Dynamical Developments in Saturn's Rings

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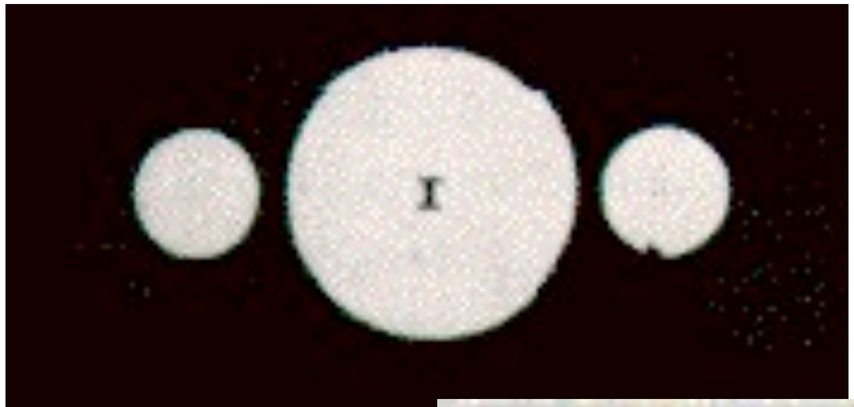
with thanks to

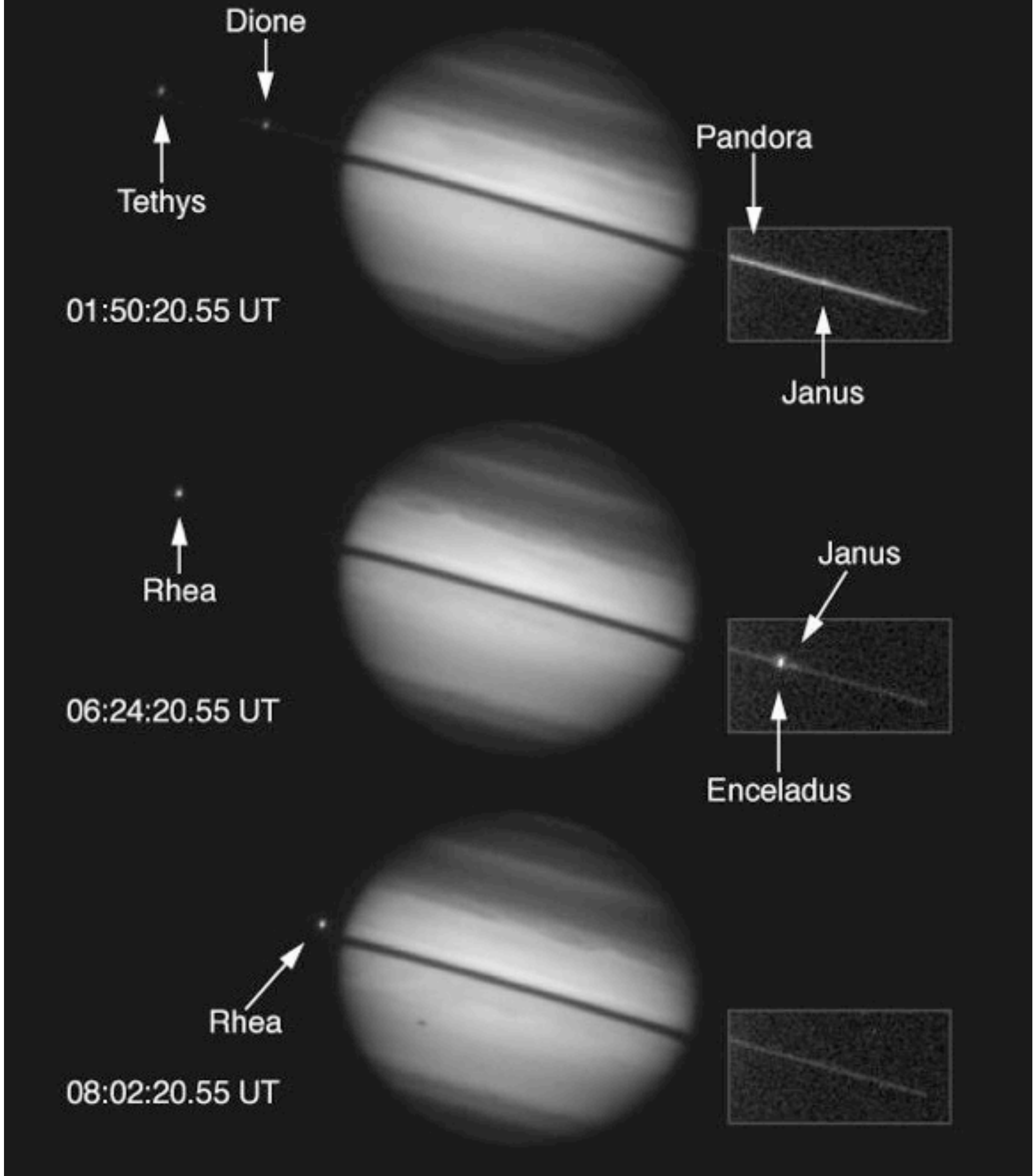
Matt Tiscareno, Glen Stewart,
and many people on the Cassini/Huygens mission
and my co-authors in 1985:
Frank Shu, Chi Yuan, Jack Lissauer, and Jeff Cuzzi

Outline

- A brief history of Saturn's rings
- Overview of structure of main rings
- Density and bending waves excited by satellites
- Density waves excited by oscillations in Saturn
- Self-gravity (Julian-Toomre) wakes and viscous overstabilities
- Propellers
- Vertical structure of rings
- Outer edges of B Ring and A Rings
- The enigmatic F Ring
- Origin of Saturn's rings

1610 - 1883





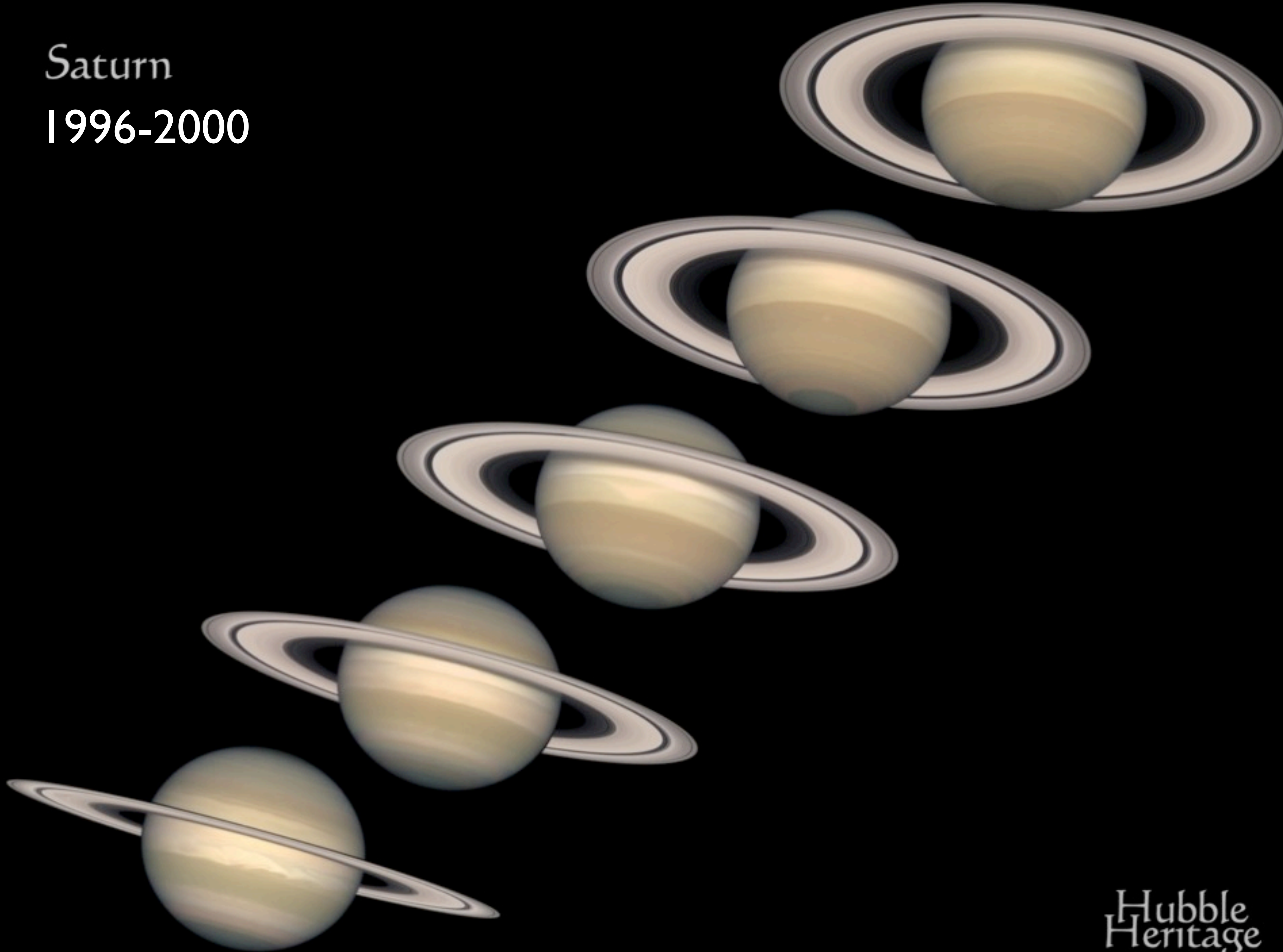
Saturn Ring-Plane Crossing
May 22, 1995

HST • WFPC2

PRC95-25c • ST ScI OPO • June 5, 1995 • A. Bosh (Lowell), NASA

Saturn

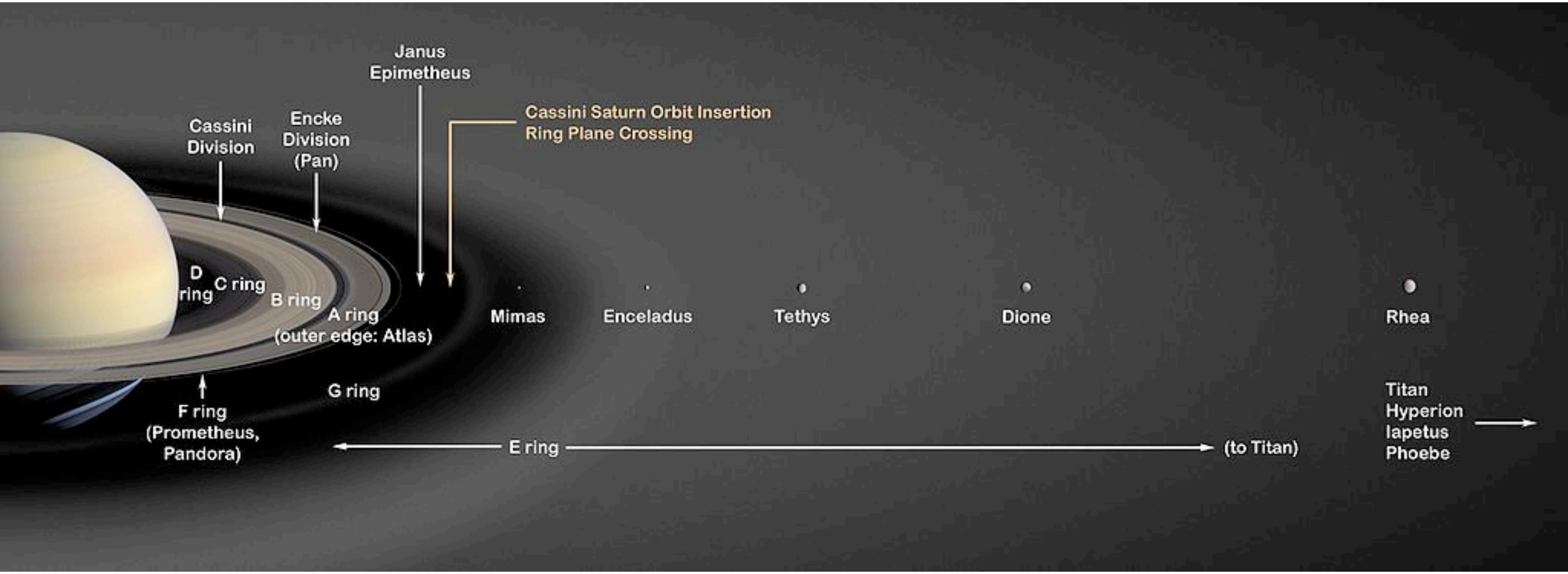
1996-2000



NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC01-15

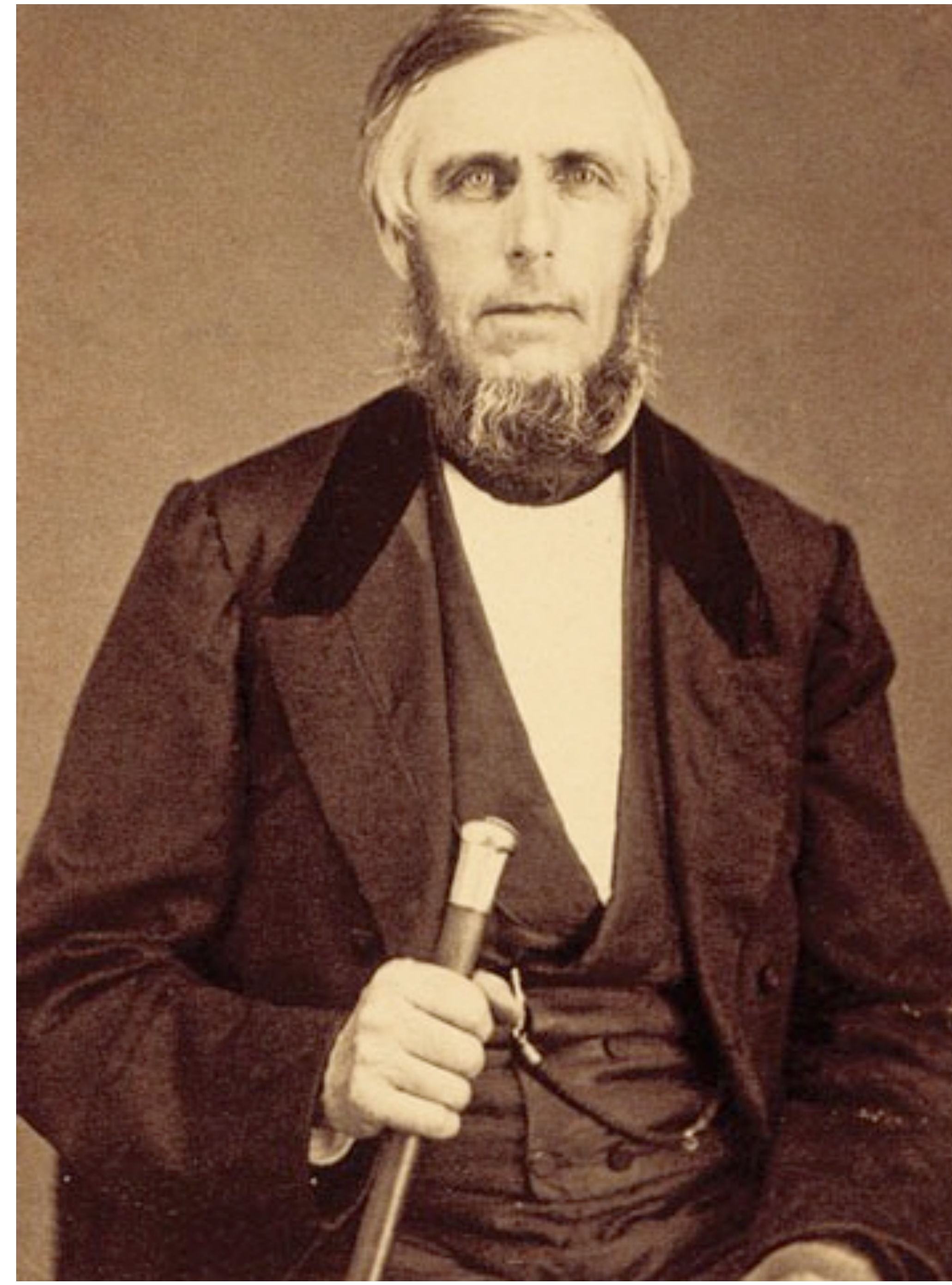
History of Saturn’s Rings Before 1900

- **1610**: Galileo discovers that Saturn has “servants”, “ears” or “handles”. These appendages disappear in 1612 and reappear in 1613.
- **1655**: Huygens infers that Saturn is surrounded by a thin ring.
- **1675**: Cassini discovers the Cassini Division.
- **1787**: Laplace suggests that the rings consist of many ringlets.
- **1789**: Herschel discovers Mimas and Enceladus, the inner two classical satellites.
- **1852**: Lassell finds that the Cassini Division and C Ring are translucent.
- **1856**: Maxwell concludes that “the rings must consist of disconnected particles”.
- 1866: Kirkwood points out that divisions in the asteroid belt and Saturn’s rings are associated with commensurabilities in mean motions.
- 1888: Keeler discovers the Encke Gap from Lick Observatory.
- 1895: Keeler discovers the differential rotation of Saturn’s rings.


Janus
Epimetheus
Cassini Saturn Orbit Insertion
Ring Plane Crossing
Cassini
Division
Encke
Division
(Pan)
D
ring
C ring
B ring
A ring
(outer edge: Atlas)
F ring
(Prometheus,
Pandora)
G ring
Mimas
Enceladus
Tethys
Dione
Rhea
E ring
(to Titan)
Titan
Hyperion
Iapetus
Phoebe

Kirkwood on Gaps in the Asteroid Belt and Saturn's Rings

"The first statement Kirkwood made of the asteroid gaps, apparently, and also of the gaps in the rings of Saturn, was before the Buffalo meeting of the American Association for the Advancement of Science, in August 1866. This particular meeting of the Association was 'originally appointed to have been held at Nashville, Tenn.' in 1861... 'In the mean time, the great rebellion breaking out, the meeting was not, of course, called together, as that place was not either a fit or a safe one for loyal members to visit.'"



- Daniel Kirkwood, *Proceedings AAAS* **15** (1967), quoted by Helen Sawyer Hogg, *J. Royal Astro. Soc. Canada* **44**, 163 (1950).

METEORIC ASTRONOMY:

A TREATISE

ON

SHOOTING-STARS, FIRE-BALLS,

AND

AEROLITES.

BY

DANIEL KIRKWOOD, LL.D.
PROFESSOR OF MATHEMATICS IN WASHINGTON AND JEFFERSON COLLEGE.

PHILADELPHIA:
J. B. LIPPINCOTT & CO.
1867.

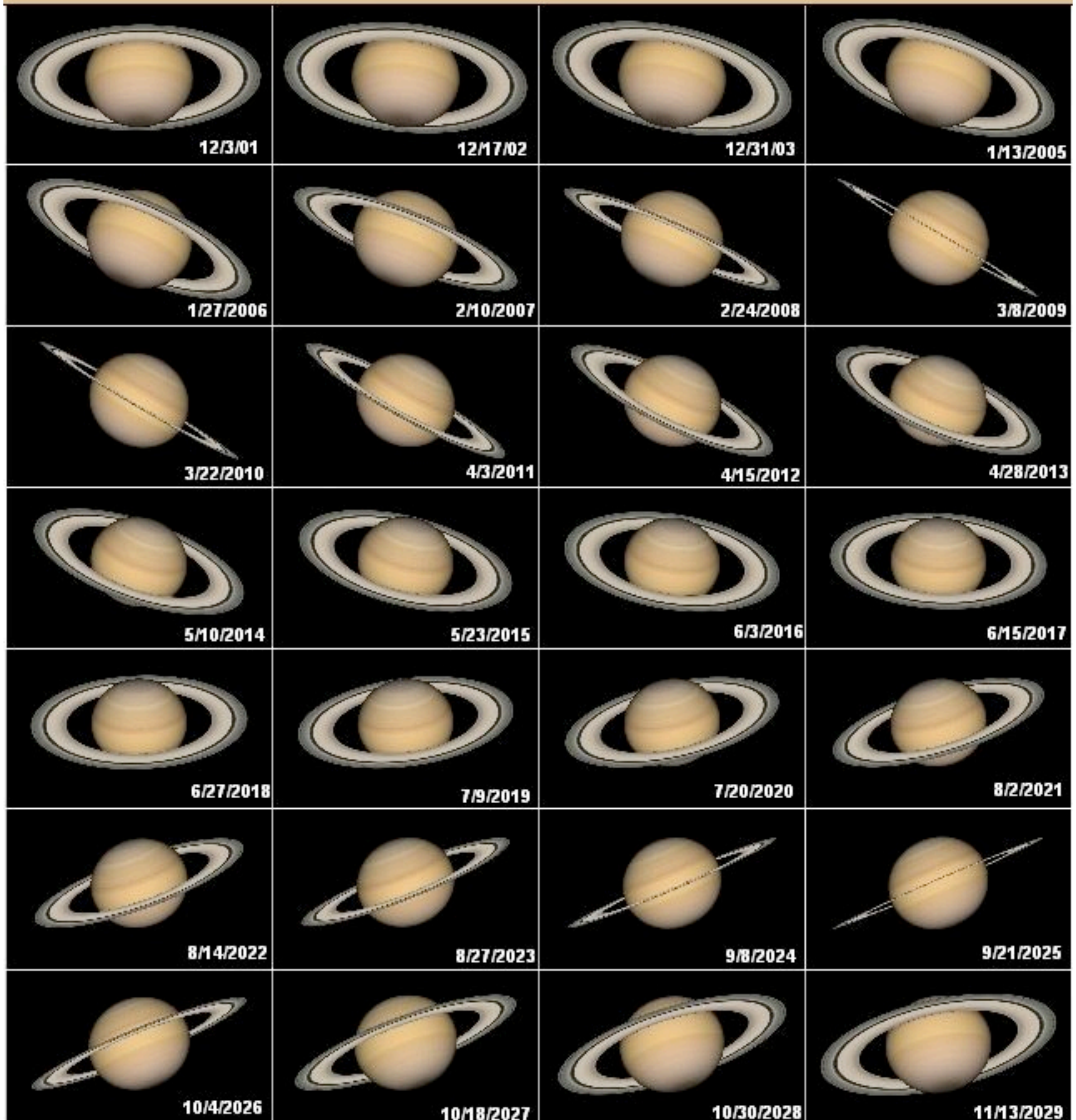
TABLE II.—The Rings of Saturn.

	Struve.	Encke.	Mean.	In Semi-diam. of Saturn.
	"	"	"	
Equatorial radius of the planet............	8·9955			
Ext. semi-diameter of exterior ring.........	20·047	20·2225	20·13475	2·23830
Int. semi-diameter of exterior ring.........	17·644	18·0190	17·83150	1·98230
Ext. semi-diameter of interior ring..........	17·287	17·3745	17·30575	1·92380
Int. semi diameter of interior ring..........	13·334	13·3780	13·35600	1·48470
Breadth of interval...	00·407	00·6445	00·52575	0·05844

The period of a satellite revolving at the distance, 1·9238, the interior limit of the interval		=10h.	50m.	16s.
One-sixth of the period of	Dione .	=10	56	53
One-third "	Enceladus.	=10	59	22
One-half "	Mimas .	=11	18	32
One-fourth "	Tethys .	=11	19	36
And the period of a satellite at the distance, 1·9823, the exterior limit of the interval		=11	28	3

The interval, therefore, occupies precisely the space in which the periods would be commensurable with those of the four members of the system immediately exterior. Particles occupying this portion of the *primitive* ring would always come into conjunction with one of these satellites in the same parts of their orbits. Such orbits would become more and more eccentric until the matter moving in them would unite near one of the apsides with other portions of the ring. *We have thus a physical cause for the existence of this remarkable interval.*

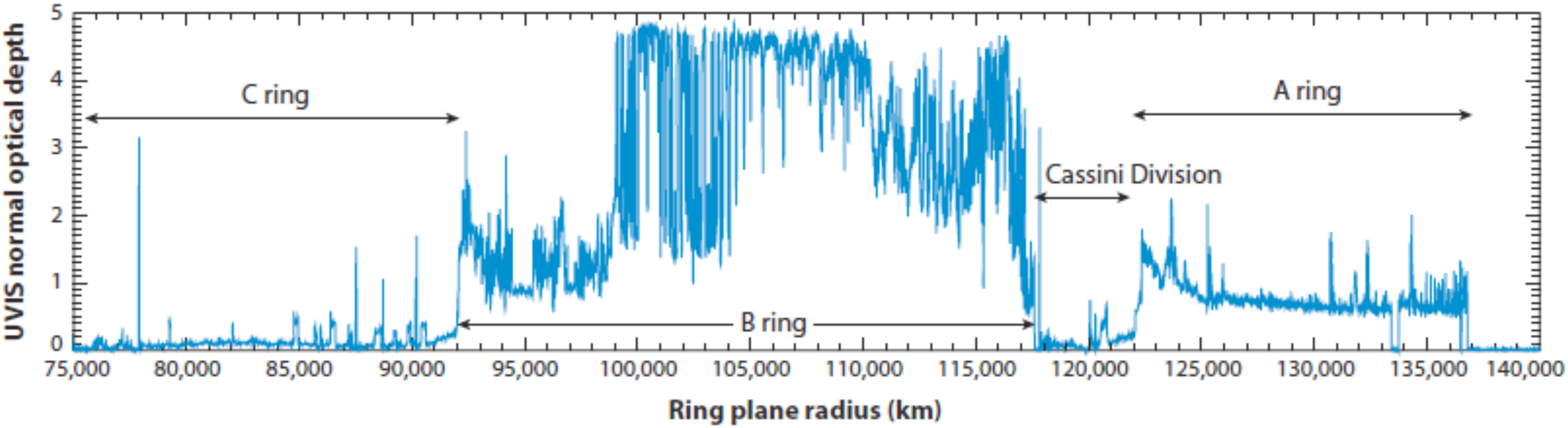
Saturn Oppositions: 2001 - 2029

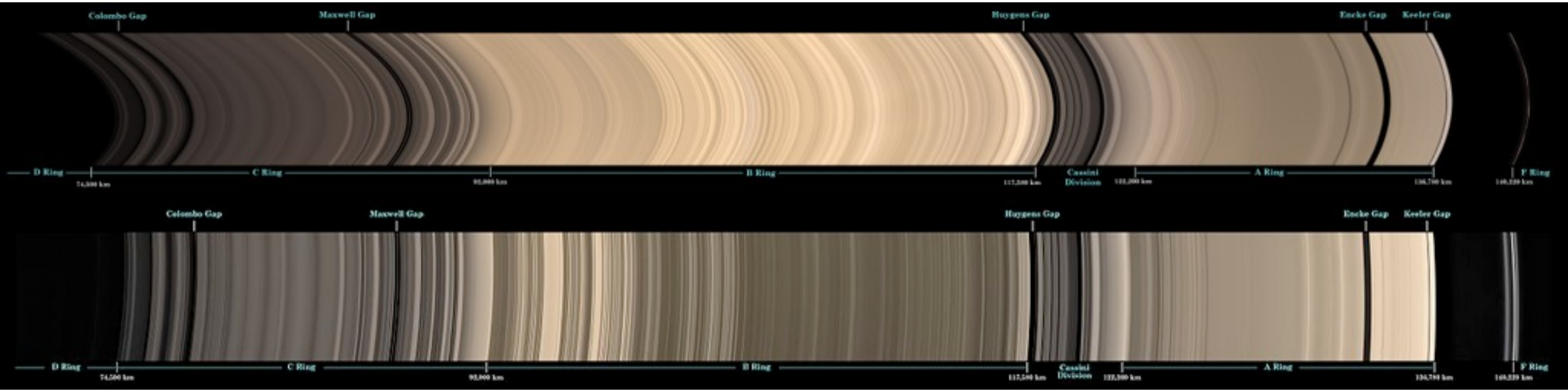


Cassini arrival

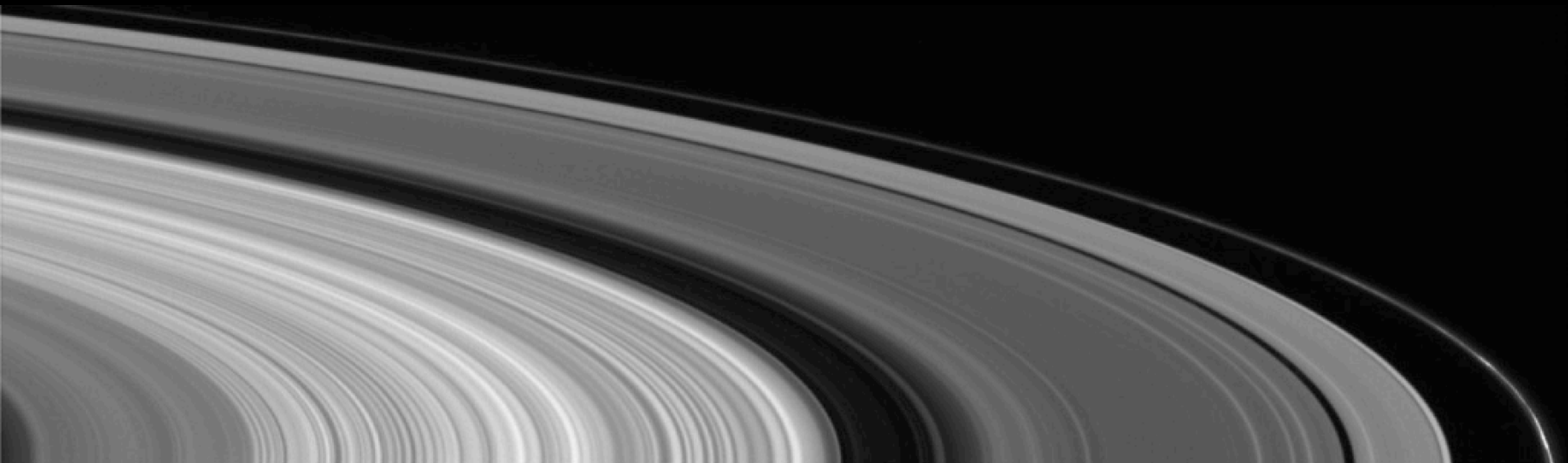
equinox

Cassini end of mission

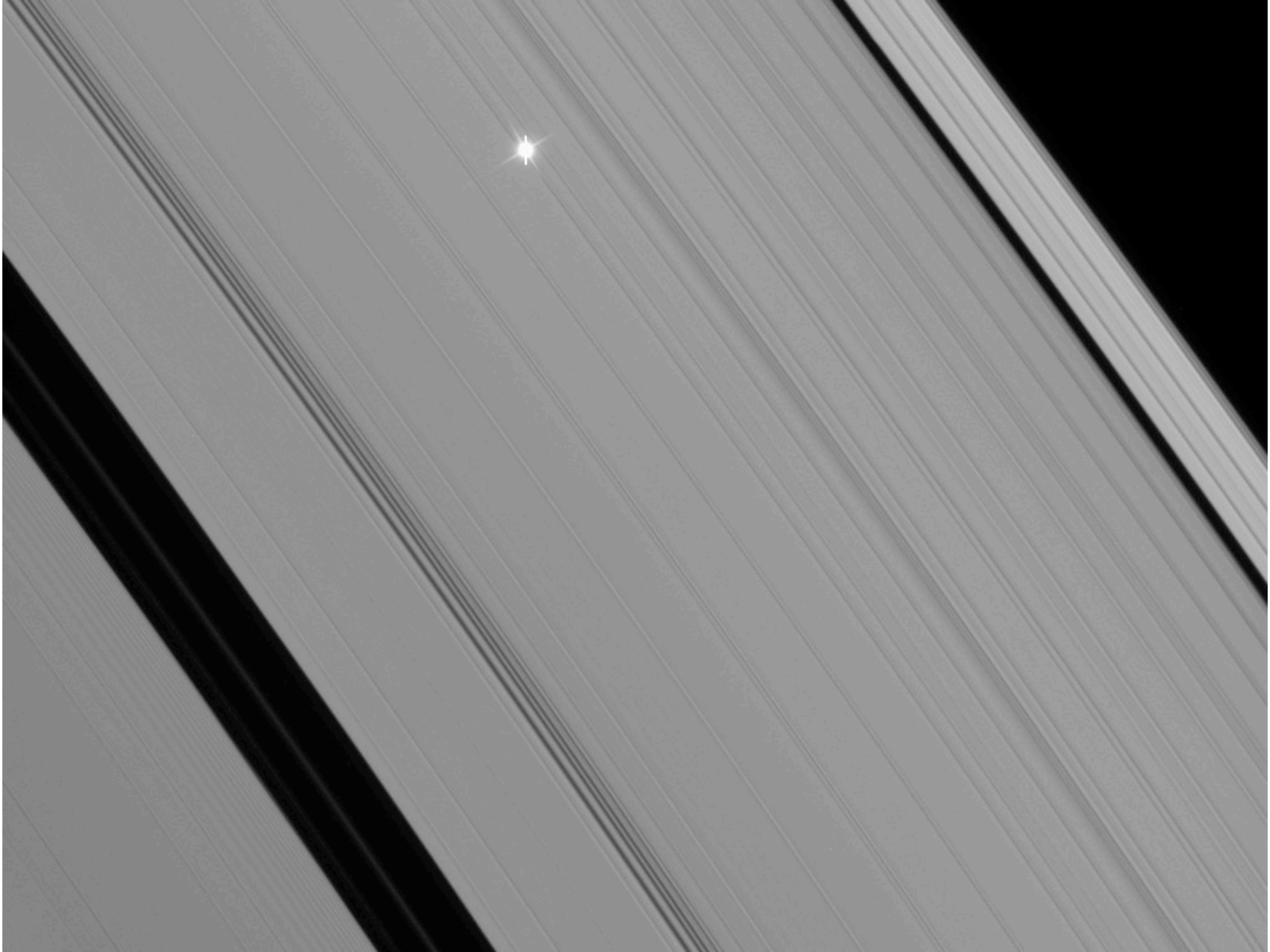

UVIS normal optical depth
0
1
2
3
4
5
C ring
B ring
Cassini Division
A ring
75,000
80,000
85,000
90,000
95,000
100,000
105,000
110,000
115,000
120,000
125,000
130,000
135,000
140,000
Ring plane radius (km)

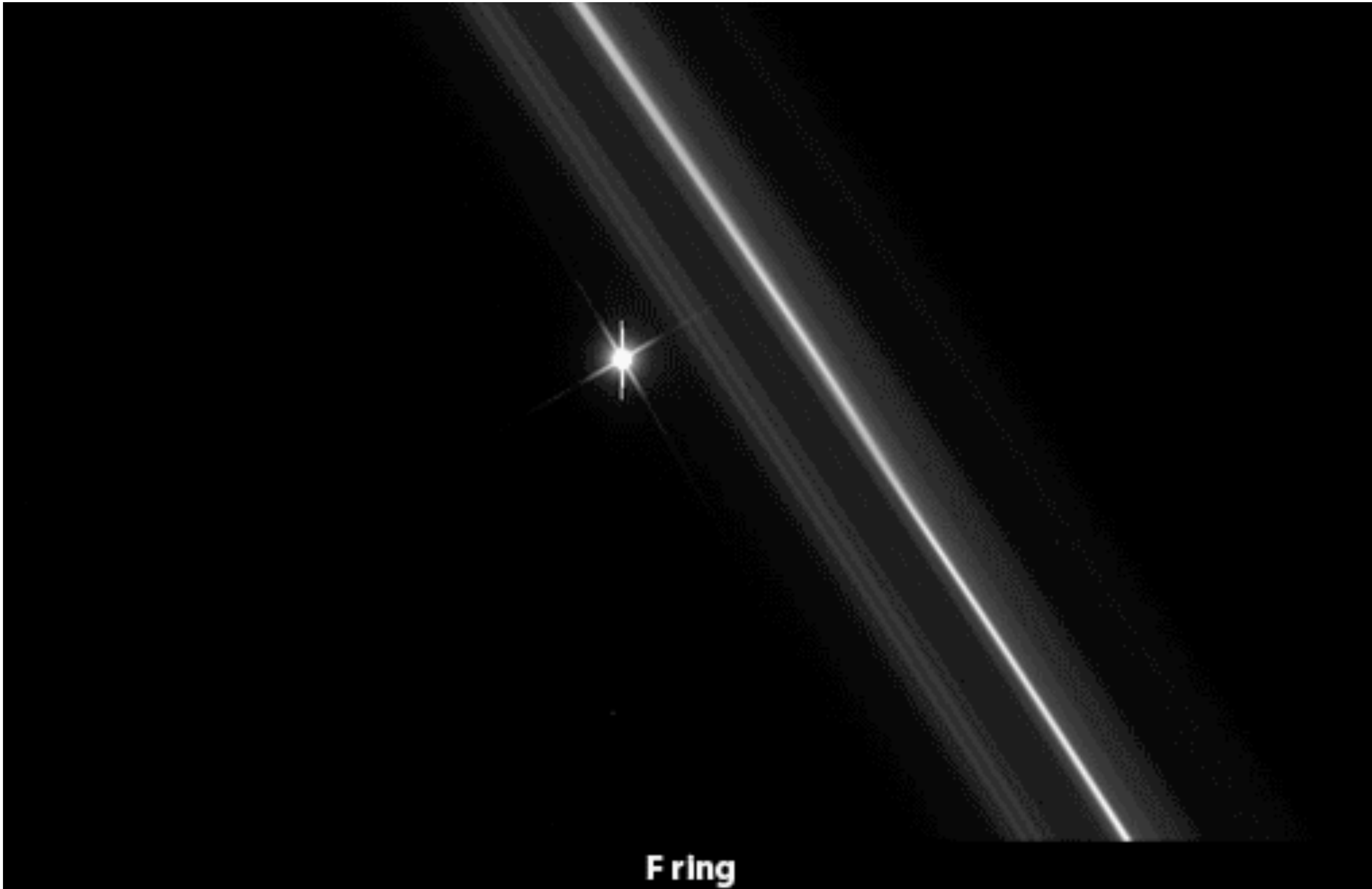

Colombo Gap
Maxwell Gap
Huygens Gap
Encke Gap
Keeler Gap
D Ring
C Ring
B Ring
Cassini Division
A Ring
F Ring
Colombo Gap
Maxwell Gap
Huygens Gap
Encke Gap
Keeler Gap
D Ring
C Ring
B Ring
Cassini Division
A Ring
F Ring

Character of Saturn's Main Rings

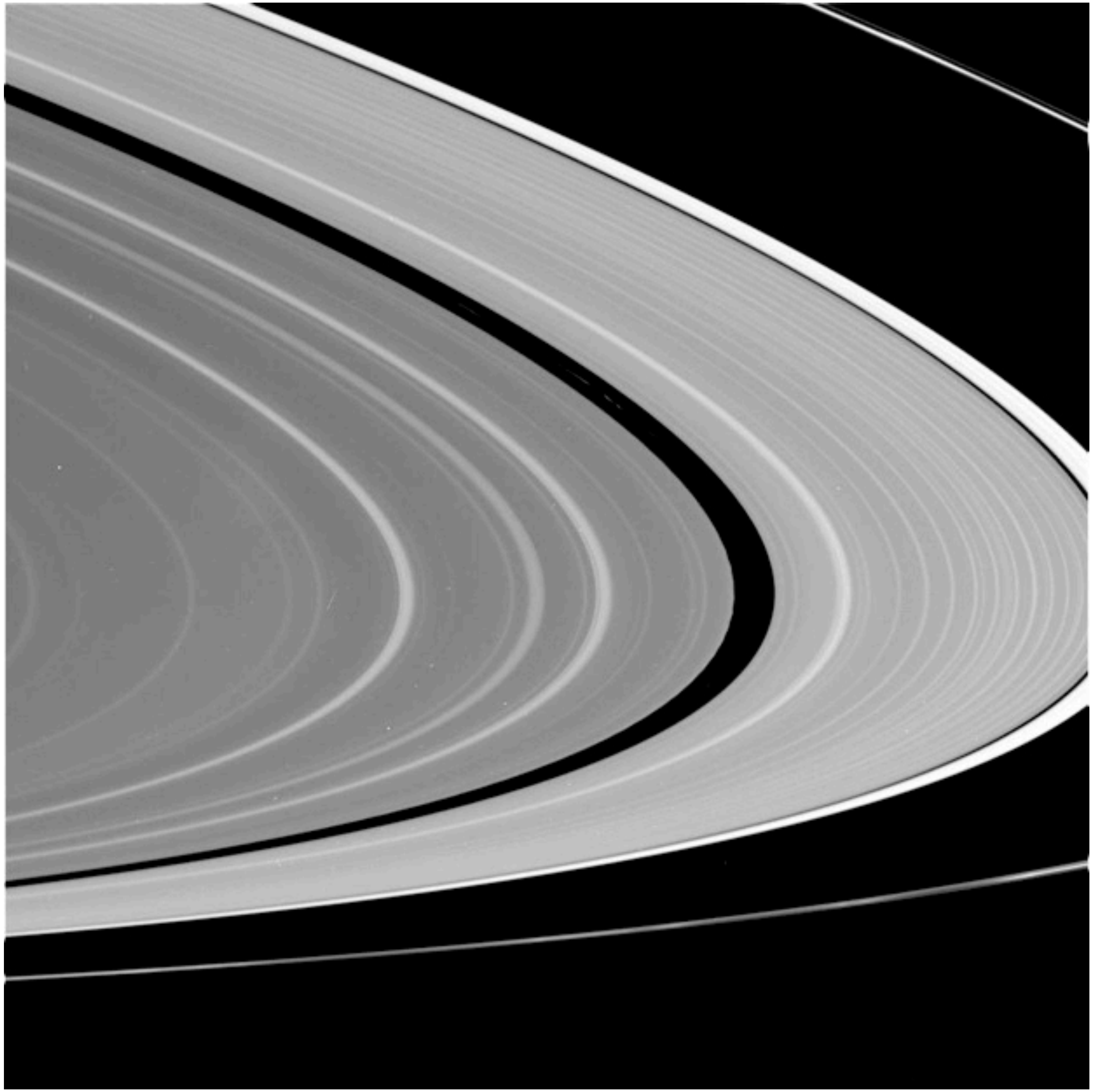


- Total mass of rings ~ mass of Mimas (moon with 200-km radius)
- Ring particles follow power-law size distribution between centimeters and meters; relatively few larger bodies.
- Water ice with minor "reddish" contaminant
- Typical optical depths $\sim 0.1 - 5$
- The best-understood structure is set by embedded and external moons.




F ring

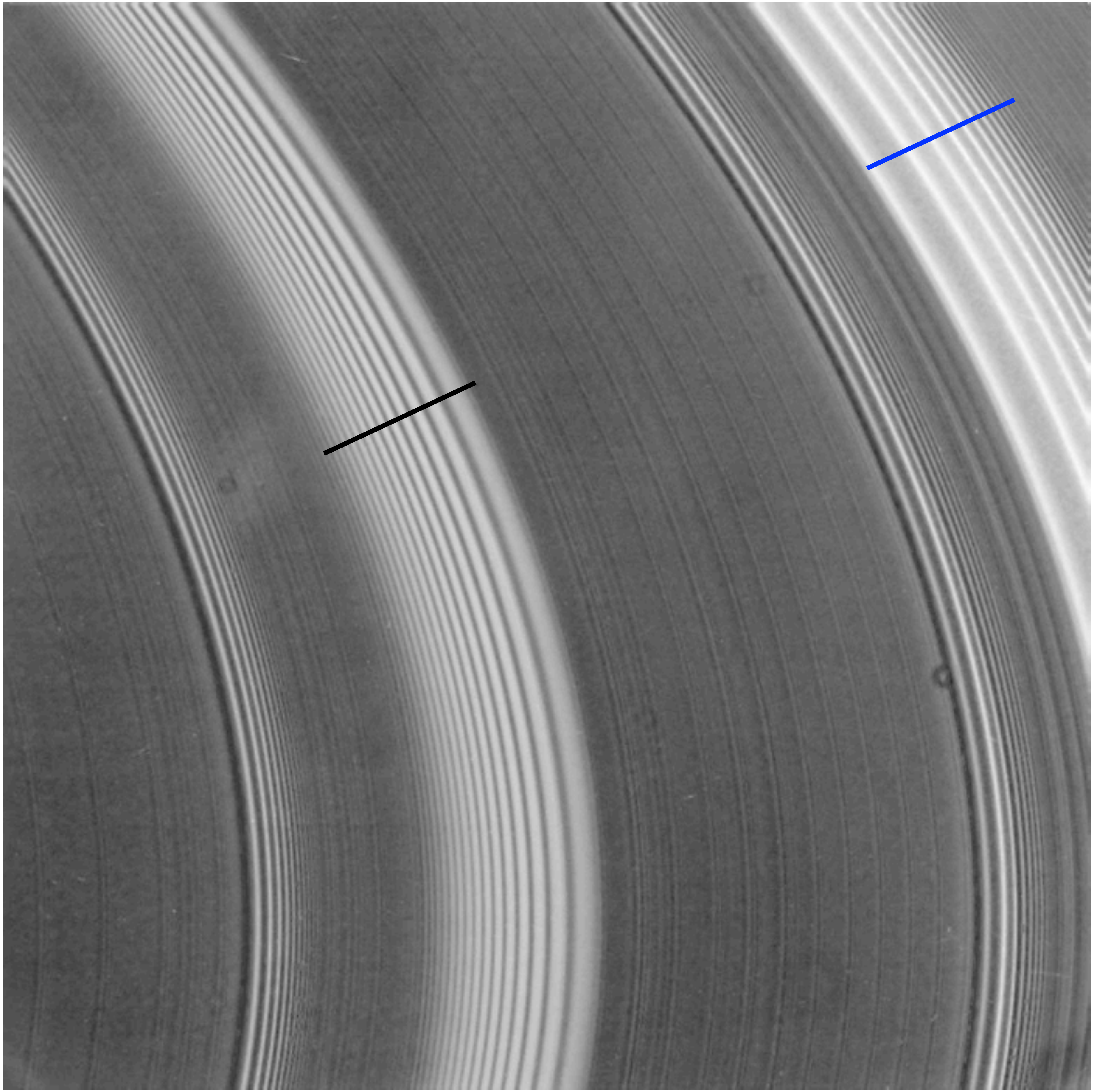
Spiral Density and Bending Waves in the A Ring



Cassini Wide-Angle Camera, image N1467351539

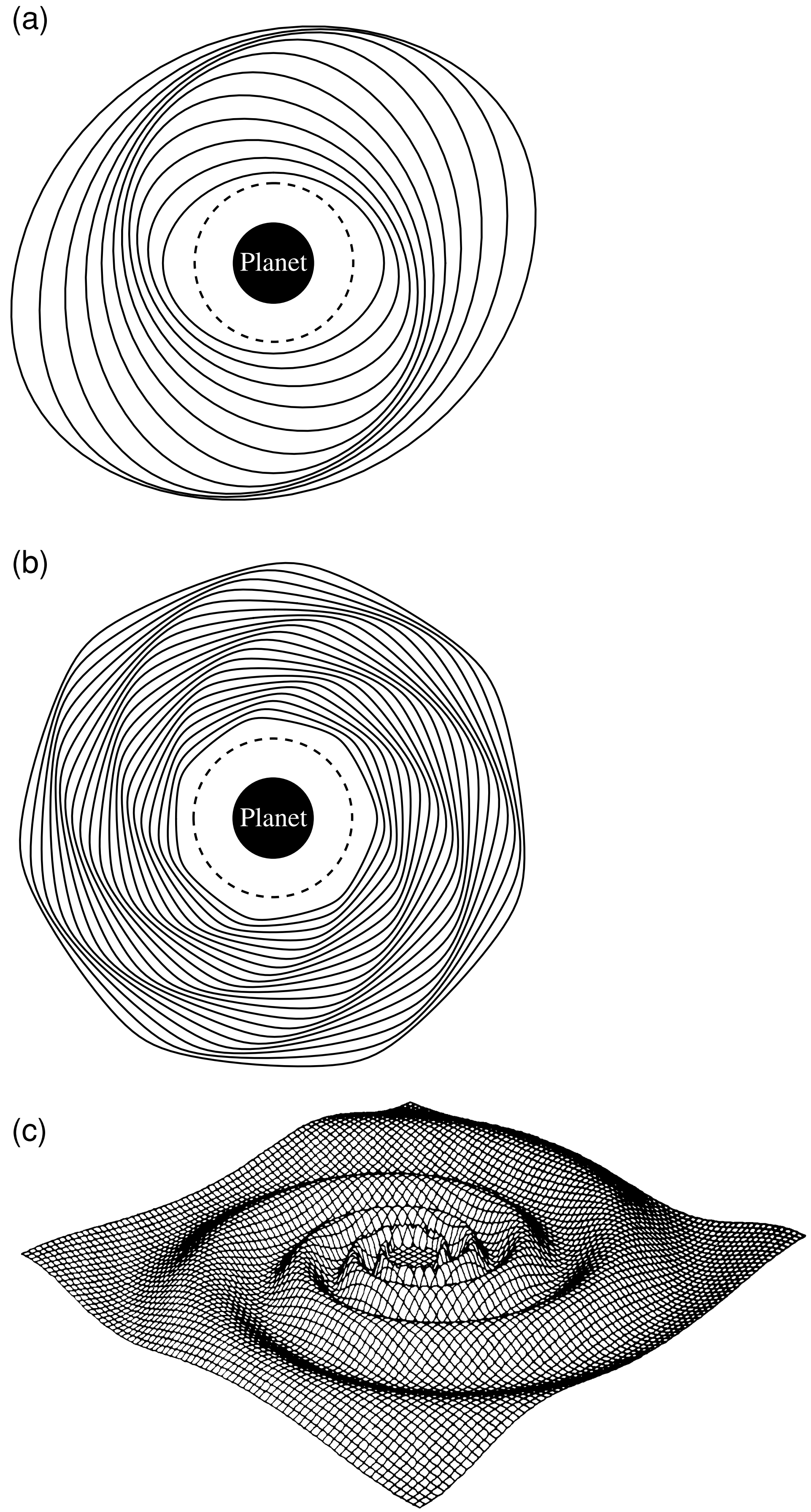
Mimas 5:3 bending wave

Mimas 5:3 density wave



Waves are denoted by l:(m - 1), where m = azimuthal wavenumber. At Mimas 5:3 waves, particle orbits ~ 5 times for 3 orbits of Mimas.

Cassini Narrow-Angle Camera, image N1467351539



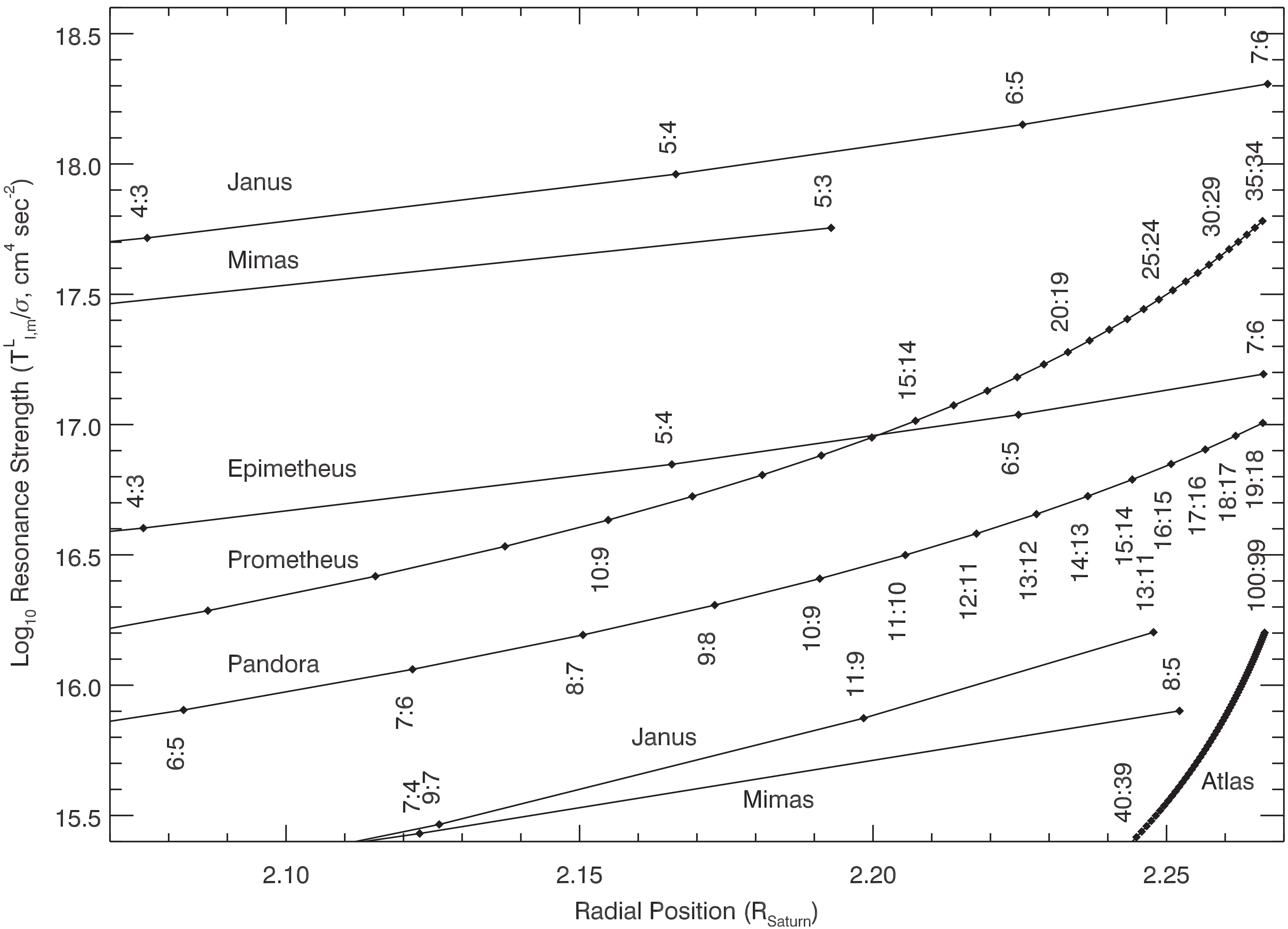
Low-m density wave

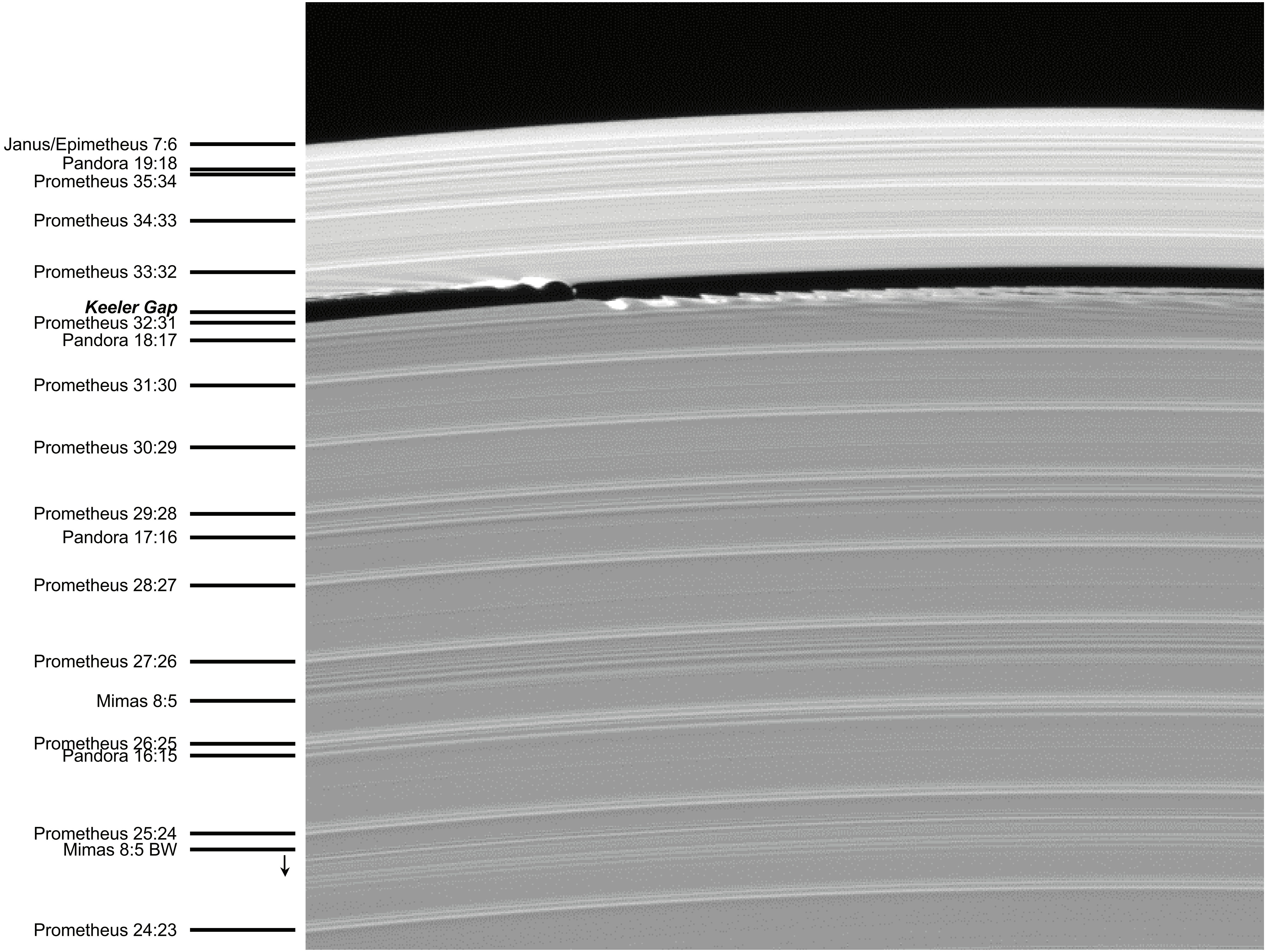
High-m density wave

Bending wave

Waves are very tightly wound because ring mass << Saturn's mass.

Predicted Strengths of Lindblad Resonances in A Ring

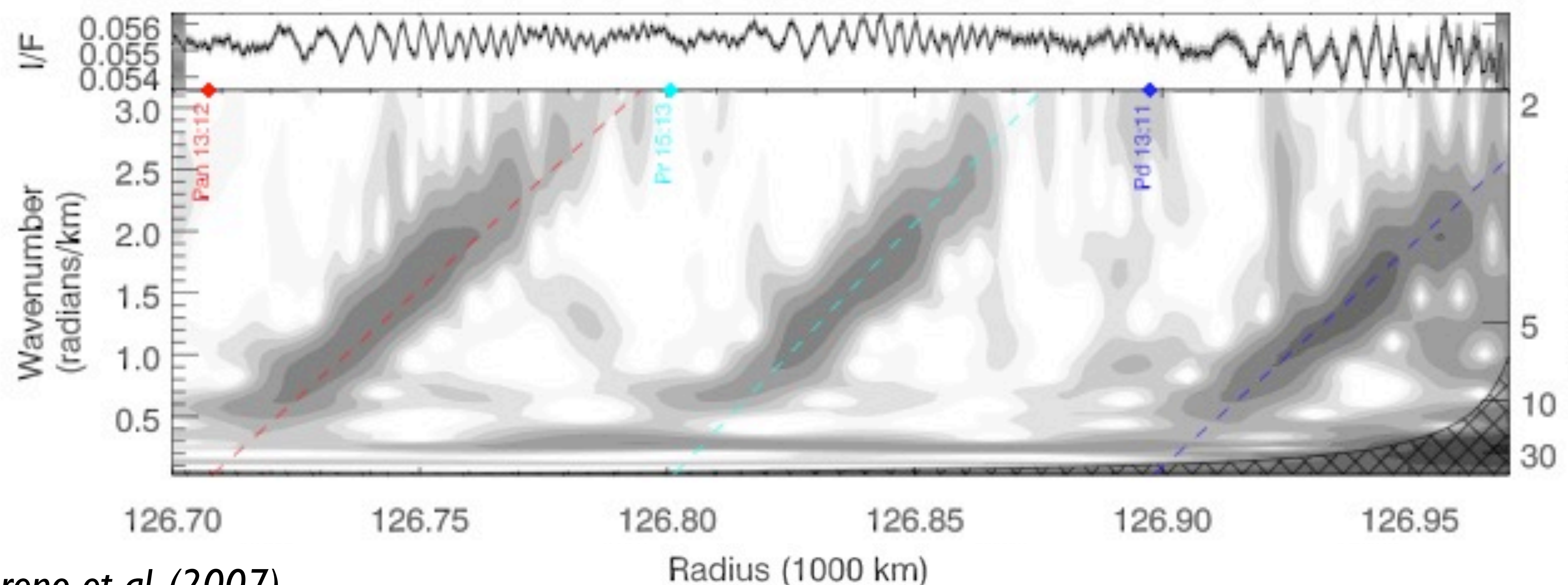




Janus/Epimetheus 7:6
Pandora 19:18
Prometheus 35:34
Prometheus 34:33
Prometheus 33:32
Keeler Gap
Prometheus 32:31
Pandora 18:17
Prometheus 31:30
Prometheus 30:29
Prometheus 29:28
Pandora 17:16
Prometheus 28:27
Prometheus 27:26
Mimas 8:5
Prometheus 26:25
Pandora 16:15
Prometheus 25:24
Mimas 8:5 BW
Prometheus 24:23

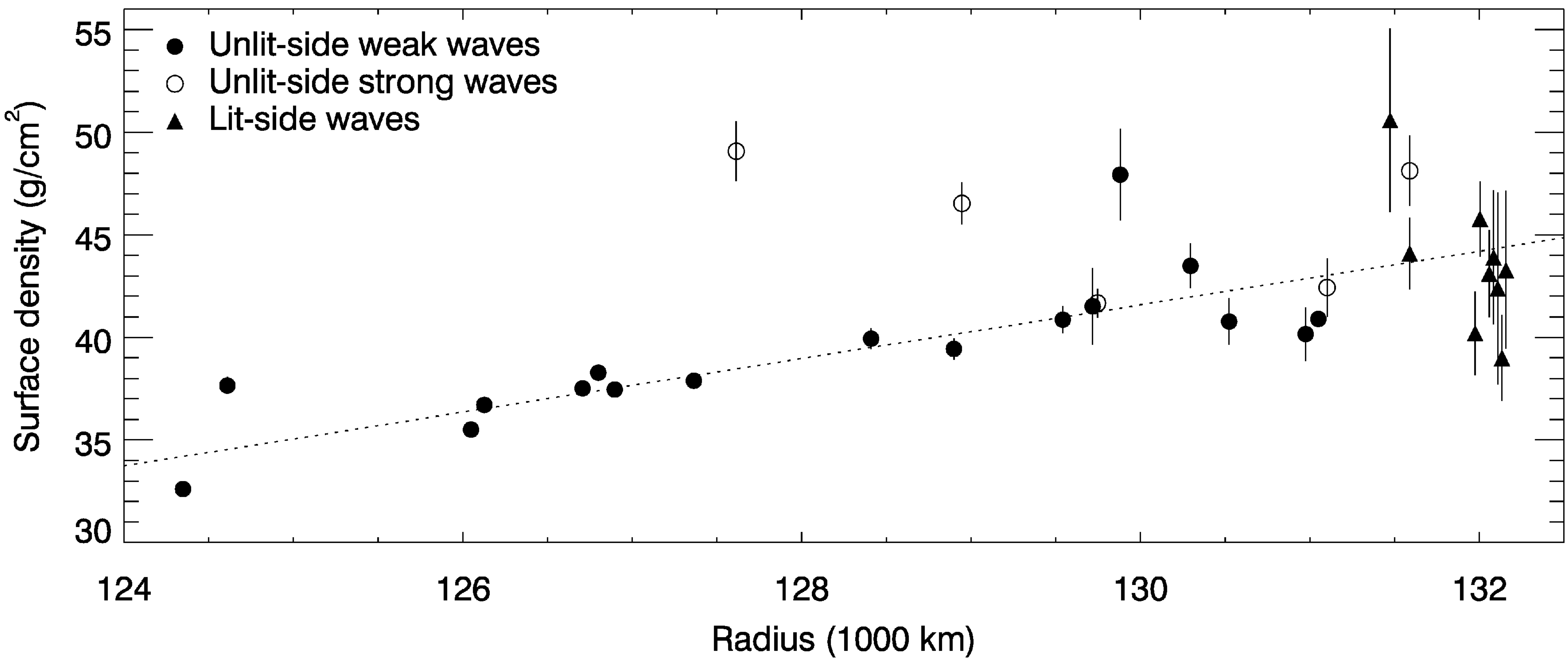
Spiral Waves as Probes of the Rings

- Ring particle orbits line up coherently at resonance with moon
- Resulting wave propagates through the ring, either as a density wave or a bending wave
- Wavenumber ∝ (m-1)×distance from resonance/surface mass density → can use waves to determine surface mass density
- Cassini can detect much weaker (linear) waves than Voyager could → easier to analyze
- Can also infer rings' viscosity from rate of wave damping



Tiscareno et al. (2007)

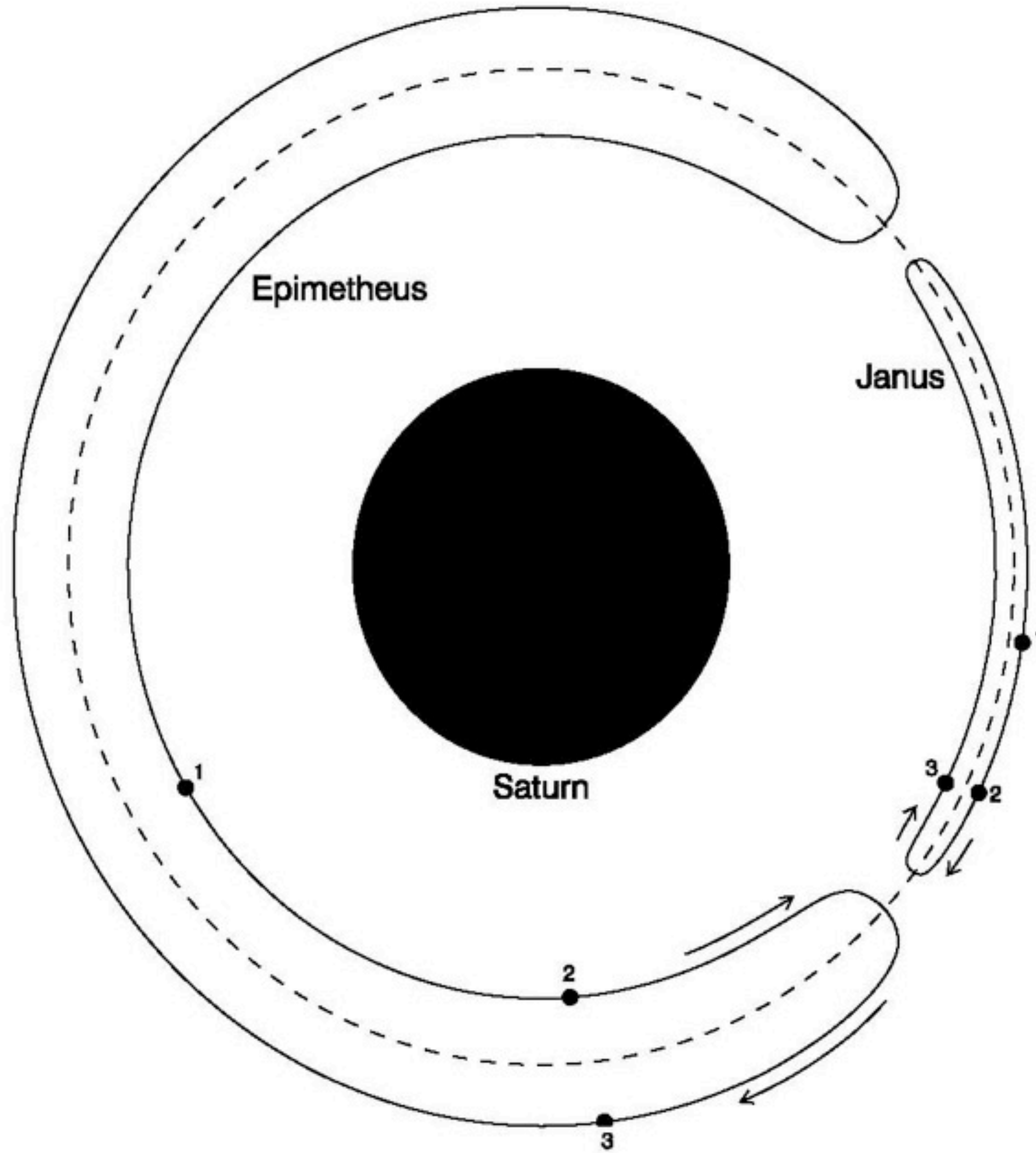
Ring Surface Density in Mid-A Ring



Tiscareno et al. (2007)

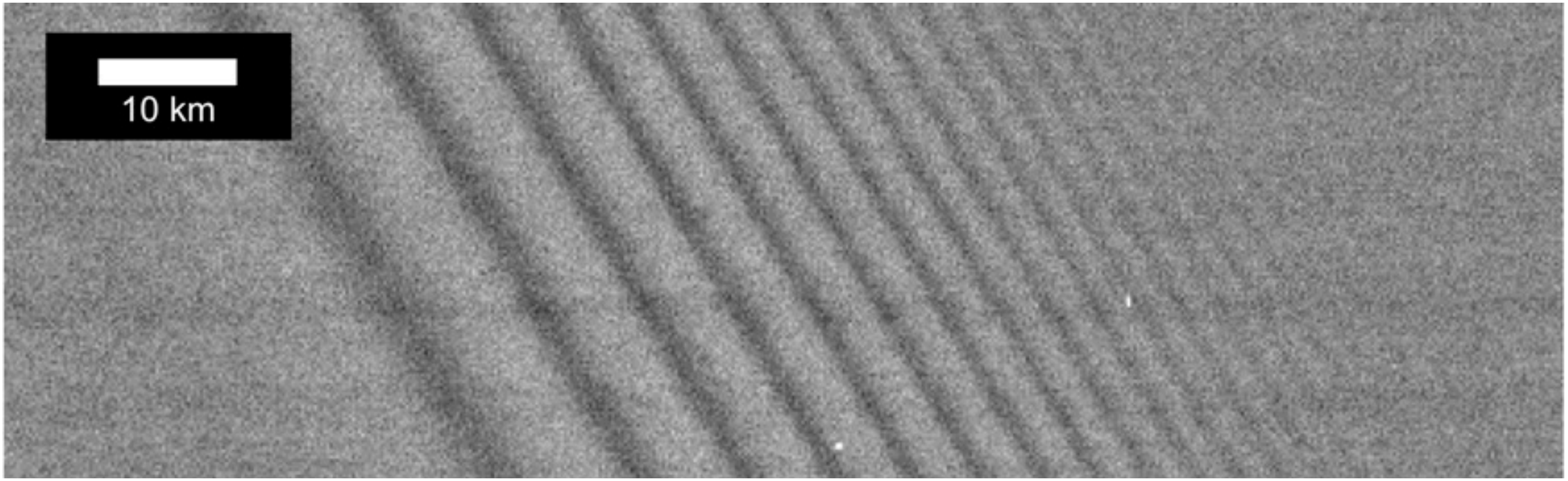
Janus and Epimetheus

- Coorbital moons "swap" orbits every 4 years.
- How do rings respond to change in forcing?



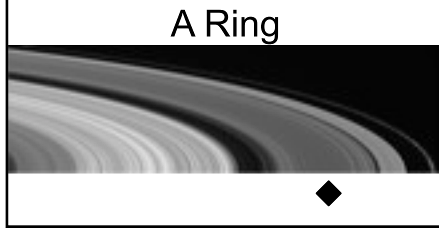
- *Difference in semi-major axes ~ 50 km*
- *Mass of Epimetheus/mass of Janus ~ 0.3*

Spiral Density Waves



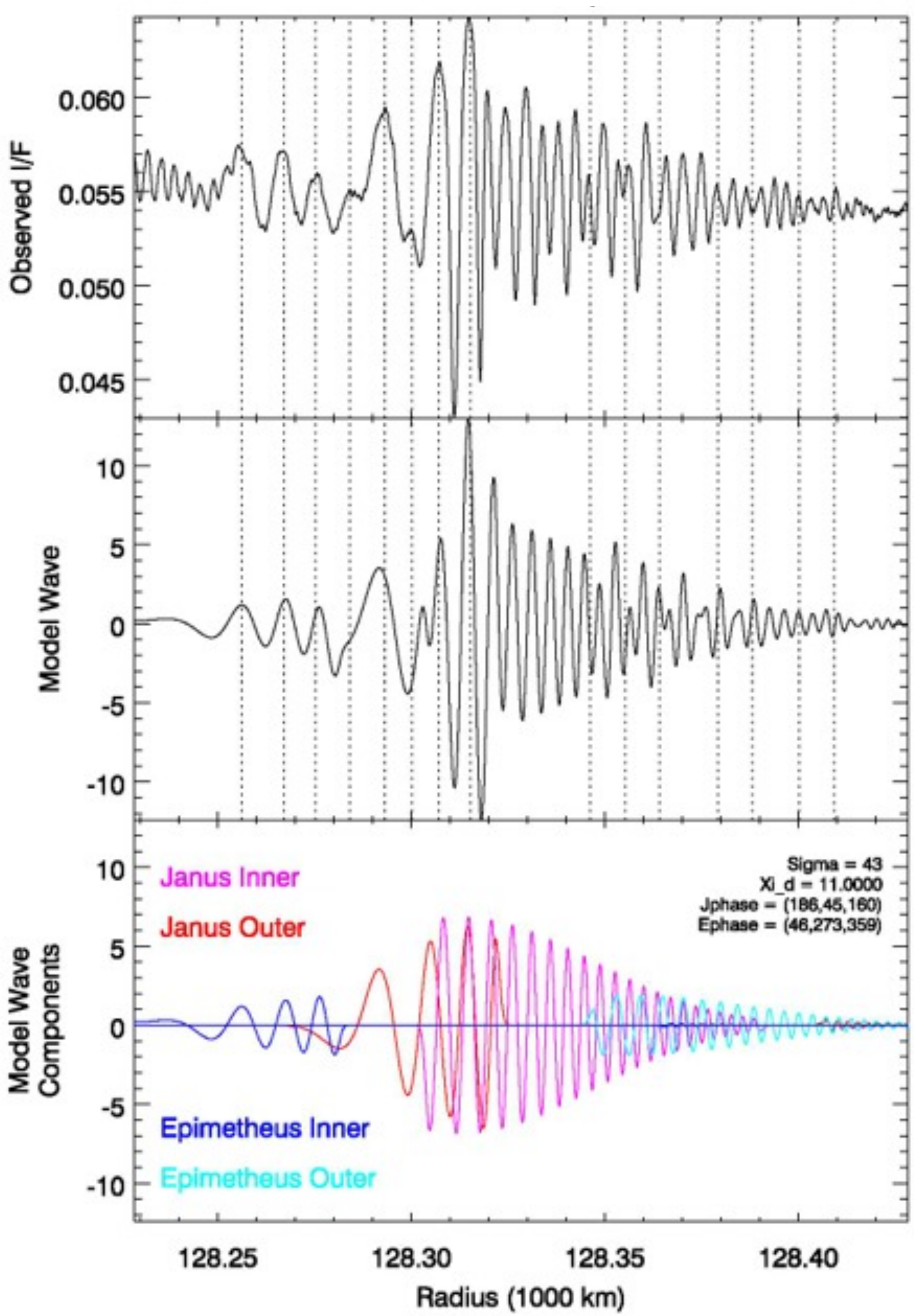
- Waves appear to be a static phenomenon
- But group velocity $v_g = \pi G\sigma/$□~ 10-20 km/year in the A Ring
- Spiral waves propagate for ~ 100 km, so information takes years to travel through wave region

Janus/Epimetheus 9:7 Density Wave

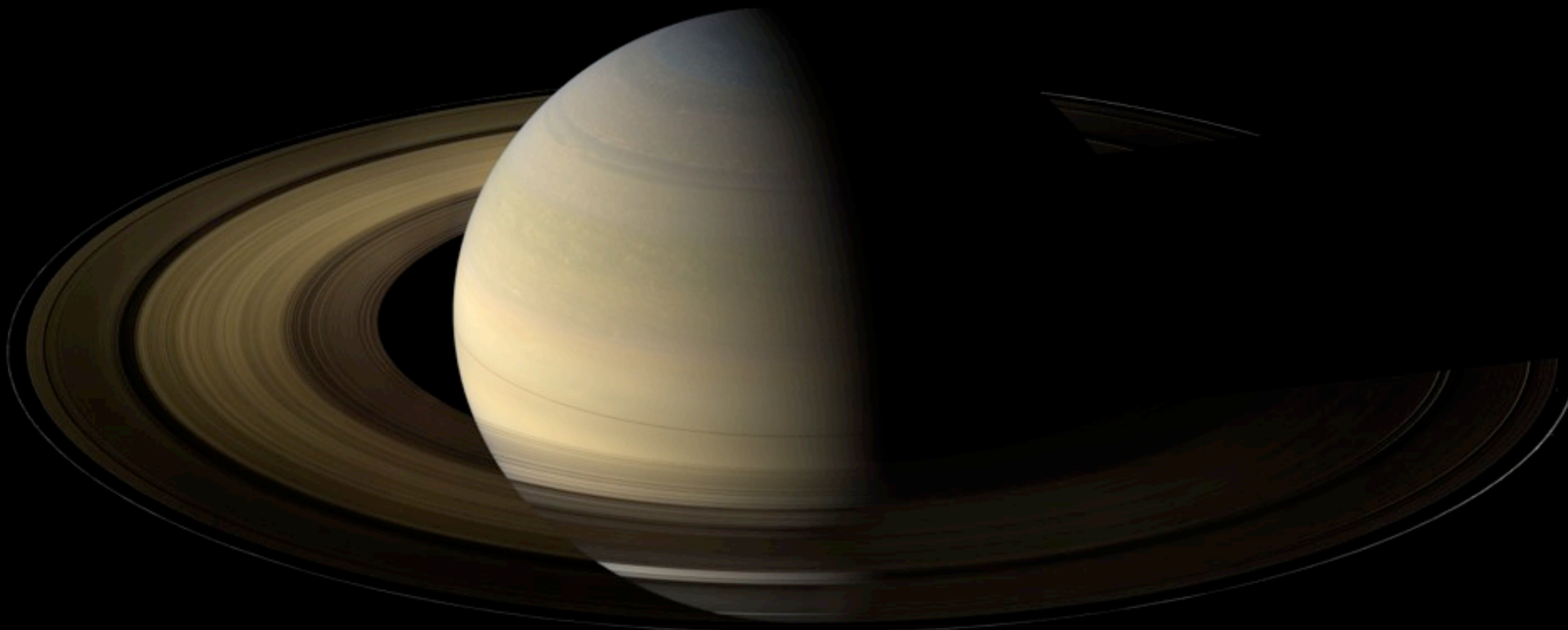


- Waves due to coorbital moons have unusual and complex morphologies
- Model assumes truncated wave segments based on moons' changing orbits
- Weak waves are linear, so can superpose segments
- Complex structure is qualitatively explained

Tiscareno et al. (2006)

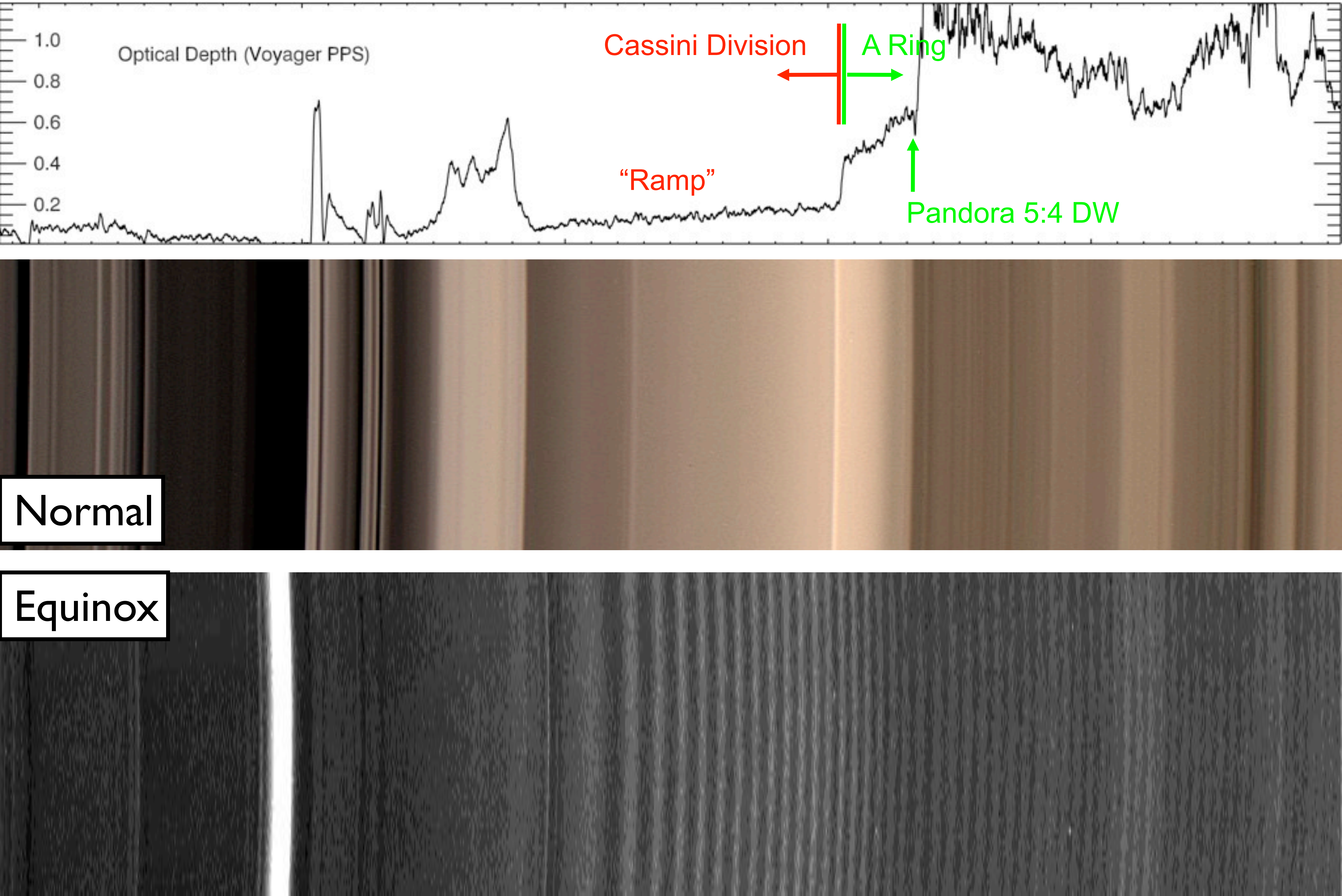


Equinox



- Sun shines nearly edge-on to the rings
- Rings are very dark (especially where not illuminated by Saturn)
- Enhanced visibility of vertical structure

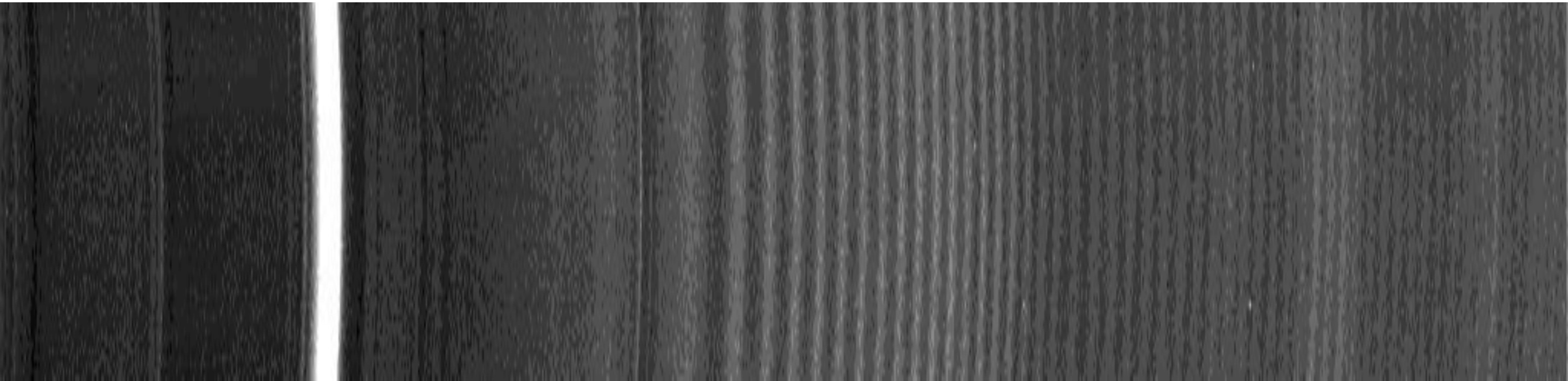
Equinox



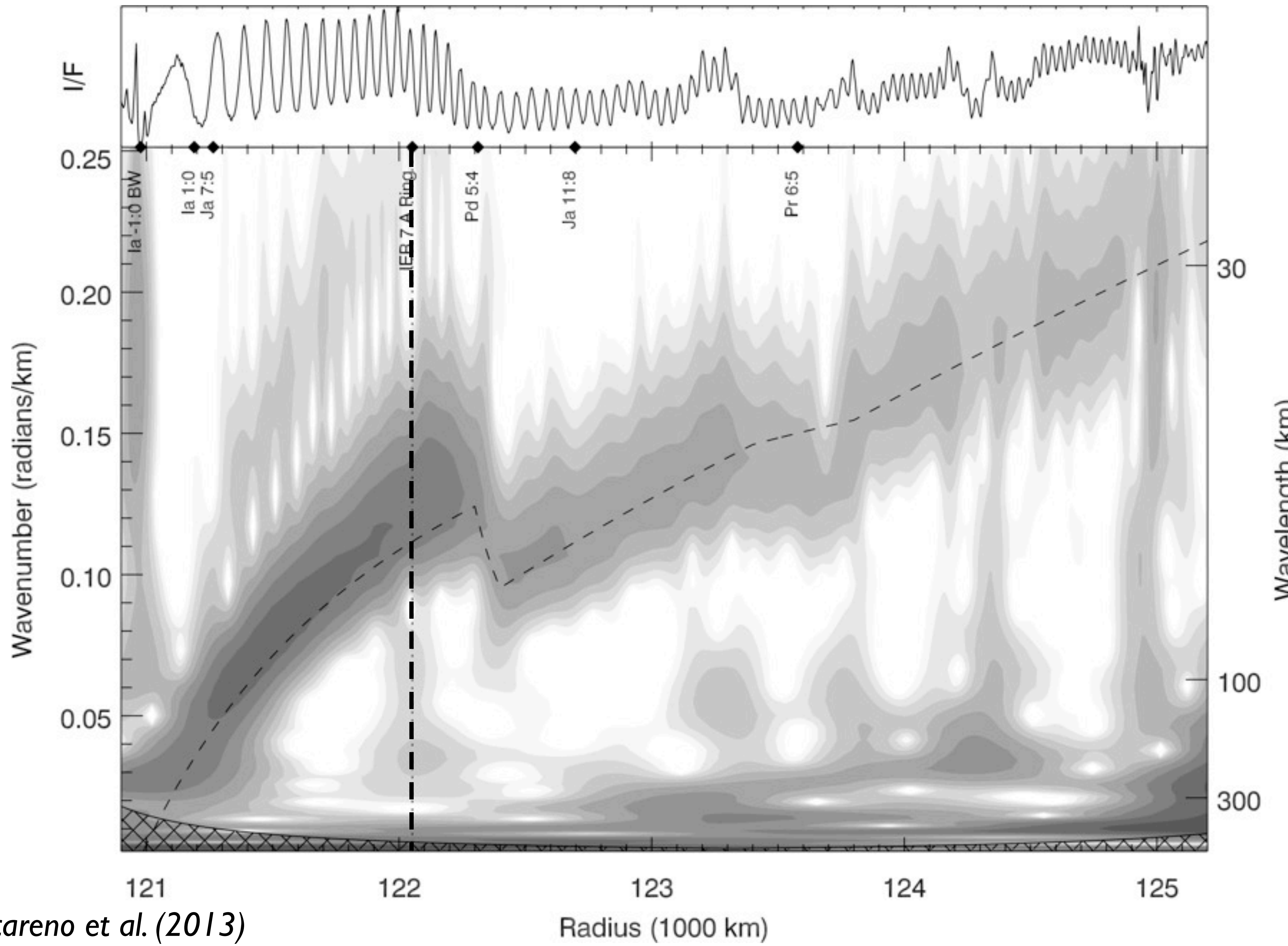
1.0
0.8
0.6
0.4
0.2
Optical Depth (Voyager PPS)
Cassini Division
A Ring
"Ramp"
Pandora 5:4 DW
Normal
Equinox

The Iapetus -1:0 Bending Wave

- Iapetus' mean motion commensurate with precession of inclined ring particle's orbital plane (latter is retrograde)
- Bending waves are a coherent organization of ring particle inclinations
- Resonance of this type first described for the Titan -1:0 wave in the C Ring (Rosen and Lissauer 1988)
- Although it is a bending wave, it propagates outward
- Identified by Cuzzi, Lissauer, and Shu (1981) as the Iapetus 1:0 density wave, then not reported again for 29 years



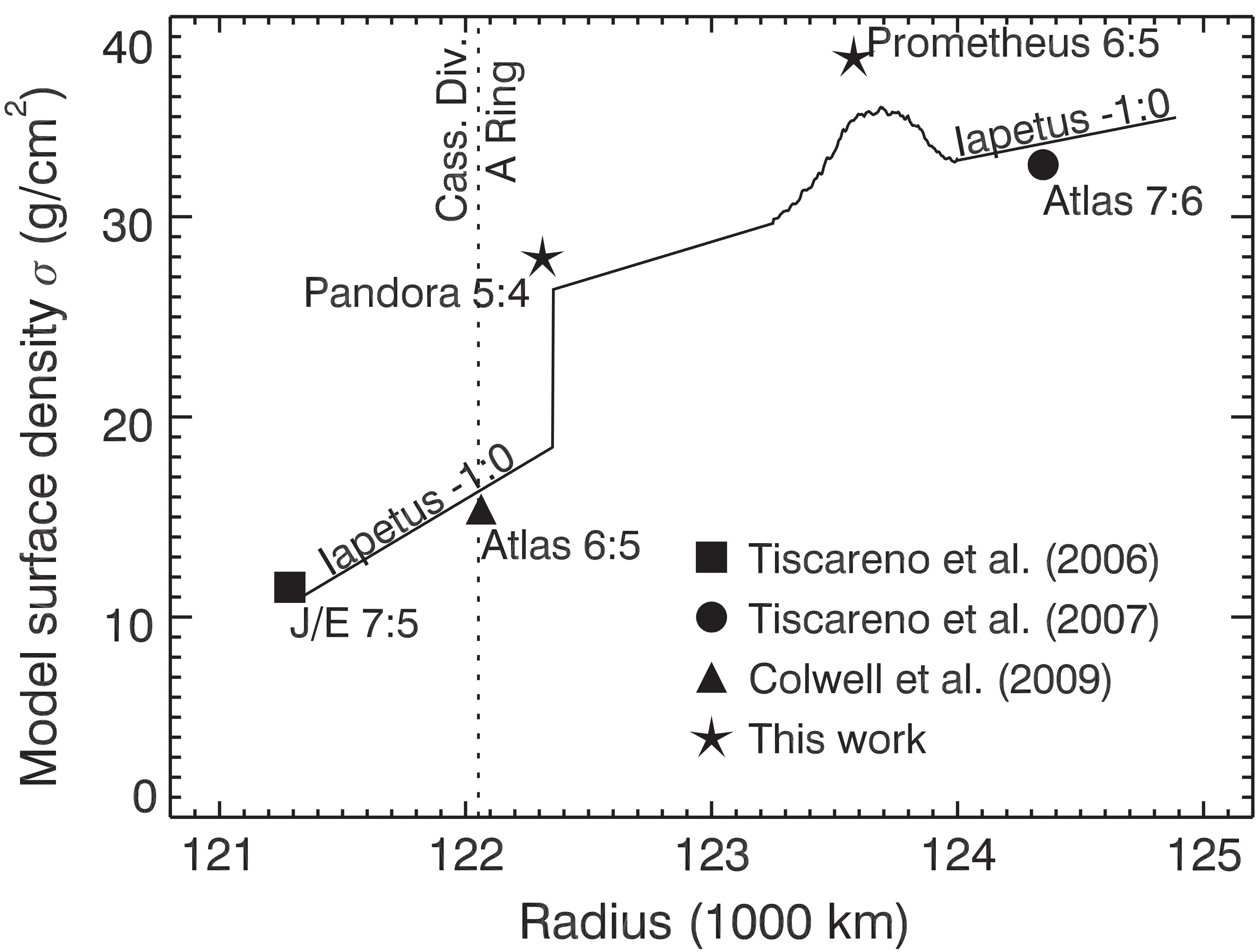
Surface Density Profile



Tiscareno et al. (2013)

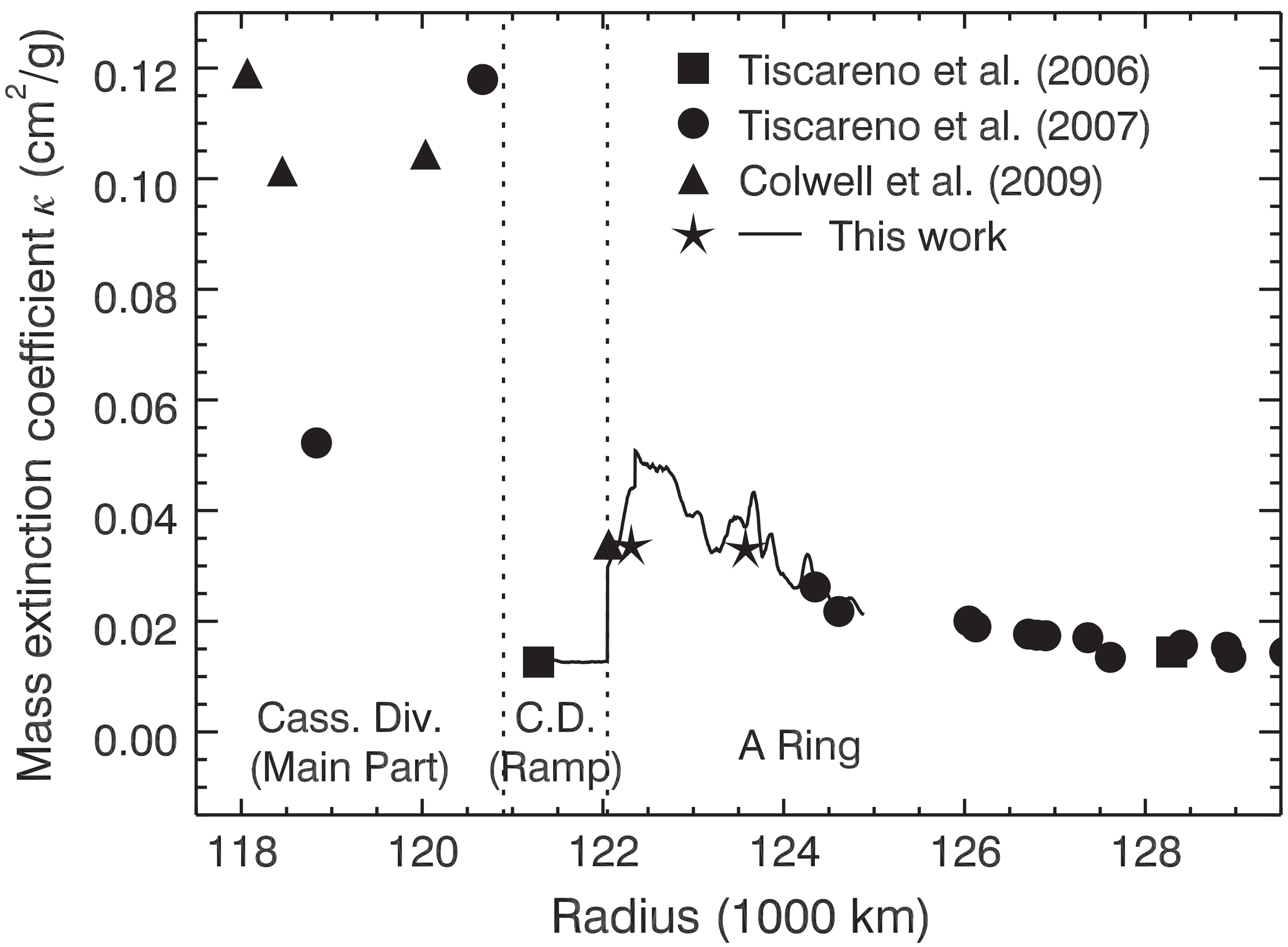
Surface Density Profile of Outer Cassini Division/Inner A Ring

- Best-fit simple density profile
- Good agreement with previous surface density values from more localized waves
- No significant change across A Ring edge!
- Sharp increase in surface density at Pandora 5:4 density wave



Mass Extinction Coefficient

- Optically-interacting surface area, per unit mass ($\kappa = \tau/\sigma$, where τ = optical depth, σ = surface mass density)
- Large extinction coefficient (small particles?) in Cassini Division
- Extinction drops by ~10x (very large particles?) in CD Ramp
- Increases again by factor of 3 at A Ring "inner edge"



small particles

big particles

C Ring Waves Due to Oscillations in Saturn

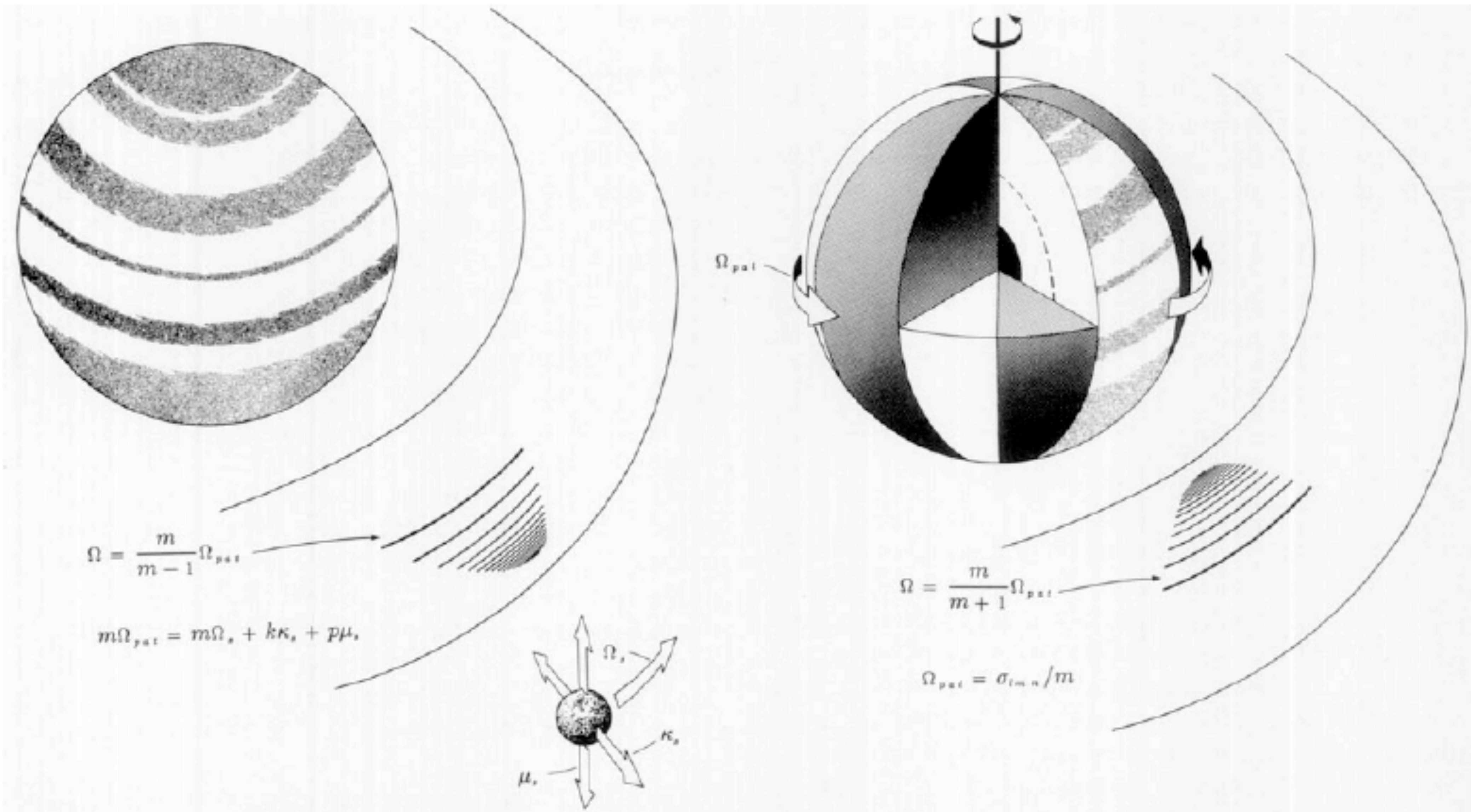


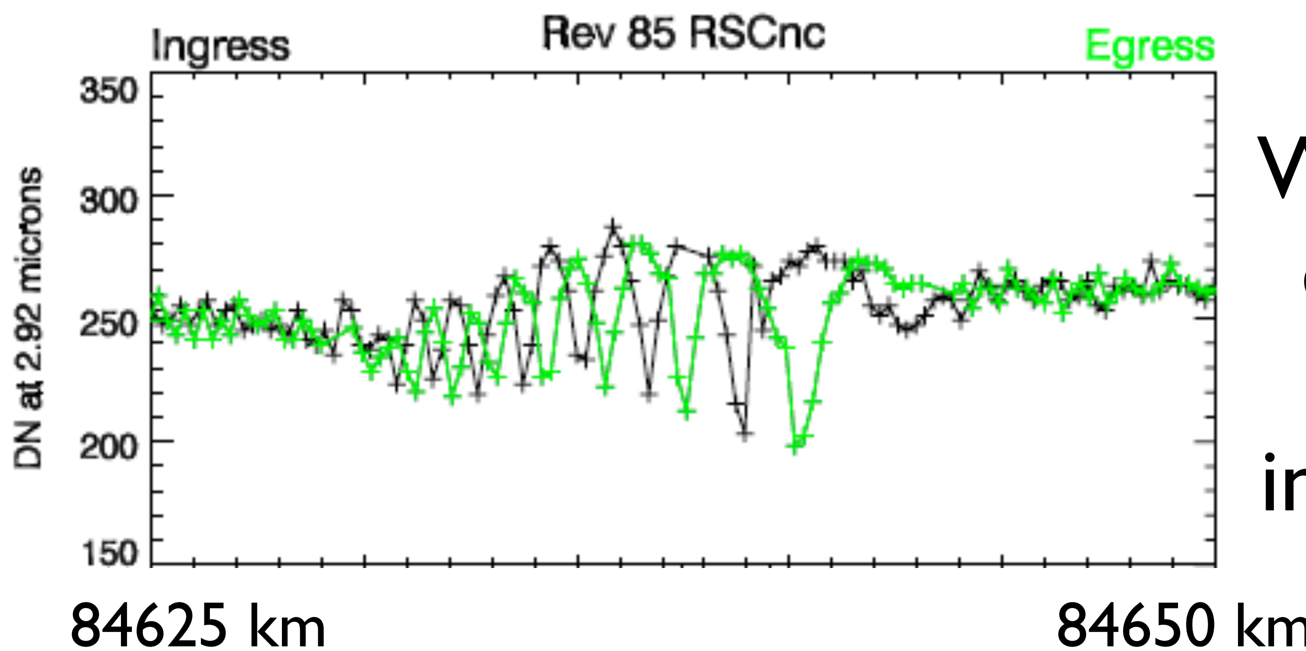
FIG. 3. Comparison of density wave launched by a satellite at an inner Lindblad resonance (left) with a density wave launched by a planetary oscillation mode at an outer Lindblad Resonance (right). Note that satellites produce inner resonances and oscillation modes outer resonances. Waves launched at outer Lindblad resonances propagate toward the planet; waves launched at inner Lindblad resonances propagate away from the planet. The propagation direction is reversed for vertical resonances.

Marley and Porco 1993

l = 4, $|m|$ = 4
Marley and Porco 1993

Three strongest predicted modes:
2f ($l = |m| = 2$)
3f ($l = |m| = 3$)
4f ($l = |m| = 4$)

Six C Ring Waves in VIMS Occultations



Wave phases for two cuts differ by ~180º (at fixed distance, maxima in ingress, minima in egress).

$$\tau(r, \lambda, t) \simeq \tau_0 + \Delta\tau(r) \cos \phi(r, \lambda, t),$$

$$\phi(r, \lambda, t) \simeq |m|(\lambda - \Omega_p t) + \phi_r(r).$$

$$\phi_r(r) \simeq \left[3(m-1) + J_2 \frac{21}{2} \left(\frac{r_S}{r_L}\right)^2\right] \frac{M_S (r - r_L)^2}{4\pi\sigma_0 r_L^4} + \phi_0$$

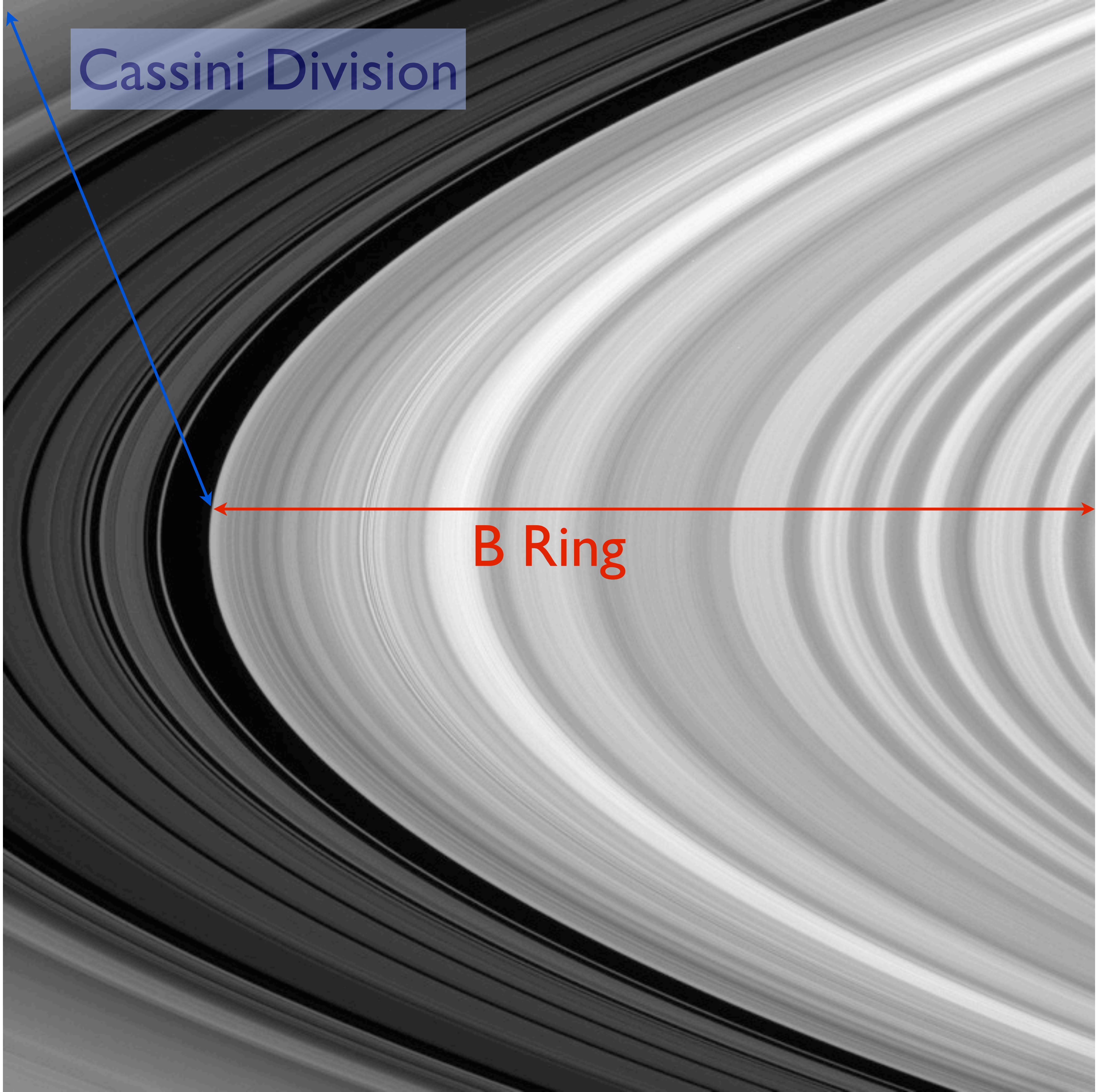
Hedman and Nicholson 2013

C Ring waves appear to be excited by non-radial oscillations in Saturn.

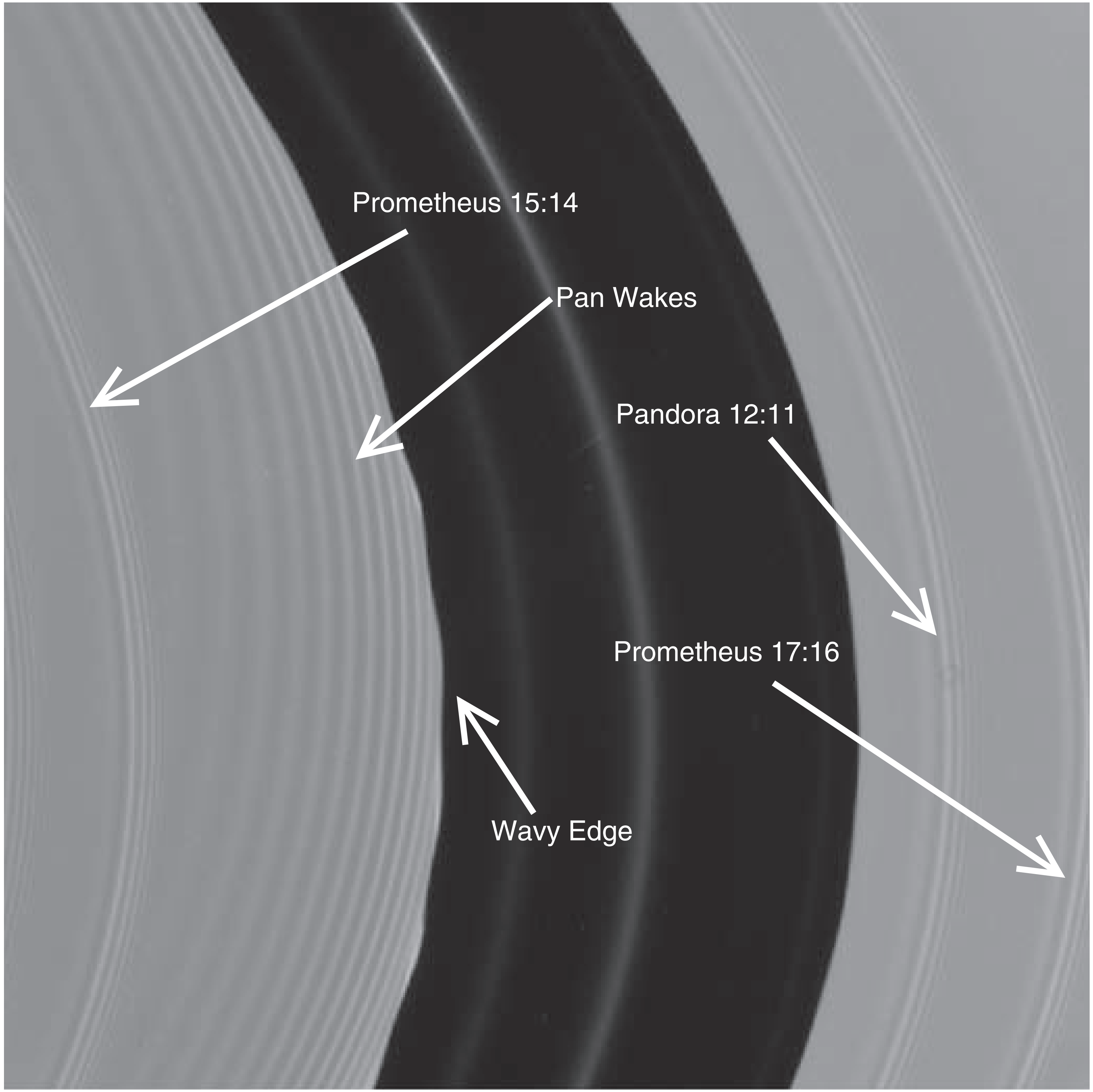
- Put together many occultations → infer m number of wave, pattern speed
- Wave at 80980 km → m = -4
- Waves at 82000, 82060, and 82210 km → $m = -3$
- Waves at 84640 and 87190 km → $m = -2$
- Agrees with prediction of Marley and Porco (1993), except for multiple waves with same m.

Implications for Internal Structure of Saturn

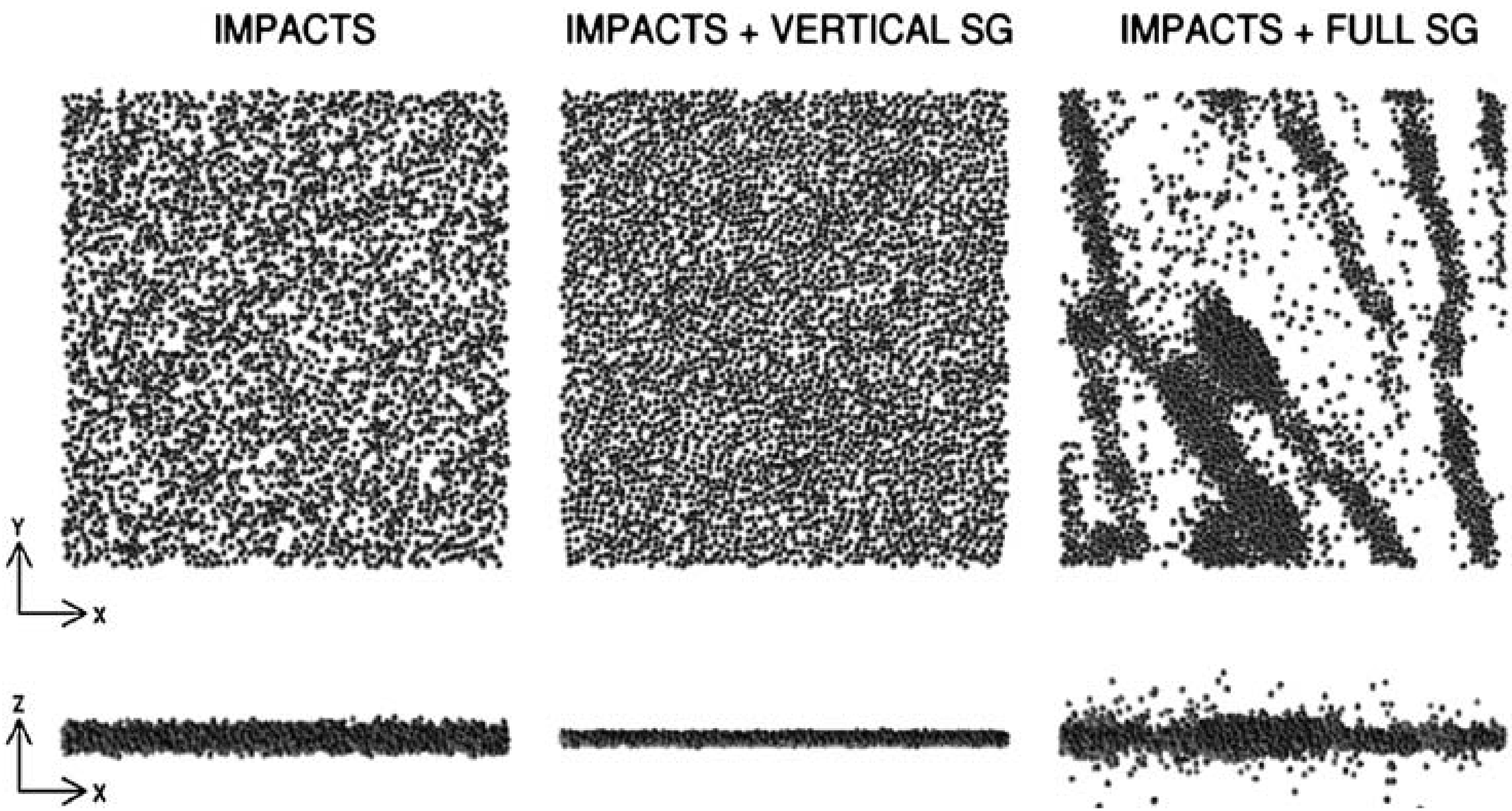
- Hedman and Nicholson (2013): "If we assume that the planetary oscillations are stochastically excited, then this long coherence time implies a correspondingly high quality factor Q for these oscillation modes."
  - Oscillation periods of the modes in Saturn's frame ~200 minutes
  - Modes are coherent for > 300 days → $Q > 2\pi$ (300 days)/200 minutes ~10,000
  - By contrast, analysis of astrometric measurements of Saturn's moons indicate that Saturn's tidal Q is between 1000 and 2000 (Lainey et al. 2012).


Cassini Division
B Ring

Encke Gap and Surroundings



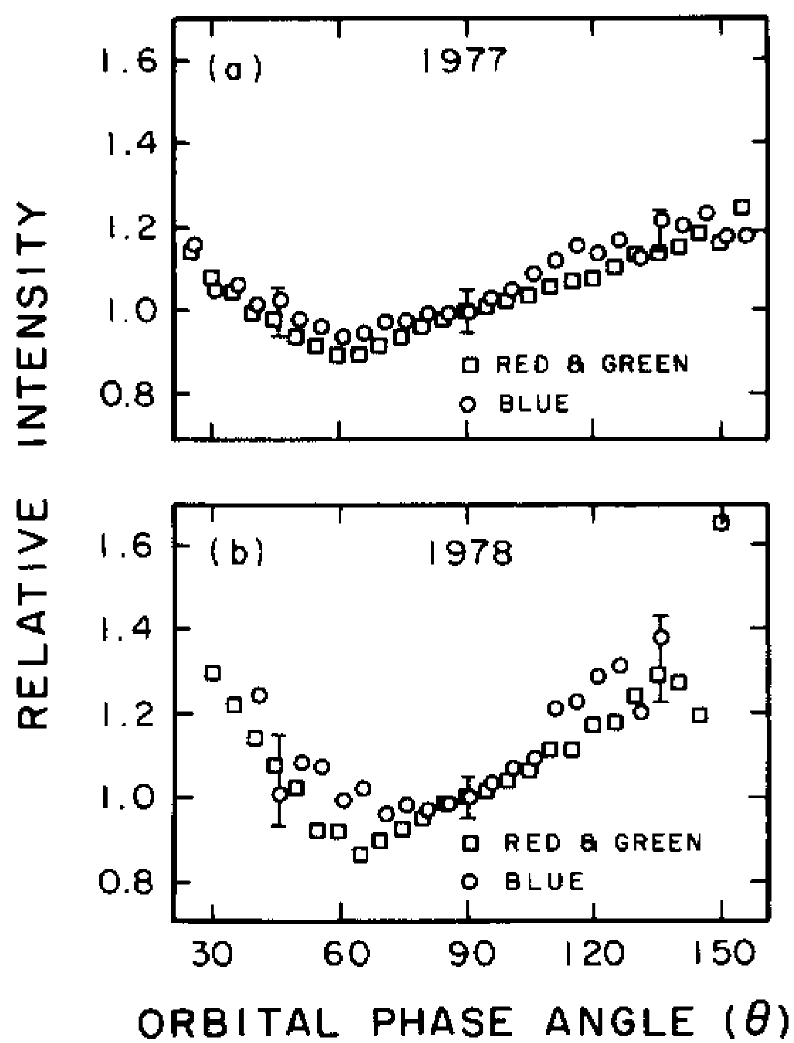
Self-Gravity Wakes



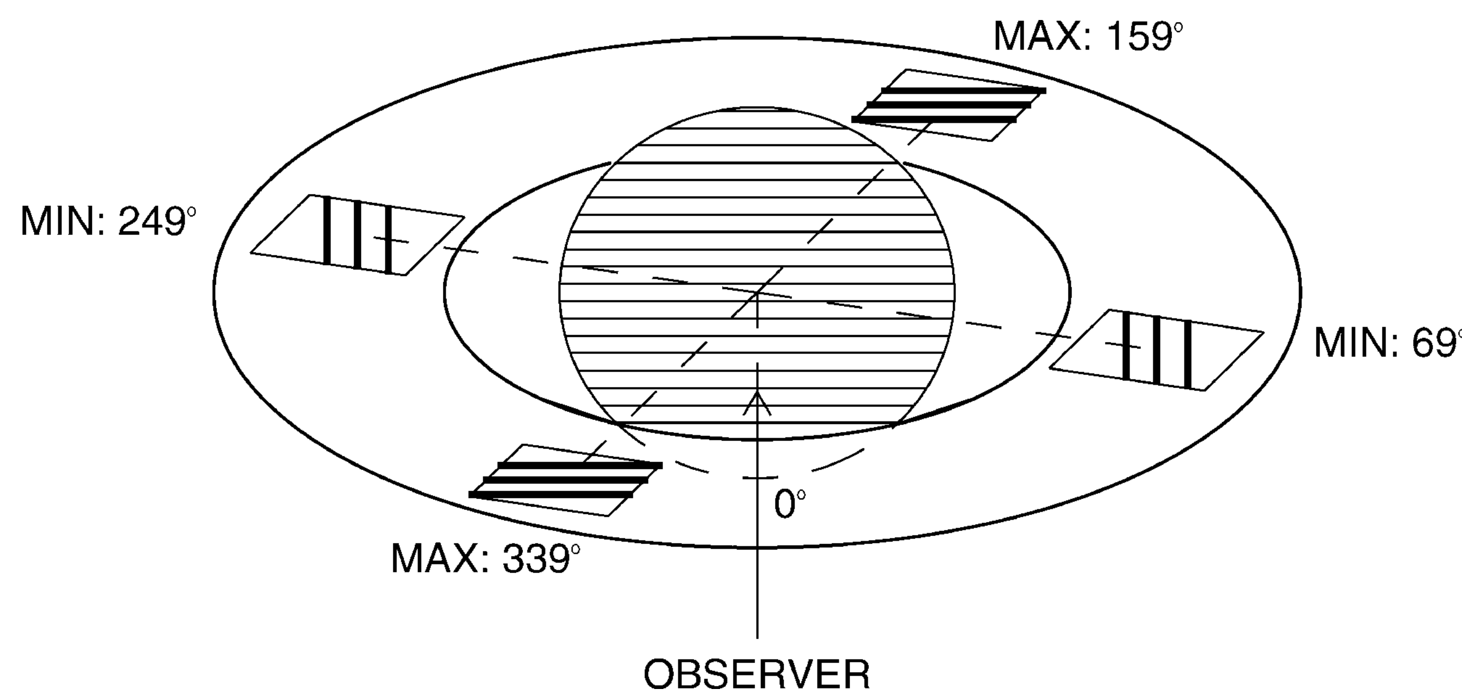
Radial spacing between wakes of order $\lambda_{cr} = 4\pi^2 G\sigma/\kappa^2$ ~ 50-100 m

Salo (1995), in Schmidt et al. (2009)

“Azimuthal asymmetry” of A Ring was known before Voyager and explained in terms of Julian-Toomre “density wakes”, now called “self-gravity wakes”.

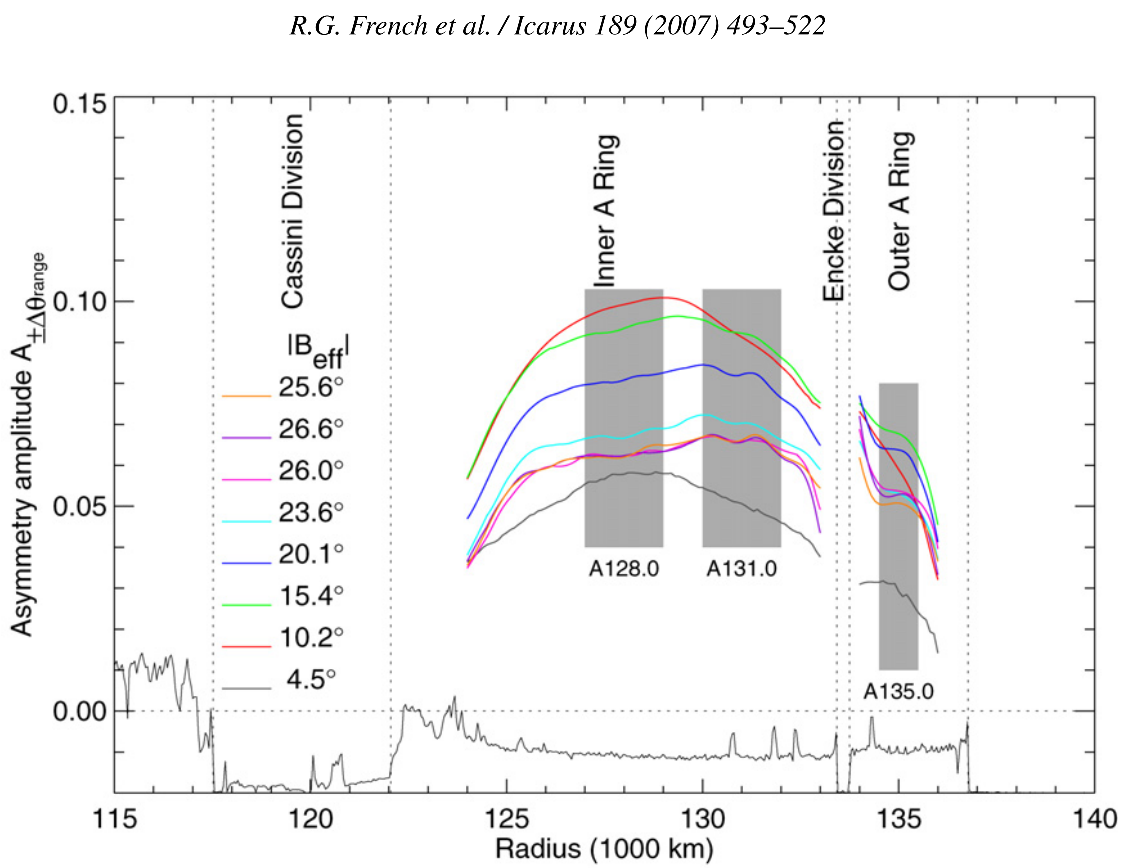


Thompson et al. 1981

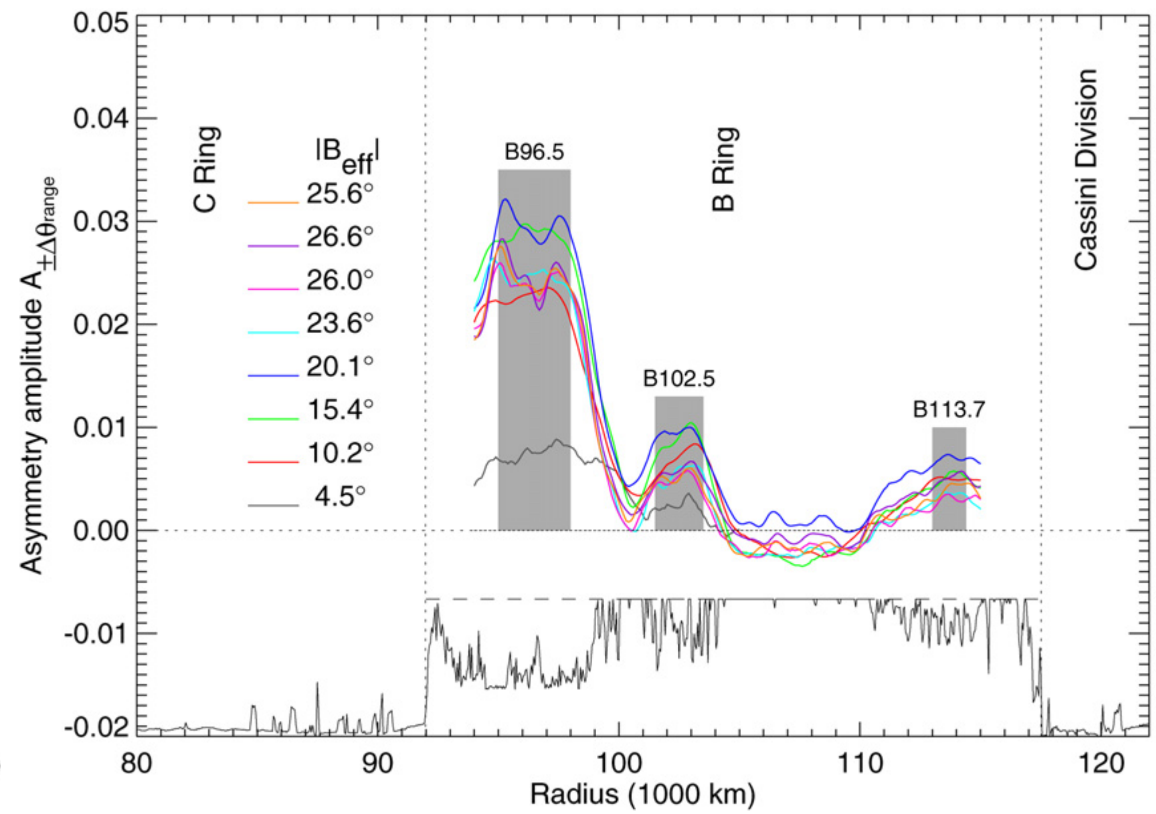


Salo et al. 2004

HST found azimuthal asymmetry in the B Ring as well.



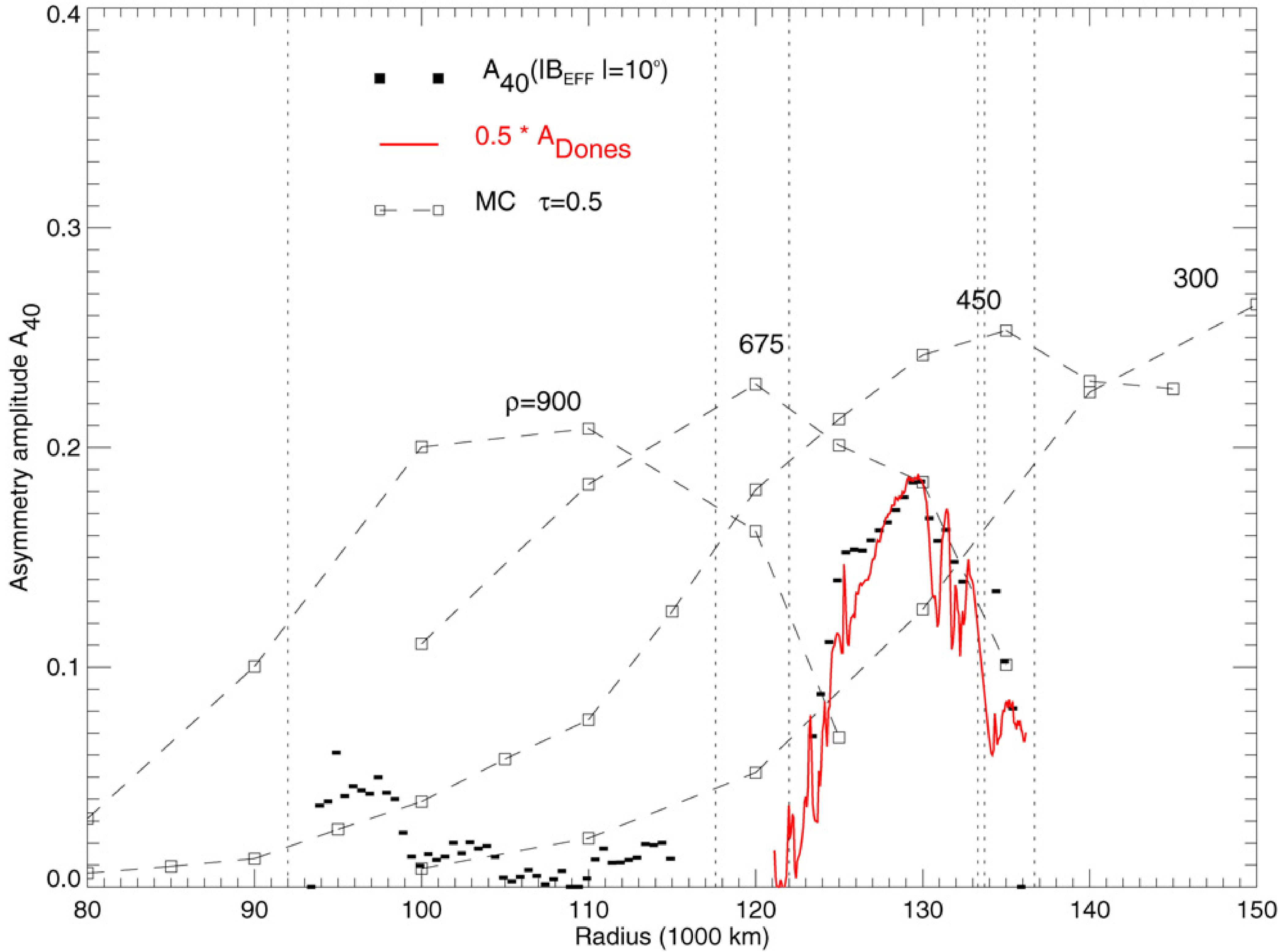
A Ring



B Ring

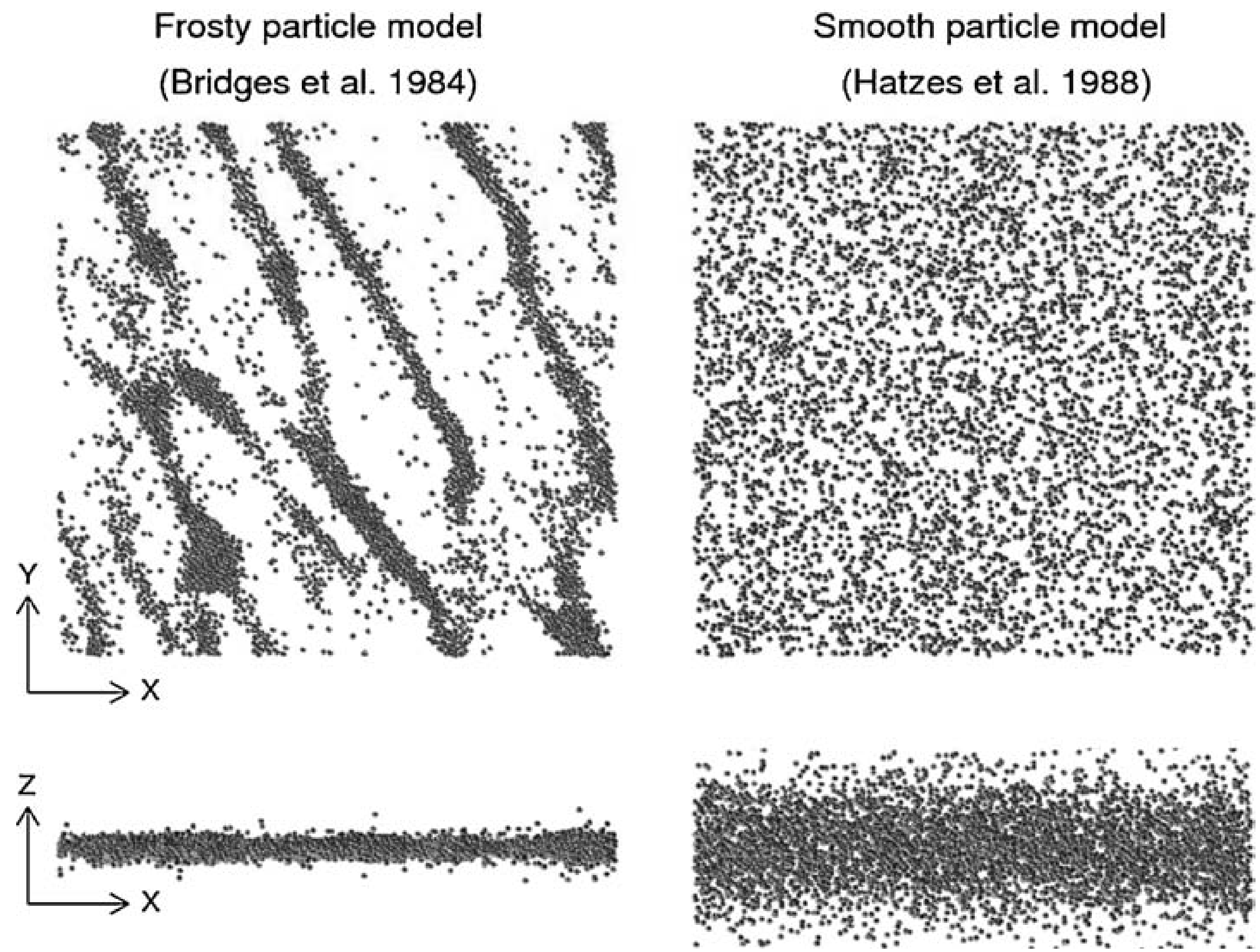
Self-gravity wakes are present throughout much of the two densest rings.

Amplitude of asymmetry peaks in mid-A Ring →
suggests ring particles have density ~ half that of solid ice



French et al. 2007

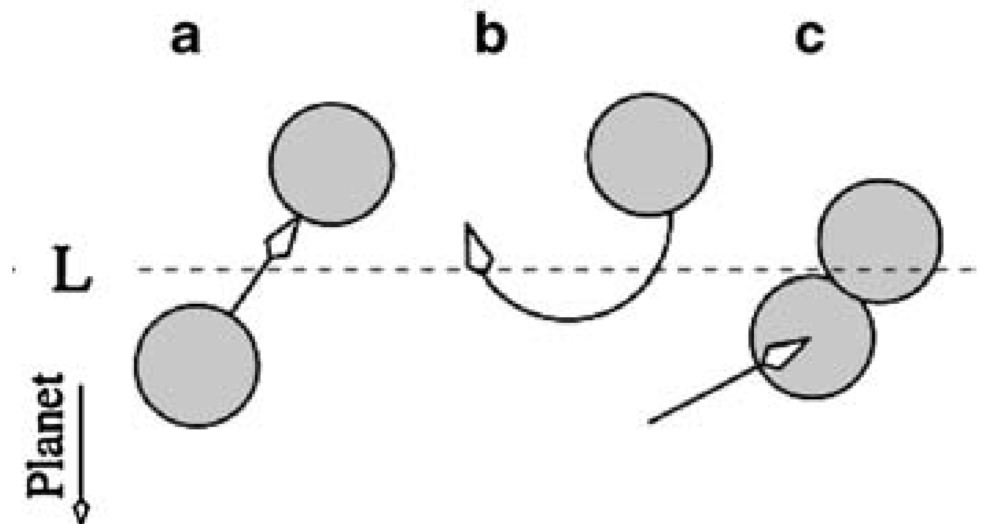
Effect of Particle Elasticity



Simulations suggest ring particles are lossy, underdense.

Salo (1995), in Schmidt et al. (2009)

Ring Viscosity

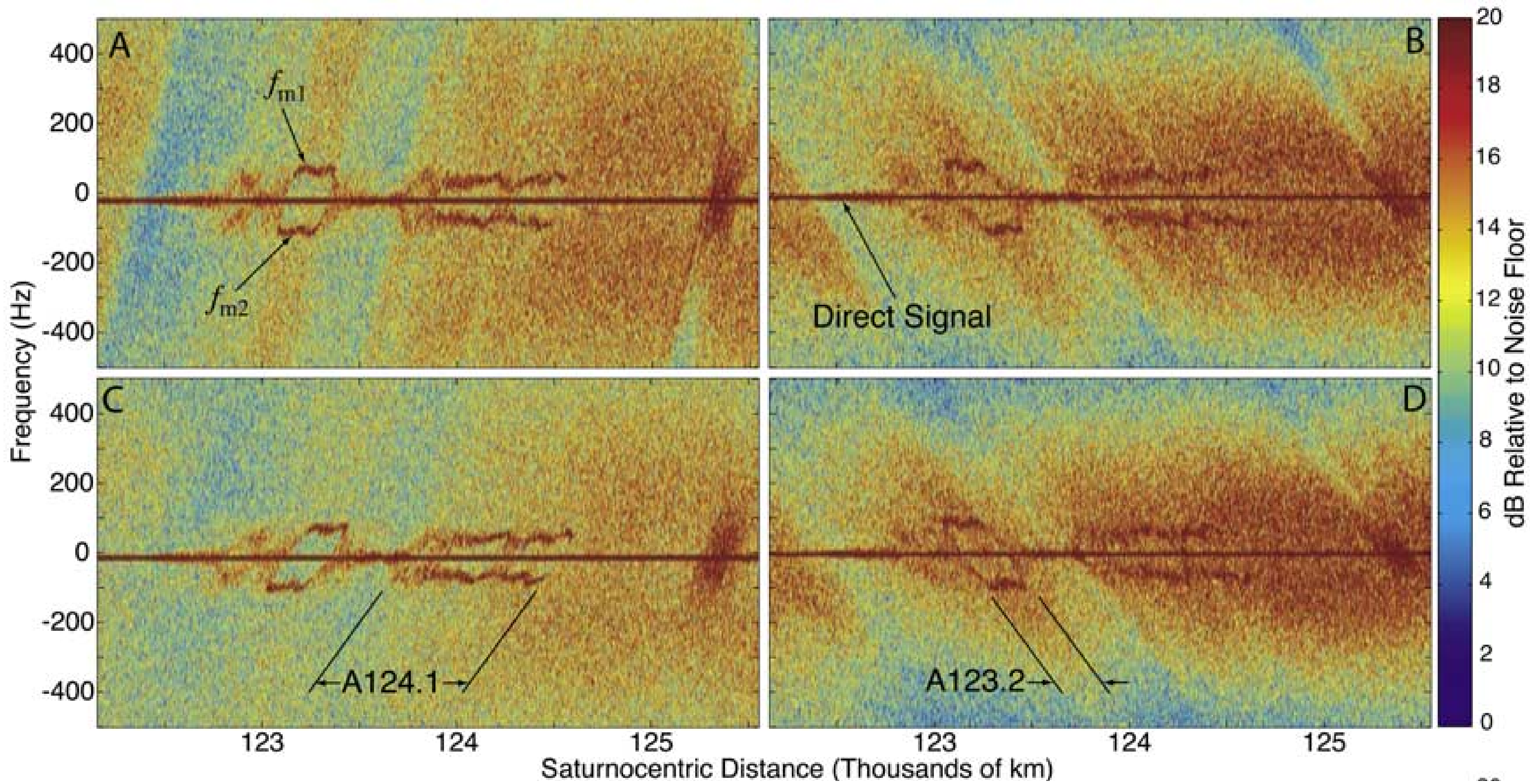


Local Non-local

• Non-local kinematic viscosity ~ $L^2\Omega$, where L is radial scale of momentum transport and Ω is orbital frequency
• Uniform ring: L ~ particle size ~ meters
• Ring with wakes: L ~ Toomre length ~ many tens of meters
→ viscosity is dominated by wakes

Schmidt et al. (2009)

Possible Detection of Viscous Overstability in Cassini Radio Occultations

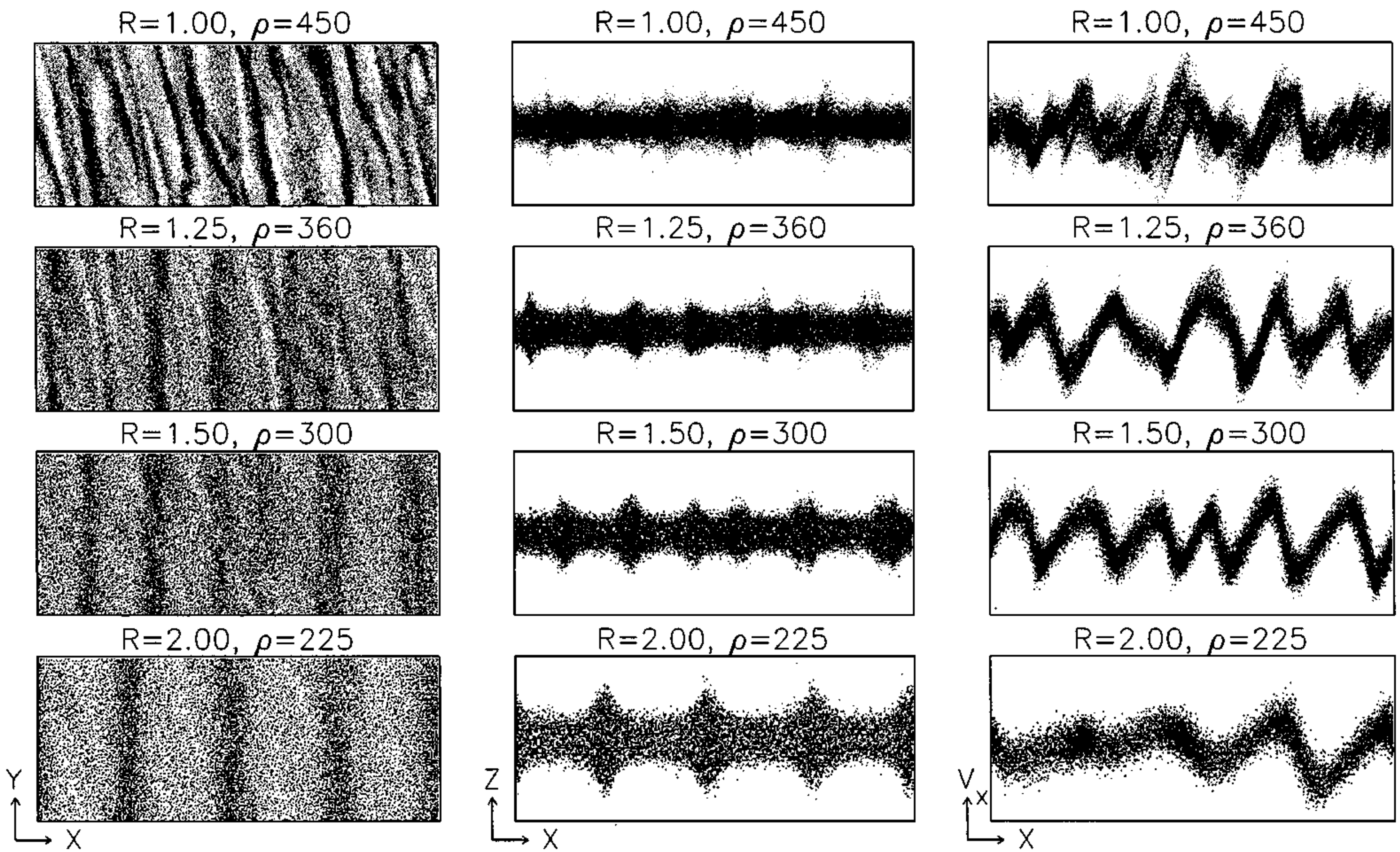


Radial variations in A and B Rings with
λ ~ 100 – 250 meters and cant angle = 0 ± 3°.

Thomson et al. 2007

Wakes and Viscous Overstabilities

Wakes



Viscous
Overstabilities

Viscous overstability can occur if viscosity is steeply rising function of surface mass density.

Salo, Schmidt, and Spahn 2001

$$r_h \equiv \frac{R_{Hill}}{R_1 + R_2} = \left(\frac{\rho_0}{3\rho_{plan}}\right)^{1/3} \left(\frac{a}{r_{plan}}\right) \frac{(1+\mu)^{1/3}}{1+\mu^{1/3}}$$

measures importance of ring self-gravity relative to tidal force

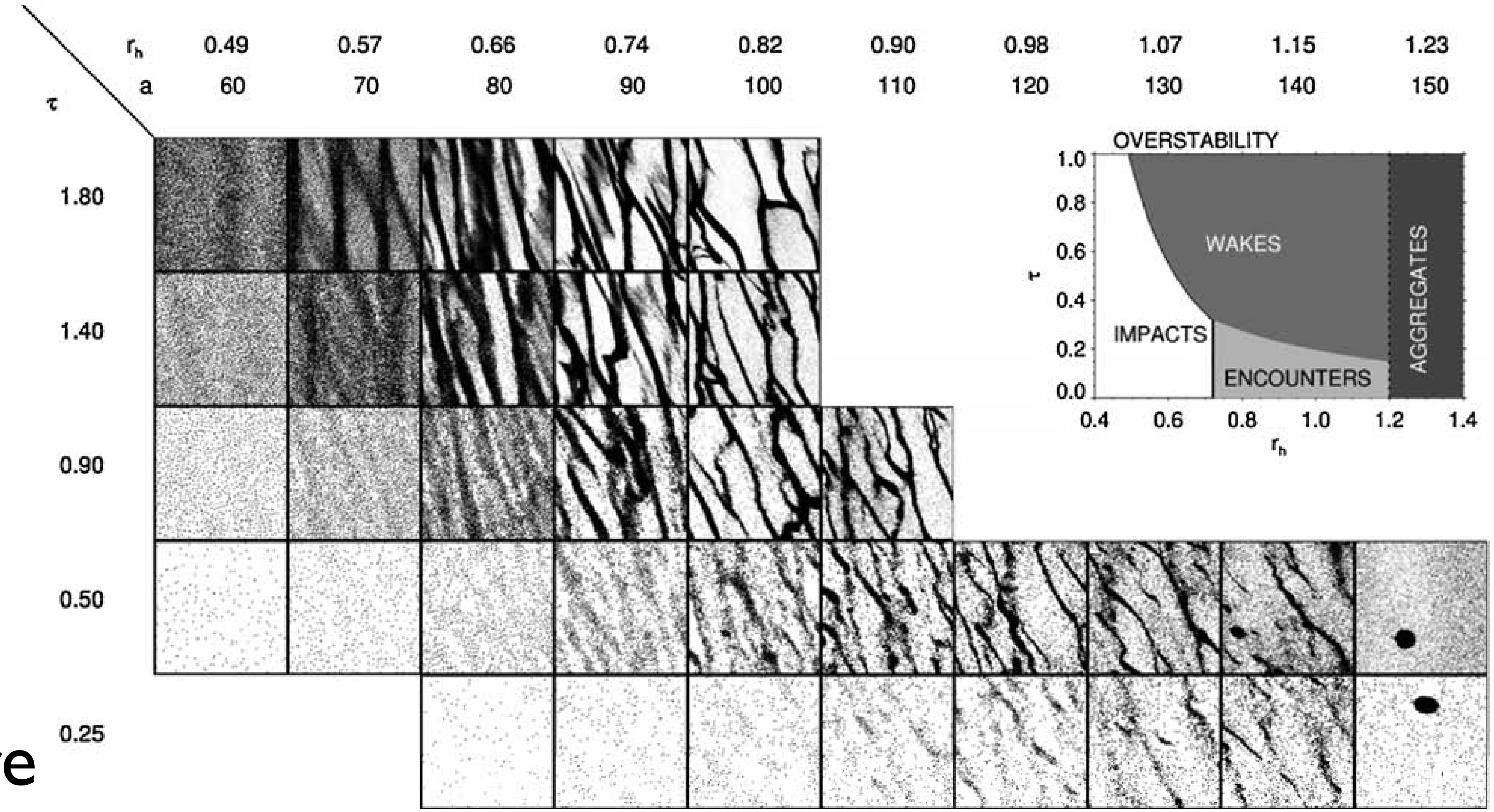
R_{Hill} = mutual Hill radius, R_1 and R_2 are radii of particles, ρ_0 = density of particles, ρ_{plan} = density of Saturn, a/R_{plan} = semi-major axis of particles in units of Saturn radii, μ = mass of particle 1/mass of particle 2

- r_H = 0.6 in C Ring to 1.1 in A Ring for solid-ice, identical particles (ρ = 0.9 g/cm^3, μ = 1)

- r_H = 0.5 in C Ring to 0.9 in A Ring for low-density, identical particles (ρ = 0.45 g/cm^3, μ = 1)

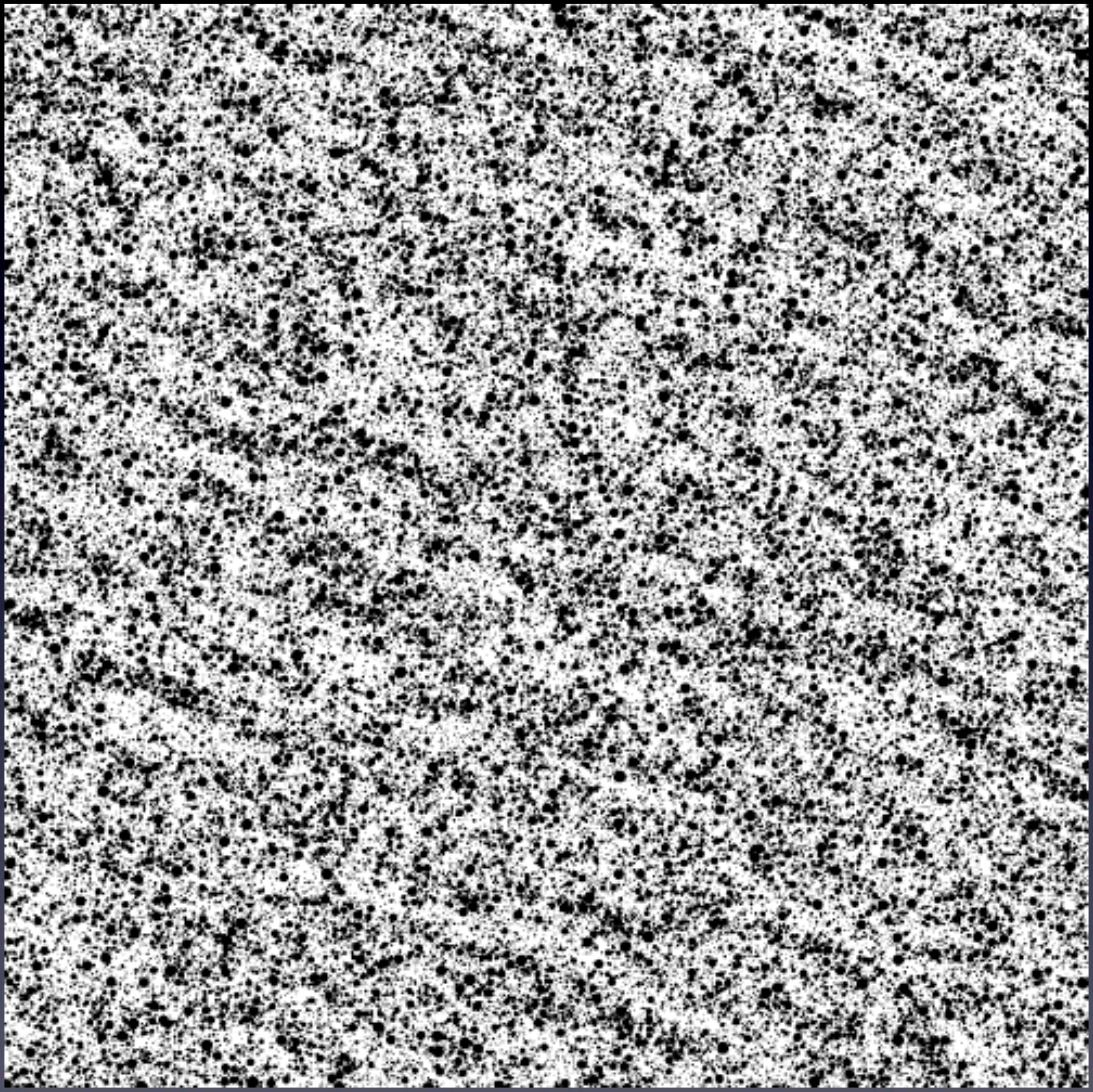
Schmidt et al. 2009

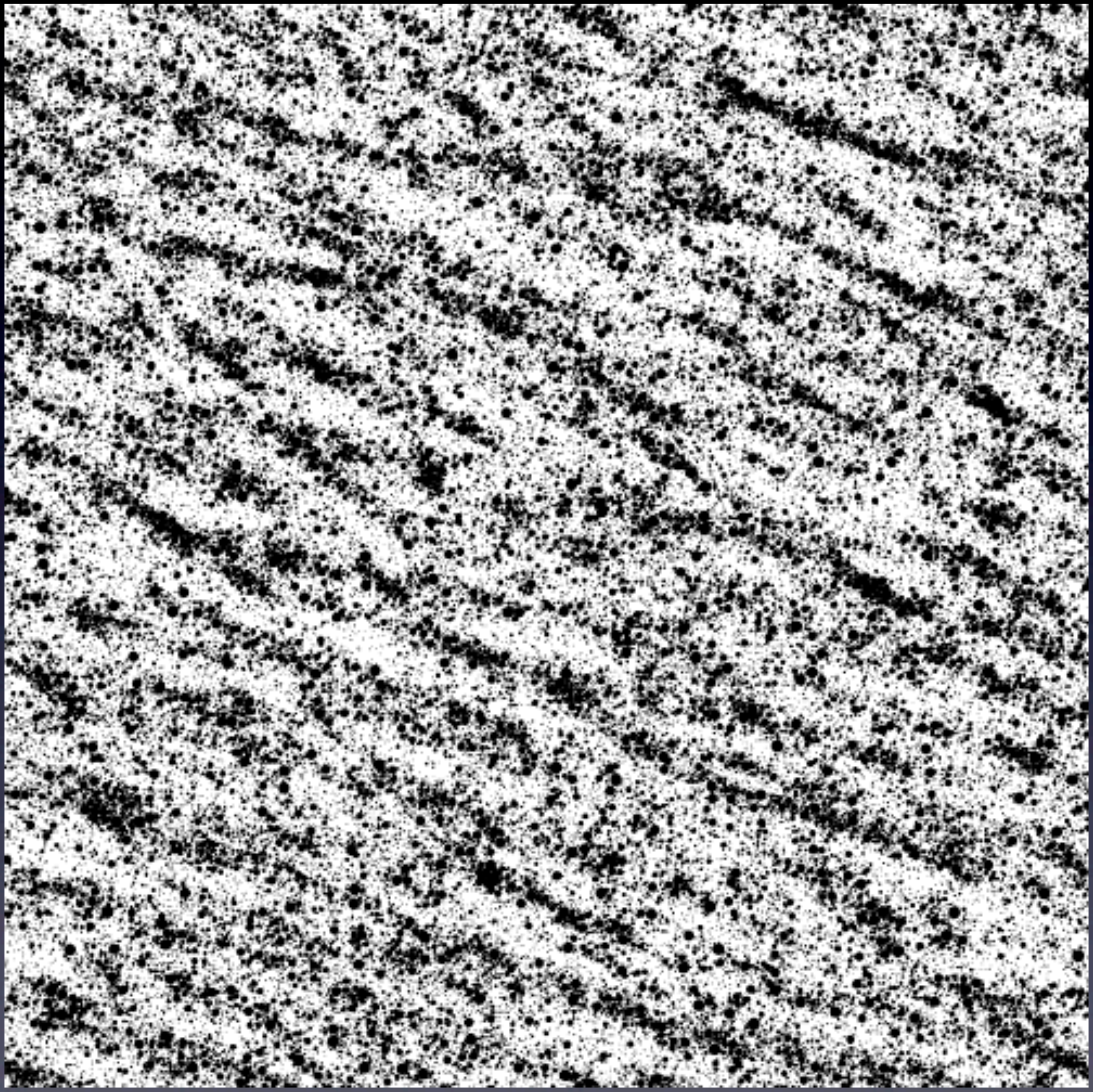
farther from Saturn →

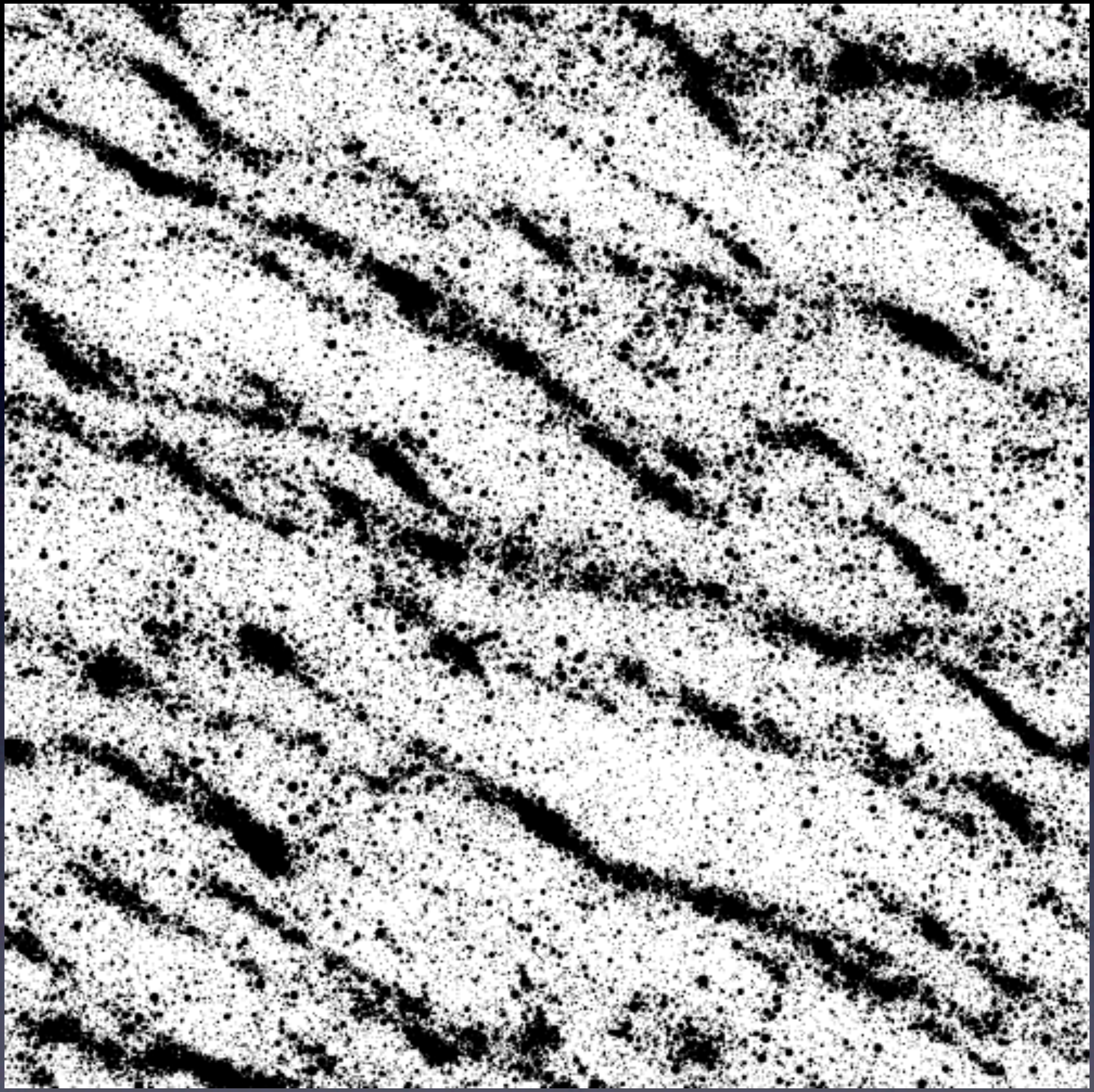


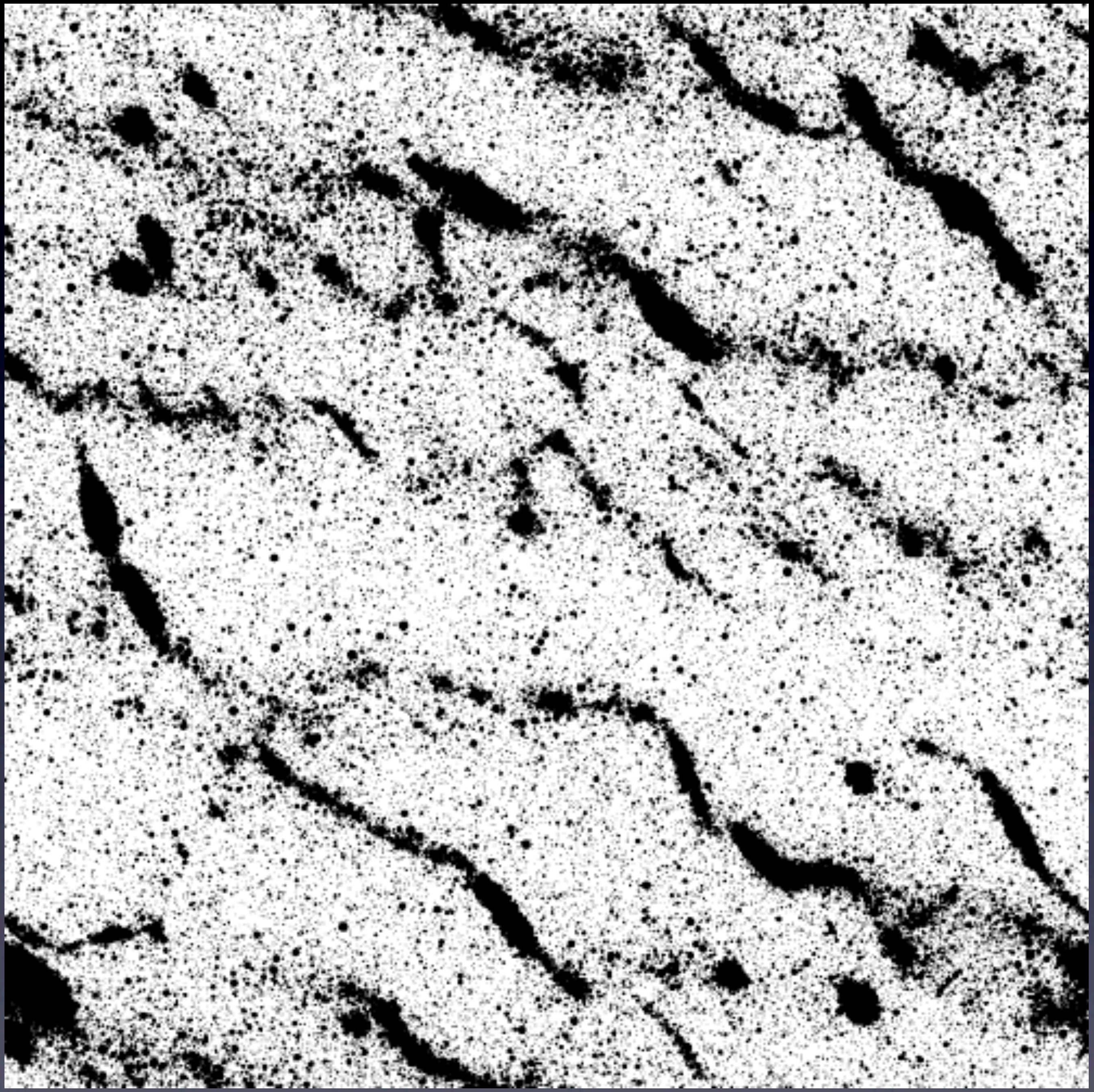
↑ more material

Schmidt et al. (2009)

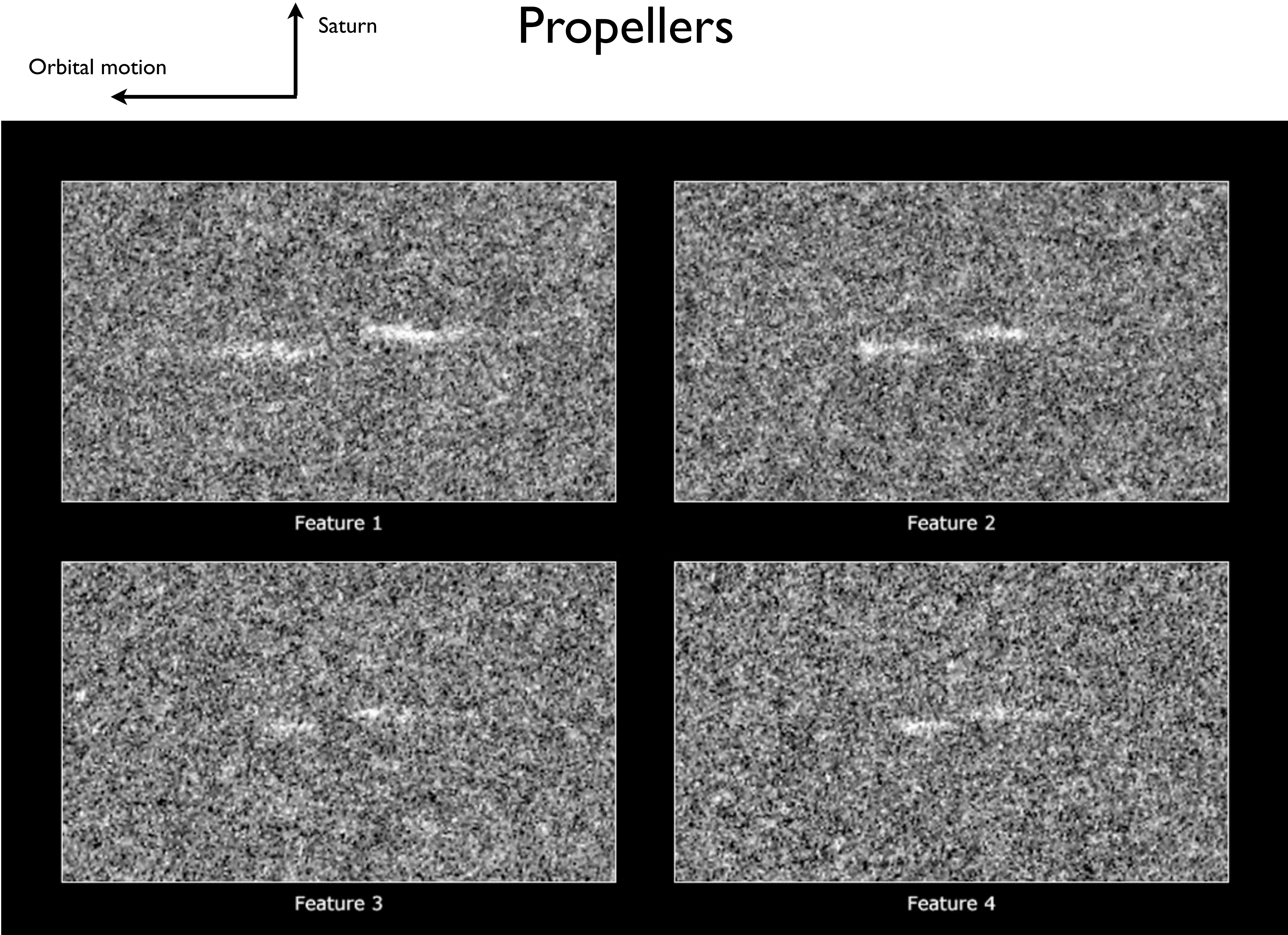






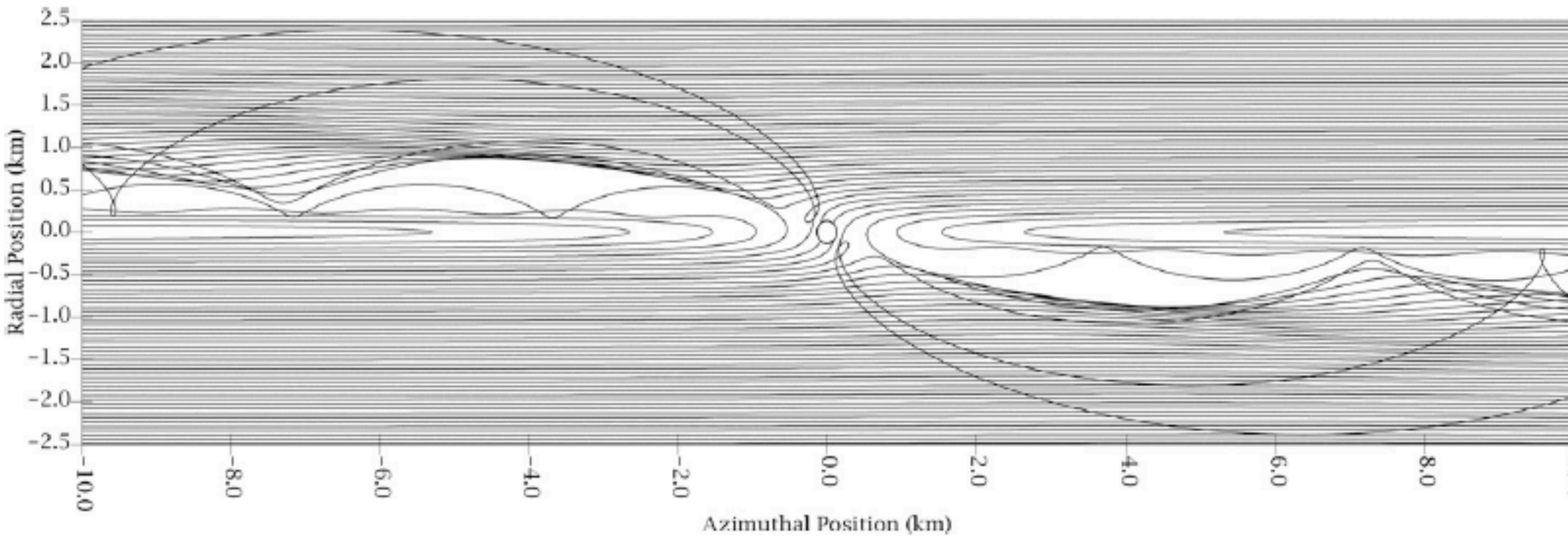


Propellers

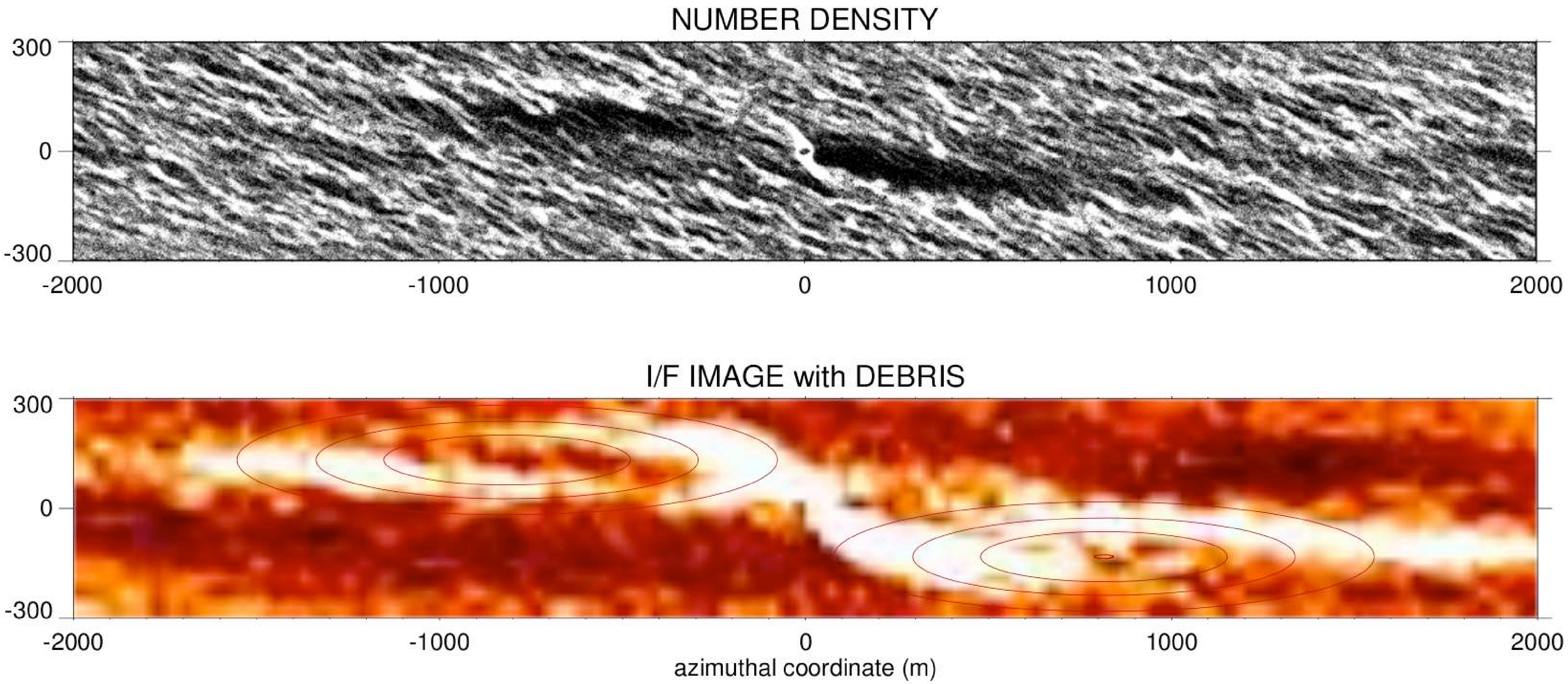


Saturn
Orbital motion
Feature 1
Feature 2
Feature 3
Feature 4

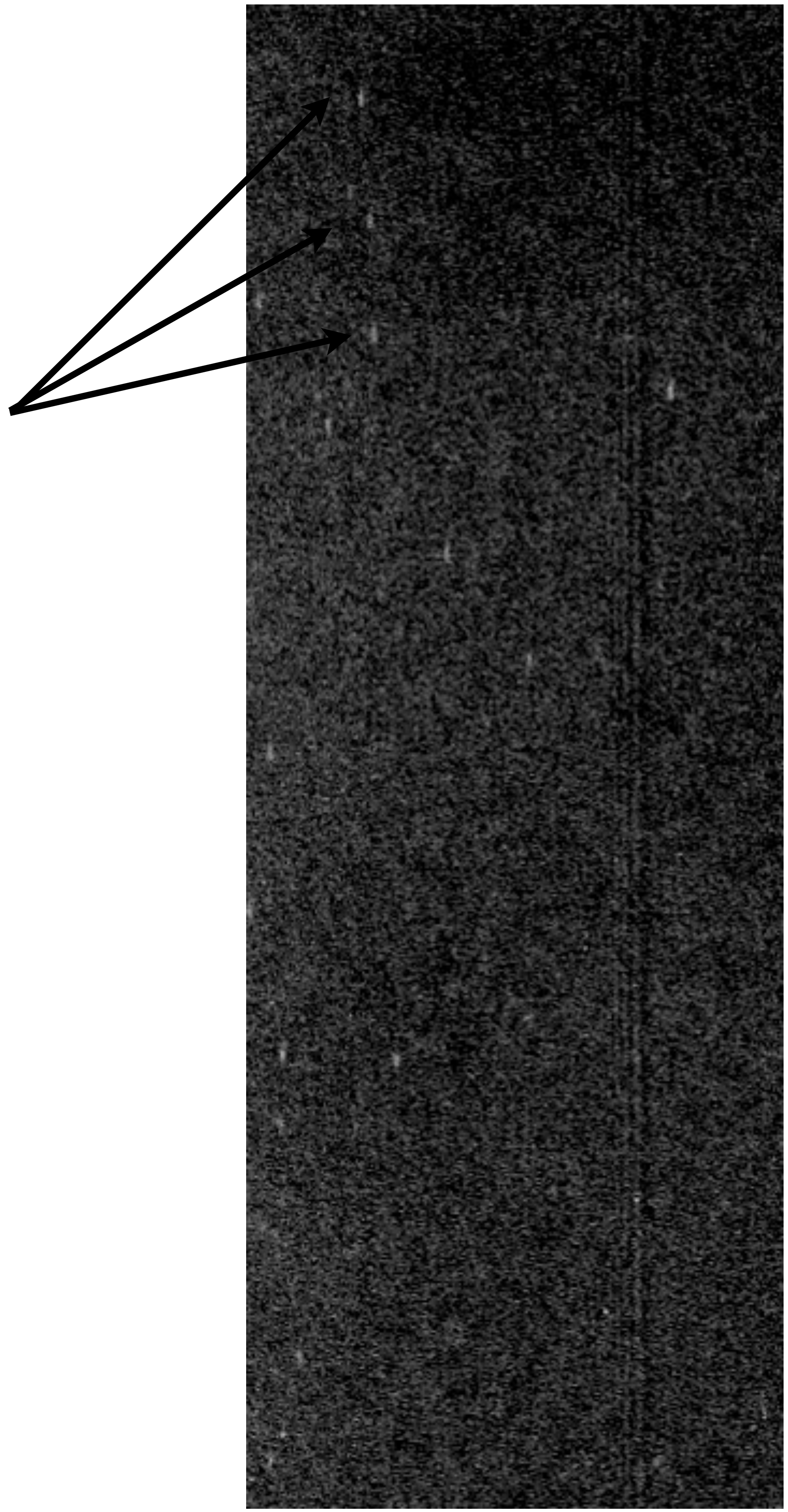
Particle Streamlines Near Small Embedded Moonlet Without Self-Gravity or Collisions



Lewis and Stewart 2009

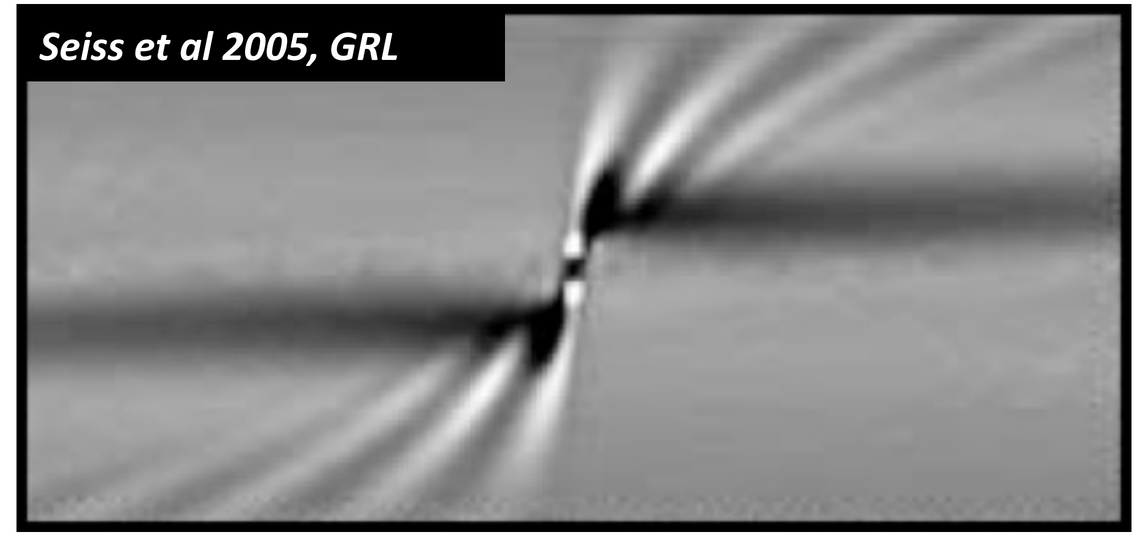


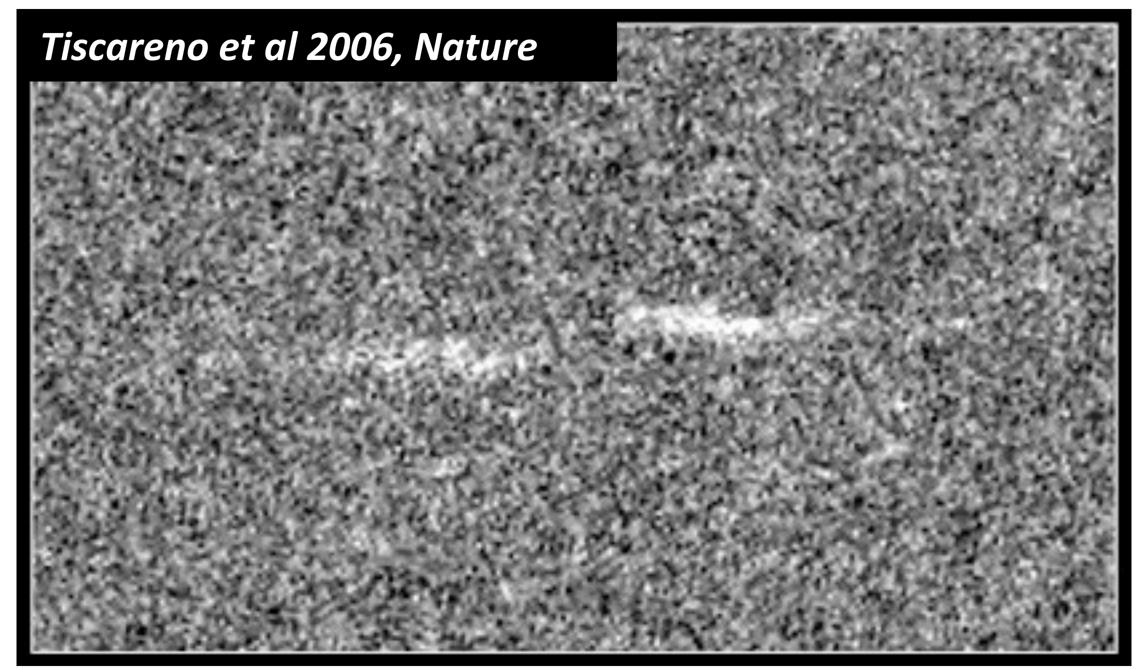
Sremčević et al. 2007, in Schmidt et al. 2009

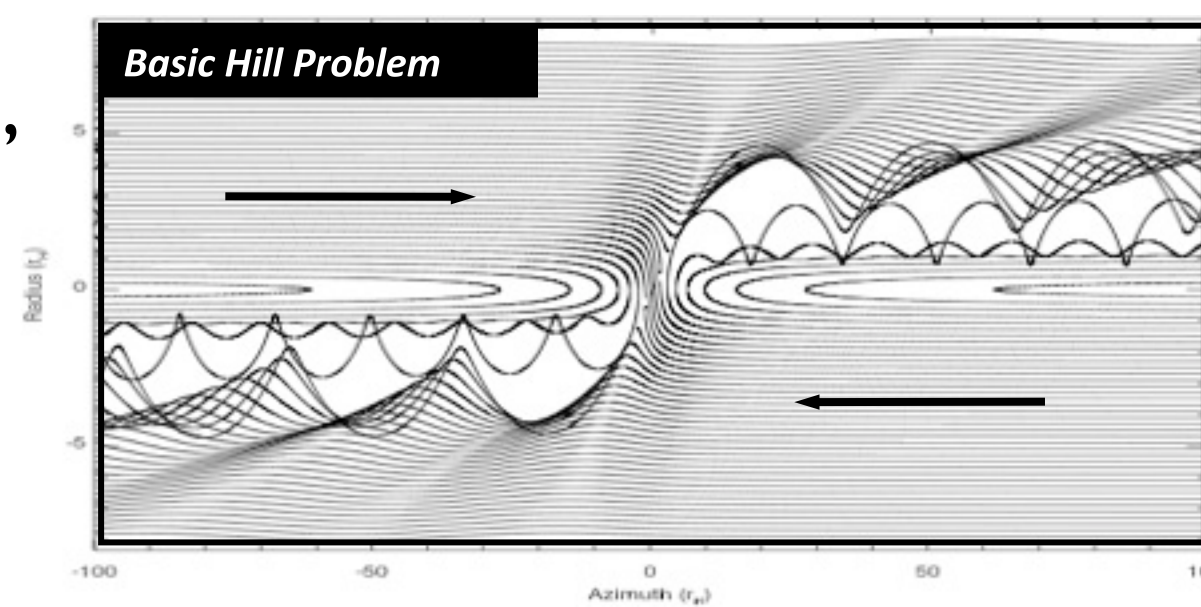


Propellers in the A Ring

- Biggest ring particles (smallest moonlets) can’t open a full gap, but disturb nearby longitudes.
- Propeller-shaped structure surrounding embedded moonlets was predicted before Cassini arrived at Saturn.
- Density contours are similar to those in Hill’s problem, but self-gravity and collisions are important.
- Longitudinal extent determined by ring viscosity.
- Non-uniform radial distribution: “belts” in mid-A Ring (near where azimuthal asymmetry is strongest) and outside Encke Gap.







Propellers are predicted to form when ring self-gravity is weak.

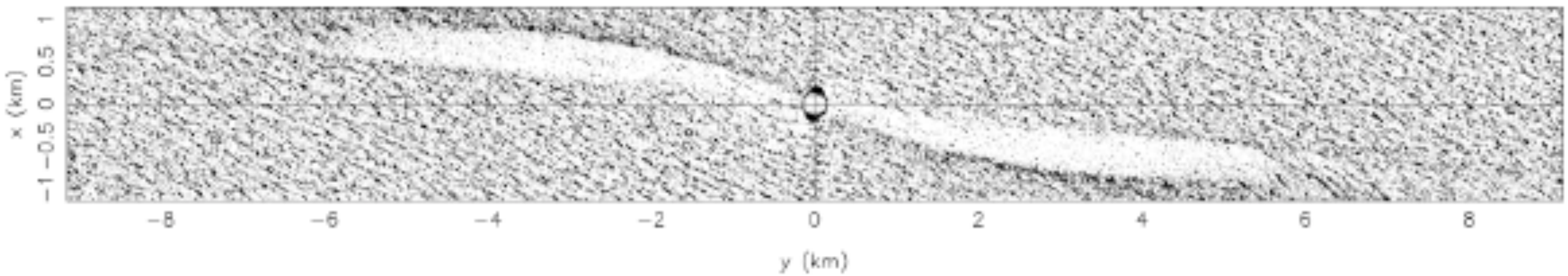


Figure 1. Snapshot of low surface density model at $t = 1.0T_K$. The initial surface density is $\Sigma_0 = 62$ g cm^{-2}. The circle at the center of the computational box is the moonlet. A propeller structure is visible around the moonlet.

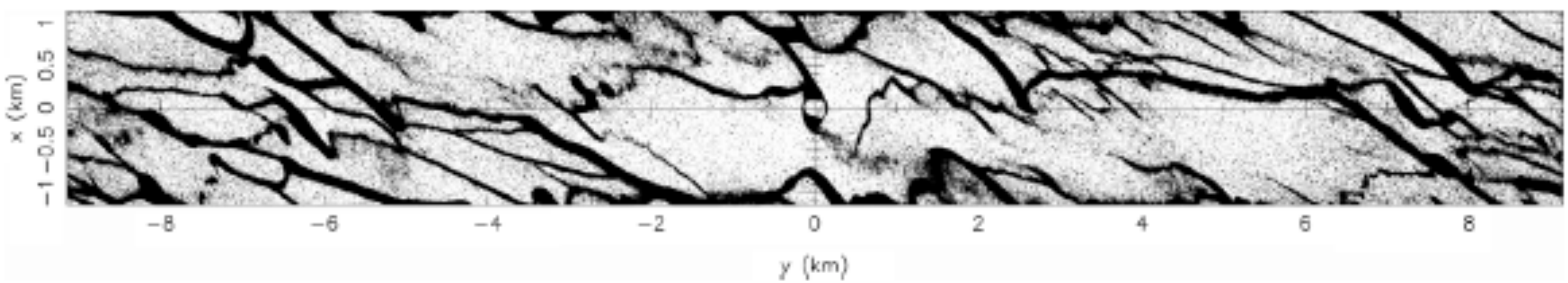
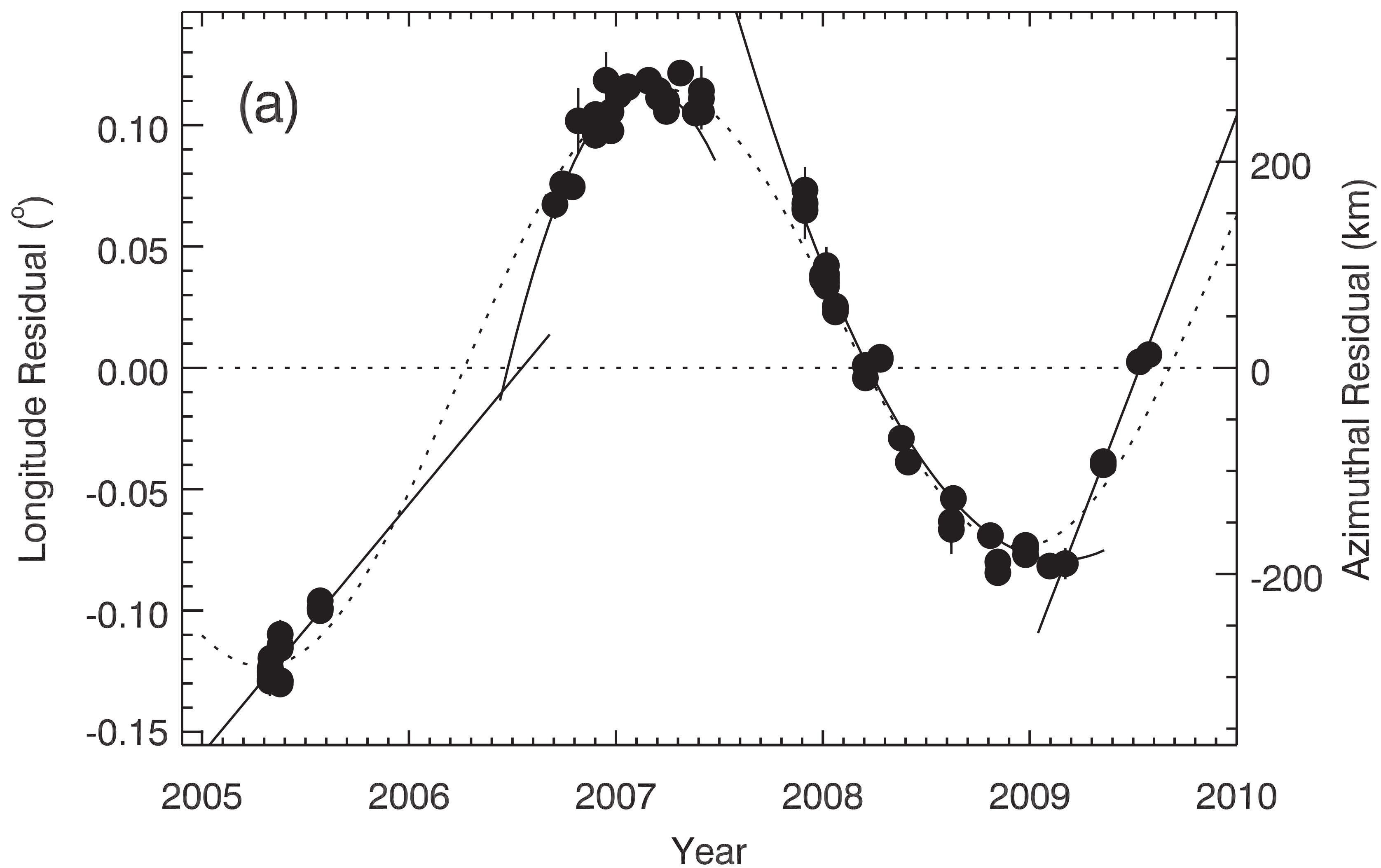


Figure 2. Same as for Figure 1, but for the high surface density model with $\Sigma = 414$ g cm^{-2} at $t = 4.0T_K$. Strong gravitational wakes form and a propeller structure is not clearly observed.

Michikoshi and Kokubo 2010

Non-Keplerian Orbital Motion of Propellers

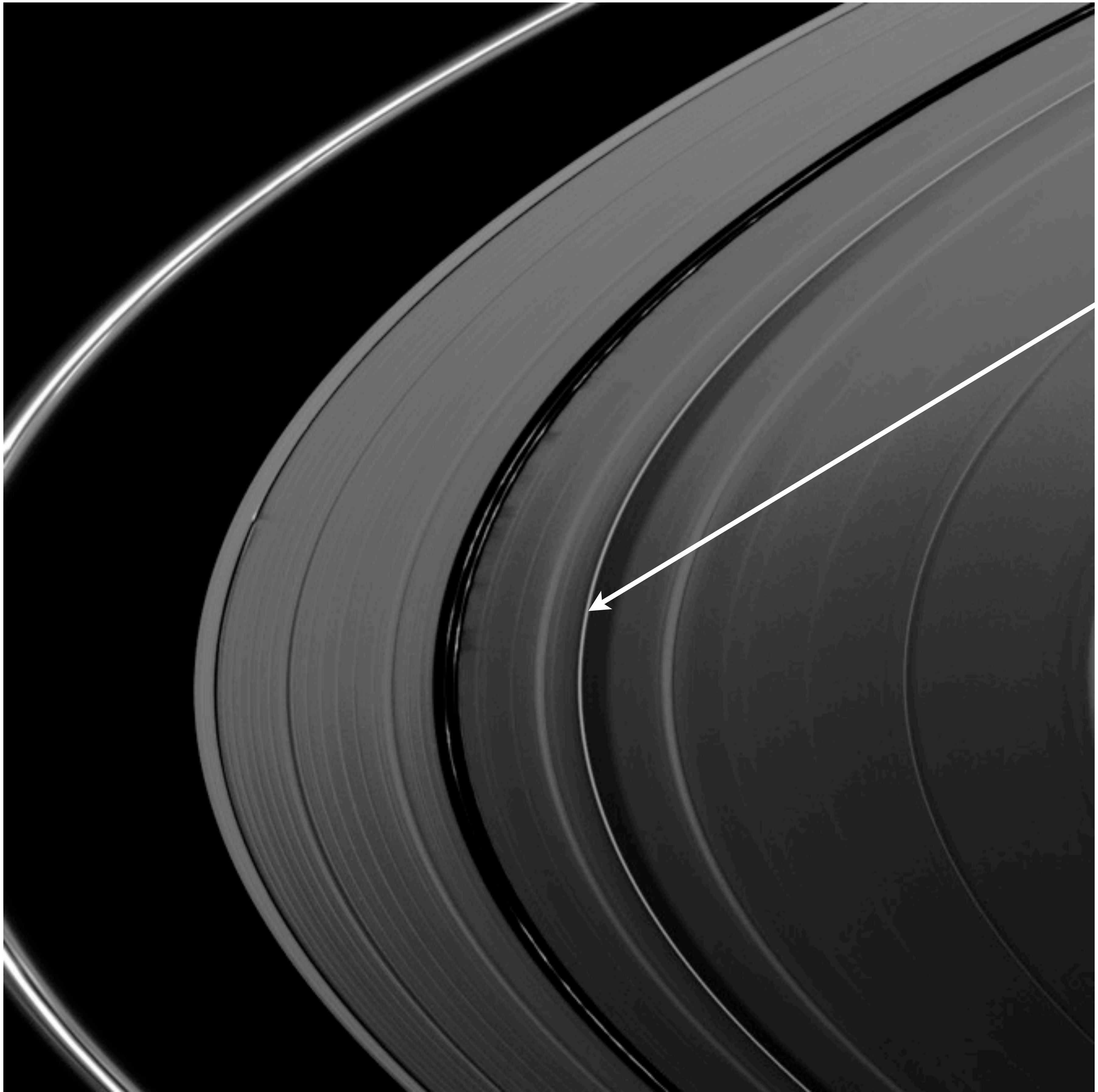


Longitude residuals of propeller Blériot

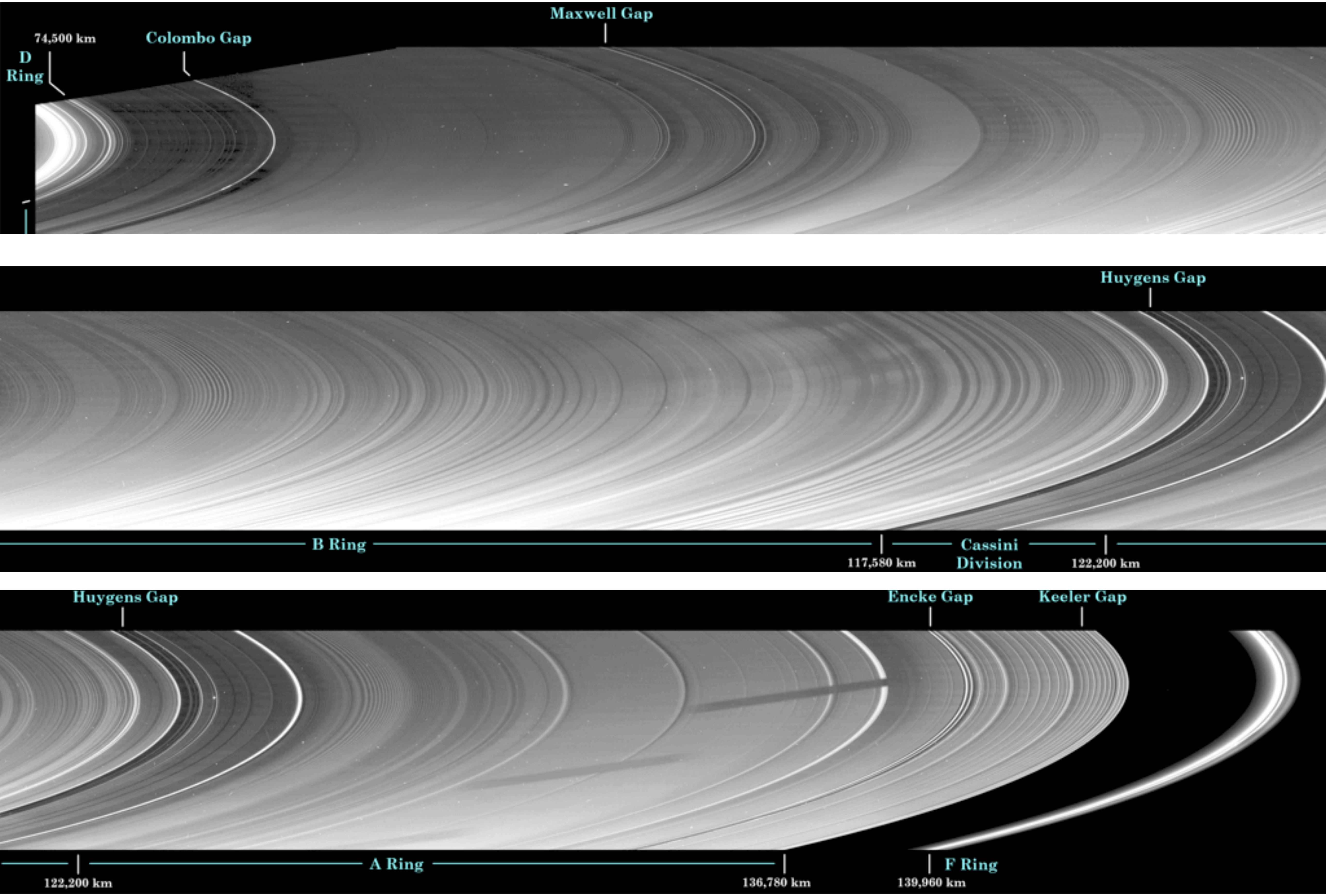
Tiscareno et al. 2010

Probably due to gravitational interaction with nearby ring material, but mechanism is not clear.

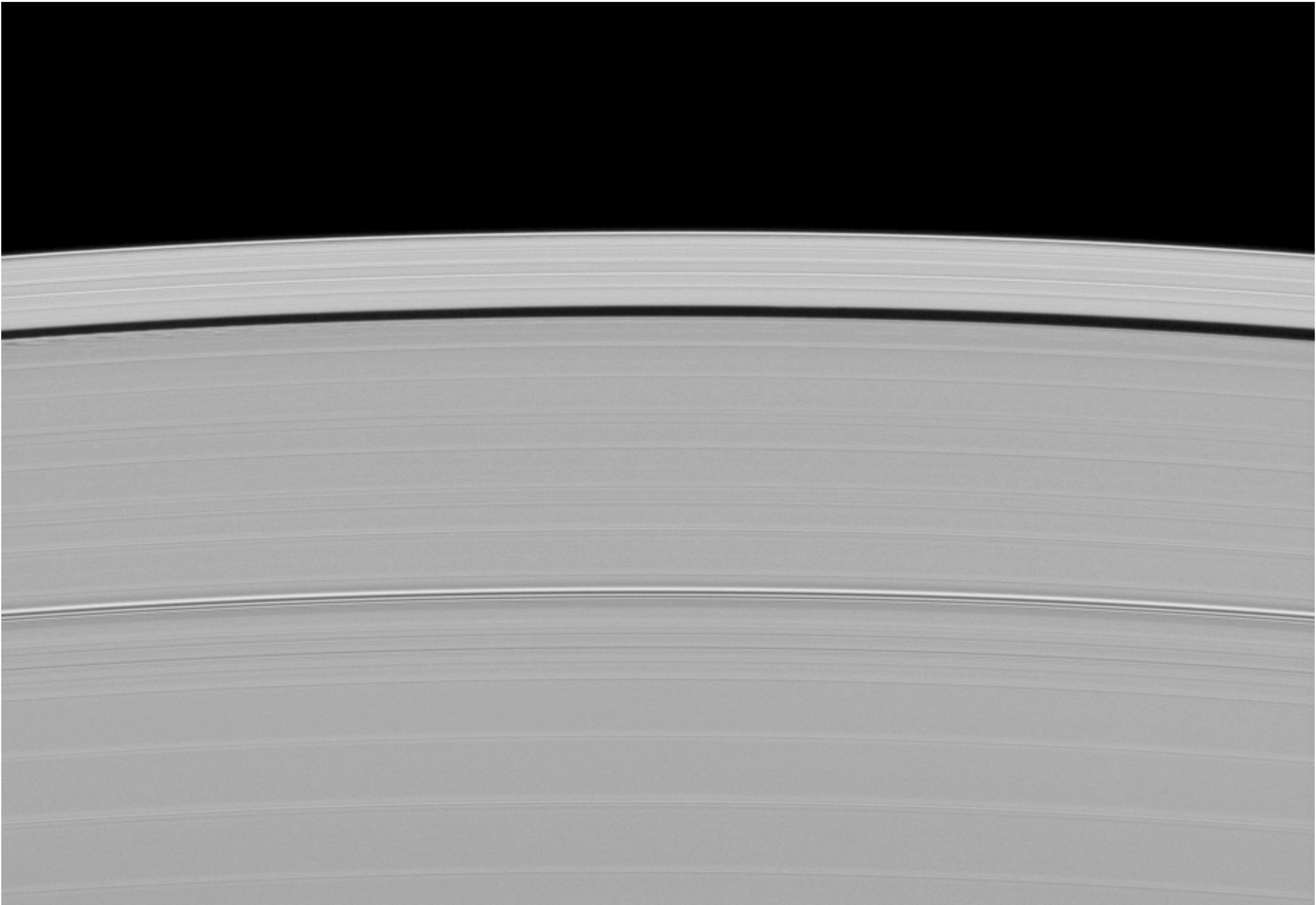
Vertical Structure Seen Near Equinox

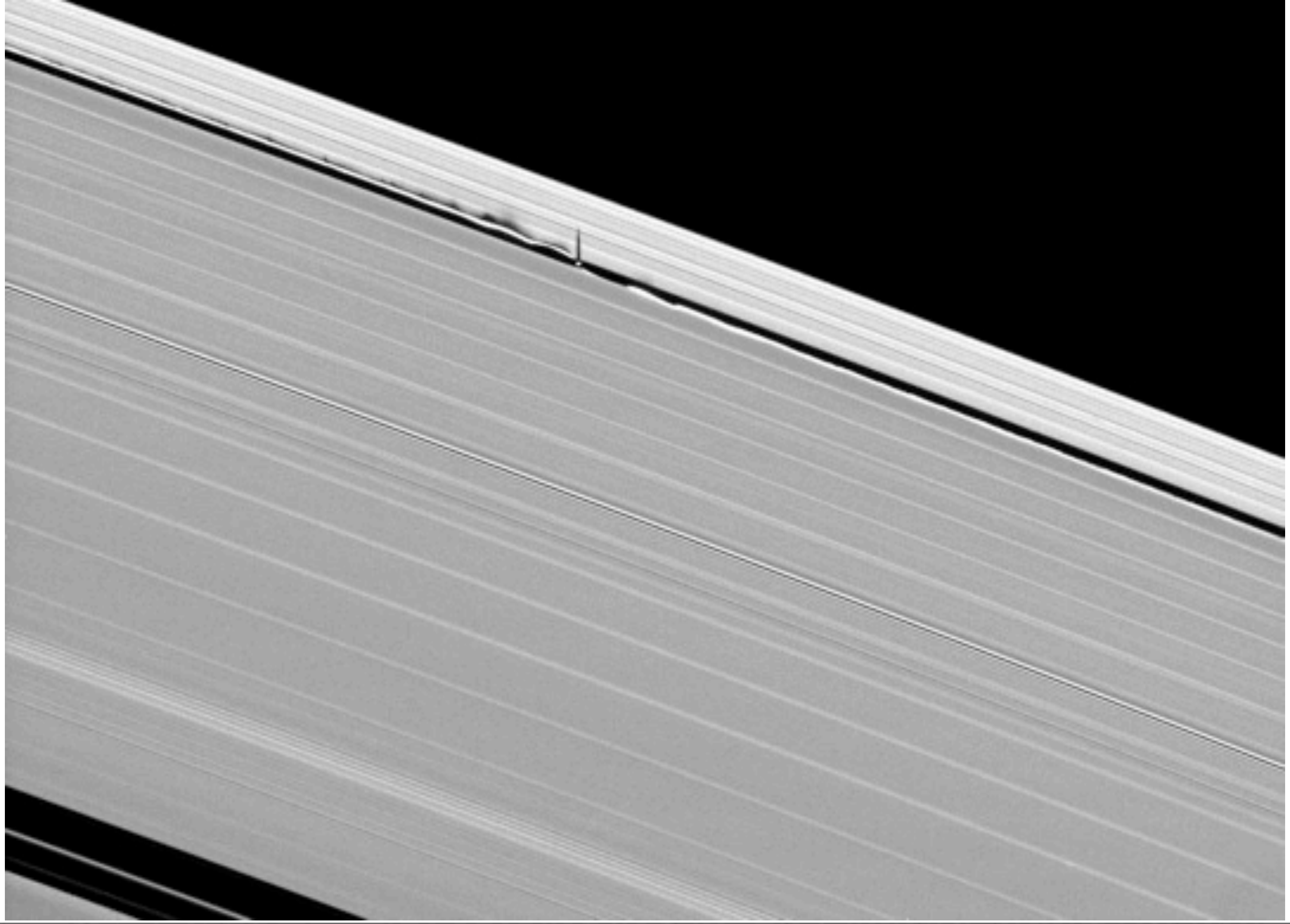
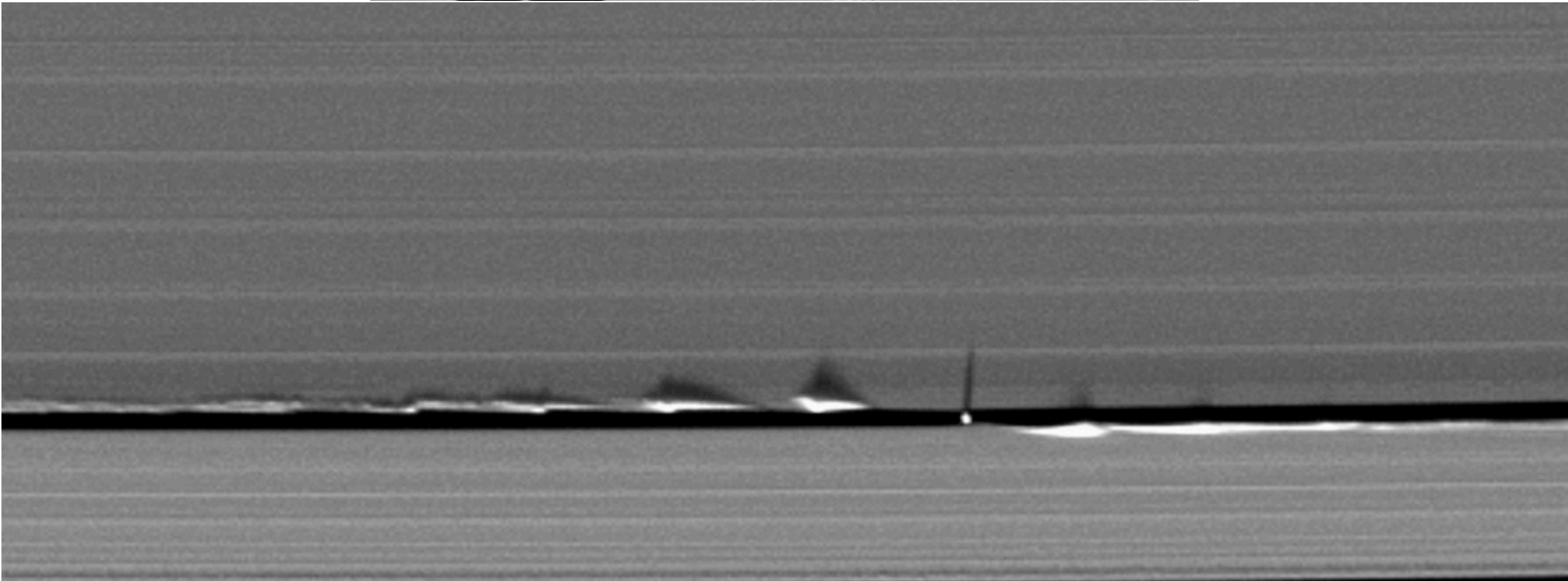


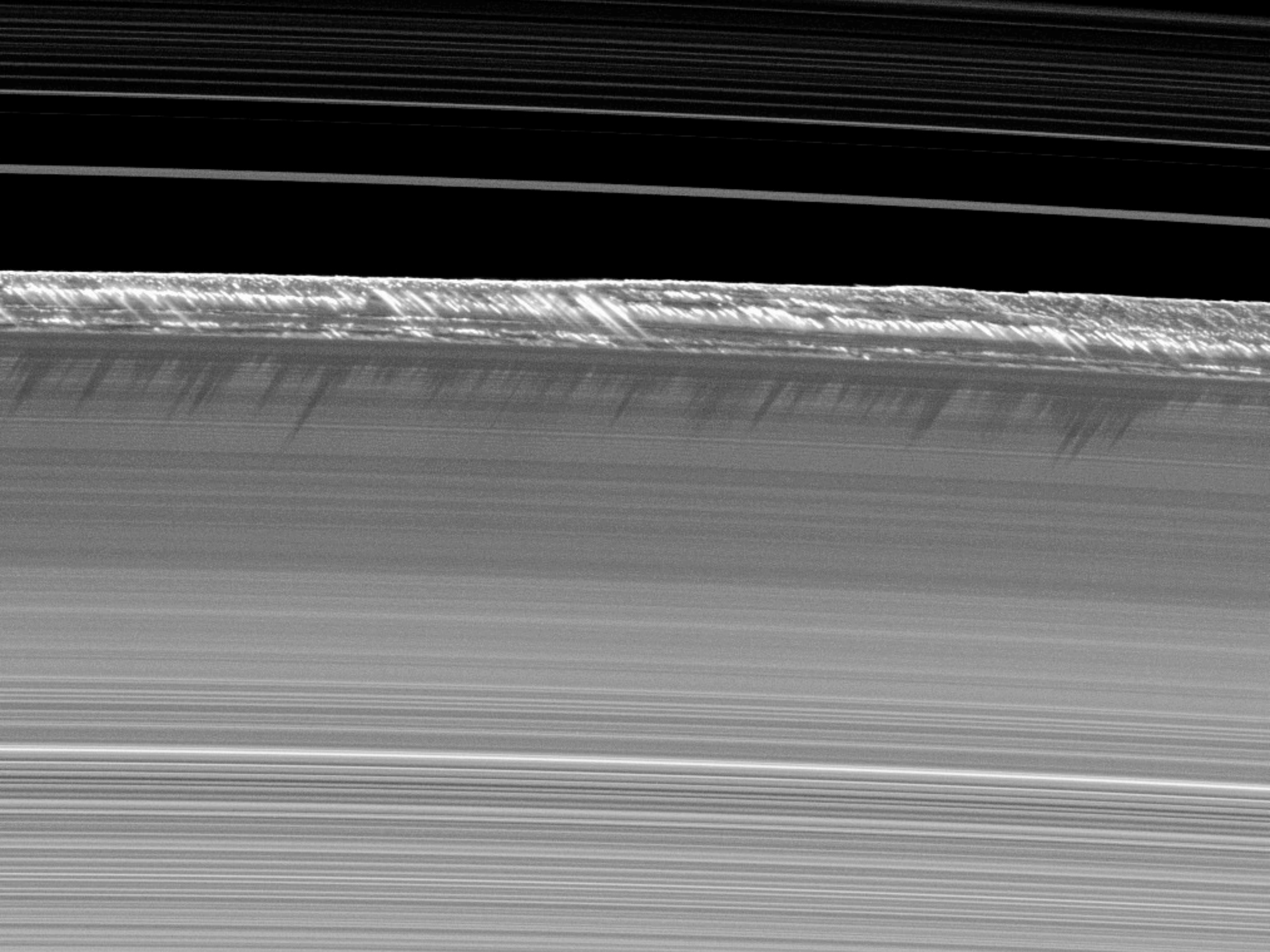
Mimas
5:3
bending
wave



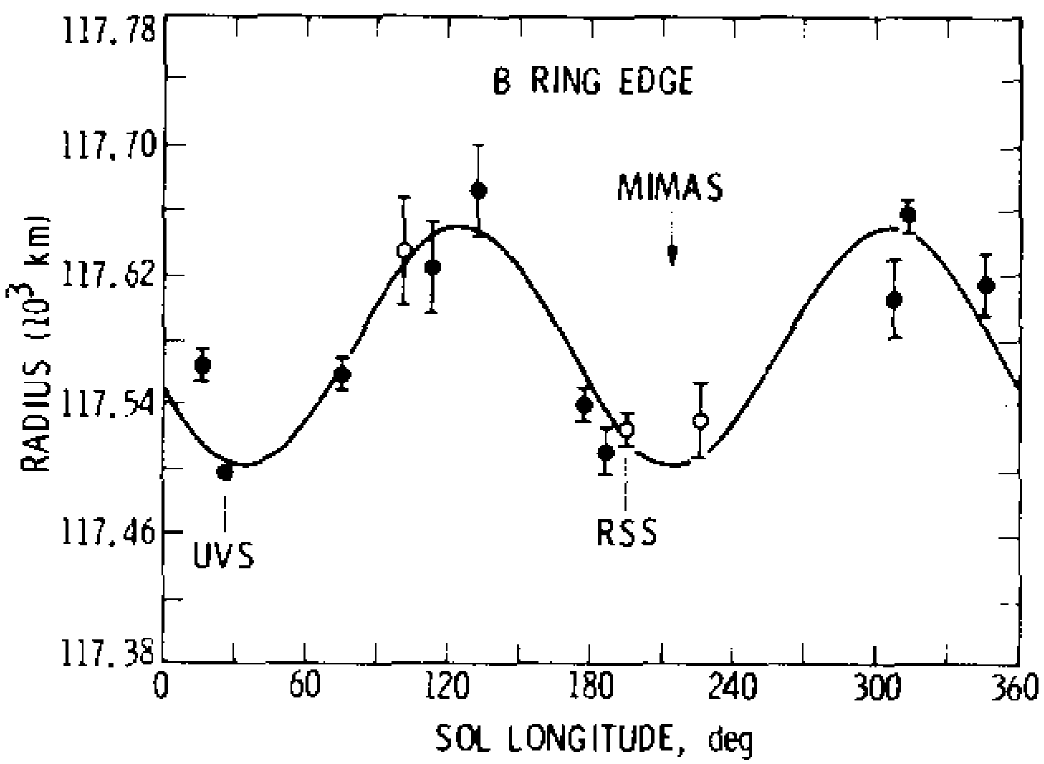
Maxwell Gap
74,500 km
Colombo Gap
D
Ring
Huygens Gap
B Ring
117,580 km
Cassini
Division
122,200 km
Huygens Gap
Encke Gap
Keeler Gap
122,200 km
A Ring
136,780 km
F Ring
139,960 km

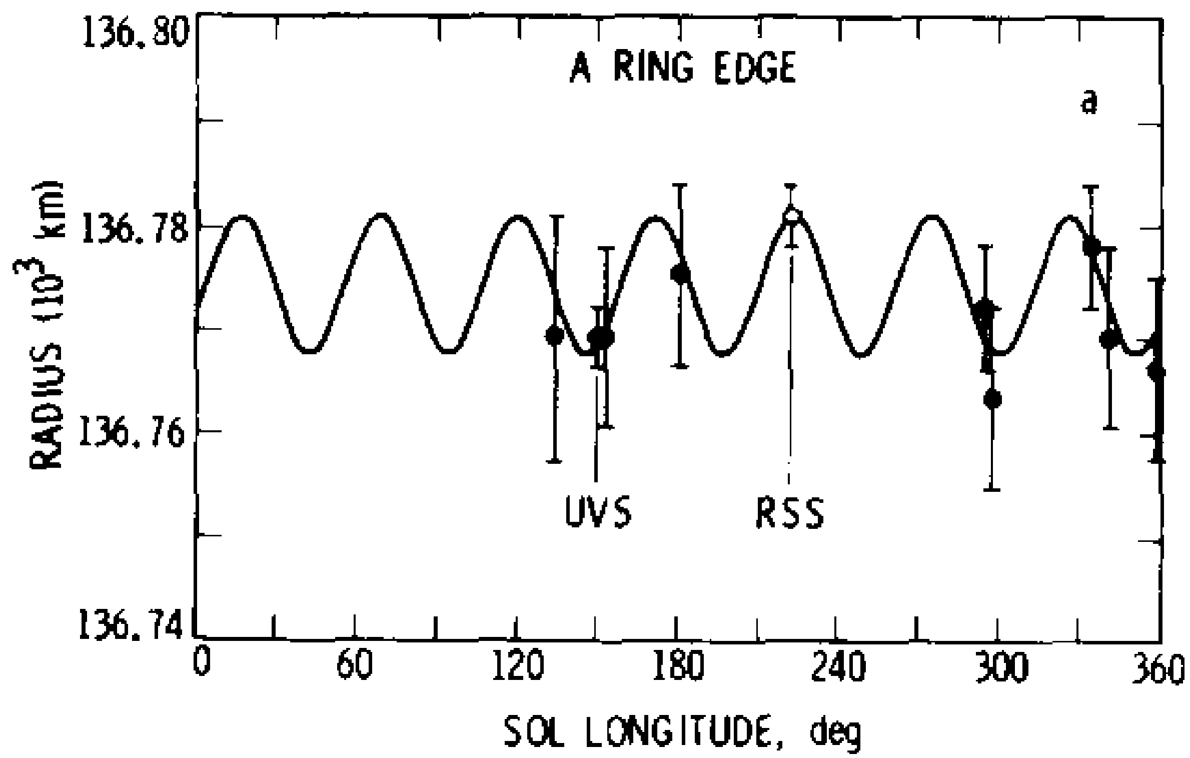




Outer Edges of the B Ring and A Ring





m = 2 pattern, periapse aligned with Mimas [edge is near Mimas 2:1 ILR]

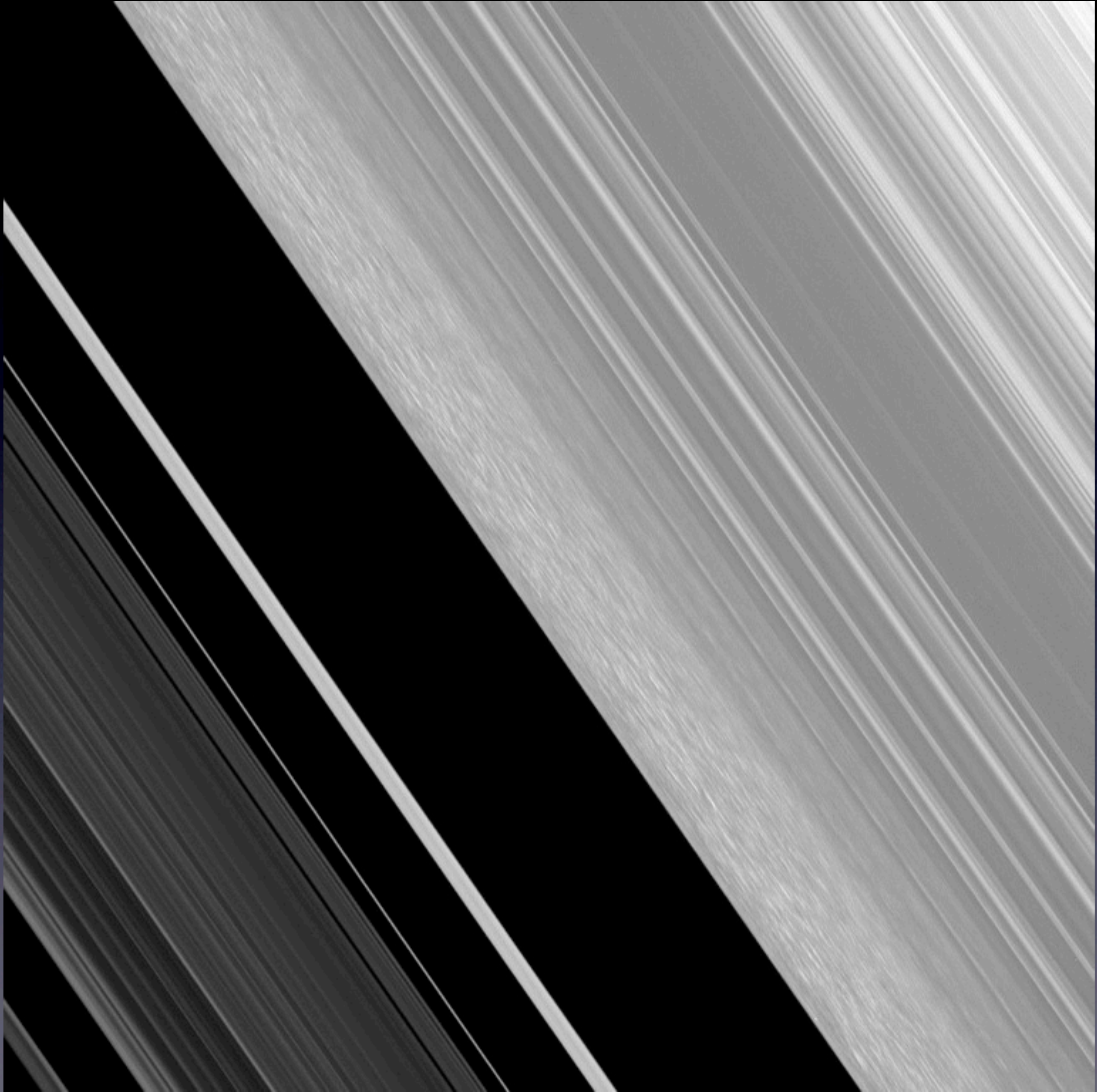
m = 7 pattern, [edge is near Janus/ Epimetheus 7:6 ILR]

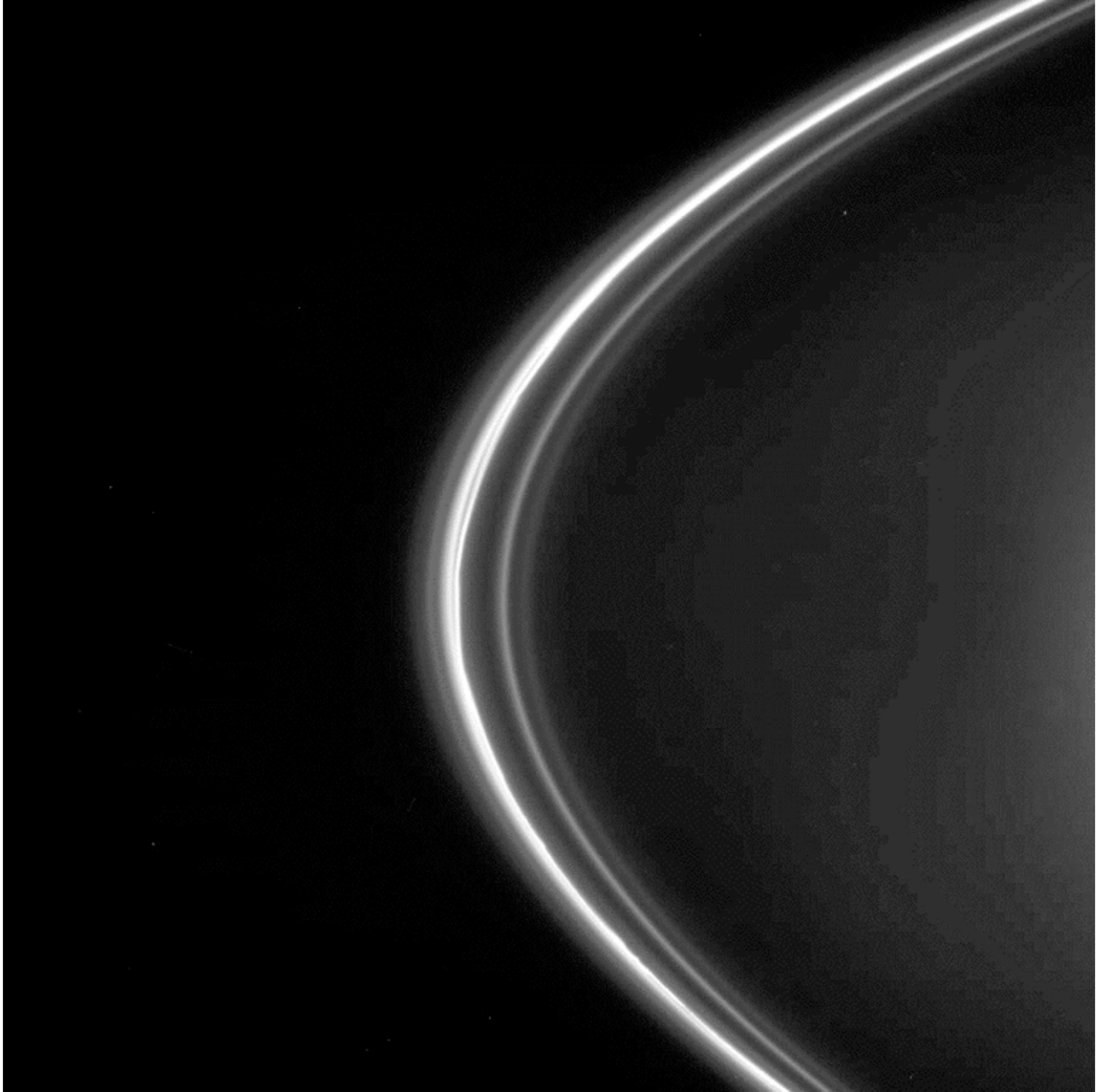
Porco et al. 1984

- Spitale and Porco (2010) find the expected m = 2 forced distortion of the outer edge of the B Ring, plus evidence for unforced m = 3, m = 2, and m =1 modes

- m = 1 mode interpreted as a viscously overstable self-excited density wave. This behavior is possible if ring particles are closely packed (Borderies et al. 1985).

- Spitale and Porco (2009) find m = 7 distortions due to Janus and Epimetheus, plus unexplained structure.





Rapid Changes in the F Ring

F Ring structure includes:

- “Streamers” and “channels” due to gravitational perturbations by Prometheus when it approaches the ring (and, to a lesser extent, the more distant Pandora)
- “Jets” and kinematic spirals due to small moonlets embedded in the ring

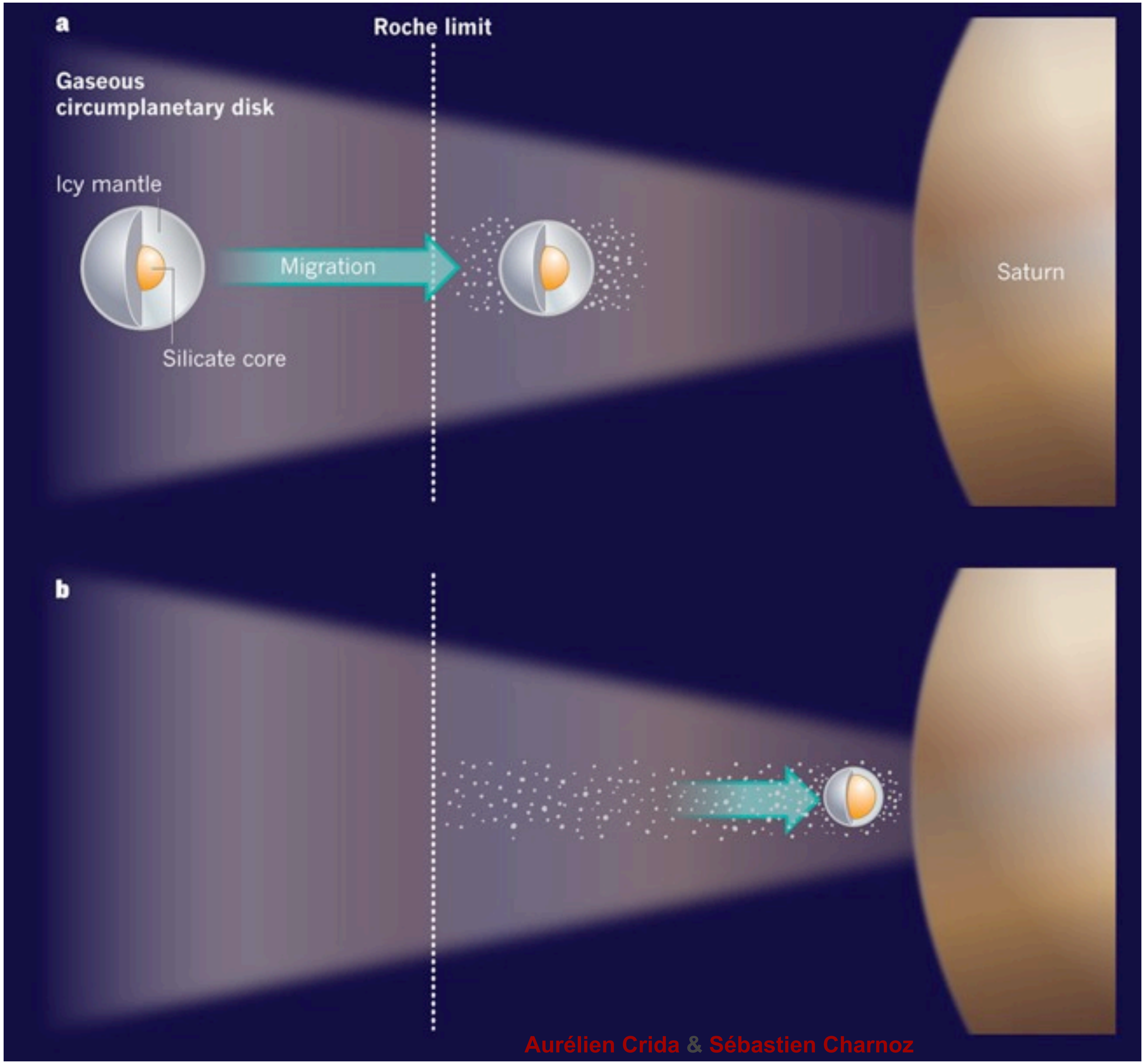
Pandora
(outer F Ring "shepherding satellite")

Models for the Origin of Saturn's Rings

- (Remnant of primordial Saturn sub-nebula)
- Stranded satellite disrupted by comet
- Tidally disrupted Centaur
- Tidal stripping of Titan's evil twin

Ring Age

- Popular view after Voyager:
  - Rings may be “young” (~100 million year old)
  - Idea based on theoretical arguments about
    - ring-satellite interactions
    - contamination by interplanetary dust
- Speculation now:
  - Rings likely to be ancient, but are recycled into new forms



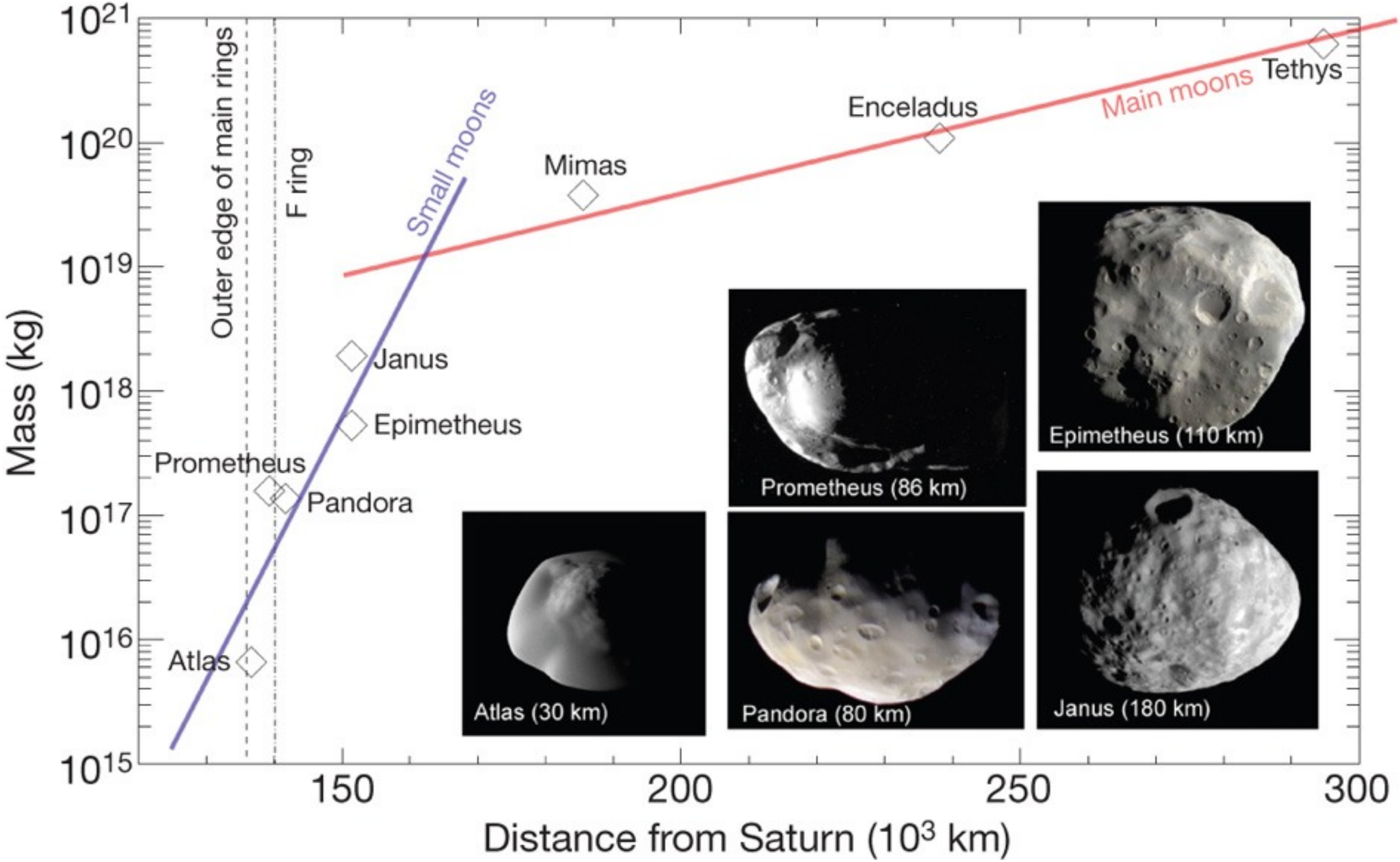
Aurélien Crida & Sébastien Charnoz
Nature **468**, 903–905 (16 December 2010)
doi:10.1038/nature09738

Titan-sized satellite is differentiated (or differentiates as it evolves inward) [Canup 2010].

Canup (2010) Scenario for Ring Origin

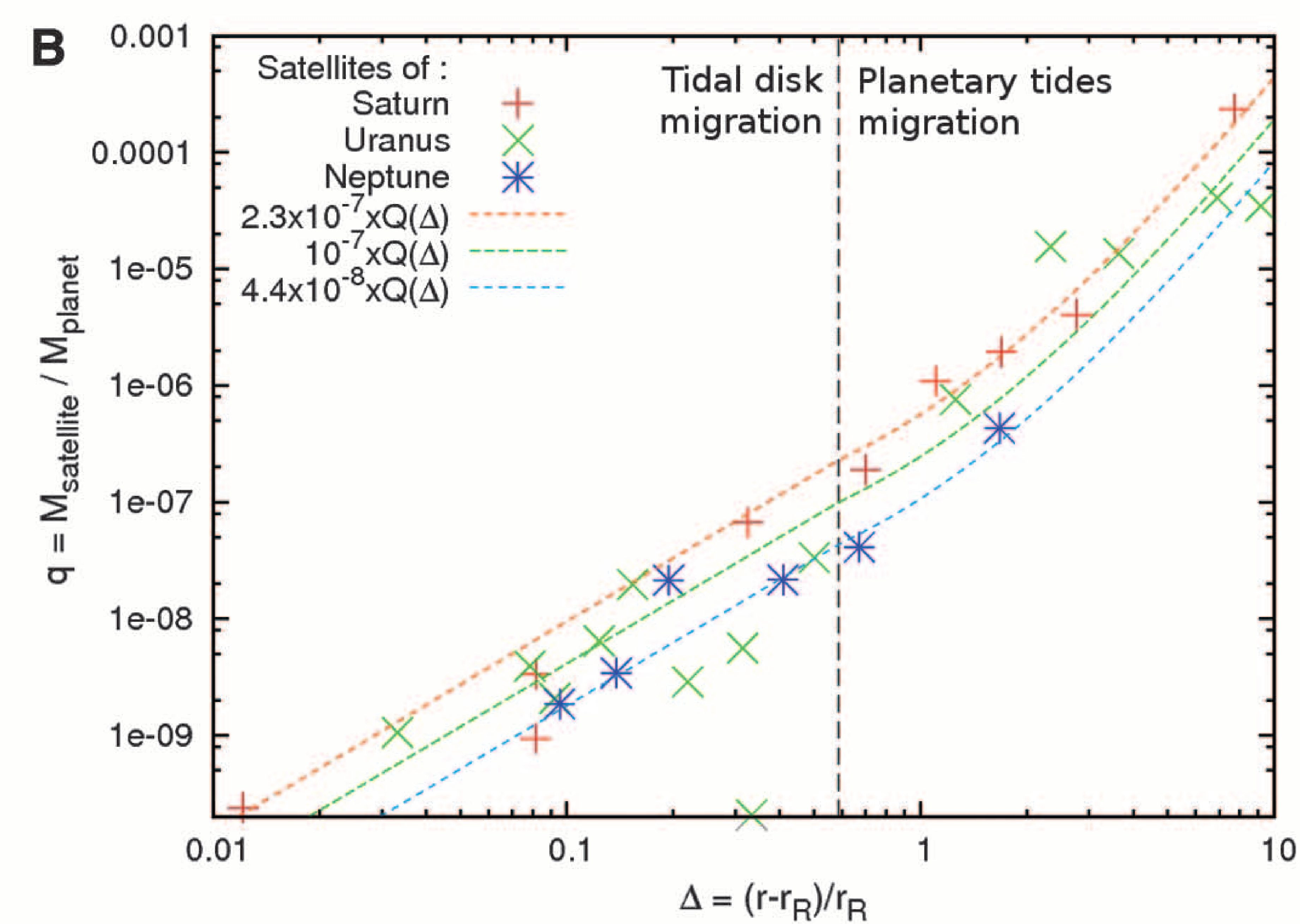
- A Titan-like satellite undergoes Type I migration toward Saturn near the end of the planet's formation.
- Satellite is already differentiated or becomes differentiated by tidal heating as it moves inward.
- Tides strip material from satellite's icy shell
- Core collides with Saturn before it can be disrupted → produces massive icy ring with little contamination
- Collisions between particles spread ring
- Material that spreads outside Roche limit coagulates into satellites.
- Satellites evolve outward due to torques from rings and tides from Saturn.

courtesy of Greg Prichard



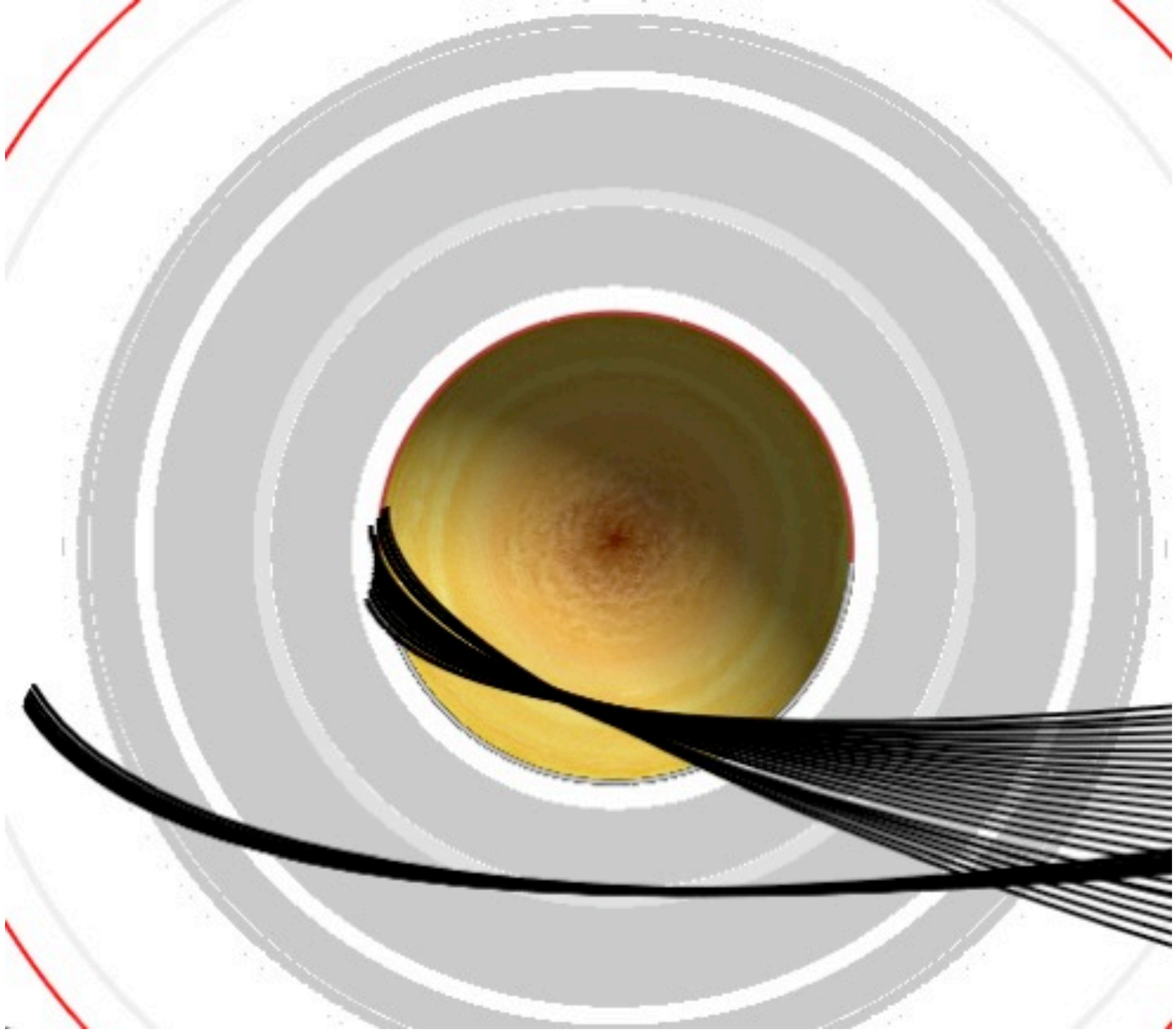
Charnoz et al. (2010)

Satellite Mass



Distance

Crida and Charnoz (2012)



“Proximal” Orbits in 2016 and 2017 should determine mass of rings.


Thank you!