Astro 7 - Chap 11, 12b: The Jovian Planet Systems and Pluto

- Jovians: Jupiter, Saturn, Uranus, Neptune: TOTALLY different planets than our familiar next door neighbors
- They formed beyond the frost line – so **ices** could form and **seed** the early stages of agglomeration. There's a lot more ice-type raw material than rock-type raw material, so you get bigger planets!

The Outer Plants: Hydrogen/Helium Giants

- 97% of early solar nebula was hydrogen and helium, roughly the same composition of Jupiter and Saturn, who, combined, are most of the mass of the planetary system.
- Cold temperatures, high mass allow much of these light atoms to be held by gravity for these 4.6 billion years
- Rocky cores surrounded by deep layers of H, He.

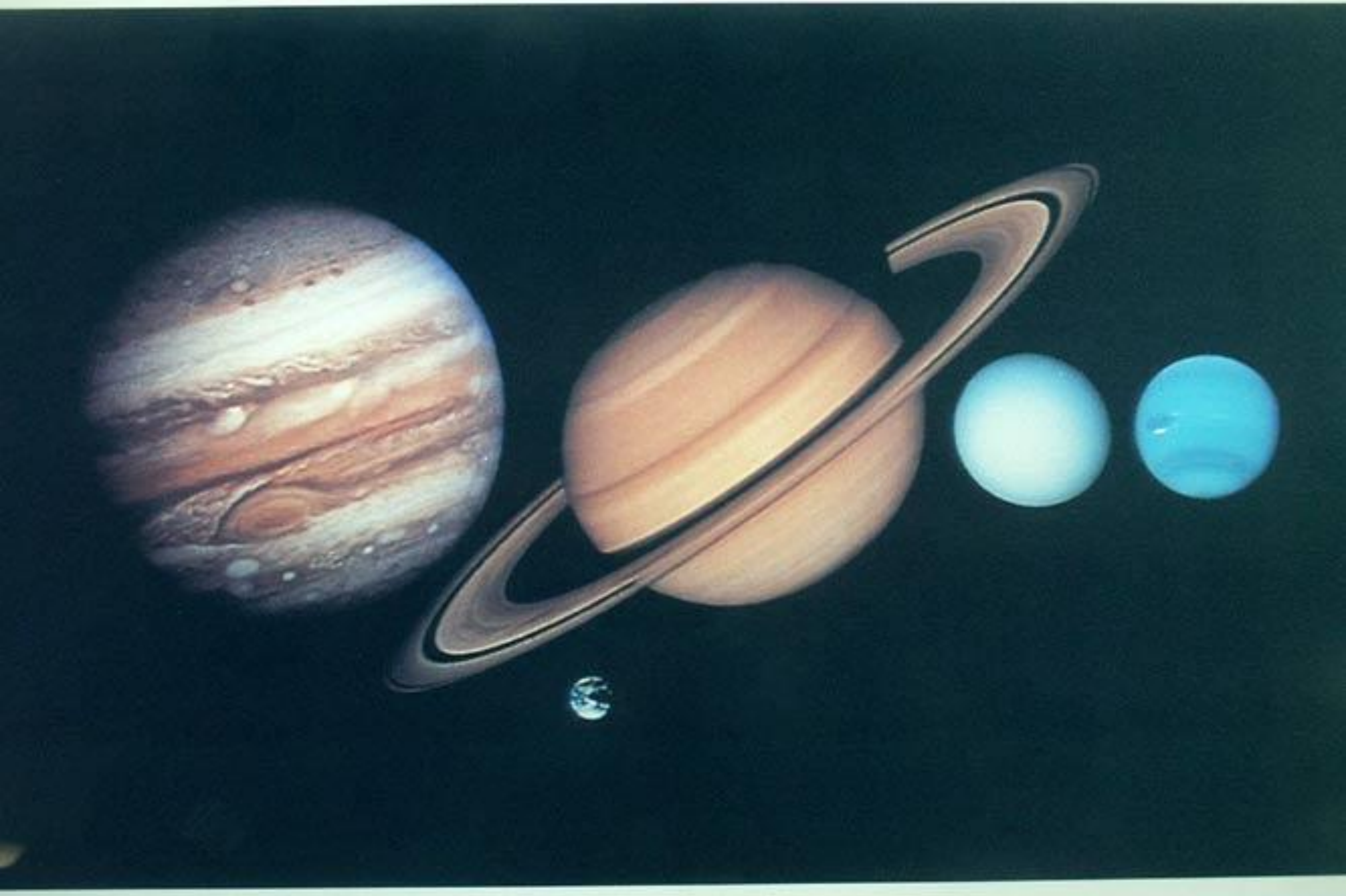
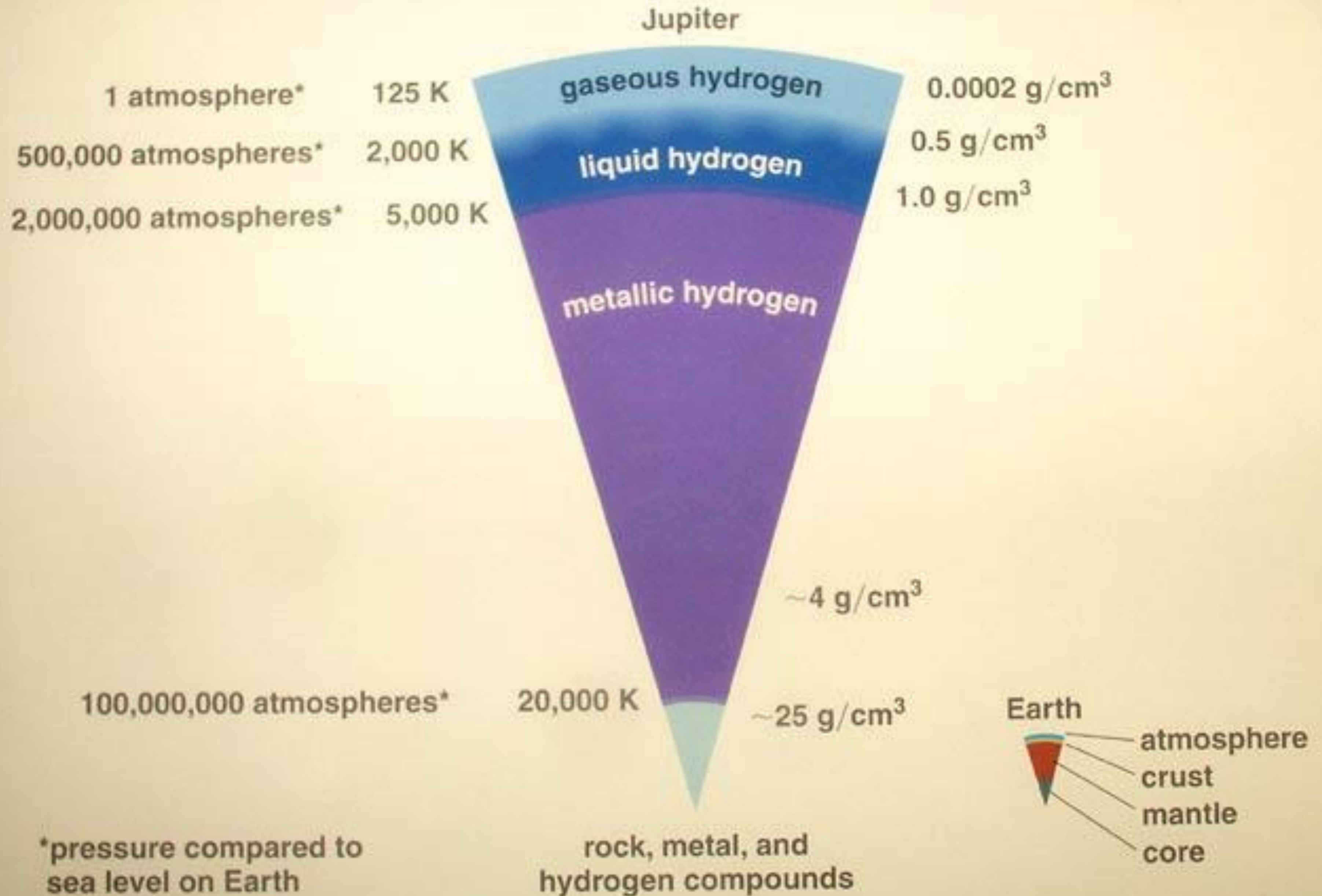
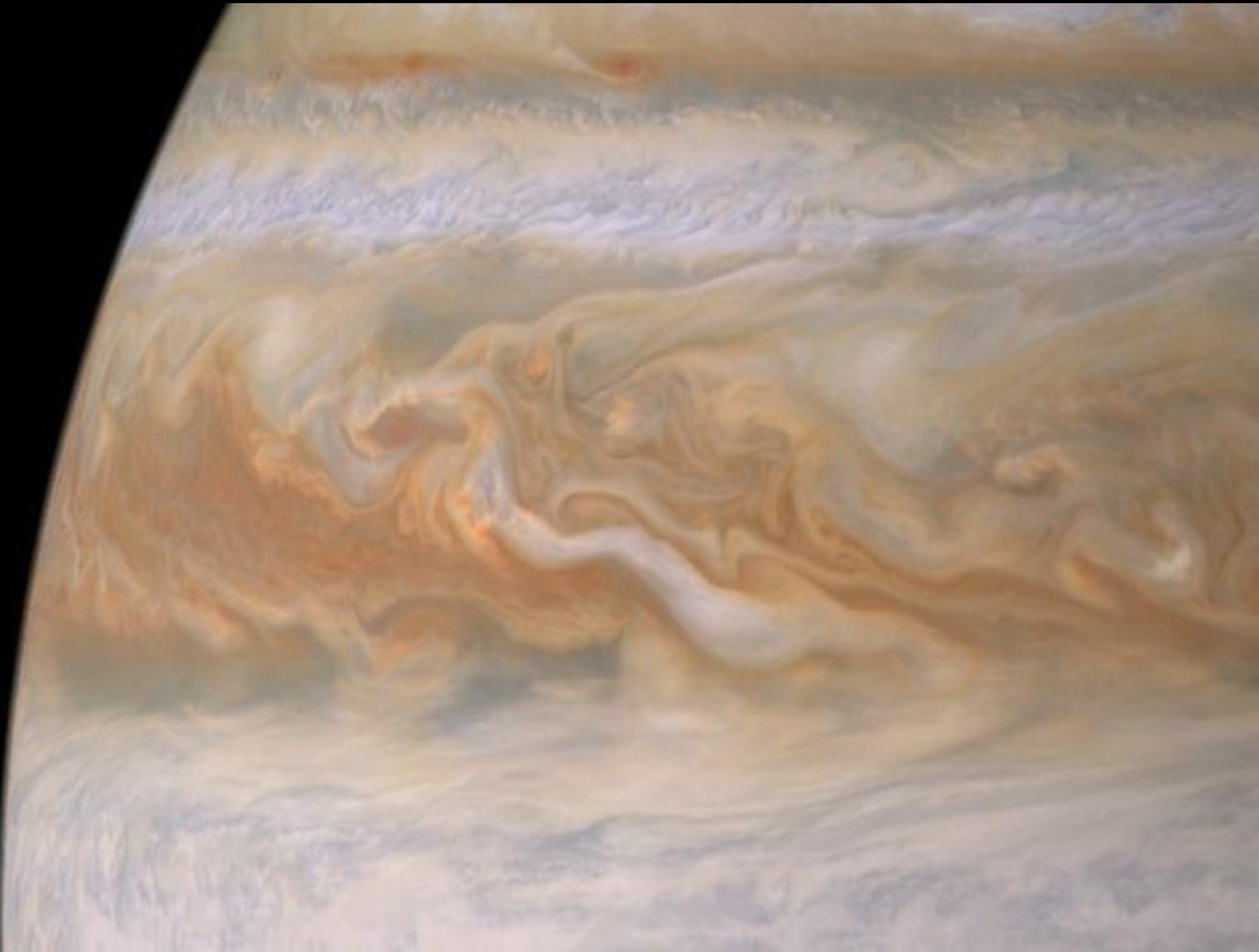


Figure 9.2 Internal structure: Jupiter vs. Earth



Jupiter is a Stormy Planet

- High temperatures deep inside mean strong convective flow in the atmosphere.
- The rapid rotation (“day” = 12 hrs) and large diameter means very strong velocity gradient from equator to poles.
- So, strong Coriolis force, twice that of Earth, making atmospheric motions turn into circulations – like hurricanes
- Result is lots of big storms…

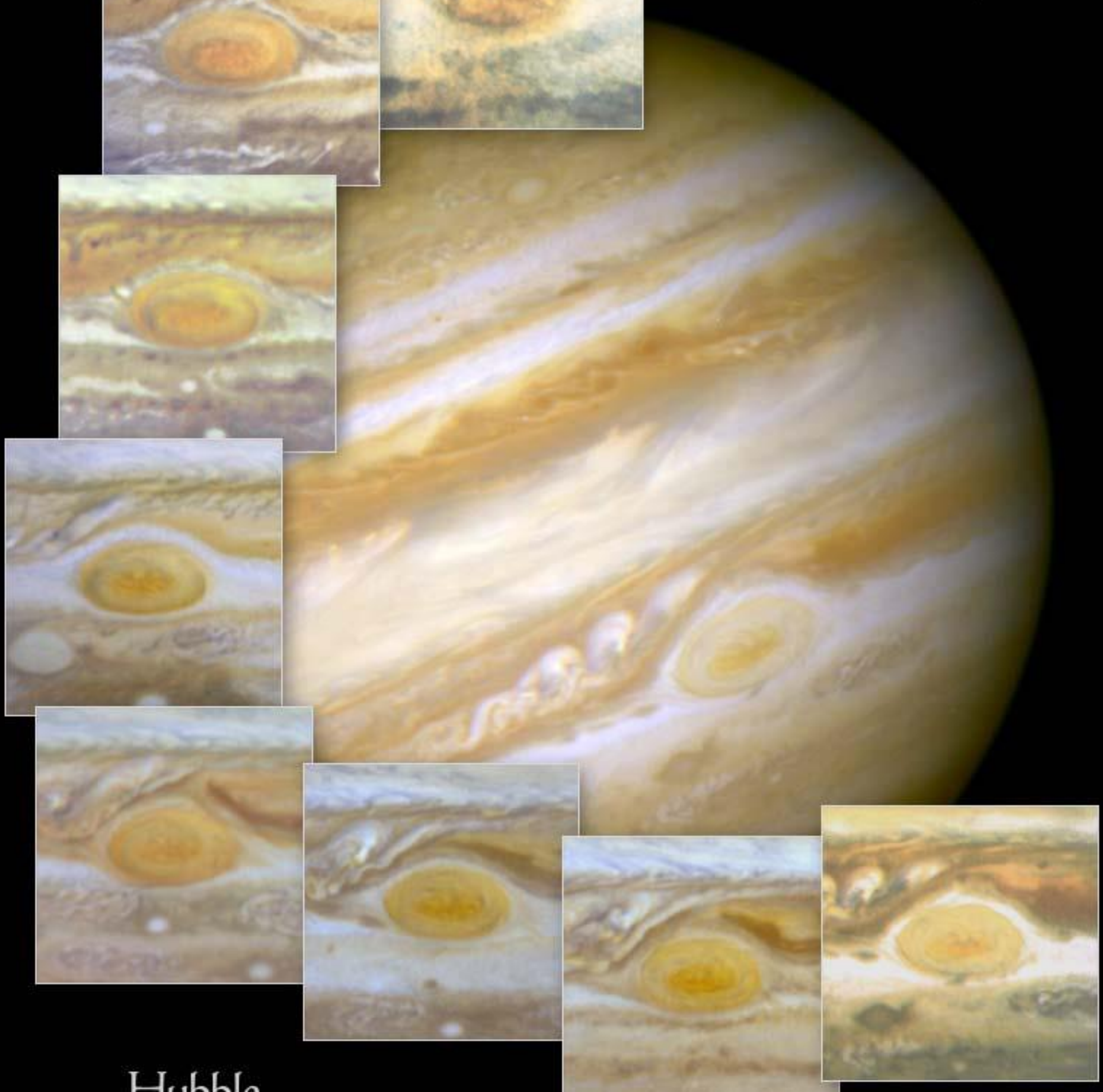


The Great Red Spot

- As big as 3 Earth’s side-by-side in diameter
- This is a **high pressure (=anti-cyclone) system**. Winds are spiraling away from the Great Red Spot. Analog is the high pressure system which parks over the Nevada during much of the Autumn, sending dry winds over California making it our fire season.
- Jupiter’s storms usually last months or maybe a year or so, but the Great Red Spot has been on Jupiter since we first put a telescope on it to see; over 400 years now.

Speculation – The Great Red Spot Origin

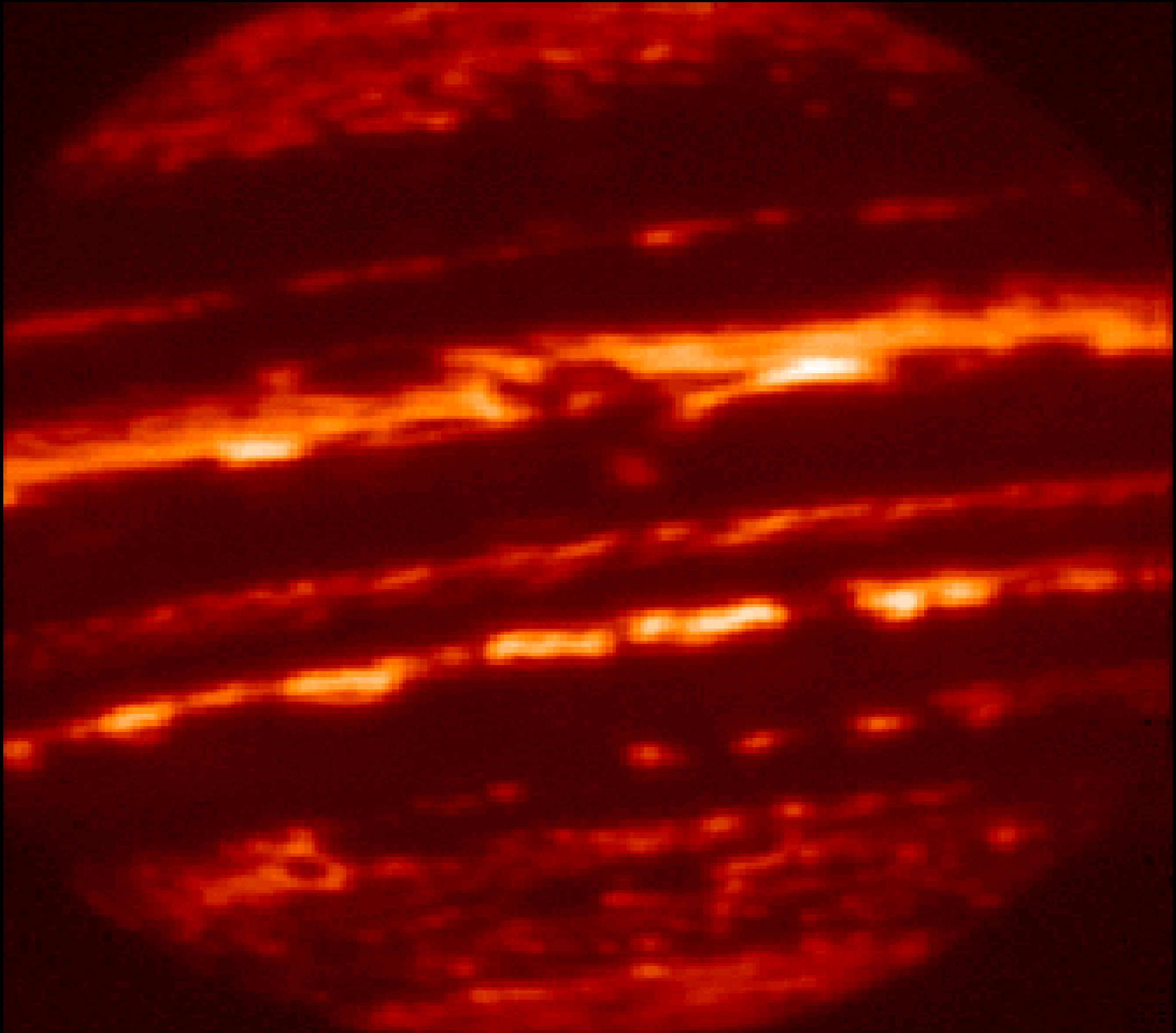
- An impact, and the heat generated by the slow infall to the denser hotter layers beneath is converting gravitational potential energy into additional heat, and a high pressure area, which could easily last for centuries or millennia or longer.
- We've seen several visible impacts of comets onto Jupiter in the past 20 years.



Hubble

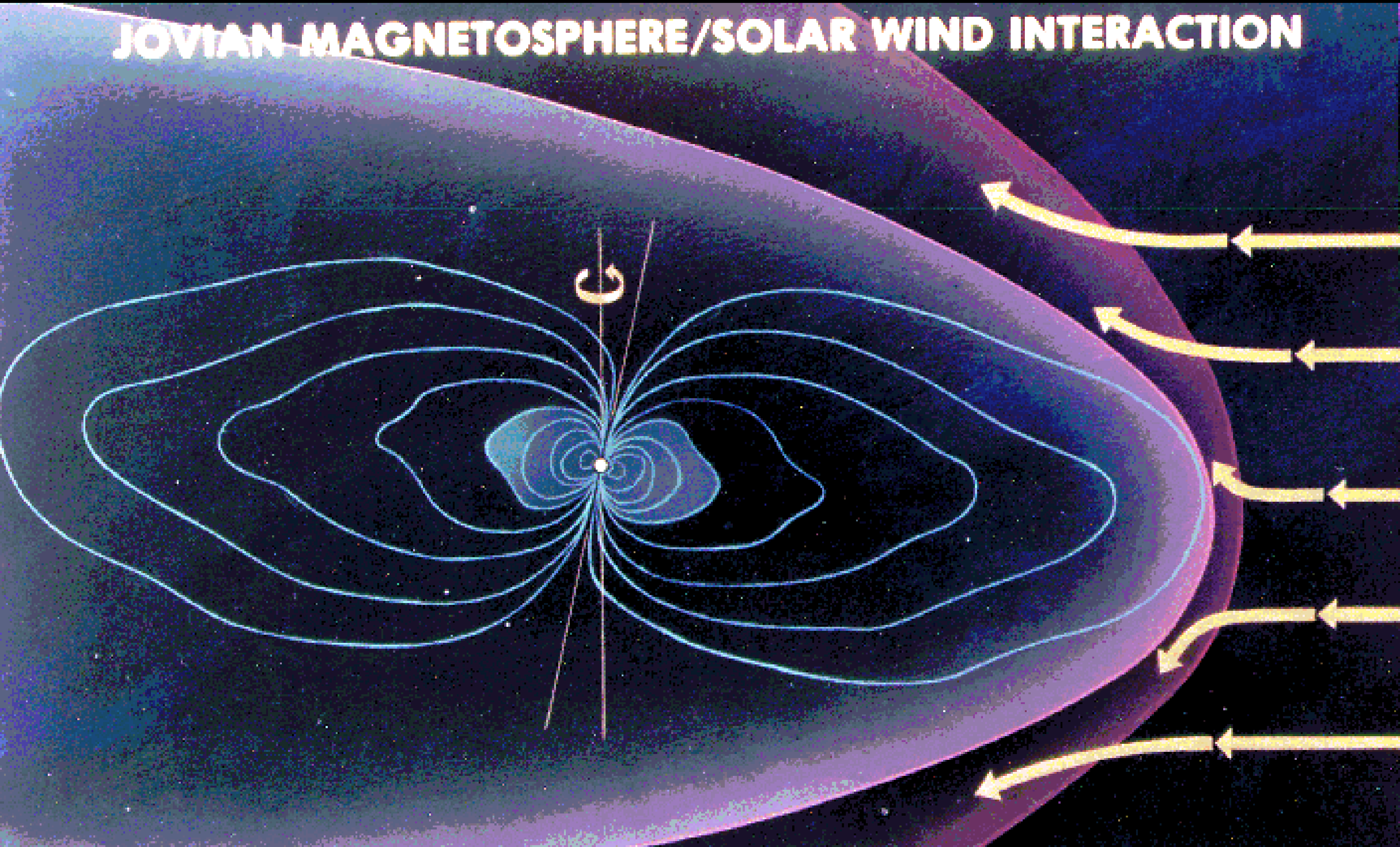
Jupiter gives off more heat than it receives from the sun. It's HOT under those cold ammonia clouds of the outer atmosphere

- Why? The heat of formation takes a LONG time to dissipate, but mainly its because it is still slowly collapsing, converting gravitational potential energy into heat
- You can see the hotter layers in infrared pictures…



Jupiter has the right ingredients for a Strong Magnetic Field…

- Rapid rotation
- Hot interior and strong temperature gradient driving convection of…
- An electrically conducting interior – in this case, liquid hydrogen under so much pressure it behaves like a metal – electrically conducting, good heat conductor too.
- The result – the most powerful magnetic field of any planet – by far.


JOVIAN MAGNETOSPHERE/SOLAR WIND INTERACTION

How a Magnetic Field Acts on Charges…

- Magnetic “field lines” are a visualization which helps us see how charges will interact with that field
- Charges will spiral around the field line direction. In other words, they feel a sideways force to their direction of motion, and sideways to the field line direction
- Hence, field lines “channel” charged particles so they must move **along** the field line direction, not perpendicular to it
- This channels solar wind particles so they impact the atmospheres of planets near the north and south magnetic poles
- At these spots, we see the atmosphere glow from the ionization of the atmosphere atoms and recombination (exactly like fluorescent light bulbs) – we call this : Aurorae

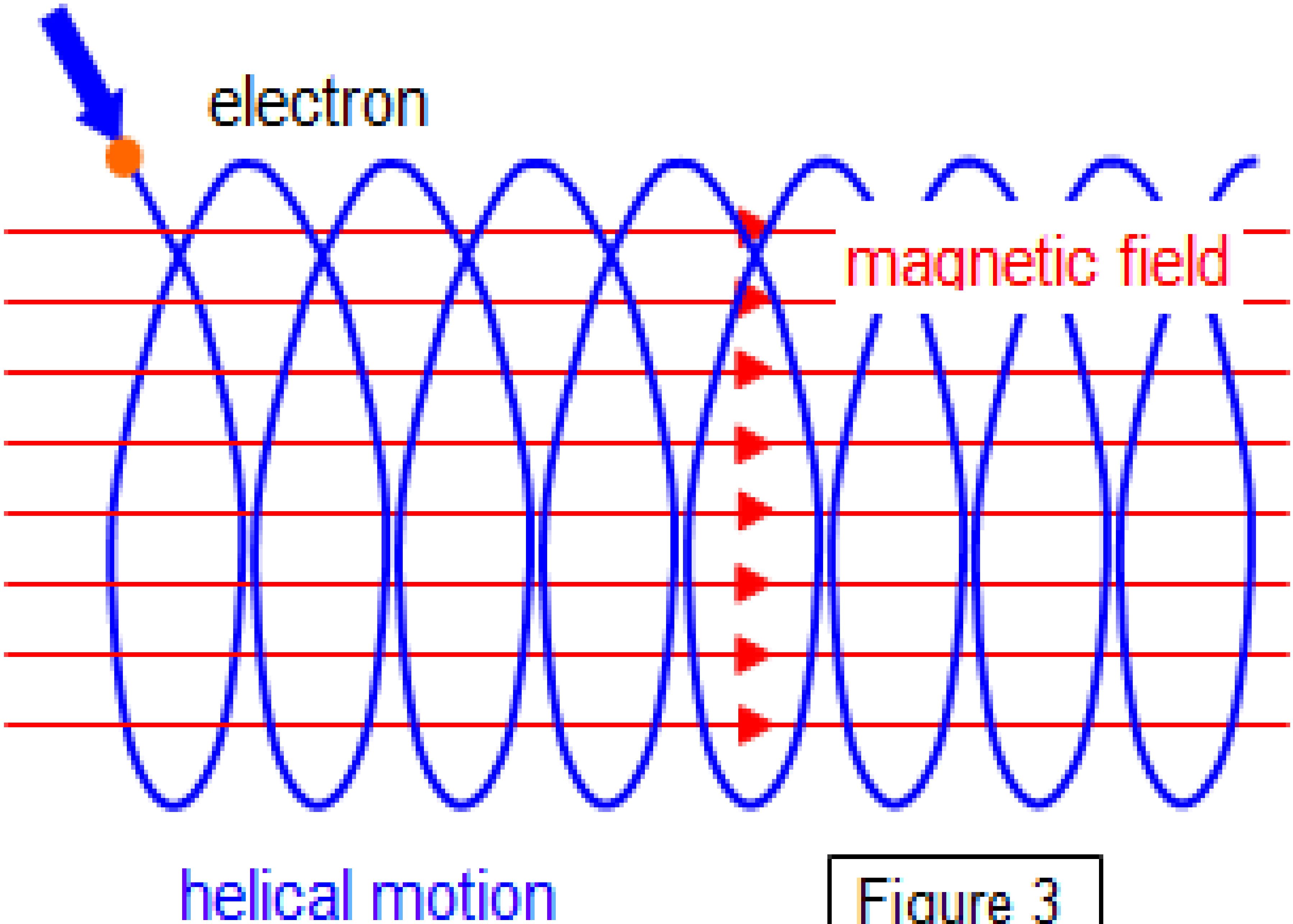
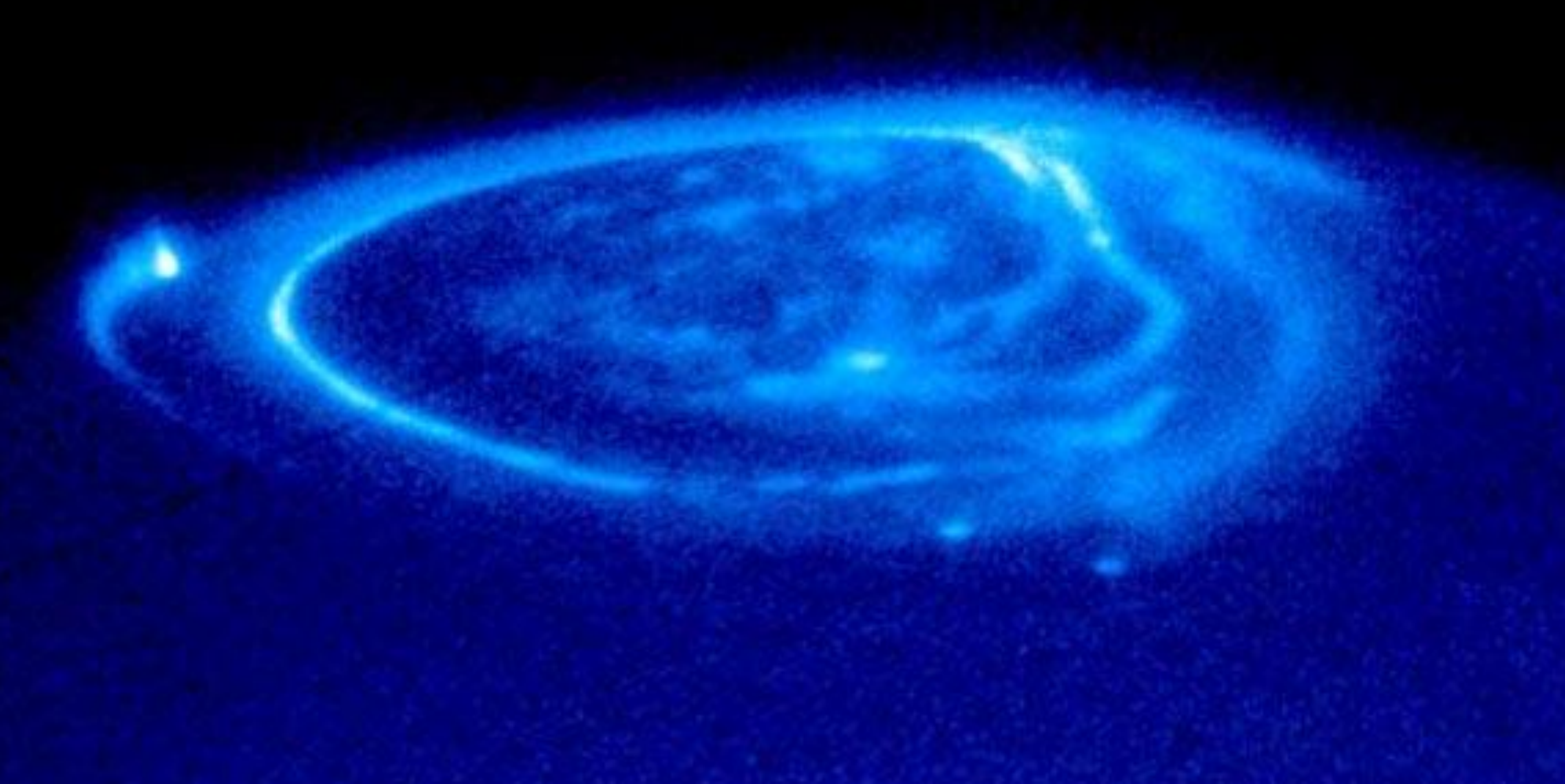
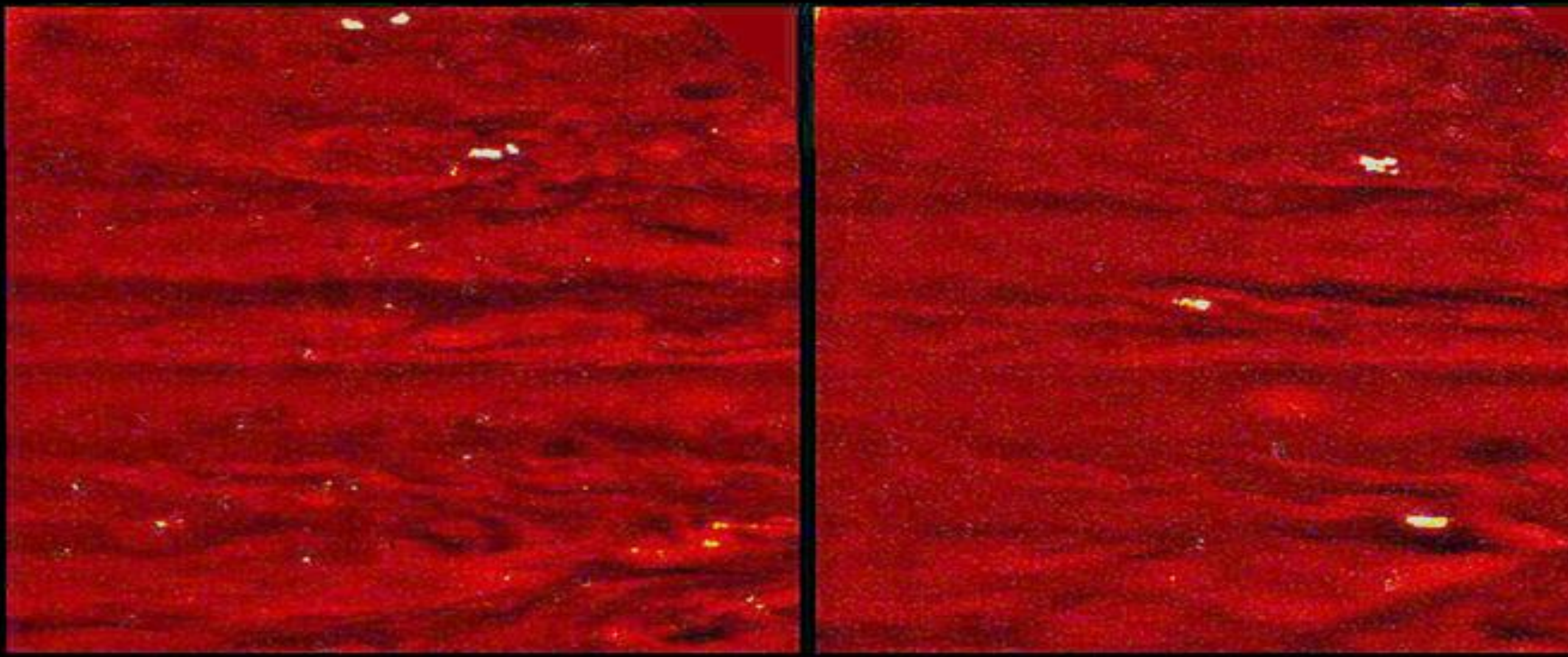


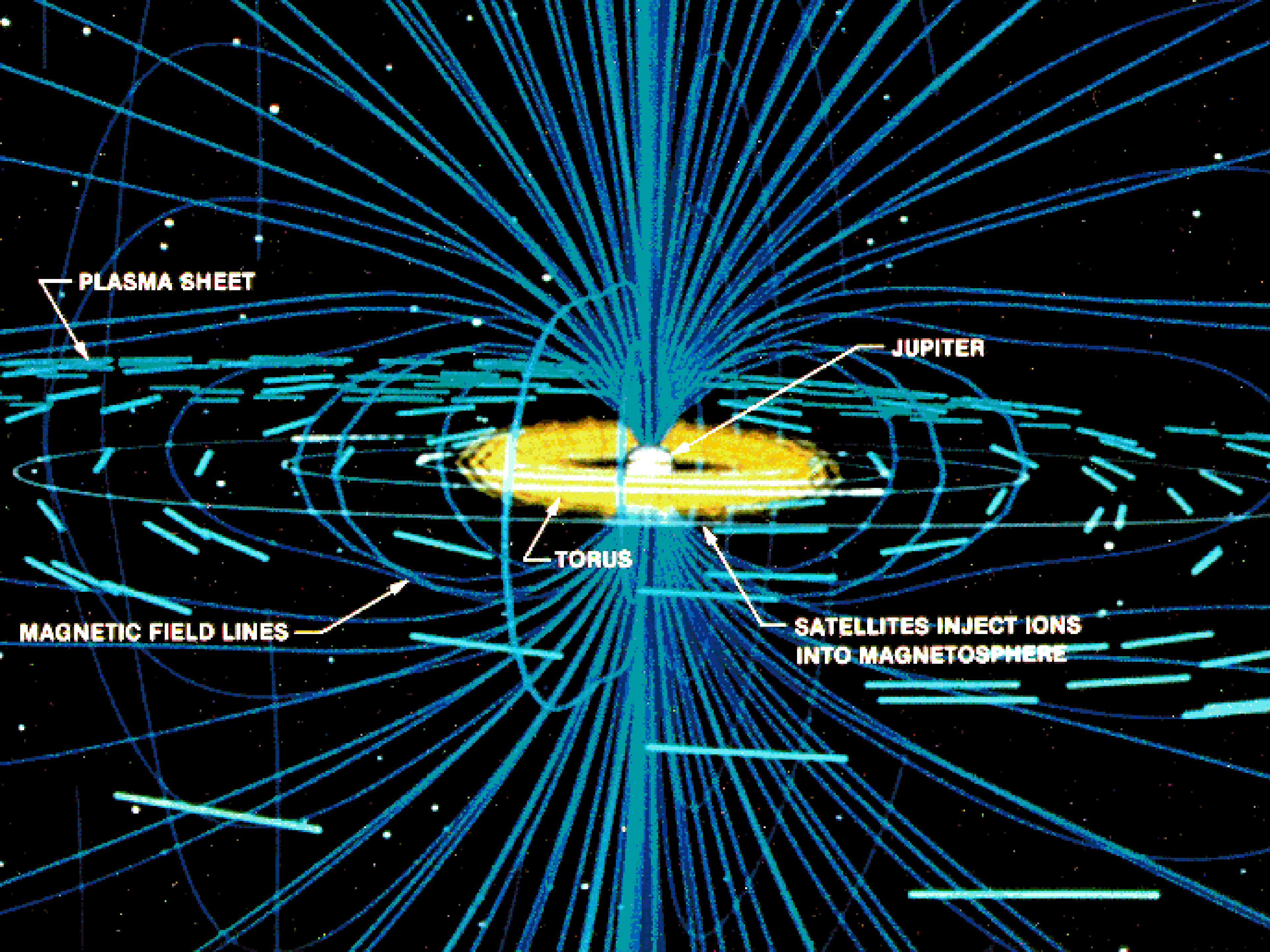
Figure 3

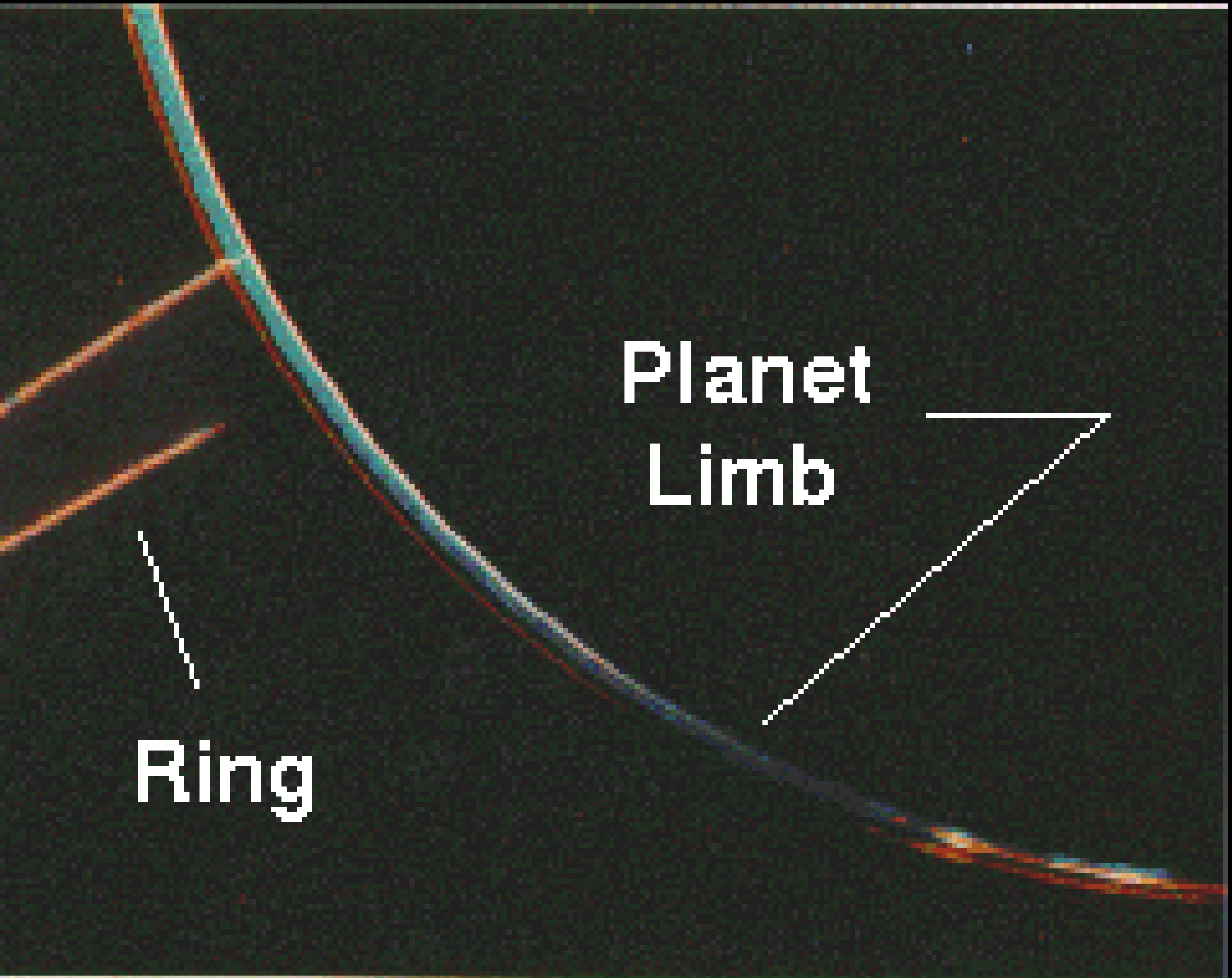
Jupiter’s Aurora

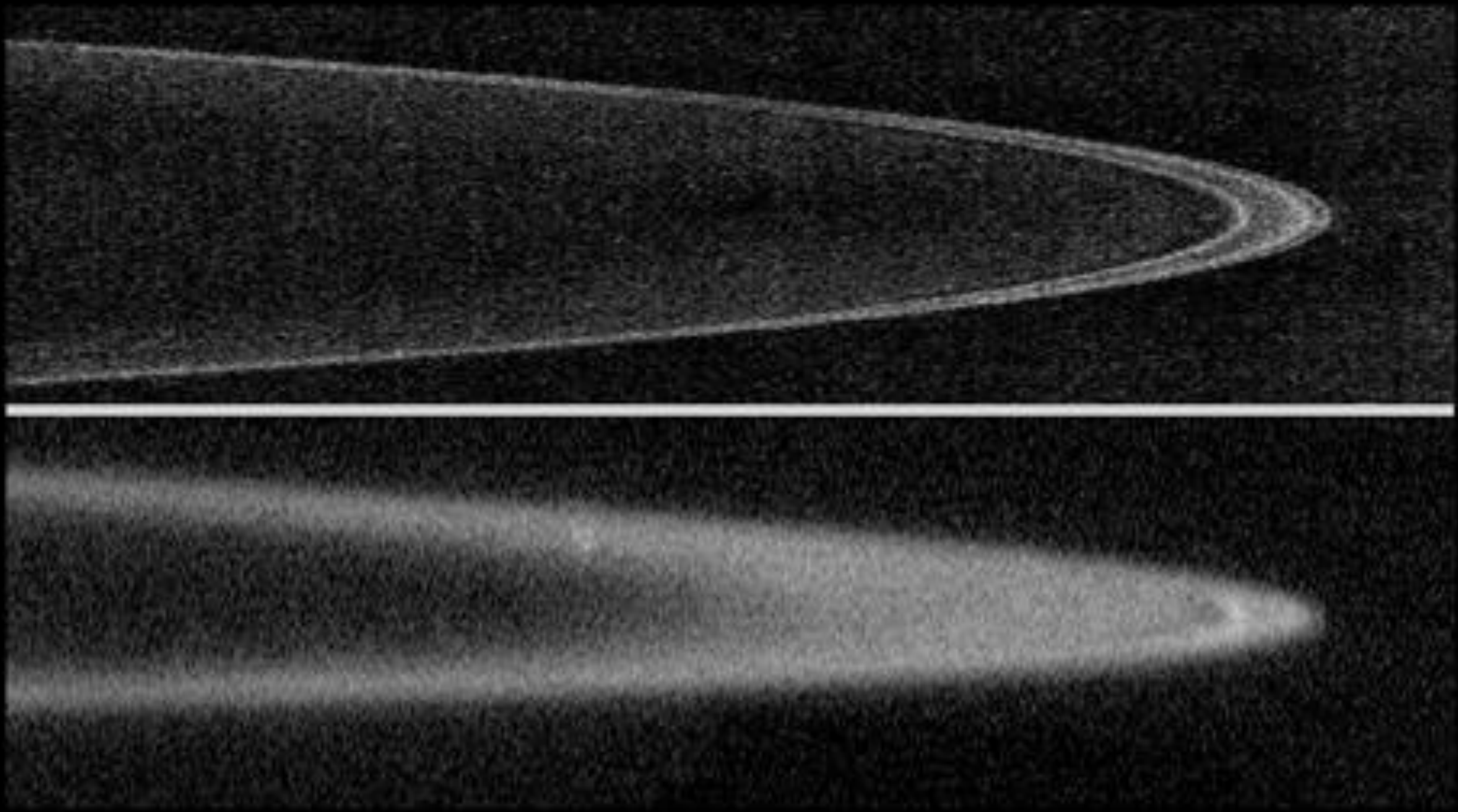


The strong convection leads to lightning (bright spots here)

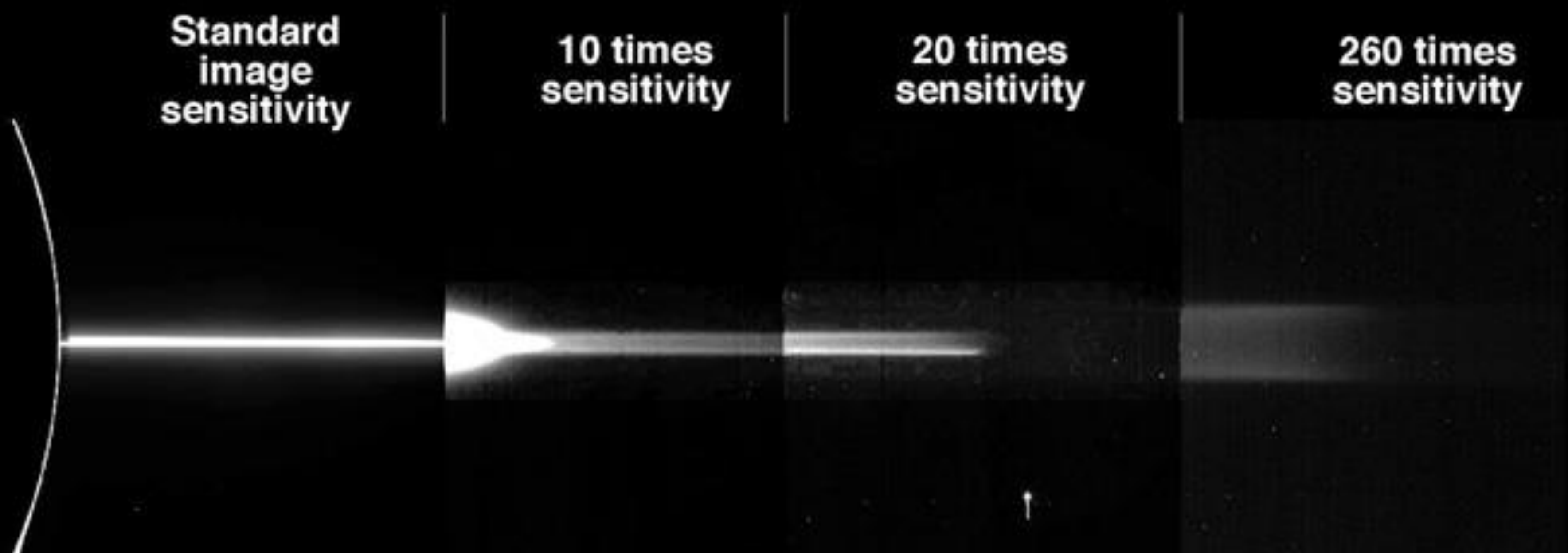



PLASMA SHEET
JUPITER
TORUS
MAGNETIC FIELD LINES
SATELLITES INJECT IONS
INTO MAGNETOSPHERE

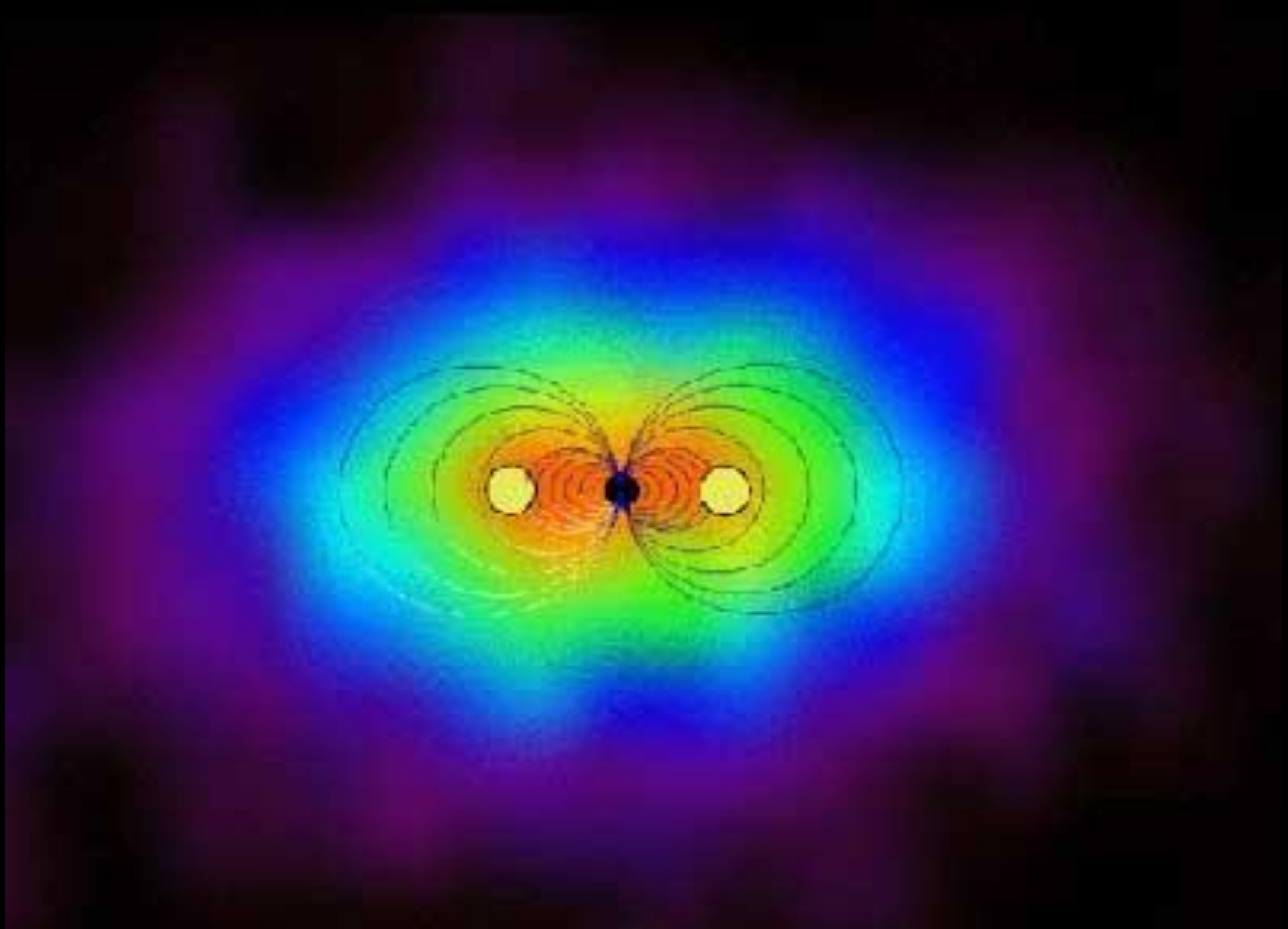

Planet Limb
Ring



Jupiter's Ring, Seen Edge-on



Radio emission from electrons spiraling in Jupiter's magnetic field



Origin of Jupiter’s Ring?

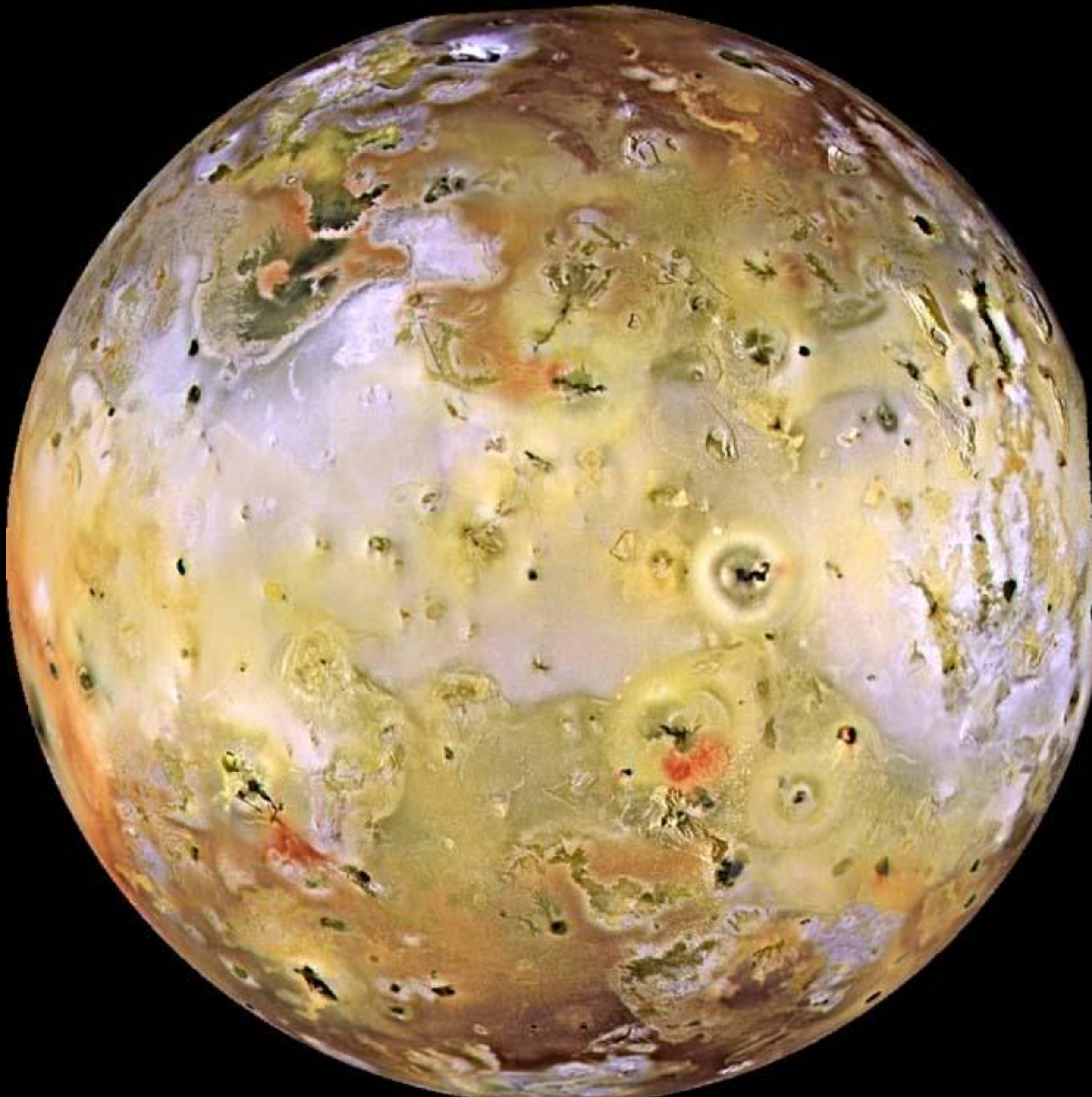
- Might be the remnants of a comet (icy dirtball) that was captured into an orbit and the ices eroded away by the ions trapped in the magnetic field
- But current best guess is that it’s material launched into orbit around Jupiter by Io’s volcanoes. The ring is made up of micron-sized particles, like volcanic ash.

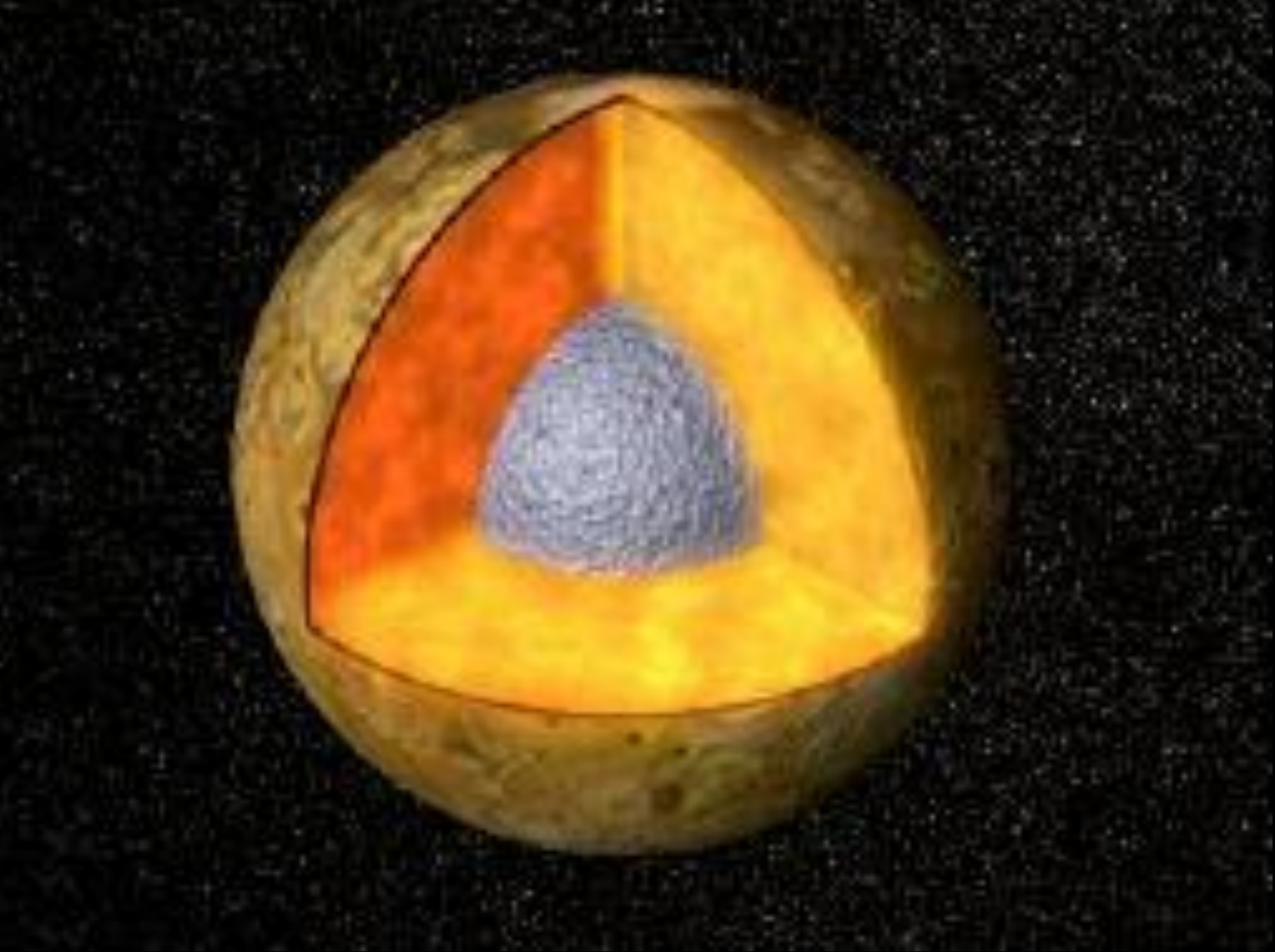
Jupiter's Moons – 63 at last count

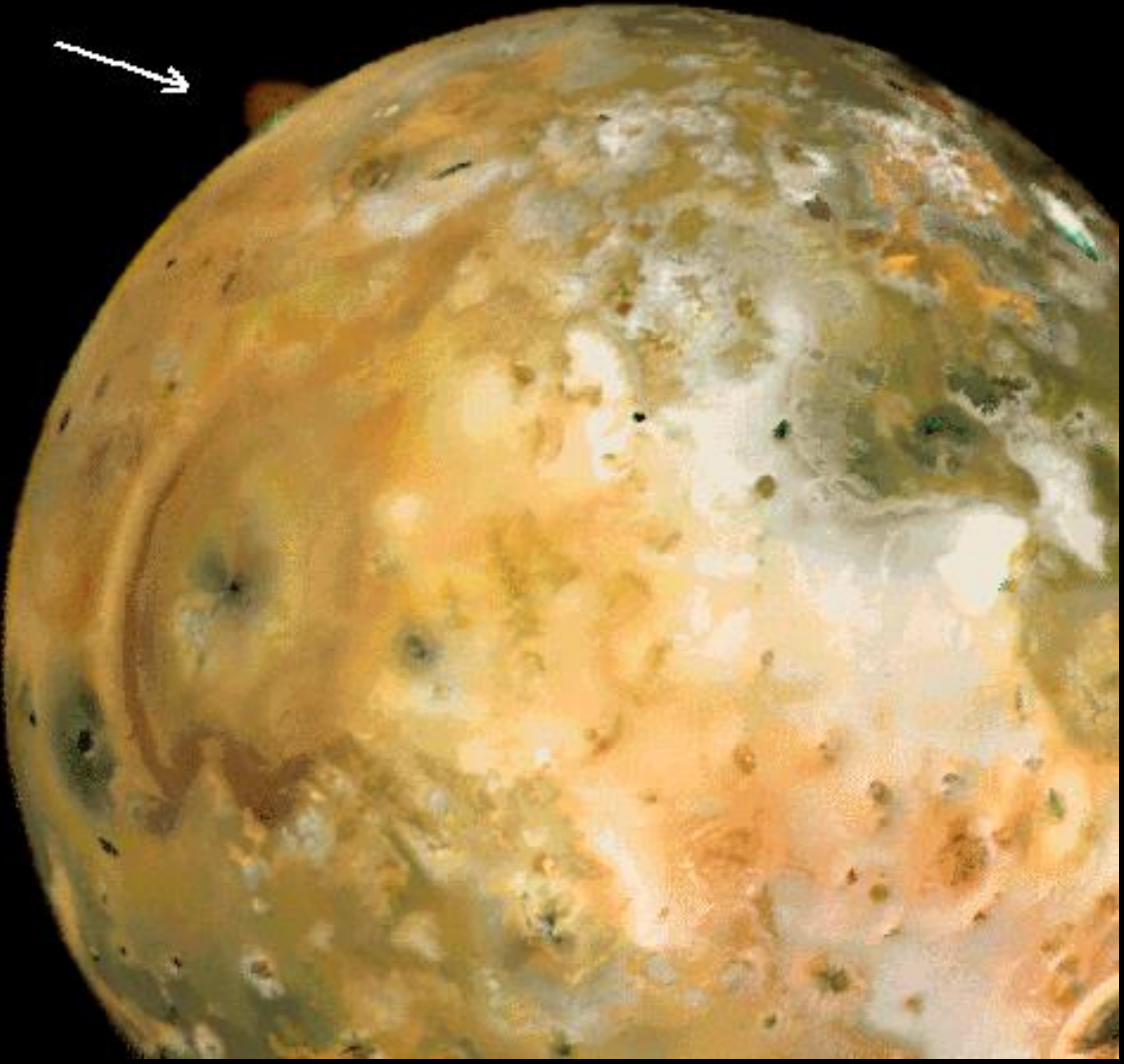
- The 4 big ones are roughly the size of our own moon – 1,500 – 3,000 miles across
- From closer to farther, they are: Io, Europa, Ganymede and Callisto
- Io's orbit is a bit elliptical, and only a couple Jupiter diameters away from Jupiter – this has a huge effect on the properties of this little moon

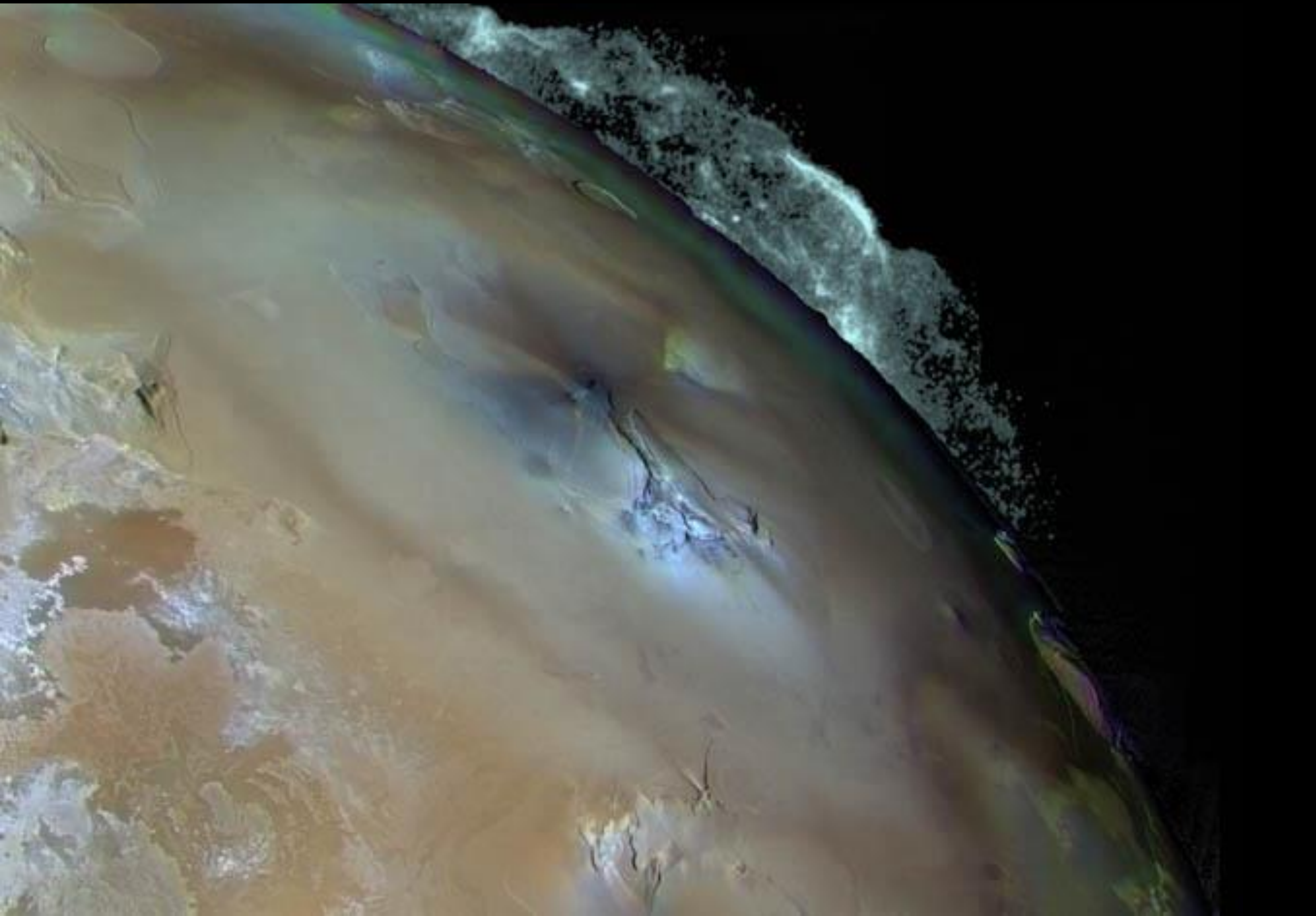
Jupiter's huge gravity and the closeness of Io means it experiences strong tidal stretching

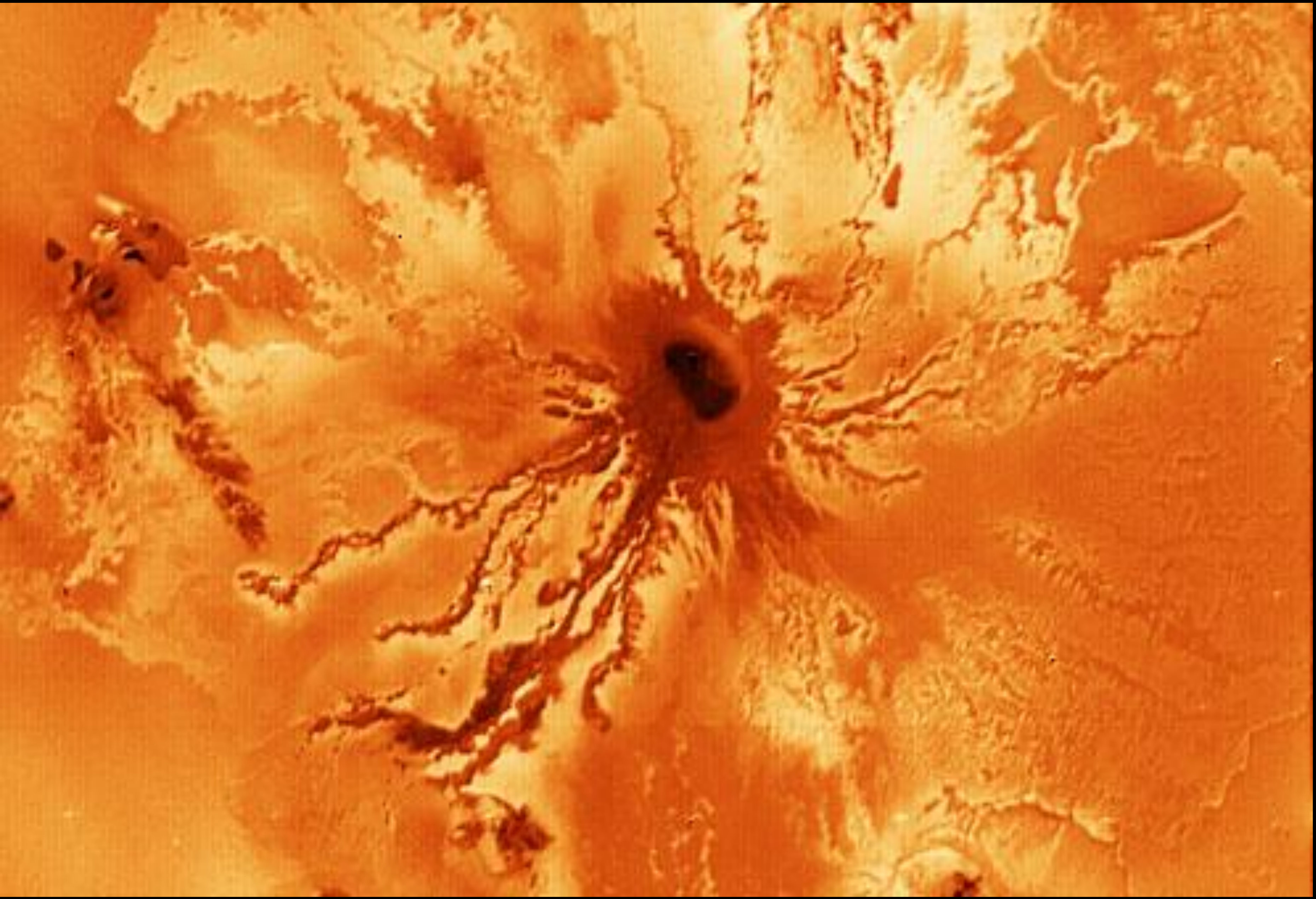
- This tidal force varies from weaker to stronger as Io goes from closer to farther from Jupiter in its slightly elliptical orbit. This rhythmic squeezing and stretching of the moon heats the interior – *tidal friction*
- It's surprisingly effective. The volcanoes have vent temperatures of 2,000F, melting sulfur, a relatively light element that is rich in the upper layers, and vaporizing any water or other icey type materials.

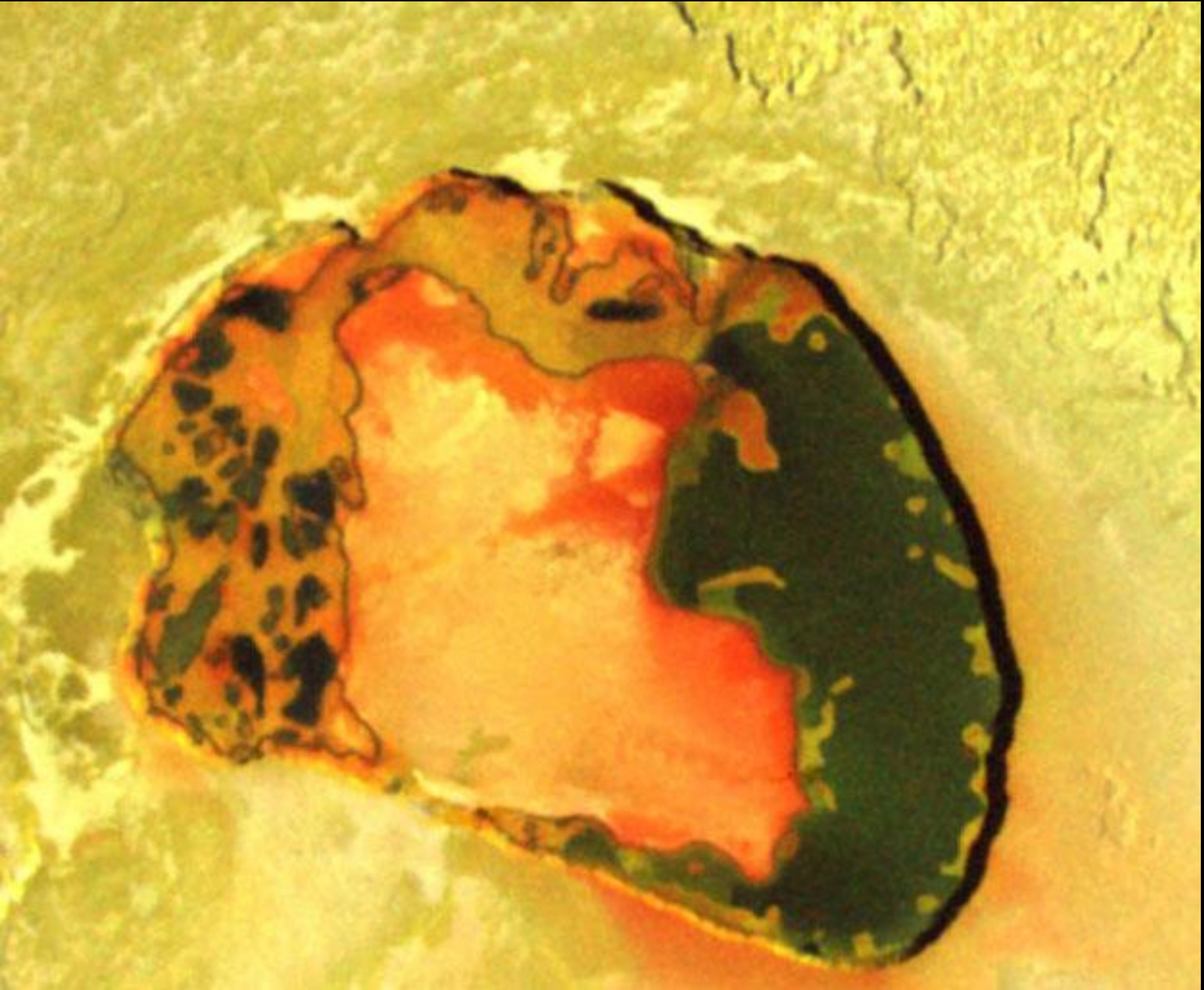


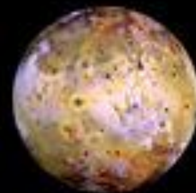






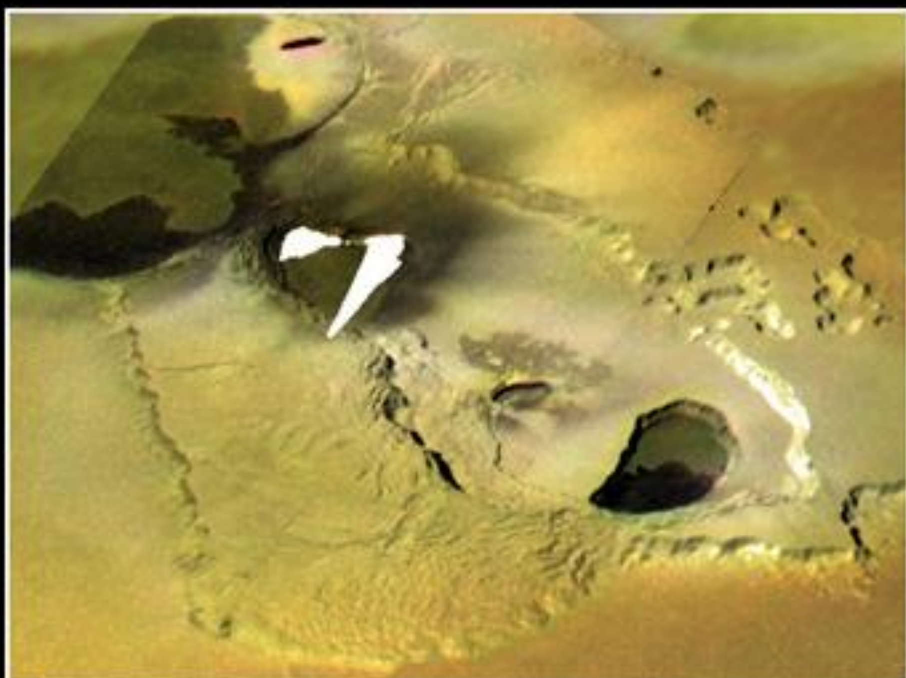




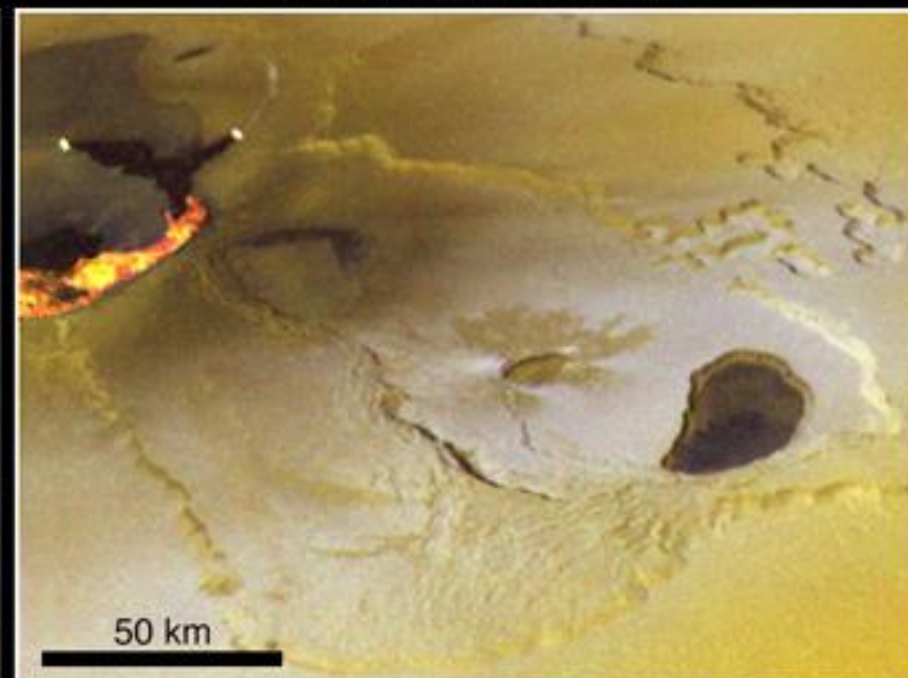


Io — Tvashtar Catena

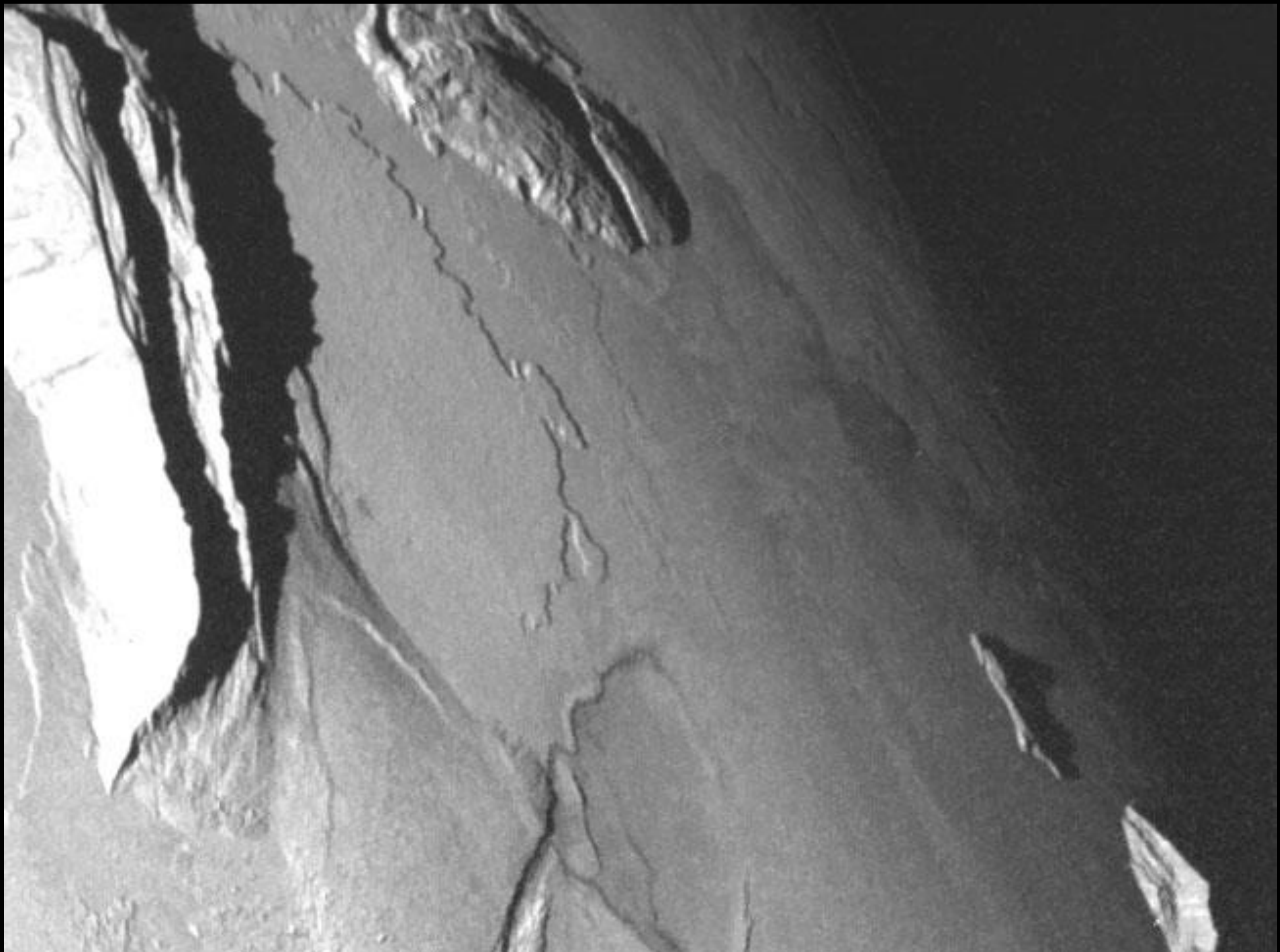
I25 (26 Nov 1999)
+ C21 low-resolution color



I27 (22 Feb 2000)
visible wavelength data
+ IR data of active lava flow



Io surface shows no craters – says volcanic rain is heavy and constant, filling in impact craters rapidly

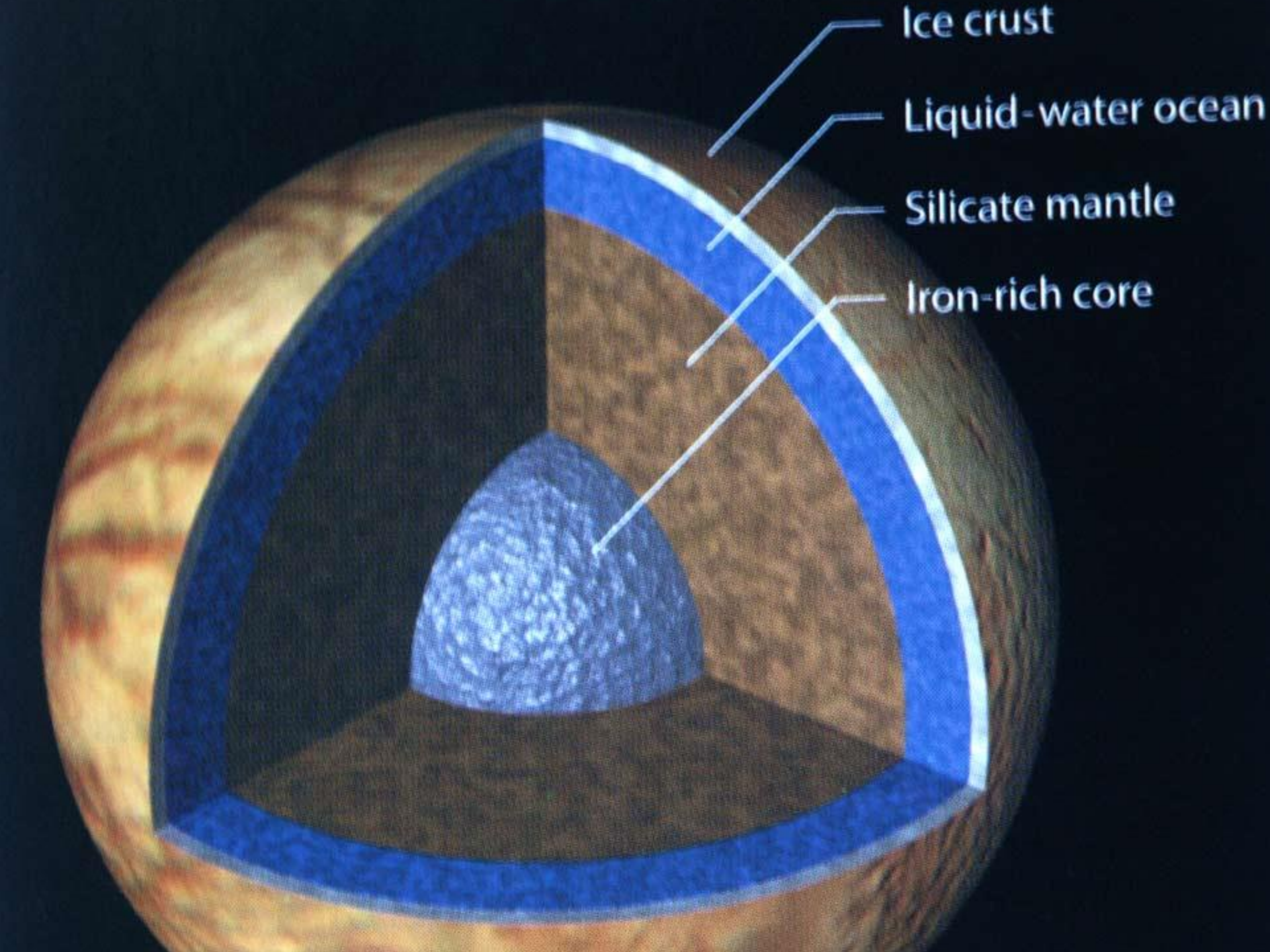


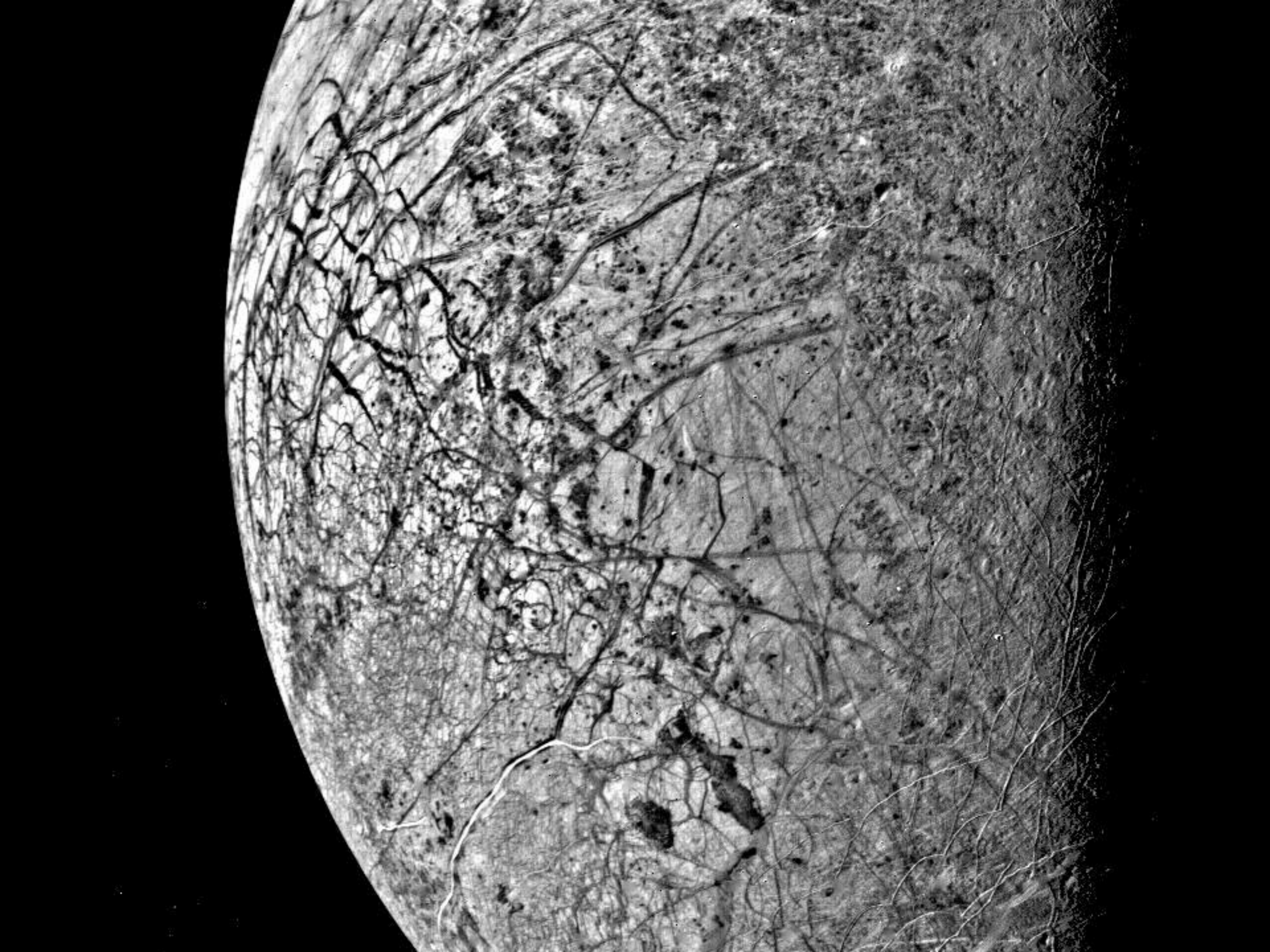
Summary on Io

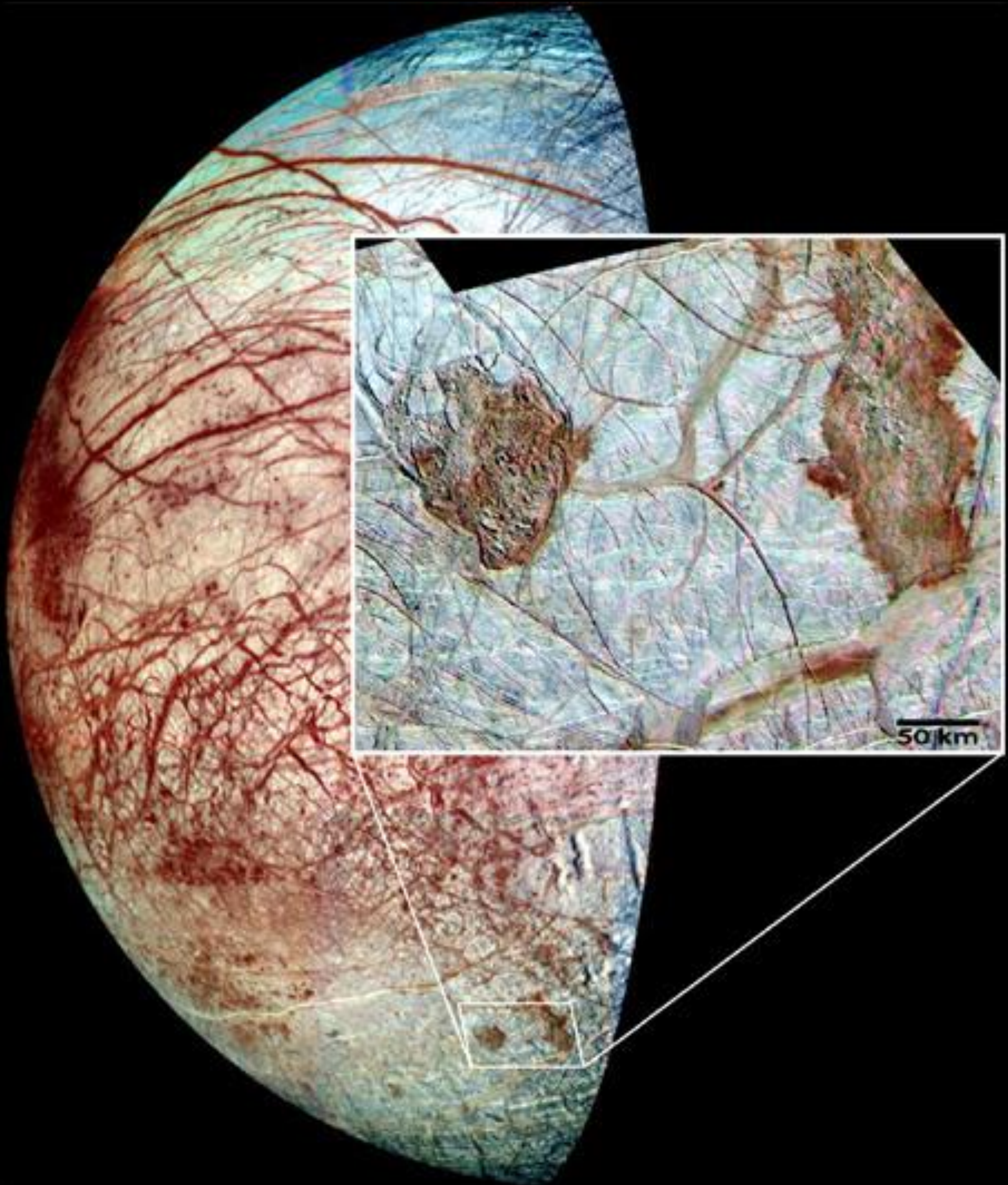
- Io is stretched more, then less, then more, then less…etc for each and every 42 hr orbit.
- This converts orbital kinetic energy into thermal energy, heating the interior above the melting point of sulfur (239F or 115C), and it burbles up through cracks to make volcanoes.
- Constant volcanic eruptions quickly fill in all craters that may have existed
- Volcanic particles can escape Io's weak gravity. And eventually friction decays the particles' orbits and the material settles onto Jupiter
- These compounds of sulfur especially, are the source of Jupiter's dramatic colors on its clouds.

Europa – Also tidally heated, but less so

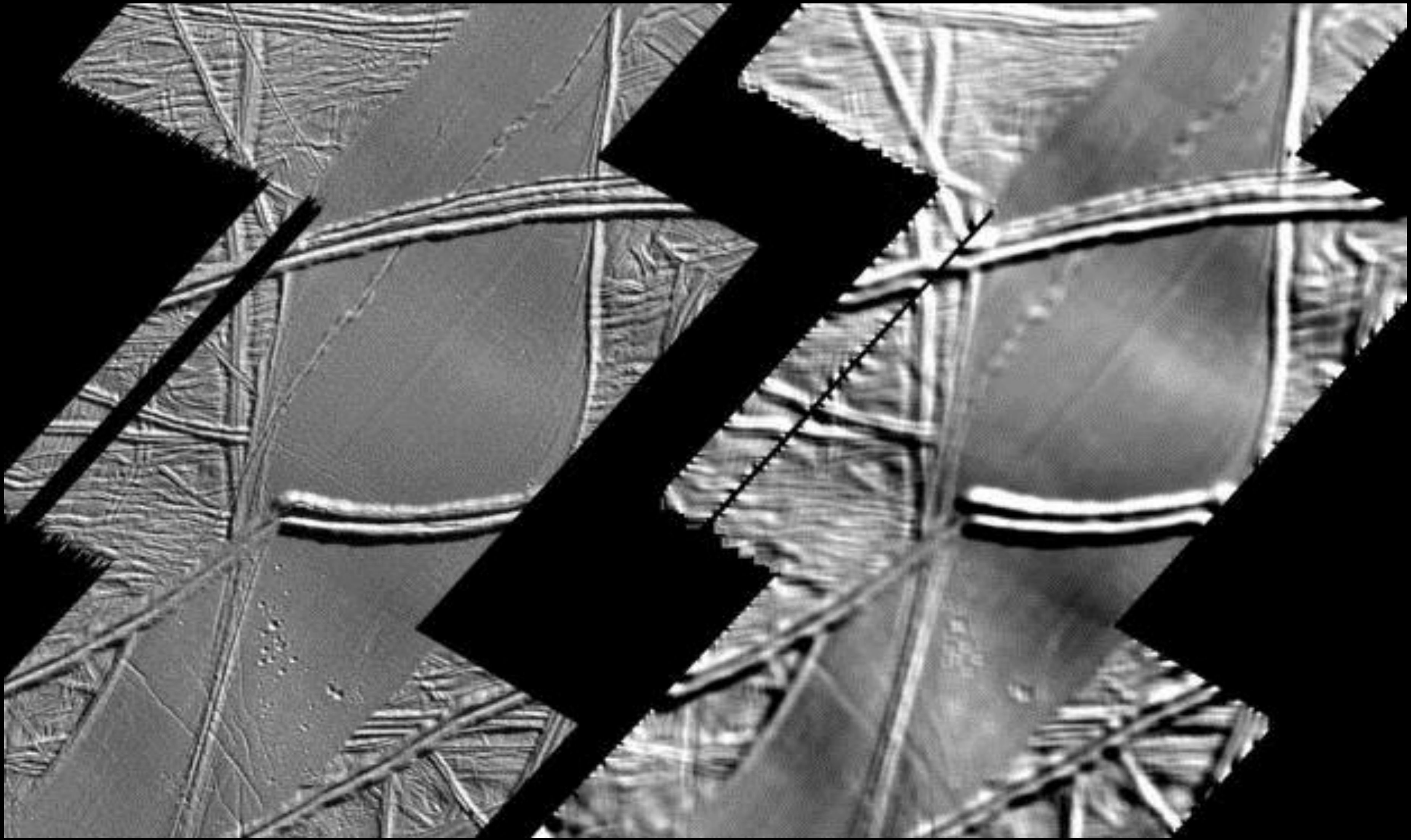
- It was not so hot as to evaporate water away. Water is a very common molecule.
- Europa is an arctic world of salt water covered by ice
- Cracks show characteristics of salt-water pressure ridges
- Intriguing… salt water ocean warm enough to support life, is what the evidence suggests.

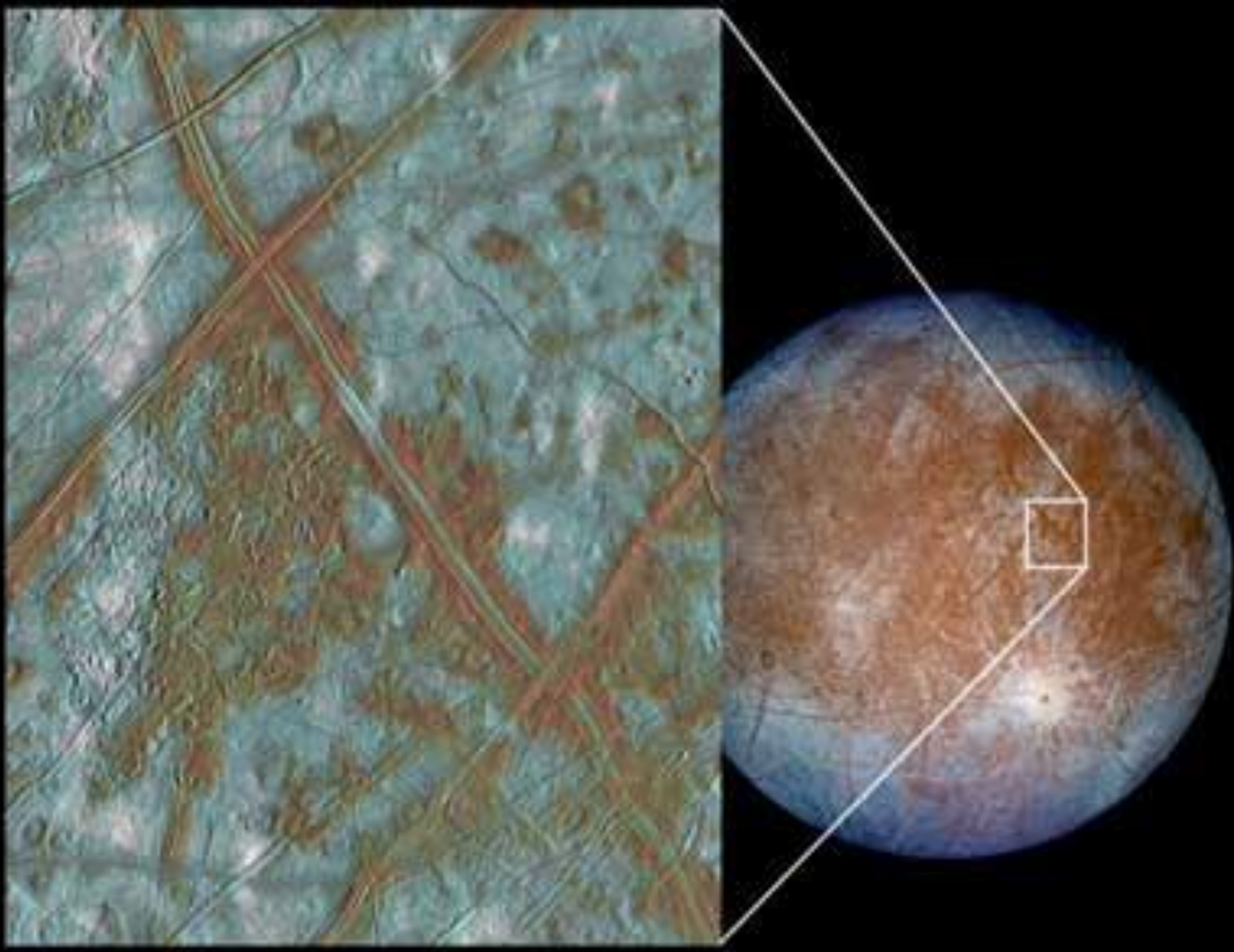

Ice crust
Liquid-water ocean
Silicate mantle
Iron-rich core

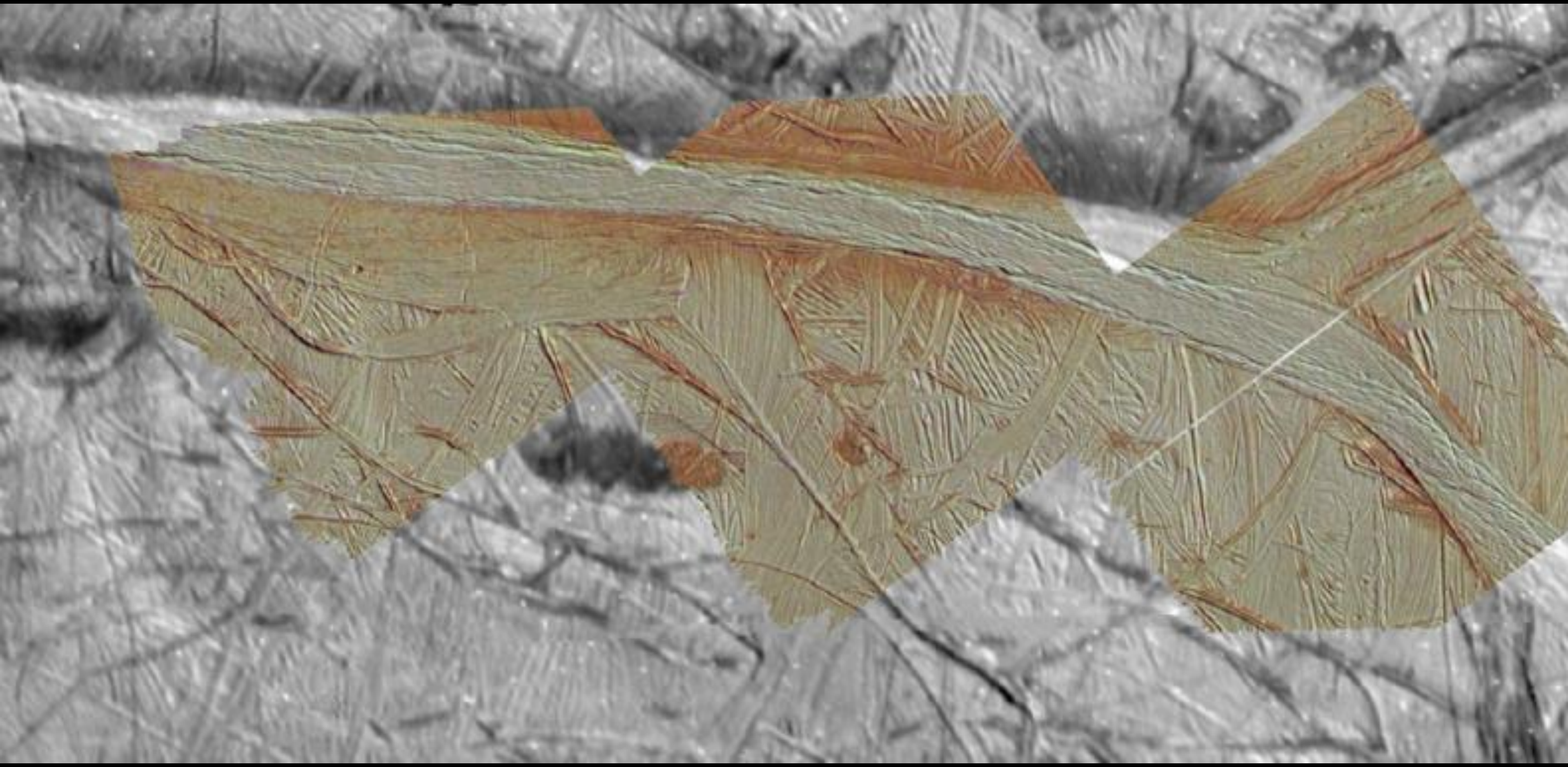



50 km

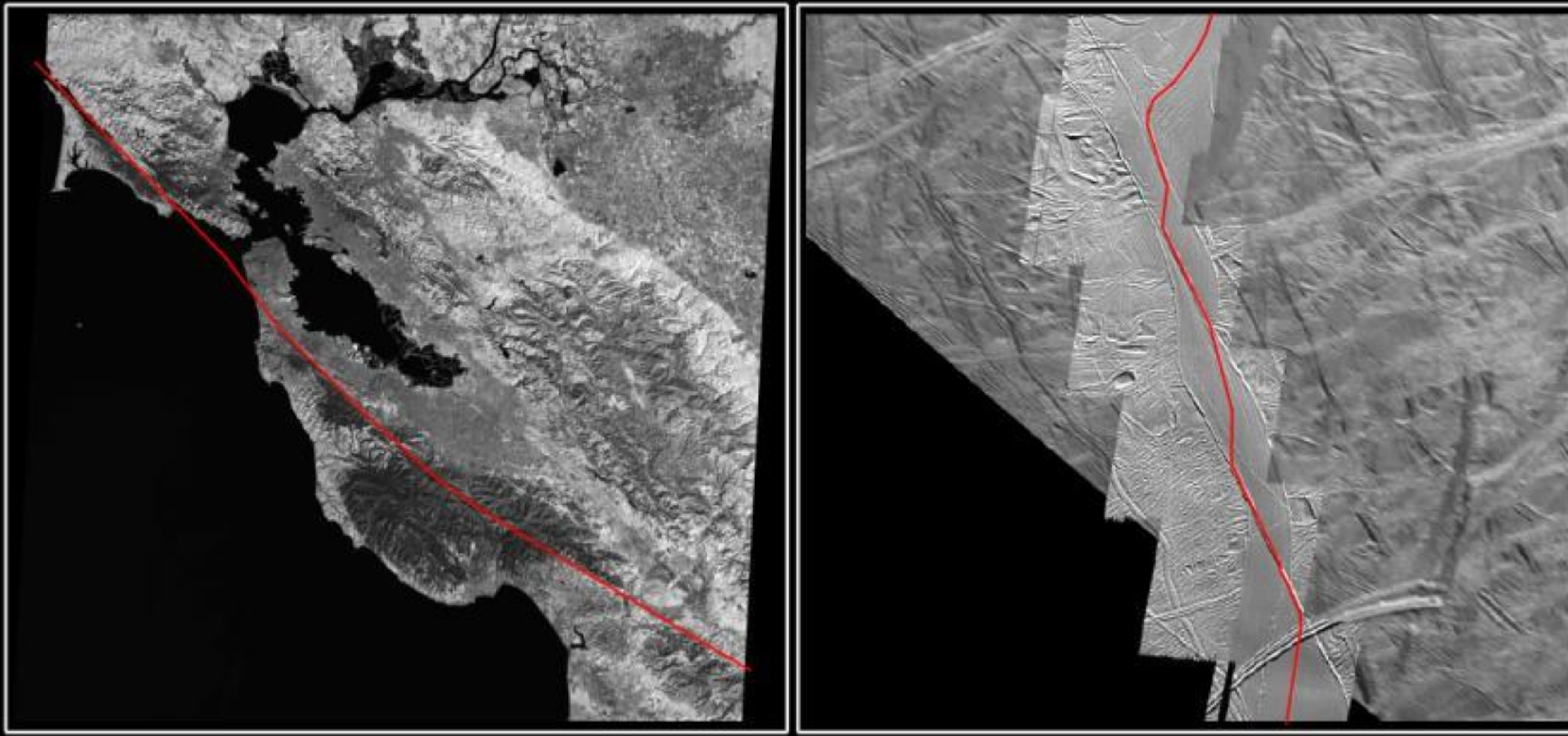
Pressure ridges, sharpened by image processing. The Reddish color likely mineral salt evaporate



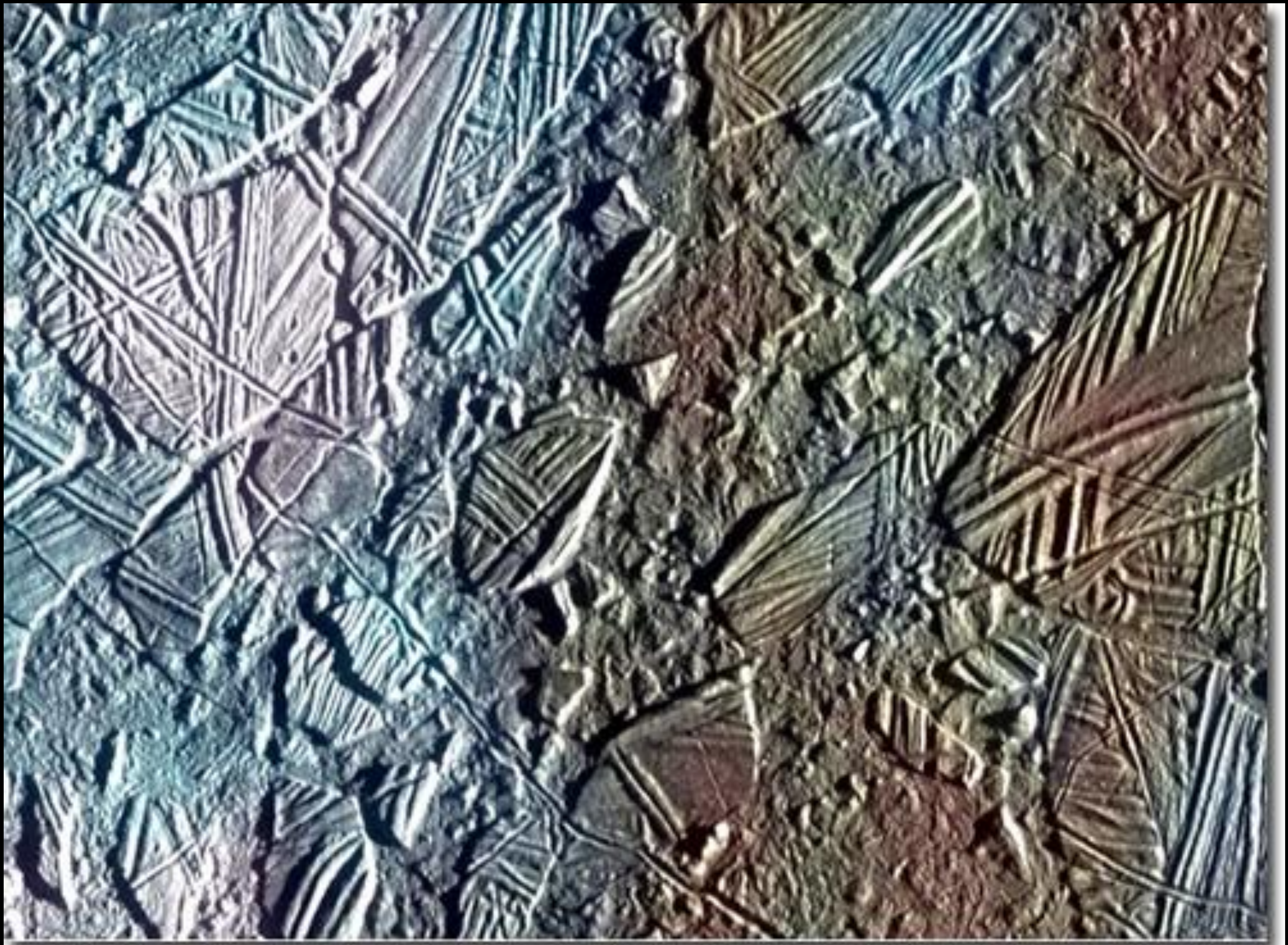




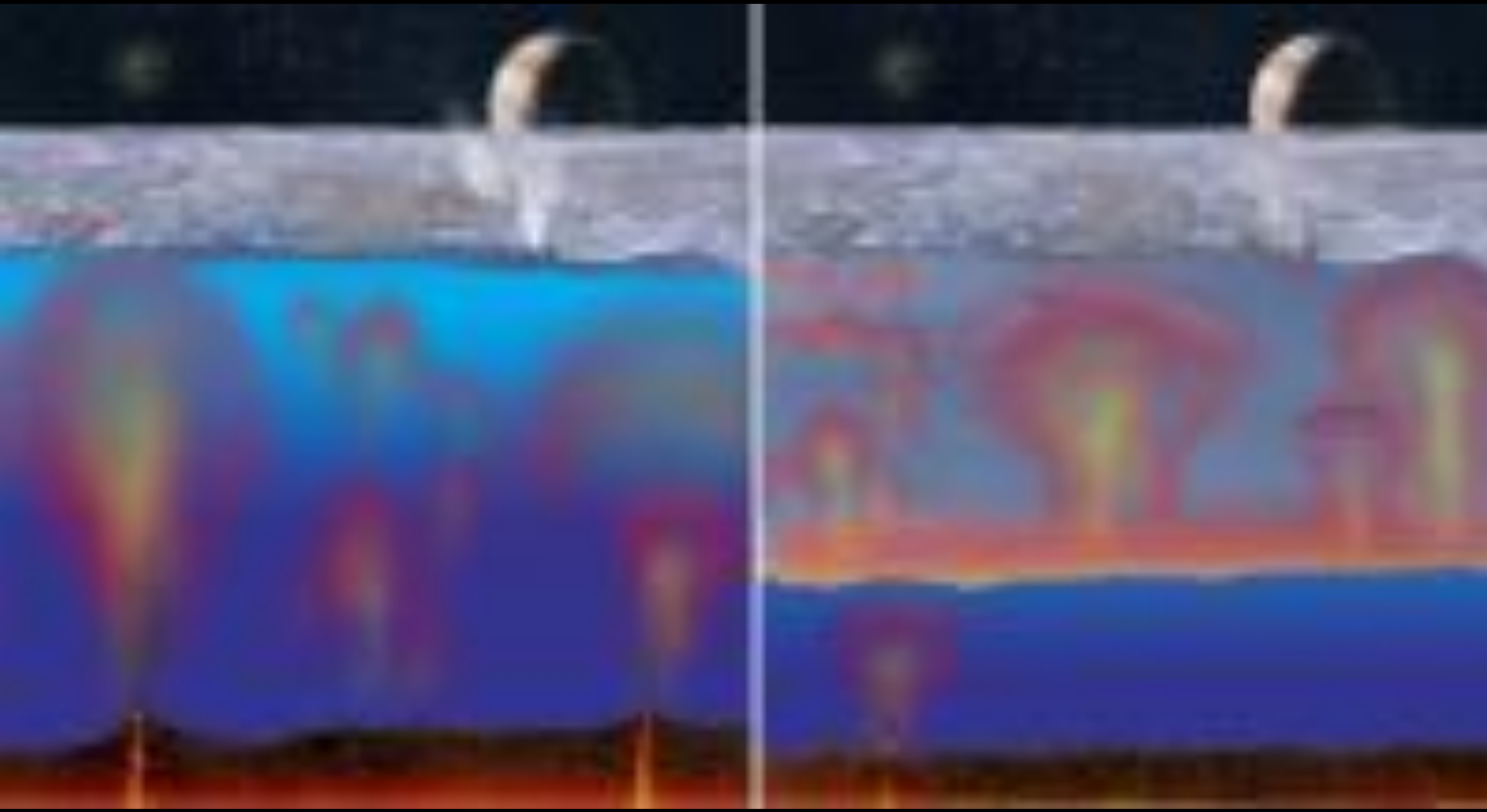
Strike-Slip Faults: Earth vs. Europa



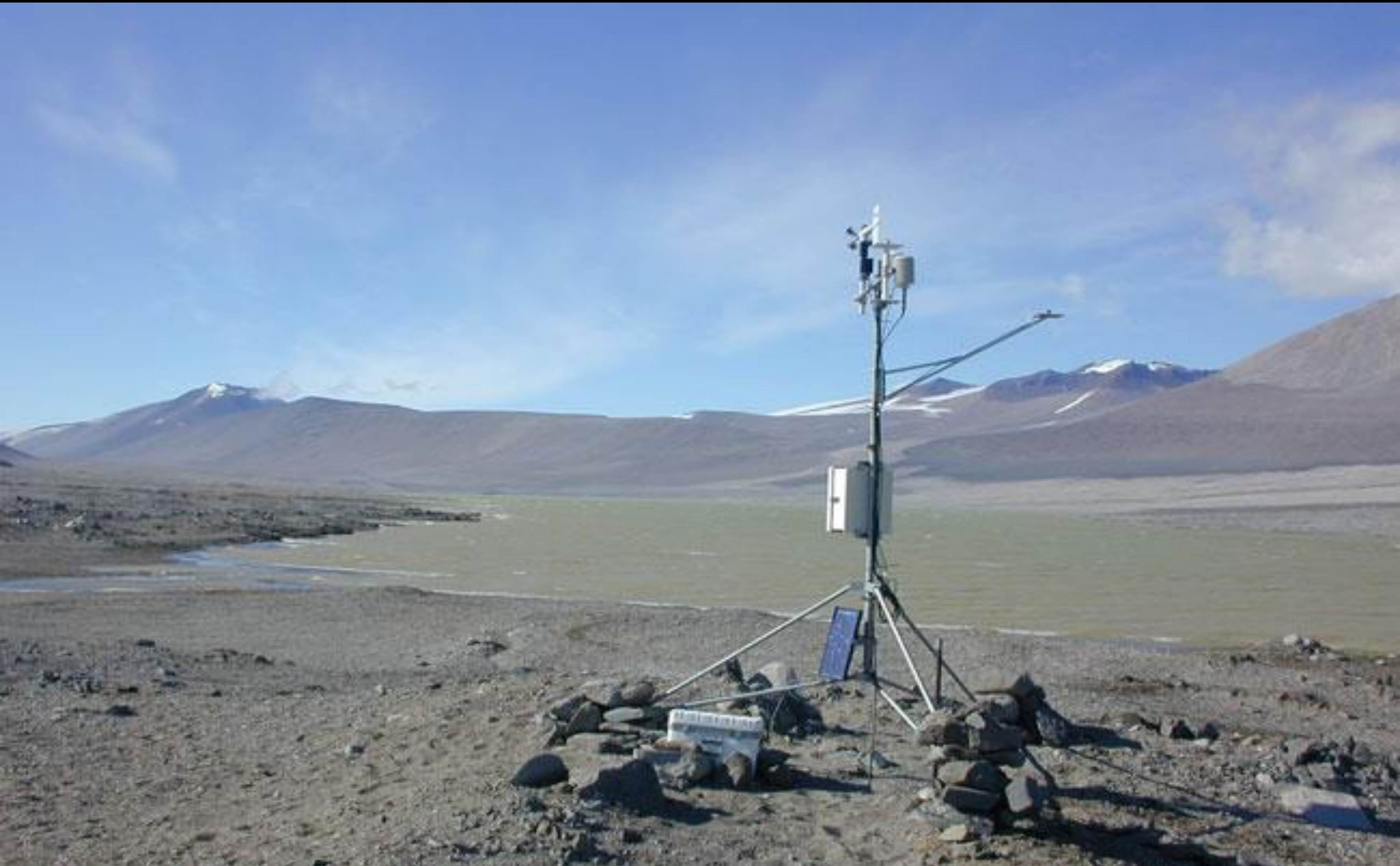
Visual look of freeze-thaw-freeze episodes



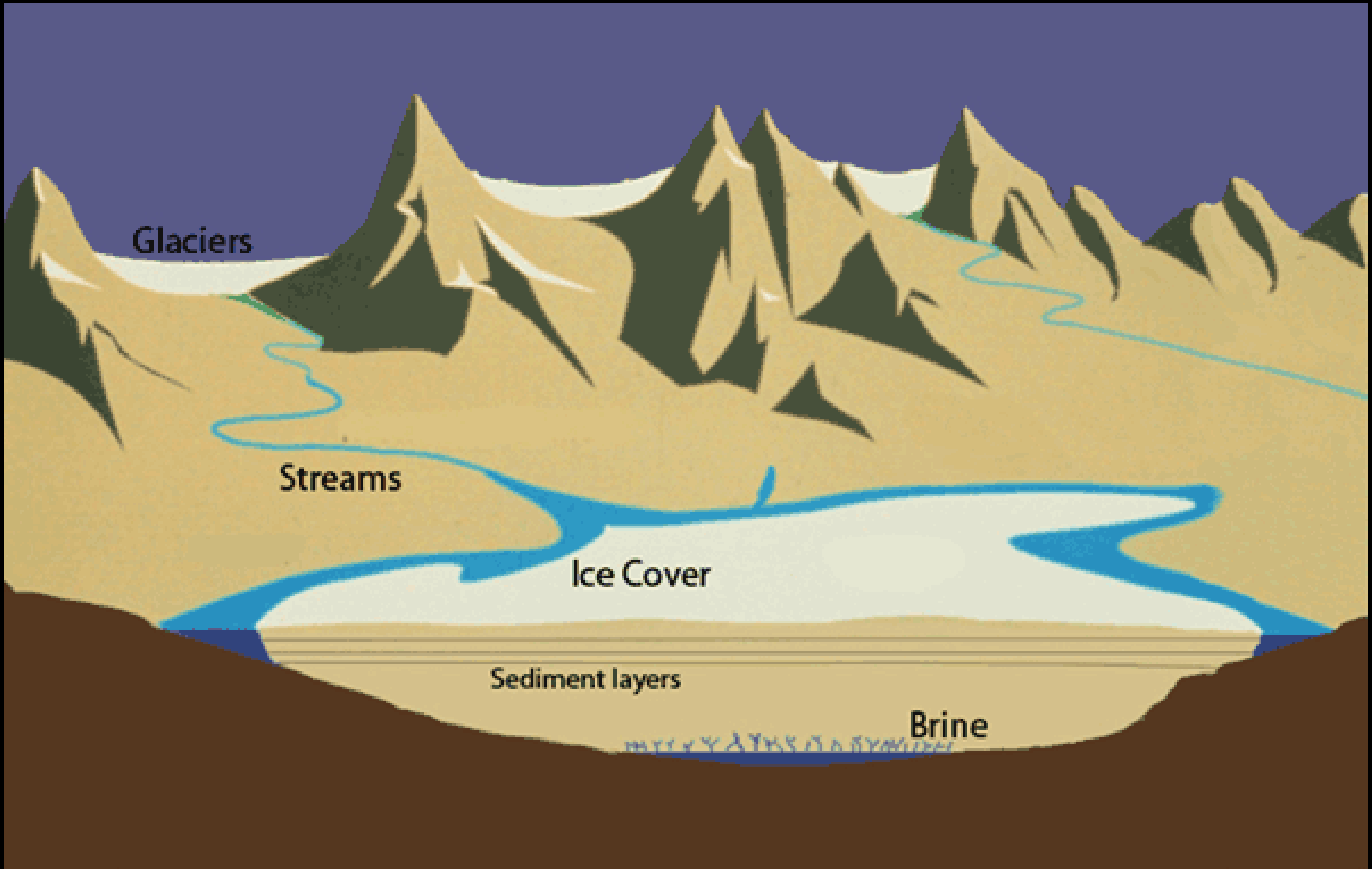
A model - thermal vents from the hot core drive convection in the ocean, driving “tectonics” in the ice crust



Antarctica’s Lake Vida – closest analogue to Europa?

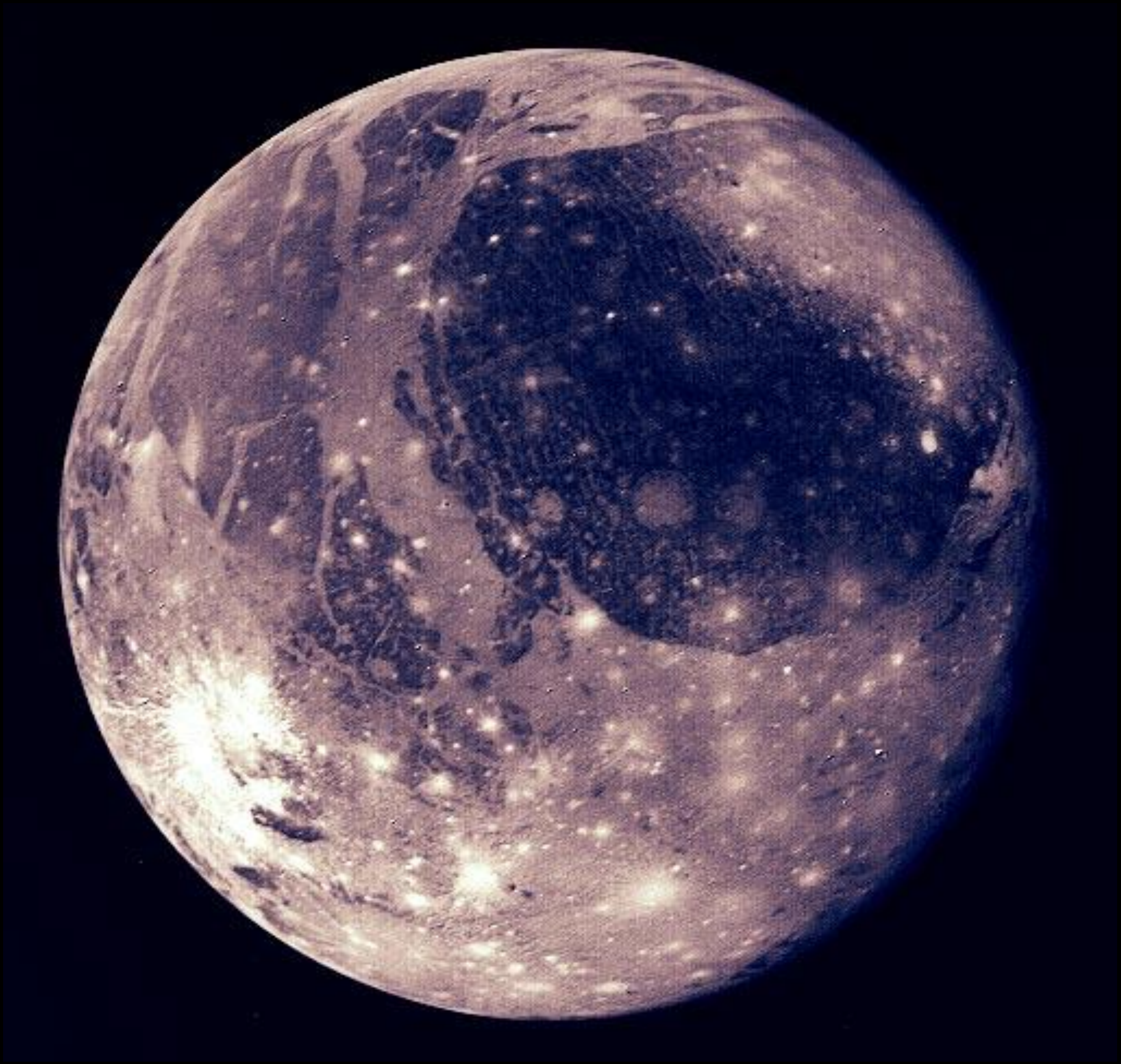


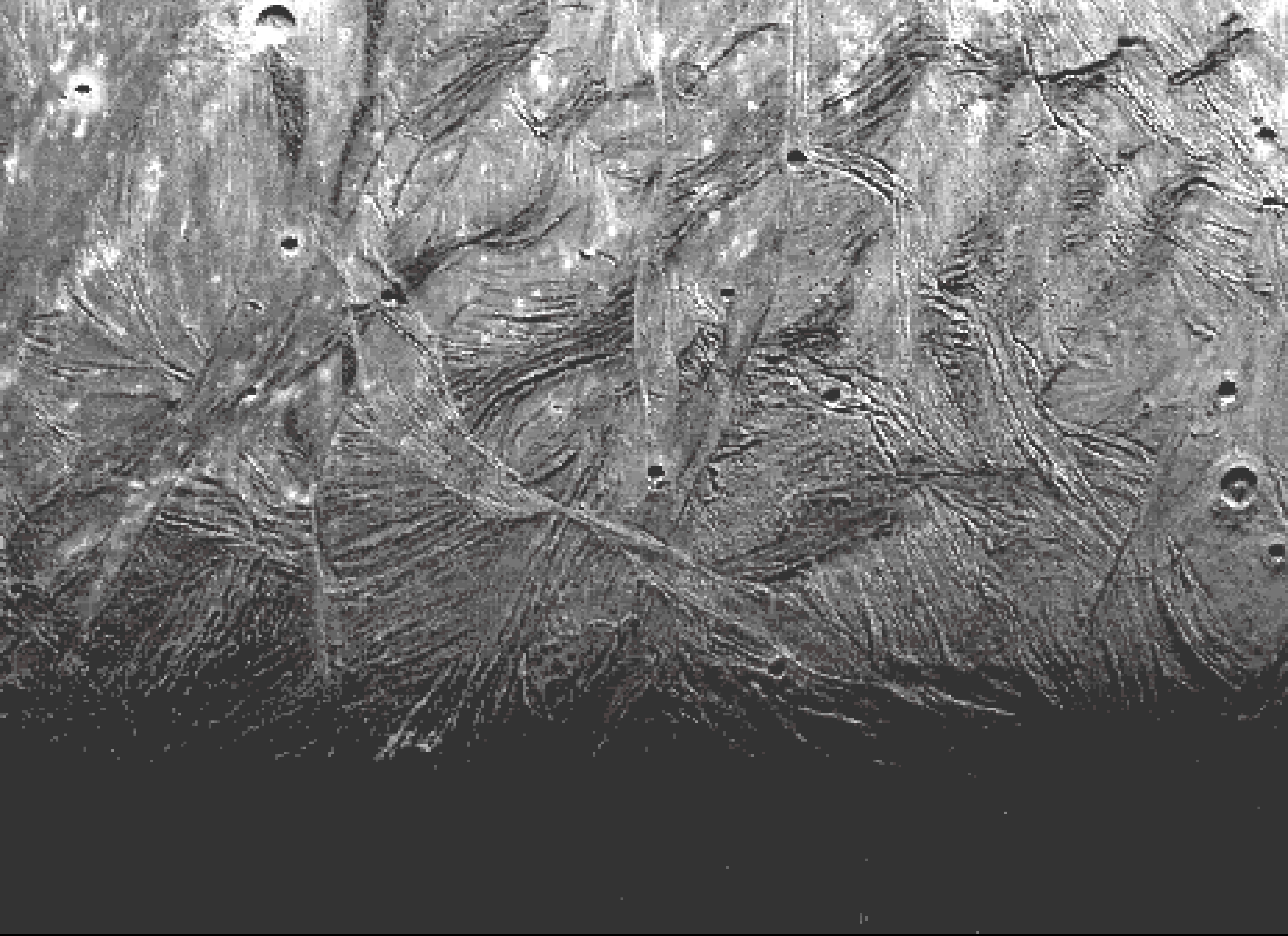
Despite being very dark (<1% sunlit vs surface), much saltier than ocean, and covered with permanent ice, the brine layer at the bottom is full of microbial life

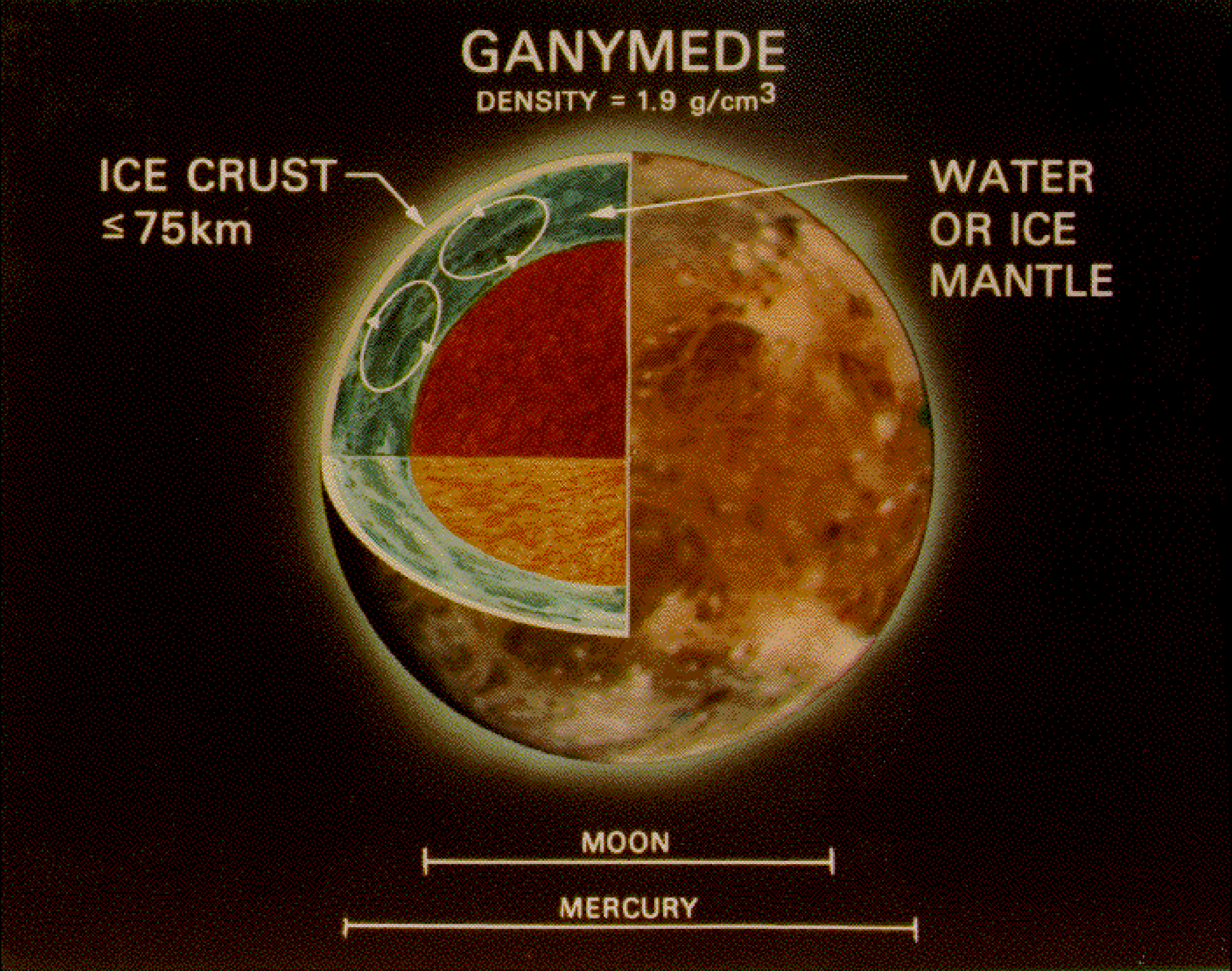


Ganymede…

- Farther from Jupiter; less tidal heating.
- But bigger than any other moon in the solar system, bigger than Mercury (3200 miles)
- This helped it retain some heat, and tidal heating is still able to make an ice/slush layer deep under the surface ice
- Not believed to be tectonically active now, but was in the distant past… see these wrinkles?



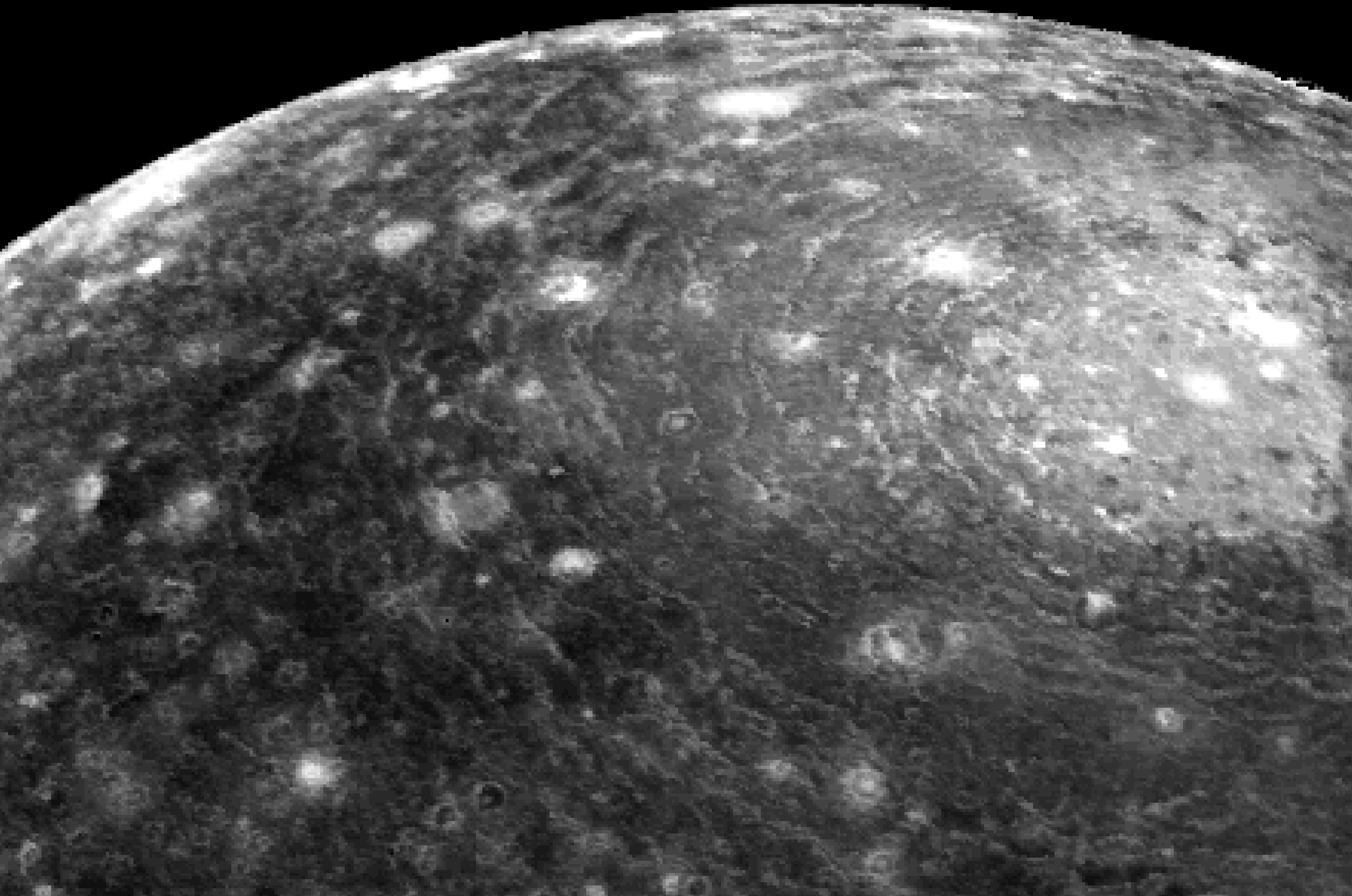


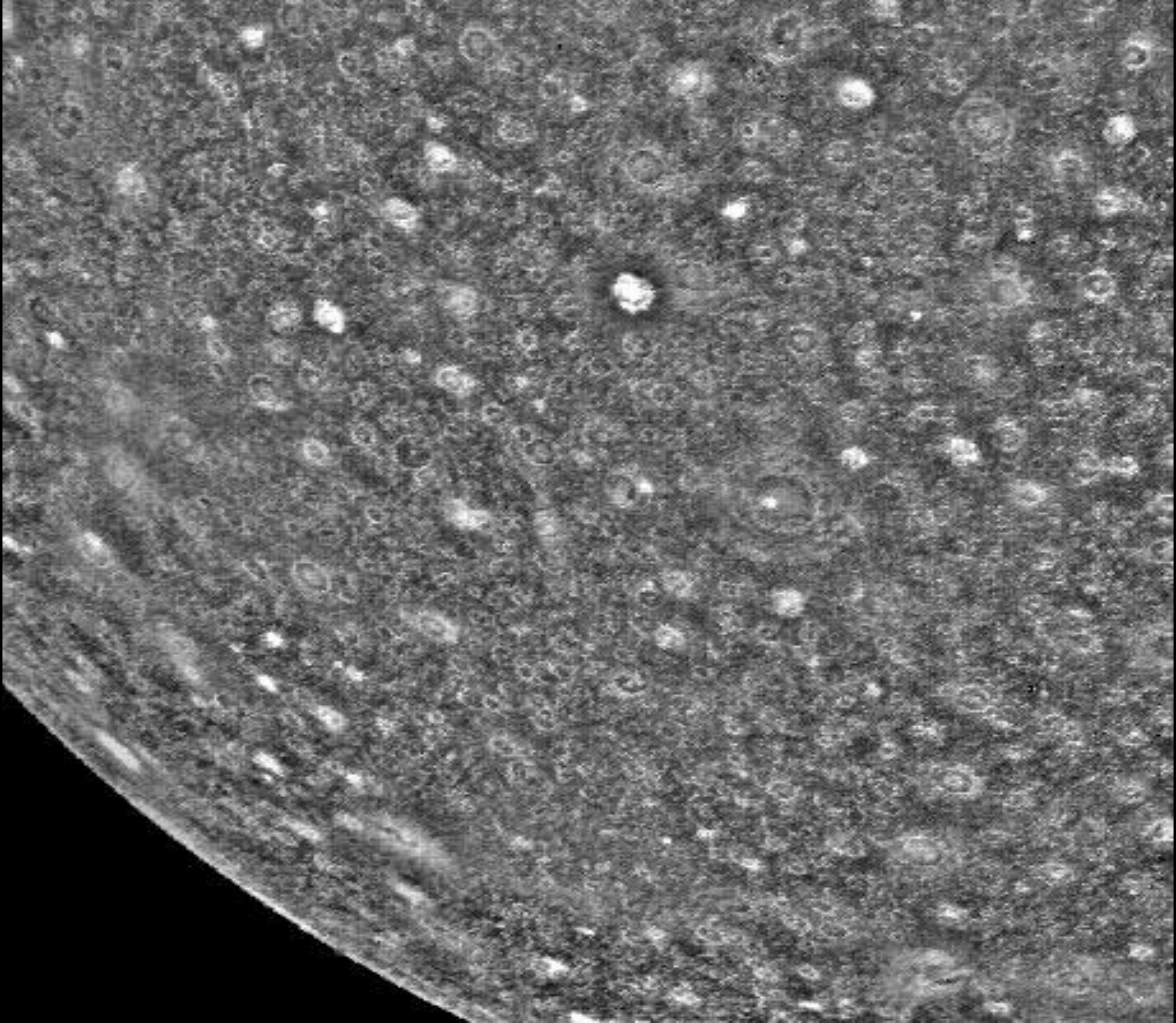


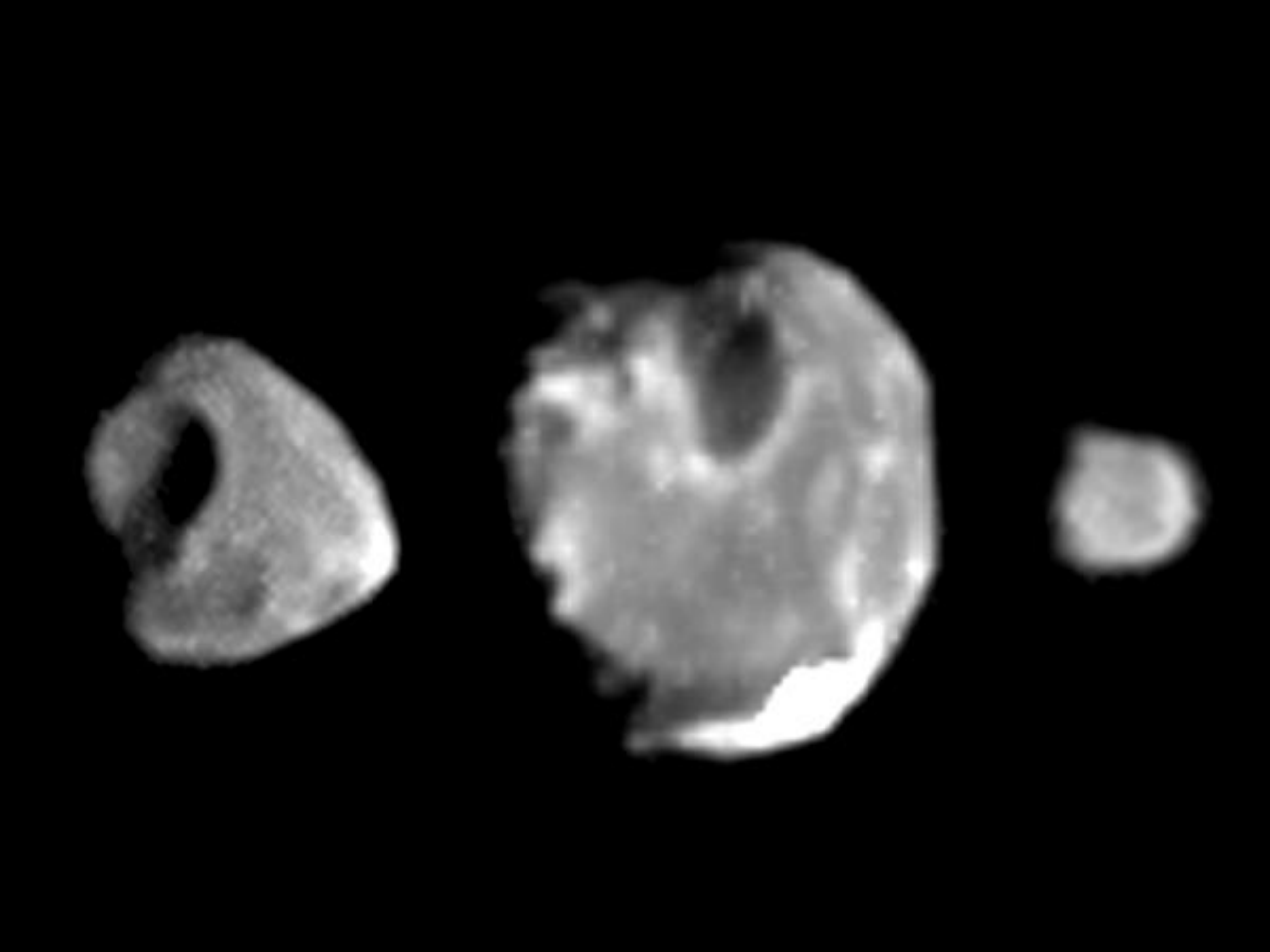
GANYMEDE
DENSITY = 1.9 g/cm3
ICE CRUST
≤ 75km
WATER
OR ICE
MANTLE
MOON
MERCURY

Callisto – Last and Farthest of the Galilean Moons

- Note the ancient surface, which you can tell because of the many impact scars.
- Tidal friction goes as $1/r^3$, and this far from Jupiter (4.5 times farther than Io), Callisto experiences only **1% of the tidal heating as Io.** Not enough to melt ice.
- Hence, any watery ocean is at least dozens of km and probably more, beneath unbroken ice. Ancient surface.





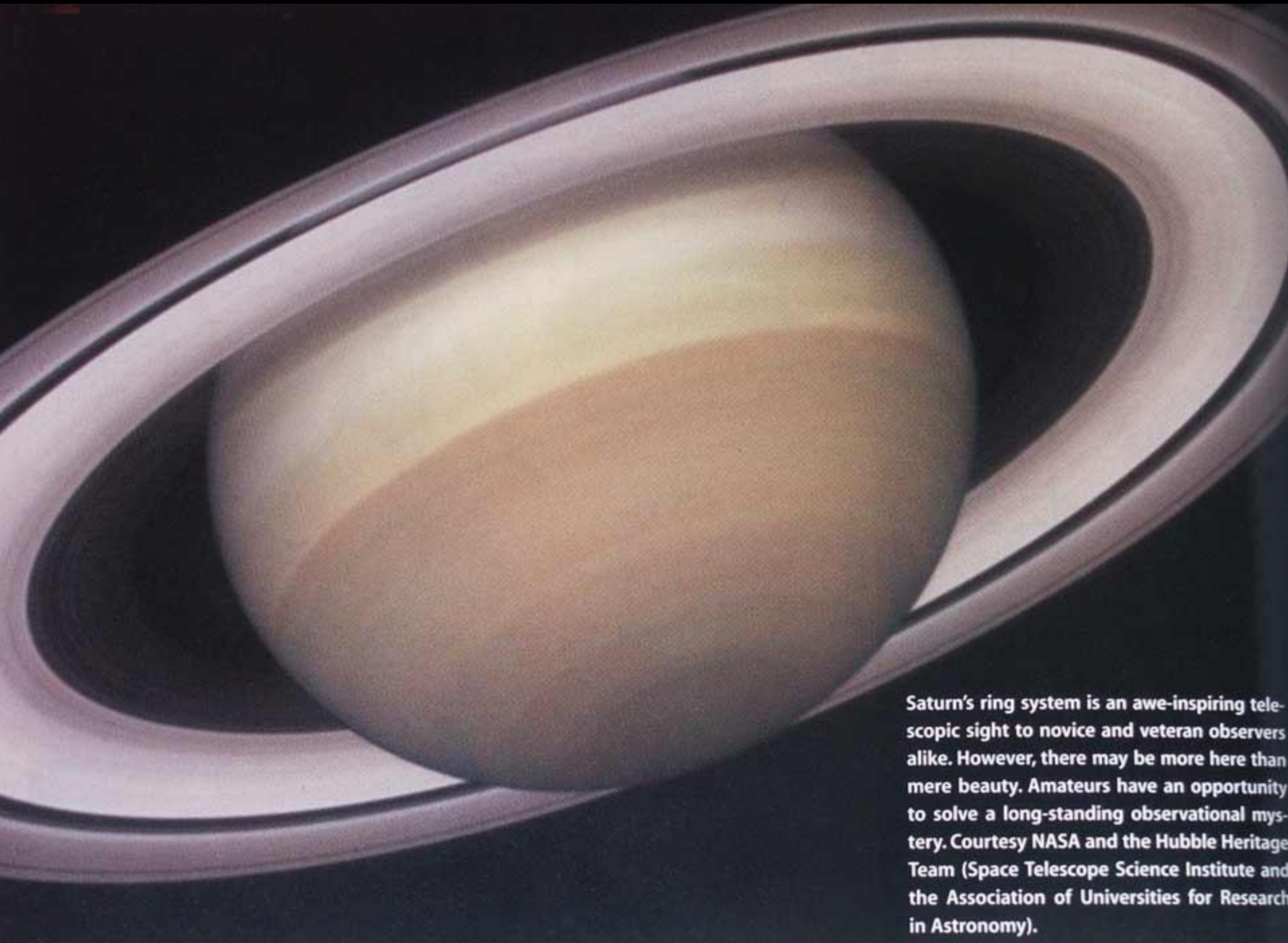


None of Jupiter's Moons have true atmospheres, climates

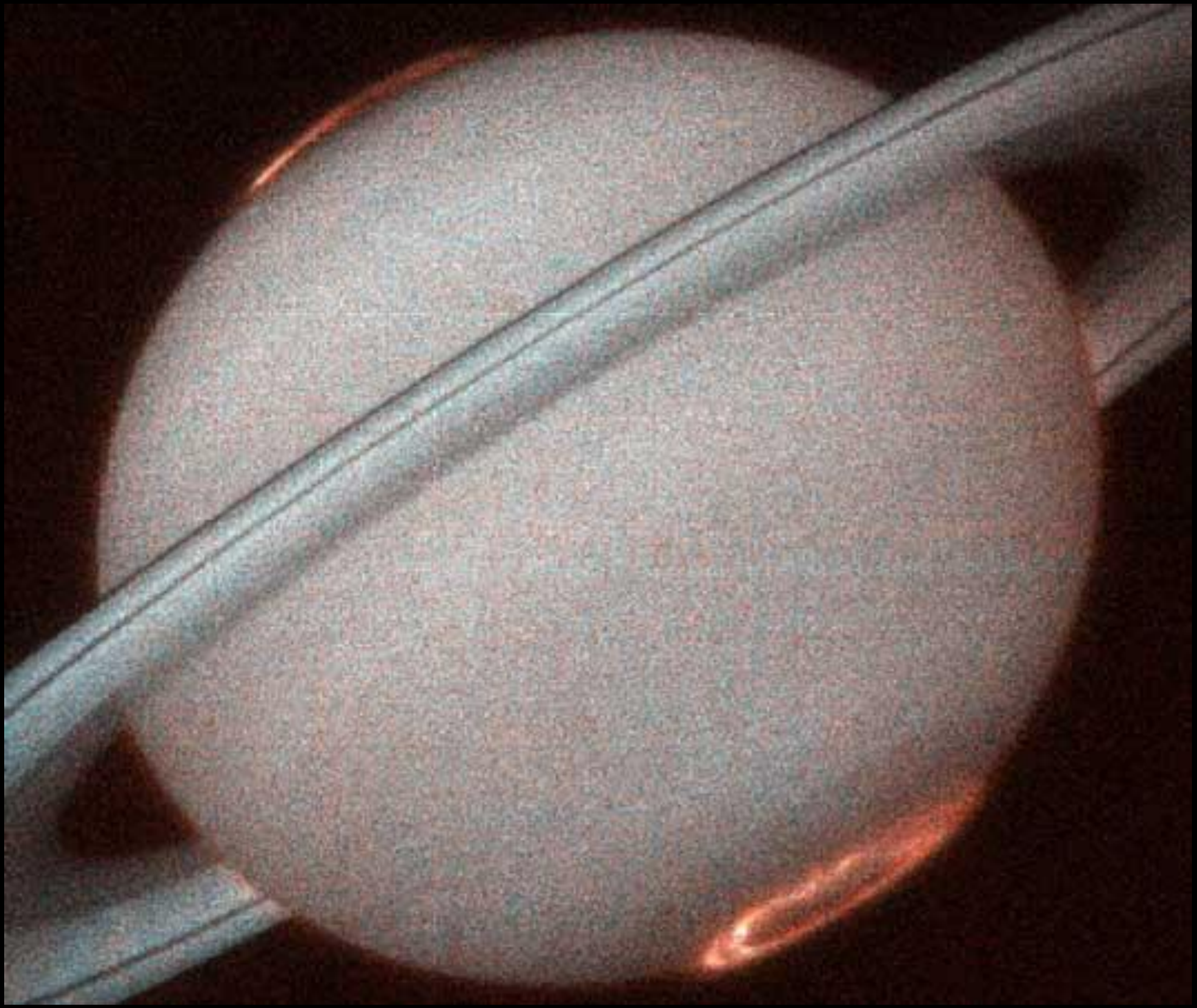
- Not enough gravity to hold an atmosphere.
- It may also be that solar wind particles held in Jupiter's powerful magnetic field act to strip away any primitive atmosphere they may have once had
- No atmosphere, no weather**, no climate..** but interesting nonetheless

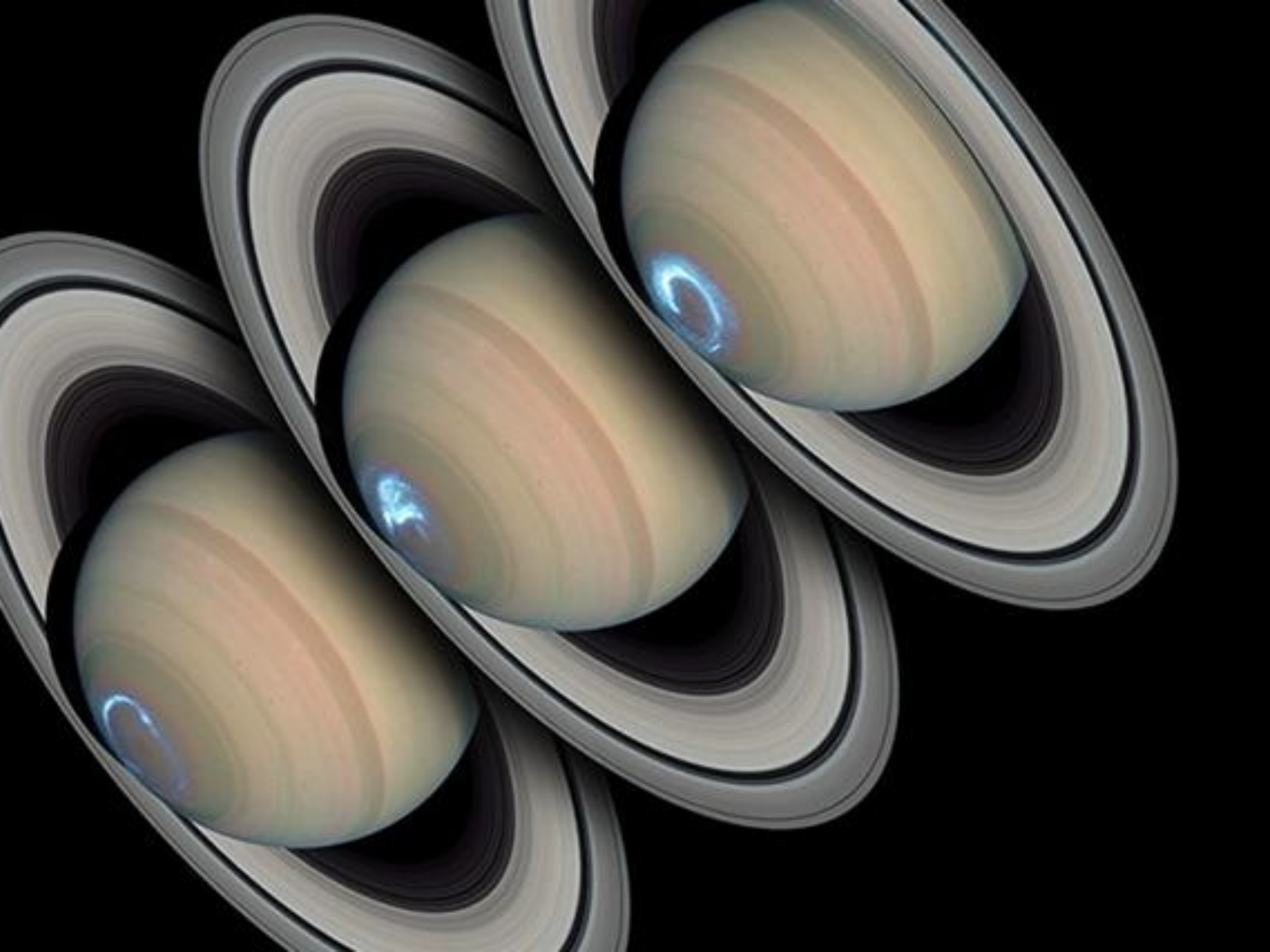
Saturn

- Slightly smaller than Jupiter, but much less massive. Not enough mass (gravity) to compress the hydrogen into a thick liquid layer like Jupiter
- So, it’s mostly a gaseous hydrogen and helium atmosphere
- Most obvious feature – very reflective and massive rings



Saturn's ring system is an awe-inspiring telescopic sight to novice and veteran observers alike. However, there may be more here than mere beauty. Amateurs have an opportunity to solve a long-standing observational mystery. Courtesy NASA and the Hubble Heritage Team (Space Telescope Science Institute and the Association of Universities for Research in Astronomy).

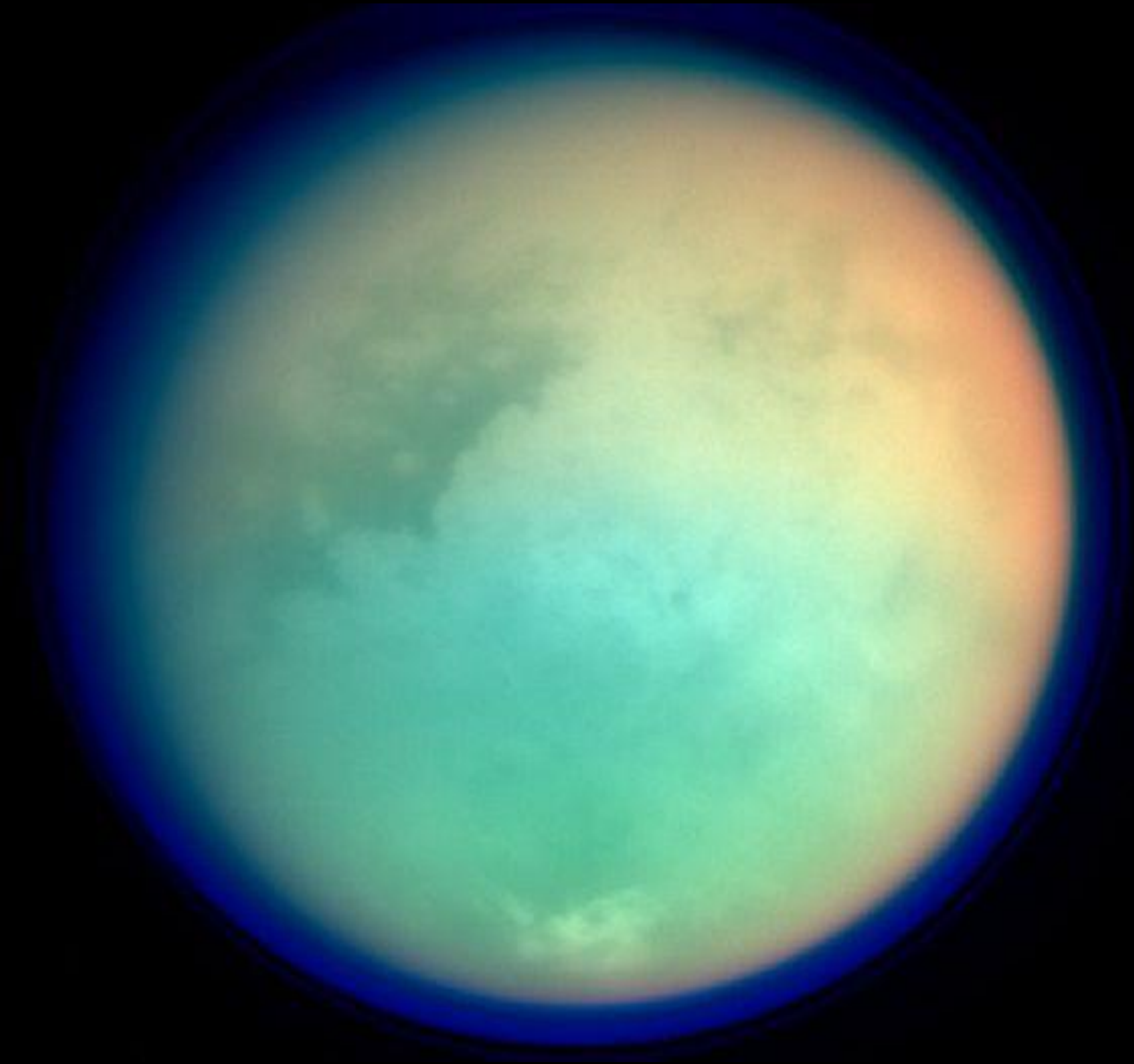


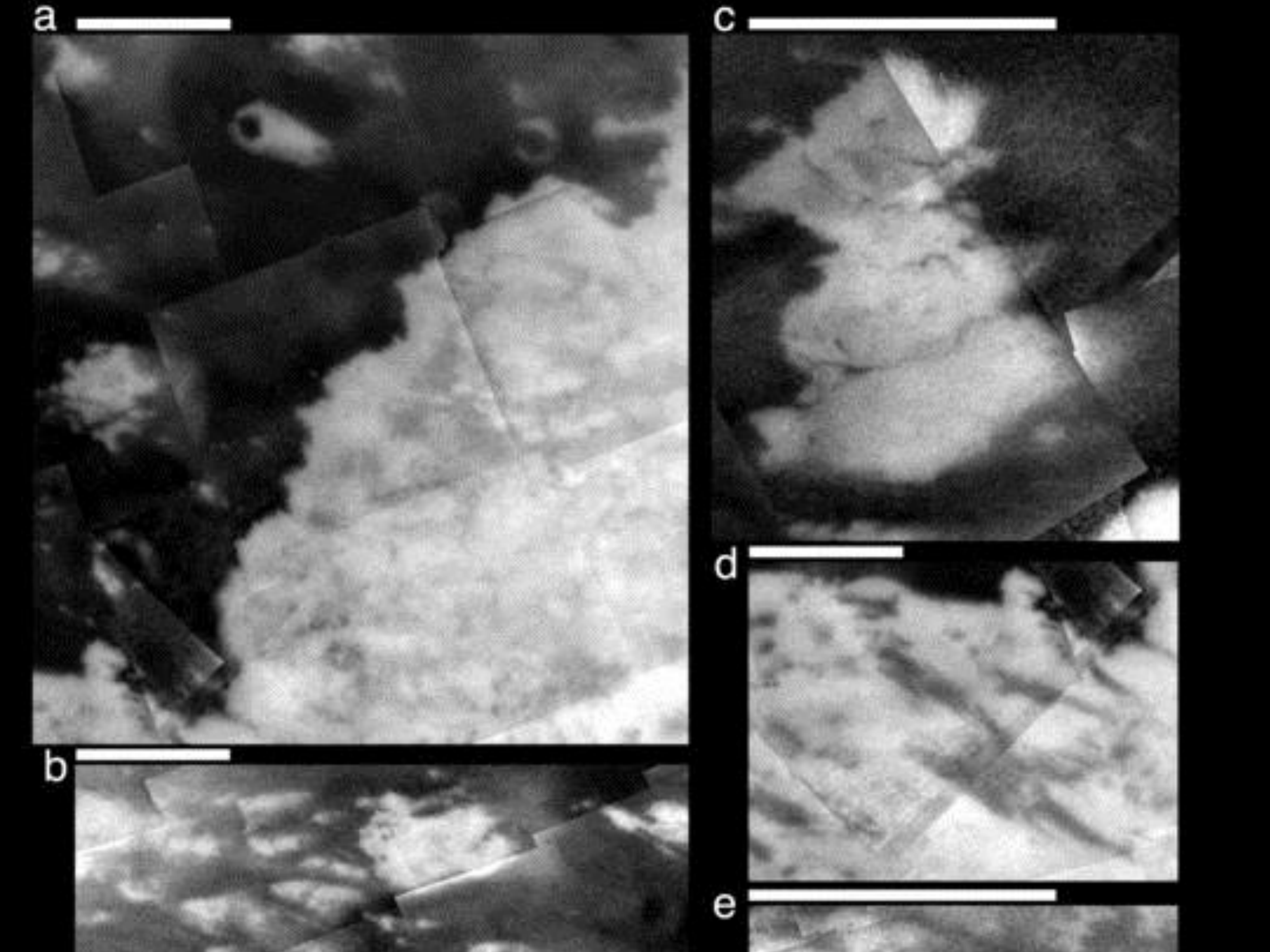


Titan – Only Moon in the Solar System with a Significant Atmosphere – Same pressure as Earth!

- Not a great atmosphere, though
- Made of…. **Smog**!
- Actually, mostly Nitrogen (like Earth), but with hydrocarbons making a strong photochemical smog component.
- Atmospheric pressure is just like Earth but because it's so cold it's 10x denser!
- Like a very cold L.A.
- **Bummer, Dude!**

Photochemical Smog

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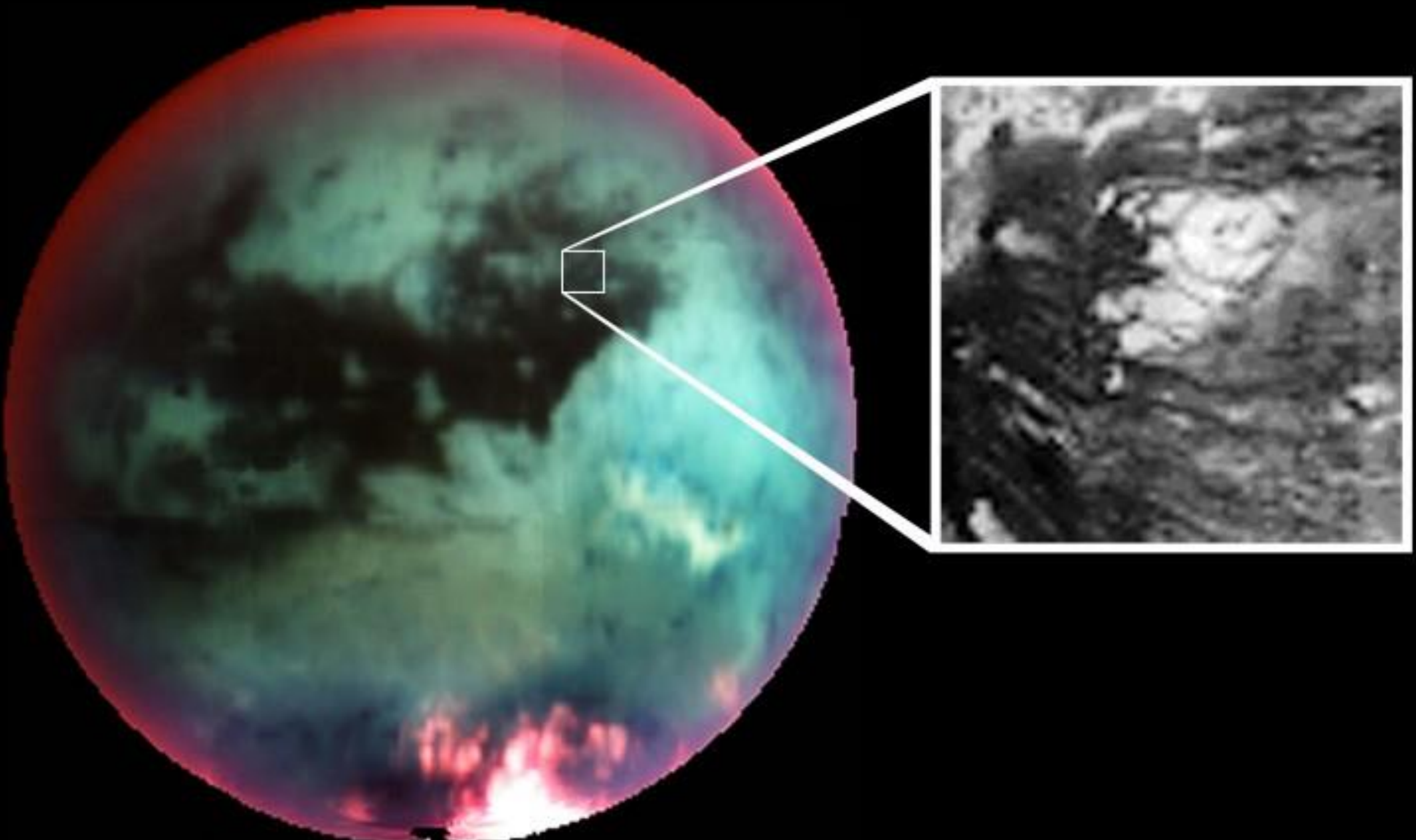
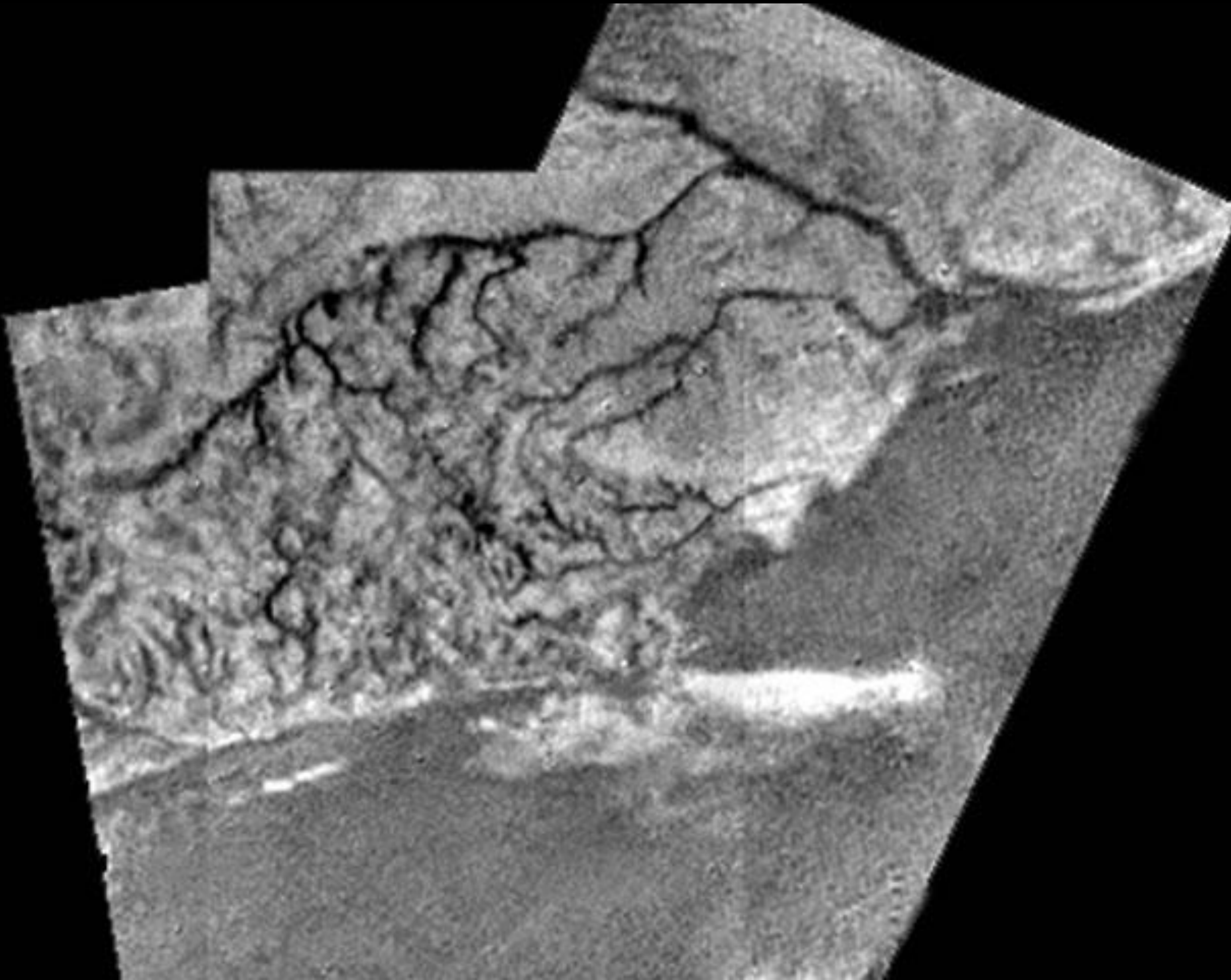
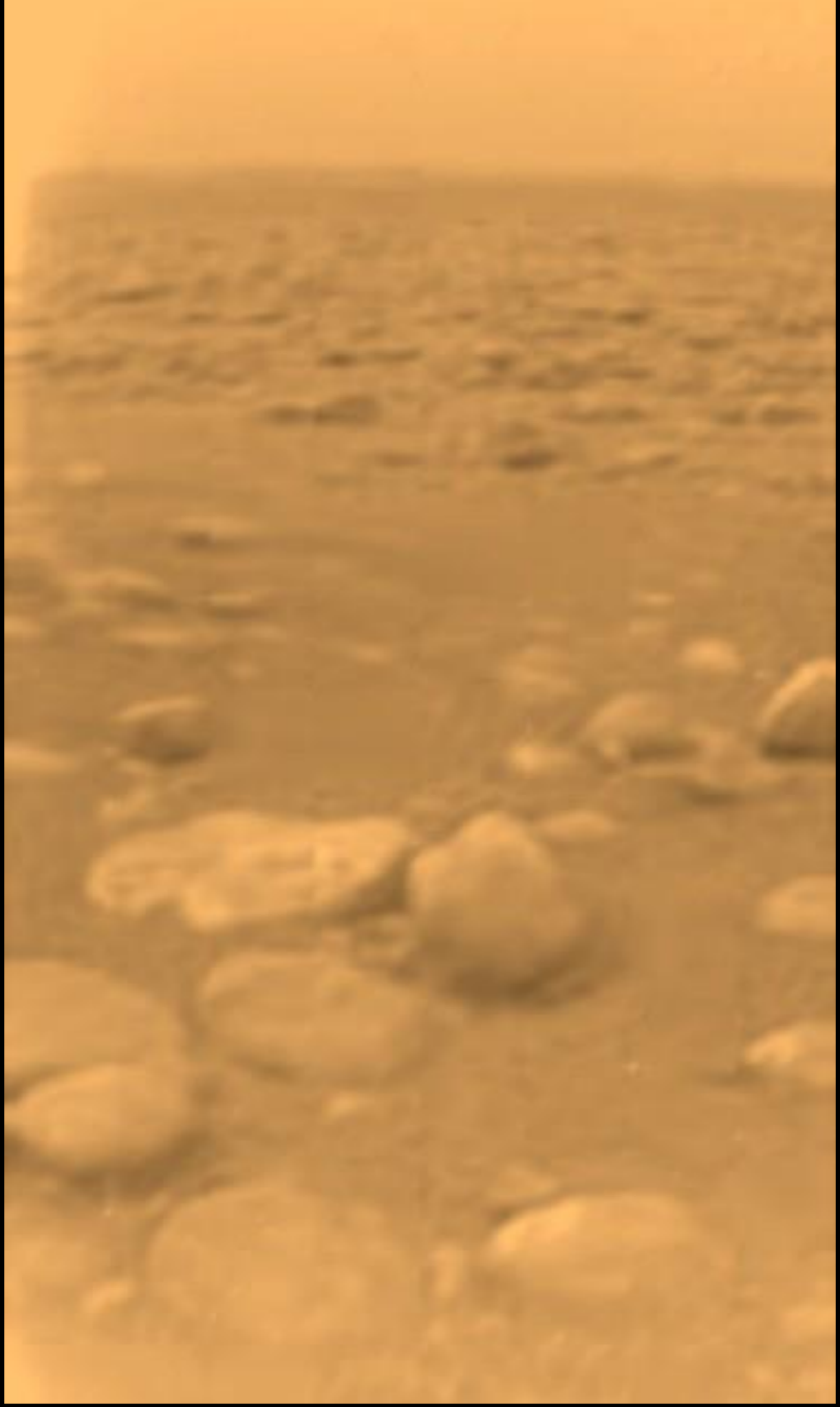


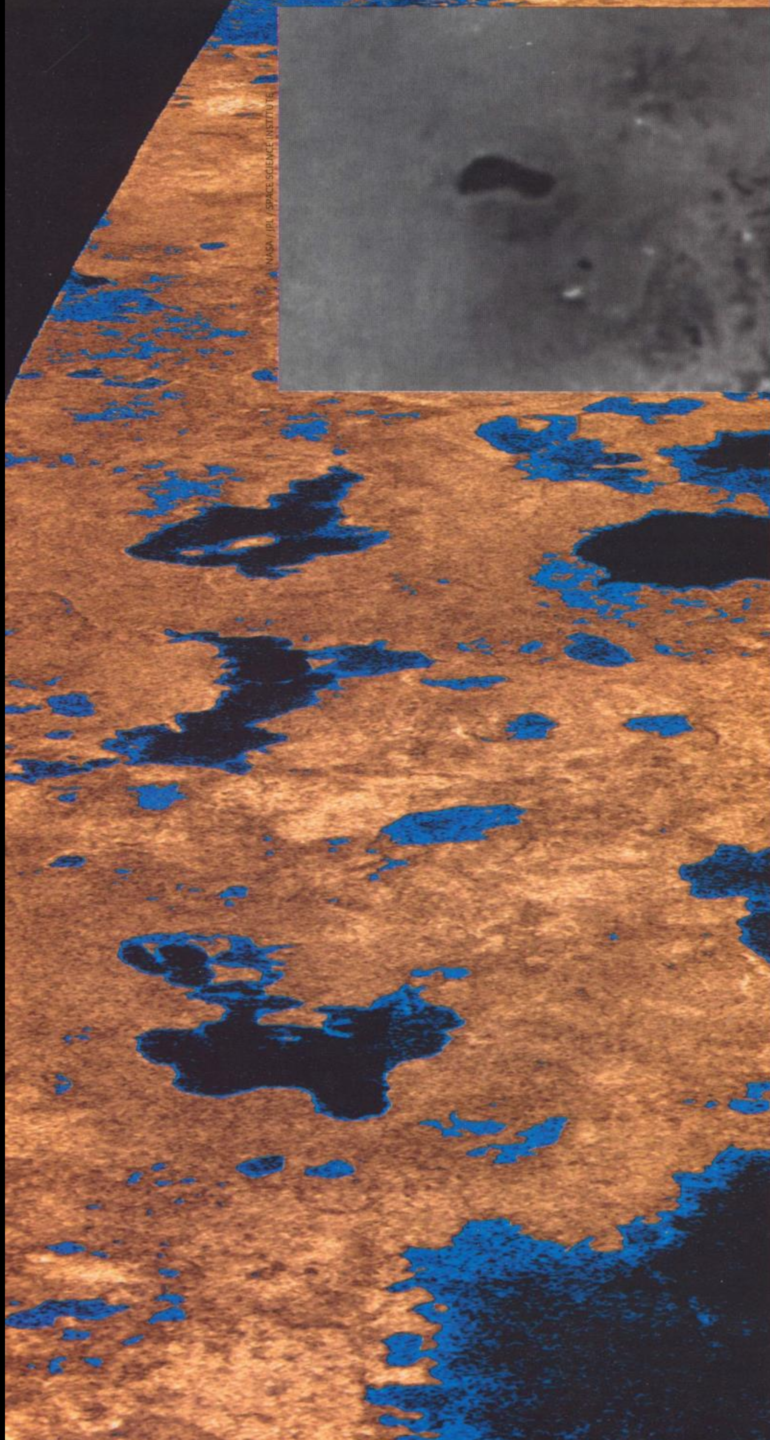
Titan's methane rivers and dry lake beds

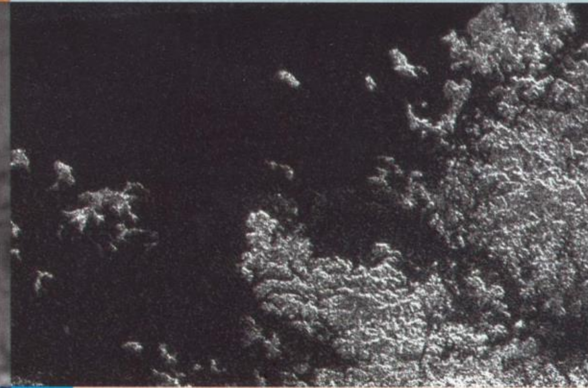




- The Huygens lander, on Titan.
- Stream-rounded boulders of water-ice, stained by a smoggy atmosphere
- Sitting on a dry lake bed, with frozen methane ice crystals just below the surface

Methane lakes, surrounded by water ice





NASA / JPL

LAND OF LAKES ***Left and above:*** **Cassini's radar has revealed numerous flat, smooth features, mainly at high northern latitudes, which scientists have interpreted as lakes. This view has been confirmed by recent spectral analysis. Titan and Earth are the only bodies in the solar system to have liquid bodies on their surface. The colors in the left image represent radar reflectivity, not what you'd see.** ***Above left:*** **Cassini imaged Ontario Lacus in near-infrared light. This feature is similar in size and shape to Lake Ontario, and is located near Titan's south pole. Recent spectral observations have confirmed the presence of liquid ethane.**

Splish, Splash

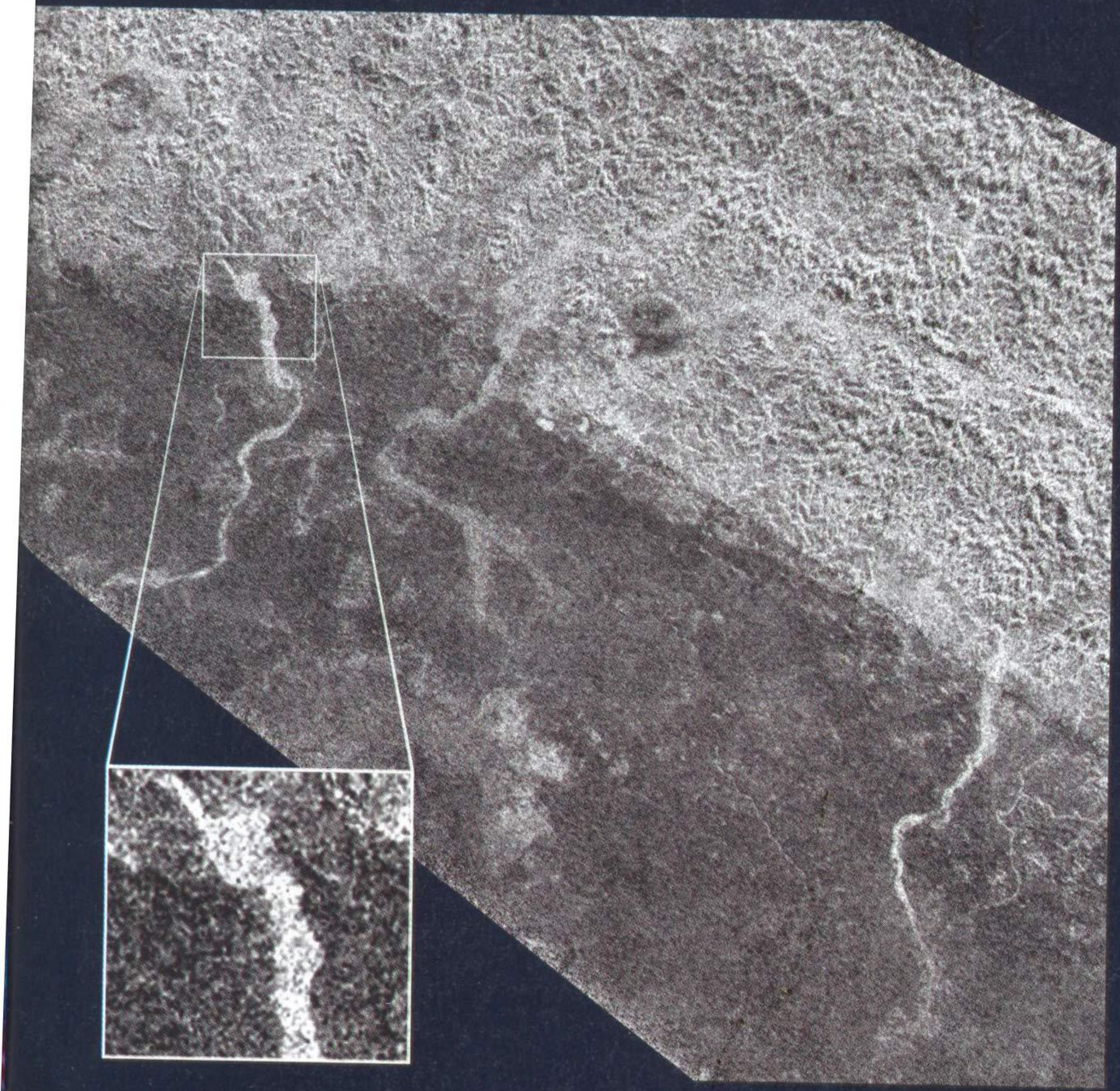
Huygens didn't see any surface puddles because, we now realize, it landed in Titan's equivalent of a vast desert. There are big pools of liquid on the surface — but they're in the polar regions. Cassini first spotted clusters of dark polar patches in 2005, and they've tantalized our science team ever since.

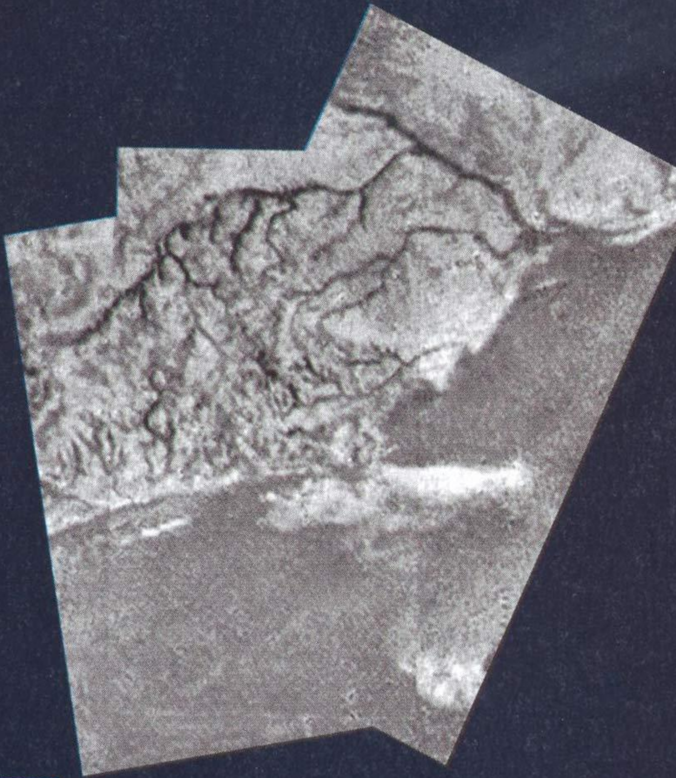
Initially the evidence for true hydrocarbon lakes was circumstantial. They appear really dark in both radar scans and infrared images. The radar result is consistent with nearly mirror-smooth surfaces that reflect Cassini's radar emissions away from the spacecraft and out into space. The infrared darkness implies that clear liquid extends so far down that photons of light are absorbed before they can scatter off suspended particulates.

The lake hypothesis reached its splash point last December, when Cassini's Visual and Infrared Mapping Spectrometer (VIMS) got a good look at a conspicuous dark region near the south pole known as Ontario Lacus. VIMS analyzed the feature's reflectivity between 2 and 5 microns, infrared wavelengths at which the atmosphere is transparent. A handful of absorption lines match the ones expected for liquid ethane — finally, we had our long-sought "smoking gun" for fluid-filled reservoirs (November issue, page 19).

Close-ups of Ontario Lacus from that flyby also reveal what may be mudflats and a surrounding bathtub ring.

NASA / JPL



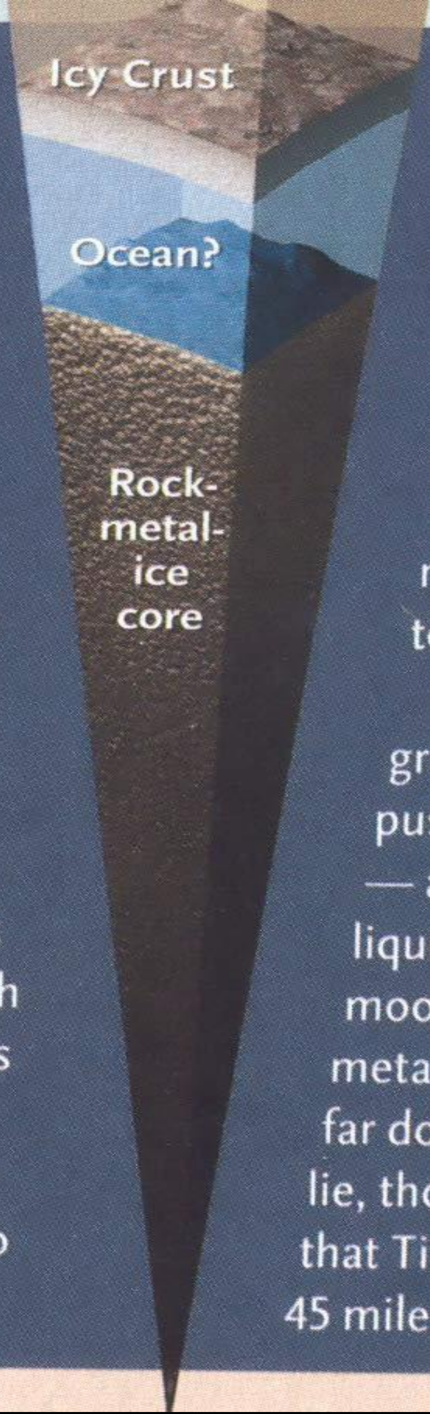


RIVERBEDS *Left:* Cassini's radar instrument has found dry riverbeds all over Titan. The channels come in all sizes and in both smooth and rough textures. They were presumably carved by liquid hydrocarbons running downhill. *Right:* As Huygens parachuted to Titan's surface, its descent camera imaged dark channels flowing into what appears to be a dry lakebed. The channels are currently dry, but they indicate recent fluvial activity fed by rainfall.

The Spin on Titan

Last year, Titan threw Cassini's radar scientists a real curve. They were unable to match up surface features wherever one of the instrument's long image swaths overlapped another. The coordinates of a given surface feature could be off by up to 25 miles (40 km) from one swath to the next.

The team had assumed that Titan's obliquity (axial tilt) was zero. If instead the pole could drift by nearly a half degree, the observations fit together much better. Yet even with the revised polar tilt, the radar images continued to show offsets of up to 2 miles — and they were getting larger. Incredibly, the moon's spin seemed to be speeding up!



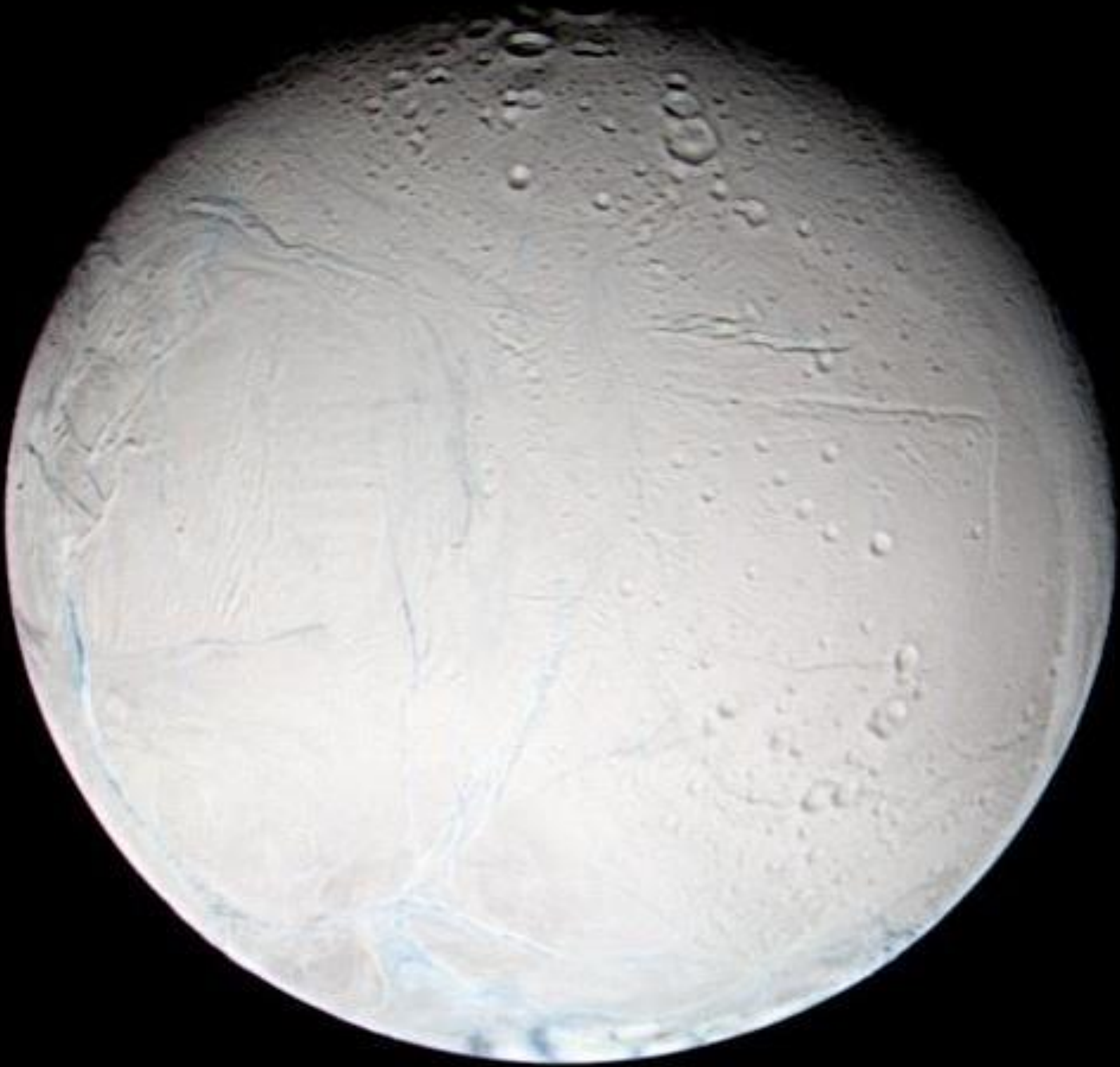
Tides from Saturn should force Titan to keep one hemisphere constantly facing the planet, just as the Moon's near side always faces Earth. Motions within Titan's dense atmosphere can affect the spin rate slightly, but not if they have to tug the moon's entire mass.

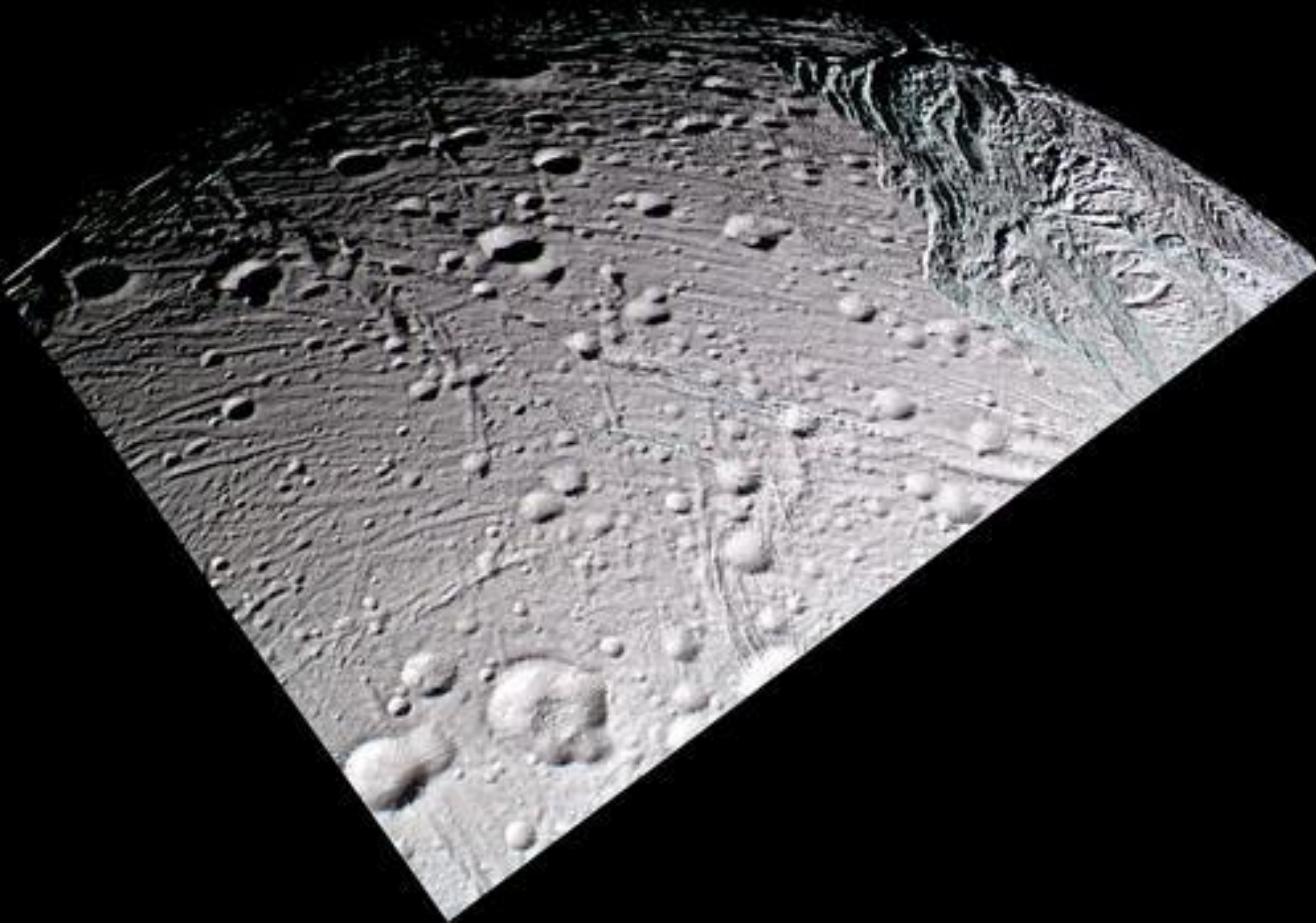
The only way to explain the growing mismatch is if the winds push only on Titan's icy crust — and that's only possible if a liquid-water mantle separates the moon's crust from its rock-and-metal core. We're not yet sure how far down this lubricating layer might lie, though the radar team estimates that Titan's ice crust might be about 45 miles thick.

AN ABODE FOR LIFE?

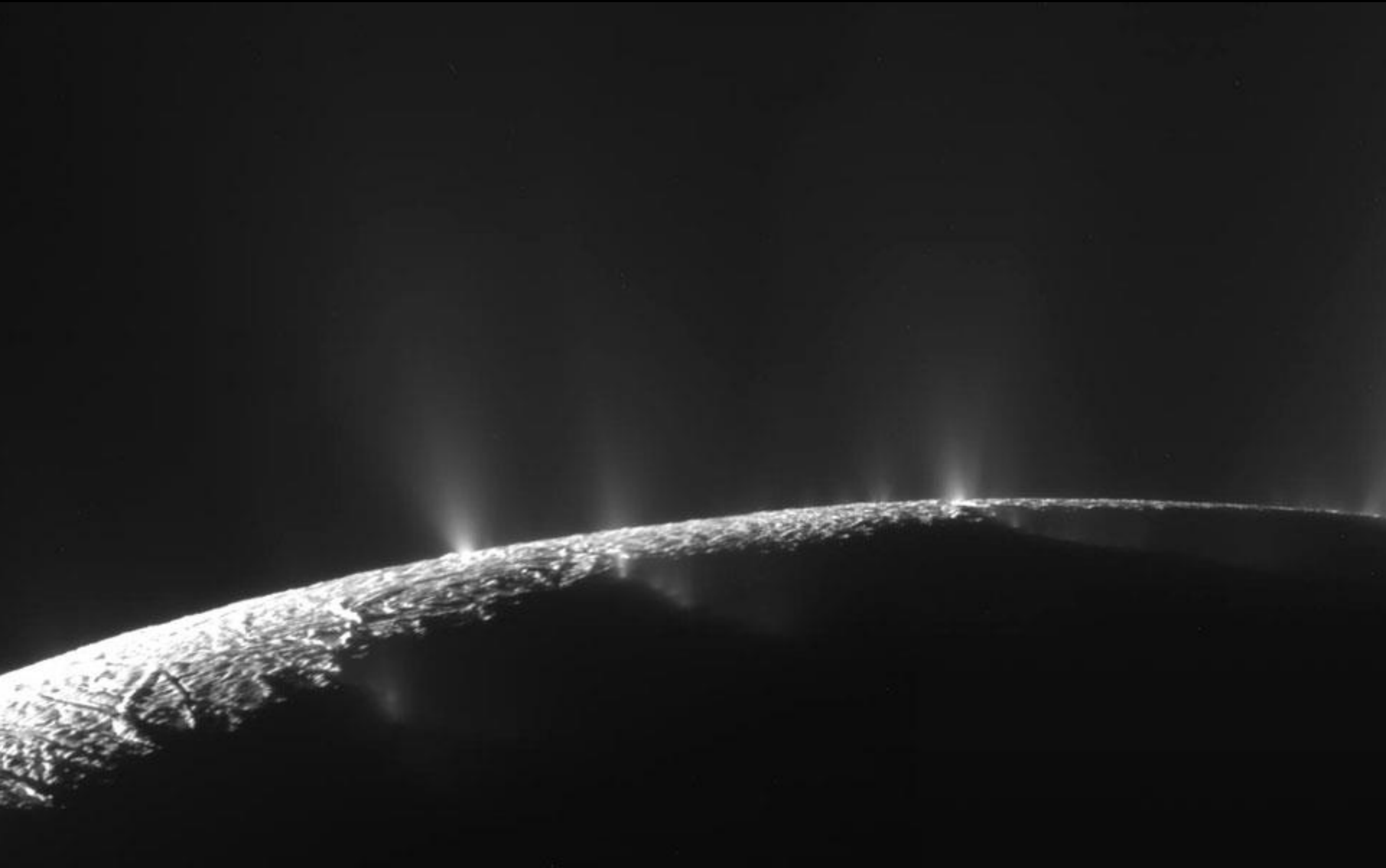
Titan's surface abounds with organic molecules and water ice, but its frigid temperatures offer bleak prospects for life. At Titan's –290°F (–179°C) surface temperatures, chemical reactions slow to a crawl, limiting the ability of complex molecules to form. But Titan's interior is warm enough to sustain liquid water. Given the plethora of life's building blocks on Titan, scientists cannot rule out the possibility that the moon harbors biological activity deep underground.

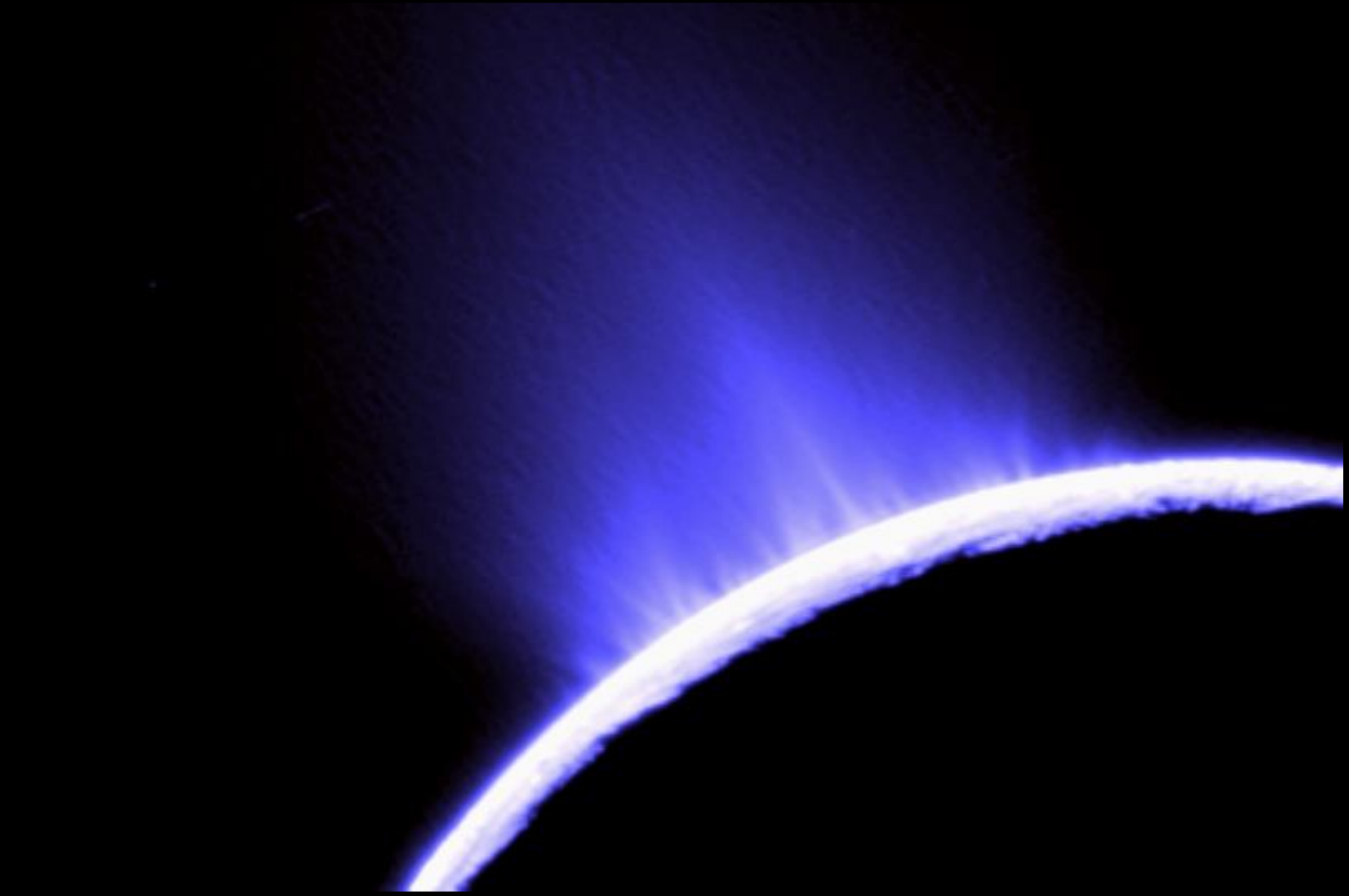
Enceladus





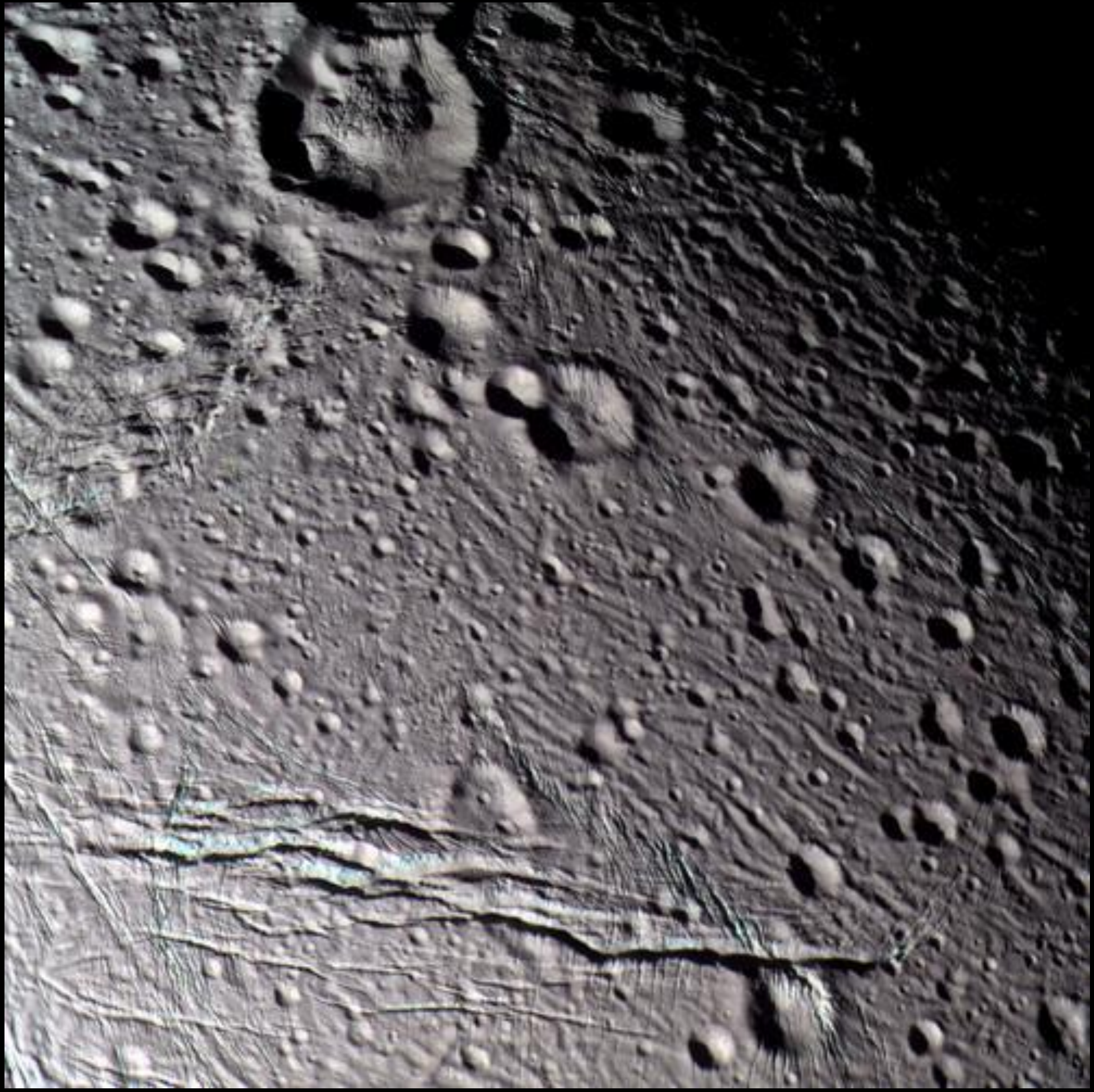
Geysers of water turned to snow. Tidal heating warms the otherwise frigid ice to melt, escape through cracks





- And here’s a short video of the bright Belt of Orion star Epsilon Orionis being occulted by the plume of Enceladus, as seen by the Cassini spacecraft in March ‘16 (link)
- Occultations by atmospheres produce differential refraction-induced brightenings and fadings. Inverting the resulting photometry with optics equations, allows temperature and density profile to be inferred

Overlaying cracks at angles, tells of episodic tidal cracking of surface



Iapetus

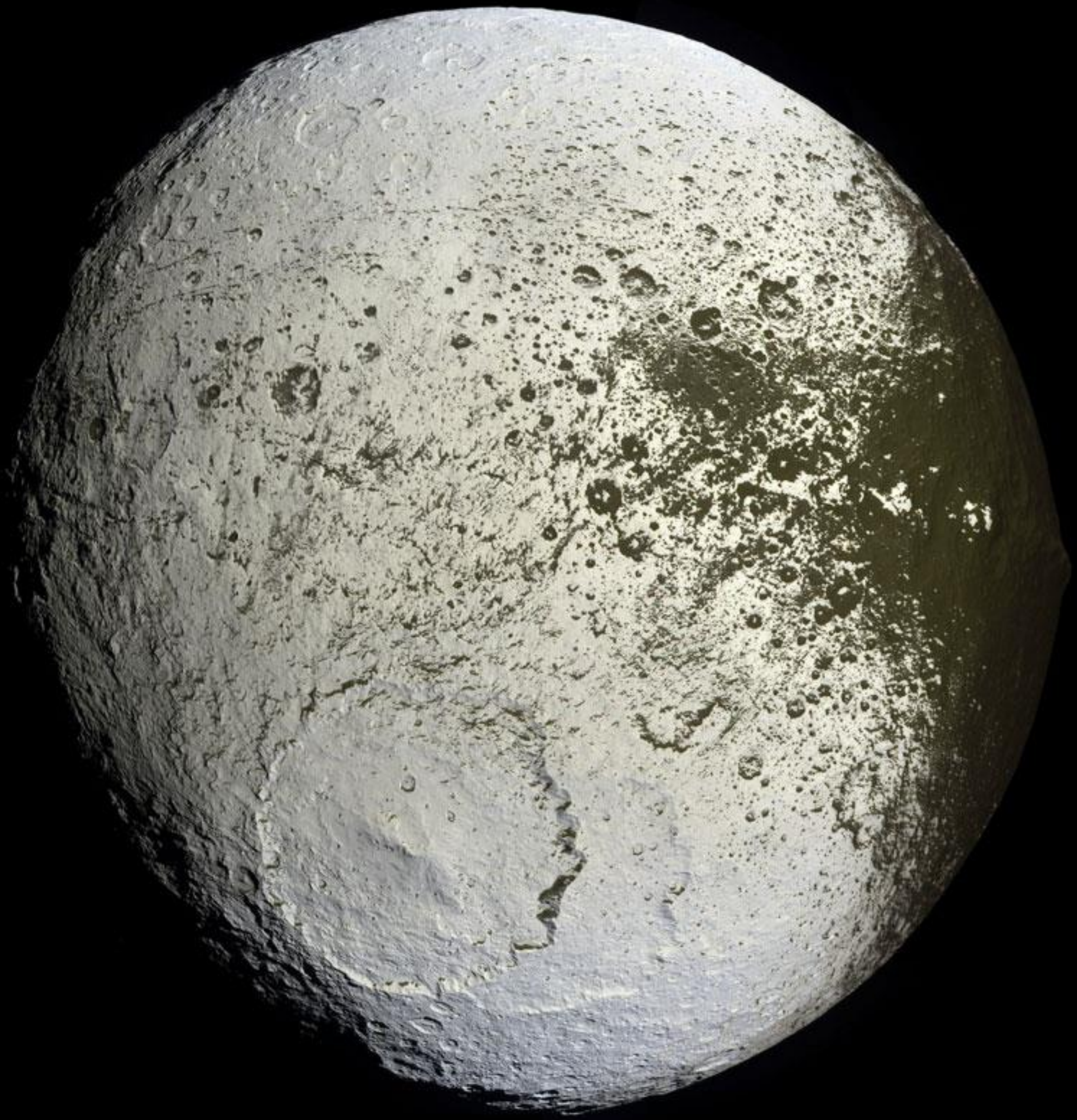
- We’ve known since the first telescopes that something was weird about this moon. It was 3x brighter when seen on one side of Saturn compared to when it’s on the other side.
- Clearly, one side must be very reflective, and the other side very dark
- And too, the moon must be tidally locked with Saturn, so it keeps the same fact towards Saturn always
- This last was not a surprise; virtually all moons in the solar system do this, including our own. The tidal braking time scale is much less than the 4.5 billion years since the beginning
- **Iapetus has a “Dark Side” and a “Bright Side”**

And, it’s got a large mountain range following the Equator most of the way around the circumference. It looks like one of those old-fashioned toilet tank floats

Or, more tastefully, a walnut

The “Walnut Ridge” on the Equator

The other hemisphere is icy and bright



“You Don’t Know the POWER of the Dark Side!”

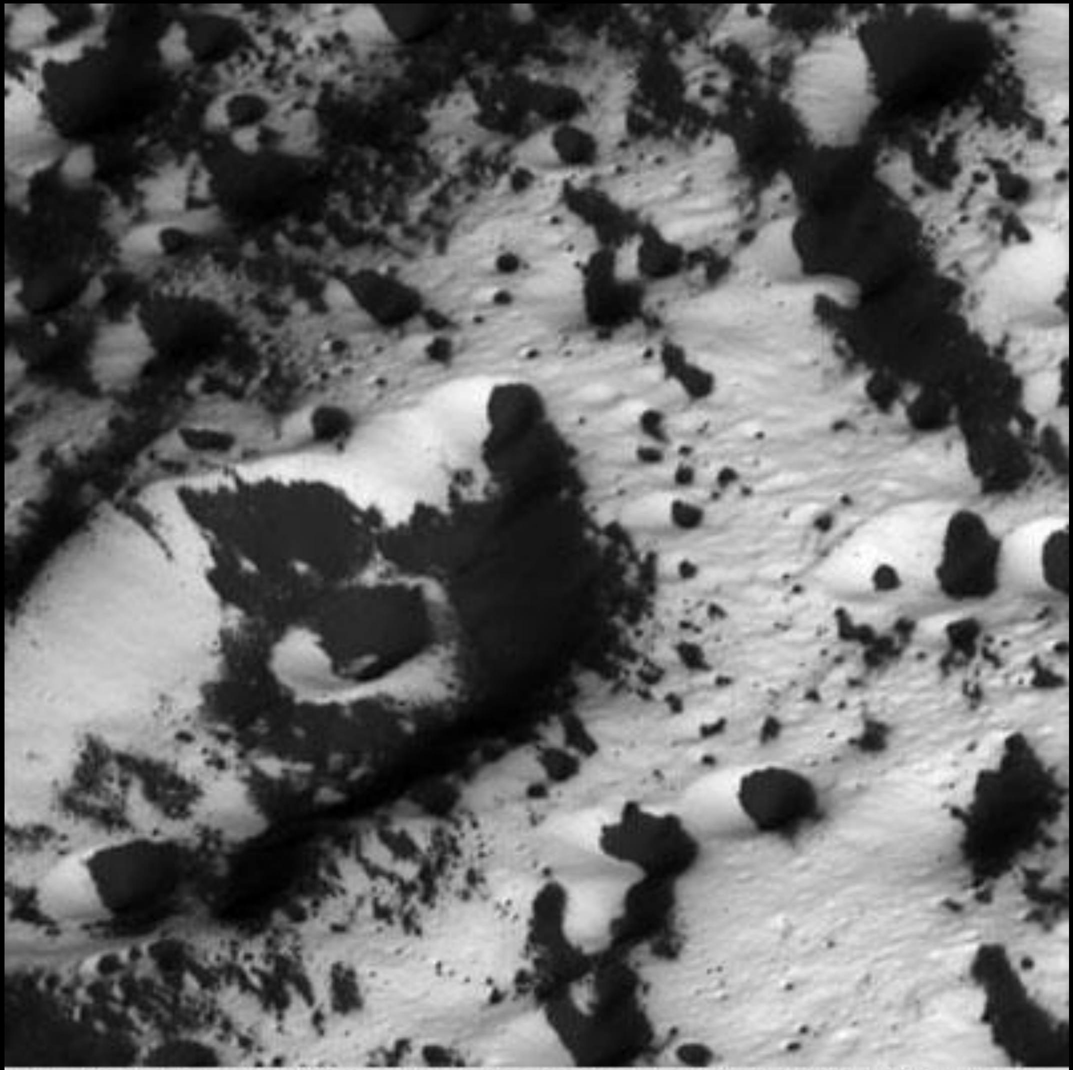
The Dark Side Material…

- **…** is lag (residue) from the sublimation (evaporation) of water ice on the surface of Iapetus, possibly darkened further upon exposure to sunlight
- Iapetus has the **warmest daytime** surface temperature and **coldest nighttime** temperature in the Saturnian system even before the development of the color contrast; about 25 Fahrenheit difference
- So ice preferentially sublimates from the **Dark side**, and freezes onto the Bright Side, especially at the even colder poles.
- Over geologic time scales, this would further darken the Dark Side and brighten the rest of Iapetus, creating a ***positive feedback thermal runaway process*** of ever greater contrast in albedo, ending with all exposed ice being lost from the Dark Side.
- After a billion years at current temperatures, dark areas of Iapetus would lose about 20 meters of ice to sublimation, while the bright regions would lose only 0.1 meters, not considering the ice transferred from the dark regions.

This model explains the distribution of light and dark areas, the absence of shades of grey, and the thinness of the dark material covering Cassini.

- The redistribution of ice is made easier by Iapetus's weak gravity, which means that at ambient temperatures a water molecule can migrate from one hemisphere to the other in just a few hops

But the trailing side is covered with Carbon Dioxide Ice

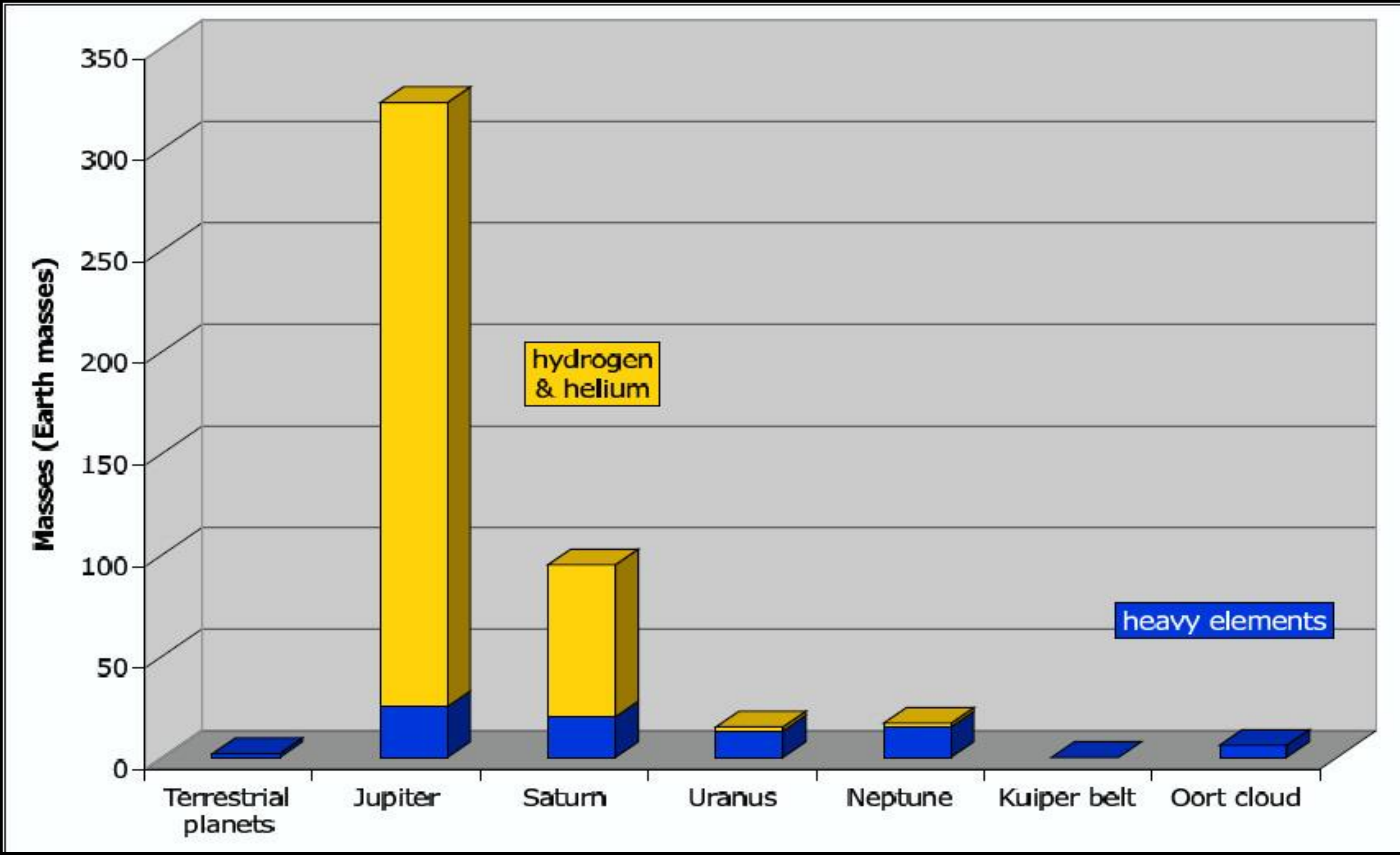


Cassini image shows terrain in the transition region between Iapetus' dark leading hemisphere and its bright trailing hemisphere. Image courtesy of NASA/JPL/Space Science Institute.

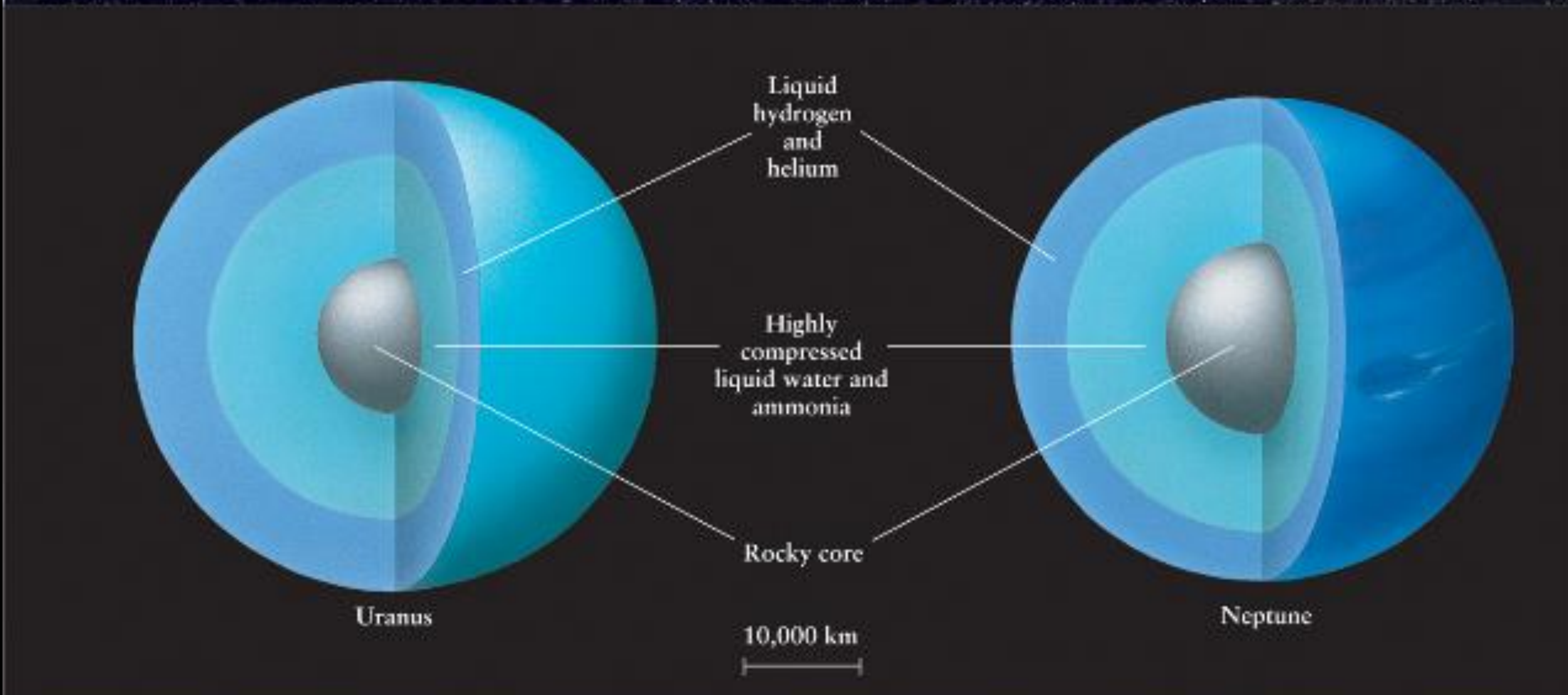
Hyperion – The SpongeBob Moon! (animation)

- Hyperion’s dark spots are made of hydrocarbons, and the white material is mostly water ice, but a bit too of CO_2 “dry ice”.
- The dark hydrocarbons absorb more sunlight and heat and sublimate their way down making the dimpled surface, is the best current idea of why it looks so bizarre
- Like dirt globs on the side of a snowy road melt holes in the snow

Uranus and Neptune; Instead Dominated by Heavy Elements



Internal Structures of Uranus and Neptune

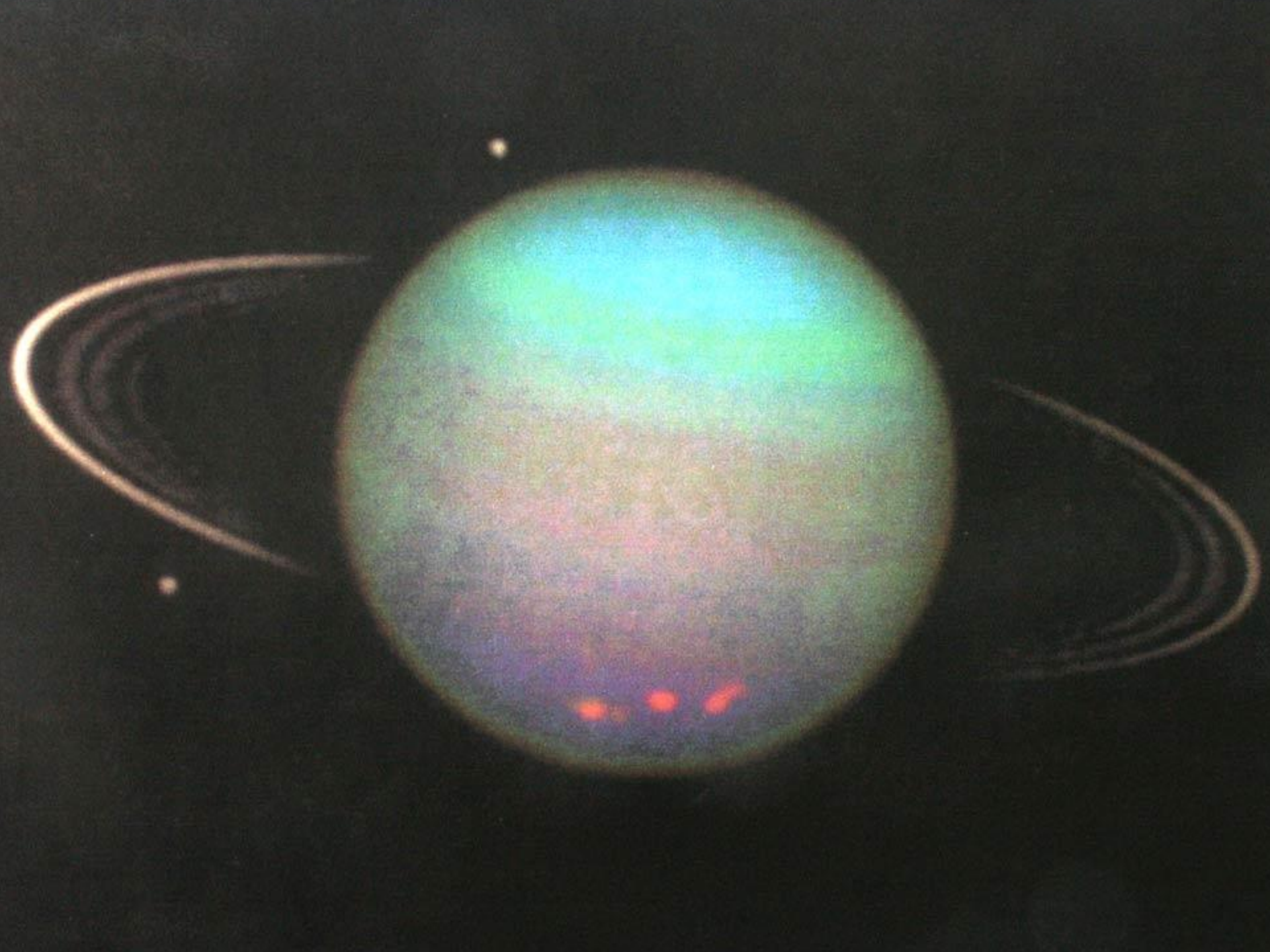


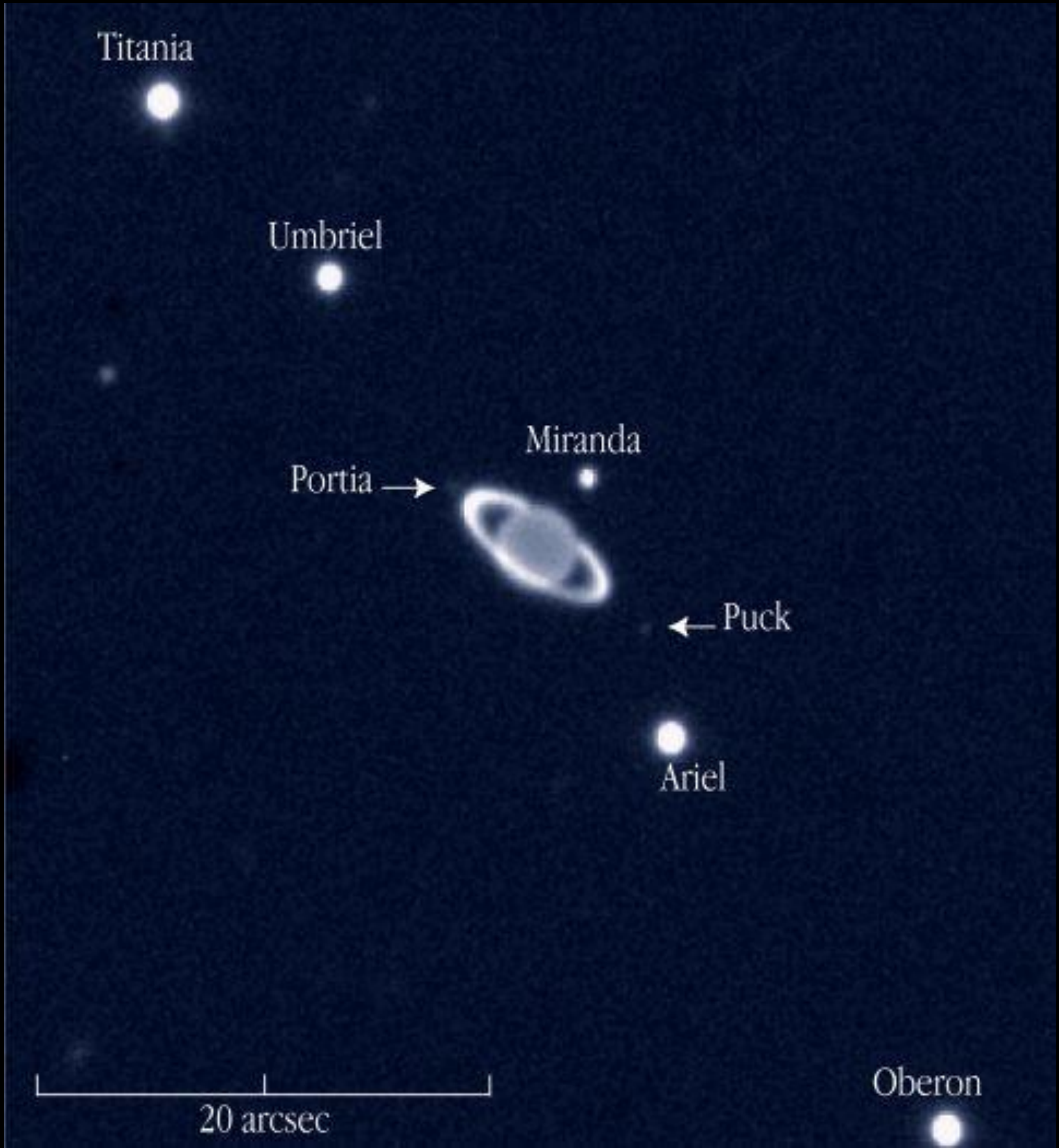
Both Uranus and Neptune have

- a rocky core, resembling a terrestrial planet
- a mantle of liquid water with ammonia dissolved in it
- an outer layer of liquid molecular hydrogen and liquid helium

Uranus

- About 5 times the diameter of Earth.
- Mass of 14 Earth's
- Too little mass to create a liquid hydrogen core. Hydrogen, Helium atmosphere, and large rocky core.
- Colored Blueish/Greenish by methane (CH_4), which absorbs red sunlight.



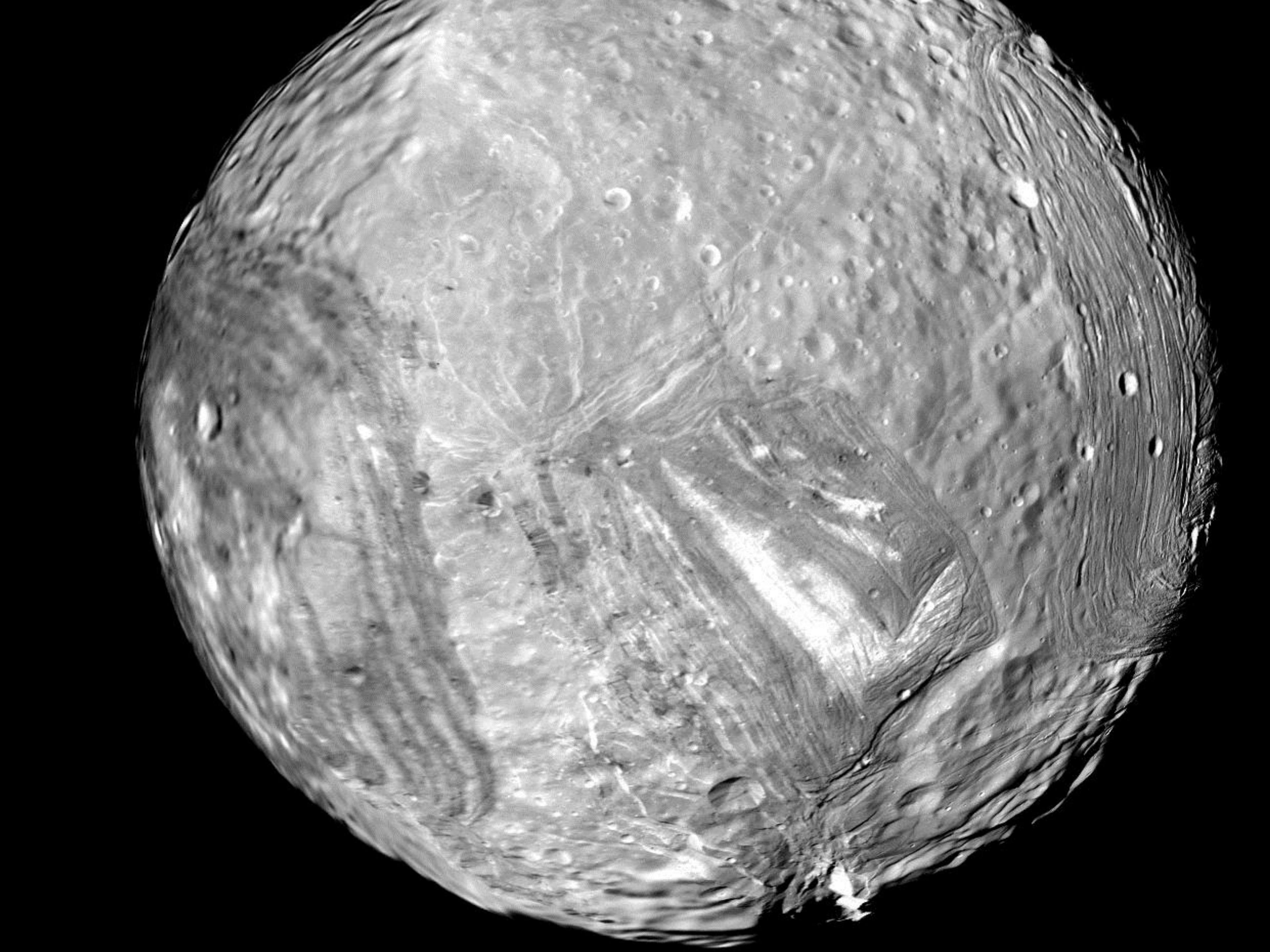

Titania
Umbriel
Miranda
Portia
Puck
Ariel
Oberon
20 arcsec

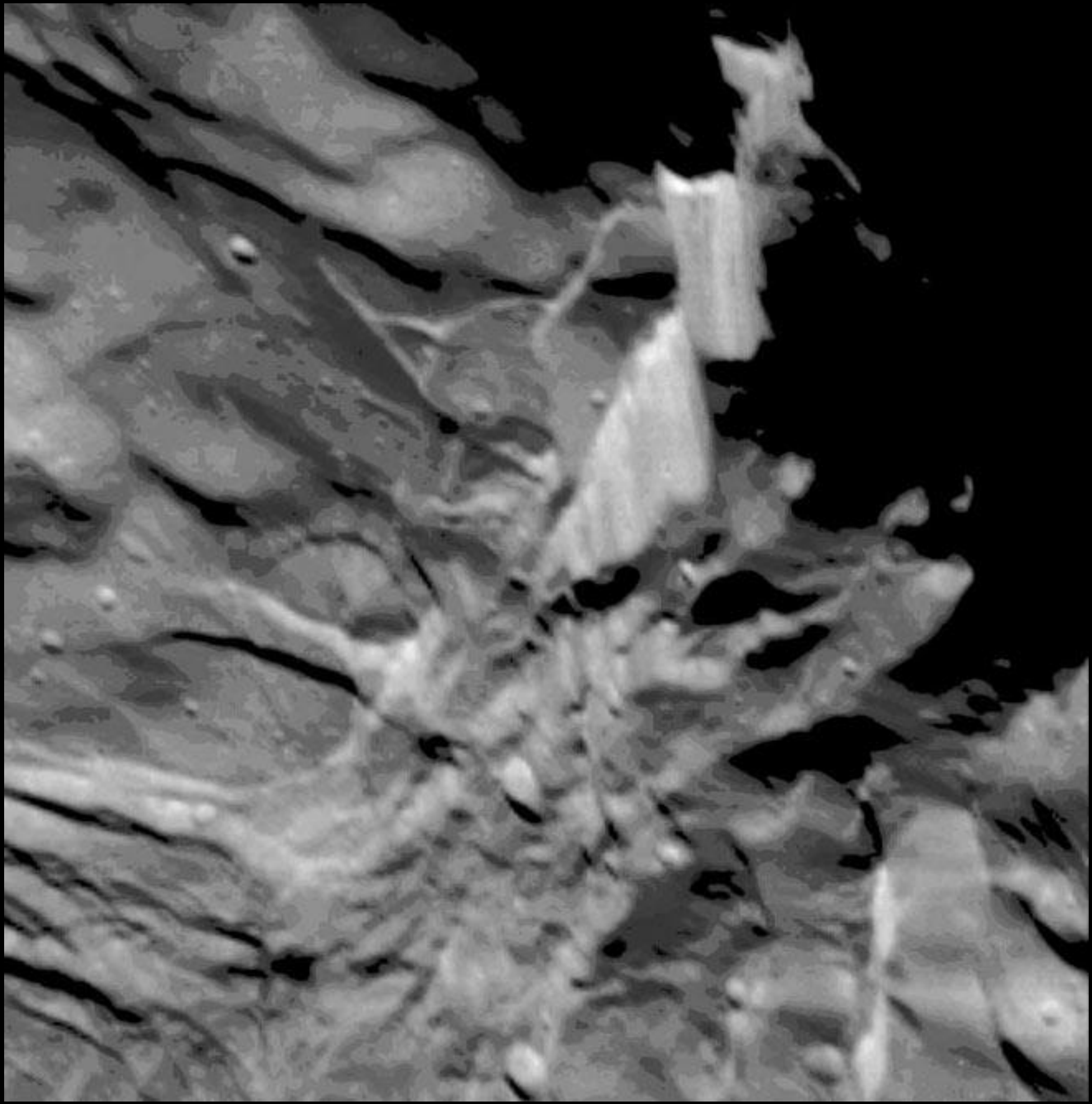
None of the Moons Have Enough Mass to Generate Enough Gravity to Hold an Atmosphere

- So, no climate to speak of…
- The moons are ice covered; water ice and carbon dioxide ice mostly, with some dust

Oberon

Miranda

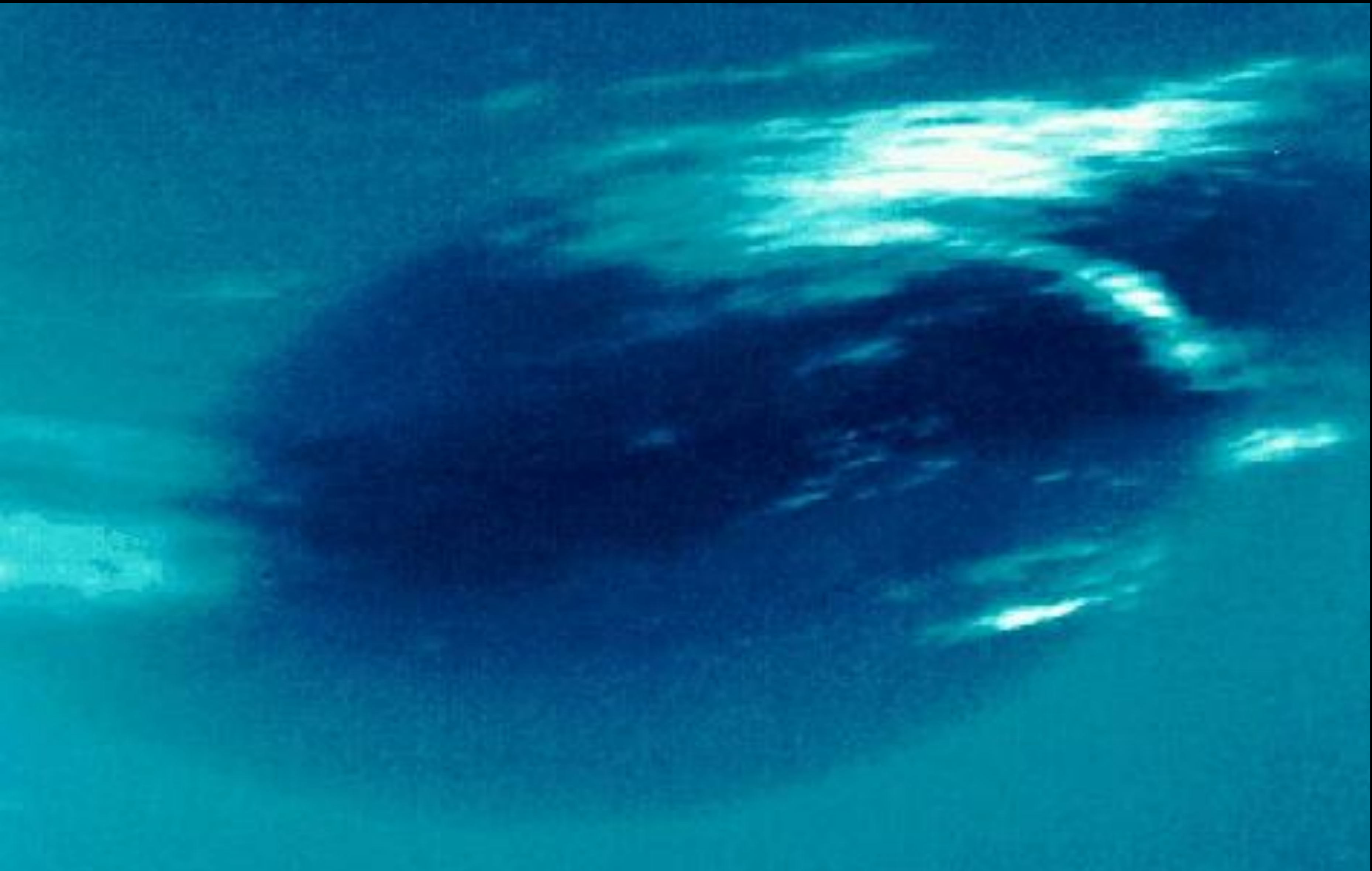


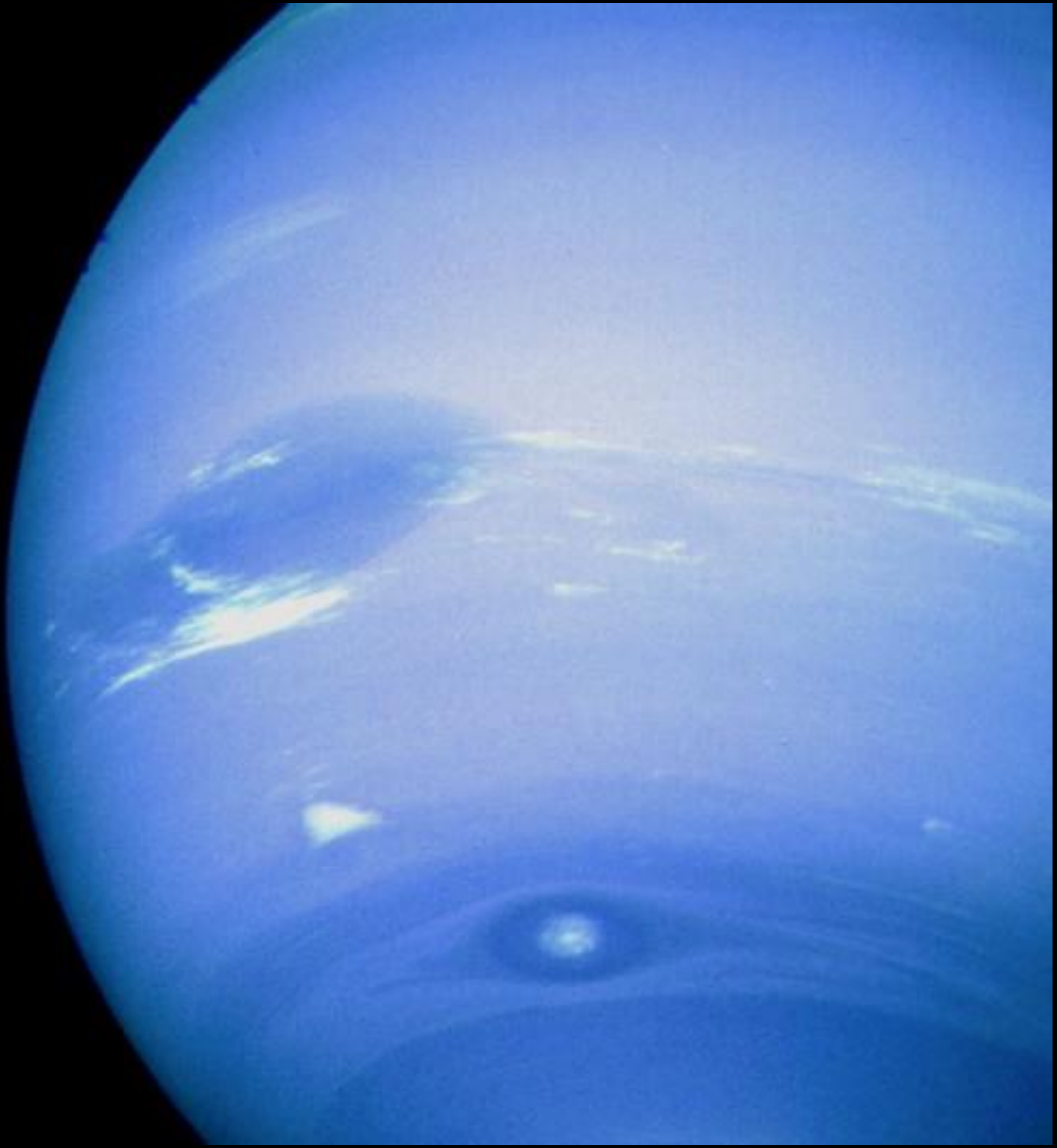


Neptune

- Mass of 17 Earth's
- Structure very similar to Uranus
- Hydrogen 80%, helium 19%, and methane 1%, in the upper atmosphere
- Large rocky core
- 1300 mph winds! Drive powerful large storms as large as Earth
- Belted, like Jupiter, with strong Coriolis forces due to rapid rotation period of only 17 hrs and deep atmosphere rotates differentially

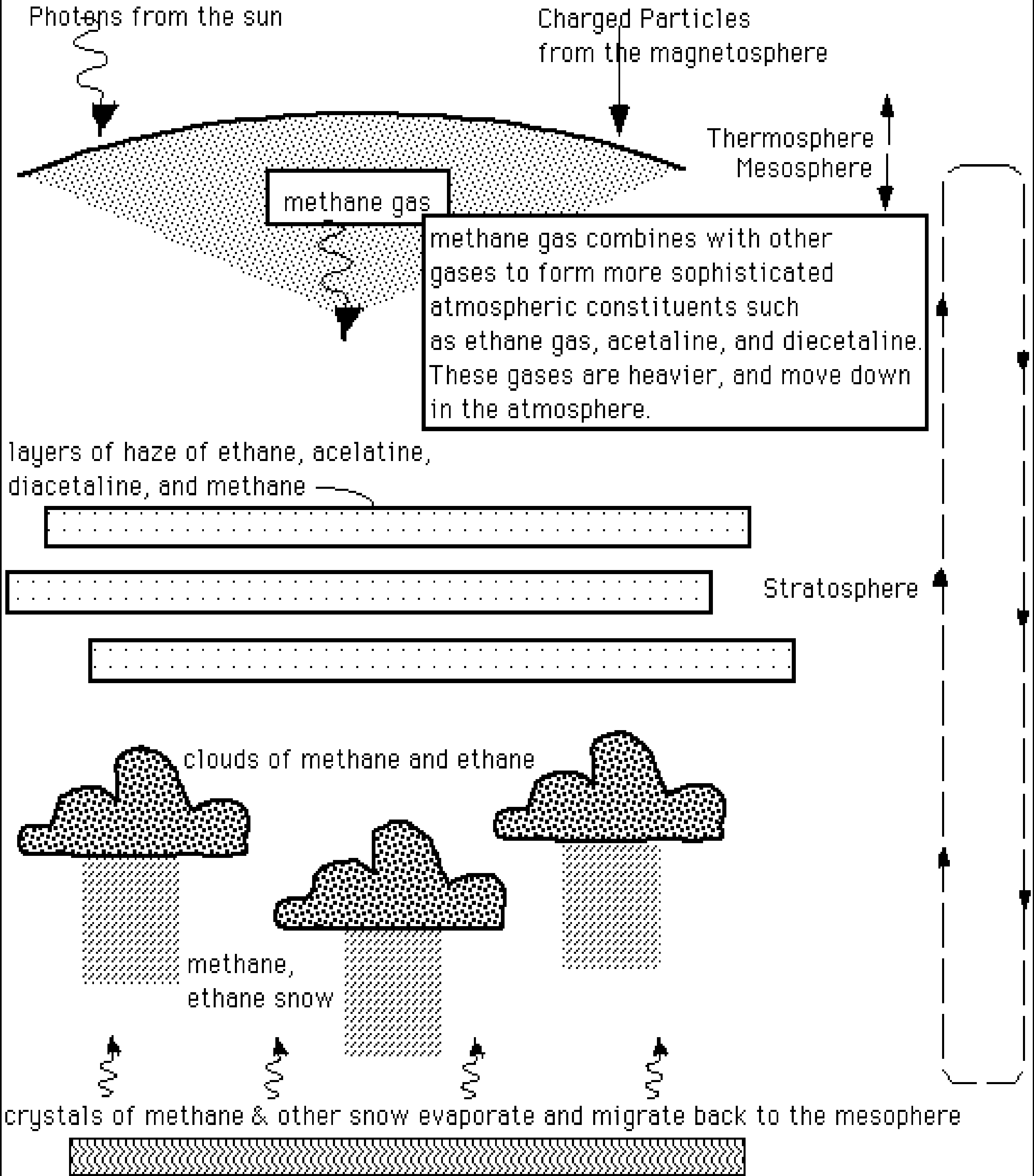
Neptune's Great Dark Spot; A Temporary Storm, Photo'd only Once, by Voyage Flyby





Stormy, 800 mph winds, Cirrus Clouds of Frozen Methane.

The Methane Cycle on Neptune and Uranus…



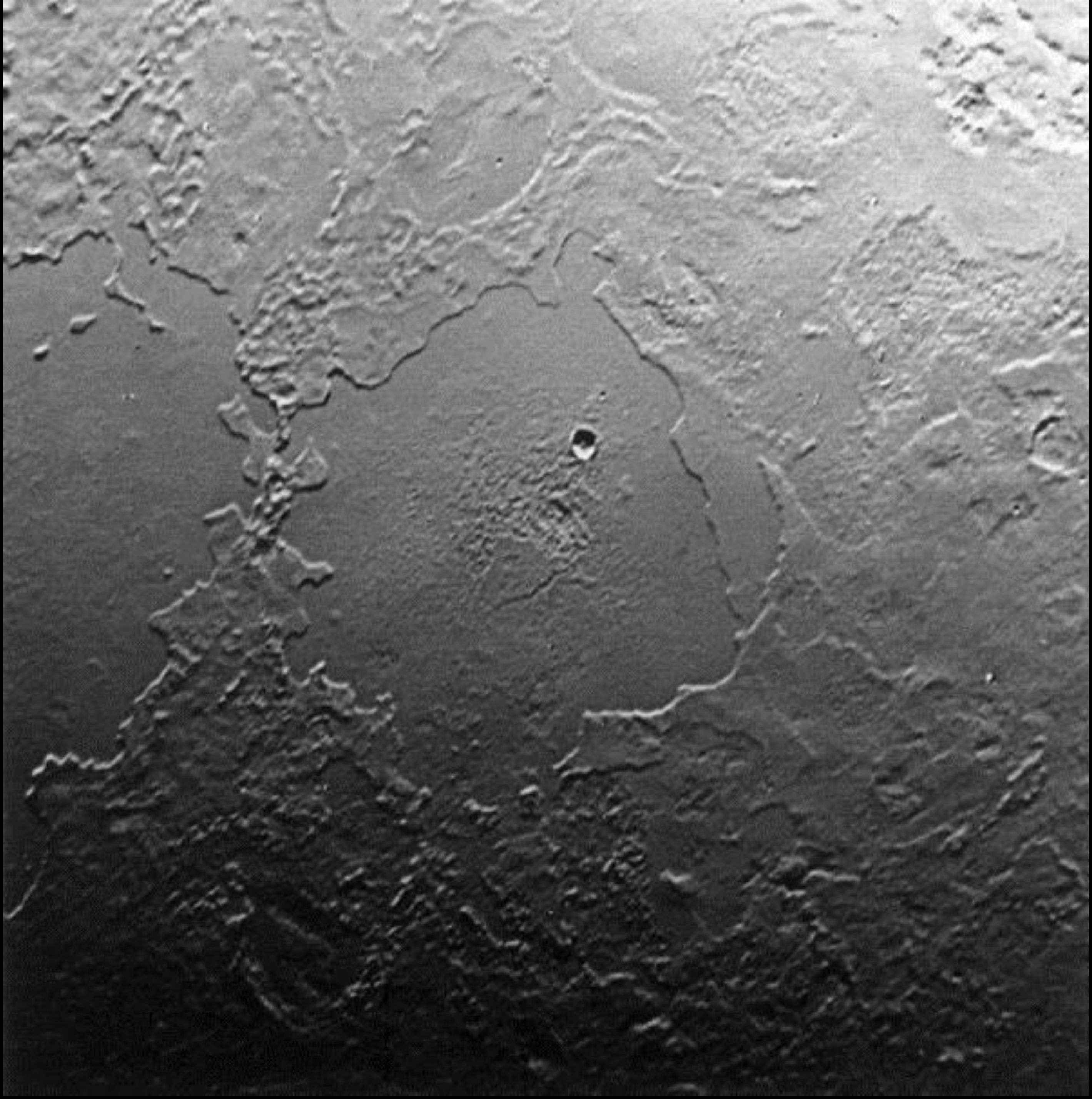
The Methane Cycle: Solar UV breaks up lightweight methane, the C and H combine to make heavier organics, which then fall, till they hit the cooler tropopause, freeze into "ice" crystal clouds which fall further into the warmer troposphere till they remelt and pyrolize into lighter volatiles like methane, and lightweight methane drifts back upward to complete the cycle.

One Big Moon - Triton

- Triton orbits Neptune in a very elliptical ellipse, orbits backwards from Neptune's spin
- Impossible if formed from the same protoplanetary condensation as Neptune, so must be a captured former Kuiper Belt Object.
- Triton at -400F, has extremely thin atmosphere of N_2 molecular nitrogen, which freezes in polar area, and unfrozen gas in "cantelope skin" mid/low latitudes
- Black surface plumes of carbon from geysers of organic melting beneath frozen nitrogen crust in polar areas

Climate on Triton. Bone-chillingly Cold. Always.

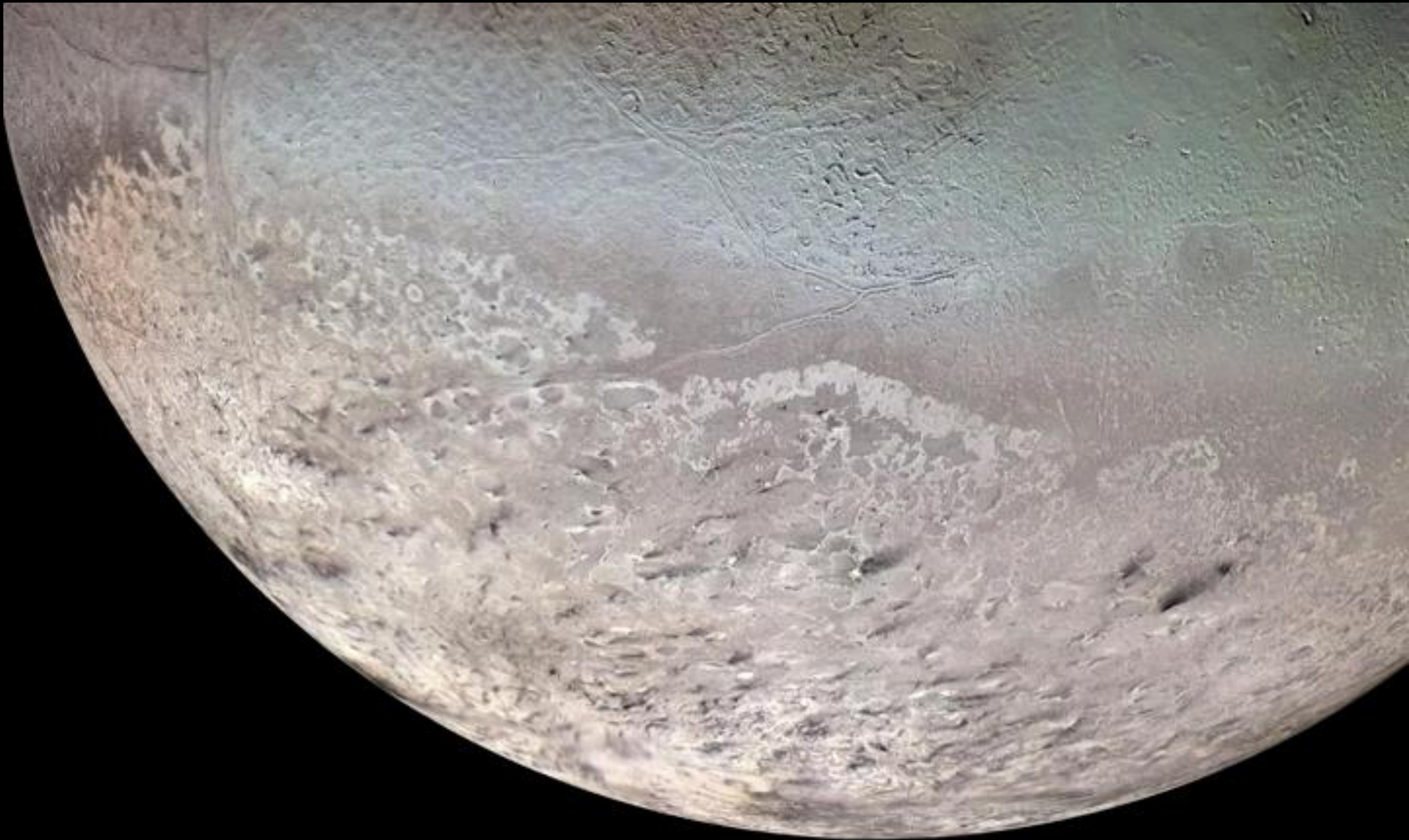
- Triton has an extremely thin atmosphere of molecular nitrogen N_2 about 1/70,000th the pressure of sea level Earth
- At about -400F, this N_2 is near the freezing point. It is a thin gas in mid/low latitudes, but freezes onto the ground in polar regions
- Black surface plumes of carbon from geysers of organics melting/vaporizing beneath frozen nitrogen crust in polar areas
- Solar heating is microscopic way out here more than 2 billion miles from the sun. Not much energy to drive a vigorous climate, and not much atmosphere to work with either.



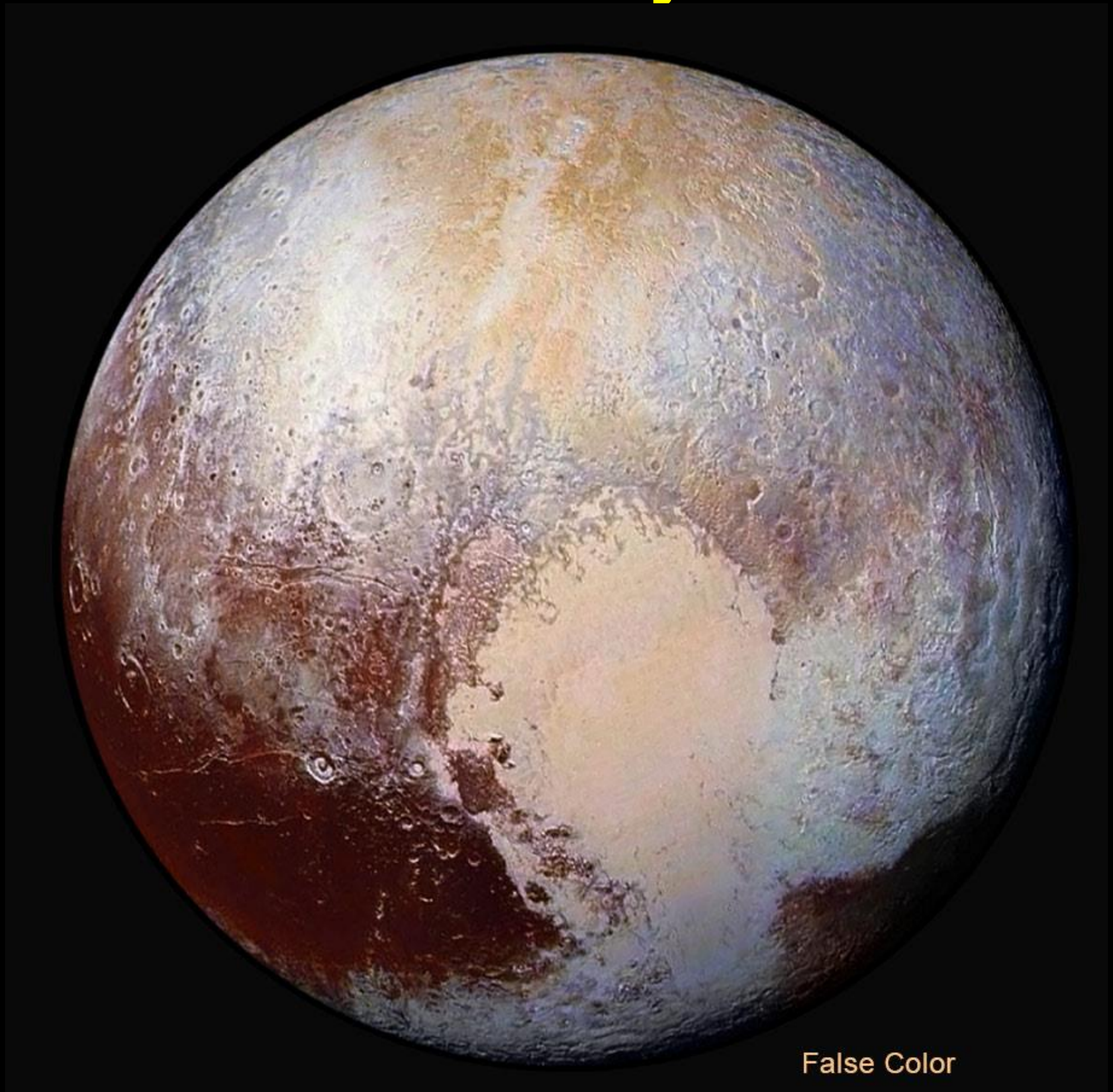
Geologically young (a billion years or so?) surface, with faults, few craters, mostly water ice “cantelope” surface with puzzling dimples, in low latitudes

Cryo-volcanos of water/ammonia or water/organics which melt at very low temperatures to form a cryo-”lava”, which has flooded these basins. Note impact ejecta at center. Surface ices are water and nitrogen

Triton: “Cantelope” tropics, icy nitrogen poles with black carbon plumes from geysers



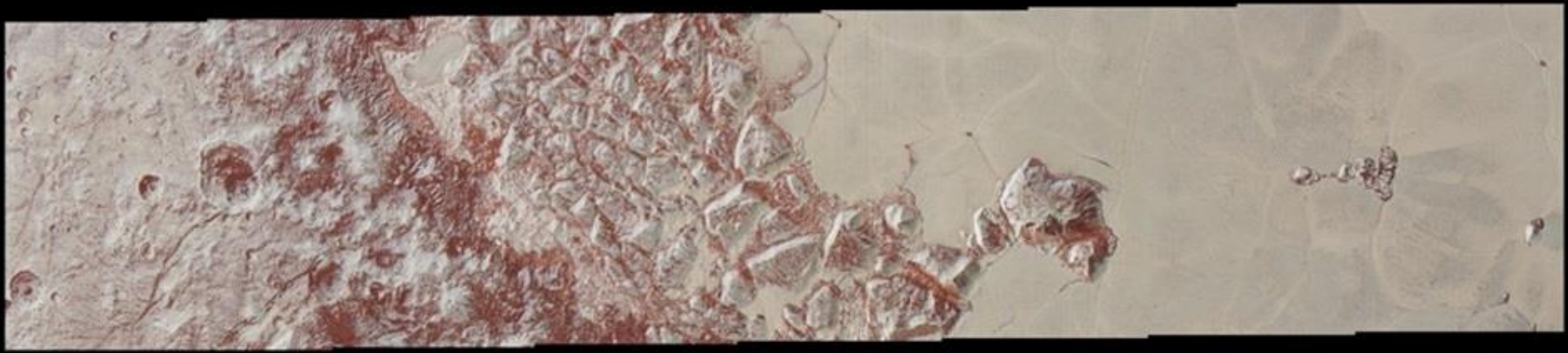
Pluto – largest of the Kuiper Belt Objects



Internal Chemical composition

- ~70 percent rock
- ~30 percent **water ice**.
- Internal structure: probably a **rocky** core surrounded by a mantle of **water ice**, with more exotic ices such as **methane**, **carbon monoxide** and **nitrogen ice** coating the surface.

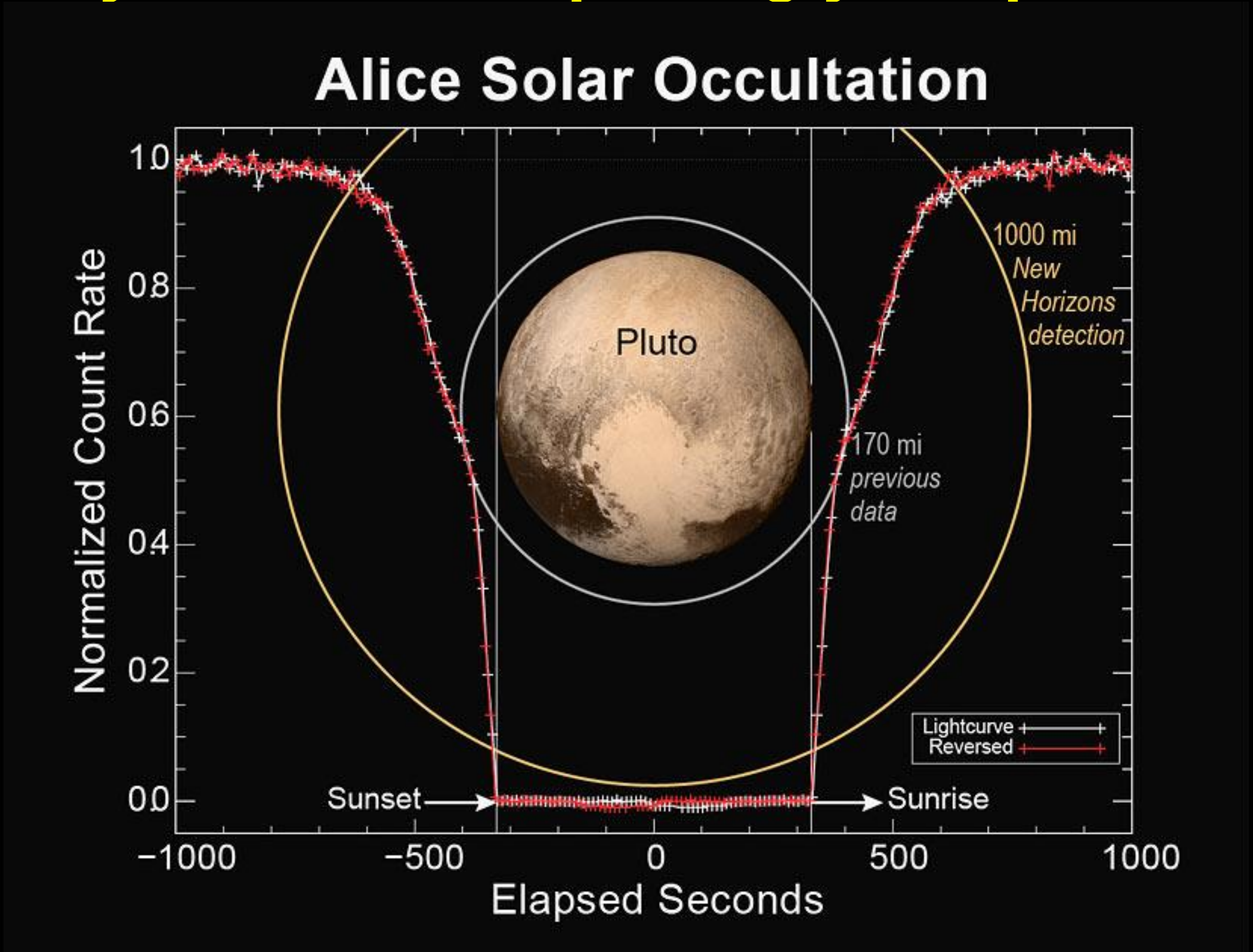
Surface: nitrogen ice covered plains and hard-frozen water ice and cryovolcanic (ammonia/water ice mixture) highlands



Flat plains of Nitrogen ice surround these islands of hard water ice. Nitrogen sublimates and refreezes in a cycle every year on Pluto

Pluto does have an atmosphere, but only 1/100,000th the pressure of Earth's. Here, New Horizon spacecraft photographs a "total eclipse of the sun" by Pluto, showing the blue Rayleigh-scattering of sunlight off nitrogen molecules

This is the main component of the atmosphere, like Earth: molecular nitrogen N_2. Very thin, but surprisingly deep in extent



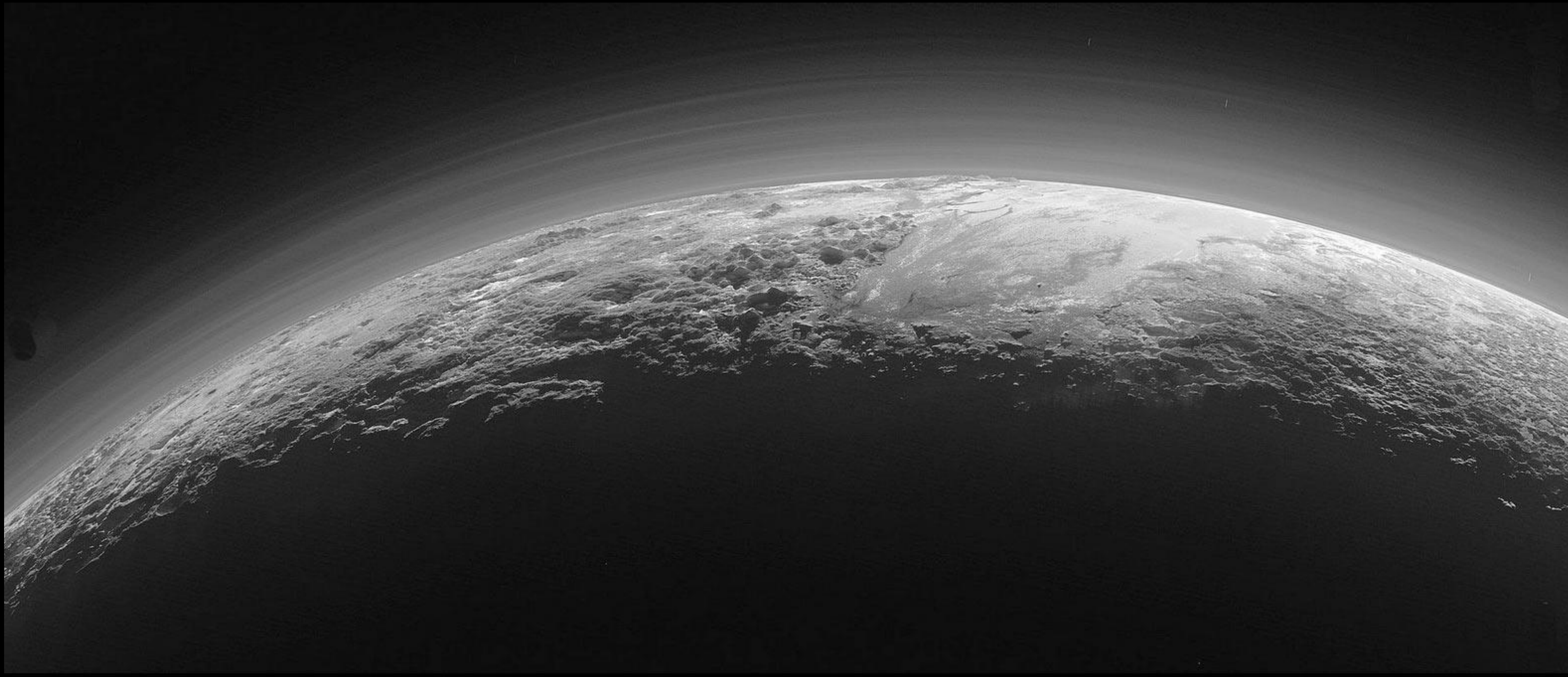
Atmospheric Chemical Composition

- **99.9% nitrogen N2**
- ~0.25% methane, from New Horizons
- ~0.06% carbon monoxide CO
- Cosmic ray impacts catalyze much smaller amounts of ethylene, acetylene, HCN, and nitriles

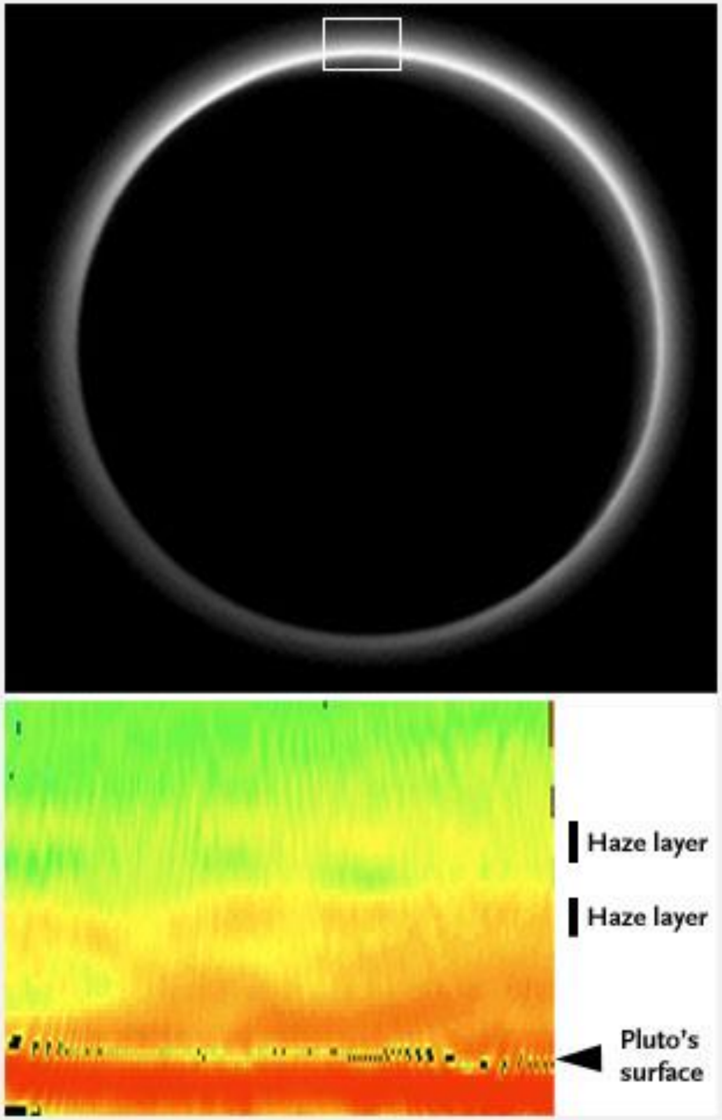
The Atmosphere Layers

- No, or almost no, troposphere. 1 km deep at most. Troposphere is heated from the ground below, ends at tropopause where it transitions to the stratosphere
- It's all stratosphere above that.
- Processes in the stratosphere layer are not yet well understood. Temperature lower than expected given the methane greenhouse effect (methane is ~0.15% of atmosphere)
- Possibly cooling due to CO; similar process as CO2 cools our own stratosphere.

In addition to atmosphere, there's layers of aerosol haze of likely complex compounds



Haze with multiple layers in the atmosphere of Pluto. Part of the plain Sputnik Planitia with nearby mountains is seen below. Photo by *New Horizons*, taken 15 min after the closest approach to Pluto.



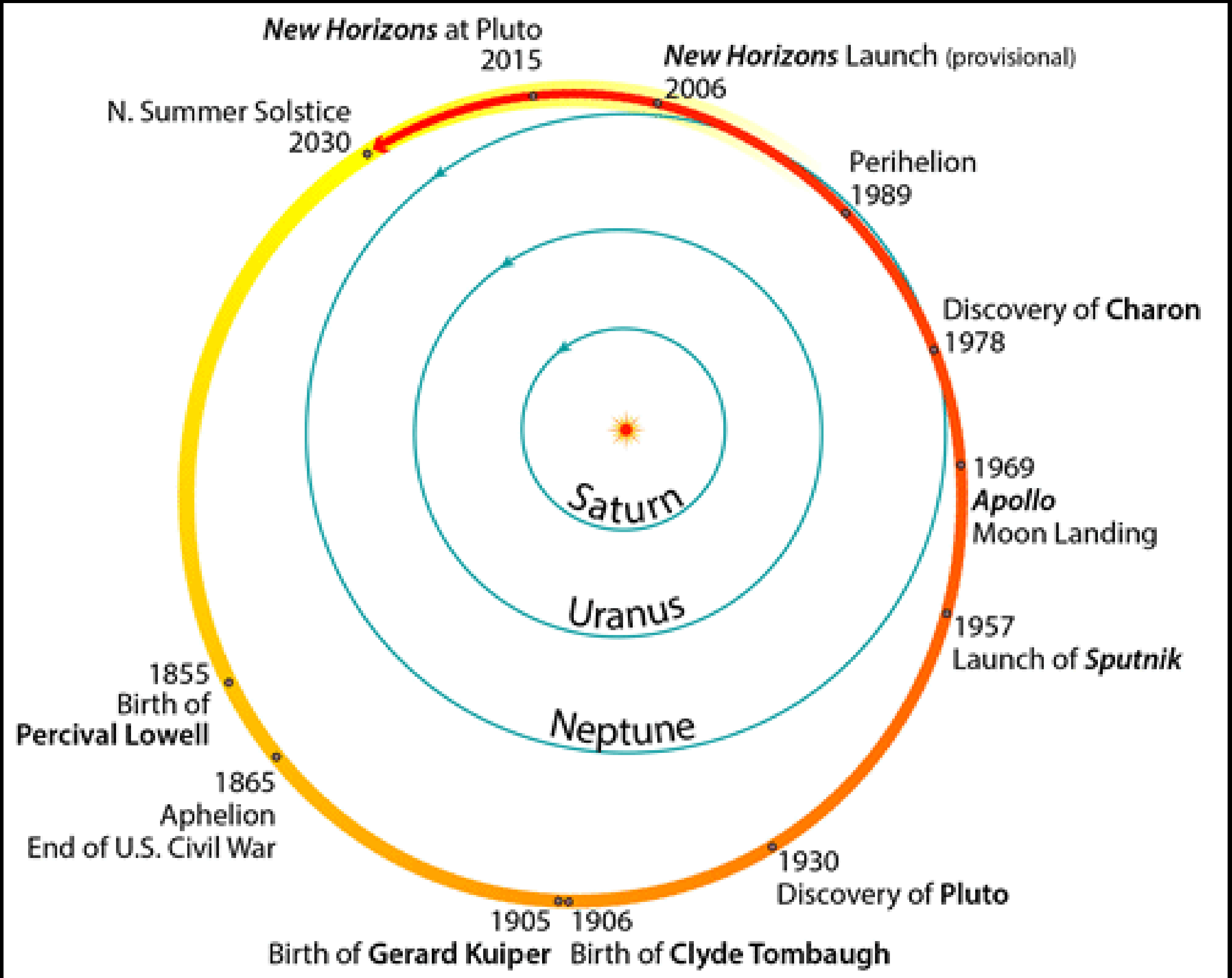
About 7 hours after coming closest to Pluto on July 14, 2015, New Horizons slipped into Pluto's shadow and captured this view of its tenuous yet hazy atmosphere backlit by the Sun. The haze extends much farther than expected, and it contains at least two distinct layers.
NASA / JHU-APL / SWRI

Aerosol haze density shown by color

Seasons on Pluto

- The northern hemisphere spring happens to coincide with perihelion (closest to sun) in its 248 year orbit. This was in 1989.
- Thermal inertia means that it's still getting warmer and atmosphere denser today 28 years later
- Atmosphere gets denser because north polar cap (now in sun) is made of nitrogen ice and nitrogen sublimates at the low temperature of -400F, about Pluto's average temperature. Denser atmosphere means better holding heat

Highly elliptical orbit means gets only 36% as much solar energy at farthest than at closest to sun



Pressure varies widely due to nitrogen's sensitive vapor pressure near sublimation. Yet the temperature doesn't change much, only 10K over the Pluto year

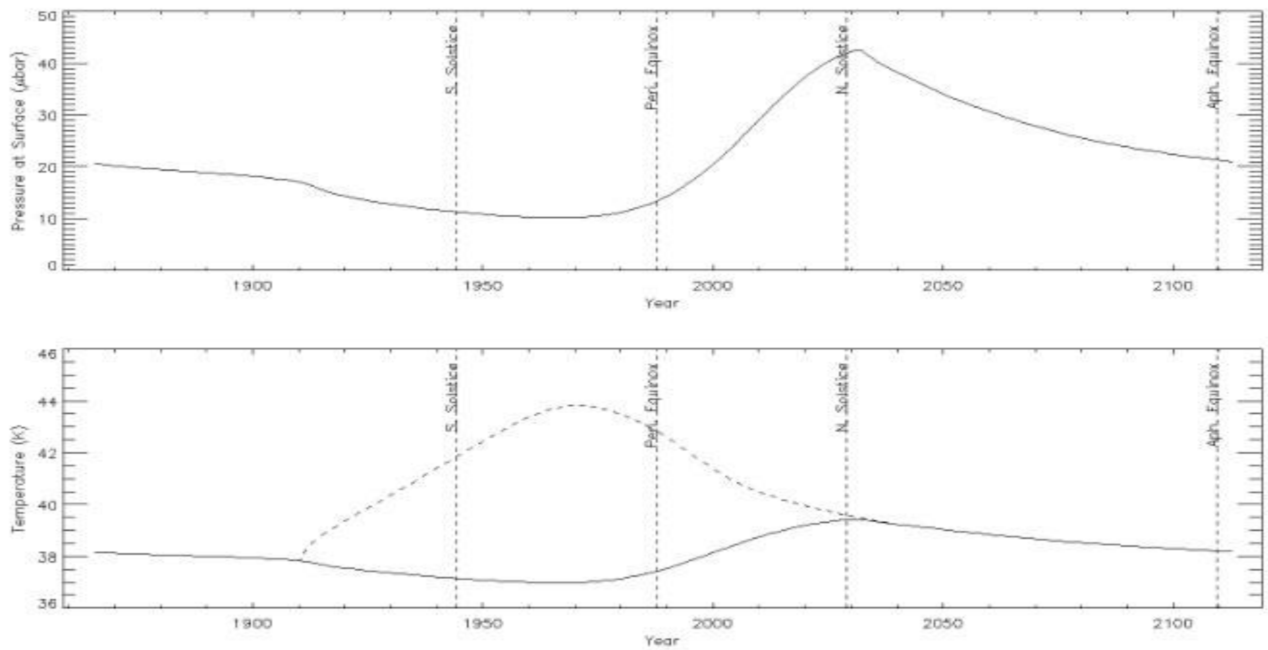


Fig. 3. The surface pressure (top panel) and temperature (lower panel) over a Pluto year for a typical PNV case. The surface pressure reaches a minimum of ~10 microbar. The temperature of the N_2 ice (solid line) and of a mid-southern latitude (-60°, dashed line) are indicated. At any given time, all the N_2 ice on Pluto's surface is at the same temperature due to the transfer of energy from condensation and sublimation. Bare, N_2-ice free regions can have temperatures higher than the ice temperature, as seen from 1910 to 2030 above. Southern solstice, equinox at perihelion, northern solstice, and equinox at aphelion are indicated for the current Pluto year.

The reason appears to be…

- …the large heat exchange happening as nitrogen changes phase from solid to gas and back. The latent heat of sublimation buffers the temperature changes.
- A distant analog is the large heat capacitance provided by our own ocean as water exchange from liquid to vapor, buffering Earth's temperature changes.
- True because the liquid/ice/vapor point of water is near Earth's natural temperature, just as molecular Nitrogen's is for Pluto

Key Points – A7 Chap 11: Climate on Jovian Planets and Moons

- Jupiter, Saturn, Uranus, Neptune all have **Hydrogen** as their largest component, from ices beyond the "frost line"
- High mass and cold temps allowed big atmospheres to be retained against the two atmospheric loss mechanisms: impacts, and leakage by escape if molecules too fast or too hot
- Jupiter is still slightly collapsing giving off gravitational potential energy as heat
- Saturn has condensing helium turning to rain deep inside, also causing it to give off more heat than it gets from sun (the latent heat of condensation).
- Only moon w/ an atmosphere: Titan (has hydrological cycle with methane)
- Fast rotation in all outer planets makes for strong "banded" atmospheres
- Cloud tops: ammonia on Jupiter and Saturn, and methane on Uranus and Neptune
- All outer planets have rocky cores surrounded by H, He rich deep atmospheres.
- Jupiter gravity high enough to make liquid metallic hydrogen interior, highly conductive, strong magnetic field
- Neptune has fastest winds in the solar system, over 1300 km/hr
- **The methane cycle** on Uranus/Neptune: solar UV breaks up methane, which combines to make heaviers, which fall, condense to clouds, melt and pyrolize back to methane at hotter low levels, which convects back upwards