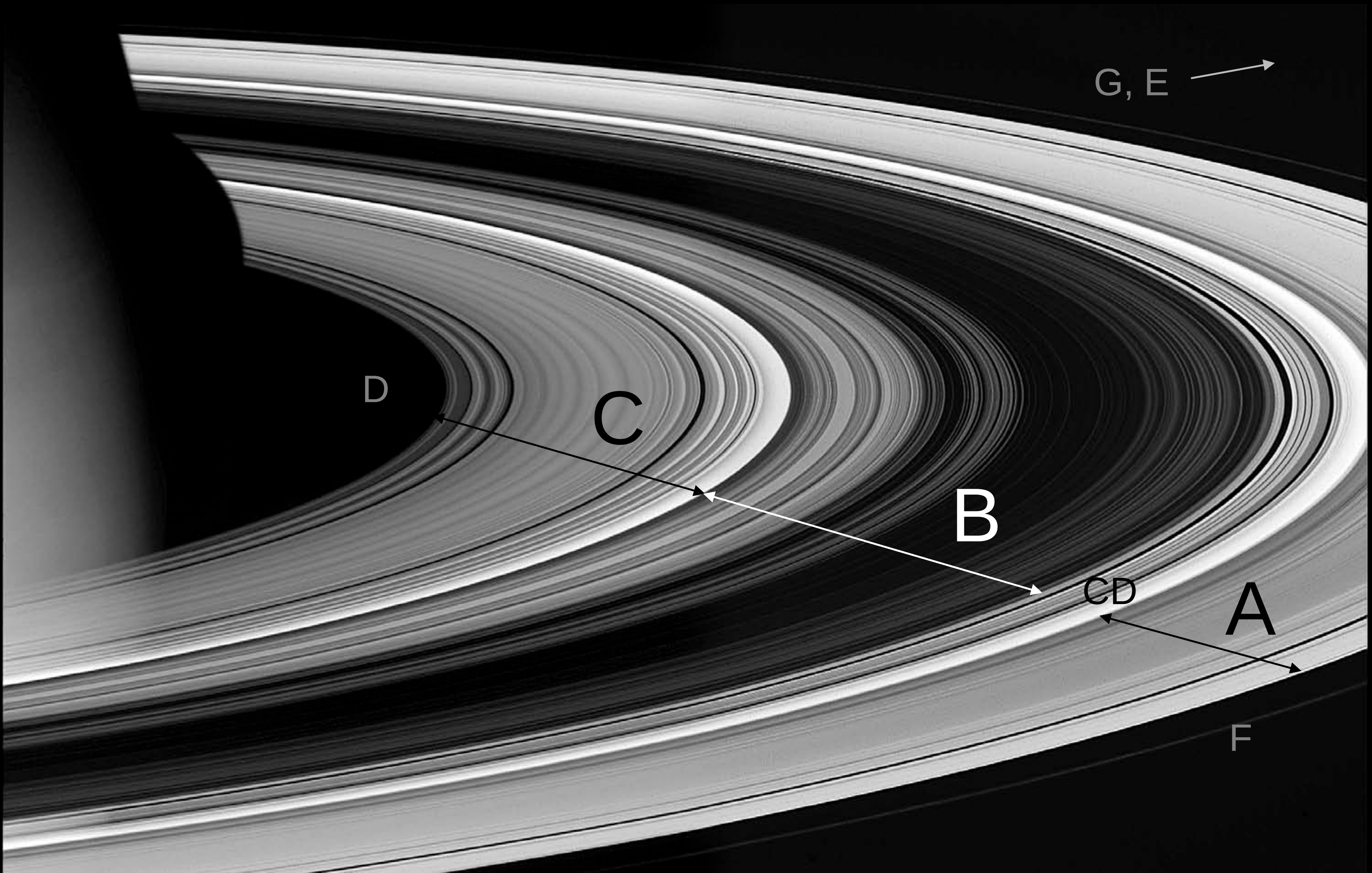
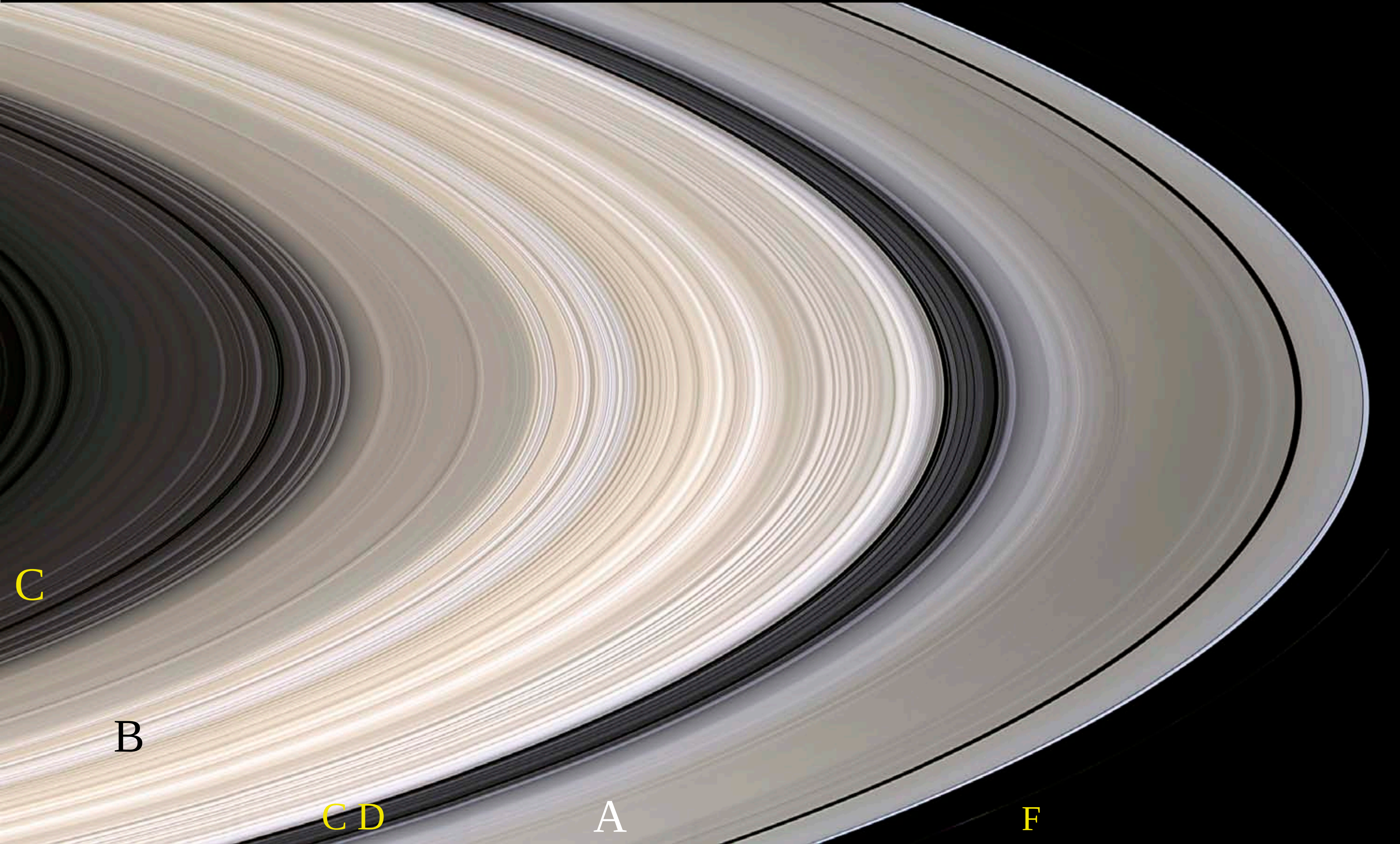
Cassini 6-year CHARM review
Rings and Dust

Jeff Cuzzi

The Dark Side



Away from the Dark Side



General review last year's CHARM; here emphasize progress this year

•Equinox campaign revealed many surprises about ring vertical structure

•B ring edge is more complex than a simple m=2 Mimas-dominated ellipse, and may gravitationally cause puzzling (moonlet-free) Cassini Division gaps (but one wide gap has a new ring - suggests small moonlet there at least)

•New results on microstructure (wakes and waves) and time variations

•Giant "propellers" are moving radially: like protoplanetary disk "migration"?

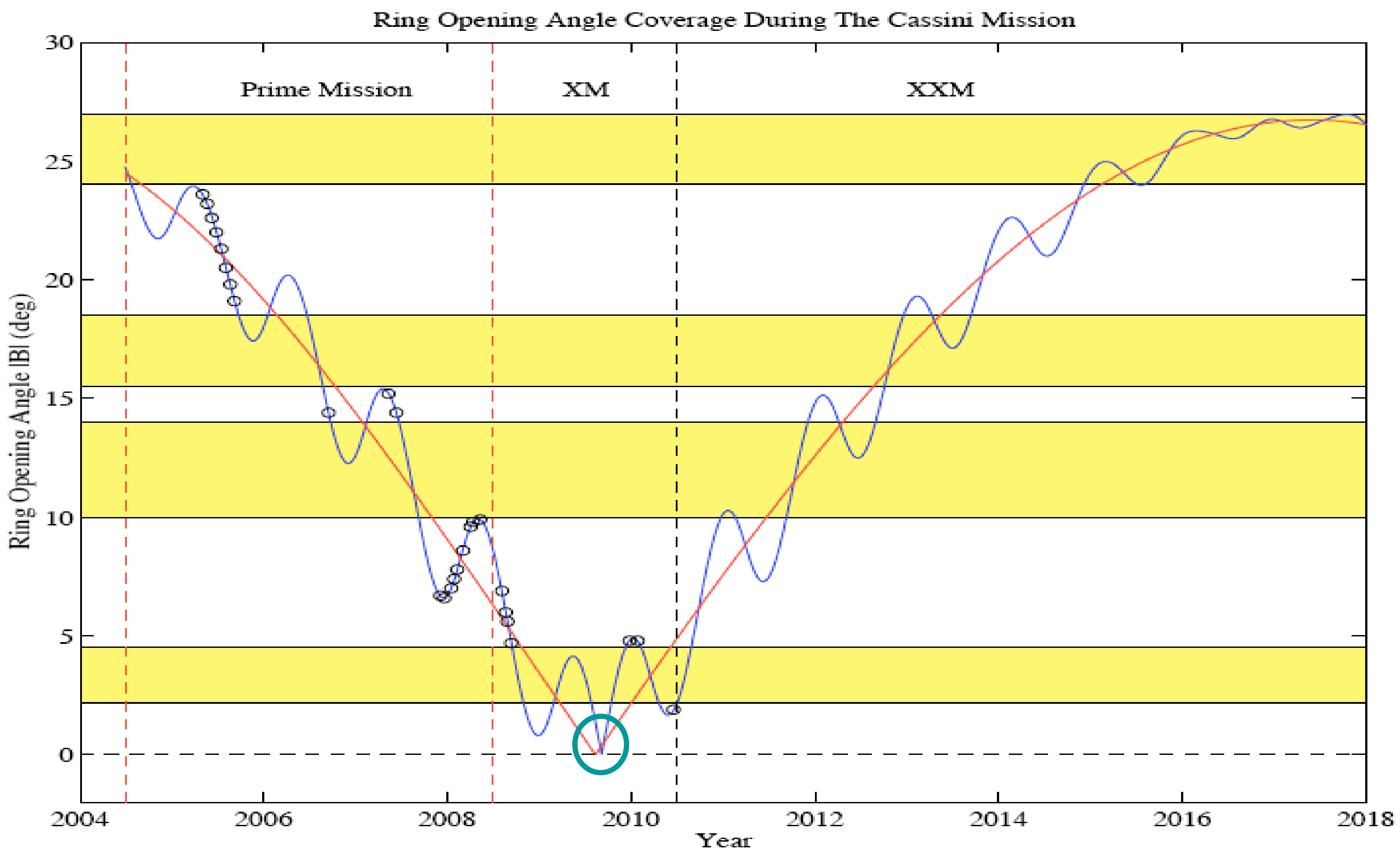
•F ring more increasingly perturbed by Prometheus; new jet, clump, and fan structures suggest embedded bodies

•Ring composition, meteoroid impacts, and spokes

•No "rings" around Rhea (and not much dust or anything else either)

•Several chapters in "Saturn from Cassini-Huygens" (Springer); review article in Science (March 19); 200 papers and meeting talks

Equinox observations



Opening angle affects insolation, ring temperature, RSS transmission, spoke occurrence frequency, diffuse ring structure

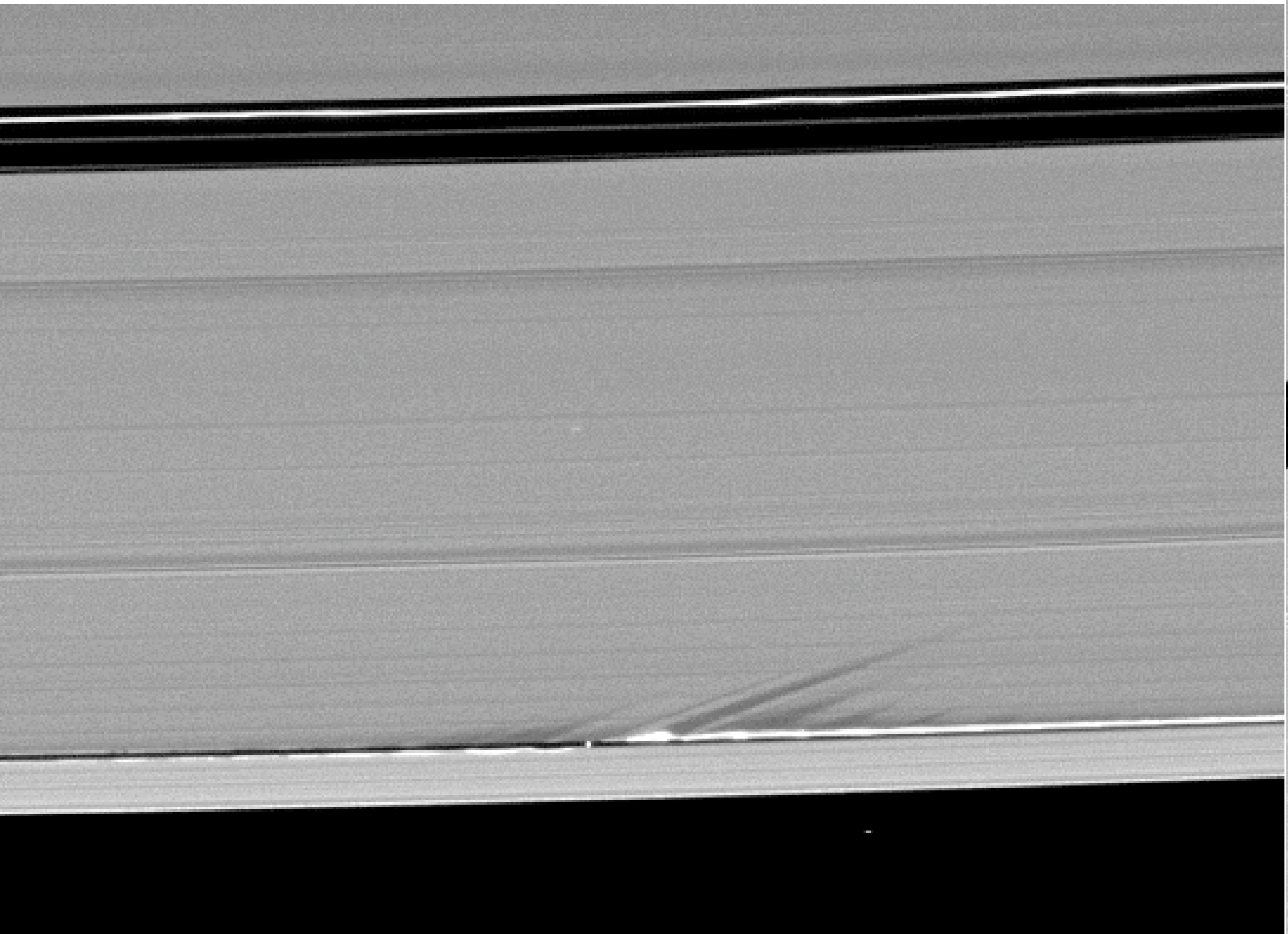
Followed by a Moon Shadow

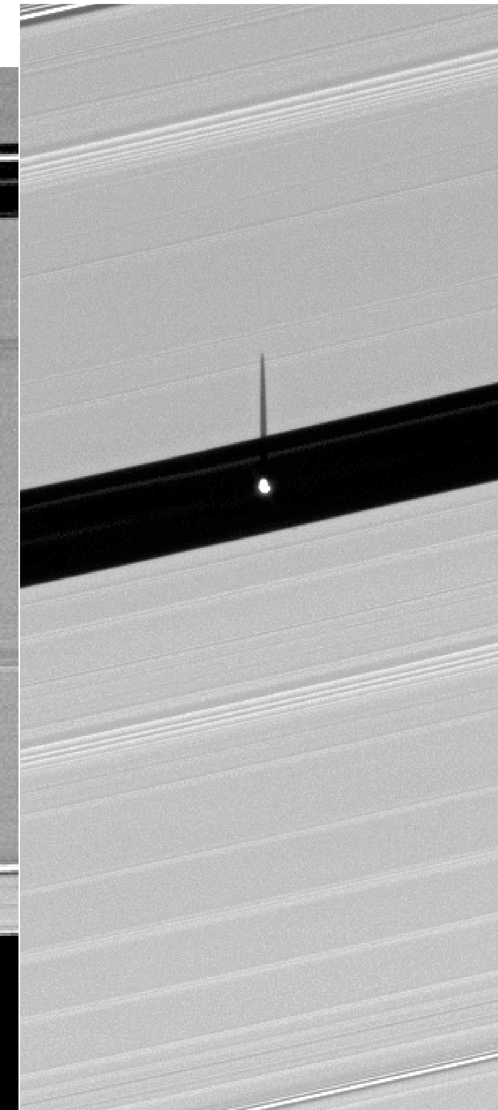
Moon shadows were frequently cast on the main rings around Saturn's August 2009 equinox. These observations may help measure vertical warping in the A and B rings, but their properties are complex as shown below.

A sequence of shadows of the moon Mimas is recorded as the moon's shadow moves across the face of the rings opposite to Cassini. The shadow is faint or obscured where it lies on optically thicker material, which is illuminated by brightly lit Saturn more intensely than by the sun near equinox.

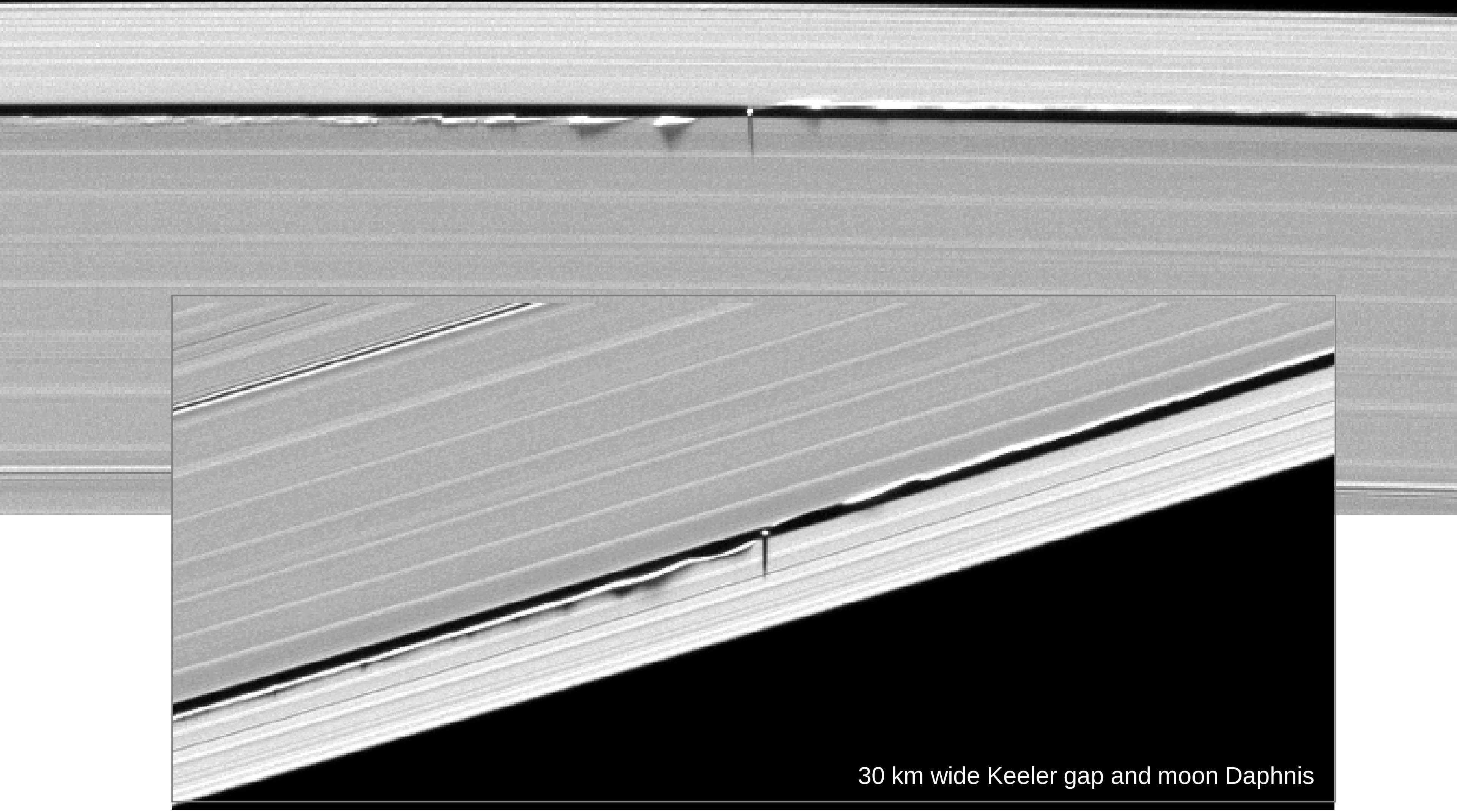
ISS observations at equinox at very low sun angle detect vertical relief

These ongoing observations of the shadow of Pan in the Encke gap (right) and the shadow of the flipped-up edges of the Keeler gap (below), both taken closer to equinox and recently released, clearly show that the Encke gap does NOT have flipped-up edges.



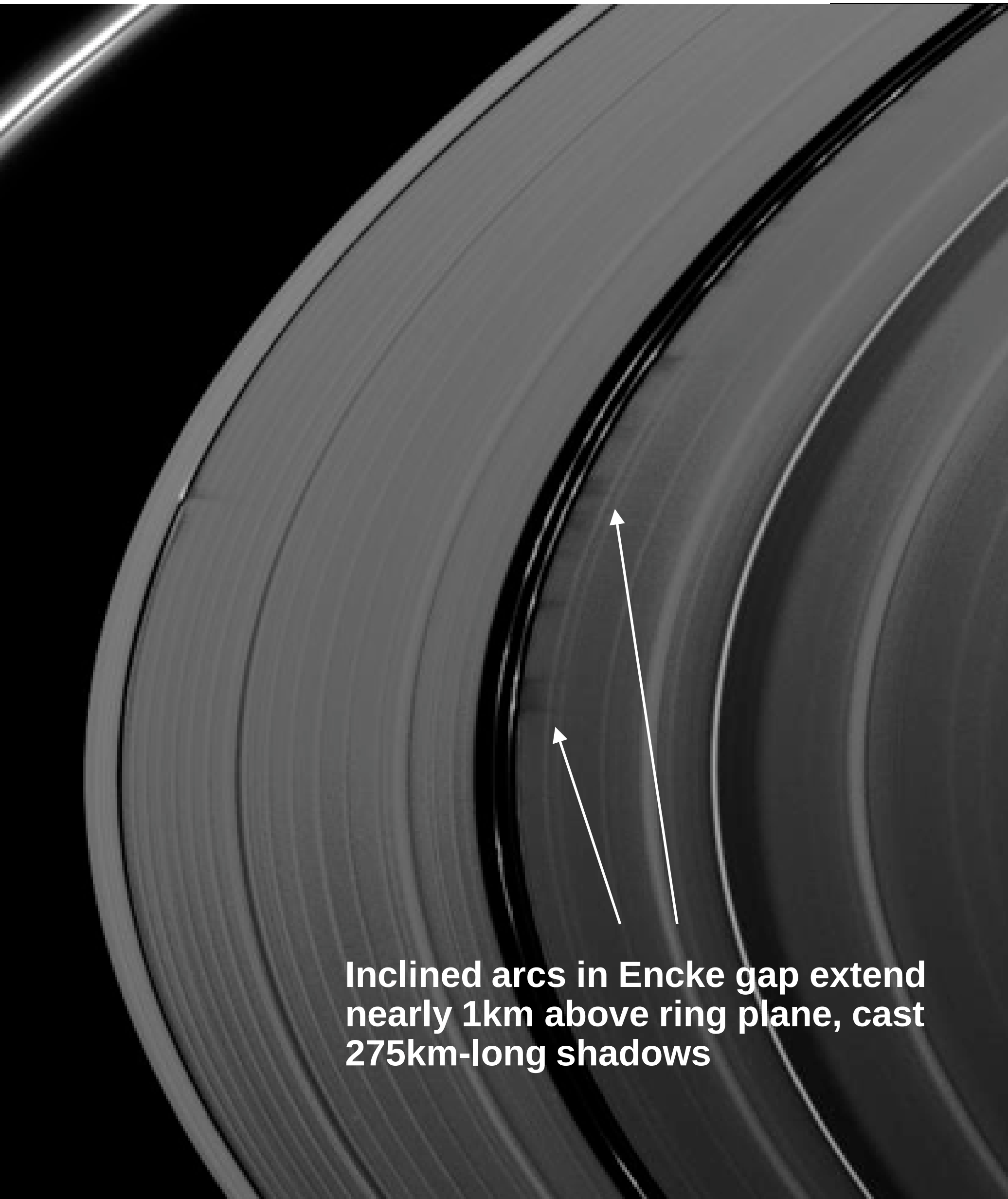


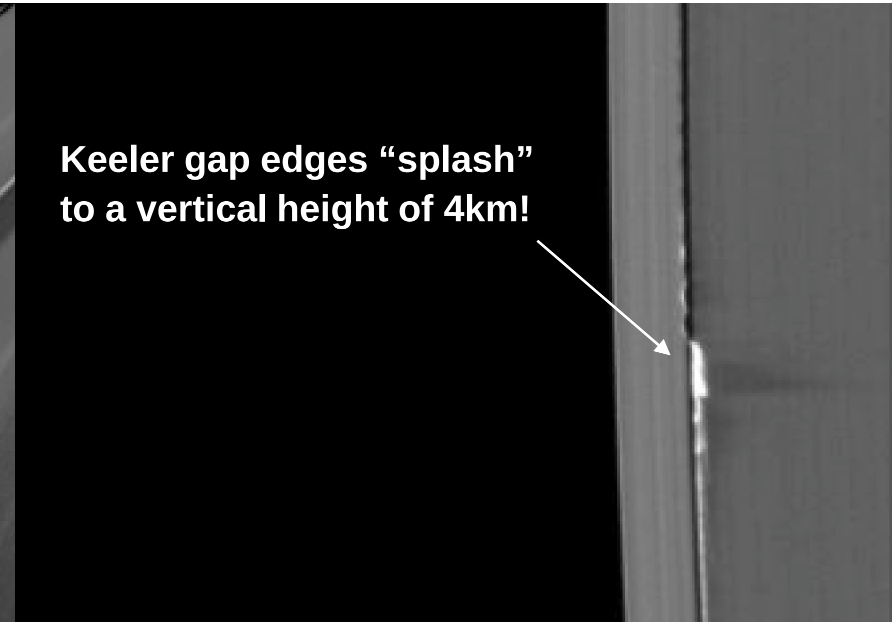
Observations as equinox approaches, at very low sun angle

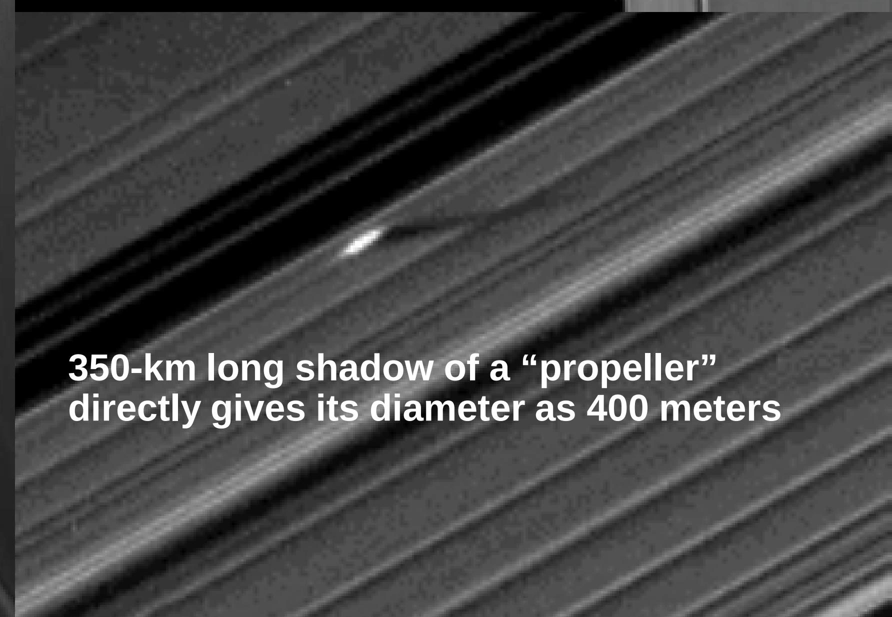


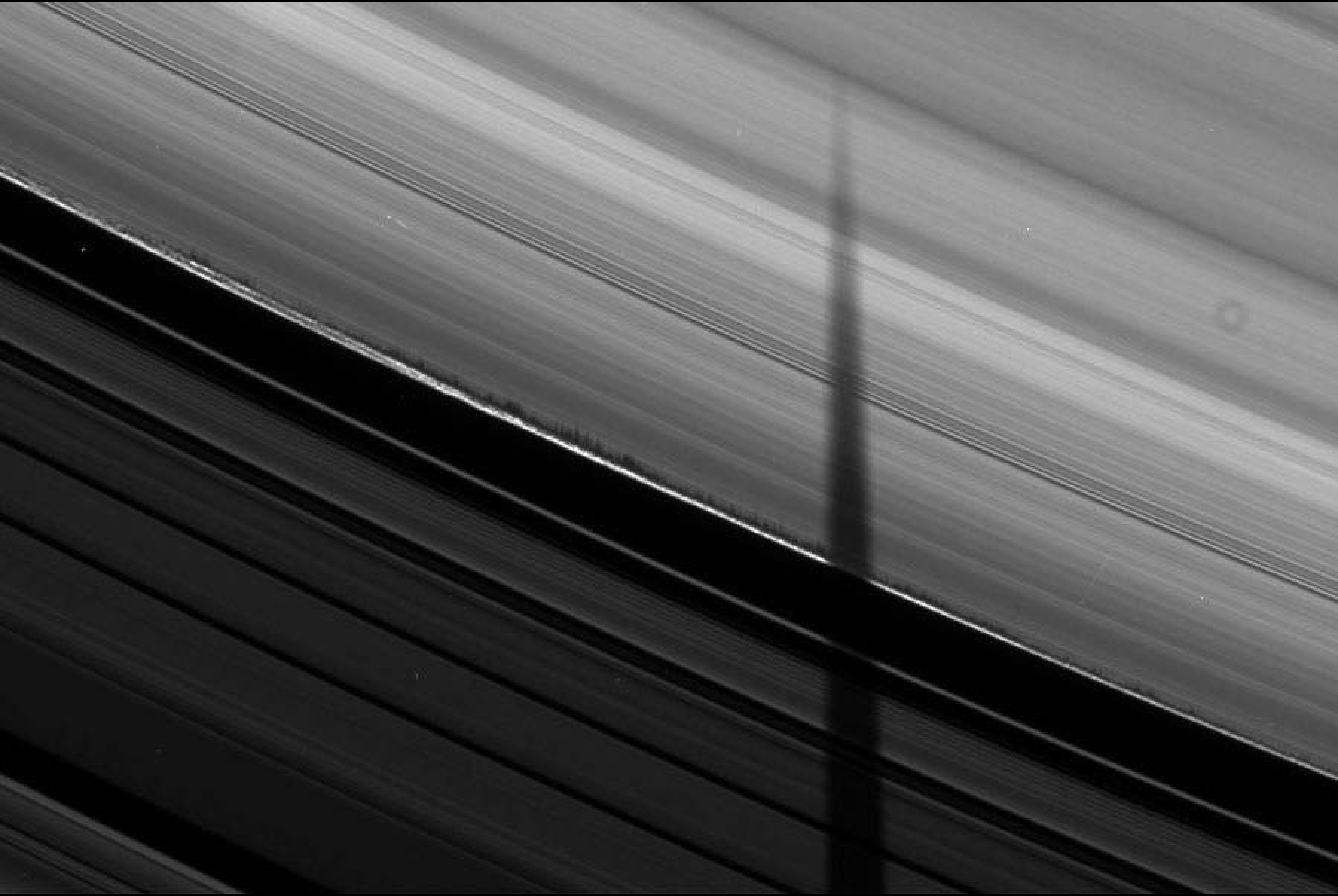
30 km wide Keeler gap and moon Daphnis

Vertical relief in the Encke gap *ringlet* but not *edges*, and elsewhere

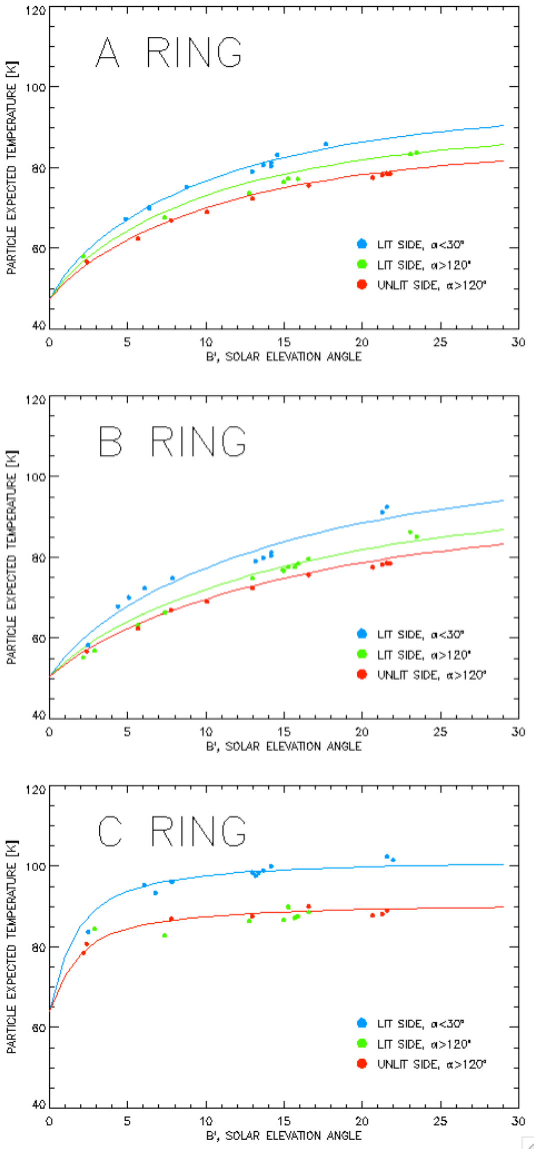








CIRS: Ring Temperature Change with Solar Elevation



Temperatures of A, B and C rings decrease with decreasing solar elevation

Model fits include phase angle dependence and shadow hiding

Blue curve: Lit rings, low phase angle

Green curve: Lit rings, high phase angle

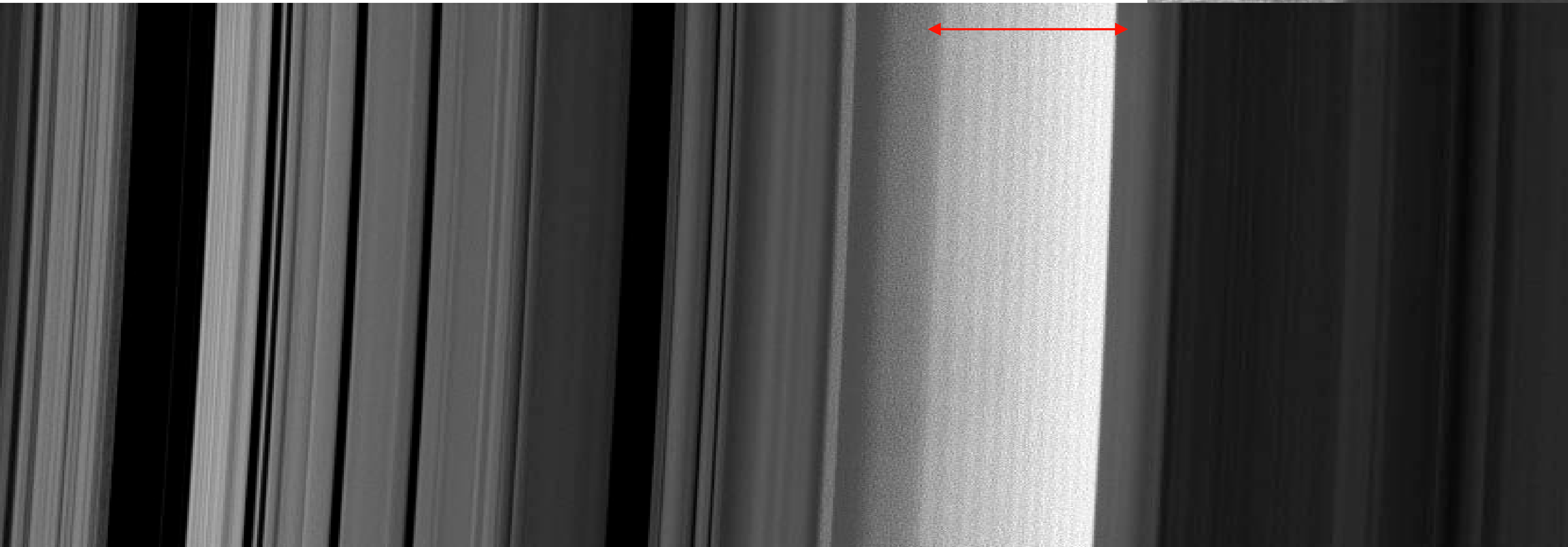
Red curve: Unlit rings, high phase angle

From Flandes et al., 2009

Nature Vol. 292 20 August 1981

Density waves in Saturn's rings

Jeffrey N. Cuzzi*, Jack J. Lissauer† & Frank H. Shu†
*Ames Research Center, NASA, Moffett Field, California 94035, USA
†Department of Astronomy, University of California, Berkeley 94720, California, USA



Nature Vol. 292 20 August 1981

Bending

~~Density~~ waves in Saturn's rings

Jeffrey N. Cuzzi*, Jack J. Lissauer† & Frank H. Shu†

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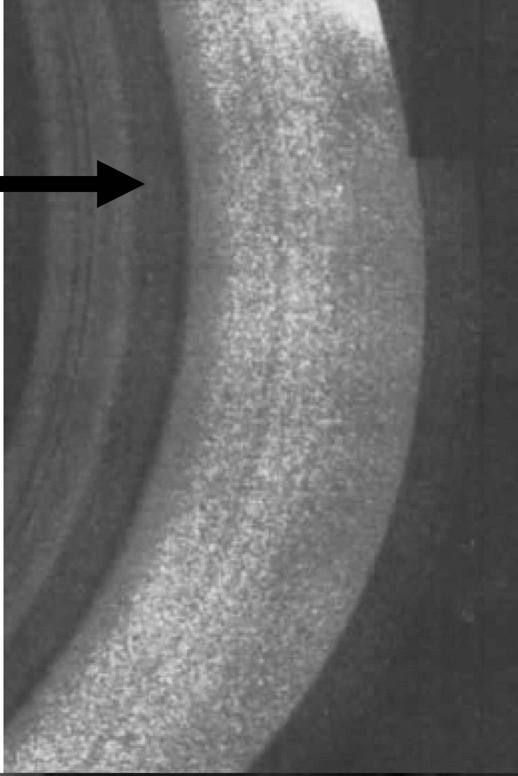
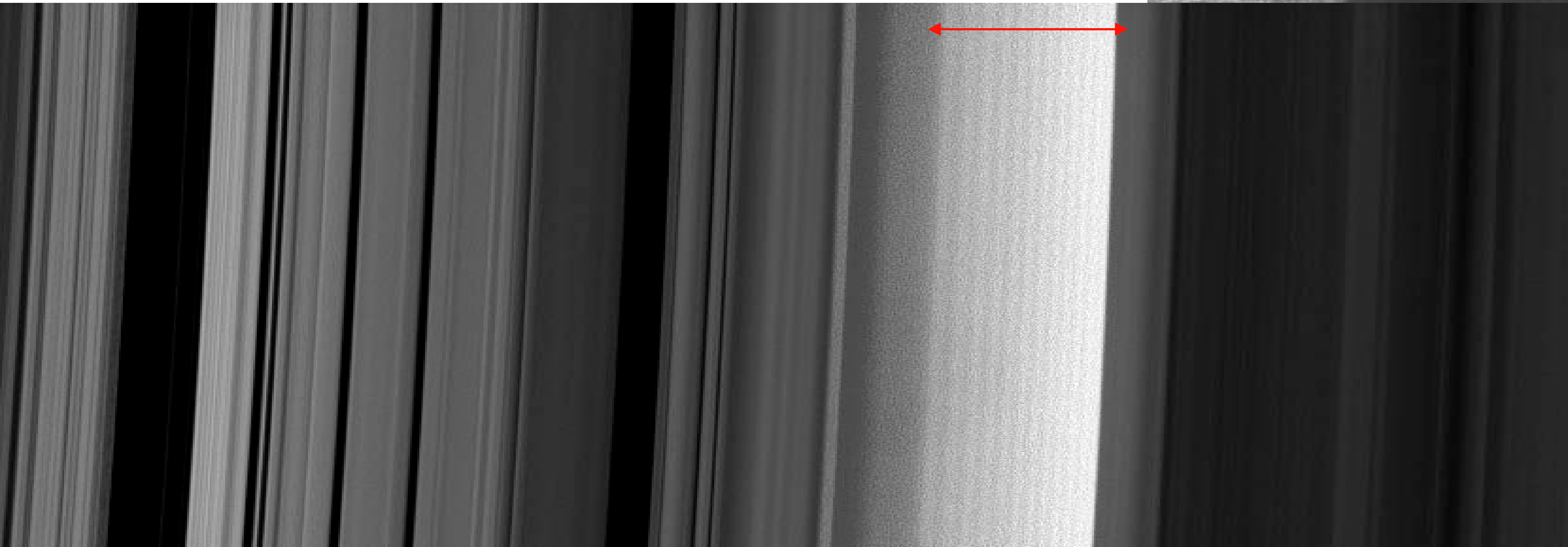
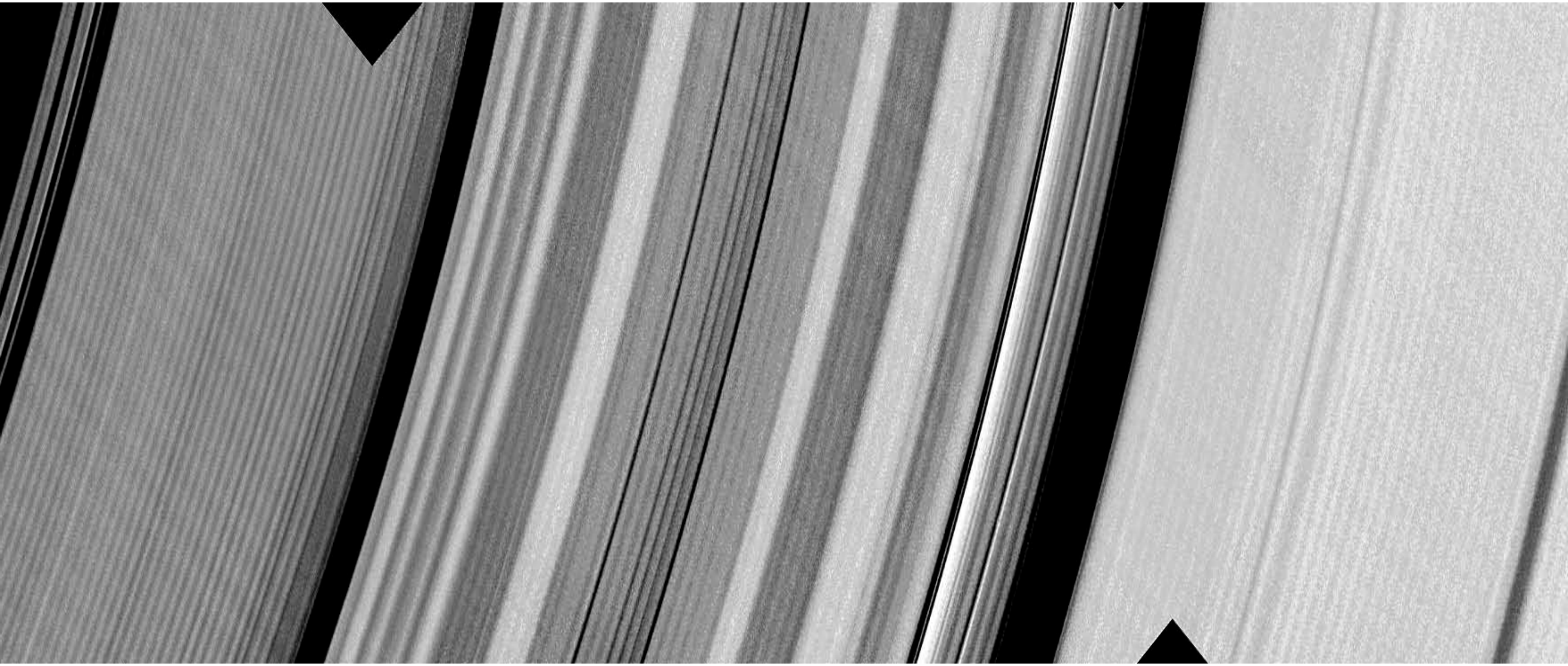


"Nodal" bending waves were first observed in the C ring by Rosen and Lissauer (Science, 1988). At the time Lissauer (personal communication) suggested to me that such a "bending" wave might be the cause of the feature we identified as a density wave (same satellite and implications, though). No structure was seen in this band by Cassini arrival until this year when it reappeared, at very low sun elevation angle, proving it to be a vertical ripple structure or bending wave, rather than a compressional density wave structure (which should have been observable since Cassini arrived, and/or by occultations). (Tiscareno et al DPS 2009). Structure crosses A ring inner edge, showing mass density changes little.



Ripples in the rings (1)

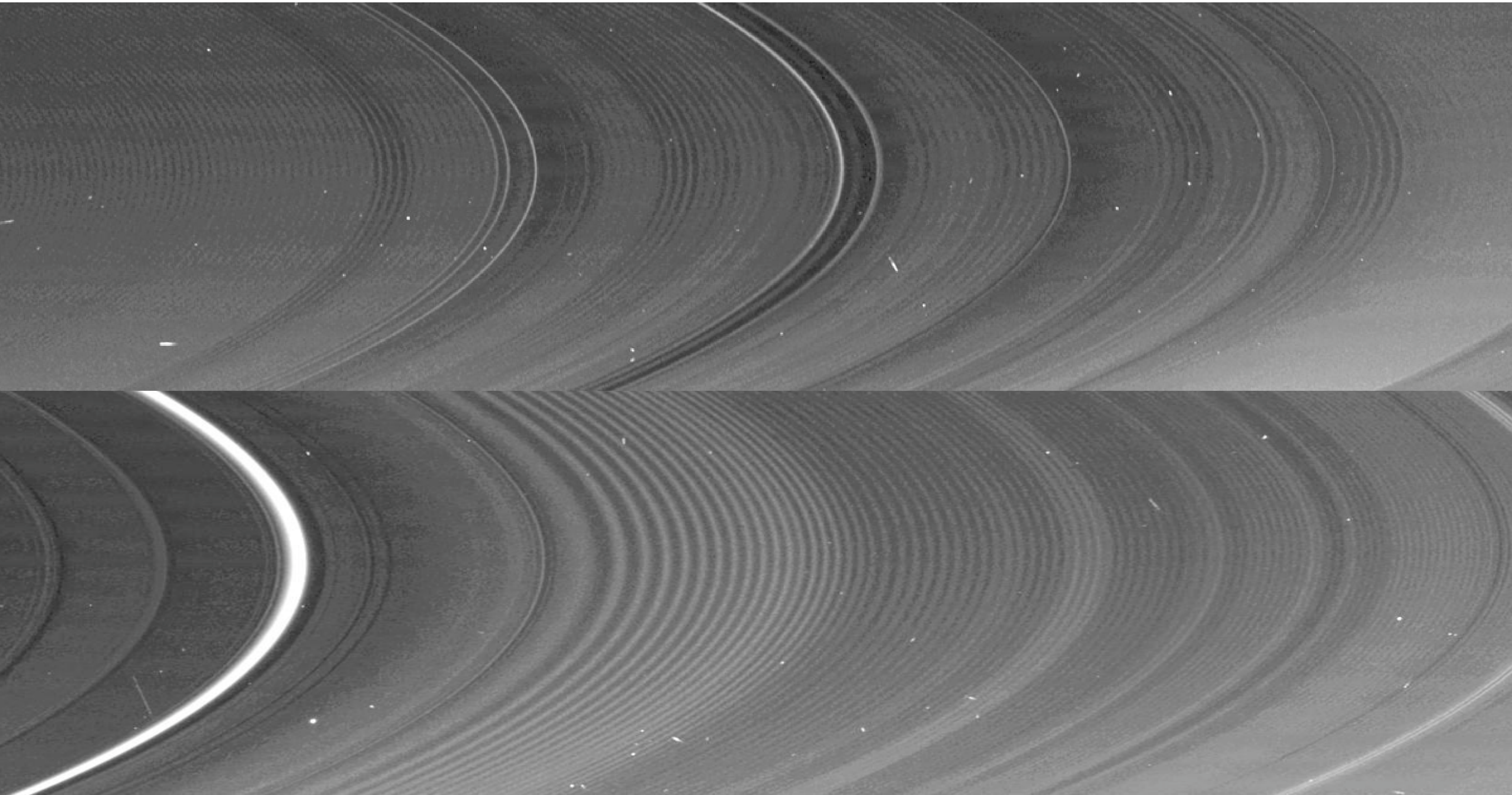
This ISS mosaic clearly shows a ripple pattern extending across the inner C ring - a pattern previously only hinted at in the very faint D ring off to the right. Subsequent images show the ripple propagating across the entire C ring. The ripple is thought to arise from a 25-year ago event of some kind that instantaneously tilted the entire D (and now also C) rings away from Saturn's equator plane; the ripple is the result of this warp winding up into a corrugation as the particle orbits precess differentially.



Ripples in the rings (2)

Two selections form a single mosaic at Equinox show the C ring ripple propagates throughout the entire C ring (top). The inner B ring edge is the dark feature at right. In the bottom panel a different ripple pattern is seen crossing a wide swath of the inner A ring; this is due to a spiral bending wave driven by Iapetus, first observed by Voyager and thought to be a density wave. Cassini observations show it clearly to be a bending wave; the wave is seen clearly in the Cassini division ramp where it was first seen, and its wavelength changes only slightly as it propagates into the A ring - this shows that the mass density contrast between the inner A ring and the ramp is less than had been thought

(Tiscareno et al DPS 2009)



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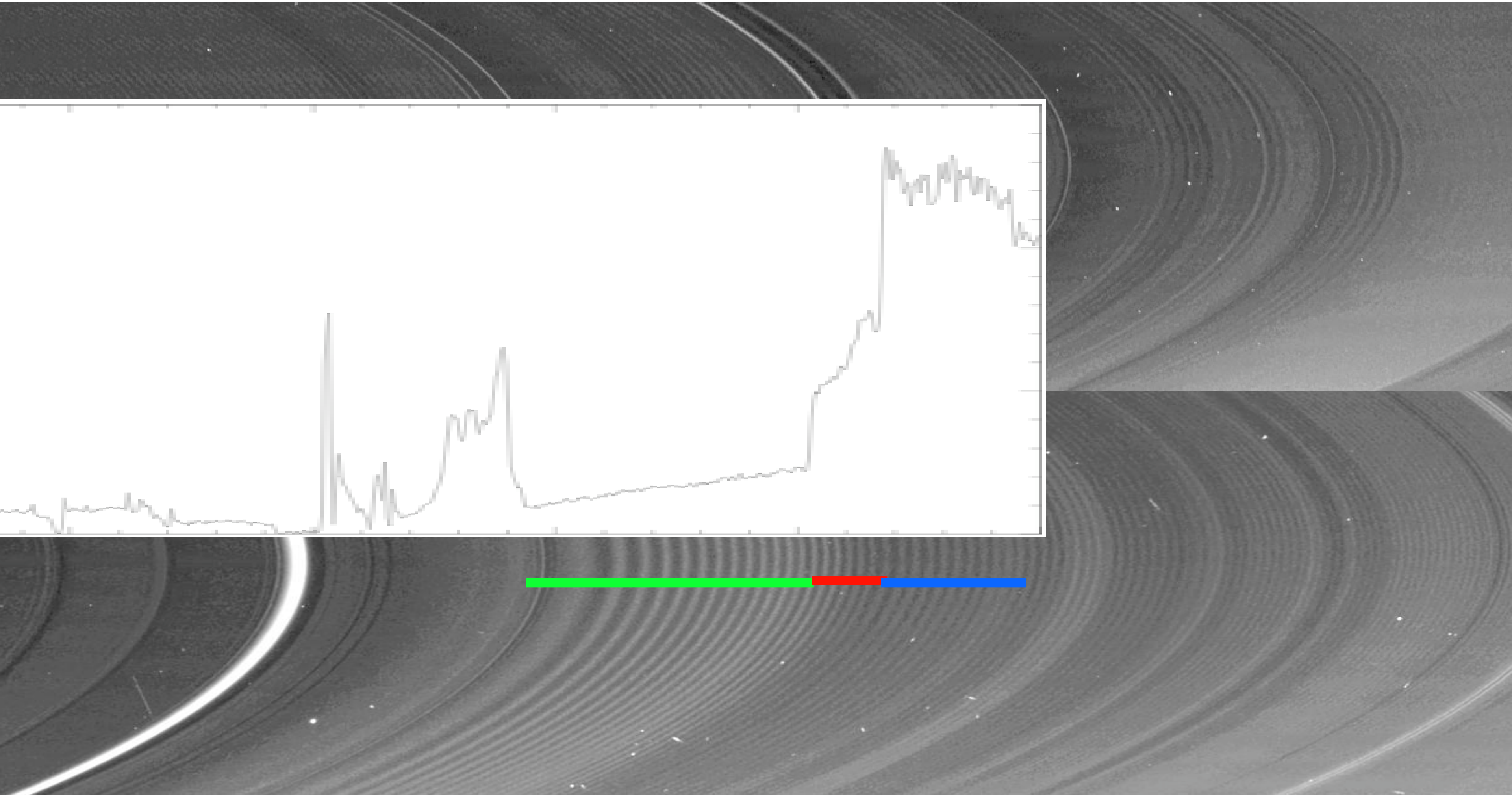
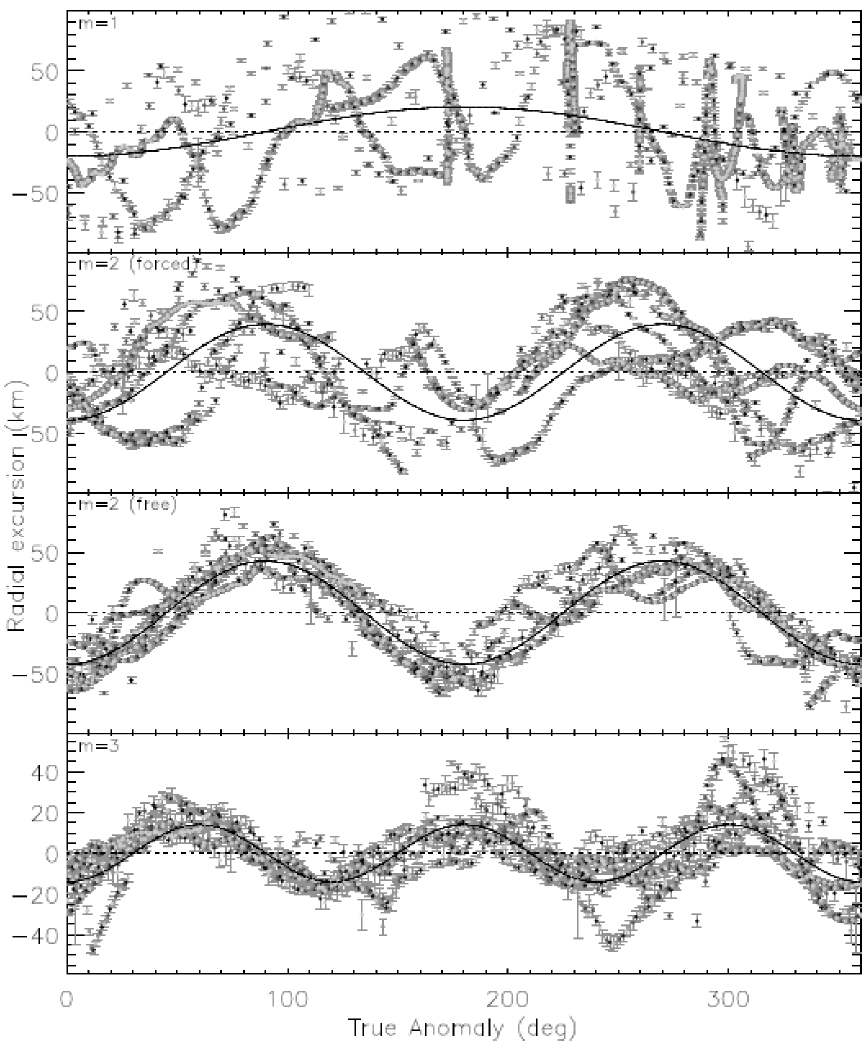
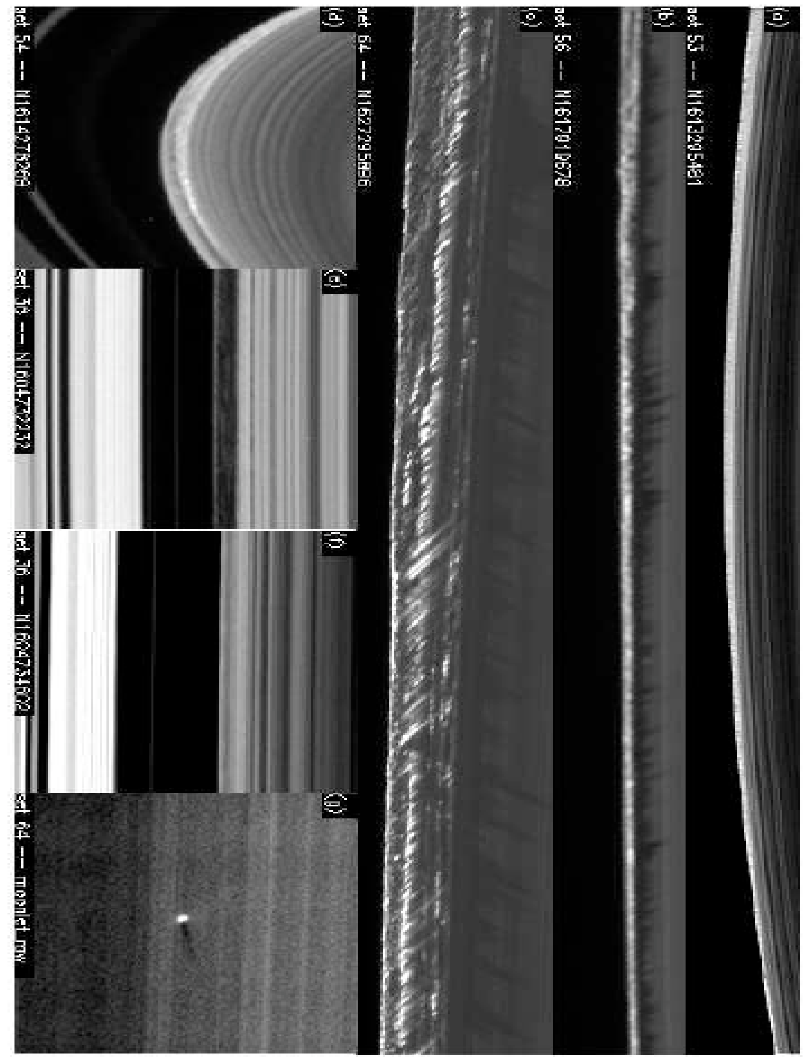


The floppy edge of the B ring (Spitale and Porco 2010)

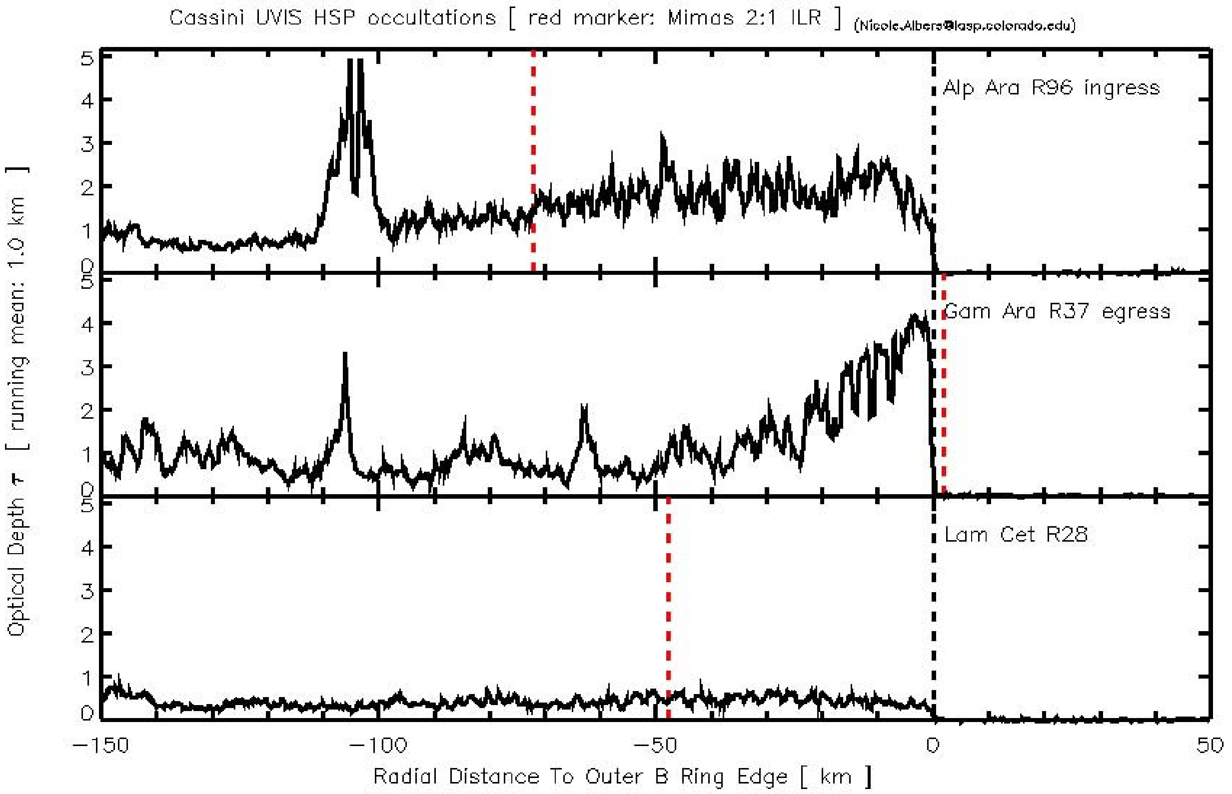
The outer edge of the B ring, known to show an m=2 mode which was believed fixed to Mimas, in addition supports a “free”, probably viscously driven, m=2 mode as well as m=1 and 3 modes. The shape of the edge is thus always fluid and changing. In addition, unseen bodies in two disturbed regions introduce spikes and glitches in the radial and vertical directions, some seen at equinox.





UVIS: transient structure at the B ring edge

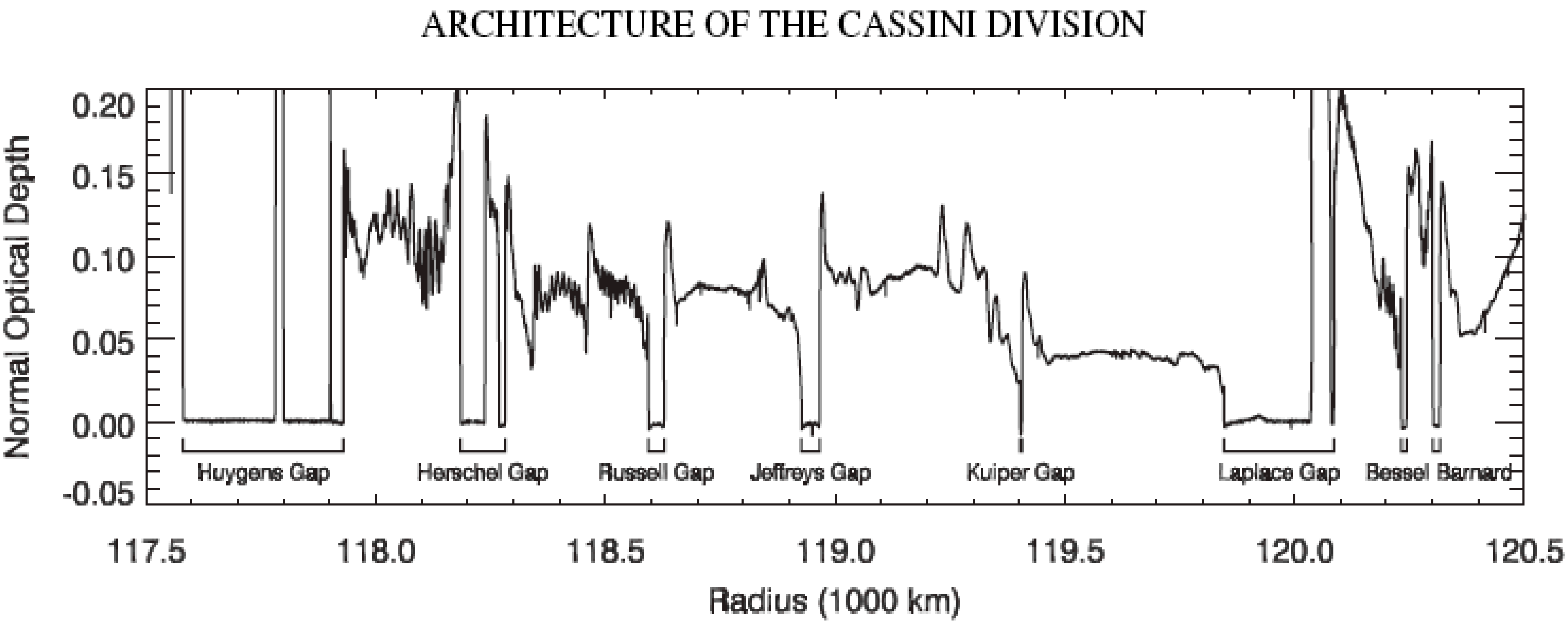
A close look reveals that structure on the outer edge of the B ring is quite transient, even after allowing for the elliptical outer edge “breathing” with the known influence of the Mimas 2:1 resonance. These transient structures suggest that some combination of Mimas’ gravitational forcing, and compressional motions of the ring “fluid”, disrupt the smooth nature of the ring, inconsistent with simple models of the rings.



Albers et al 2010

Why have no moonlets been found in the Cassini Division (CD) gaps?

Below is a high-precision radial scan taken by VIMS; many of these, at many times and longitudes, map out the longitudinal structure of the gaps. Imaging searches for embedded moonlets as the cause of these empty gaps - as in the Encke and Keeler gaps - has been unsuccessful ever since Voyager.

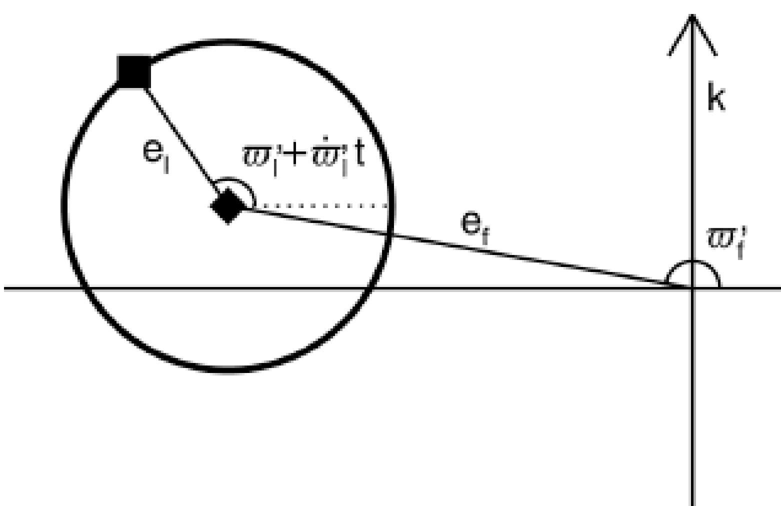


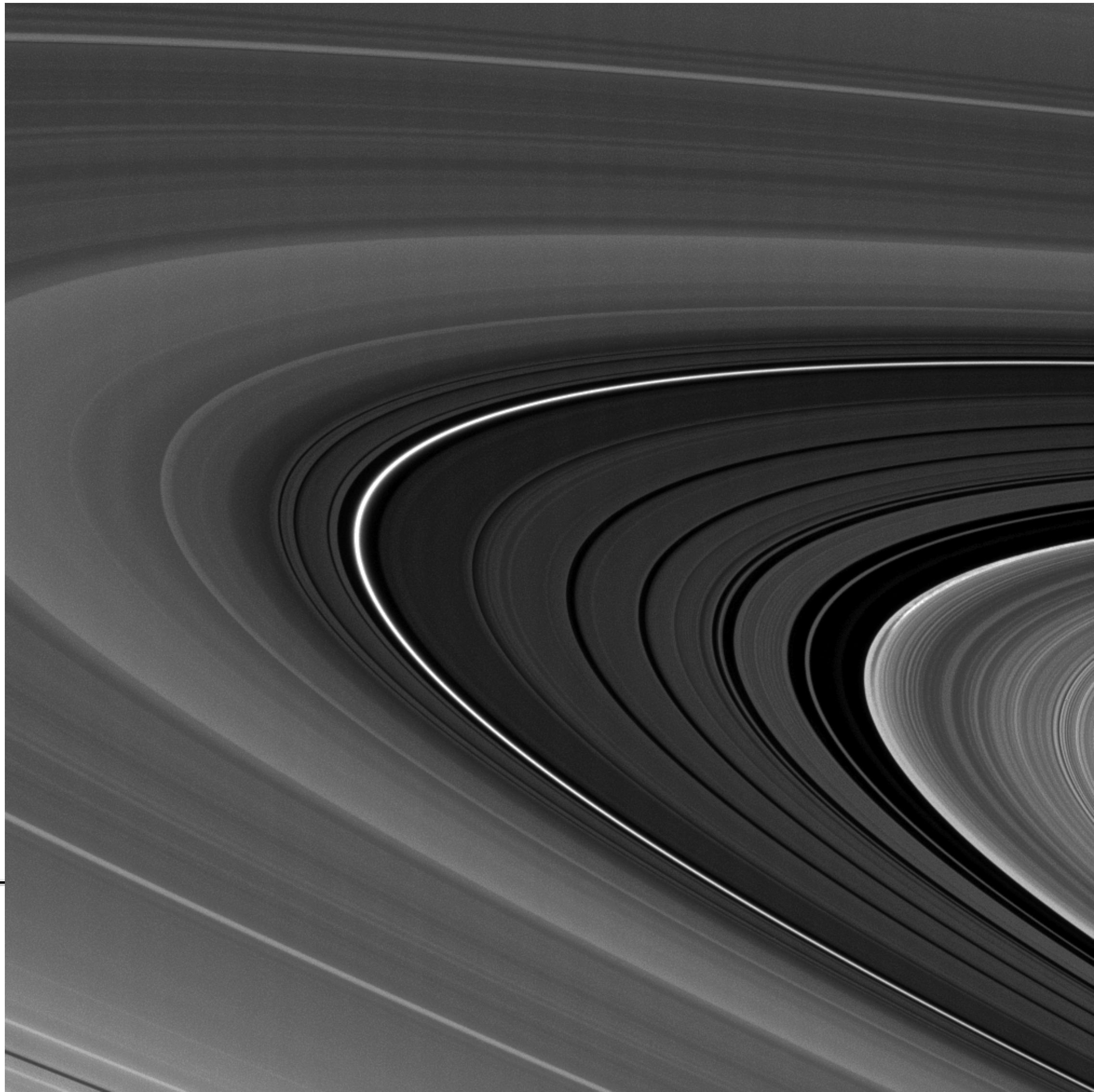
Hedman et al (2010) have arrived at a novel explanation by which four empty CD gaps might be cleared without the need for embedded moonlets. The theory suggests that the distorted edge of the B ring itself (see previous slides) moves at just such a rate to produce the observed gaps - with their observed spacings and the slightly elliptical inner edges they all display.

“Charming” Heliotropic ringlet in the Laplace gap of the Cassini Division

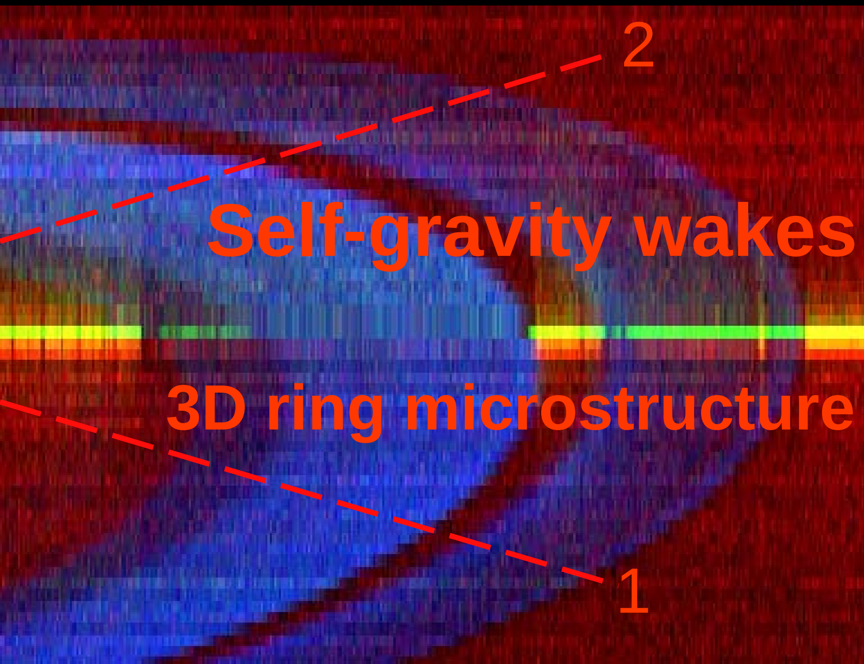
A year or so after SOI, a brand-new ringlet appeared in the “outer rift” of the Cassini Division (the Laplace gap); this so-called “charming” ringlet is known to be dominated by small particles because of its great brightness at high phase angles (below right; center). This ringlet was never seen by Voyager. Its occurrence in the center of the gap suggests there is indeed a small moonlet in residence there.

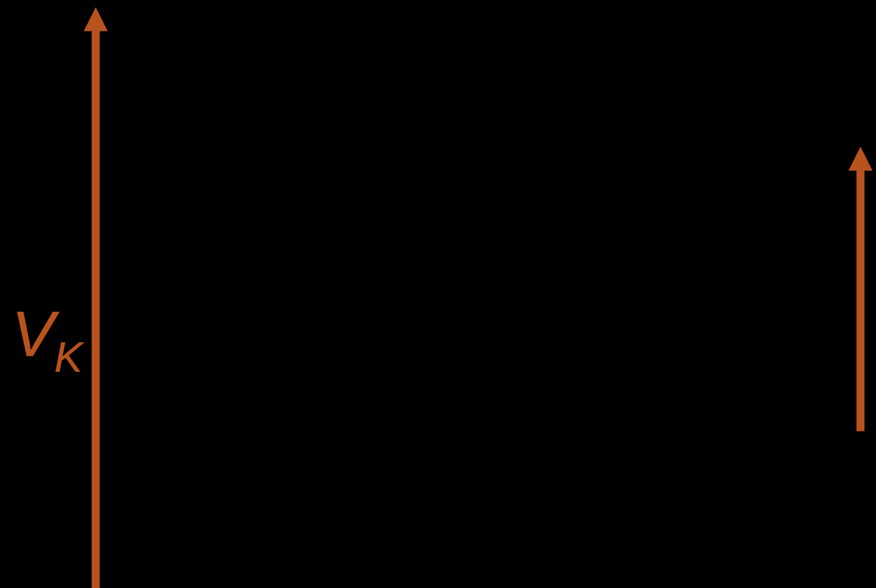
Recently Hedman et al (2010) have shown from studies of the orbit of the ringlet, that the long axis of its orbit is mostly pointed towards the sun, but moves around slightly. They show that the tiny pressure of sunlight can explain the dominant eccentricity (e_f below) and inclination, which vary seasonally with the sun’s elevation angle. However the deviation from this steady forcing (e_1 below) is a “free” eccentricity which might reflect the initial conditions of the impact that created the ringlet in the first place.



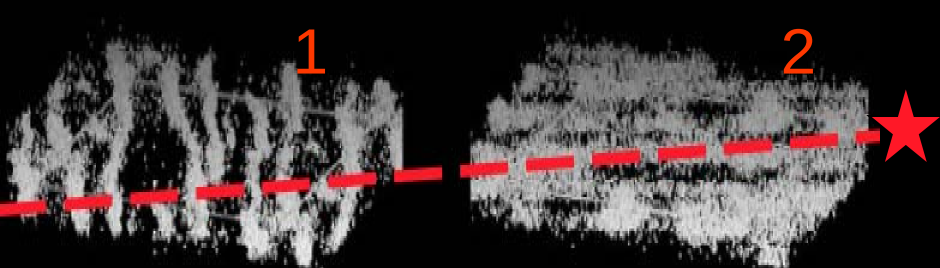


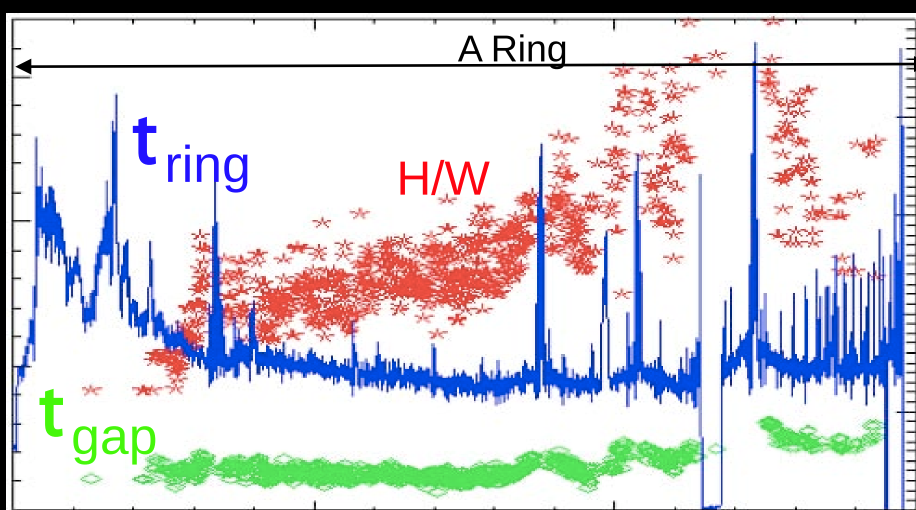
Dynamic processes responsible for ring structure:
Self-Gravity wakes





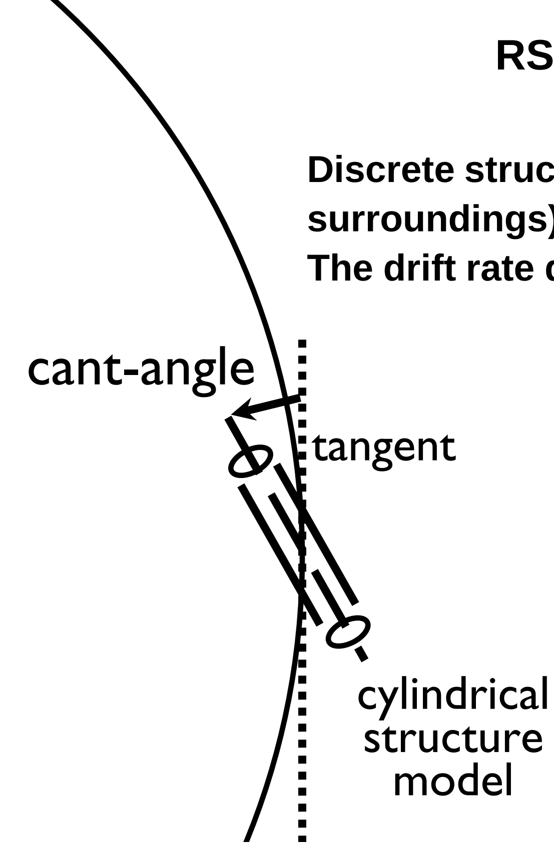
Stellar occultations by the rings give a 3D CAT-scan of ring microstructure on few-meter scales





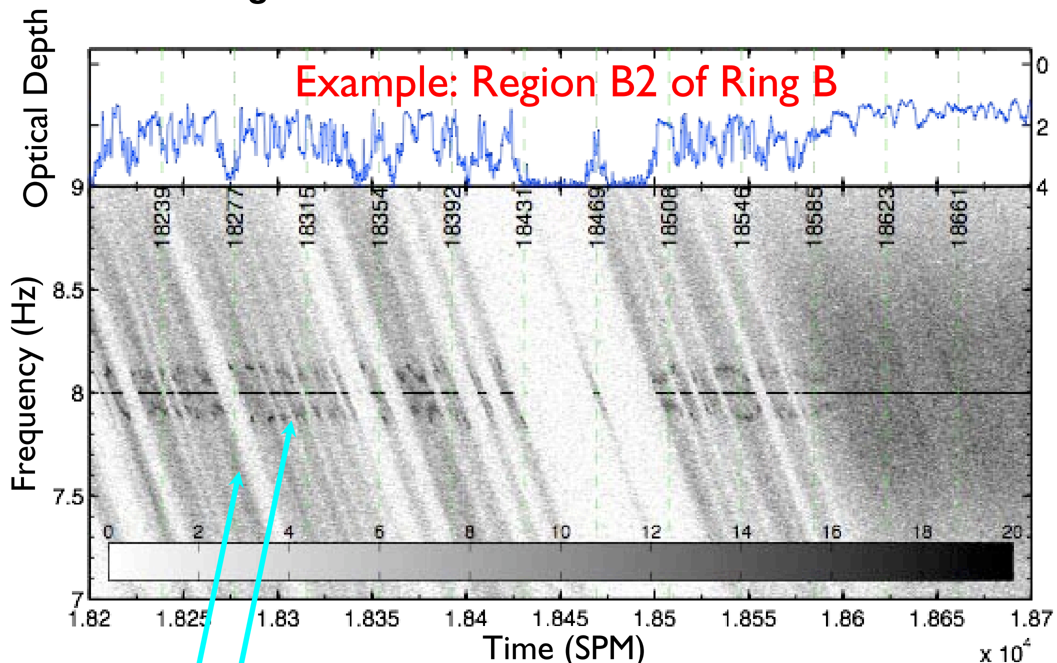
RSS: distinguishing self-gravity wakes from other microstructure

Discrete structural features (those having different scattering strength than their surroundings) are seen to drift in frequency as they move through the antenna beam. The drift rate depends on the local cant angle of microstructure within the features.



Self-gravity wakes are canted

Salo et al., 2004



- Quasi-Periodic 100-200 m-λ (Overstability) Microstructure
- “Traditional” Gravity Wakes Microstructure

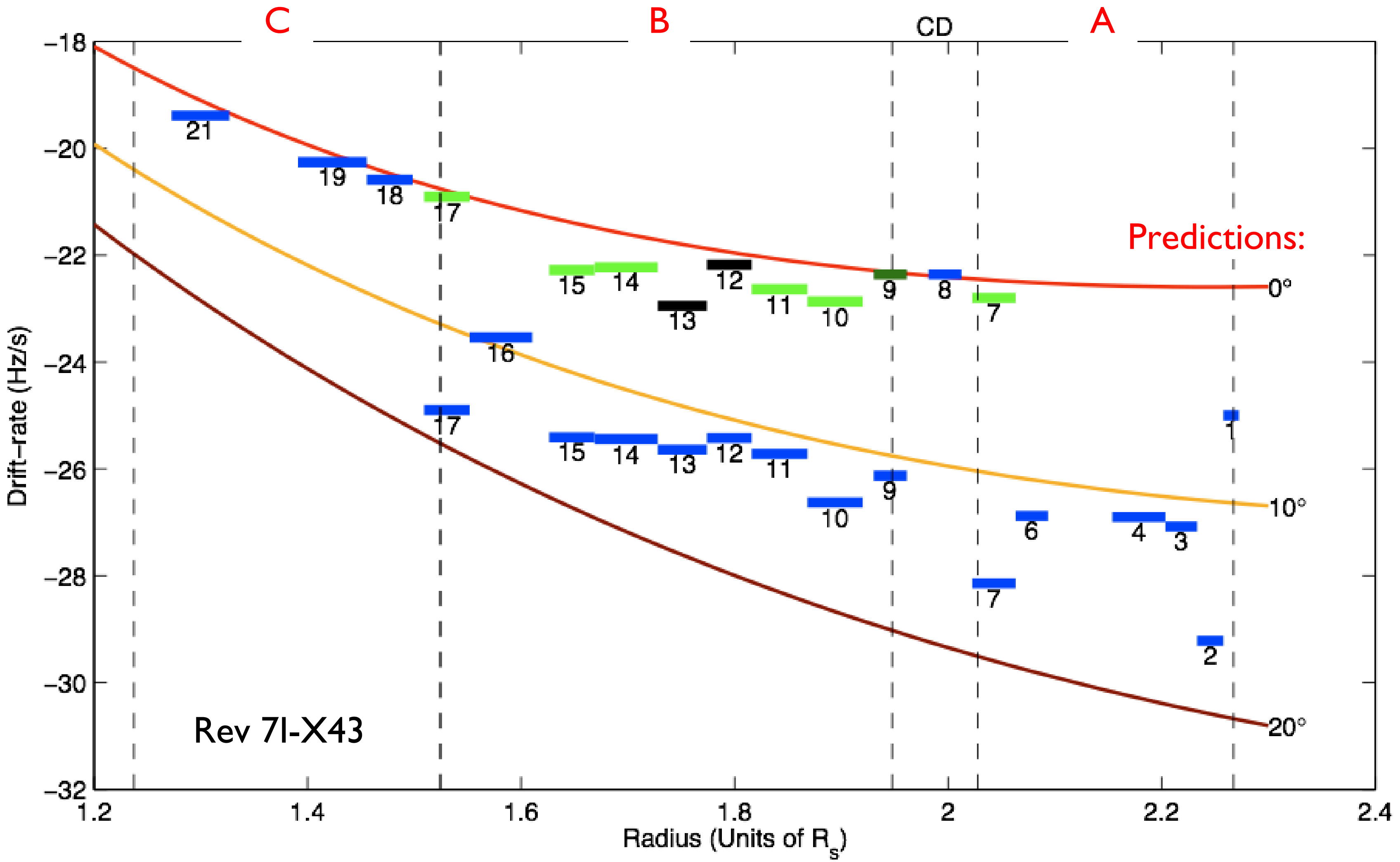
■ Doppler drift-rate of the the two types of ring microstructure can be estimated independently over nonoverlapping frequency bands

■ Different drift-rates, hence different cant-angles, are implied by the data

Marouf, Wong, et al, in prep

RSS: distinguishing self-gravity wakes from other microstructure

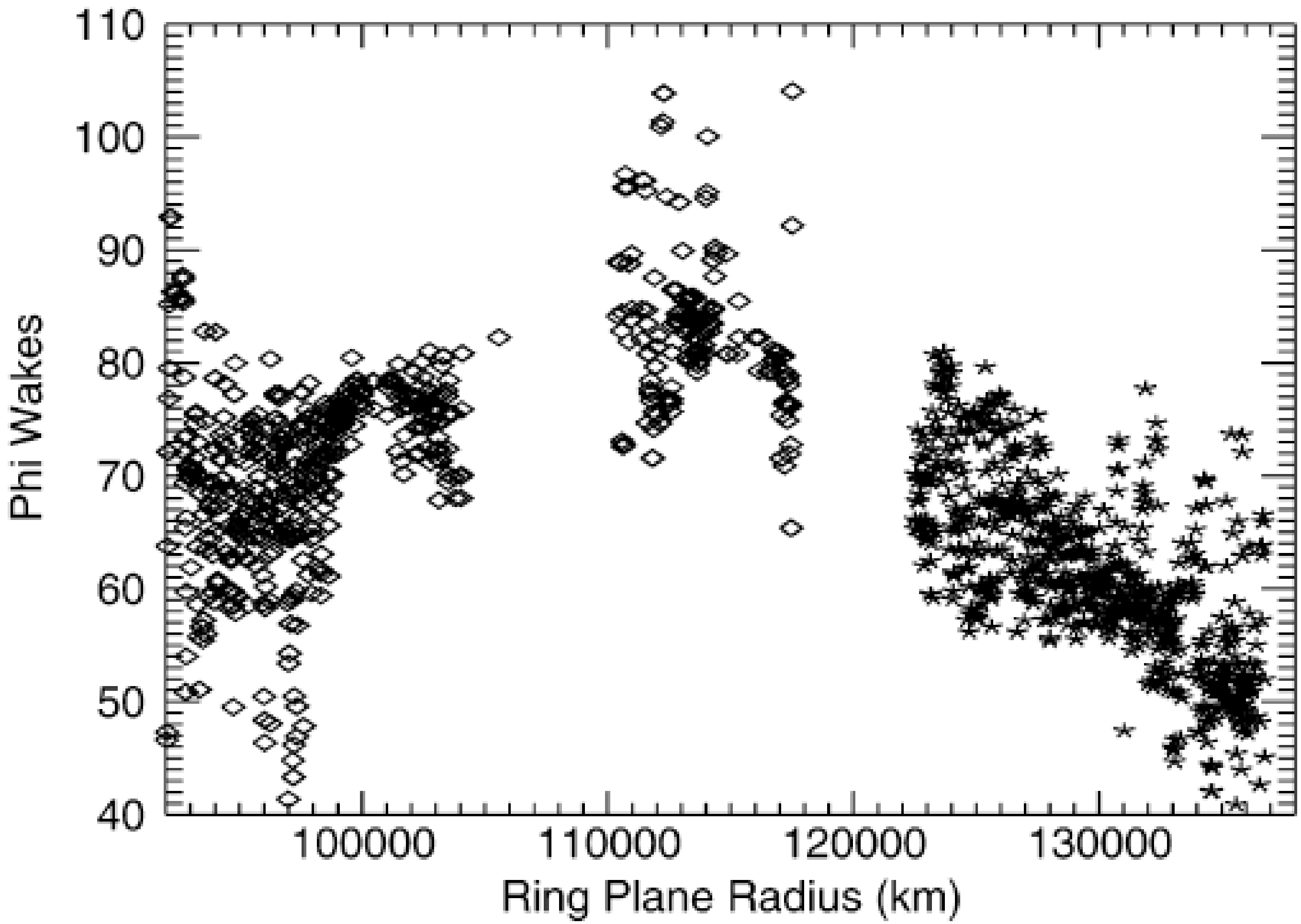
Two different populations are clearly seen: axisymmetric 100m structure at 0º and (presumably) self-gravity wakes canted at 15º. The reason these canted structures are not seen at 20-30º in the A ring (as in stellar occultations and theoretical predictions) is a puzzle which is under study.



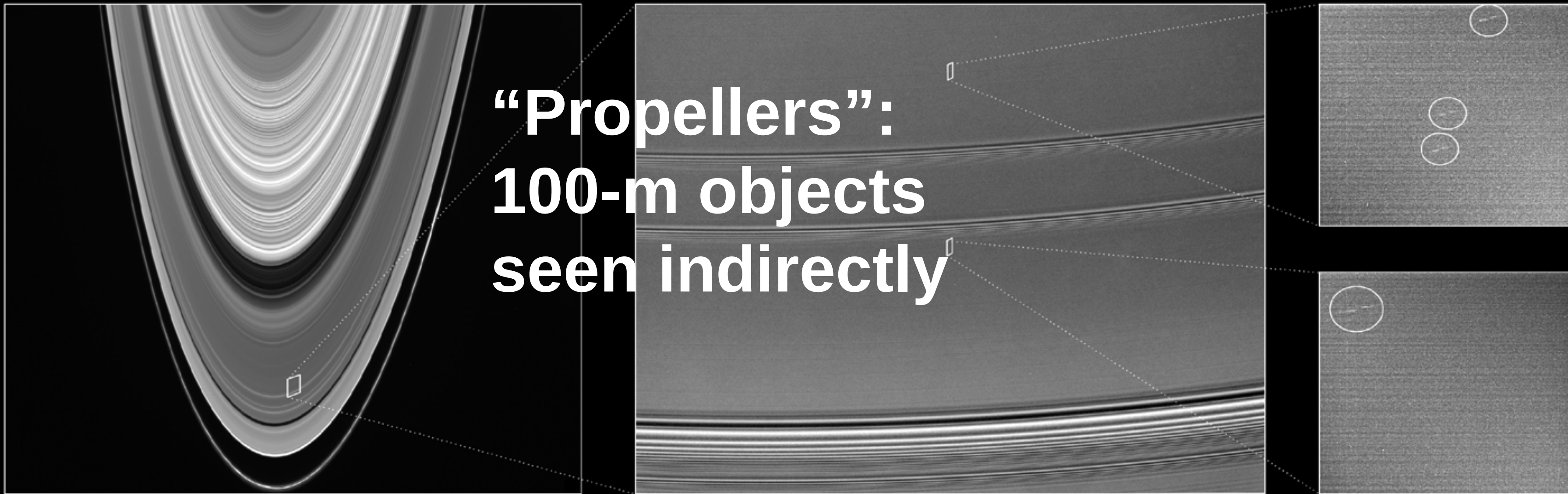
EAM & KW: Cassini RSS

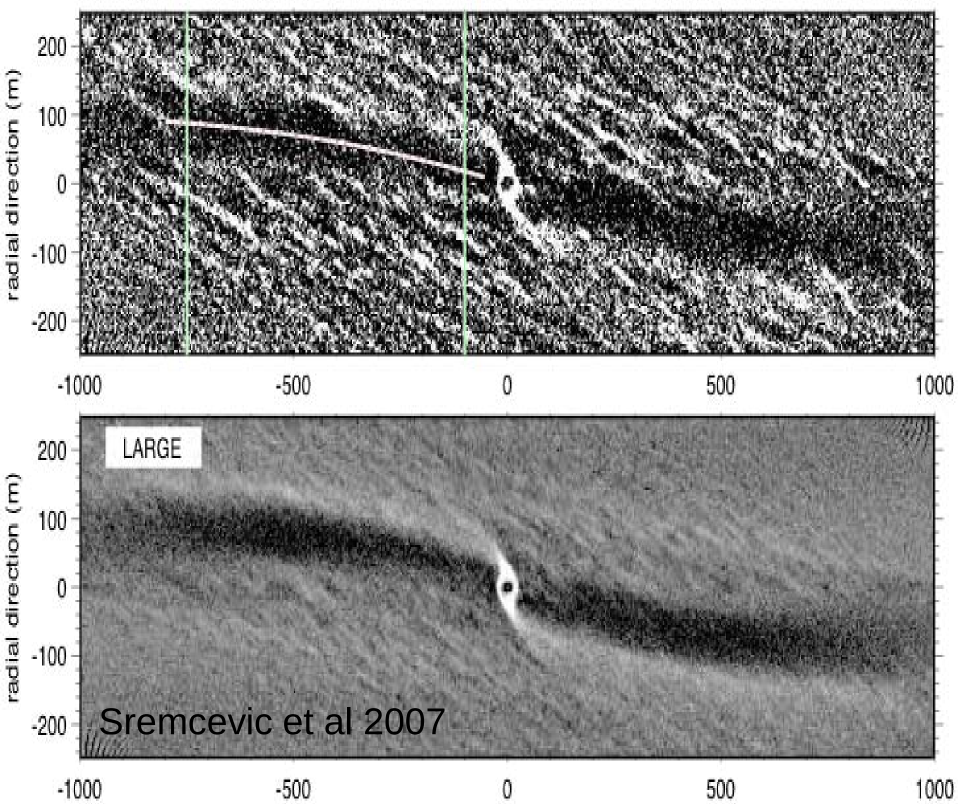
UVIS: slightly different results on self-gravity wakes

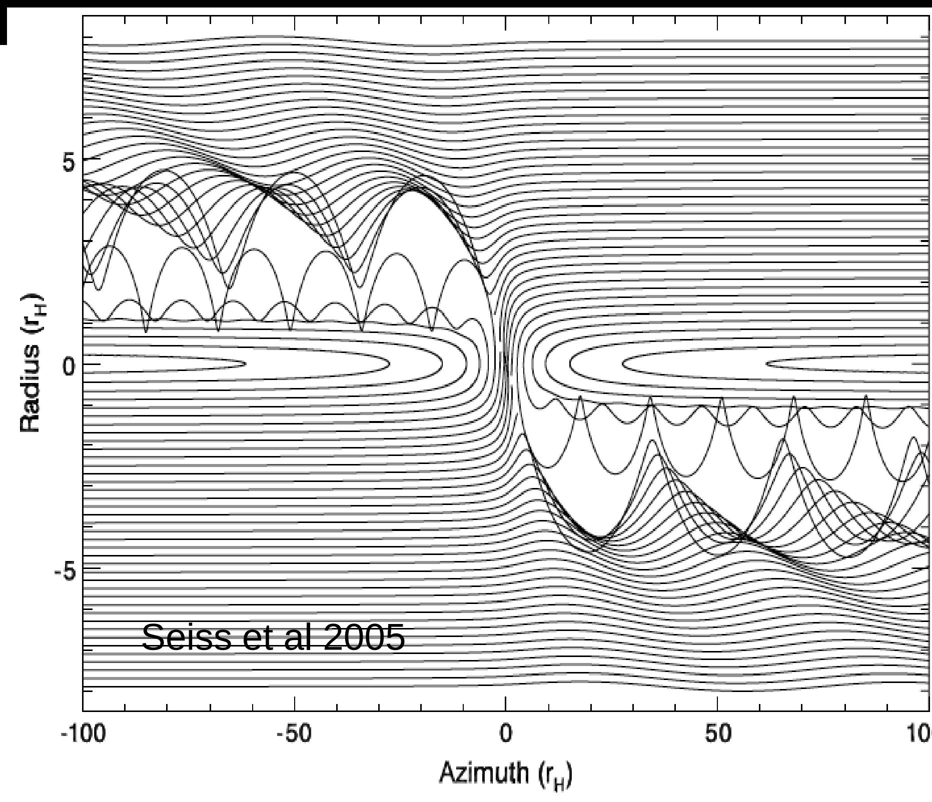
UVIS observations of ring fine structure are shown here as Phi= (90º - cant angle). Note that in the A ring, the cant angle is 20-40º, as predicted by theory, whereas the cant angle decreases to 15-20º in the inner B ring because of the stronger shear there (from Colwell et al 2007).



"Propellers": 100-m objects seen indirectly







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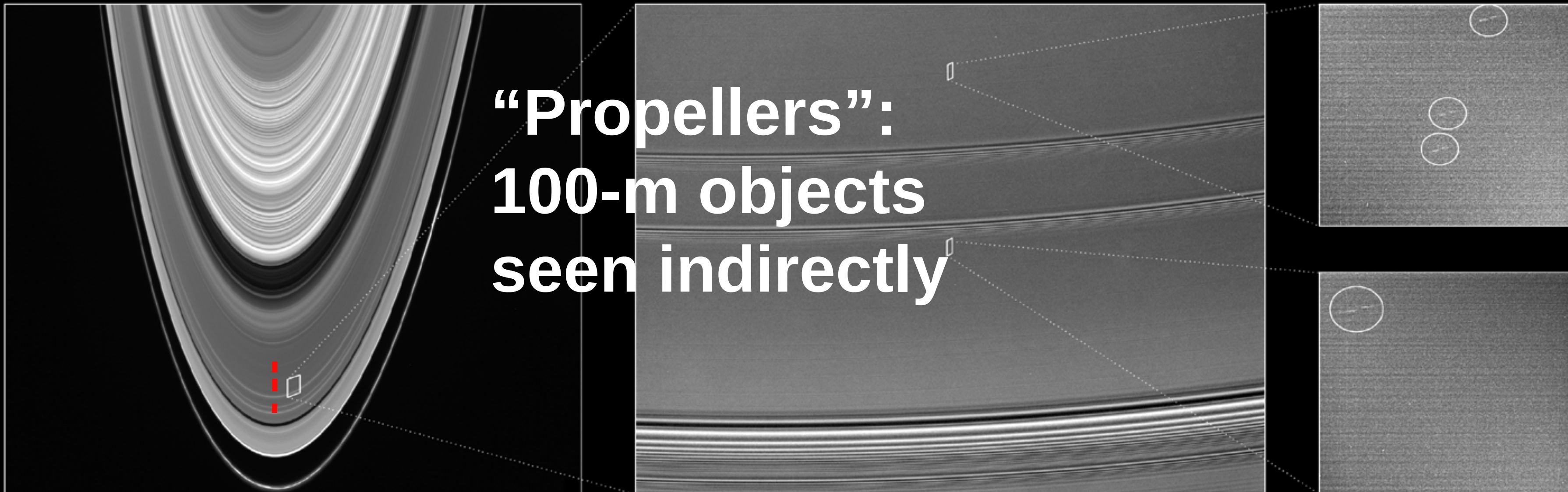
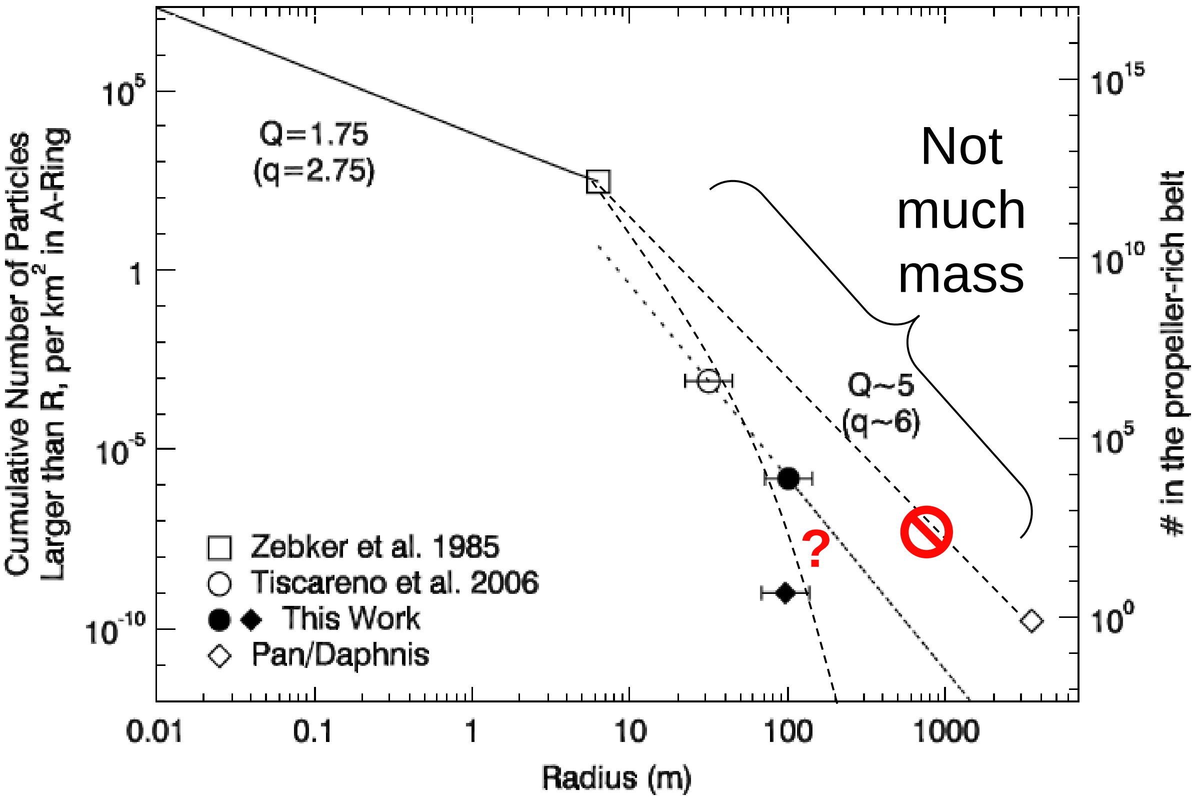
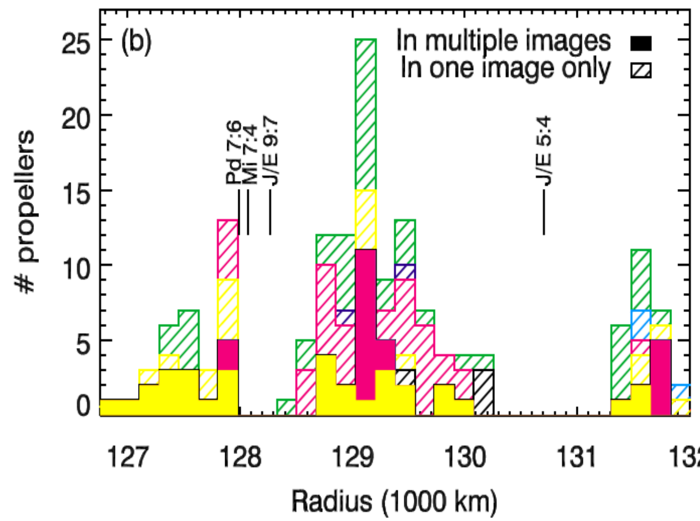
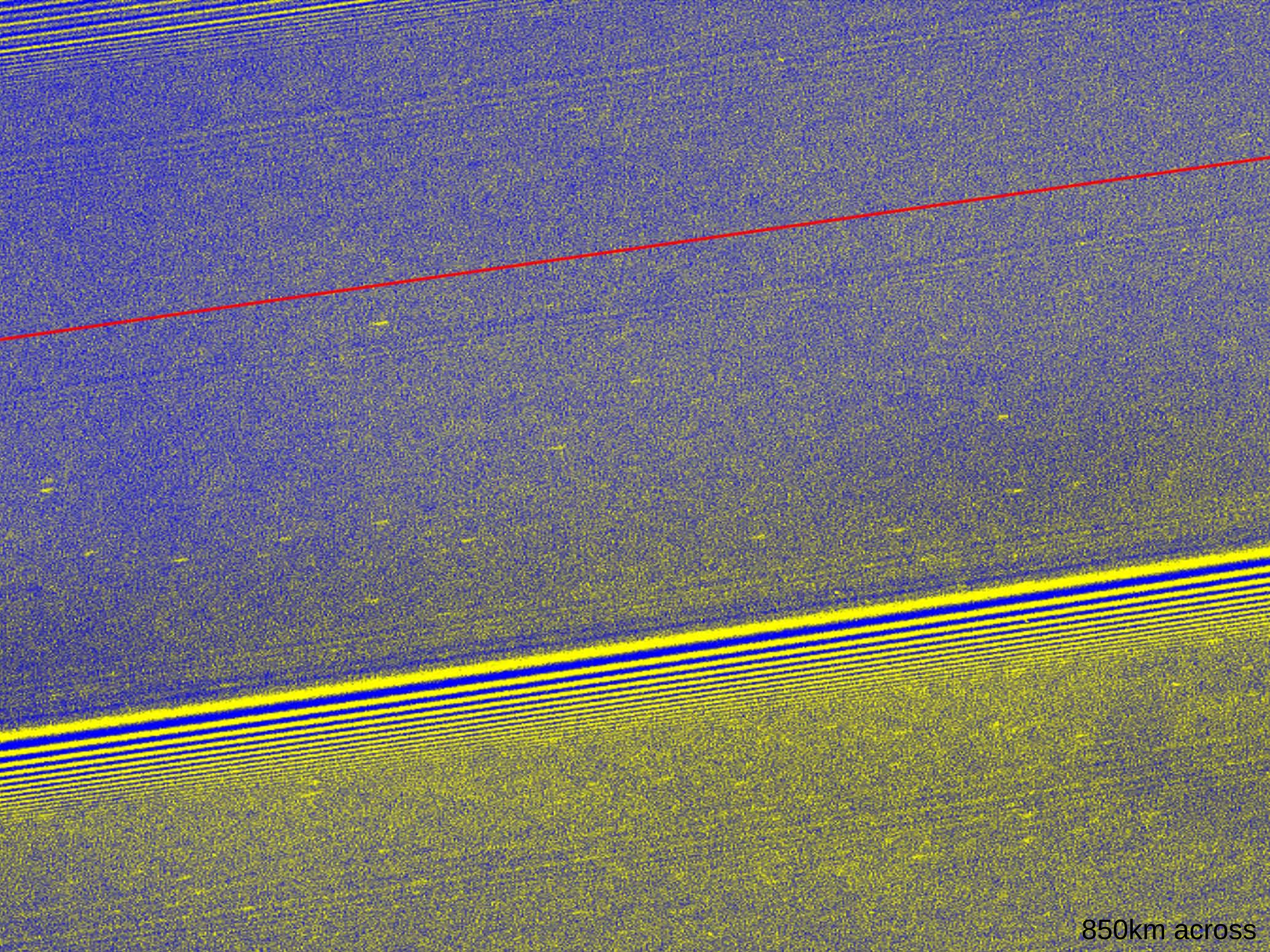




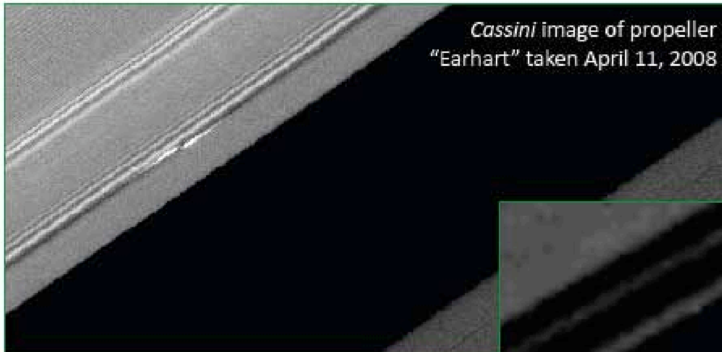
Sremcevic et al AJ 2007

- Tiscareno et al AJ 2007




850km across

Migrating moonlets in Saturn's rings reflect solar system beginnings



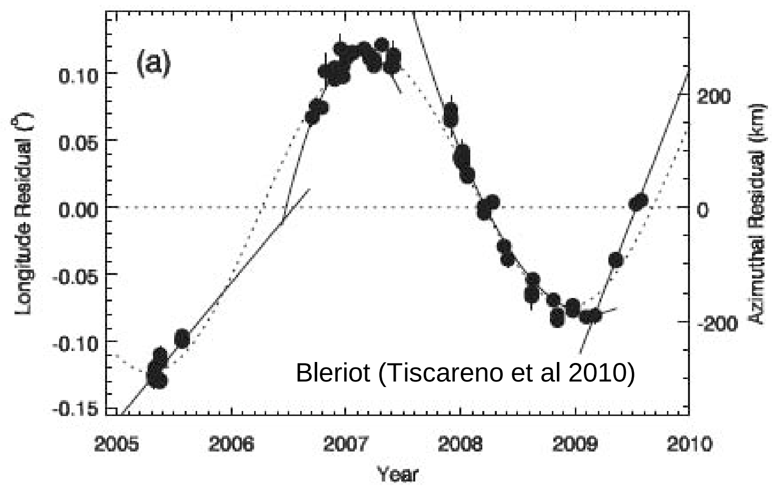
A "propeller" moon orbits Saturn while embedded in the disk of Saturn's rings

For the first time, Cassini scientists are tracking moons that do not orbit in empty space.

A "propeller" structure casts a shadow on the disk

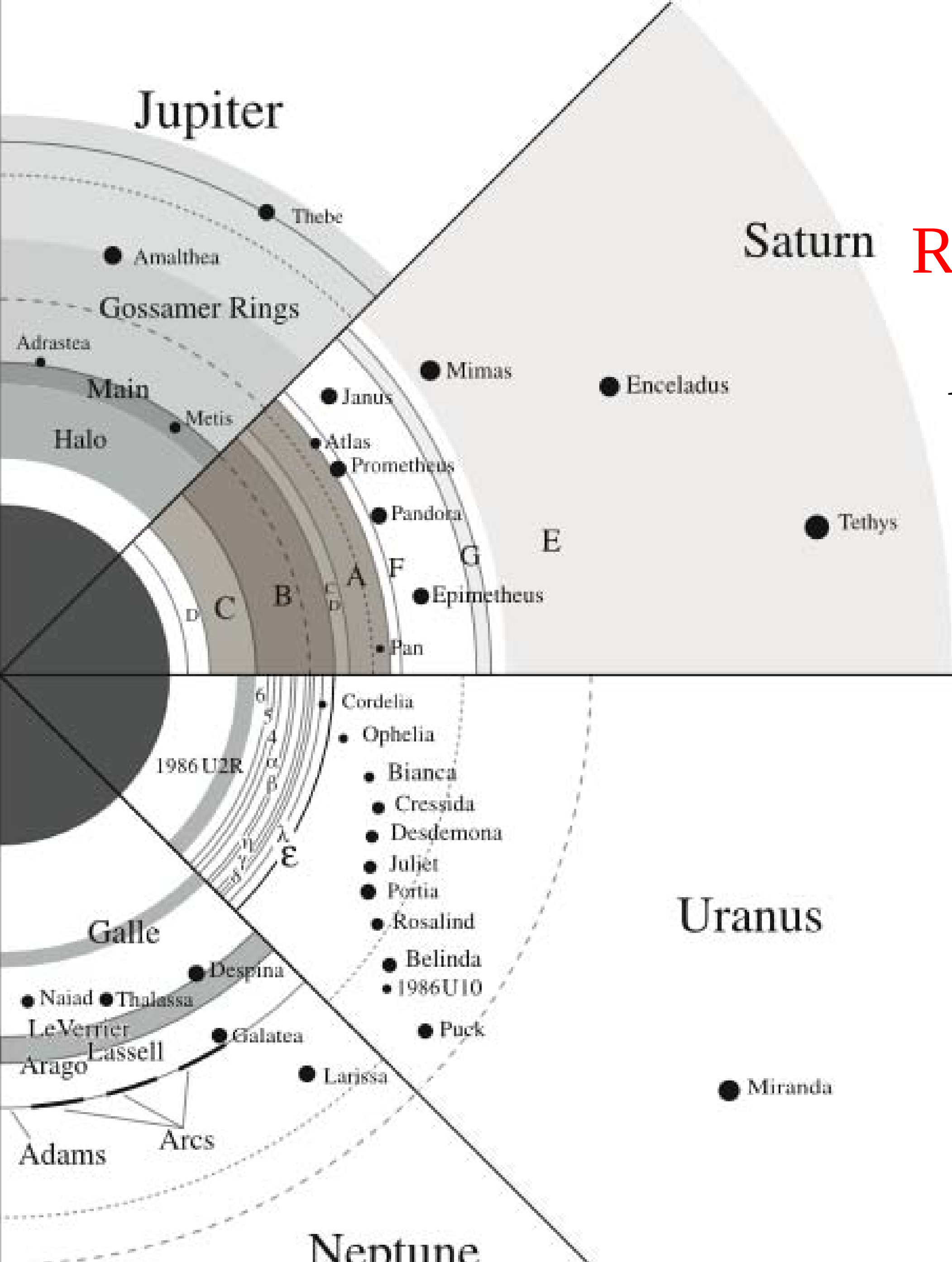
Do they interact with their disk like baby planets do?

Tiscareno et al 2010

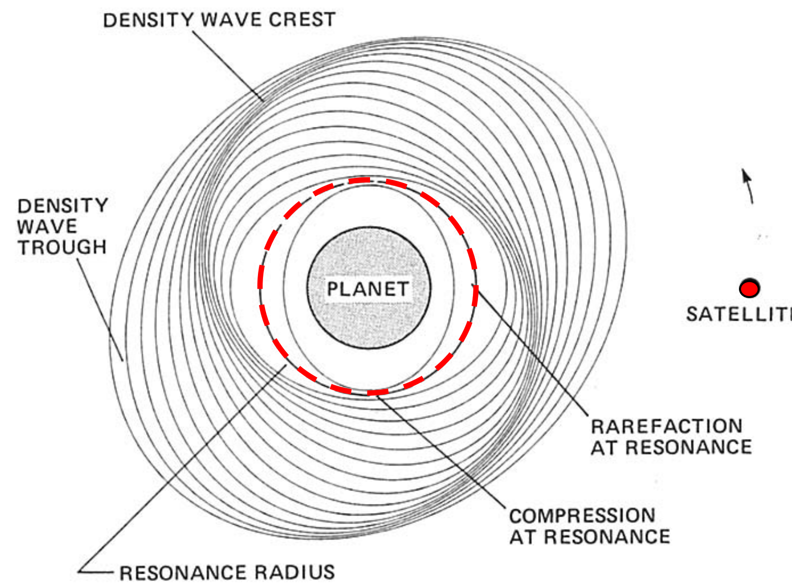


Propeller objects do not seem to be moving uniformly, as in the traditional theory of "type 1 migration". They might be responding to other clumps and irregularities in the rings. There may be lessons learned here for how planetesimals and planetary cores migrate in protoplanetary disks.

Rings and ringmoons closely mixed in and near Roche zones of parent planets

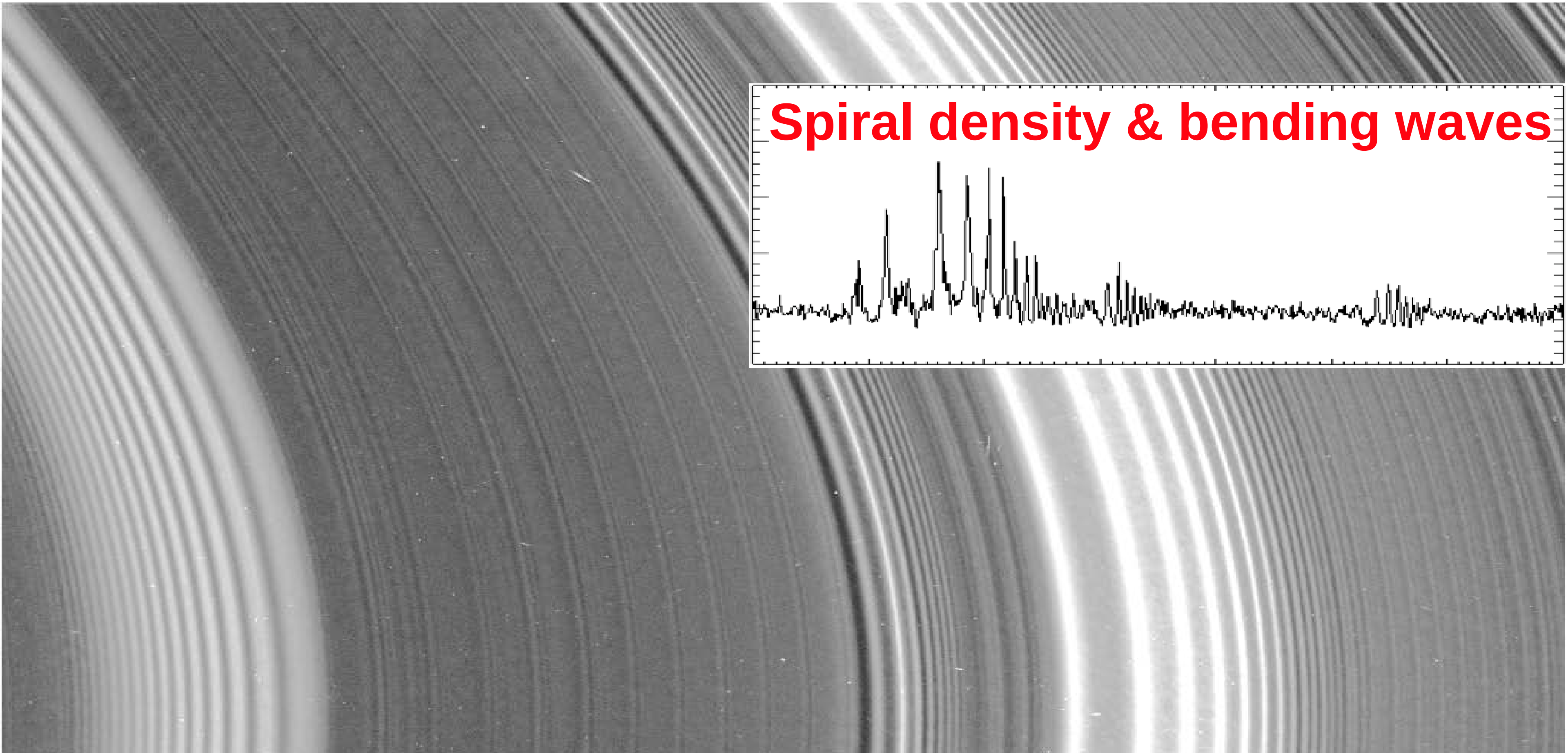


At orbit resonances, moons' tiny forces are amplified many times



Ring self-gravity creates spiral pattern rotating with moon

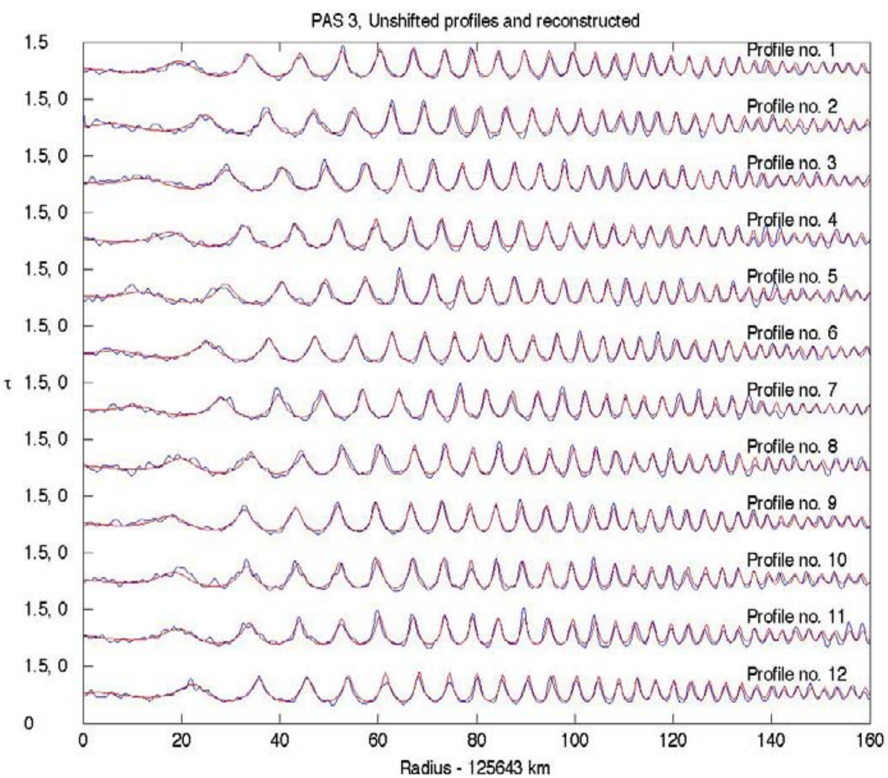
Dynamic processes responsible for ring structure

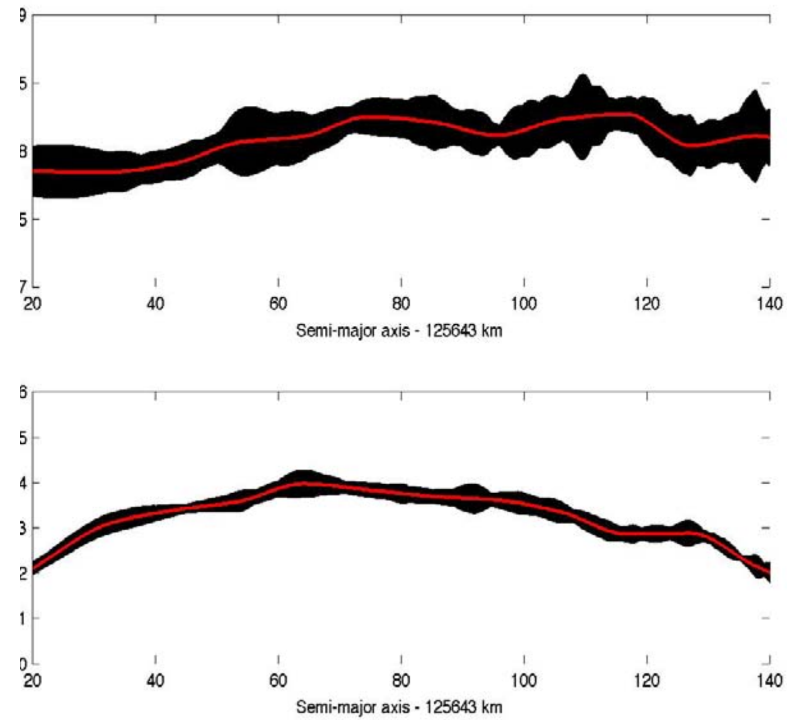


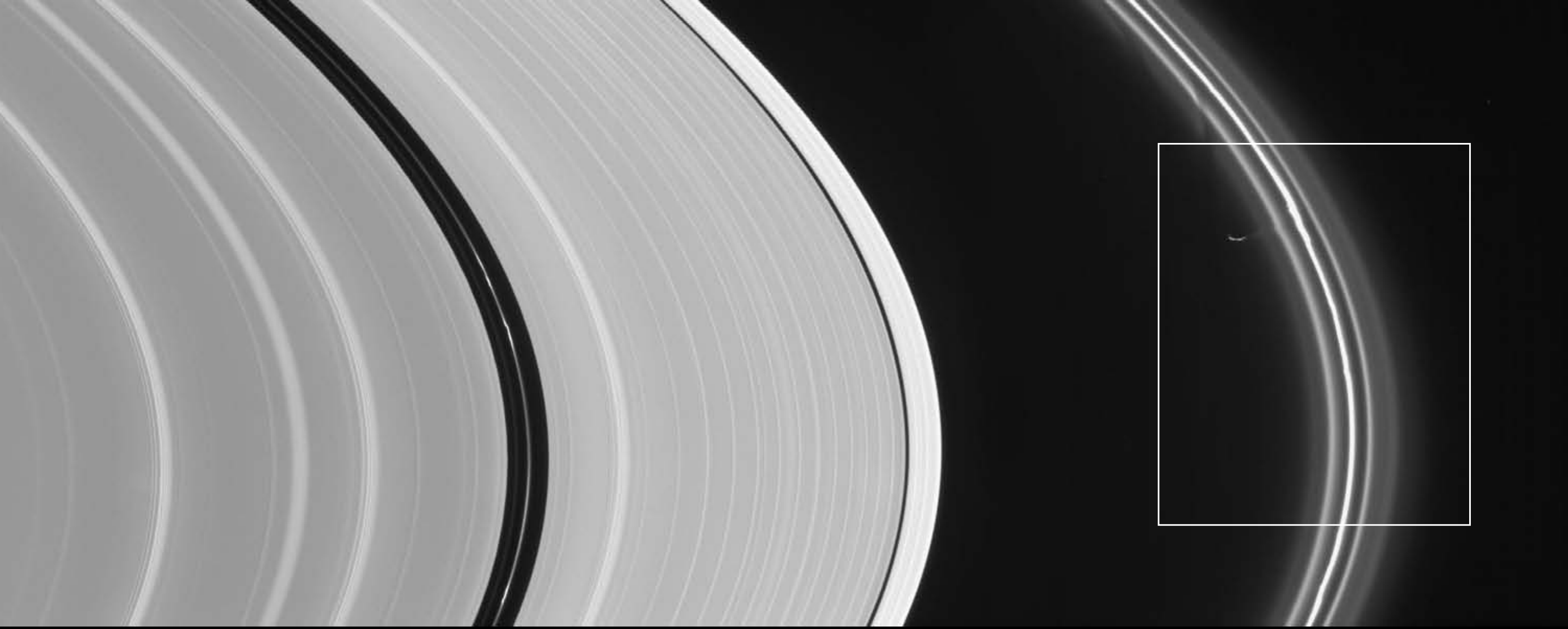
Cassini UVIS, VIMS, and ISS data have observed 10x Voyager sample;
Wavelength and location: *ring surface mass density* (key for ring age)
Amplitude and damping: *moon's mass and* ring viscosity;
Showed that *all* ringmoons have densities ~ 0.5 g/cm^3: rubble piles

Surface mass density profiles from spiral density waves (RSS)

New models by Rappaport et al (2009) allow multiple RSS occultation profiles through a given spiral density wave to be combined in the same analysis, using the longitude variability inherent in the wave to remove sampling uncertainty (see left panel below), and determine the radial variation of surface mass density through which the wave is propagating, along with a nonlinearity parameter associated with wave forcing (right panel below). It is extremely important to understand the mass density implications of spiral waves because this is the only way to directly measure the rings' surface mass density. In the last quarter, the number of RSS profiles suitable for analysis was increased from 8 to 12, also.







Multiple strands;
Prometheus, Pandora,
and other new objects

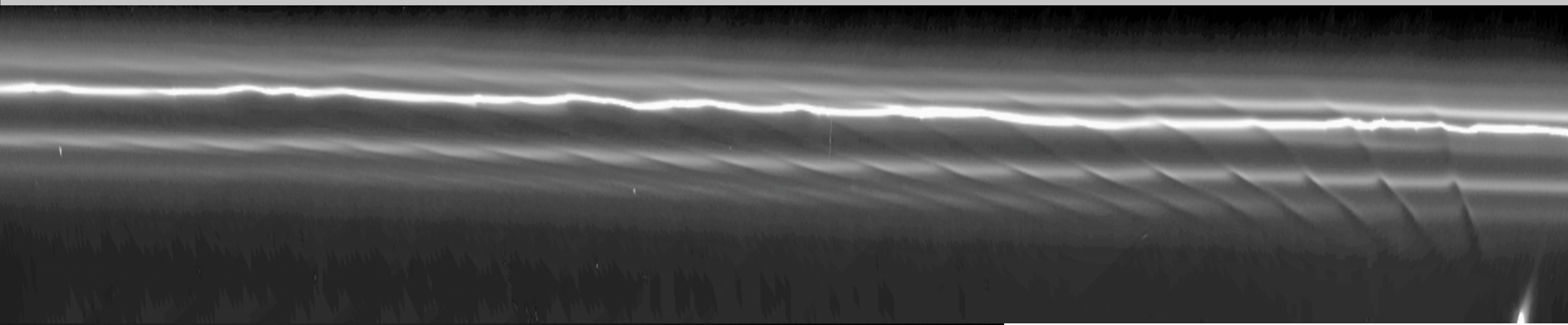
Outer A ring

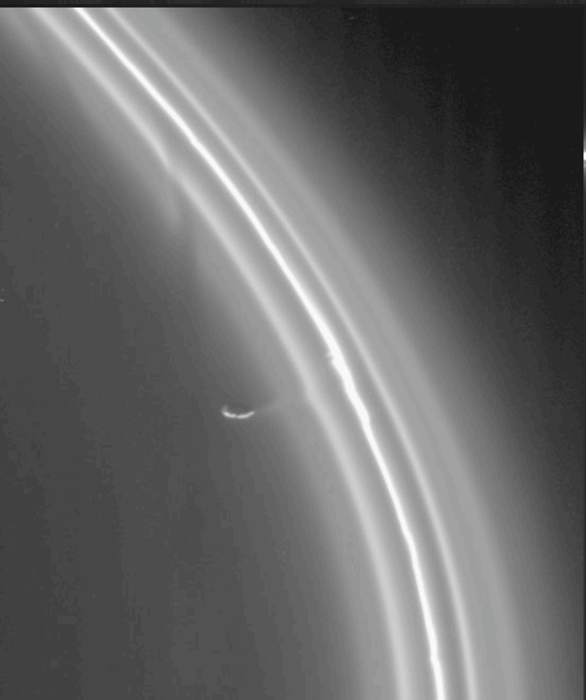
F ring

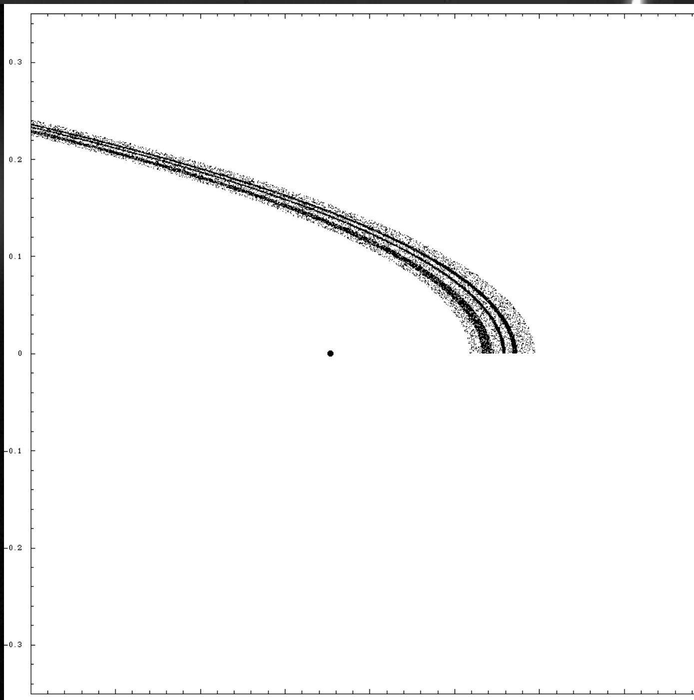
10,000km or 6000 miles

The F ring - a moonlet belt?

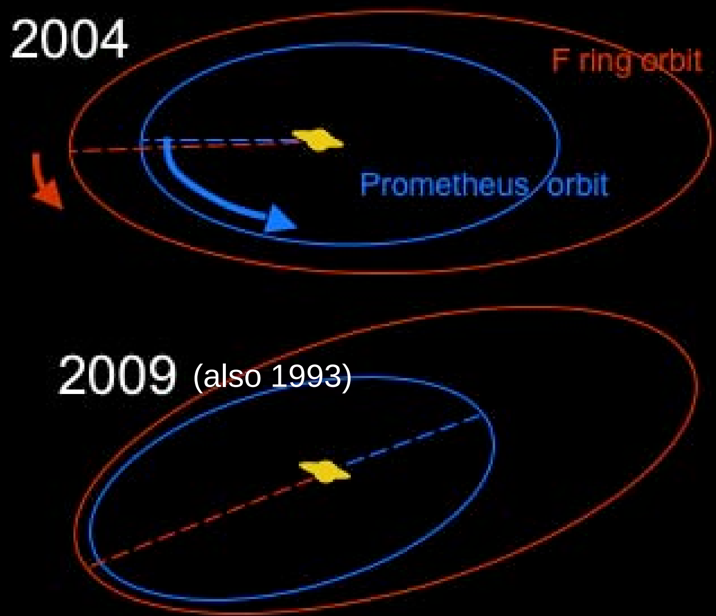
The stranded F ring has been a puzzle since Voyager. Cassini found that the number and location of the main strands changes on several month timescale, although the narrow “core” has remained constant. Gravitational effects of the nearby eccentric ringmoon Prometheus cause the channels and streamers. Both Prometheus and its companion “shepherd” Pandora are on chaotic orbits, and probably many other sizeable objects in the region are, as well.

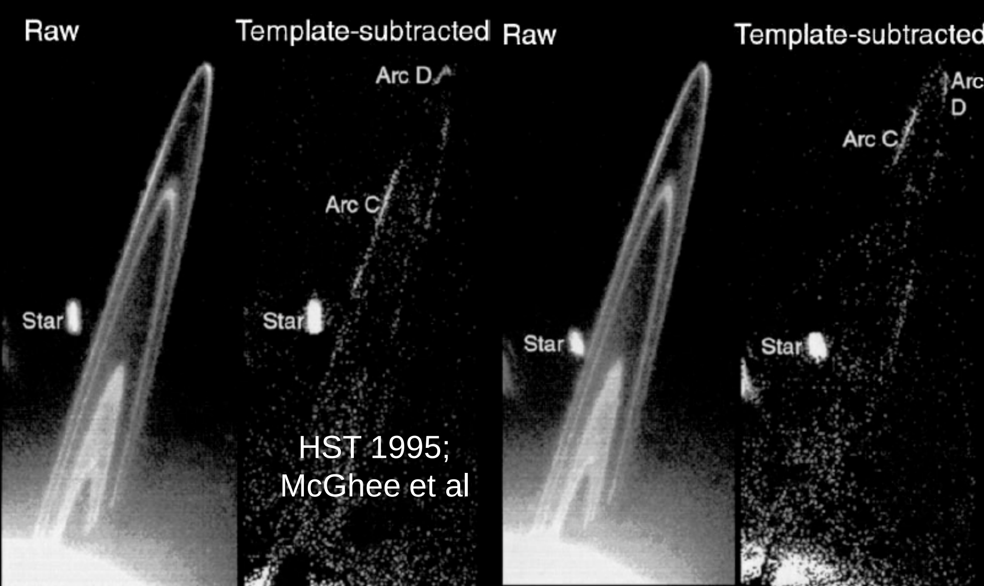


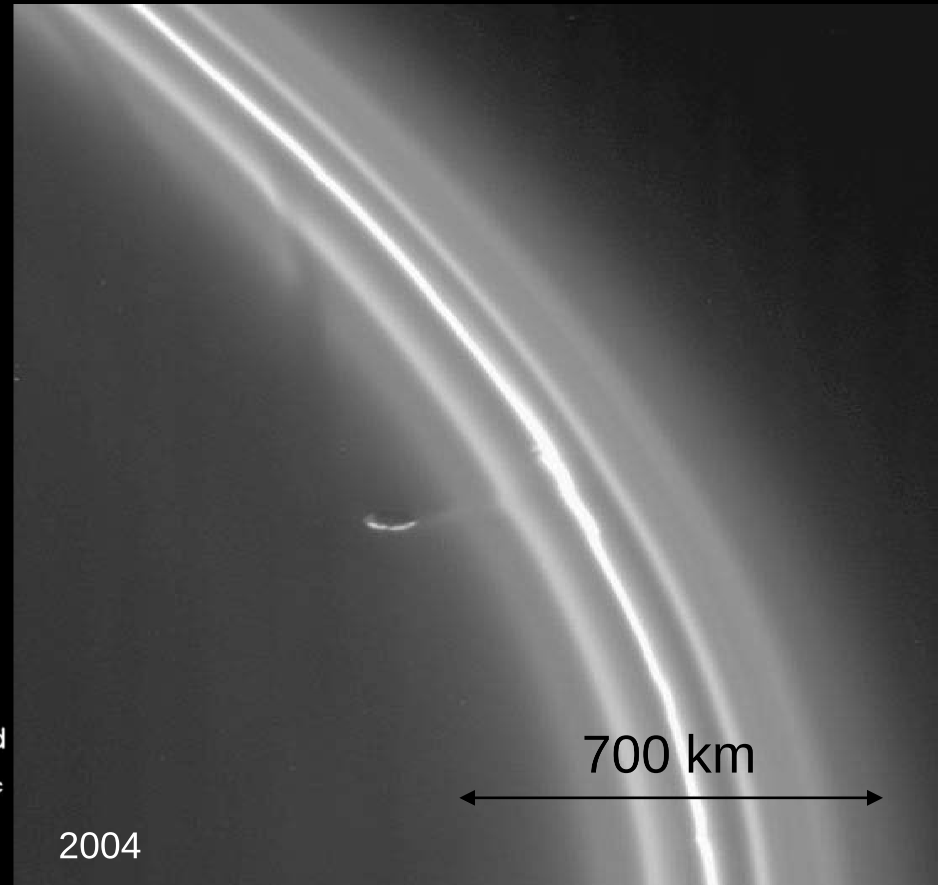


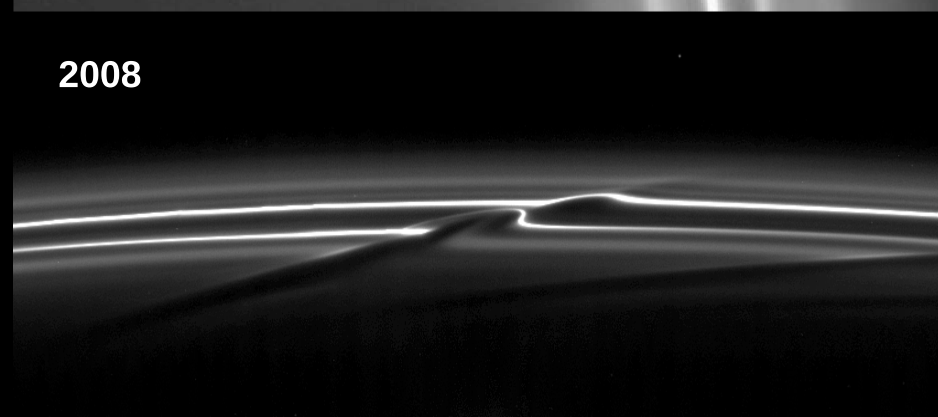


Prometheus: “Nemesis” of the F ring? Need a few more years to tell..





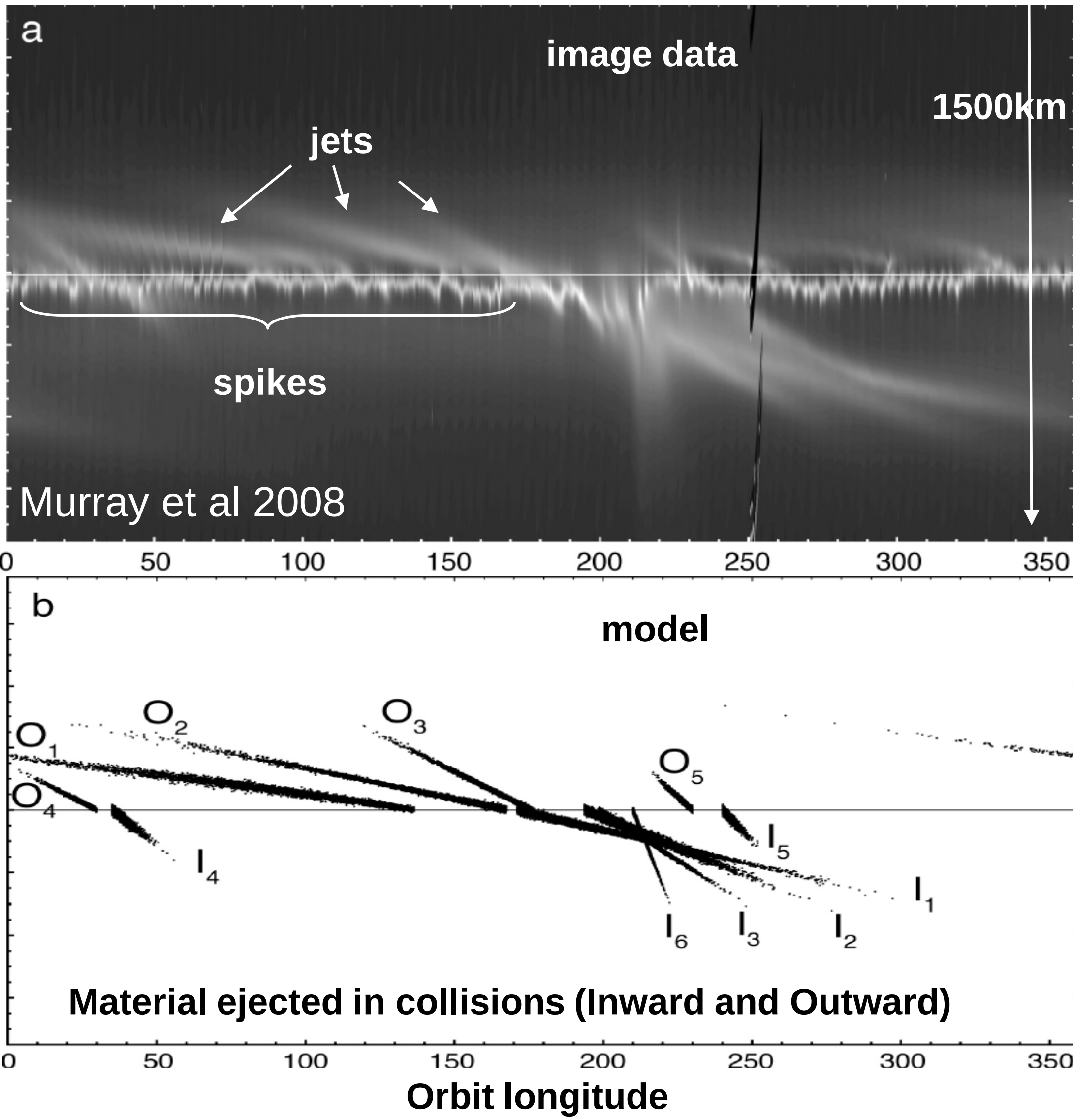




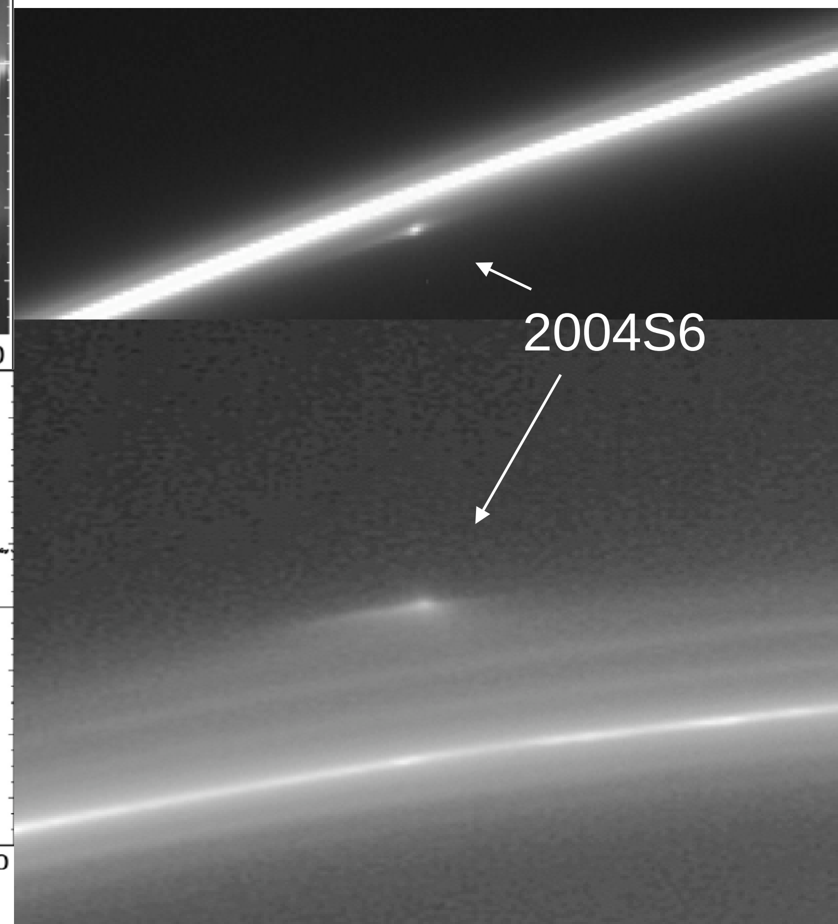
F region contains numerous km-size moonlets, which get excited by Prometheus and Pandora, and then disturb the ring strands,

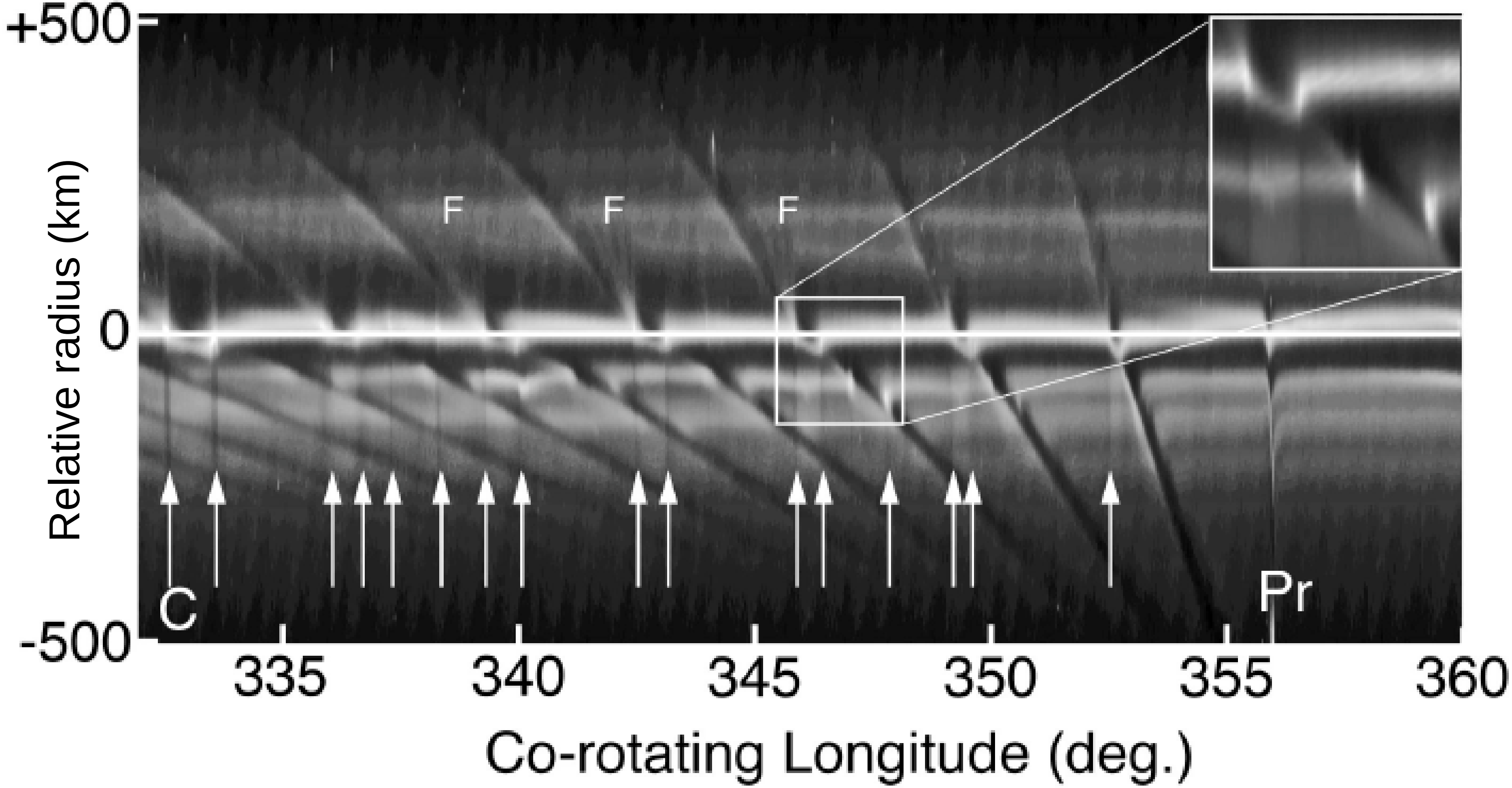
AND

Fewer objects on more dramatically crossing orbits, few of which have been detected

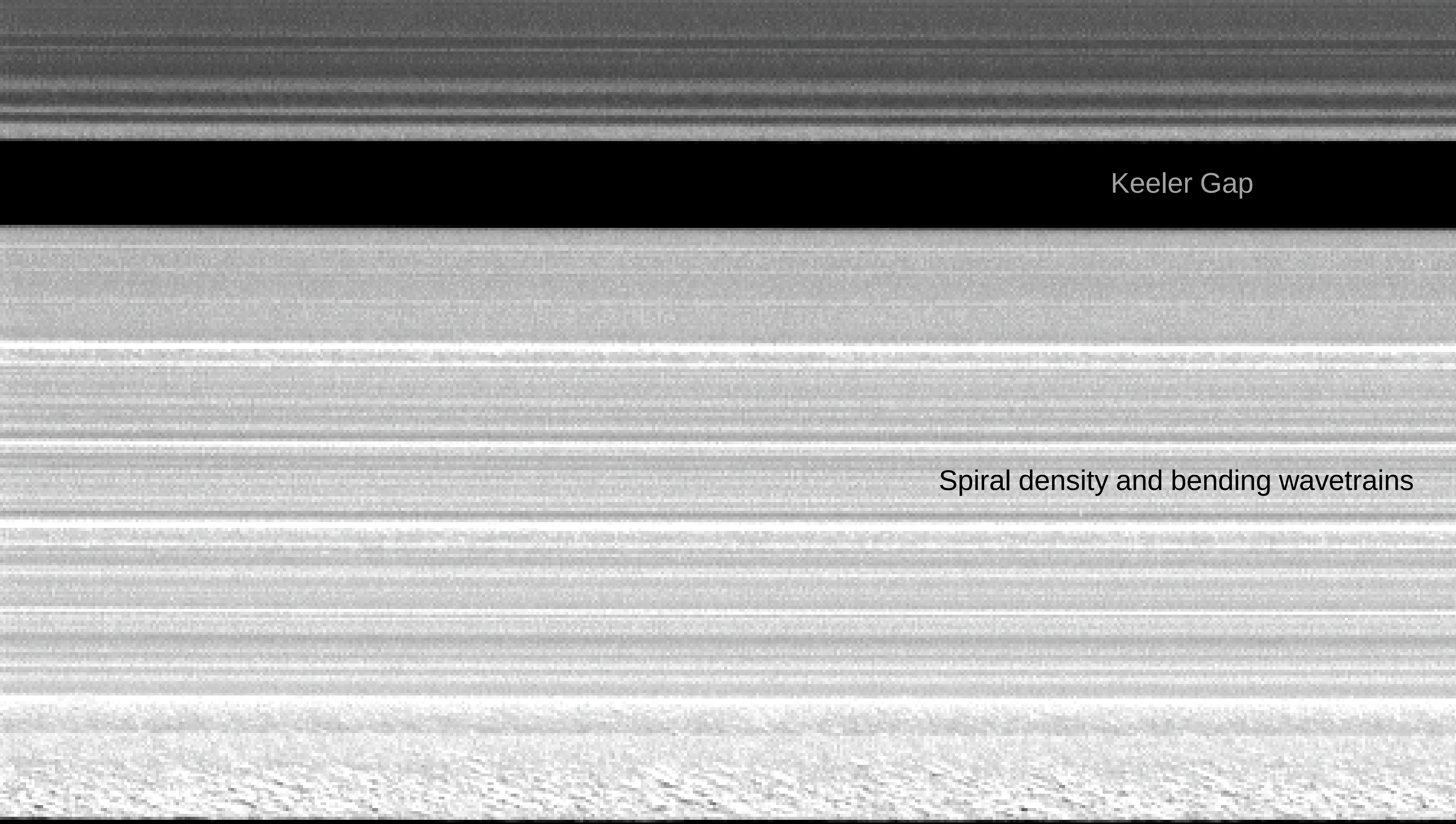


2004S6 has an eccentric orbit that crosses the F ring, leading to collisions





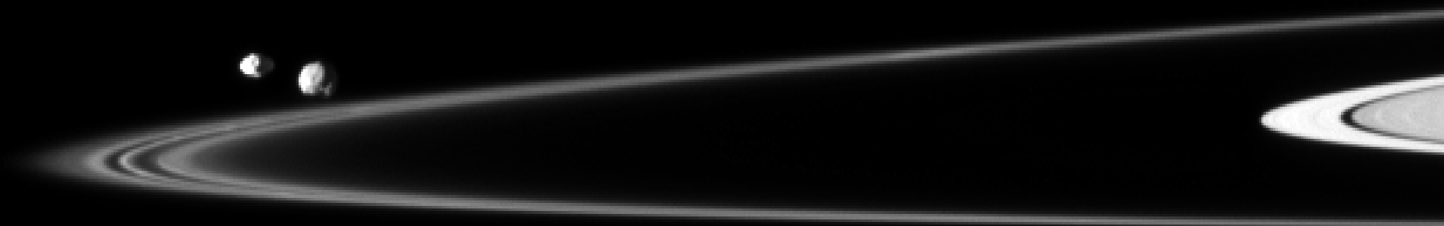
F ring observations near equinox show shadows of clumps (arrows) and “Fans” (F) where possibly locally produced (and/or temporary) mass concentrations perturb nearby material, smaller examples of how Prometheus perturbs the F ring on larger scales (large diagonal channels (Beurle et al 2010).

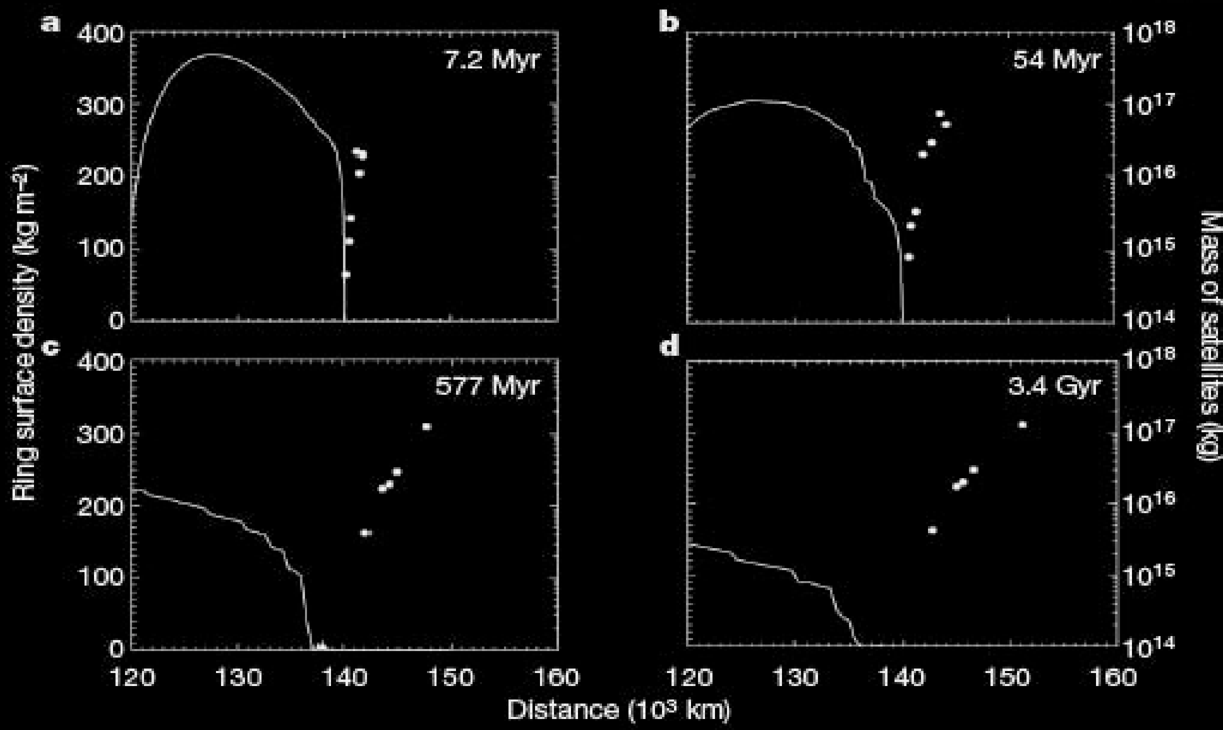


Extreme gravitational clumping at the very outer edge of Saturn’s A ring

Origin of the ringmoons: within the main rings?

Charnoz et al (Nature, 2010; see also Burns 2010) have reported new full evolutionary models in which gravitational accretion at the edge of the Roche zone leads to massive ringmoons such as Pandora and Epimetheus (shown here), discovered by Cassini to be rubble piles, which then evolve away from the rings under their own density wave torques. The stranded F ring seen here might be only the result of a recent disruptive encounter between members of this still-evolving tribe of moons. The new model shows that most of the orbital evolution occurs in only a few hundred million years - possibly consistent with a young age for the rings.

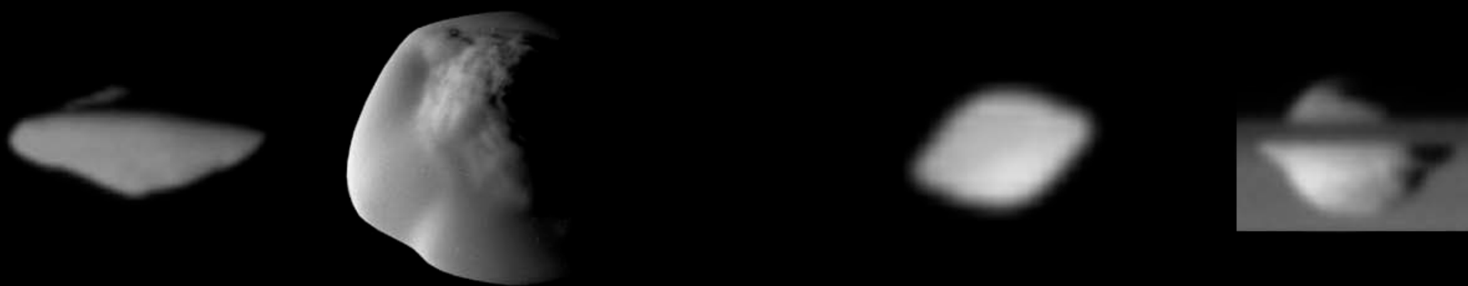




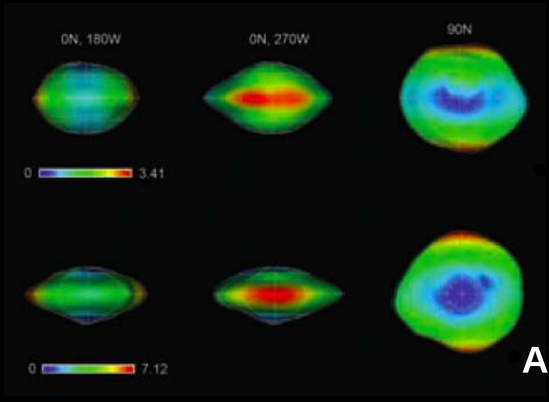
All ringmoons are underdense, filling their “Roche lobes”, and are probably accretion-limited rubble piles with dense central cores

(which might be of different composition)

Atlas Pan

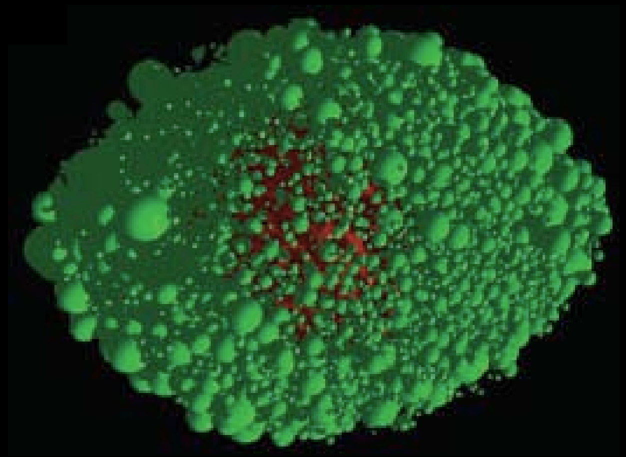


20 km



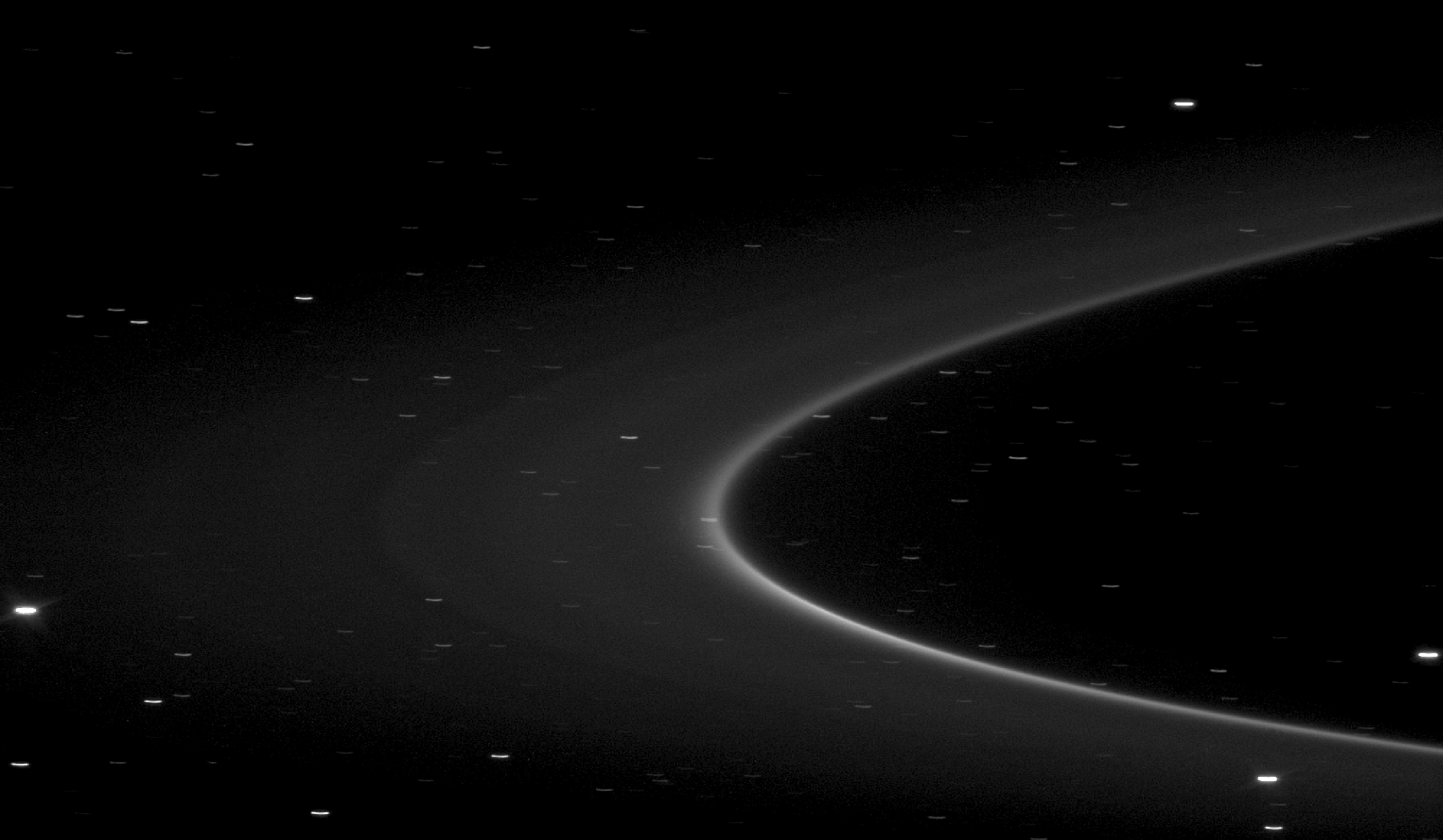
PAN

ATLAS



Porco et al 2007

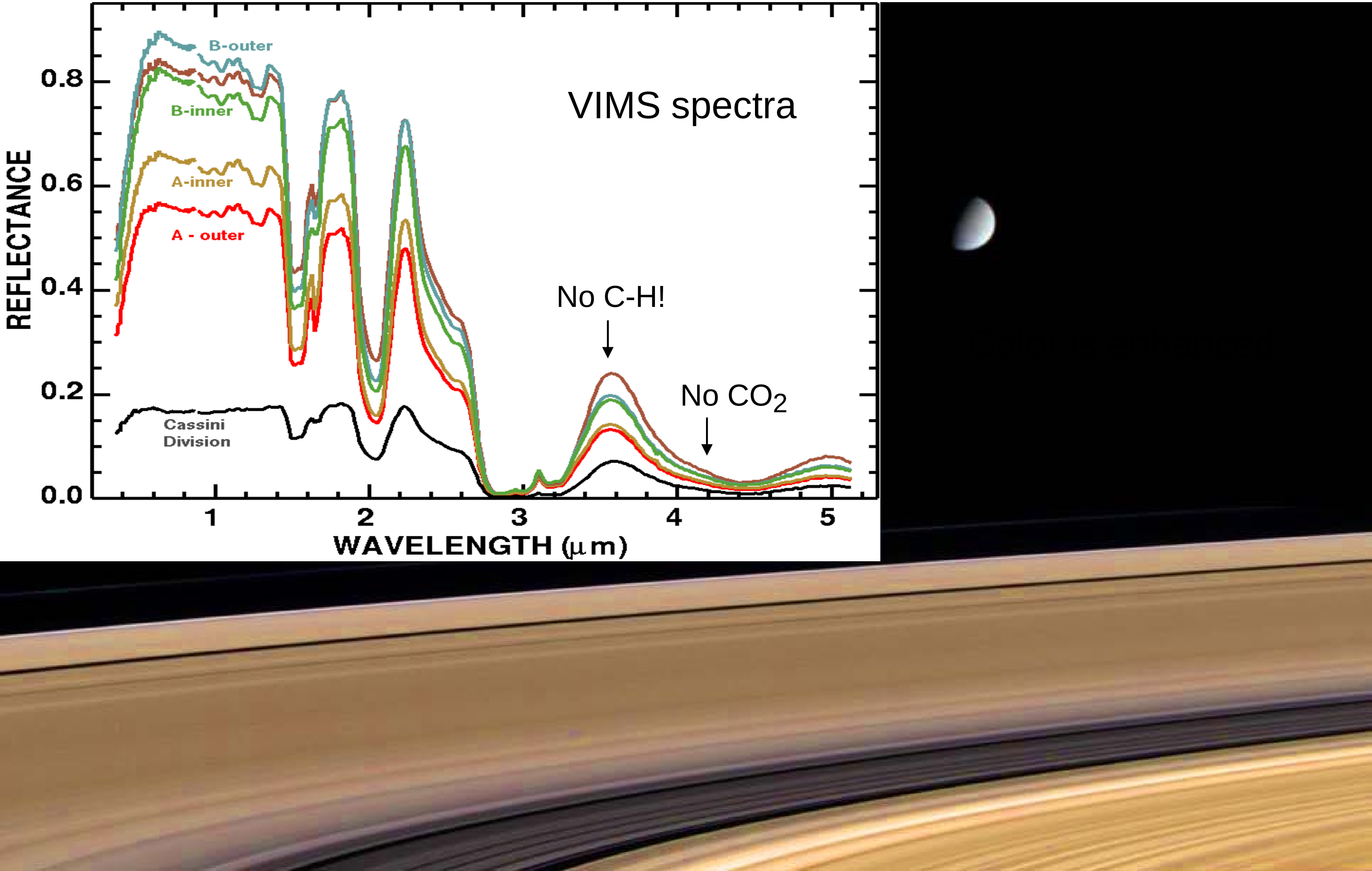
Source of the G ring arc (Hedman et al 2010)

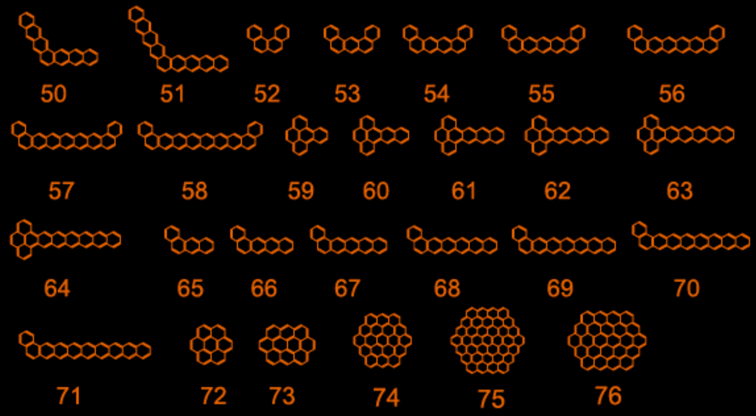


Tiny Aegeon, less than 1km across and invisible in this image, is thought to be the source of the rubble and dust making up the arc (bottom left) that supplies the full G ring

Chemical composition and size distribution of ring material

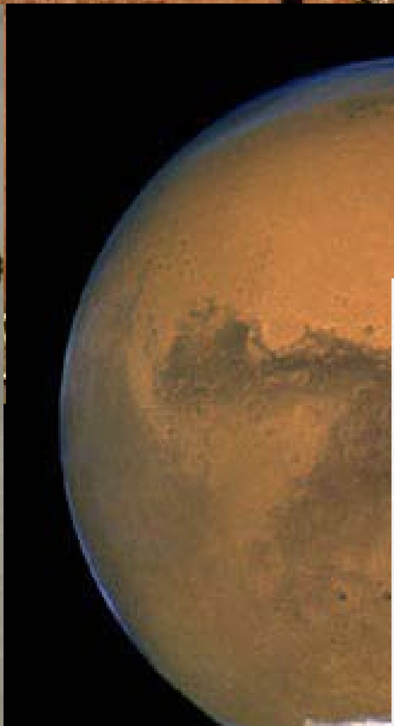
Cuzzi et al 2010; The Saturn System from Cassini-Huygens

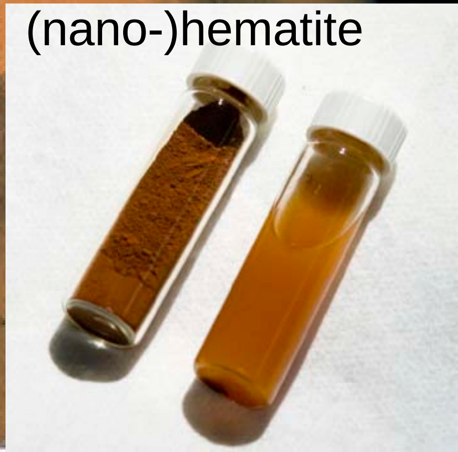




Why are the rings reddish?
“organic” or inorganic origin?
Lack of spectral features
Suggests nano-inclusions

Cuzzi et al 2010; Saturn from Cassini-Huygens

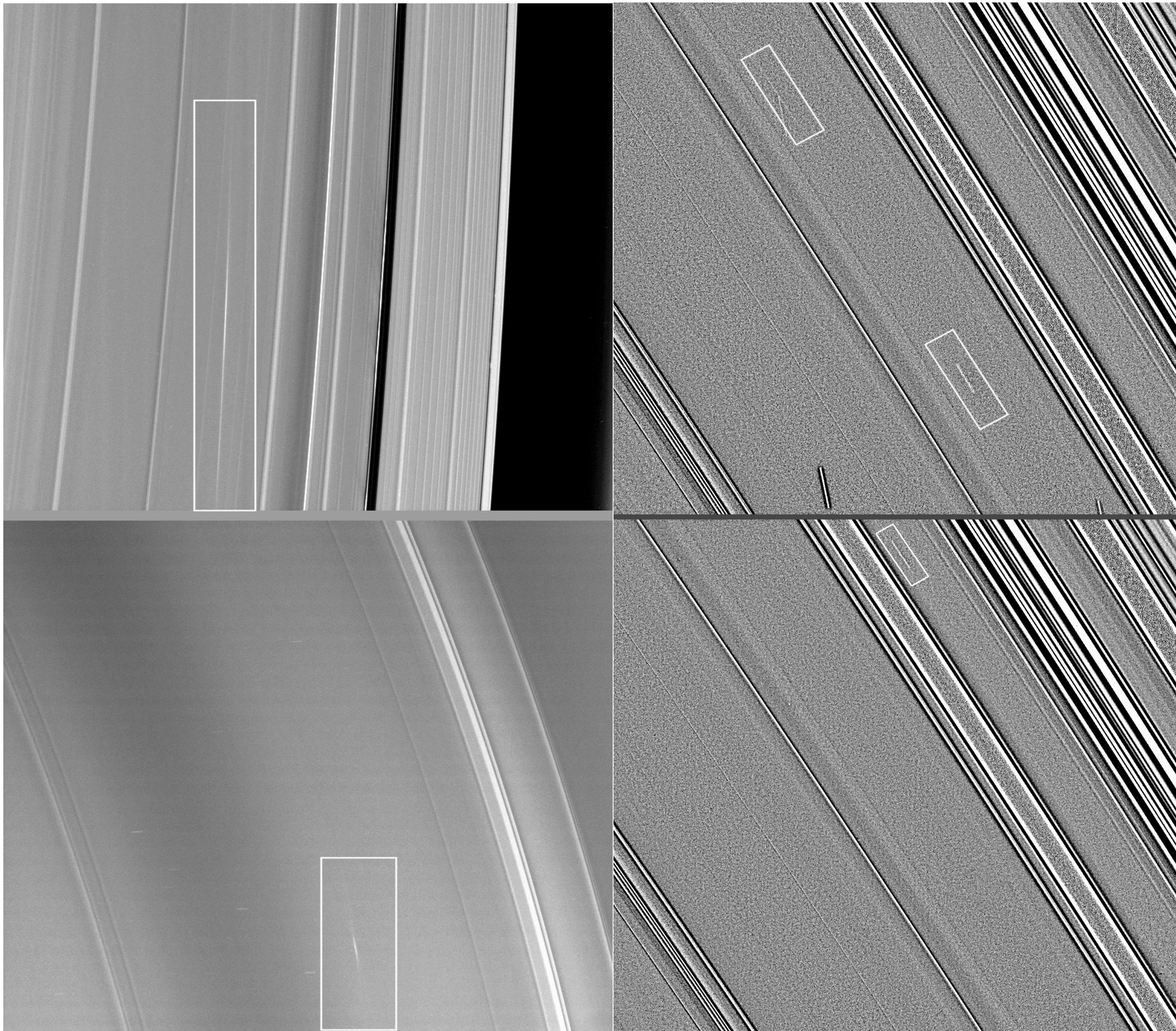




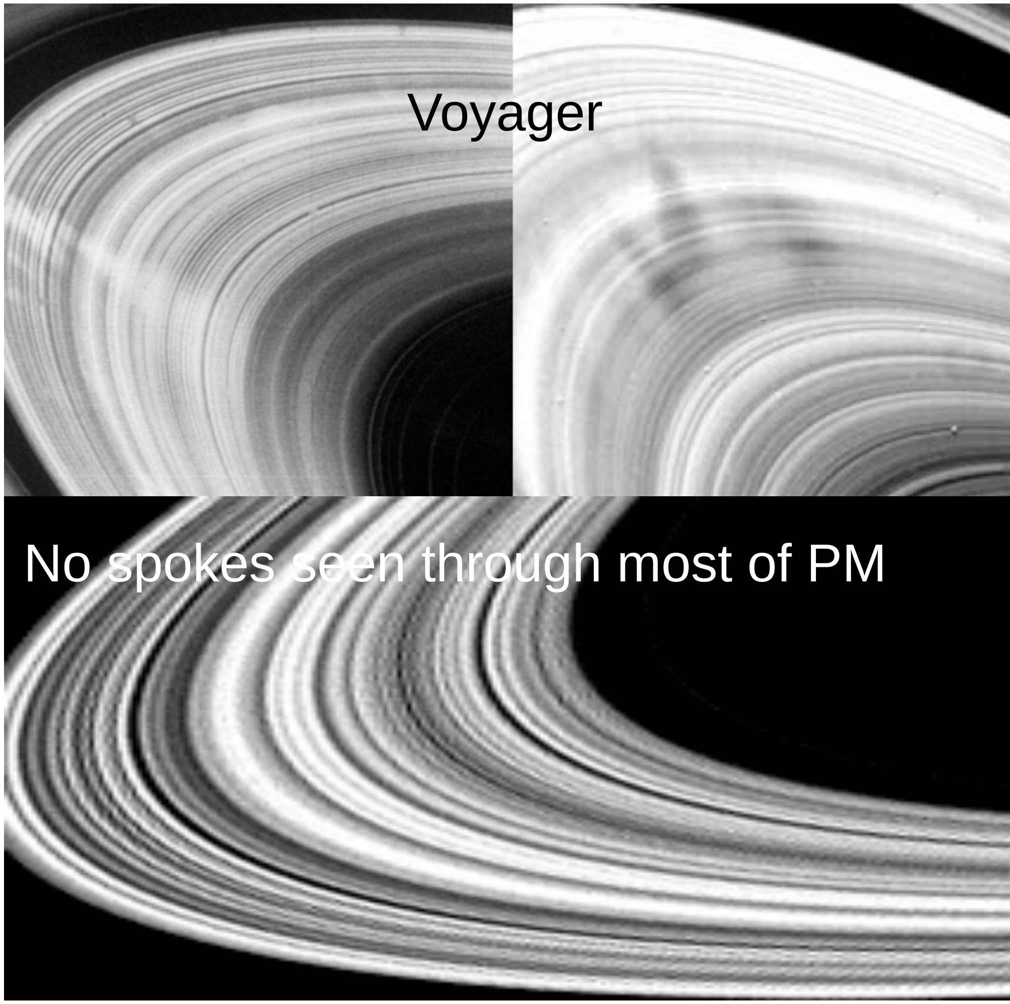
Impacts on the rings observed directly

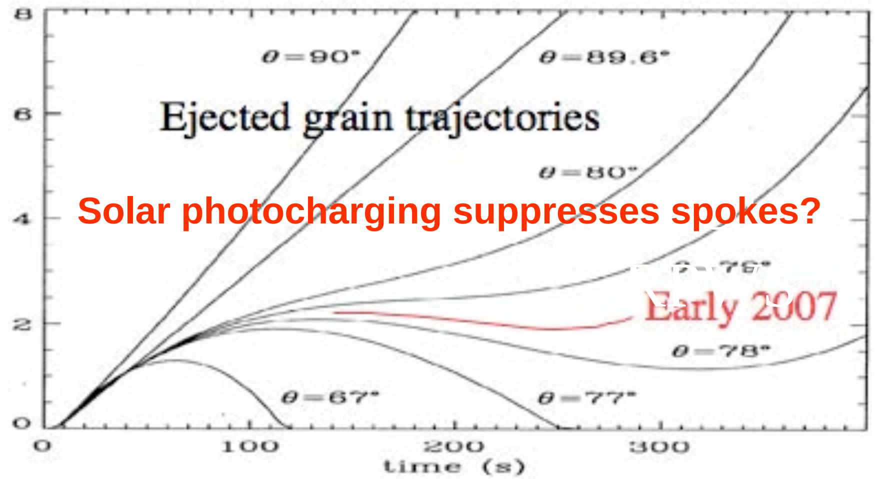
ISS has observed impacts on the rings by what are thought to be meter-or-smaller size meteoroids.

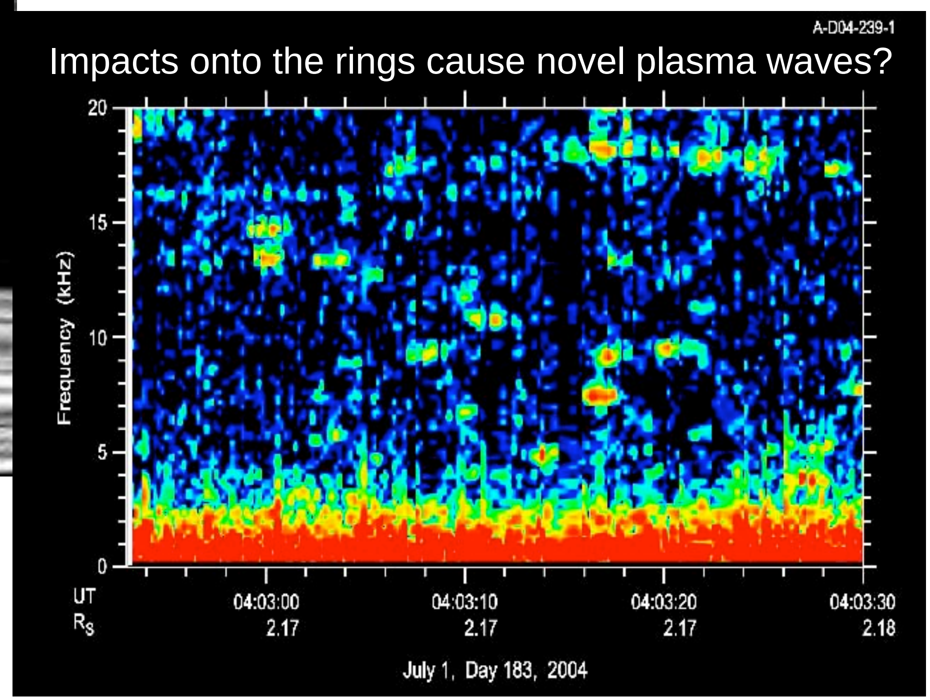
Meteoroid infall on the rings has long been thought to be connected to pollution and darkening of the ring ice, and perhaps to the triggering of “spoke” formation, but this is the first time impacts have been observed directly.



Ring-magnetosphere, -ionosphere, and -atmosphere interactions

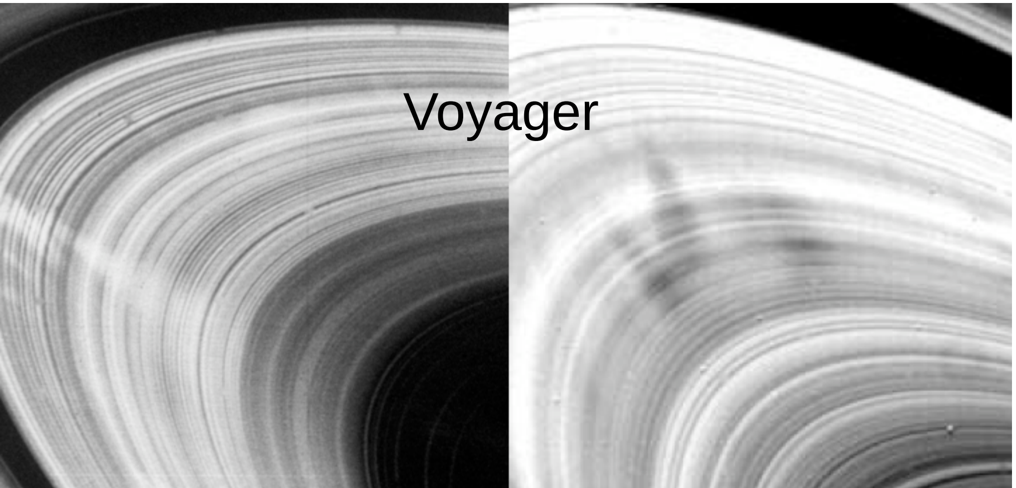


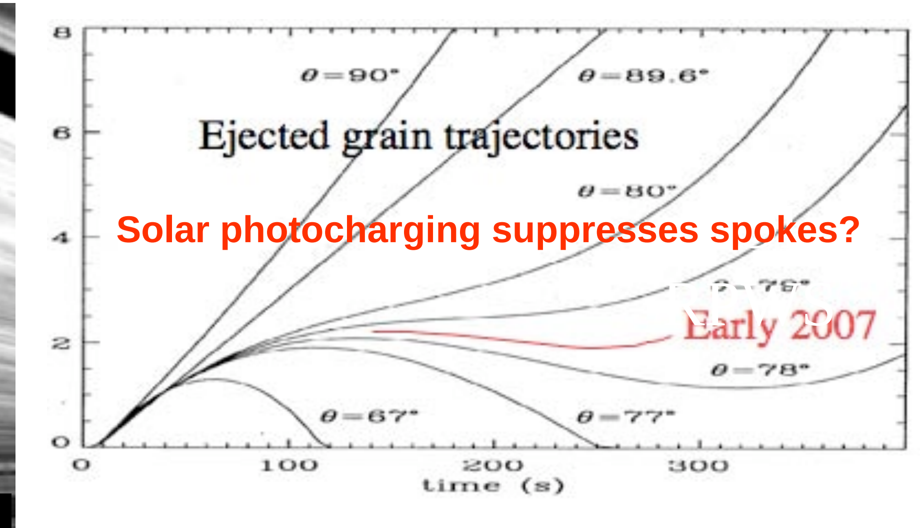


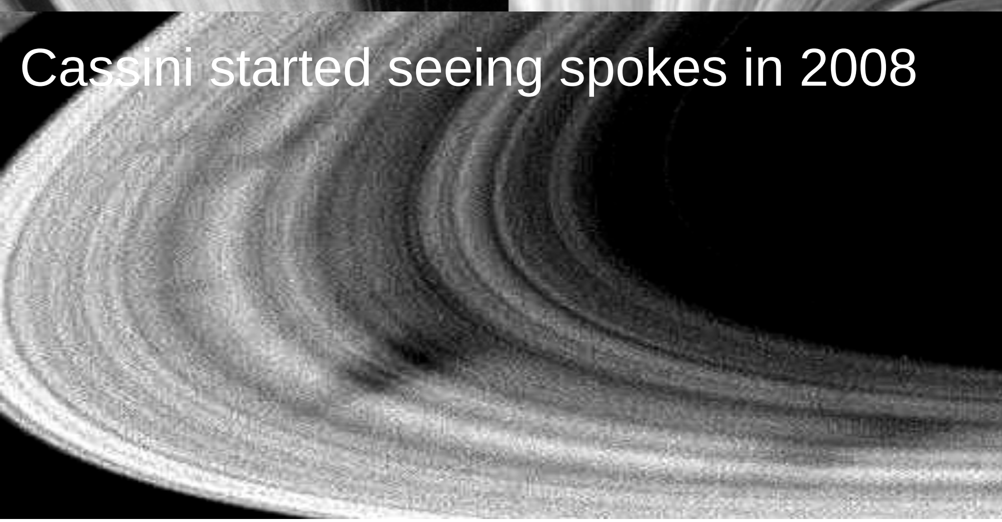


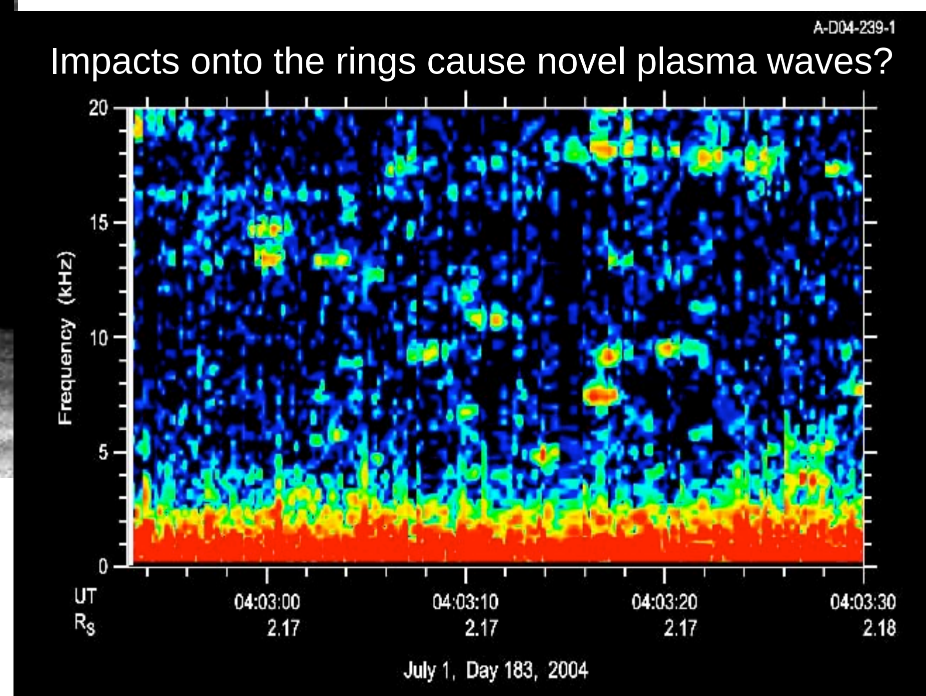
New type of electromagnetic (Lorentz) resonance seen in D, A-F regions might help constrain slipping SKR period

Ring-magnetosphere, -ionosphere, and -atmosphere interactions

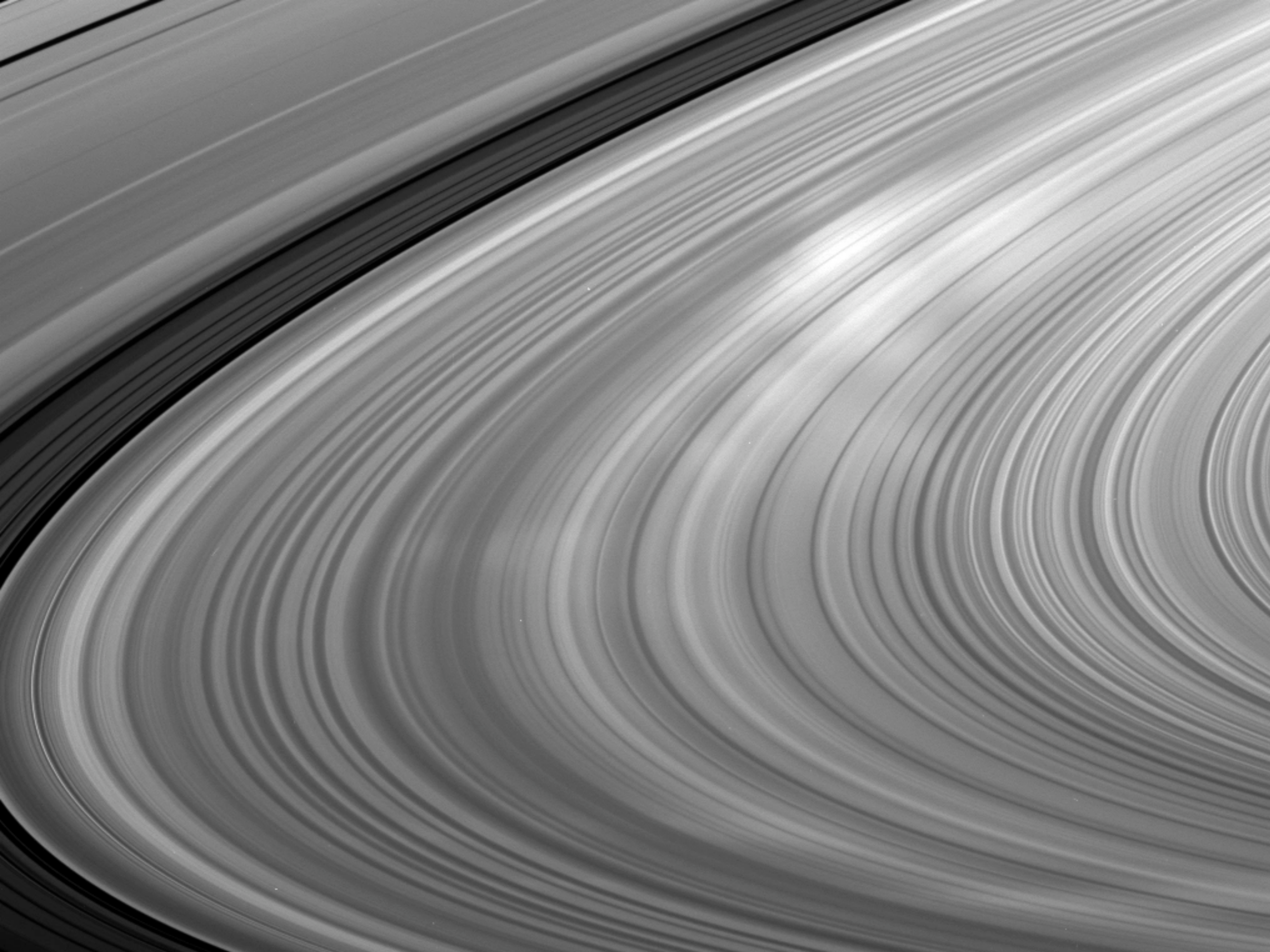






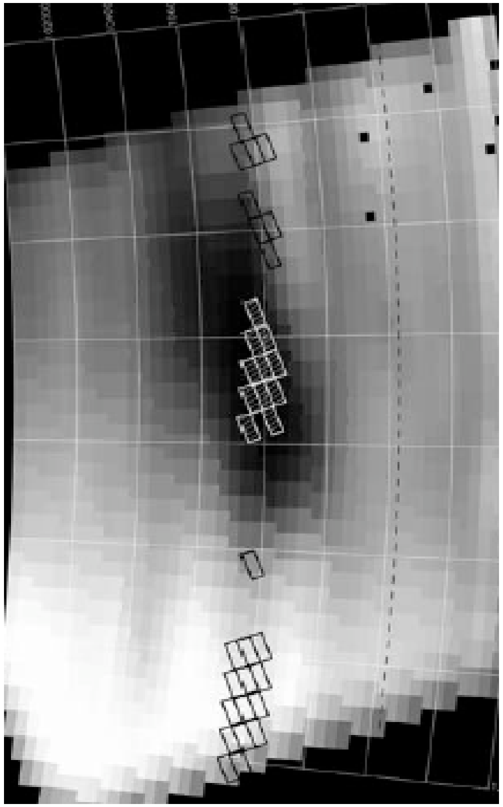


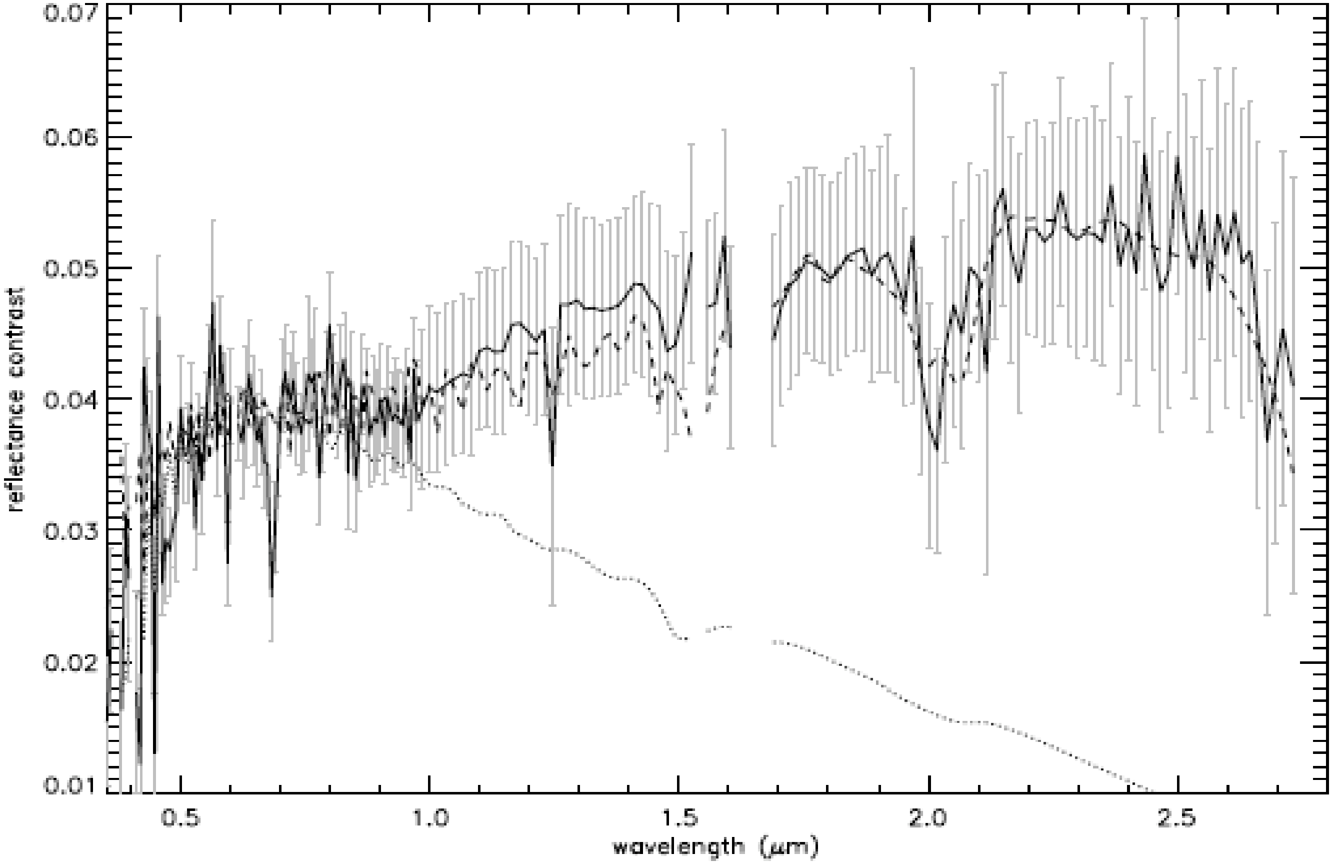
New type of electromagnetic (Lorentz) resonance seen in D, A-F regions might help constrain slipping SKR period



The “color” of spokes, and the spoke particle size distribution (VIMS)

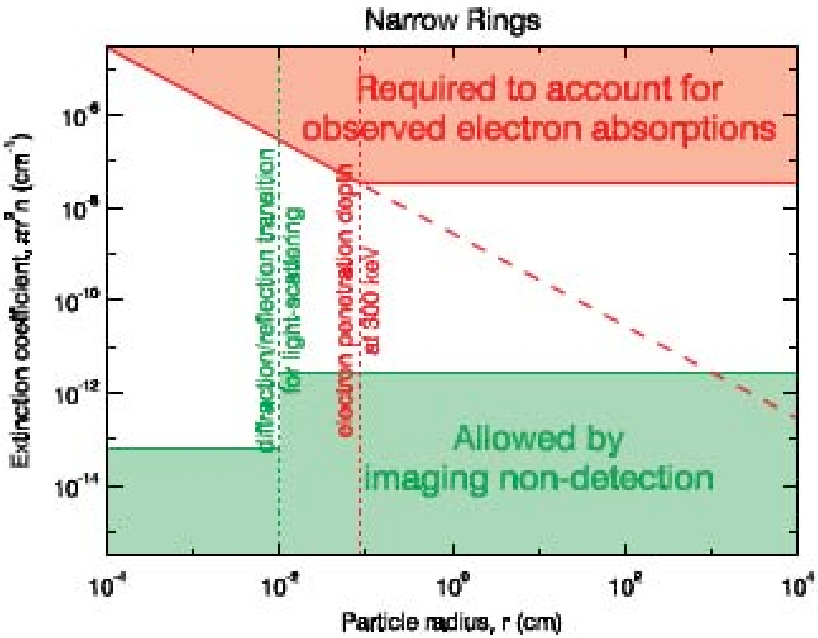
D’Aversa et al (2010) used VIMS multispectral data to measure the contrast of a spoke (left) from surrounding regions. This spectrum (right) shows strongly increasing contrast from 0.35 - 0.6 microns - indicative of a particle size in the micron size range - but the high contrast continues to much longer wavelengths - suggesting a broader size distribution than previously believed.

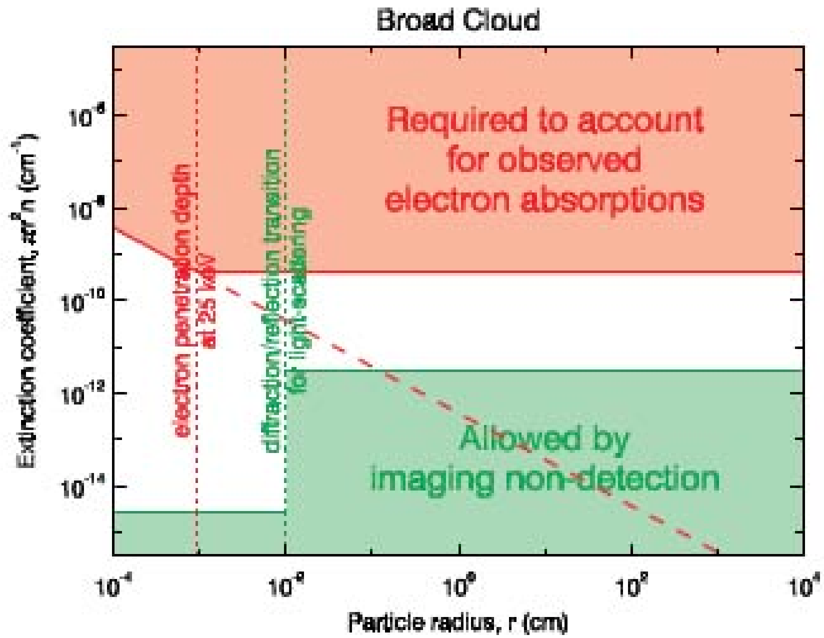


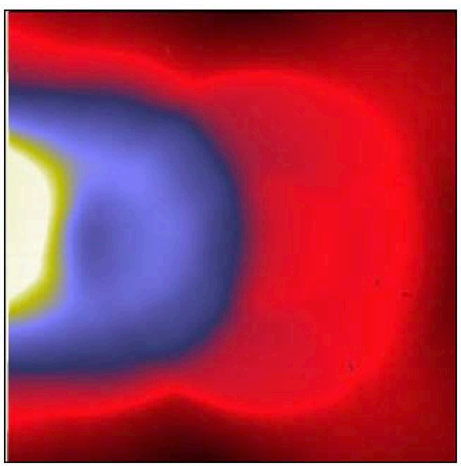


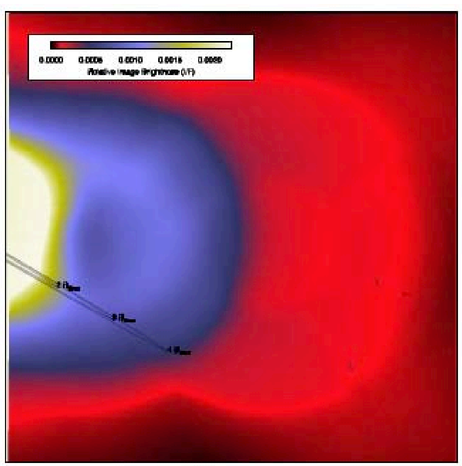
No rings around Rhea (Tiscareno et al 2010, in press)

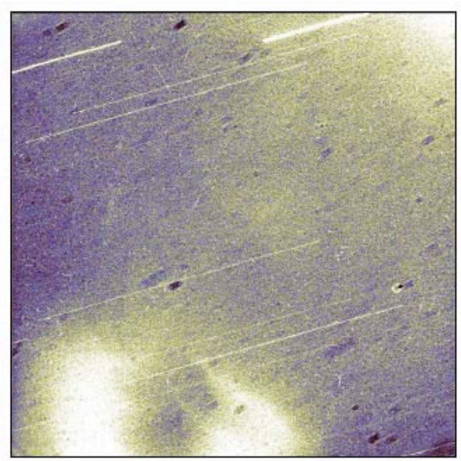
Analysis of long-exposure low- and high-phase-angle images of the region of Rhea's putative equatorial rings, taken at very low incidence angle, give sensitive constraints on the amount of particulate material (green regions) inconsistent with the amount needed to explain puzzling magnetospheric absorptions (orange regions) for either narrow rings or a thick cloud.

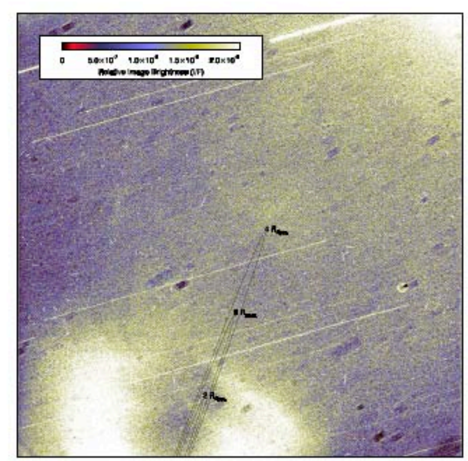












Backup

Six Years of Saturn (invited Science Review Article by the Rings WG)

Review Article for Science published (March 19 issue; J. Cuzzi, J. Burns, and 23 other members of the Rings Working Group) along with Science cover. Detailed Supporting Online Material gives basic physics and background material along with several illustrative movies (next slide). “Nugget” provided to HQ at their request. A considerable amount of press interest included interview requests from a variety of US-based and international media organizations.

Cassini has revealed that the entire Saturn system is very dynamic, with the rings evolving before our eyes. The rings are more dynamic than had been thought before Cassini, with some structure evolving in weeks or months. The narrow, stranded F ring, lying just outside the main rings, is routinely blasted by km-size icebergs crossing it on unpredictable orbits. The entire outer edges of the main A and B rings slosh back and forth, instead of maintaining fixed (if distorted) patterns. The puzzle of the rings' origin and age remains. Their color is more closely related to local icy moons than remote denizens of the outer solar system. Determining their age will require two key measurements Cassini has yet to make.

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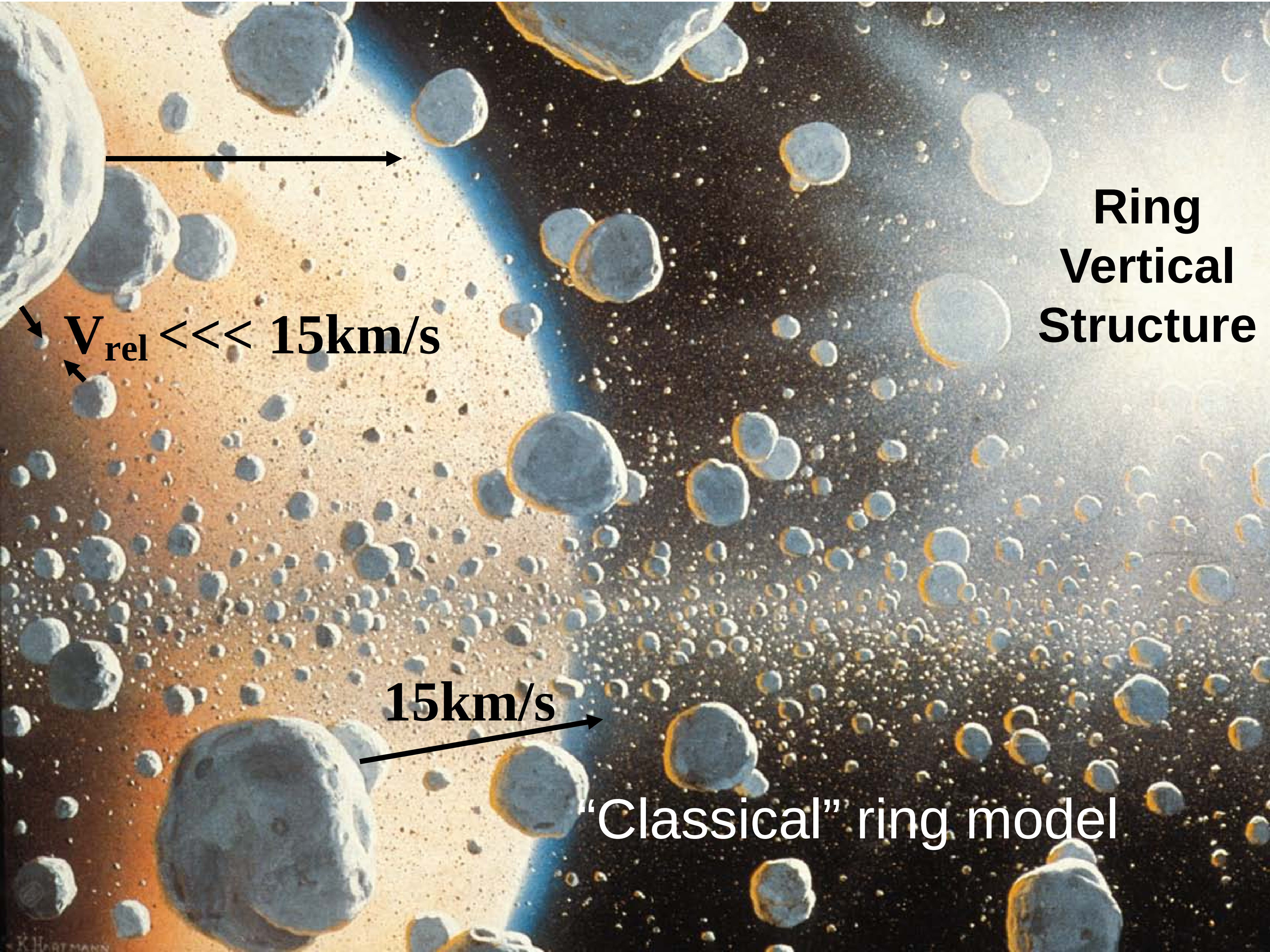
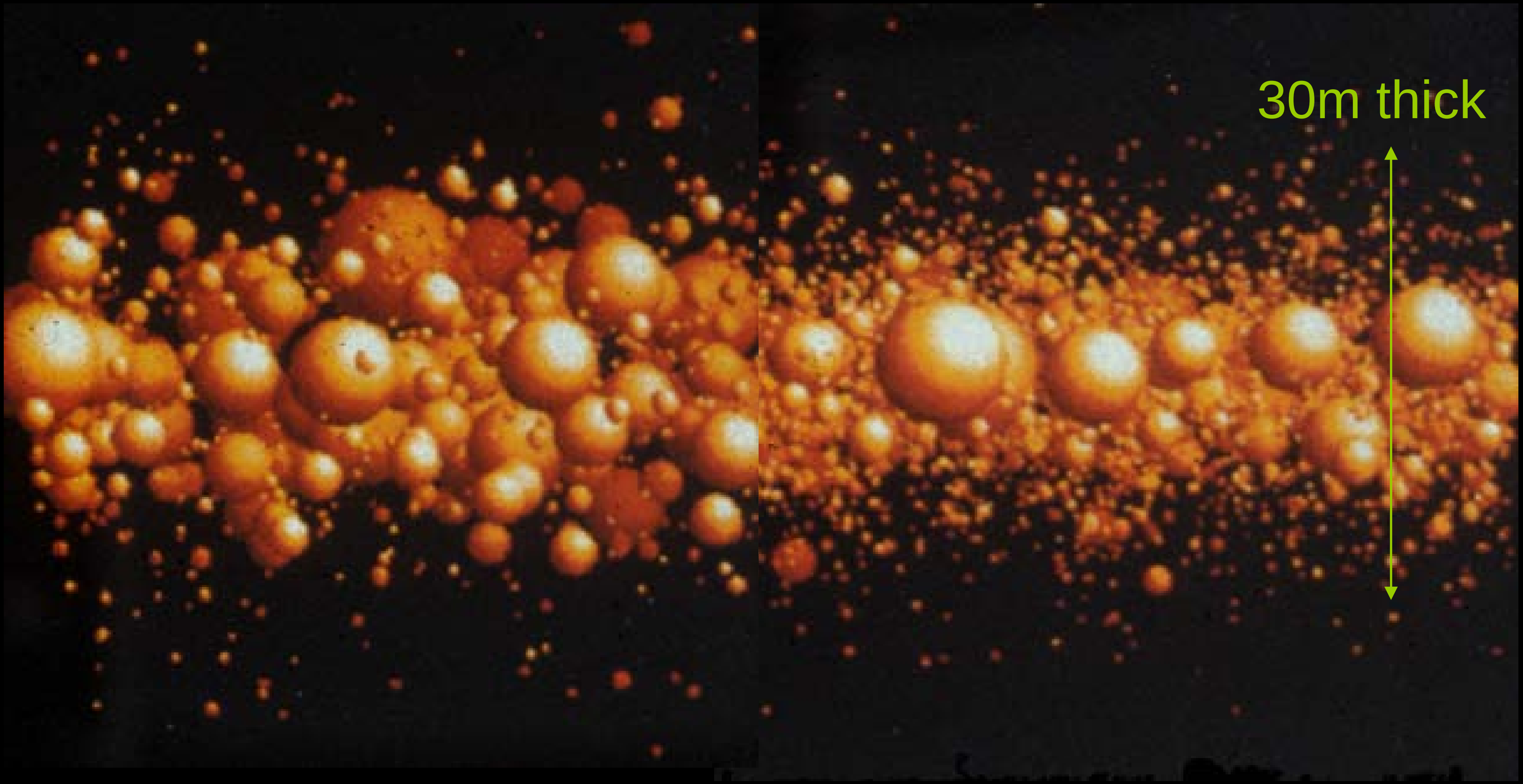

V_{rel} <<< 15km/s
Ring
Vertical
Structure
15km/s
"Classical" ring model

A more modern, densely packed ring model



Gentle collisions & weak gravity between particles give the rings the quality of a viscous fluid