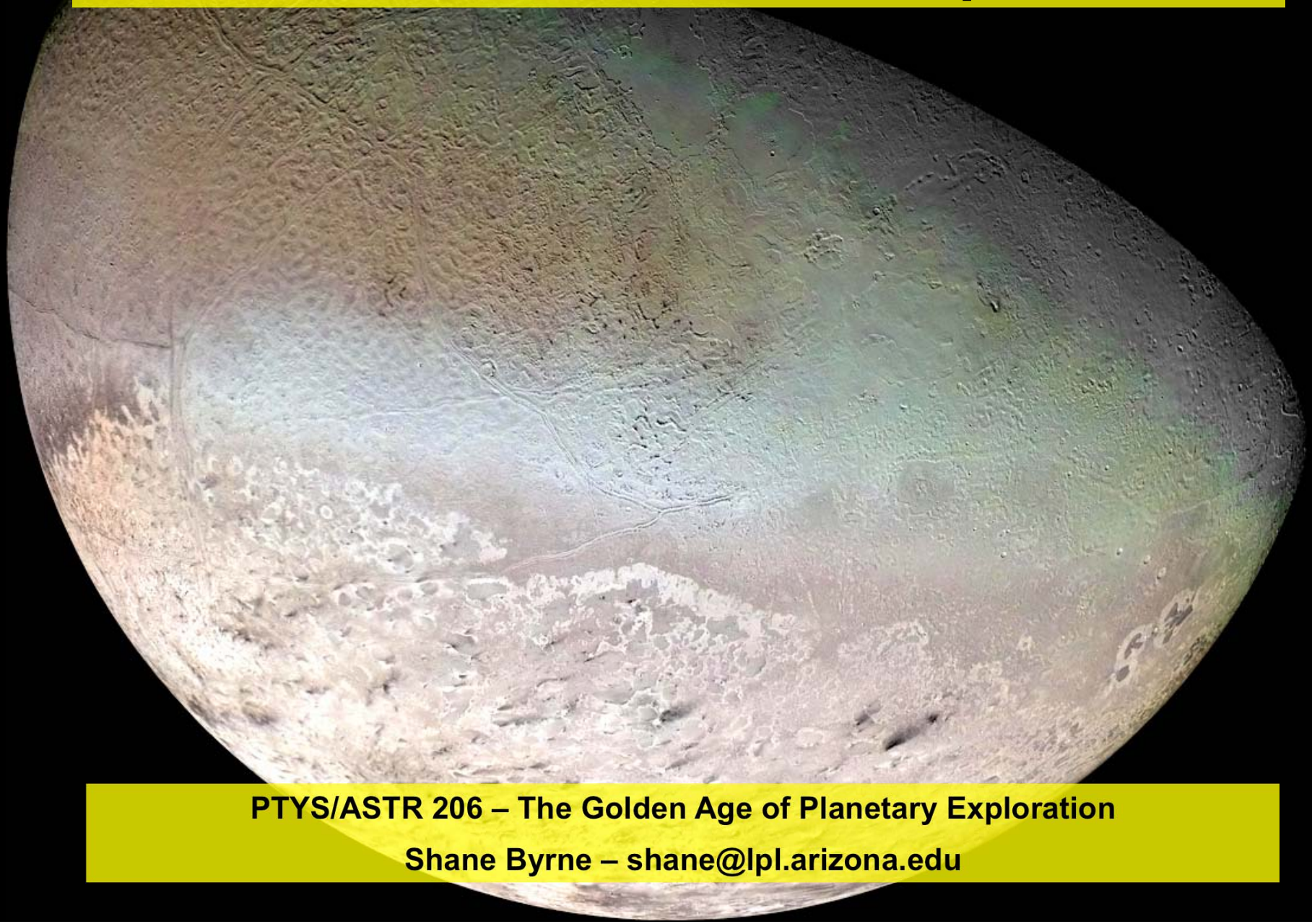
- **Announcements**
  - **HW5 due now**
  - **50% credit if submitted next Tuesday**

Moons of Uranus and Neptune

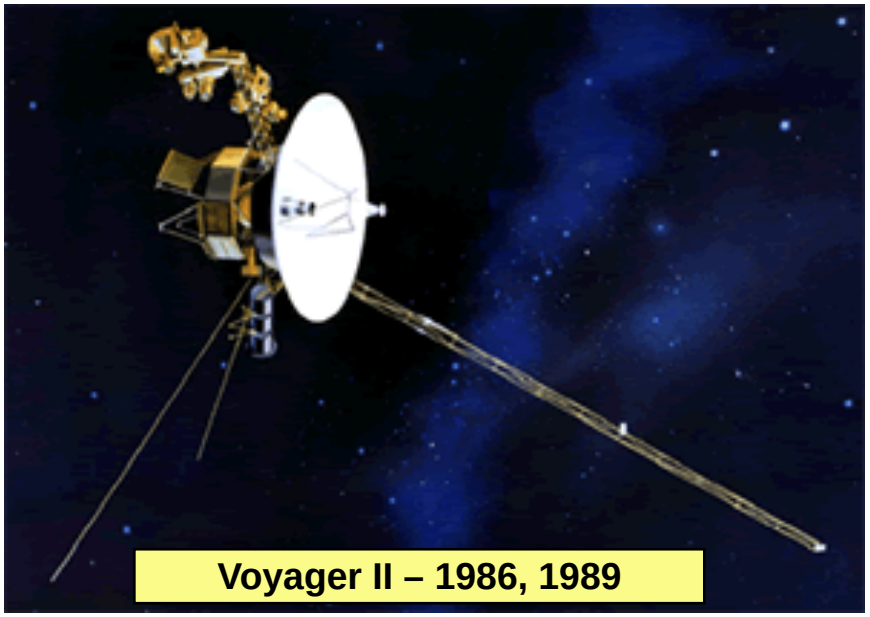


PTYS/ASTR 206 – The Golden Age of Planetary Exploration

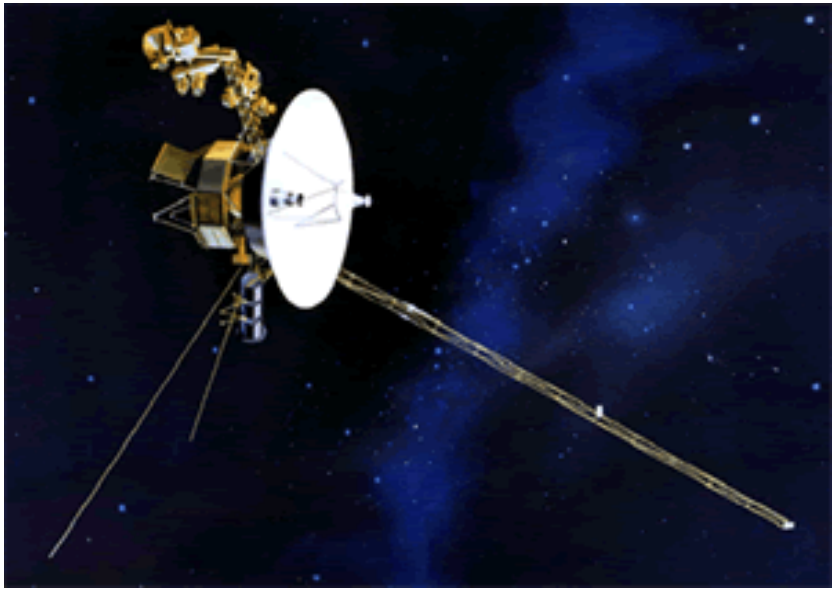
Shane Byrne – shane@lpl.arizona.edu

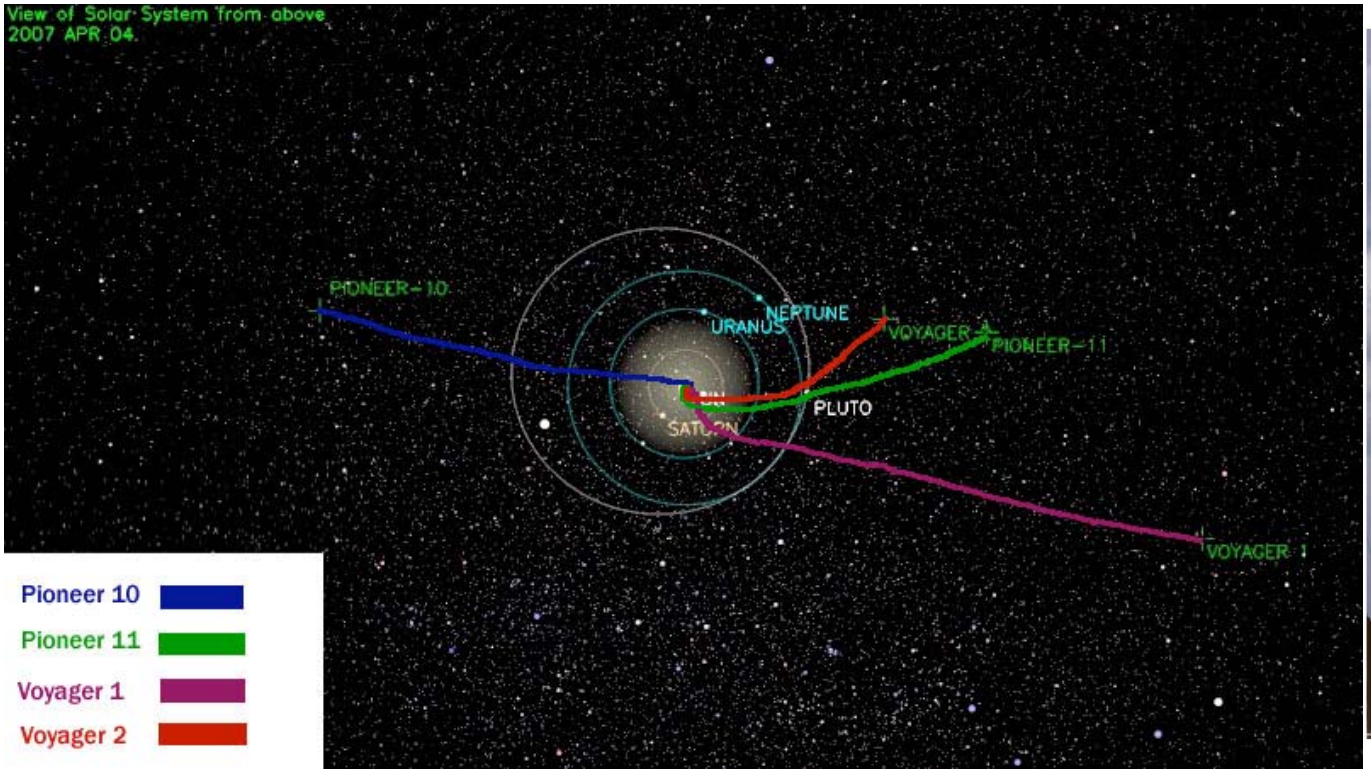
In this lecture…

- Voyager encounters
- Rocky again?
  - Where's the oxygen?
- Moons of Uranus
  - Geologic activity on some
  - Curious Miranda
- Moons (or lack of) around Neptune
  - Triton
  - Capture of Triton and its effects

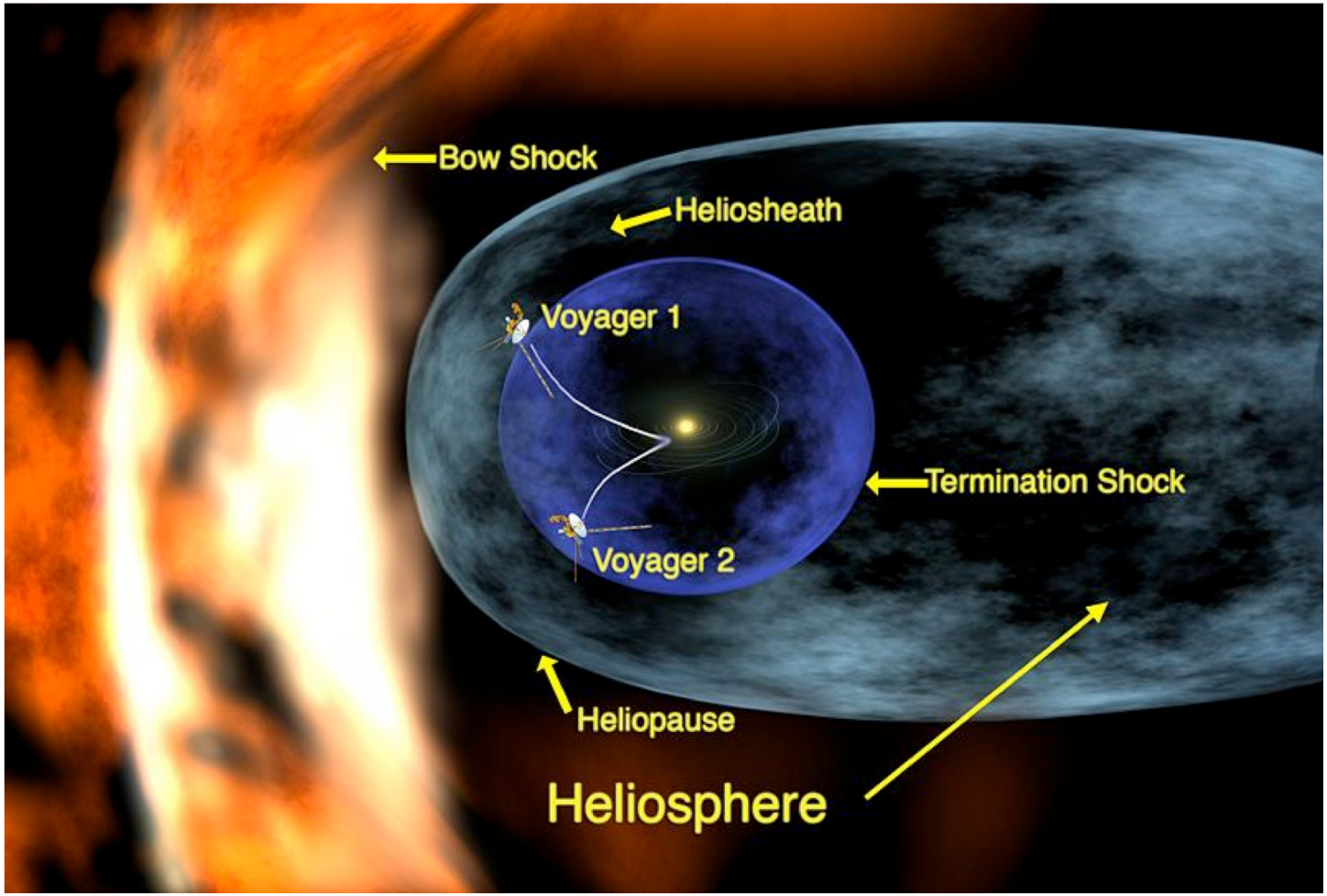

Voyager II – 1986, 1989

- Launched 1977
- Currently at 108 and 88 AU
- Speed ~16 km s^{-1}
- Most instruments now switched off
  - but there's still one thing left to do…

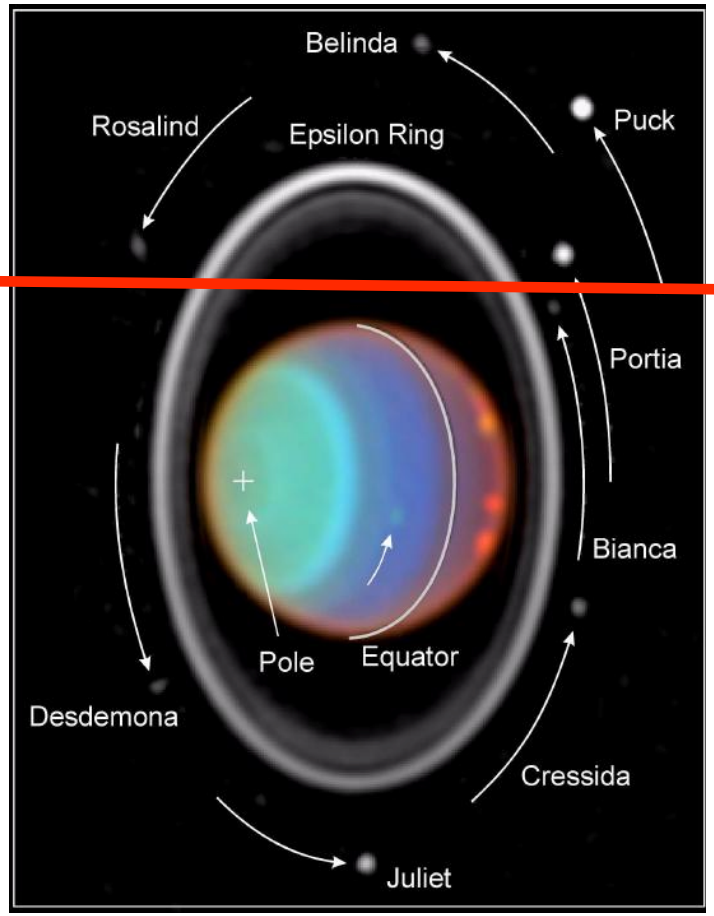




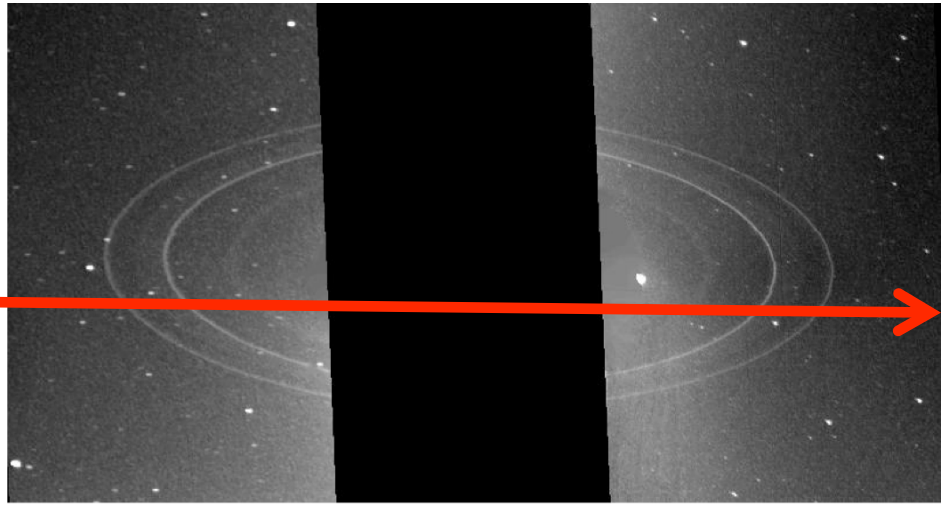
- Voyager I & II are about to become the first interstellar spacecraft
- The stream of particles coming from the sun stalls at the Heliopause
- Voyager I is starting to feel this, voyager II will follow soon
- Missions will probably end in the 2020s



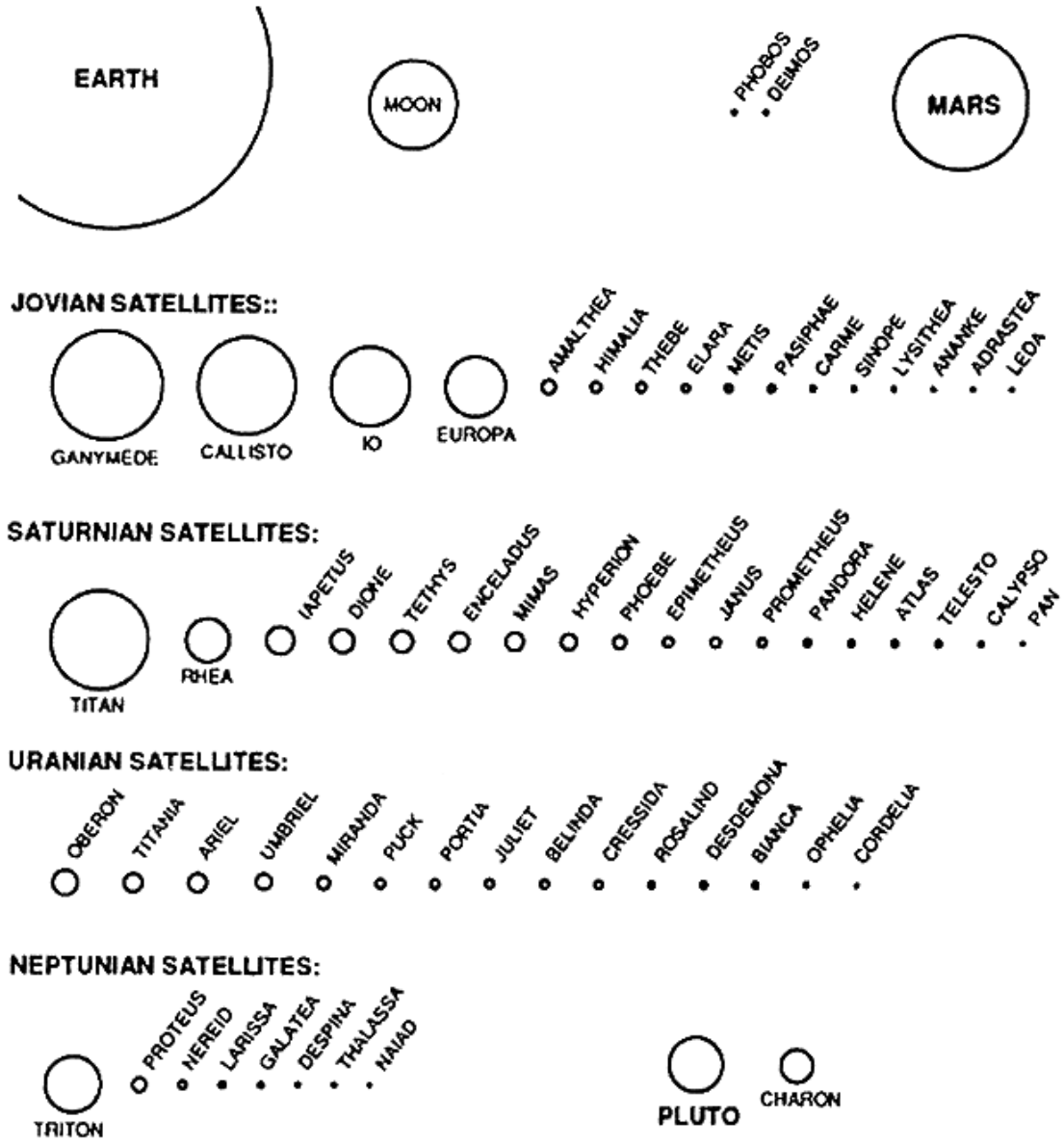
- **Voyager II flyby very different in each case**
  - **Uranus – Voyager passed through the equatorial plane**
    - **Got a good look at only one Moon**
  - **Neptune – Voyager passed along the equatorial plane**



Uranus 1986



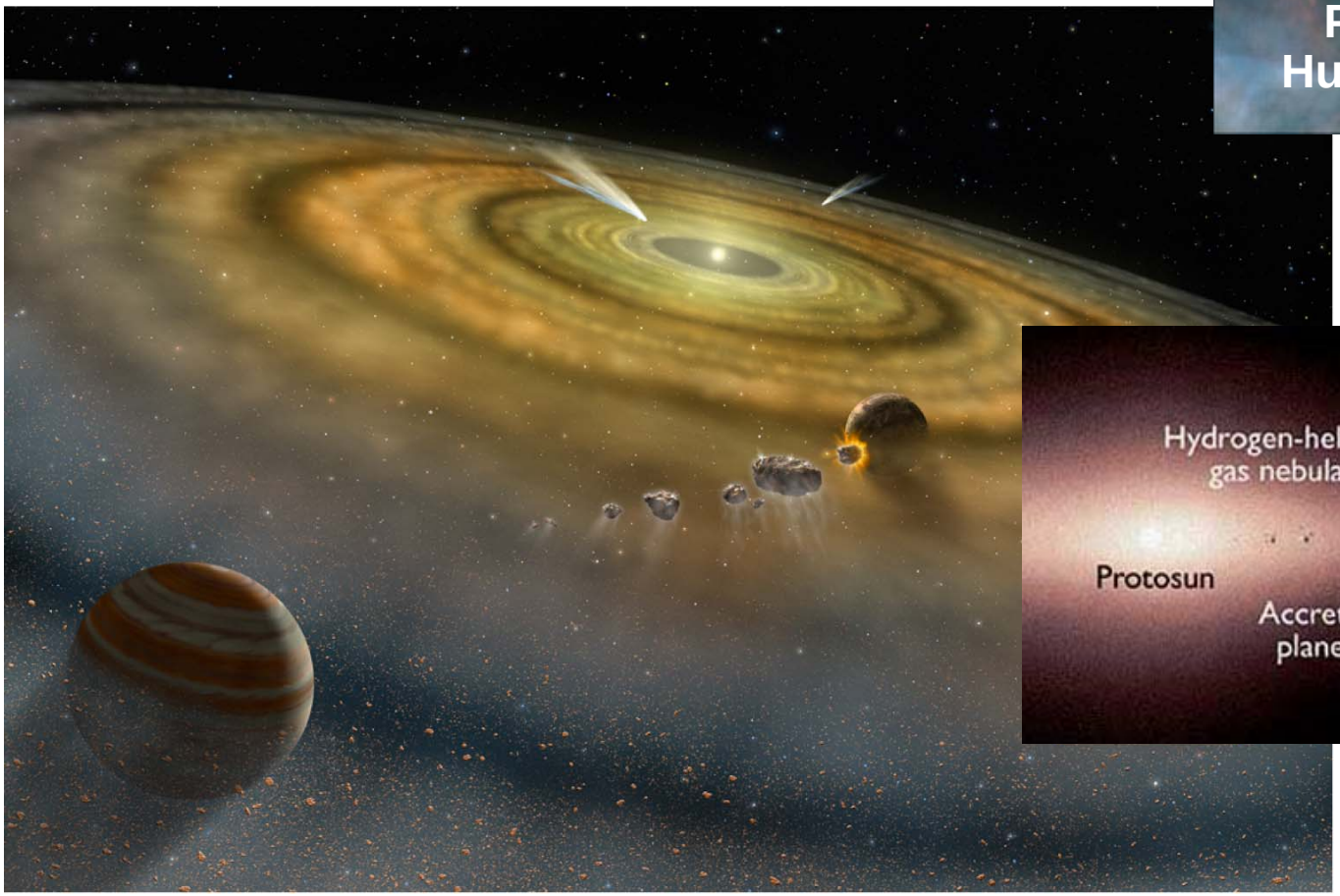
Neptune 1989

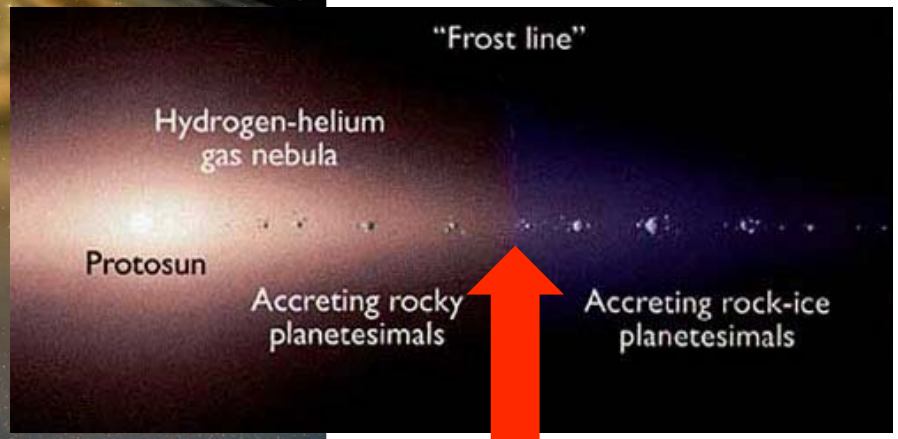


- **Uranian Moons small**
  - **13 inner moons among the rings**
  - **5 'mid-sized' satellites**
  - **~10 irregular, distant satellites**
  - **Named after characters from works of Pope & Shakespeare**

- **Neptune has very few Moons**
  - **Triton is pretty large**
  - **…and the reason why other moons are scarce**

- **Solar system formation**
  - **A disk dominated by hydrogen and helium**
  - **Warmer closer to the center**
    - **Inner planets iron rich and rocky**
    - **Outer planets get bulked up with water ice**





Transition in the asteroid belt

- **Jupiter forms like a mini solar system**
  - **Rocky bodies close in**
  - **Icy bodies further out**

	Distance (R_J)	Density Kg m^{-3}
Io	5.9	3530
Europa	9.4	3020
Ganymede	15	1940
Callisto	26.4	1850

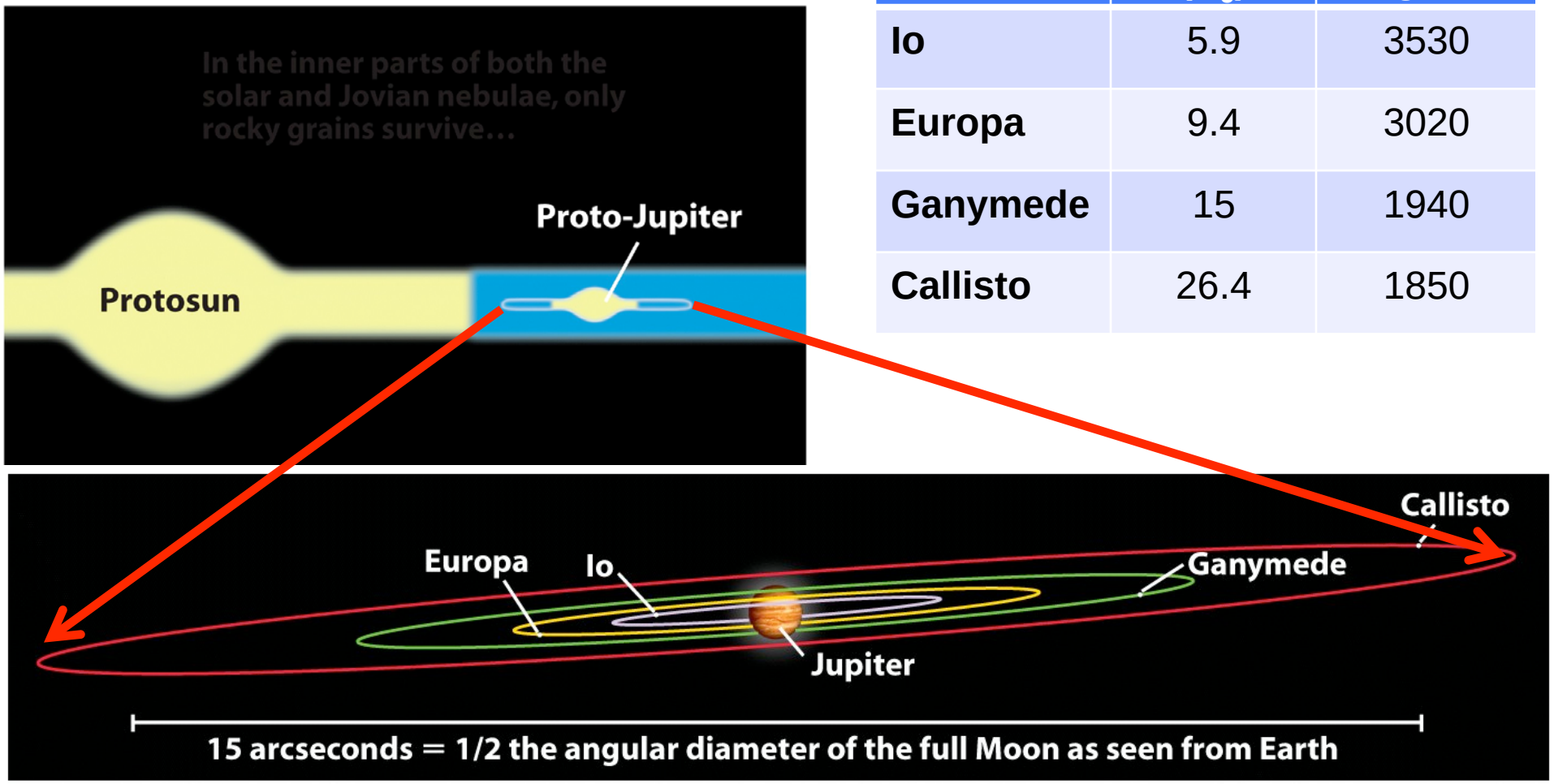
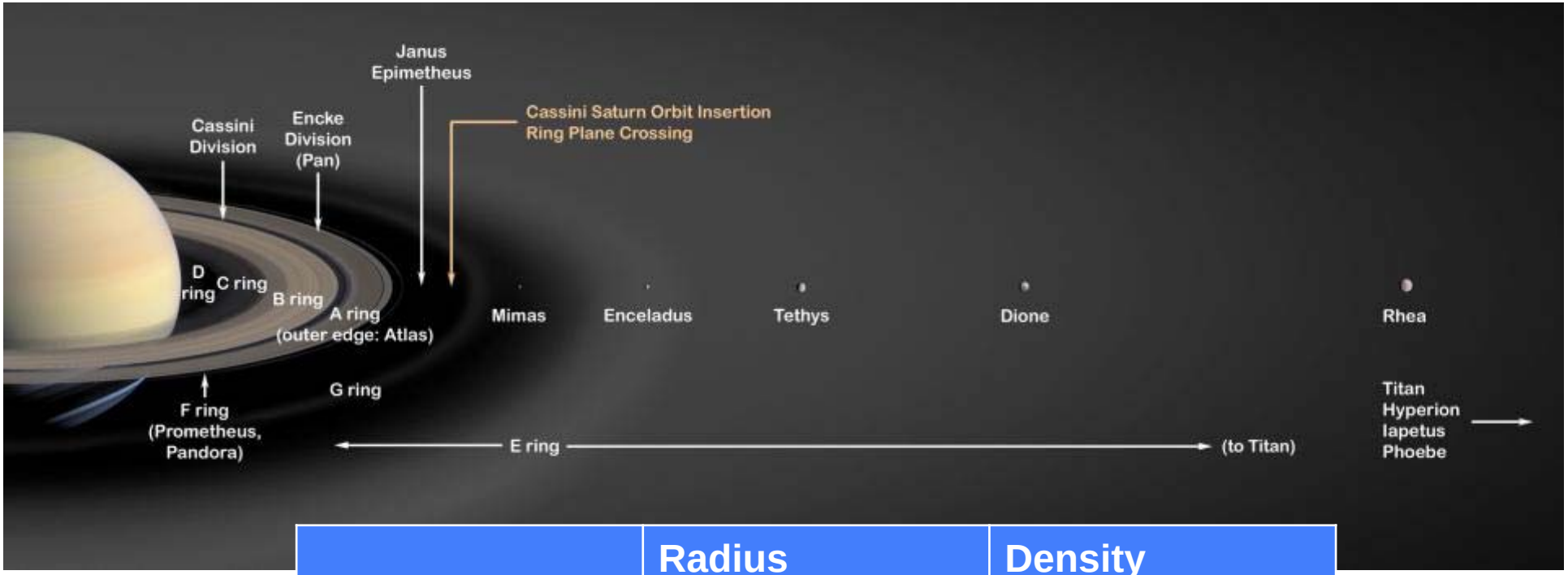


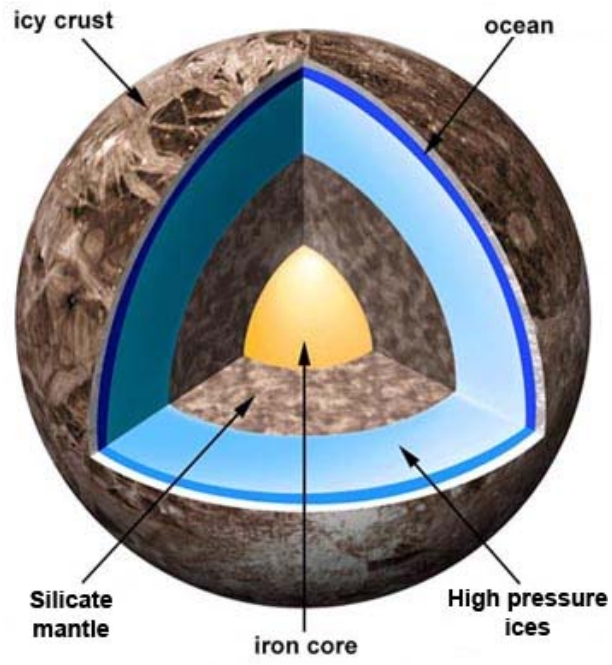
Figure 13-1
Universe, Eighth Edition

- **Saturn's satellites are mostly icy**



	Radius	Density
Mimas	196 km	1170 kg m^{-3}
Enceladus	250 km	1600 kg m^{-3}
Tethys	530 km	970 kg m^{-3}
Dione	560 km	1480 kg m^{-3}
Rhea	764 km	1230 kg m^{-3}
Iapetus	720 km	1034 kg m^{-3}

- **Inner solar system** ➔ **All Rock**
- **Jupiter's Moons** ➔ **Rock and Ice**
- **Saturn's Moons** ➔ **Mostly ice**
- **Uranus/Neptune's Moons** ➔ **??**

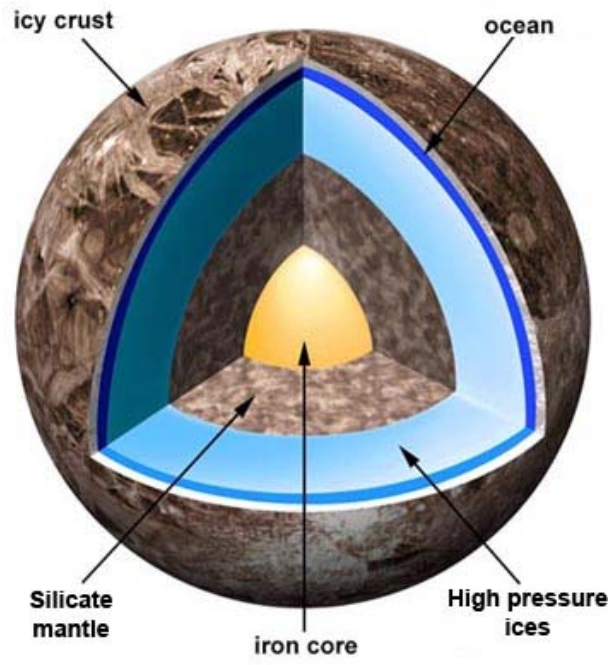


Ganymede (Jupiter)

Iapetus (Saturn)

Titania (Uranus)

- **Inner solar system** ➔ **All Rock**
- **Jupiter's Moons** ➔ **Rock and Ice**
- **Saturn's Moons** ➔ **Mostly ice**
- **Uranus/Neptune's Moons** ➔ **Less ice….**



Ganymede (Jupiter)

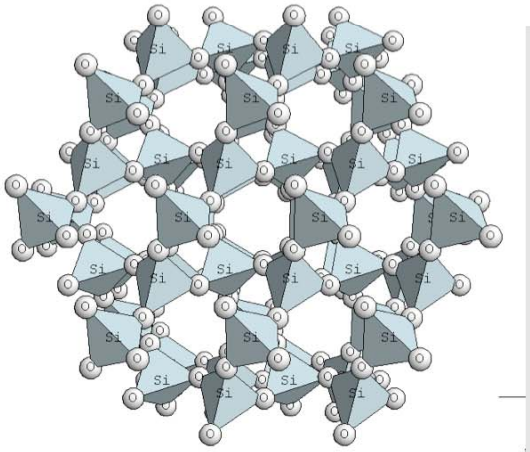
Iapetus (Saturn)

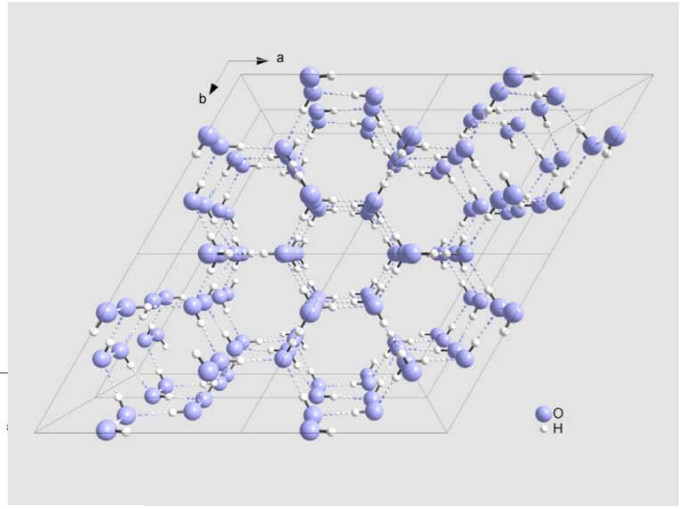
Titania (Uranus)

- **Uranus satellites have more rocky stuff… not less**
  - **How did that happen??**
  - **Miranda is an exception**

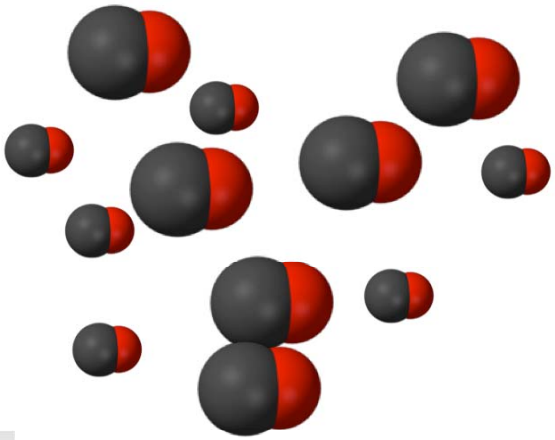
	Titania	Ariel	Oberon	Umbriel
Diameter	**1580km**	**1158km**	**1525km**	**1170km**
Density	**1700 kg m^{-3}**	**1700 kg m^{-3}**	**1600 kg m^{-3}**	**1400 kg m^{-3}**

- **What happens to oxygen…**
  - **In the inner solar system it makes rocks – Si O_4**
  - **At Jupiter/Saturn it makes more water ice – H_2 O**
  - **At Uranus/Neptune it makes carbon monoxide – C O**





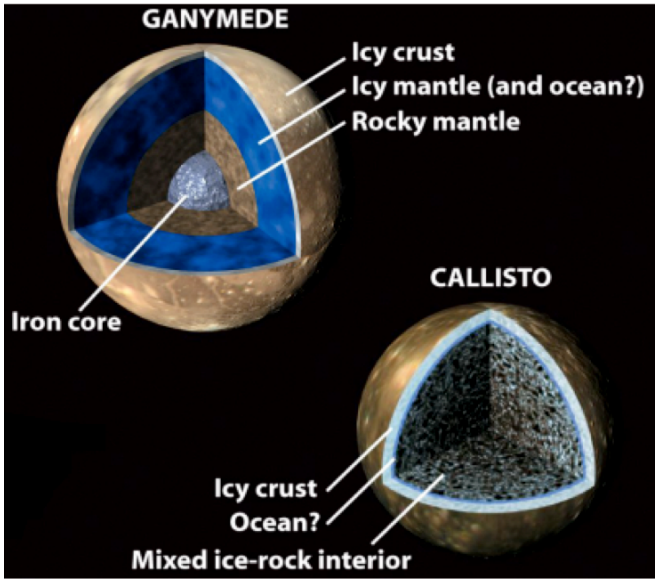
Decreasing Temperature



CO Freezes only at 68K

Carbon monoxide ice on Pluto and comets etc…

- The result is that satellites of Uranus (and Neptune) are
  - Small
  - Have a higher proportion of rocky material than at Saturn
  - Satellites of Uranus are 50-65% rock

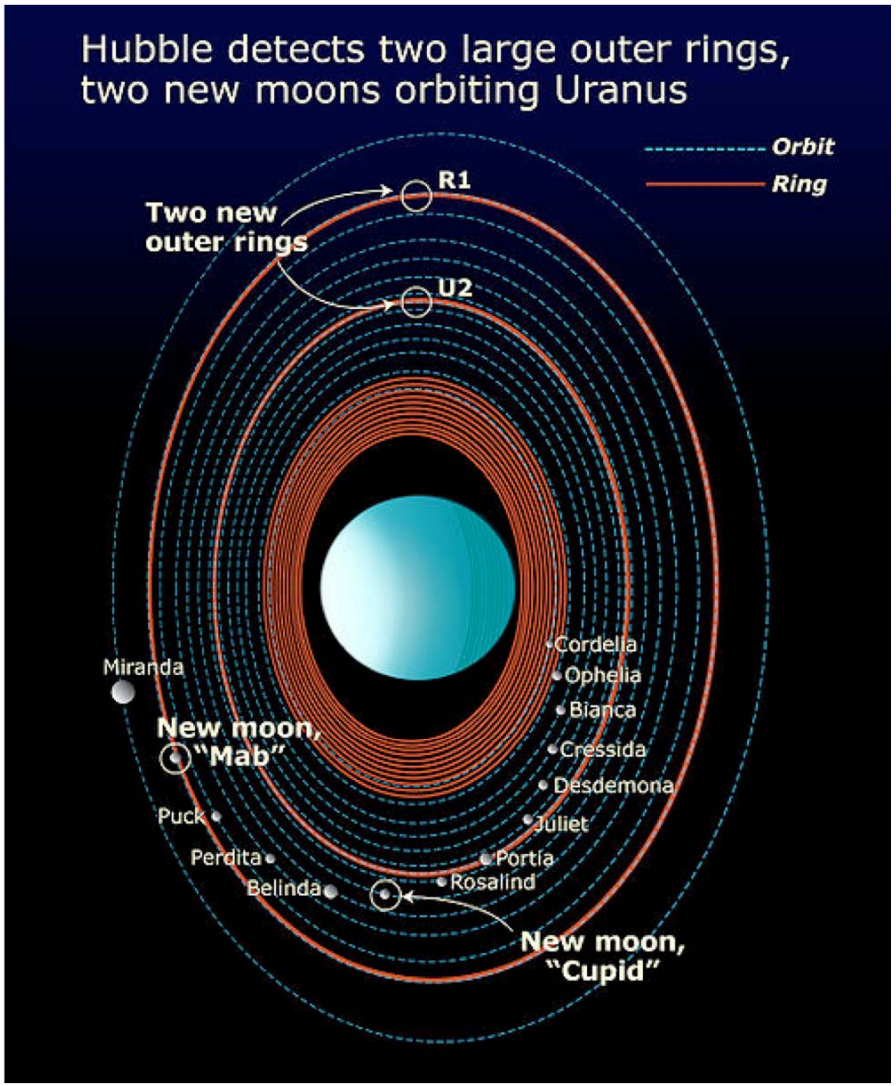


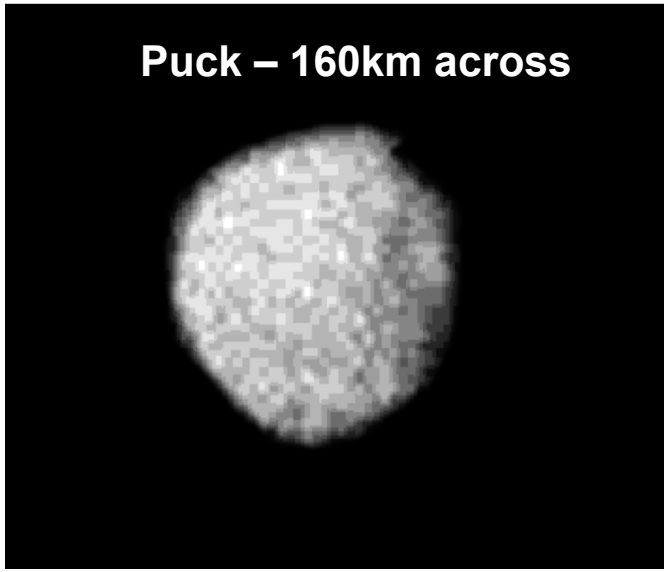
- We don't know if they're differentiated
- Not too dissimilar from Ganymede & Callisto
  - Except they're small
  - Probably no iron core
- The same happens for various other elements
  - Less important than Oxygen

	Warmer Jupiter ~ 5AU Saturn ~10 AU	Cooler Uranus ~19 AU Neptune ~30 AU
C	CH_4	CO
O	H_2O	CO
N	NH_3	N_2

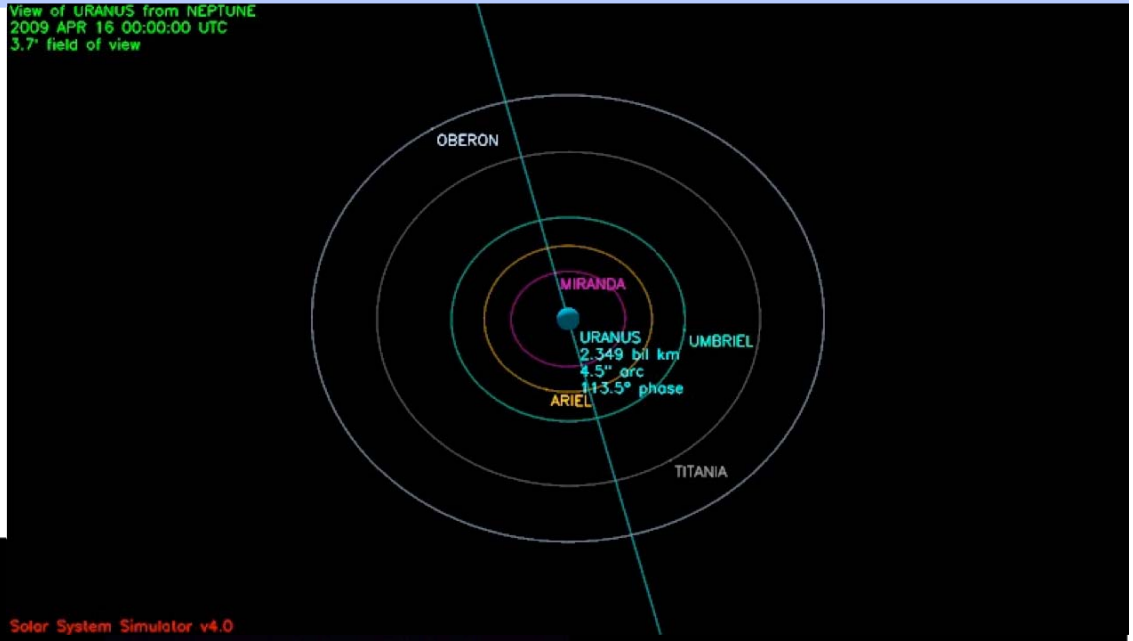
Moons of Uranus

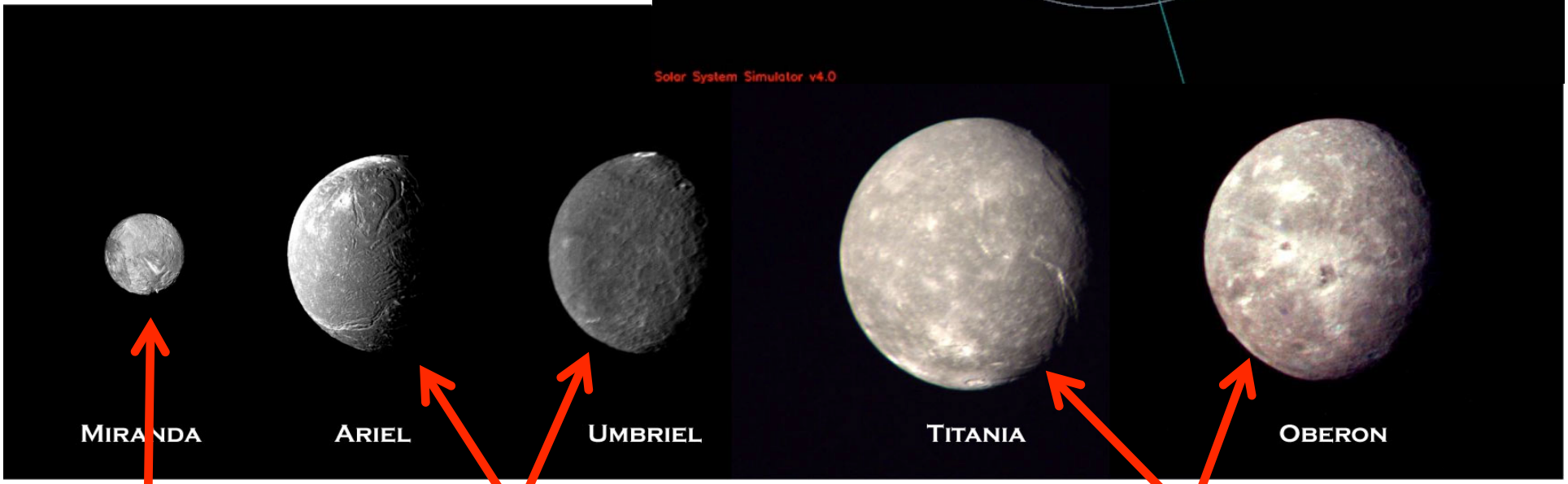
- Uranus has 13 inner moons
  - Very dark objects, albedo < 10% (like the rings themselves)
  - Water-ice coated with organic compounds
  - Cordelia and Ophelia shepherd the ε ring
  - Mab is a source of Uranus's outermost μ ring
  - Rings probably generated by moon-moon collisions





- There are five much larger ‘regular’ satellites
  - Encounter geometry means that only one satellite was well imaged
  - The south-polar region of each Moon was seen





470km

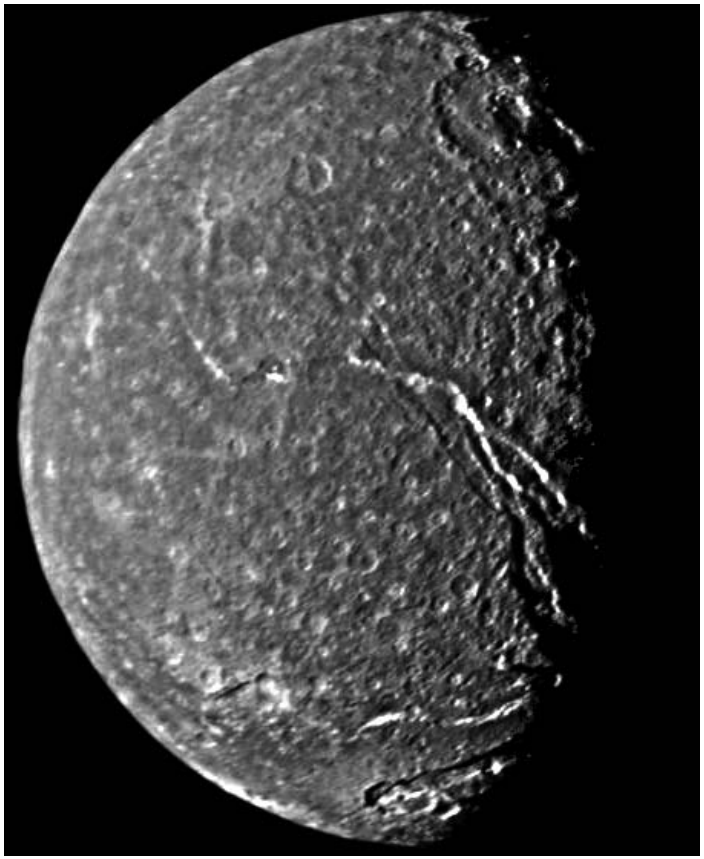
Good pictures from Voyager

1100-1200 km

1500-1600 km

Not so good pictures from Voyager

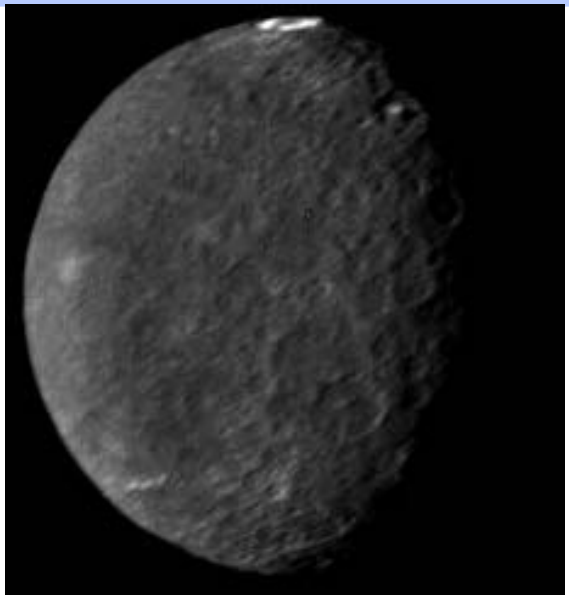
- Oberon and Titania: ~1500km across
- Oberon
  - Poor imaging
  - Large craters visible
    - Bright ejecta
    - Dark floor deposits



- Titania
  - Fault bounded canyons
  - Massive extension
    - Shrinking surface layer
    - Expanding core
  - Faults cross-cut impact craters
  - Fewer large crater than Oberon

- Similar in size to Rhea at Saturn
  - …but much more activity here
  - Higher silicate levels provide more heat

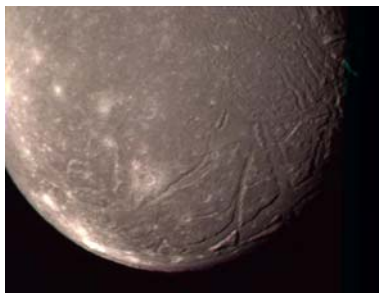
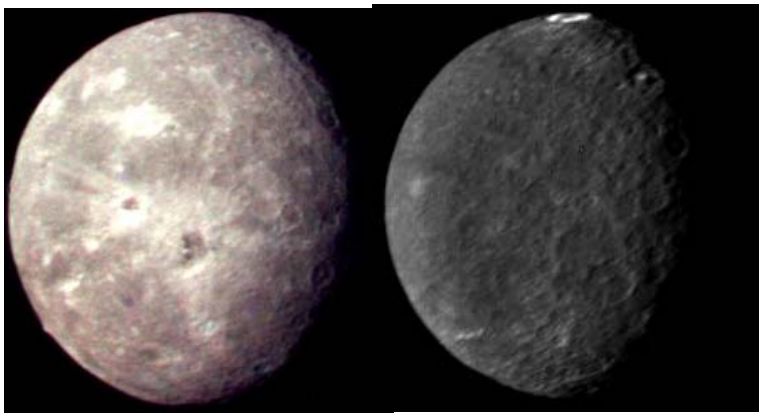
- Umbriel and Ariel: ~1100km across
- Umbriel
  - Craters are the only landform
  - No endogenic geology visible
  - Volatiles concentrated in polar regions



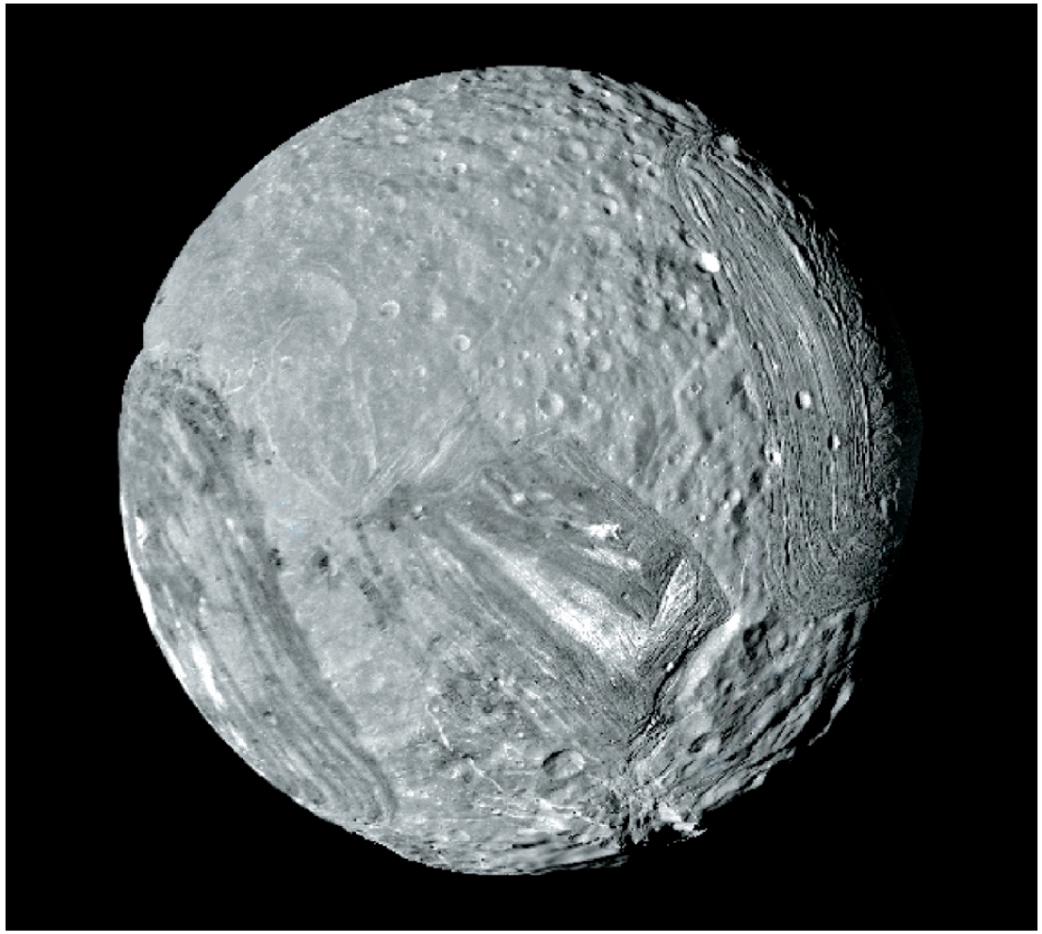
- Ariel
  - Extensive network of fault bounded canyons
  - Canyon floors resurfaced by viscous flows
    - Upbowing cross-sections with central sinuous troughs
  - Mix of surface ages implies long-lived activity
  - Tidal heating in the past ??

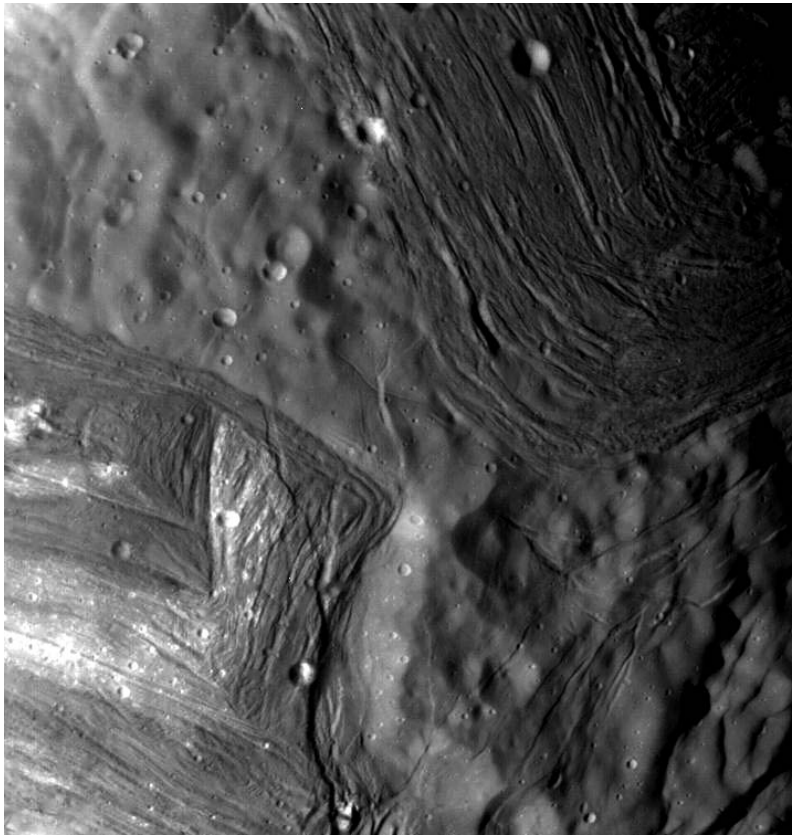
- **Density not size determines amount of activity**
  - **Higher density caused by having more rock**
  - **More rock means more heat from radioactive elements**
- **Past tidal heating also a possibility**

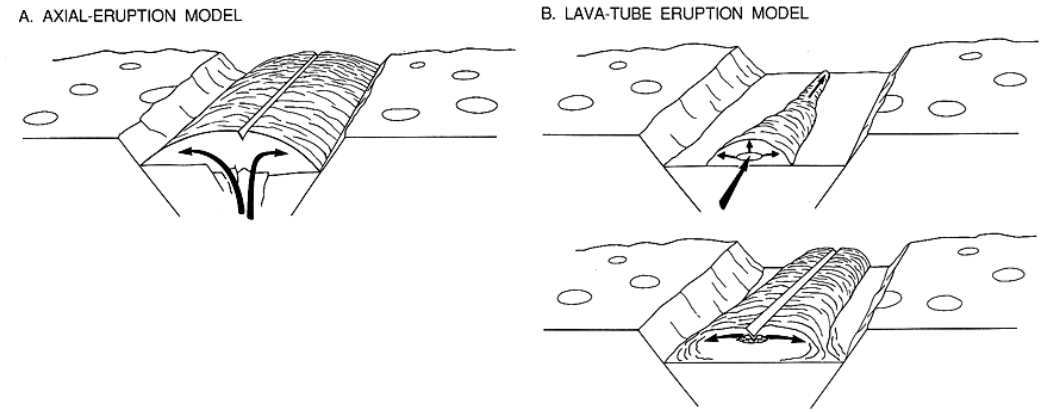
	Active		Inactive	
	Titania	Ariel	Oberon	Umbriel
Diameter	1580km	1158km	1525km	1170km
Density	1700 kg m^{-3}	1700 kg m^{-3}	1600 kg m^{-3}	1400 kg m^{-3}
Albedo	0.3	0.4	0.2	0.2

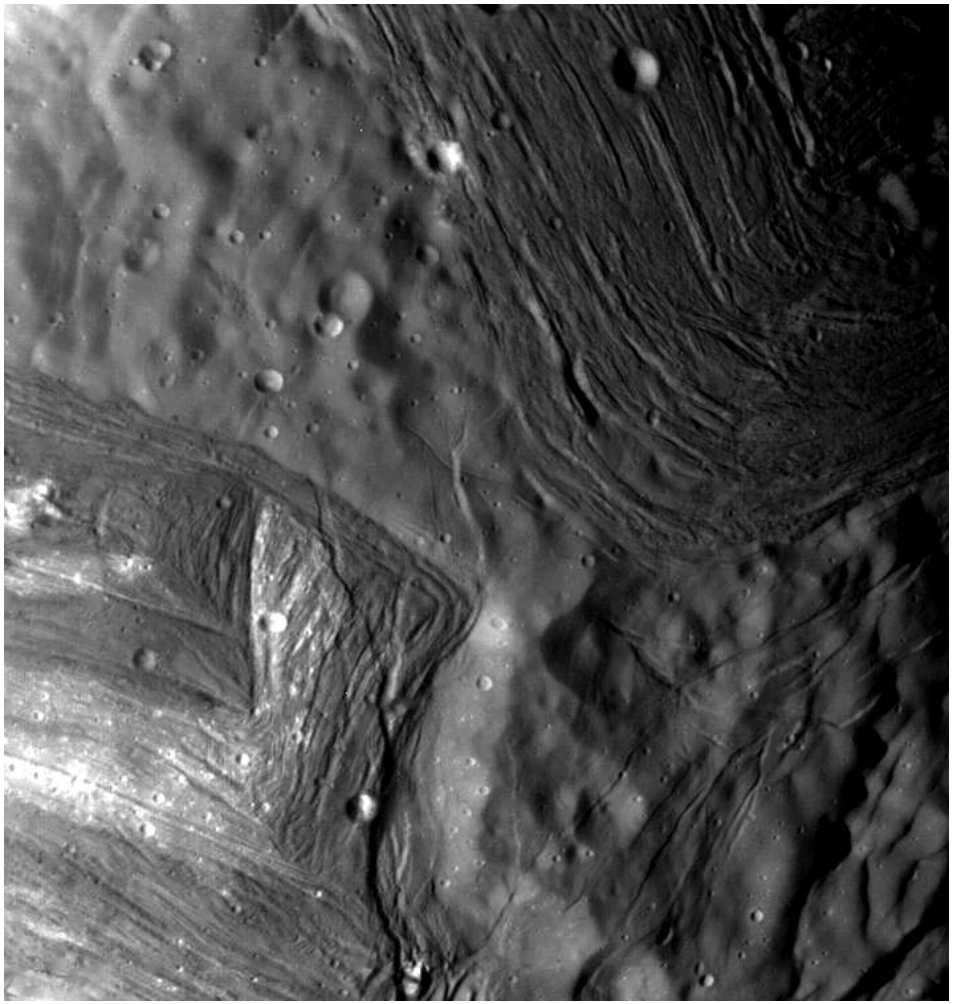
- **Miranda: 472km across**
  - **Discovered by Kuiper, 1948**
  - **Old cratered plains – uniform**
  - **Coronae**
    - **Tectonic disruption of surface**
    - **Infilling with very viscous magmas**





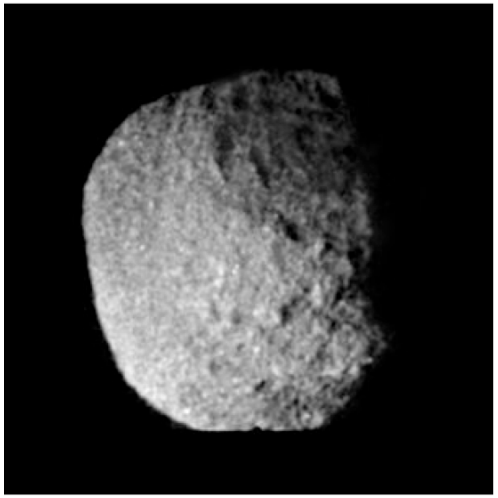


- **Small size makes activity hard to explain**
  - **Low density means little rock**
  - **…and little radiogenic heat**
  - **Energy must have been tidal**
  - **Resonance with Umbriel might also explain Miranda's 4º orbital inclination**
- **System may have slipped out of a resonance that Europa and Io have today**
  - **Pulled the plug on Miranda's geologic activity**

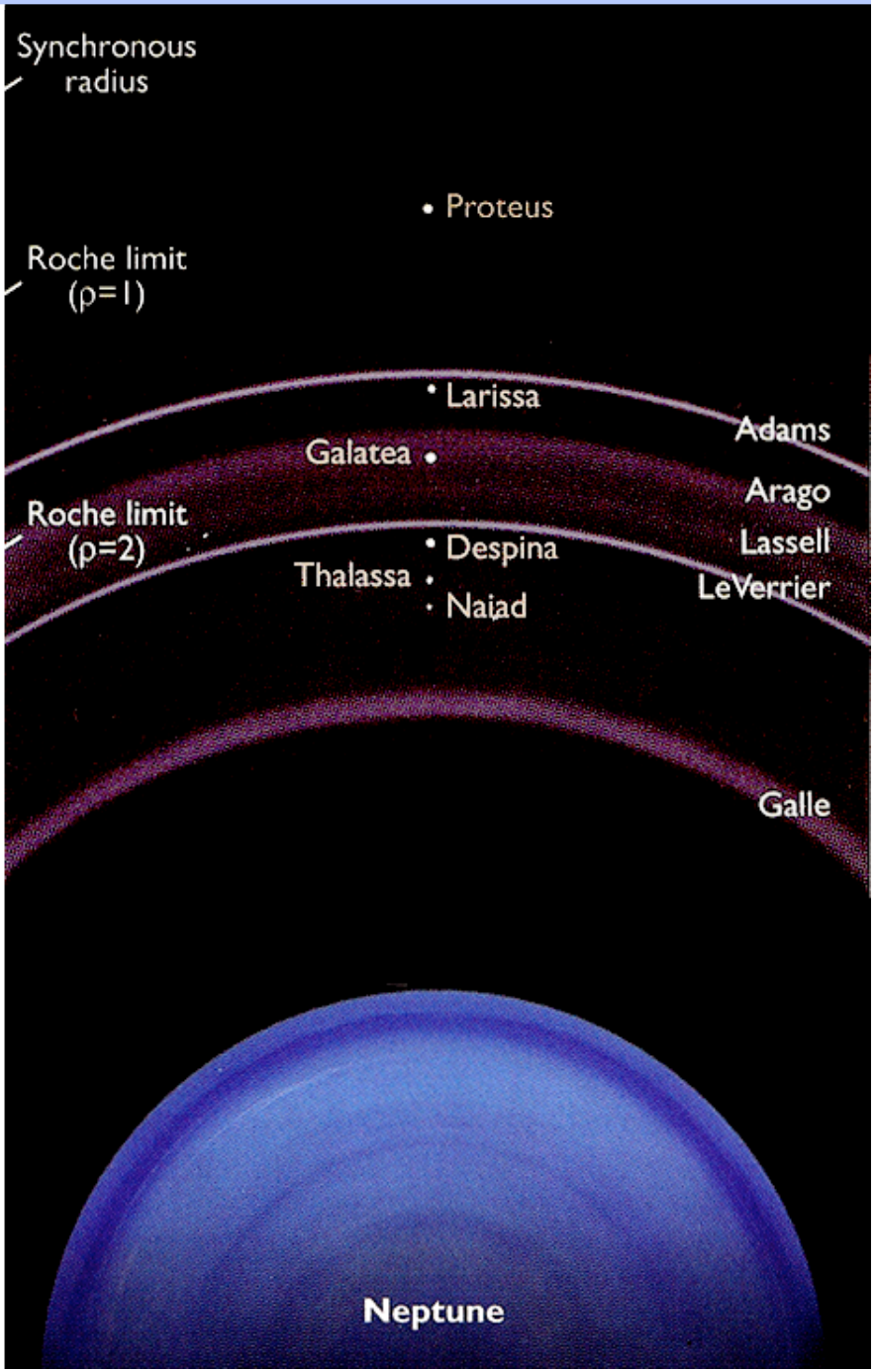


Moons of Neptune

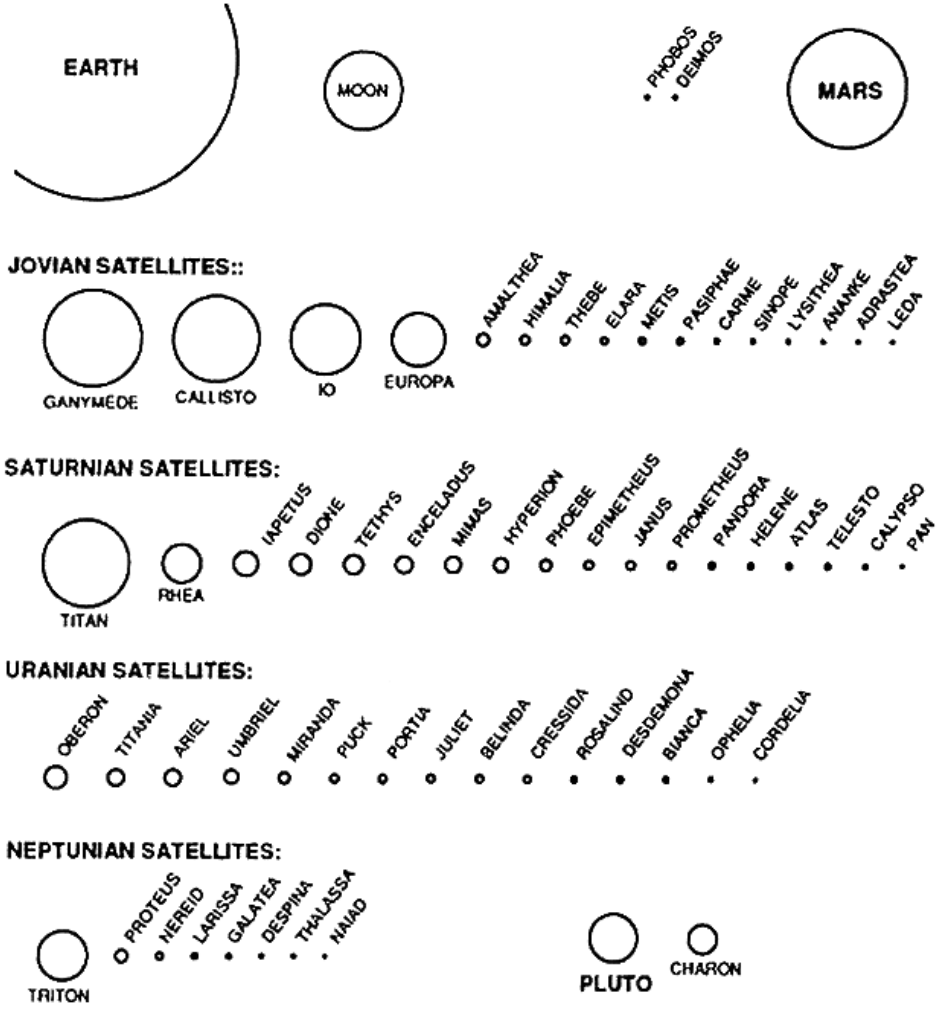
- **Small inner satellites**
  - **Largest is Proteus – 400km in diameter**



  - **Other inner satellites herd ring particles**



- **Neptune's moons are most famous for… not being there**
  - **Outside 5 Neptune radii there are only two moons – Triton and Nereid**
  - **Why so few moons? – It's all Triton's fault**



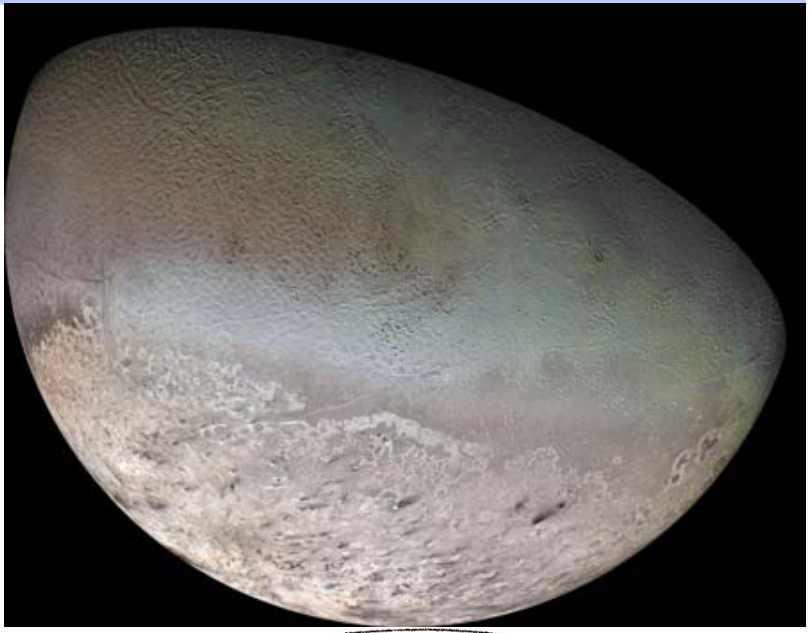
Triton

table 7-2 The Seven Giant Satellites

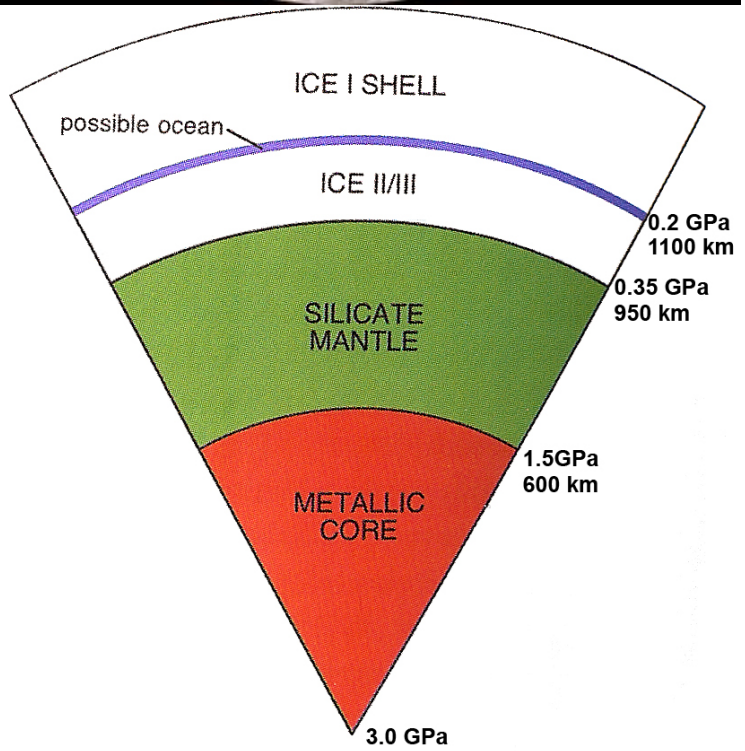
	Moon	Io	Europa	Ganymede	Callisto	Titan	Triton
Parent planet	Earth	Jupiter	Jupiter	Jupiter	Jupiter	Saturn	Neptune
Diameter (km)	3476	3642	3130	5268	4806	5150	2706
Mass (kg)	7.35×10^{22}	8.93×10^{22}	4.80×10^{22}	1.48×10^{23}	1.08×10^{23}	1.34×10^{23}	2.15×10^{22}
Average density (kg/m^3)	3340	3530	2970	1940	1850	1880	2050
Substantial atmosphere?	No	No	No	No	No	Yes	No

(JPL/NASA) R I V U X G

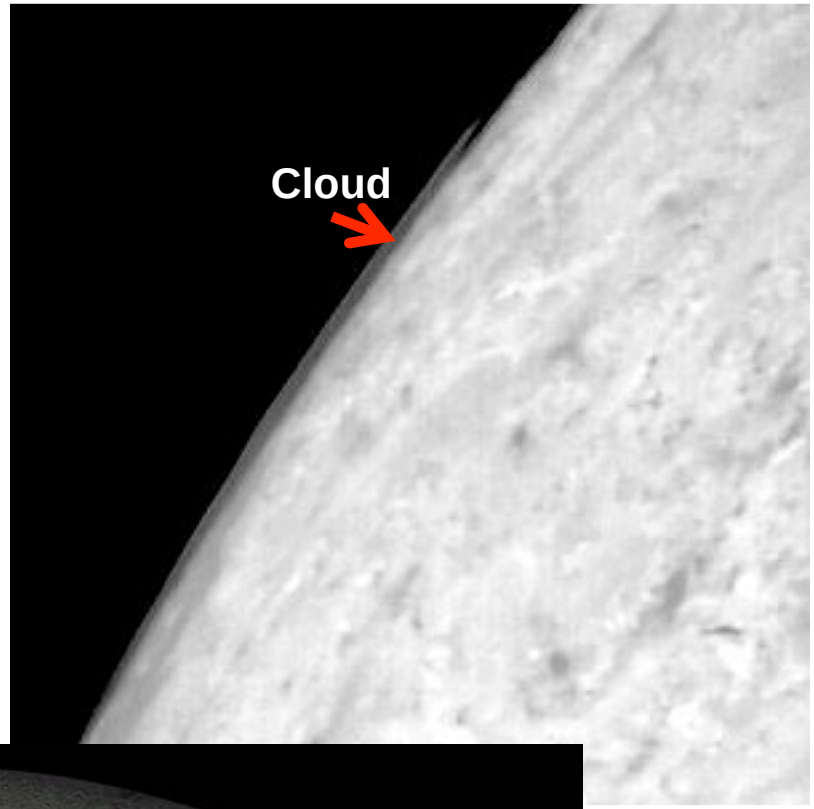
That's a bit unfair. Triton has a thin nitrogen atmosphere



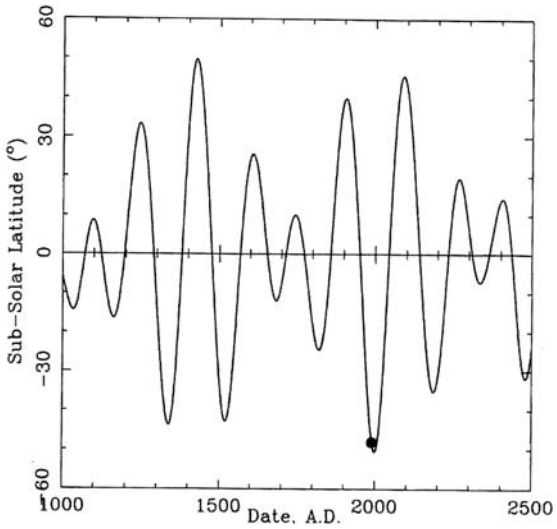
- **Perfectly circular orbit (14.33 R_N)**
  - **No current tidal heating**
  - **Retrograde orbit**
  - **Density – 2050 kg m^{-3}**
- **Spiraling inward**
  - **Will reach the Roche limit in ~3.6 billion years**
- **Structure probably close to Ganymede**
  - **Complete differentiation**
  - **Ice I shell thickening downwards**
  - **Ice II/III shell thickening upwards**
  - **Sandwiched ocean expected**

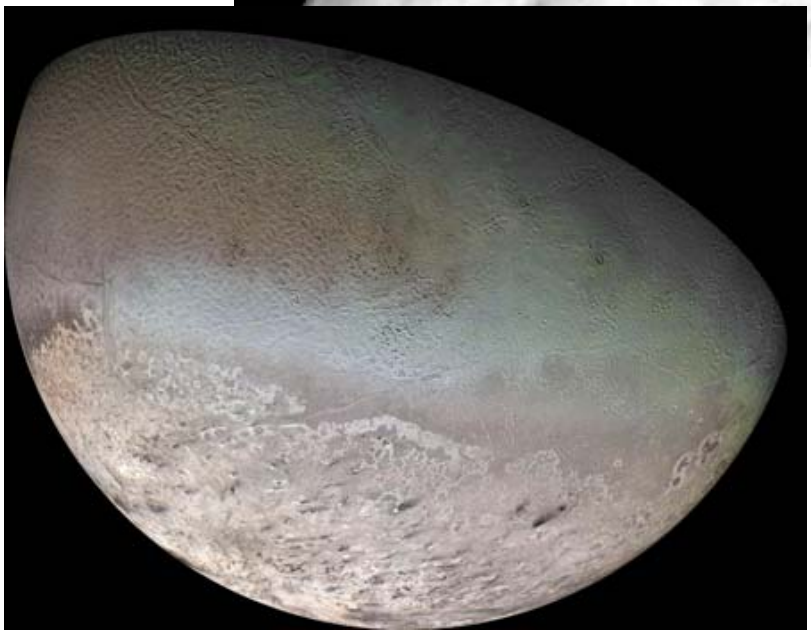


- **Triton has a thin nitrogen atmosphere**
  - **Pressure is 19 micro-bars**
  - **1/50000th of Earth's pressure!**

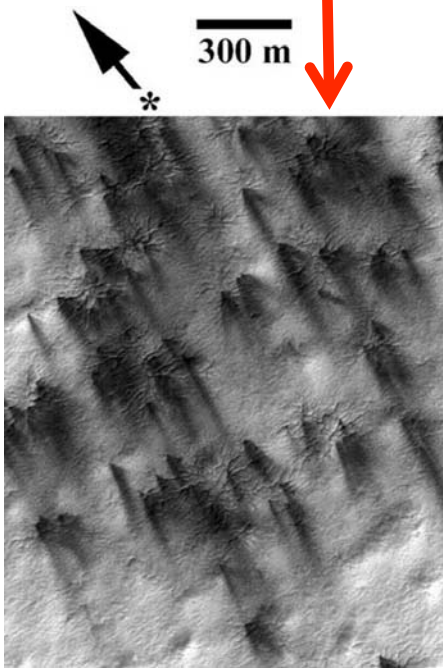


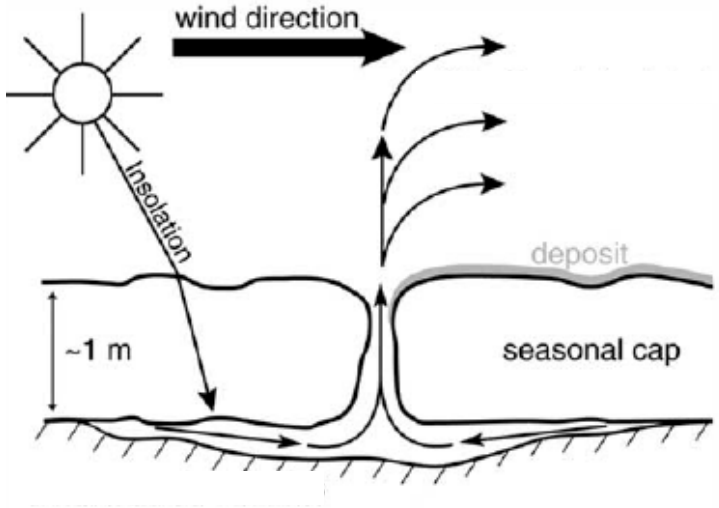
- **High reflectivity (~85%)**
  - **Very cold surface 38-39 K**
  - **Nitrogen freezes into ice in the winter polar regions**
  - **Sublimates back into a gas in the summer polar region**
  - **Very similar to CO_2 on Mars**



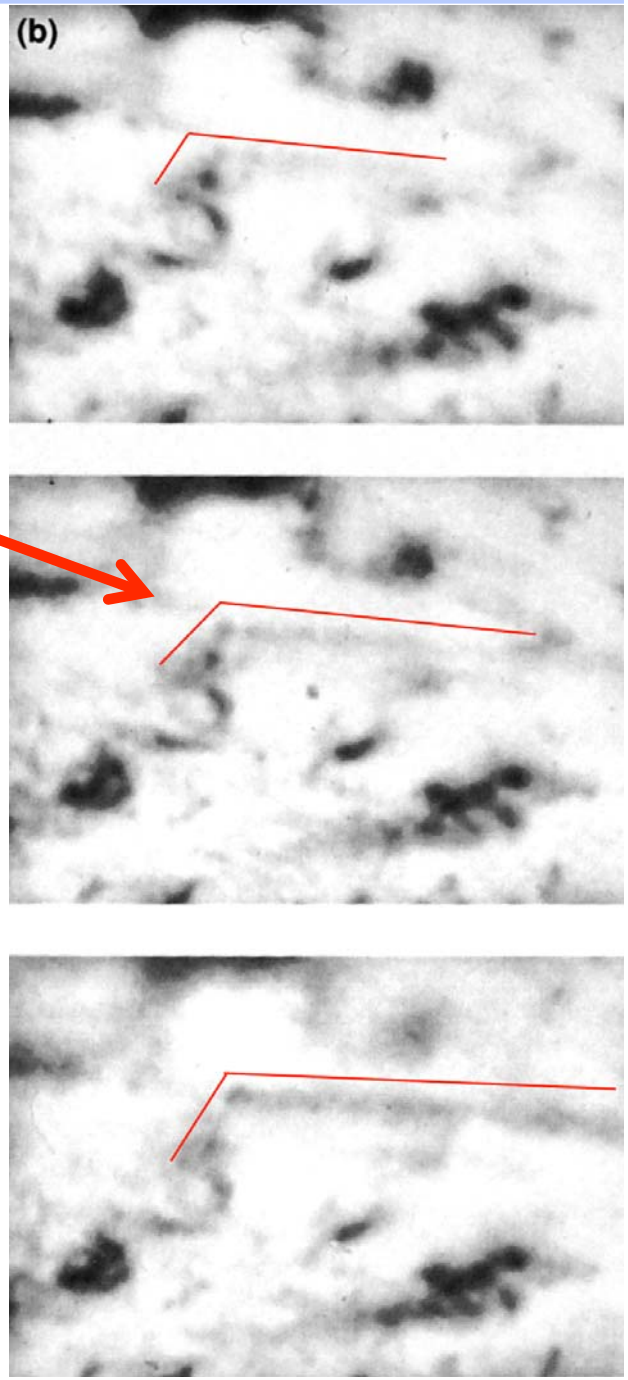


- N_2 ice quickly anneals into a transparent layer
  - Seasonal frost → transparent slab
- Incident solar radiation absorbed beneath the ice
  - Subsurface sublimation
  - Nitrogen gas escapes in jets (~8km high)
    - Implies a 230 m s^{-1} flow!
  - Similar to CO_2 jets on Mars

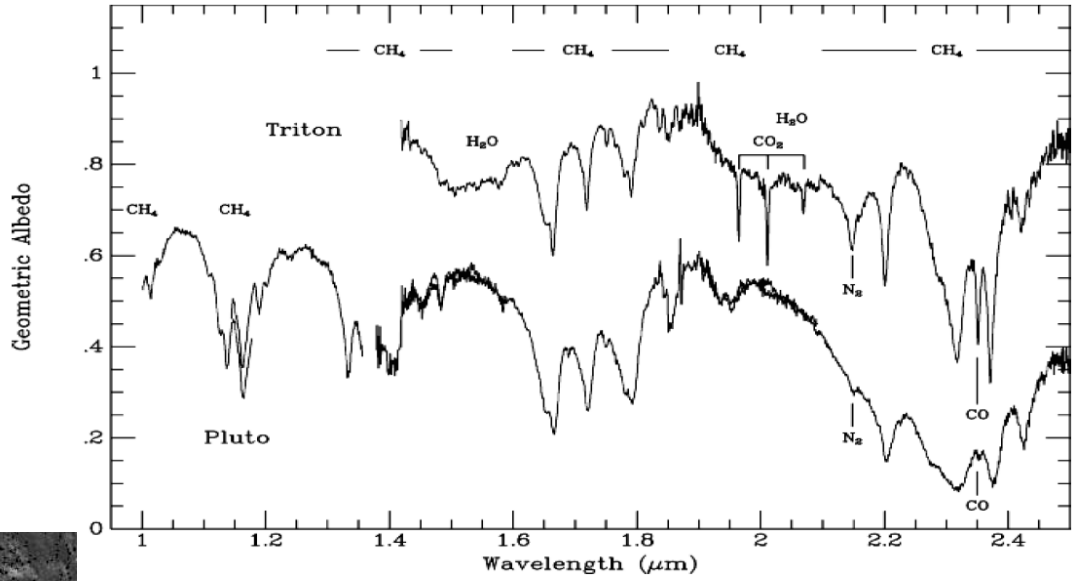


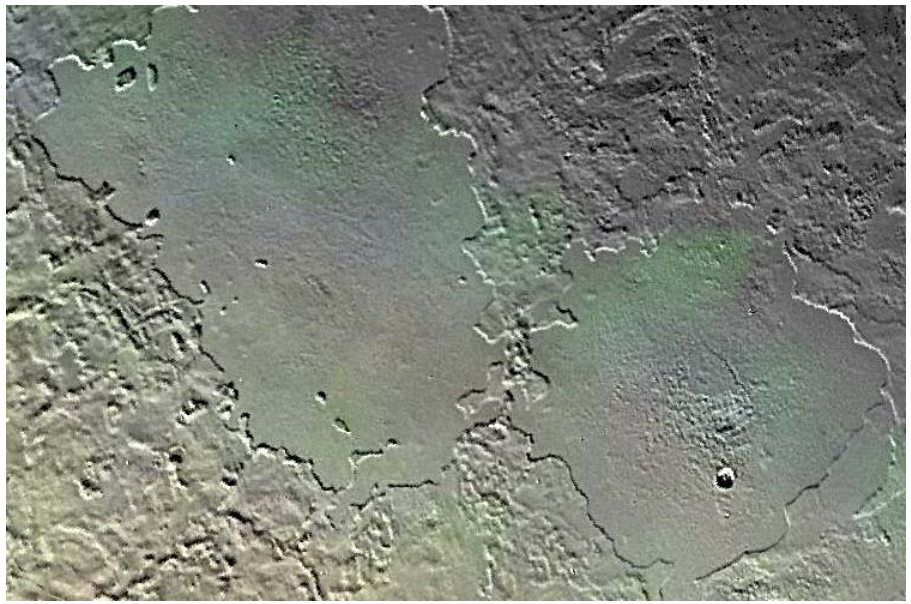


Piqueux et al., 2003



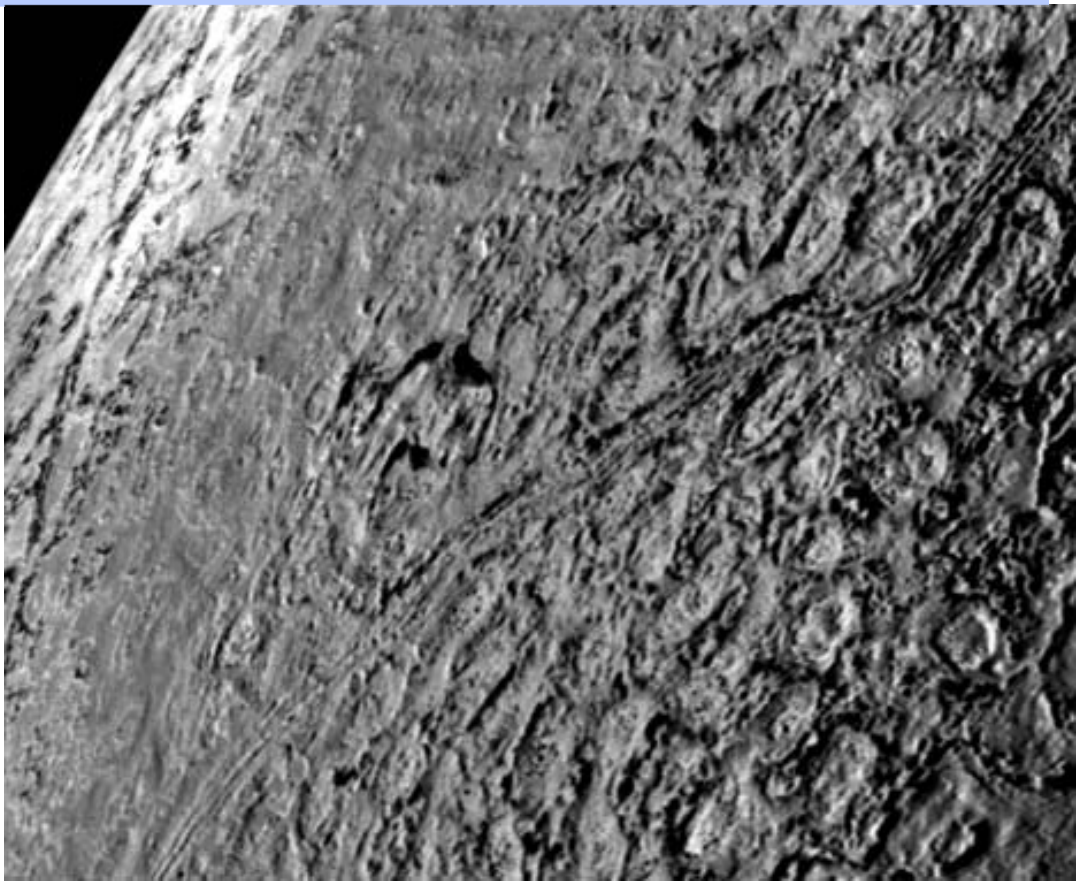
- **Surface composition similar to Pluto and Kuiper belt objects**
  - **Nitrogen, Carbon monoxide and methane ices**
  - **'Bedrock' is water and carbon dioxide ices**

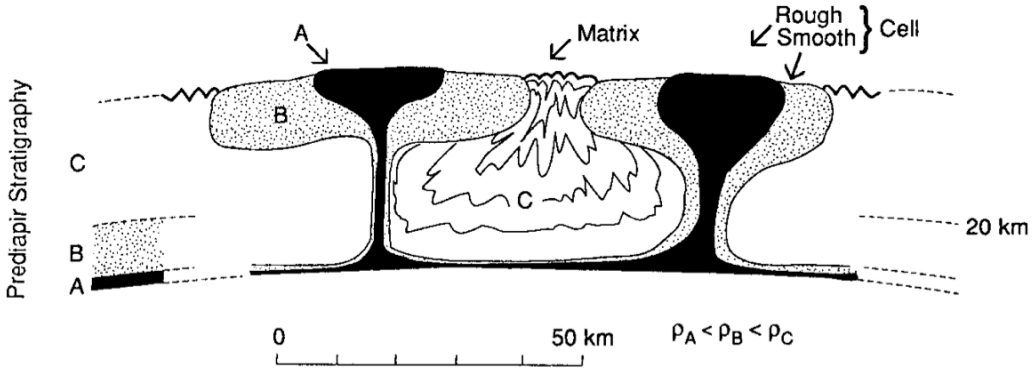




- **Lots of evidence for cryovolcanism**
  - **Water mixed with ammonia so that it can stay liquid**

- ‘Cantaloupe’ terrain
  - Close packed elliptical features
  - Regularly spaced
  - Non-overlapping
- Rising blobs of low density ice
  - ‘Diapirs’



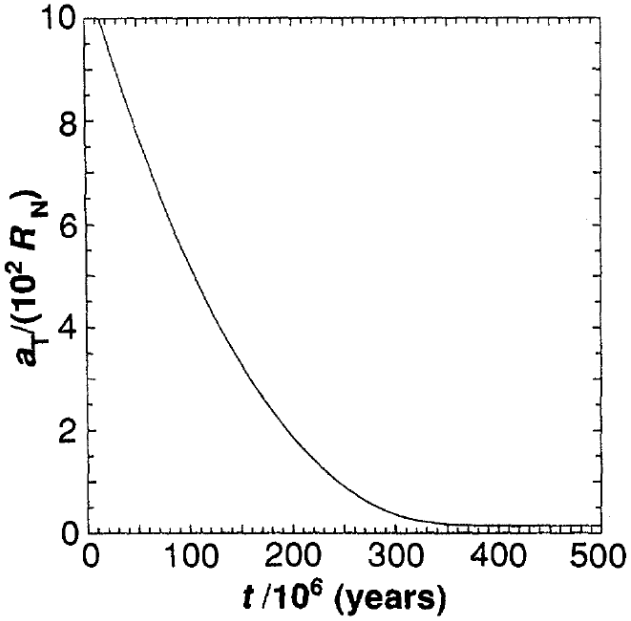


- **Where did Triton come from?**
  - **Very different than other satellites of Uranus and Neptune**
  - **Similarities to Pluto and Kuiper Belt**
  - **Retrograde orbit points to it being a captured object**

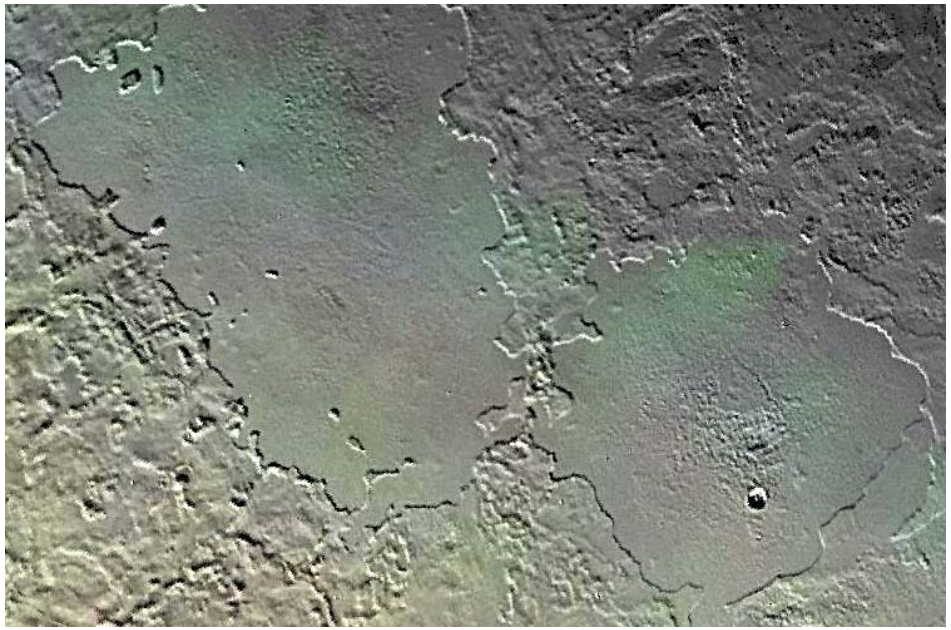
- **Gravitational capture needs some dissipate energy**
- **Did Triton…**
  - **Hit another moon of Neptune**
  - **Hit another Kuiper Belt Object that happened to be passing by**
  - **Come in as a binary system and have its twin escape**

Pluto and Charon
Binary Kuiper Belt Objects

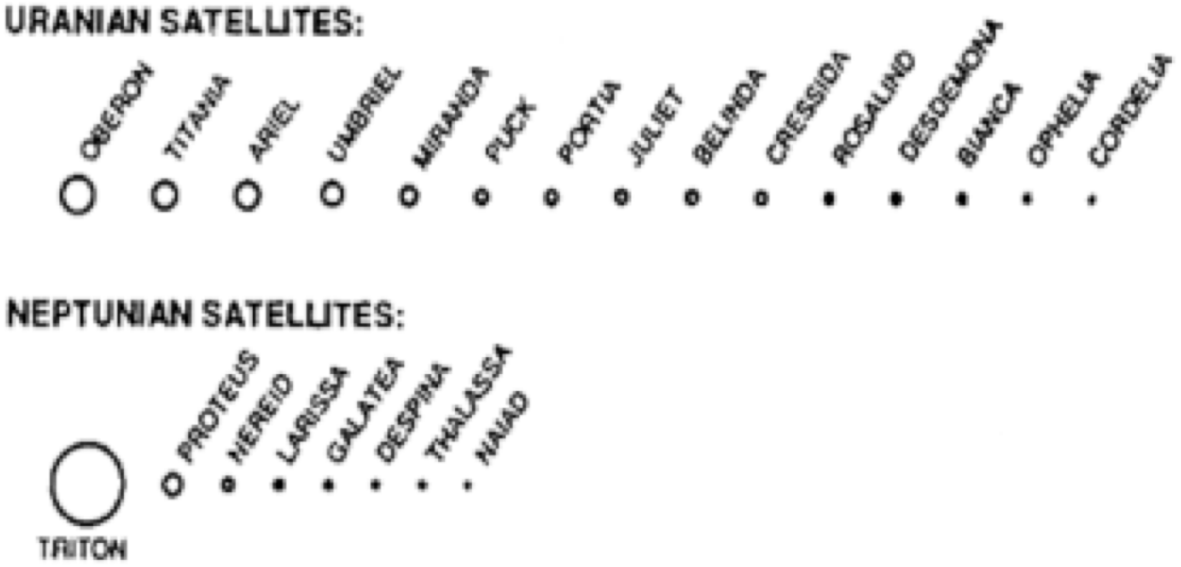
- Triton captured into large and highly eccentric orbit
  - Tidal forces reduce the orbital eccentricity
- Tides are still shrinking Tritons orbit
  - It will pass Neptune's Roche limit in about 3.6 billion years
  - …which means the end of Triton



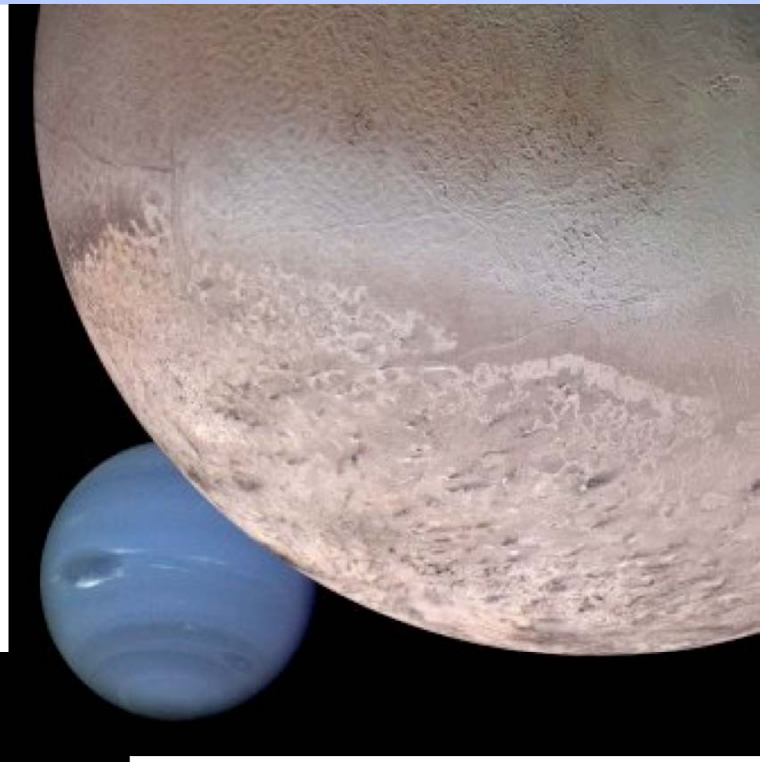
- Triton was severely heated by tides
  - Melting generates liquid layer
  - Runaway heating
    - Whole body perhaps molten
    - Lots of cryovolcanism
  - Complete differentiation easy
  - Greenhouse atmosphere
    - Surface temps 100-200K

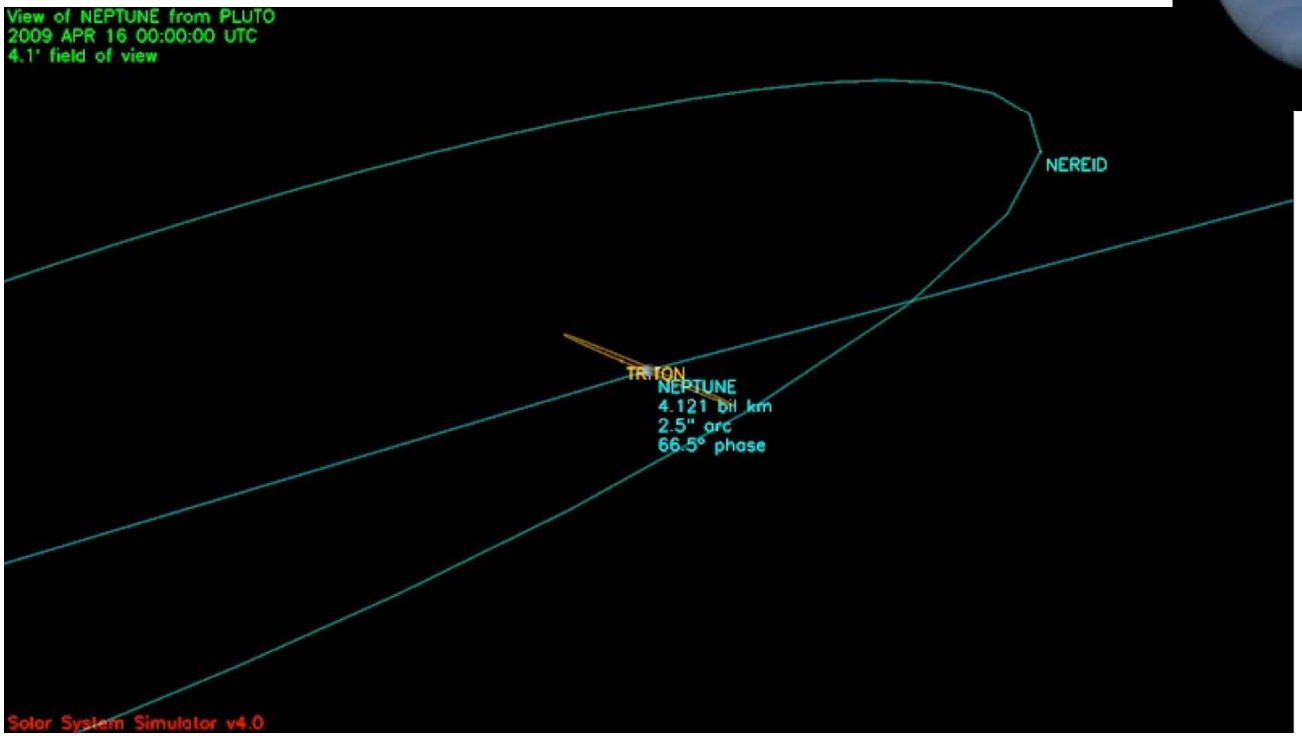


- **What about the rest of Neptune's system?**
  - **The other moons did not escape unscathed from Triton's capture**
  - **Interactions with the massive Triton flung them into disordered crossing orbits**
  - **Many moon-moon collisions probably resulted in a ring system**
  - **Many more moons were probably thrown into Neptune**



- **Capture of Triton**
  - **Removes all moons more that 5 Neptune-radii from the planet**
  - **Only Nereid (340km) survived this**
    - **Ended up in a very far flung orbit**
    - **Inclined by 28º**
    - **Very eccentric**





In this lecture…

- Voyager's 30 year mission
  - Nearing the edge of the solar system
- Satellites of Uranus and Neptune are denser than you'd expect
  - Oxygen gets tied up as the gas carbon monoxide
  - Less water ice so the rock percentage is higher
- Satellites Of Uranus
  - Inner satellites are dark like the rings they produce
  - Regular satellites show past geologic activity
  - Miranda had extreme activity that was abruptly terminated
- Neptune lacks a well developed satellite system
  - Triton is likely a captured half of a binary Kuiper Belt Object
  - Capture melts Triton and destroys a lot of other moons

Next: Pluto and the rest of the Kuiper belt

- **Reading**
  - **Chapter 14 to revise this lecture**
  - **Chapter 14 for next lecture**