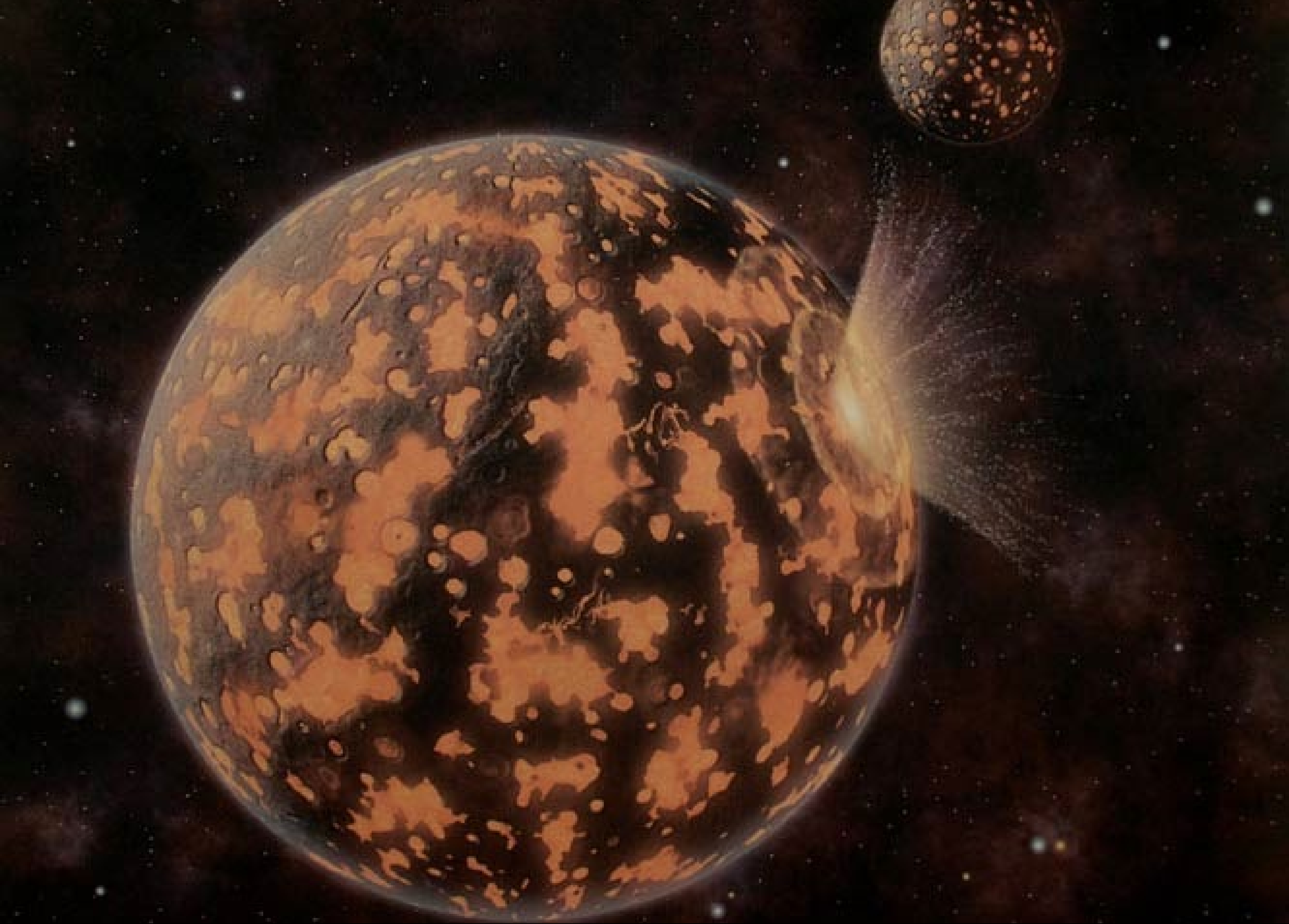
Astro 5: Life on Our Neighbors – the Solar System Planets?

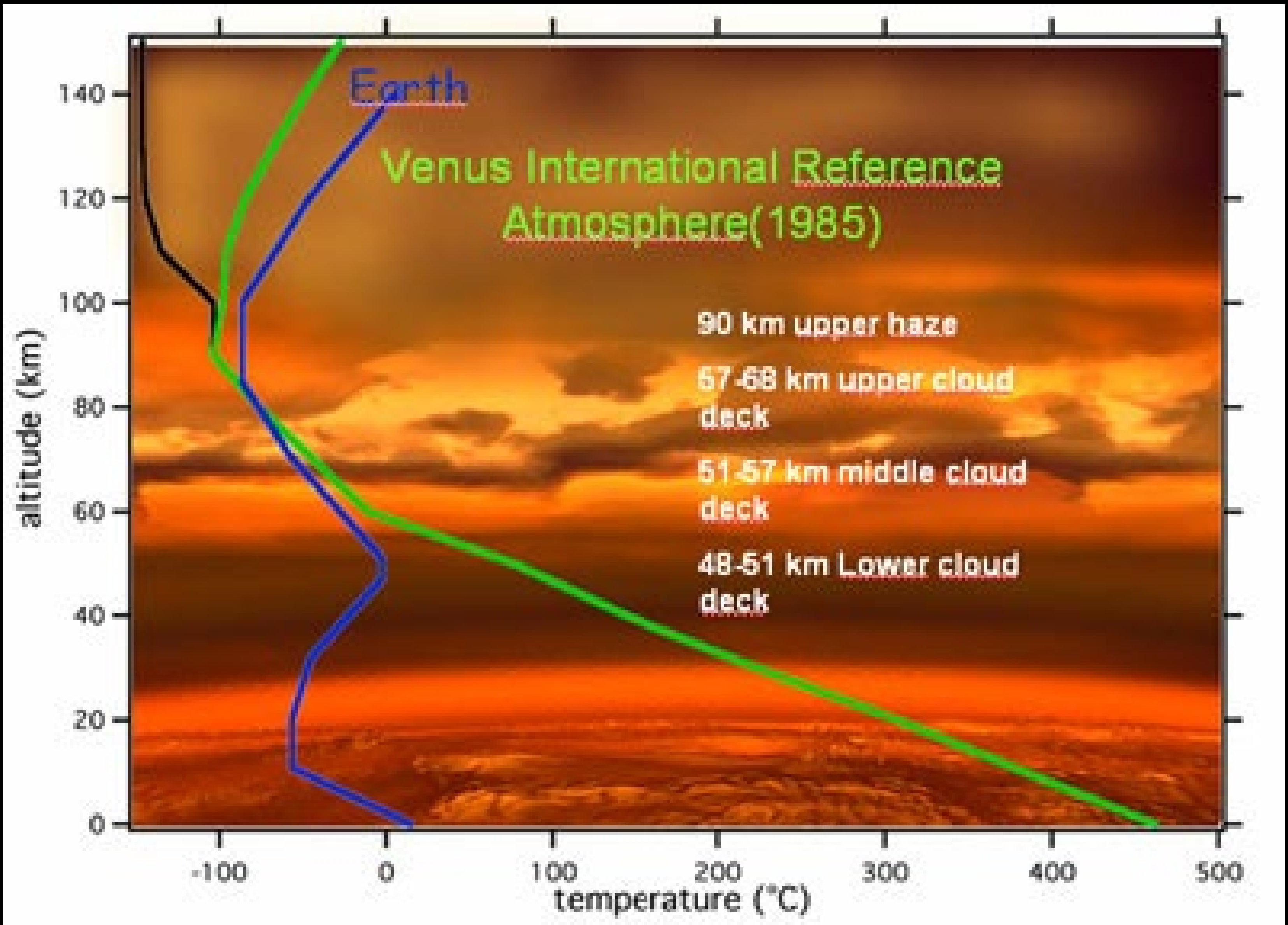


Venus – Similar to Earth in Size and Surface Gravity

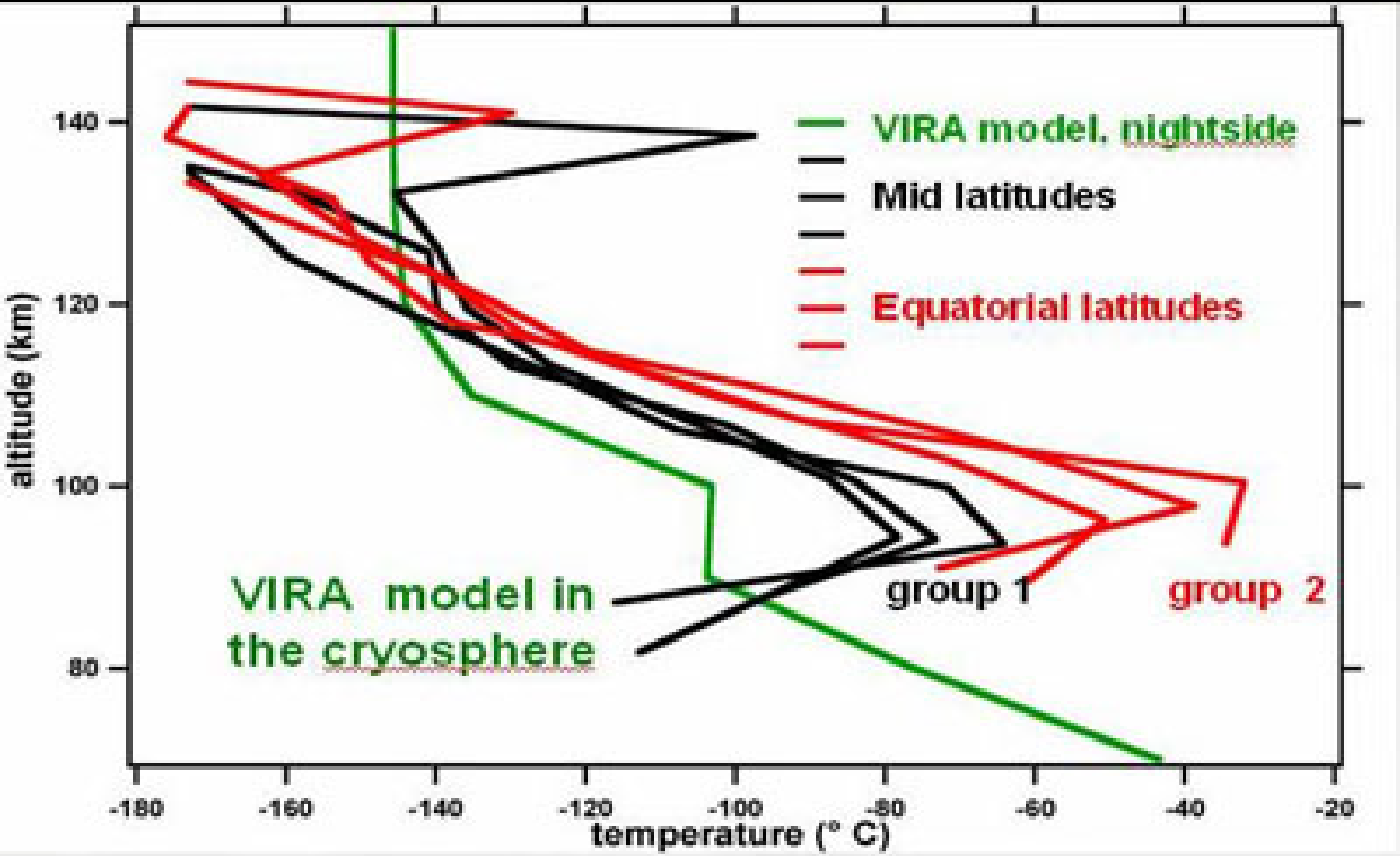
Early Venus

- With sun 25% dimmer, climate may have been similar to present Earth
- Water is a very common molecule, delivered to all planets via comet impacts and meteorites – likely meaning…
- Venus had an ocean, most likely.
- Early atmosphere composition? No direct evidence, of course, so we don't really know.
- Today's atmosphere is almost pure CO2

Before "Venus Express" – Best guess atmosphere profile…



After ESO's "Venus Express". Note this is only the very highest (>70,000 meters) coldest thinnest part of the atmosphere (below, opaque due to sulfuric acid droplets)



Key discovery of Venus Express…

- Dry! The water vapor in the atmosphere at present, if condensed to liquid, would make a layer around the planet of only 3 cm deep (*vs.* ~500,000 cm for Earth)
- At top of atmosphere, solar UV breaks apart H_2O into H and O2. O2 combines with surface geology to make oxides, while the Hydrogen escapes to space. Result? Water destroyed progressively.
- **The current measured escape rate of H strongly suggests that Venus had an ocean, and it lost it fairly early in its history**

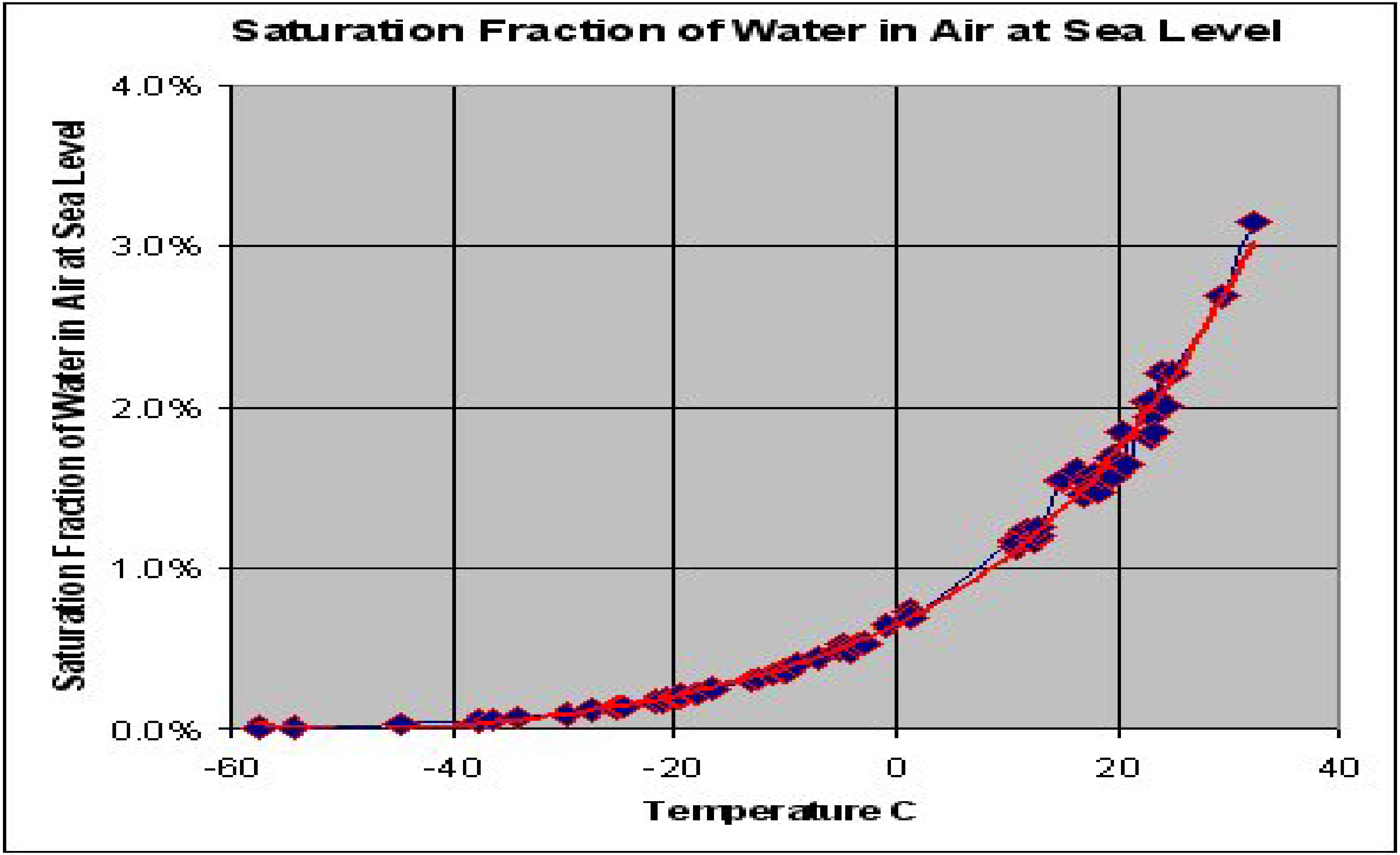
The Runaway Greenhouse Syndrome

- CO_2 greenhouse causes rising temperatures, which cause more water to evaporate from the ocean, raising the absolute humidity of the atmosphere because warmer air can hold more water vapor.
- But water vapor is itself a greenhouse gas and so raises the temperature further…
- **An amplifying feedback cycle**
- **When the water vapor absorption becomes too effective, rising surface temperatures are unable to radiate through the opaque atmosphere, temperatures keep rising and the oceans continue to evaporate until the vapor pressure in the upper stratosphere reaches high levels**

Where does the Ocean Water Vapor go?

- Runaway starts when the solar UV in the upper stratosphere dissociates the H2O into O2 and H2 at a sufficiently high rate
- The hydrogen escapes to space, being very light weight and moving fast (“leakage”),while the oxygen eventually combines with elements at the surface. Both are lost from the atmosphere
- When the ocean has lost all of its liquid water, and dissociation continues in the stratosphere, eventually the planet turns bone dry, and then atmospheric temperatures cool somewhat, as outgoing IR absorption by water vapor decreases.
- But since CO2 is the major absorber, and it does not rain out, nor dissociate, so the planet’s fate is sealed.
- **This was the fate of Venus**

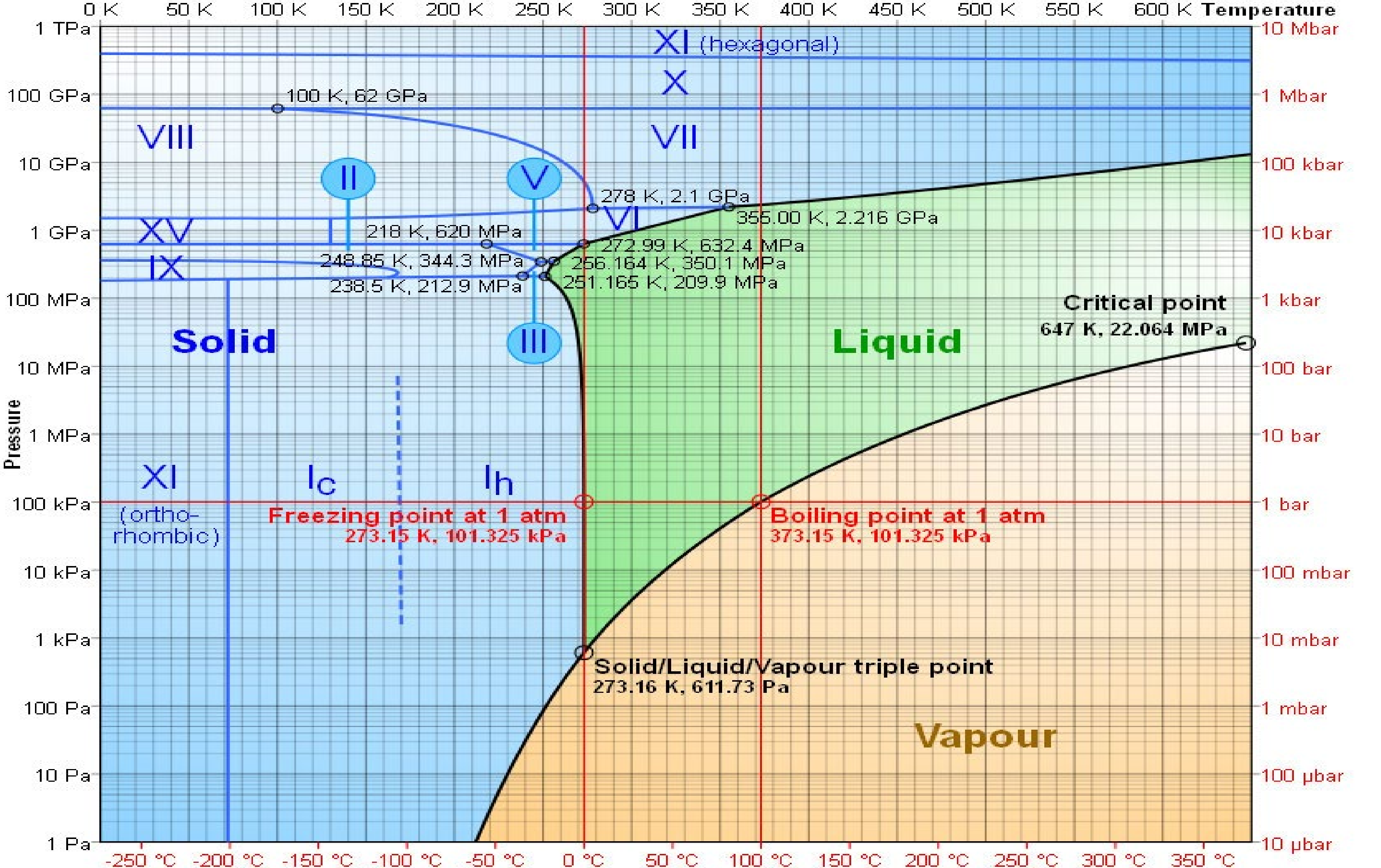
Hotter air can hold MUCH more water as vapor, before it gets so soggy it turns to rain and falls out



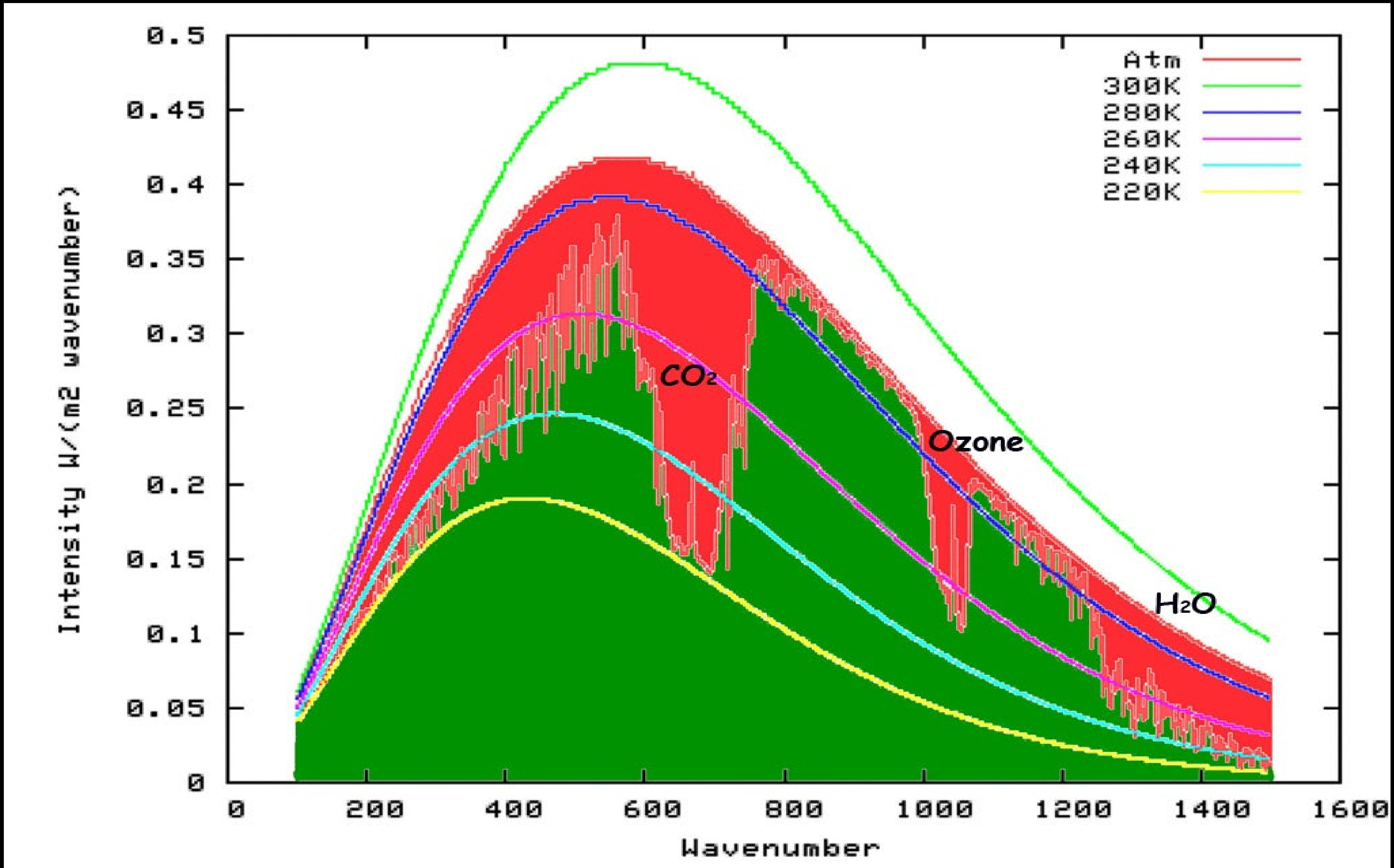
Notice: Saturation Humidity ***Accelerates*** Upward with Temperature

- We in this room are about T= 20 C on this curve.
- The acceleration in this curve helps initiate the “runaway” feedback cycle.
- When water vapor levels rise into the upper stratosphere, where it cannot rain back out, and where the solar UV is strong…
- UV will dissociate the H2O and thus lower the humidity and this readies this air to accept more H2O from below
- This continues until all water has been destroyed.

Ice comes in a lot of different ways to pack those water molecules



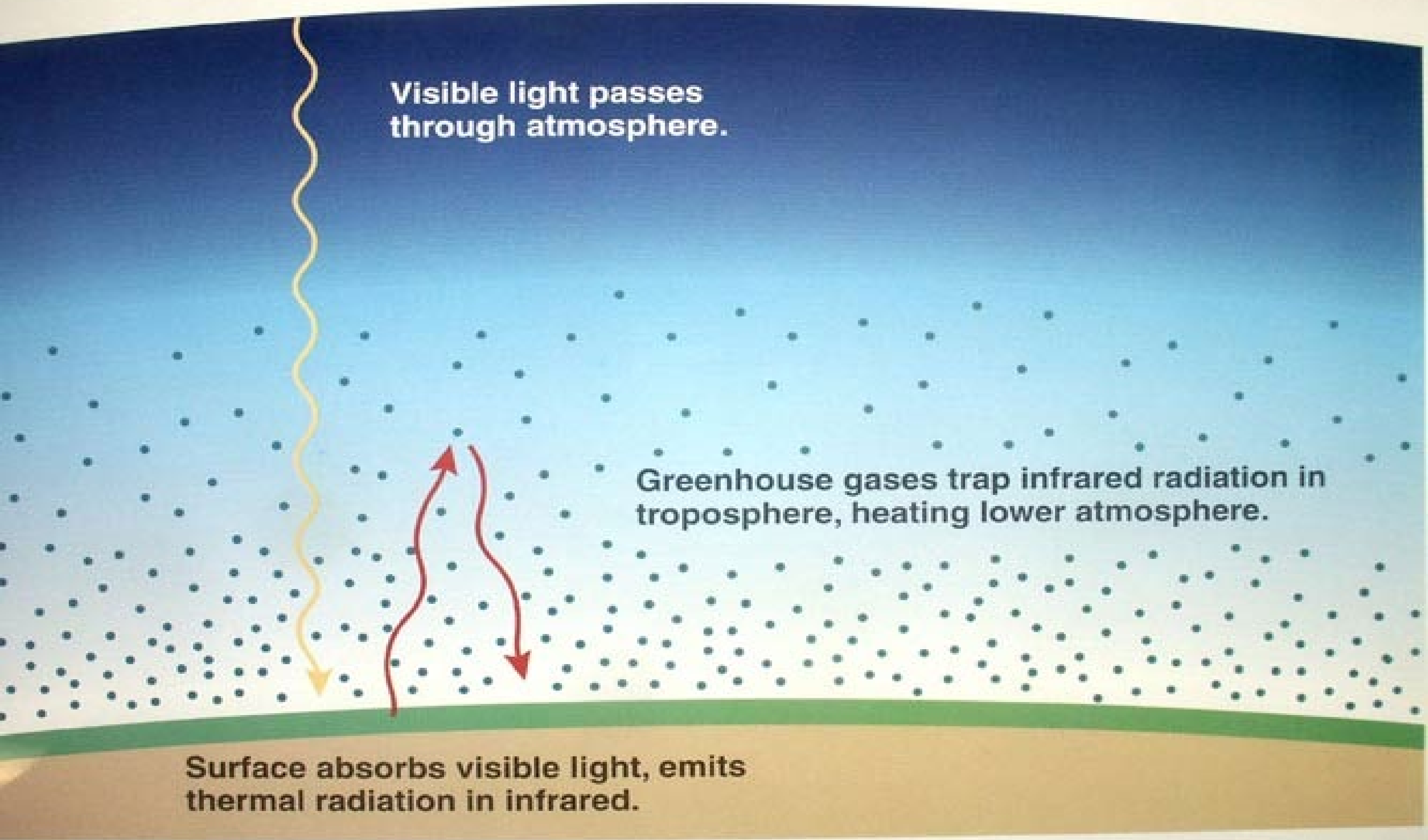
Earth atmosphere transparency, at pre-industrial 280ppm CO_2 (today is 428ppm!). the absorption bands of water vapor, ozone, and especially CO_2 prevent a significant amount of Earth radiation from escaping. Water vapor absorption fraction is higher at higher temperatures



The Greenhouse Effect

- The sun radiates as a 5800K thermal radiator, putting most of its light into the visible band. A Greenhouse gas is transparent at these wavelengths – the light goes down to the surface and heats it up.
- The surface then will radiate as a thermal radiator, in this case, a few hundred K and this is in the far Infrared band
- The IR band has large absorption bands for GHG's, so heat transport through the atmosphere back out into space is slow, requiring a higher surface and lower atmosphere temperature to drive the gradient high enough to transmit the heat upward.
- The atmosphere heats up, reradiates and some of this radiates back to the surface where it further heats the ground.
- This continues until the upper atmosphere is hot enough to radiate all that is received from the sun and temperature equilibrium is restored.
- **Net effect – a hotter lower atmosphere and surface**

The Greenhouse effect



As the water vapor level rises…

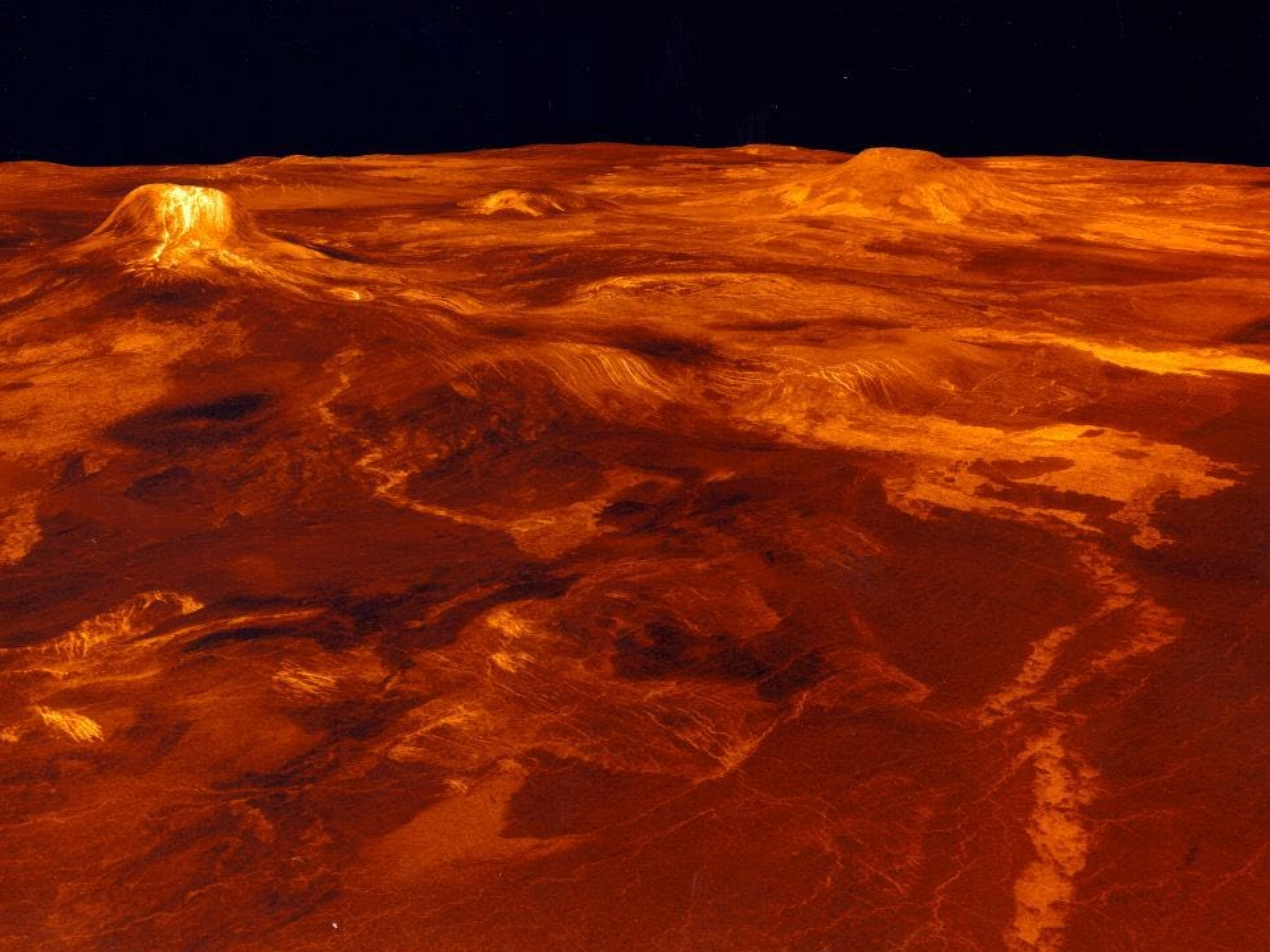
- Greenhouse heating rises, forcing more water vapor, forcing more heating…. An amplifying feedback which runs away!
- Until the oceans turn to vapor, which rises to the upper atmosphere, where…
- H_2O is split by solar UV into O_2 and H
- The O_2 combines with rocks to make oxides (e.g. iron oxide, aluminum oxide, etc)
- H, as we saw, will escape Venus' gravity into space
- The atmosphere is then left with CO_2, and little else.
- **But, Venus has no ability to make CO_2 into rock, no plate tectonics, and no carbon cycle like the Earth has (more on that later).**
- **That's bad….**

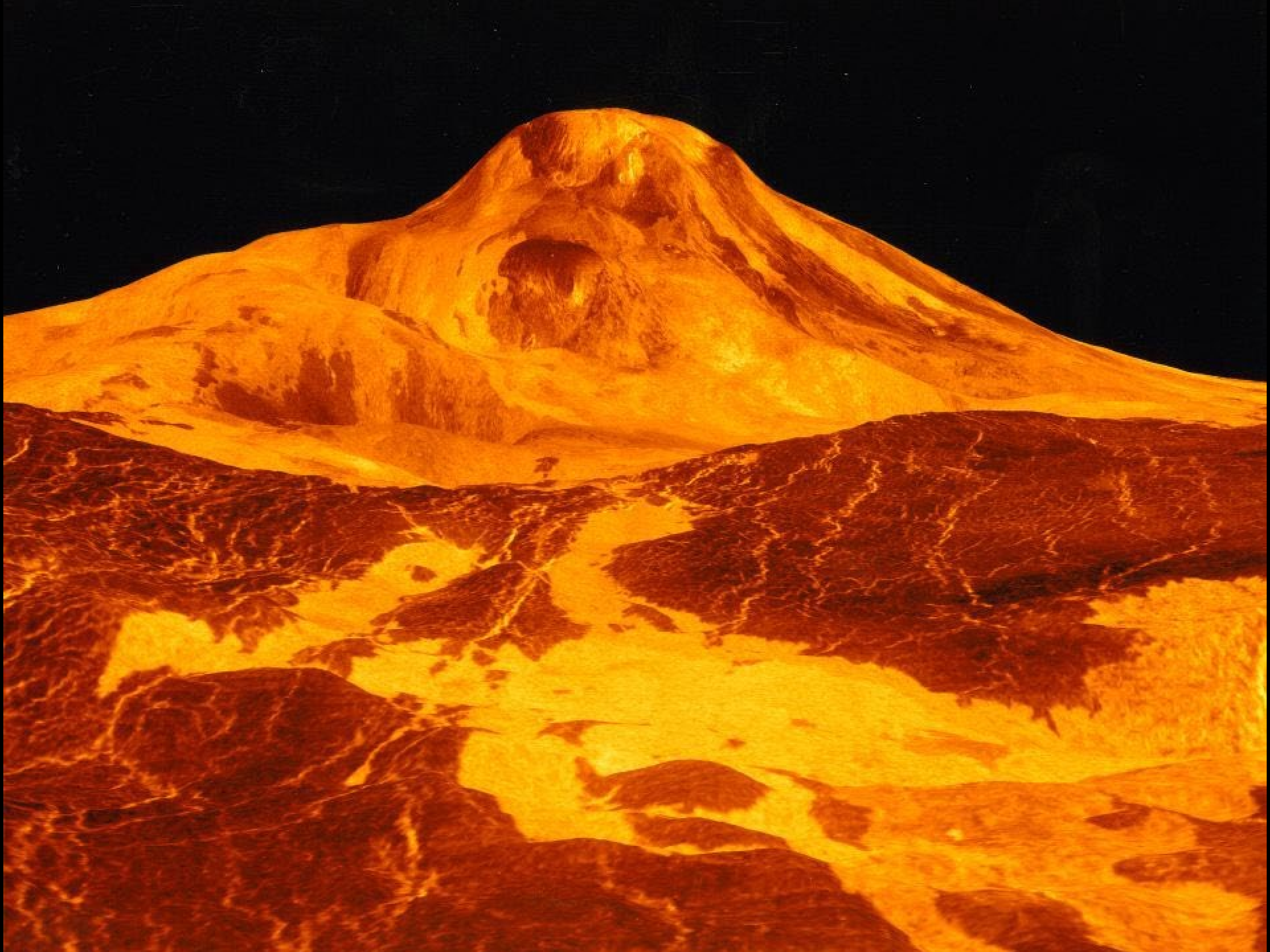
Why no plate tectonics on Venus?

- Need rapid spin rate to drive plate tectonics, but Venus rotates only once in 243 days (and backwards relative to most planets)
- Early collision took away ~all of its rotation?
- Venus year is 224 Earth days
- It has estimated ~100,000 volcanoes, but not driven by tectonics like on Earth. Probably just a very thin crust.
- 60 km up, is a layer of thick opaque sulfuric acid droplets – sulfur from volcanoes?
- These are very reflective – that's one reason Venus is so bright in our evening sky
- High reflectivity also keeps temperatures from being EVEN hotter on Venus

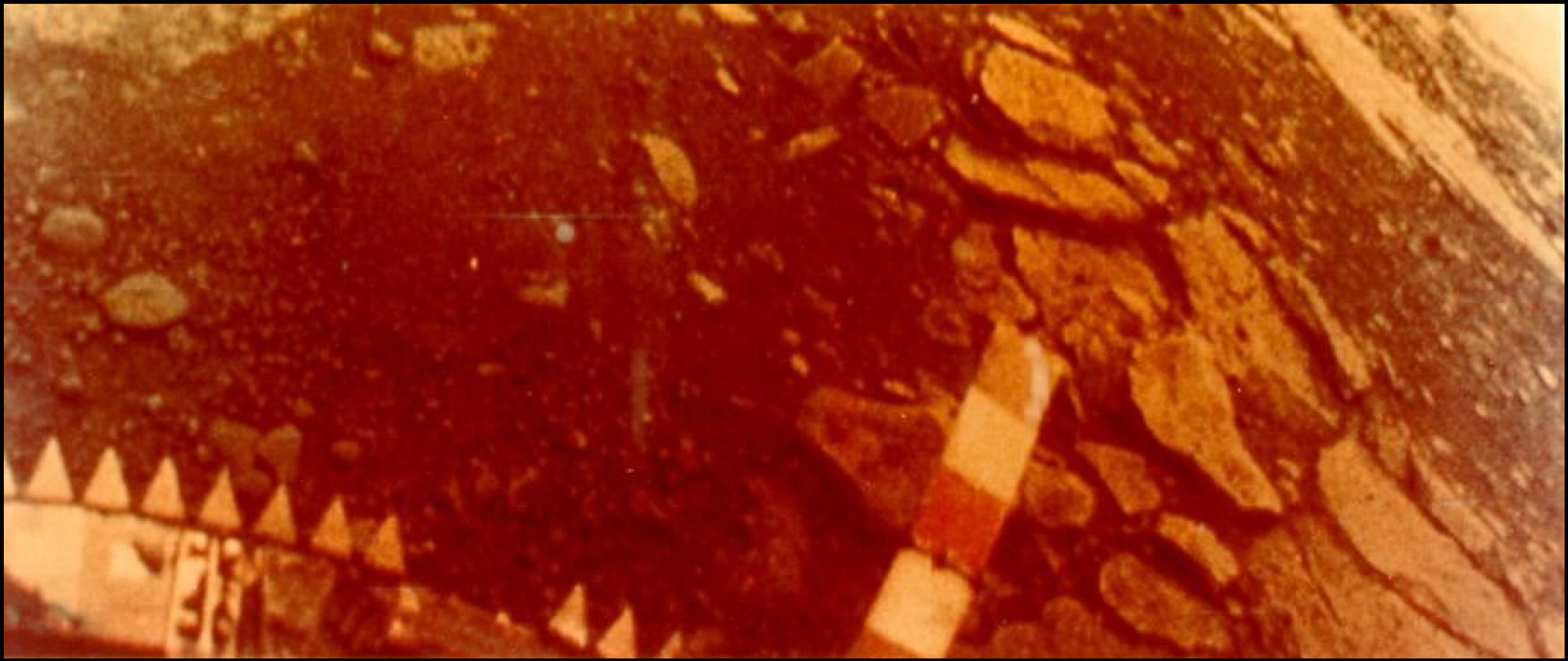
Net Result…

- A ~pure CO_2 atmosphere, with a bit of Nitrogen.
- Surface temperatures of 735K ~ 900F
- Atmospheric pressure 100x that of Earth.
- The high density effectively heats the night side almost as much as the day side.
- And poles too.
- Now see radar image reconstructions from the Magellan Mission, of Venus…





Soviet's Venera Lander, photo of Venus' Surface. Baked flat rocks Ancient mud flat?. Fuels speculation of ancient ocean billions of years ago



In Fact, We Can Do Better than Speculate…

- By measuring the escape rate of hydrogen from the top of the atmosphere, by our Venus Express mission, we were able to then extrapolate backwards in time, using some reasonable physics and history of the sun’s luminosity, and infer that indeed **Venus likely had an ocean for a time after it was born.**

Hints of tell-tale life in high atmosphere?

Phosphine in the cool upper atmosphere of Venus??

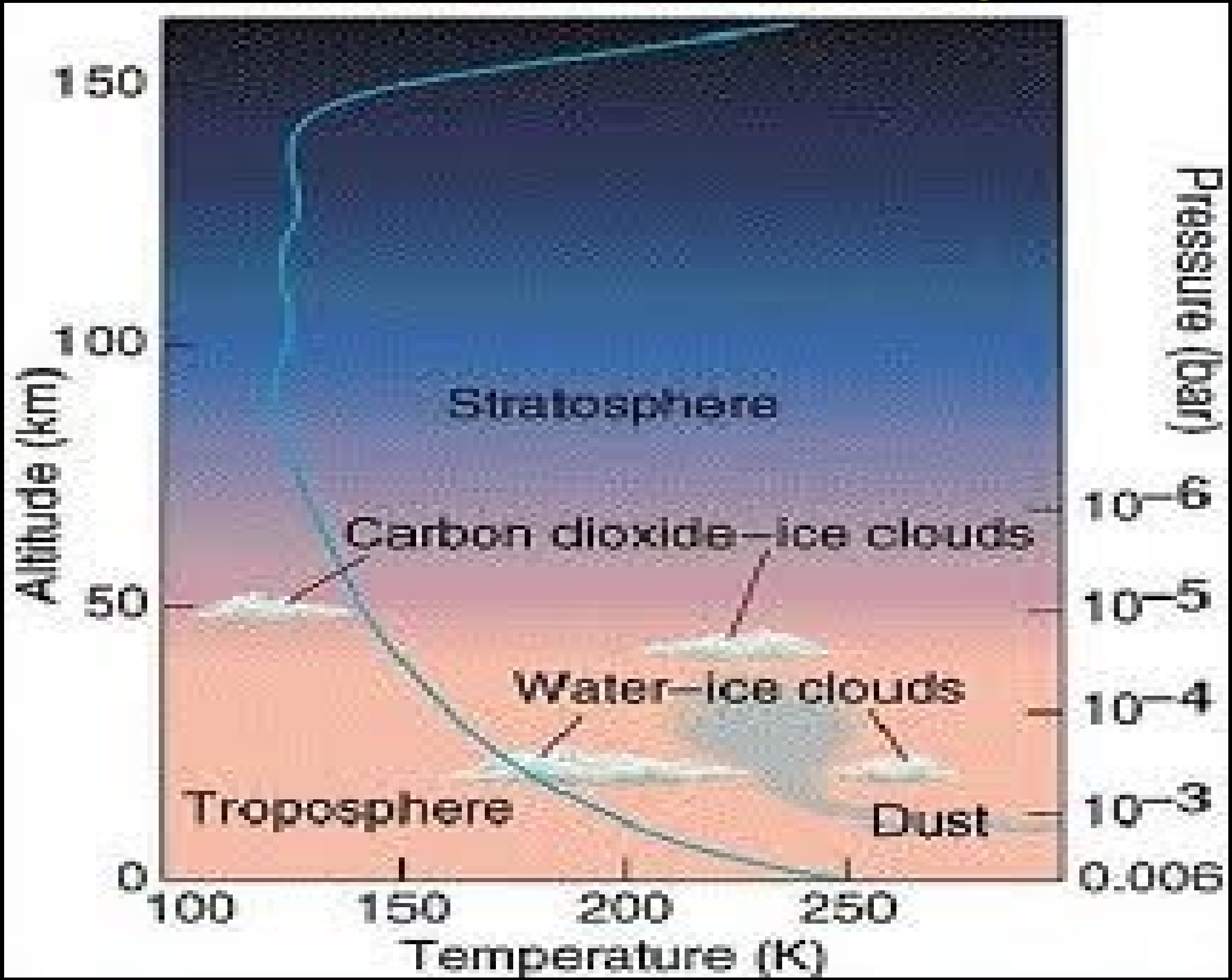
- *“a 2020 announcement that claimed to have discovered the presence of phosphine in Venus' atmosphere was refuted by follow-up observations from NASA's recently-retired SOFIA aircraft in late 2022. (**source**)*
- *Despite this, Dr. David Clements, a reader in astrophysics in the Department of Physics at Imperial College London, recently told Universe Today that "there is something odd going on in the atmosphere of Venus. The phosphine signature from ground based telescopes has not gone away"*

- *“Venus is a very challenging environment for life of any kind,” Seager says.*
- *There is, however, a narrow, temperate band within Venus’ atmosphere, between 48 and 60 kilometers above the surface, where temperatures range from 30 to 200 degrees Fahrenheit. Scientists have speculated this layer is likely the only place where it would survive. <u>And it just so happens that this cloud deck is where the team observed signals of phosphine.</u>*
- *“This phosphine signal is perfectly positioned where others have conjectured the area could be habitable,” Petkowski says.*

Future of Venus Climate?

- More of the same, only worse
- Solar luminosity will slowly rise.
- Venus can’t get any drier
- Perhaps the volcanoes may slowly diminish, since the crust may thicken (slowly) with time. This may reduce sulfuric acid content, which would probably reduce the albedo, absorbing more incoming solar radiation
- Hot and getting hotter, likely forecast

General Structure of Mars Atmosphere Today



Mars Rover "Curiosity" Finds Clues…

- …As to how Mars lost so much atmosphere – it finds the current atmosphere is much enriched in the heavy *vs* lighter isotopes for Argon and Carbon, vs. the abundances found in the older Martian rock found in Antarctica
- Lighter isotopes would be more easily lost to outer space by thermal leakage, as at a given temperature, they move faster.
- Thus, leakage to outer space over long periods of time (*vs.* all at once, in Impact Cratering) has apparently played the dominant role in atmosphere loss
- This supports indirectly the solar wind – weak magnetic field theory for atmosphere lost, as this would be a mechanism for enhanced loss to outer space
- See announcement here

Ancient Martian Climate Has Some Twists, it Seems

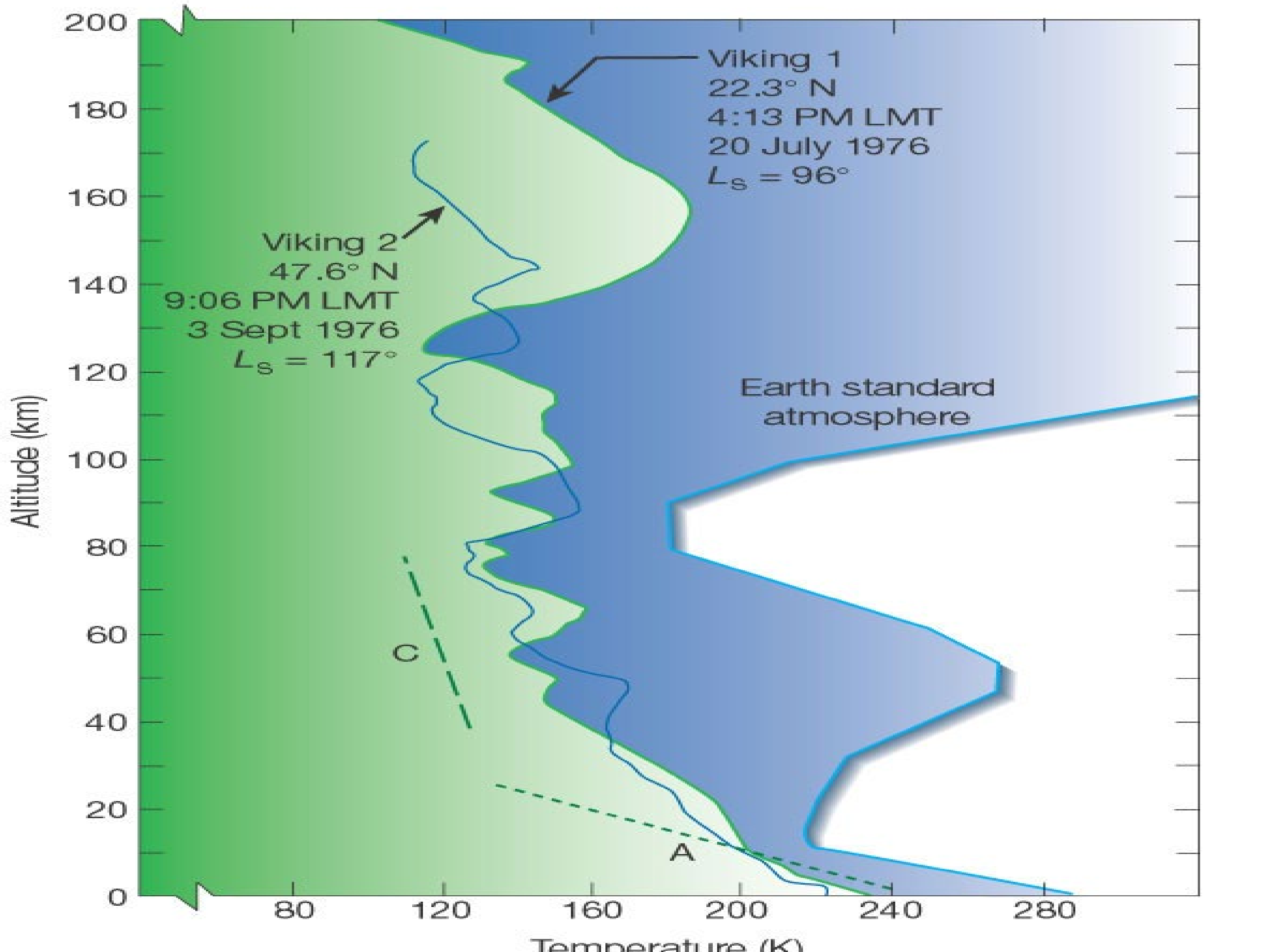
- In Gale Crater, where Curiosity has been poking around, we find no evidence of carbonate rocks, limiting the amount of CO_2 the atmosphere may have had at the time the rocks were laid down.
- Yet the evidence for a liquid ocean billions of years ago is strong.
- We don't have a new theory which reconciles the evidence for low CO_2 (a few millibars worth of atmospheric CO_2, at most) and yet a warm enough climate billions of years ago when the sun was dimmer, to permit the very rocks which indicate low CO_2 to yet have been formed at the bottom of a liquid water lake.
- Interesting 2017 article on this here

New Organic Chemistry Discovery in a "Curiosity" drill core at Gale Crater…

- *"The rock was rich in clay, sulfur, and nitrates. All three materials help preserve organic compounds. Also present was methane with a carbon signature that, on Earth, often points to presence of life."*
- Detected: 10-, and 11-carbon complex organic molecules

Mars Atmosphere Layers: Not Like Earth's

- Viking missions in mid 70's found Mars atmosphere generally cools consistently with increasing altitude, although data shows smaller scale variations. Noise? Real?
- There is no real Stratosphere because there is no heating via Ozone absorption of solar UV like there is on Earth.

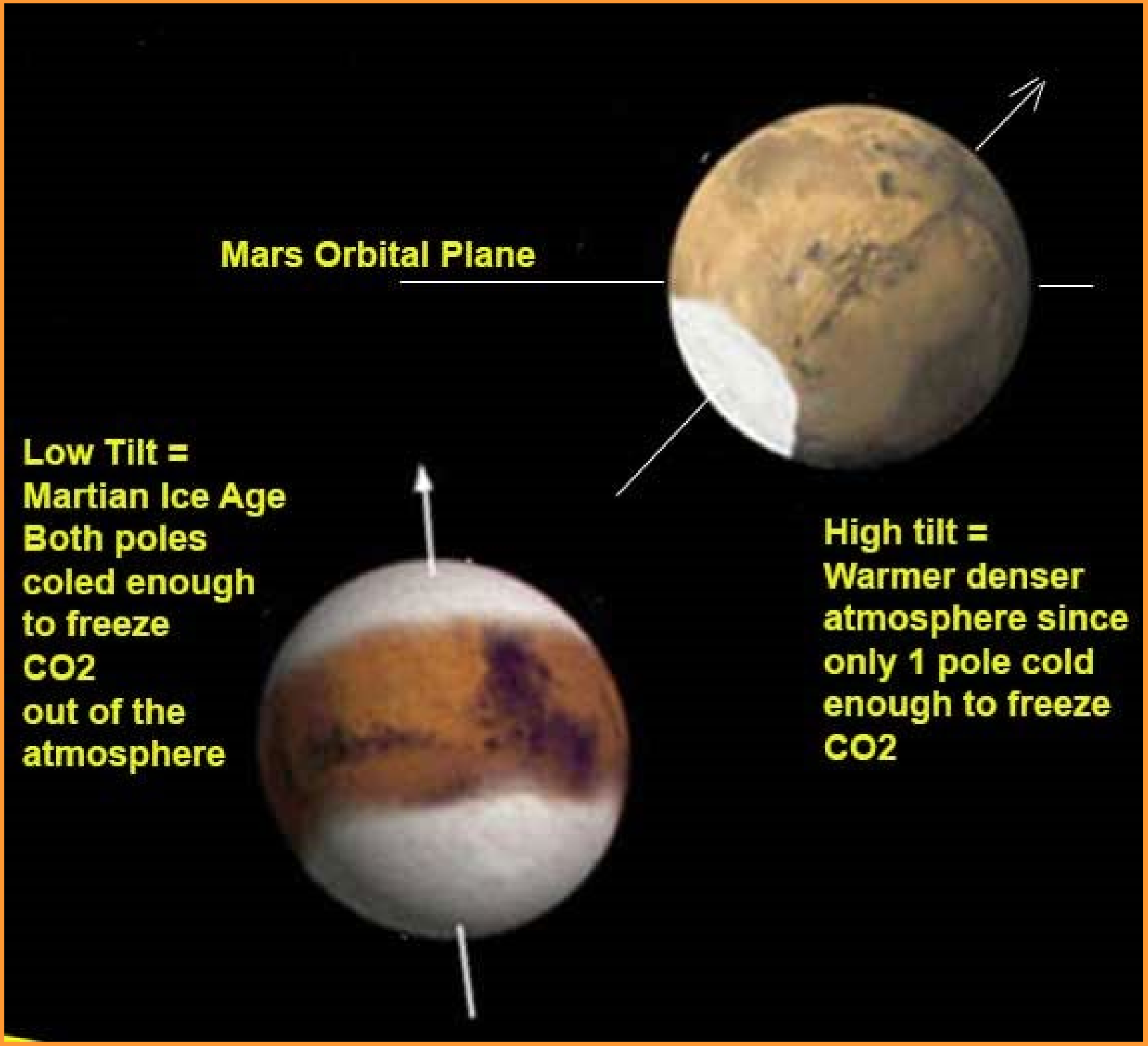


Viking 1
22.3° N
4:13 PM LMT
20 July 1976
L_S = 96°
Viking 2
47.6° N
9:06 PM LMT
3 Sept 1976
L_S = 117°
Earth standard
atmosphere
C
A
Altitude (km)
Temperature (K)
0
20
40
60
80
100
120
140
160
180
200
80
120
160
200
240
280

How Does Mars Atmosphere Change with Axis Tilt?

- Mars spin axis tilt varies from near zero to well over 45 degrees (~million year cycles) because not stabilized by a massive moon like we have
- When near zero tilt, neither pole gets enough heat to ever thaw, and we get a Martian Ice Age, with atmospheric CO2 freezing out and onto both poles extensively, so - thinner atmosphere, colder
- **Large tilt corresponds to thicker, warmer atmosphere (study source: Laskar 2002)**
- Today, near 23 degrees, poles alternate, getting icy with the seasons, and an intermediate climate.

At low tilt, both poles are cold enough to freeze CO_2 out of the atmosphere. When nearer ~45 degrees or more, one pole gets enough full day sunlight that all the CO_2 ice melts, and the CO_2 atmosphere gets thicker, warmer (both water and CO_2 are greenhouse gases)



Small Tilt = Martian Ice Age

Now… Life <u>Beyond</u> the Habitable Zone?

- Yes, it’s possible:
- As long as liquid water is available, and an energy source, and there is protection from the cold and other killers, then life of some sort is possible (but maybe we can’t talk to it!)

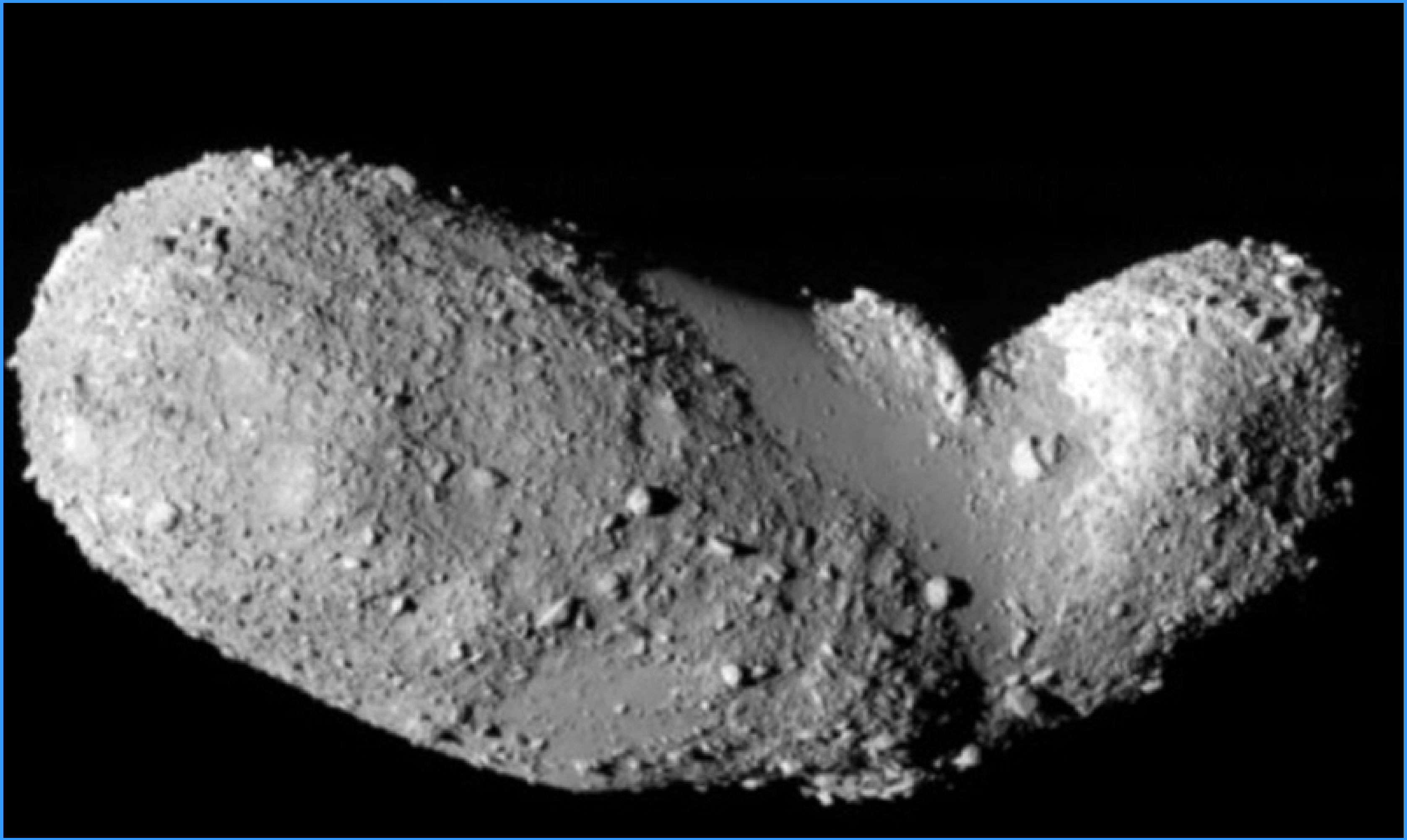
- But Rick – what about Zion! In “The Matrix”!

Asteroids: Bringers of Organics to Earth?

- Our first attempt to bring pristine samples of an asteroid to Earth for study, was the **Hayabusa I Mission.**
- I was lucky enough to be selected to be part of the advance Ground Team, doing spectrophotometry of the re-entry of the space craft over the **Outback of Australia, in 2010**.
- A great science adventure!

I'm calculating the sky position to guide the team to early acquisition of the spacecraft

But, We Only Got a Few Grains; from Asteroid Itokawa. Not Enough to Learn Much



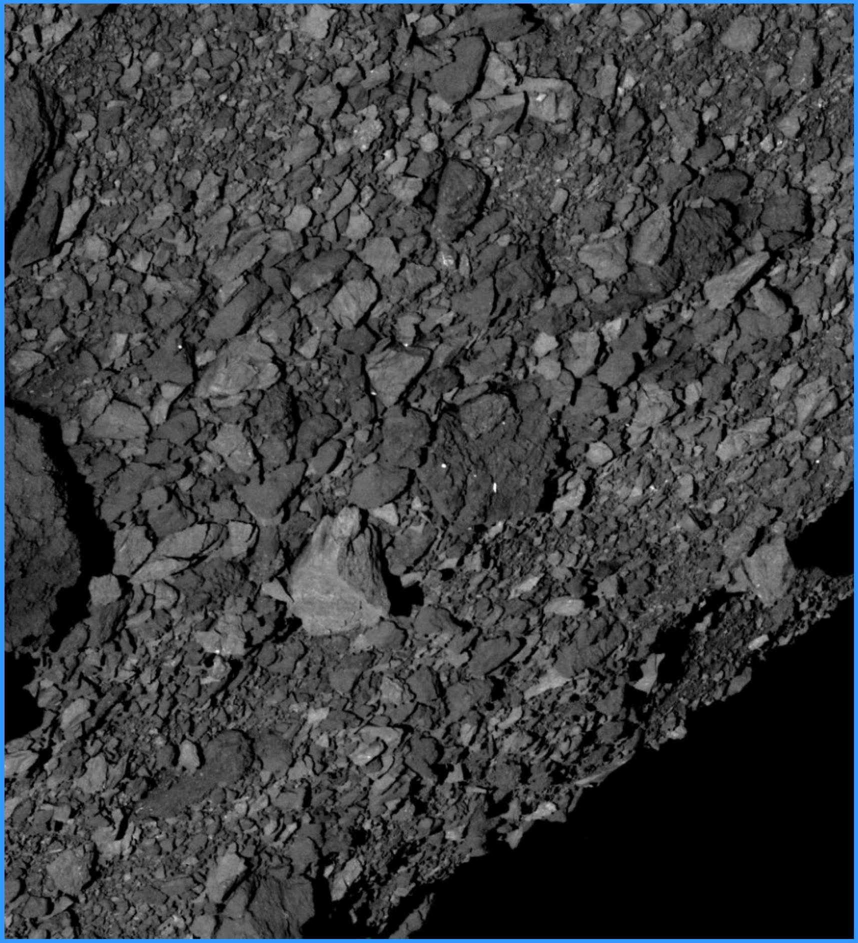
More Successful was Hayabusa 2, which retrieved in 2020 a much larger sample of sub-surface material

- From asteroid Ruguyu.
- The asteroid reflection spectra indicated it was carbon rich, as is more common in the outer asteroid belt.
- But accidental contamination after return to Earth led to Earth microbe colonization. :*(

Mistakes Learned; Astronomers Then Sent OSIRIS-Rex to Asteroid Bennu

- Big success! Link has 4min excellent video of highlight discoveries
- Samples contained 14 of the 20 Amino Acids that Earth life uses to build proteins.
- And – all 5 nucleotide bases which connect DNA and RNA spirals!
- And - both left-handed LH and right-handed RH Aminos. On Earth, life is left-handed only.

Big Rocks; at center is half-basketball court!



Bennu – a Rubble Pile, Grav Re-assembled from Collision Debris

Asteroids: Some Conclusions

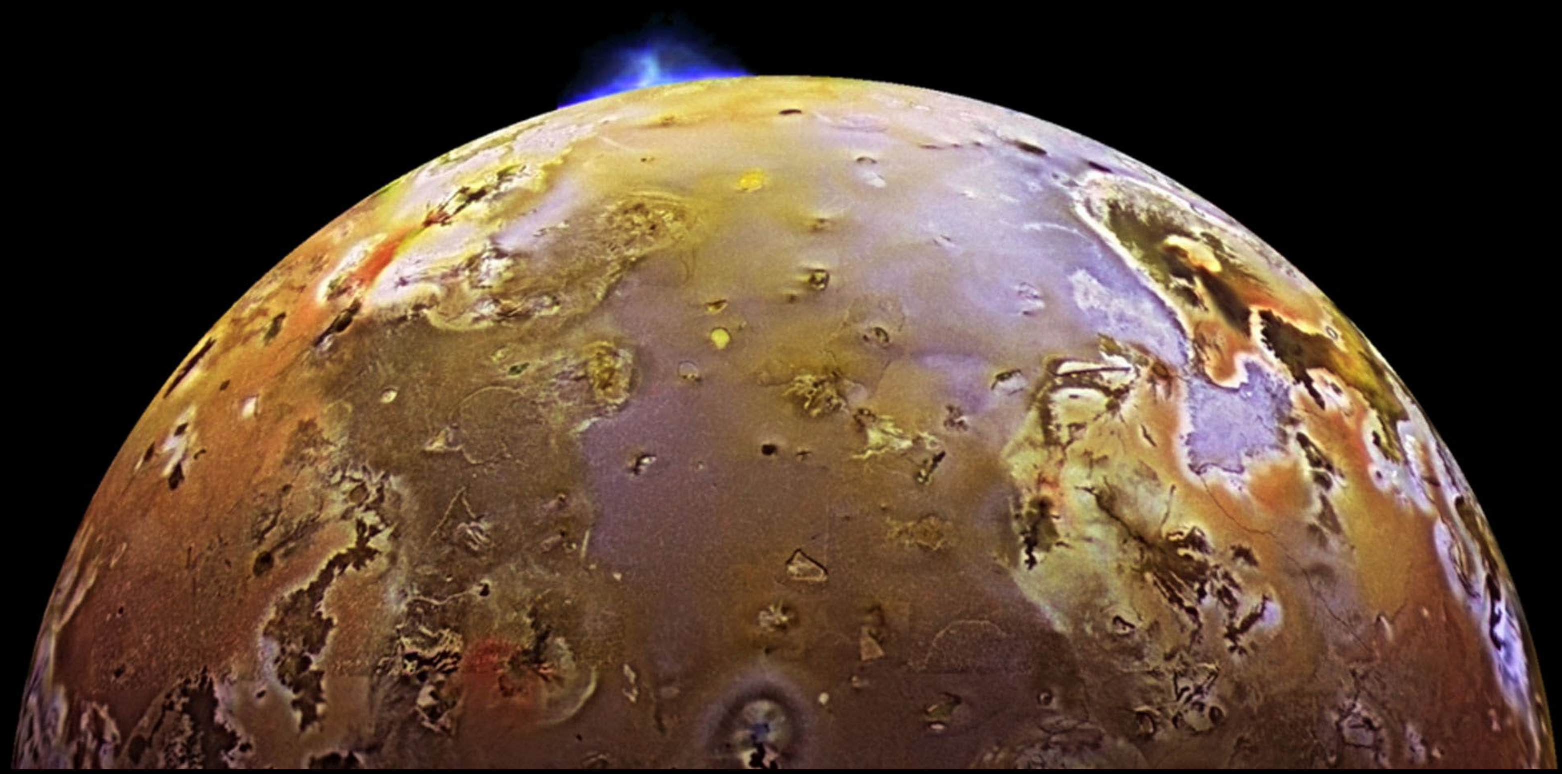
- It looks like the building blocks of life could have gotten a head start from the arrival of early asteroids to primitive Earth.
- Why did Earth life choose LH aminos and LH DNA and not RH? After all, RH versions would have worked just as well.
- **This suggests that the big step from Aminos to Life didn't happen easily and often around the globe.**
- We already saw evidence for this rarity in the step from primitive to advanced multi-cellular life.

Instead…

- **Hypothesis:** Once life got going from a rare happy incident with LH molecules, then the RH versions may have just been food for LH life
- RH versions got gobbled and digested soon, never getting the long complex chance to turn themselves into life, independently
- "Early bird gets the worm"

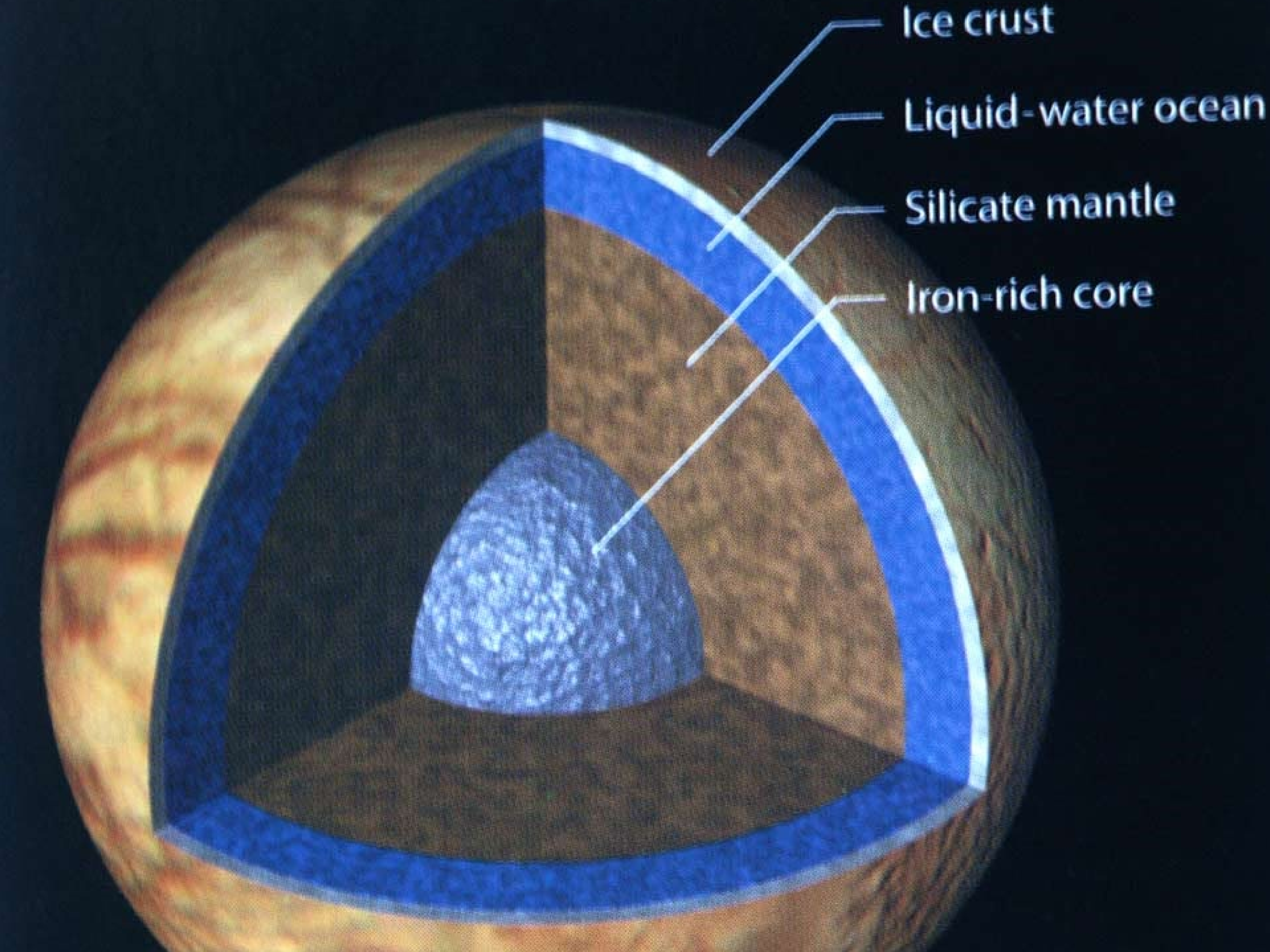
Jupiter and Beyond. Cold, but still not Impossible for Life…?

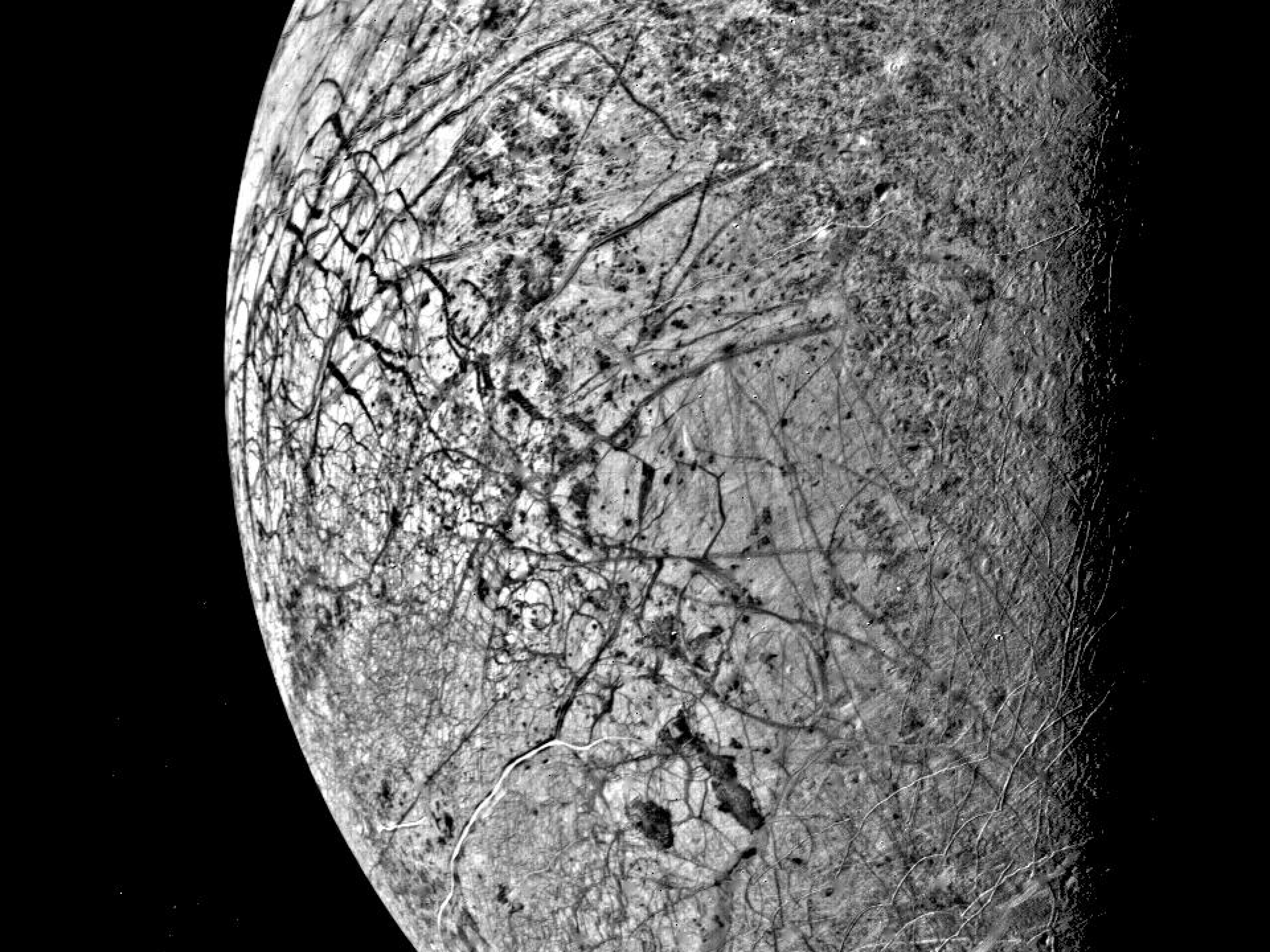
Io, closest to Jupiter, strong tidal heating has melted all ice, vaporized, gone to space. The rocky remains are covered with active volcanoes. Hostile to fragile organic molecules

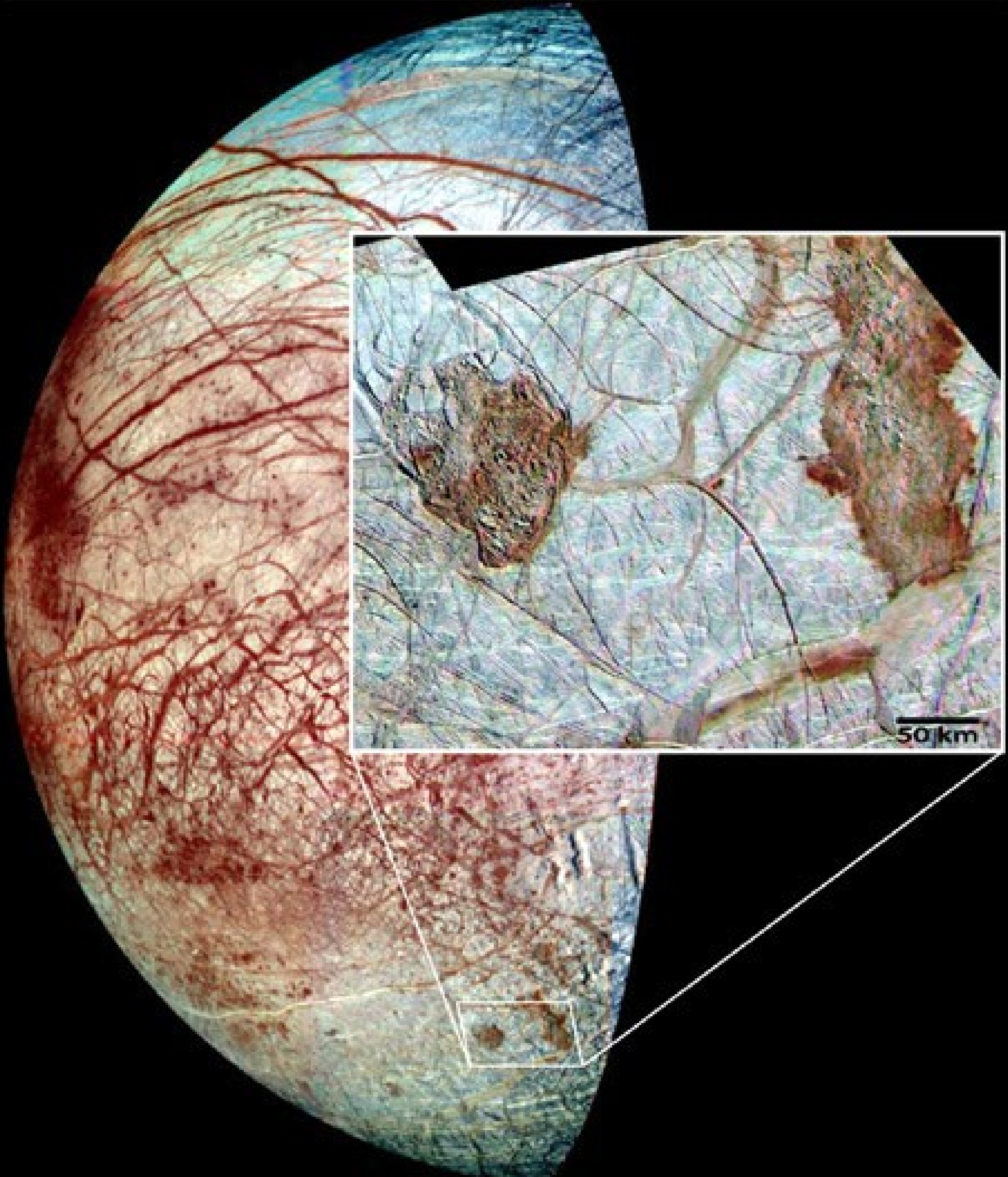


Europa – Also tidally heated, but less so

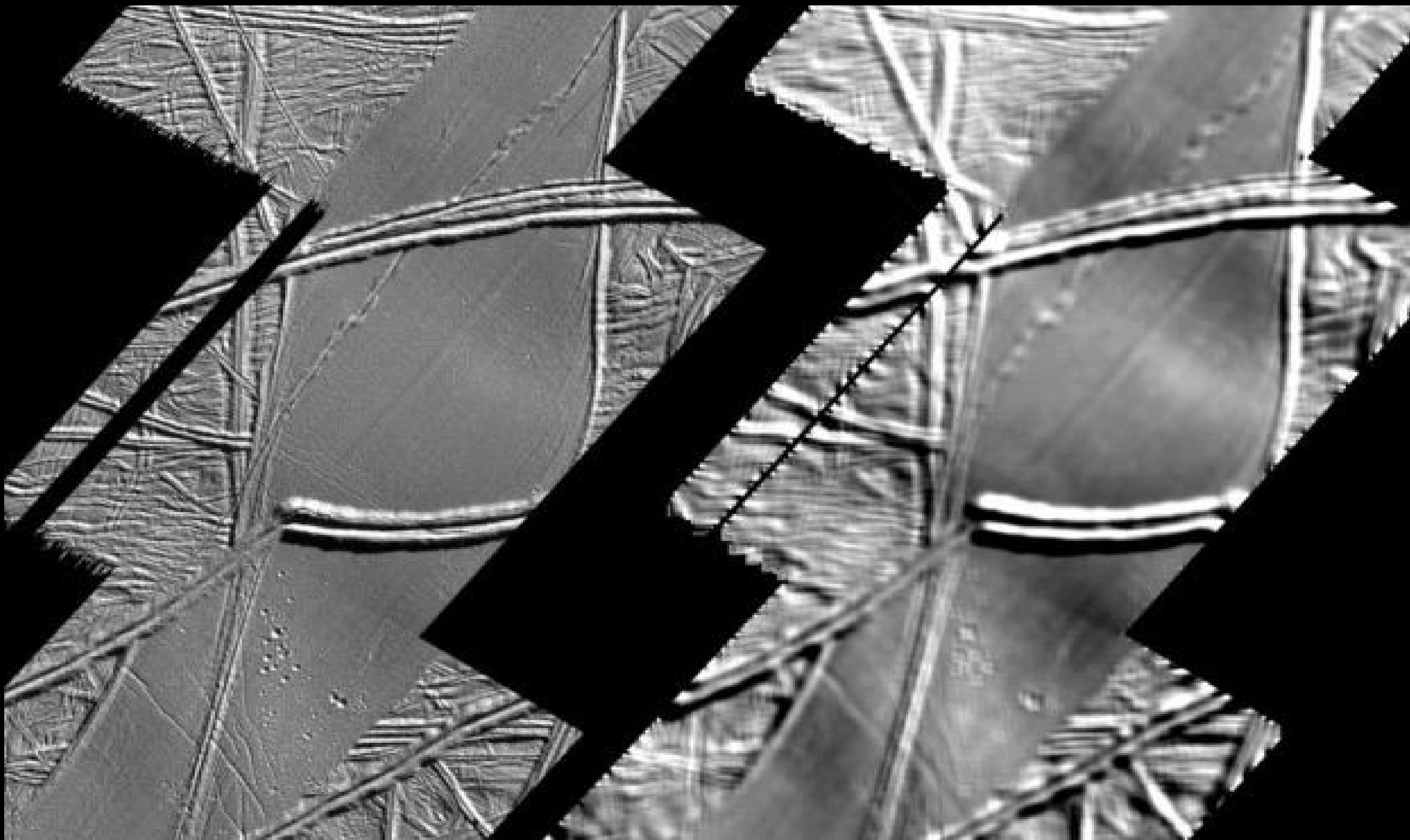
- It was not so hot as to evaporate water away. Water is a very common molecule.
- Europa is an arctic world of salt water covered by ice
- Cracks show characteristics of salt-water pressure ridges
- Intriguing… salt water ocean warm enough to support life, is what the evidence suggests.

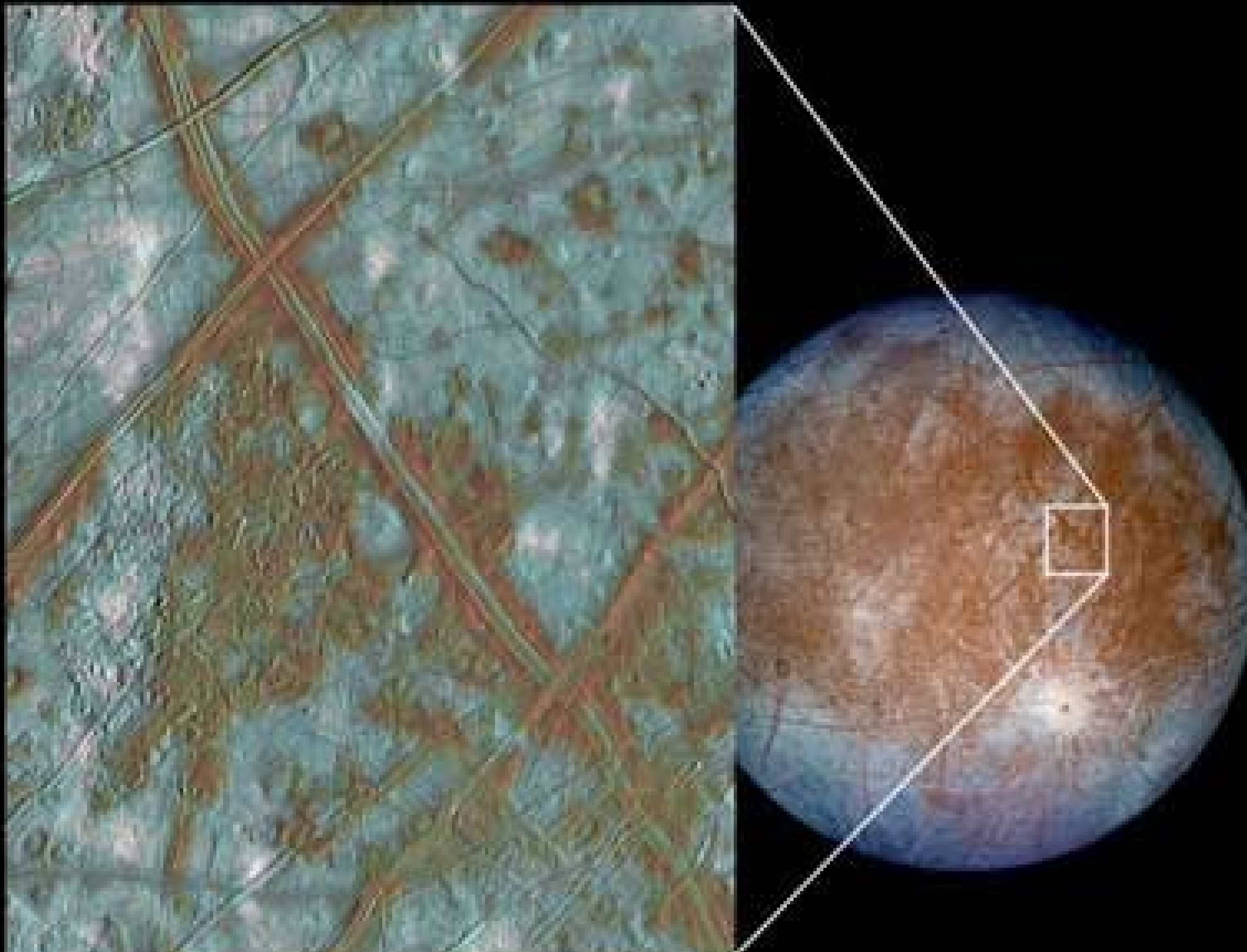

Ice crust
Liquid-water ocean
Silicate mantle
Iron-rich core



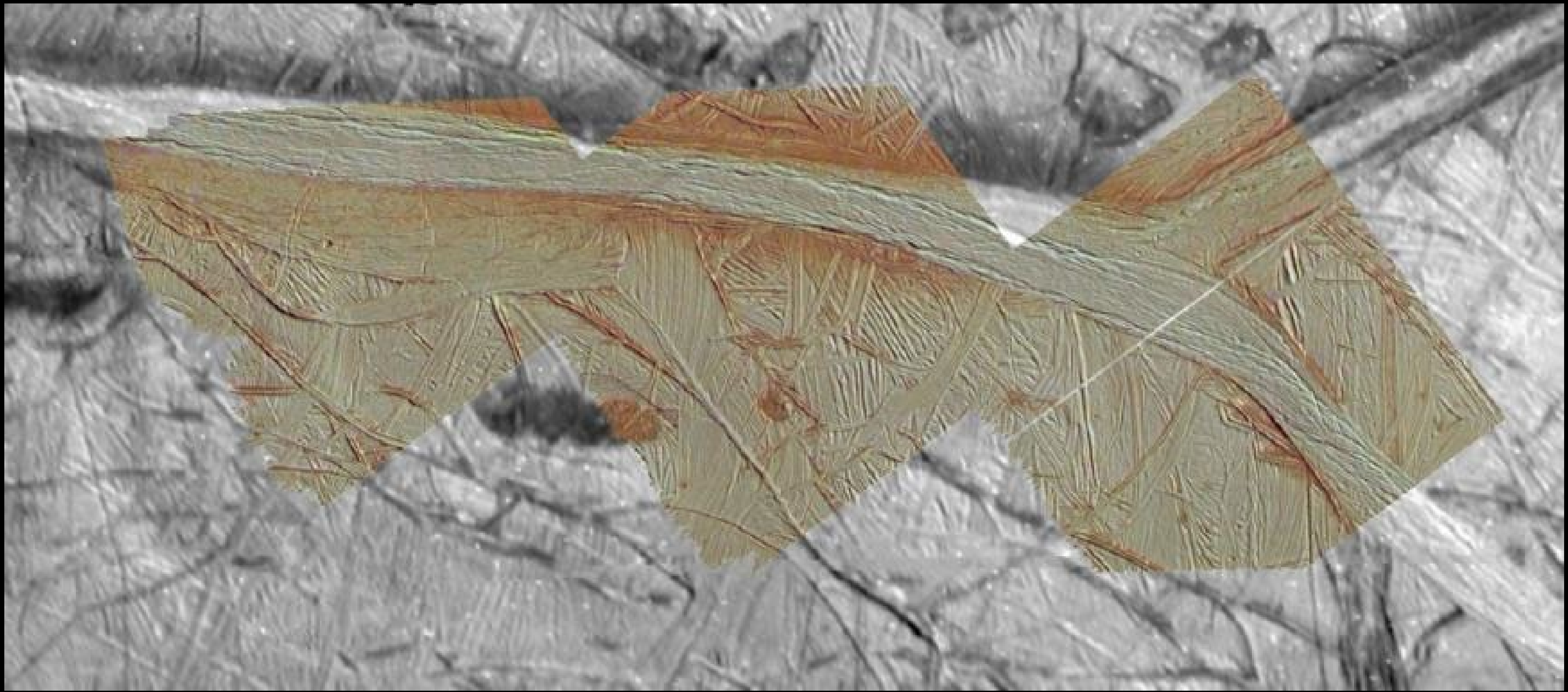

50 km

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

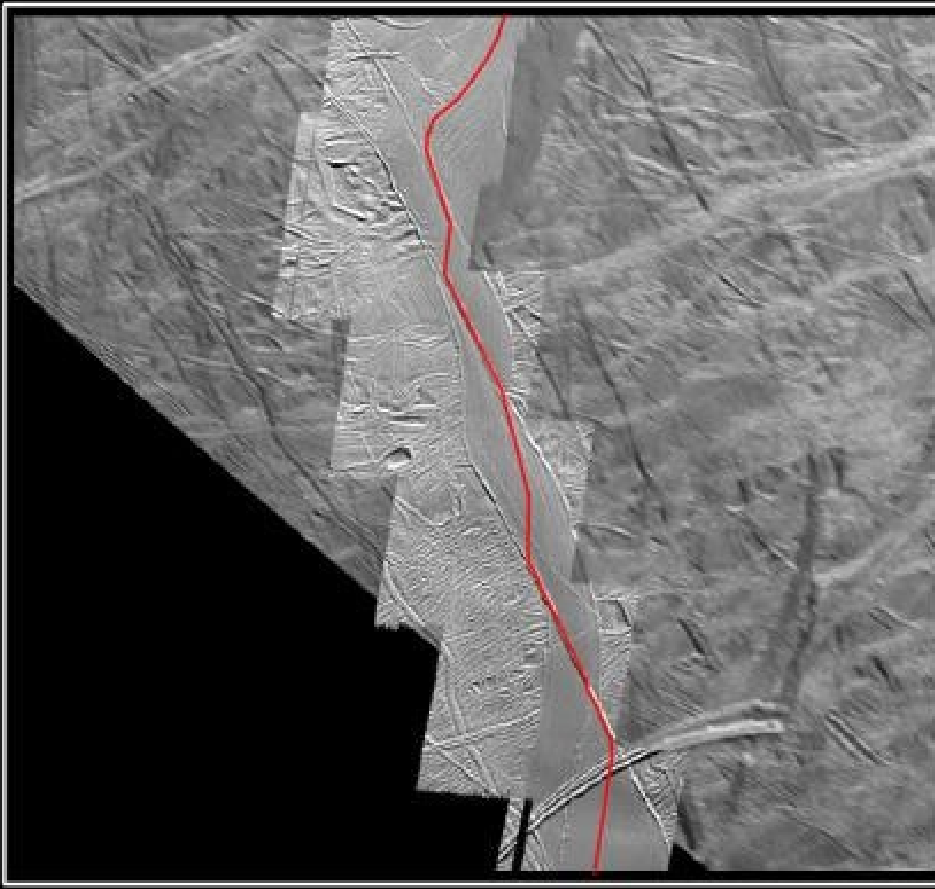




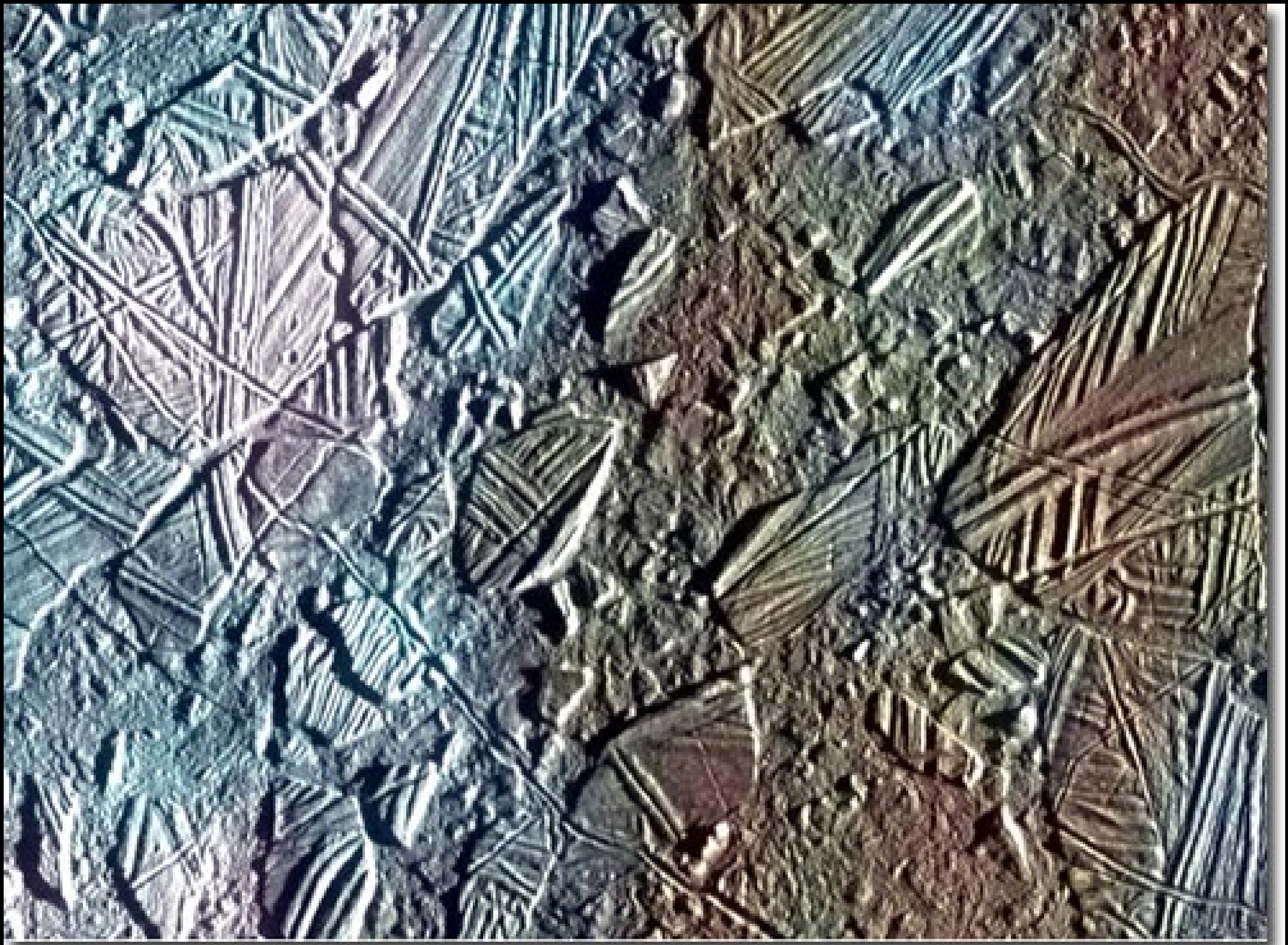
Brown briney ridged cracks. Salt water ocean underneath. Warm enough for life as we know it.



Strike-Slip Faults: Earth vs. Europa

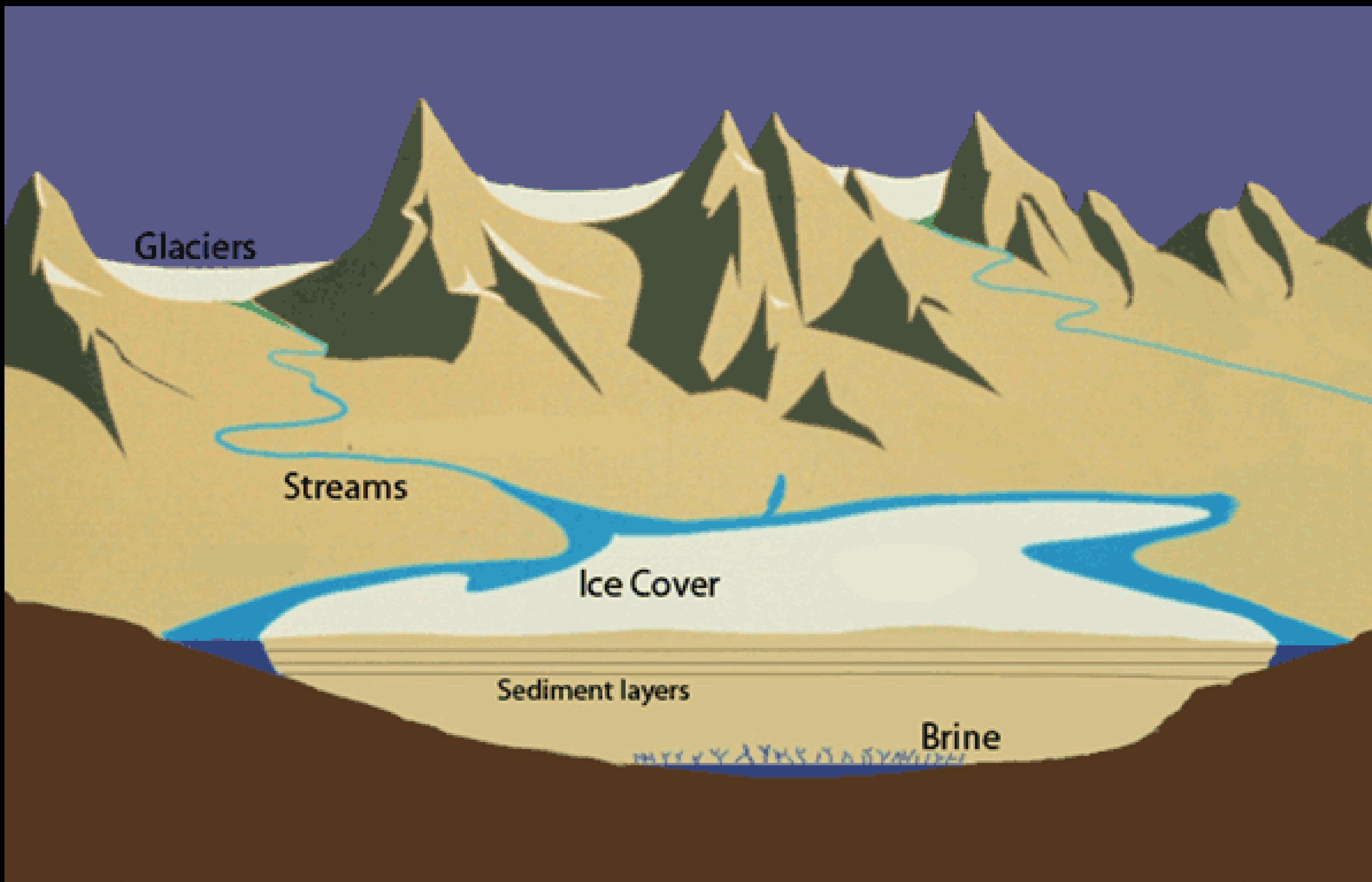


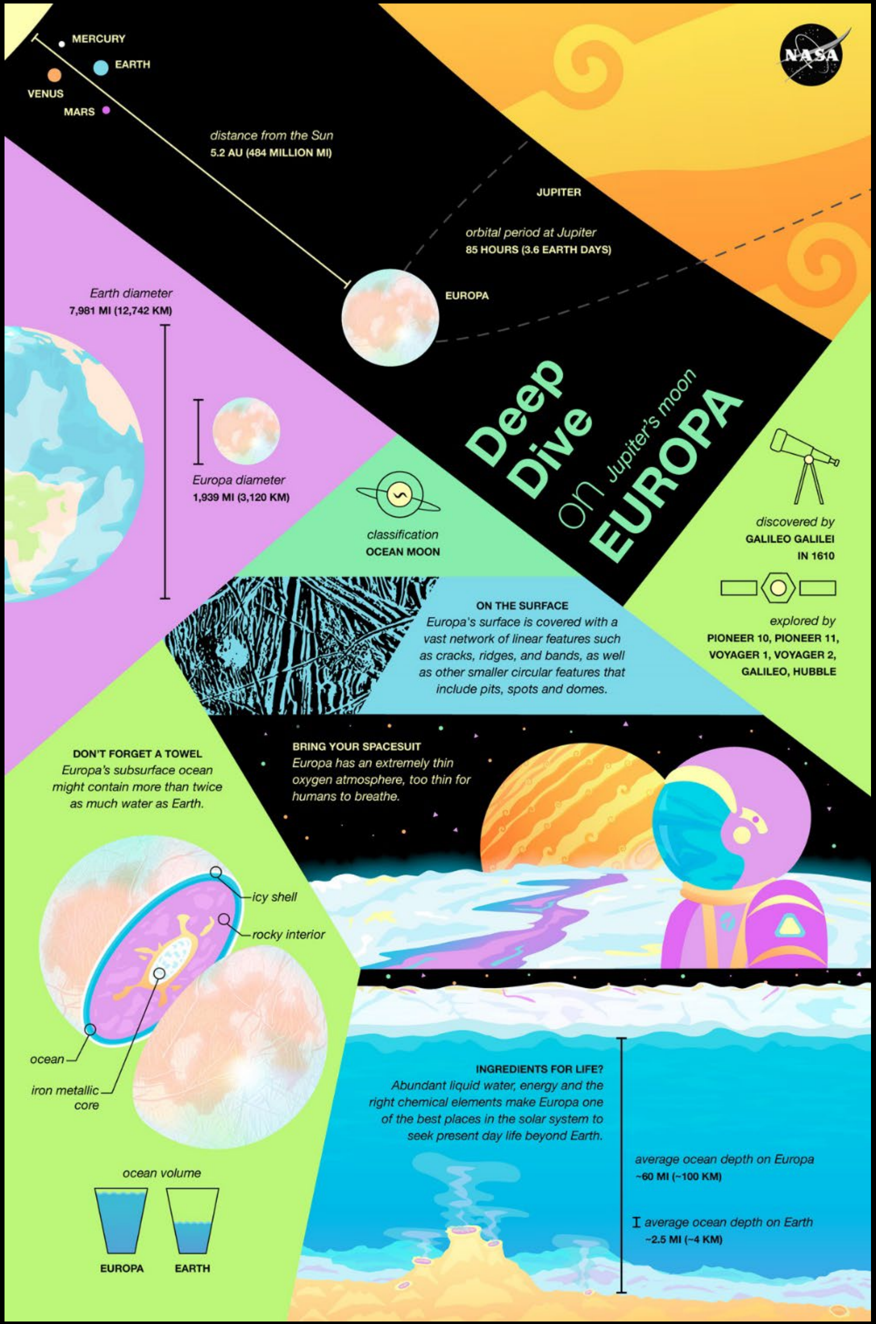
Visual look of freeze-thaw-freeze episodes



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





NASA is sending the Clipper Mission to Europa

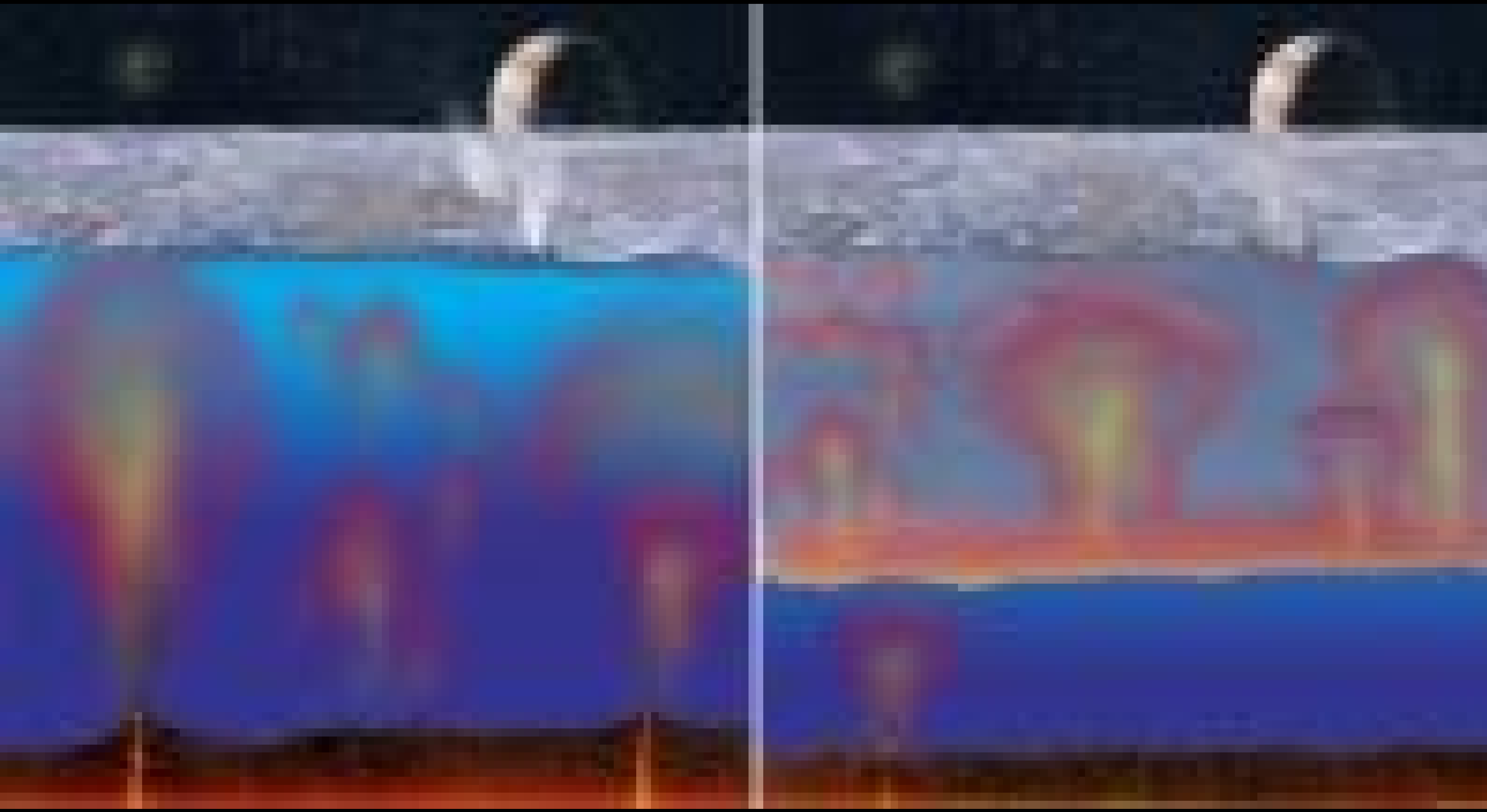
NASA Clipper Mission – Examining Europa in Detail

Clipper: Solar Powered - Array as big as a basketball court

Clipper Mission: 4min video

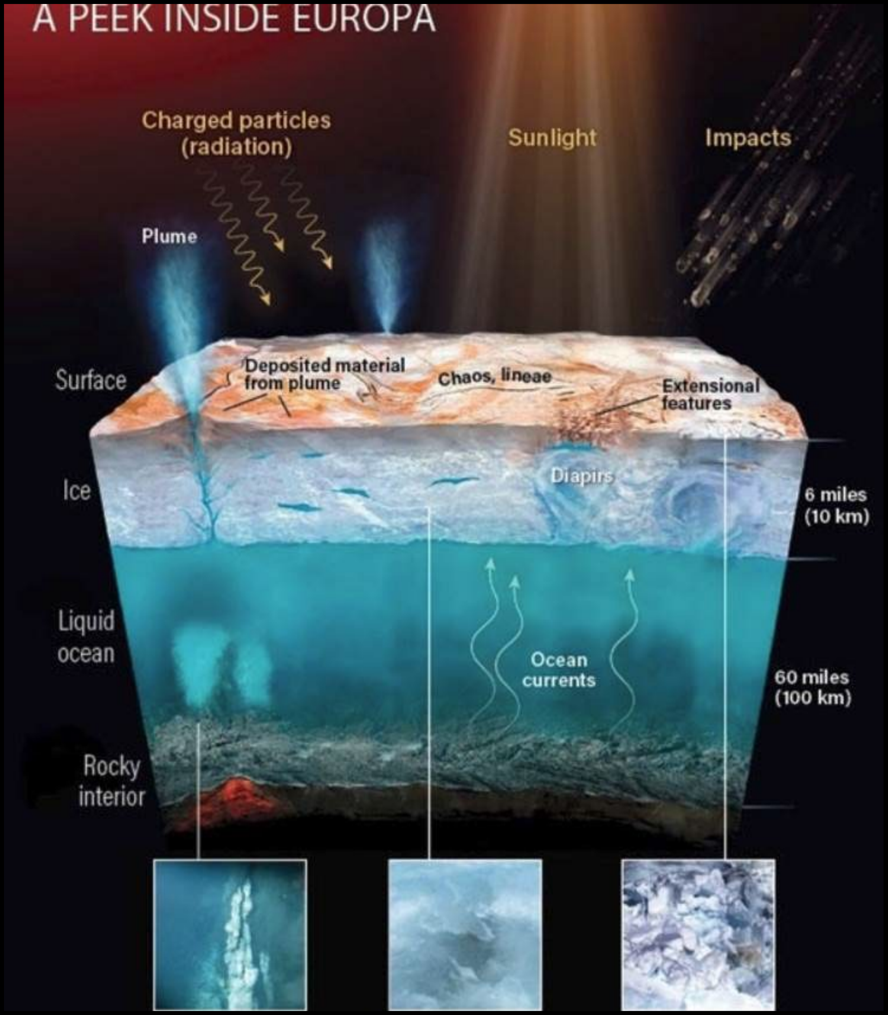
- 9 instruments: 5 imagers and spectrographics
- 4 “sniff” the near orbit environment
- Orbiter; not a lander
- 1/3” thick aluminum “vault” protects from the equivalent of 1 million chest X-rays of high speed radiation particles

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



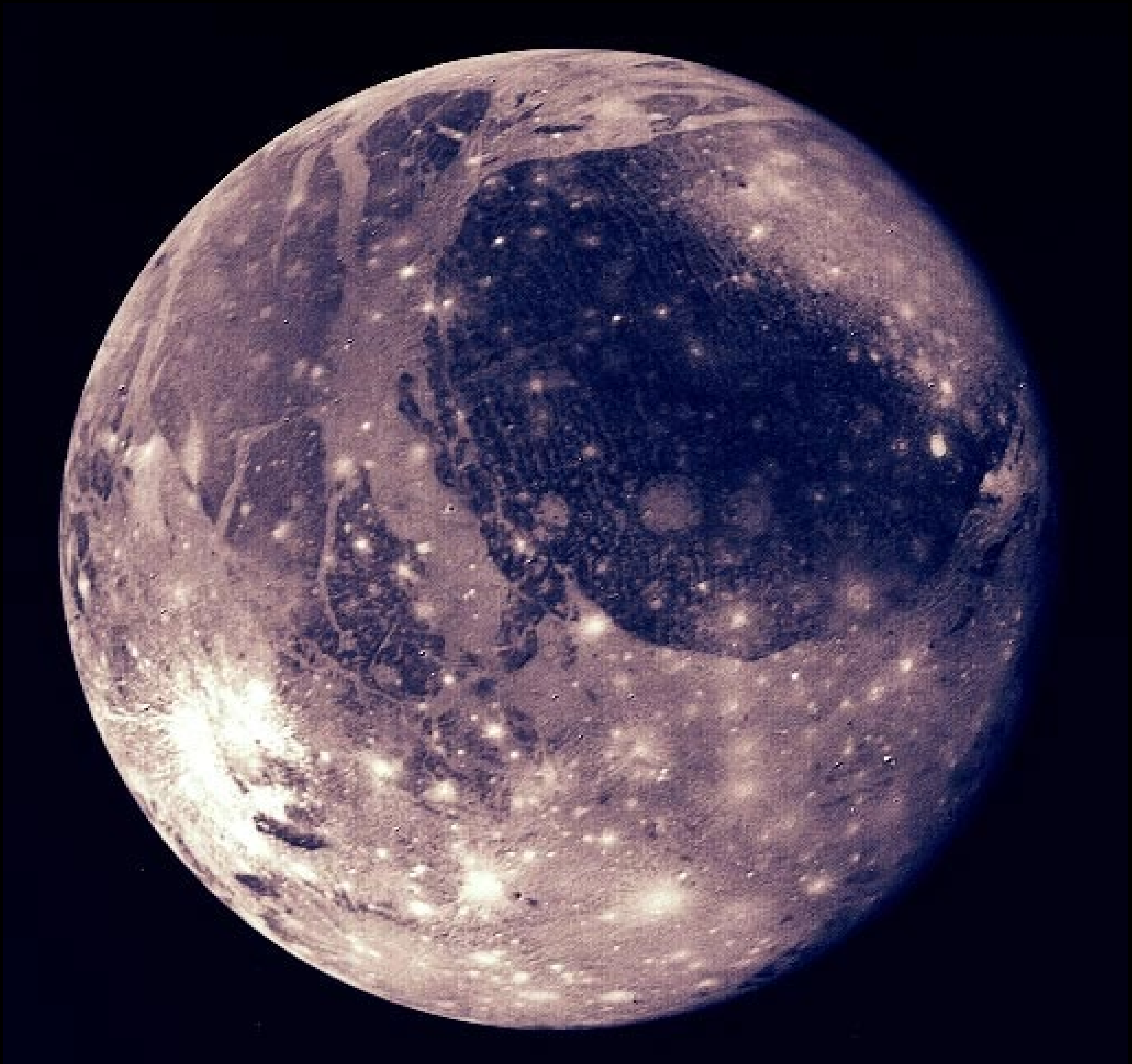
Life on Europa?

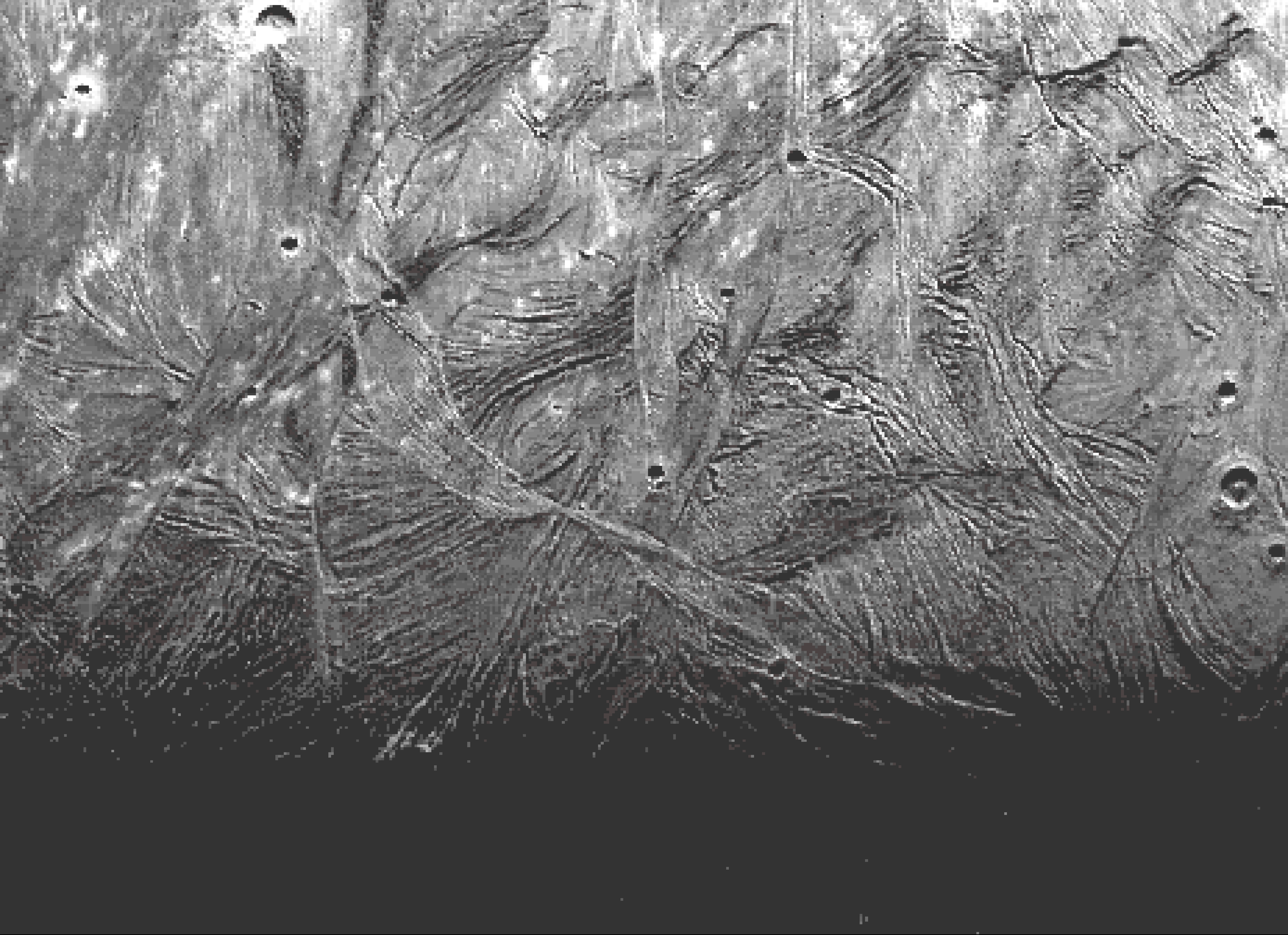
- Life in Europa; 14min video NASA
- If life is in the oceans of Europa, it's much less likely that it got transmitted there from Earth, or that Earth received it from Europa.
- It would argue for life being more common in the Galaxy, if it can arise independently on two worlds in the same solar system

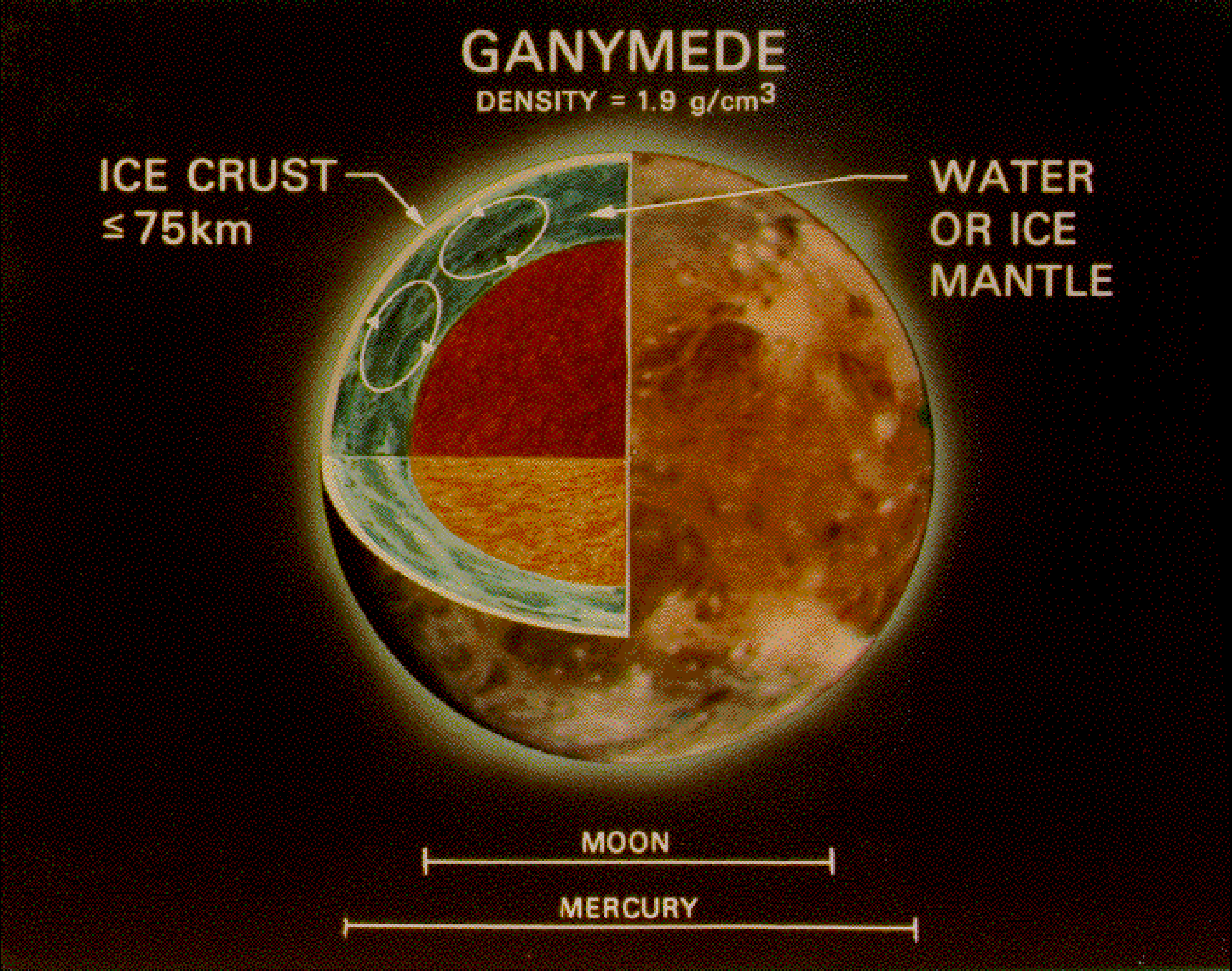


Ganymede…

- 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?

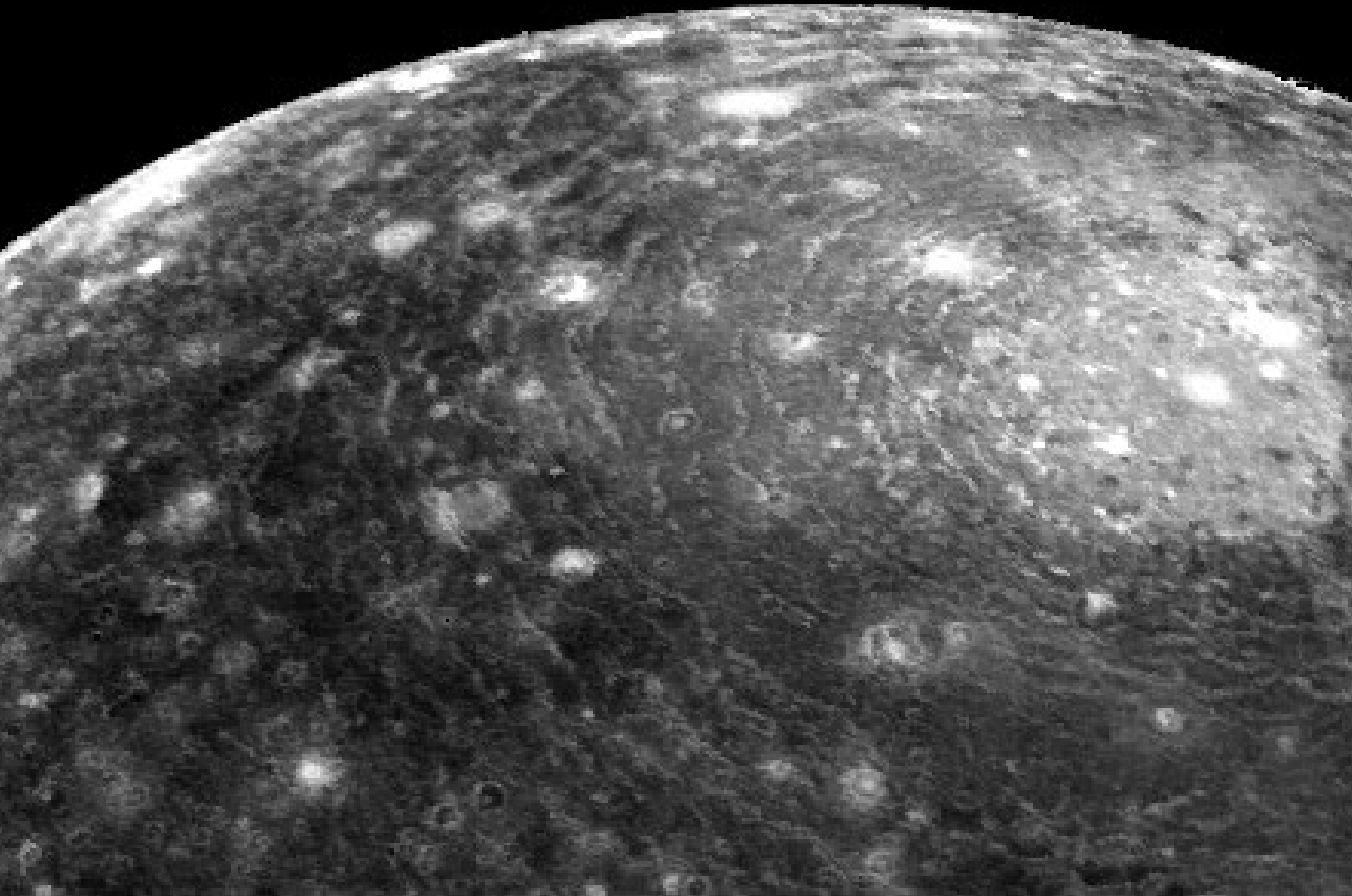


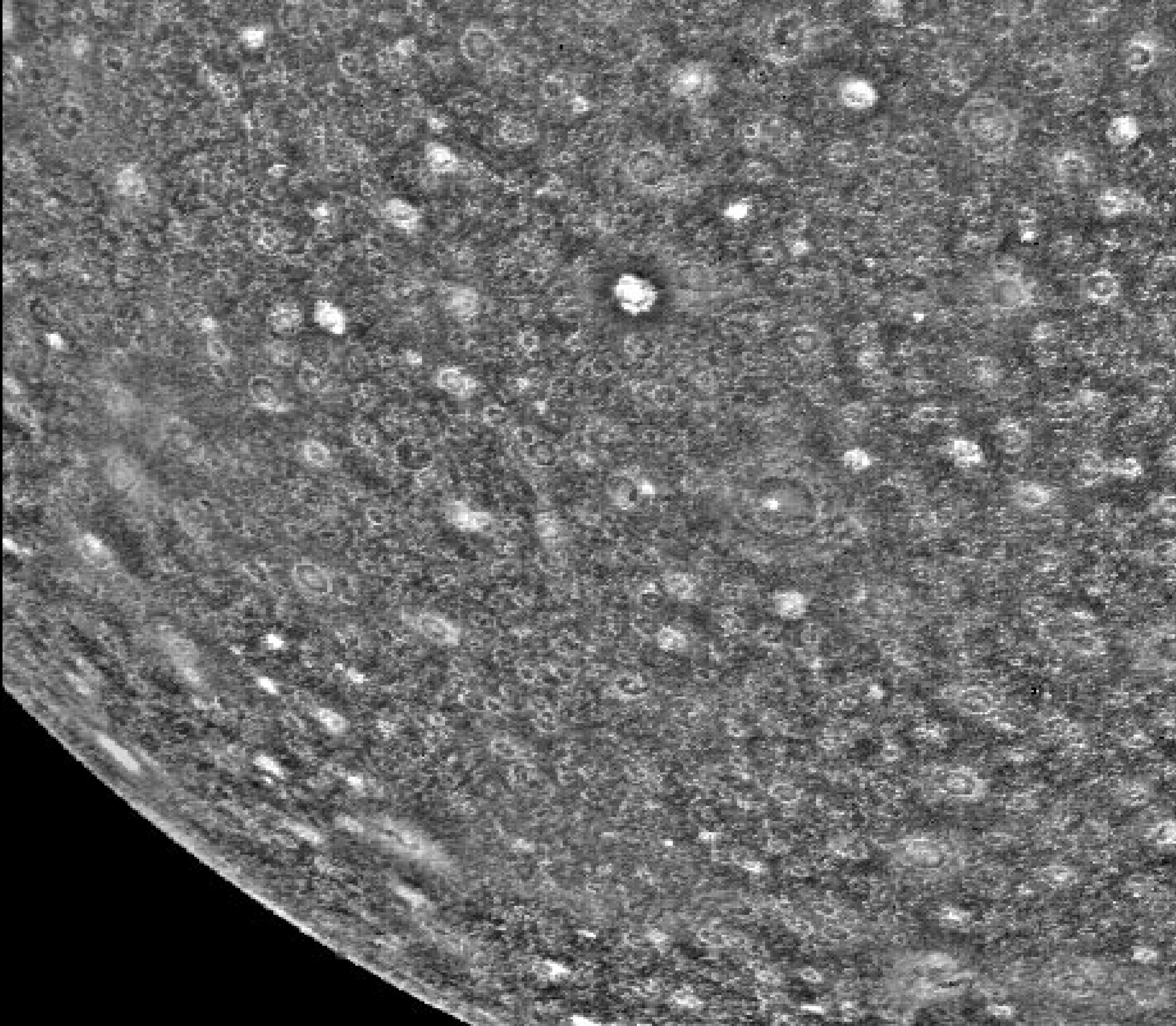



GANYMEDE
DENSITY = 1.9 g/cm3
ICE CRUST
≤ 75km
WATER
OR ICE
MANTLE
MOON
MERCURY

Callisto – Last and Farthest of the Galilean Moons

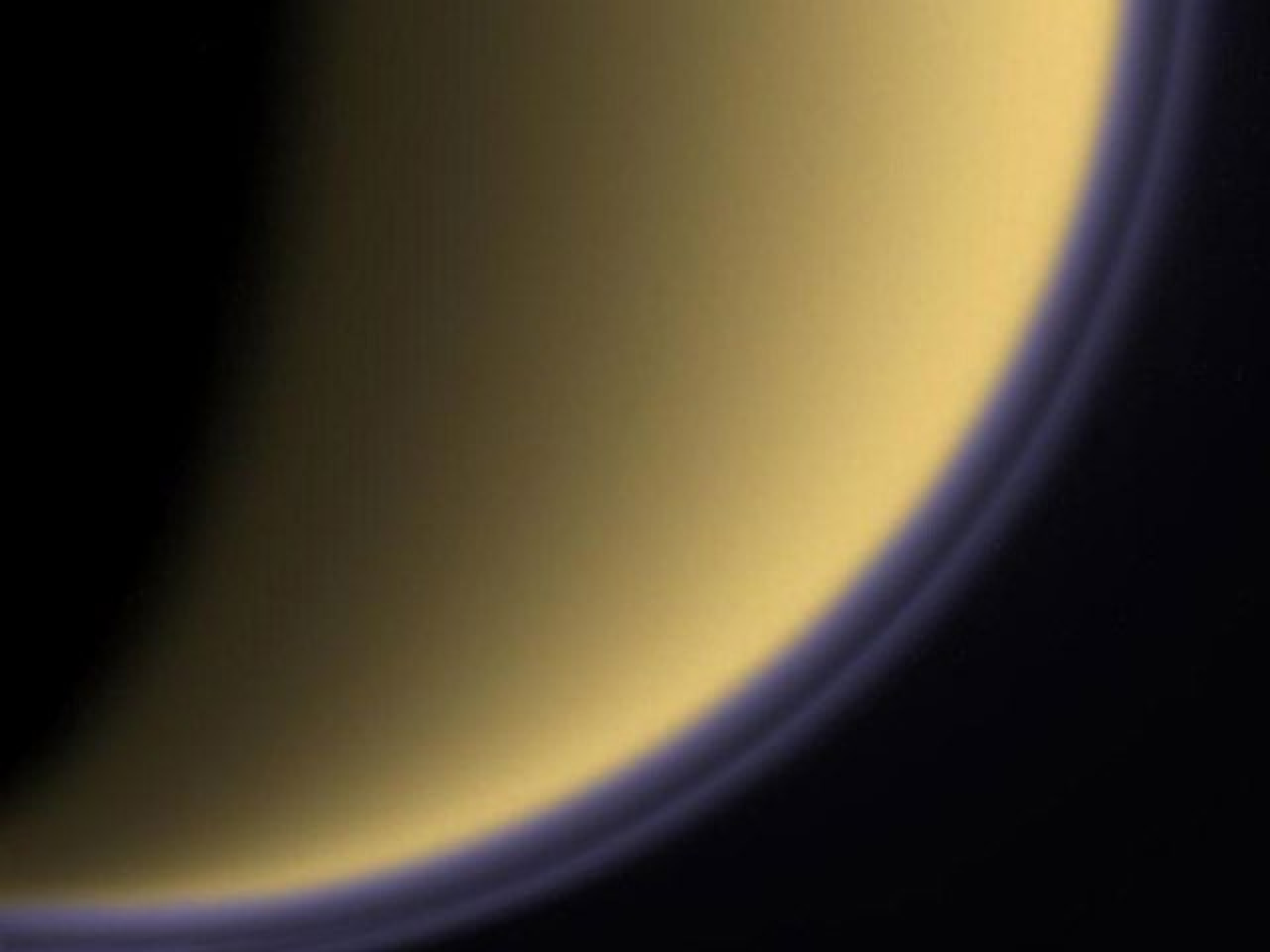
- Note the ancient surface, which you can tell because of the many impact scars.
- Tidal friction goes as $1/r^3$, and this far from Jupiter (4.5 times farther than Io), Callisto experiences only **1% of the tidal heating as Io.** Not enough to melt ice.
- Hence, any watery ocean is at least dozens of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



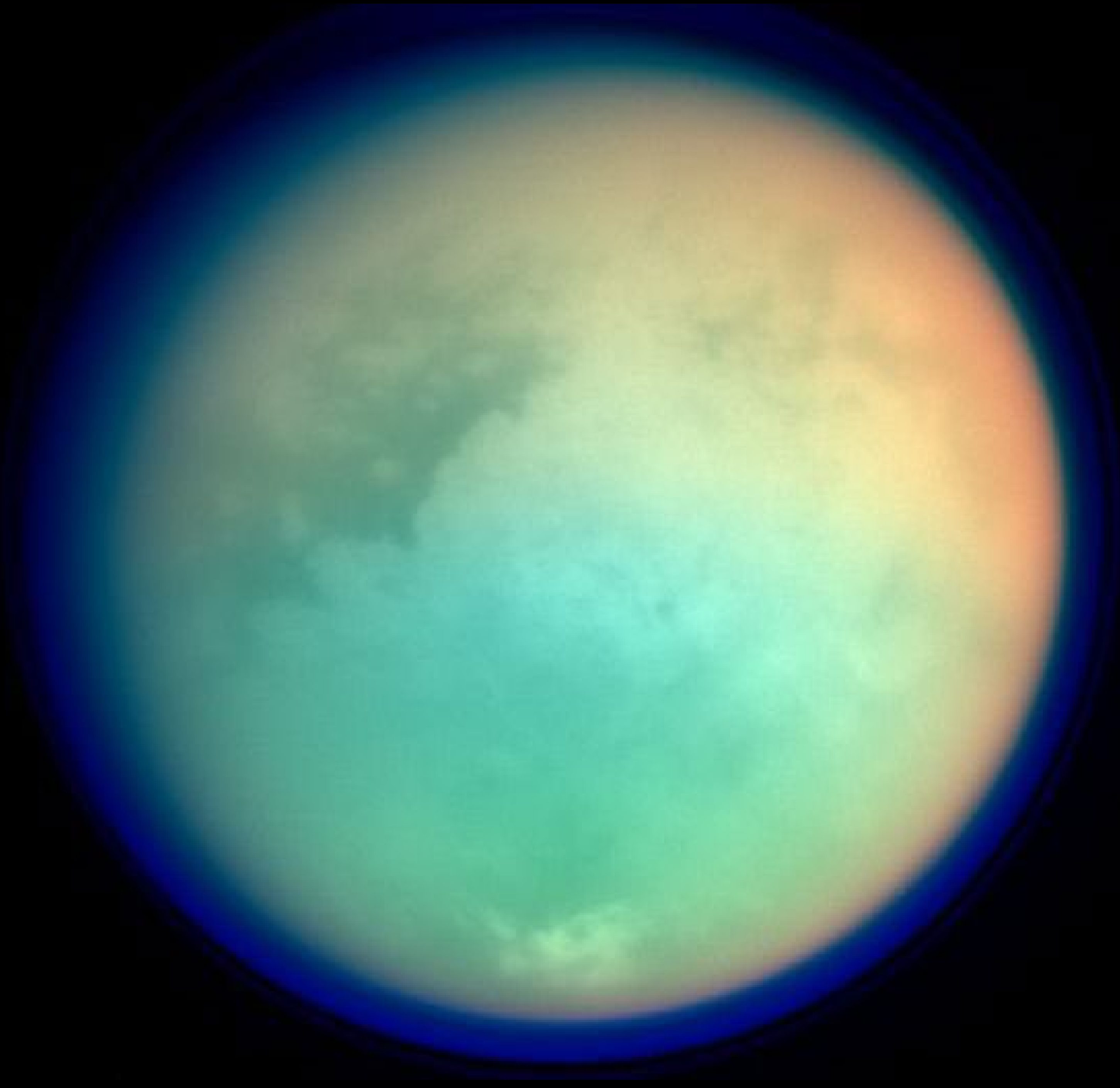


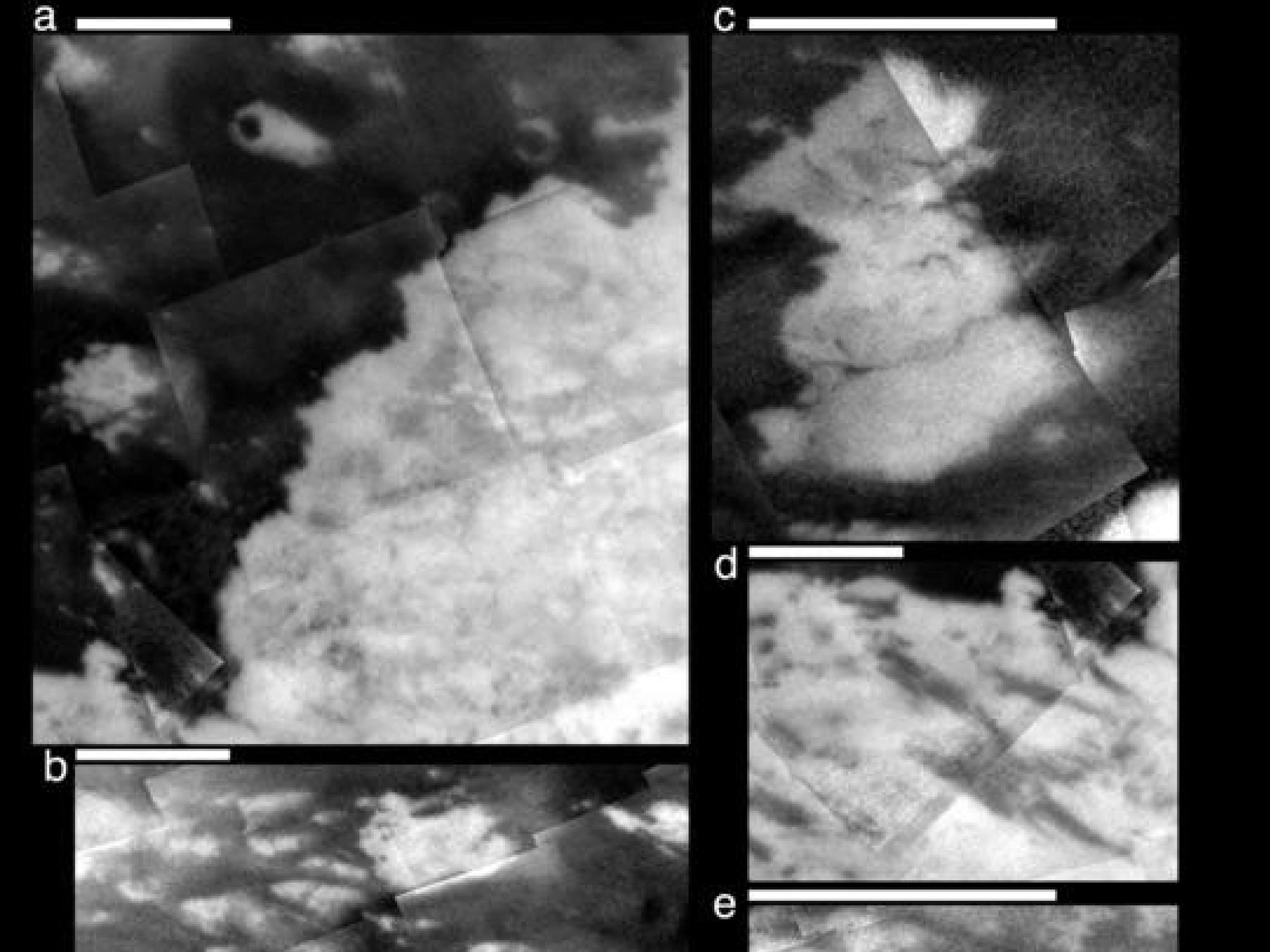
Titan – Only Moon in the Solar System with a Significant Atmosphere – Same pressure as Earth!

- 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





a
b
c
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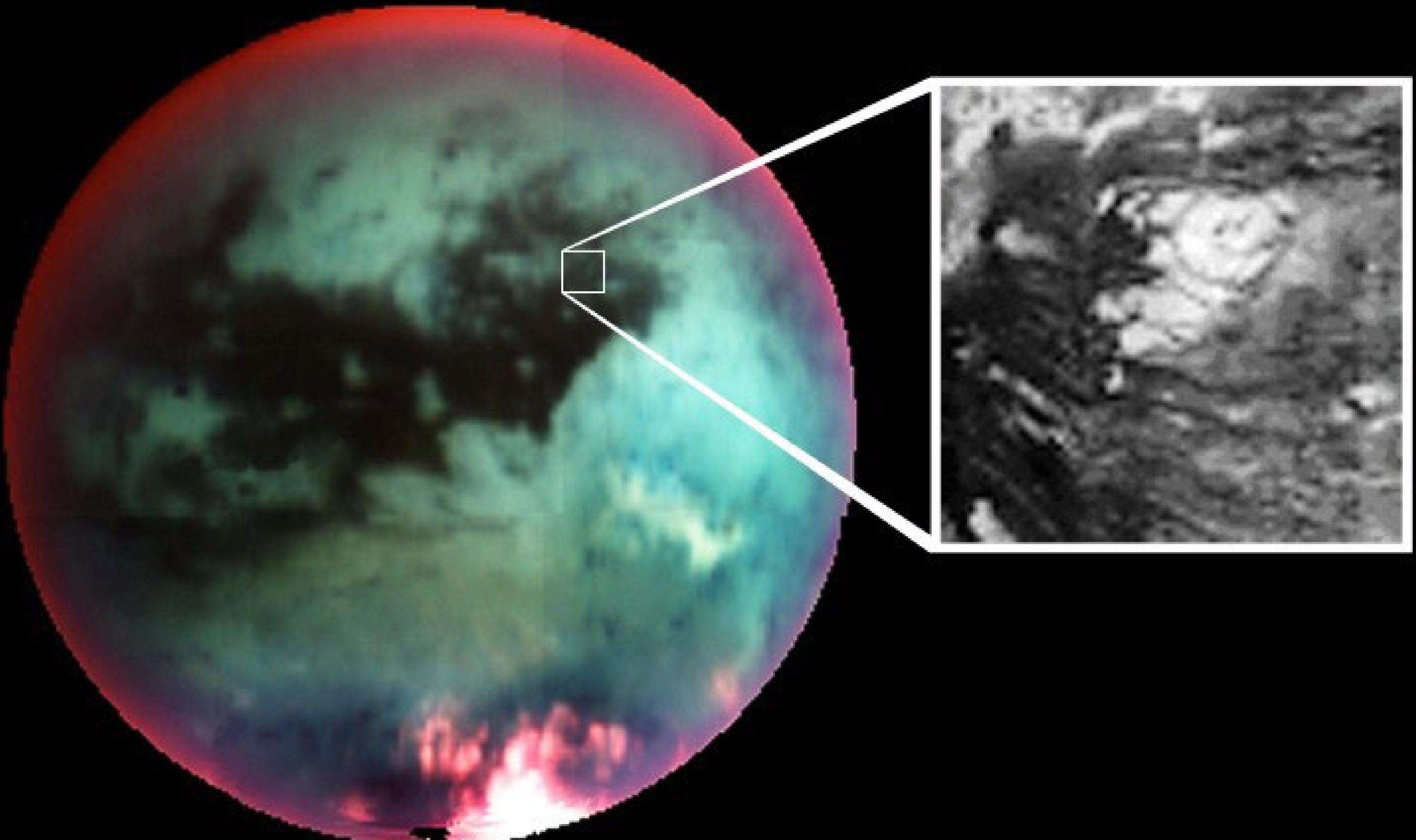
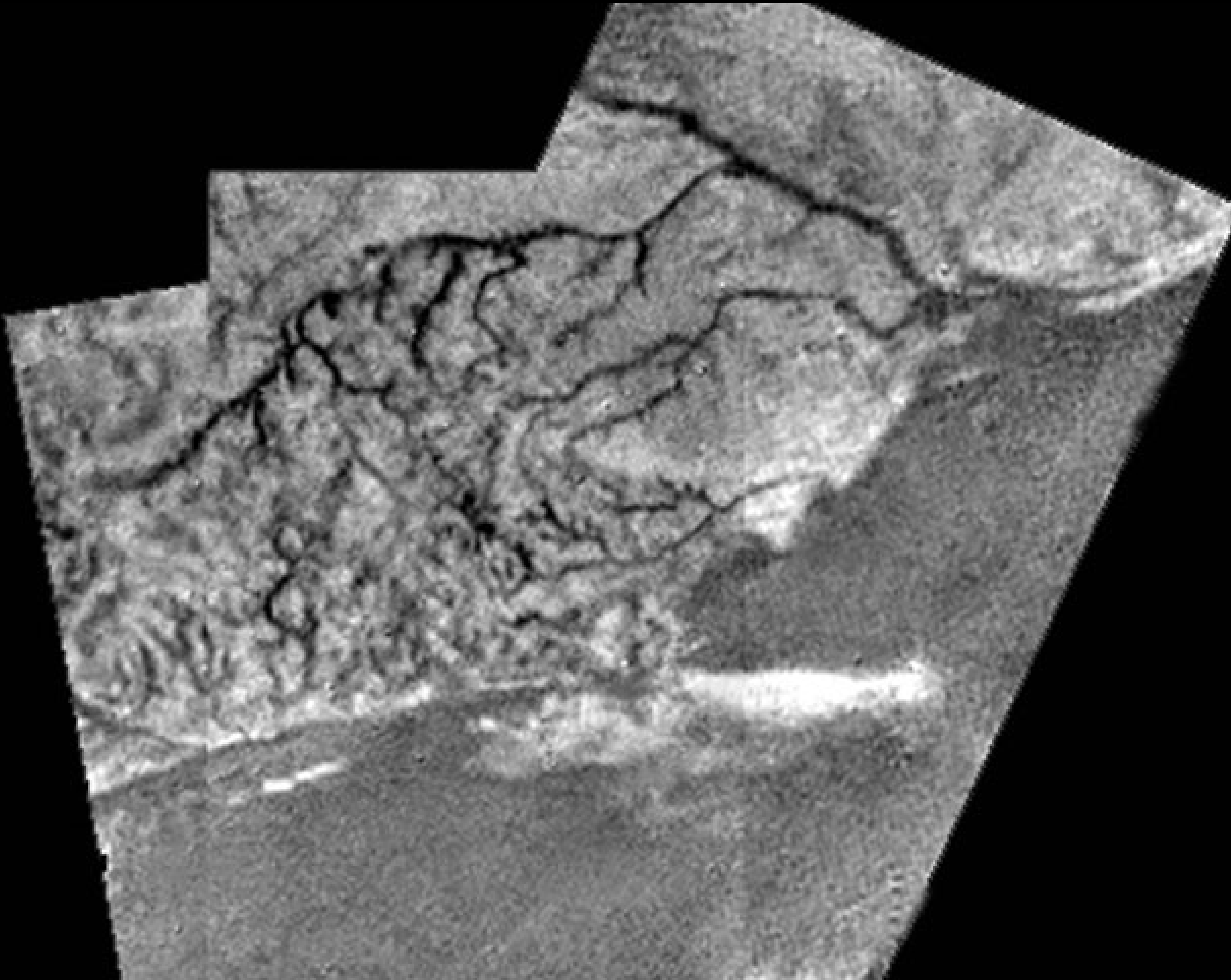
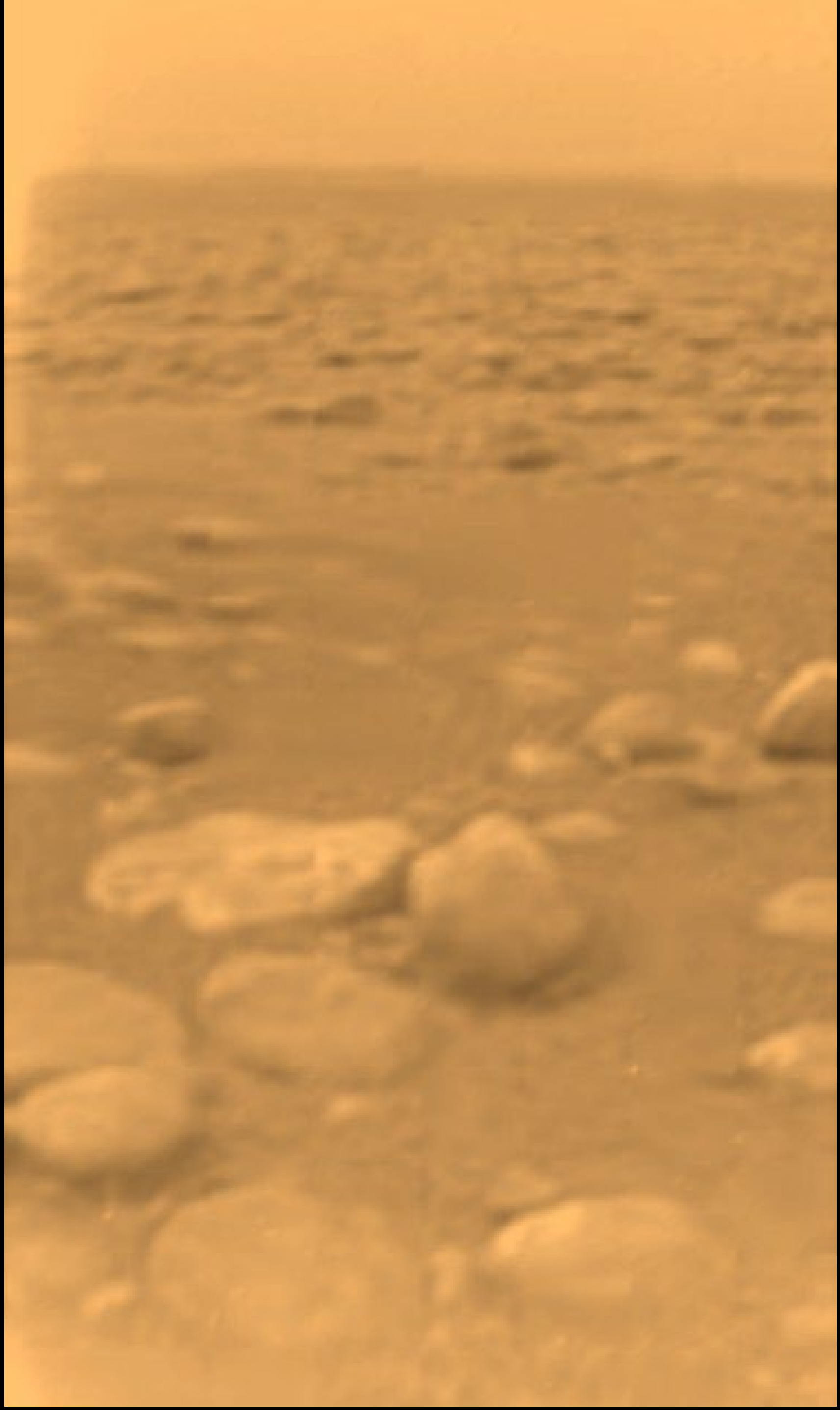
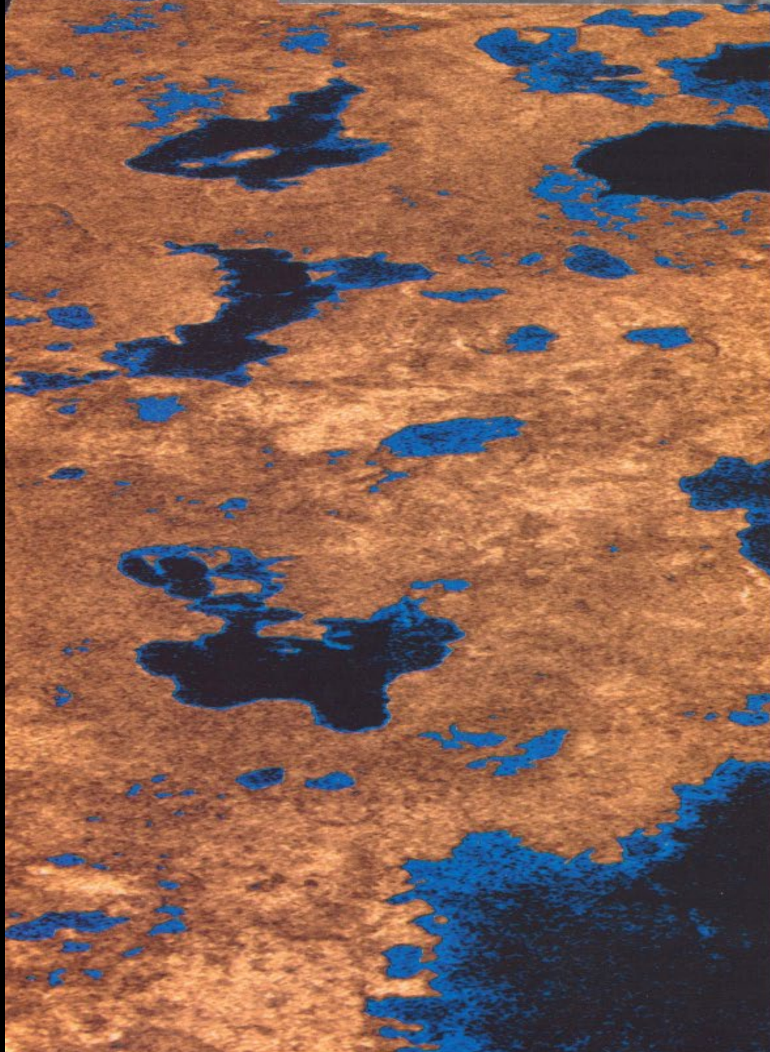


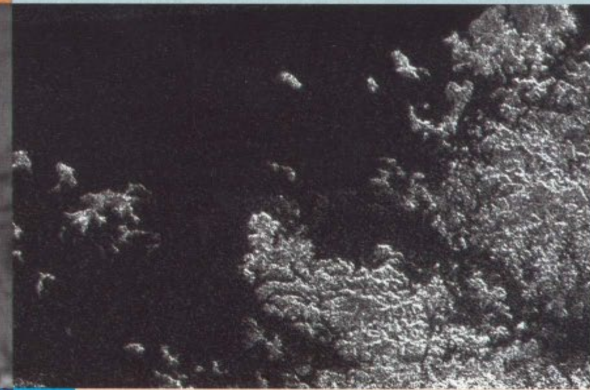
Titan's methane rivers and dry lake beds





- 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





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

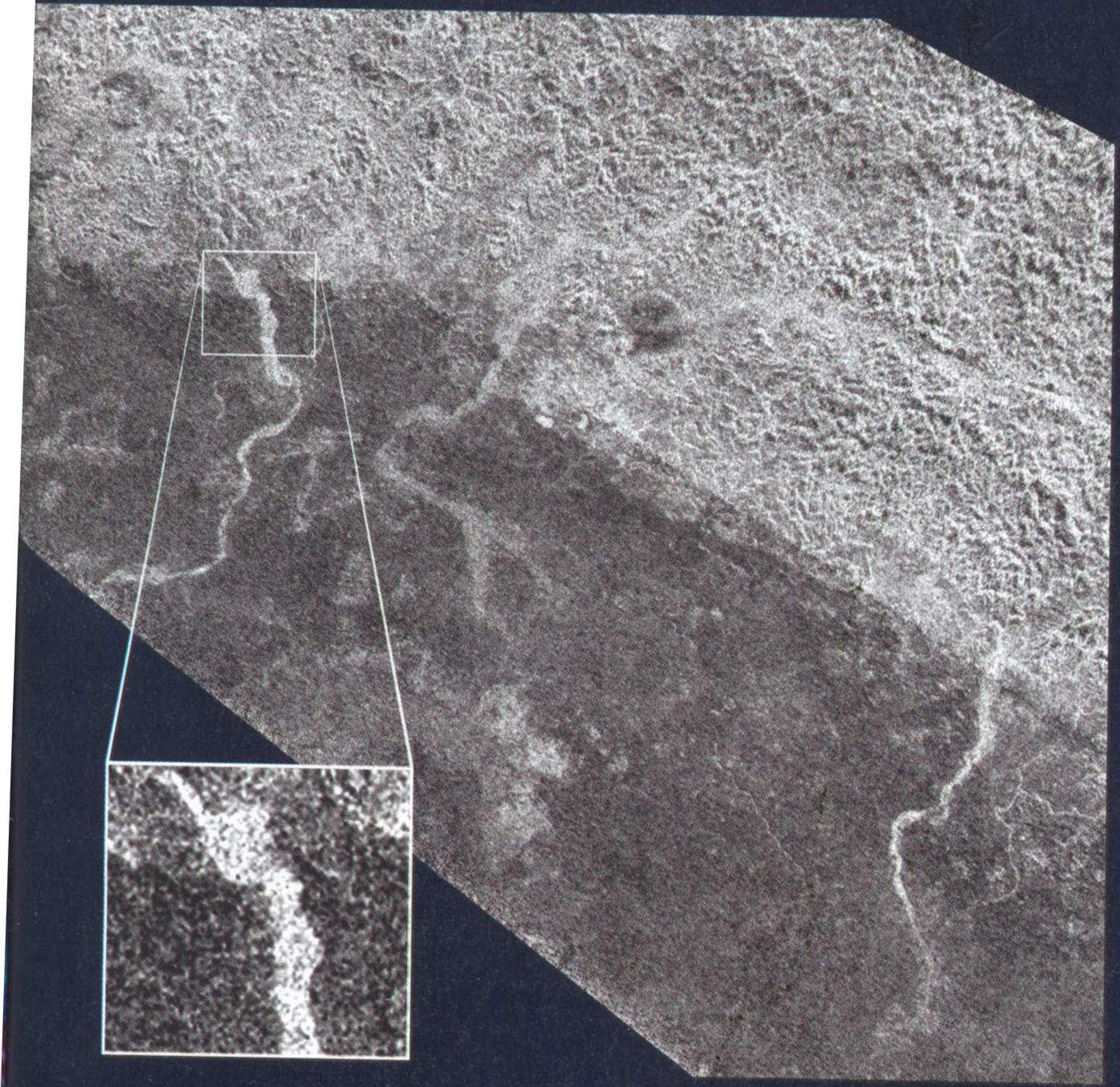
Huygens didn't see any surface puddles because, we now realize, it landed in Titan's equivalent of a vast desert. There are big pools of liquid on the surface — but they're in the polar regions. Cassini first spotted clusters of dark polar patches in 2005, and they've tantalized our science team ever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

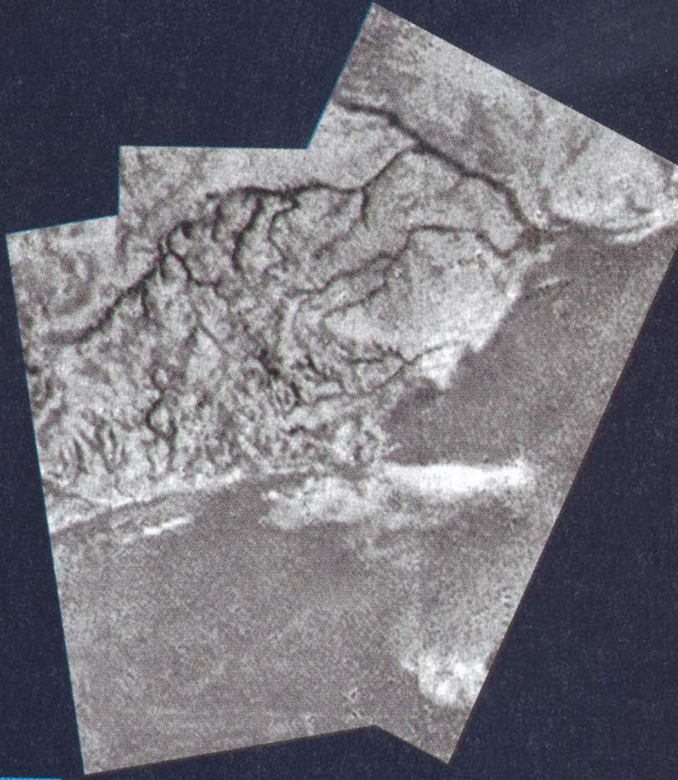
Initially the evidence for true hydrocarbon lakes was circumstantial. They appear really dark in both radar scans and infrared images. The radar result is consistent with nearly mirror-smooth surfaces that reflect Cassini's radar emissions away from the spacecraft and out into space. The infrared darkness 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.

Methane lakes, surrounded by very hard water ice crust, floating on a deep subsurface ocean of… liquid water we calculate.



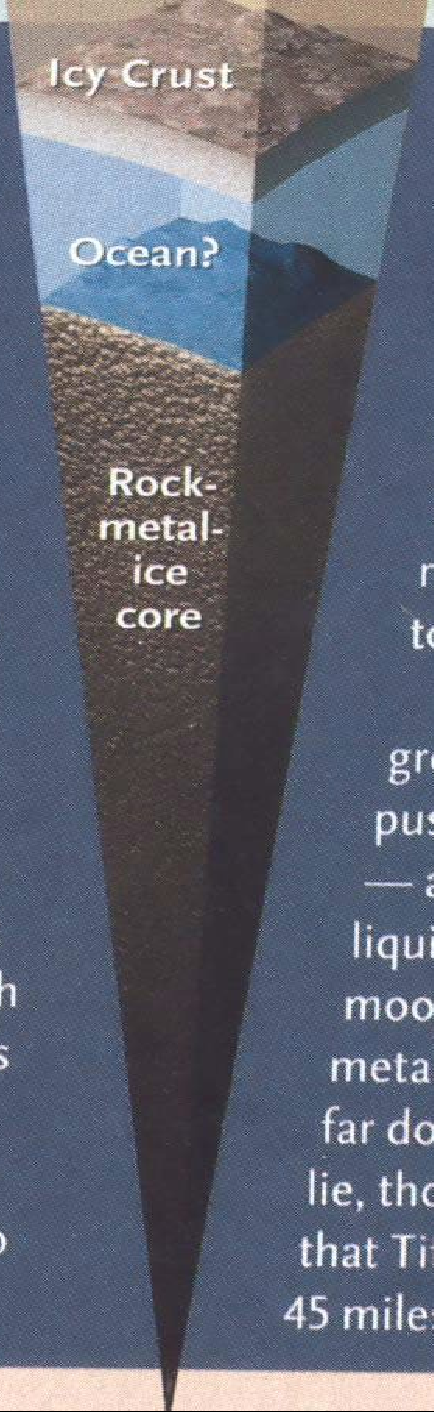


RIVERBEDS *Left:* Cassini's radar instrument has found dry riverbeds all over Titan. The channels come in all sizes and in both smooth and rough textures. They were presumably carved by liquid hydrocarbons running downhill. *Right:* As Huygens parachuted to Titan's surface, its descent camera imaged 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!



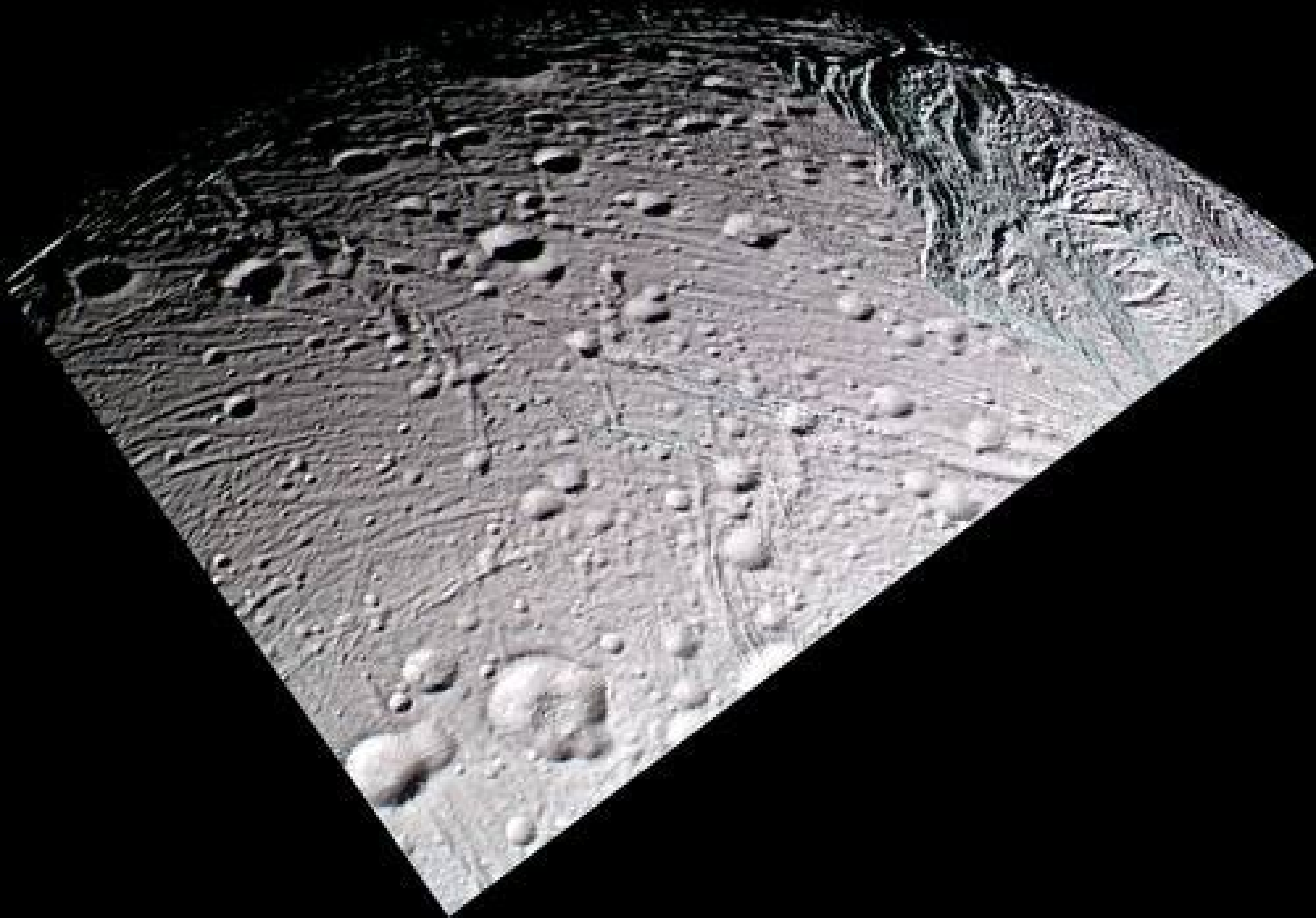
Tides from Saturn should force Titan to keep one hemisphere constantly facing the planet, just as the Moon's near side always faces Earth. Motions within Titan's dense atmosphere can affect the spin rate slightly, but not if they have to tug the moon's entire mass.

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.

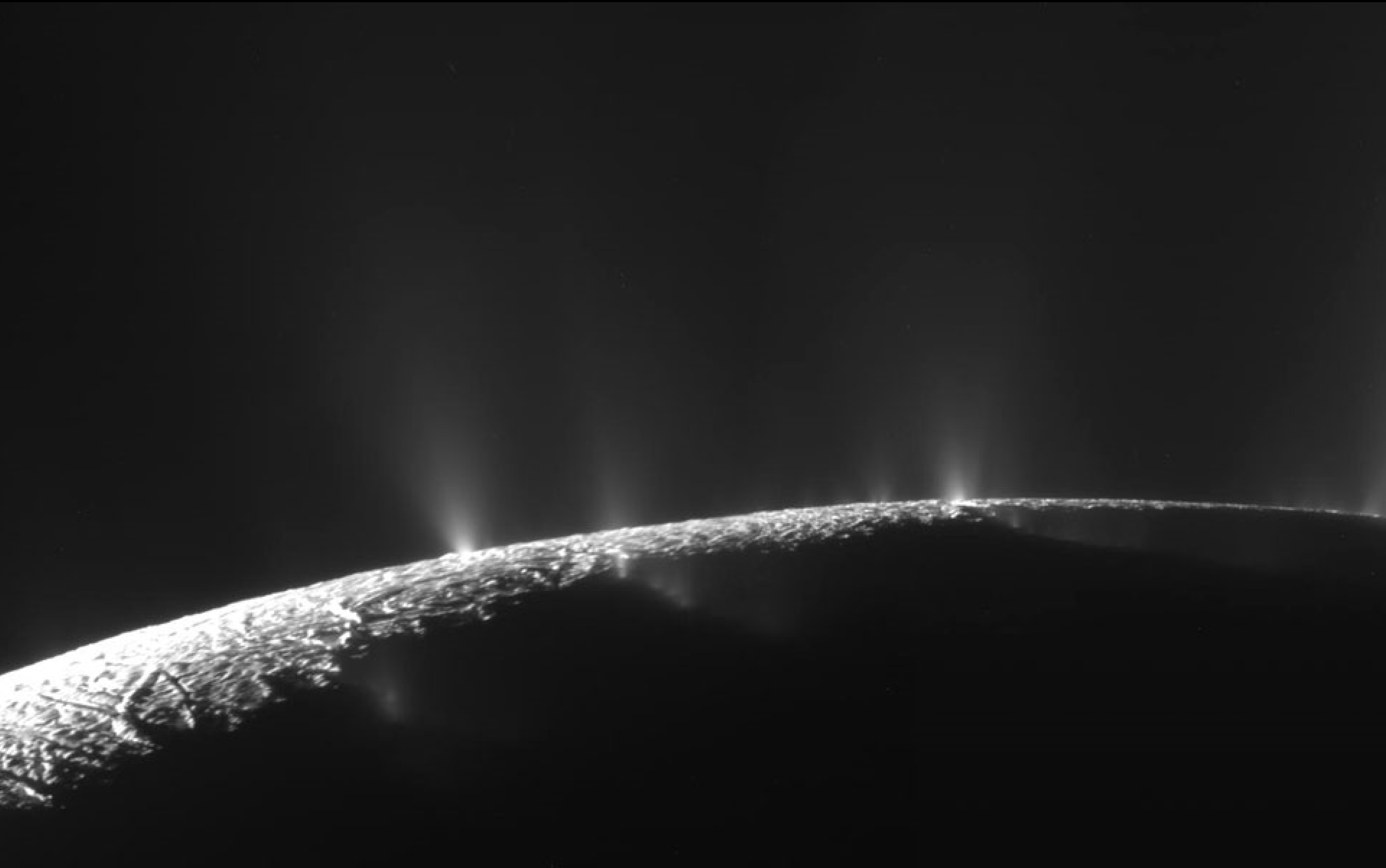
AN ABODE FOR LIFE?

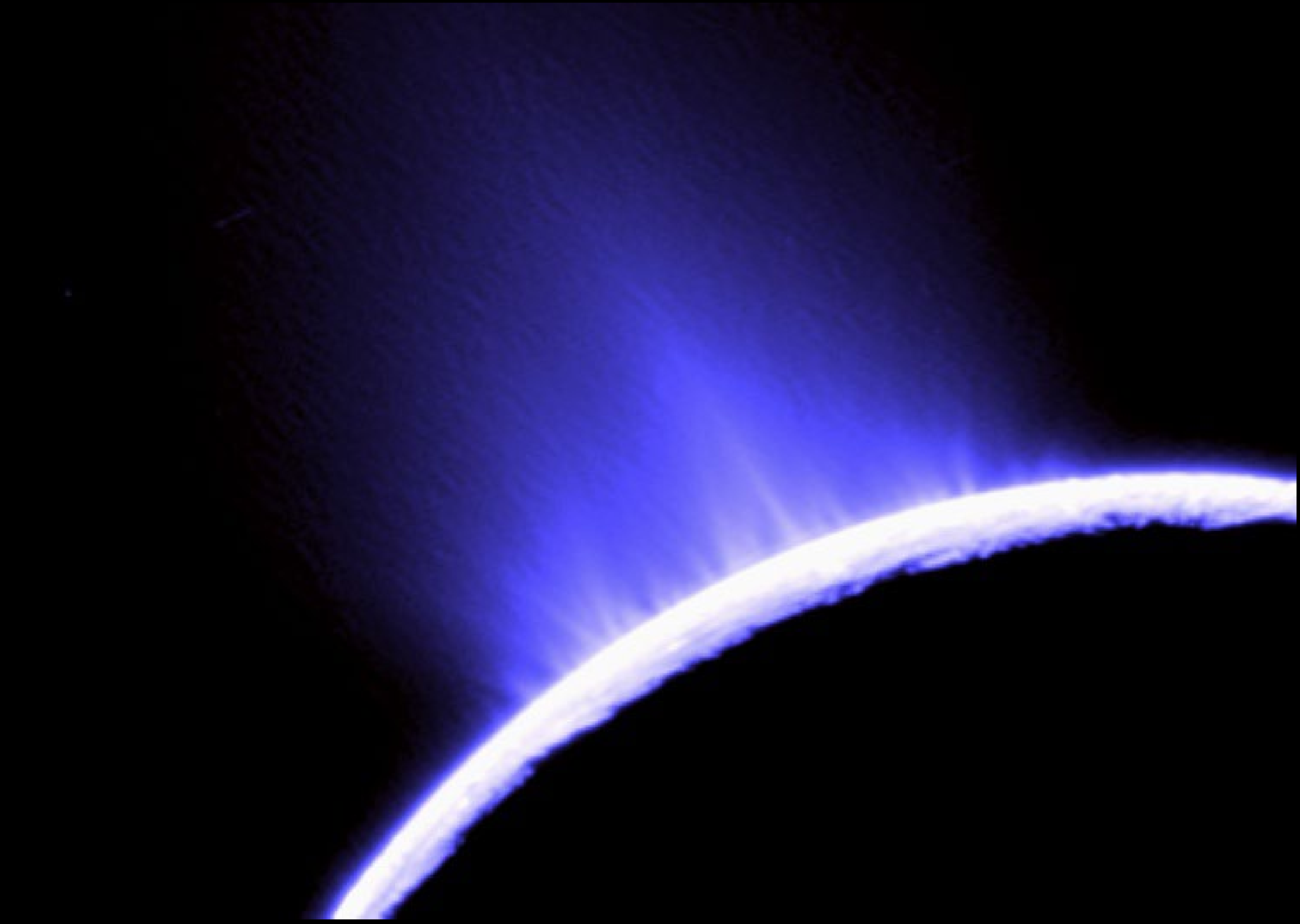
Titan's surface abounds with organic molecules and water ice, but its frigid temperatures offer bleak prospects for life. At Titan's −290°F (−179°C) surface temperatures, chemical reactions slow to a crawl, limiting the ability of complex molecules to form. But Titan's interior is warm enough to sustain 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

Some Key Points:

- Surface temperature and gravity determine how well you keep your atmosphere against leakage
- Loss mechanisms: Leakage of lighter molecules, impact cratering, ablation by solar wind if have only a weak magnetic field
- **Understand the greenhouse effect!**
- Mercury and our moon, too hot and too low gravity to retain any atmosphere, no mag fields didn't help either, for moon
- CO2 dominates both Mars and Venus; heaviest common molecule
- **Runaway greenhouse effect**: rising temps add water in upper atmosphere, dissociated by solar UV, lost to space – this was Venus' fate
- Mars atmosphere has thinned progressively over 4.5B years due to no protection from solar wind (weak mag field).
- Mars and Venus both likely had moderate temperatures and oceans of water early in their history, rising solar luminosity drove Runaway Greenhouse on Venus, and loss of atmosphere via weak magnetic field drove away most of Mars atmosphere and water destruction
- **Mars climate over past millions of years: denser warmer atmosphere when axis tilt is high, cold thin atmosphere and "Ice Age" when tilt is small. Mars has no large moon to stabilize spin axis orientation**