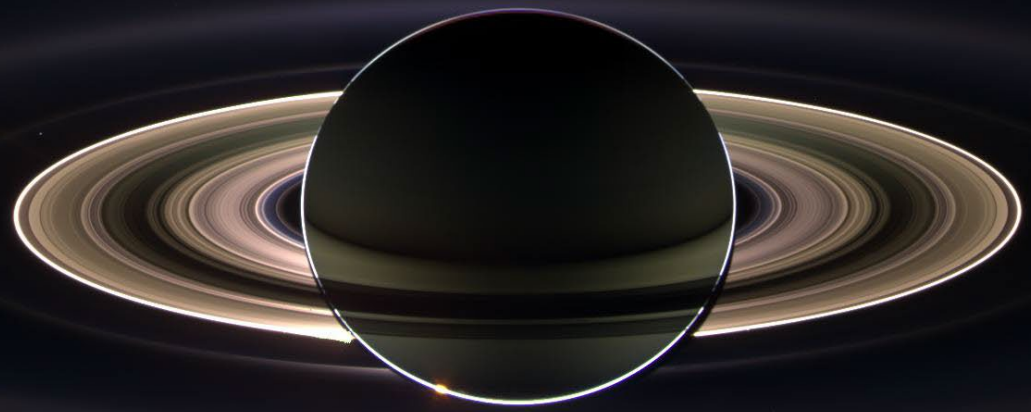
Today in Astronomy 111: rings

- Tour of the Solar system's four ring systems.
- Tides, tidal disruption, and the Roche limit.



Saturn and rings A-G, seen from the planet's shadow. The night side is illuminated faintly by ring-light. Note the blue dot between the F and G rings, around 10 o'clock. (*Cassini* /JPL/NASA)

Saturn's rings and orbital resonances

The first rings – Saturn's – were first seen by Galileo in 1610, and first realized to be rings by Huygens in about 1655.

- Galileo referred to the limbs of the rings as **ansae**, Latin for "handles". We still do.

- Seven main rings, most comprised of many narrow rings.

- Extremely flat: they're about 1000 cm thick, and about 10^{10} cm wide.
  - A scale model of a ring made of printer paper would be about 1 km wide.

- The narrow rings are separated by gaps that are usually empty save for small moons – particularly large ring particles – orbiting therein.

- Many of the rings and gaps clearly match the mean-motion resonances of the moons within the gaps.

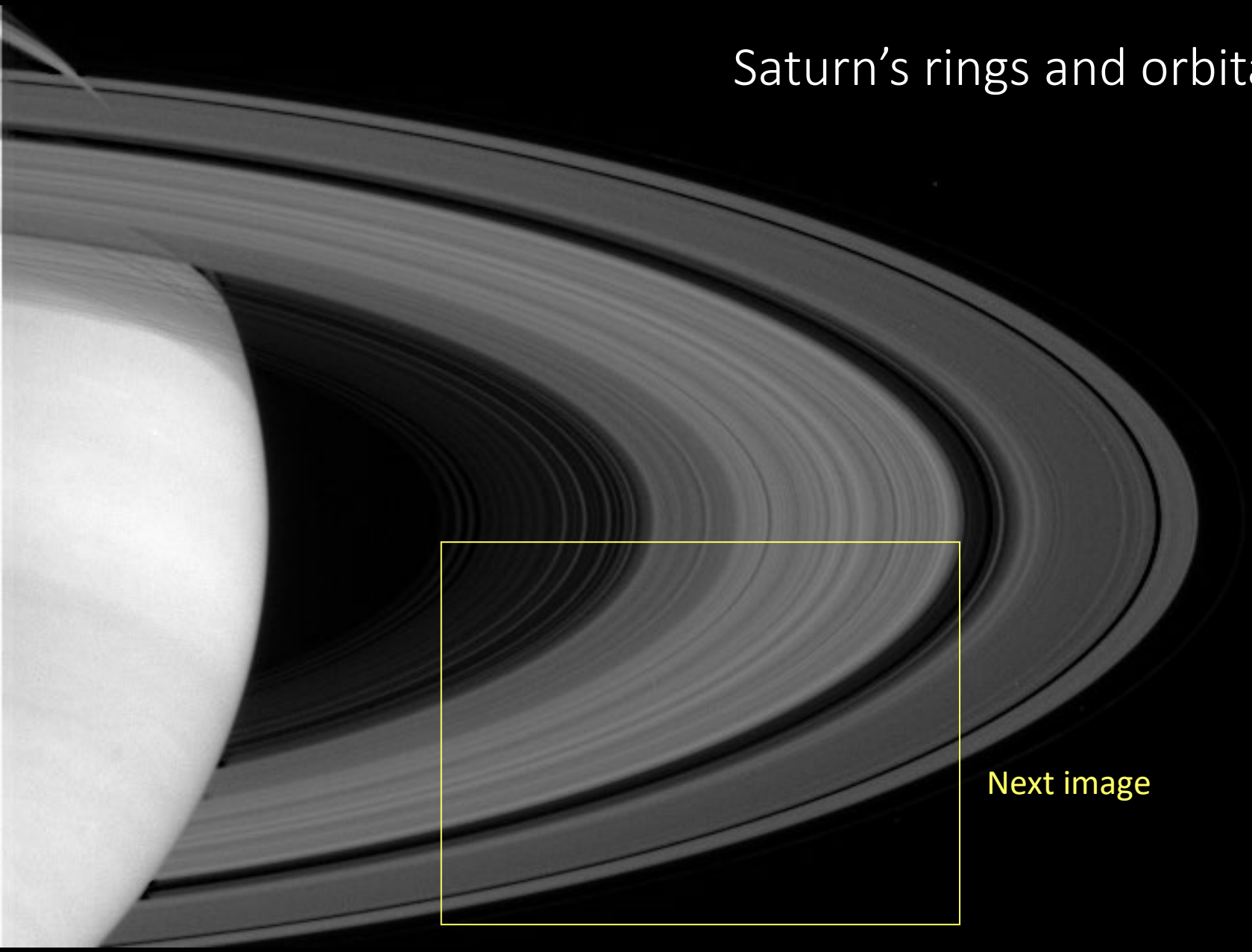
- Very icy particles – water ice, mostly – with **large albedo**: A_b = 0.3-0.5 for the brighter rings.

Saturn’s rings and orbital resonances (continued)



Cassini/NASA/JPL

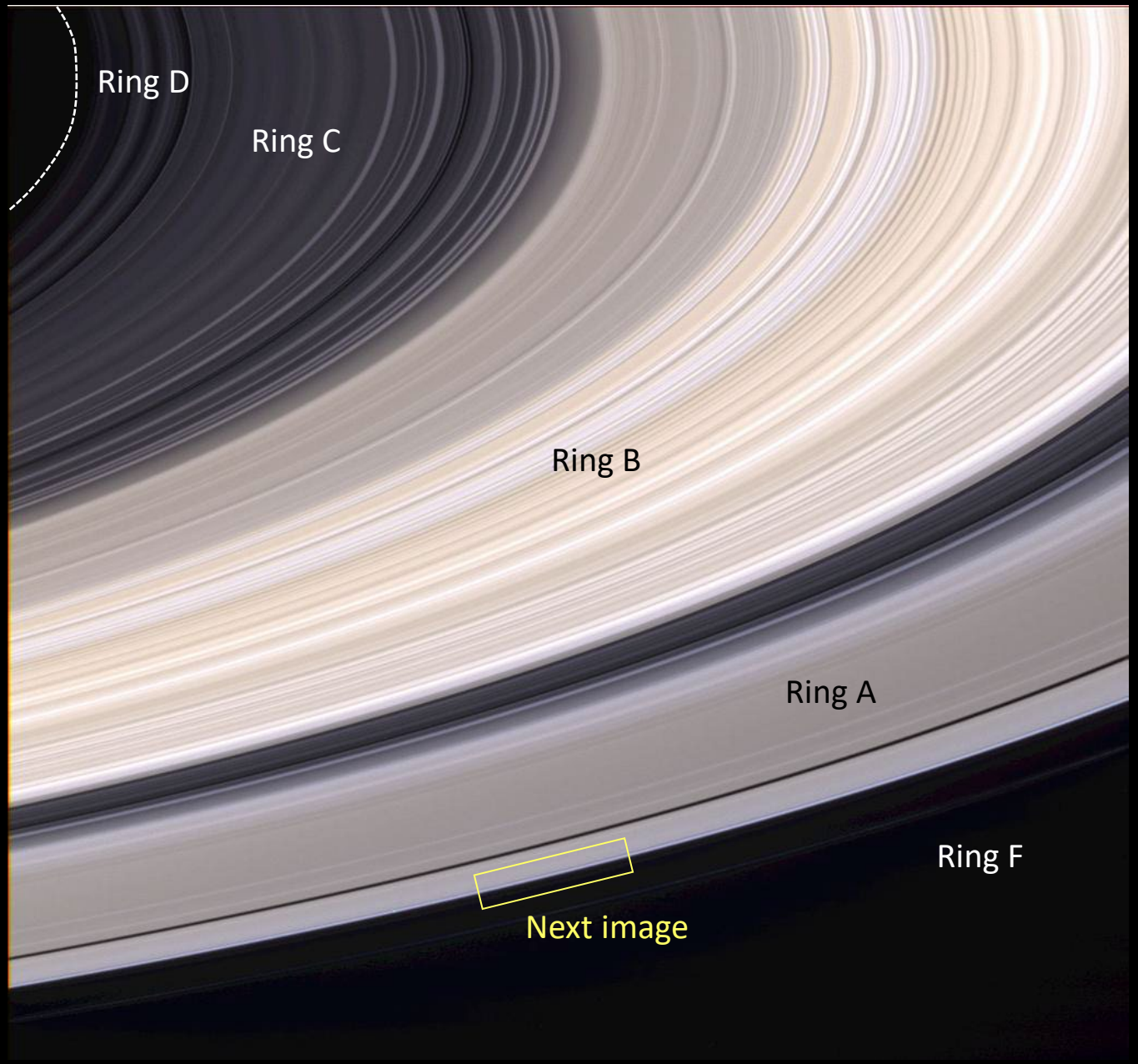
Saturn’s rings and orbital resonances (continued)



Next image

Cassini/NASA/JPL

Saturn's rings and orbital resonances (continued)



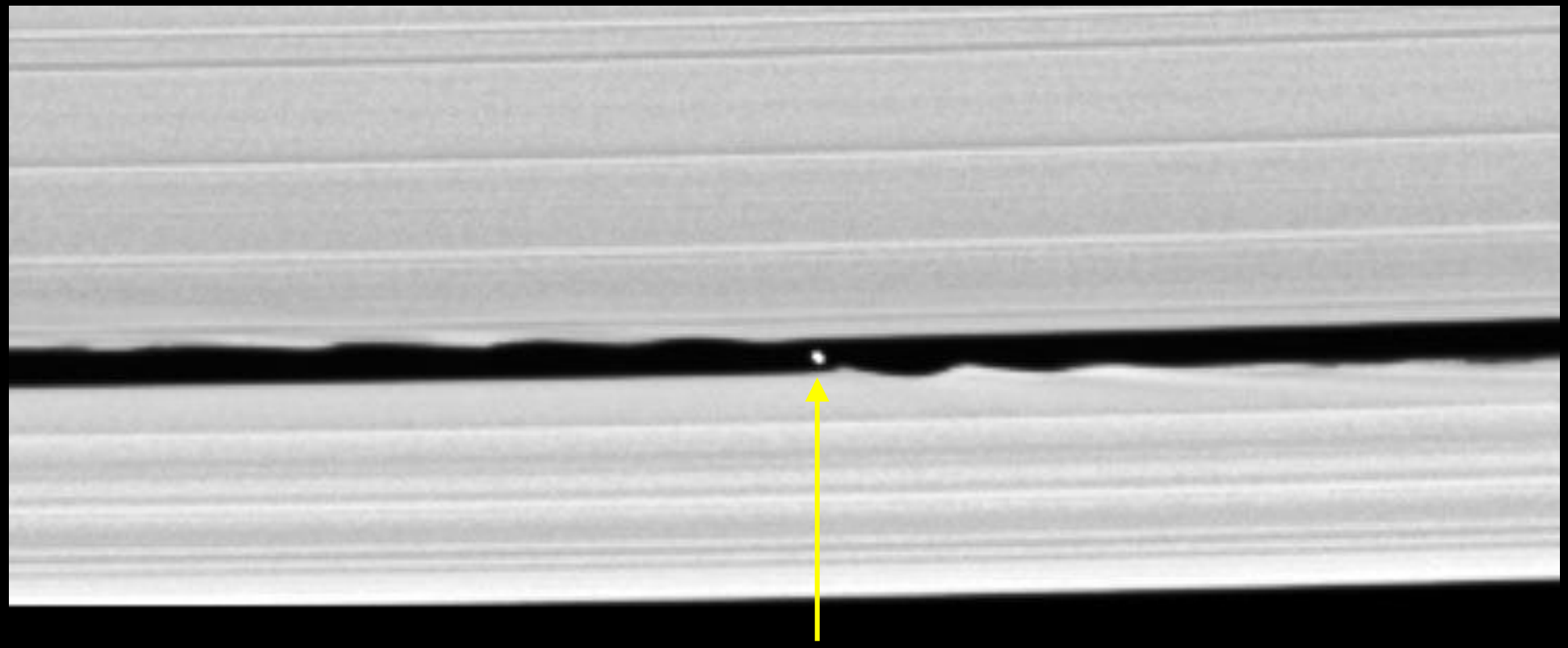
Cassini division between B and A:

- 1 arcsec wide, as seen from Earth
- 2:1 mean motion resonance with the moon Mimas

Encke gap

Cassini/NASA/JPL

Saturn’s rings and orbital resonances (continued)



The Keeler gap near the outer edge of the A ring, and the moon (Daphnis) that’s responsible for it.

Cassini/NASA/JPL

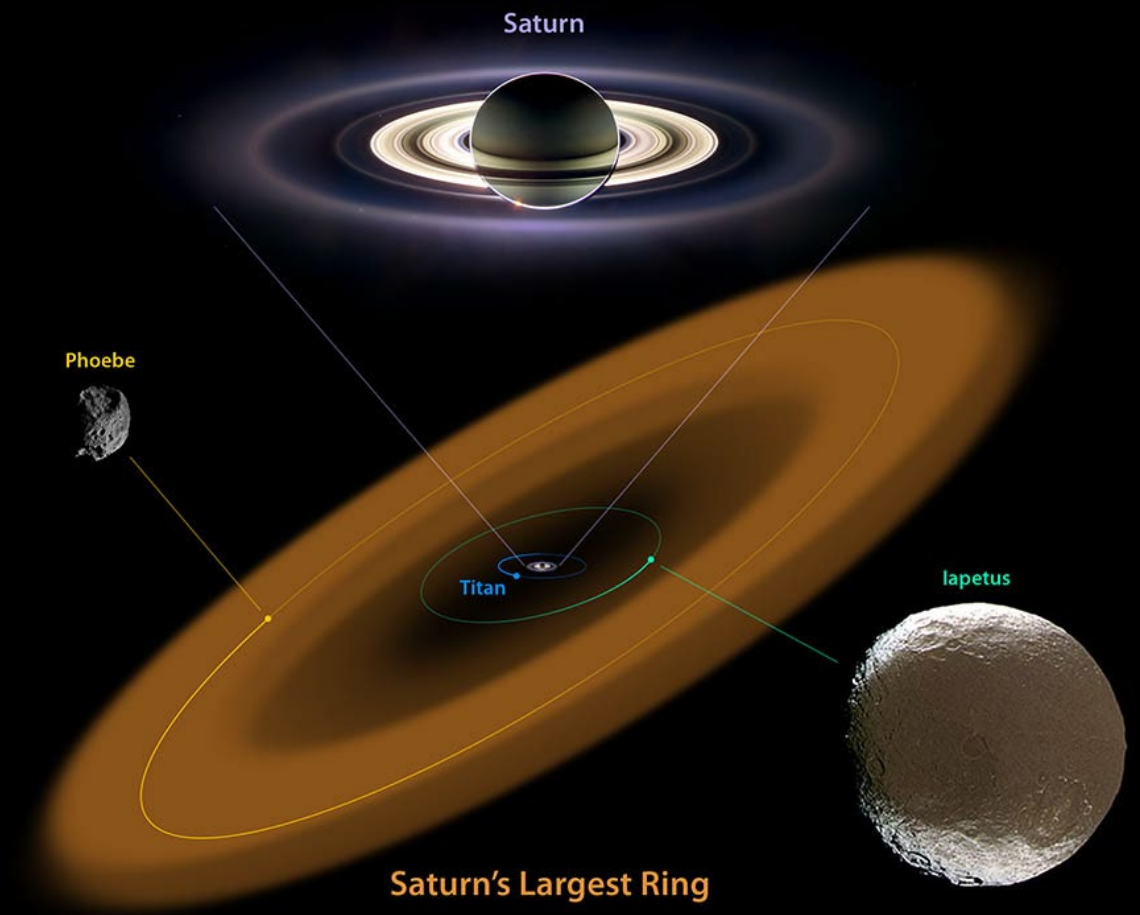
Saturn ring vital statistics

	Radius	Albedo	Thickness	Surface density	Eccentricity
	(km)		(m)	(gm cm^{-2})	
Saturn equator	60,268				
D inner edge	66,900	~0.01			
D outer edge	74,510				
C inner edge	74,658	0.12 - 0.30	5	1.4 - 5	
Titan ringlet	77,871			17	0.00026
Maxwell gap	87,491			17	0.00034
C outer edge	92,000	0.2	5	7	
B inner edge	92,000	0.4 - 0.6	10	20 - 100	
B outer edge	117,580				
Cassini division		0.2 - 0.4	20	18 - 20	
A inner edge	122,170	0.4 - 0.6	30	30 - 40	
Encke gap	133,589				
Keeler gap	136,530				
A outer edge	136,775	0.4 - 0.6	30	20 - 30	
F ring center	140,180	0.6			0.0026
G inner edge	170,000		1.E+05		
G outer edge	175,000				
E inner edge	181,000		1.E+07		
E outer edge	483,000		1.E+07		

The Phoebe ring

In 2009, an even larger ring was detected at mid-infrared wavelengths by the Spitzer Space Telescope.

- It covers radii 6-18$\times 10^6$ km, and is tilted 27° from the A-B-C-D-E-F-G ring plane.
- It contains the small, retrograde-orbiting moon Phoebe, and is probably formed from this moon's material.
- We will discuss its nature when we come to Iapetus.



Verbiscer, Skrutskie & Hamilton 2009

Uranus's rings

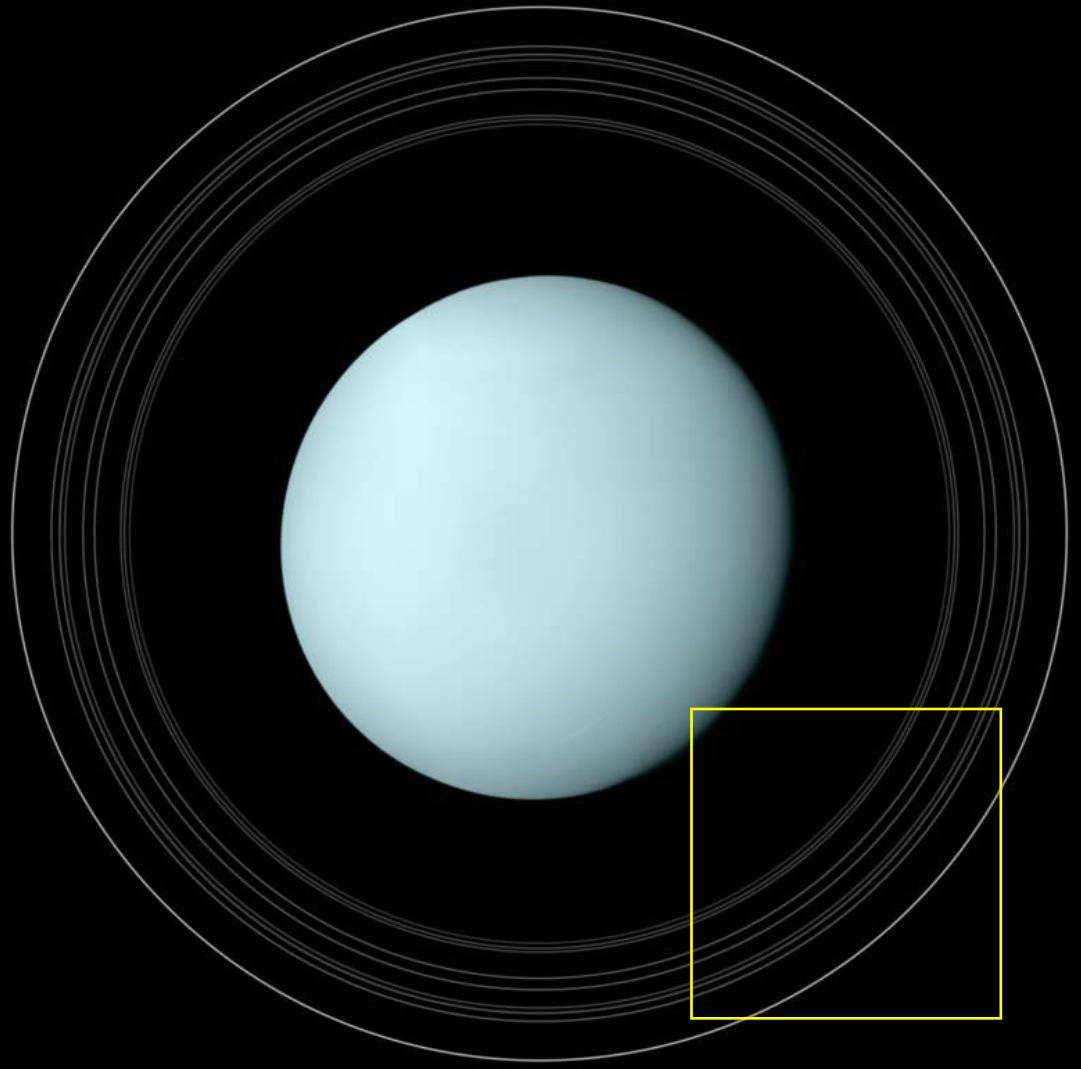
The second ring system discovered: in 1977, by Ted Dunham and Jim Elliot using the NASA Kuiper Airborne Observatory.

- Discovered by observing Uranus **occulting** (= passing in front of; transiting) a star.
    - The original intent of the experiment was to use the starlight to probe the structure of Uranus's upper atmosphere; the observers were mildly surprised by the rings.
- Ten narrow rings are observed from our distance, but viewed close up by Voyager 2 they appear to have structure not unlike Saturn's.
- The rings are not shiny, though; the **ring particles have small albedo**, A_b = 0.01-0.02: like the darker asteroids.
- And there aren't as many ring particles per ring area, either, as there are in Saturn's rings.

Uranus's rings (continued)

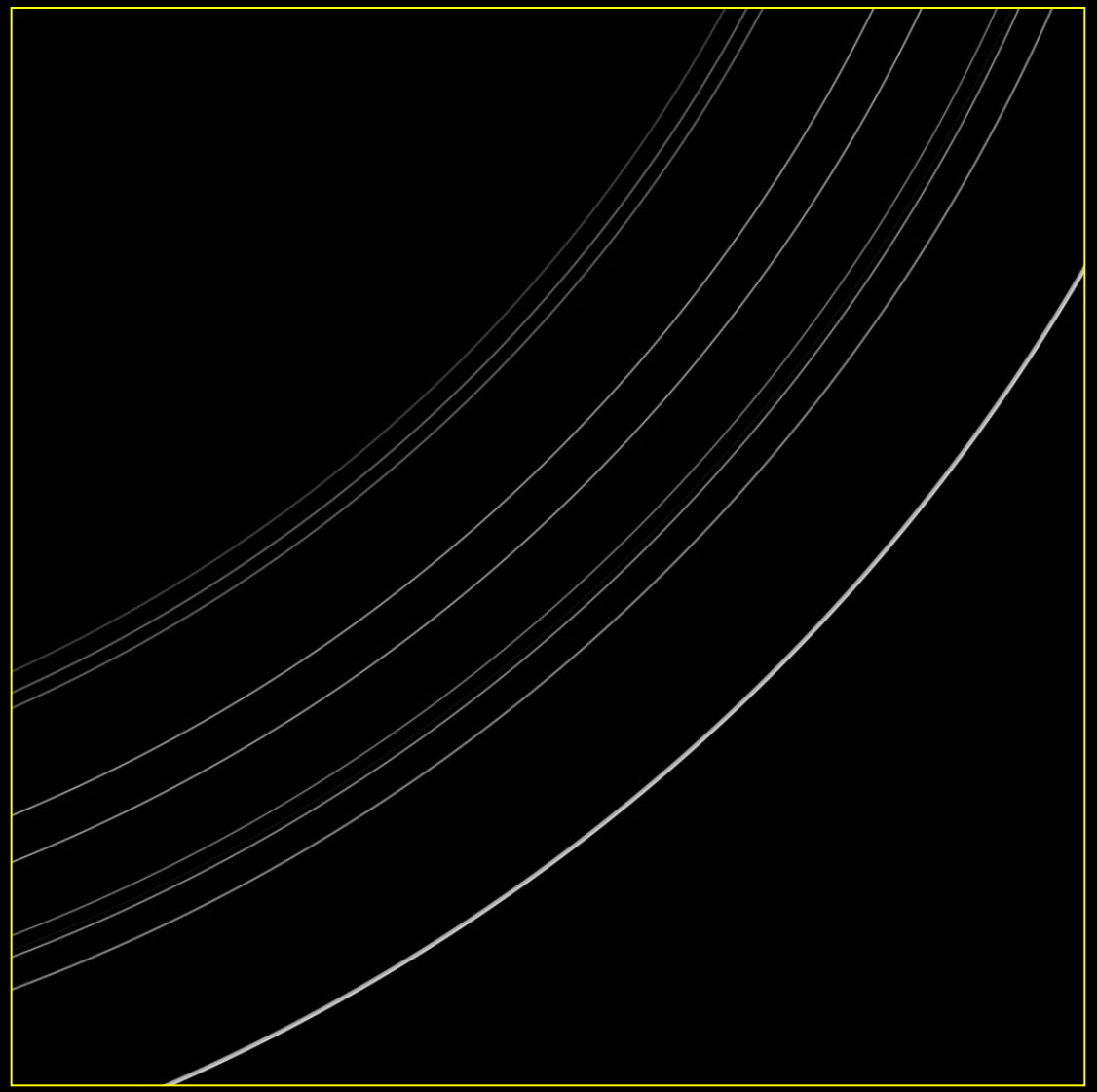
Voyager 2 image of Uranus and its rings, as processed by Calvin J. Hamilton. From the outside: ε, δ, γ, η, β, α, 4, 5, and 6.

Area of next image



Uranus's rings (continued)

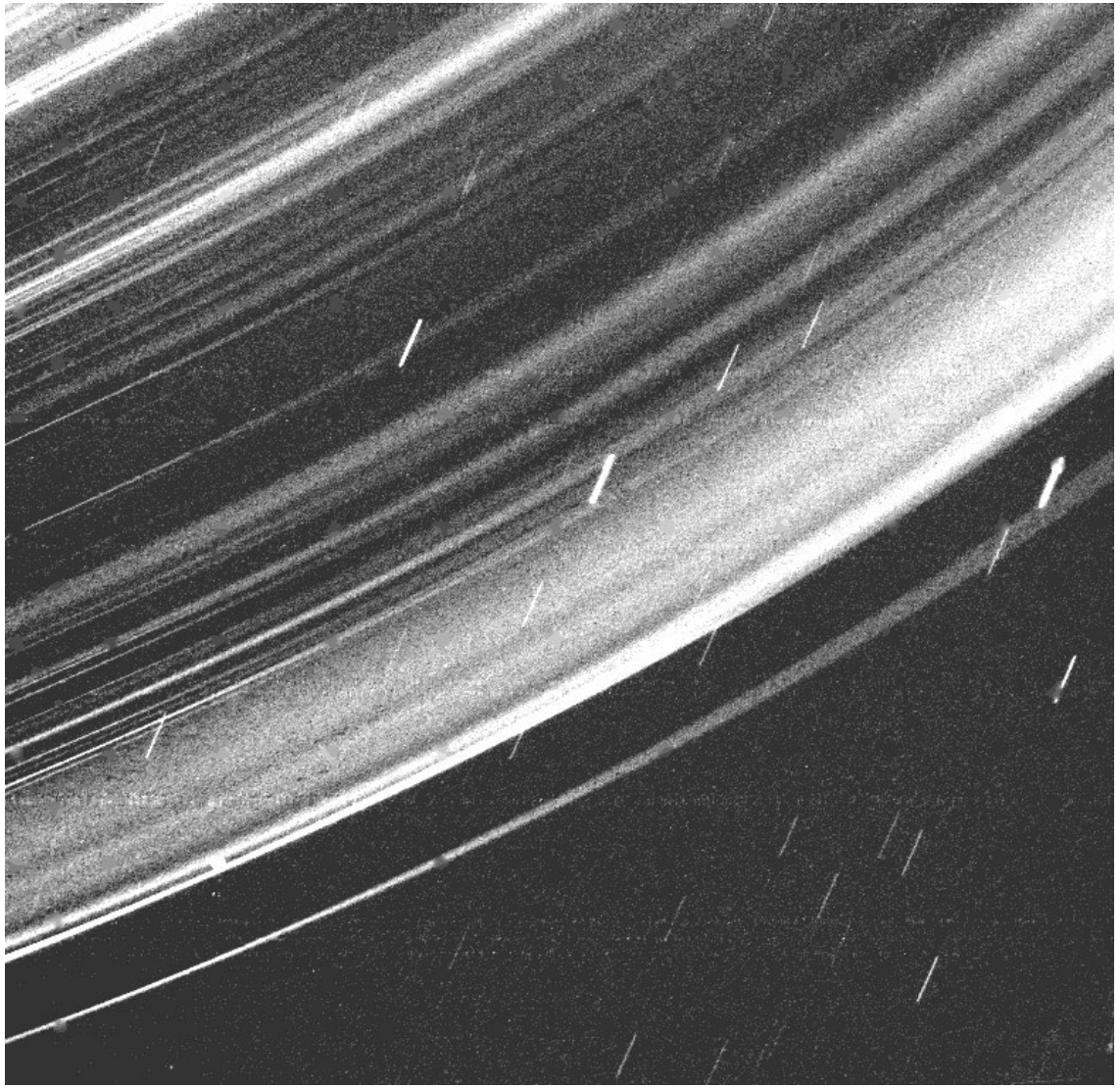
Voyager 2 image of Uranus and its rings, as processed by Calvin J. Hamilton. From the outside: ε, δ, γ, η, β, α, 4, 5, and 6.



Uranus's rings (continued)

Longer exposure on the Uranian rings by Voyager 2.

- Note that background stars shine right through the rings.
- Compare this with Saturn's main rings, through which we can't see stars, and which cast dark shadows on the planet.



Uranus rings vital statistics

	Radius (km)	Albedo	Width (km)	Eccentricity
Uranus equator	25,559			
6	41,837	0.015	~1.5	0.001
5	42,235	0.015	~2	0.0019
4	42,571	0.015	~2.5	0.001
α	44,718	0.015	4 - 10	0.0008
β	45,661	0.015	5 - 11	0.0004
η	47,176	0.015	1.6	
γ	47,626	0.015	1 - 4	0.0001
δ	48,303	0.015	3 - 7	
λ	50,024	0.015	~2	
ε	51,149	0.018	20-96	0.0079

Jupiter's rings

Discovered in 1979 by Voyager 1, these rings were almost immediately thereafter also detected with ground-based telescopes on Earth.

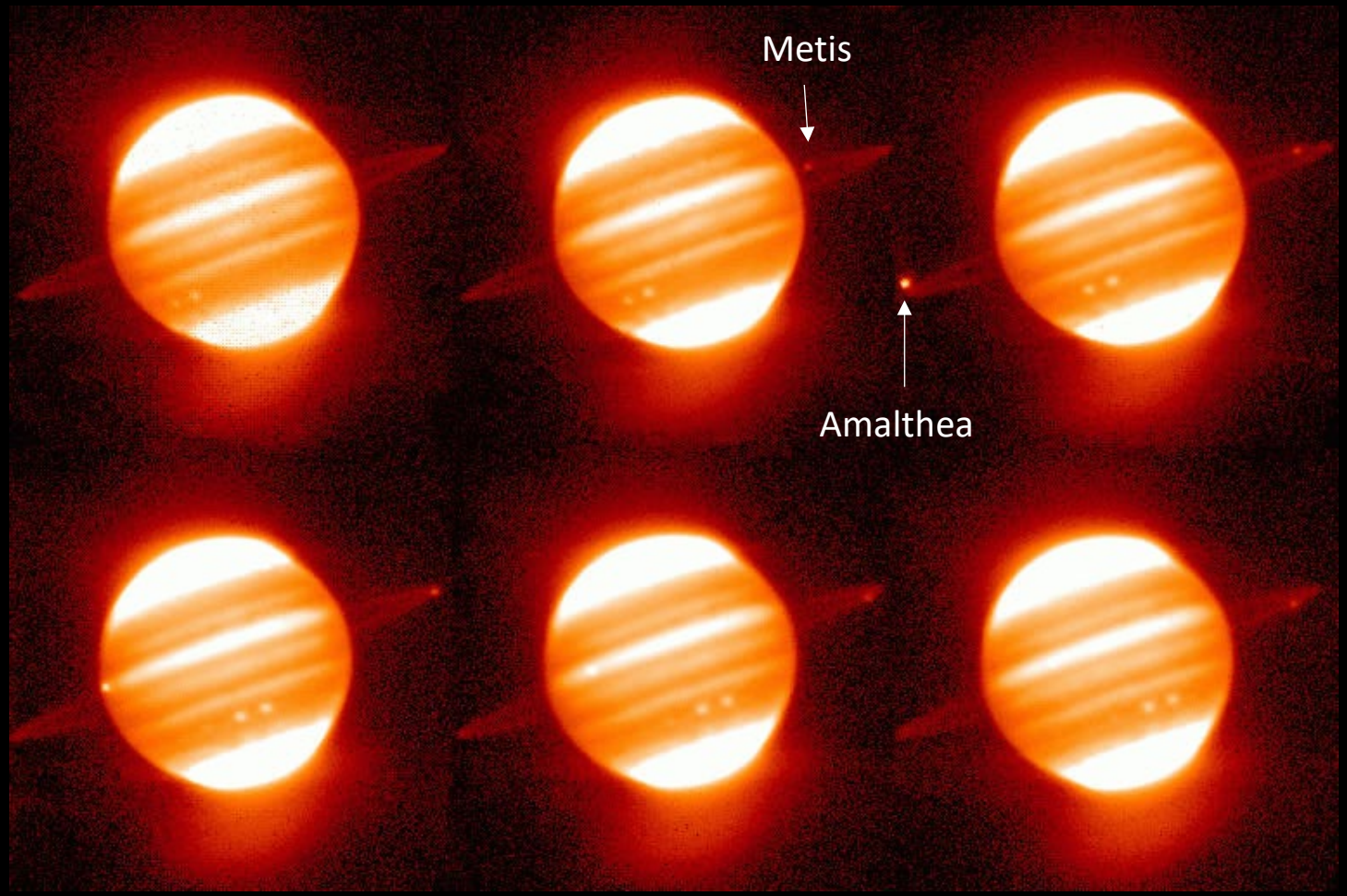
- A good way to see them from the ground is to observe at the center wavelength of a strong atmospheric absorption in Jupiter.
    - This dims the planet relative to the rings, as the rings have no gas.
    - There are several bands of methane at near-infrared wavelengths which are generally used in this manner.
- The main ring is **shepherded** by two small satellites, named Metis and Adrastea (inside and outside, respectively).
    - Their orbits are very close together, and they trap the ring's material with their gravitational perturbations on small particles whose orbits stray between.
- A faint halo can be seen above and below the main ring, about a factor of ten fainter.

Jupiter’s main ring, seen from the planet’s shadow



Galileo/JPL/NASA

Jupiter, main ring, and one of its shepherd satellites

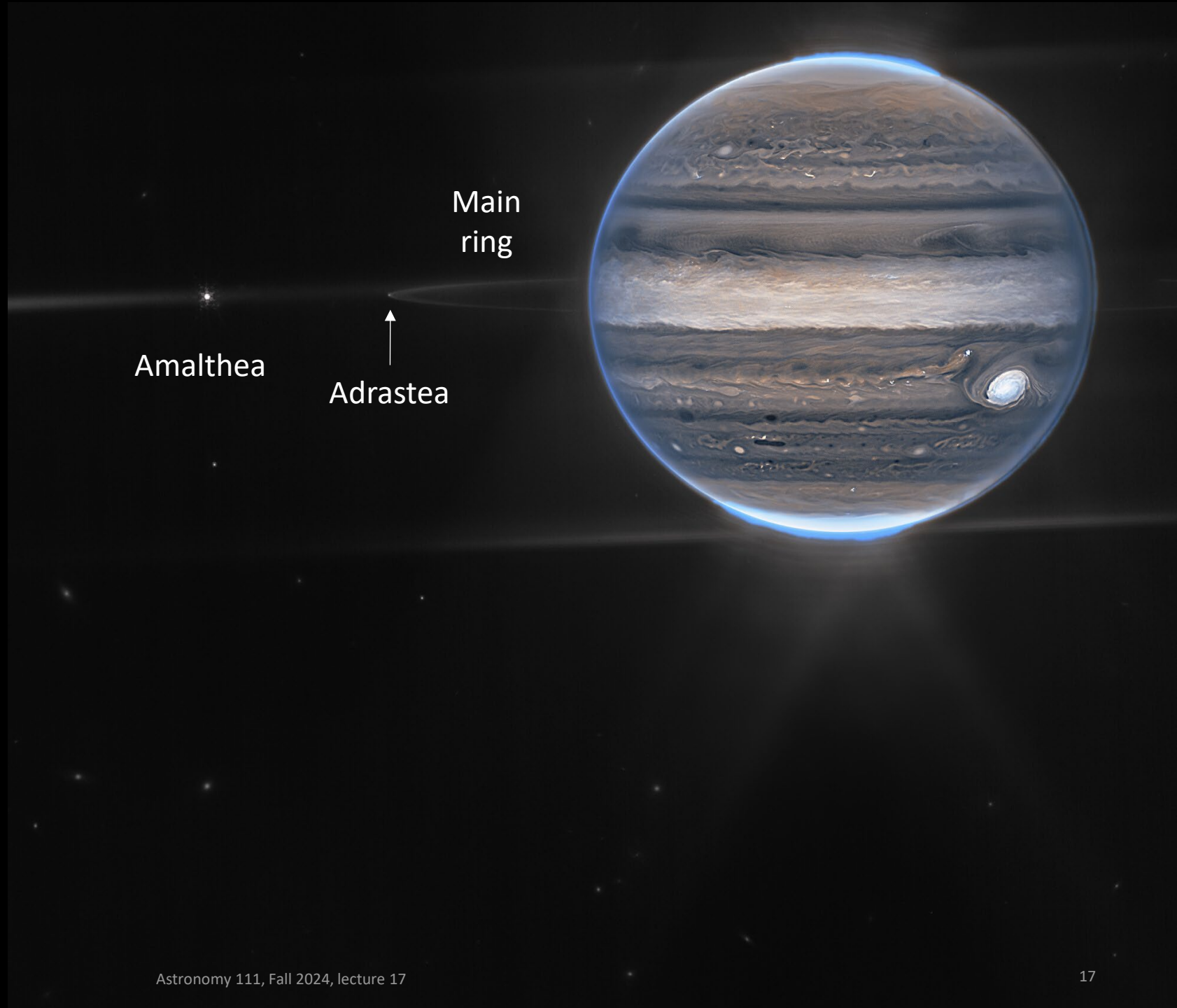


Near-infrared image sequence -- λ = 2.17 μm, in a methane band -- taken in 1994 at the NASA IRTF (Mauna Kea, HI). Metis is the larger of the two moons which shepherd the ring; Amalthea orbits well outside the ring.

Jupiter, rings, and shepherds from JWST

Amalthea gossamer ring

Aurora, and auroral light scattered within the camera



λ = 1.5 and 2.12 µm, NIRCam
JWST/NASA

Jupiter ring vital statistics

The rings have low density – even the main one – and have very low albedo, even lower than most asteroids:

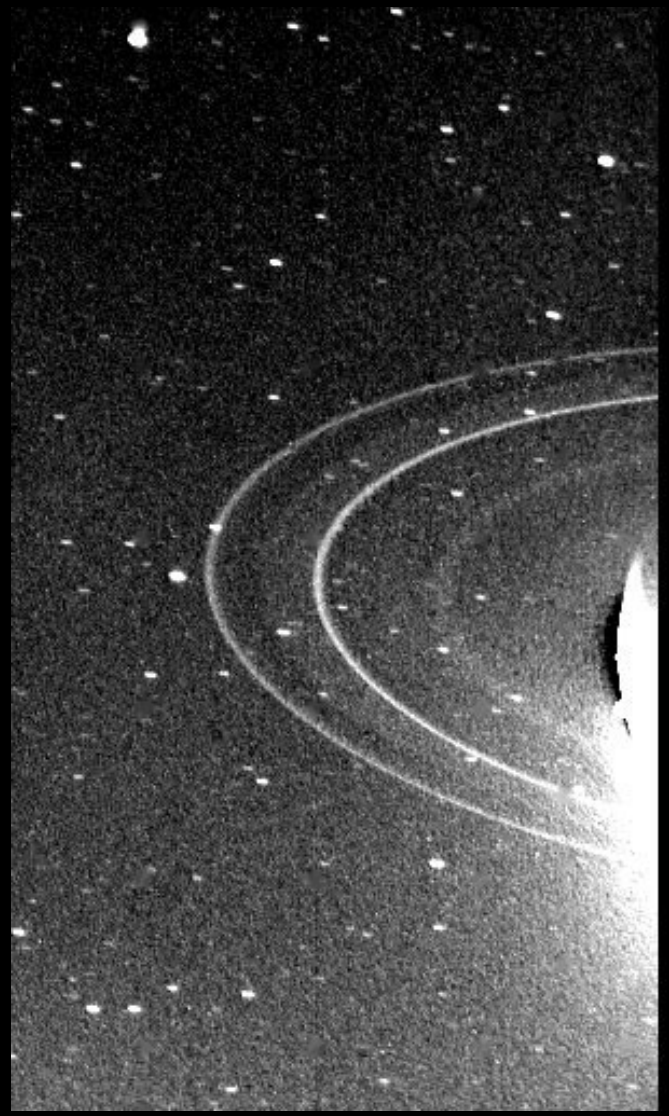
	Radius (km)	Albedo	Surface density (gm cm^{-2})
Jupiter equator	71,492		
Halo	100,000 - 122,000		
Main ring	122,000 - 129,000	0.015	5×10^{-6}
Amalthea gossamer ring	129,200 - 182,000		
Thebe gossamer ring	182,000 - 224,900		

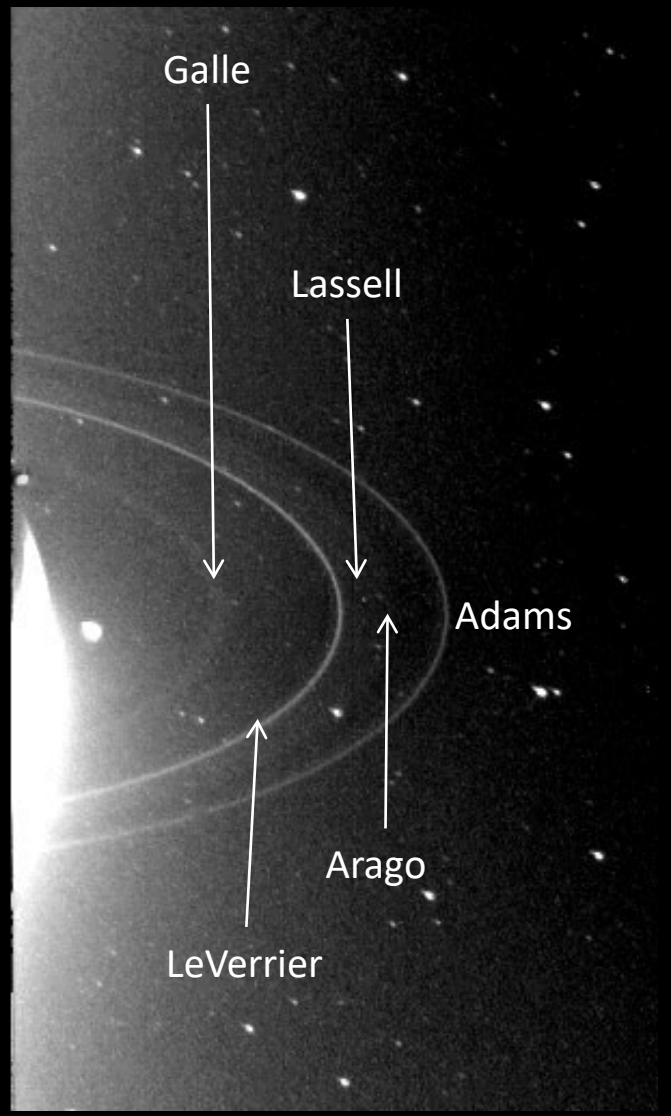
Neptune's rings

So by the mid 1980s every stellar occultation of Neptune was scrutinized for ring evidence.

- Results inconsistent and controversial: there appeared to be incomplete arcs rather than smooth, continuous rings like those of the other giant planets.
    - Interesting false alarm: the first "ring" occultation turned out to be the discovery of the small moon Larissa (Reitsema et al. 1981).
- Voyager 2 arrived in 1989 to find six narrow rings that completely circle the planet.
- But one of them ("Adams") has some sections brighter than others, in the sense that the albedo is larger by a factor of about 3 than the rest of the ring. The cause is still under investigation.

Neptune’s rings (continued)



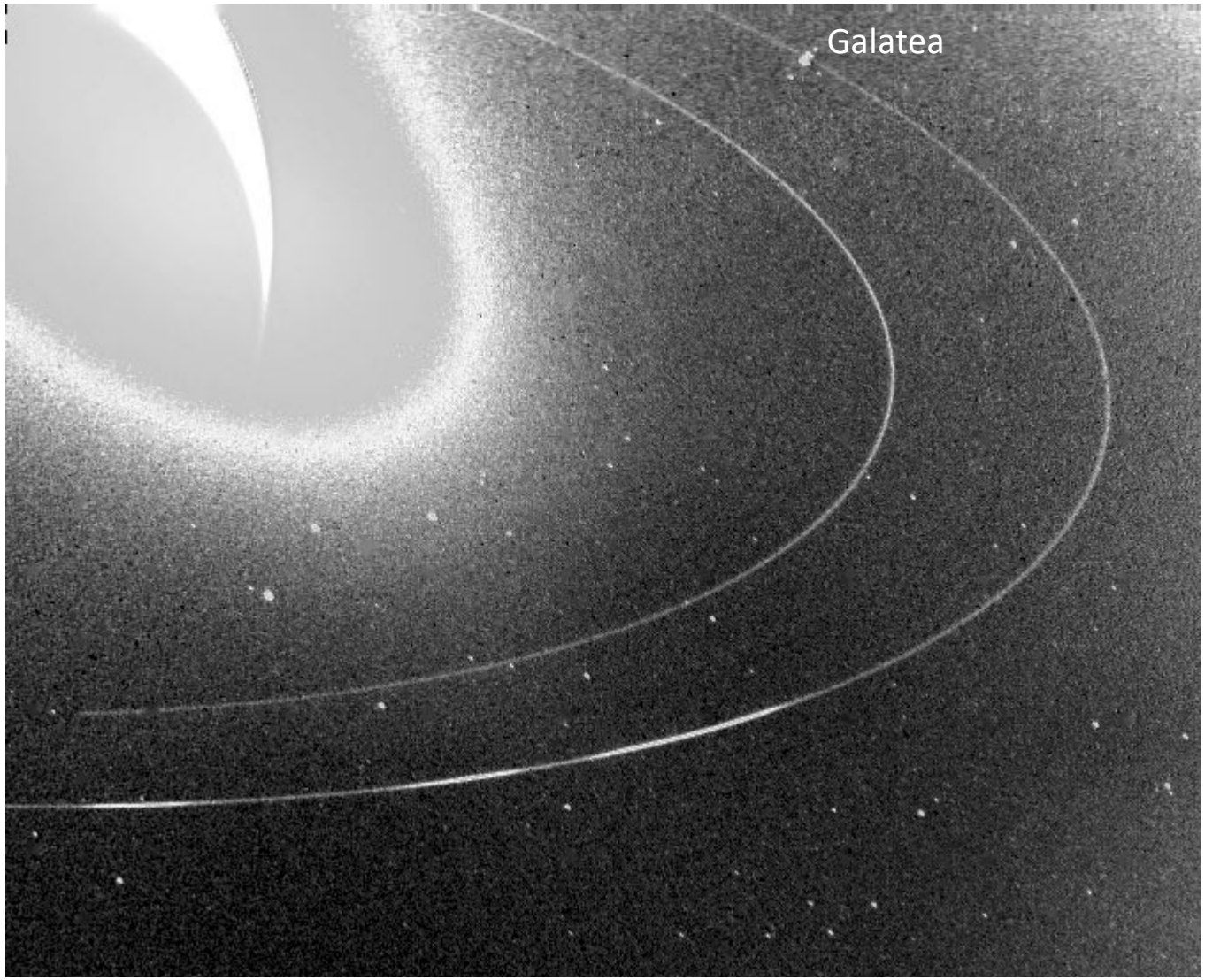


Voyager 2/JPL/NASA

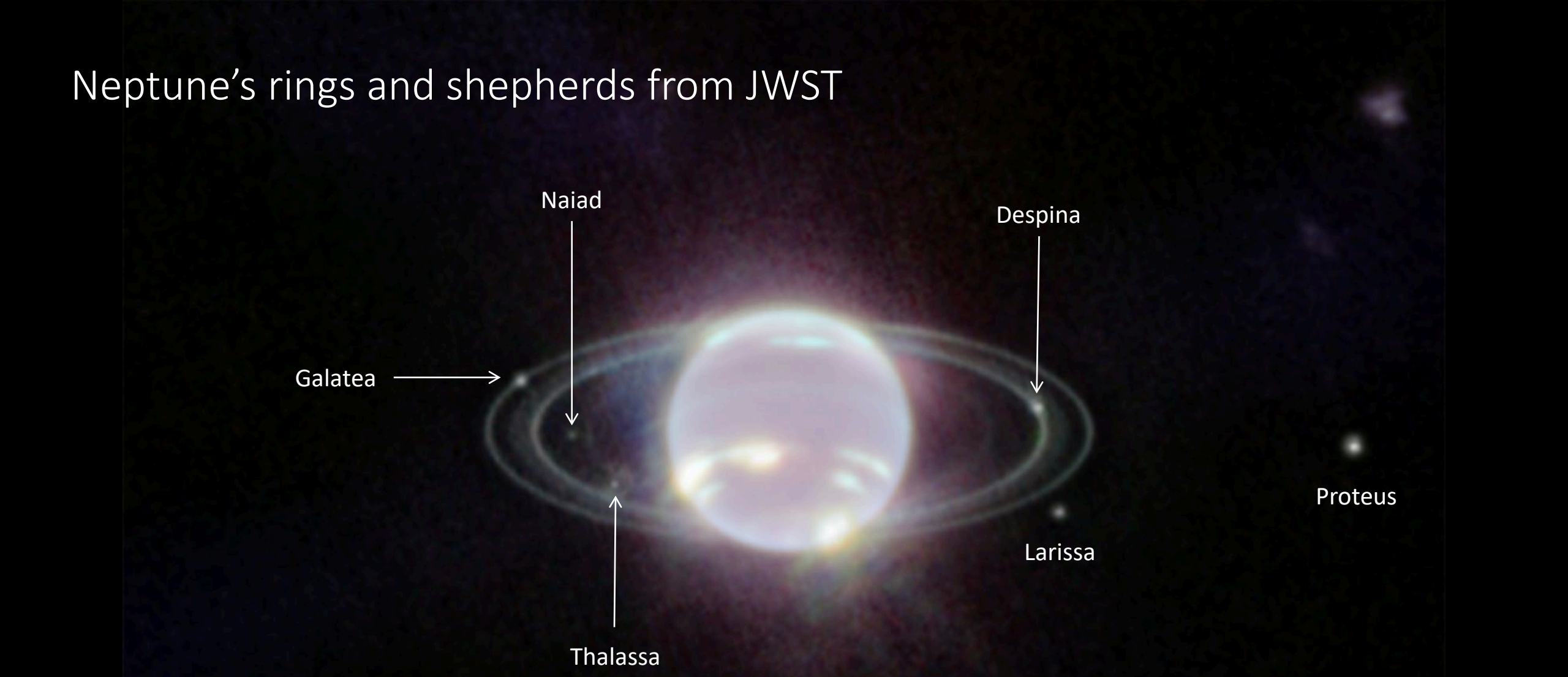
Neptune’s rings (continued)

Arcs in the Adams ring, by Voyager 2 (JPL/NASA): Liberté, Egalité, Fraternité (left-right).

And the small moon Galatea, which apparently shepherds the ring.



Neptune’s rings and shepherds from JWST



λ = 1.5 and 2.12 µm, NIRCam
JWST/NASA

Neptune rings vital statistics

Ring	Radius (km)	Albedo	Width (km)	Name
Neptune equator	24,766			
Galle	41,900	0.015	2000	Discoverer of Neptune.
LeVerrier	53,200	0.015	110	He who predicted Neptune's position for Galle.
Lassell	53,200	0.015	4000	First to claim sight of a ring around Neptune (spurious).
Arago	57,200		< 100	Great French physicist who encouraged LeVerrier's work.
Unnamed	61,950			
Adams	62,933	0.015	50	Independently predicted Neptune's position, pre-discovery.
Arcs in Adams Ring:				
Courage	62,933		15	Dubiously associated with revolutionary mottos.
Liberté	62,933		15	One of many mottos of the first French Revolution, perhaps coined by Robespierre.
Egalité 1	62,933	0.04	15	
Egalité 2	62,933	0.04	15	
Fraternité	62,933		15	

Common features of the rings

- None of the ring particles are very big.
  - The rings can't be solid, as first explained by Maxwell, and first verified observationally by Keeler.
  - Lots of rocks and dust even when mostly ice.
  - Moonlets and shepherd satellites no larger than ~20 km diameter, like Metis, Adrastea, *etc.*
- They all have complex, but well-defined, structure determined by orbital resonances with shepherd satellites and outer, regular moons.
  - Ringlets and gaps
  - Waves: bending waves, spiral waves, braids, ripples
- They do not contain much material.
  - Saturn's ring is by far most massive, at about 10^{-6} Earth masses. One could make a small, 100-200 km diameter, moon out of it.

Origin of the rings

The rings are probably debris from collisions among the system of moons of each planet, and as such may be considered leftovers from the planet-formation process.

- As we will discuss toward the end of the semester, giant planets (and stars) form from **disks**.
- Each planet's equator and main moon system lines up with the ring plane.
- Each ring lies within the **Roche limit** for its material and its host planet: **a moon made in the same location from all the ring material would be torn apart by tidal forces**, which is why the debris hasn't coalesced into moons.
- The Roche limit is the closest that a moon can be brought to a planet without being ripped apart by tidal forces.

Which, finally, brings us to tides…

Tidal accelerations

Tides are **differences** in force or acceleration between two positions in an object, such as its near and far sides.

- First, consider a moon of size $\Delta r \times \Delta \ell$ in the radial and azimuthal directions, a distance r from a planet of mass M, that **isn't in orbit** (i.e. has zero orbital angular momentum L):

$$g = -\frac{GM}{r^2}$$

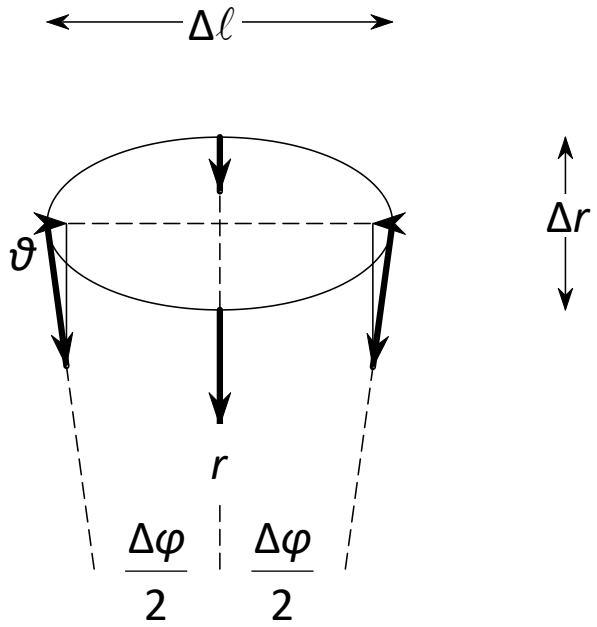
$$g_{tr} = \frac{dg}{dr}\Delta r = \boxed{\frac{2GM}{r^3}\Delta r}$$

Radial tide (stretch)

$$g_{t\varphi} = -2\frac{GM}{r^2}\cos\vartheta = -2\frac{GM}{r^2}\sin\frac{\varphi}{2}$$

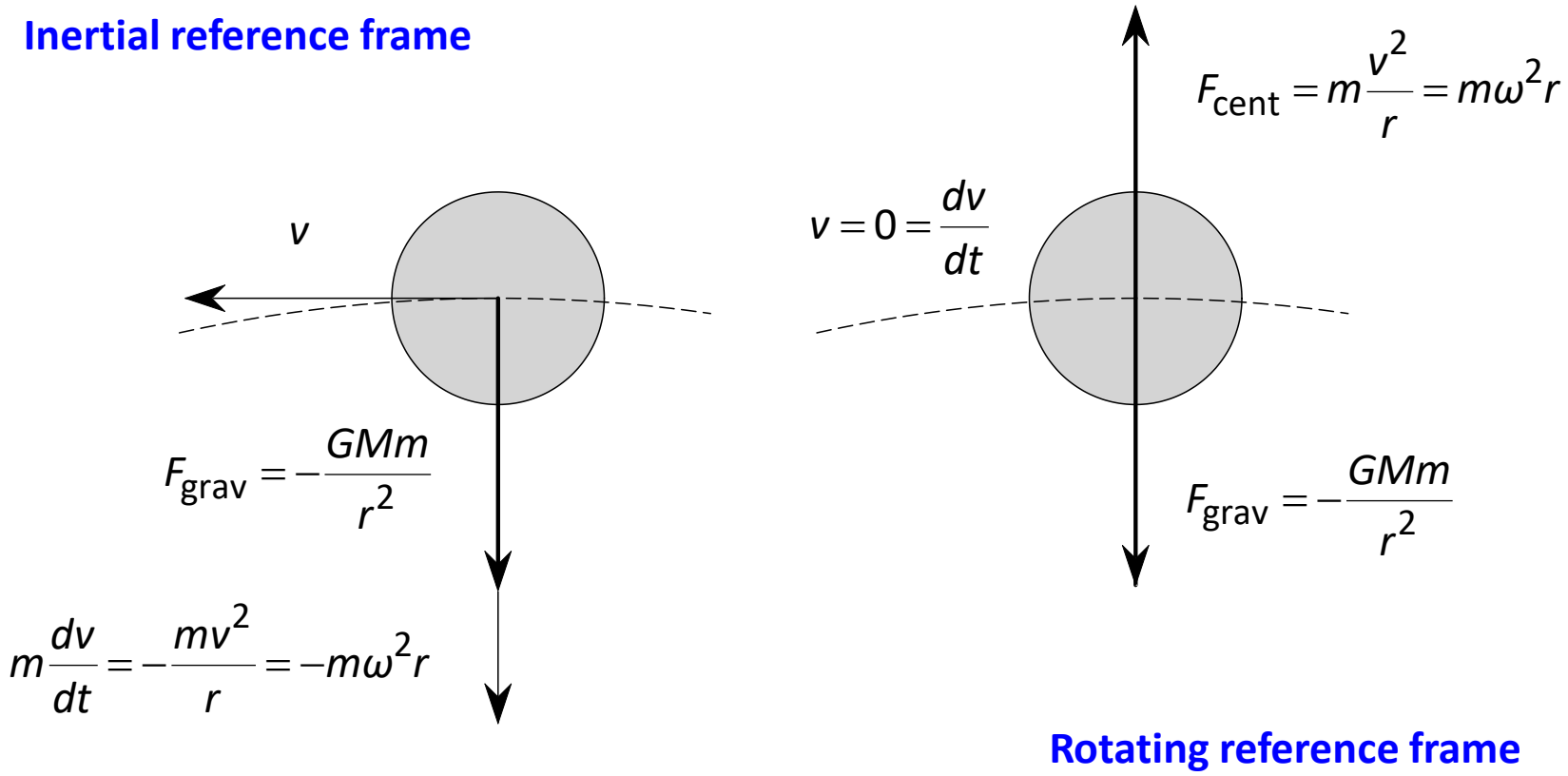
$$\cong -2\frac{GM}{r^2}\frac{\Delta\varphi}{2} = -\frac{GM}{r^3}r\Delta\varphi = \boxed{-\frac{GM}{r^3}\Delta\ell}$$

Azimuthal tide (compression)



Tidal accelerations (continued)

- Next, a moon that revolves, in a reference frame rotating with the revolution. Here are the forces at its center:



Tidal accelerations (continued)

- Consider just the larger, radial, component of accelerations, and consider a moon in orbit around planet with mass *M*. The effective acceleration in the moon's (revolving) reference frame involves force from the planet, and centrifugal force from orbital motion. At the moon's center,

$$g_{eff}(a) = -\frac{GM}{a^2} + \omega^2 a = 0 \quad \Rightarrow \quad \omega^2 = \frac{GM}{a^3} \quad .$$

a = moon's orbital radius

- And a distance *r* away from the planet, along a radial line through the moon's center, but not necessarily at its center:

$$g_{eff}(r) = -\frac{GM}{r^2} + \frac{GM}{a^3} r$$

a = moon's orbital radius
r = radius from planet's center

Tidal accelerations (continued)

- The radial tidal acceleration in this case is

$$g_{tr} = \frac{dg_{eff}}{dr}\Delta r = 2\frac{GM}{r^3}\Delta r + \frac{GM}{a^3}\Delta r \cong \frac{3GM}{a^3}\Delta r \qquad \text{if } R<<r$$

- Suppose this is such a big difference that it equals the acceleration of the moon's own gravity. If the moon (mass m) is spherical with uniform density ρ and radius R, this condition is given by

$$\frac{Gm}{R^2} = \frac{3GM}{a^3}R$$

$$\frac{G}{R^2}\left(\frac{4\pi}{3}R^3\rho\right) = \frac{3G}{a^3}\left(\frac{4\pi}{3}R_{\text{planet}}^3\rho_{\text{planet}}\right)R$$

Tidal accelerations (continued)

- Or, cancelling common factors,

$$a = R_{\text{planet}} \left(\frac{3\rho_{\text{planet}}}{\rho} \right)^{1/3} \cong 1.44 R_{\text{planet}} \left(\frac{\rho_{\text{planet}}}{\rho} \right)^{1/3}$$

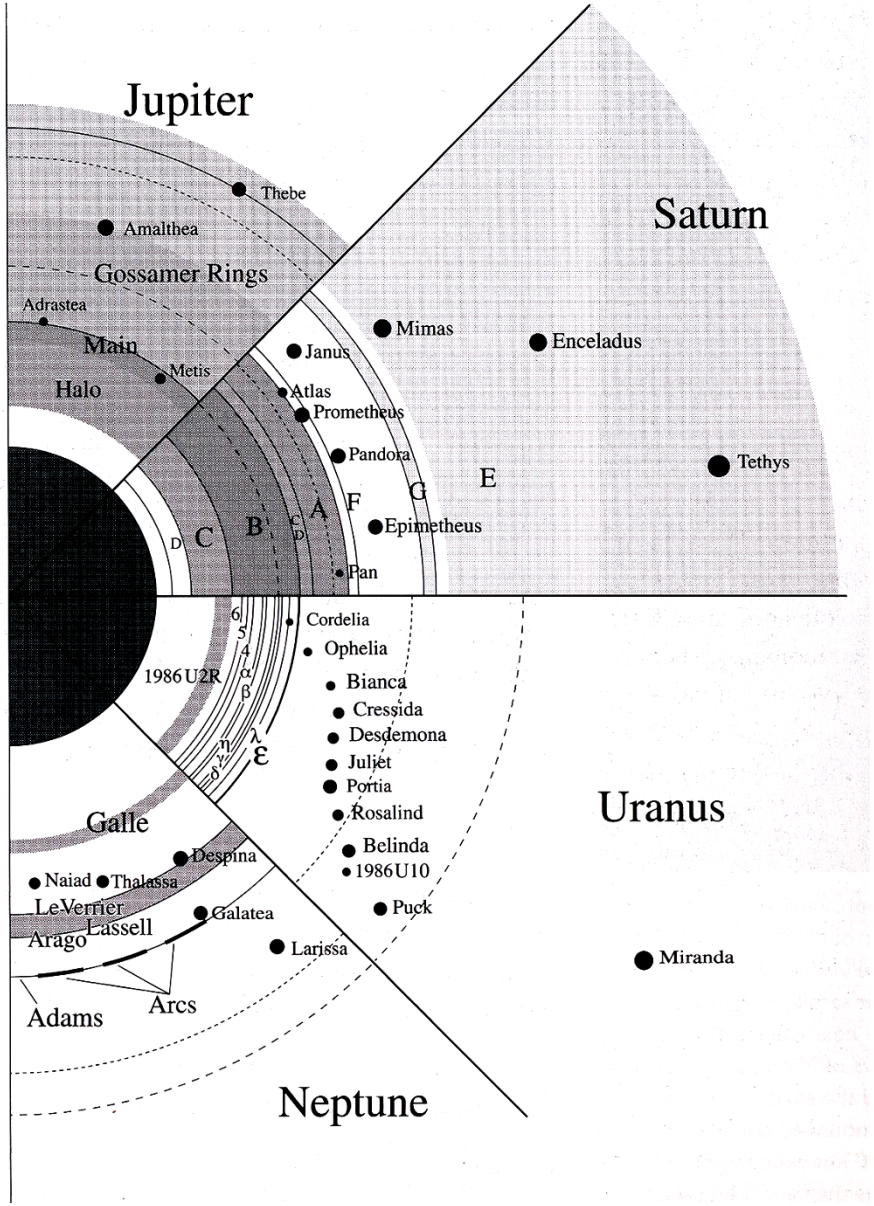
- **If the moon is placed in an orbit with radius smaller than this value of *a*,** its gravity cannot hold it together against the tidal forces, and **it will break apart.**

- If one accounts also for the azimuthal tide too, and the stretch/compression of the moon in response to the tides, there's a slight change; one gets (Roche 1847):

$$a_{\text{Roche}} \cong 2.46 R_{\text{planet}} \left(\frac{\rho_{\text{planet}}}{\rho} \right)^{1/3}$$

Roche limit

Distribution of rings and satellites



Scaled to each planet's radius.

- - - - - - - orbit synchronous with planetary rotation.

..... Roche radius for objects of density 1 gm/cm^3.