An Overview of Cassini's Major Findings Regarding Saturn's Magnetosphere

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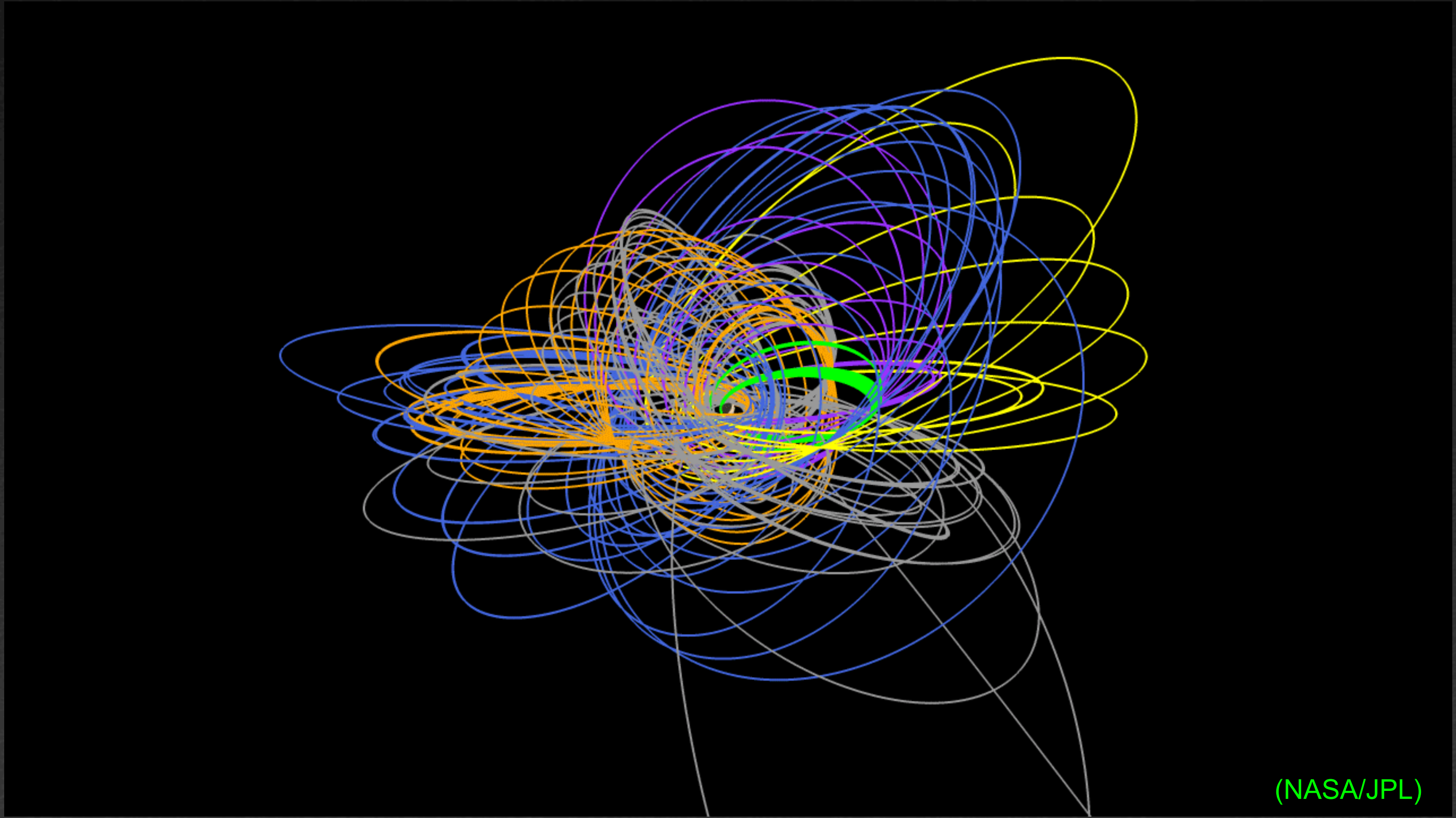
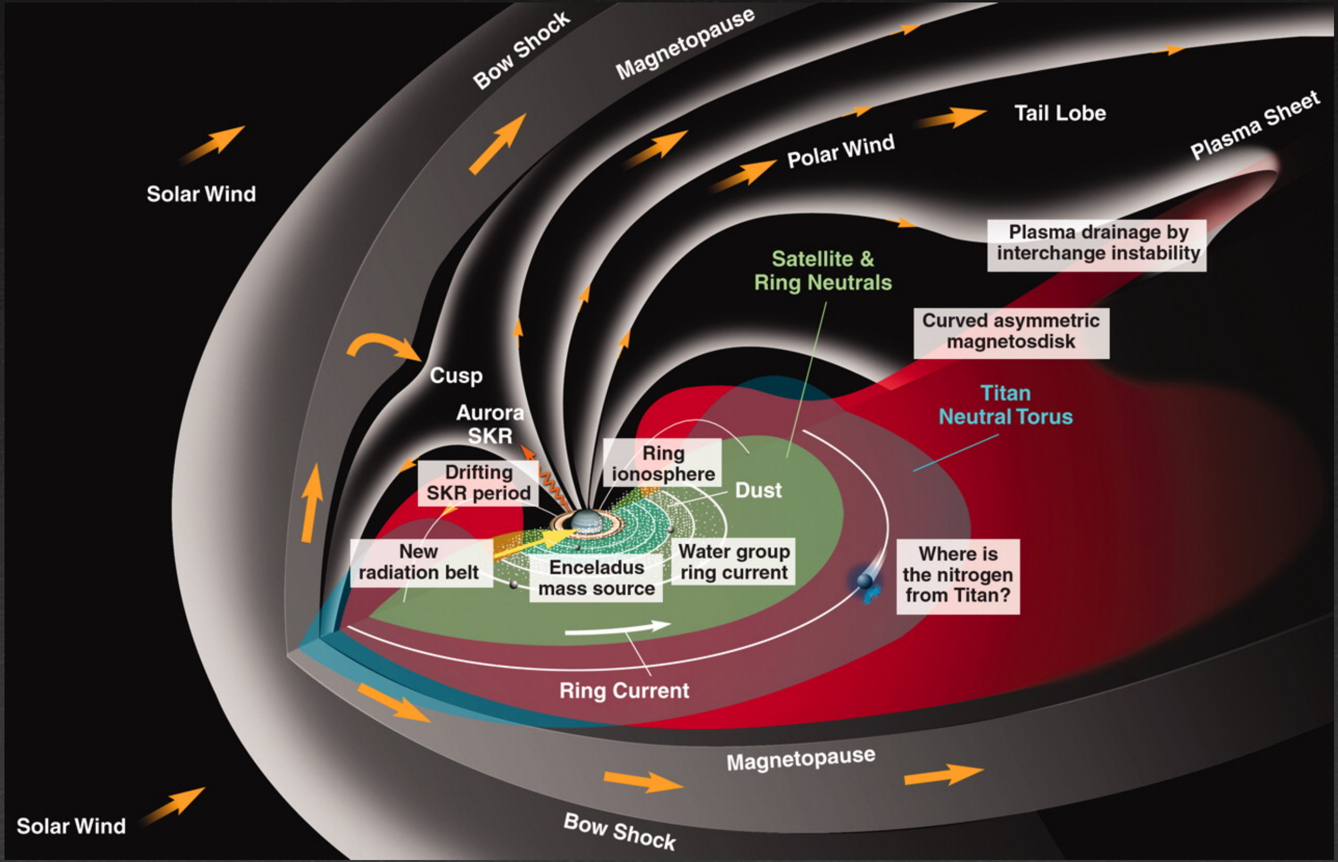
Cassini Orbits

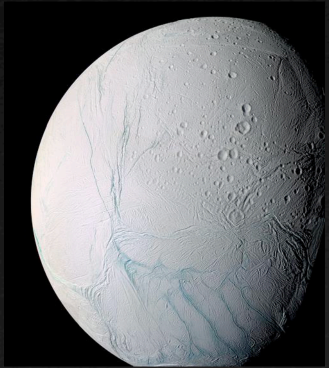


Cassini View of Saturn's Magnetosphere

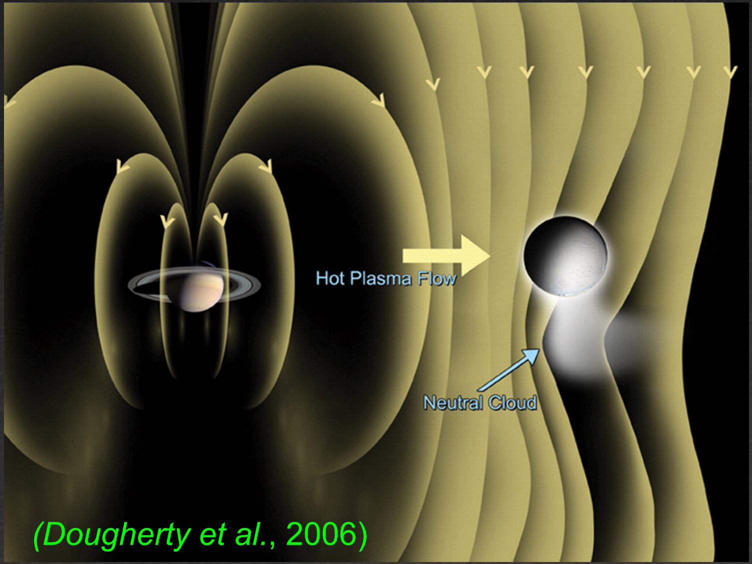


(*Gombosi & Ingersoll*, 2010; Background figure from the MIMI team)

Enceladus and its water plumes

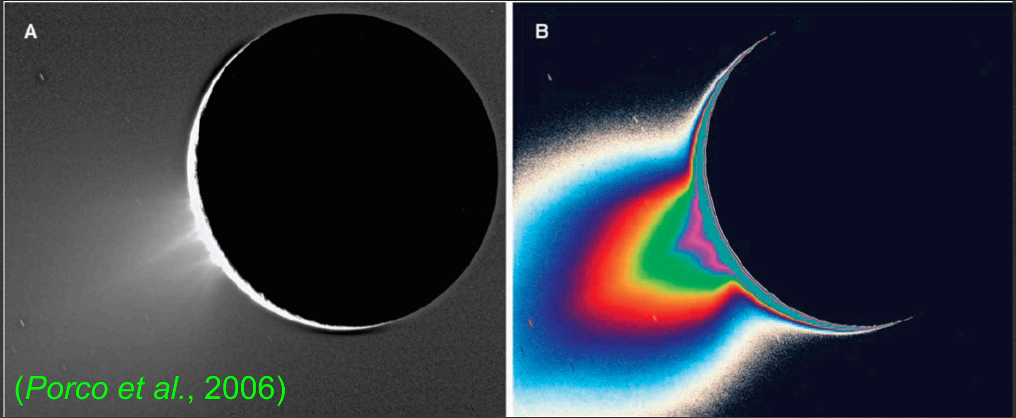


- MAG data first hinted at the presence of a significant plasma source at Enceladus (*Dougherty et al.*, 2006)



(Dougherty et al., 2006)

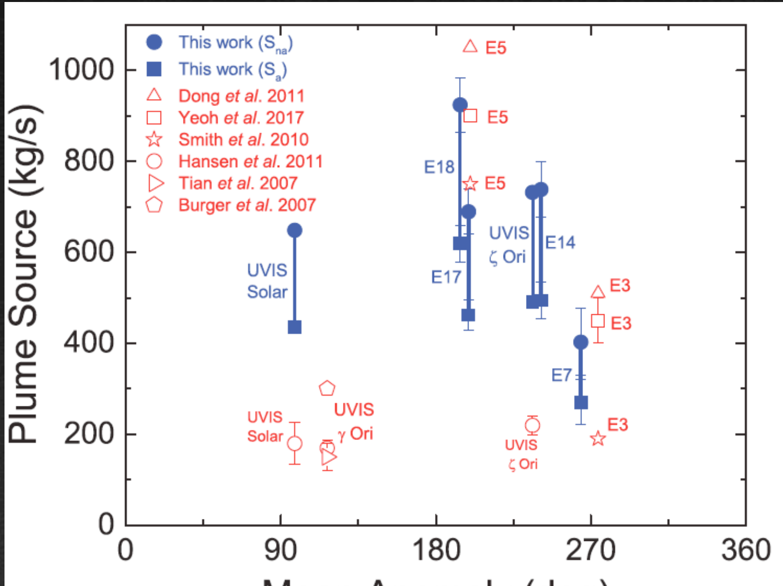
- Subsequent observations from follow-up flybys by a suite of instruments (imaging, INMS, CAPS, CDA, RPWS, UVIS, etc.) confirmed that there are water plumes near the south pole.



(Porco et al., 2006)

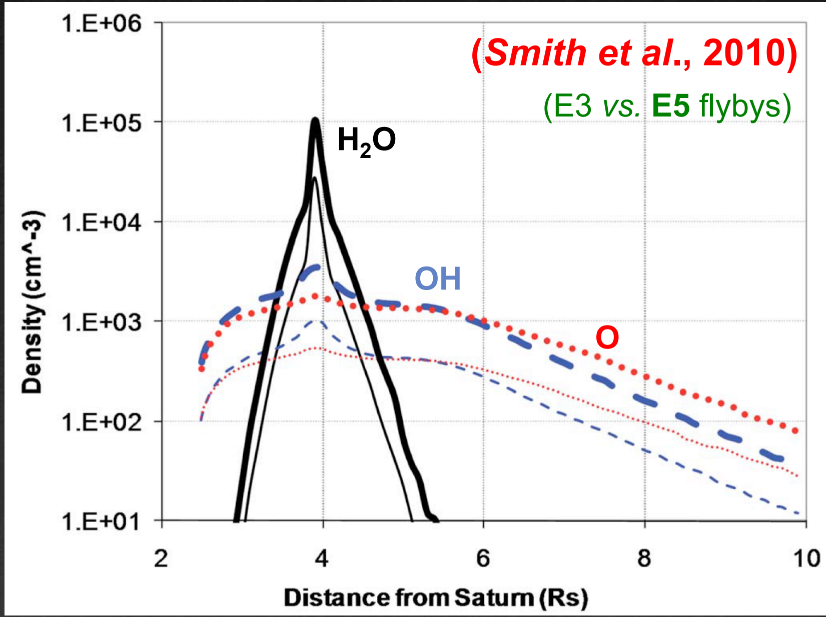
Enceladus' Plumes & Extended Neutral Cloud

Variability of plume source rate



(*Teolis et al.*, 2017)

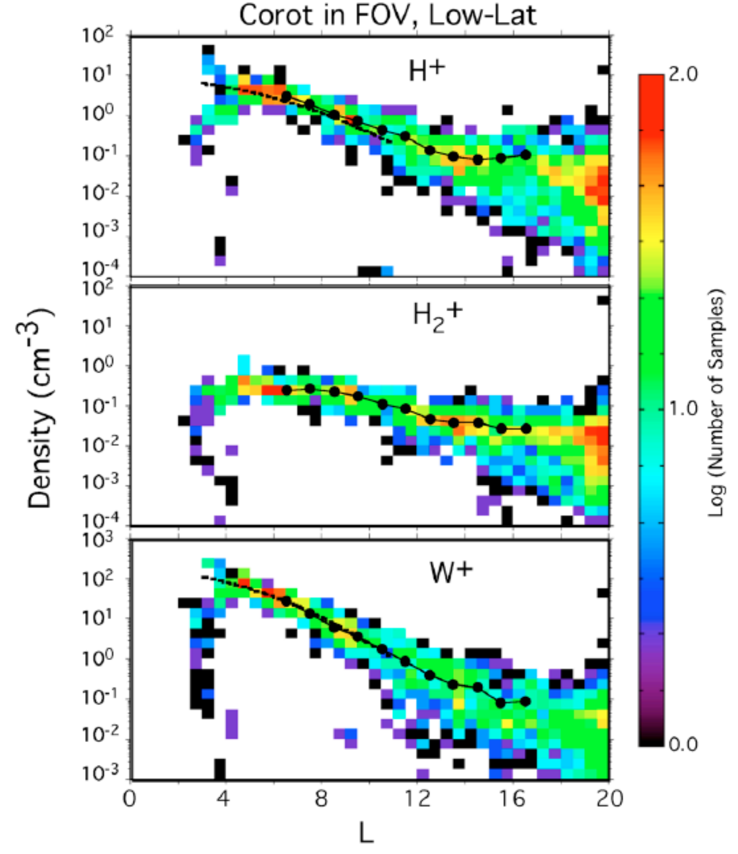
Variability of neutral profiles



- Estimates of plume source rate range from 150 kg/s to ~ 750 kg/s (e.g.,*Jurac and Richardson*, 2005; *Hansen et al.*, 2006, 2017; *Burger et al.*, 2007; *Cassidy and Johnson*, 2010; *Fleshman et al.*, 2010; *Smith et al.*, 2010)

- Only a fraction (10% - 30%) of neutrals are ionized, supplying water-group ions to Saturn's magnetosphere (*Jurac and Richardson*, 2005; *Fleshman et al.*, 2010; *Bagenal and Delamere*, 2011)

Plasma vs. Neutral



(*Thomsen et al.*, 2010)

- ❖ Water-group ions dominate plasma density (*Thomsen+*, *Wilson+*, *McAndrews+*, *Livi+*)
- ❖ Neutrals dominate over ion density over a broad radial range around Enceladus' orbit
  - Opposite to the situation at Jupiter

  (*Mauk et al.*, 2009; *Bagenal and Delamere*, 2011)

Highly Axisymmetric Internal Field

- Cassini MAG data from prior to the F-ring and proximal orbits gave an upper limit on the dipole tilt of 0.06°.
- New data from the grand finale place tighter constraints
  - See presentations by *Dougherty et al*. and *Cao et al.*

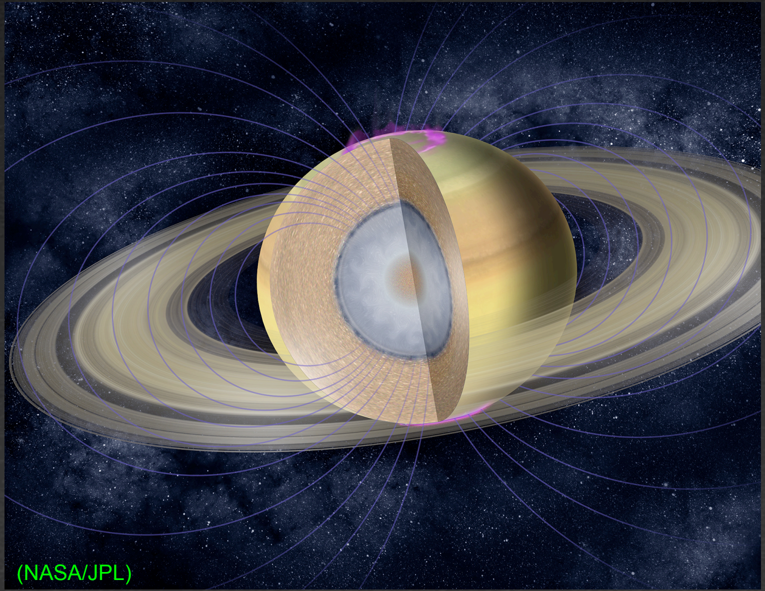
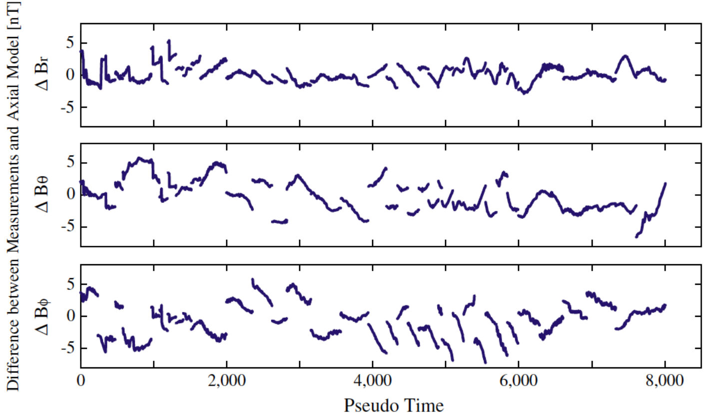


Table 2

Coefficients of axisymmetric models for Saturn based on Cassini observations inside L = 3.8 Rs from Rev 3 to Rev 126. The SPV model (Davis and Smith, 1990) based on Pioneer 11, Voyager 1 and 2 measurements and the Z3 model (Connerney and Acuna, 1982) based on Voyager 1 and 2 measurements are also presented here for comparison. All values are in units of nT (nanotesla). One Saturn radius is 60,268 km in all three models.

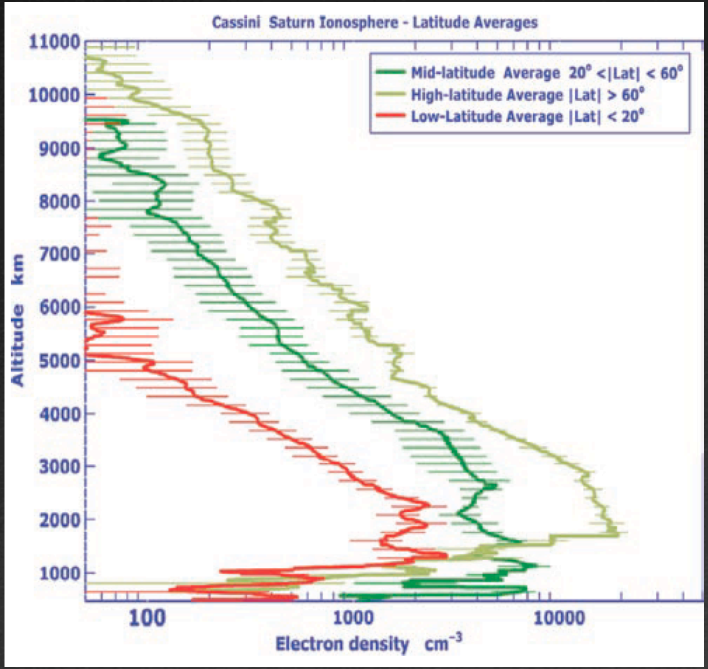
Coefficients	Cassini (Rev 3–126)	SPV	Z3
g_1^0	21,191 ± 24	21,225	21,248
g_2^0	1586 ± 7	1566	1613
g_3^0	2374 ± 47	2332	2683
$(g_4^0)^*$	(−70 ± 243)		
$(g_5^0)^*$	(−148 ± 1070)		
G_1^0	−13 ± 1		
RMS	2.2		



(*Dougherty et al*., 2005, 2018; *Burton et al*., 2010; *Cao et al*., 2011)

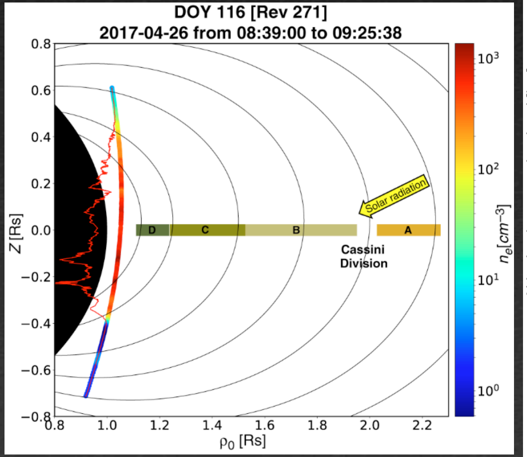
Saturn's Ionosphere

Electron density profiles from radio occultation

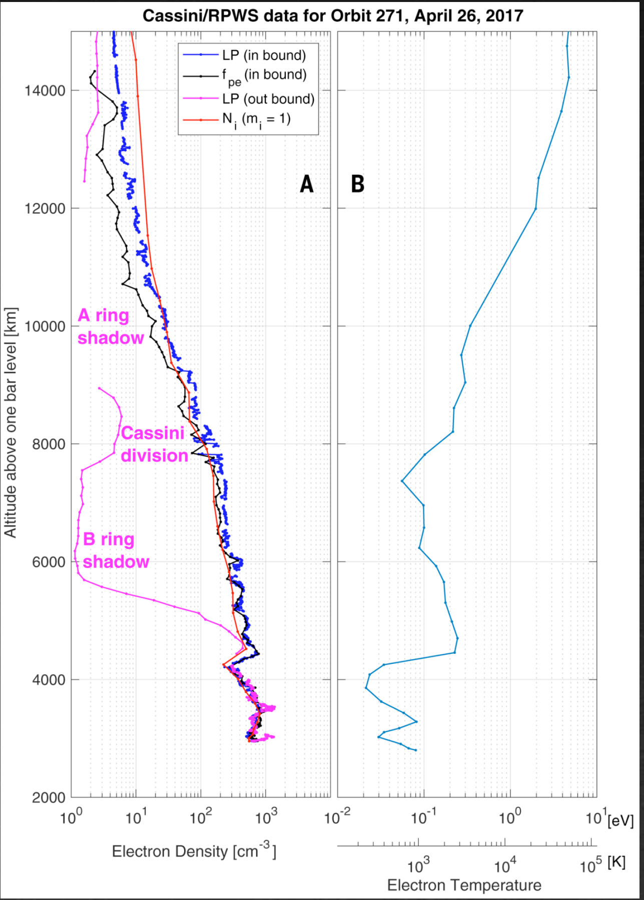


(*Kliore et al.*, 2009)

In-situ measurements by RPWS



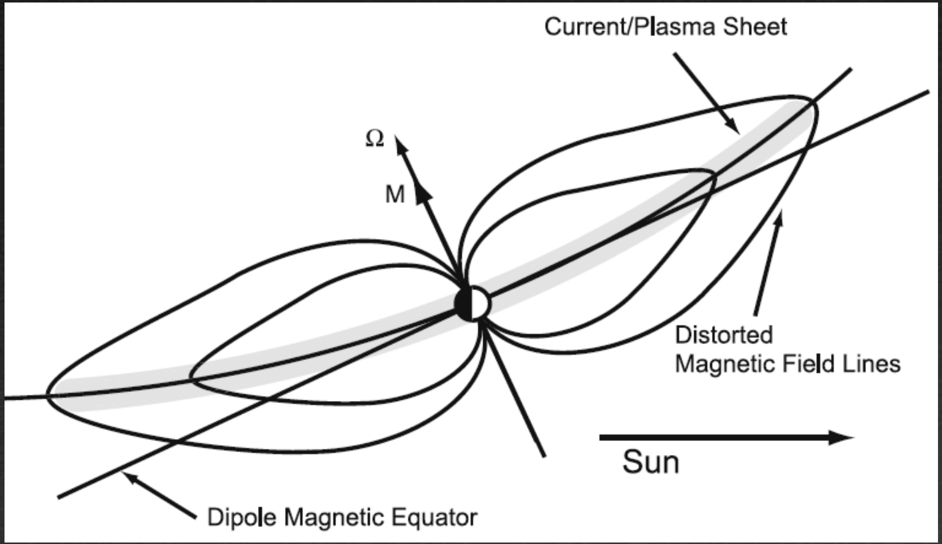
(*Wahlund et al.*, 2017)



See presentation by *Hadid* et al.

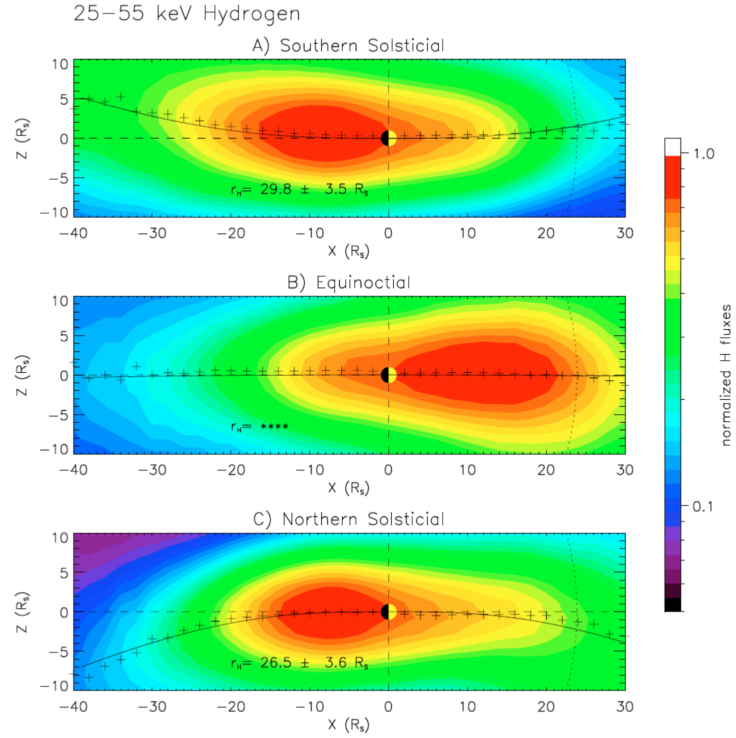
Global Magnetospheric Structure
- Current Sheet -

Warped current sheet



(*Arridge et al.*, 2008)

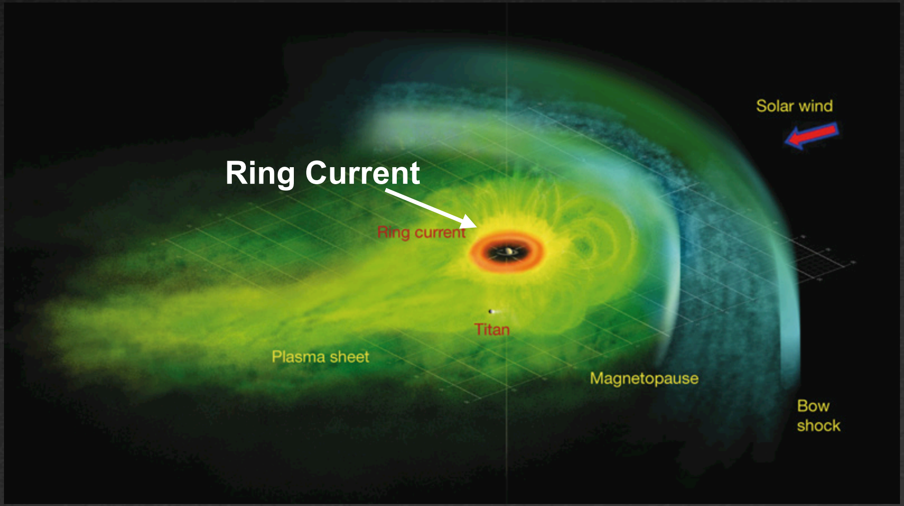
ENA maps of global structure



(*Carbary and Mitchell*, 2016)

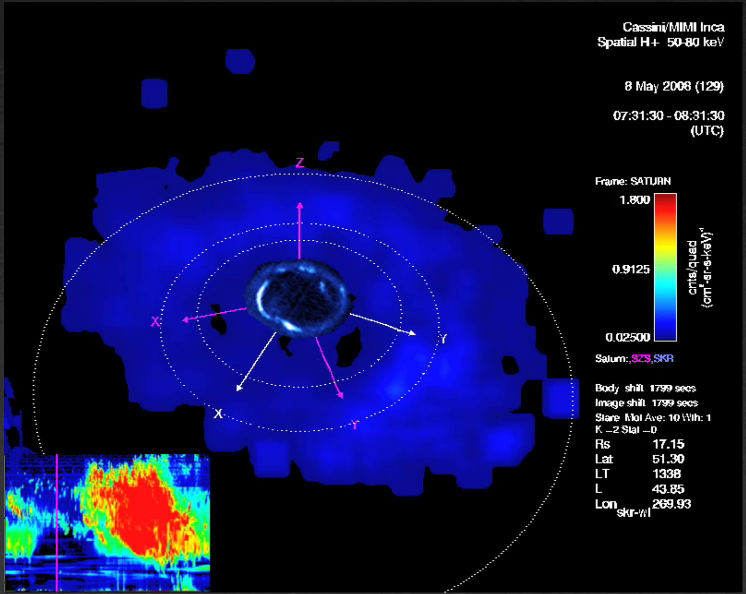
Global Magnetospheric Structure
- Ring Current -

Dynamic ring current



(*Krimigis et al.*, 2007)

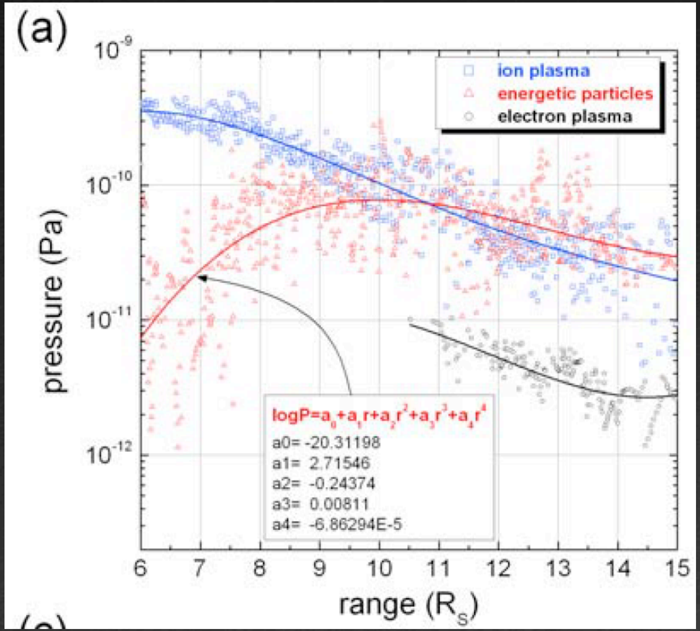
ENA imaging of the ring current



(*Mitchell et al.*, 2009)

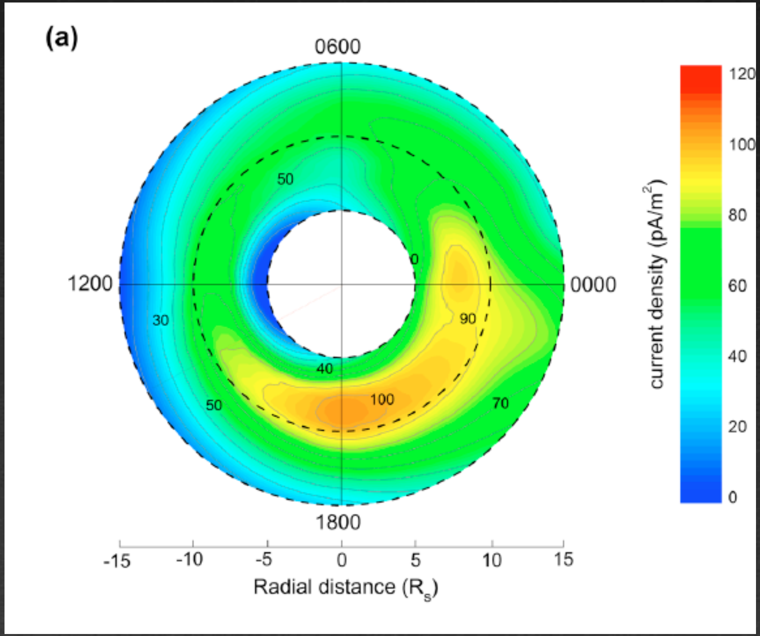
Global Magnetospheric Structure
- Ring Current -

Thermal plasma *vs.* Energetic particles



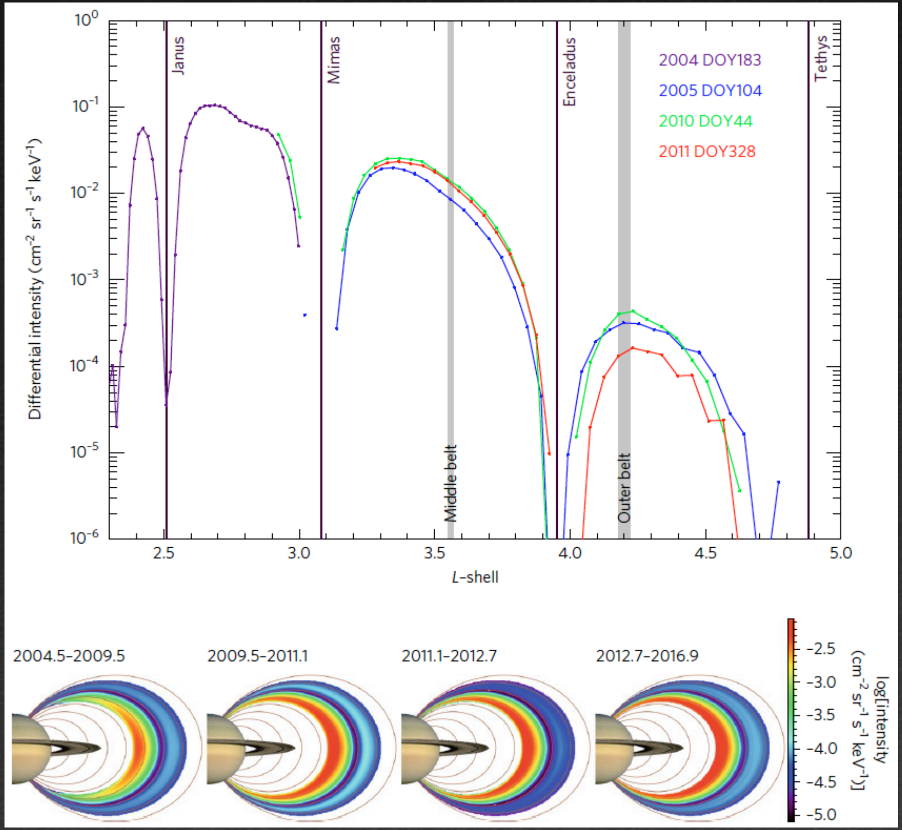
(*Sergis al.*, 2010)

Local time variations



(*Sergis al.*, 2017)

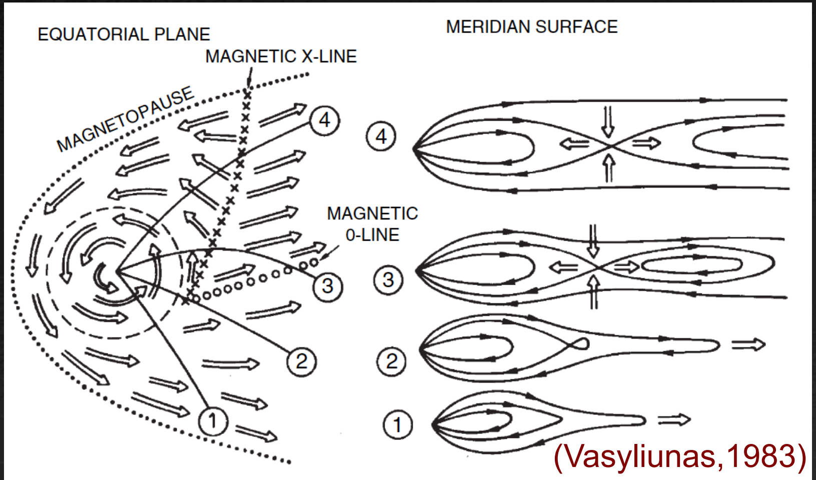
Global Magnetospheric Structure
- Radiation Belts-



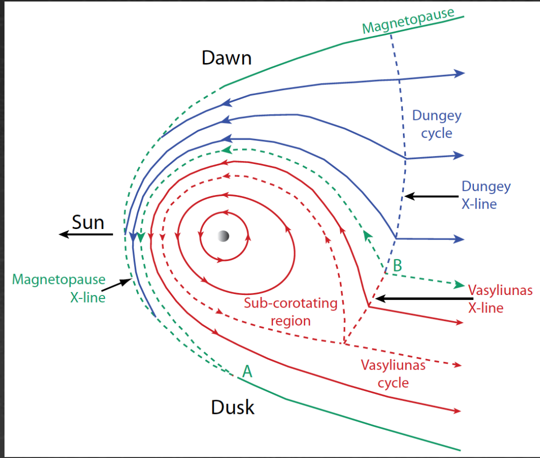
(*Kollmann al.*, 2017)

- Long-tern variations of Saturn's proton belts measured by Cassini MIMI
- The main belts appears to have little variation over a solar cycle, inconsistent with predictions based on variations in galactic cosmic ray intensity.
- Changes in radial diffusion may account for the relatively short time-scale (1-2 yr) variations.

Global Convection

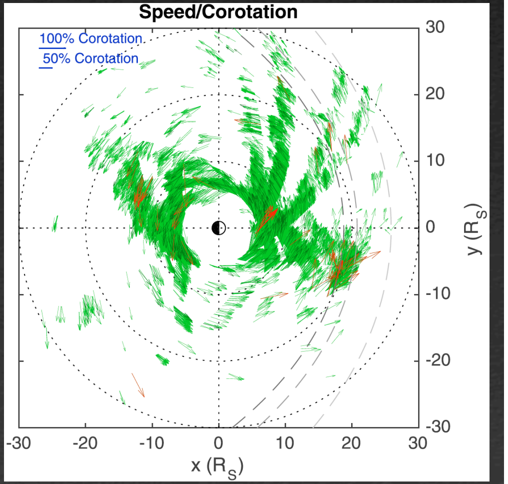


Vasyliūnas Cycle + Dungey Cycle

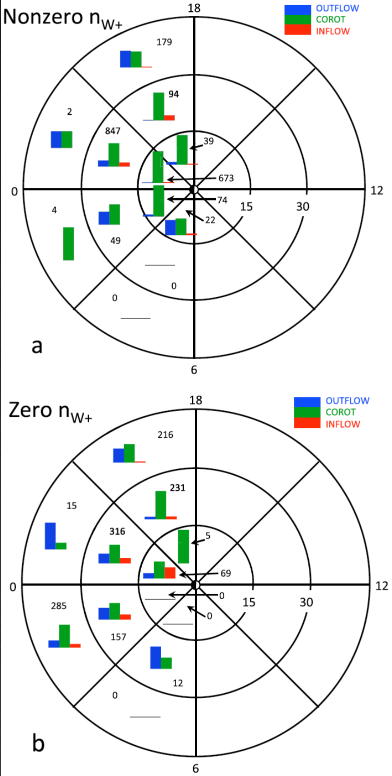


(Cowley et al., 2004)

Measured Plasma Flows (CAPS)



(Wilson et al., 2017)

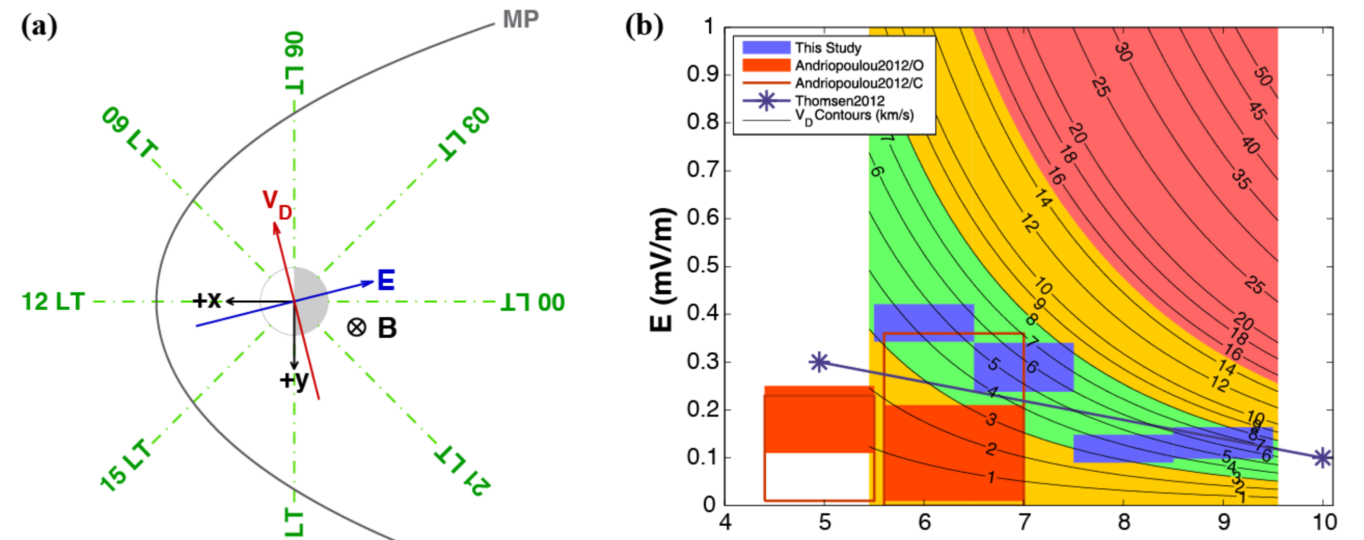


(Thomsen et al., 2014)

Noon-to-Midnight Electric Field

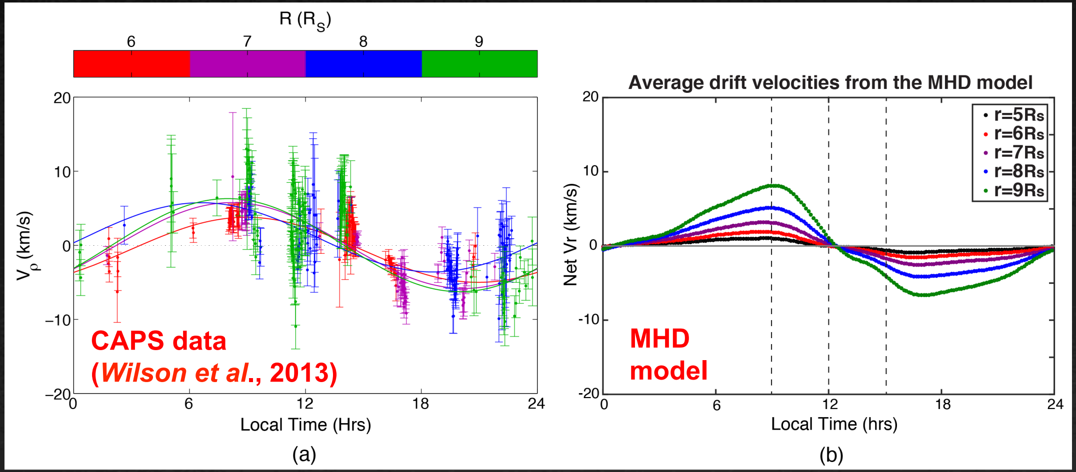
❖ An unexpected noon-to-midnight electric field in the inner magnetosphere:

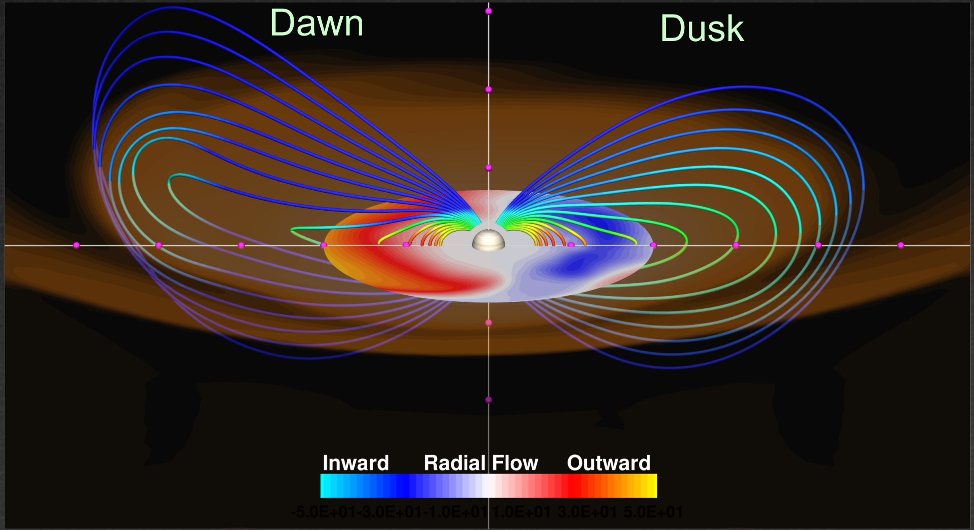
- Dawn-dusk asymmetry in the magnetic configuration (*Arridge et al*., 2015)
- Ring absorption of energetic particles (*Paranicas et al*., 2010)
- Displacement of satellite micro-signatures (*Roussos et al*., 2007; *Paranicas et al*., 2010; *Andriopoulou et al*., 2012, 2014)
- Day-night asymmetry of plasma temperature (*Thomsen et al*., 2012)
- Dawn-dusk asymmetry in plasma radial flows (*Wilson et al*., 2013)



(*Wilson et al*., 2013)

Interpretation based on MHD Simulation





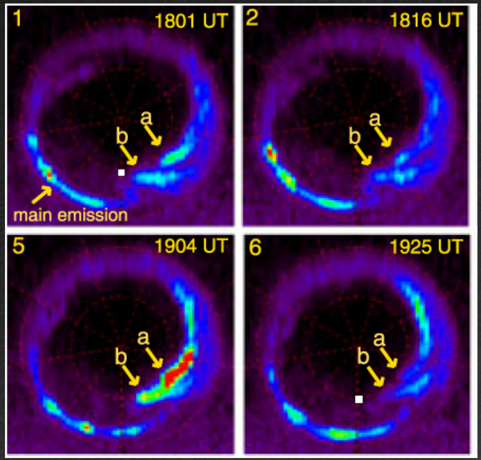
- ❖ Charged particles move easily along the magnetic field in response to both *rotational stresses* and *changing pressure*.
- ❖ The field lines are more 'stretched out' on the dawn side, where the *rotational stresses* are dominant, and less 'stretched out' on the dusk side, where *pressure gradients* dominate. This lopsidedness produces local-time dependent inward and outward flows similar to what is observed by Cassini.
- ❖ This mechanism may also account for similar asymmetry observed at Jupiter

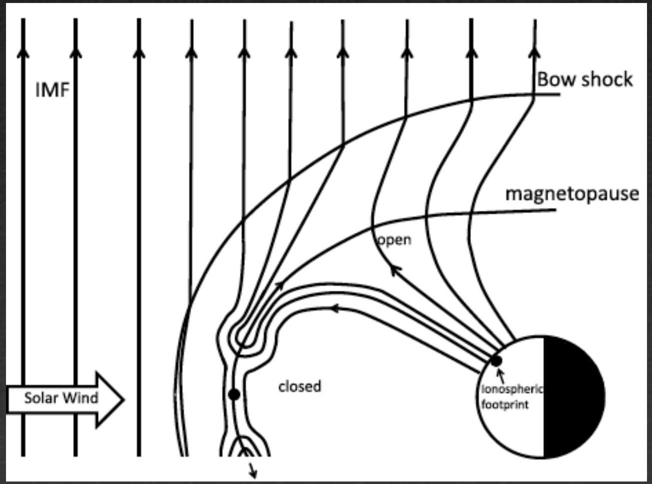
(*Jia and Kivelson*, 2016)

Solar Wind Interaction at Magnetopause

In-situ and auroral evidence of magnetopause reconnection

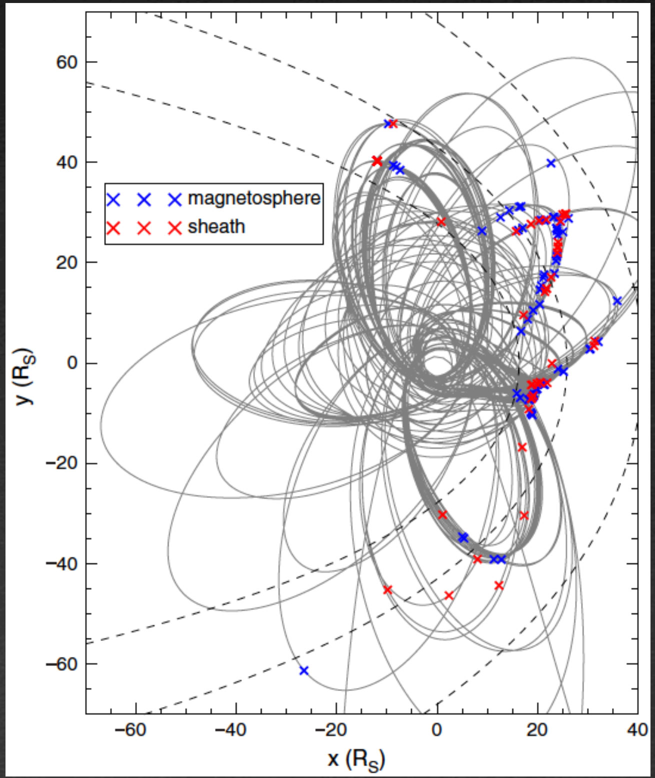
(e.g., *McAndrews et al.*, 2008; *Badman et al.*, 2013; *Radioti et al.*, 2011, 2013; *Jasinski et al.*, 2016)





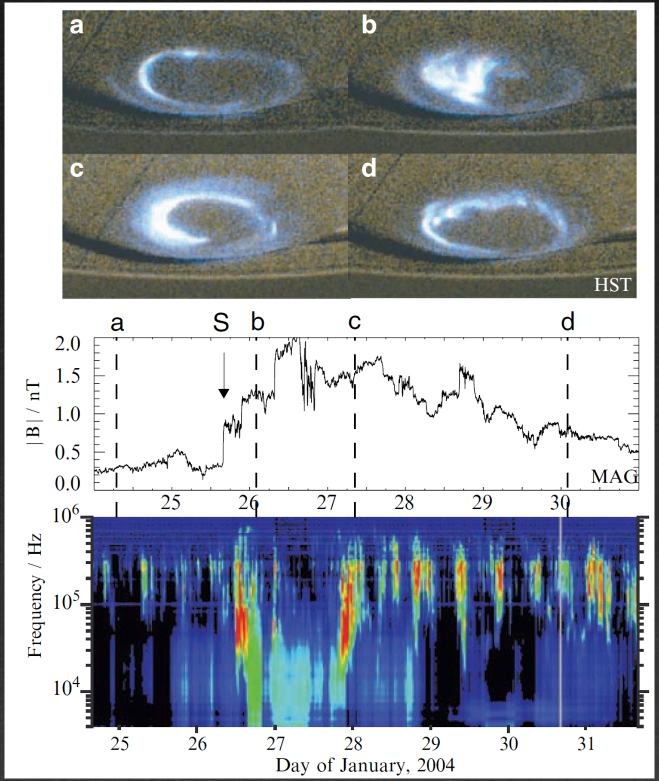
Kelvin-Helmholtz wave occurrence

(*Masters et al.*, 2012; *Delamere et al.*, 2012)



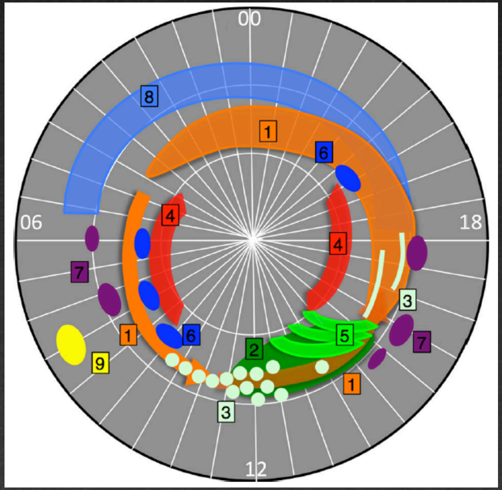
Auroral Structure and Dynamics

2004 HST + Cassini Campaign



(*Crary et al.*, 2005; *Clarke et al.*, 2005; *Kurth et al.*, 2005; *Cowley et al.*, 2005)

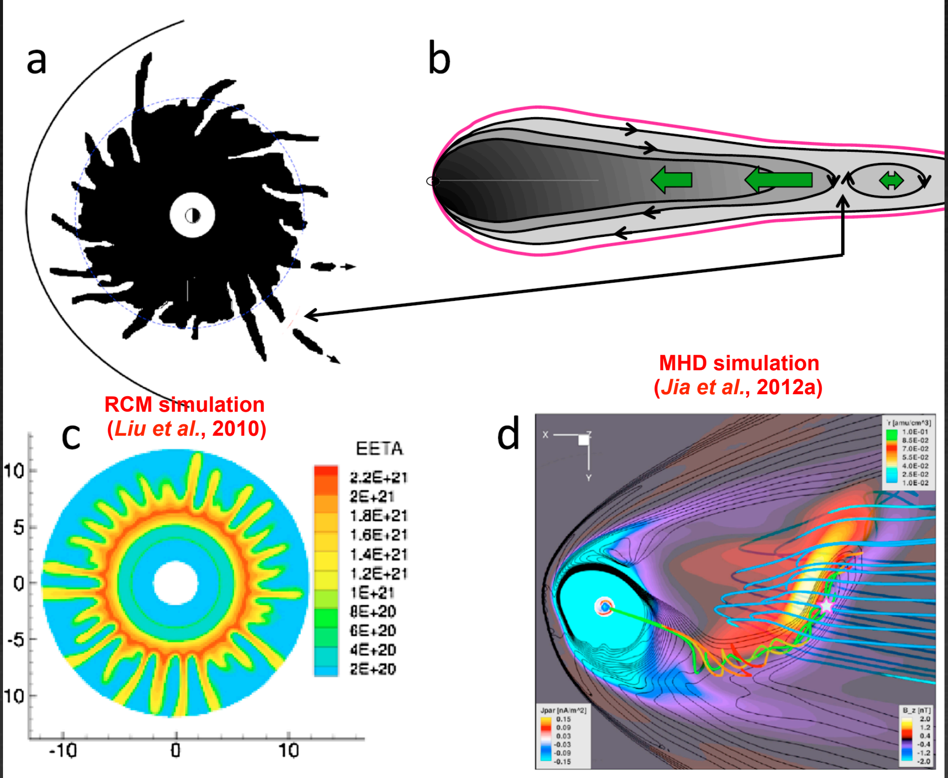
Schematic based on HST and Cassini-UVIS observations



(*Grodent*, 2014)

1. Main emission
2. Cusp emission
3. Small scale spots and arcs
4. Poleward auroral arcs
5. Bifurcations
6. Poleward auroral spots
7. Signatures of injections
8. Outer emission
9. Enceladus footprint

Plasma Transport

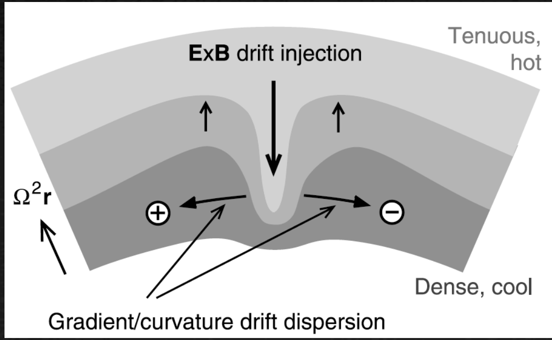


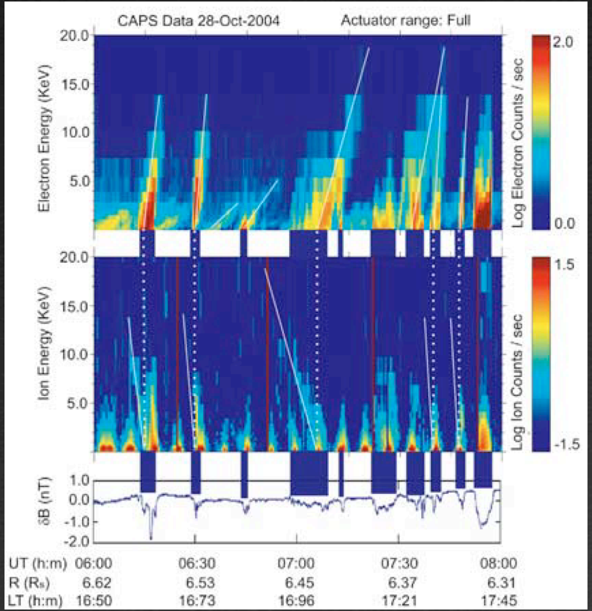
(*Thomsen*, 2013)

- ❖ Enceladus-generated plasma is transported outward and removed from Saturn's magnetosphere through multiple steps (e.g., Saturn book chapters by *Mauk et al.*, 2009; *Gombosi et al.*, 2009; *Krupp et al.*, 2018).
  - Inner/middle magnetosphere
    - Centrifugally-driven interchange
  - Outer magnetosphere:
    - Magnetic reconnection
    - Viscous interaction
    - Diffusive process ("Drizzle")

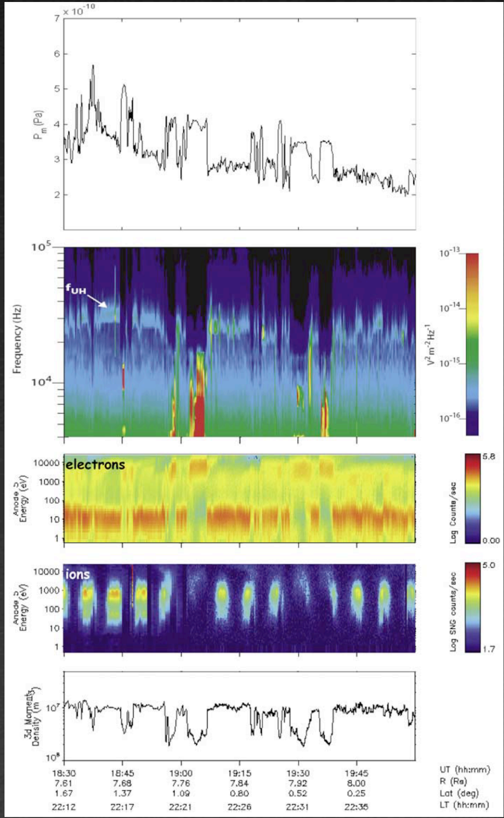
Plasma Transport: Interchange

Multi-instrument characterization of interchange injections

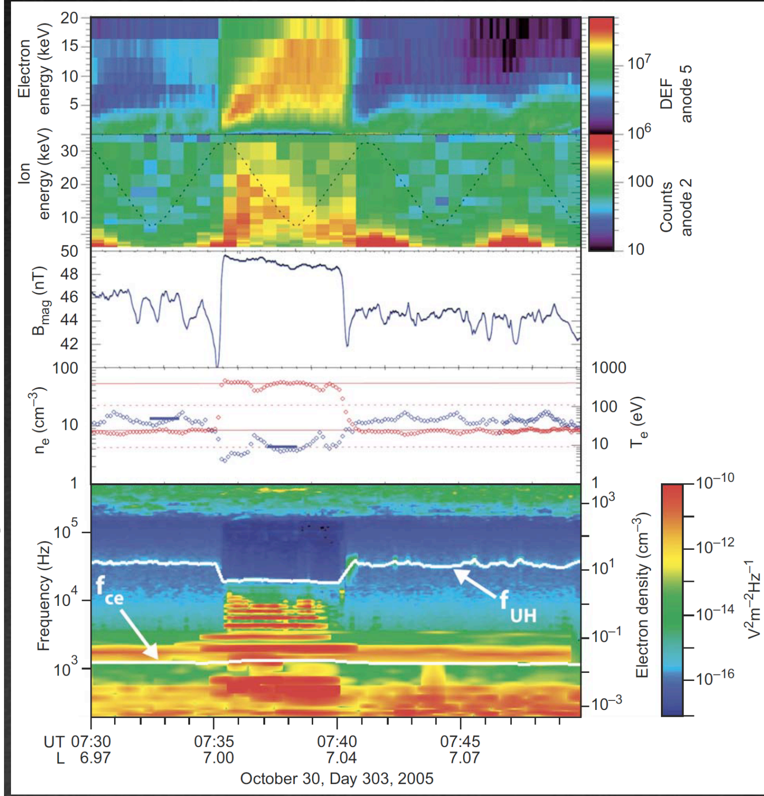




(*Hill et al.*, 2005)



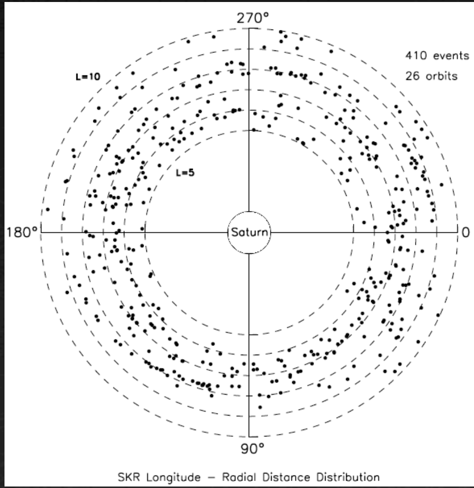
(*Andre et al.*, 2007)



(*Rymer et al.*, 2009)

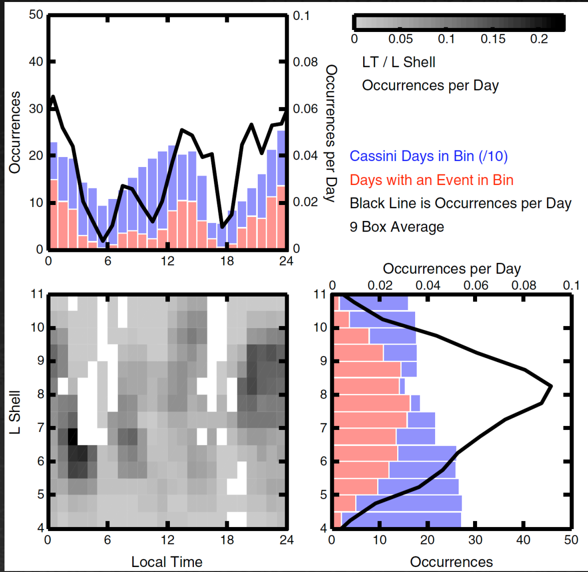
Plasma Transport

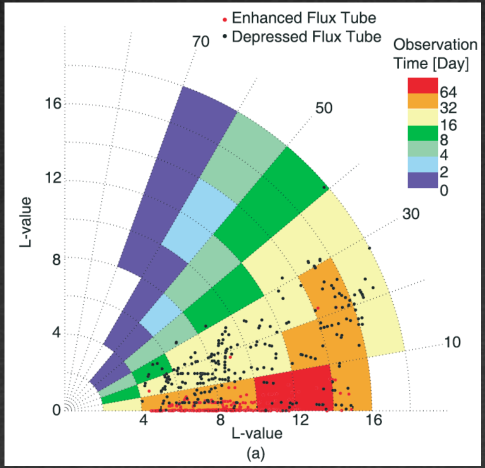
- Interchange Statistics-



CAPS survey [2004 – 2006]
(*Chen et al.*, 2008)

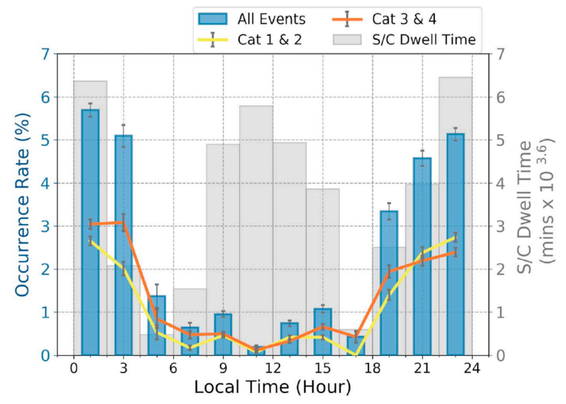
RPWS survey [2004 – 2011]
(*Kennelly et al.*, 2013
Hospodarsky+, this meeting)



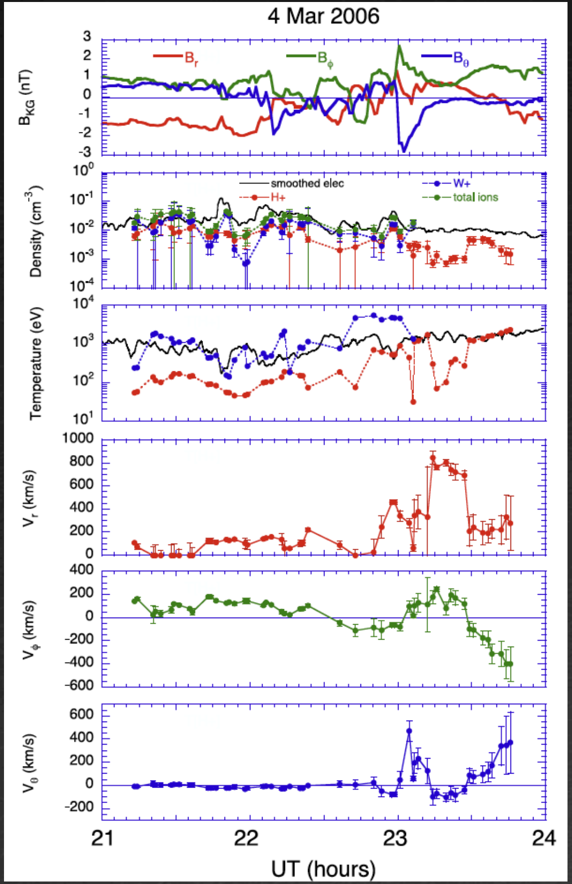


MAG survey [2004 – 2015]
(*Lai et al.*, 2016)

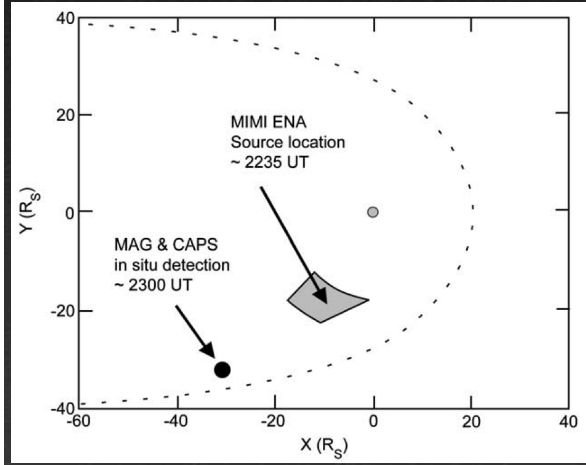
MIMI survey [2004 – 2016]
(*Azari et al.*, 2018
Azari+, this meeting)



Tail Reconnection & Plasmoids

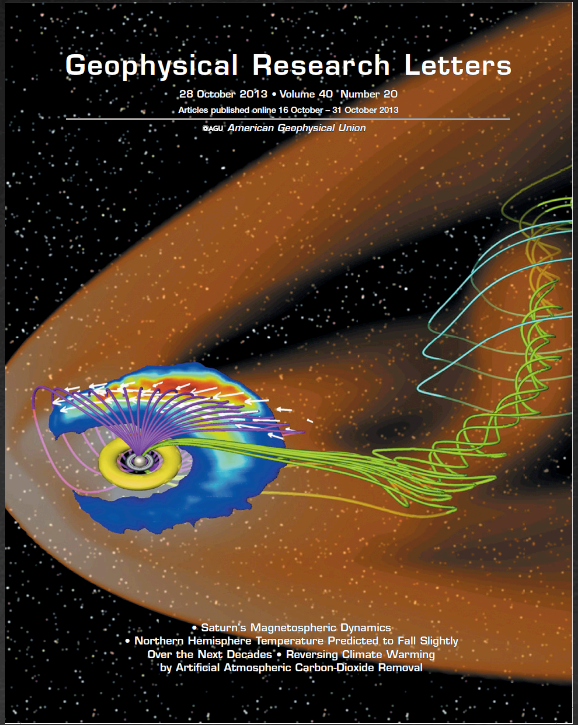


In-situ measurements of reconnection products



(*Hill et al.*, 2008)

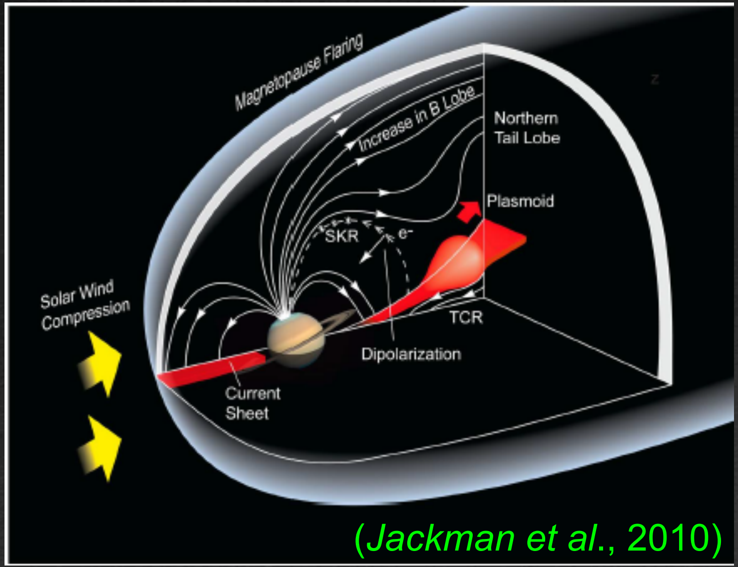
Link between tail reconnection and particle injection and ENAs



(*Jia et al.* [2012a] MHD model + ENA map from INCA by *Mitchell et al.* [2010])

Tail Reconnection & Plasmoids

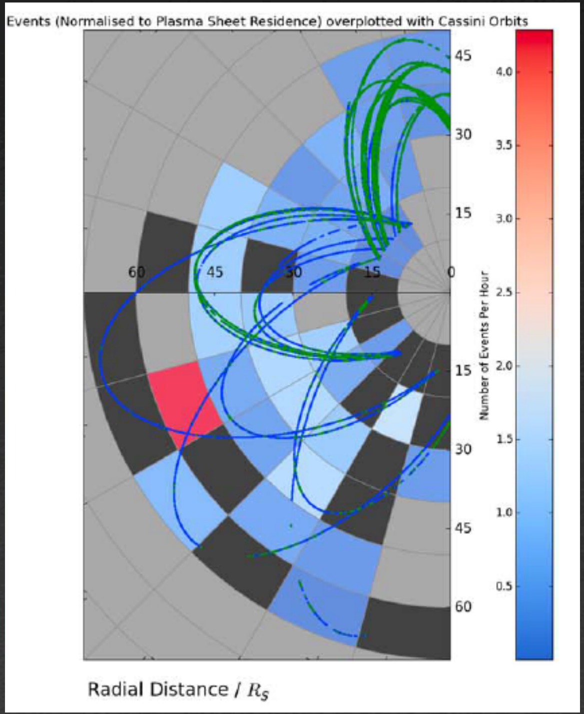
Search for reconnection signatures in Cassini data



(*Jackman et al.*, 2010)

- Plasmoid, dipolarization, travelling compression region, LFEs in wave spectra, etc.
- Few long-duration (a few hours) reconnection events observed (*Arridge et al.*, 2015; *Thomsen et al.*, 2015)

Occurrence rate of reconnection events

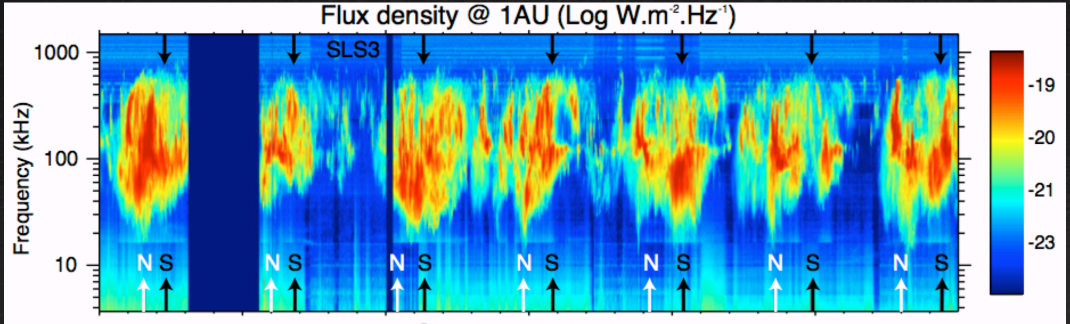


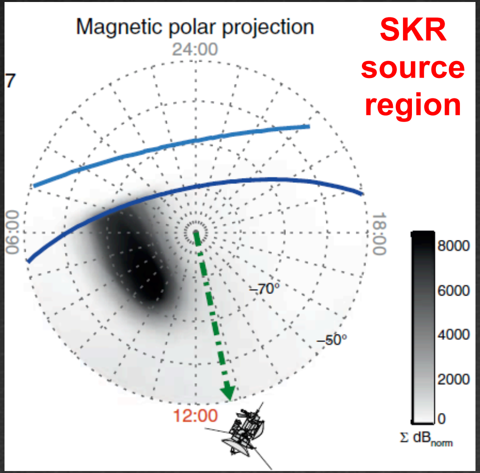
(*Smith et al.*, 2016)

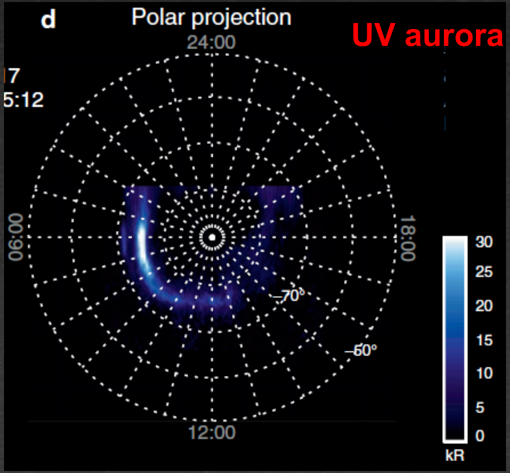
- Imbalance between mass removed by identified plasmoids and Enceladus' input

Saturn Kilometric Radiation (SKR)

RPWS spectra







(*Lamy et al.*, 2009)

- Frequency range: 3 – 1200 kHz
- Modulated by planetary rotation
- Sources located at high latitude (70° to 80°)
- Similar kind of emissions seen at Earth, Jupiter & Uranus

See presentation by *Kurth et al.*

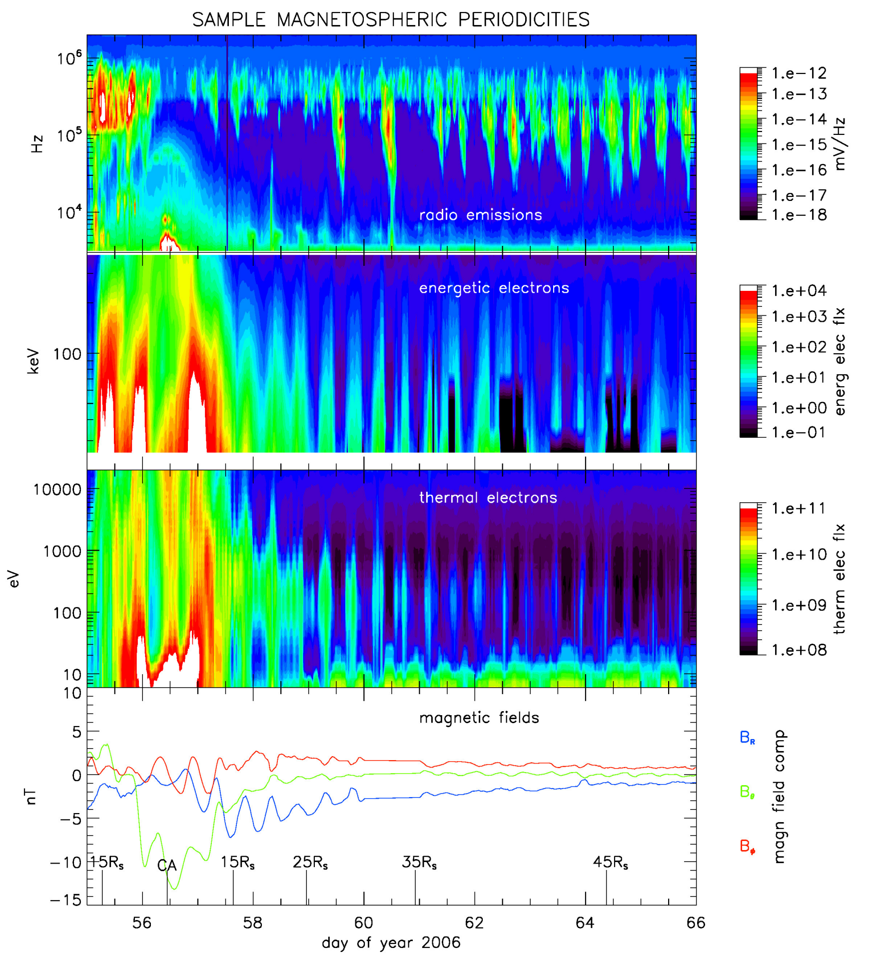
Ubiquitous Planetary Period Oscillations

SKR

Energetic e⁻

Thermal e⁻

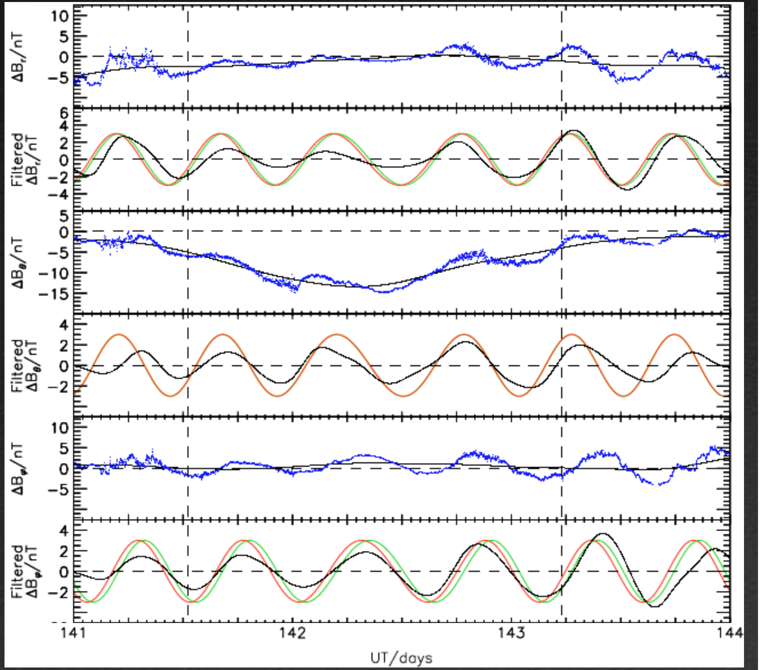
Magnetic Field

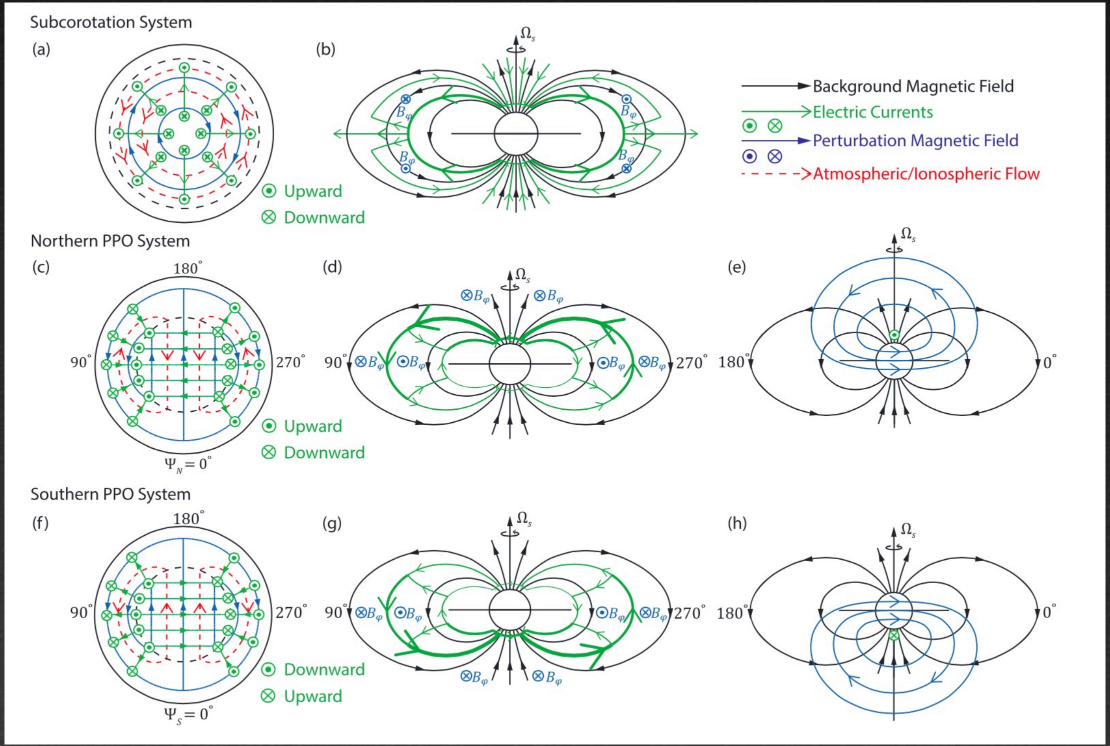


(from Saturn book chapter by *Carbary et al*., 2018)

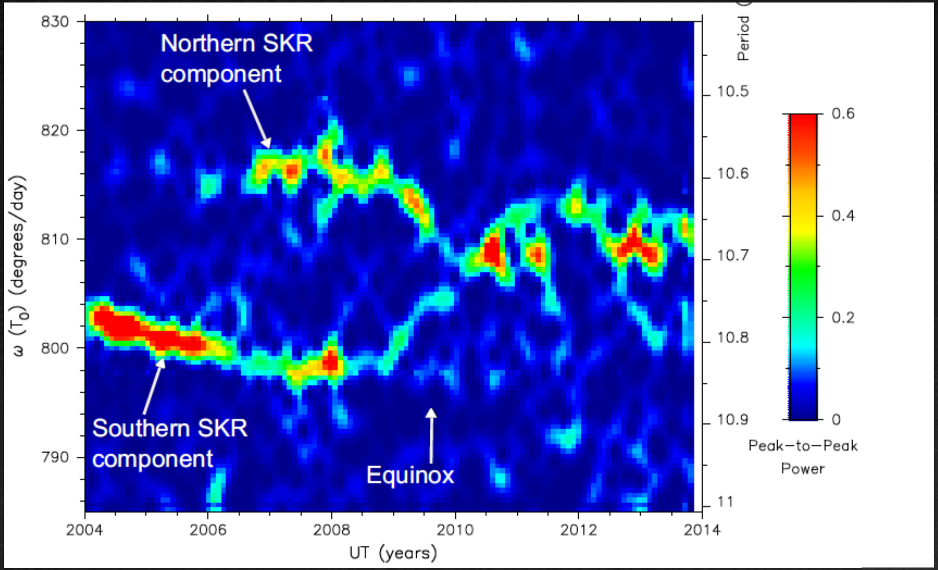
- Magnetic perturbations (Espinosa+Dougherty, Southward+Kivelson, Cowley, Andrews, Provan, Hunt)
- Plasma density (Gurnett, Burch, Ramer)
- Auroral hiss, Narrowband emissions (Gurnett, Ye)
- Energetic charged particle fluxes (Paranicas, Carbary, Brandt)
- ENA fluxes (Paranicas, Carbary)
- Boundary locations (bow shock, magnetopause, plasma sheet) (Clarke, Arridge, Provan, Carbary, Thomsen)
- Plasmoid release, ENA bursts, Interchange injections (Mitchell, Jackman, Kennelly)
- Aurora (Nichols, Carbary)

Conceptual Model of FAC Systems



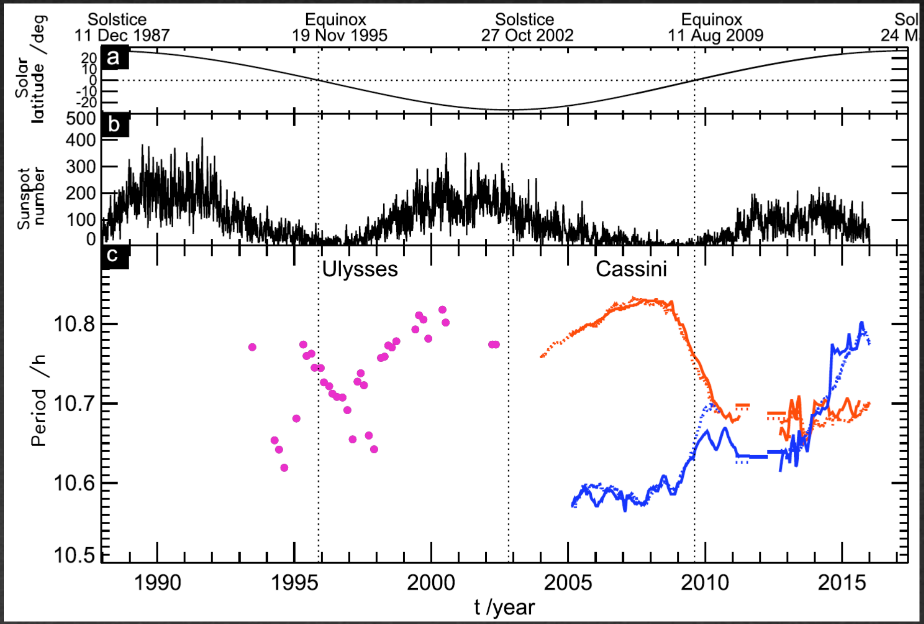


(*Andrews et al.*, 2008; *Provan et al.*, 2011; *Cowley et al.*, 2016; *Hunt et al.*, 2018)



(*Gurnett et al.*, 2009 & 2010; *Fischer et al.*, 2016)

- SKR period drifts at ~ 1% per yr (e.g., *Galopeau and Lecacheux*, 2000; *Kurth et al.*, 2007)
- A second SKR period in the northern hemisphere (*Gurnett et al.*, 2009)
- The two SKR components converge near Equinox (*Gurnett et al.*, 2010)

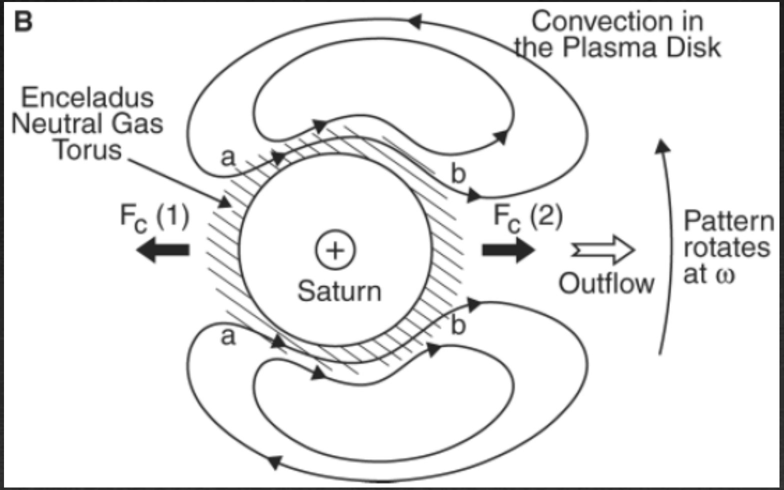


- They became well separated after 2013-2014 (*Fischer et al.*, 2016; *Provan et al.*, 2016; Lamy, 2017; *Ye et al.*, 2016, 2018)
- Earlier SKR measurements by Voyagers and Ulysses also show two components
- Appear to have seasonal dependence

(*Provan et al.*, 2016, 2018)

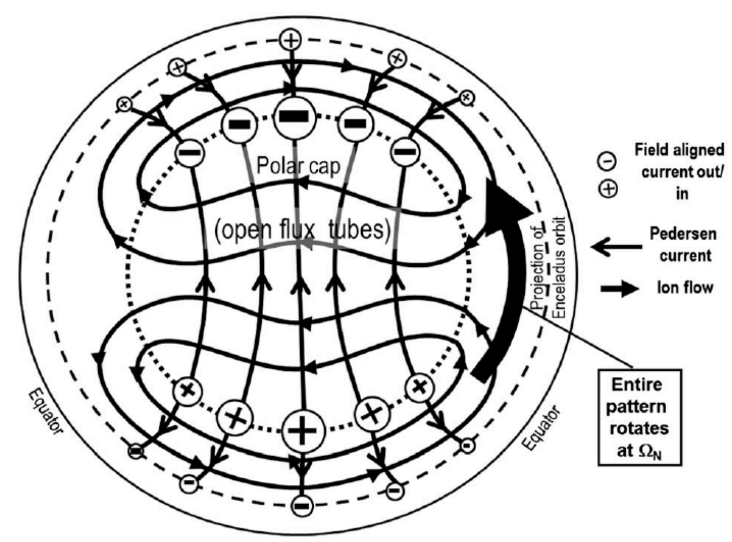
Models of Magnetospheric Periodicities

Conceptual Model of Two-cell Magnetospheric Convection



(*Gurnett et al*., 2007)

Conceptual Model of Polar Cap Oscillation

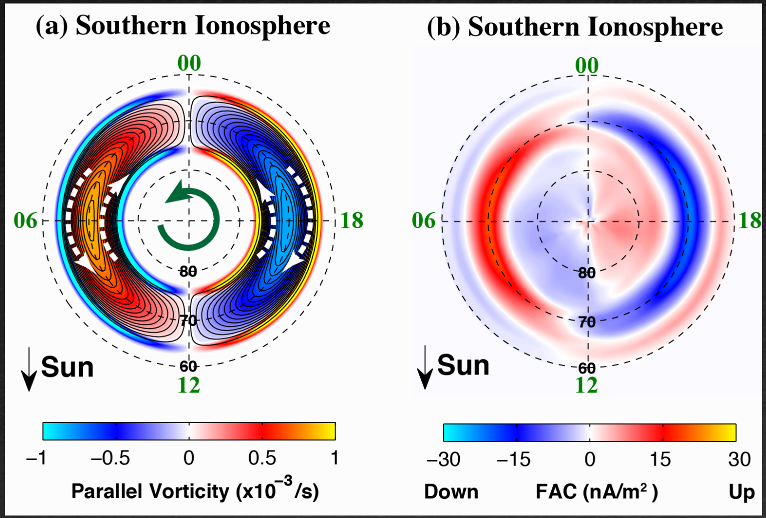


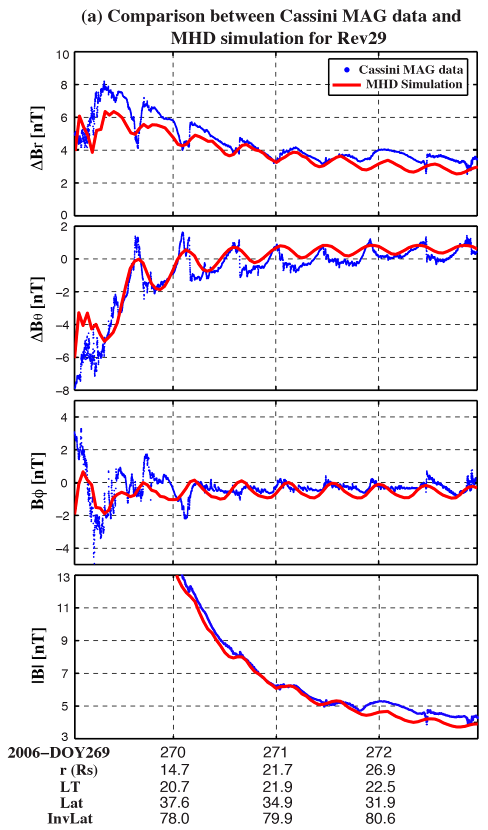
(*Southwood and Cowley*, 2016)

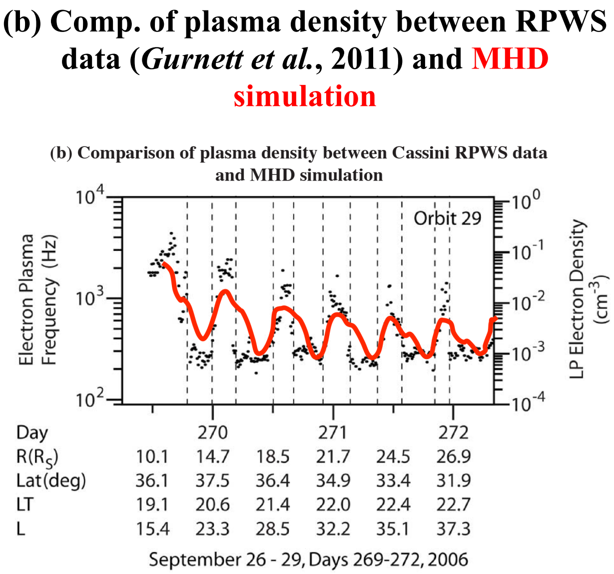
❖ Many models and theories were proposed to explain the periodicity:
- Magnetospheric origin (*Gurnett+; Goldreich+Farmer; Khurana+; Burch+; Brandt+Mitchell; Hill; Winglee+*)
- Atmospheric/Ionospheric driver (*Smith*; *Jia+Kivelson*; *Southwood+Cowley*)

Atmospheric Vortex Model

(*Jia et al.*, 2012b, 2016; *Jia and Kivelson*, 2012, 2016; *Kivelson and Jia*, 2014)







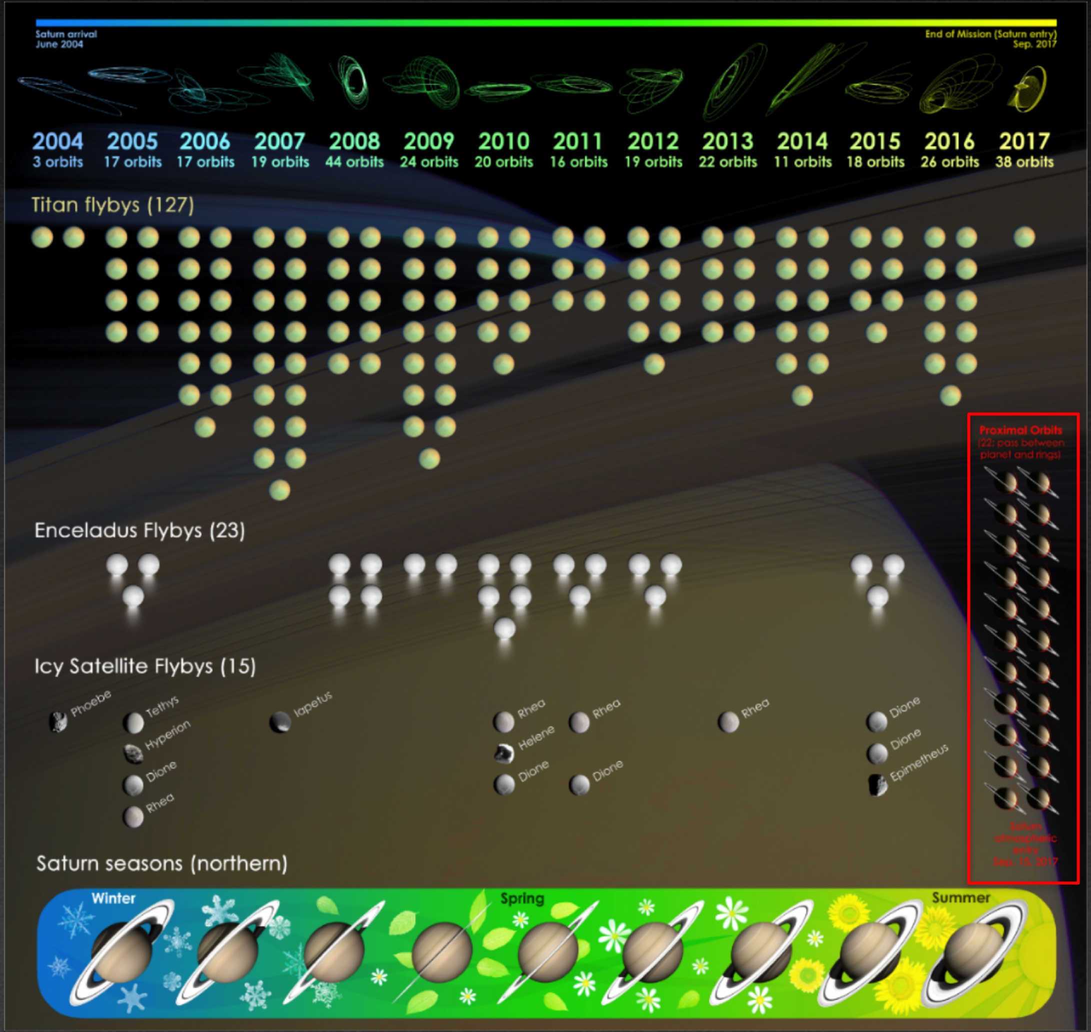
- Place the driver in the atmosphere
- Couples ionospheric vortical flows with the magnetosphere in an MHD model
- Reproduces a host of observed periodic phenomena

(*Jia et al.*, 2012b)

Cassini Orbits and Moon Encounters

- Orbits: 294
- Titan Flybys: 127
- Enceladus Flybys: 23
- Icy Satellite Flybys: 15

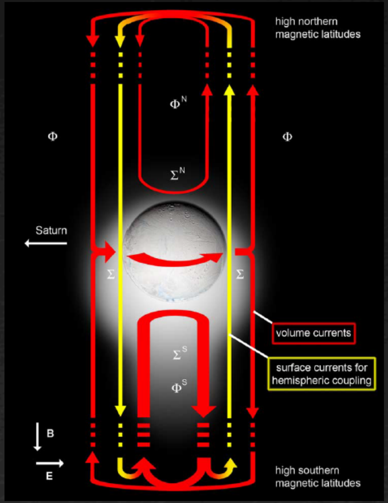
See a review by *Simon et al.* (2015) on plasma interactions with Saturn's moons



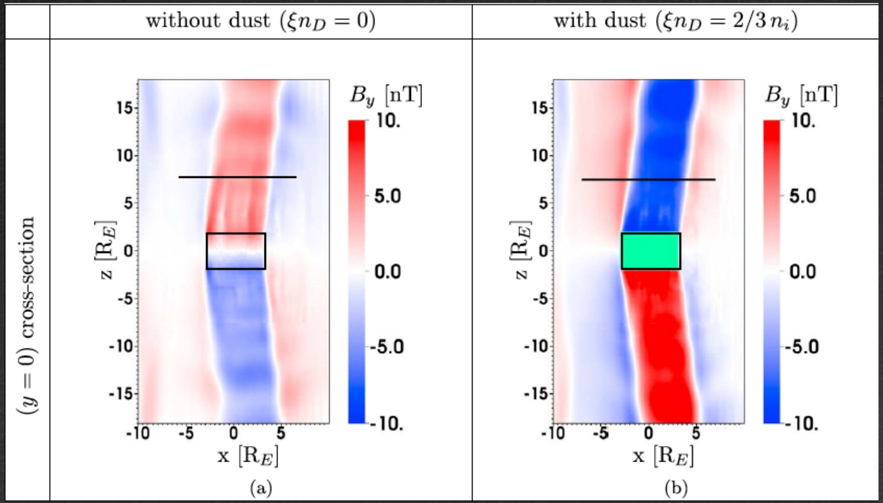
(NASA/JPL)

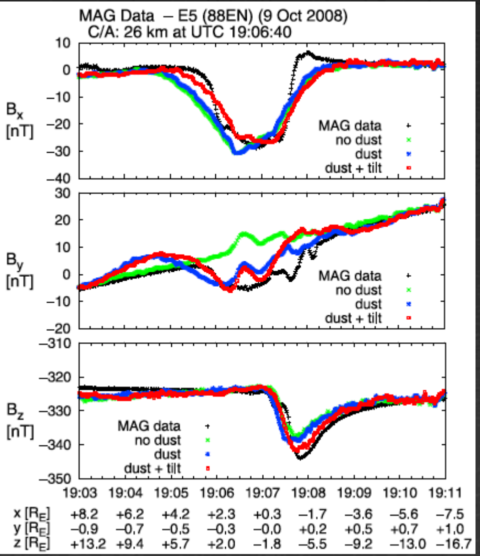
Plasma-gas-dust interactions at Enceladus and in the E-ring

- Plasma interaction with the plumes produces asymmetric Alfvén wings (e.g., *Saur et al.*, 2007; *Jia et al.*, 2009).
- Dusty plasma effects
  - Electron absorption by sub-μm dust grains causes imbalance between densities of free electrons and ions (ne < 0.1ni) within the plume and E-ring (*Yaroshenko et al.*, 2009; *Farrell et al.*, 2009; *Morooka et al.*, 2011; *Wahlund et al.*, 2009).
  - Negatively charged dust particles make ions the primary current carriers producing the so-called “anti-Hall effect”.



(*Saur et al.*, 2007)

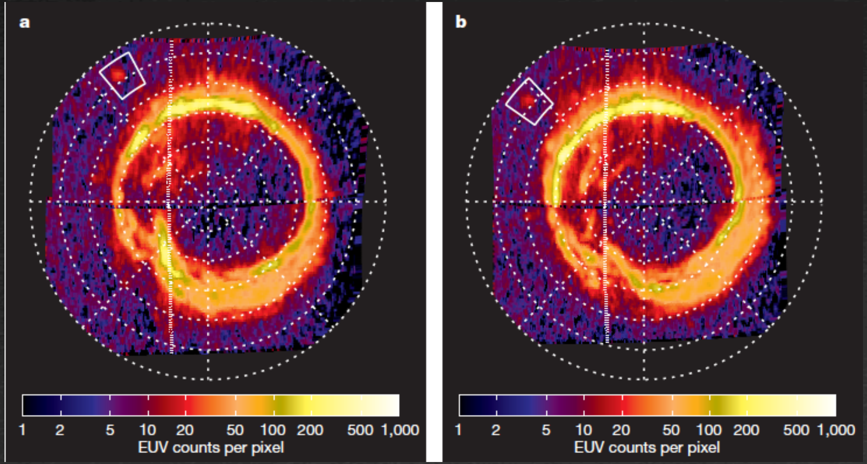




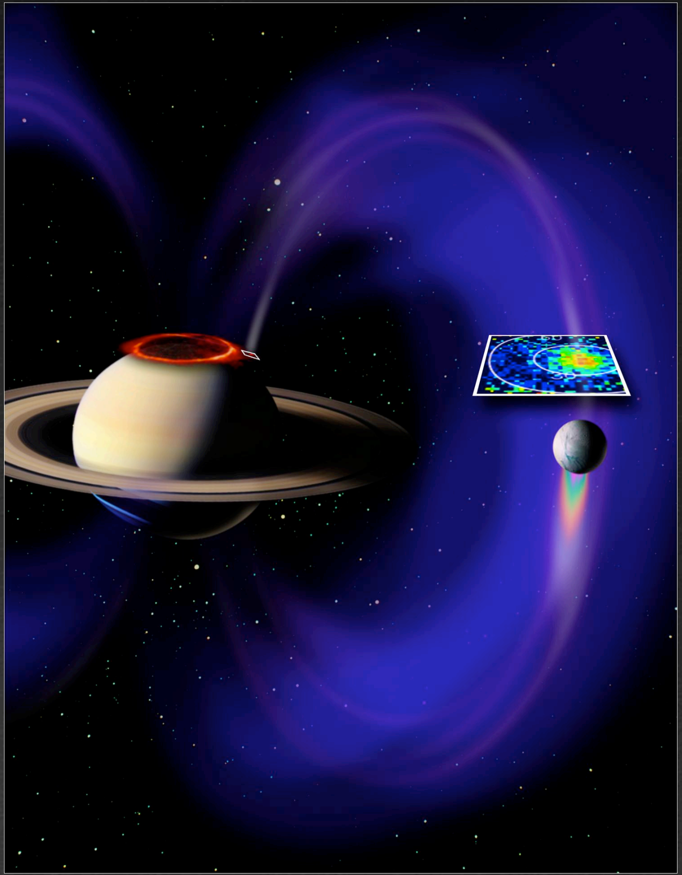
(*Kriegel et al.*, 2011)

Enceladus' Auroral Footprint

Successive EUV images of Saturn's aurora from Cassini/UVIS

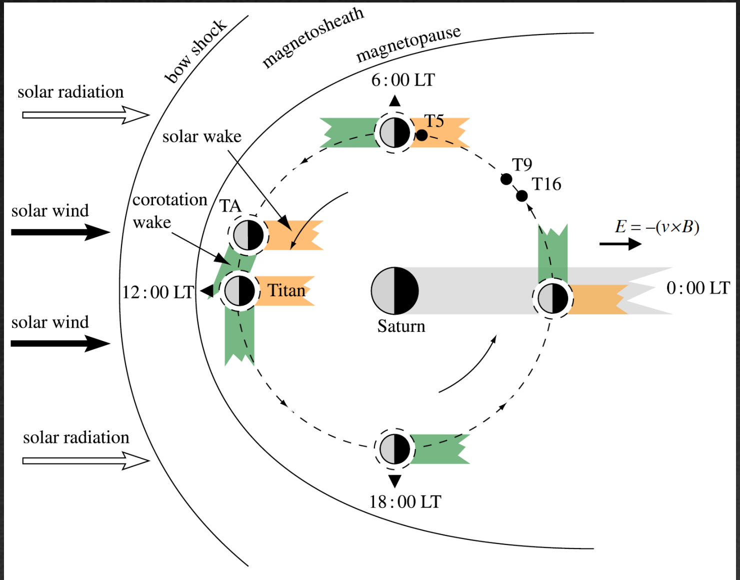


(*Pryor and Rymer et al.*, 2011)

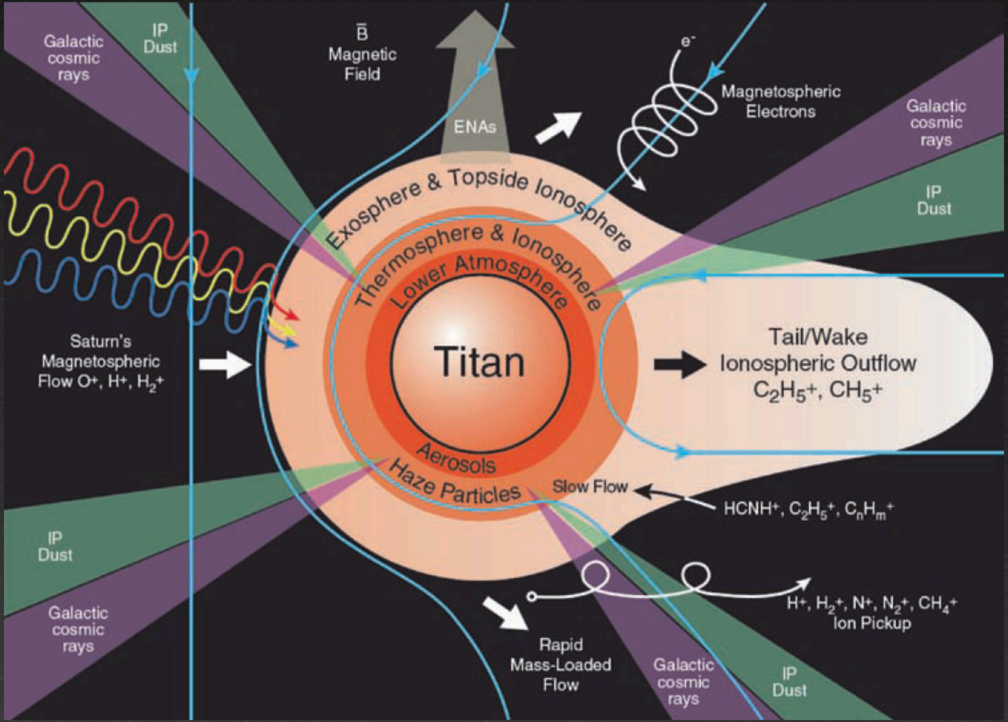


- Enceladus' footprint is about an order of magnitude dimmer than Io's footprint.
- Intense plasma waves were detected by RPWS close to Saturn when Cassini traversed a flux tube connecting Saturn to Enceladus (*Sulaiman et al*., 2018)

Titan and Its Induced Magnetosphere

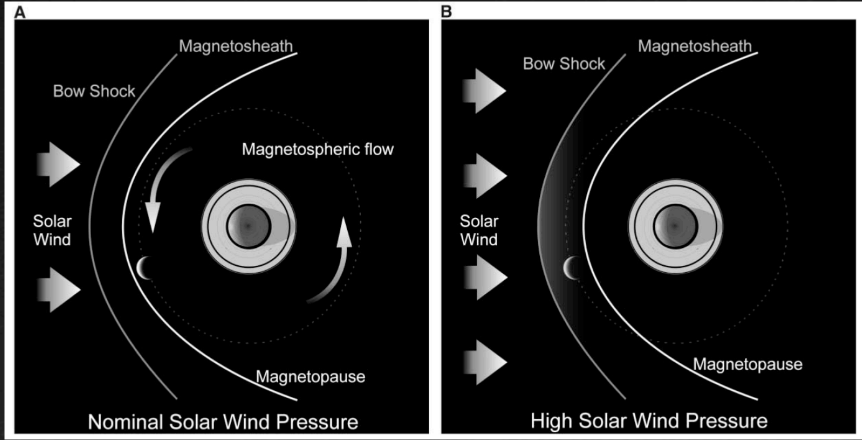


(*Coates et al.*, 2009)

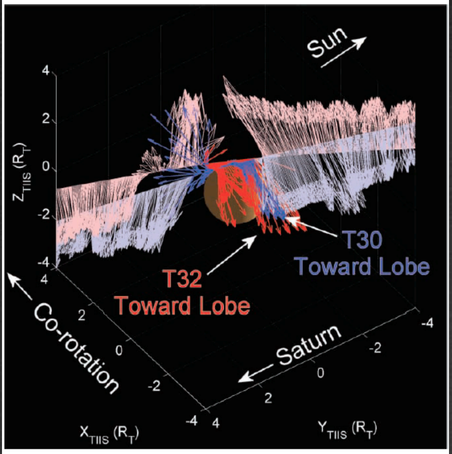


(*Sittler et al.*, 2009)

Titan in Saturn's Magnetosheath

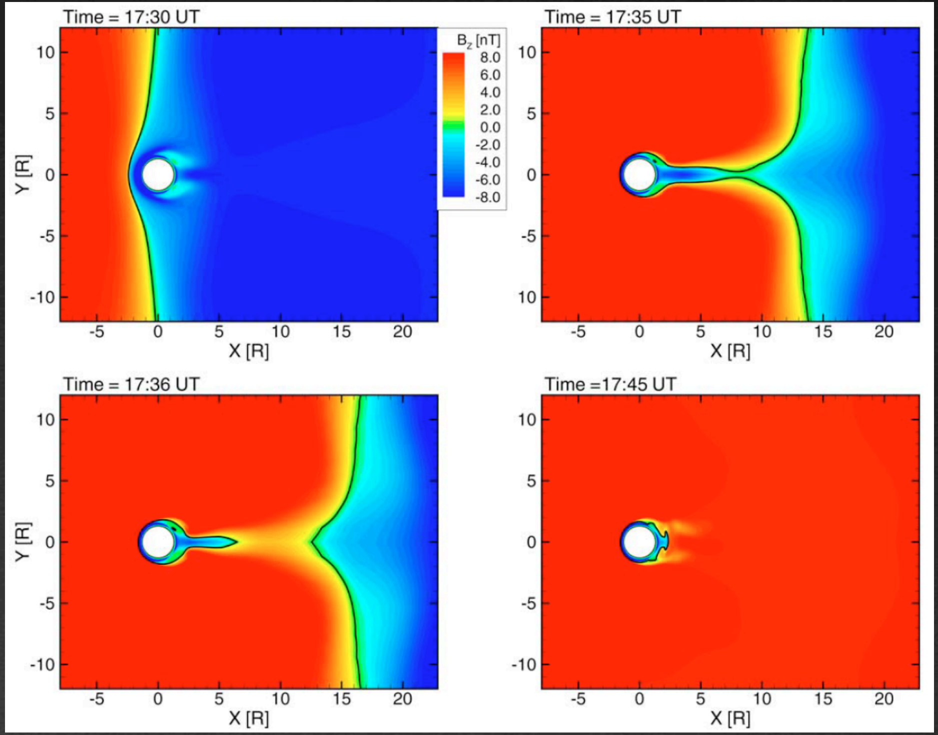


(*Bertucci et al.*, 2008)



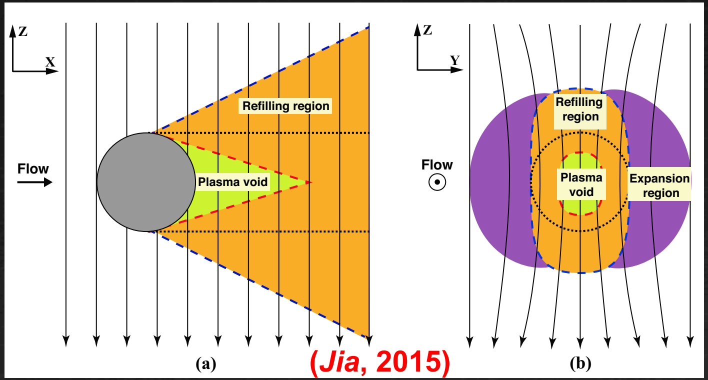
"Fossil" magnetic fields in Titan's ionosphere

BATSRUS simulation with time-varying upstream conditions



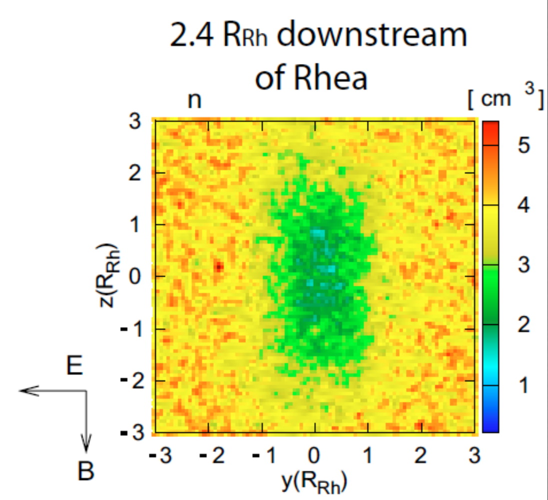
(*Ma et al.*, 2008)

Plasma Interactions at Other Icy Moons



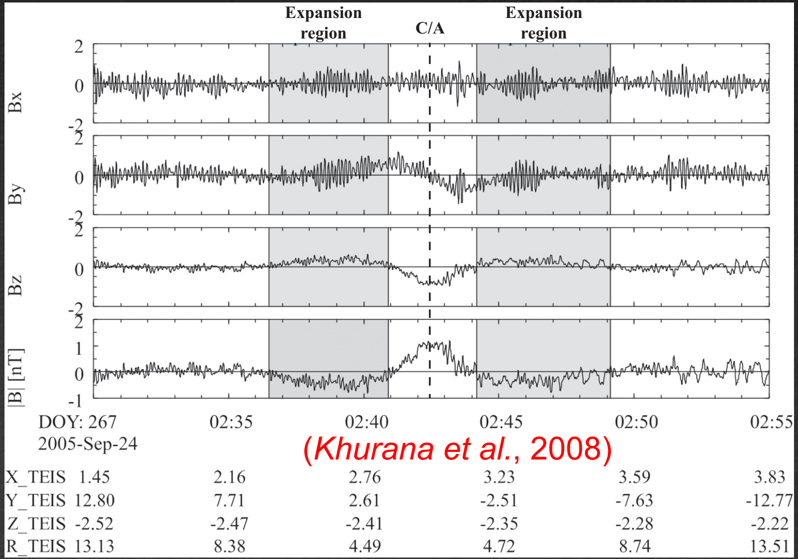
(*Jia*, 2015)

- ❖ Tethys, Dione, and Rhea
  - No appreciable intrinsic field; thin exosphere (*Teolis*+2010; *Tokar*+2012; *Buratti*+2018)
  - Interact with sub-Alfvénic and trans-sonic plasma flows (*Khurana*+2008; *Roussos*+2008)
  - Space Weathering (*Schenk*+2011; *Howett*+2011; *Paranicas*+2014)
  - Complex wake structure (*Roussos*+2012; *Krupp*+2013)



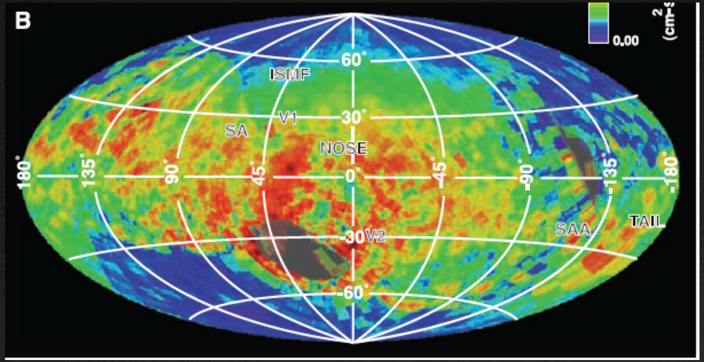
Hybrid sim. of Rhea's wake

(*Roussos et al.*, 2008)



(*Khurana et al.*, 2008)

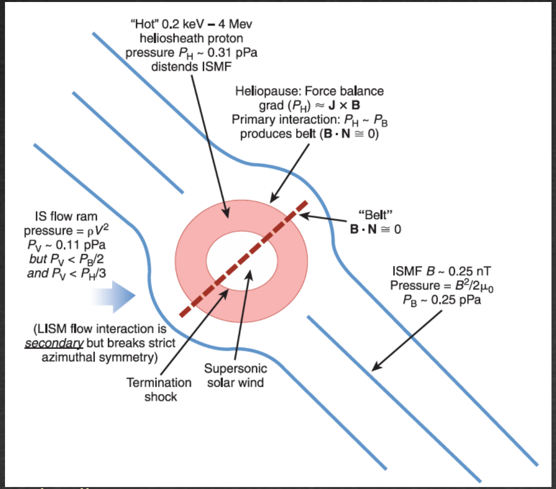
Cassini's Contribution to Heliospheric Science

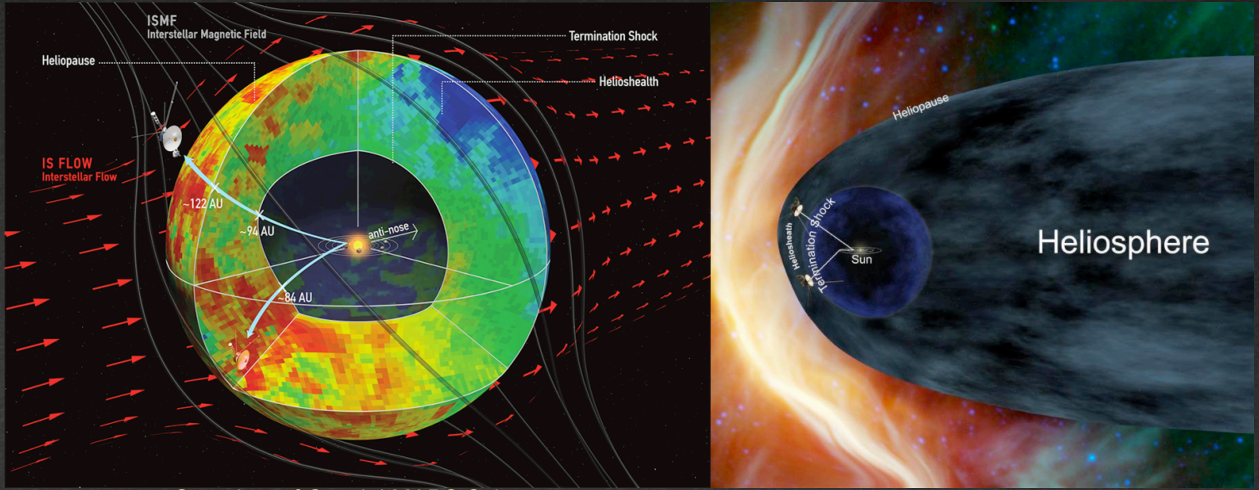


(*Krimigis et al.*, 2009)

❖ ENA imaging by Cassini/MIMI, in conjunction with IBEX and Voyager observations, provides new insights into the interaction of the heliosphere with the local interstellar medium.

(*Dialynas et al.*, 2017)





Open Questions

- Internal rotation rate and internal magnetic field
  - Origin of magnetospheric periodicities
  - Seasonal variation

- Plasma transport and loss mechanisms
  - Mass and magnetic flux budget
  - Interchange
  - Implications for Jupiter and other rotating magnetospheres

- Solar wind influence
  - Reconnection vs. viscous interaction

- Satellites
  - Enceladus: plume-magnetosphere interaction, habitability
  - Titan: heavy ions and negative ions, absence of neutral torus
  - Other icy moons: complex wake structure