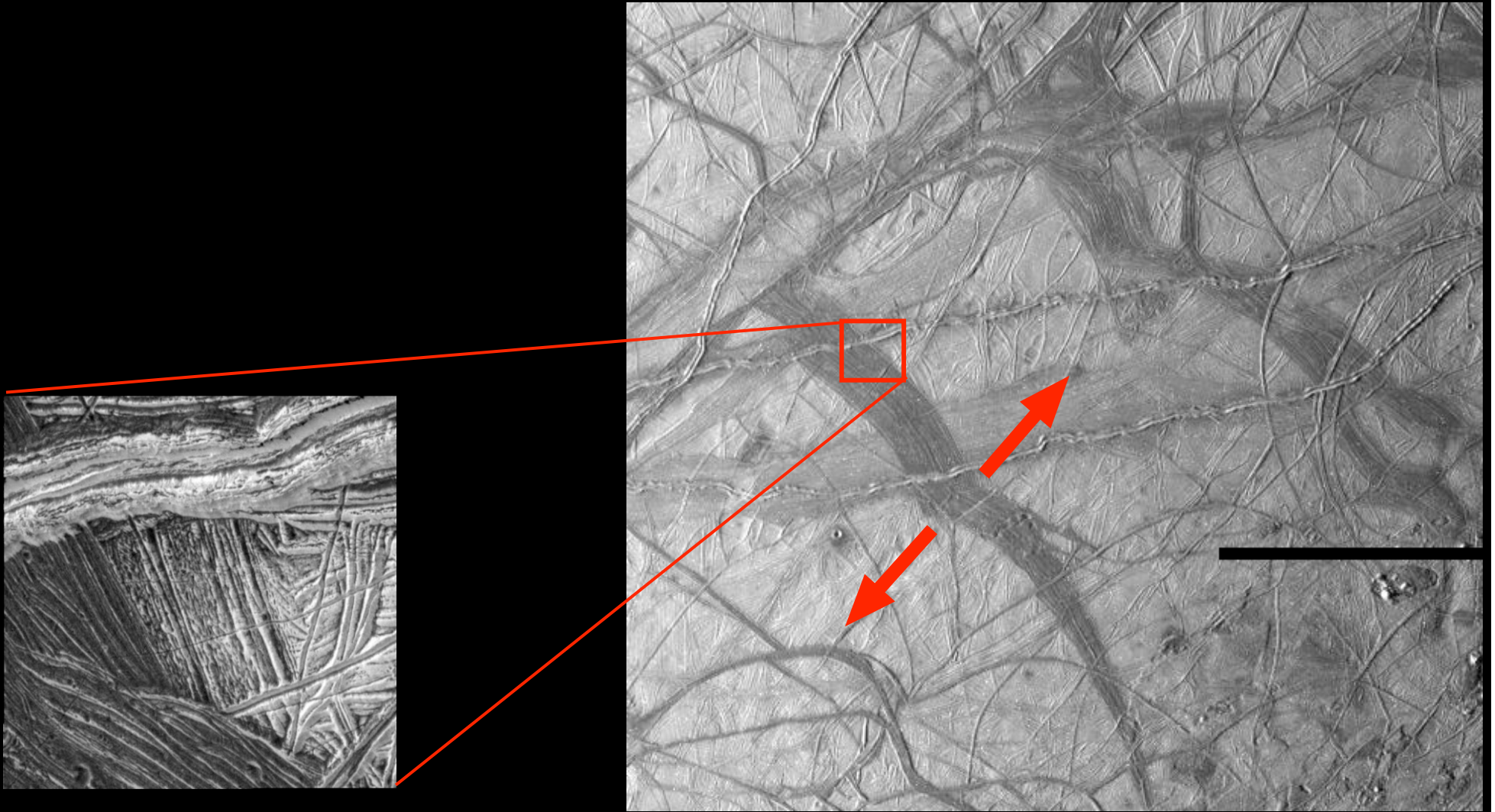
On Earth, volcanic *fissure eruptions* occur when magma flows through a long crack, often caused by plate movement. These fissures usually clog up with in a few hours, confining the eruption to discrete vents along the fissure. On Europa, the long ridges suggest that eruption continued along the whole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

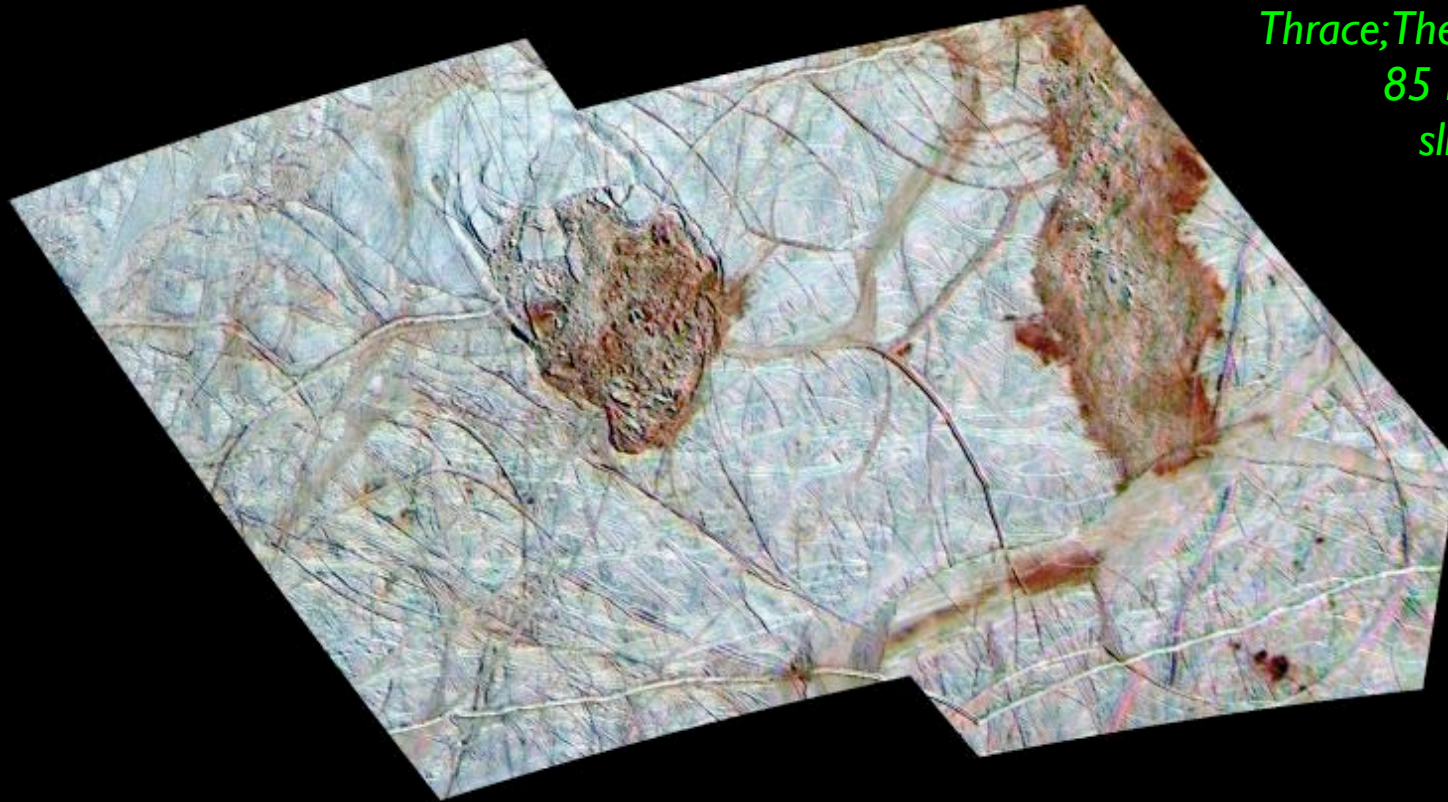




A region in the northern hemisphere showing brown, linear (double) ridges criss-crossing over a geologically older, smoother surface, bluish in tone. The blue surface is composed of almost pure water ice. Dark spots, several kilometres in diameter, are distributed over the surface. The concentration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

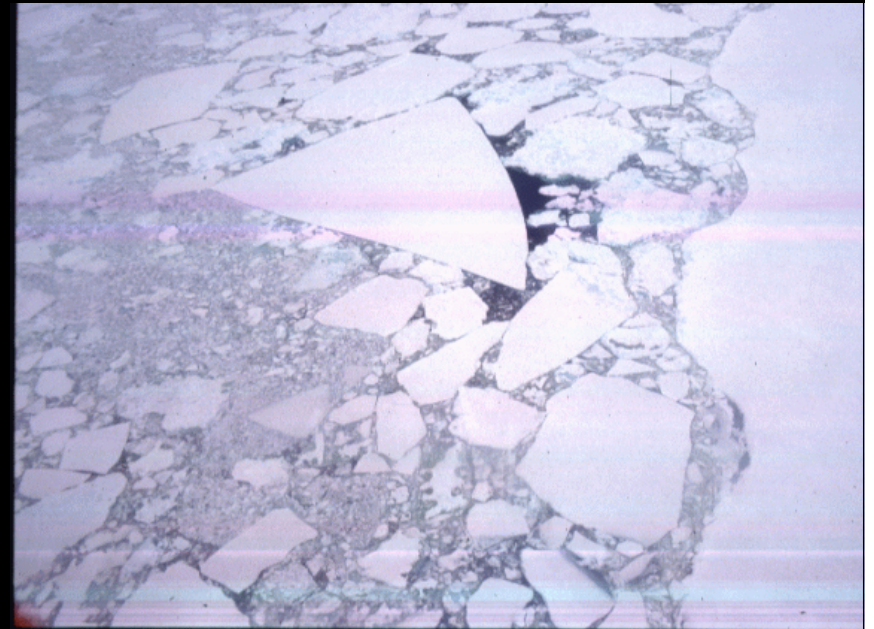
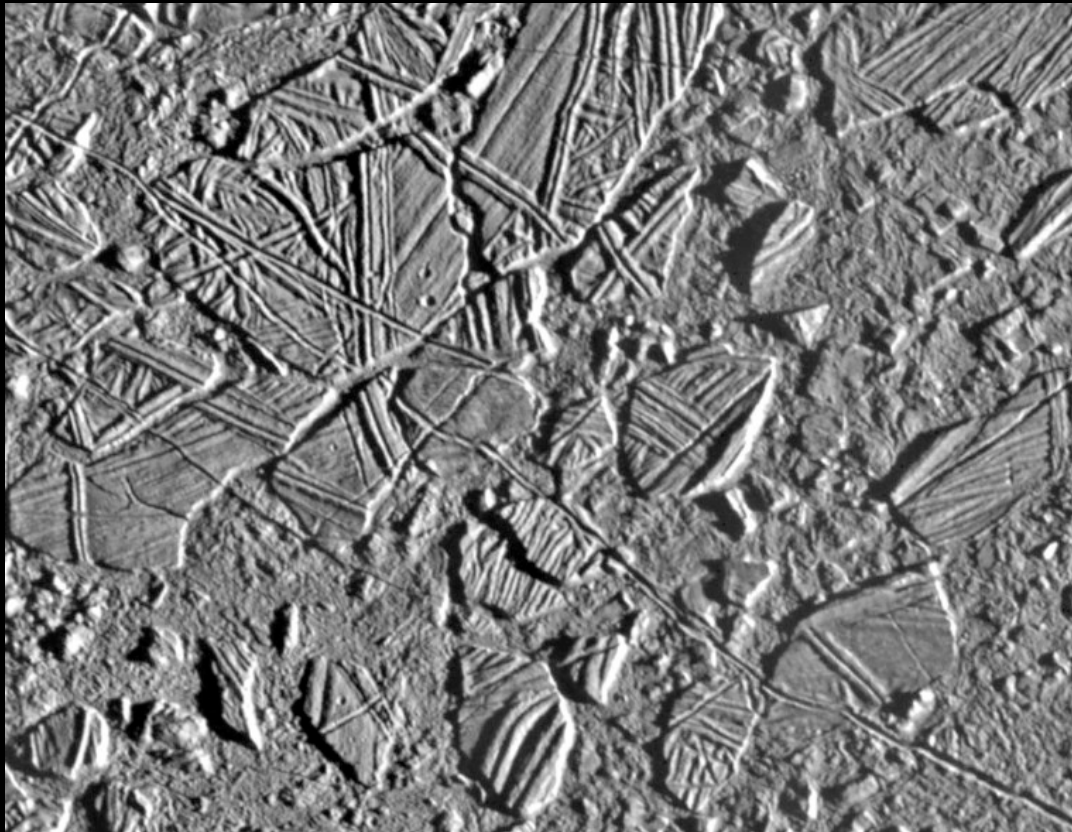




Galileo mosaic of Thera (left) and Thrace; Thera is about 70 km wide by 85 km high and appears to lie slightly below the level of the surrounding plains.

Thera and *Thrace* are two dark, reddish regions of enigmatic terrain that disrupt the older icy ridged plains. Spectral data suggest the regions are rich in magnesium sulfate. One model for the formation of these and other chaos regions on Europa is complete melt-through of Europa's icy shell from an ocean below.

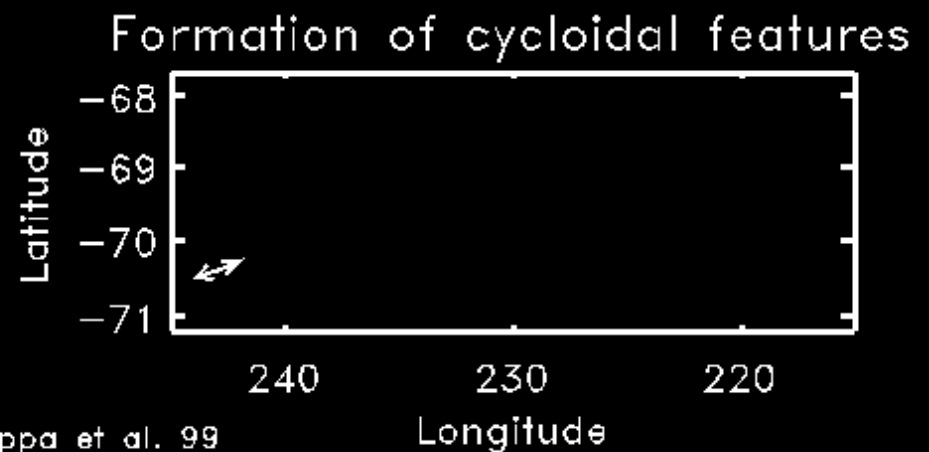
The *Conamara Chaos* is a region of bright terrain which has broken into a multitude of irregular fragments 1–10 km across, whose edges are cliffs 100–200m high. This is the clearest evidence for a subsurface ocean, topped by an ice crust only a few kilometres thick.



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).



Europa has a series of distinctive *cycloidal ridges*: long arc structures that cut across other terrain. Models show that, if the ice is thin, a crack in the surface will propagate in an arc because of the changing tidal stress during the day.



Hoppa et al. 99
LPL, Univ. of Arizona

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

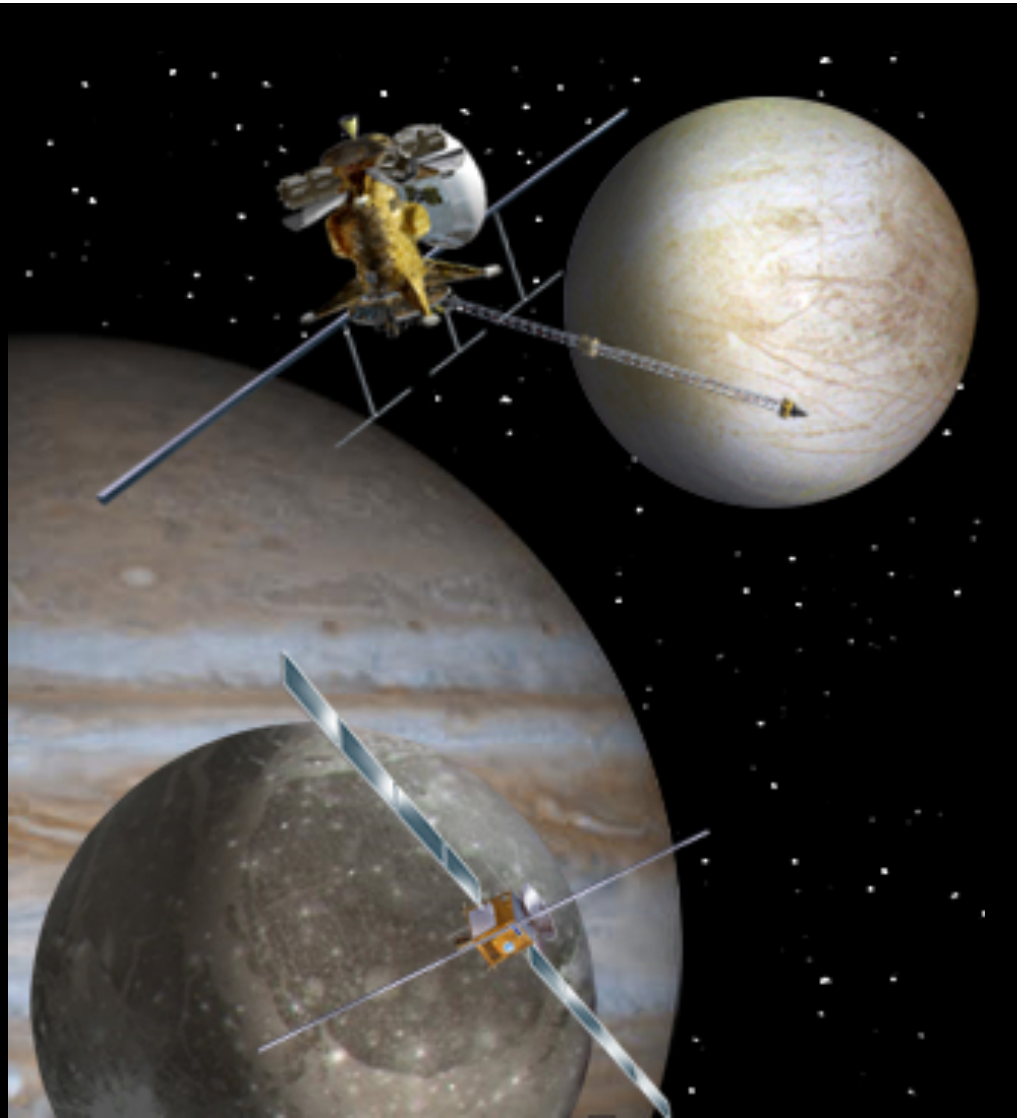
We also have no idea how long it took to form the features we see. The spreading could be slow like on Earth's sea floor (cm per year), in which case the double ridges would take 50,000 years to form; or they could form in hours, if they form like a Hawaiian erupting fissure.

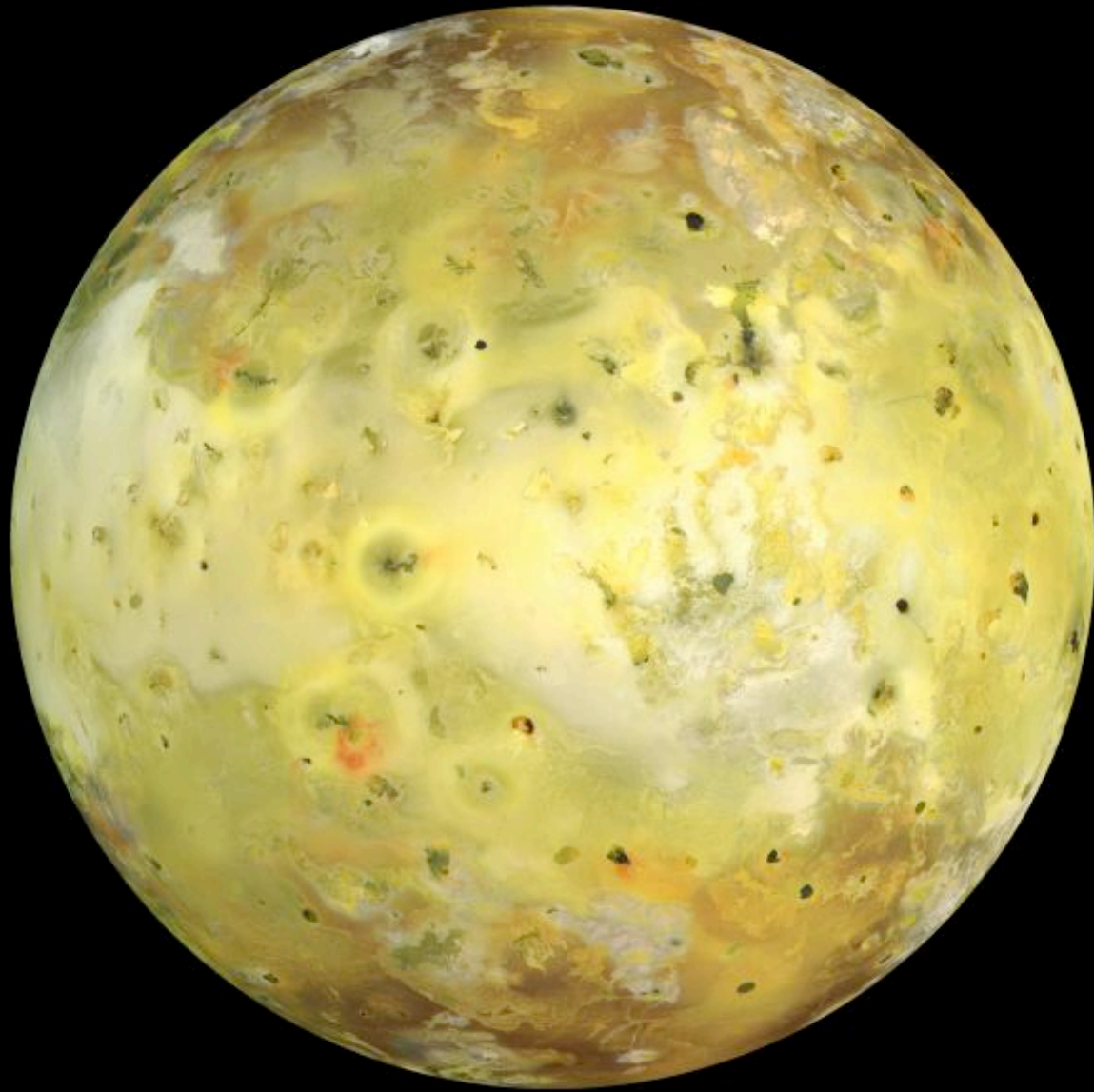
It seems likely that if Europa has been active as recently as a few million years ago, it probably still is.

In February 2009 NASA's next flagship mission was announced.

The *Europa Jupiter System Mission* would launch two orbiters, one built by NASA to study Europa, and the other by ESA to study Ganymede. Launch was announced for 2020, with a scheduled arrival time in 2026.

However, in April 2011, ESA announced that due to NASA's budget constraints, it is planning to proceed alone with a Jupiter mission, renamed the *Jupiter Icy Moon Explorer*.





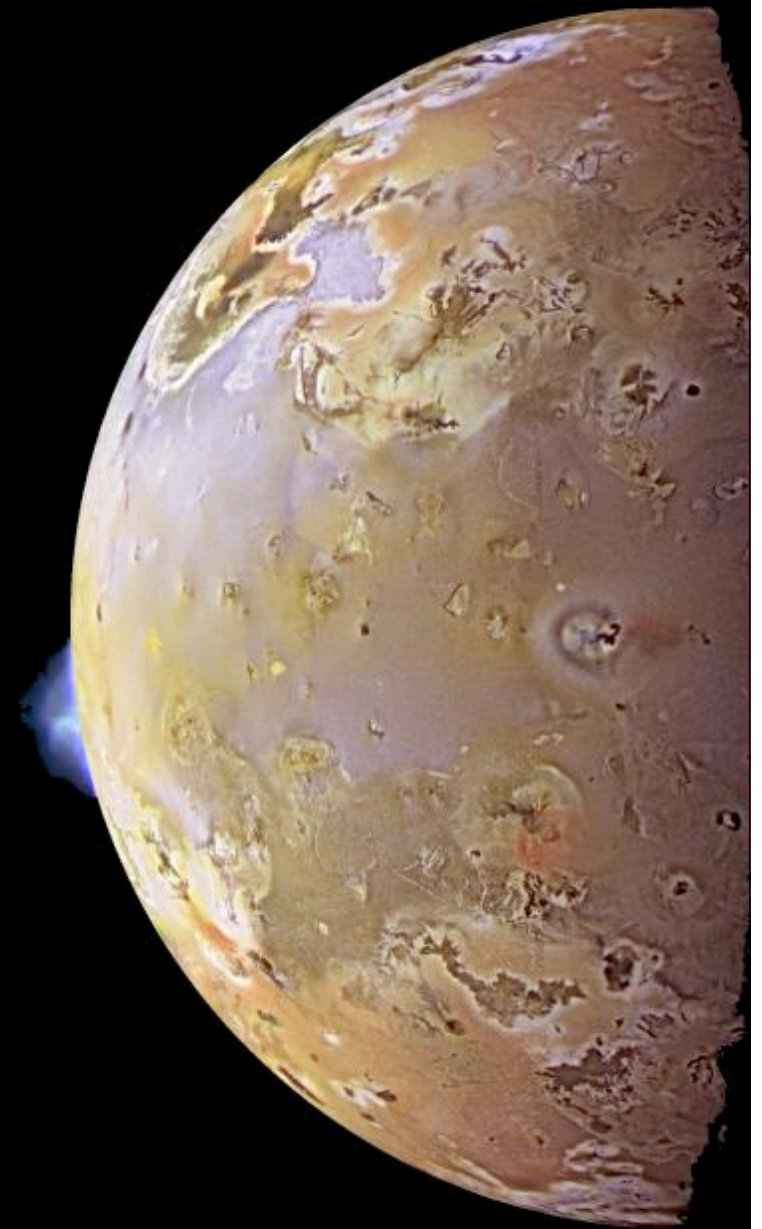
Io

– *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 $\bar{\omega}_i$ 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

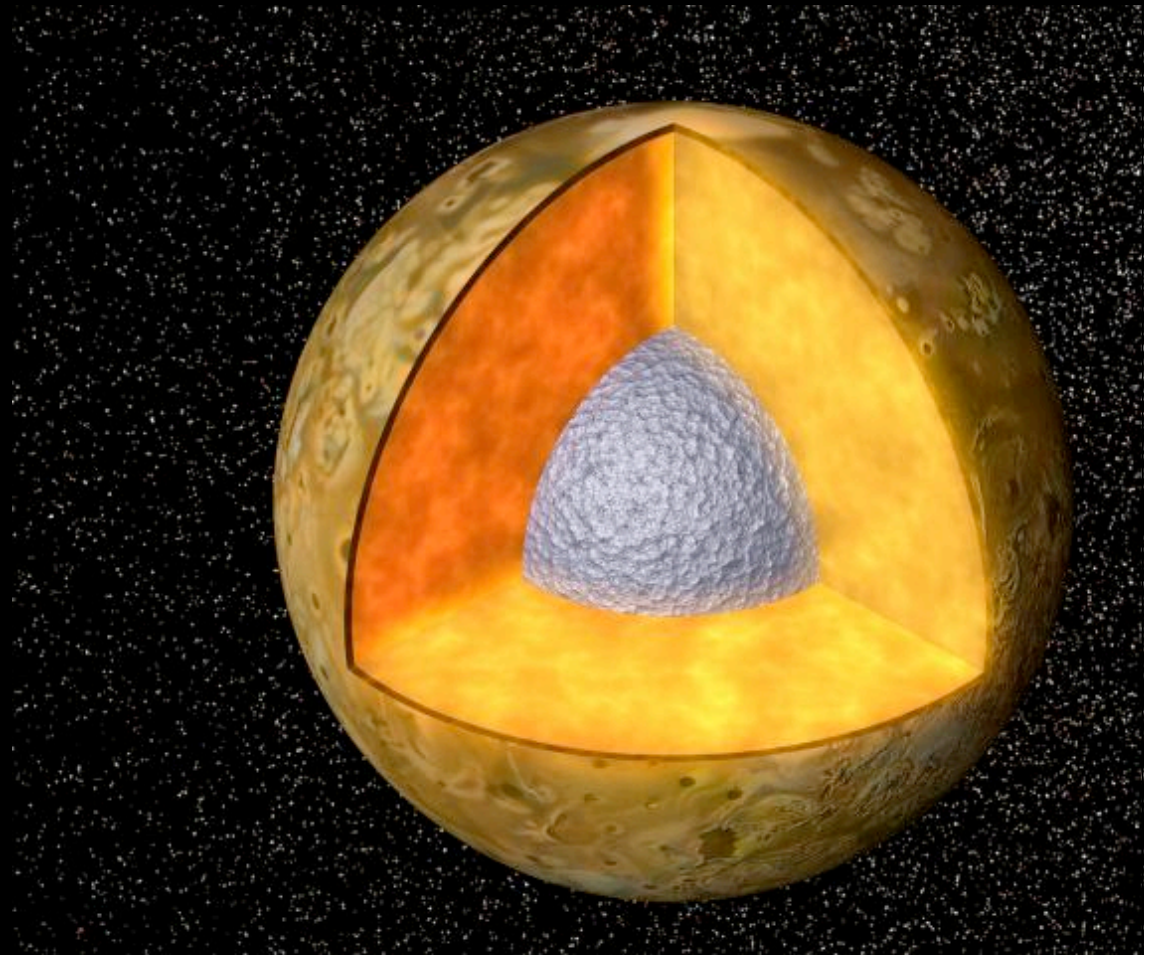
observational error such that $\lambda_1 - 3\lambda_2 + 2\lambda_3 = 180^\circ$ with no observed libration amplitude. This is the well-known Laplace relation and is often called simply the libration. In addition, the mean motions of 1 and 2 and, separately, of 2 and 3 are nearly in the ratio 2:1

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

compared to $n_2 = 101.375/\text{day}$. The nearness of the two sets of mean motions to the 2:1 commensurability suggests that some of the resonance variables $\lambda_1 - 2\lambda_2 + \bar{\omega}_1$, $\lambda_1 - 2\lambda_2 + \bar{\omega}_2$, $\lambda_2 - 2\lambda_3 + \bar{\omega}_2$, and $\lambda_2 - 2\lambda_3 + \bar{\omega}_3$ 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-

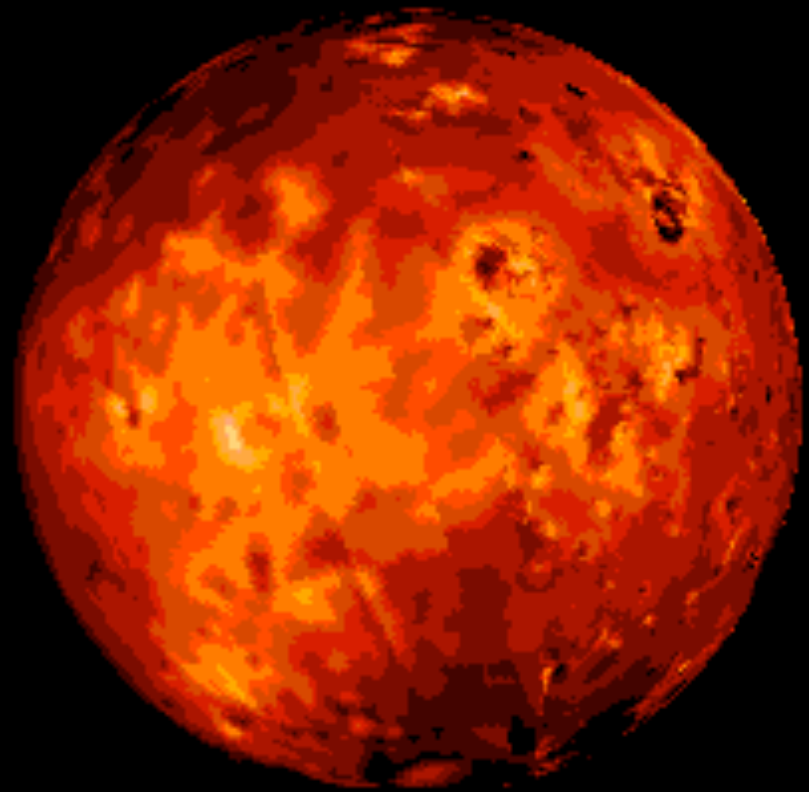
Paper published by Stanton Peale et al., one week before Voyager I encountered Jupiter in 1979

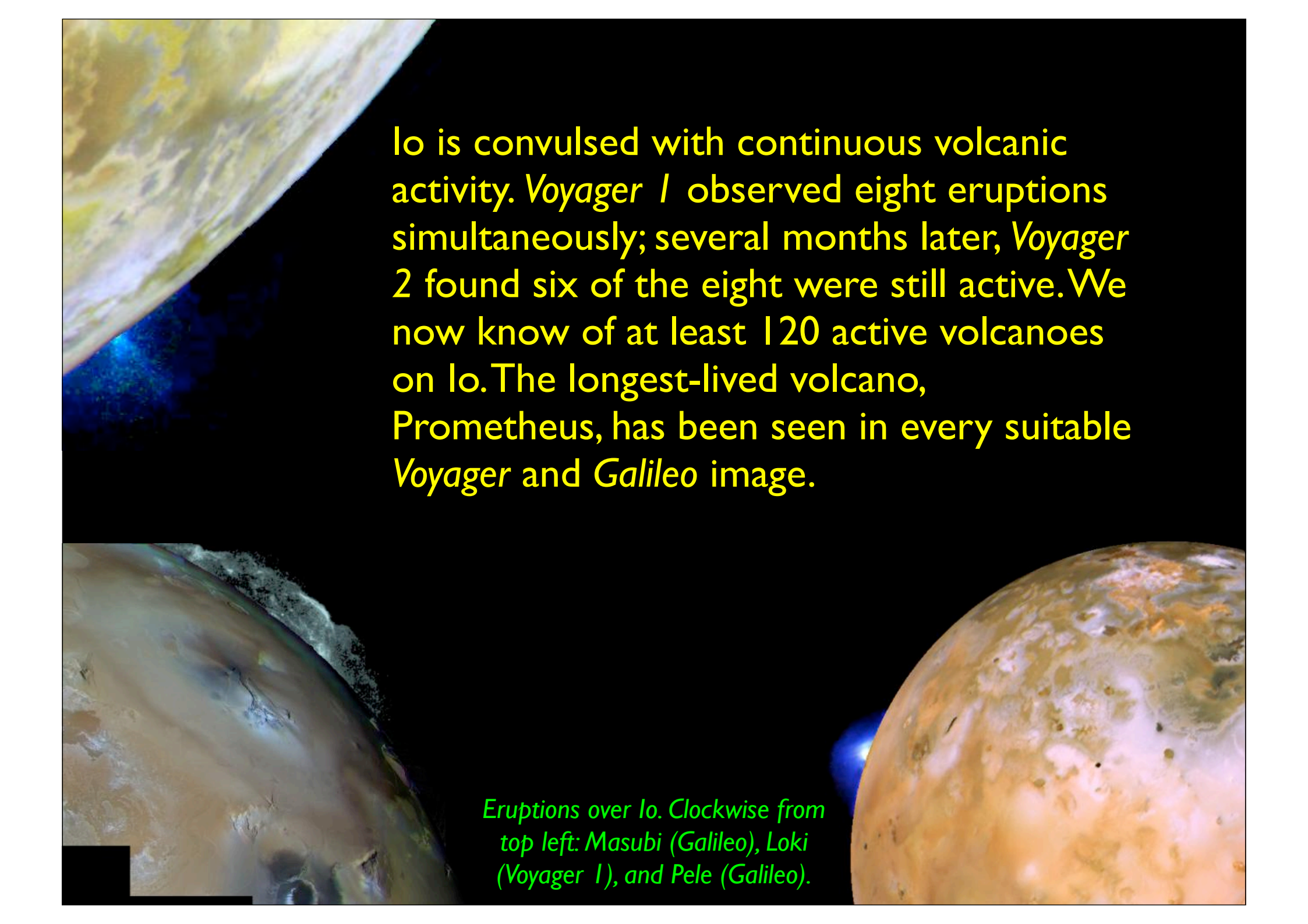
Io's density suggests its interior must be rocky, with little or no ice content. Gravity data from *Galileo's* close flyby show that it has a dense core, probably iron mixed with sulphur. Surrounding the core is a silicate mantle, covered by a crust, at least partly sulphur, about 50 km thick.



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.

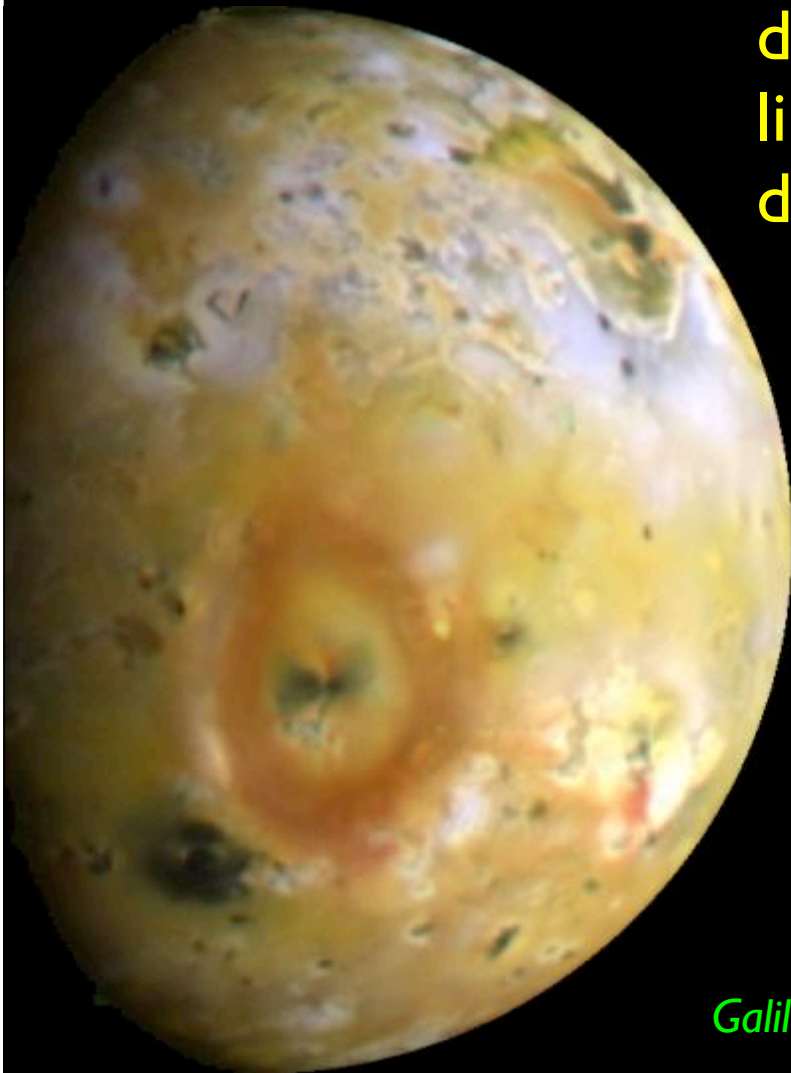




Io is convulsed with continuous volcanic activity. *Voyager 1* observed eight eruptions simultaneously; several months later, *Voyager 2* found six of the eight were still active. We now know of at least 120 active volcanoes on Io. The longest-lived volcano, Prometheus, has been seen in every suitable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



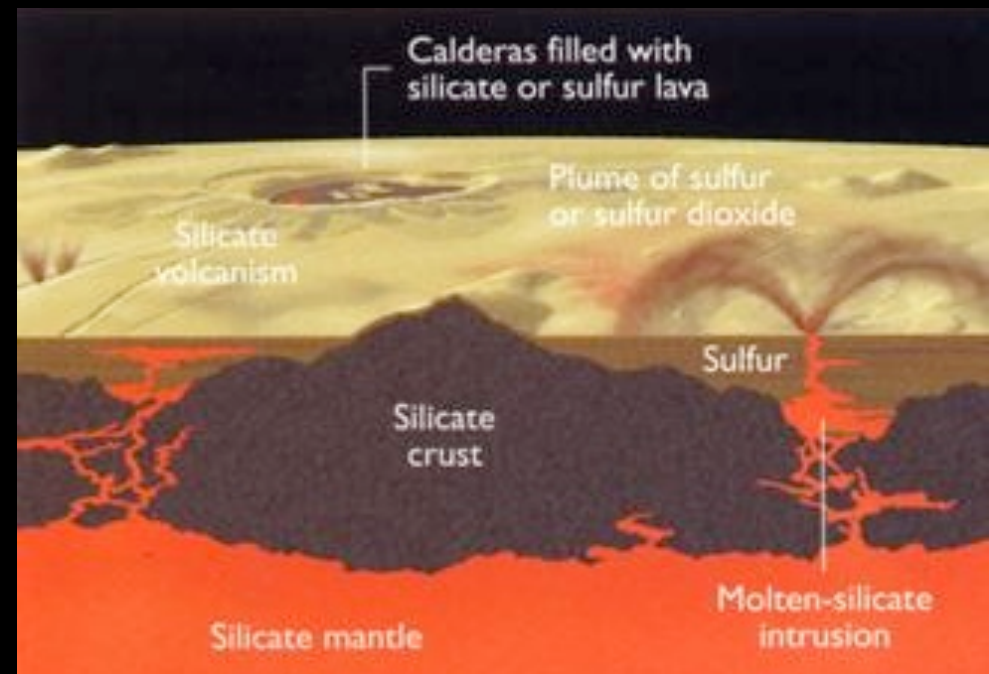
Galileo image of Pele.

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.



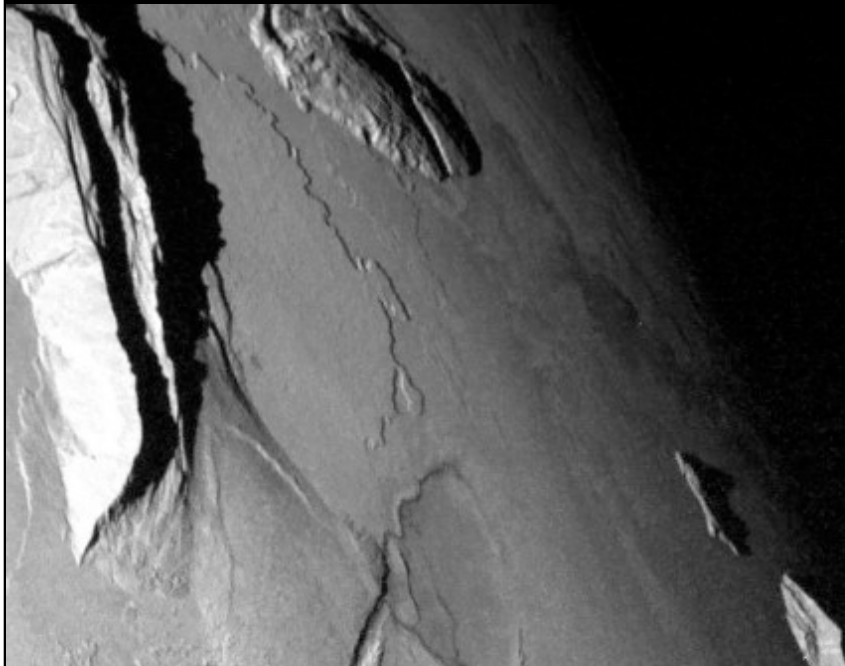
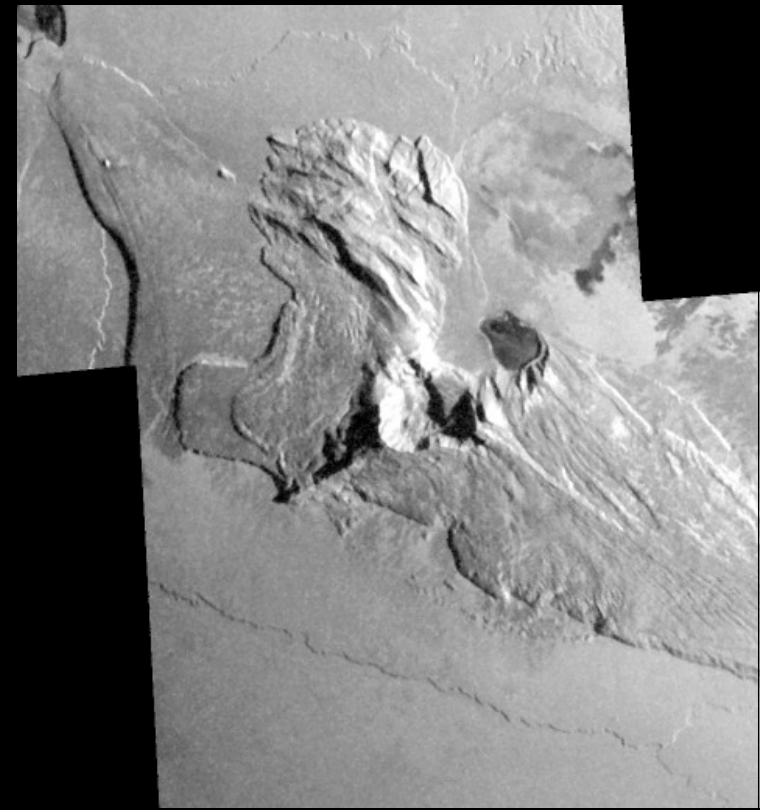
An active eruption at Tvashtar Catena, caught in action in November 1999 by Galileo. The false colour image shows the newly erupted hot lava as yellow-white because of infrared emission. The picture is about 250 km across.

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



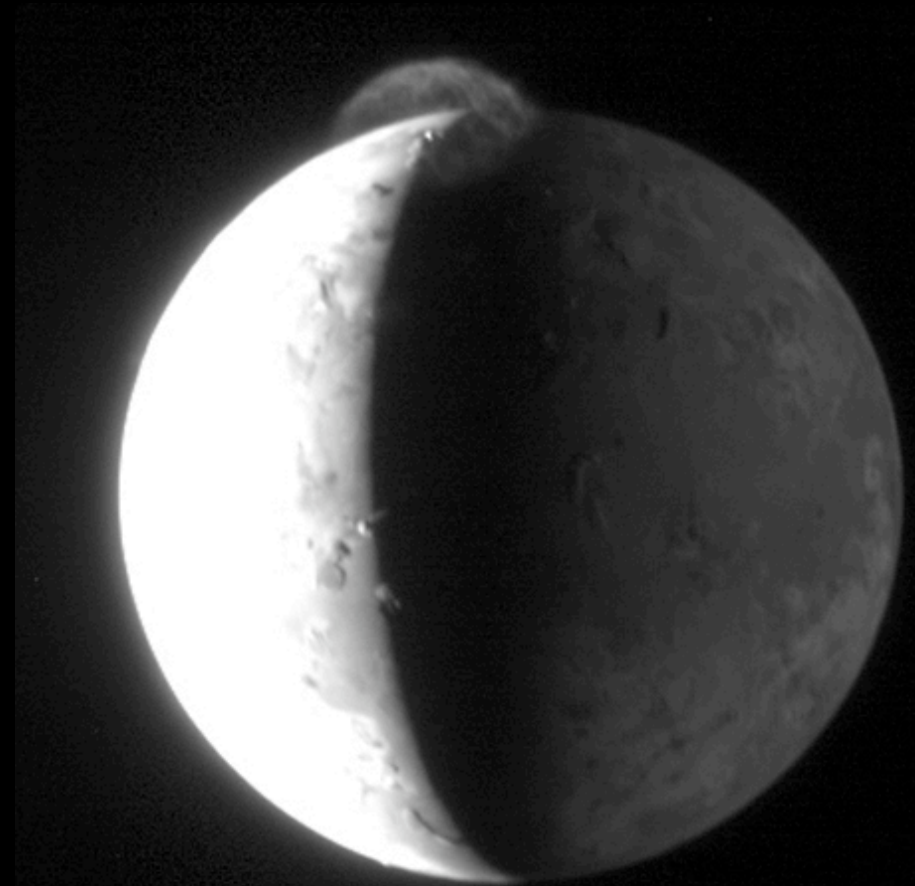
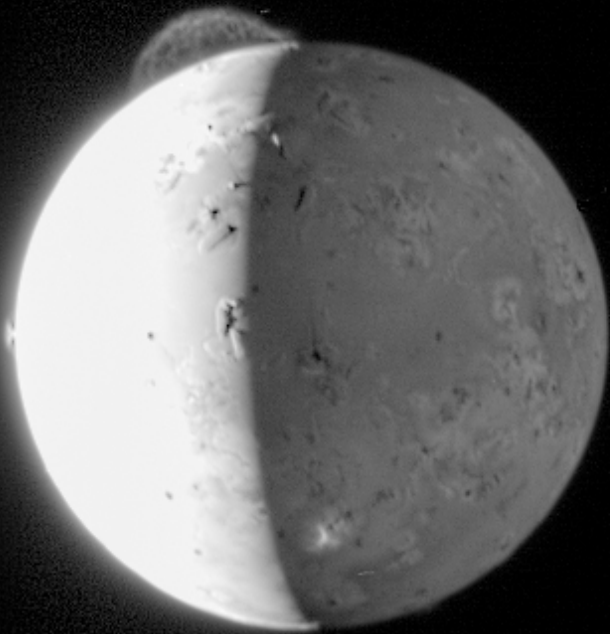
Schematic depiction of the major phenomena found on Io.

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.



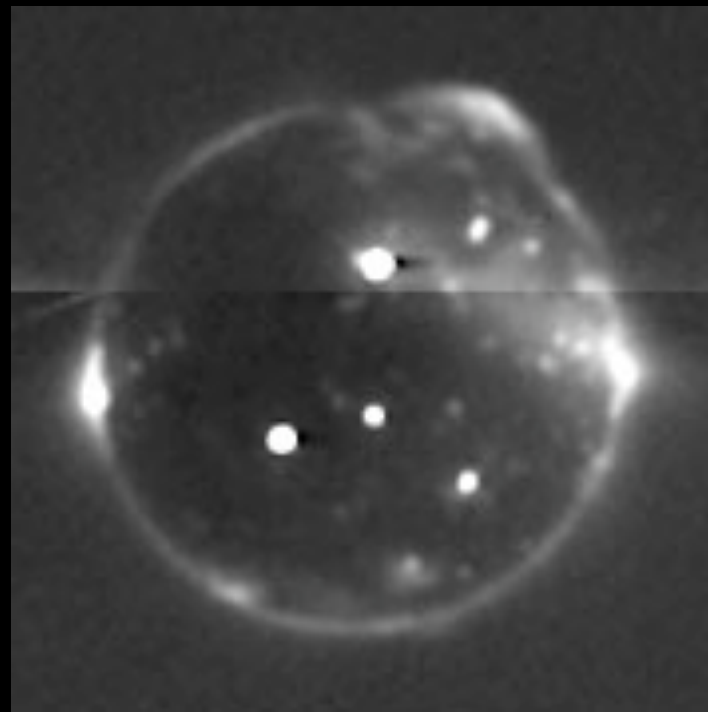
Mountains on Io: Tohil Mons (above) and Mongibello Mons (left). An older mountain with more subdued topography can be seen near the top centre of this image.

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.

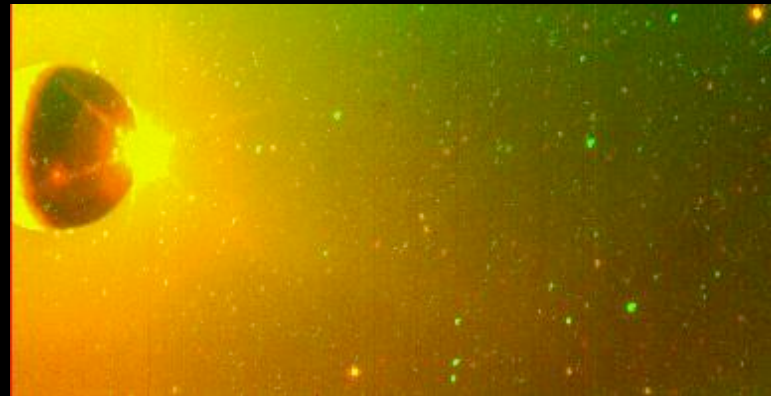
Reiden
Pele



new volcano

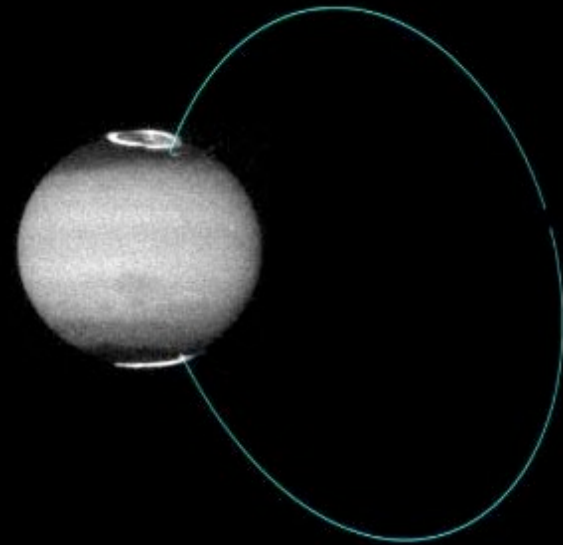
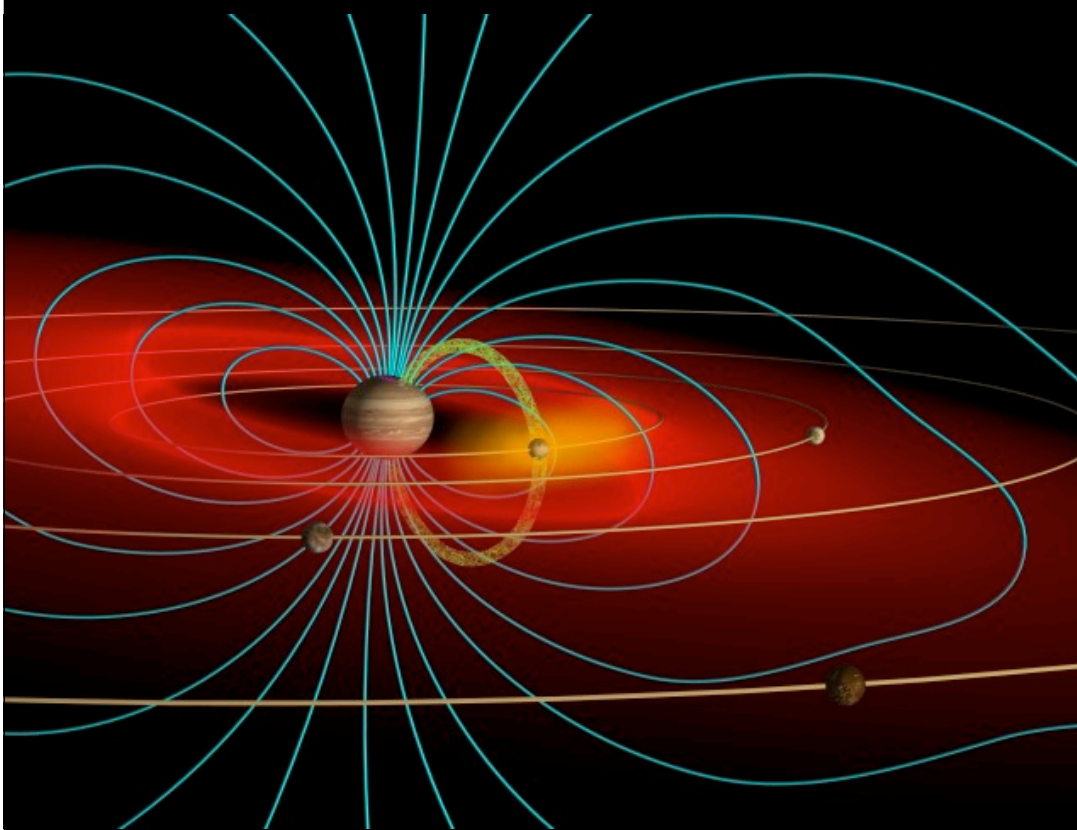
Marduk

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.

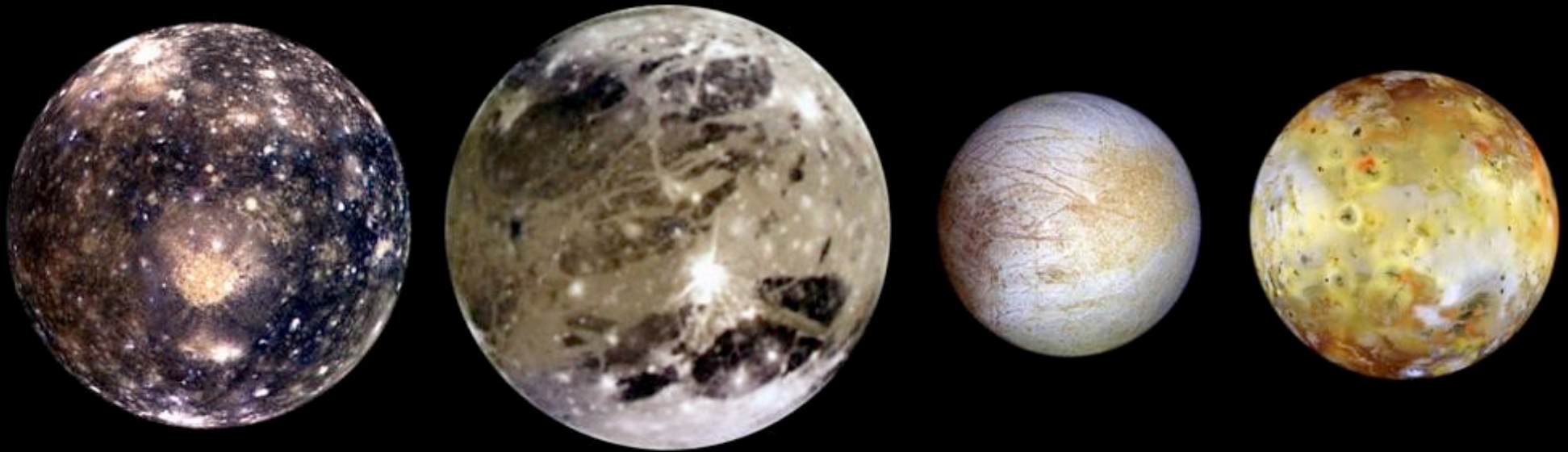




“There’s one lesson we learned from
Voyager: Nature is much more inventive
than our imaginations”

– *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 →



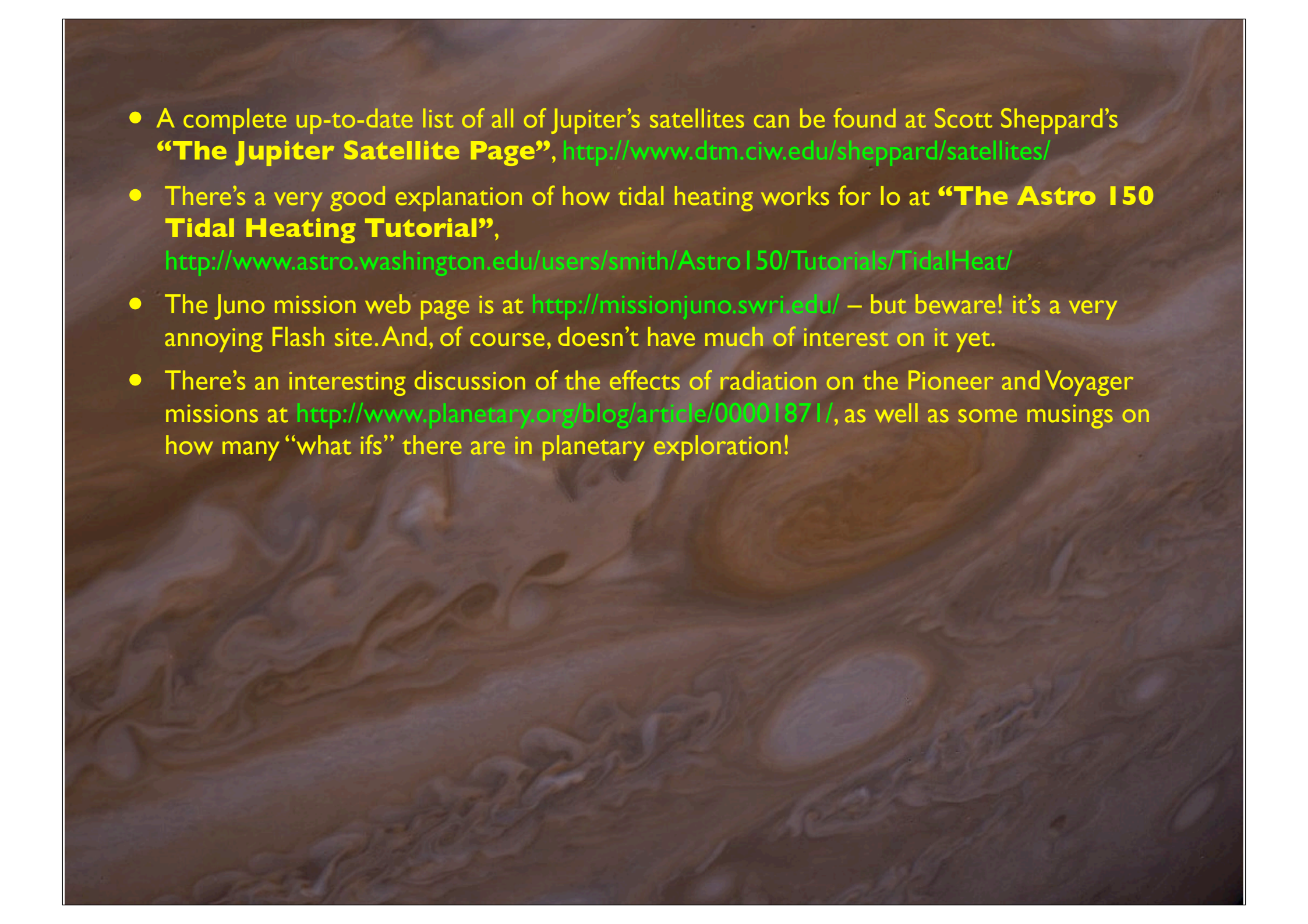
Next week...

... 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.

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- 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://www.astro.washington.edu/users/smith/Astro150/Tutorials/TidalHeat/>
 - The Juno mission web page is at <http://missionjuno.swri.edu/> – but beware! it's a very annoying Flash site. And, of course, doesn't have much of interest on it yet.
 - There's an interesting discussion of the effects of radiation on the Pioneer and Voyager missions at <http://www.planetary.org/blog/article/00001871/>, as well as some musings on how many "what ifs" there are in planetary exploration!

Sources for images used:

- Background image: Voyager image of the Great Red Spot, PIA01527 from NASA Planetary Photo Journal, <http://photojournal.jpl.nasa.gov/catalog/PIA01527>
- 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>
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- Jupiter atmosphere structure; and Belts and zones: from Atmospheres of Jupiter and Saturn, http://zebu.uoregon.edu/~imamura/121/lecture-13/jupiter_atmosphere.html
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- 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 magnetosphere: from http://www2.jpl.nasa.gov/galileo/images/230-949Ac_s.gif

- 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 I showing Valhalla: <http://photojournal.jpl.nasa.gov/catalog/PIA00080>
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- Ganymede cutaway: <http://photojournal.jpl.nasa.gov/catalog/PIA00519>
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- 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>
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- Europa from Voyager: <http://photojournal.jpl.nasa.gov/catalog/PIA01970>. Pwyll crater: <http://photojournal.jpl.nasa.gov/catalog/PIA01661>

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