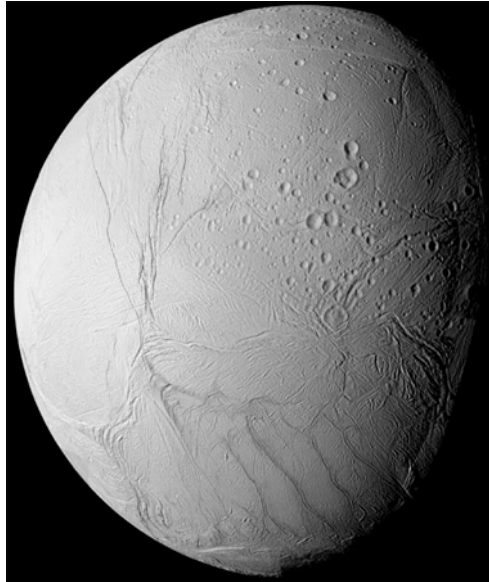


# **Lecture 12:**

## ***Giant Planet Moons and Rings***

**Saturn's moon  
Enceladus**



**Please remind  
me to take a  
break at 12:45 pm**

**Claire Max**  
**November 4<sup>th</sup>, 2010**  
**Astro 18: Planets and Planetary Systems**  
**UC Santa Cruz**

# Halliday Lecture Wed Nov 17th



The UC Santa Cruz Department of Astronomy and Astrophysics  
and the UCO/Lick Observatory present the tenth Halliday Lecture

Registration

Wednesday, November 17, 2010 | 7:00 p.m.  
Rio Theatre 1205 Soquel Ave, Santa Cruz  
OPEN TO THE PUBLIC - NO CHARGE



the Physics of Eternity."

Astronomer **Greg Laughlin** is a Professor at the University of California at Santa Cruz. He is a leader in the field of extrasolar planet detection, and is also an expert on the long-term fate of the Earth, the Solar System, the Galaxy, and the Universe. He is co-author of the well-received popular book "The Five Ages of the Universe" Inside

A new chapter in human history is about to open in which we will know, for the first time, whether Earth-like planets exist around other stars.

Greg Laughlin, Professor of Astronomy at UCSC, will take the audience on a guided tour of the bizarre menagerie of planets that have been detected so far, and he will show how he and his colleagues are using the new Automated Planet Finding Telescope at Lick Observatory to push the envelope in locating habitable planets orbiting the Sun's nearest stellar neighbors.



*This lively and engaging lecture is designed for the general public. It is presented as a part of the Halliday Lecture Series, which promotes public awareness and appreciation for astronomy. This year's lecture has been generously sponsored by Robert Sieker. We seek your help and support in keeping these lectures going. For information on giving,*

*please visit: [www.astro.ucsc.edu/support](http://www.astro.ucsc.edu/support)*

**<http://community.ucsc.edu/hallidaylecture2010>**

# ***How to use the web for research***

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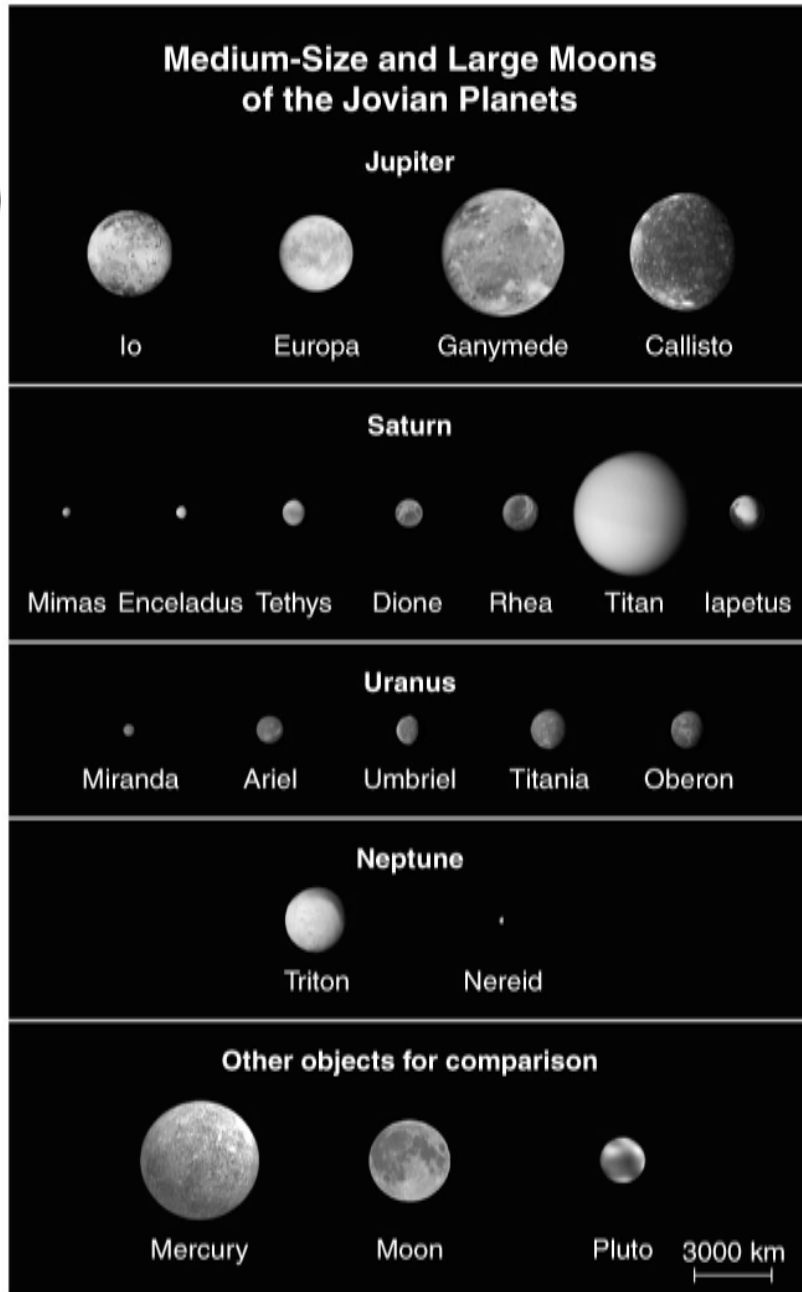
- **The good, the bad, and the ugly**
- **Internet Research Methods**
- **A few of the reputable sites in planetary sciences:**
  - **NASA**
  - **European Space Agency (ESA)**
  - **The Planetary Society**

# ***Main points: Giant Planet Moons***

---



- **Why can active geology occur on much smaller worlds when they are made of ice rather than rock?**
  - Ices soften and melt at much lower temperatures than rock, allowing icy volcanism and tectonics at surprisingly low temperatures in the outer Solar System.
- **What makes Io so volcanically active?**
  - Interior heating, caused by the tidal forces of Jupiter and the other Galilean moons, as Io moves through its elliptical orbit.
- **Why do we suspect a subsurface ocean on Europa?**
  - Photos show evidence of water flows and fountains on the surface, magnetic field measurements support the presence of a salty ocean, and there is enough tidal heating to melt a thick layer of ice beneath the surface.



# Medium and Large Moons

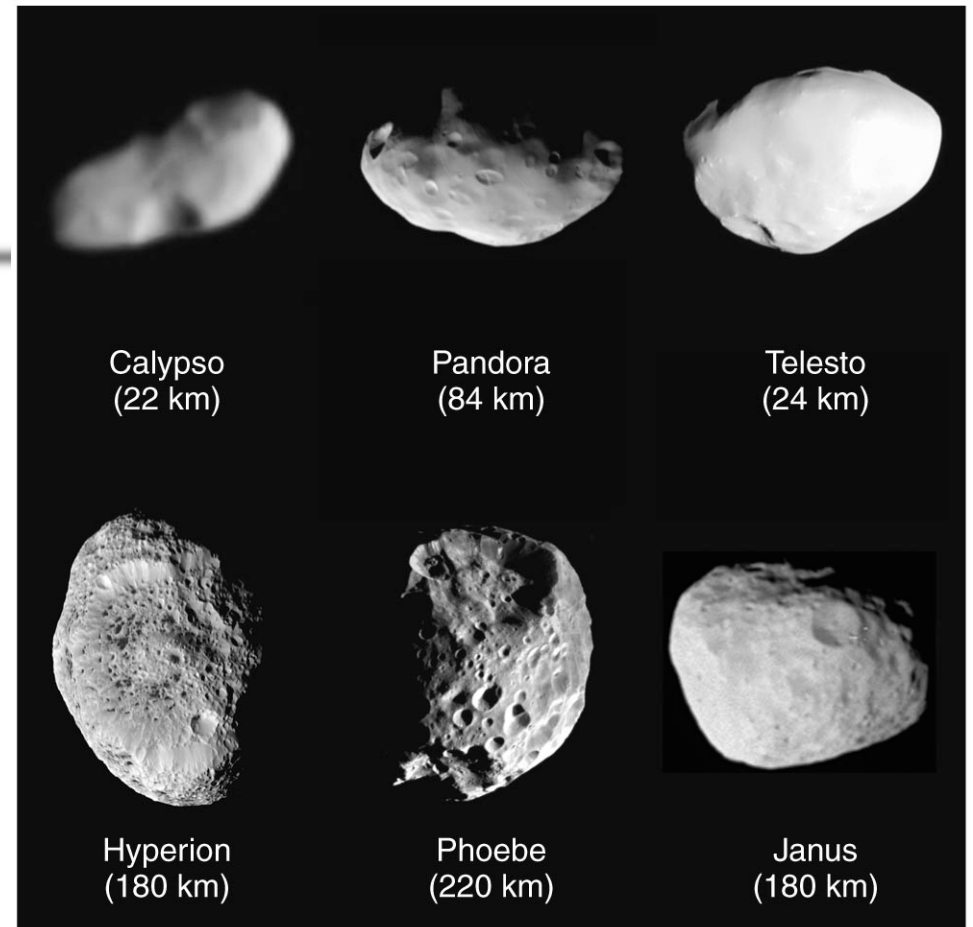


- **Enough self-gravity to be spherical**
- **Have substantial amounts of ice**
- **Formed in orbit around jovian planets**
- **Circular orbits in same direction as planet rotation**

# ***Small Moons***

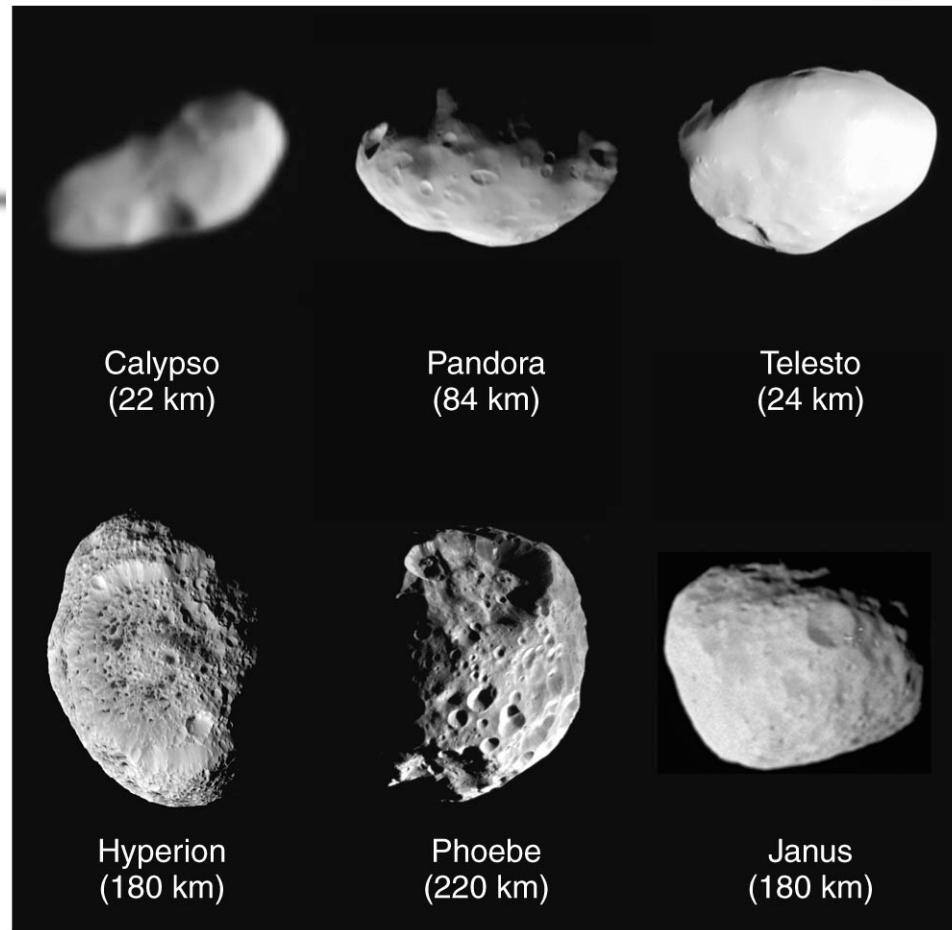
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- **These are far more numerous than the medium and large moons.**
- **They do not have enough gravity to be spherical: Most are “potato-shaped.”**
- **Captured asteroids or comets, so their orbits do not follow usual patterns.**



# Small Moons

---



- **They are captured asteroids or comets, so their orbits do not follow usual patterns.**

***You might think these moons are too small for active geology to occur***

---



- **You would be wrong!**
- **Terrestrial planets are made mostly of rock**
- **Jovian moons are made mostly of ice**
- **Ices melt at lower temperatures than rock.**
  - **Less heating is required to have molten cores**
  - **Volcanism and tectonics can occur**
- **There is another heat source besides Sun.**
  - **Tidal heating of the interior plays a more important role; radioactivity contributes too**

# ***The Large Jovian Moons are very active***

---



- **Jupiter**

- **Io**                      **sulfur volcanoes**
- **Europa**                **world of water ice, subsurface liquid**
- **Ganymede**            **active ice world**
- **Callisto**                **dead & dirty ice world**
- **(Jupiter has > 60 known moons!)**

- **Saturn**

- **Titan**                    **thick atmosphere (N<sub>2</sub> & CH<sub>4</sub>)**
- **Enceladus**              **warm-water volcanoes**

- **Neptune**

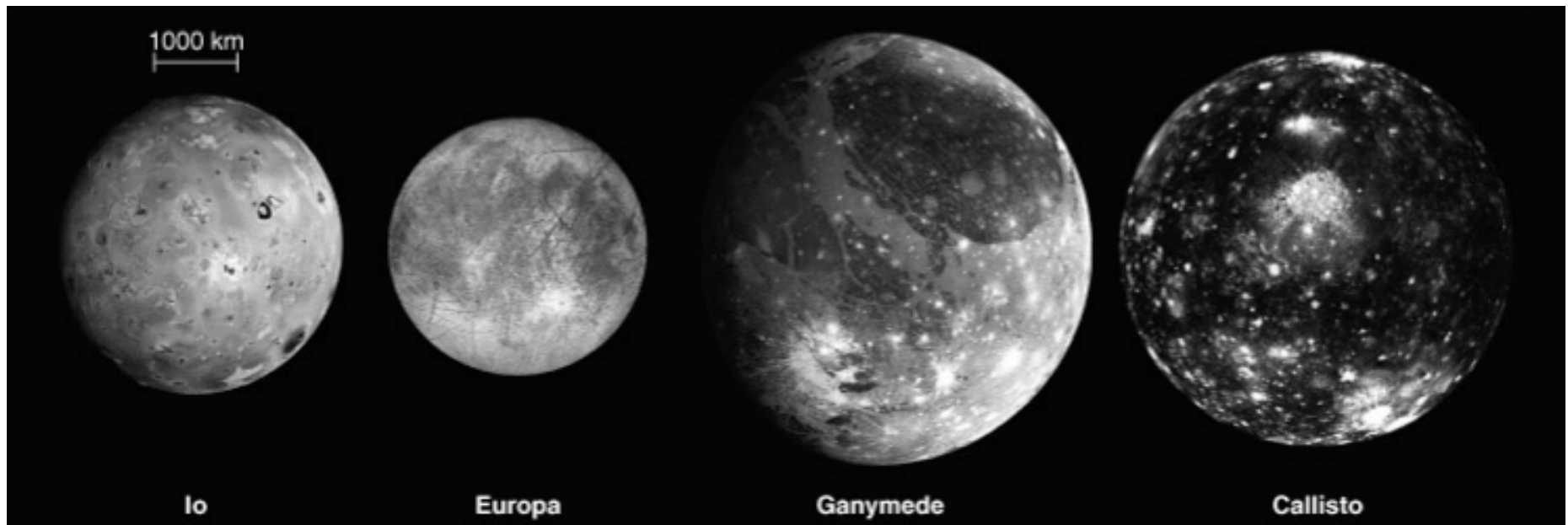
- **Triton**                    **nitrogen volcanoes, retrograde orbit**

# ***Large Moons of Jupiter***

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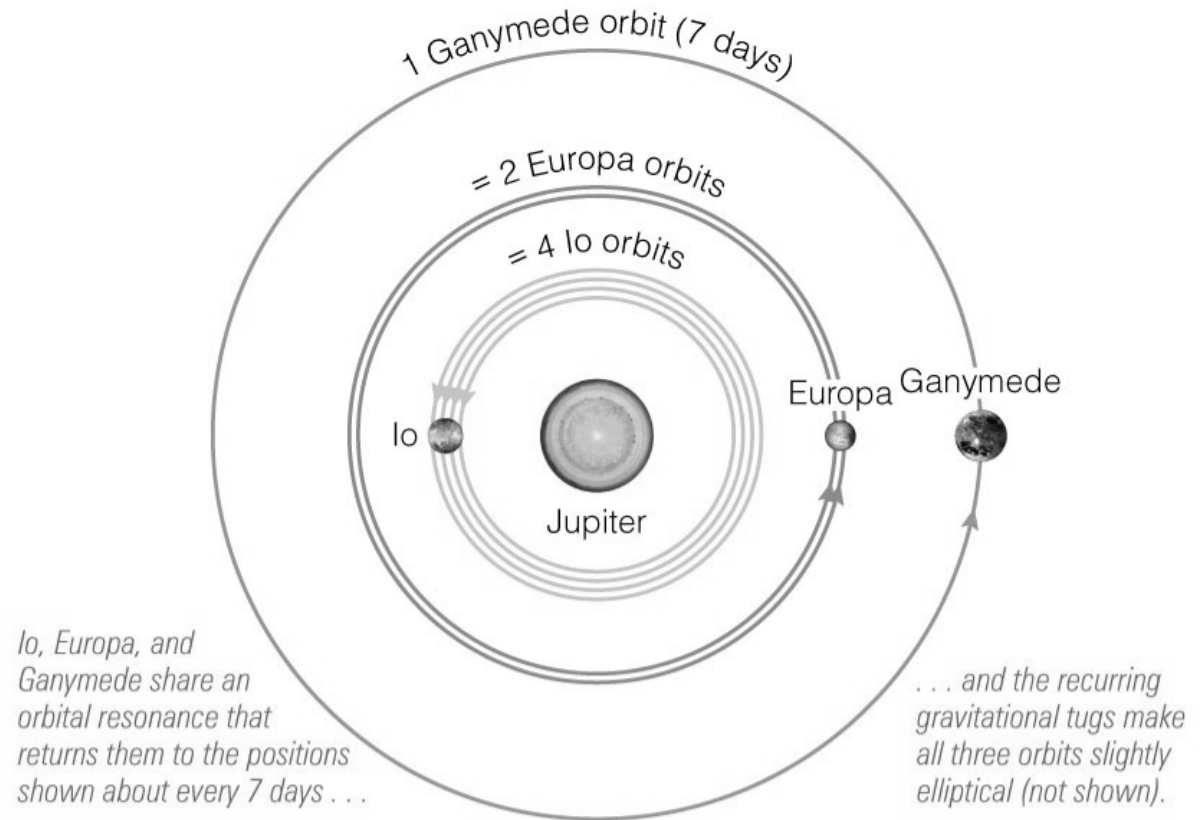
- **“Galilean” moons: the four biggest ones**
- **Discovered by Galileo**
- **Closest to Jupiter**



# ***Orbital Resonances play a role too***



- **Every 7 days, these 3 moons line up.**
- **The tugs add up over time, making all 3 orbits elliptical.**



Animation of Io's tidal heating

# ***Io: Jupiter's closest moon***

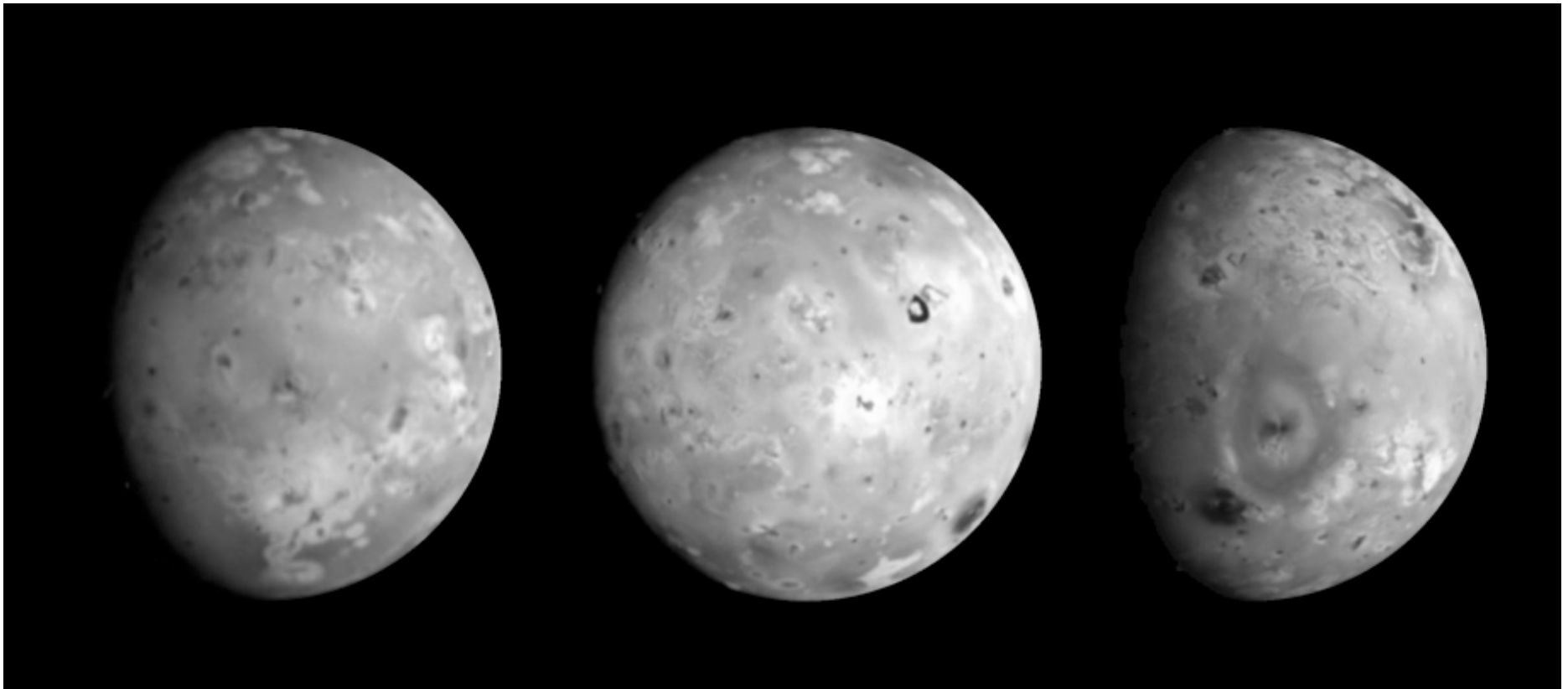
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- **Jupiter's tidal forces flex Io like a ball of silly putty.**
  - **Friction generates heat**
  - **Interior of Io is molten**
- **Volcanoes erupt frequently.**
  - **Sulfur in the lava accounts for yellow color**
  - **Surface ice vaporizes and jets away**
  - **Lava is hotter than on Earth**
- **Evidence of tectonics & impact cratering is covered over by the lava flows.**

# ***Three views of Io, from Galileo spacecraft at Jupiter***

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# ***Io Volcanoes: Two Kinds***

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**Eruptive**



**Effusive (lava flows)**

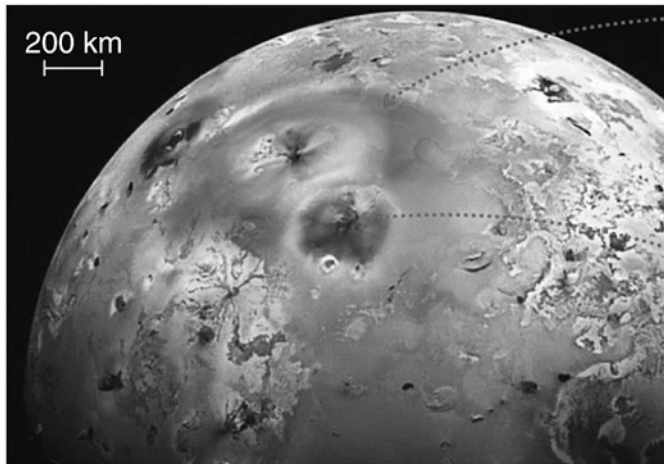
# ***Can see heat from Io's volcanoes in infrared adaptive optics images***

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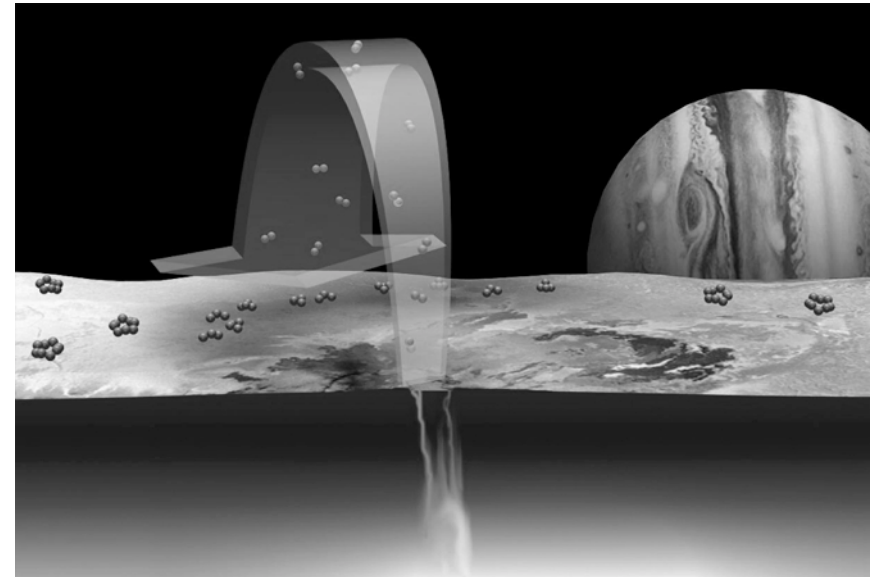
- **F. Marchis, UC Berkeley and Team Keck**

# What makes red rings around Io's volcanoes??

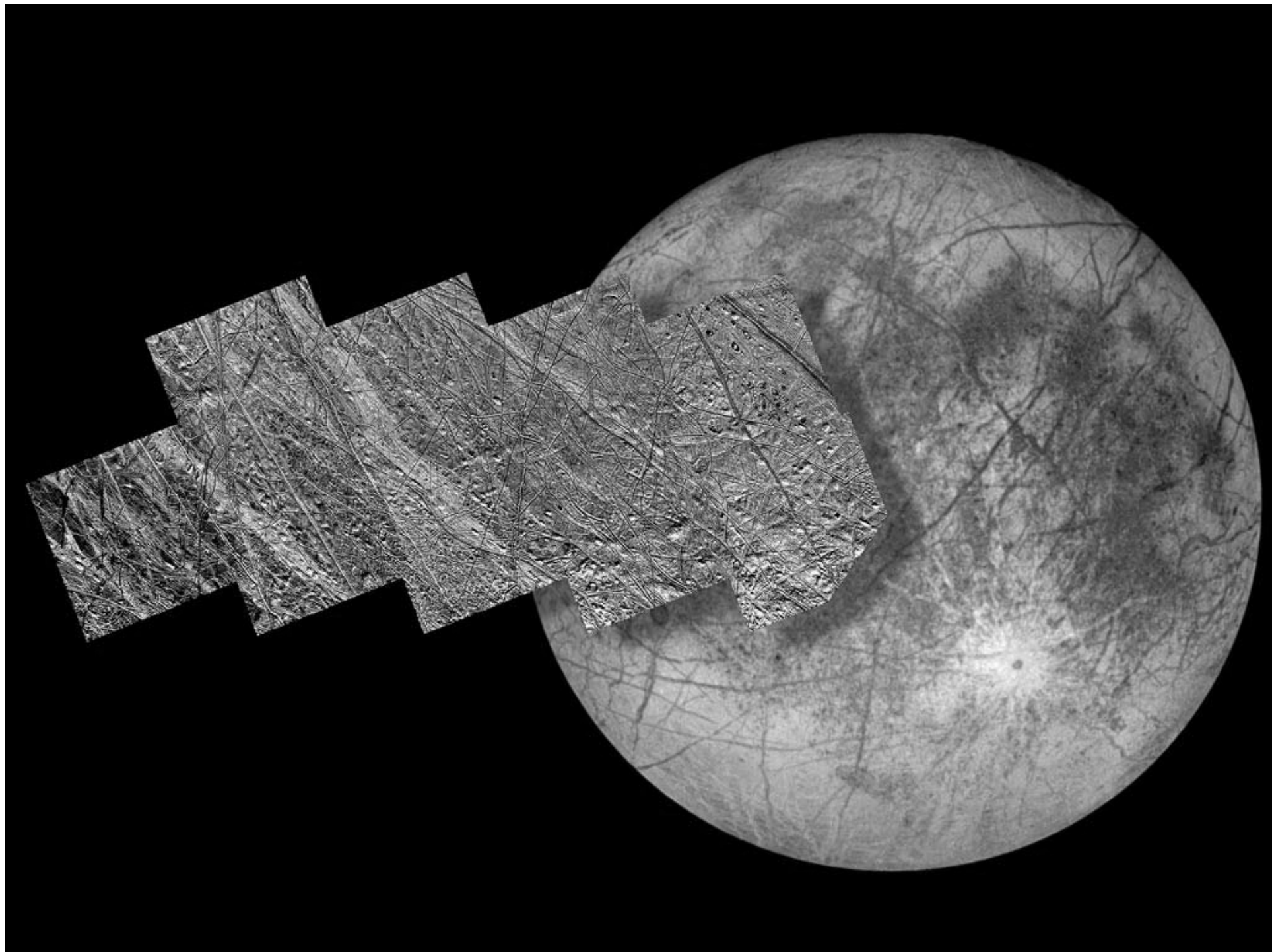


Some sulfur-rich volcanoes deposit red, orange, or yellow fallout.

An eruption during the Galileo mission produced dusty fallout that covered an area larger than Arizona in a matter of months.

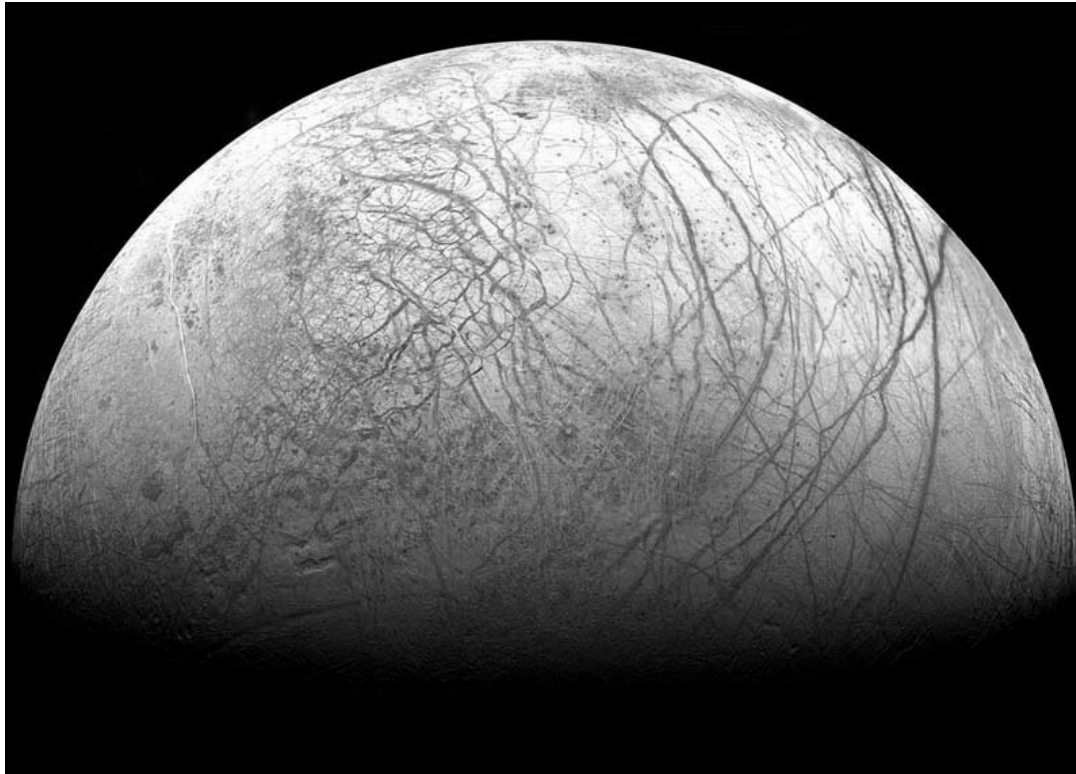


- **Sulfur ejected from vents**
- **Makes red / orange colored rings where it lands**
- **Gradually diffuses, fades into yellow**



# **Europa**

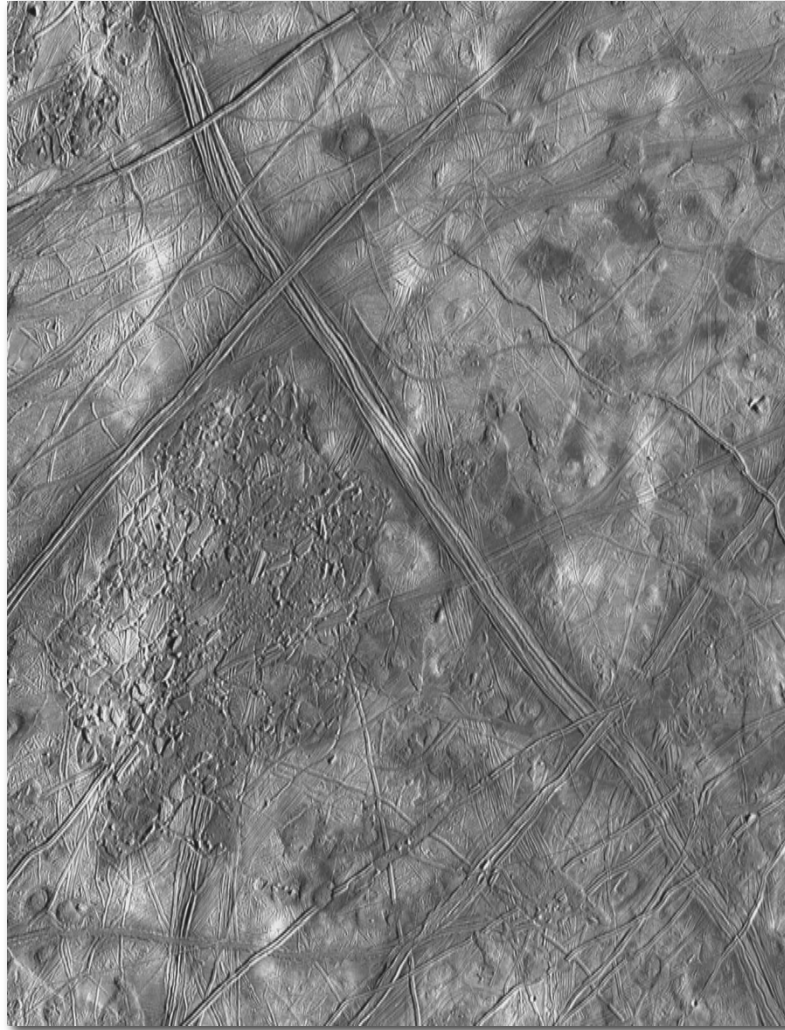
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- **Metallic core, rocky mantle, and a crust made of H<sub>2</sub>O ice**
  - **Its fractured surface tells us that Europa has active tectonics**
    - **few impact craters**
    - **double-ridged cracks**
    - **jumbled icebergs**
  - **Photographic evidence of a subsurface ocean.**
- 
- **Europa has a magnetic field. Implies liquid salt water beneath icy crust.**
  - **Where liquid water exists, there could be life!**

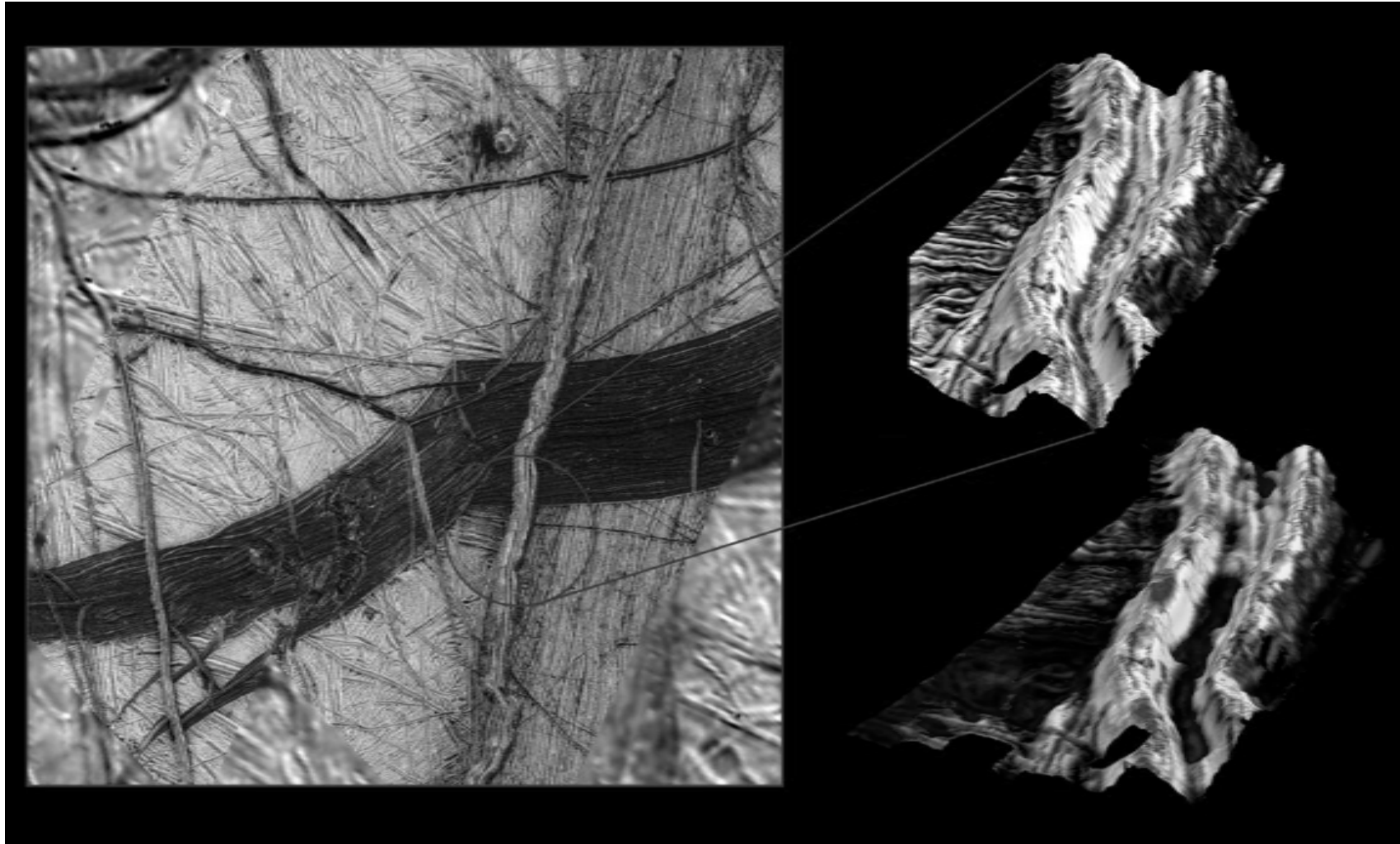
# ***Ice Rafts on Europa (ice floating on liquid water?)***

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# ***Double ridges on Europa***

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# Tidal stresses crack Europa's surface ice.



*Some regions appear to be a jumble of icebergs suspended in a place where liquid or slushy water froze.*

*Many cracks are double-ridged. The diagram (right) shows how tidal forces may create them.*

*Tidal stresses cause parts of Europa's icy crust to slowly slide past each other.*

*Frictional heating expands ice here, forming the ridge...*

*...and may melt ice here, collapsing the ridge center.*

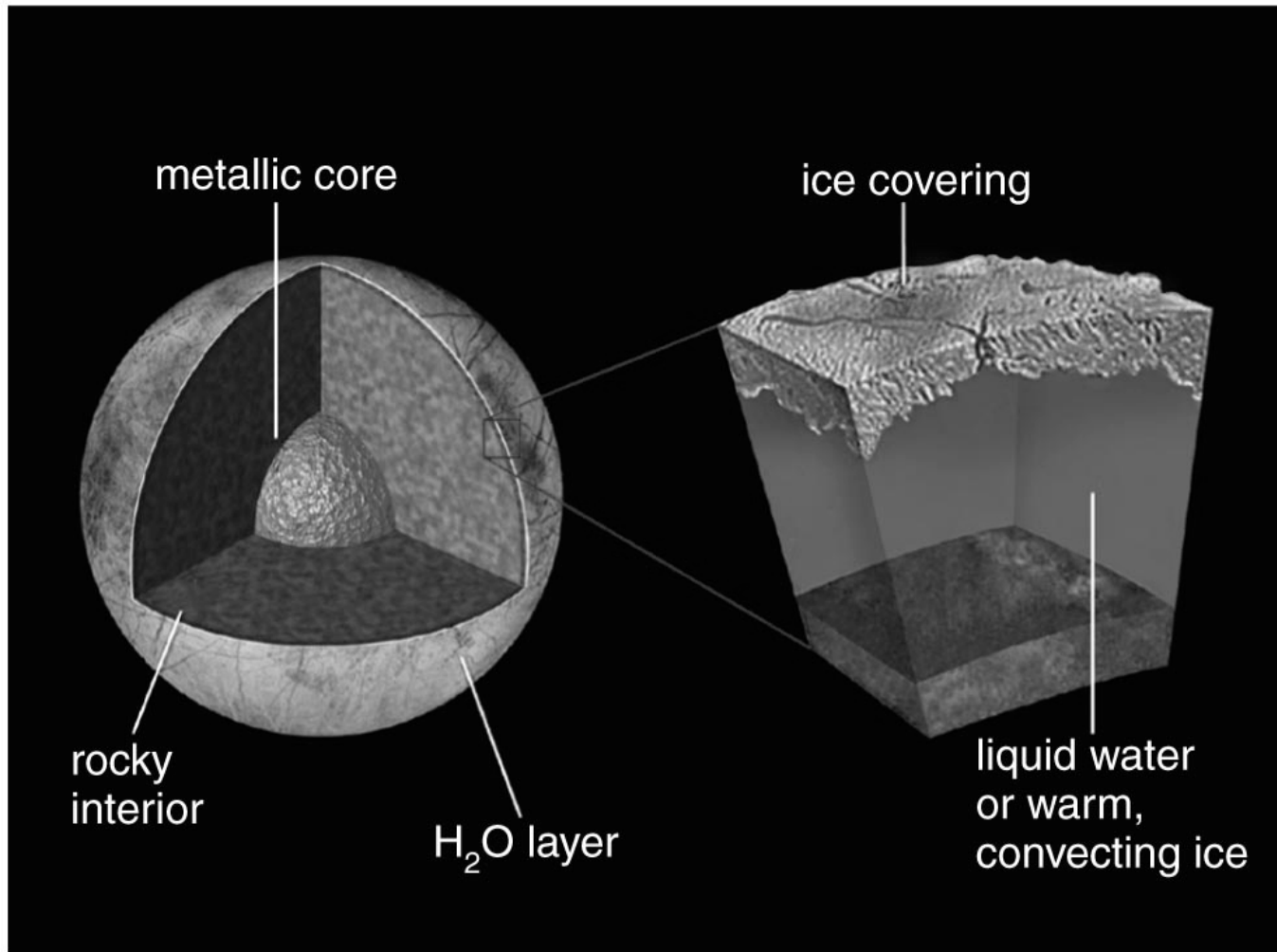
# ***Why double ridges?***

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- **“Rafts” develop high edges by banging into each other repeatedly**
- **“Rafts” drift apart**
- **Fresh water flows up into the crack**

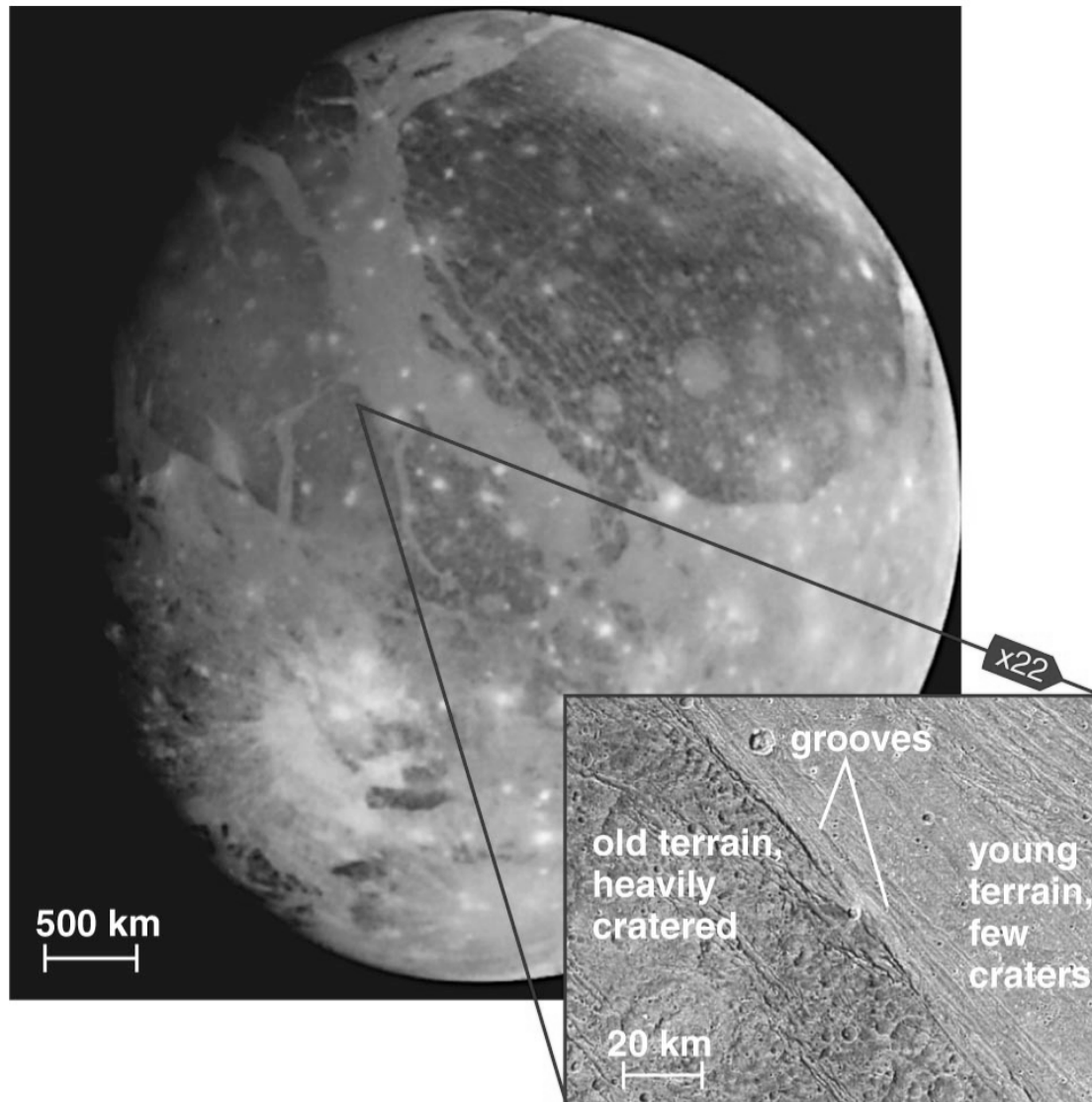
# ***Europa's interior also warmed by tidal heating.***



# Ganymede



- **Largest moon in the solar system**
- **Clear evidence of geological activity**
- **Tidal heating plus heat from radio-active decay?**



# Ganymede geological features: grooved terrain



Link to Process

Landslides

Volcanism

Flowing water

Wind

Impact cratering

Tectonics

Compare to Earth

Known Satellites

0

Period of Revolution

7.16 days

Period of Rotation

7.16 days

Distance from Sun\*

778.3 km  
483.7 mi  
\*in millions

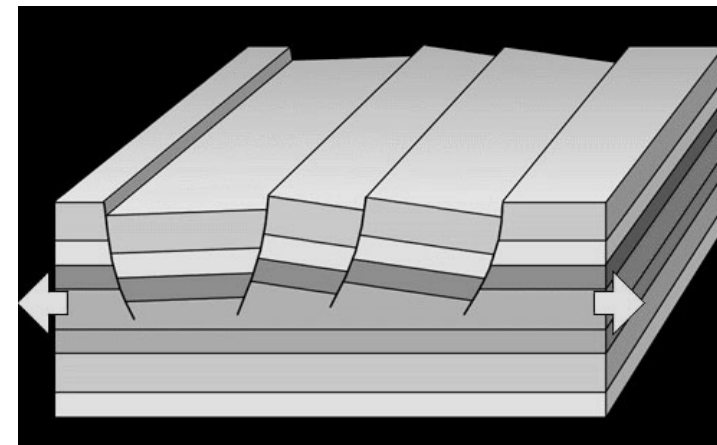
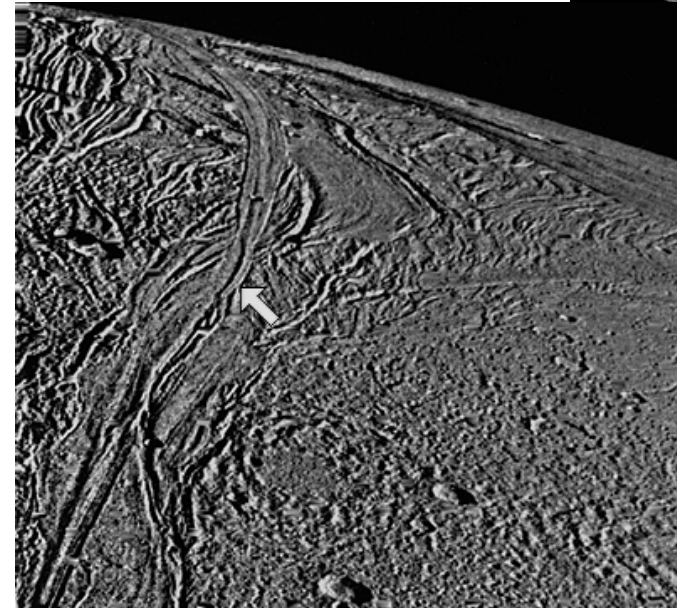
Diameter

5,280 km  
3,281 mi

Ganymede

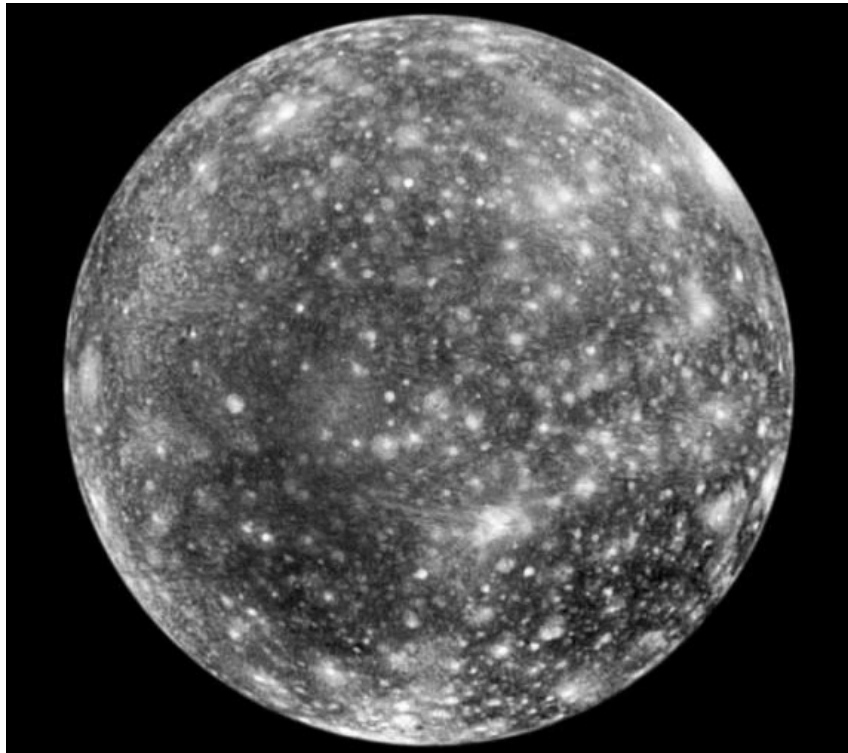
Moon

Individual bundles of grooves can be over 100 kilometers long. The pattern seems to be formed by some type of faulting, probably normal faults, accompanied by eruption of liquid water.



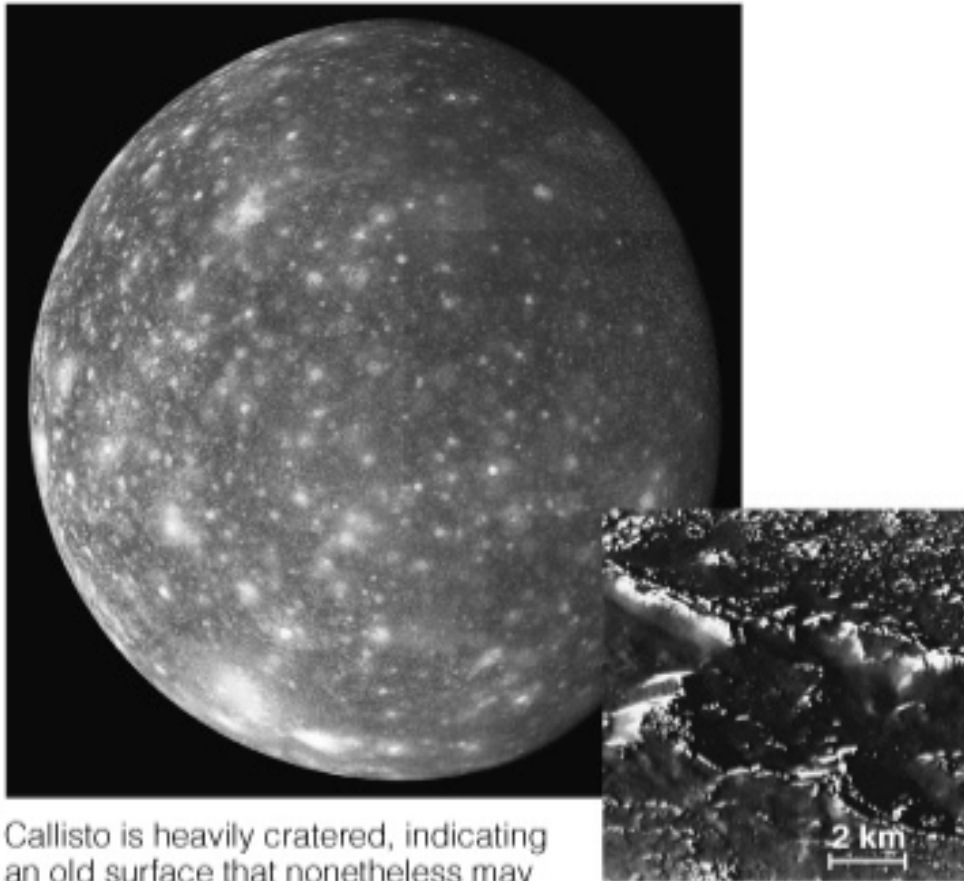
# Callisto

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- **It has an old surface.**
  - **heavily cratered, dirty ice**
  - **cratering reveals clean, white ice underneath**
  - **no evidence of tectonics**
- **Its interior did not differentiate.**
  - **rock mixed with ice**
- **It does not experience tidal heating.**
- **Yet it has a magnetic field.**
- **Could it have a subsurface ocean anyway?**

# Callisto

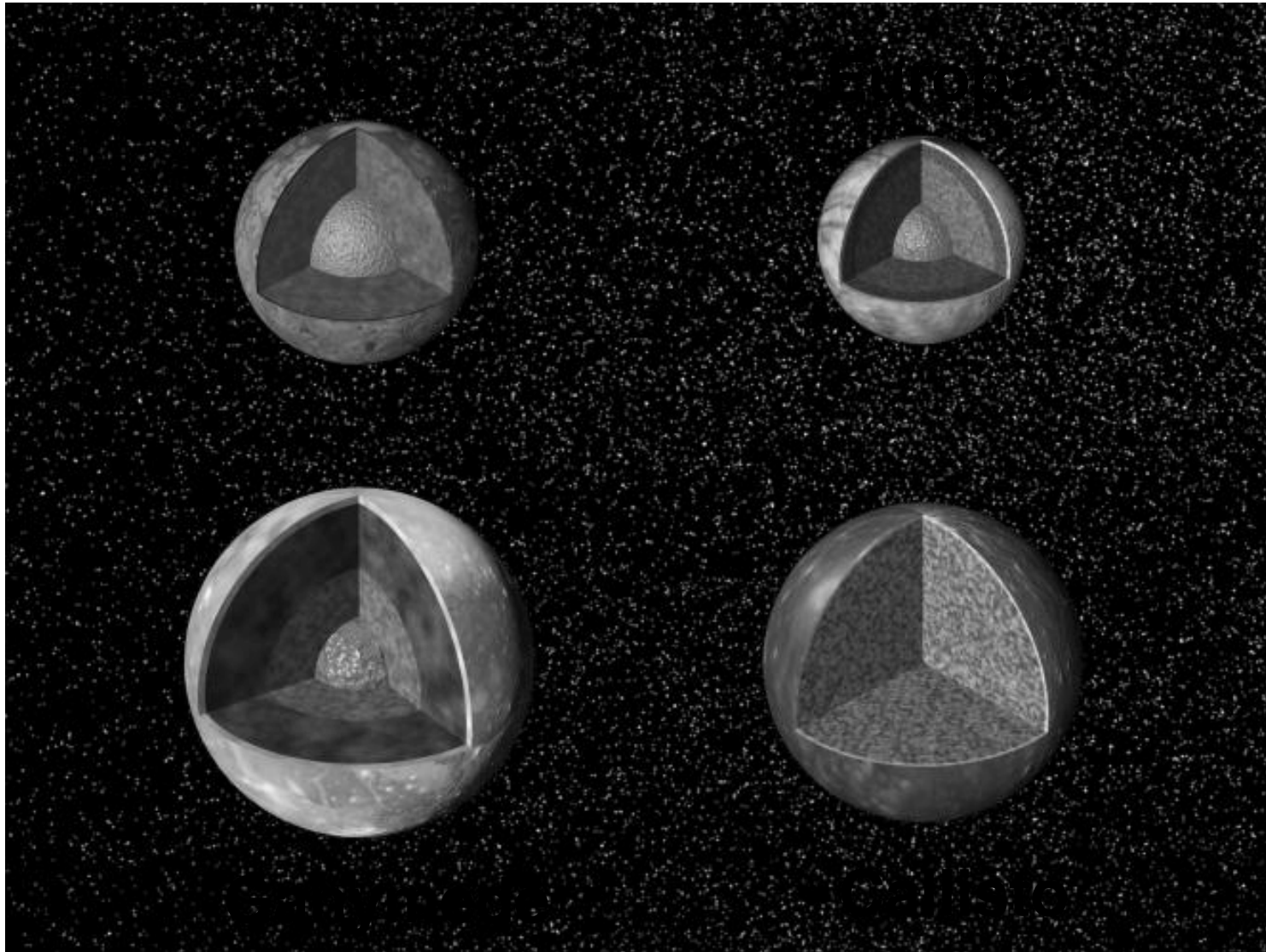


Callisto is heavily cratered, indicating an old surface that nonetheless may hide a deeply buried ocean.

Close-up photo shows a dark powder overlaying the low areas of the surface.

- **“Classic” cratered iceball.**
- **No tidal heating, no orbital resonances.**
- **But it has magnetic field !?**

# ***Galilean moons: Interior structure***

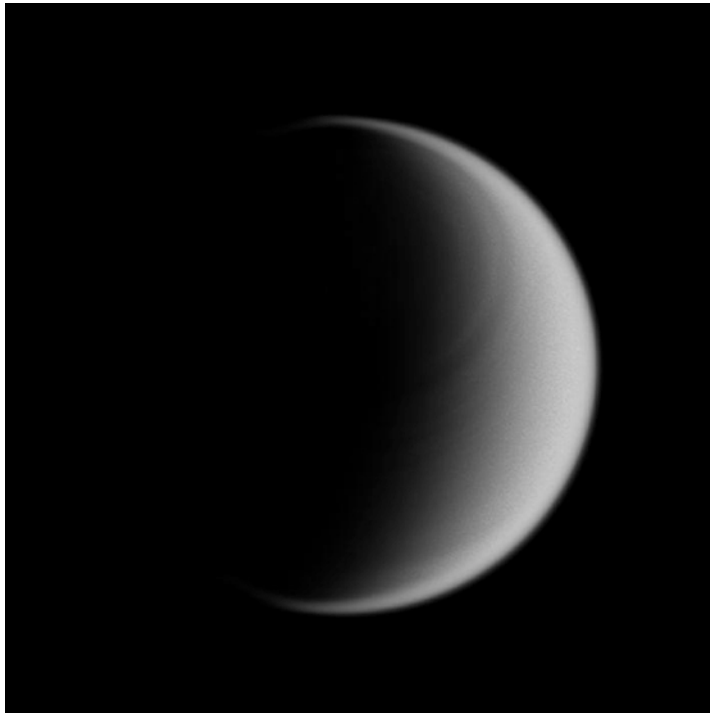


# ***Moons of Saturn***

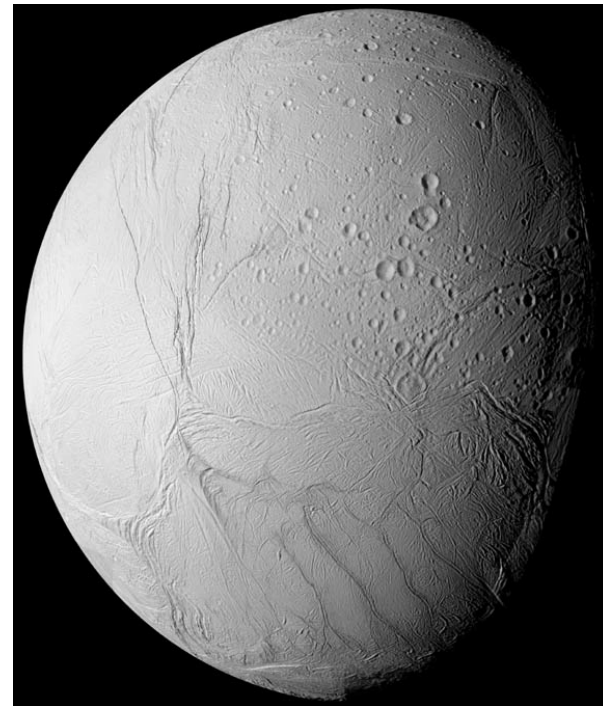
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**I'll discuss only two of them....**



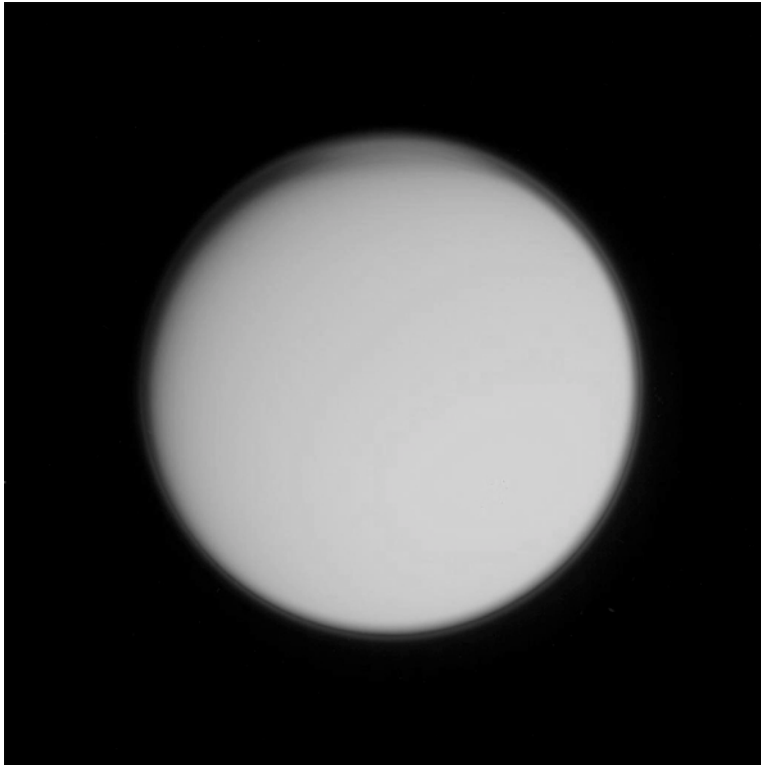
**Titan**



**Enceladus**

# ***Titan, Saturn's largest moon***

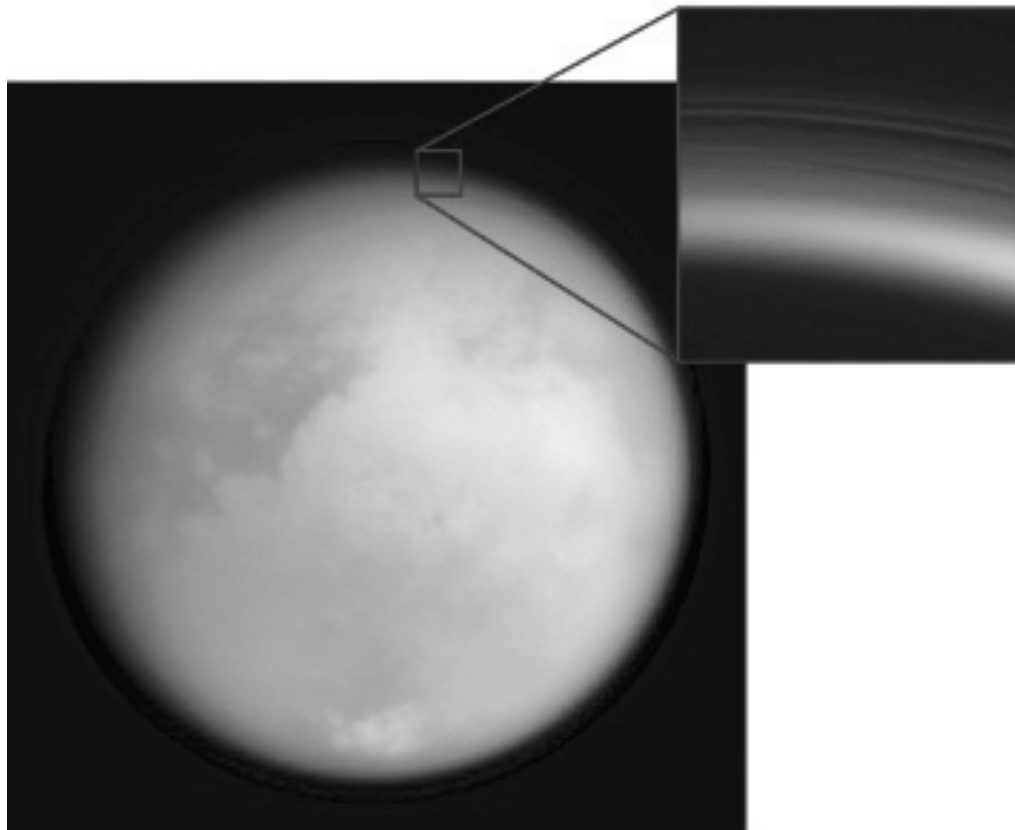
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- **Has a thick atmosphere.**
  - **Nitrogen (90%), Argon, methane, ethane**
  - **N comes from dissociated  $\text{NH}_3$**
  - **methane, ethane are greenhouse gases: surface is warmer than it should be**
  - **ethane may condense to form clouds and rain**
- **The atmosphere blocks our view of Titan's surface.**
  - **Hazy!**
- **it has large lakes of liquid hydrocarbons!**
- **Erosion may be important**

# ***Titan's Atmosphere***

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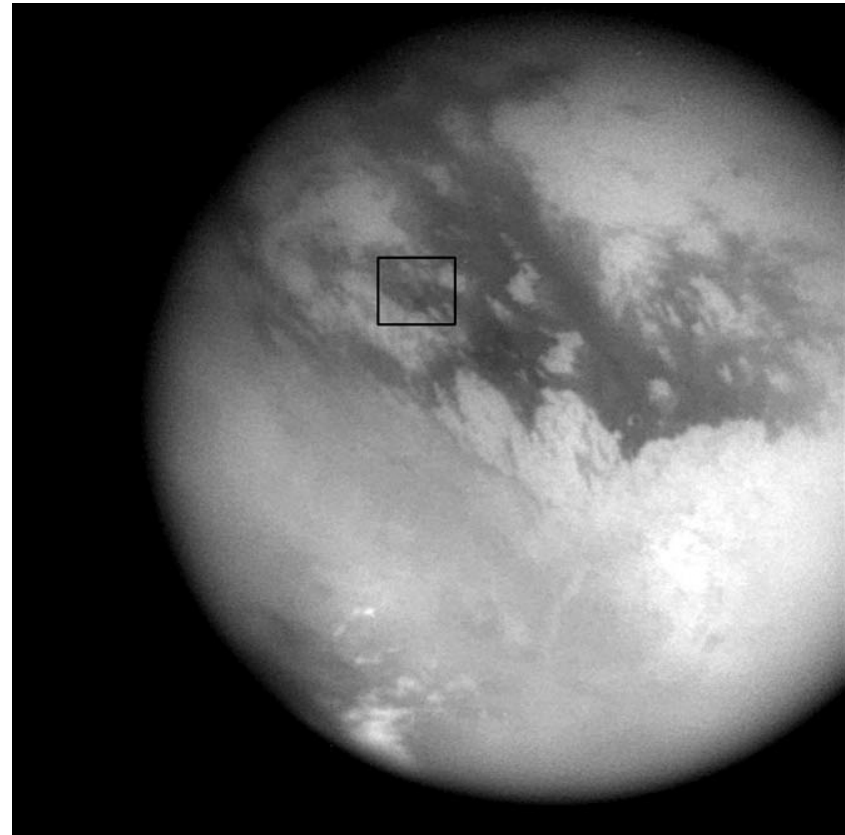
- **Titan is the only moon in the solar system to have a thick atmosphere**
- **It consists mostly of nitrogen with some argon, methane, and ethane**
- **Surface atmospheric pressure similar to ours on Earth**

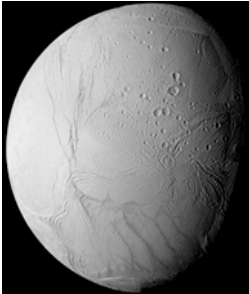
***But you can see to the surface at a few wavelengths where methane absorption is low***

---

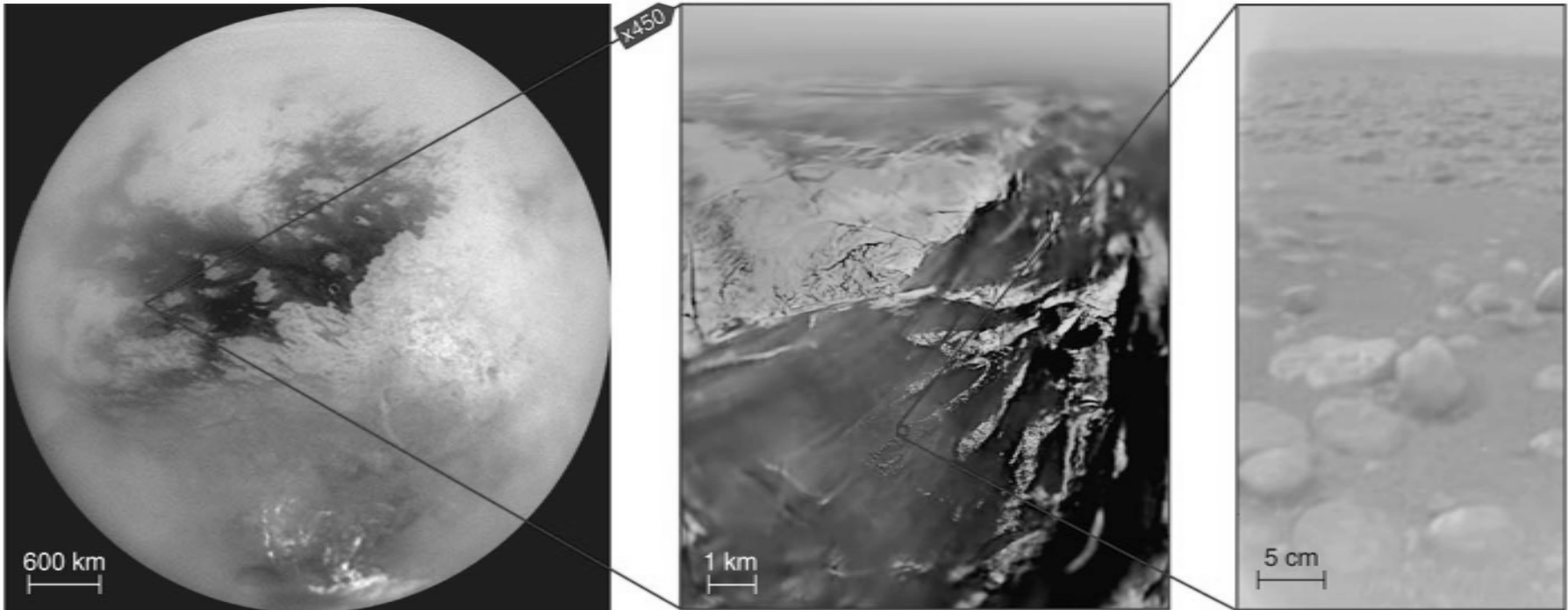


- **Cassini spacecraft sent Huygens landing probe to surface of Titan**
- **Landing site for Huygens probe**





# Titan's Surface



- ***Huygens* probe provided first look at Titan's surface in early 2005**
- **Liquid methane, "rocks" made of ice**

# ***Huygens probe landing on Titan***

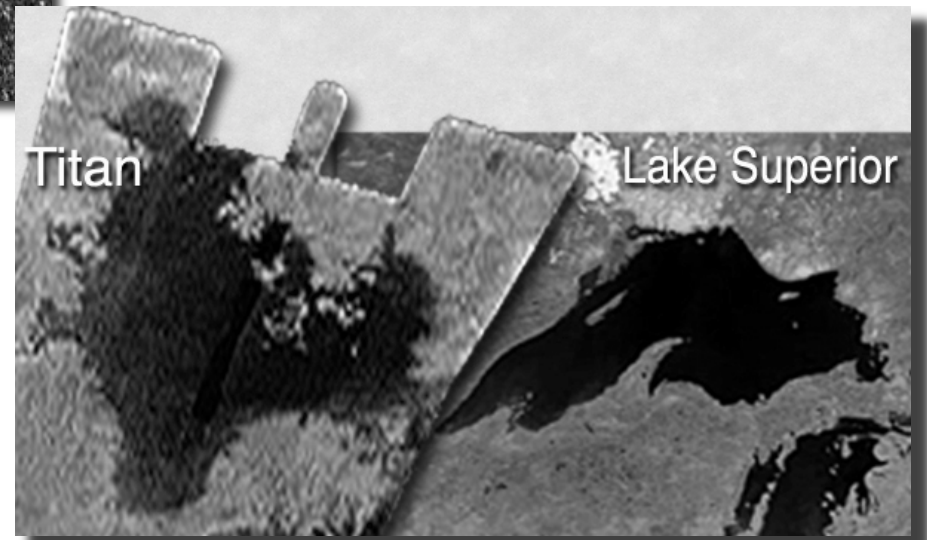
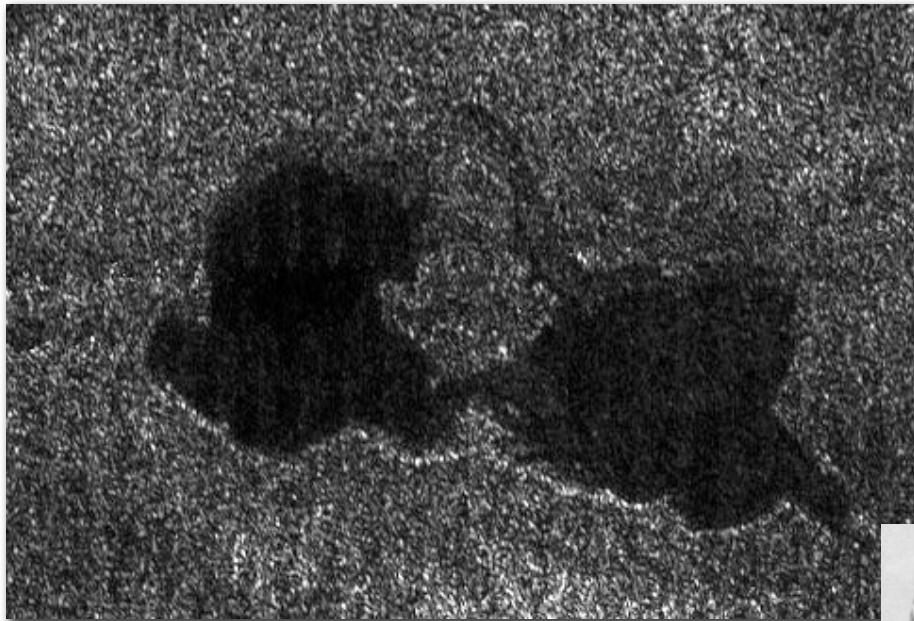
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- **Titan Landing Movie**

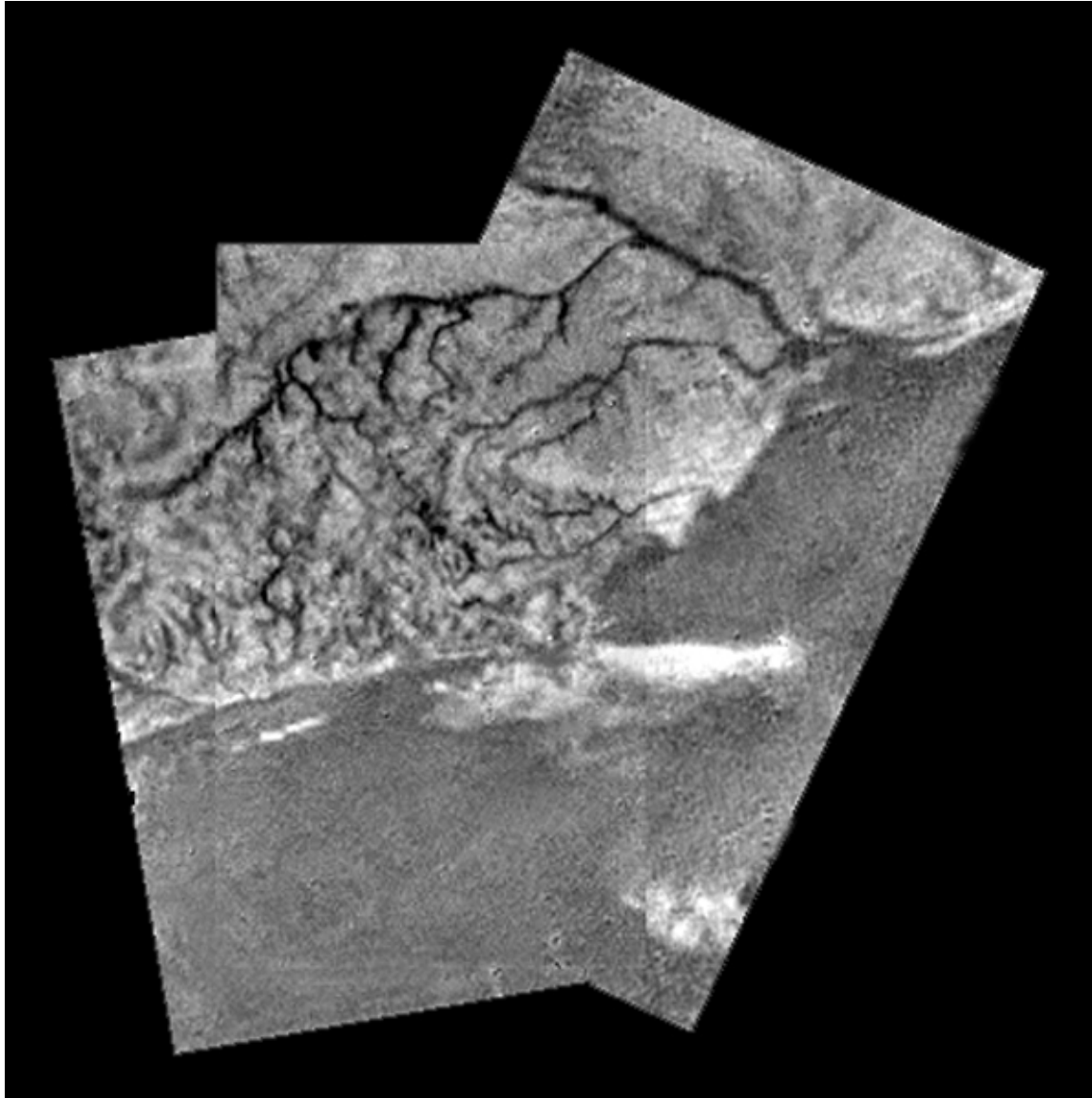
□

# ***Radar images of Titan lakes (!)***



# ***Dry riverbeds on Titan***

---



# ***Titan's "hydrological" cycle***

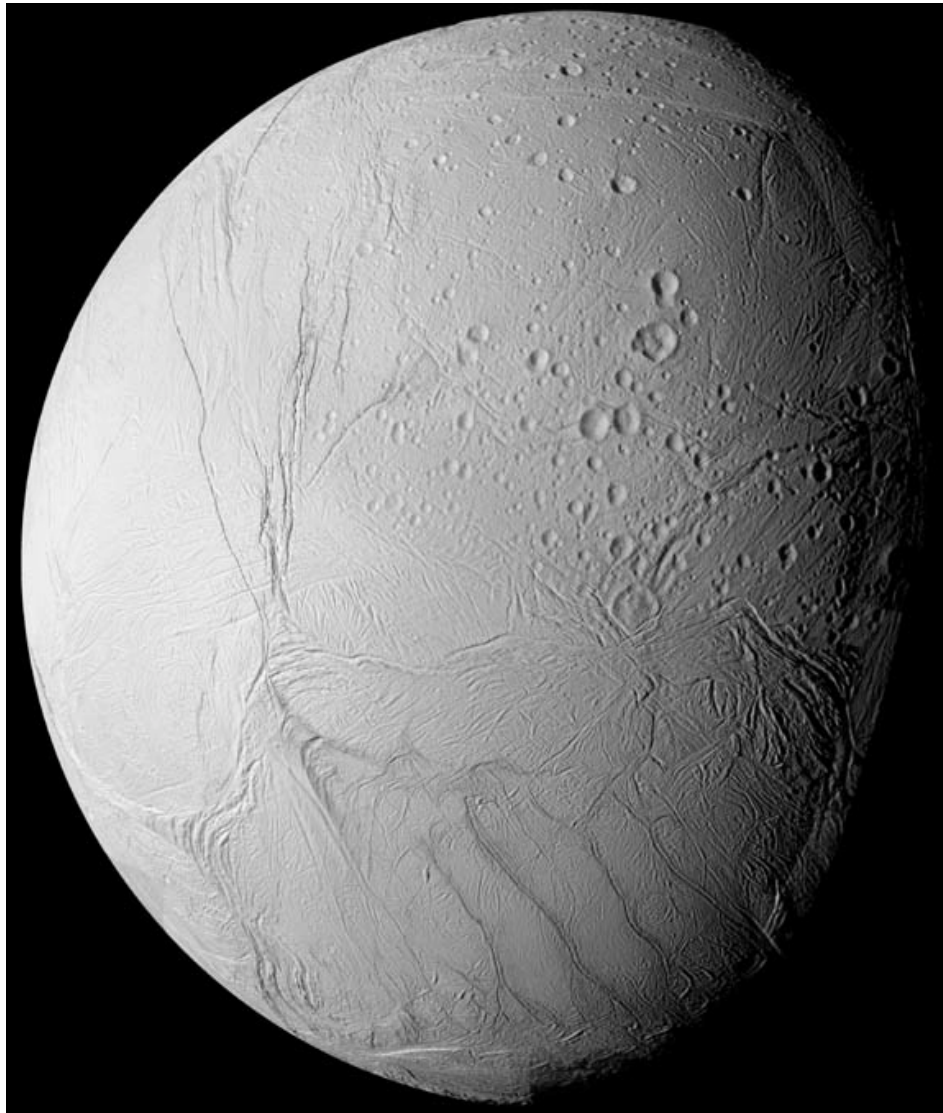
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- **Unmistakable river channels cut into Titan's terrain. So there must be some kind of rainfall, almost certainly drops of liquid methane.**
- **Raindrops would condense around the aerosol particles that Huygens lander detected.**
- **"Methane rain" and lakes of liquid hydrocarbons play the role of water on Earth.**

# ***Enceladus: one of Saturn's “medium moons”***

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- **What are the blue linear features?**

# Enceladus: one of Saturn's "medium moons"

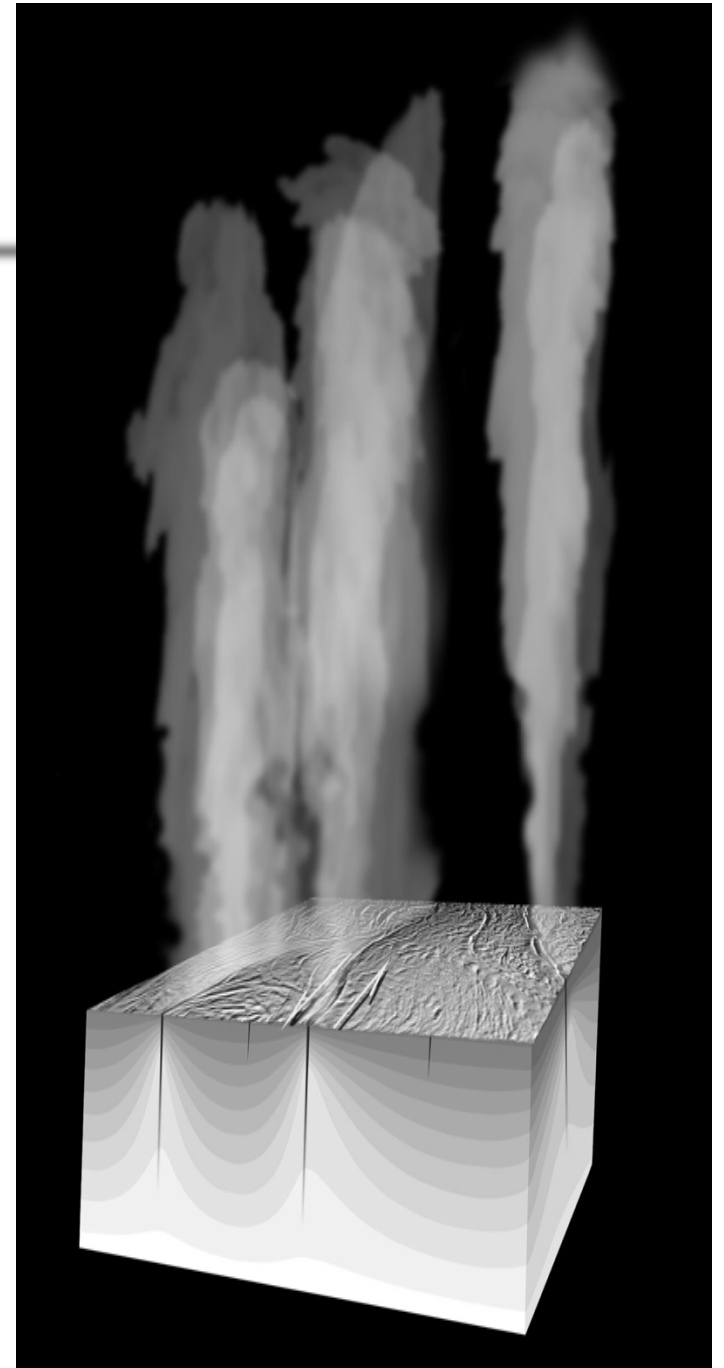
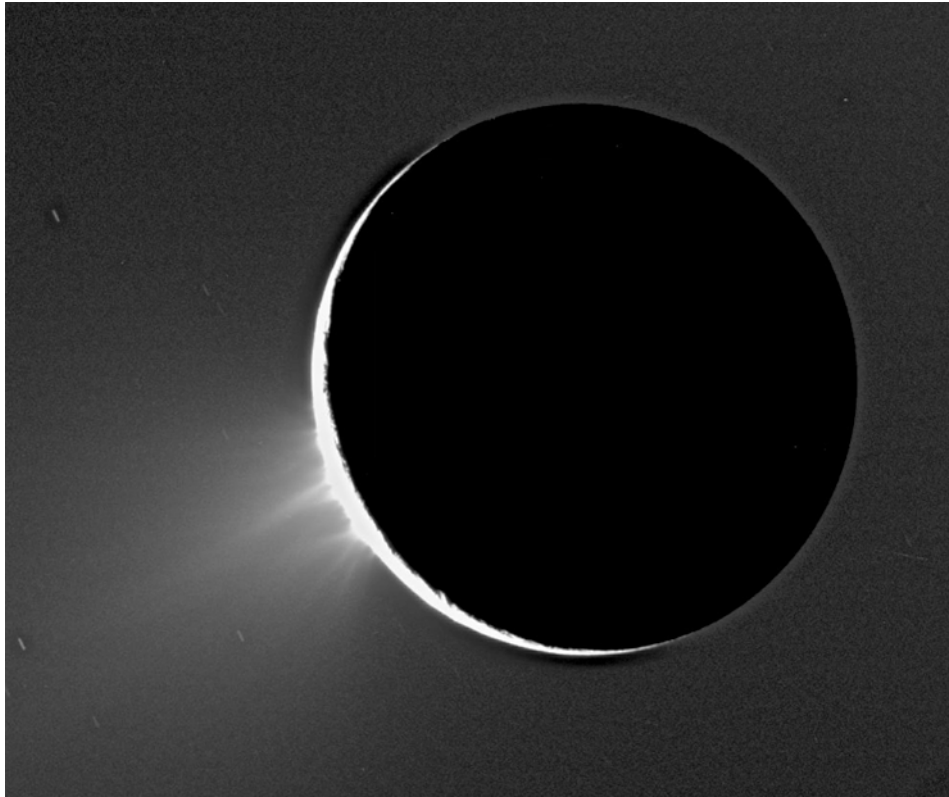


- **What are the blue linear features?**
- **Warm cracks!**

**Temperature scale**

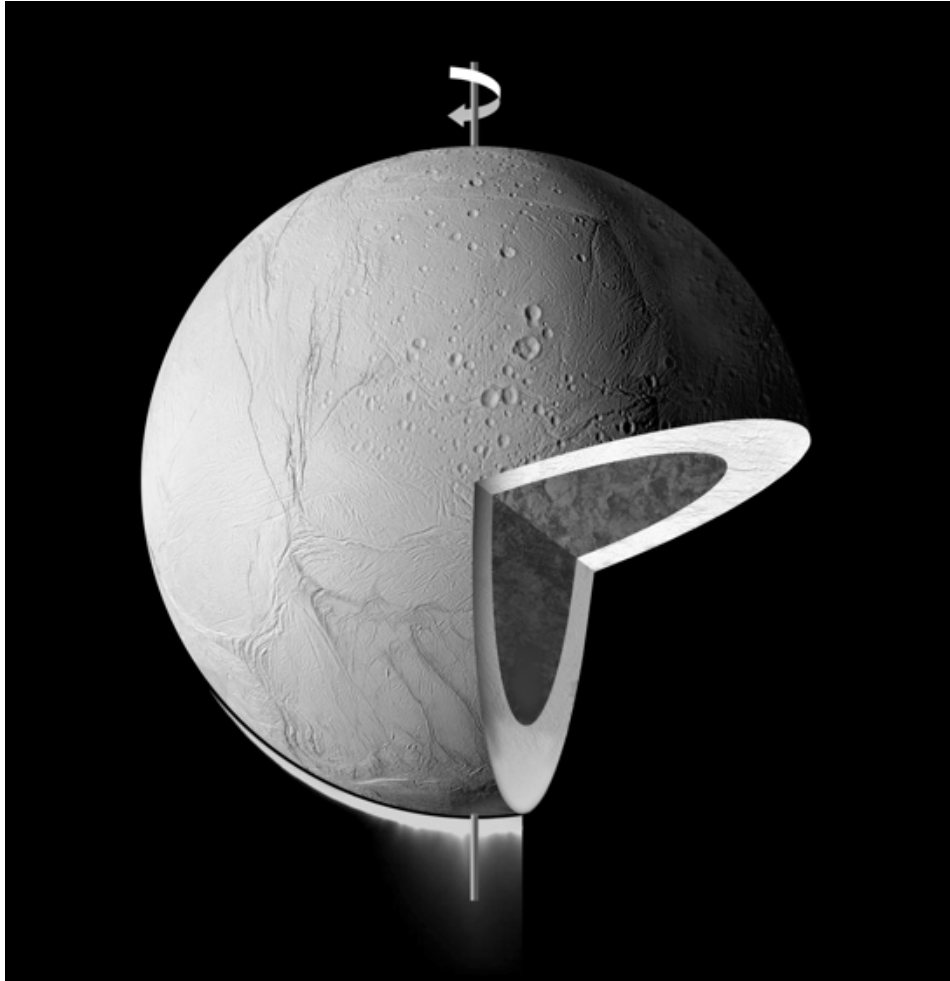
# ***Plumes from the blue cracks***

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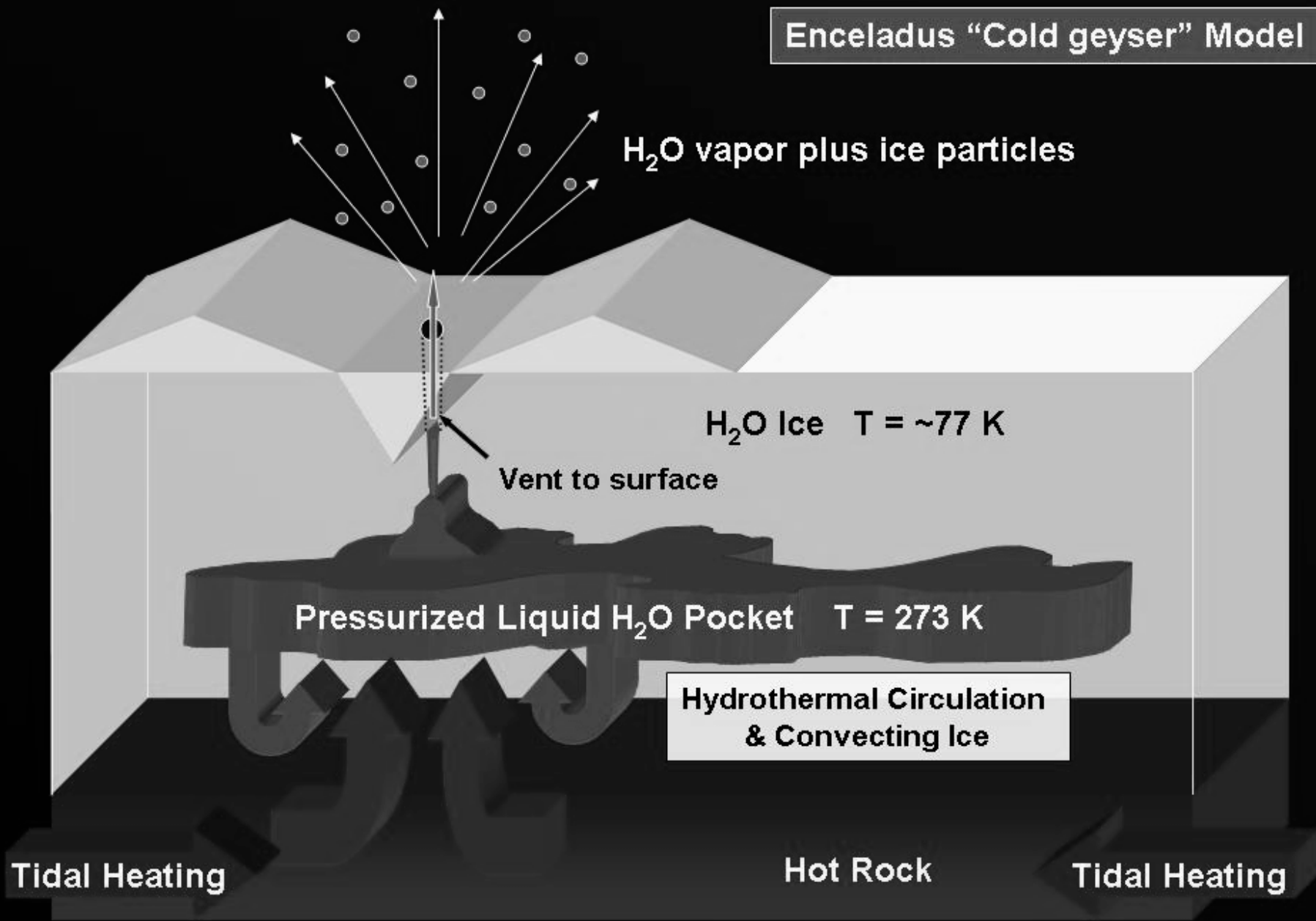
# ***Models for Enceladus plumes***

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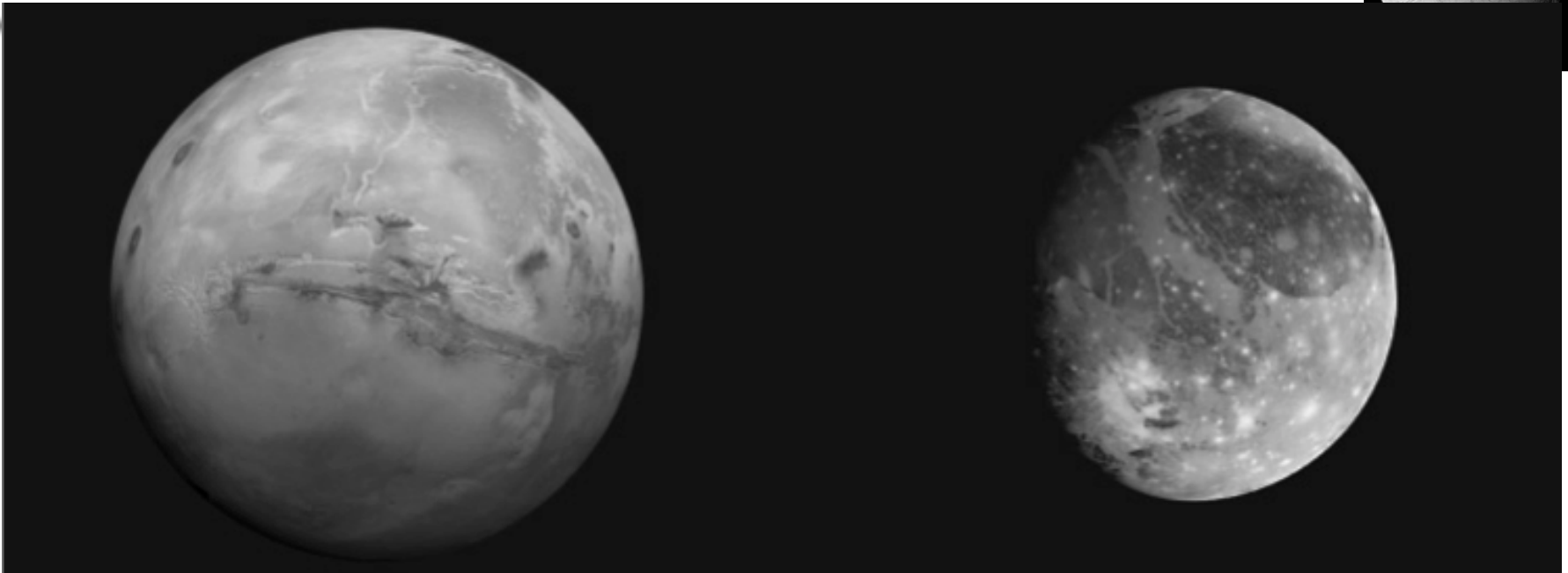
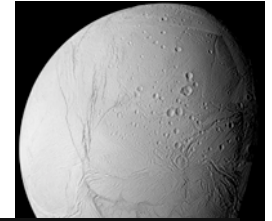


- **Southern “hot spot” ?**

Enceladus "Cold geyser" Model



# ***Rocky Planets vs. Icy Moons***



- **Rock melts at higher temperatures**
- **Only large rocky planets have enough heat for activity**

- **Ice melts at lower temperatures**
- **Tidal heating can melt internal ice, driving activity**

# ***What have we learned?***

---



- ***What kinds of moons orbit jovian planets?***
  - **Moons of many sizes**
  - **Level of geological activity depends on size**
- ***Why are Jupiter's Galilean moons so geologically active?***
  - **Tidal heating drives activity, leading to Io's volcanoes and ice geology on other moons**

# ***What have we learned?***

---



- ***What is special about Titan and other major moons of the solar system?***
  - Titan is only moon with thick atmosphere
  - Many other major moons show signs of geological activity
- ***Why are small icy moons more geologically active than small rocky planets?***
  - Ice melts and deforms at lower temperatures enabling tidal heating to drive activity

# ***Jovian Planet Rings***

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- **Topics:**
- **What are Saturn's rings like?**
- **How do other Jovian ring systems compare to Saturn's?**
- **Why do the Jovian planets have rings?**

# ***The Main Points: Rings***

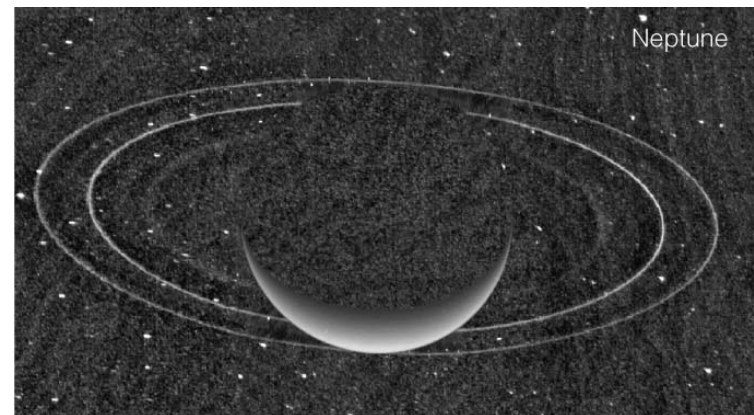
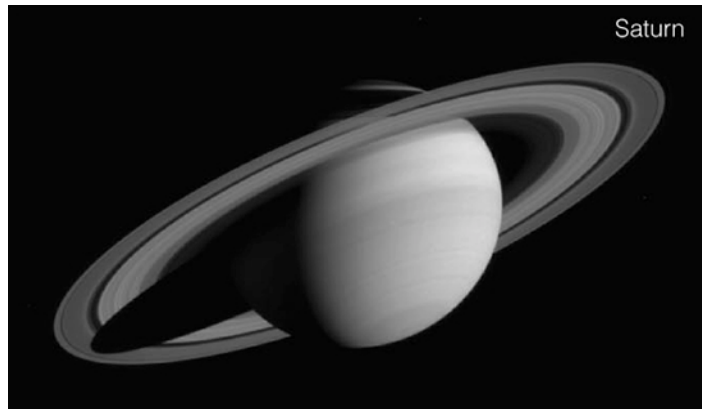
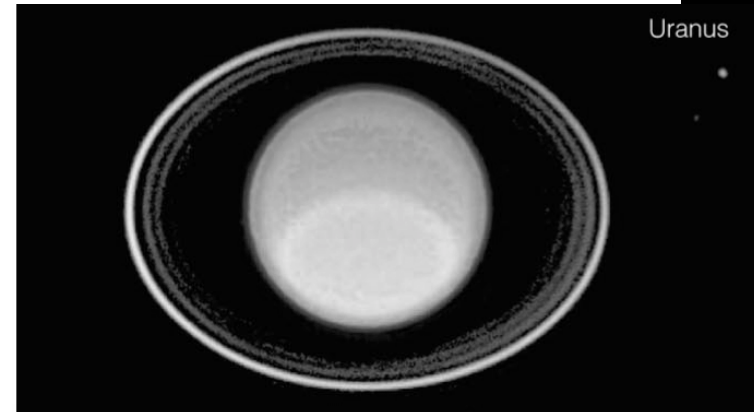
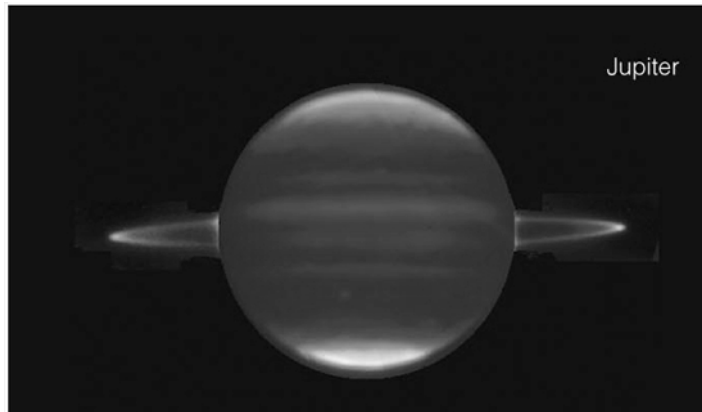
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- **All four Giant Planets have rings**
  - Chunks of rock, ice, dust in orbit around planet
- **Saturn's rings are the most massive and spectacular**
- **Formation: a moon can't survive intact within the "Roche tidal zone"**
- **Ring systems may be short-lived, always changing**
  - Each chunk in Saturn's rings has a collision with another chunk every few hours!
  - Implies that rings are always being replenished

# ***Jovian Planets: Ring Systems***

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- **All four jovian planets have ring systems**
- **Others have smaller, darker ring particles than Saturn**

# ***What are Saturn's rings like?***

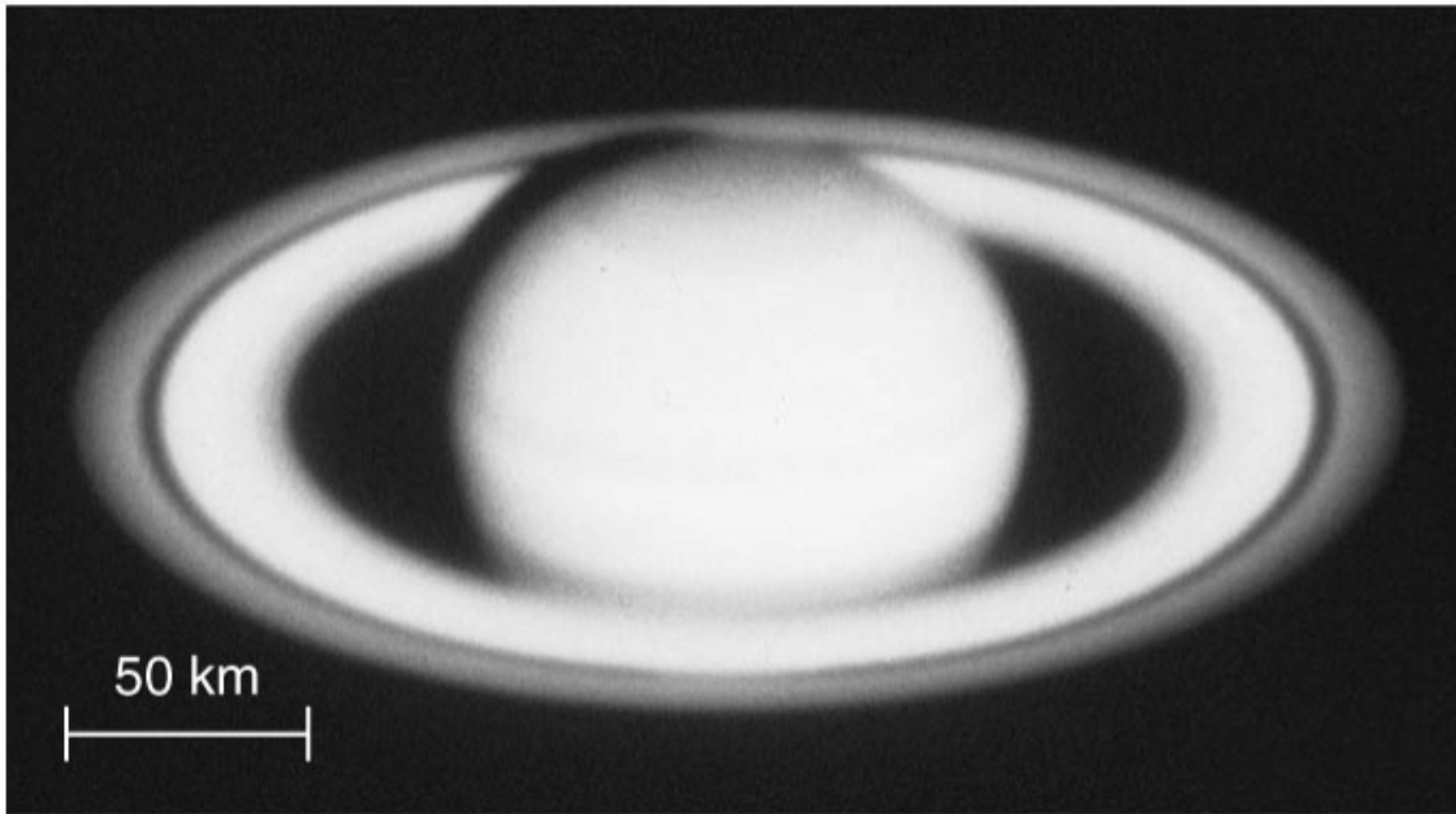
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- **They are made up of numerous, tiny individual particles**
- **They orbit over Saturn's equator**
- **They are very thin**

# ***Earth-based view***

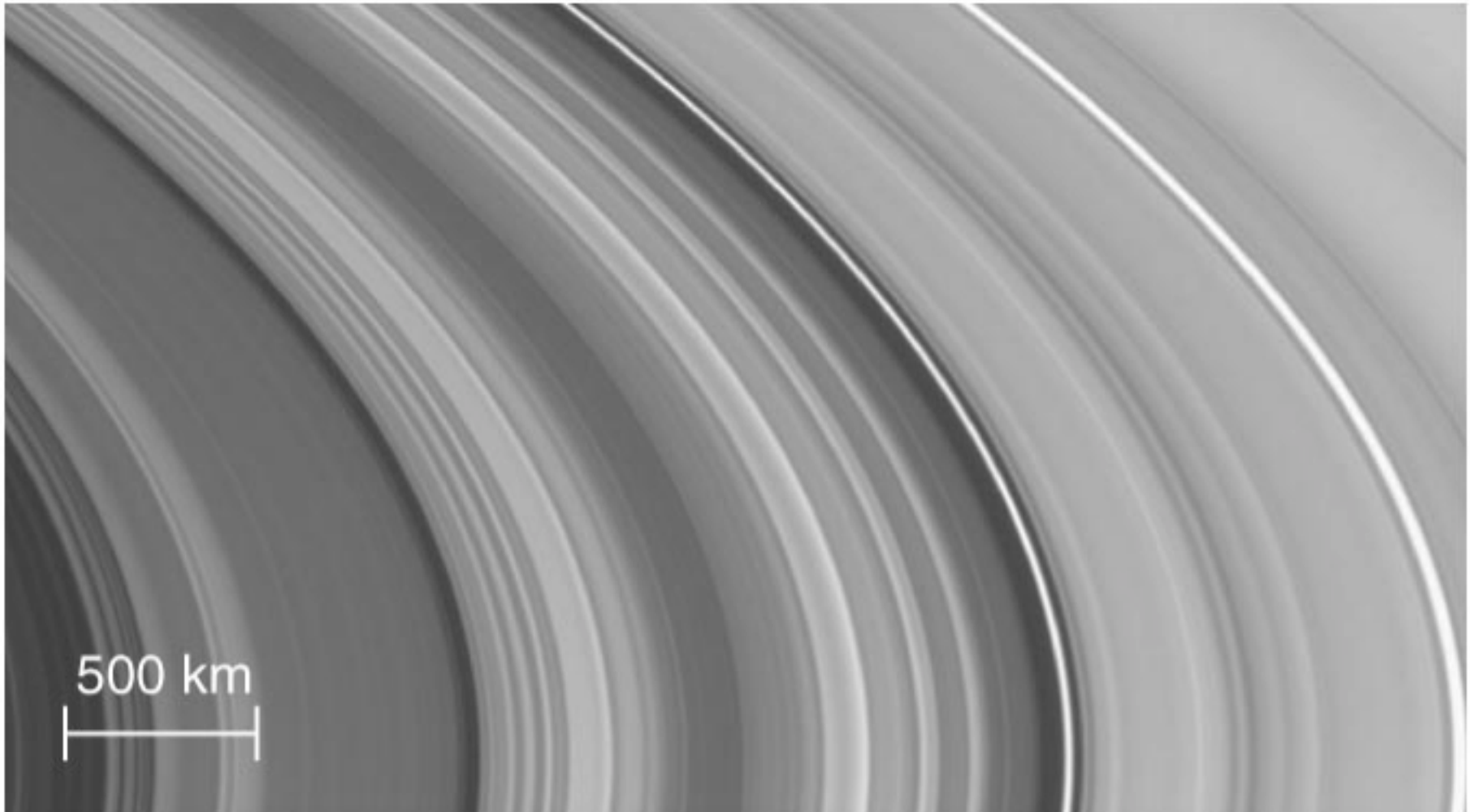
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Interactive Figure 

# ***Spacecraft view of ring gaps***

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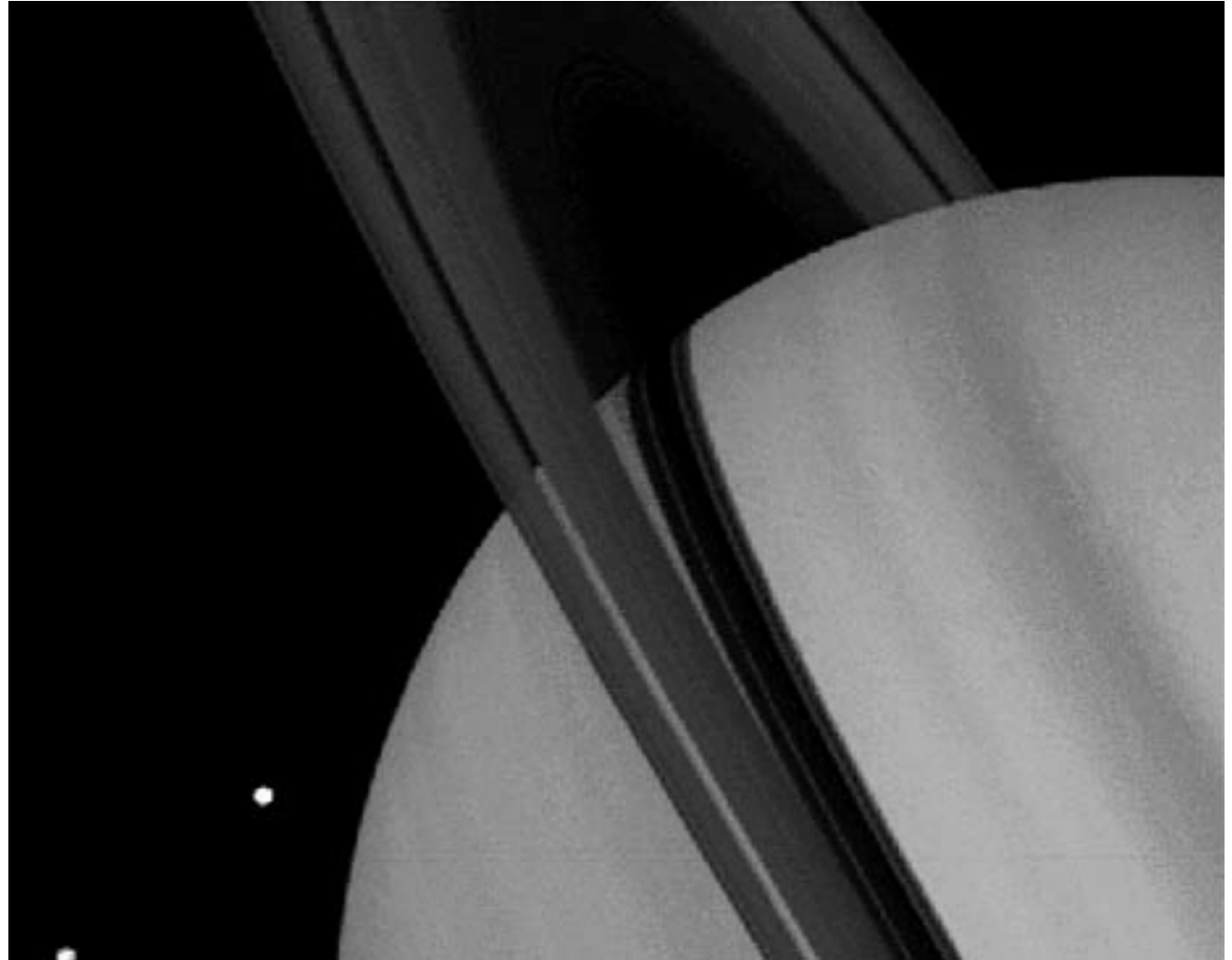


# ***Not much mass in Saturn's rings***

---

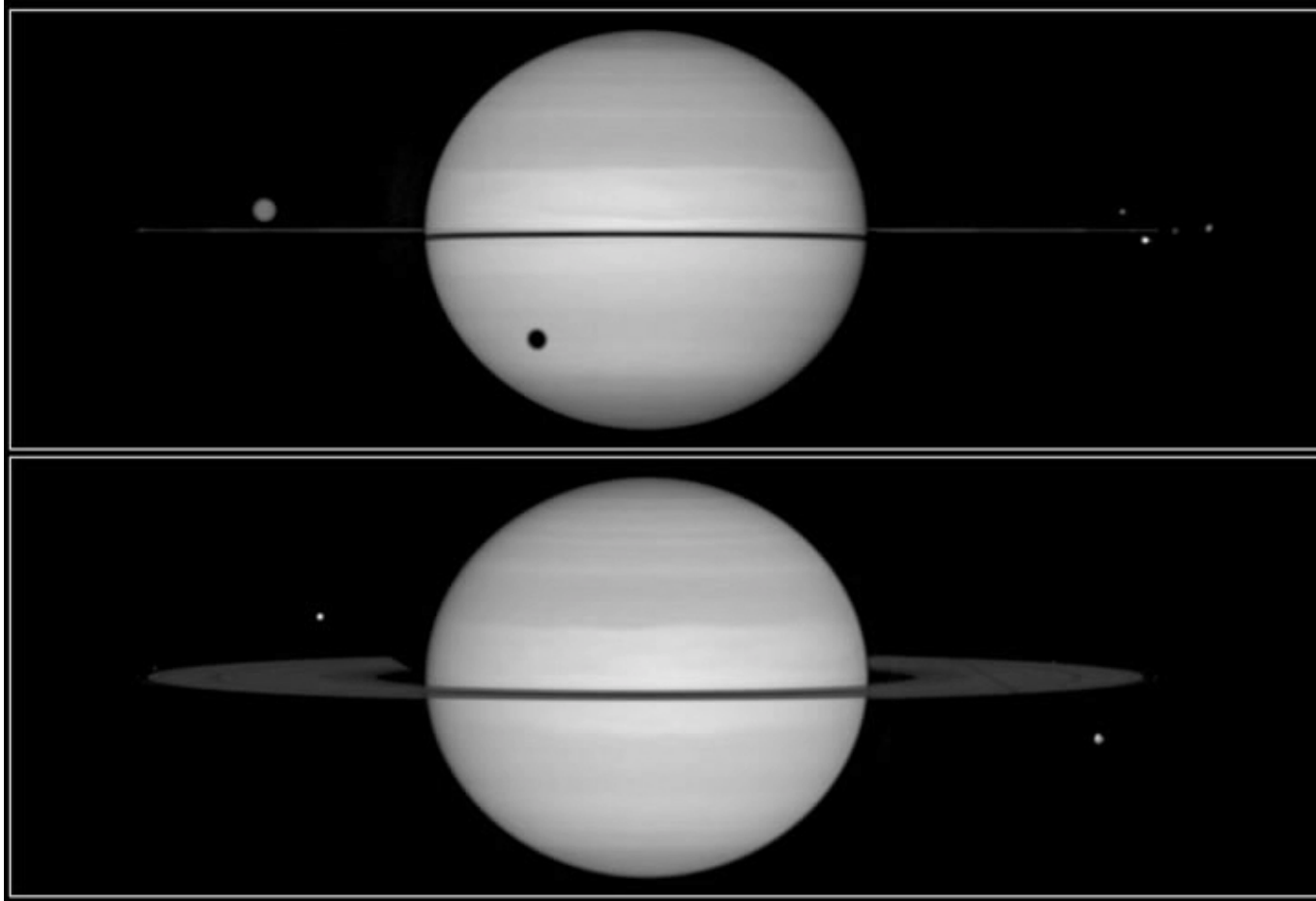


- **If gathered together, material in rings would make a sphere 500 km across**
- **Smaller than our Moon!**



# ***Saturn's rings are very thin***

---



# ***Saturn's rings are very thin***

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- **Movies from the Cassini spacecraft**
- <http://photojournal.jpl.nasa.gov/archive/PIA12795.mov>

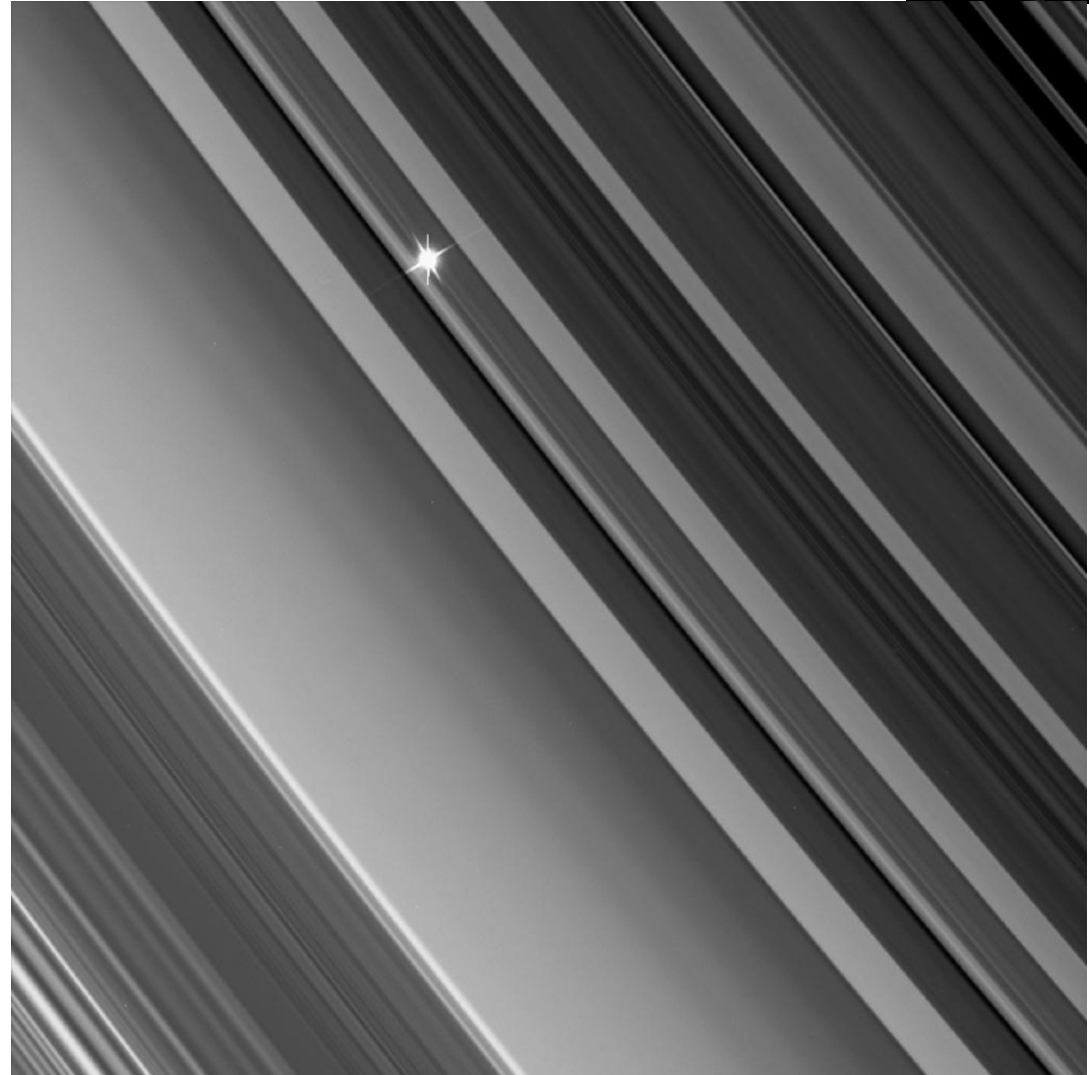
**Saturn's rings are 270,000 km in diameter, but only about 30 meters thick!**

# ***Saturn's rings are very thin***

---

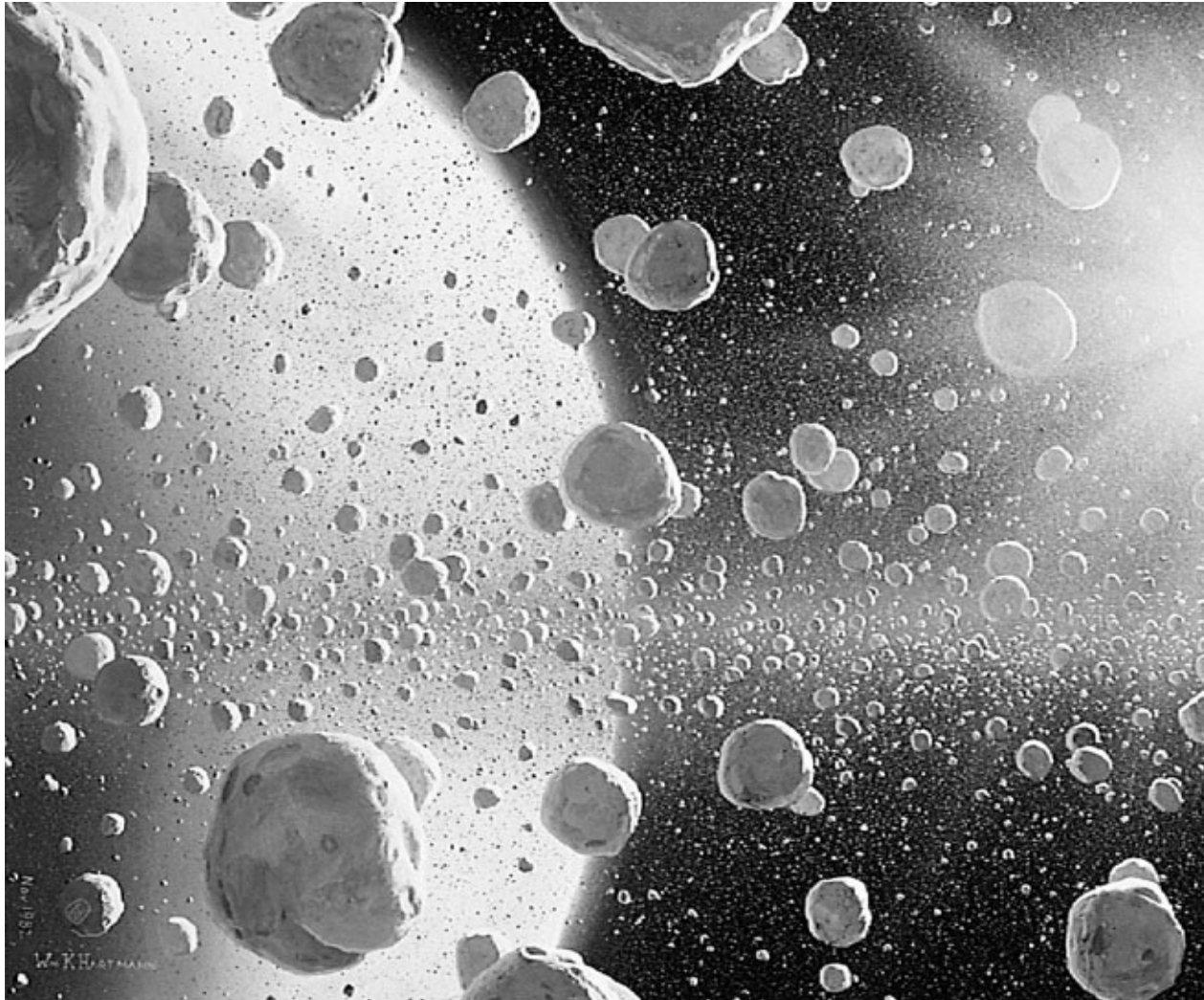


- **A star is seen clearly on opposite side of Saturn's rings (Cassini image)**



# ***Artist's conception of close-up***

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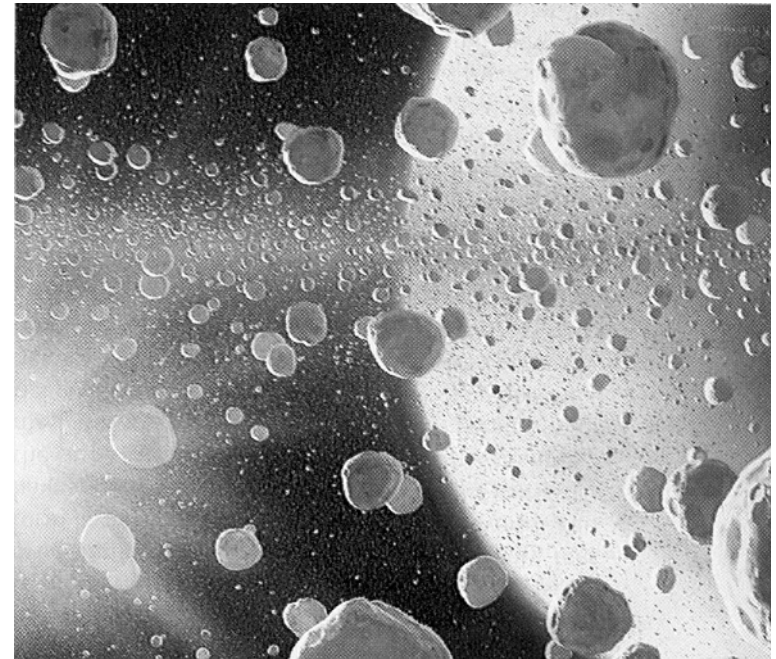


# ***Saturn's rings are probably a transient phenomenon***

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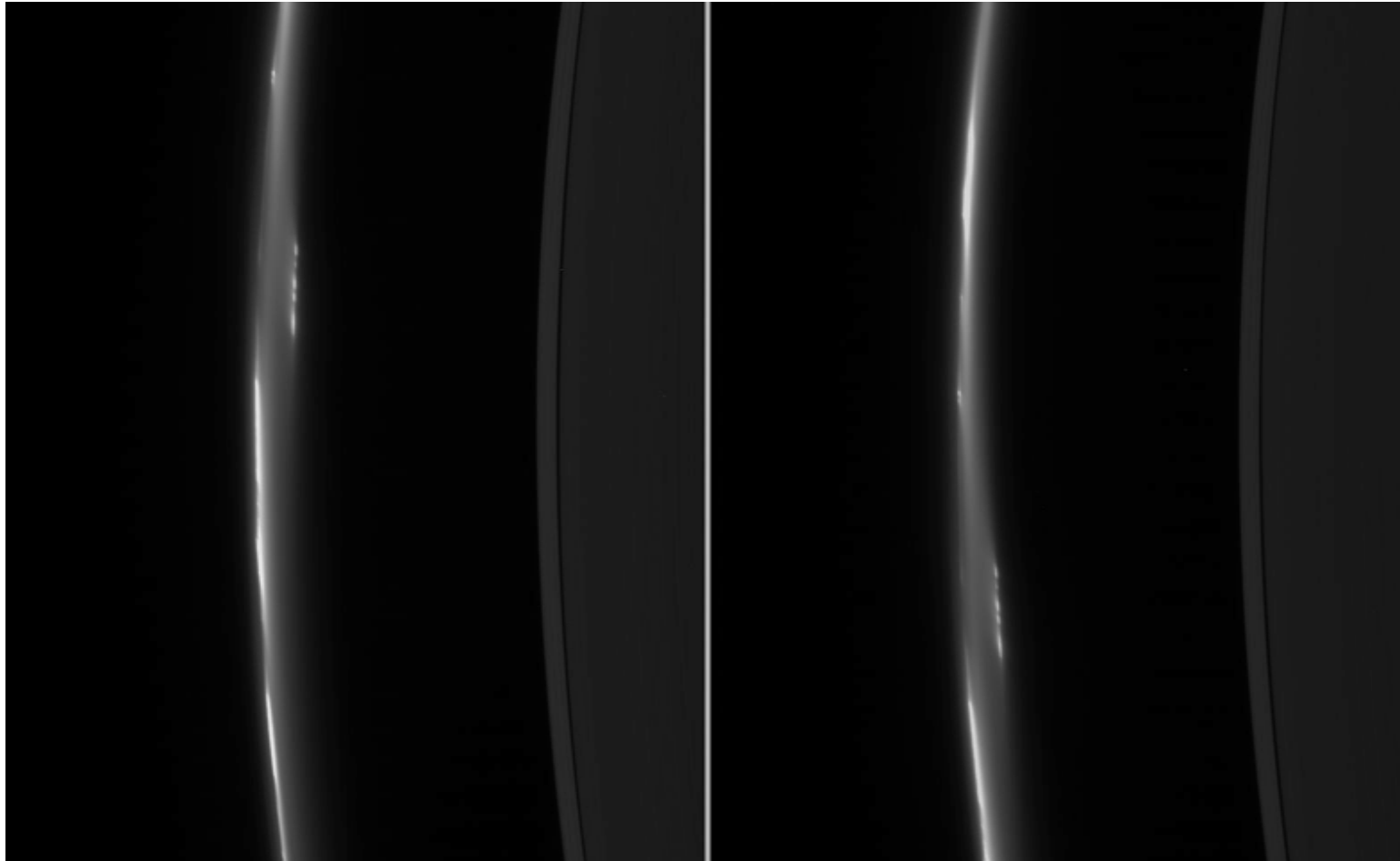


- **Each chunk of rock and ice in Saturn's rings collides with another one every few hours**
- **Must grind up smaller chunks into tiny pieces**
- **Needs mechanism for regeneration: collisions of some of Saturn's small moons?**
  - **Not well understood yet.**



# ***A collision caught in the act (?)***

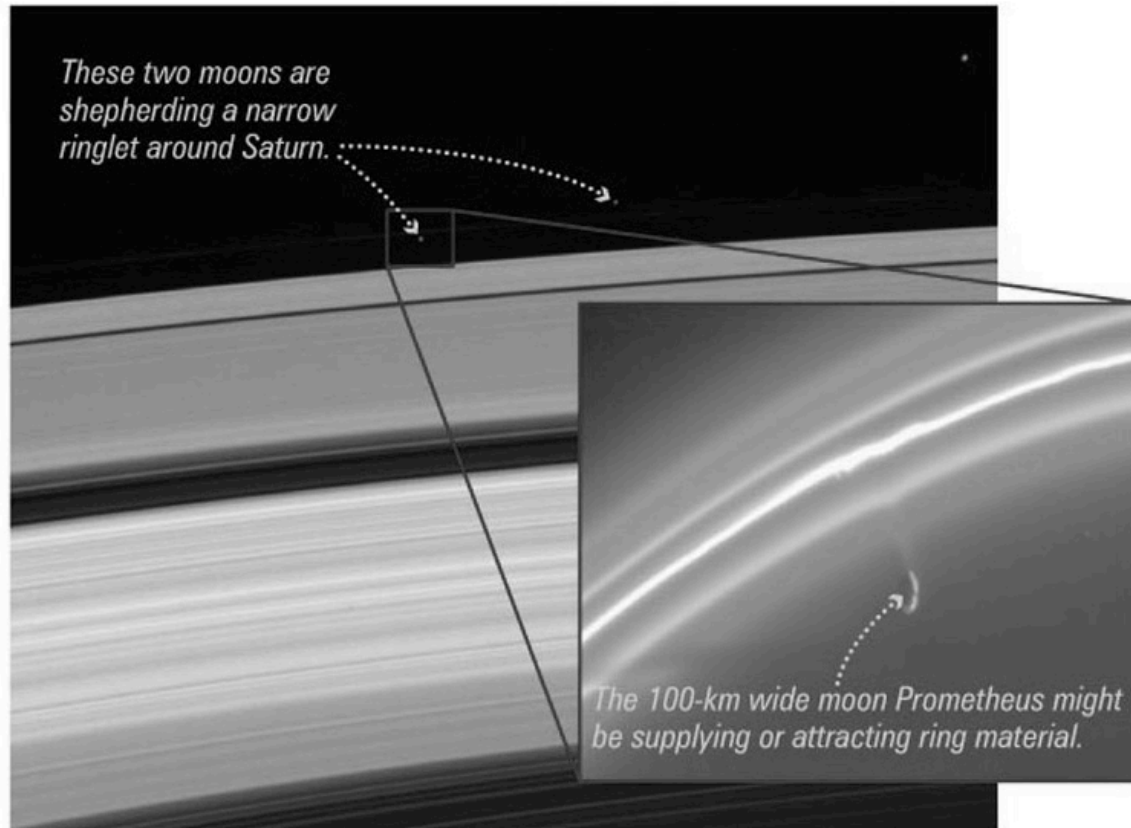
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# Shepherd Moons

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- **Pair of small moons can force particles into a narrow ring**

# ***Shepherd moons in action***

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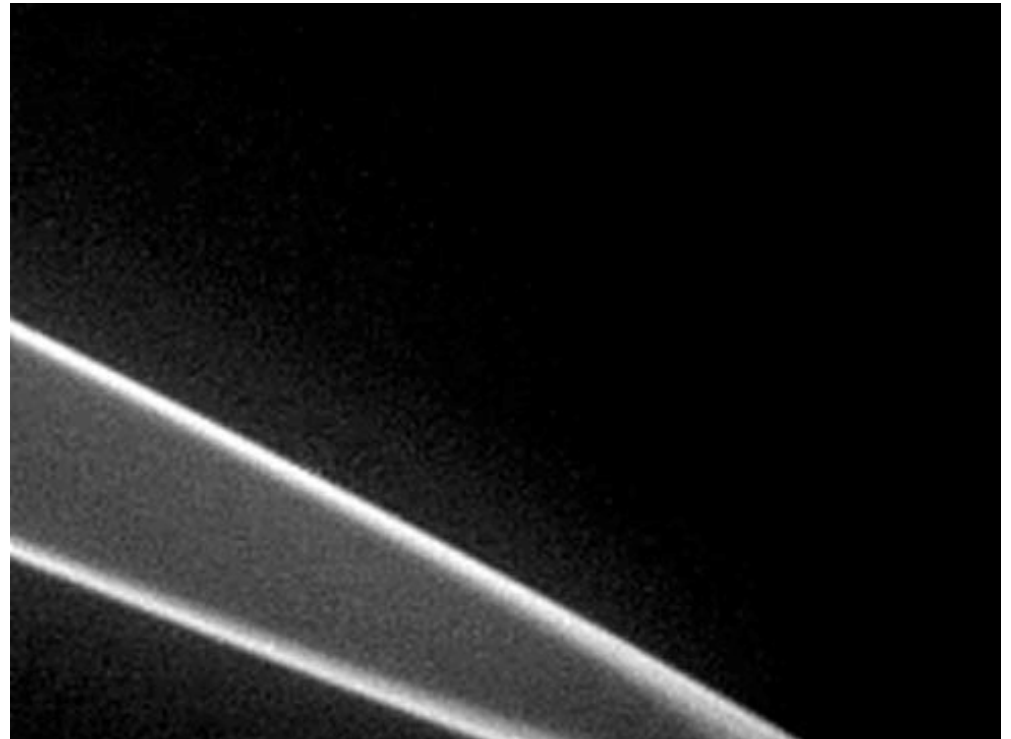
- **Prometheus and Pandora shepherd Saturn's F Ring**
  - **From Cassini spacecraft**

# ***Jupiter's ring***

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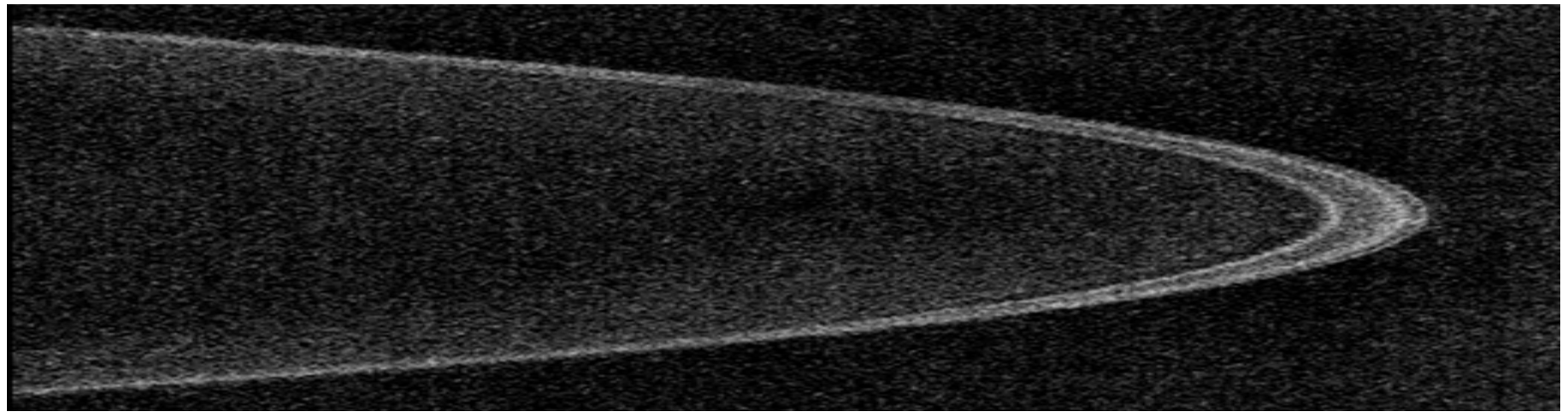
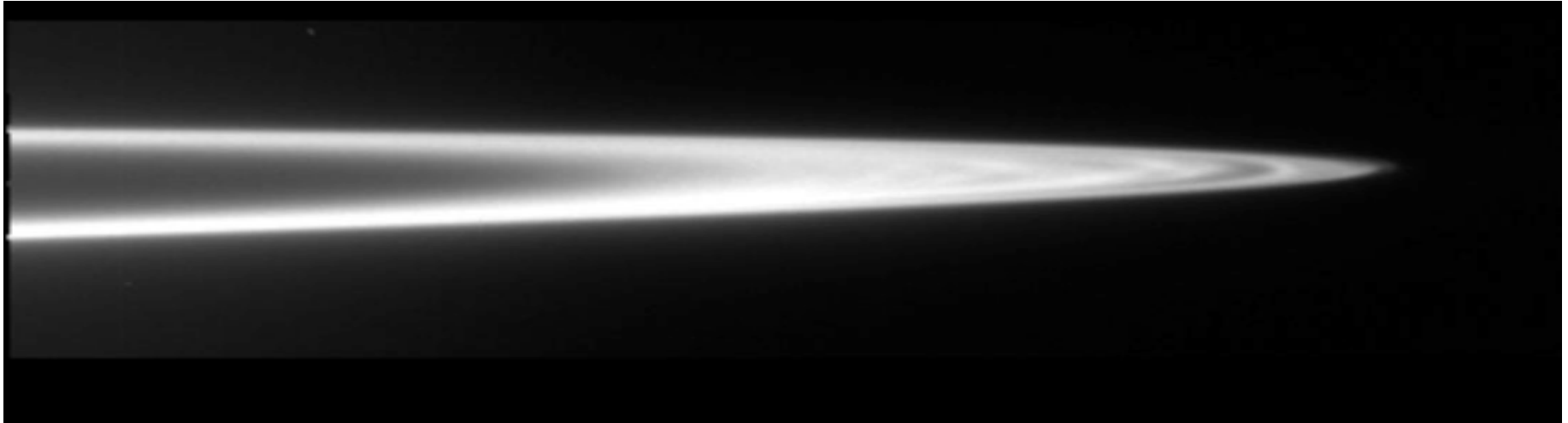


- **Not much stuff**
- **If you gathered all the material in Jupiter's ring together into a ball, it would be only 30 meters in diameter!**



# ***Jupiter's ring: other views***

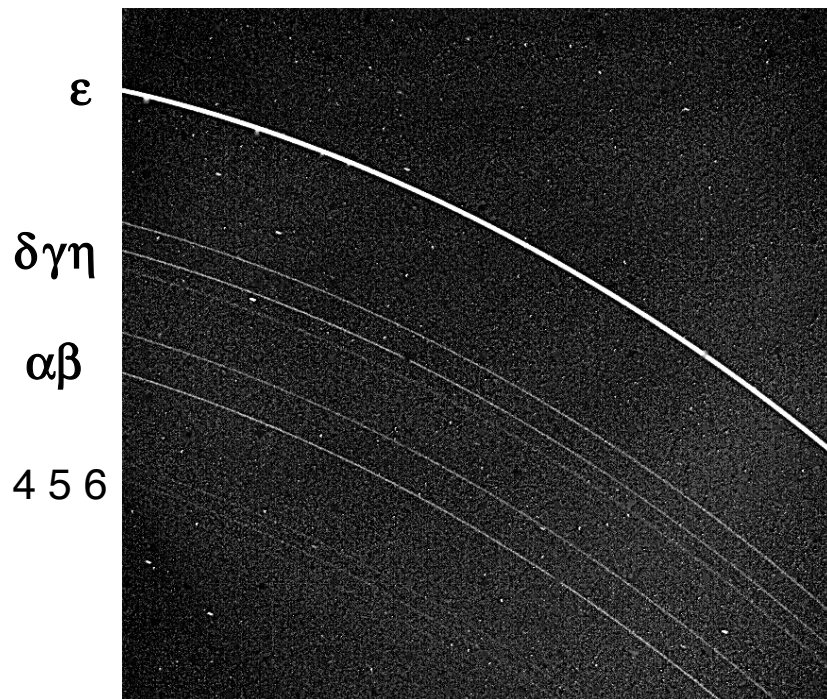
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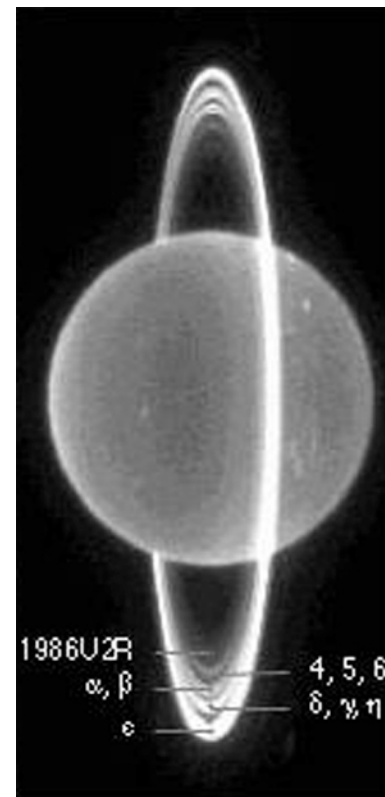
# Rings of Uranus in infrared light



Voyager: 4 groups of rings

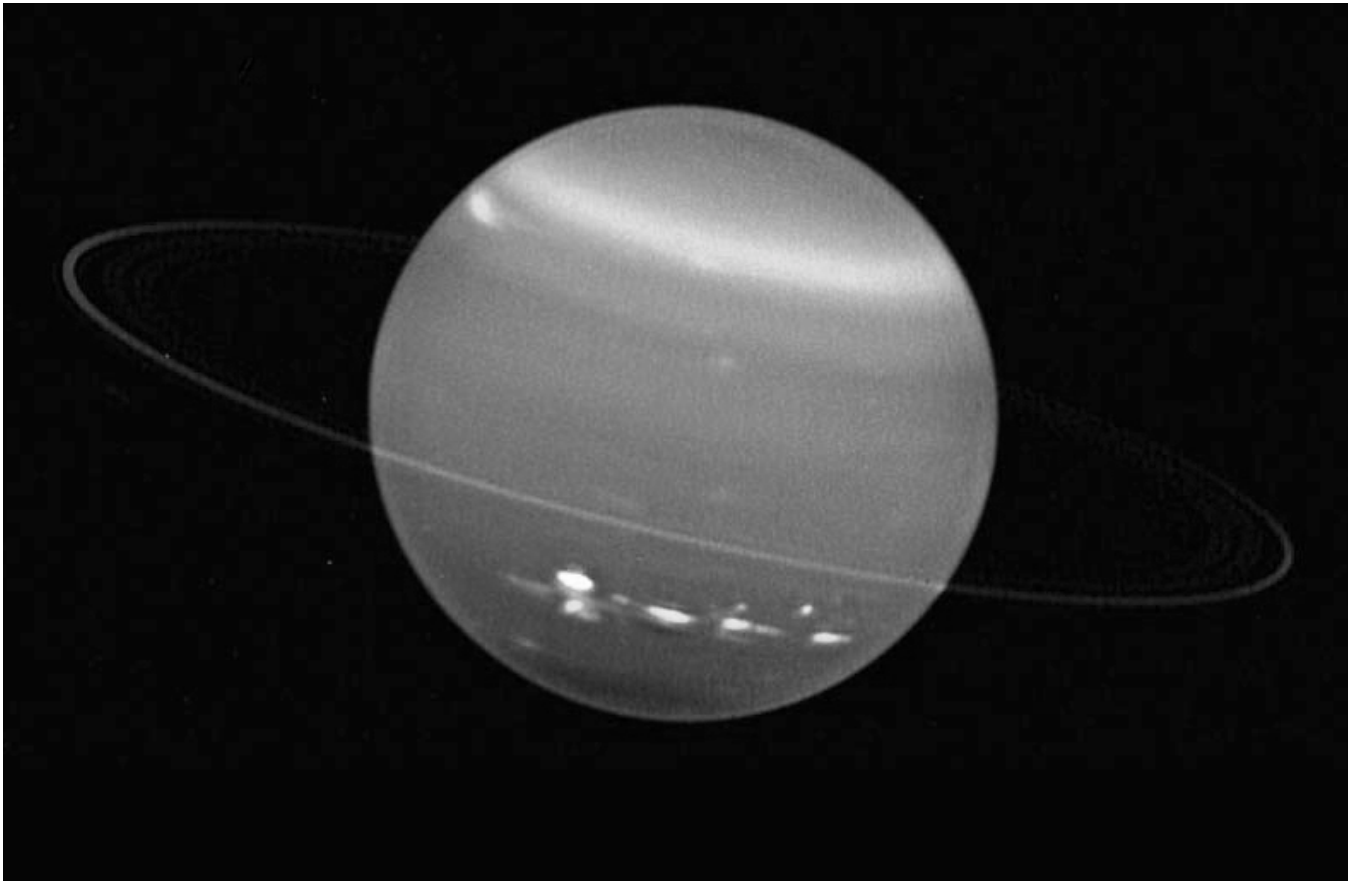


Keck Adaptive Optics, 2004  
(de Pater)



# ***Uranus rings, another view***

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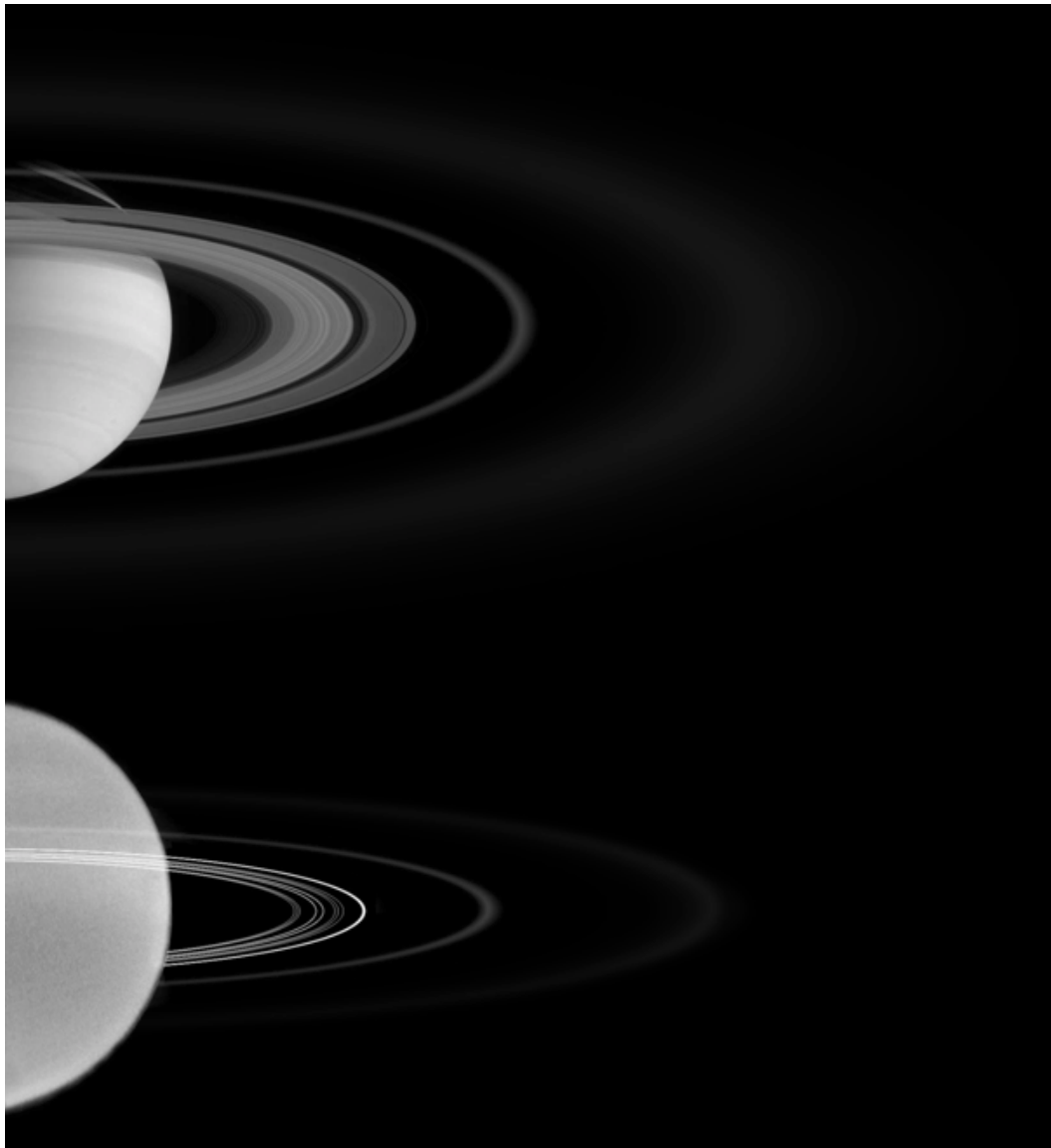


• **Credit: L. Sromovsky**

**Keck adaptive optics**

# ***Uranus: new outer ring just discovered***

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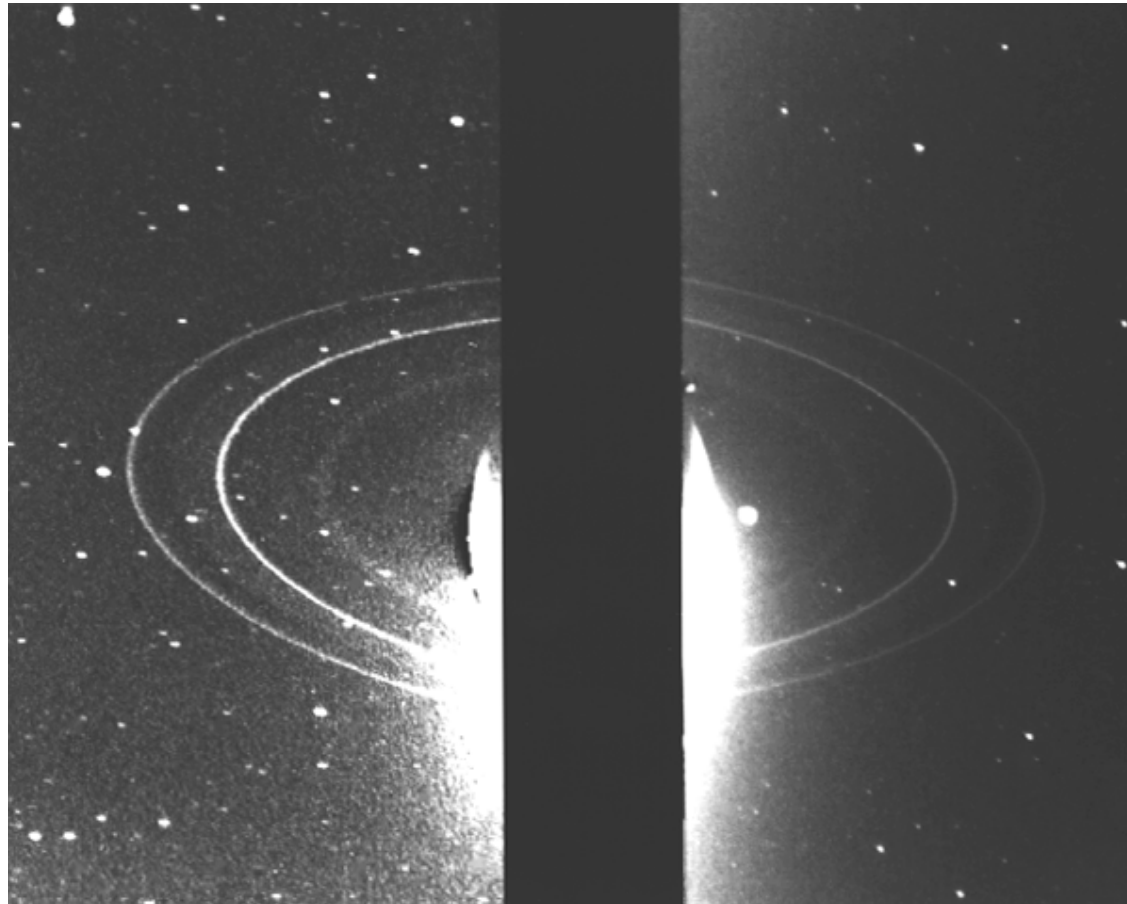
- **Imke de Pater, UC Berkeley**
- **Cartoon of Uranus vs. Saturn ring configuration**

# ***Rings of Neptune***

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- **Neptune's rings from Voyager**



# ***Roche's limit for tidal breakup of a moon, making rings***

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Mass M,  
radius R

$r_{\text{Roche}}$

two small masses m  
in orbit around planet,  
barely touching each other

$x_2 - x_1$   
◀ ▶

**Roche's limit:**

$r_{\text{Roche}}$  such that disruptive tidal force between the two small masses is just barely balanced by the gravitational attraction between them

# Roche's limit, continued

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$$r_{\text{Roche}} = 2R \left( \frac{\rho_M}{\rho_m} \right)^{1/3} \text{ where } \rho_M \text{ and } \rho_m \text{ are densities of planet and moon.}$$

Example- if moon has same density as planet:  $r_{\text{Roche}} = 2R$

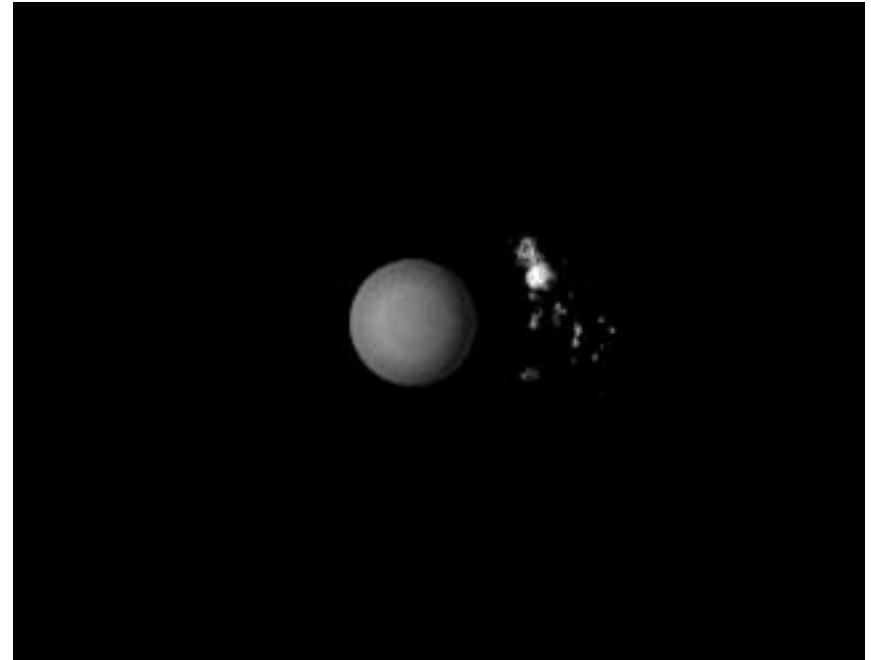
- **All Jovian planet rings exist within their respective Roche radii**
- **So if a moon entered this zone, it would break up due to tidal stresses**

# ***Theories for how rings formed***

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- **Theory 1:**
- **A satellite got disrupted when it got too close to Saturn and was ripped apart by strong tidal forces**

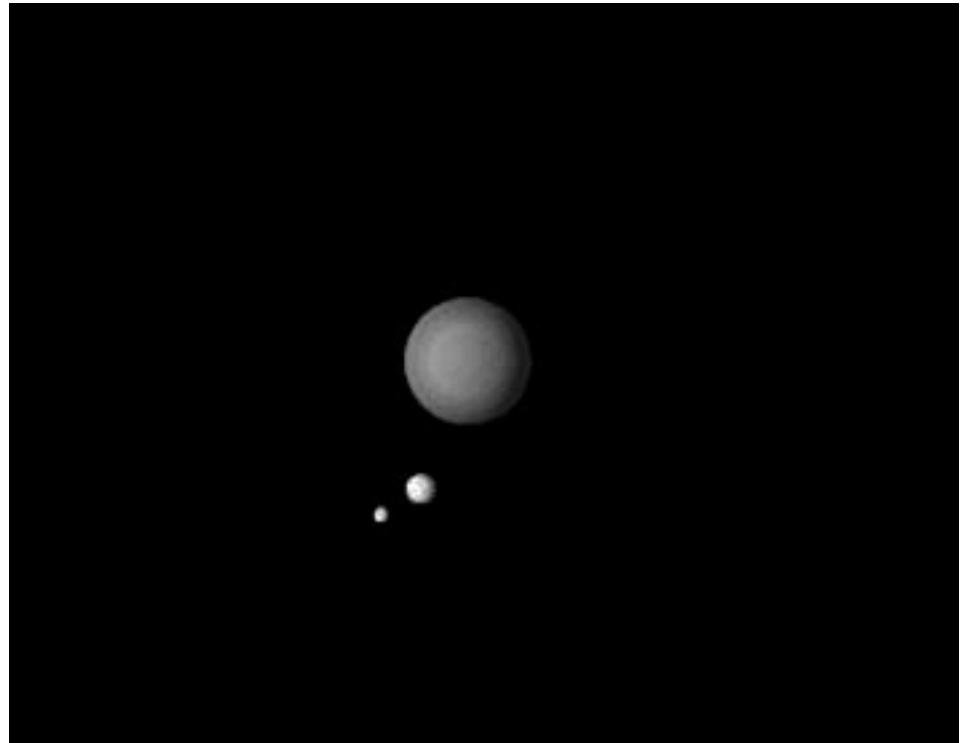


## ***Ring theory 2***

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- **A moon of Saturn was broken apart in a collision, and the remnants stayed in orbit as rings**

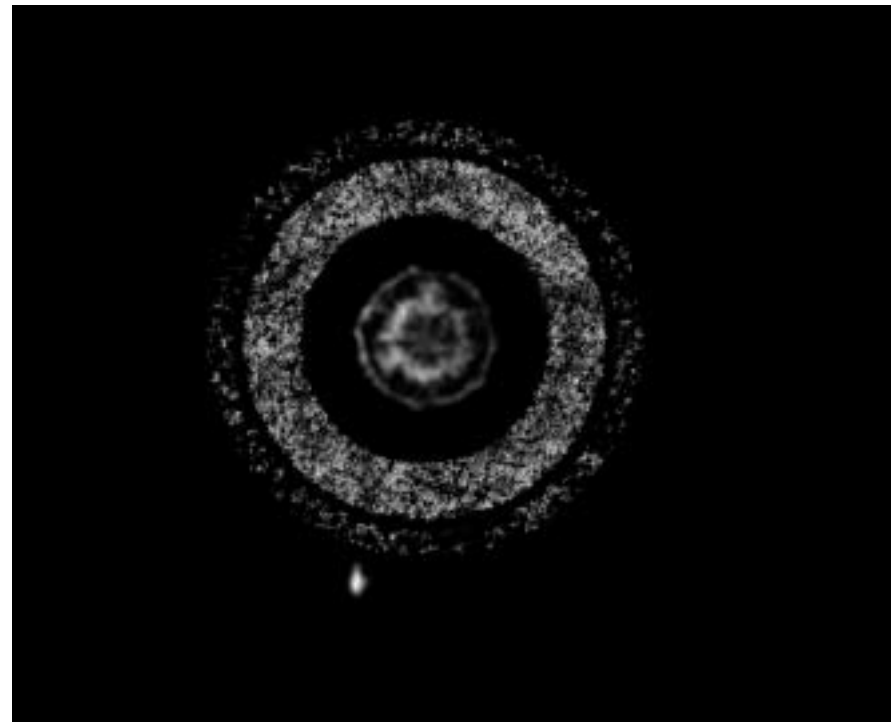


# ***Ring theory 3***

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- **Ring developed during initial formation of Saturnian system**
- **Gravitational tugs from Saturn and other moons prevented material from gathering together to form a moon**



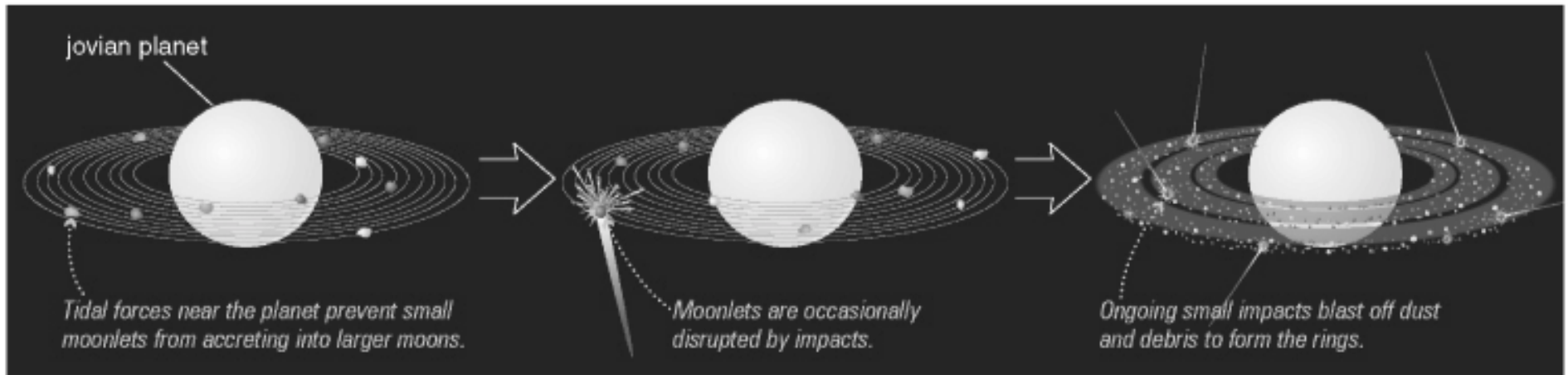
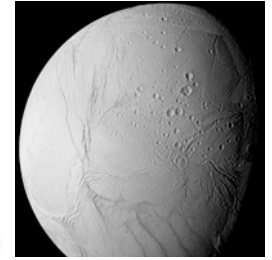
## ***But rings aren't left over from planet formation***

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- **Rings aren't leftover from planet formation because the particles are too small to have survived this long.**
- **There must be a continuous replacement of tiny particles.**
- **The most likely source is impacts with moons.**

# Ring Formation and Replenishment



- **Jovian planets all have rings because they have many small moons close-in**
- **Impacts on these moons are random**
- **Saturn's lovely rings may be an "accident" of our time**

# ***The Main Points: Rings***

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- **All four Giant Planets have rings**
  - Chunks of rock and ice, dust in orbit around planet
- **Saturn's rings are the most massive and spectacular**
- **Formation: a moon can't survive intact within the "Roche tidal zone"**
- **Ring systems may be short-lived, always changing**
  - Each chunk in Saturn's rings has a collision with another chunk every few hours!

# ***Main points: Giant Planet Moons***

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- ***What makes Io so volcanically active?***
  - **Tidal heating, caused by the tidal force of Jupiter as Io moves through its elliptical orbit, which in turn is caused by orbital resonances with Europa & Ganymede.**
- ***Why can active geology occur on much smaller worlds when they are made of ice rather than rock?***
  - **Ices soften and melt at much lower temperatures than rock, allowing icy volcanism and tectonics at surprisingly low temperatures.**
- ***Why do we suspect a subsurface ocean on Europa?***
  - **Photos show evidence of water flows on the surface, magnetic field measurements support the presence of a salty ocean, and there is enough tidal heating to melt a thick layer of ice beneath the surface.**