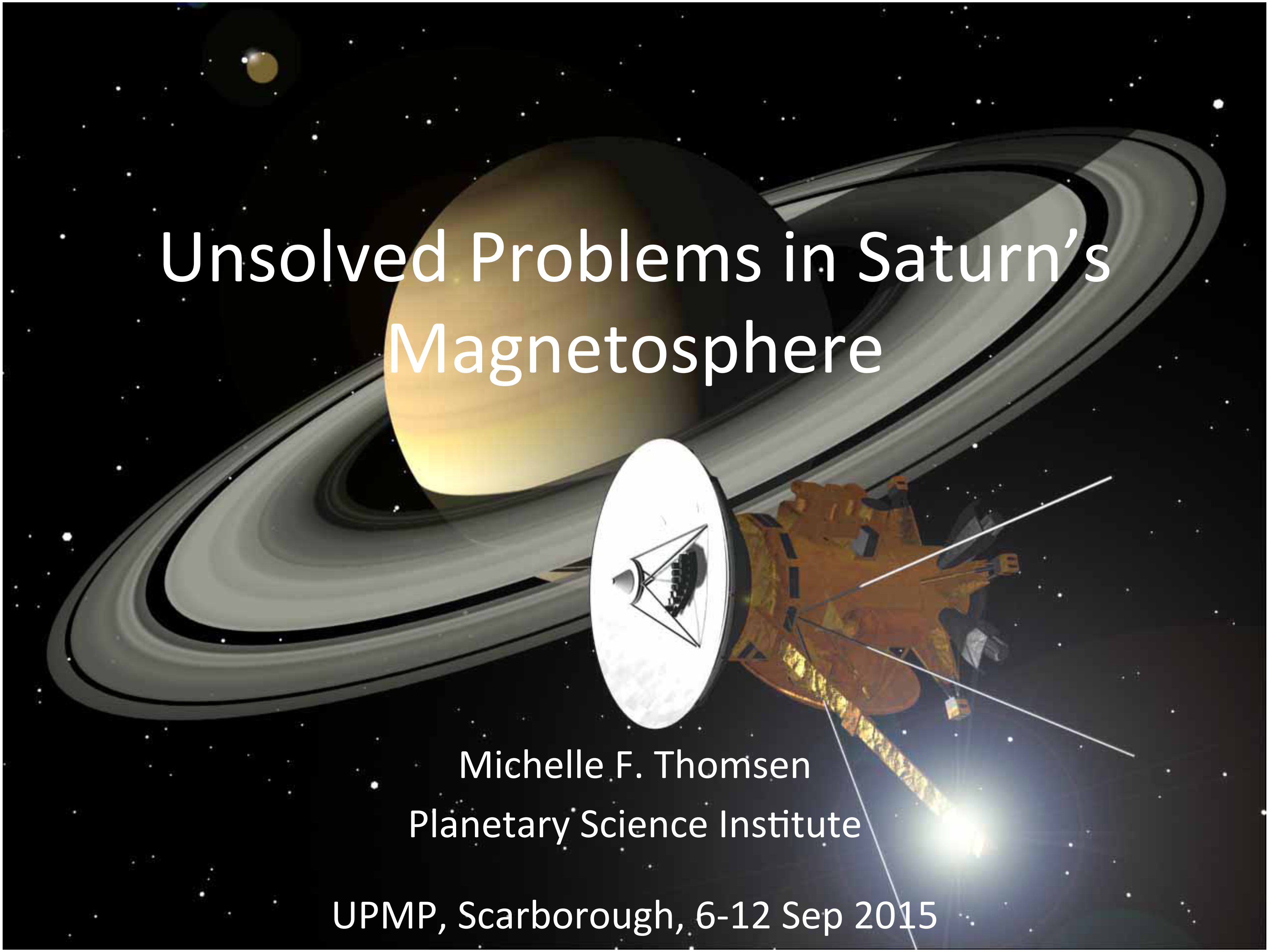

Unsolved Problems in Saturn's Magnetosphere

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Planetary Science Institute

UPMP, Scarborough, 6-12 Sep 2015

If you’ve seen one magnetosphere,

you’ve seen one magnetosphere!

Saturn's magnetospheric features:

- Radiation belts
- Plasmasphere
- Plasma sheet
- Magnetospheric tail
- Aurorae
- Bow shock
- Magnetopause
- Magnetospheric dynamics (convection, reconnection, wave-particle interactions, etc.)

But each of these is significantly different from the corresponding features at Earth!

Factors Affecting Planetary Magnetospheres

	Saturn rel. to Earth
• Size of the planet	10x
• Strength of its magnetic field	500x
• Presence of satellites and rings	Earth has none
• plasma sources	✓
• plasma sinks	✓
• dynamic interactions	✓
• imbedded magnetospheres!	✓
• Rotational period	2.5x faster
• Tilt of magnetic dipole rel. to rotational axis	~0
• Properties of external plasma (solar wind)	n~0.02x; B~0.1x merged stream regions; high M_A

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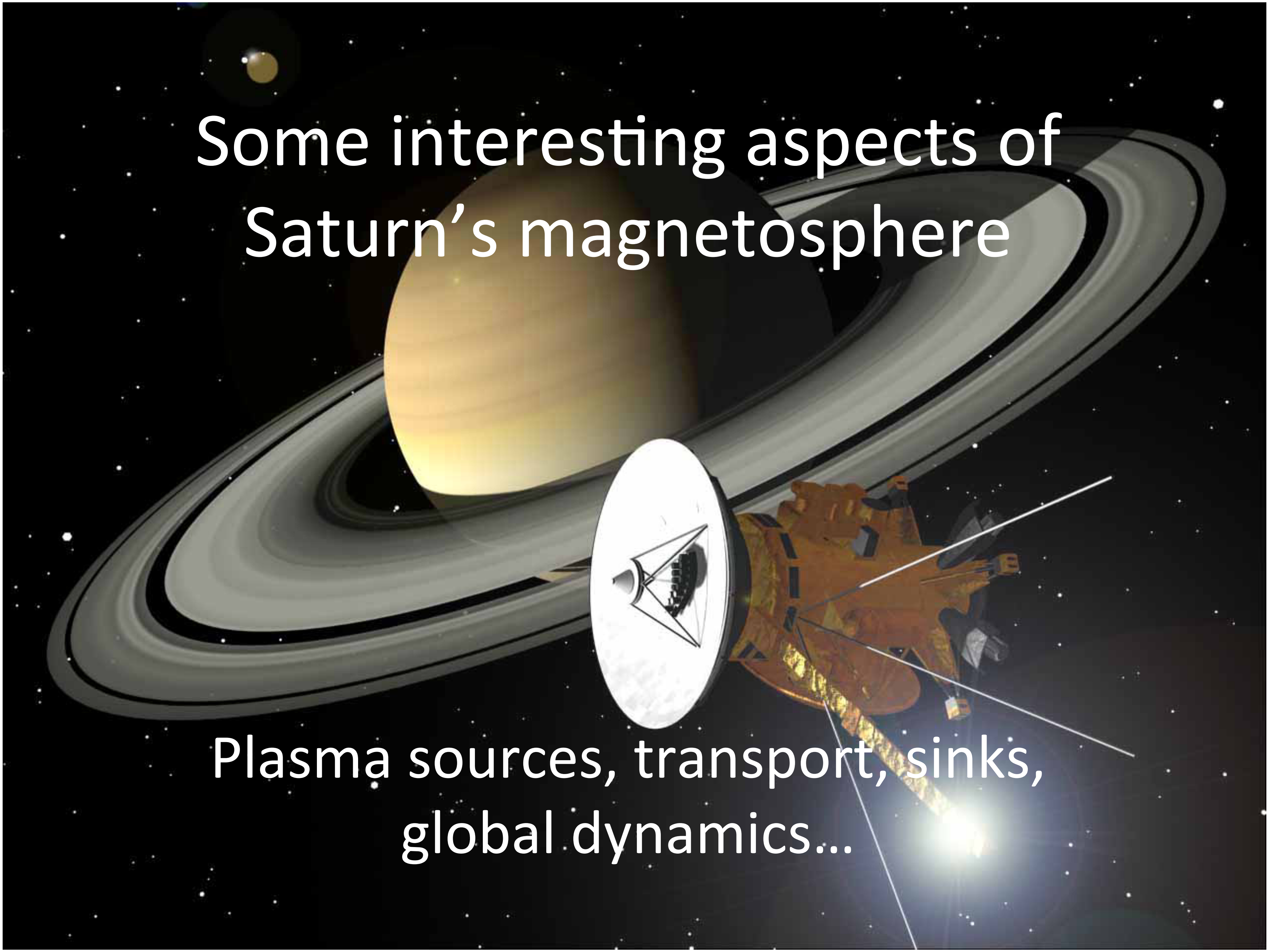
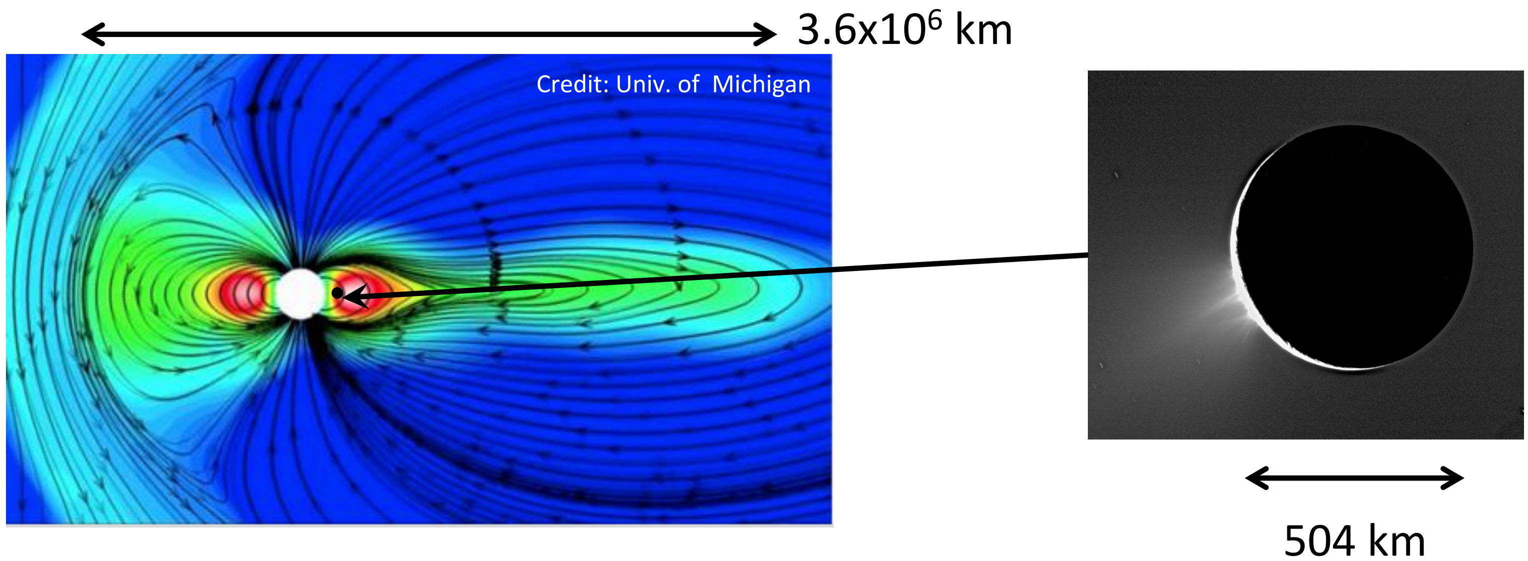
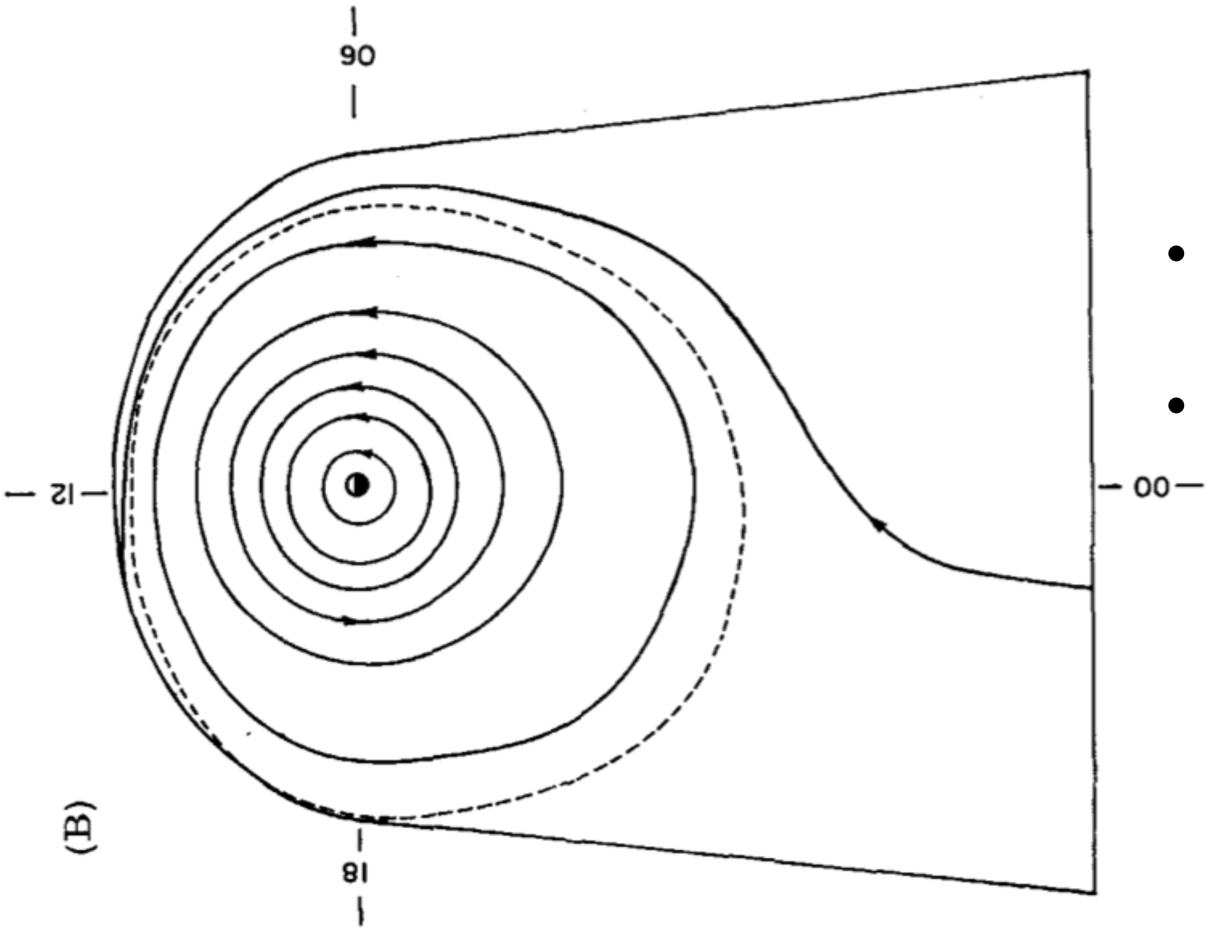

Some interesting aspects of
Saturn's magnetosphere
Plasma sources, transport, sinks,
global dynamics…



Saturn’s Magnetospheric Imperative

- Dominant source of plasma in Saturn’s magnetosphere is at low L (ionization of gas from Enceladus)
- Recombination is too slow to maintain a steady state
- All this plasma must ultimately be shed to the solar wind
- How and where does that happen?

Convection at Saturn is dominated by corotation



- Weaker interplanetary field
- Rapid rotation

Therefore, no convection plasmapause is expected.

Brice and Ioannidis, The magnetospheres of Jupiter and Earth, *Icarus*, 1970

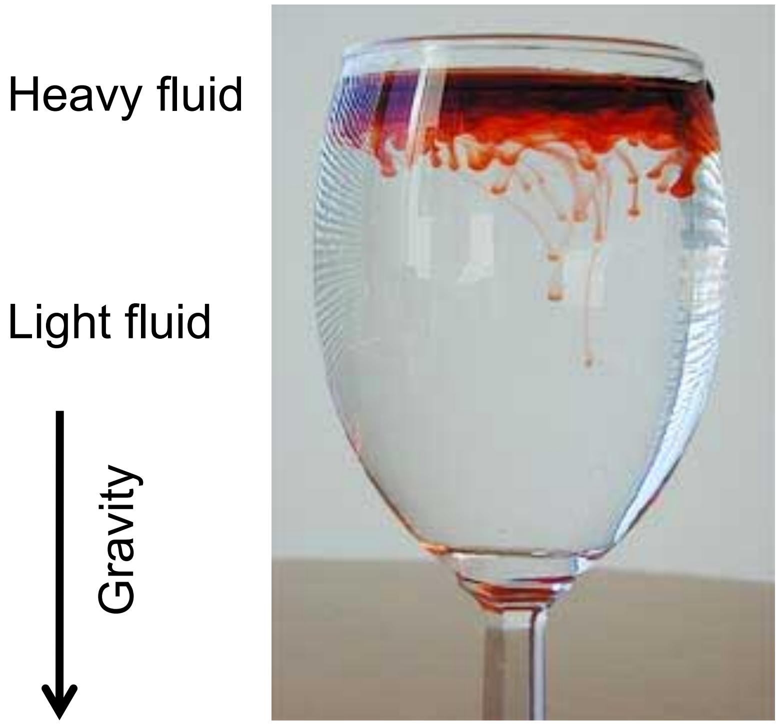
Plasma Shedding at Saturn: A Two-Step Process

1. Centrifugally-driven interchange
   - Inner to middle magnetosphere

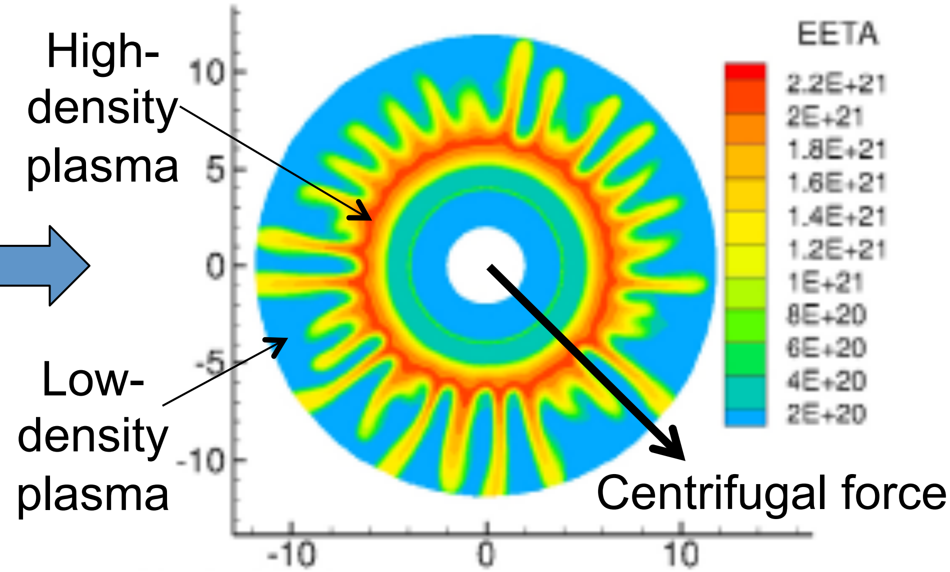
2. Tail reconnection/Plasmoid release
   - Middle/outer magnetosphere

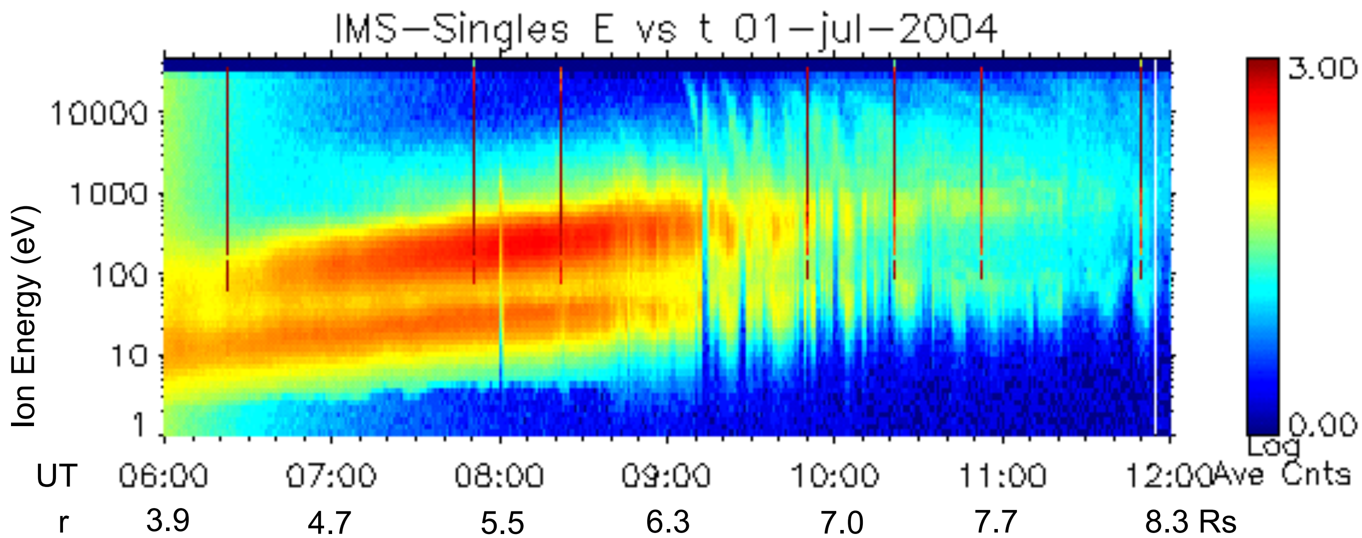
Step One: Centrifugally-Driven Interchange Instability

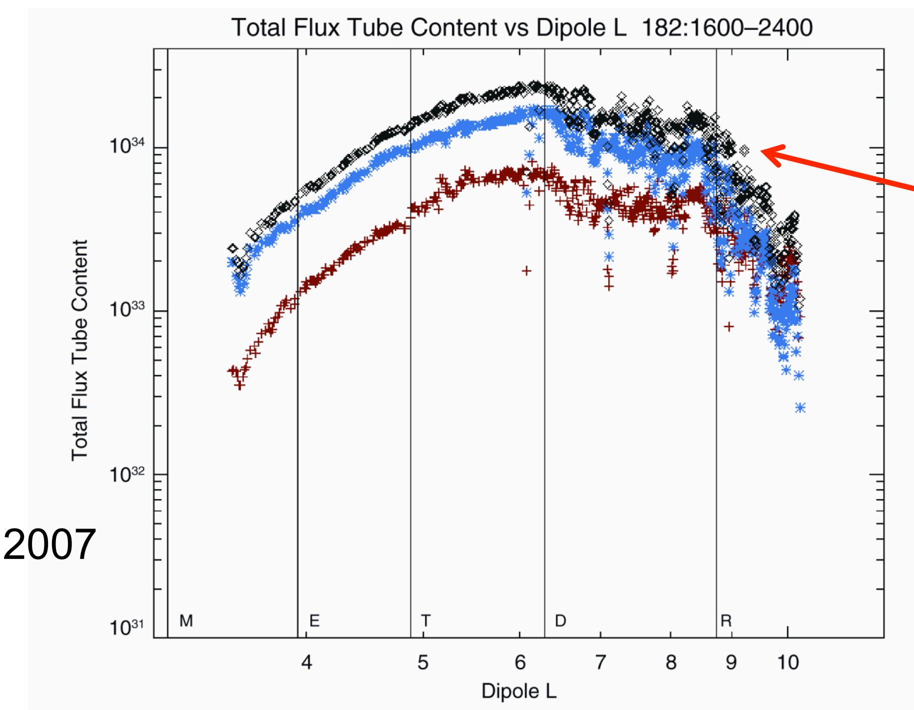
Rayleigh-Taylor Instability



Liu et al., 2010







Sittler et al., 2007

Interchange-unstable when

$$\frac{\partial \eta}{\partial L} < 0$$

where

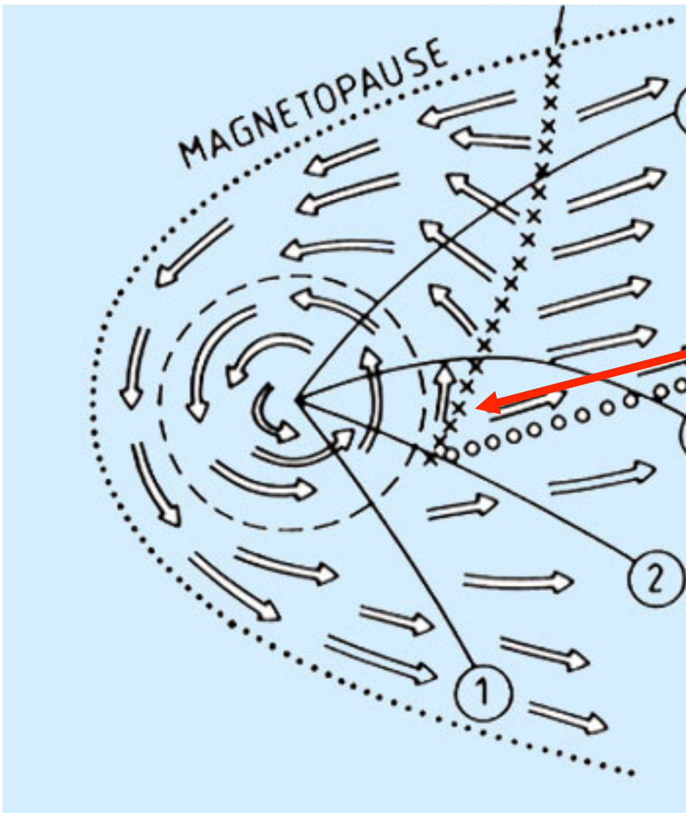
$$\eta = \int_V n\, dV$$

Southwood & Kivelson (1987)

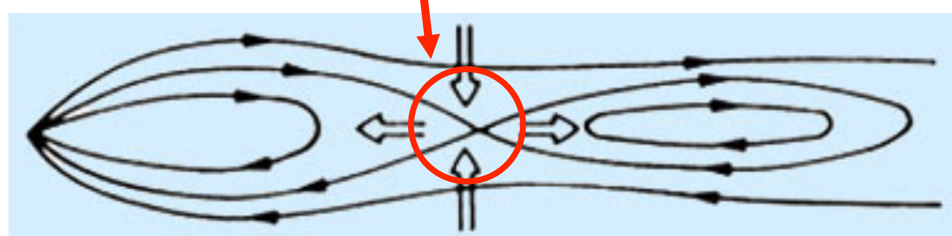
Step Two: Magnetic Reconnection of Loaded Flux Tubes

Centrifugal force -> stretched flux tubes -> **B** unable to confine

Vasyliunas, V. M., *Phys. Jov. Msp.,* 1983



Stretched flux tubes reconnect



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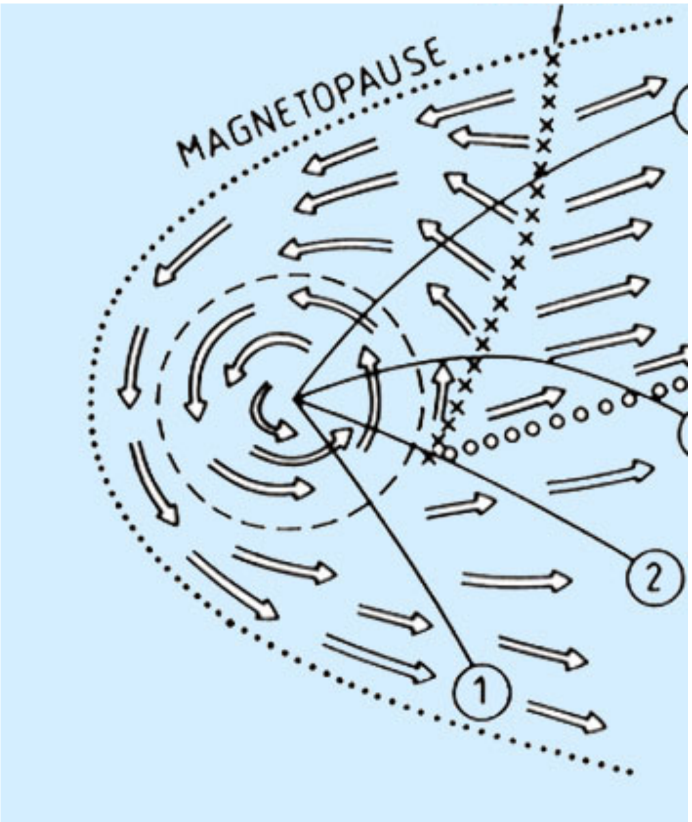
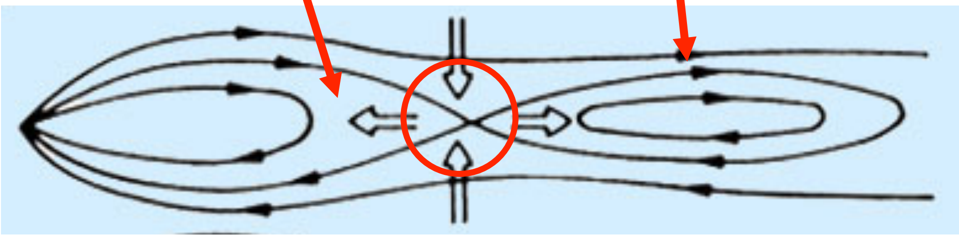


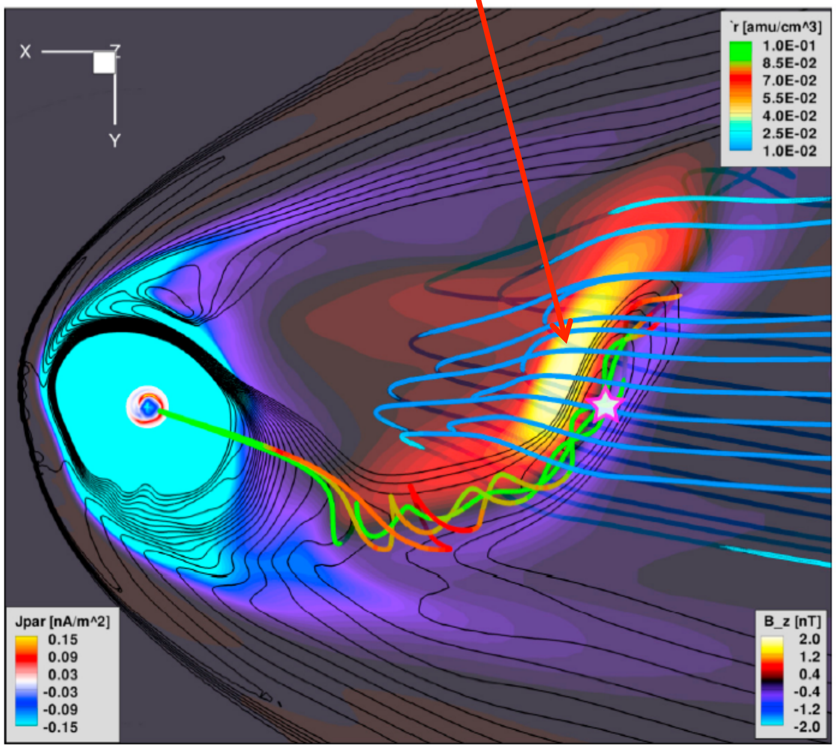
“Vasyliunas-type reconnection”

Dipolarization of returning closed flux

Departing plasmoid

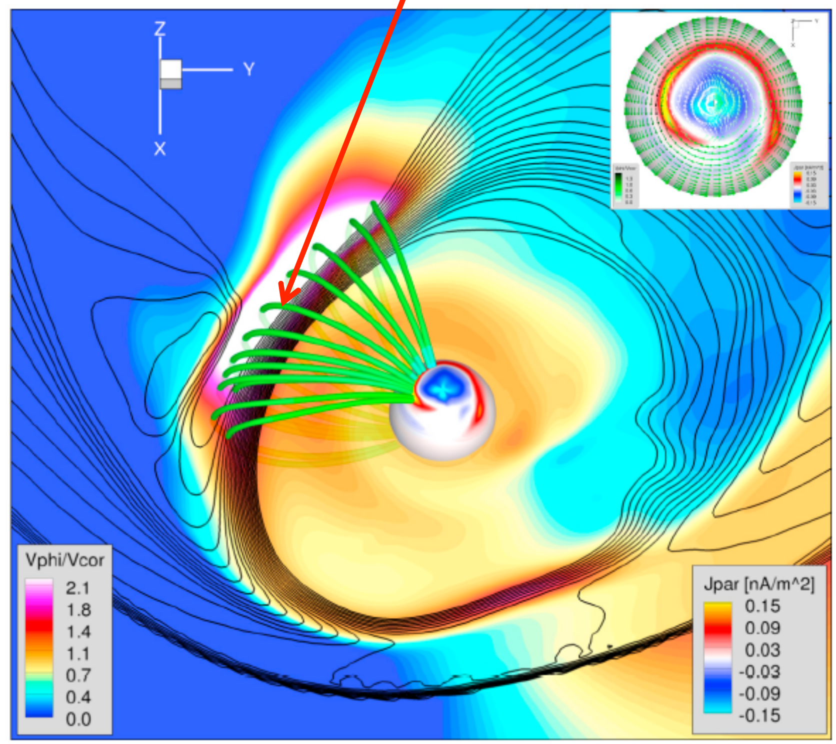


Strong tailward flows



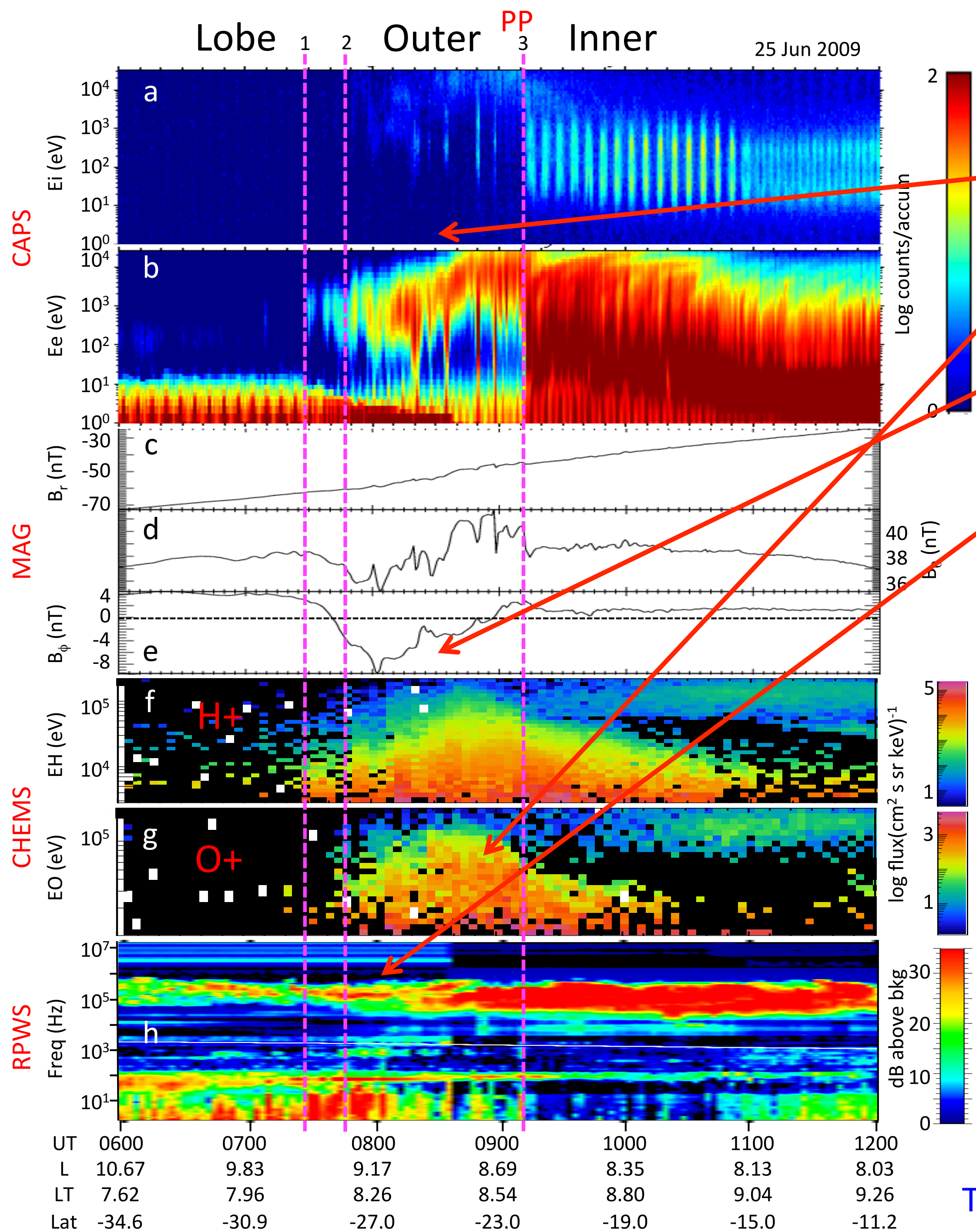
View from above the dusk meridian

Dipolarization



View from above the noon meridian

X. Jia et al., JGR, 2012

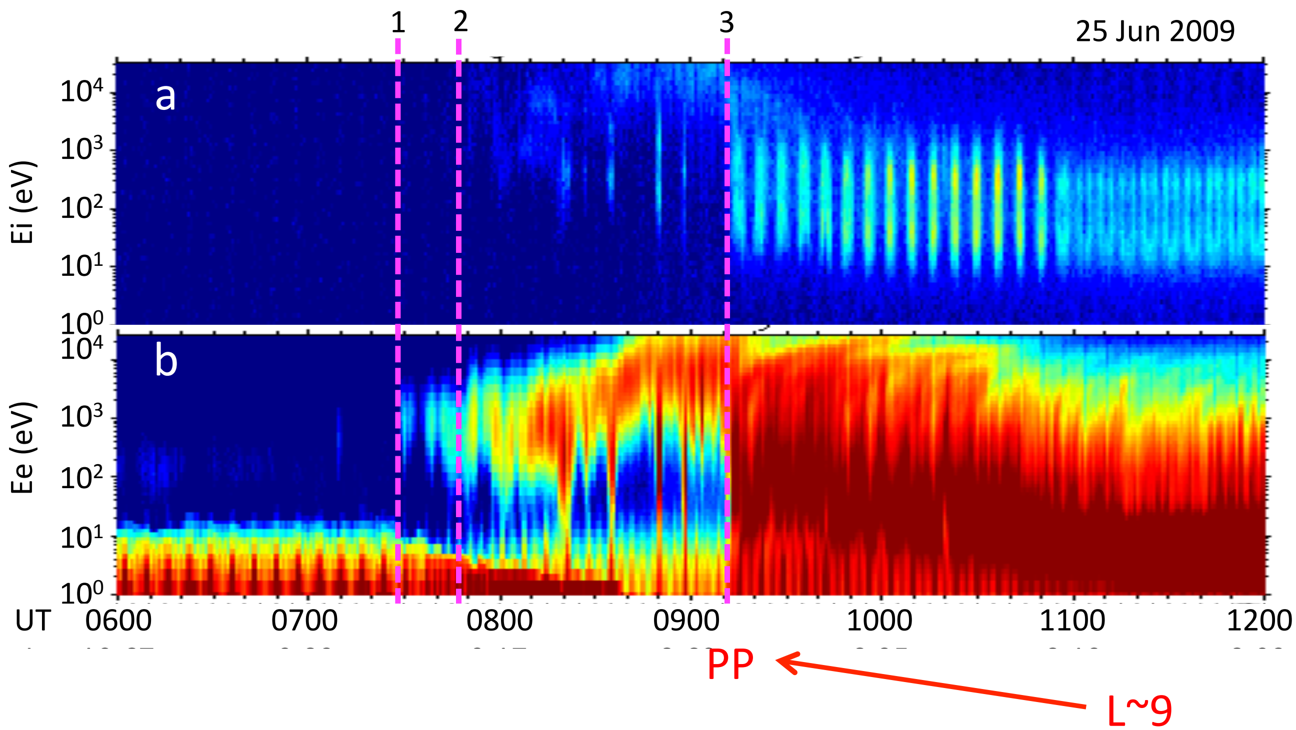


- Hot, low-density
- Significant energetic O+ fluxes
- “Leading field”=>evidence for supercorotation
- SKR enhancement and expansion to lower frequencies

Freshly injected plasma from tail reconnection of previously-closed field lines.

⇒ “Vasyliunas cycle”

Thomsen et al., 2015



Tail reconnection of loaded flux tubes

- sheds inner magnetospheric mass
- creates a sharp boundary between the dense inner-magnetospheric plasma that has escaped reconnection, and the injected hot tenuous plasma of the reconnected flux region: Plasmapause

=> Unstable to centrifugal interchange

Major Open Questions

- How important is the solar wind?
  - Magnetopause reconnection is inhibited but does occur => flux return is another imperative, which can't be accomplished with Vasyliunas reconnection.
  - Auroral signature of tail reconnection is enhanced by P_{dyn} increases.
  - Recent evidence for sustained lobe reconnection (Dungey cycle) during high P_{dyn} intervals => Does Saturn have a recurrent high-speed-stream-driven storm cycle?
  - Does it just affect the outermost L shells or is the influence more pervasive?

Major Open Questions

- Are smaller-scale loss processes ("dribble") important?
  - Observed plasmoid loss rate inadequate to shed the full load produced by Enceladus? (But see recent work by Cowley …)
  - Duskside "planetary wind"
  - Pre-dawn tail flow beyond ~15 Rs dominantly toward magnetopause

Major Open Questions

- How does interchange really work?
  - Is it strongly driven by tail dynamics?
  - Does it enable tail dynamics?
  - Does impoundment happen?
  - Is the inflow in the form of channels? Bubbles? Highly structured?
  - How much energy is carried in? How much material is carried out?
  - Is there nonadiabatic heating?

Major Open Questions

- What is the nature of the auroral/subauroral magnetosphere?
  - Interchange remnants + heated plasma from tail reconnection?
  - Local heating? Field-aligned acceleration?

Major Open Questions

- How variable is the inner magnetosphere?
  - Radiation belts?
  - Plasma source?
  - Hot population?
  - Any relation to solar wind variability?

Major Open Questions

- What causes the dawnward convection component in the inner magnetosphere?
  - Too large, wrong direction for solar-wind imposed convection as at Earth
  - Related to ongoing tail dynamics?
  - Related to magnetospheric size (wave propagation speeds)?
  - Does it show up in global MHD simulations?

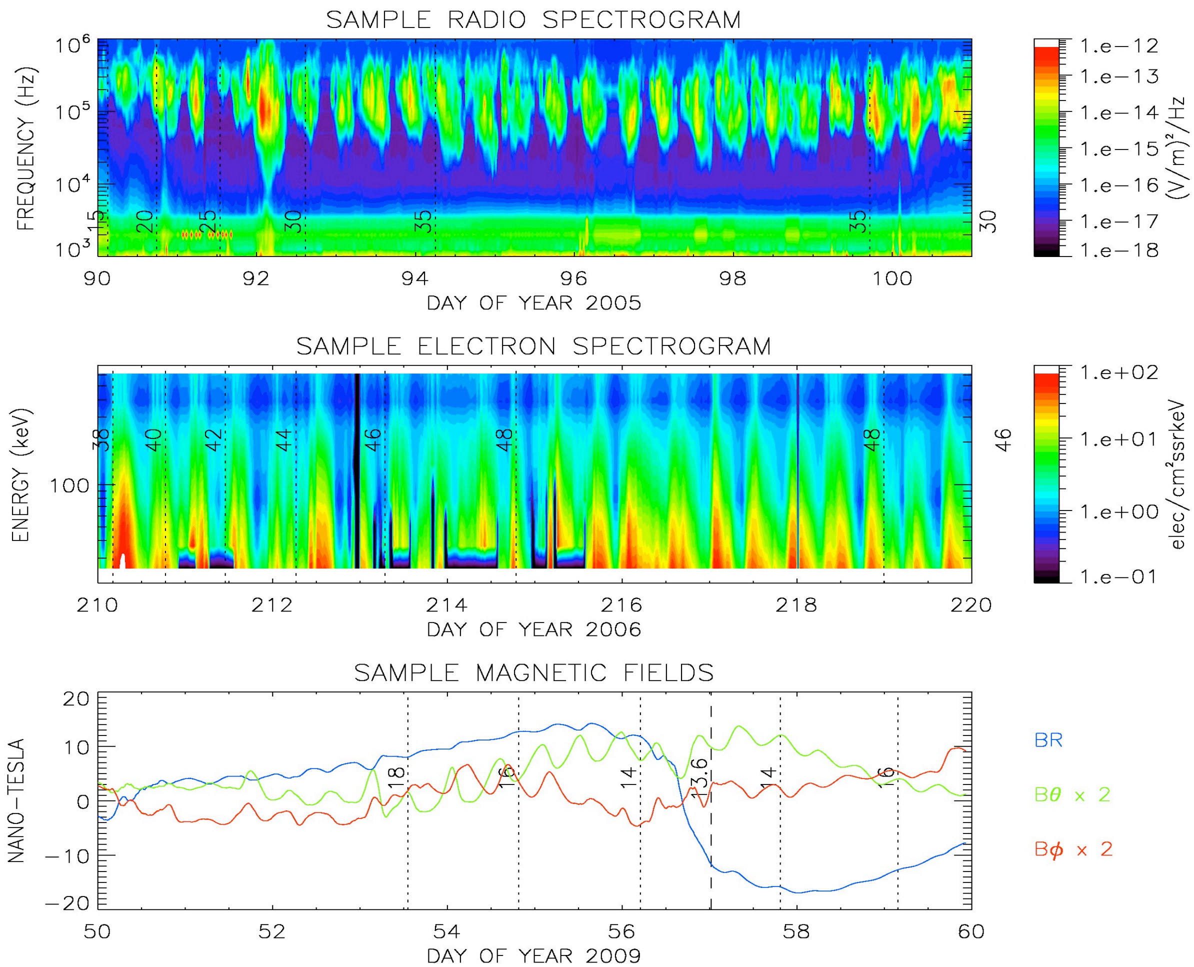
Major Open Questions

- What causes the ubiquitous periodicities at ~planetary rotation period?

Saturn Kilometric Radiation (SKR)

Energetic electrons (20-900 keV)

Magnetic Field



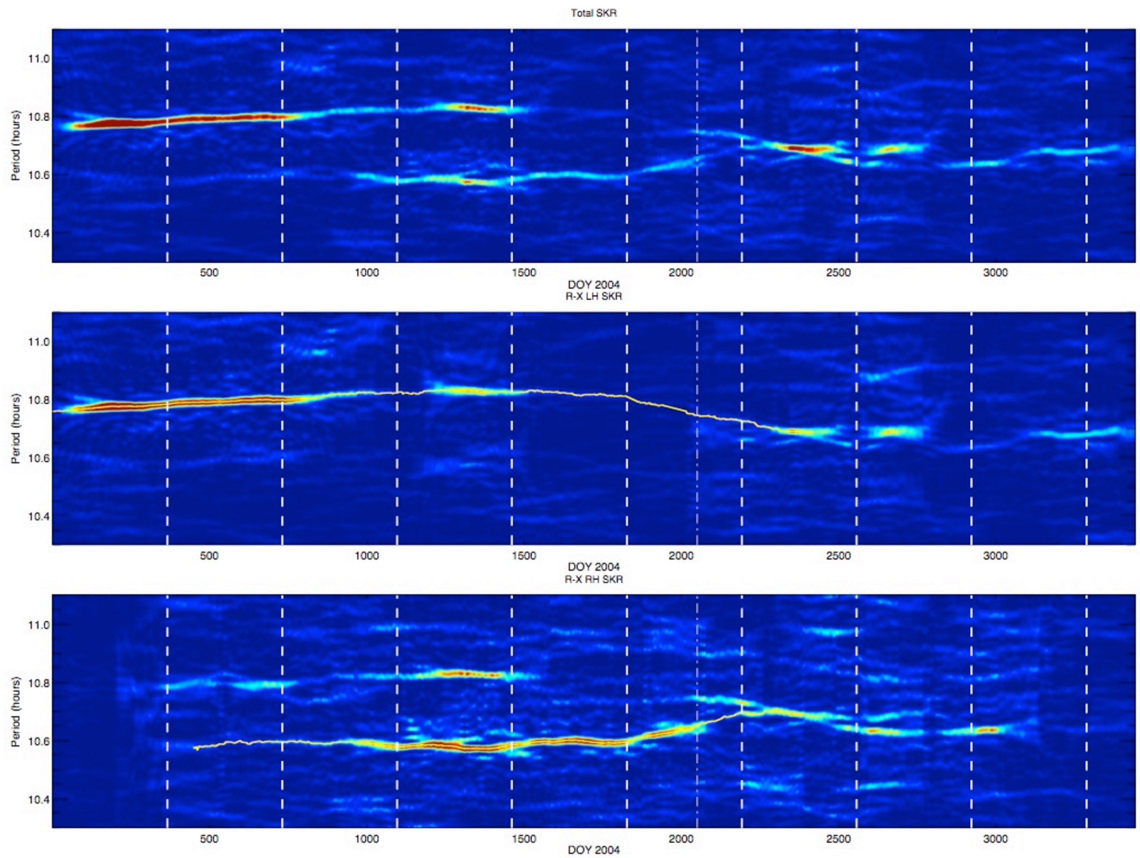
(Carbary et al., 2015, *Saturn in the 21st Century,* in review. Thanks to Tom Hill)

The SKR modulation period differs between N and S hemispheres:

Total SKR — N + S

LH SKR — South

RH SKR — North

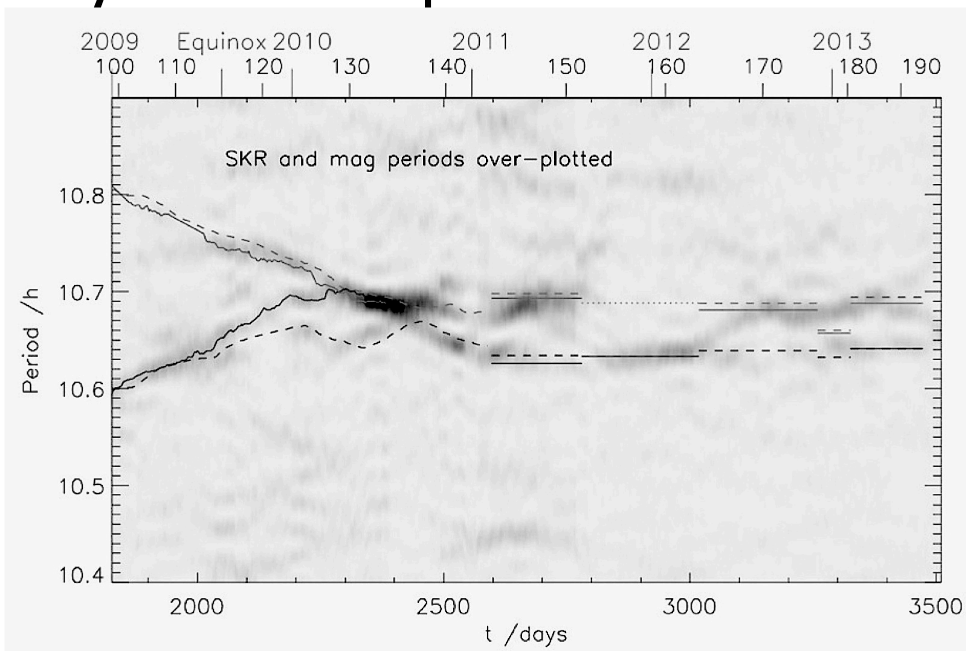


2004 05 06 07 08 09 10 11 12 13

(Lamy, 2011 *Plan. Radio Emissions VII*; Carbary et al., 2015 *Saturn in the 21st Century,* in review)

Major Open Questions

- What causes the ubiquitous periodicities at ~planetary rotation period?



  - Why does Saturn have any spin modulation?
  - Why are there two distinct periods (N, S)?
  - Why do Saturn's periods (both N and S) exhibit large (% level) time variations on seasonal time scales?

Summary

Saturn's magnetosphere is a fascinating place, with many familiar yet not-so-familiar structures and processes. Cassini observations have led to a credible framework for understanding it, but there are MANY open questions to answer before we achieve anything near the level of understanding we have of the Earth's magnetosphere.

Comparative magnetospheric studies enable us to expand our understanding and appreciation of the many wonderful ways the same physical processes can combine with different relative importance to produce unique systems.