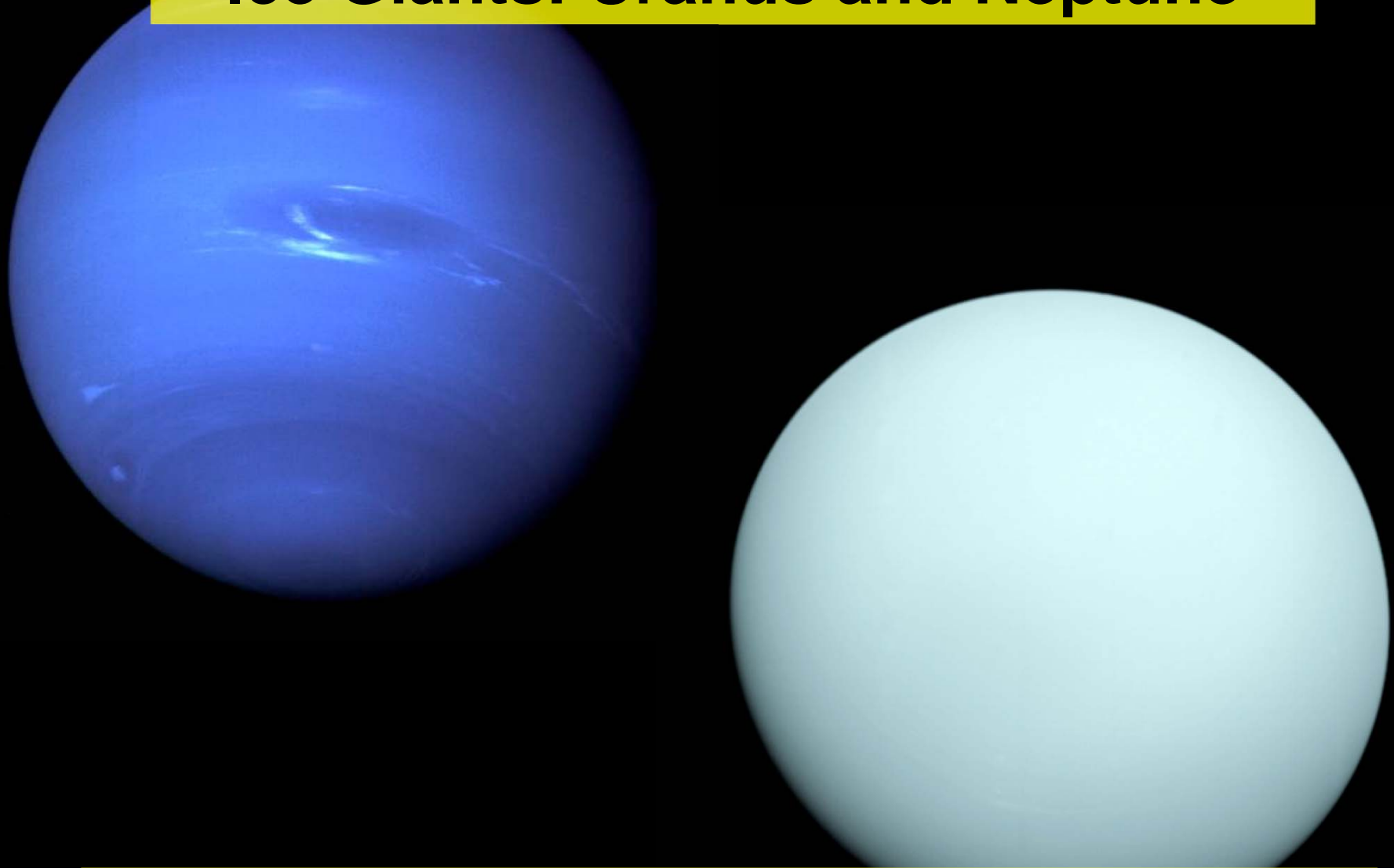




● Announcements

- Congratulations Dr. Jones!
- Priyanka will deal with HW5
 - ▶ Due Thursday
- Kevin will deal with HW6

Ice Giants: Uranus and Neptune

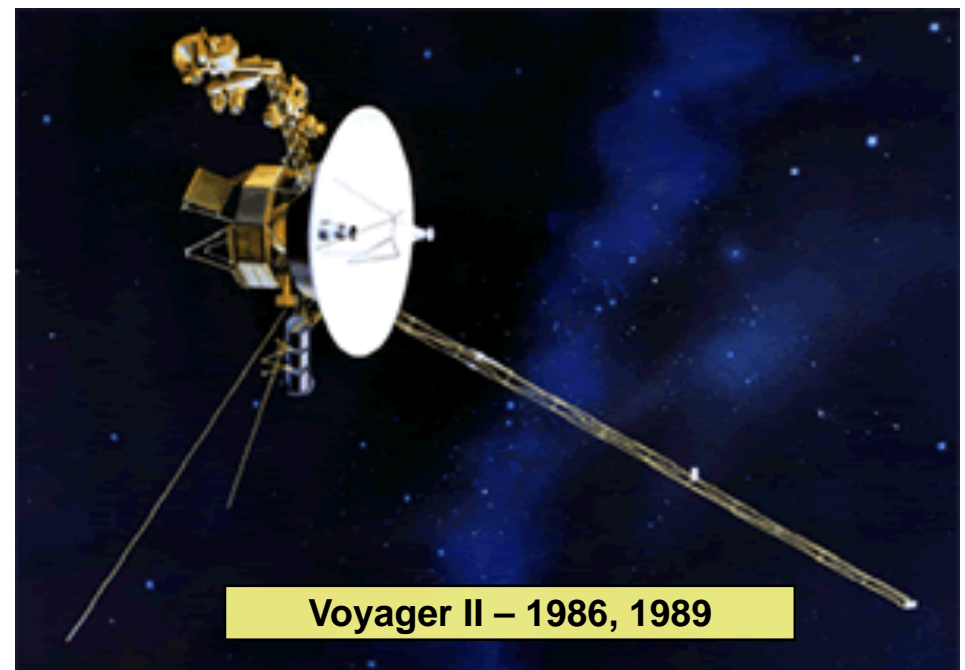
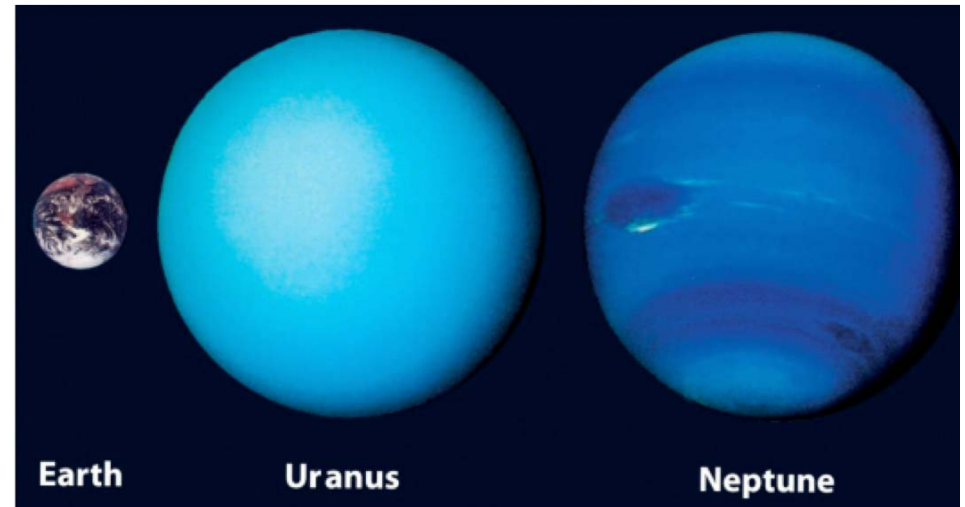


PTYS/ASTR 206 – The Golden Age of Planetary Exploration

Shane Byrne – shane@lpl.arizona.edu

In this lecture...

- Discovering Uranus and Neptune
- Unusual rotation of Uranus
- Ice giant interiors
 - Composition
 - Heat flow
 - Magnetic field
- Atmospheres
 - Composition
 - Energy sources
 - Storms and clouds
- Rings
 - Discovery and properties



● Titus-Bode law

■ Mid 1760s

- A mathematical sequence that seemed to predict the sizes of the planets' orbits

Start with	0	1	2	4	8	16	32	64	128
Multiply by 0.3	0	0.3	0.6	1.2	2.4	4.8	9.6	19.2	38.4
Add 0.4	0.4	0.7	1.0	1.6	2.8	5.2	10	19.6	38.8





- These numbers are similar to the sizes of the planets' orbits in AU
- Known solar system up to 1780 was relatively empty
 - Asteroids undiscovered
 - Uranus undiscovered
 - Neptune undiscovered
 - Pluto & Kuiper Belt undiscovered

Planet	Titus-Bode Prediction	Observation
Mercury	0.4	0.39
Venus	0.7	0.72
Earth	1.0	1.0
Mars	1.6	1.52
-	2.8	-
Jupiter	5.2	5.2
Saturn	10	9.5
-	19.6	-
-	38.8	-

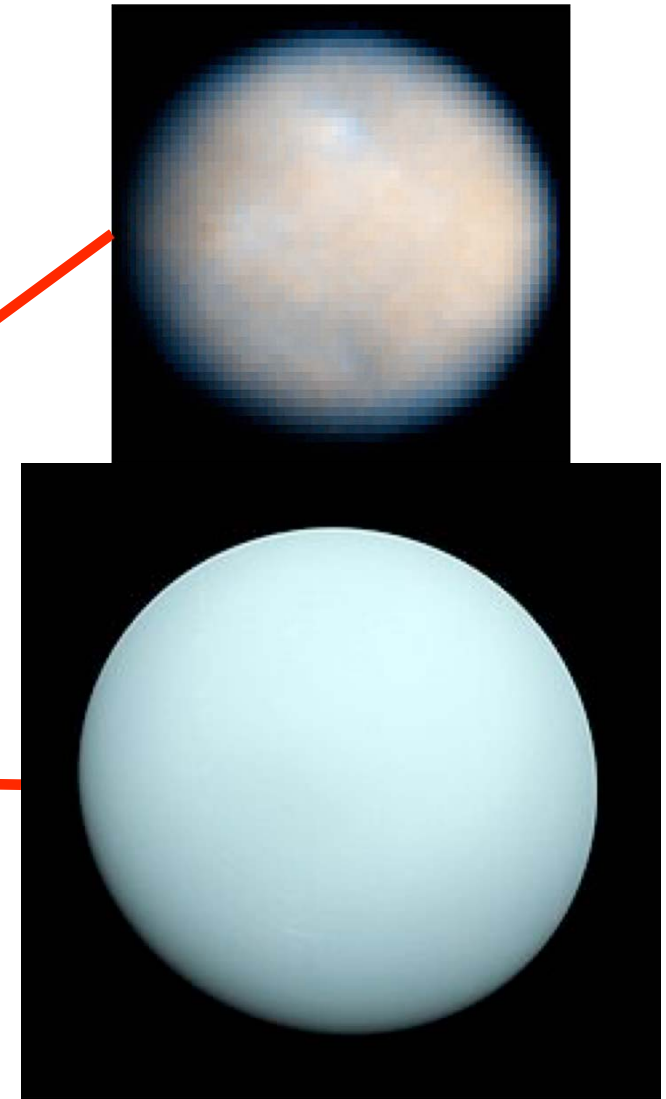
- **Uranus had been mistaken for a star by many people**
- **William Herschel in 1781**
 - **Had a homemade telescope**
 - **Used high-magnification optics**
 - **Uranus was a disk, not a point**
 - **He thought he had found a comet**
 - **His reward.... £200 / year**





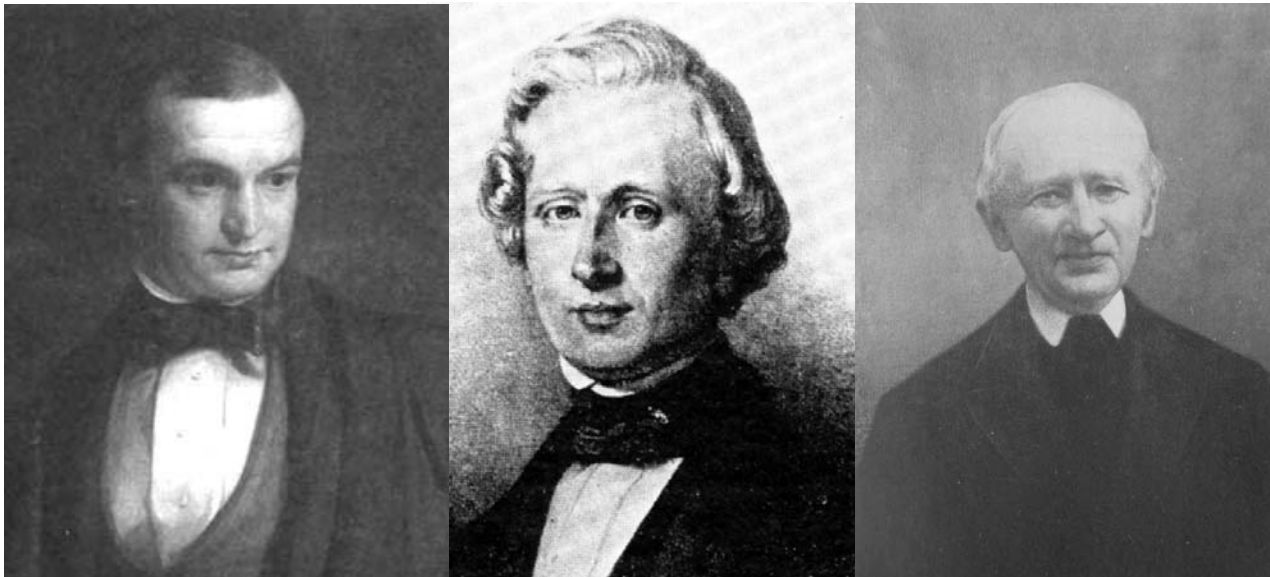
- **Titus Bode law seemed to be working great...**
 - **Uranus was discovered 1781 and fit right into this scheme**
 - **Ceres was discovered in 1801 and fit right into this scheme**

Planet	Titus-Bode Prediction	Observation
Mercury	0.4	0.39
Venus	0.7	0.72
Earth	1.0	1.0
Mars	1.6	1.52
Ceres	2.8	2.8
Jupiter	5.2	5.2
Saturn	10	9.5
Uranus	19.6	19.2
-	38.8	-



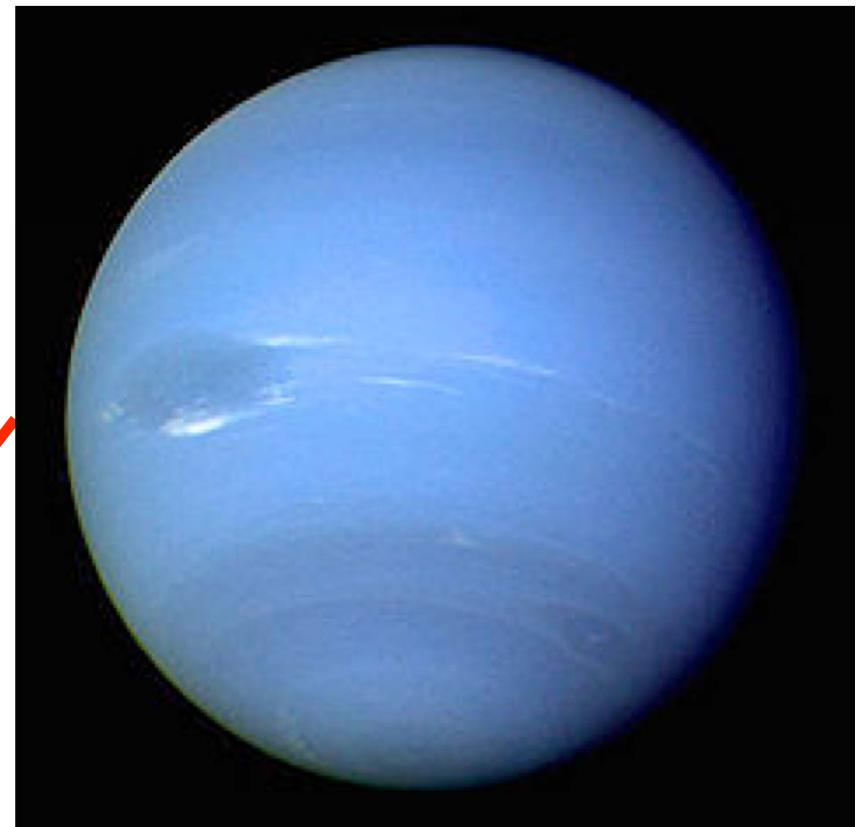
Was there more to come?

- **Something was wrong with the orbit of Uranus...**
 - Its rate of motion didn't match that expected from Newton's law of gravitation
 - Either...
 - Newton's laws were wrong
 - OR
 - There was another planet perturbing things
 - **An extra planet was independently predicted by**
 - John Adams – 1843 – but both he and English Astronomers weren't that interested
 - Urbain LeVerrier – 1846
- **Looked for and found by Johann Galle**
 - Considered a triumph for modern mathematics

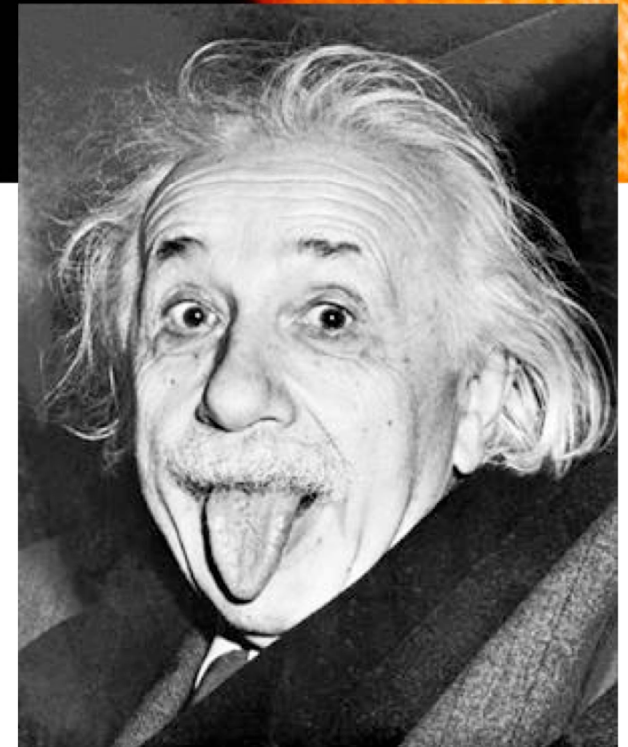
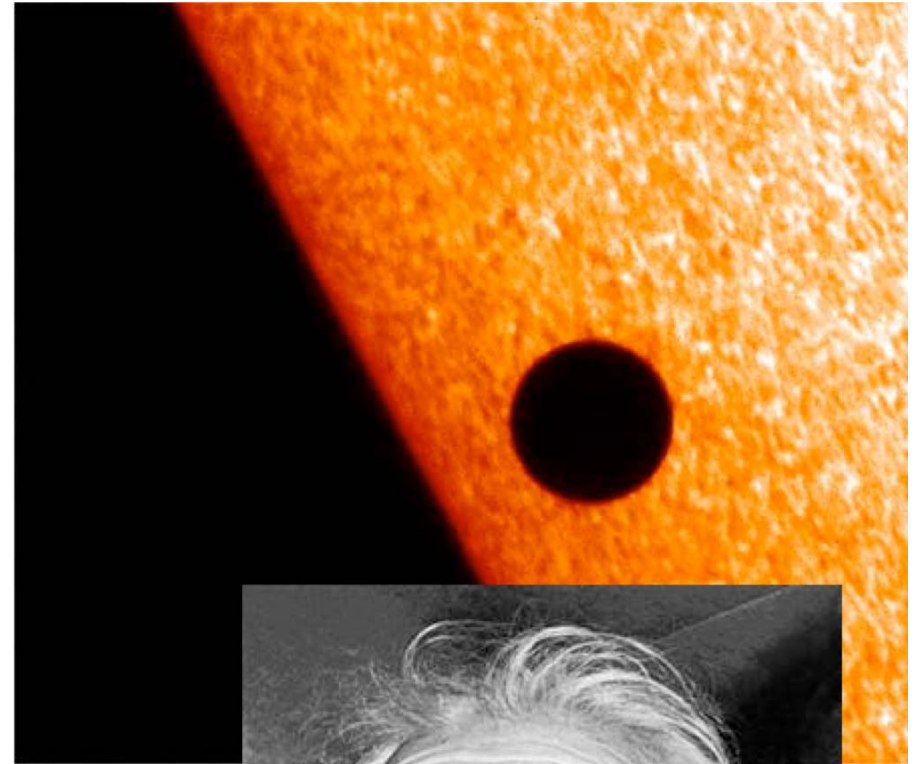


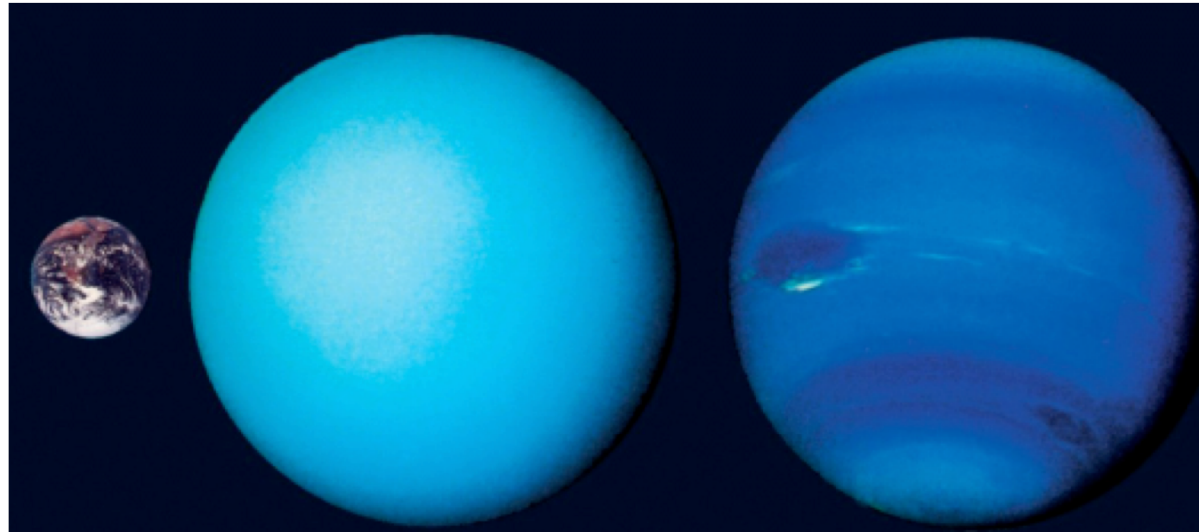
- Titus Bode law seemed turned out to be meaningless
 - Ceres wasn't a planet after all
 - Neptune didn't follow the rule

Planet	Titus-Bode Prediction	Observation
Mercury	0.4	0.39
Venus	0.7	0.72
Earth	1.0	1.0
Mars	1.6	1.52
Ceres	2.8	2.8
Jupiter	5.2	5.2
Saturn	10	9.5
Uranus	19.6	19.2
Neptune	38.8	30.1



- ...Uranus wasn't the only planet with unexpected motions
 - Mercury's orbit also couldn't be explained
 - Again, either...
 - Newton's laws were wrong
 - OR
 - There was another planet perturbing things
- Massive hunt for the planet 'Vulcan' between Mercury and the Sun
 - In this case there was no planet...
- It turns out that Newton's laws are slightly wrong...
 - Einstein's theory of general relativity can explain Mercury's motion without an extra planet



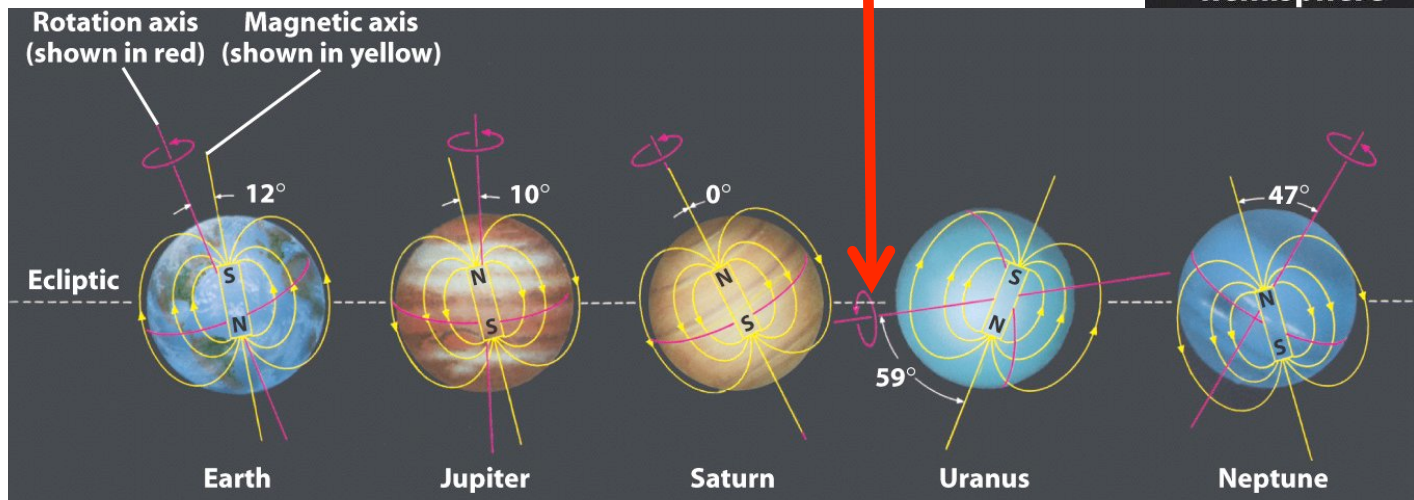
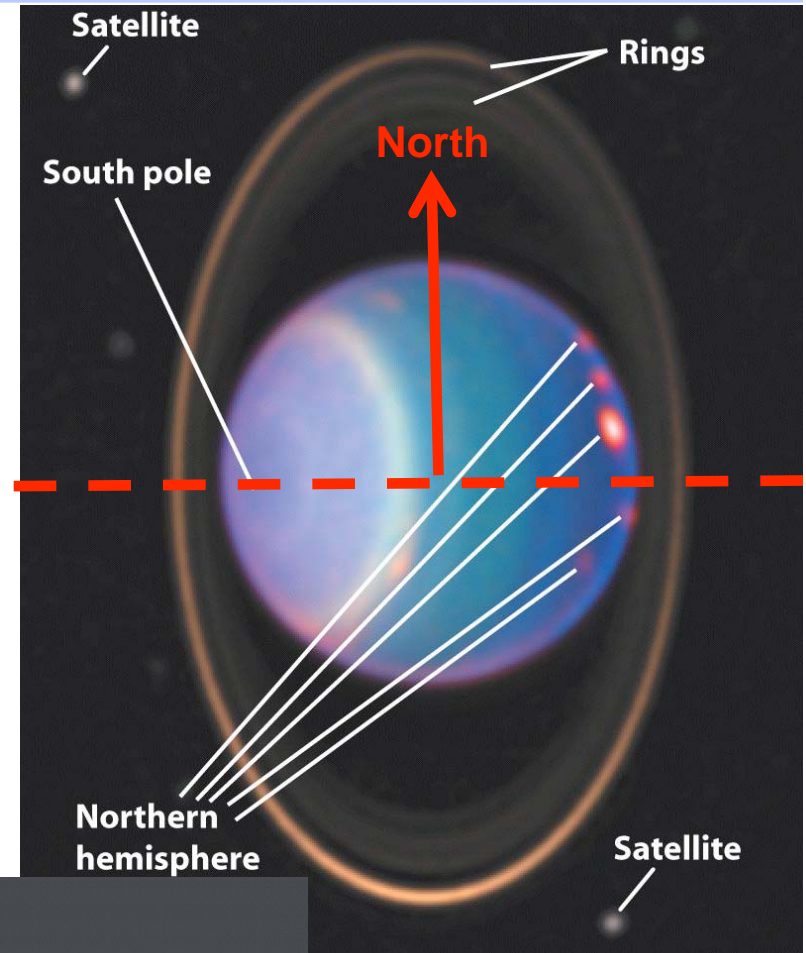


	Uranus	Neptune
Radius	25,559 km – 4.0 x Earth	24,764 km – 3.9 x Earth
Mass (Earth masses)	14.5	17
Distance from Sun	19.2 AU	30.1 AU
Cloud-top Temperature	53 K	55 K
Rotation period	17 hours	16 hours

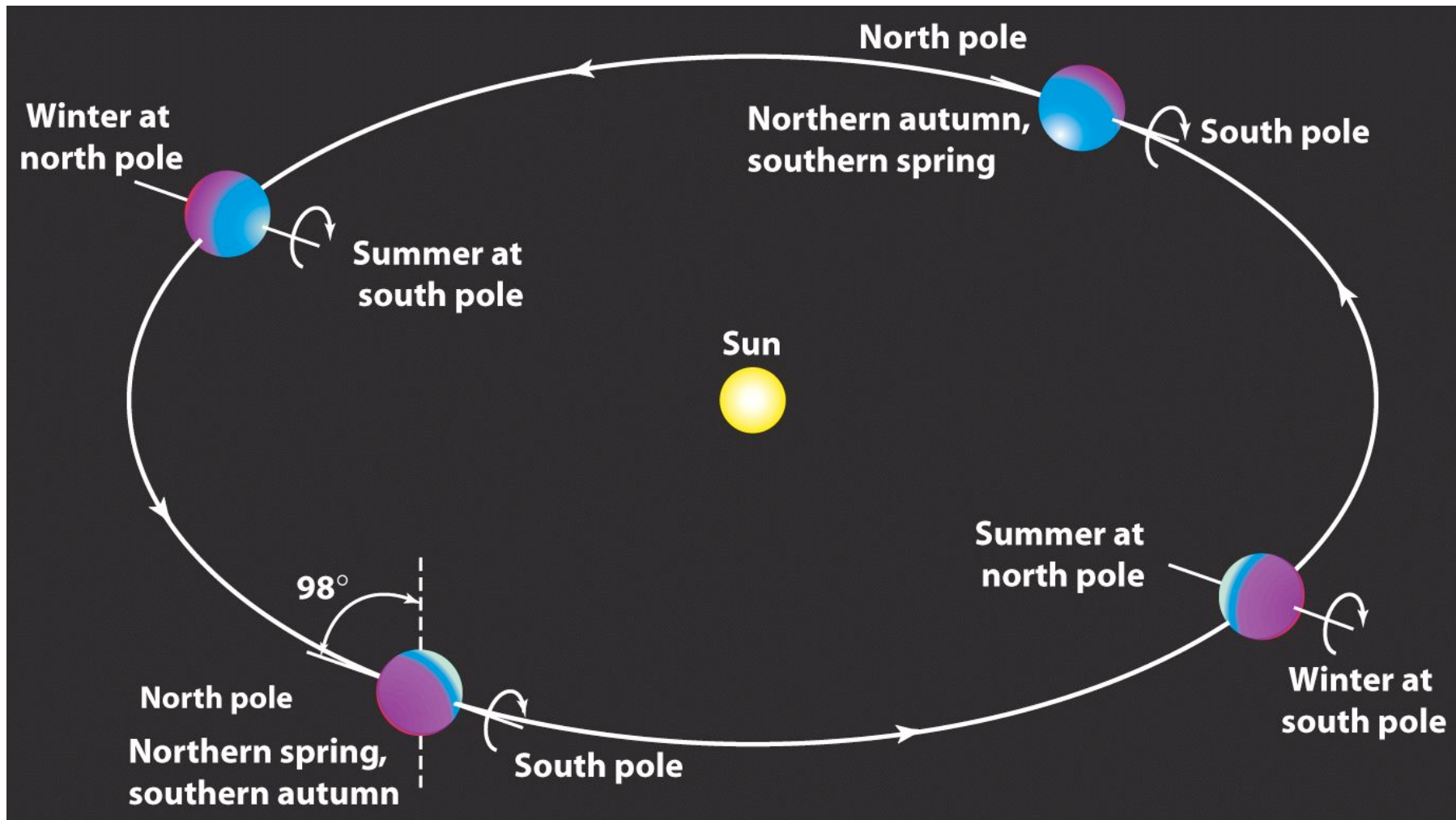
- **Neptune is more massive – but the same size as Uranus**
- **Neptune is further from the Sun – but the same temperature as Uranus**



- **Uranus spins on its side...**
 - **Moons and rings go around the equator**
 - **Axis is tilted 98° to the ecliptic**
 - Compared with Earth's 23°
- **Perhaps a result of a giant collision early in its history**

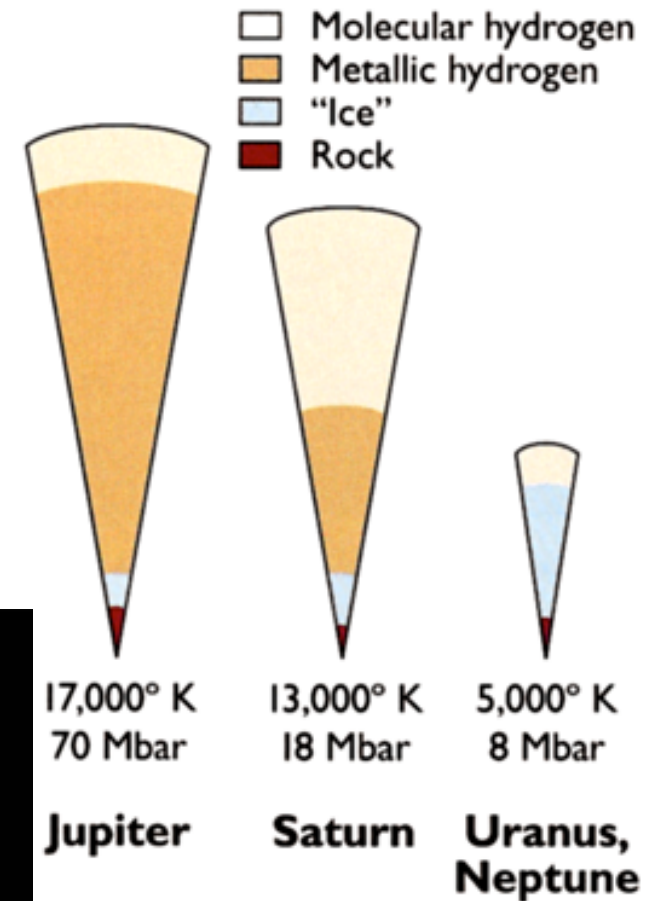
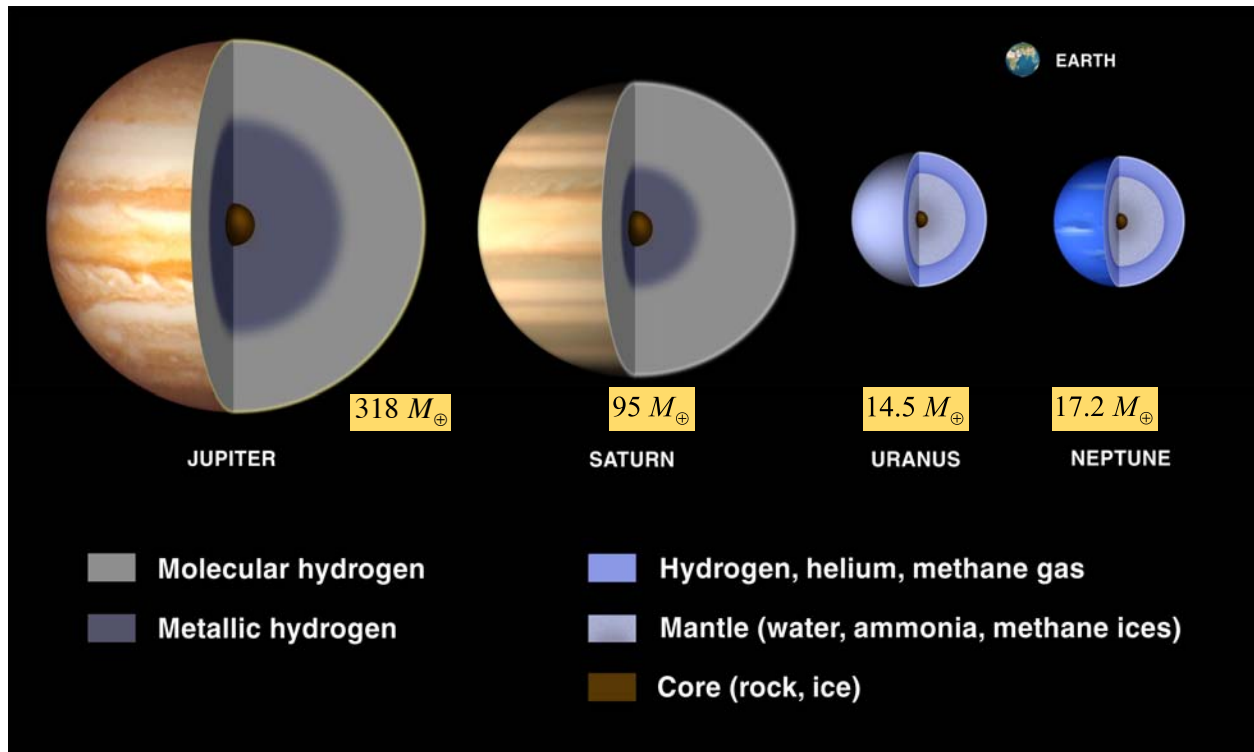


- Seasons on Uranus are very unusual
 - Orbital period is 84 years
 - ~42 years of sunlight at each pole



Interiors of Uranus and Neptune

- Very different from Jupiter and Saturn
- Uranus and Neptune are too small to generate the pressure needed for metallic hydrogen
- Outer layers are mostly hydrogen and Helium
- Core is still rocky
- “Ice” mantle is really a hot liquid



- **Rocky core is about the size of Earth**
 - **Surrounded by a thick ocean of liquid water and ammonia**
 - **Surrounded by a liquid hydrogen, helium and methane atmosphere**

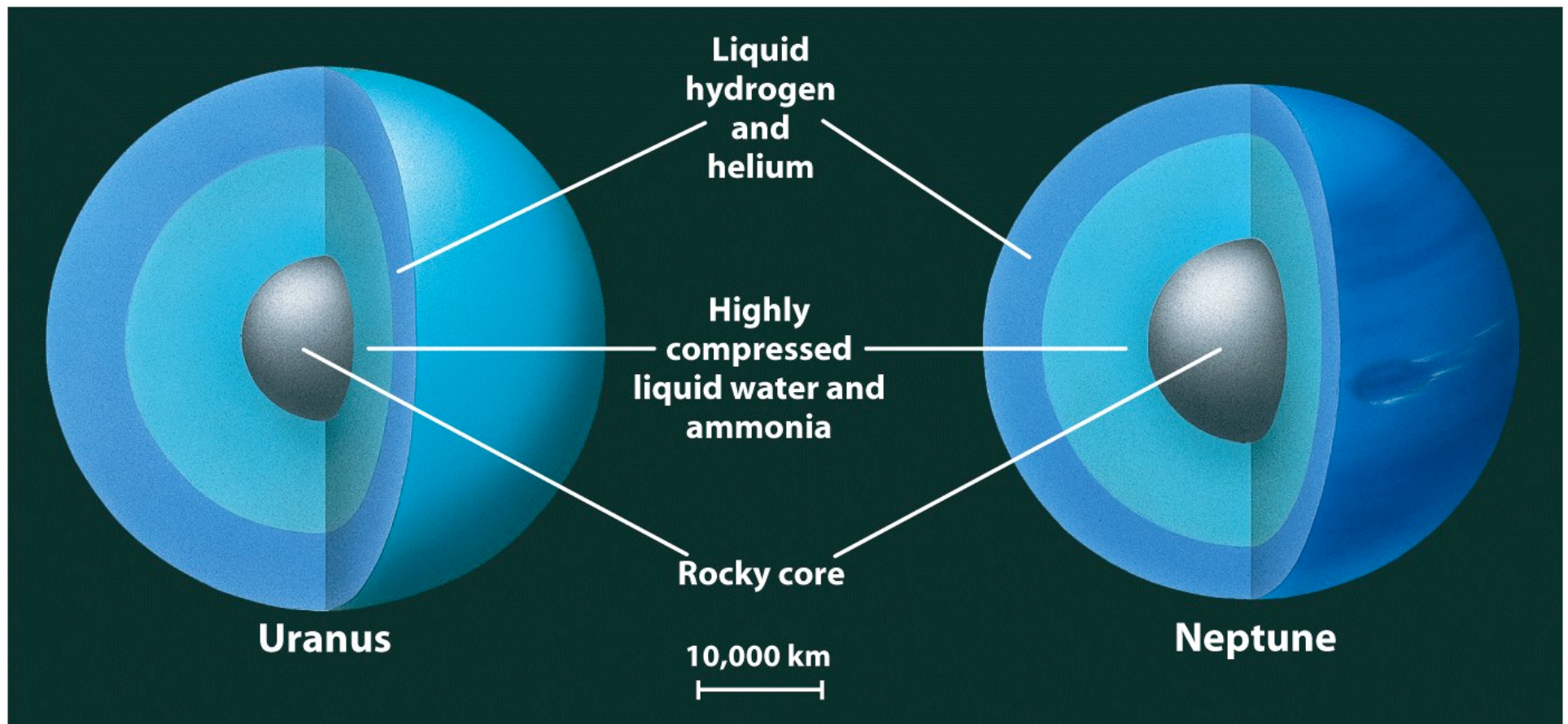


Figure 14-7

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- **How do you form Uranus and Neptune?**
- **On the one hand...**
 - High fraction of non- hydrogen/helium material argues for formation closer to the Sun
 - Forming a planet in the tenuous outer reaches of the solar nebula is very slow
- **But...**
 - They're lower mass than Jupiter/Saturn so must have formed further out
- **One possibility is planetary migration...**
 - Form Neptune and Uranus in the 5-10 AU range (Jupiter/Saturn range)
 - Then migrate these bodies to the outer solar system before they grow too large

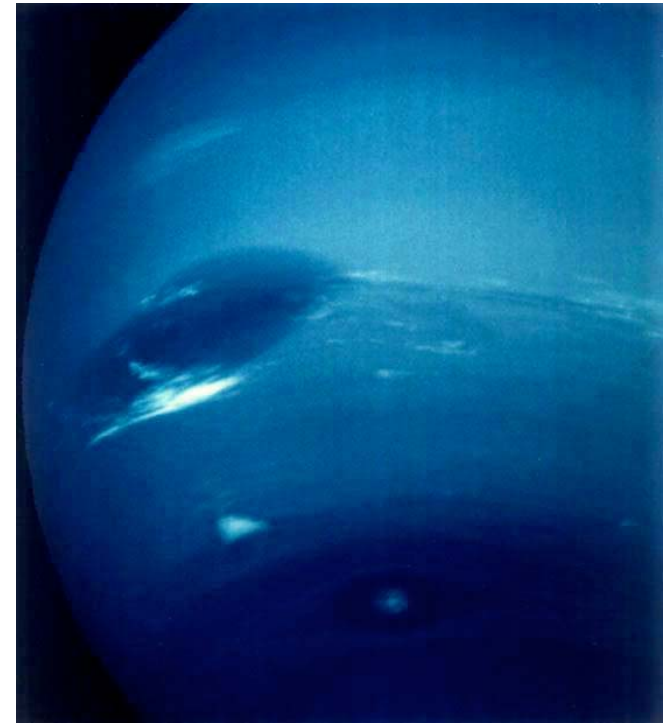
	Jupiter	Saturn	Uranus	Neptune
Density (kg m ⁻³)	1380	687	1270	1638
Mass (Earth)	318	95	14.5	17



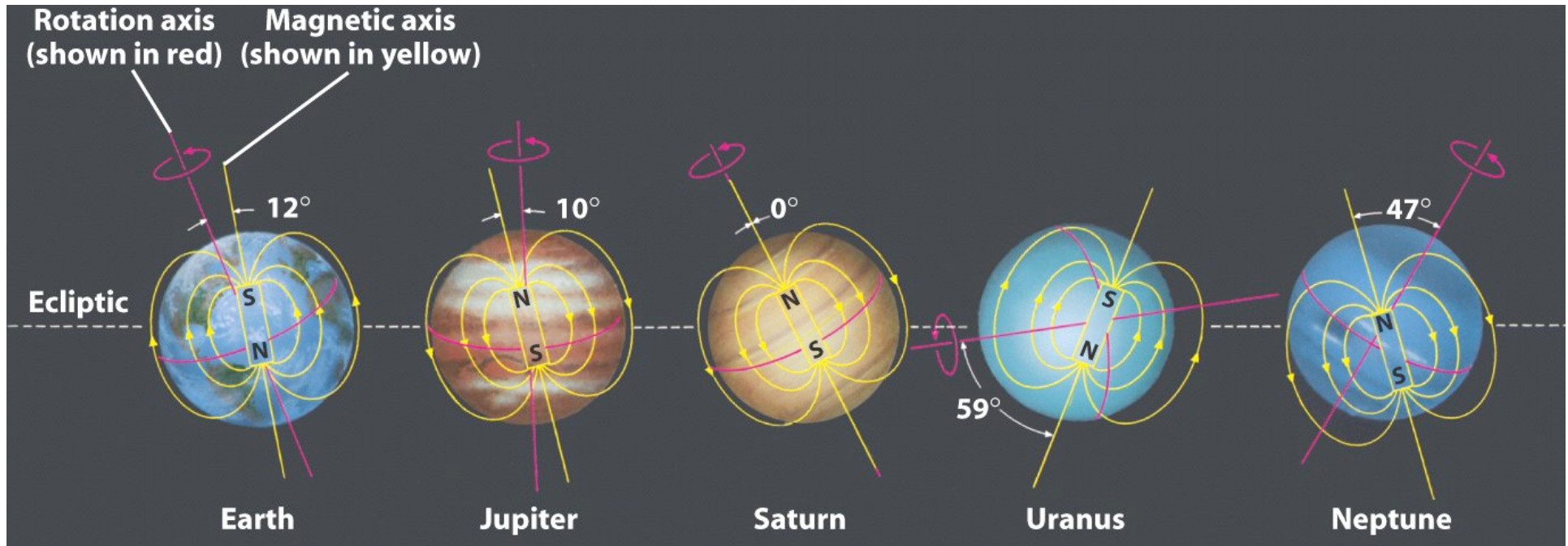
Jupiter is this dense only because its intense gravity compresses its interior

- **Neptune has a high heat flow**
 - **Emits ~2.6 times what it absorbs from the Sun**
 - **Similar to Jupiter and Saturn**
 - **Maybe caused by breakup of methane under pressure**
 - **CH₄ breaks in Carbon and Hydrogen**
 - **The carbon forms diamonds that sink**
 - **The Hydrogen rises to the surface and escapes**
 - **Neptune's core might have a diamond crust... neat!**

- **Uranus has a very low heat flow**
 - **Perhaps heat cannot escape**
 - **Perhaps much of the primordial heat was lost in a giant impact**

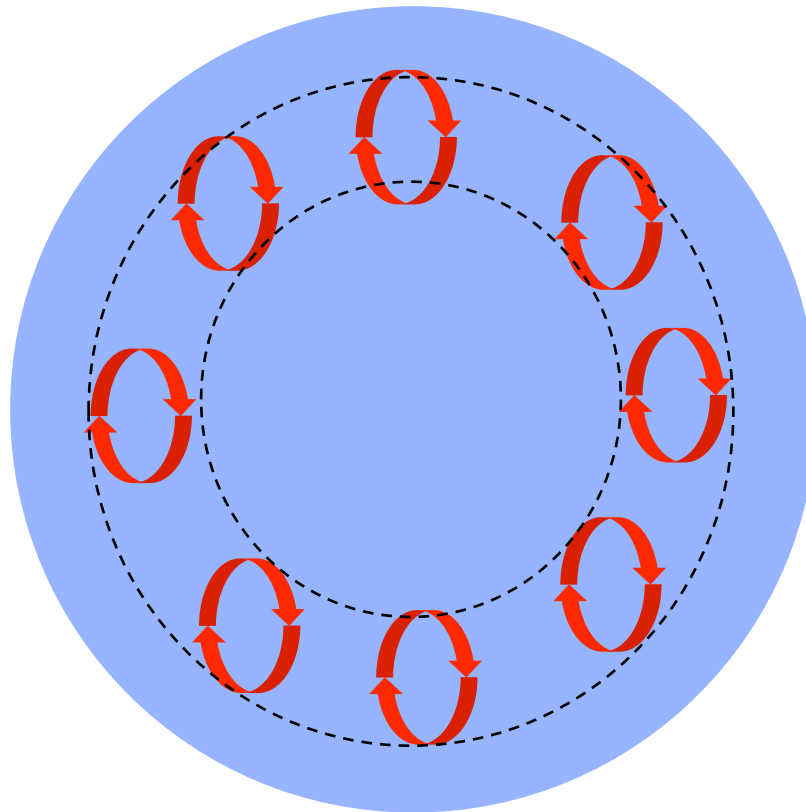


- Neptune and Uranus have unusual magnetic fields



- Dipole fields like other planets but...
 - Magnetic axes differ wildly from rotation axes
 - Center of magnetic field appears offset from center of planet

- **Fields are unusual because**
 - There's no iron core
 - There's no big envelope of metallic hydrogen
- **Fields likely caused by ionized water**
- **Convection probably in a thin shell**





Atmospheres of Uranus and Neptune

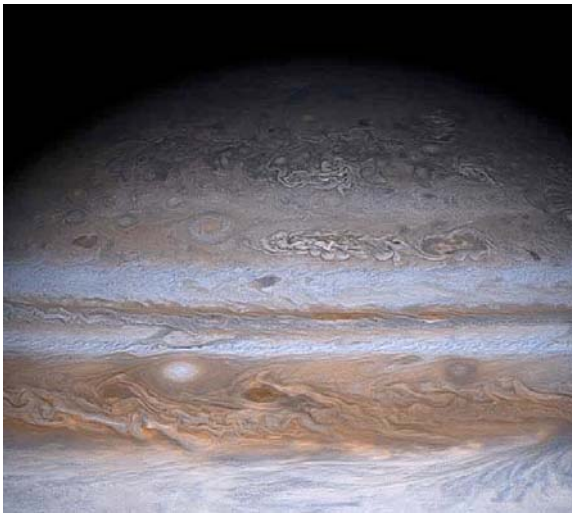
- Outer atmosphere is mostly hydrogen and helium
 - Much like Jupiter and Saturn
 - ...but all the ammonia froze and sank
- Methane levels much higher
 - Methane absorbs red light
 - Makes these planets look blue

	Uranus	Neptune
Hydrogen	83%	80%
Helium	15%	18.5%
Methane	2%	1.5%



- **Uranus and Neptune look rather boring compared to Jupiter**

- At Uranus (19.2 AU) – Solar power is 3.7 Wm^{-2}
- At Neptune (30.1 AU) – Solar power is 1.5 Wm^{-2}
- At Jupiter (5.2 AU) – Solar power is 51 Wm^{-2}



- **Internal heat also plays an important role**

- Neptune has an internal source (emits 2.6 times the energy absorbed)
- Uranus has almost no internal heat
- Neptune has more atmospheric activity even though it gets less solar energy

- **Uranus appears as a featureless ball at visible wavelengths**
 - Low heat flux from interior means very little activity
- **Infrared observations bring out more detail**
 - Shows zonal bands and storms

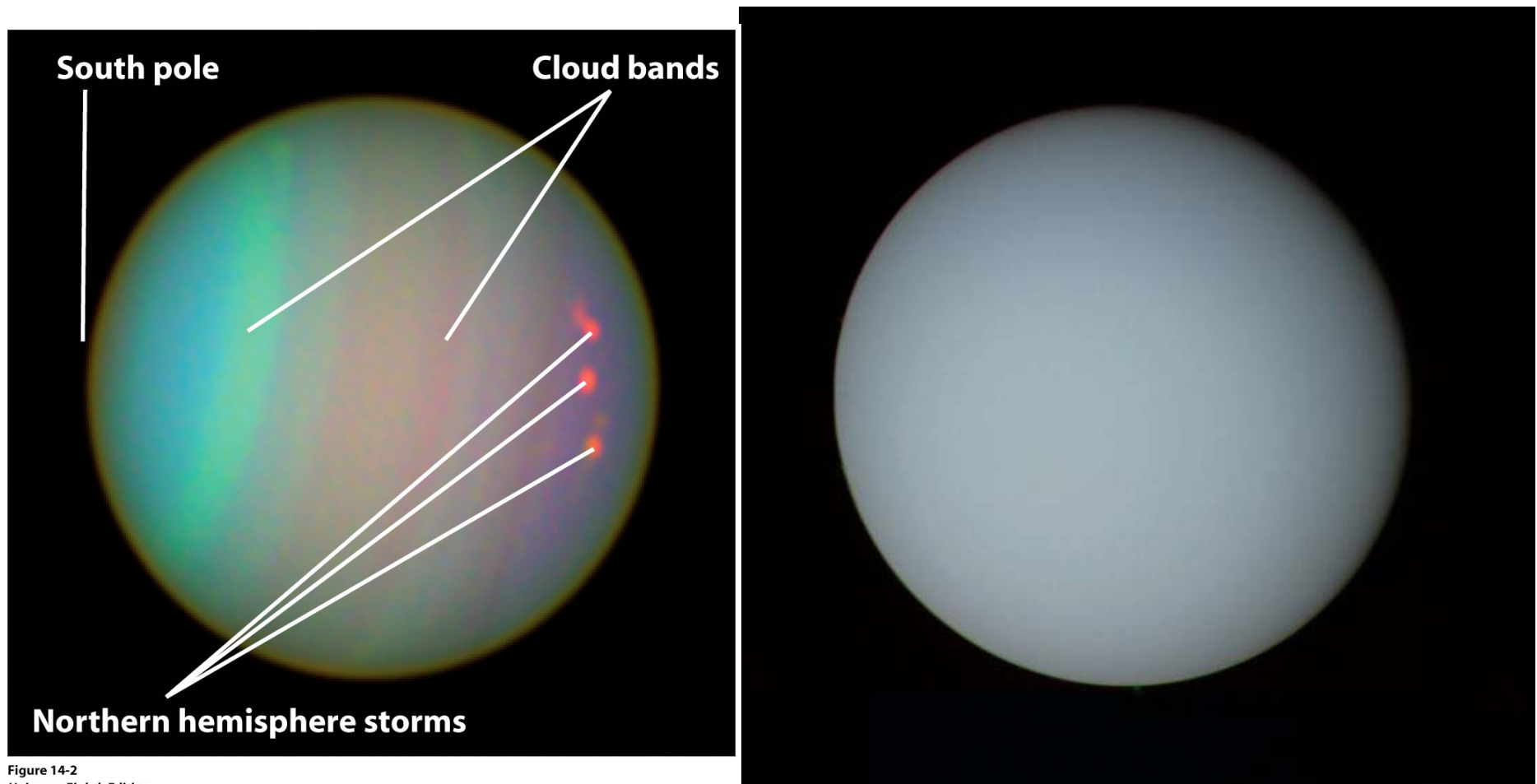


Figure 14-2
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- **Neptune has a more active atmosphere**

- Still quiet by the standards of Jupiter and Saturn
- Storm systems
- Clouds
 - ▶ Methane ice crystals
- Winds up to $250\text{-}400\text{ ms}^{-1}$
 - ▶ At cloud-tops
- All powered by internal heat

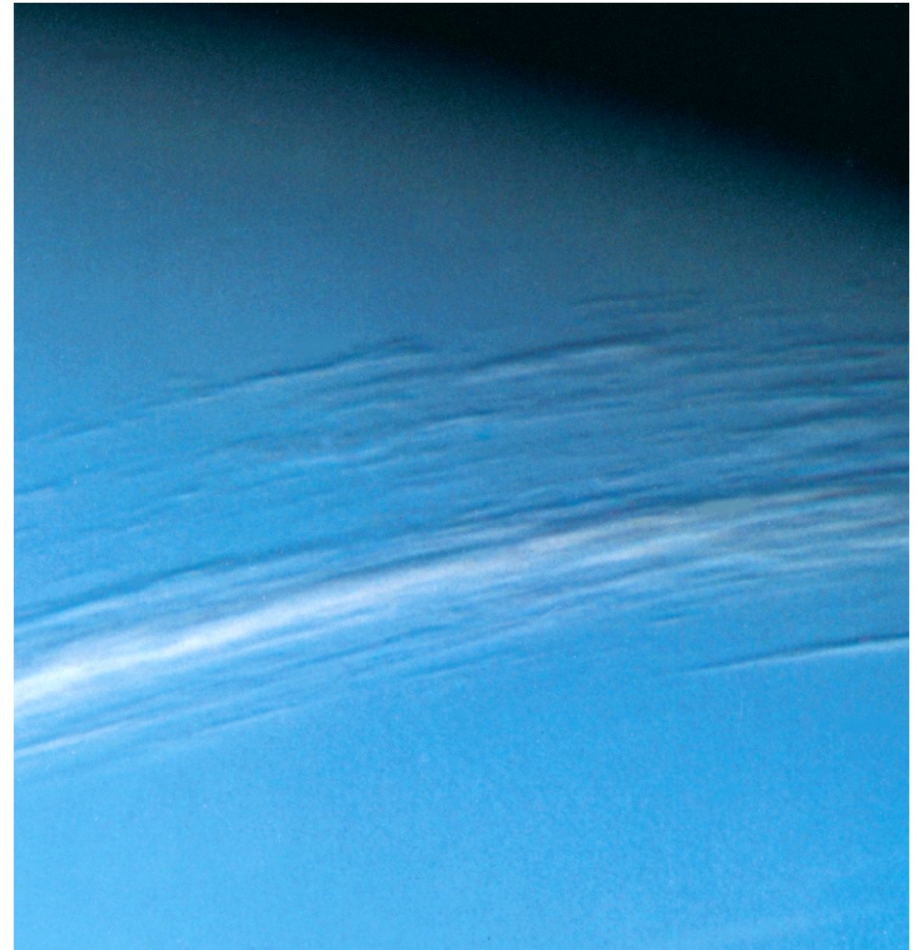
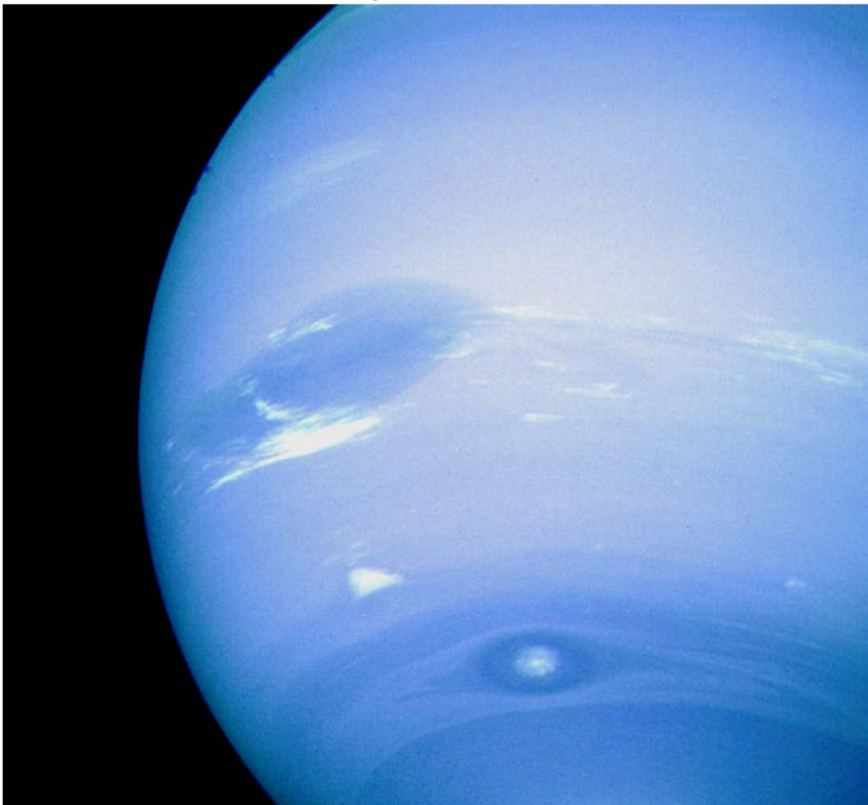


Figure 14-5
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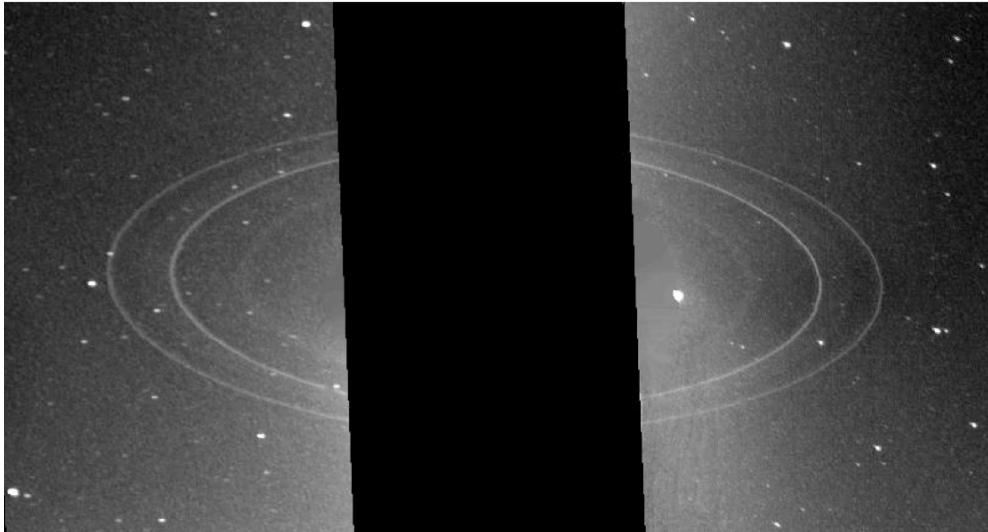
- **The great dark spot was a long-lived storm system**
 - Anticyclone, like the great red spot on Jupiter
 - Disappeared in 1994
 - Another great dark spot has appeared since then
 - Probably holes in the cloud deck that show lower layers



Rings of Uranus and Neptune

- Uranus and Neptune have a very tenuous ring system
 - Icy particles coated with silicates

Neptune



Uranus

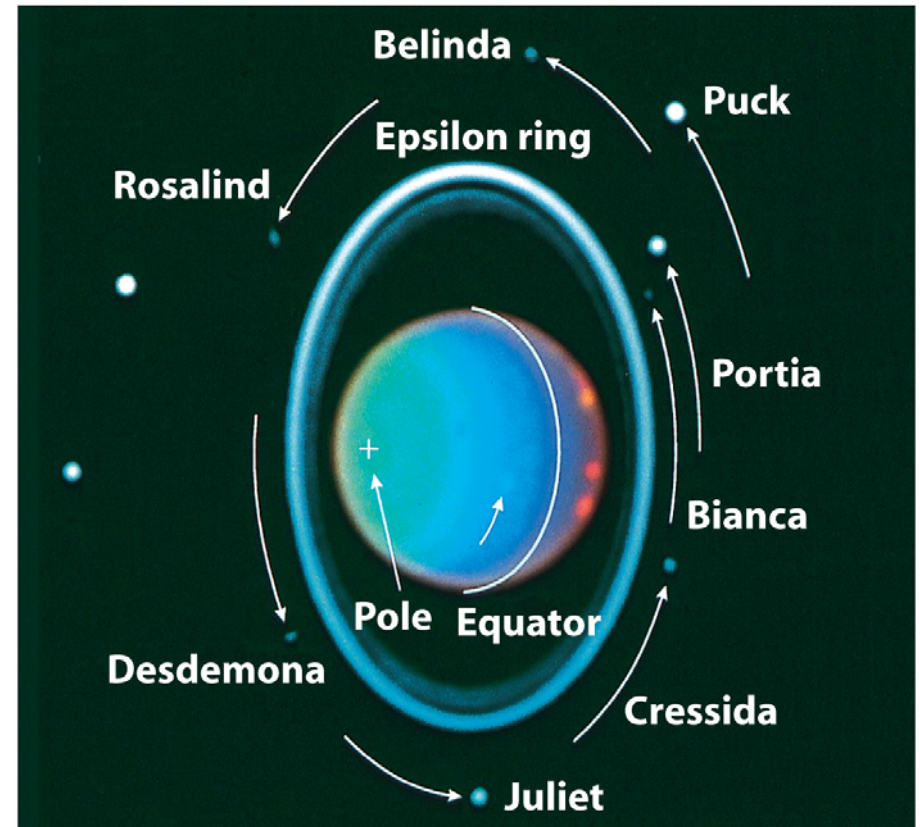
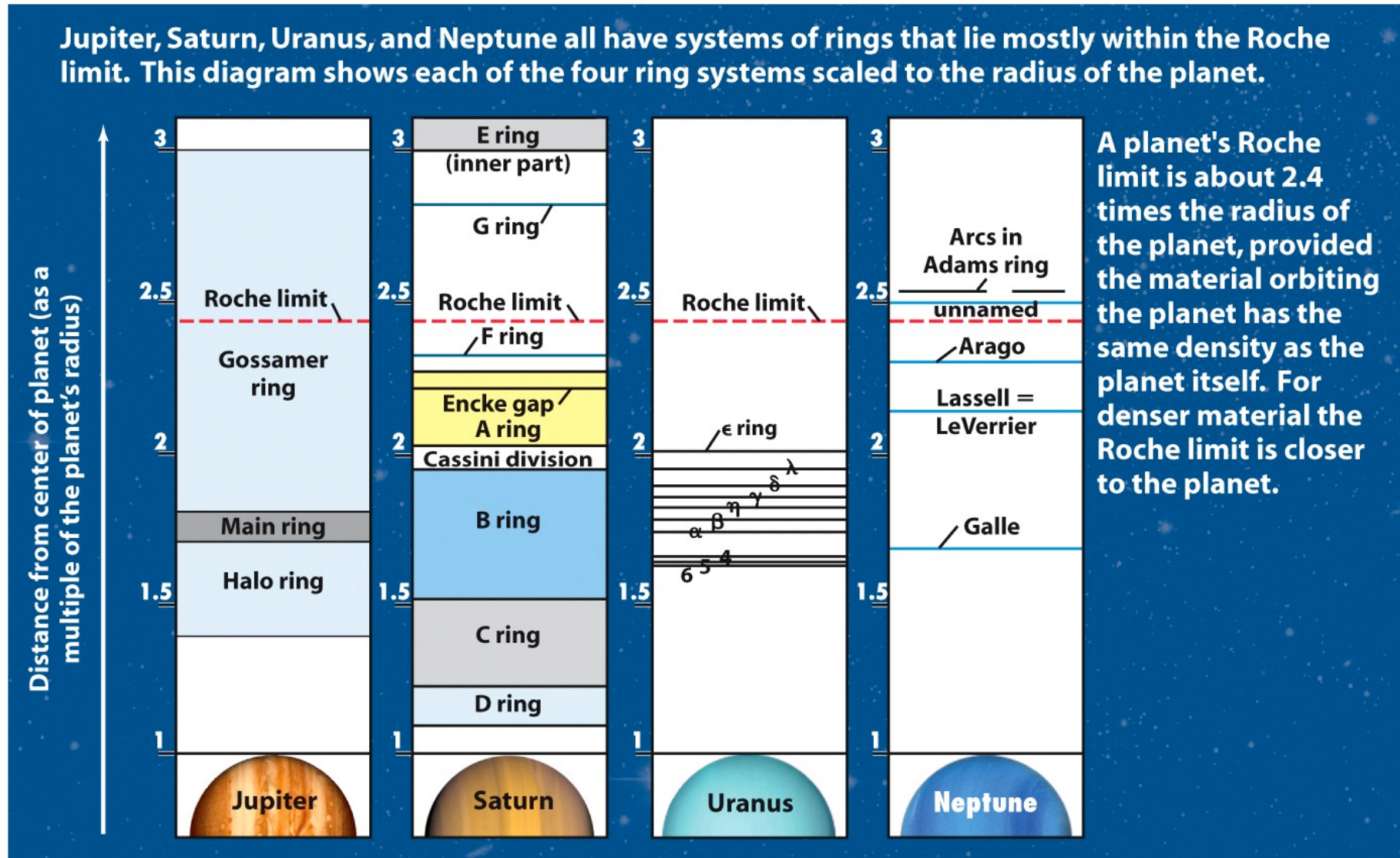


Figure 14-14
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- Ring-particles are prevented from clumping by tidal forces
 - Just like we saw at Saturn



● Rings of Uranus

- Discovered unintentionally by a stellar occultation in 1977
- Perhaps seen by Herschel 200 years earlier

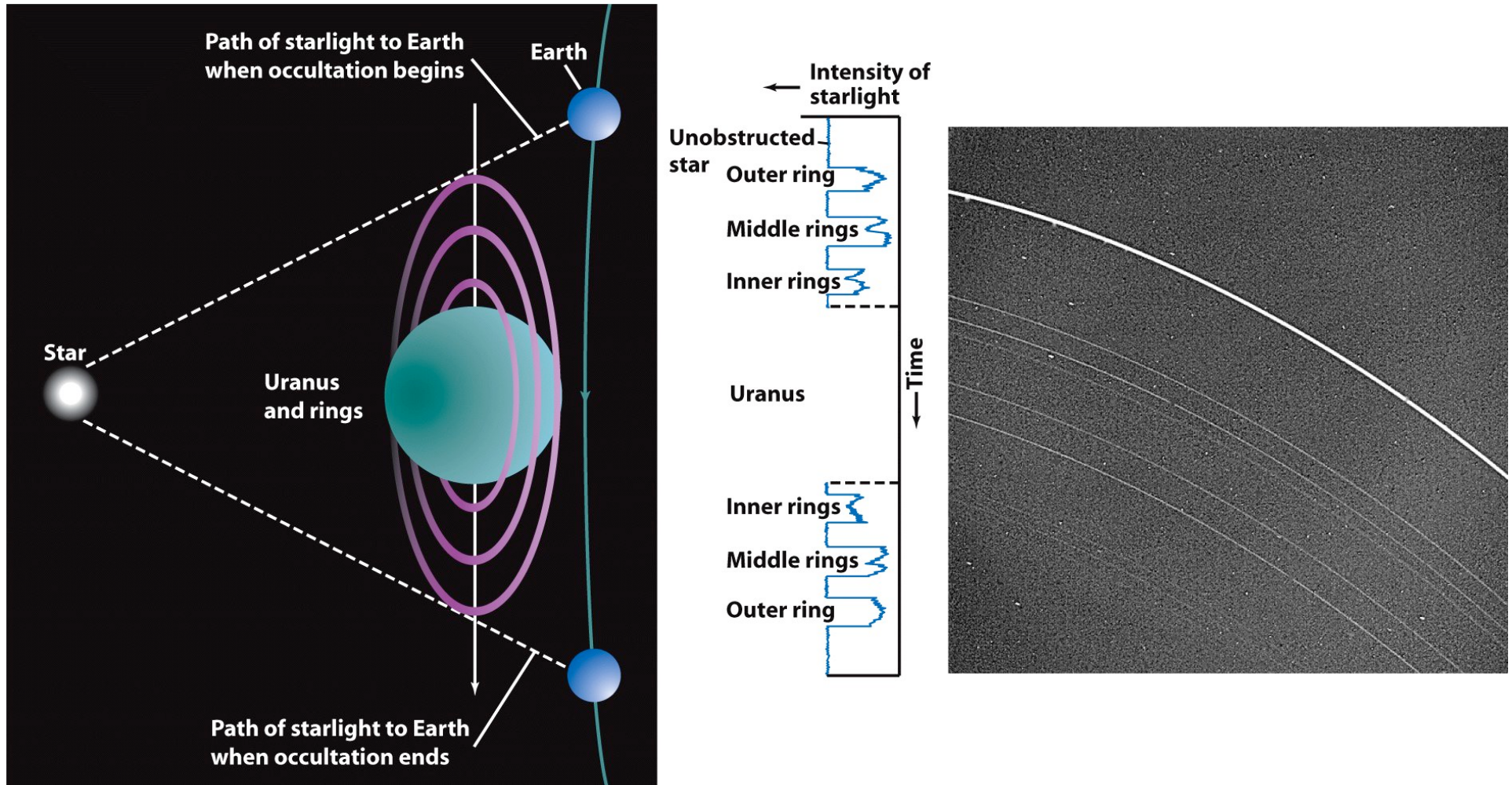
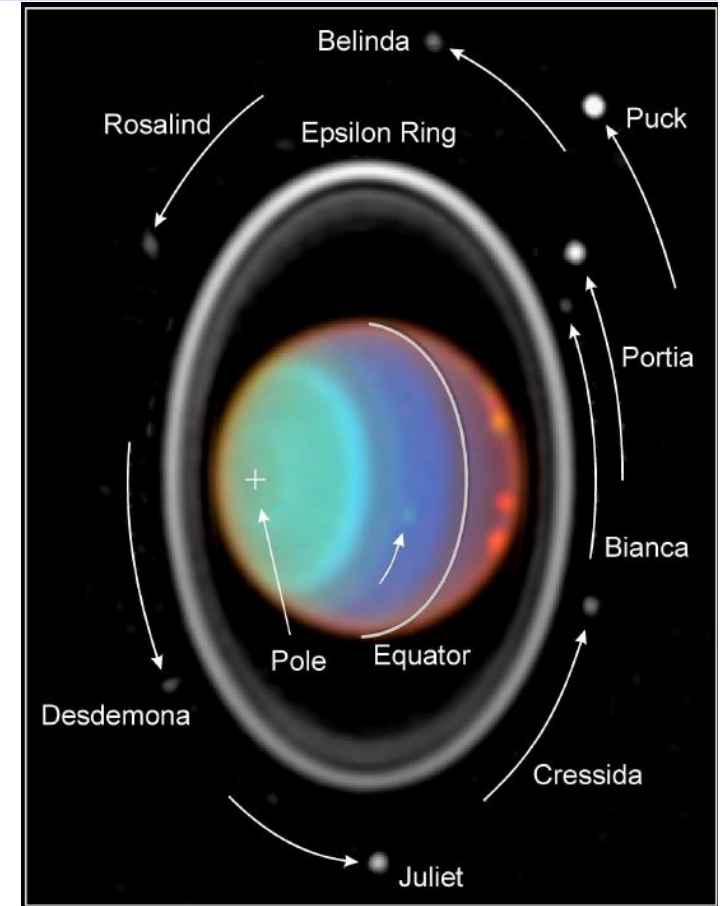
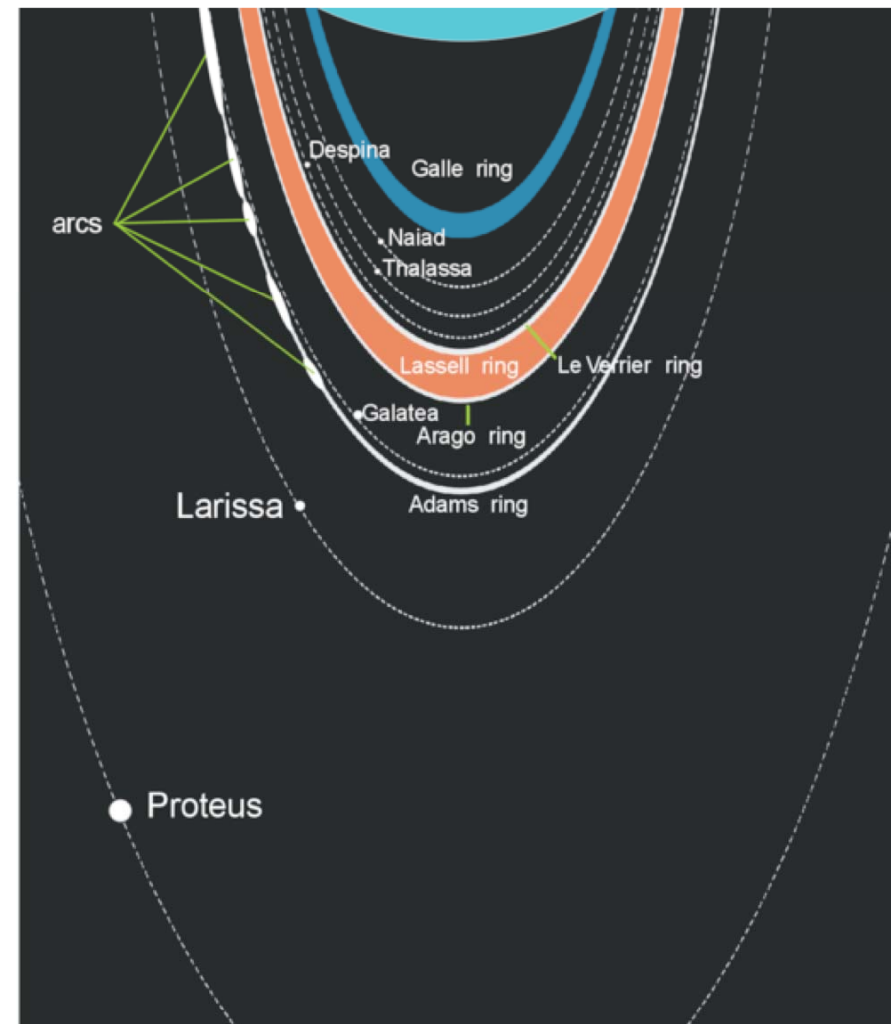


Figure 14-9
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- Rings are extremely narrow and thin
- Composed of very dark material
 - Not much water-ice
 - Methane ice coating that darkened with time
 - Ring particles bigger than Saturn's (0.2-20m)
- The epsilon ring
 - Probably only 150m thick
 - Interior and exterior shepherd moons
 - ▶ Cordelia and Ophelia



- **Neptune's rings were discovered in 1980**
 - **Named after the characters that discovered/predicted Neptune**
 - ▶ Adams, LeVerrier and Galle
 - **Rings seem to be fading... gone in 100 years!???**
 - **Adams ring is unusual**
 - ▶ Organized into 5 ring-arcs
 - ▶ These appear stable despite expectations to the contrary
 - ▶ Shepherded by the moon Galatea





In this lecture...

- **Discovering Uranus and Neptune**
- **Unusual rotation of Uranus**
- **Ice giant interiors**
 - No metallic Hydrogen
 - Ionized water provides a magnetic field
- **Atmospheres**
 - Storms driven by internal energy
 - Clouds of liquid/solid methane
- **Rings**
 - Dark and thin
 - Neptune has ring-arcs (that might be fading)

Next: Moons of Uranus and Neptune

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