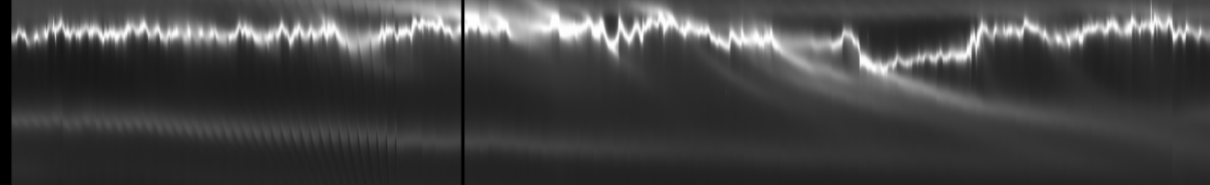


# Gravitational and Collisional Processes at Saturn's F Ring



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Rings Workshop, Boulder

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This is not a comprehensive review of the F ring, more a brief summary of what we think are the two main processes responsible for its unusual structure.

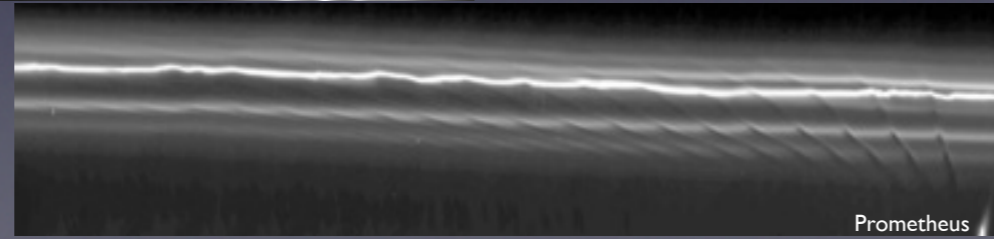
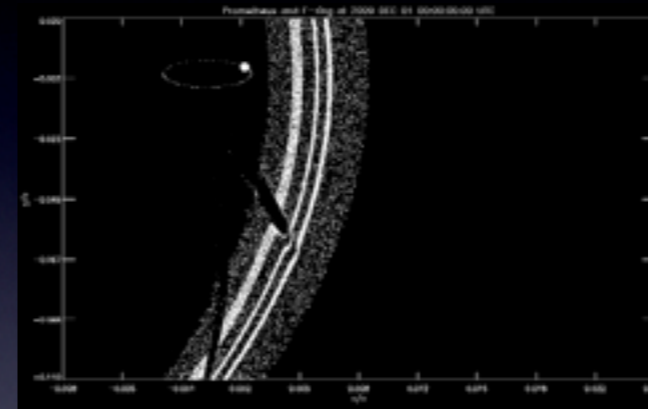
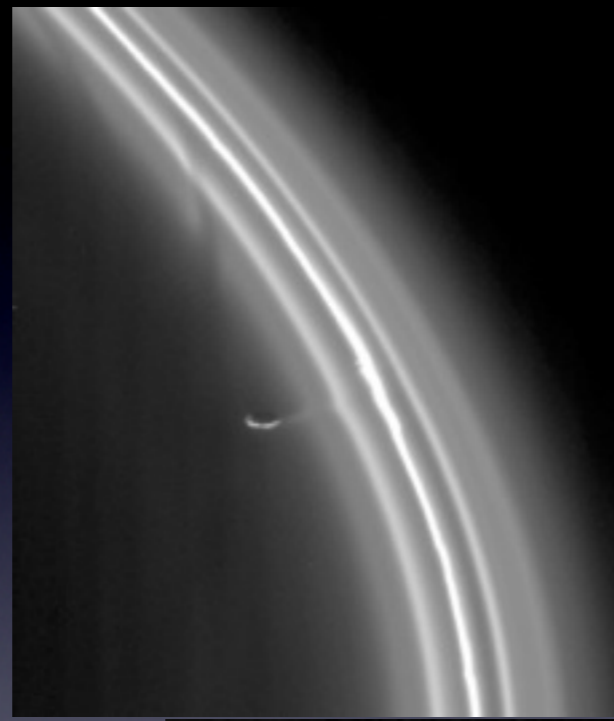
2005-103



(This is part of the lossy compressed FMOVIE from 2005; mosaic of the full movie follows later)

This shows a (i) bright core with irregular radial and azimuthal structure, (ii) multiple “strands” and (iii) regular structure induced by Prometheus as it passes.

## Prometheus forming "streamers" and "channels" in the F ring

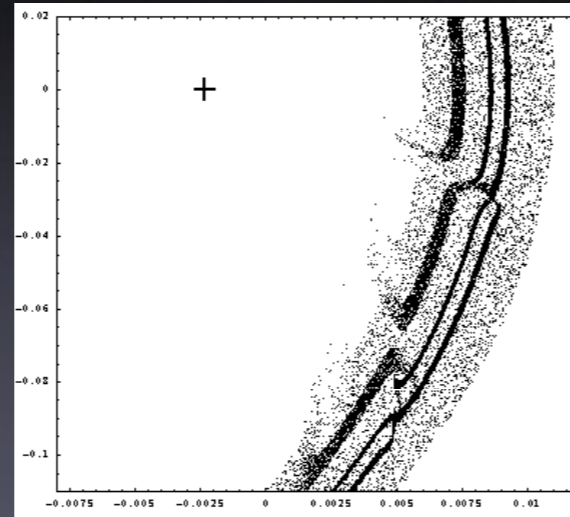


### Gravitational processes:

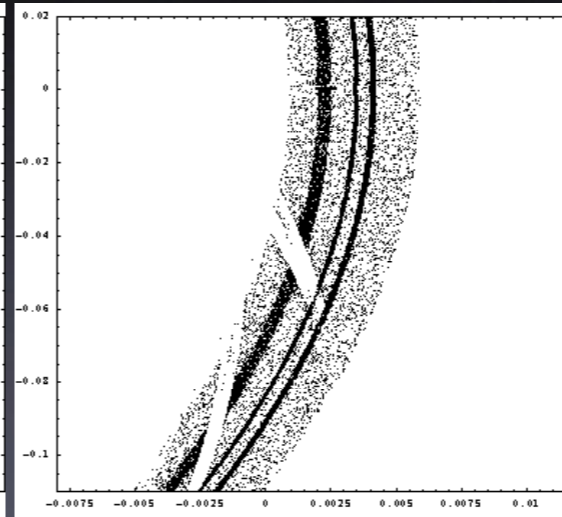
The "streamer-channel" phenomenon produced by Prometheus. Soon after its apoapse (closest approach to F ring) Prometheus' perturbation appears to drag out material ("streamer") from core. At other orbital phases it appears to produce a "channel" in the ring. One orbital period is ~16h so appearance changes rapidly. The simulation has enhanced number of particles to represent core and strands. Also, particles that encounter Prometheus are removed but clearly its gravitational effect extends beyond its radial extent. Regular pattern is produced every  $3.3^\circ$  (see lower reprojected mosaic) and although perturbation is near-instantaneous the effects of keplerian shear are very obvious.

## Prometheus perturbing F ring (anti-alignment configuration)

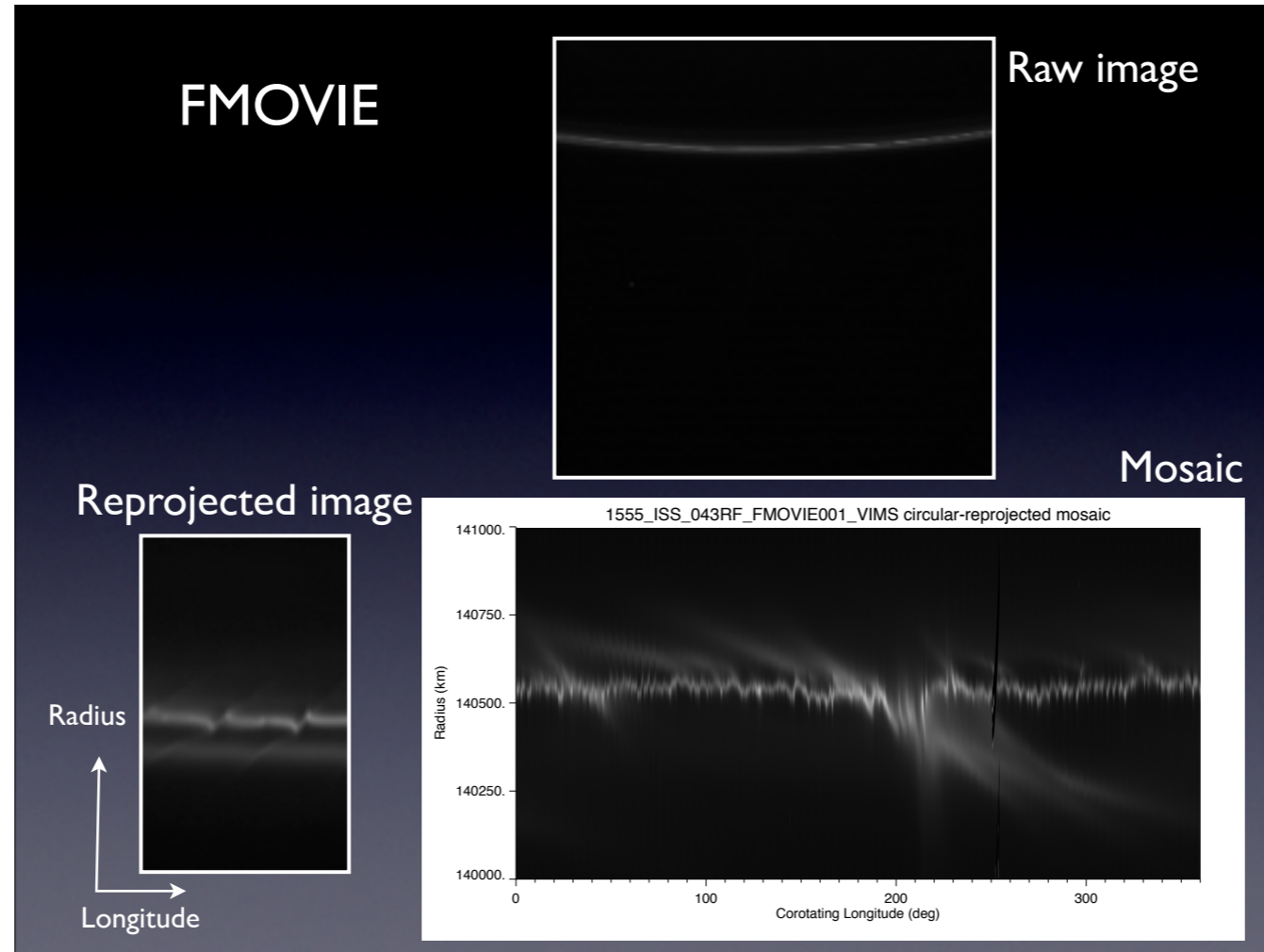
Prometheus at periapse



Prometheus at apoapse



Differential precession means that every  $\sim 19$  y the orbits of Prometheus and F ring are anti-aligned creating maximum perturbation. These two still from a movie are 0.5 orbital periods apart, illustrating how the appearance can change rapidly.



Nick C. produced this nice illustration of FMOVIEs and how mosaics are produced.

2005-103  
FMOVIE

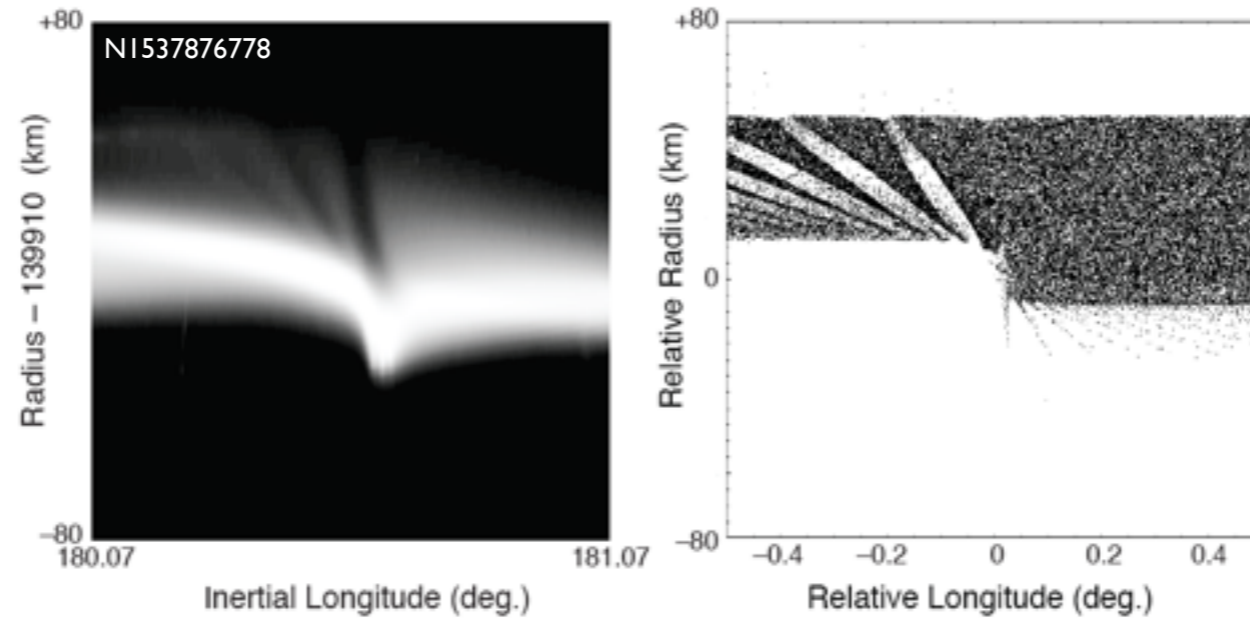
“streamer-channels”  
from Pandora

Prometheus  
and Pandora  
are near  
conjunction

“streamer-channels”  
from Prometheus

Part of the mosaic from Slide 2 clearly showing “streamer-channel” phenomenon caused by Prometheus. There is a similar but fainter structure on the top right produced by Pandora (smaller and further from core). As movie showed, the two satellites are near conjunction. Notice lots of other structure in the image, including distorted core.

## Evidence for embedded objects in the F ring core — comparison of image with simulation

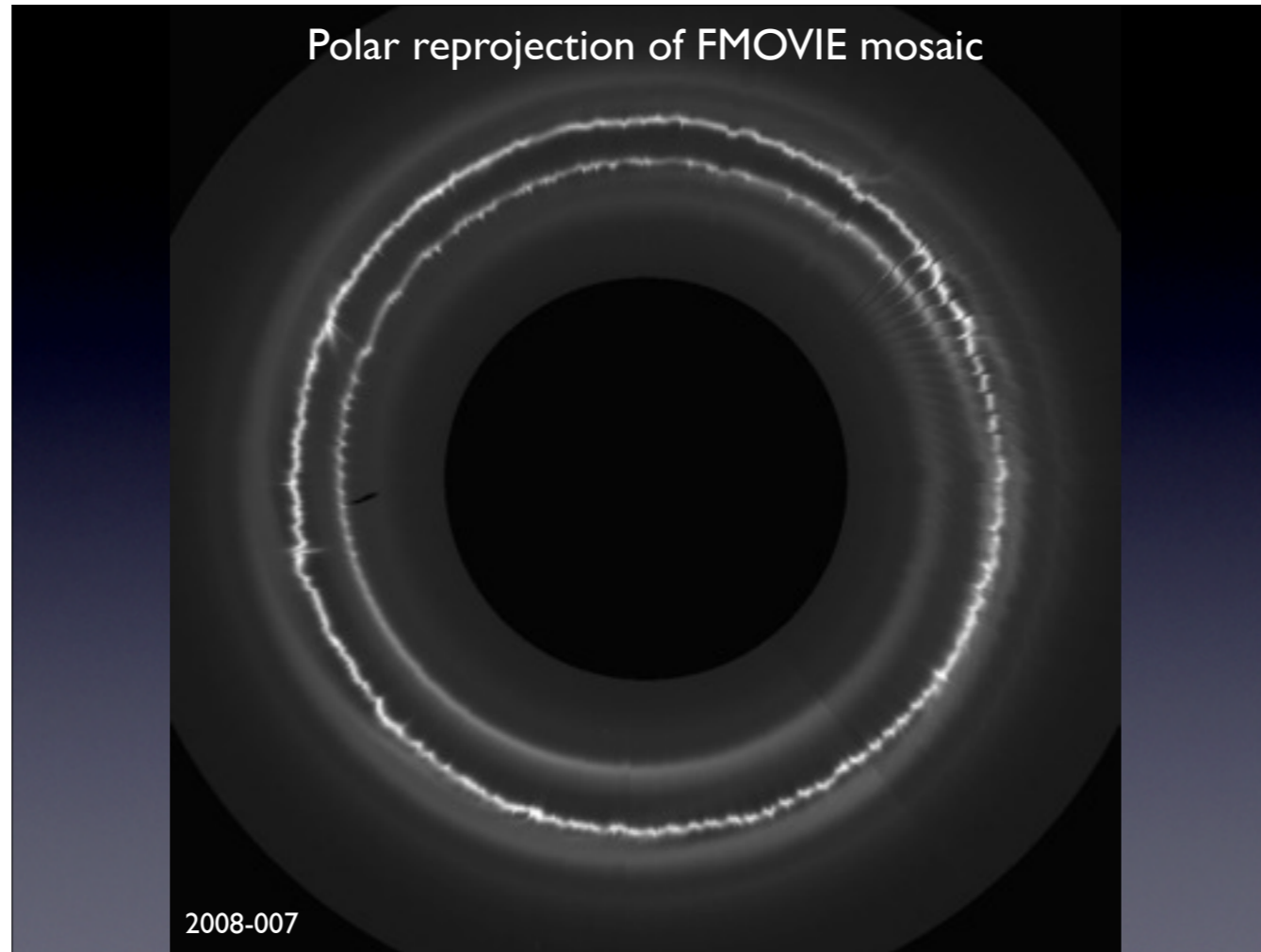


Embedded object on delta-eccentric orbit perturbs adjacent material which acts like a tracer for the gravitational effect of the object — entirely analagous to the mechanism by which Prometheus creates channels in the F ring

Gravitational processes:

“Fans” provide evidence of embedded objects that are massive enough to perturb nearby material. Time variable structure is caused by object on orbit that is eccentric w.r.t. the F ring. (An object on a the same orbit as the F ring would produce fixed structure.)

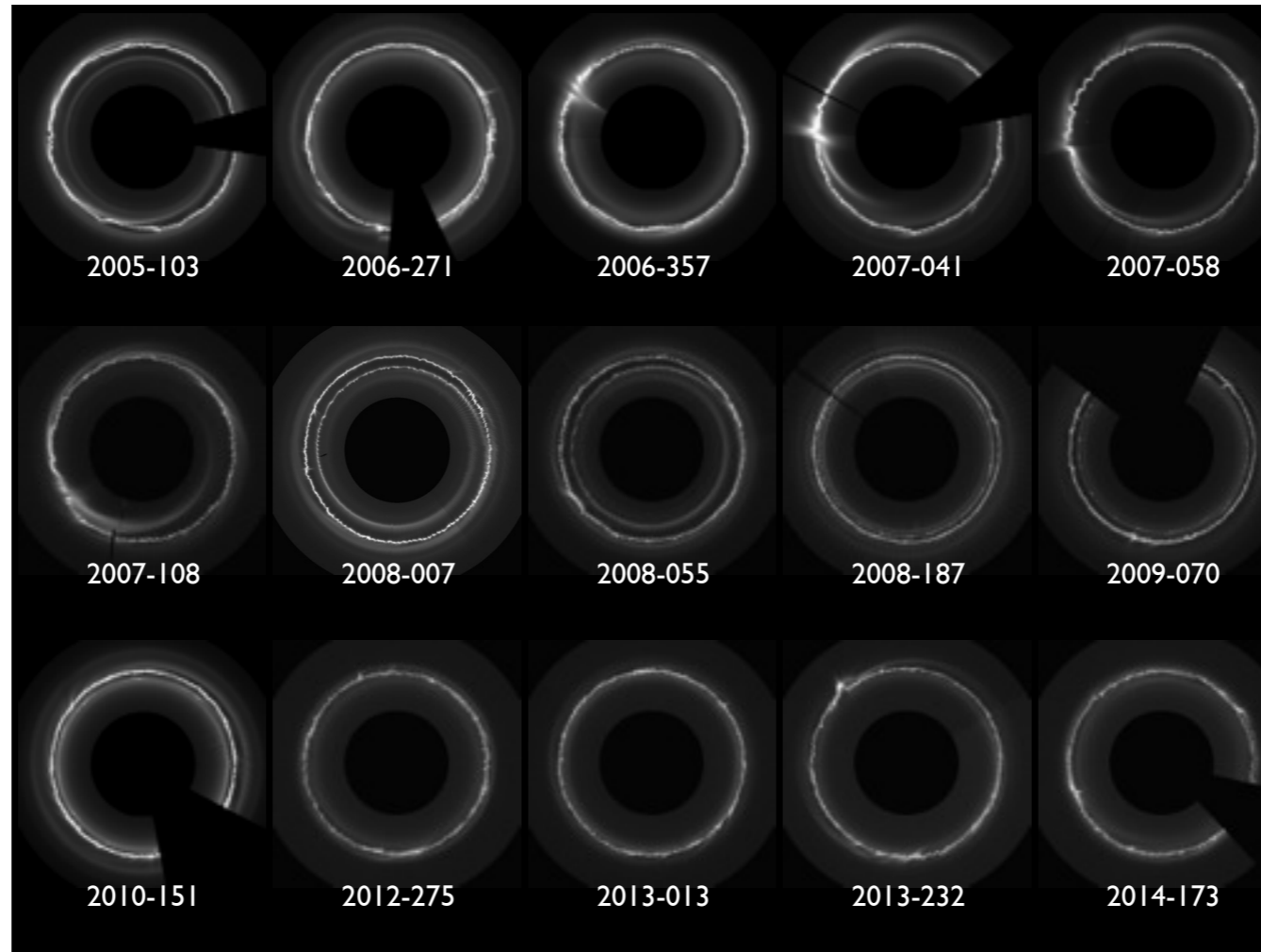
## Polar reprojection of FMOVIE mosaic



2008-007

Radius-longitude mosaics can be reprojected using polar coordinates. This highlights the fact that the “strands” are actually spiral in nature, indicative of keplerian shear affecting an initially radial structure, i.e. an initial range of semi-major axis because structures stay of one side or the other irrespective of viewing longitude. Strongly suggestive of collisional process. (Need to emphasise peculiar nature of FMOVIE — mosaic derived from observed at a fixed range of inertial longitude.) Note Prometheus “streamer-channels” starting near 2 o’clock and regular structure that trails it, regularity eventually breaking down.

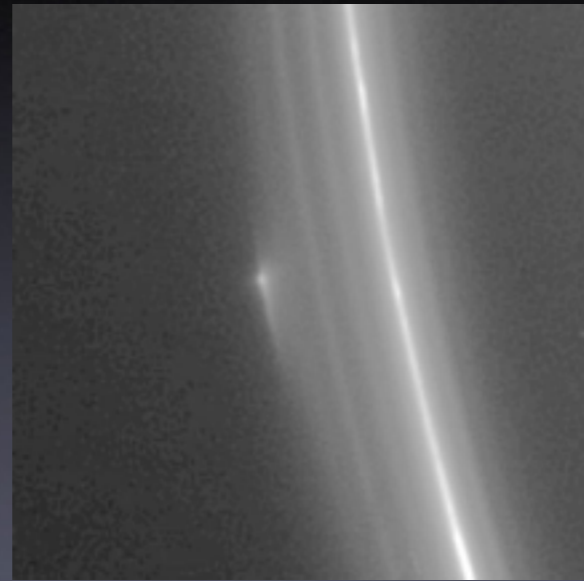




A sample of polar mosaics at different times in the mission. Note major event visible in 2006–357 and its subsequent evolution. No two mosaics are the same yet all show some degree of radial structure.

## S/2004 S 6

2005-172 Detection



2005-180 Detection

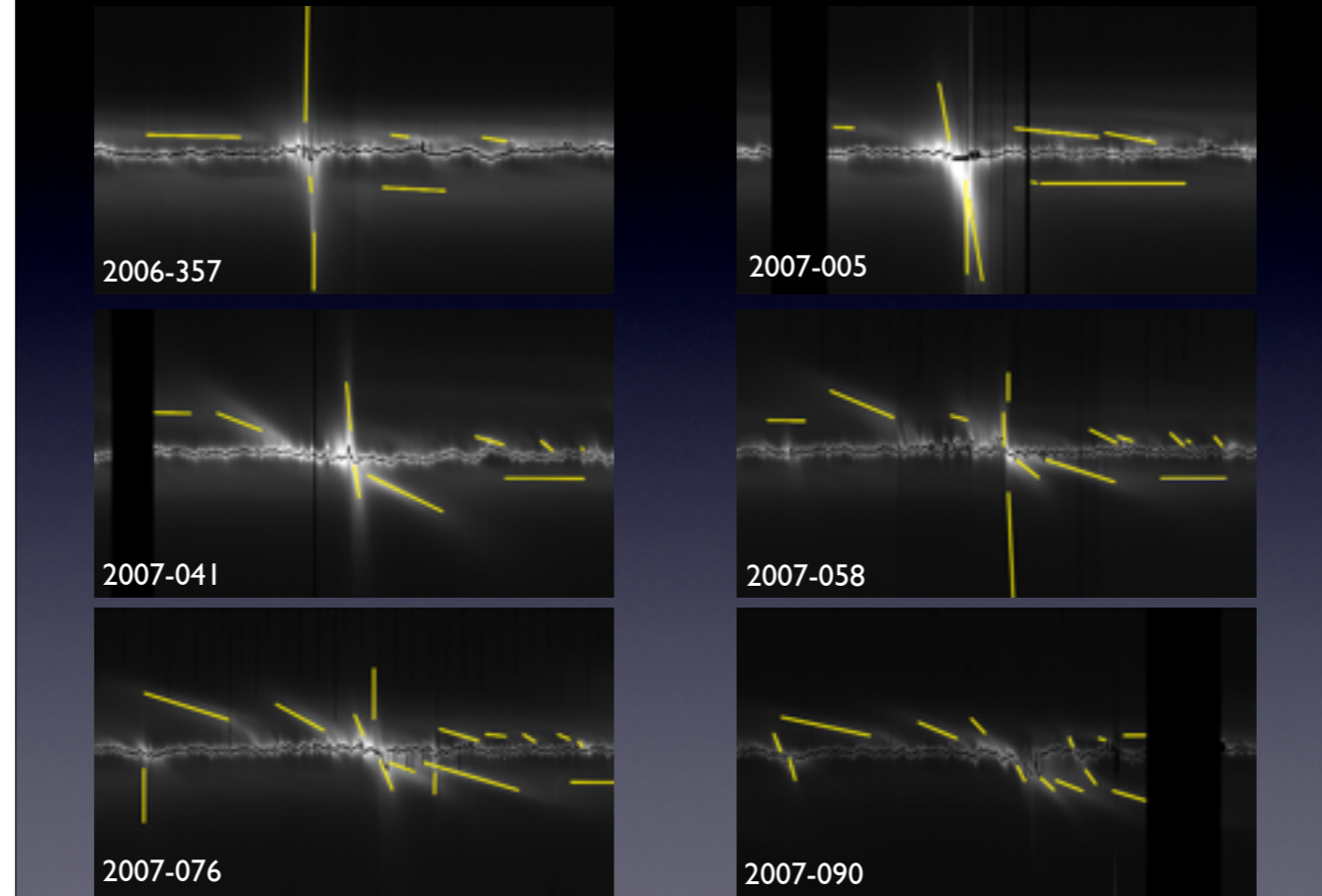


S/2004 S 6 (a.k.a. S6) is one of a number of objects that collide with the F ring to produce “jets”

### Collisional processes:

S6 is our best candidate for one of a number of objects that collide with the F ring core to produce jets. This was most obvious in the late 2006, early 2007 sequences. Note that these two images, 8 days apart, show S6 on either side of the core. Elongated nature (ahead and behind) suggesting material drifting from object.

## Evolution of F ring jets over 98 days



### Collisional processes:

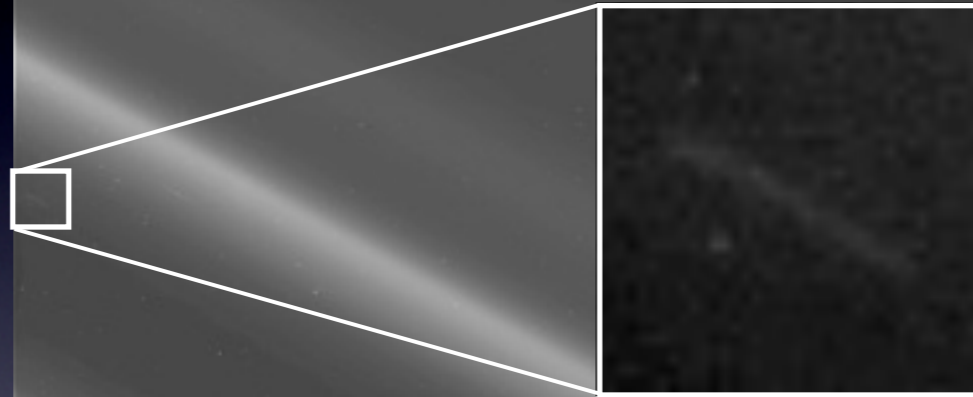
Progress of S6 along F ring core in early 2007. S6 has semi-major axis less than that of core and so in our co-rotating frame moves from left to right. All reprojected mosaics are  $\pm 750\text{km}$  w.r.t. Cooper et al. orbit model. The yellow lines denote fitted "jets" — produce of collisions between S6-like objects and core. Note that there are "jets" that are not caused by S6 — as S6 progresses other "jets" appear behind and ahead of it.

# F ring “jets”

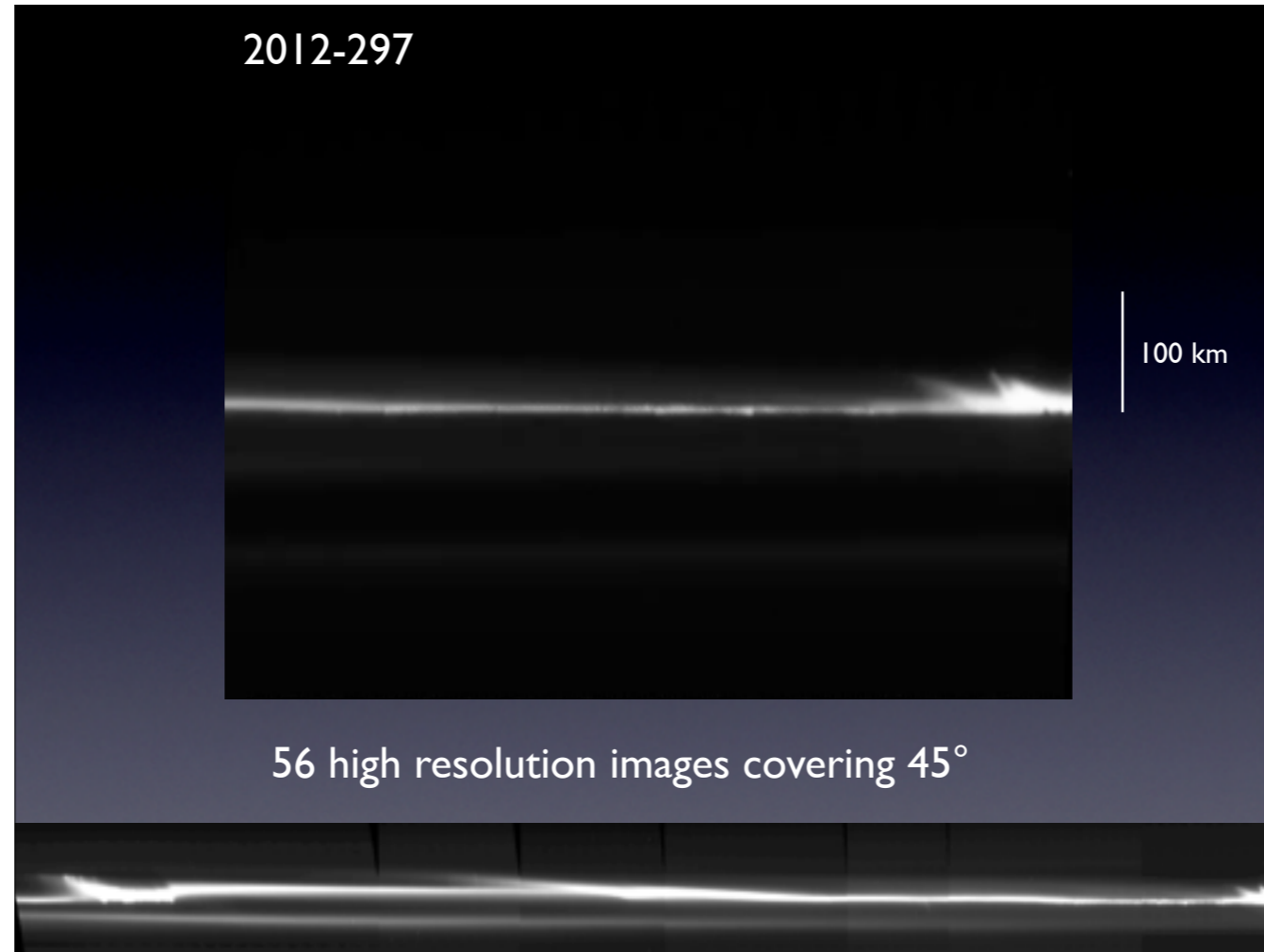
- There are  $\sim 12$  separate jets at any one time
- Visible for  $\sim 60$  days (but highly variable)
- Results imply jets are caused by a population of  $\sim 6$  objects
- During the early-2007 sequences there were 4 or 5 colliding objects, including S6
- Angle evolution is hard to fit but they do not oscillate into the core (unlike mini-jets); must have  $\Delta a > a\Delta e$
- Likely to be caused by complex, extended collisions

Summary of “jet” properties.

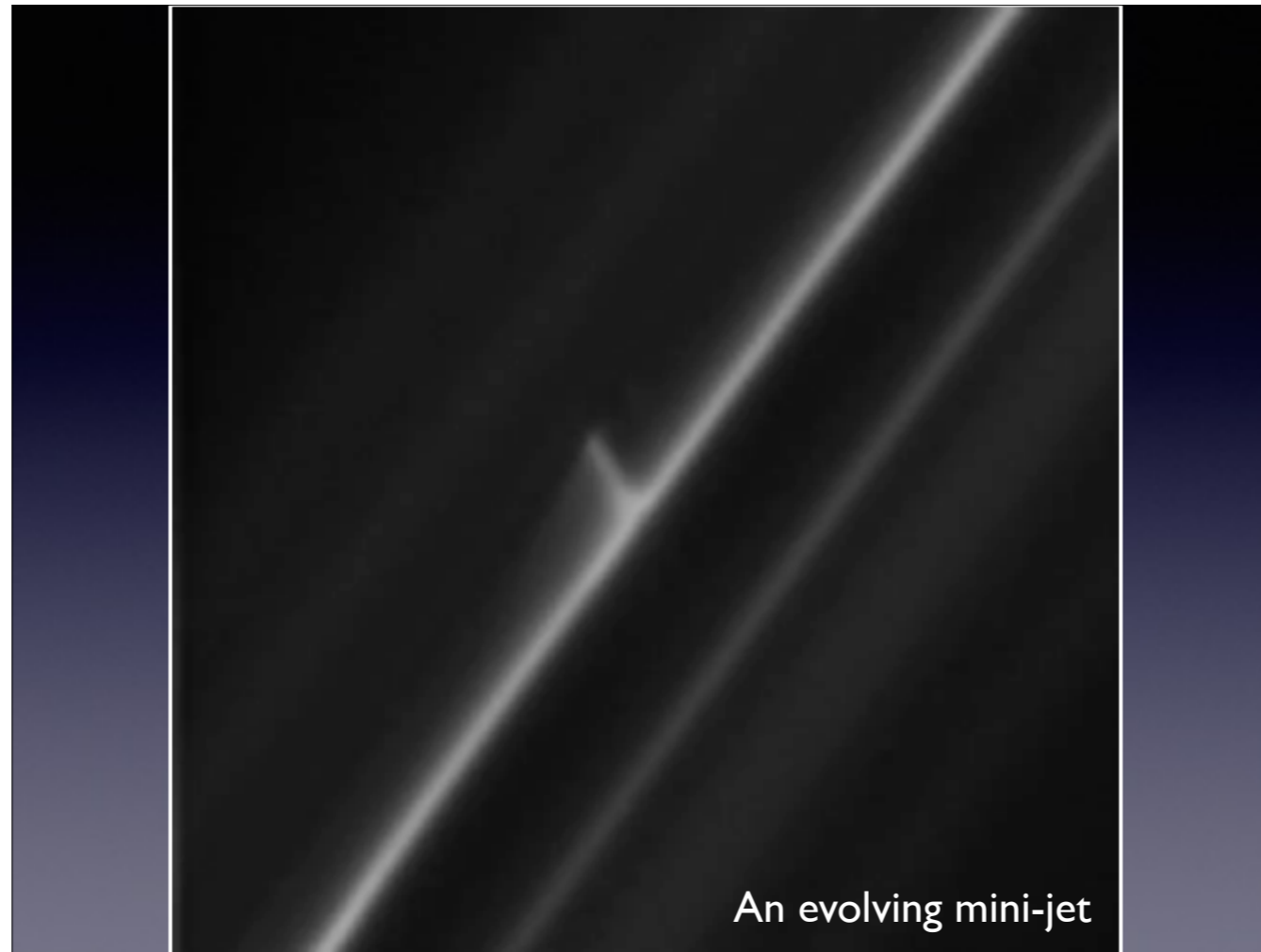
High resolution images show trails —  
evidence for small objects moving close  
to F ring core



S6's orbit means it has relative velocity  $\sim 20\text{m/s}$  w.r.t. core at impact. What about objects that are probably smaller and closer to the core? (cf. "kittens" from UVIS and VIMS occultations). Several streaks are seen in high-resolution NAC images (this is N1595328837, 820ms exposure; covers  $0.24^\circ$  in longitude).



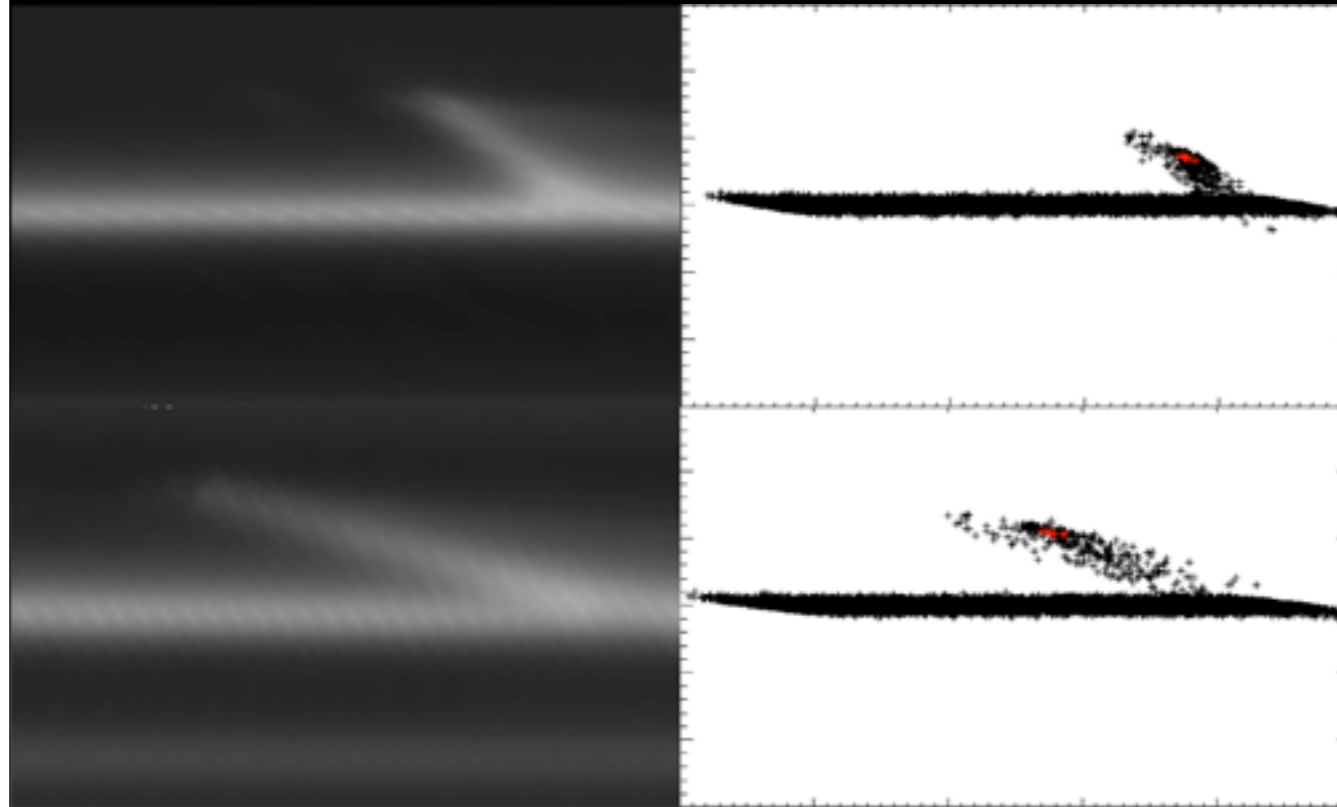
This one of our more experimental sequences where we chose drift w.r.t. core. You can spot at least two “mini-jets” – inward one at ~7s and the second outward one at ~17s. There are also multiple structures at start and end of sequence. This 45° scan is indicative of variable structure along core with wide variety of collisional phenomena.



Collisional processes:

First sequence to show evolution of classic "mini-jet" (from "streamer-channel" movie that was tracking Prometheus). Note simultaneous shearing and collapse to core.

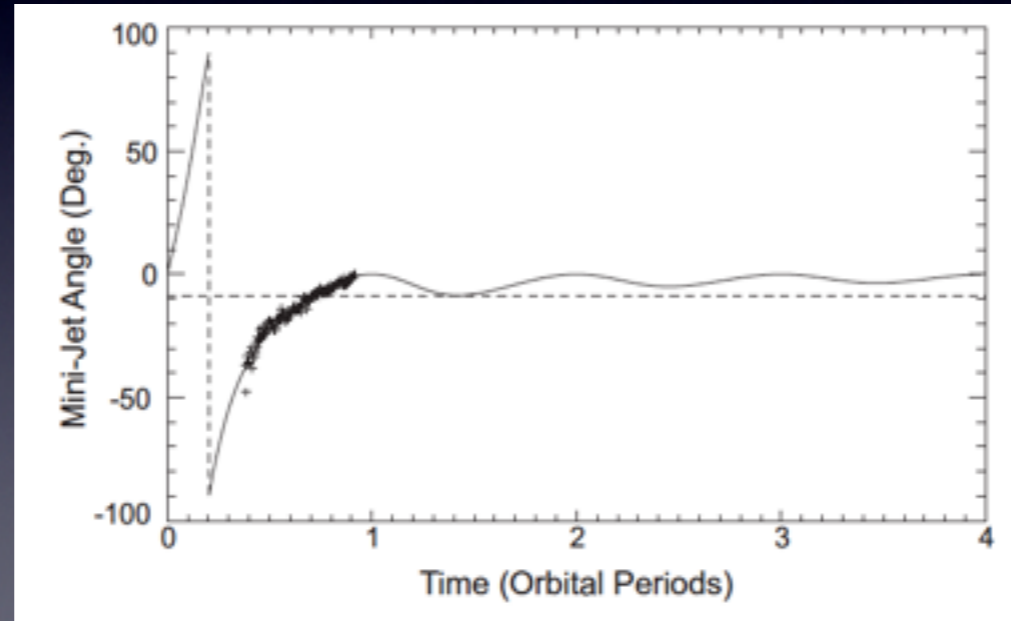
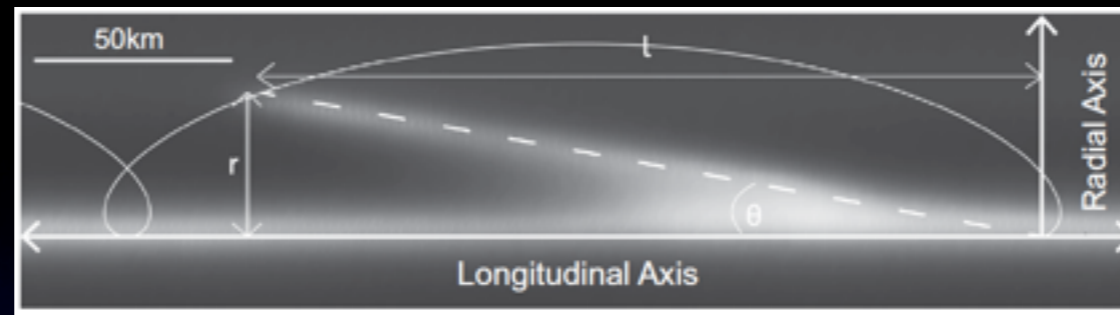
## Comparison of reprojected images with simulation



### Collisional processes:

Two frames from reprojected “mini-jet” sequence along with simulation obtained using REBOUND code in the symplectic epicycle integrator mode. (Nick A’s work.) The red points are the colliding object which is made up of 10X 100m radius particles on orbits with  $\Delta a = a\Delta e = 27\text{km}$  relative to the 20000 ring particles (black points) which are 1m radius. Collisions use a velocity dependent coefficient of restitution from Bridges et al (1984). Outcome almost independent of assumed coefficient of restitution.





Attree et al.  
(2014)

Collisional processes:

Upper: Illustration of epicyclic path superimposed on reprojected “mini-jet” image. Note that, in principle, cycle can continue but extended material is colliding with core. This will ultimately limit lifetime.

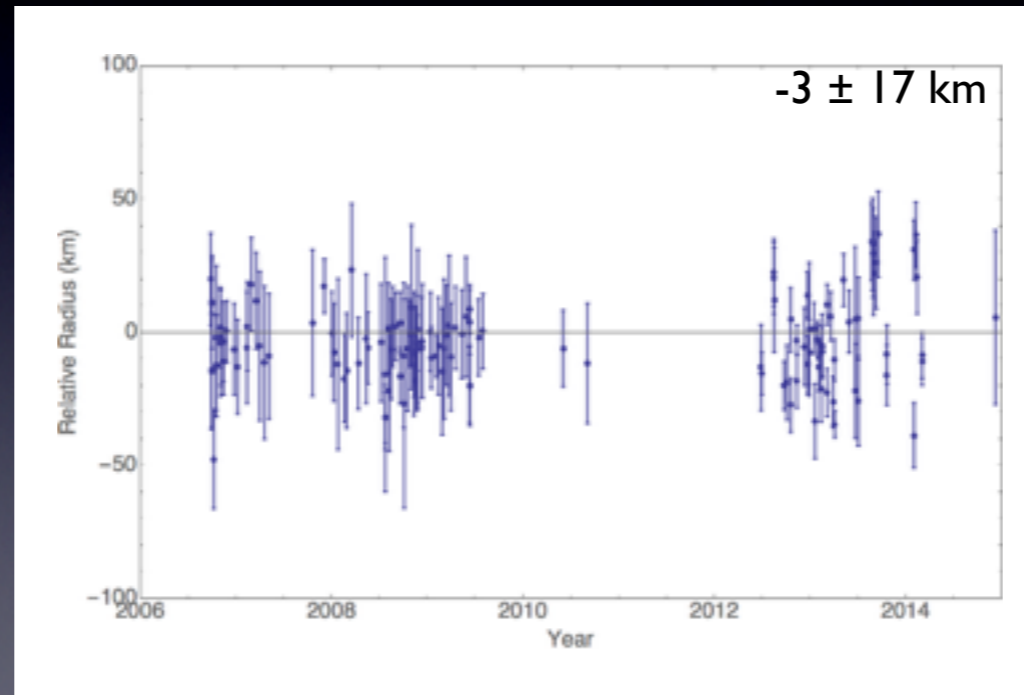
Lower: predicted evolution of “mini-jet” angle with time (similar to that used by Tiscareno et al. in ring impact Science paper — same mechanism) and comparison with measured angles.

# F ring mini-jets

- There are  $\sim 12$  separate mini-jets at any one time
- Lifespan of  $\sim 1-10$  days; limited by repeated collisions with core
- Results imply mini-jets are caused by a population of  $\sim 50$  objects orbiting close to, and colliding with the core
- Mini-jets appear to be randomly distributed around the F ring — no correlation with location of Prometheus
- Angle evolution can be fitted by simple epicycles undergoing keplerian shear; must have  $\Delta a \sim a\Delta e$

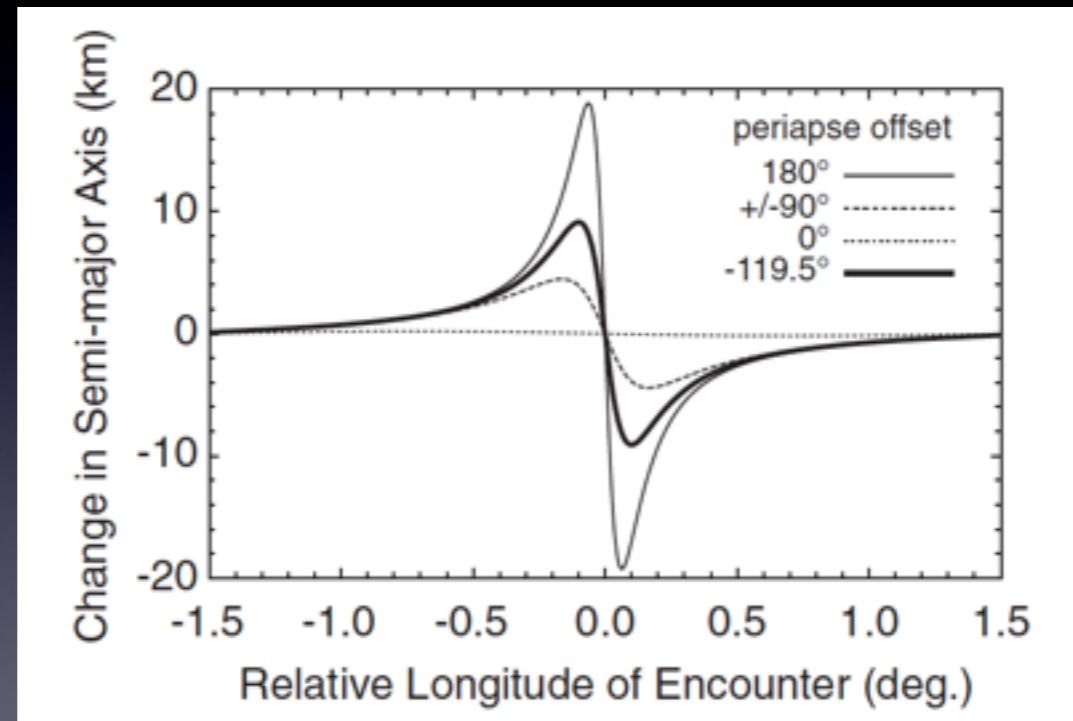
“Mini-jet” summary.

## Mean distortion of F ring core w.r.t. orbit derived by Cooper et al. (2014)



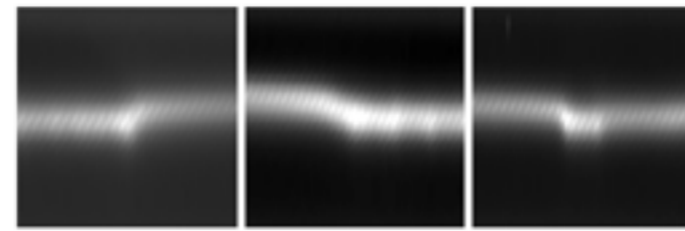
We have >140 mosaics of varying longitude ranges, including almost 20 opposite ansae sequences (very useful for understanding effect of eccentricity/periapse). Here we restrict full-resolution mosaics to within +/- 150 from predicted Cooper et al. core and measure offset of brightest pixel to estimate distortion. Variation gives indication of inherent distortion of core. This can clearly be seen in images and is most likely due to Prometheus. Gaps are due to equatorial orbits.

# Changes in semi-major axis induced by Prometheus



Beurle et al. (2010)

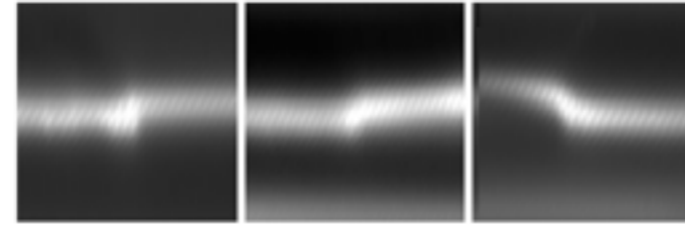
Plot of induced semi-major axis of core produced by Prometheus. (We have equivalent plots for changes in  $e$  and curly pi.) Combination of  $\delta a$  and  $\delta e$  roughly doubles radial distortion. Note that this is consistent with observed radial distortion in previous slide.



(a)

(b)

(c)



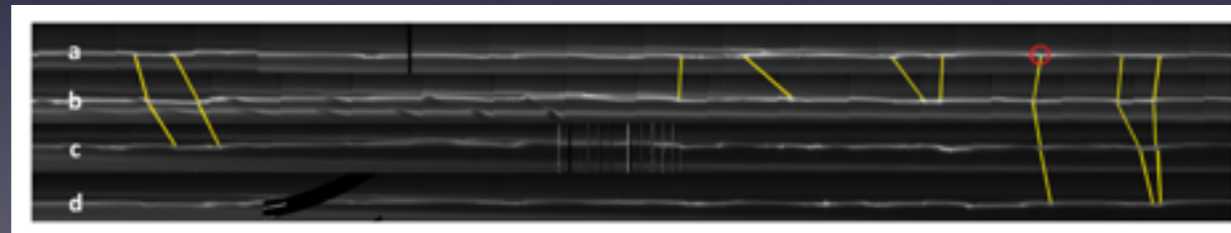
(d)

(e)

(f)

Typical localised core clumps

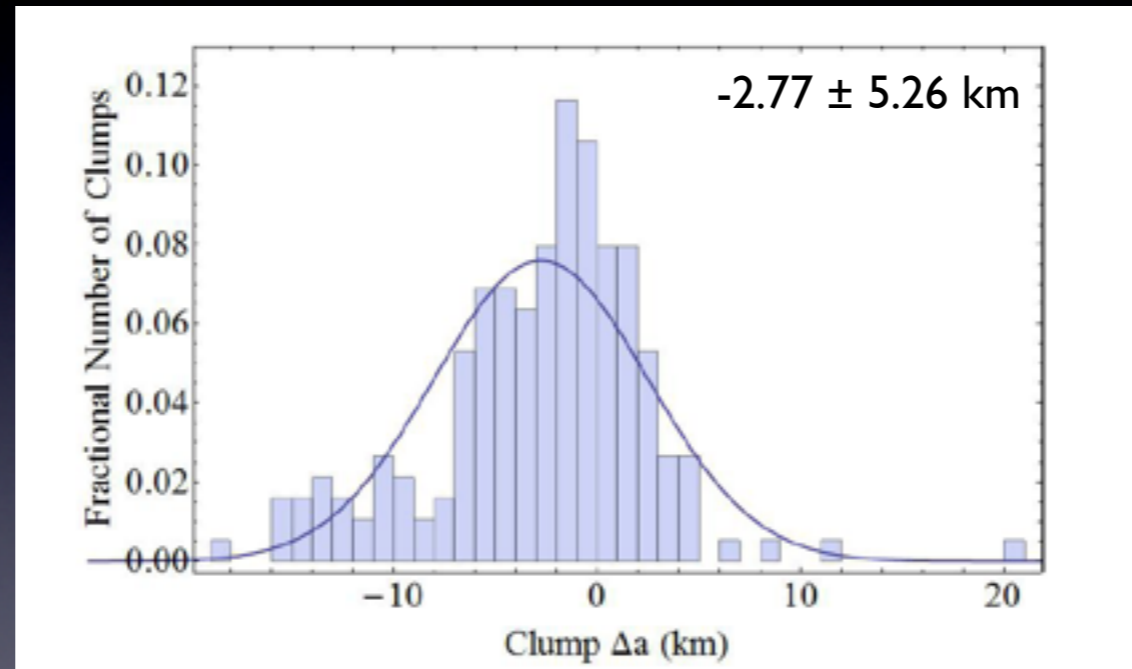
Each reprojected image covers  $0.6^\circ$  in longitude and 190 km in radius



Clumps seen in mosaics obtained on 2007-058, -076, -090 & -108

Another approach is to track clumps seen in successive mosaics. Clumps are produced as a result of Prometheus perturbations at each encounter with core — initially every  $\sim 3.3^\circ$  but they drift. Drift allows us to estimate semi-major axis. (This is from work done by Wai Fun Lam from her MSci project with me this year.)

# Semi-major axes derived from tracking of ~500 clumps in core



Longest clump lifetime observed is ~36 days

Wai Fun Lam (unpublished)

Quite symmetric spread of delta a values, consistent with what we might expect from perturbations by Prometheus (see Slide 20). Note clump lifetime estimate is consistent with the French et al. estimates from their (extended) bright clumps seen in integrated width profiles.

# Summary

- The F ring core is gravitationally perturbed by Prometheus, Pandora as well as embedded objects
- Collisions with nearby objects produce “jets” (giving rise to multiple strands) and the more localised “mini-jets”
- Distortions in core are consistent with gravitational effect of Prometheus
- Semi-major axes of clumps are consistent with gravitational effect of Prometheus
- We think that the gravitational effect of Prometheus creates the clumps which go on to form the objects that subsequently collide with the core to form “jets” and “mini-jets”

Summary slide. We think “jets” and “mini-jets” are caused by the same process but different collisional regime. Emphasise model: Prometheus creates clumps; clumps drift w.r.t. core and may survive and grow (or be destroyed); close clumps can create “kittens” and “mini-jets”; could eventually end up in S6-like orbits to create jets. Could tie in with Cuzzi et al. recent results on preferred orbit locations — currently being investigated.