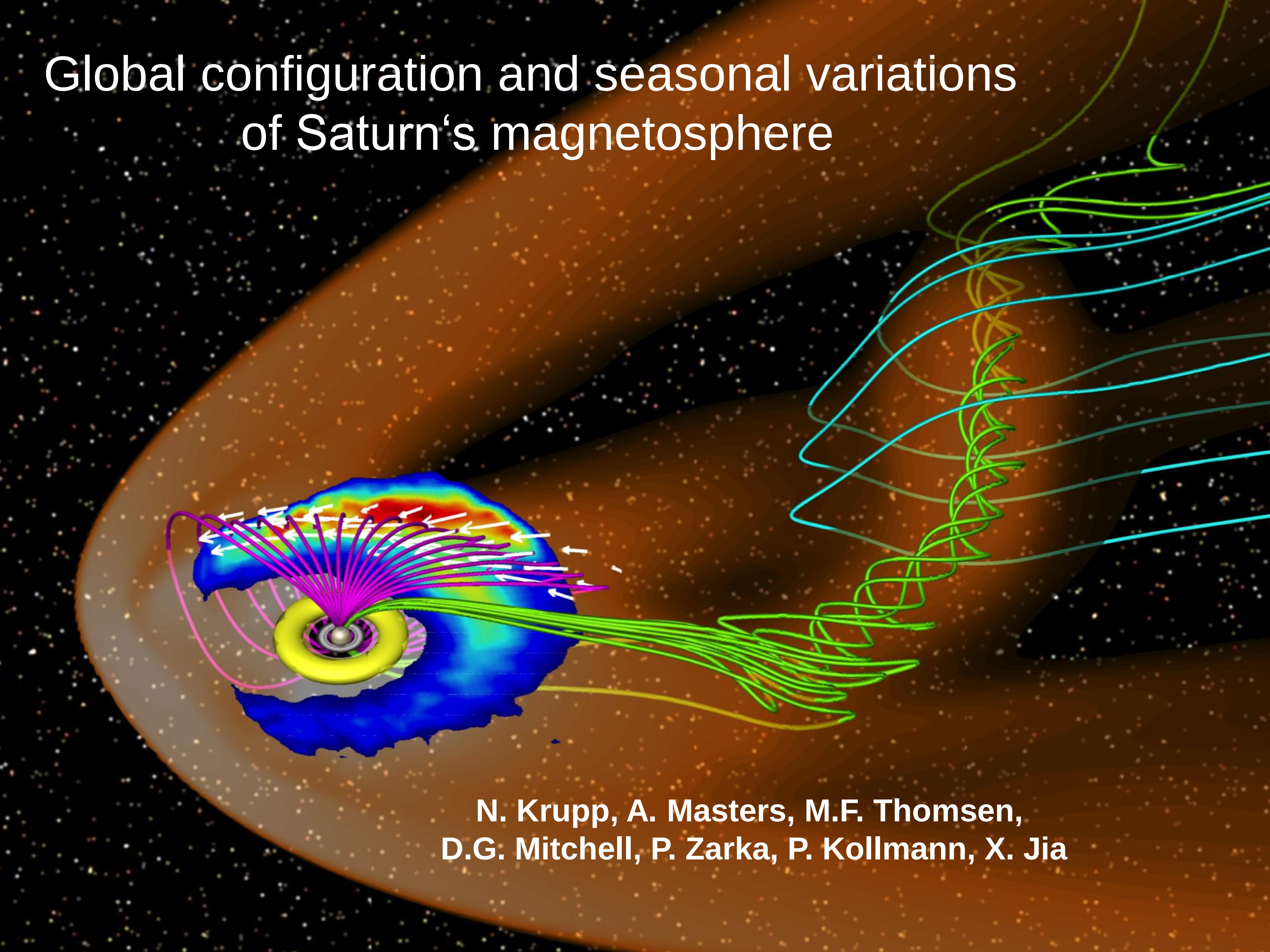
Global configuration and seasonal variations of Saturn‘s magnetosphere



**N. Krupp, A. Masters, M.F. Thomsen,
D.G. Mitchell, P. Zarka, P. Kollmann, X. Jia**

Magnetosphere chapters in Saturn book 2009

Gombosi et al.:
Saturn‘s Magnetospheric Configuration

Mitchell et al.:
The Dynamics of Saturn‘s Magnetosphere

Mauk et al.:
Fundamental Plasma Processes in Saturn‘s Magnetosphere

Kurth et al.: Auroral Processes

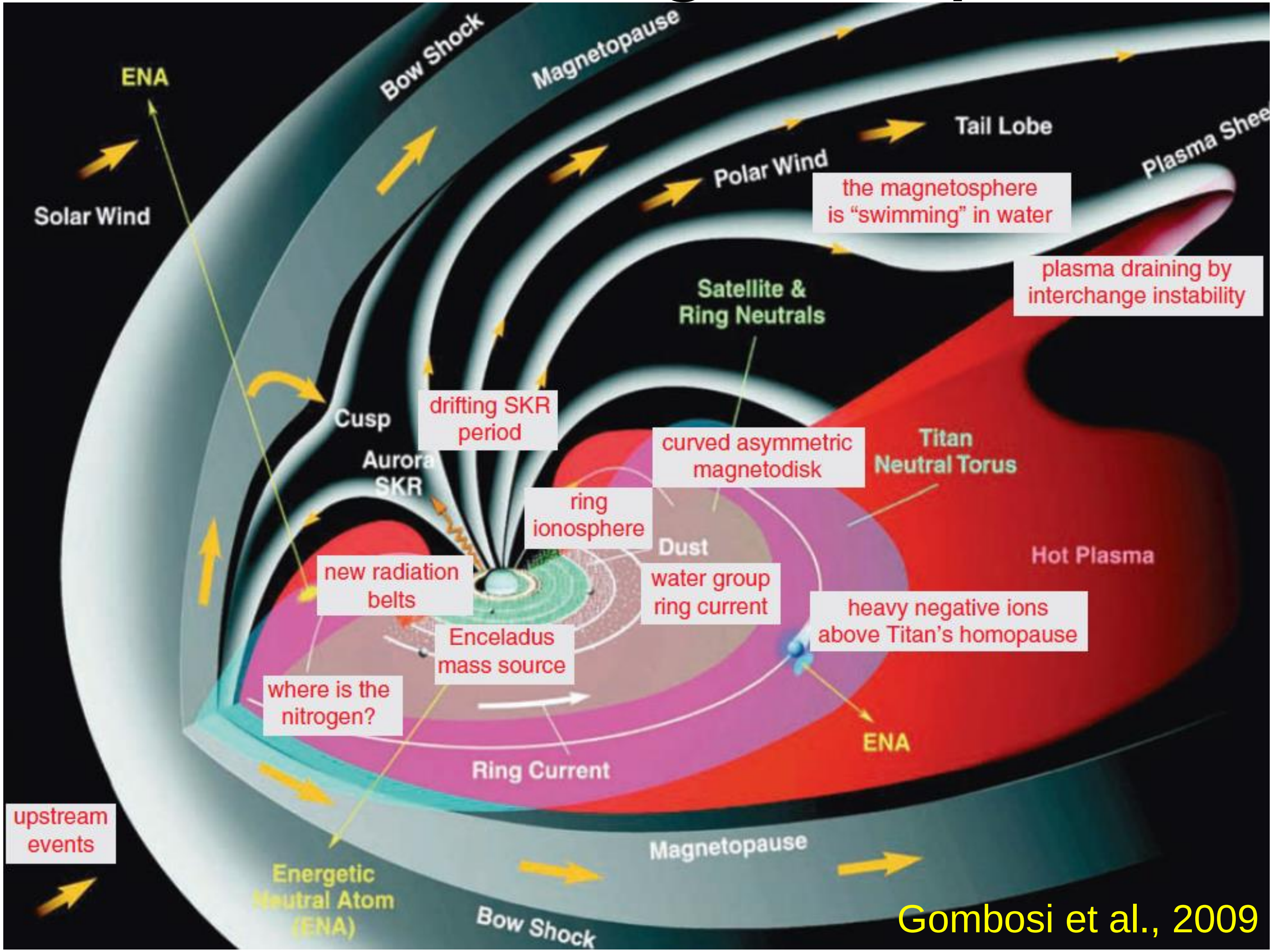
Outline of Magnetosphere chapter in the new book

1. Magnetospheric structure
2. Plasma sources
3. Transport and Magnetospheric dynamics
4. Boundary phenomena
5. Proximal and F-ring orbit magnetospheric science

Magnetospheric stucture

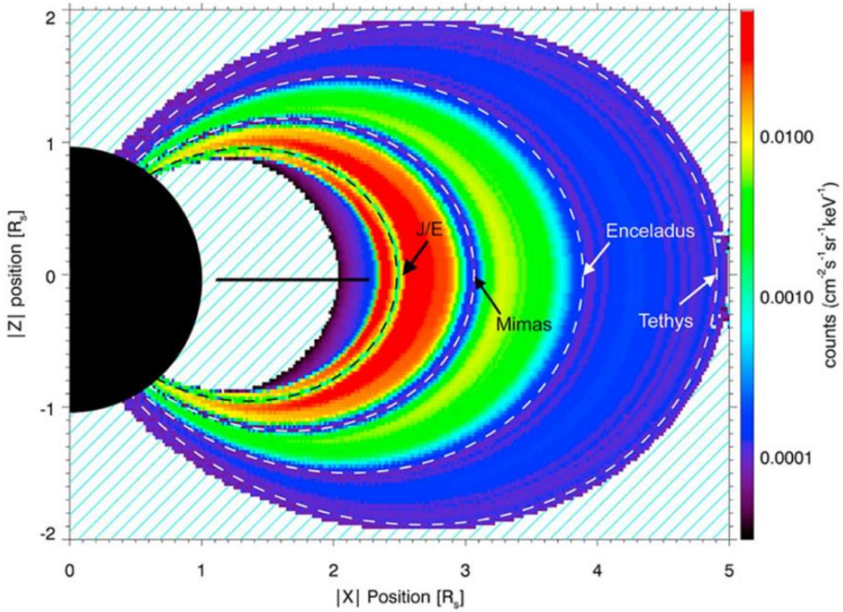
1. Radiation belts [Roussos et al., 2011, 2013; Kollmann et al. 2013]
2. Plasma properties in magnetodisk [Thomsen et al., 2010; Sergis et al., 2010; Achilleos et al., 2010, Wilson et al., 2013]
3. Global region characterizations [Arridge et al., 2011 (ISSI)]

Saturn‘s magnetosphere

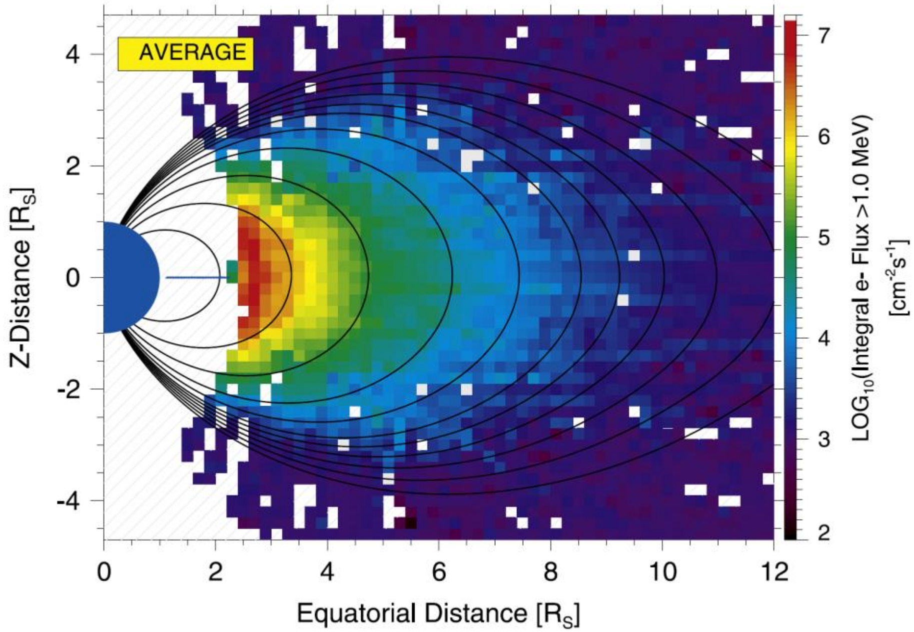


Radiation belts of Saturn

MeV Protons

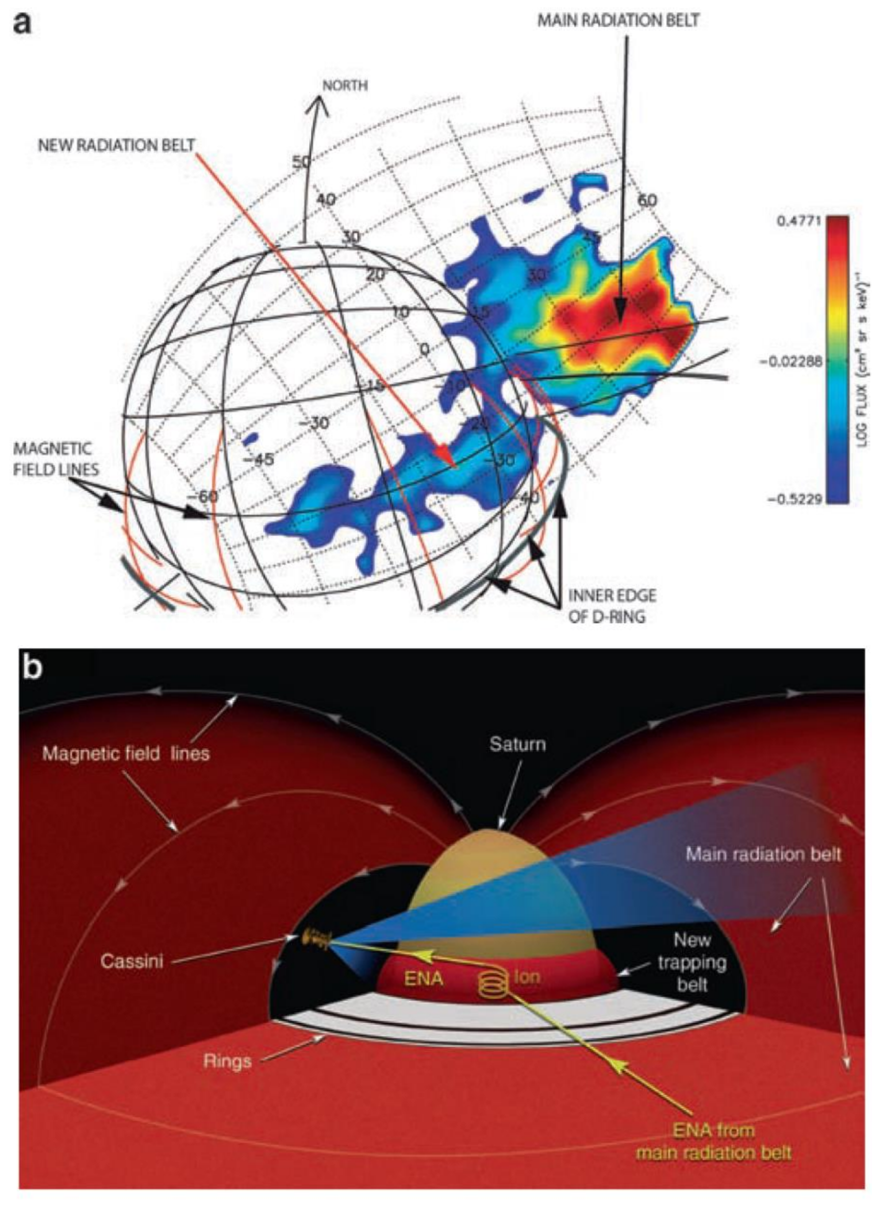


MeV Electrons

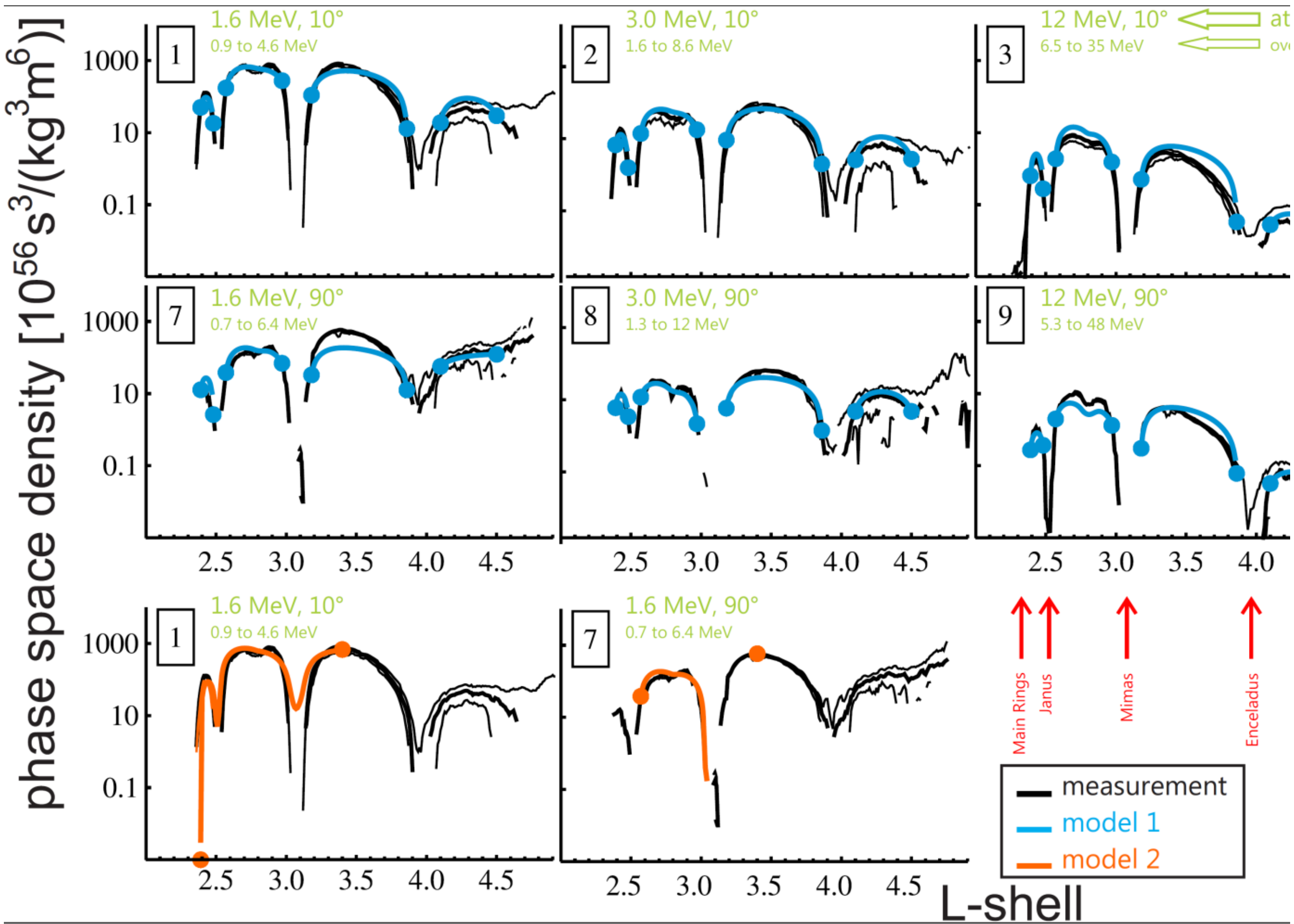


Ion radiation belt inside the D-Ring (Krimigis et al., 2004)

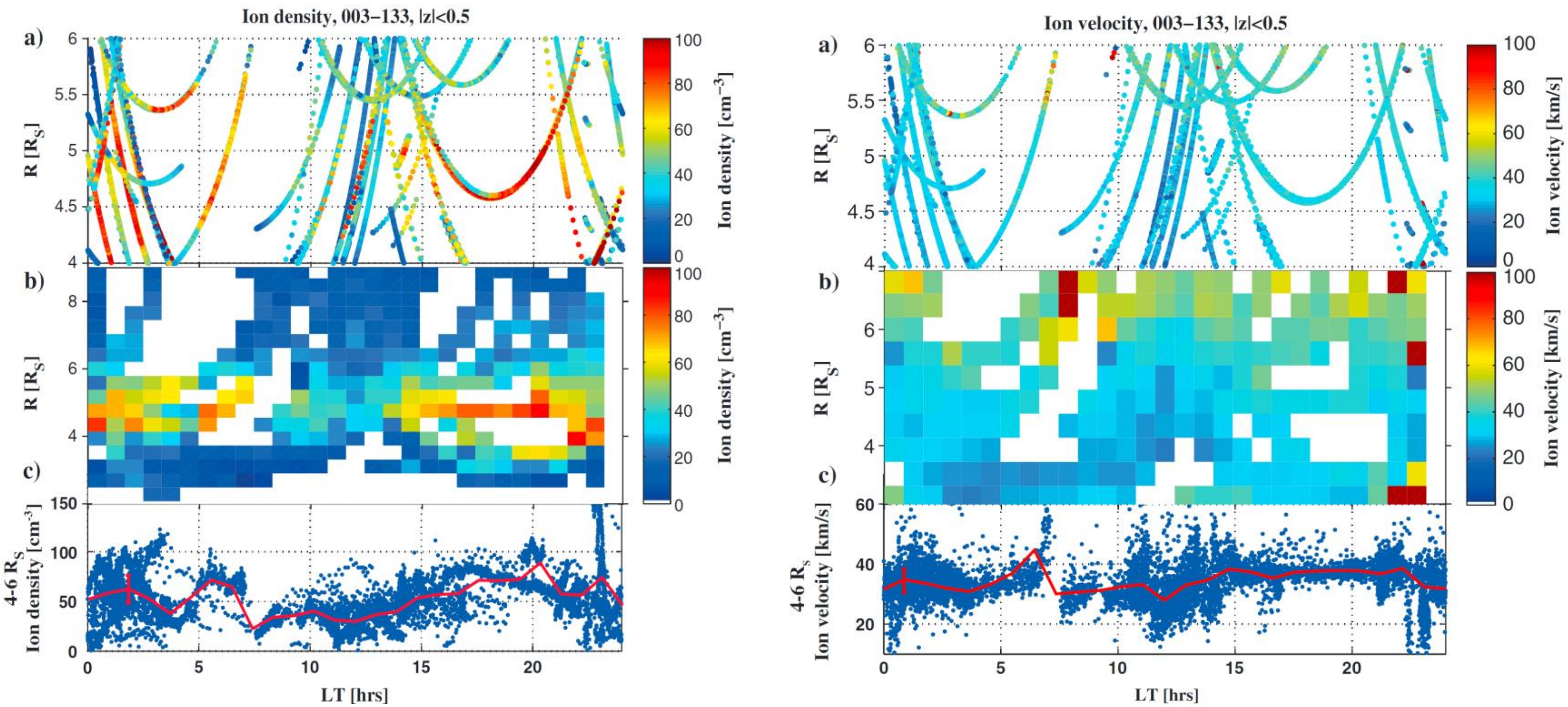
Indirect measurements remotely via ENA results.



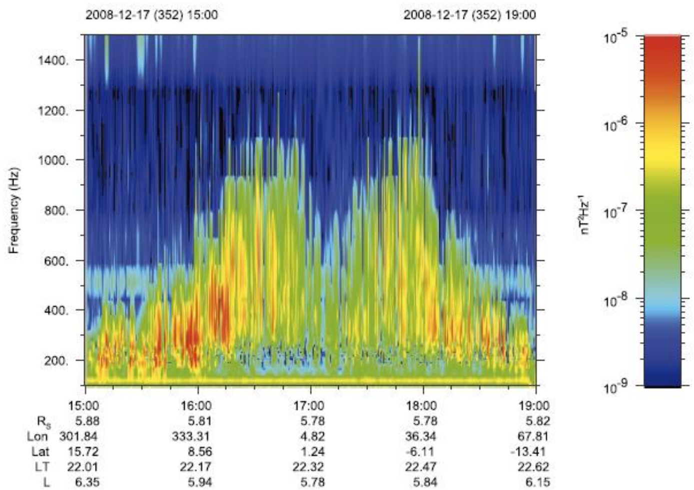
Phase phase density in Saturn‘s magnetosphere (Kollmann et al., 2013)

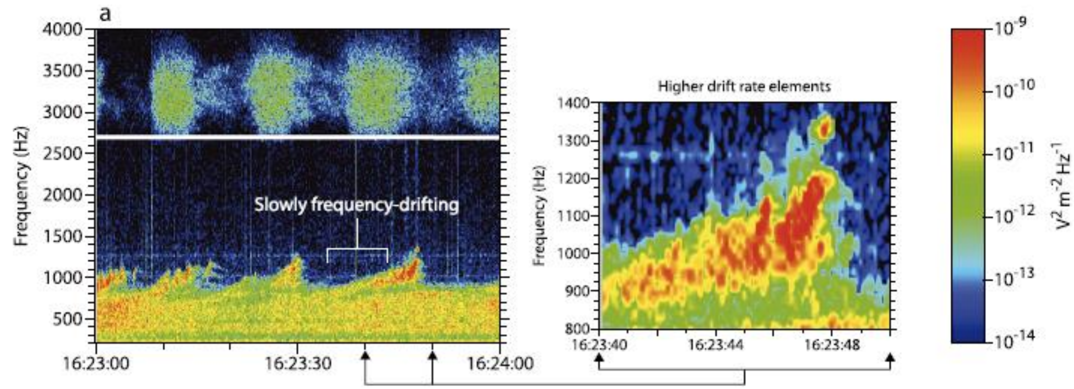


Day/night asymmetry at 4-6 RS in ion density and ion velocity (Holmberg et al. 2014)



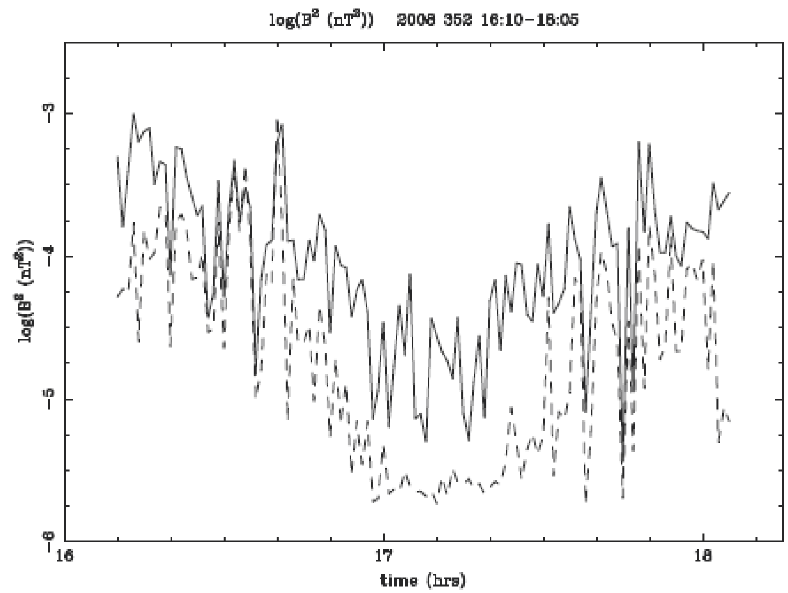
Saturn Chorus Intensity Variations





Intense chorus elements at higher latitude – evidence of non-linear growth

Chorus intensity: note minimum at equator

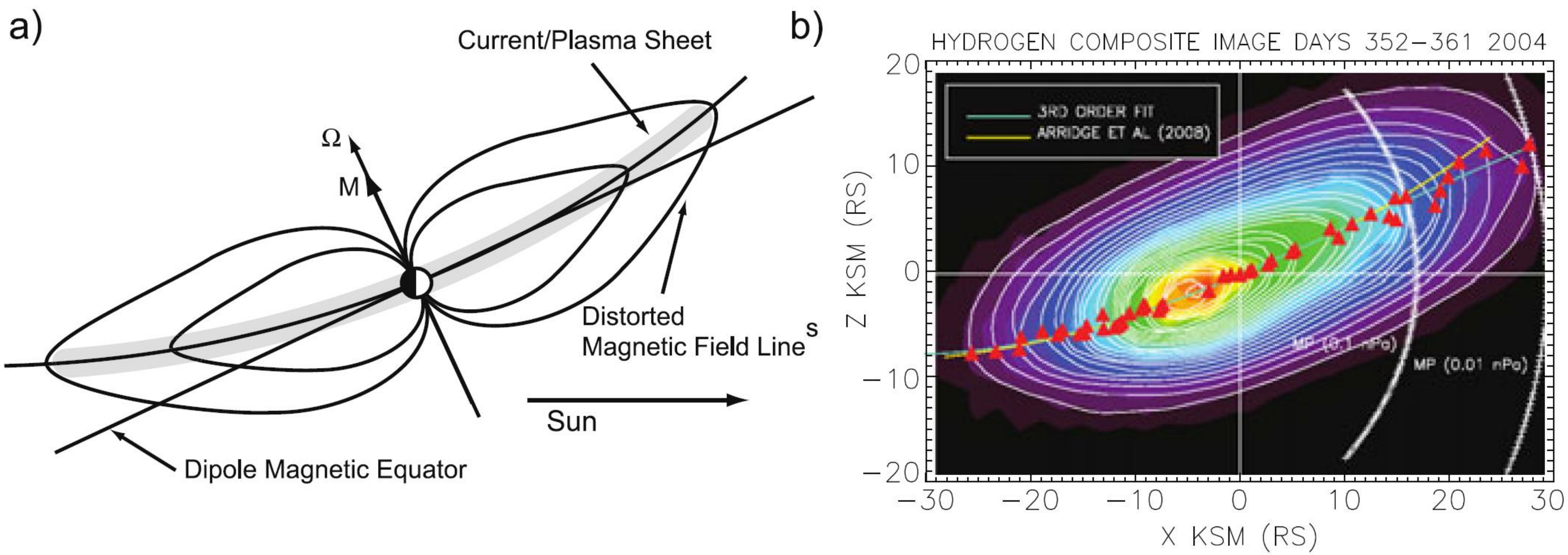


- Whistler mode chorus is important loss mechanism for particles in the radiation belts and as a mechanism for accelerating electrons to higher energies.
- At Saturn, while the equatorial region is the source of chorus, the intensity at the equator is at a minimum.
- Growth of chorus intensities at and near the equator can be well-described with a small temperature anisotropy observed in the electron distribution function by CAPS.
- At higher latitudes drifting chorus elements at higher frequencies and larger amplitudes indicate nonlinear growth. At these latitudes, the drifting emissions make up the bulk of chorus wave power.
- Chorus risers may be correlated with lower frequency electromagnetic ion cyclotron waves and electron cyclotron emissions suggesting the low frequency waves may modify the electron distribution for non-linear growth.

Chorus power: solid line – low frequencies; dashed line – high frequency chorus elements

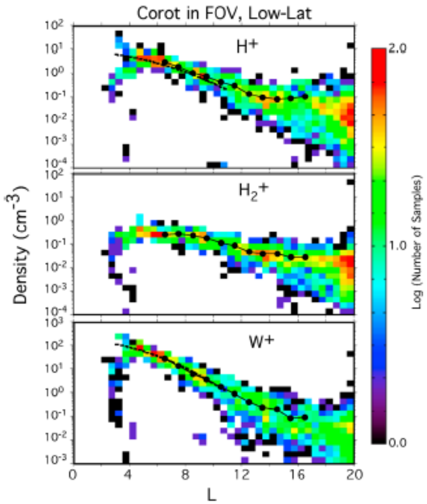
[Menietti et al., *JGR*, 2013]

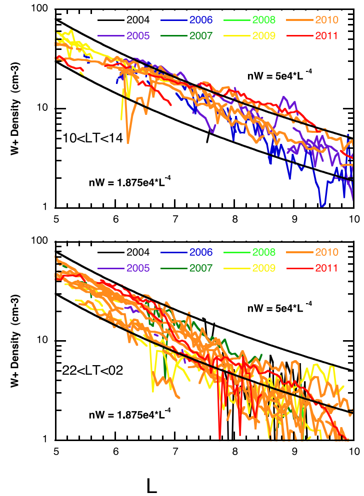
Bowl-shaped magnetodisk
Arridge et al. 2008; Carbary et al. 2008



Comprehensive Survey of Magnetospheric Plasma Properties at Saturn

Radial dependence of density

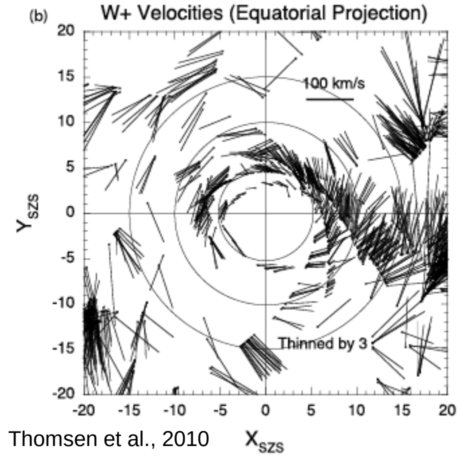




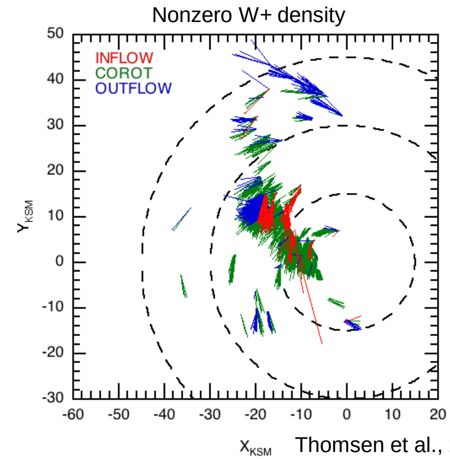
Thomsen et al., 2010

- Source of plasma is inner magnetosphere water
- No long-term variability; maximum x3 variation

Flow velocities



Thomsen et al., 2010

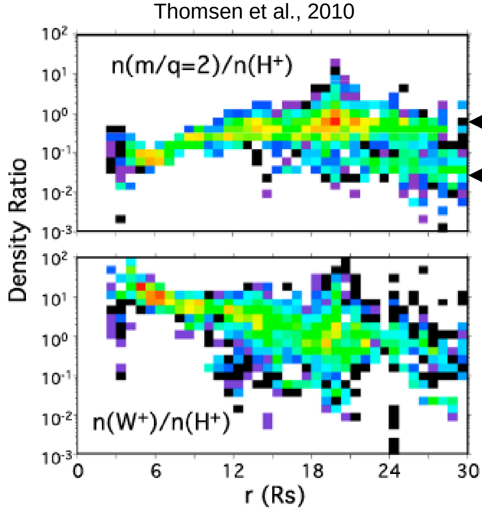


Thomsen et al., 2014

- Flows throughout the magnetosphere are dominantly corotational
- Evidence found for dusk-side planetary wind
- Net radial mass outflow with nightside mass loss ~34 kg/s

Radial dependence of composition

Thomsen et al., 2010

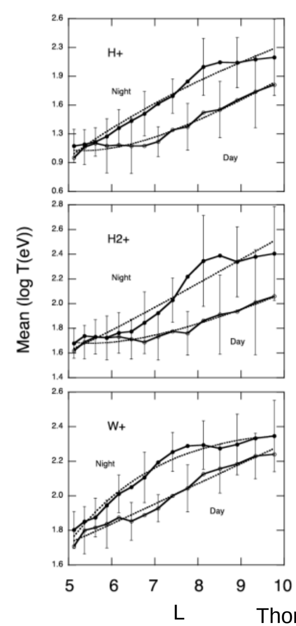


outer magnetosphere

solar wind/ magnetosheath

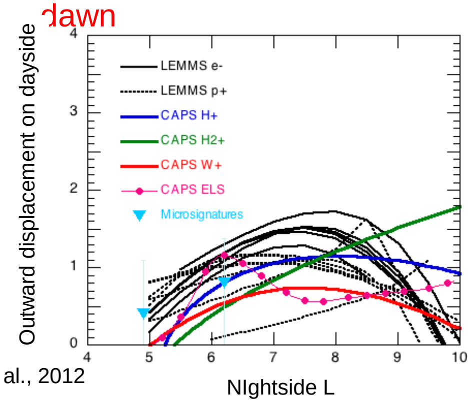
- Titan-contributed H_2^+ is major constituent of outer magnetosphere

Temperatures higher on nightside than dayside

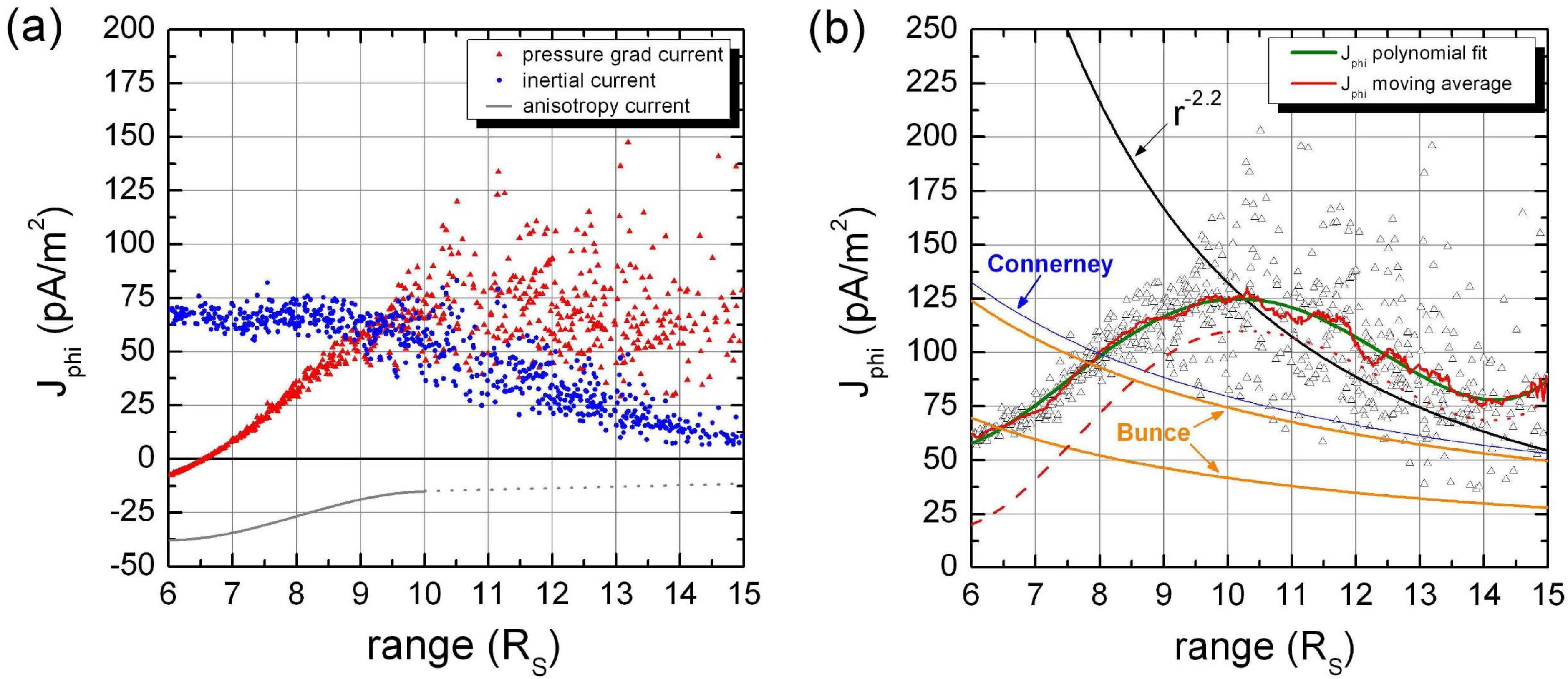


Thomsen et al., 2012

- Adiabatic heating/cooling due to radial circulation: Inward at dusk, outward at dawn



Radial profile of the Saturnian ring current density



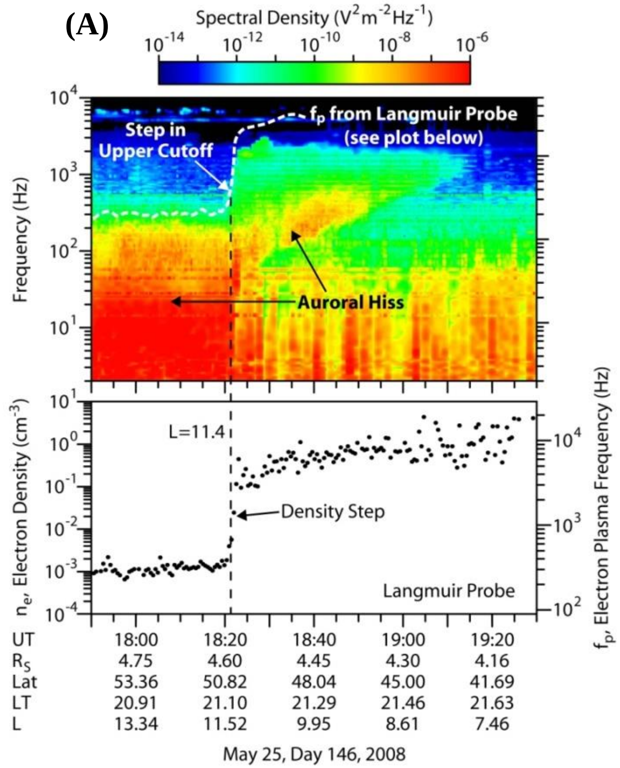
1) The ring current is inertial inside 9 R_S but becomes pressure gradient driven (and more disturbed) beyond 10 R_S.

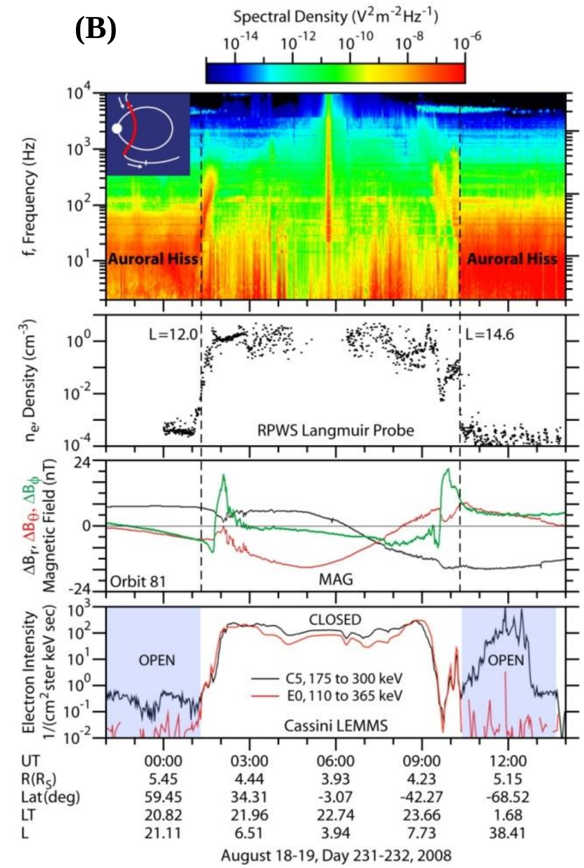
2) In contrast to widely used models (Connerney et al., Bunce et al.) **J_φ has a maximum** and drops outwards faster than 1/r (closer to $r^{-2.2}$).

Sergis et al., GRL, 2010

A plasmapause-like density boundary at Saturn
(Gurnett et al., 2010)

- During Cassini high-latitude passes in mid-2008, RPWS obtained electric field spectrums showing an abrupt step in the upper frequency cutoff of the auroral hiss emissions for 8<*L*<15 (upper panel of Fig. A).
- The frequency step coincides with a steep gradient in the density measurements by the Langmuir Probe instrument, with densities nearly three orders of magnitude higher inside the density boundary at lower L-shell values (lower panel of Fig. A).





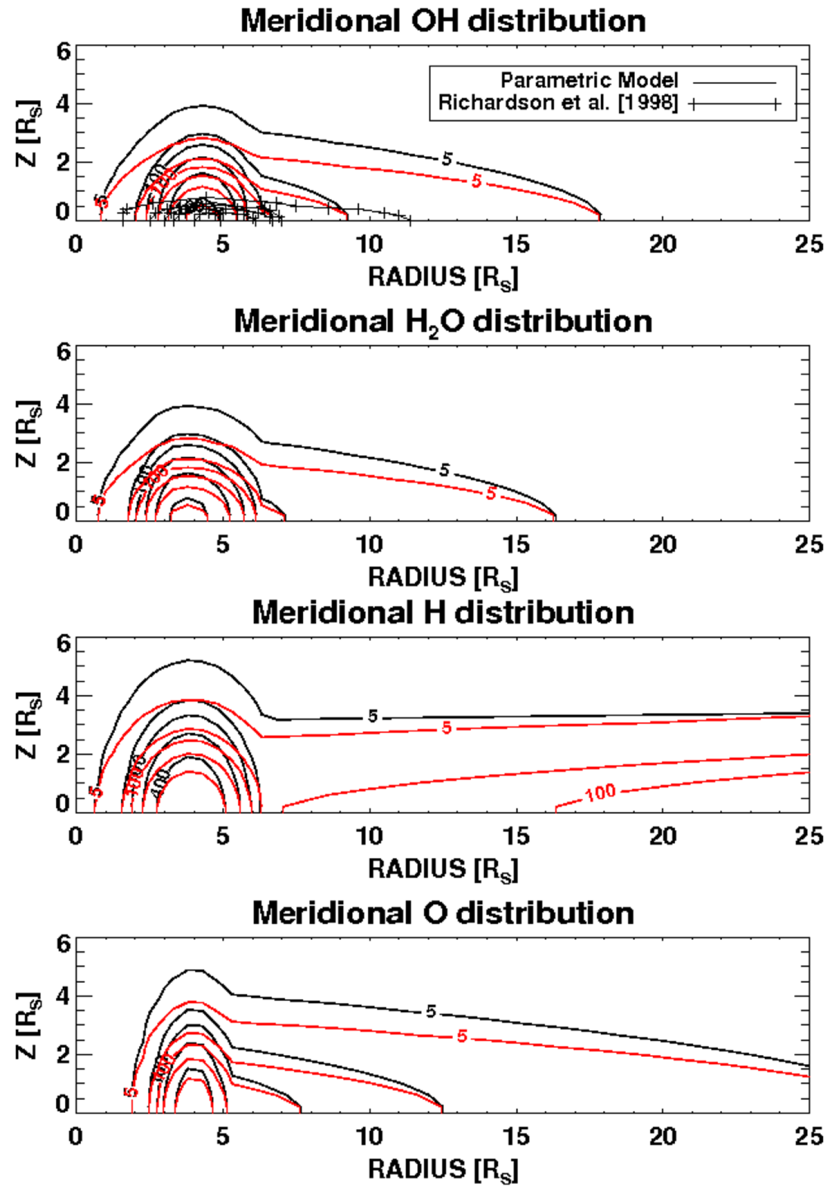
- The density boundary is observed in both the southern and northern hemispheres by RPWS and is shown to enclose a system of field-aligned currents observed by the Cassini magnetometer just inside the density boundary (third panel of Fig. B).
- Energetic electron flux measurements by the MIMI-LEMMS instrument indicate that the high plasma densities always occur in a region of closed field lines. In the low density region beyond the boundary, the magnetic field lines are often found to be open (fourth panel of Fig. B).

Plasma sources

1. Enceladus (Dialynas et al. 2013, Cassidy et al., 2010, Richardson et al, 1998)
2. CRAND process (Kollmann et al., 2011)
3. Rings (Tseng et al., 2010, 2013)

Enceladus neutral source (Dialynas et al. 2013)

Desnsity contours as derived from MIMI measurements compared to model from Richardson 1998.

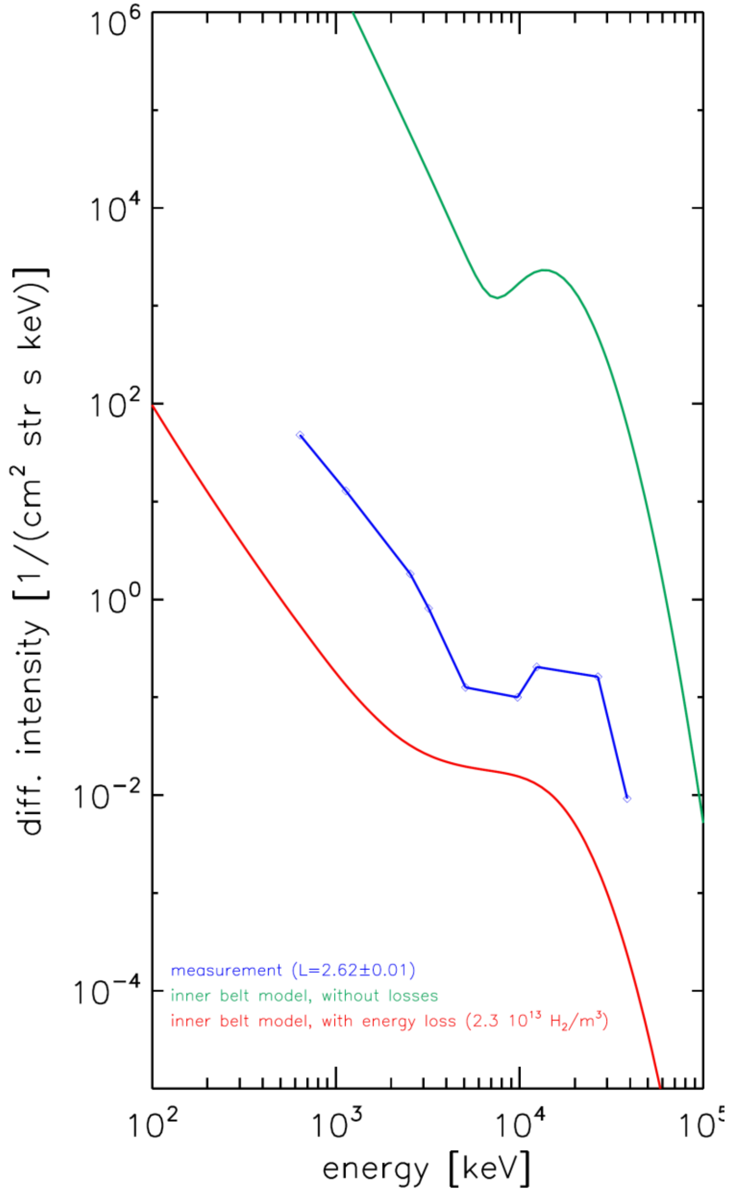


Proton energy spectrum at L=2.62 in the Saturnian radiation belts (Kollmann et al., 2013)

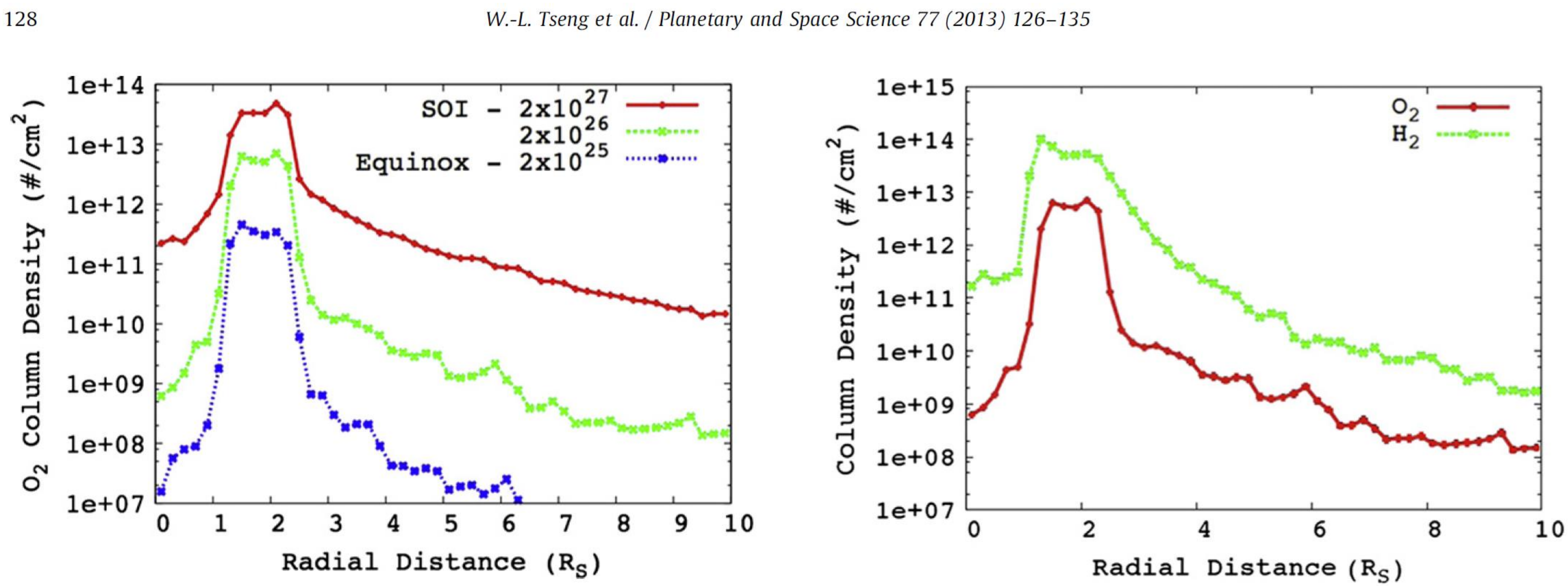
Blue: MIMI/LEMMS measurement
Green and red: models

Peak at 10-20 MeV originates from CRAND (Cosmic ray albedo neutron decay) process

Cosmic rays at GeV energies hit atmosphere and rings creating neutrons. They decay as protons in the MeV range → get trapped on field lines.



Radial distribution of neutral O2 and H2 as a function of distance (ring atmosphere source) Tseng et al., 2013



Ion molecule collisions of ring atmosphere particles
(seasonally dependent)

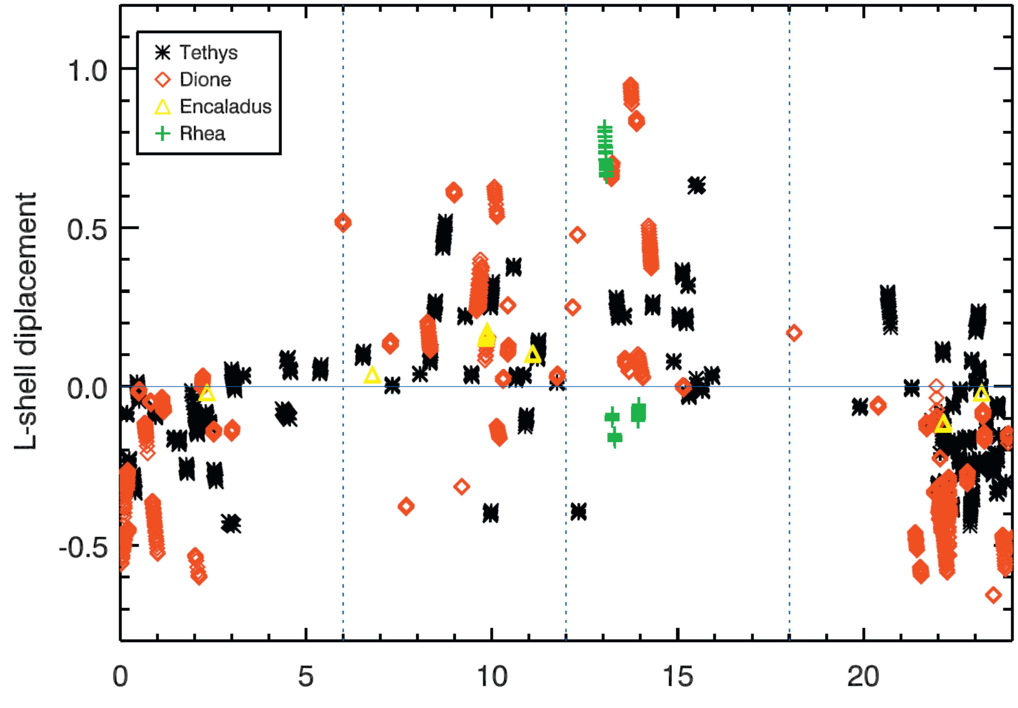
Transport and Dynamics

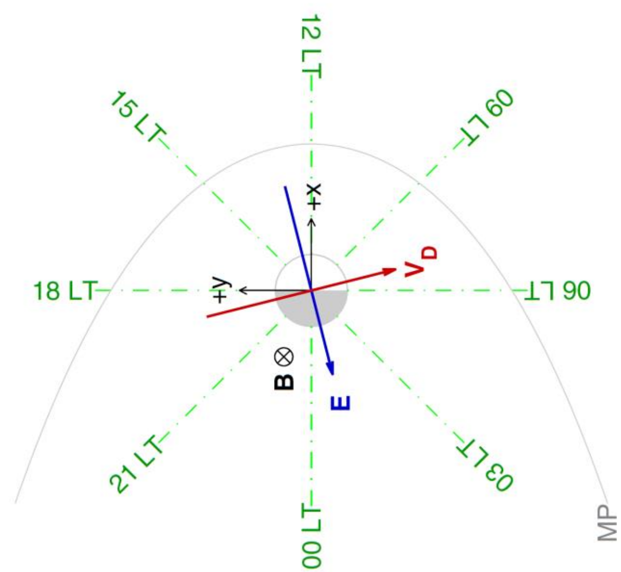
1. Additional electric field[Thomsen et al., 2012; Andriopoulou et al., 2012, 2014; Wilson et al., 2013]
2. Interchange motion [Rymer et al., 2009, Chen et al., 2010; Hill et al. 2010; Dejong et al., 2010; Liu et al., 2010; Kennelly et al., 2013
3. Injection events [Müller et al., 2010; Paranicas et al, 2010; Mitchell et al., 2009, 2012;
4. Tail reconnection and plasmoids [Jackman et al, 2014; McAndrews et al., 2009, corr. 2014; Thomsen et al., 2013, 2014; Masters et al., 2011
5. Radiation belts variability [Roussos et al., 2014]
6. Seasonal changes of plasmadisk [Sergis et al., 2013]

Electric field in the inner Saturnian magnetosphere (Andriopoulou et al. 2012, 2014; Thomsen et al., 2012; Wilson et al., 2013)

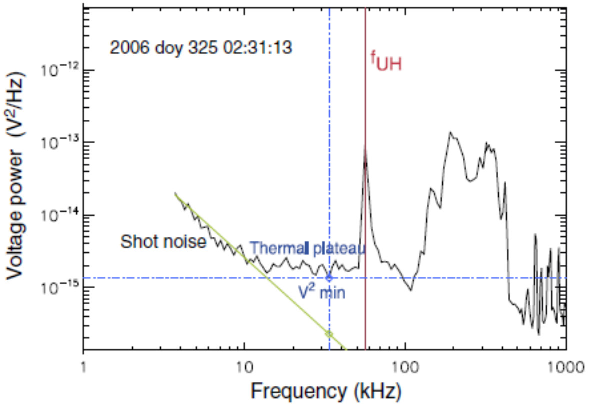
E0=0.1.0.3 mV/m

E-vector points towards 01-02 LT

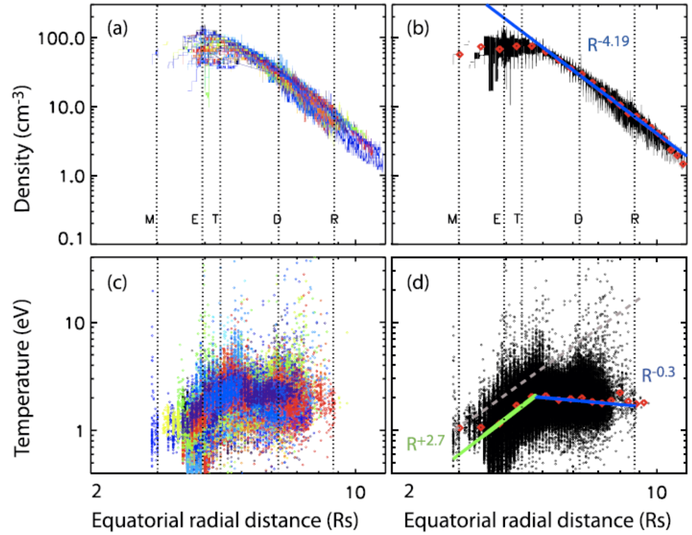


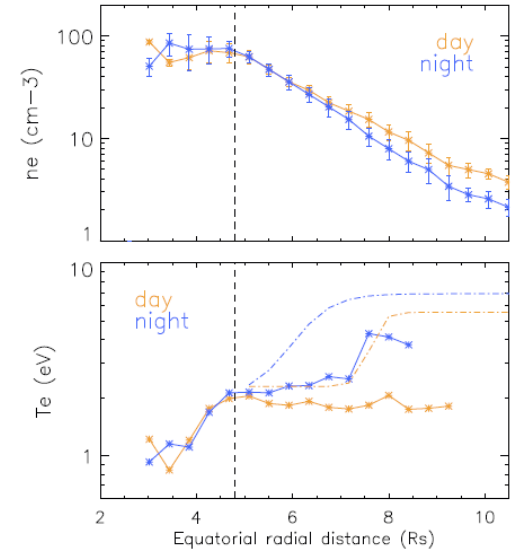


Core electron density and temperature in Saturn's inner magnetosphere

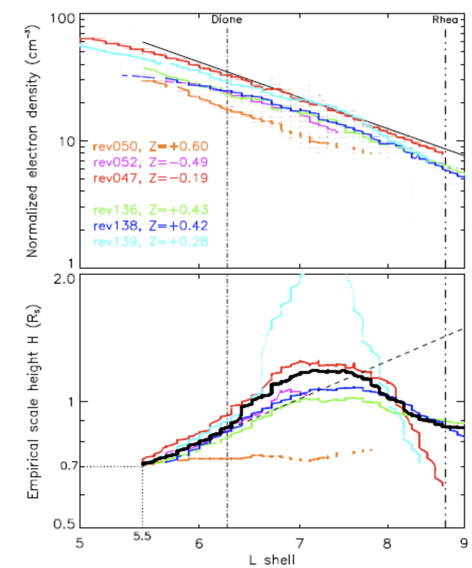


Quasi-thermal noise spectroscopy can provide information on both the electron density and core temperature.

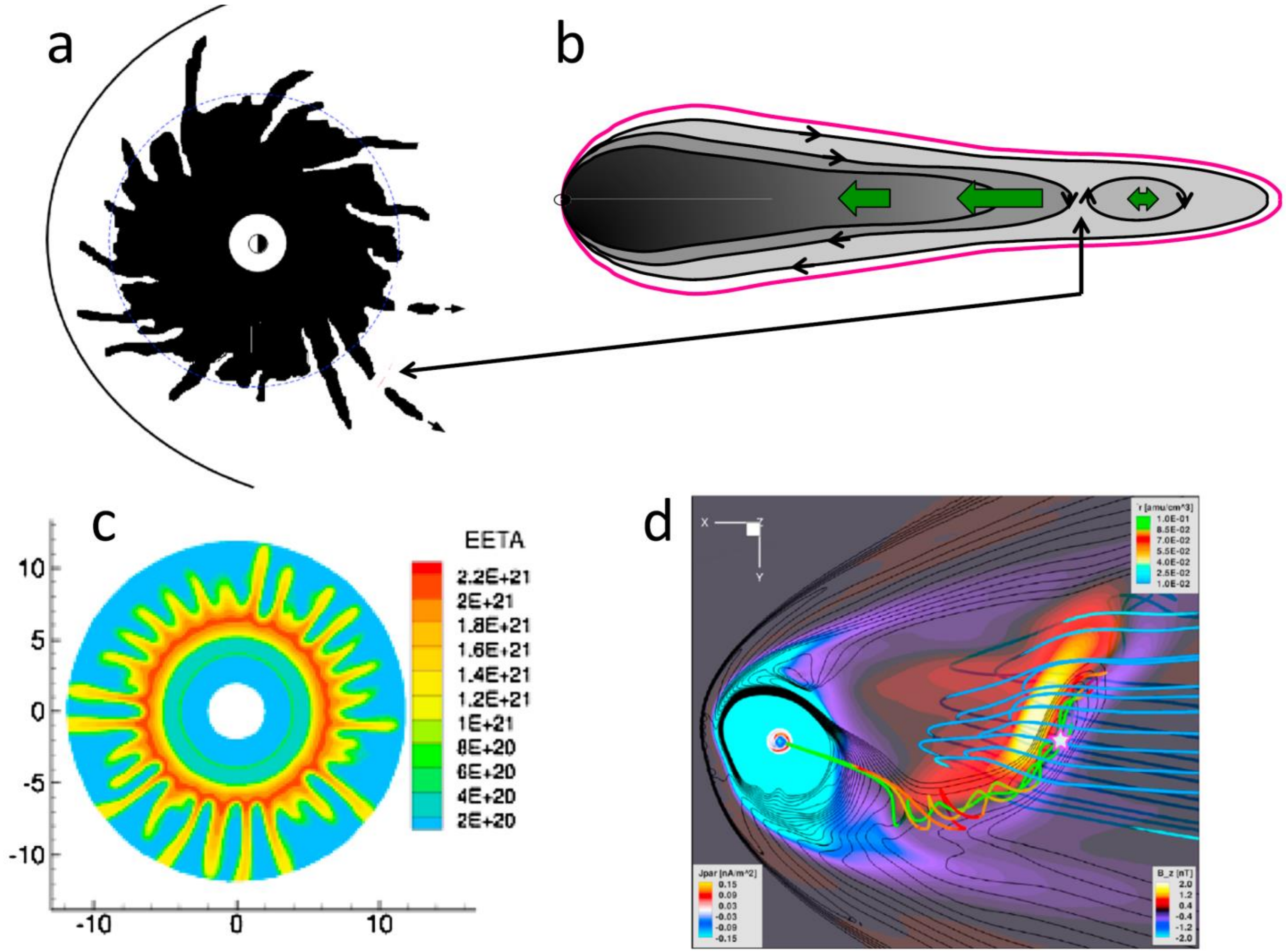




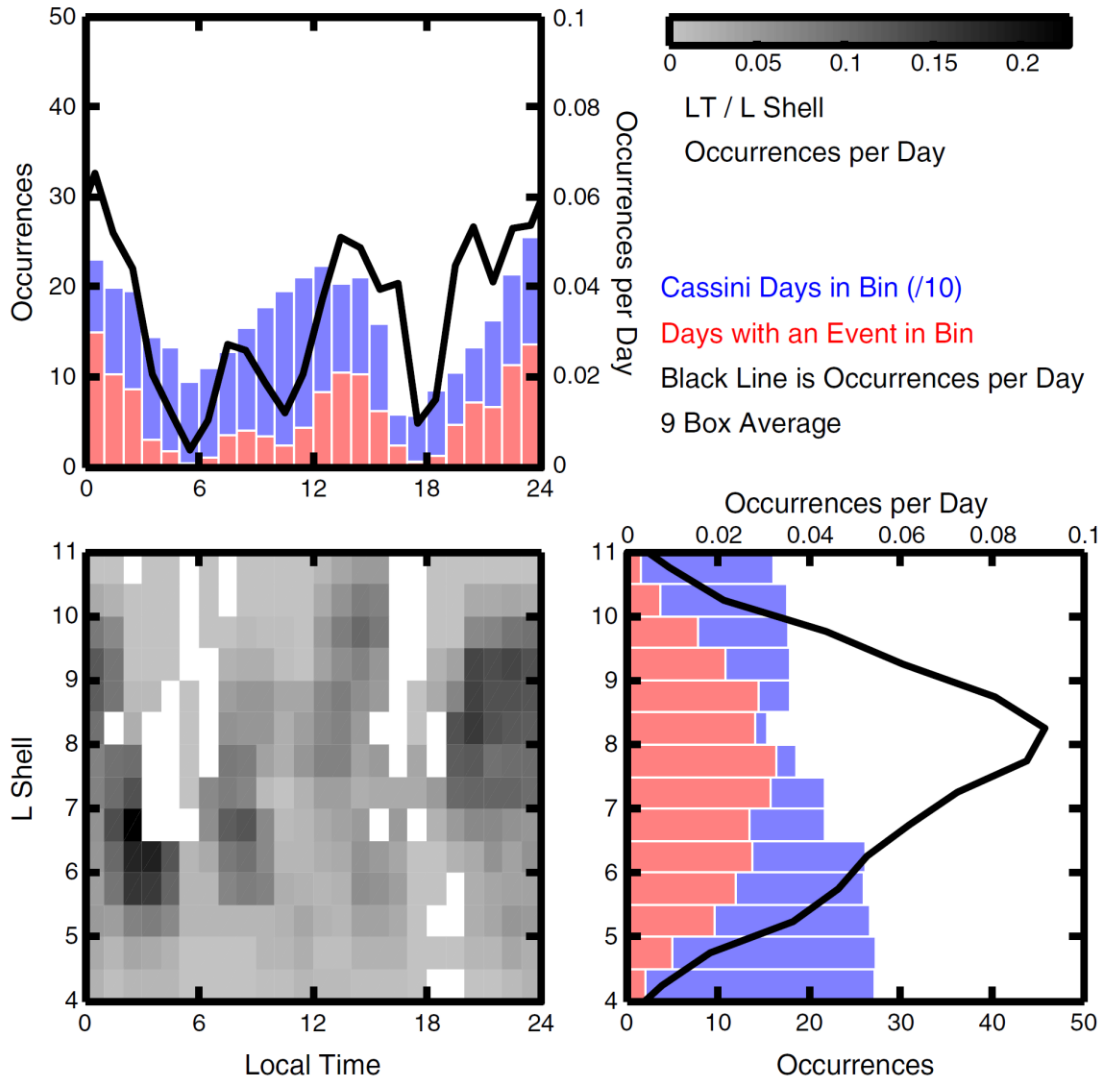
- Schippers et al. (*JGR*, 2013) have applied quasi-thermal noise spectroscopy to RPWS measurements in Saturn's inner magnetosphere (R<10 R_S) for the period 2004 – 2012 in order to derive electron densities and core temperatures in this very important magnetospheric region.
- Inside of 5 R_S they find large density variations which they attribute to variations in activity at Enceladus; the core temperature increases with distance, likely due to thermal equilibration with protons and heavy ions.
- Beyond 5 R_S the density profile is consistent with radial diffusion and the nearly flat core temperature is intermediate between thermalization with other plasma components and cooling due to outward radial diffusion.
- There is a day-night asymmetry which is consistent with a noon-midnight convective electric field.
- A bump in the plasma scale height between Dione and Rhea may be due to a pronounced corotation lag.



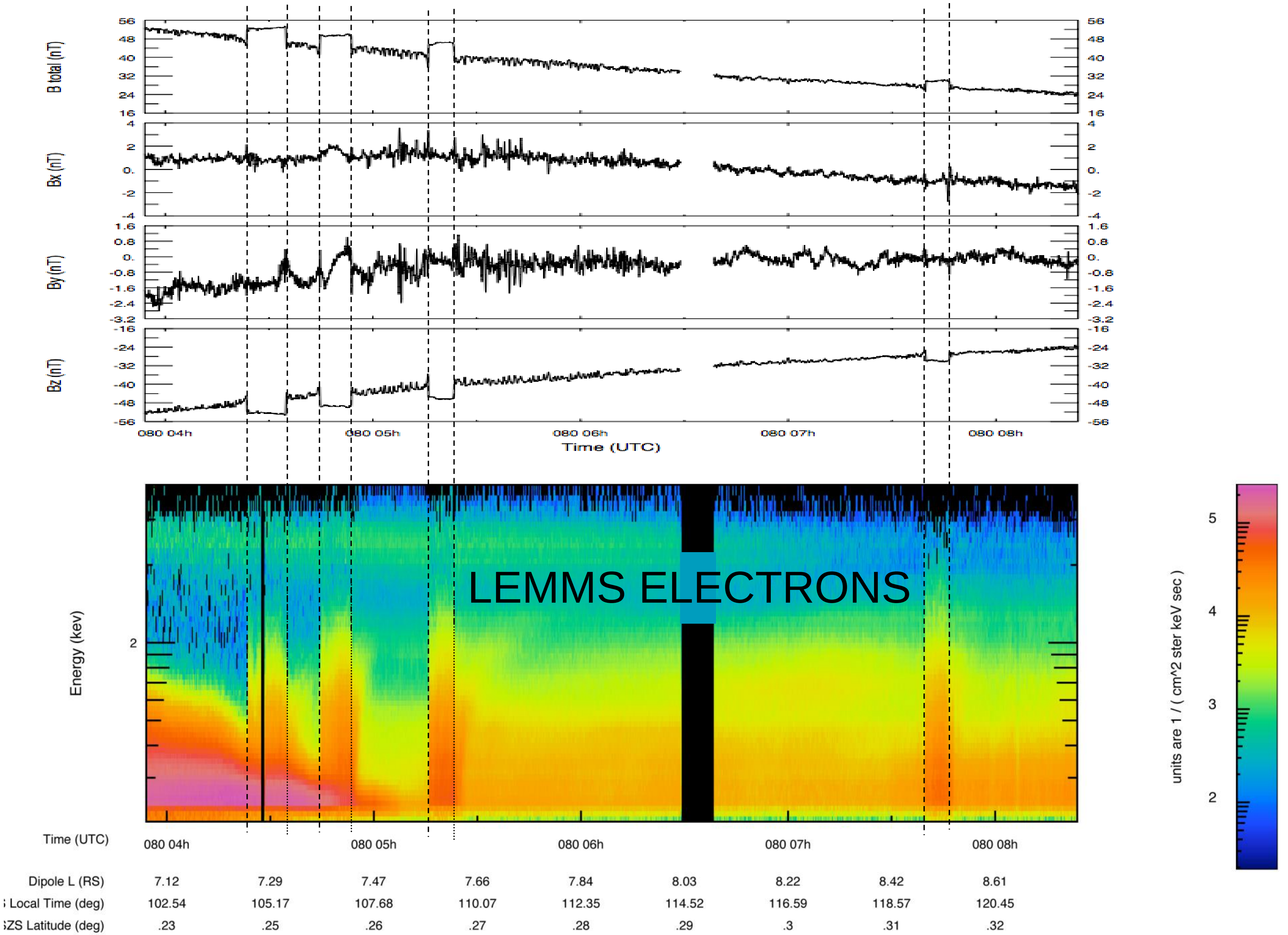
Particle transport in Saturn‘s magnetosphere (Thomsen, 2013)

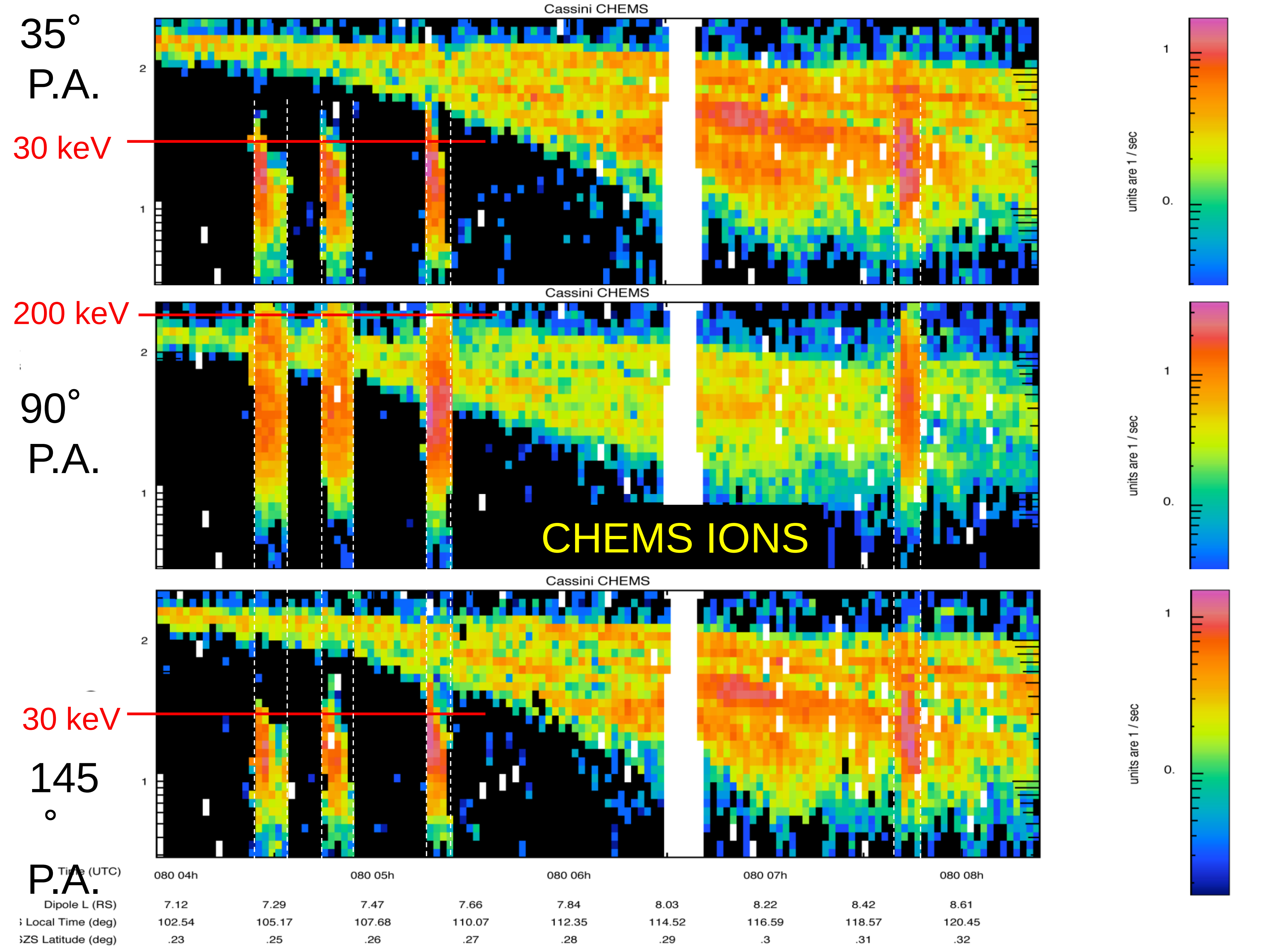


Low-energy injection statistics (Kennelly et al., 2013)

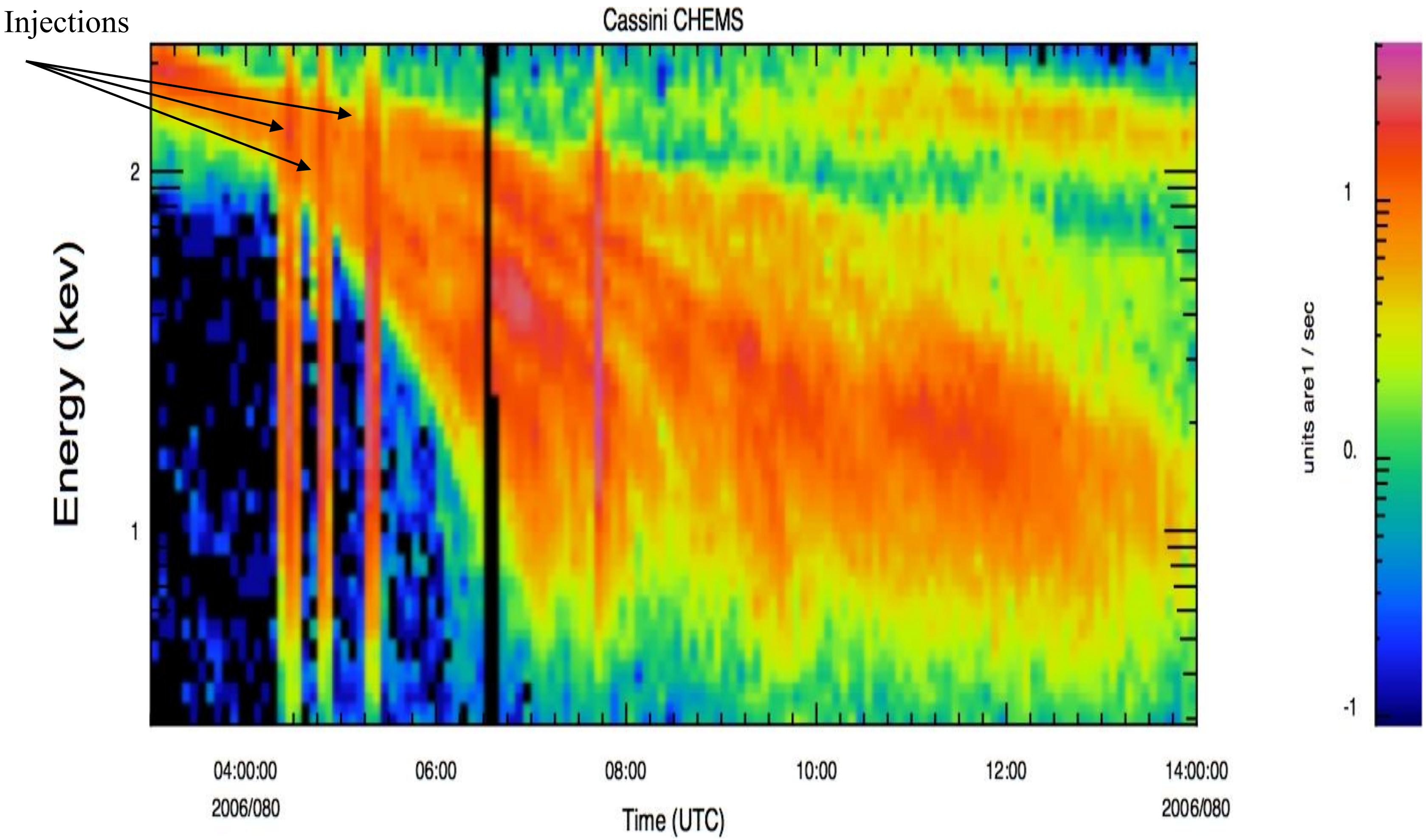


Flux Tube Interchange—injecting hot plasma at 5 – 12 Rs



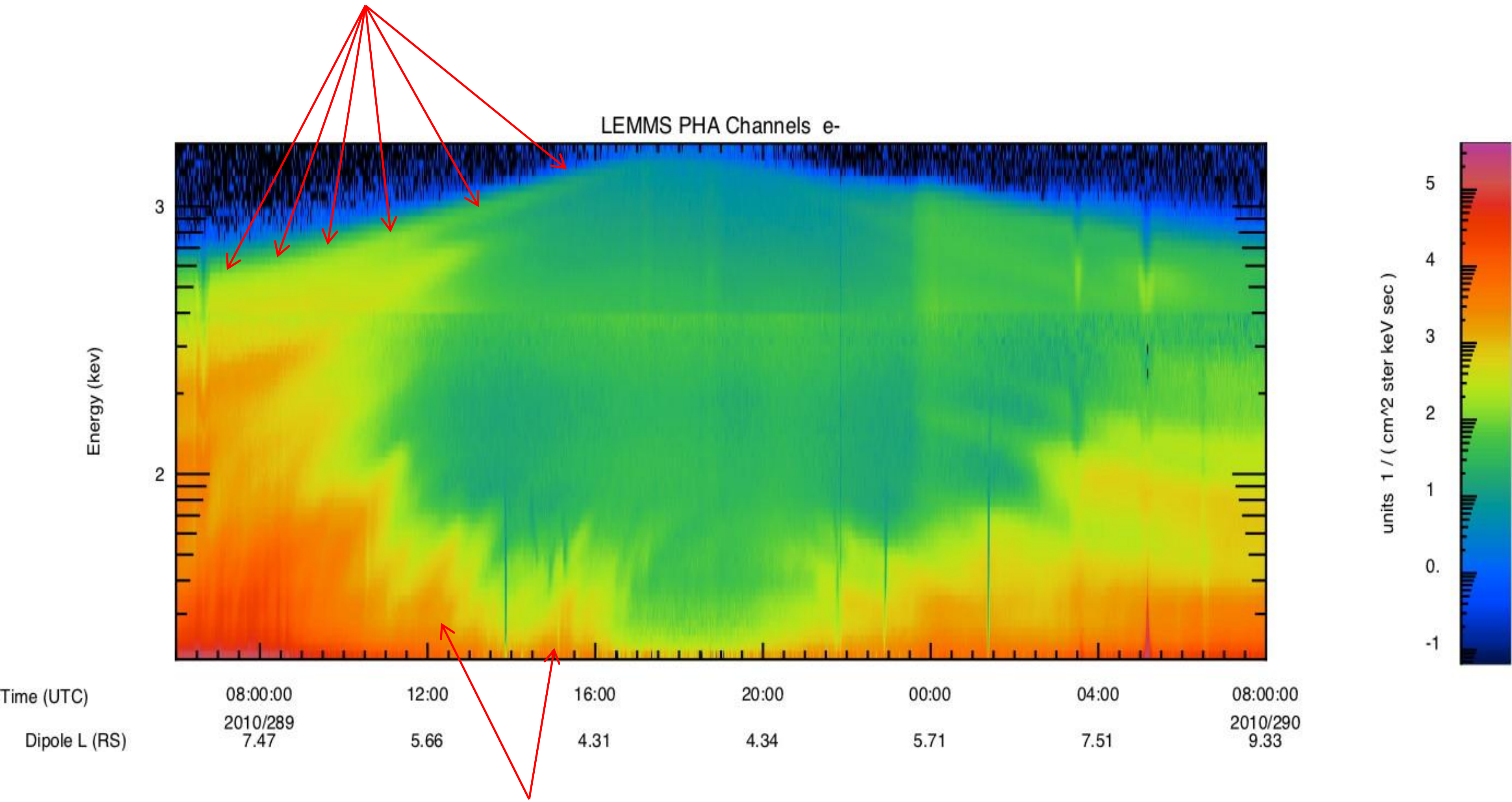


35° P.A.
30 keV
Cassini CHEMS
200 keV
90° P.A.
CHEMS IONS
145 ° P.A.
units are 1 / sec
Time (UTC)
080 04h
080 05h
080 06h
080 07h
080 08h
Dipole L (RS)
7.12
7.29
7.47
7.66
7.84
8.03
8.22
8.42
8.61
Local Time (deg)
102.54
105.17
107.68
110.07
112.35
114.52
116.59
118.57
120.45
ZS Latitude (deg)
.23
.25
.26
.27
.28
.29
.3
.31
.32



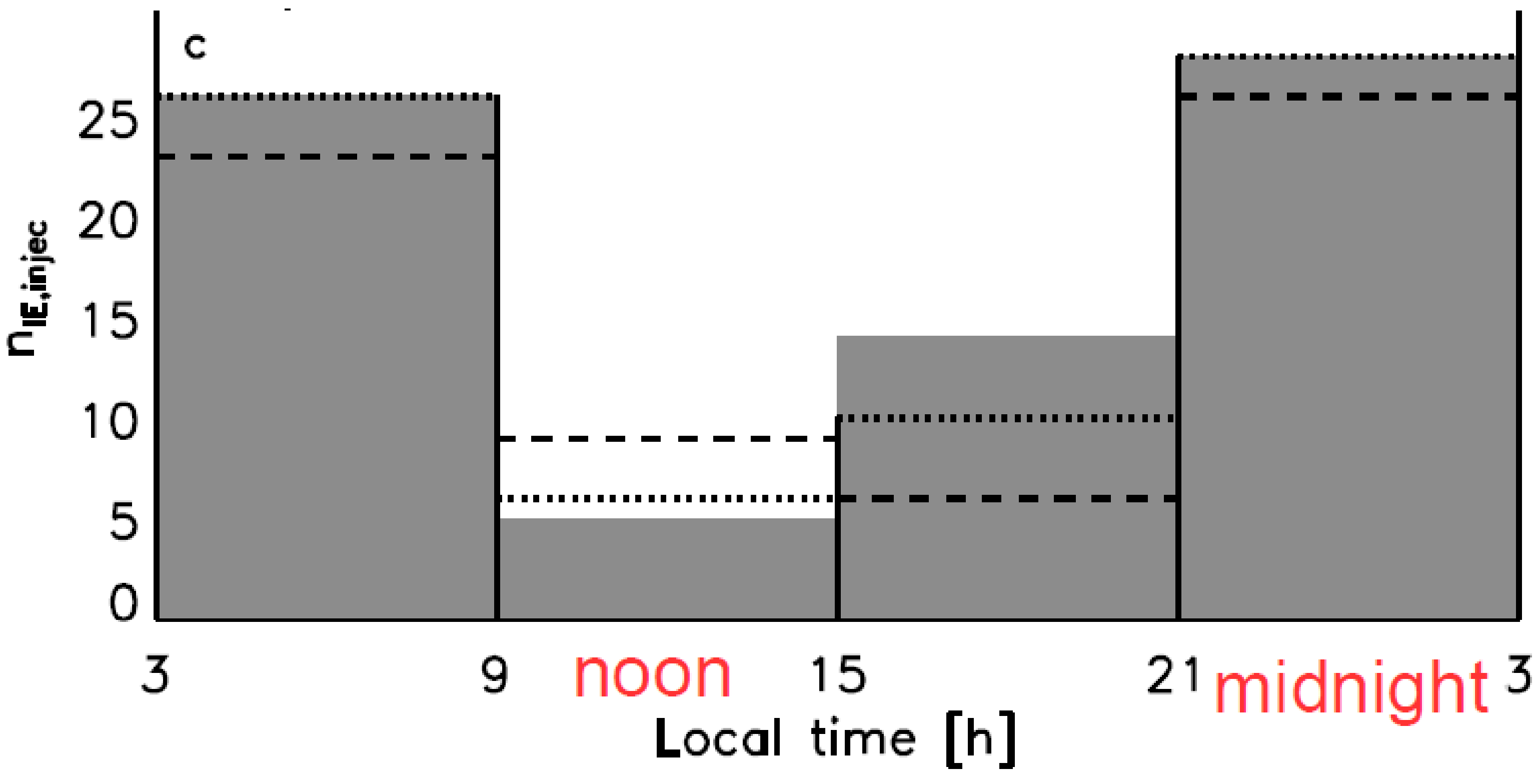
In this example, it appears that flux tubes filled with energetic protons are displacing the ambient particles (data from MIMI/CHEMS: All 3 telescopes included).

Day 2010/289 electron data. These injections to high energy appear to involve populations that span a large range of radial distances.

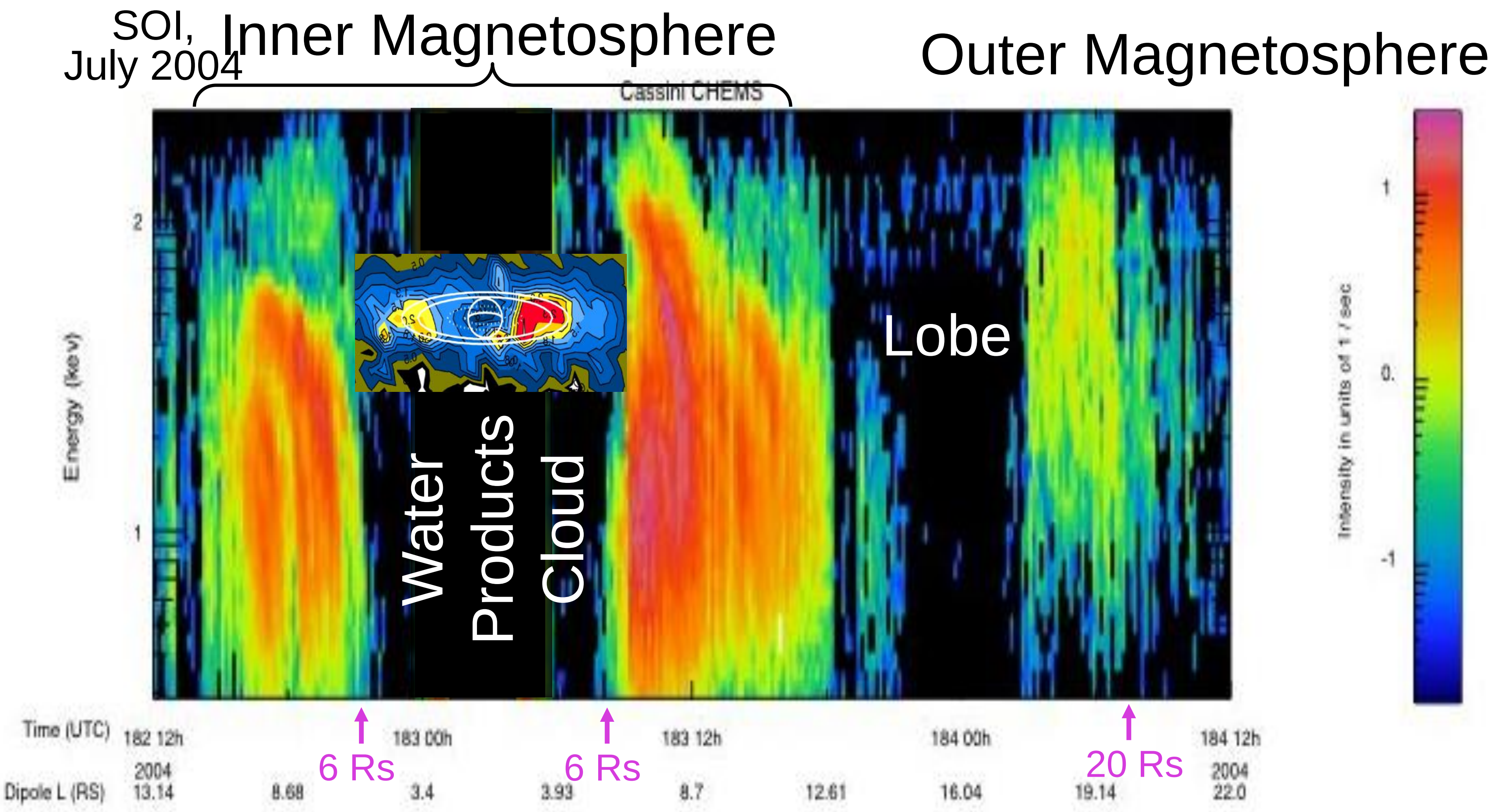


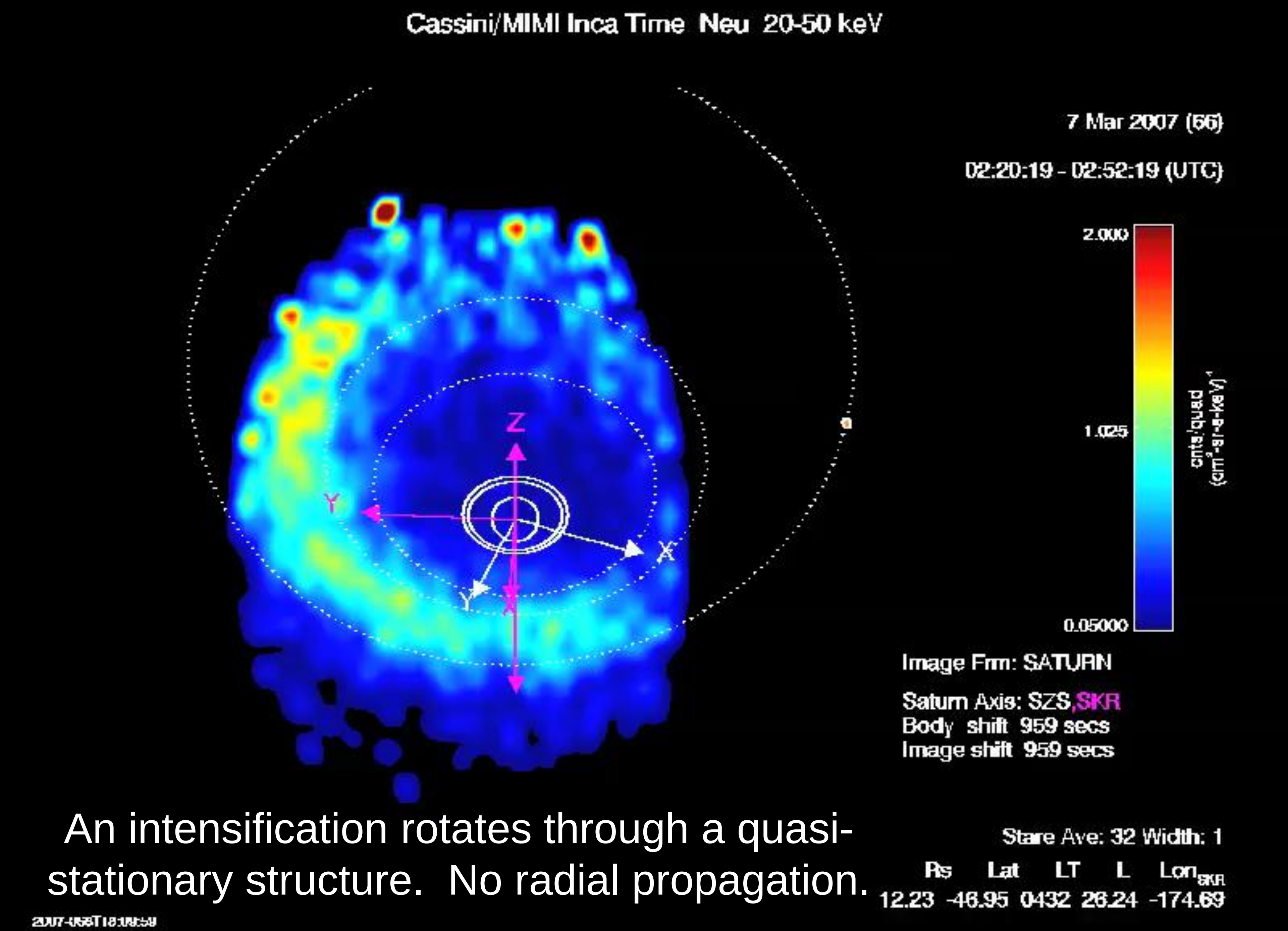
These tens of keV injections at low energy do not usually involve a wide range of L shells

Weighted distribution of the origin of electron injections in the keV range (Müller et al., 2010)

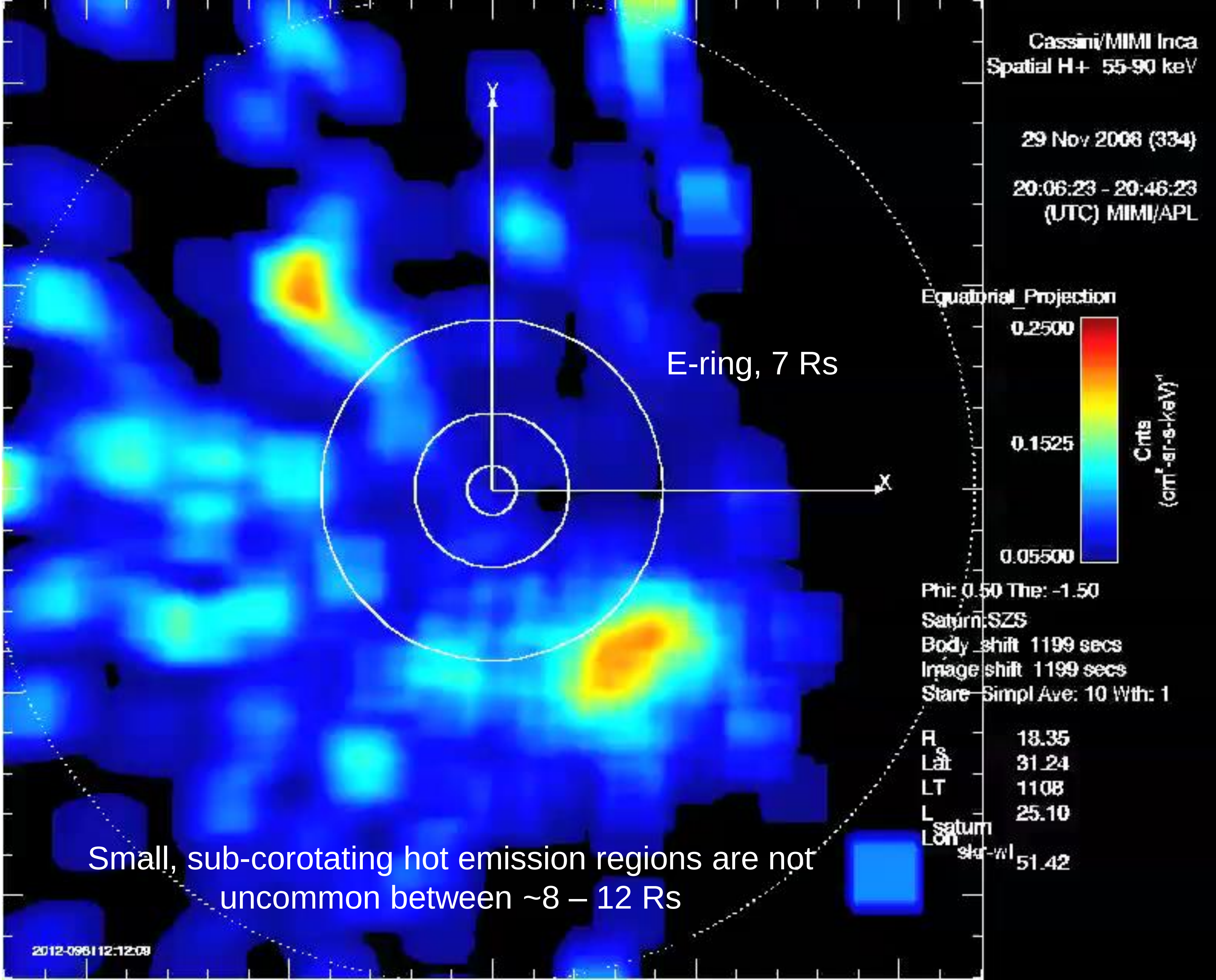


Inner magnetosphere hot plasma derives from both new and dispersed injections; the outer magnetosphere, primarily non-dispersed. *We argue the inner are flux-tube interchange, the outer post-reconnection current sheet acceleration*.





An intensification rotates through a quasi-stationary structure. No radial propagation.



Cassini/MIMI Inca
Spatial H+ 55-90 keV
29 Nov 2008 (334)
20:06:23 - 20:46:23
(UTC) MIMI/APL
Equatorial_Projection
0.2500
0.1525
0.05500
Cnts
(cm²-sr-s-keV)⁻¹
Y
X
E-ring, 7 Rs
Phi: 0.50 The: -1.50
Saturn:SZS
Body_shift 1199 secs
Image shift 1199 secs
Stare Simpl Ave: 10 Wth: 1
R 18.35
Lat 31.24
LT 1108
L 25.10
Lon 51.42
2012-096112:12:09
Small, sub-corotating hot emission regions are not
uncommon between ~8 – 12 Rs

Cassini/MIMI Inca Spatial H+ 50-80 keV

The quasi-continuous version of Type 2 emission can fill a large volume of the magnetosphere at times. Probably a region of enhanced flux tube interchange. Why? Because much of it is inside 12 Rs, where the field is ~dipolar.

6 Apr 2007 (96)

00:30:03 - 02:06:02 (UTC)

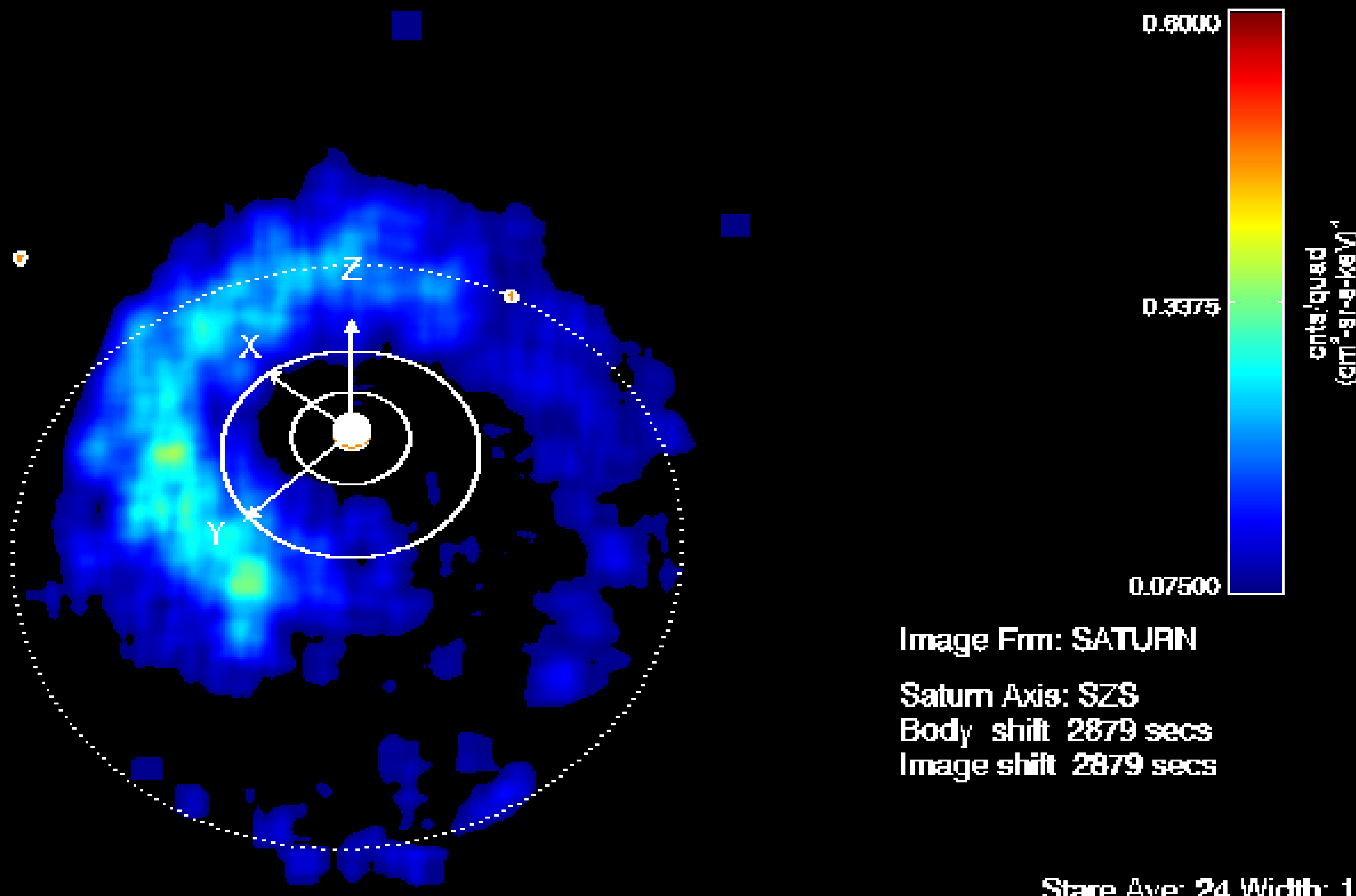


Image Frm: SATURN

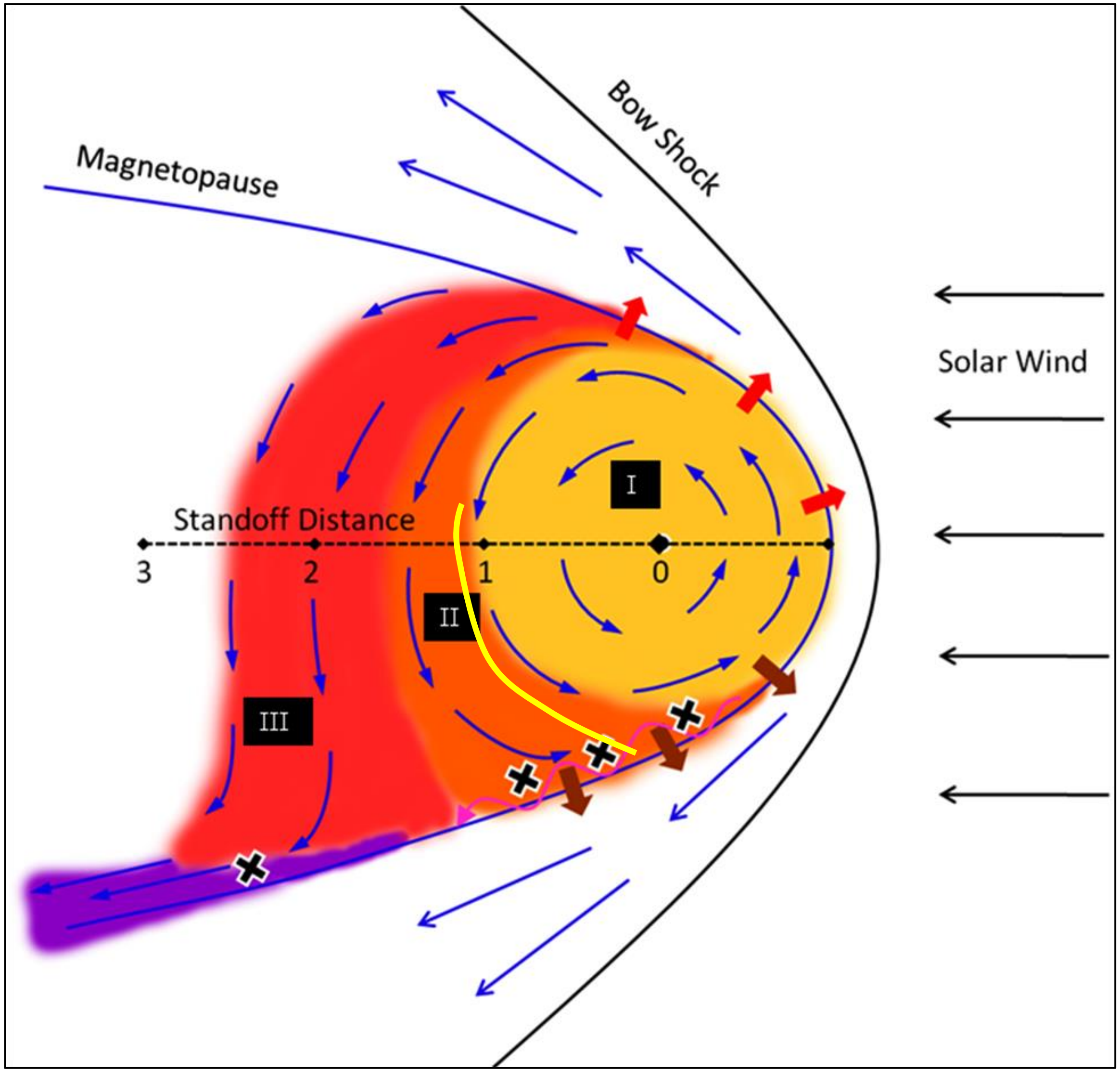
Saturn Axis: SZS
Body shift 2879 secs
Image shift 2879 secs

Stare Ave: 24 Width: 1

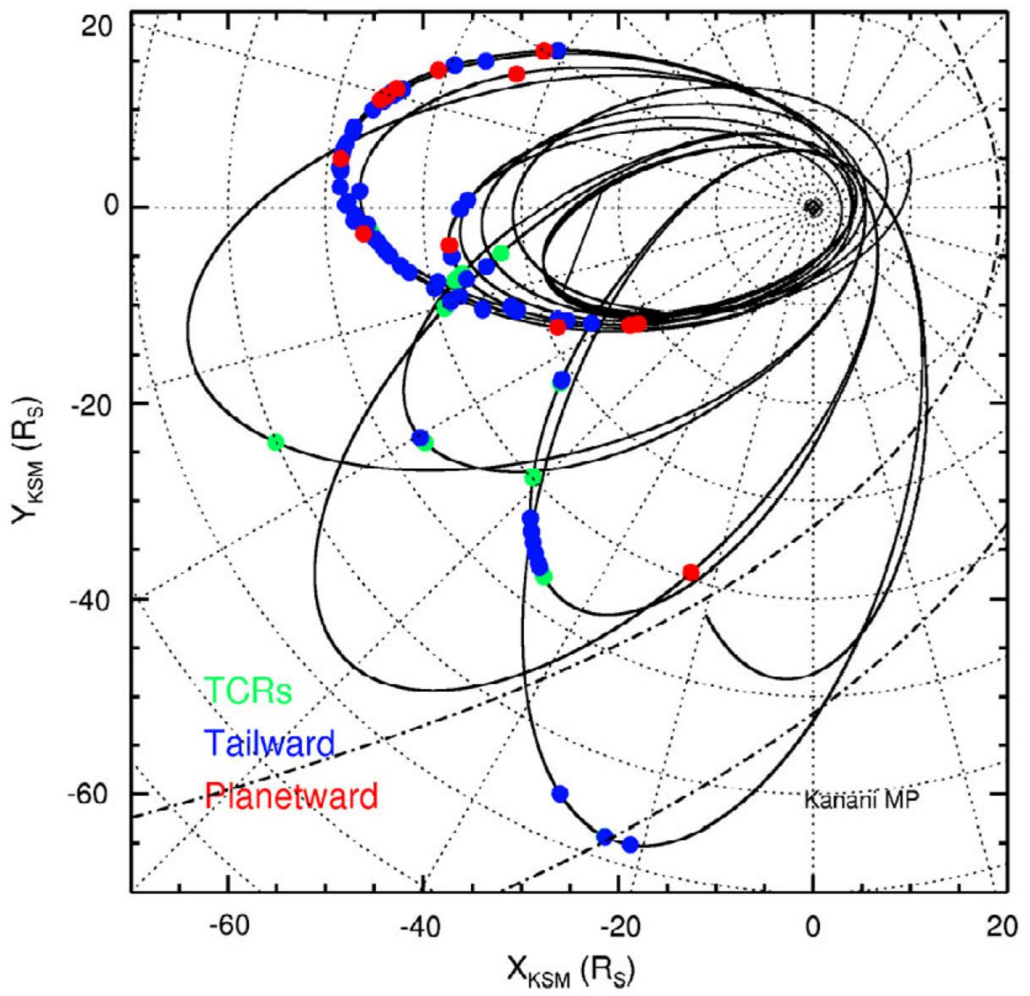
Rs	Lat	LT	L	Lon$_{SKR}$
21.55	51.15	2049	54.76	-84.97

2007-108T16:12:27

Parting thoughts:
When a plasmoid is released, where does it go?
Figure modified from one by Mark Kane



Plasmoids and travelling compression regions TCRs in Saturn‘s magnetotail (Jackman et al., 2014)



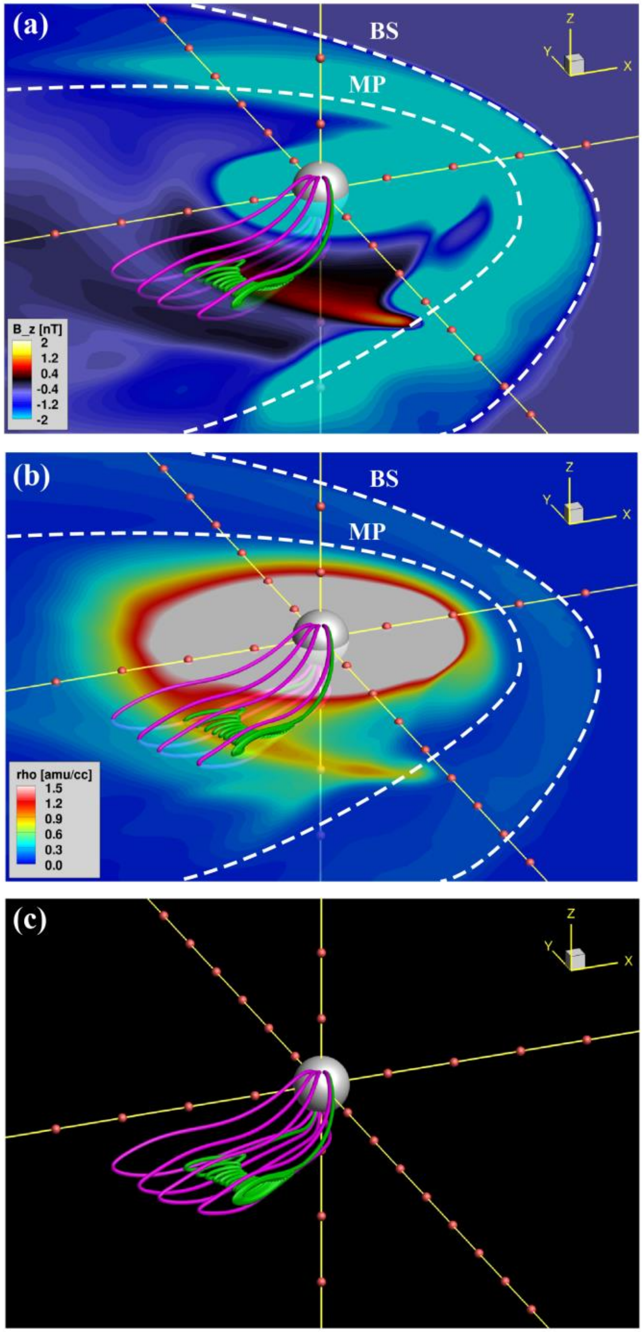
69 Plasmoids

17 TCRs

13 planet-moving events

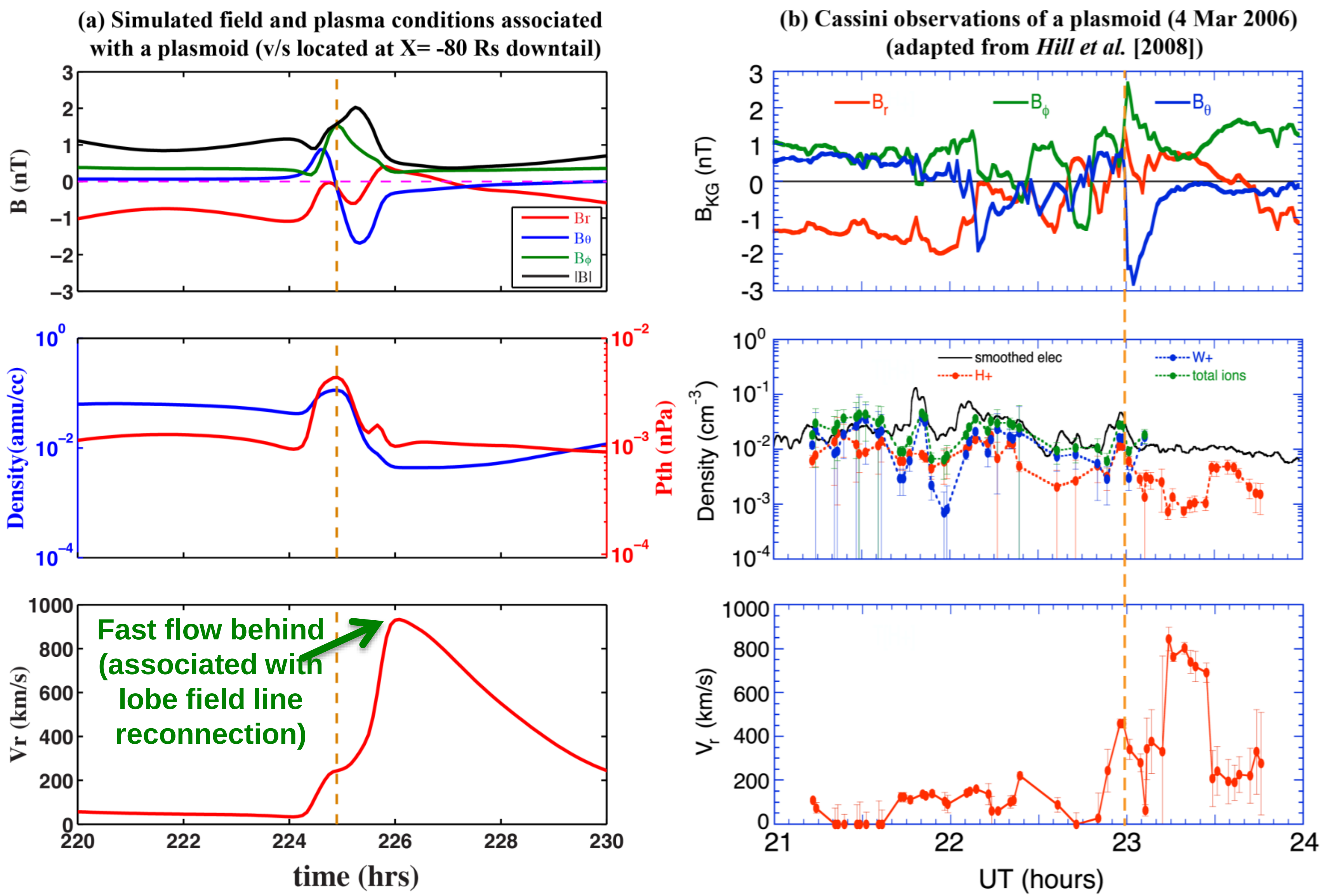
Plasmoid formation in the magnetotail

- Centrifugal acceleration of mass-loaded flux tubes leads to reconnection on closed field lines forming plasmoids, an intrinsic process in Saturn's magnetosphere ("Vasyliūnas cycle").
- Exhibit loop-like magnetic geometry with very weak core fields.
- The plasmoids, even after pinching off at the X-line, are surrounded by closed field lines and, therefore, are not moving directly downtail. They escape from the magnetosphere through the dawnside magnetopause.

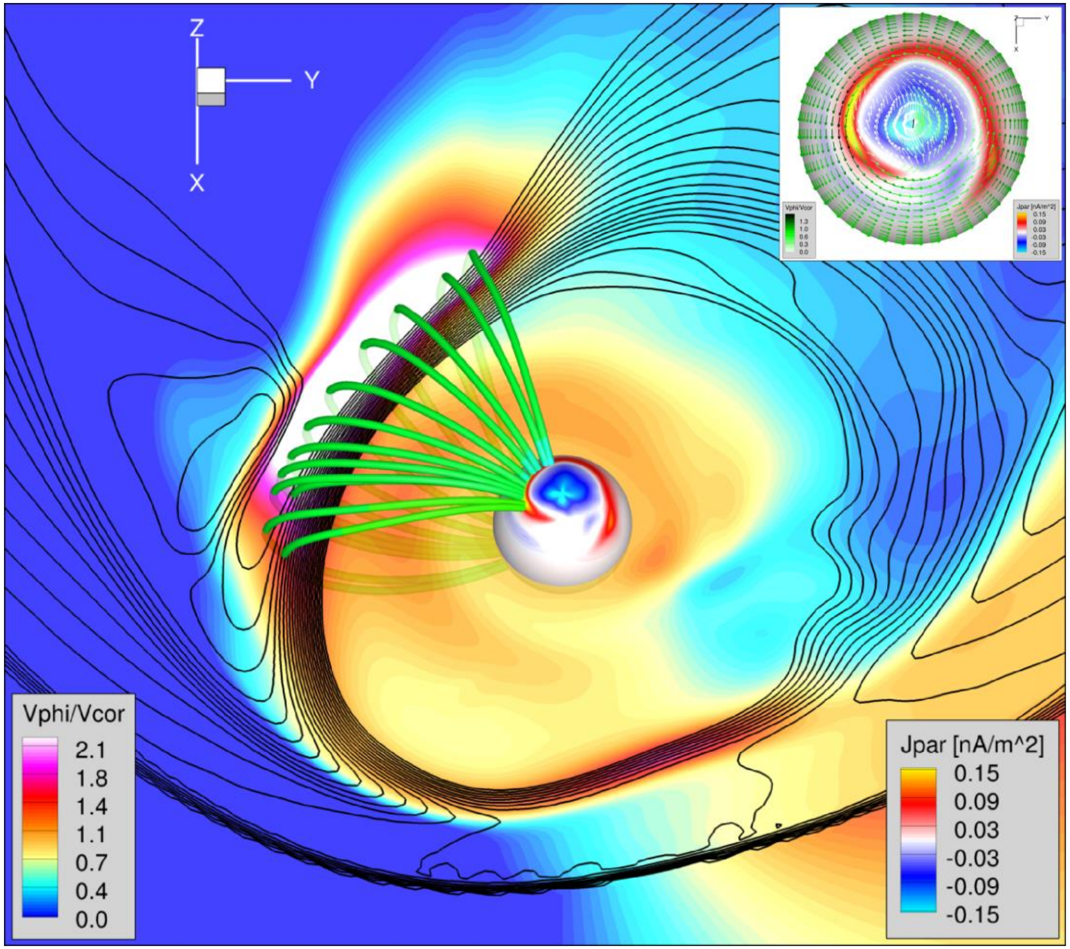


(*Jia et al*., JGR, 2012)

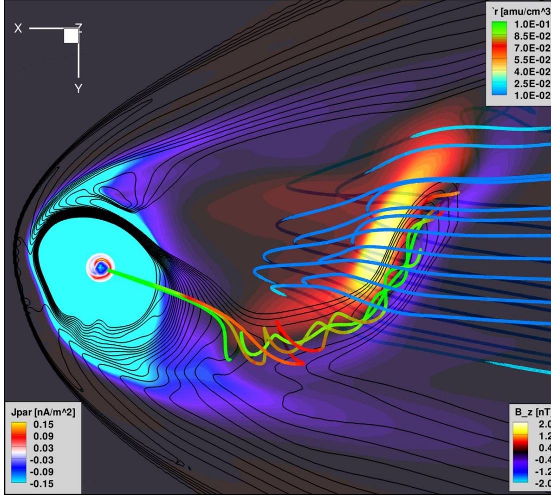
Flux-ropes in the tail and reconnection between lobe field lines



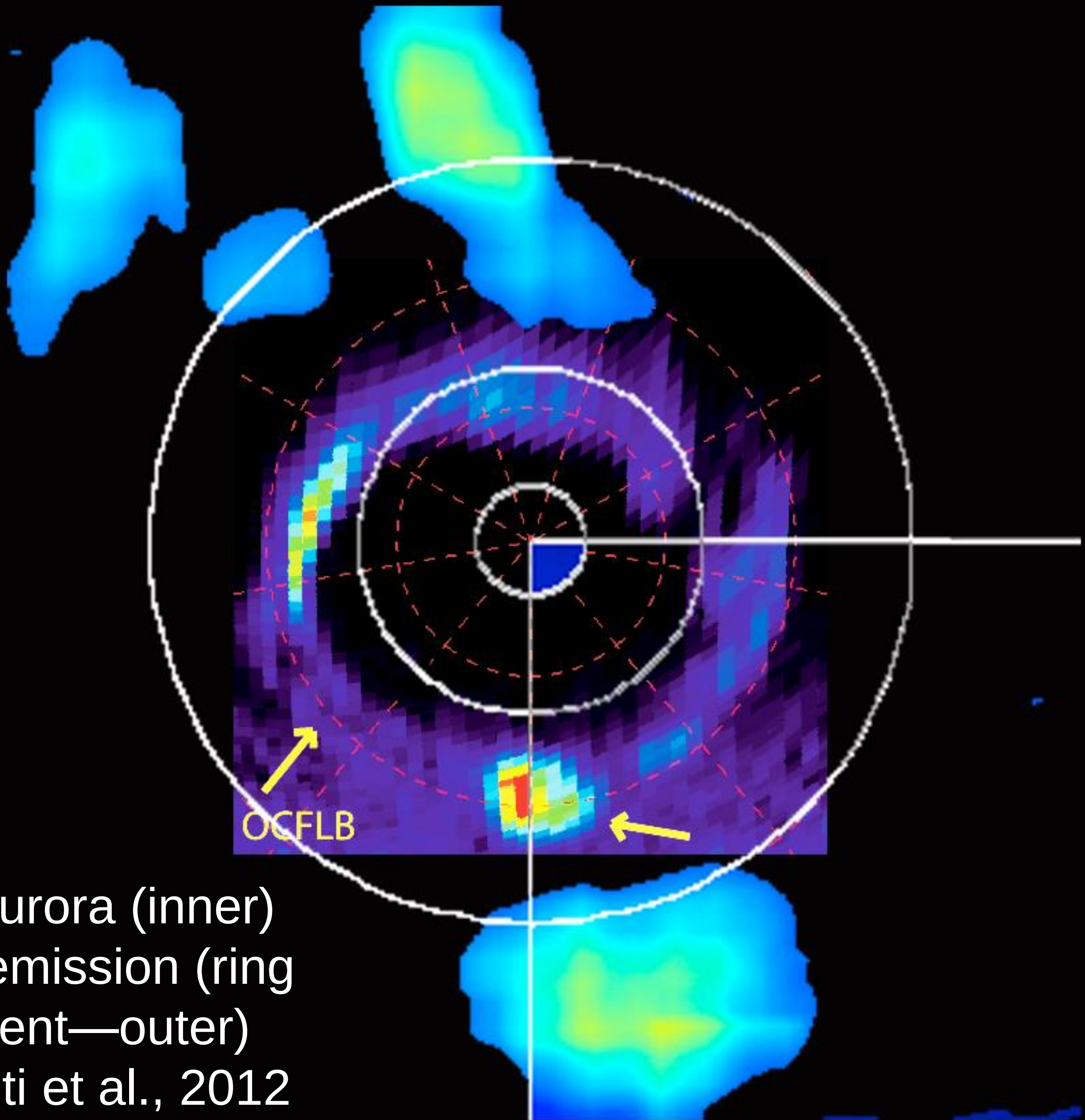
Impact of tail reconnection on the magnetosphere and ionosphere



(*Jia et al*., JGR, 2012)



- Tail reconnection also generates hot and rapidly moving return flux tubes, which can produce significant impacts on magnetosphere on the planetward side.
- As the return flux tubes move from the night side to the day side, strong FACs intensifications are seen in the ionosphere, especially on the dawn side.



UV aurora (inner)
ENA emission (ring current—outer)
Radioti et al., 2012

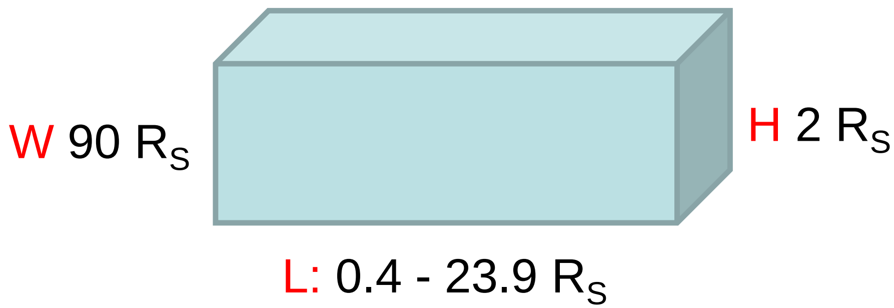
Mass Budget: Sources and Sinks

•Enceladus mass loading: 8-250 kg/s (100 kg/s average)

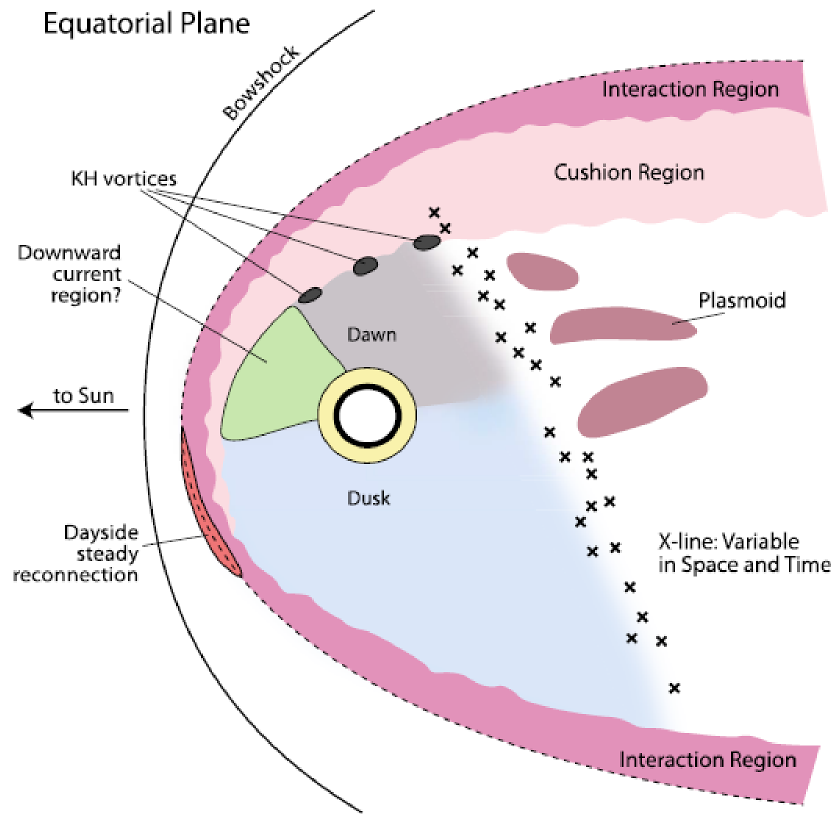
•Need 3.6 - 196 tail-width plasmoids/day to remove mass loaded into magnetosphere by Enceladus alone

•Average mass loss rate, based on observation in “viewing region”: 2.59 kg/s

Jackman et al. [2014]



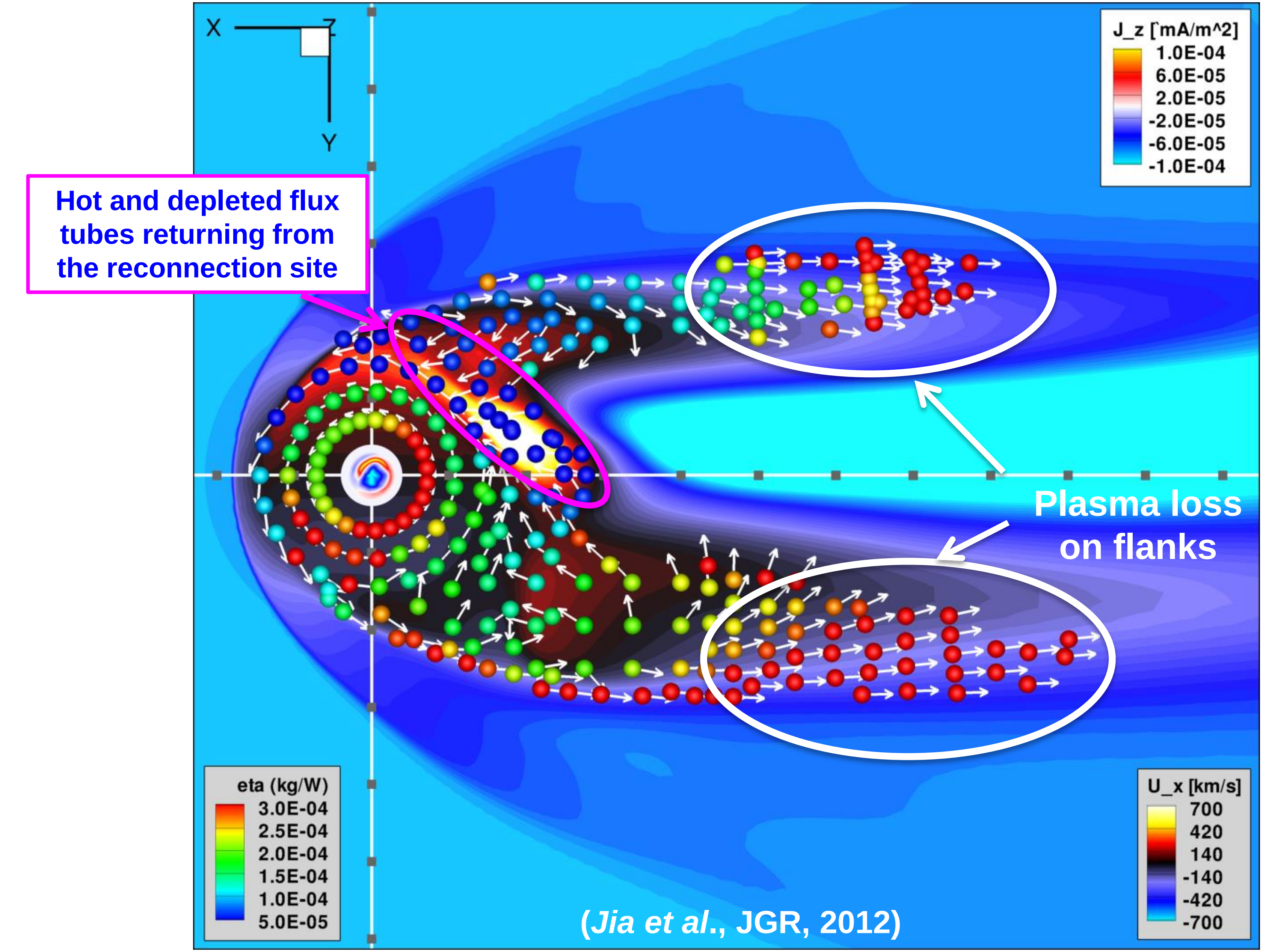
Delamere and Bagenal [2010]



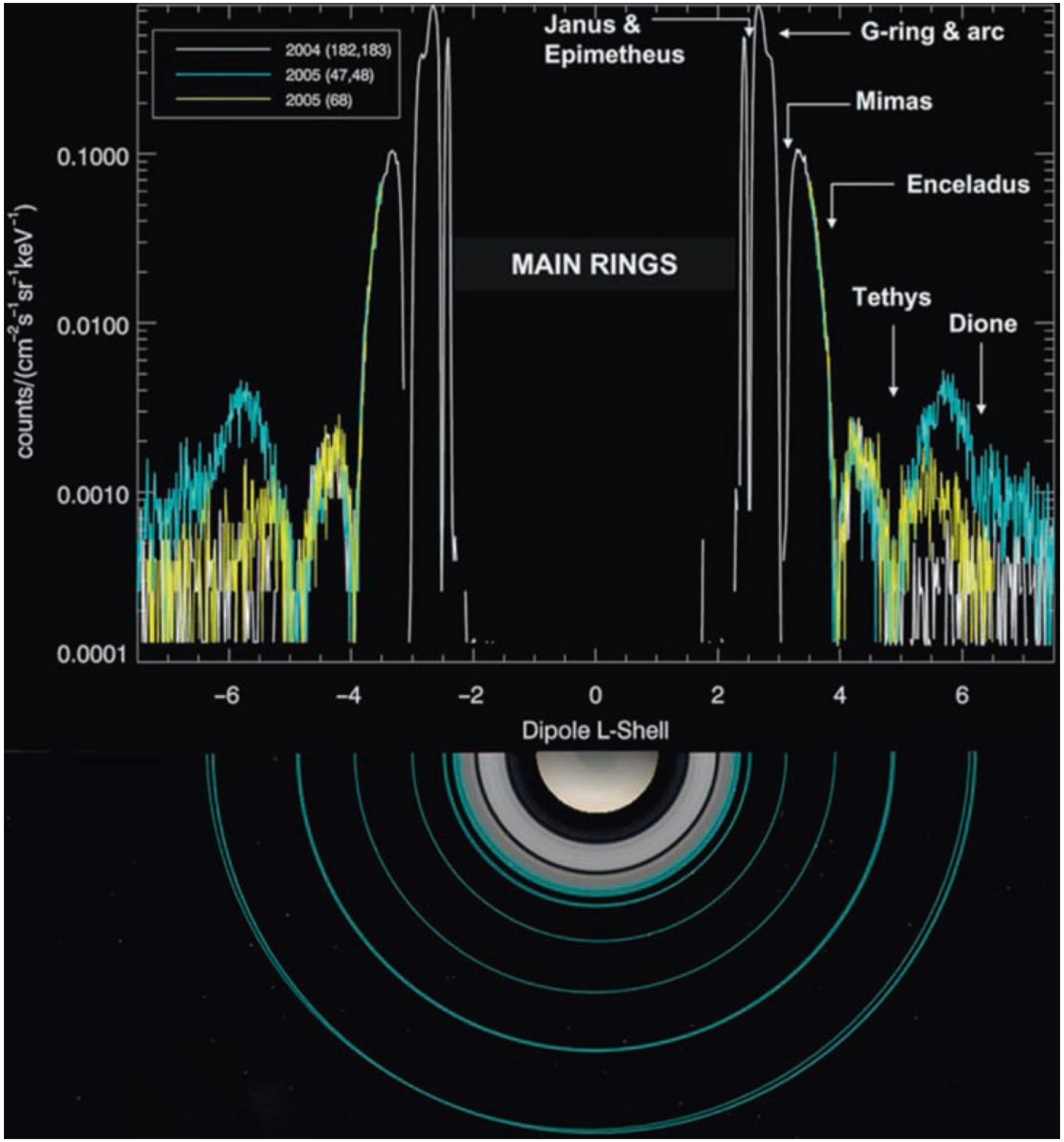
Most of the time, clear imbalance between mass in and plasmoid loss

Other mass loss mechanisms (small-scale drizzle, cross-field diffusion?) required

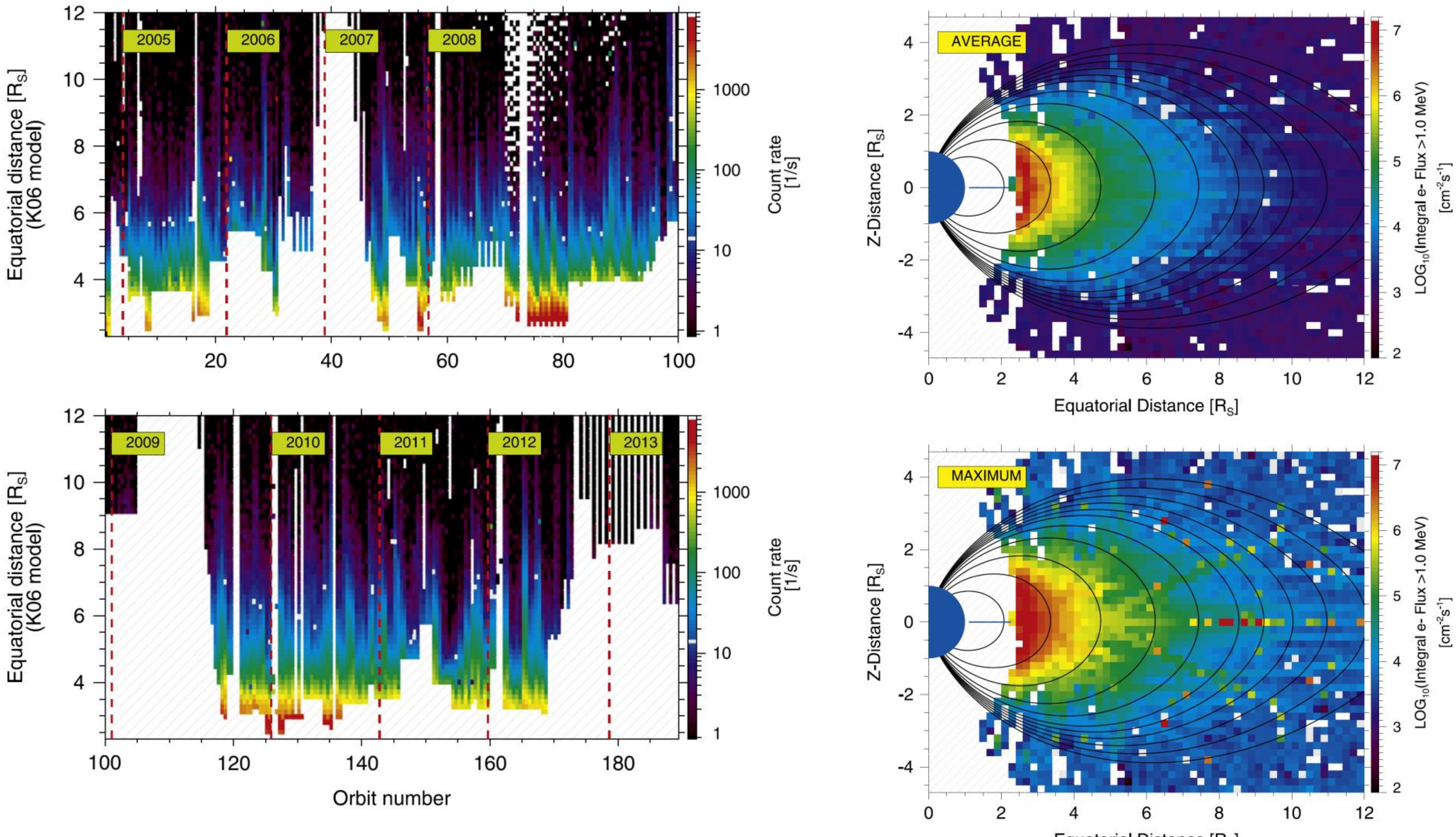
Global convection and distribution of flux-tube content (northward IMF)



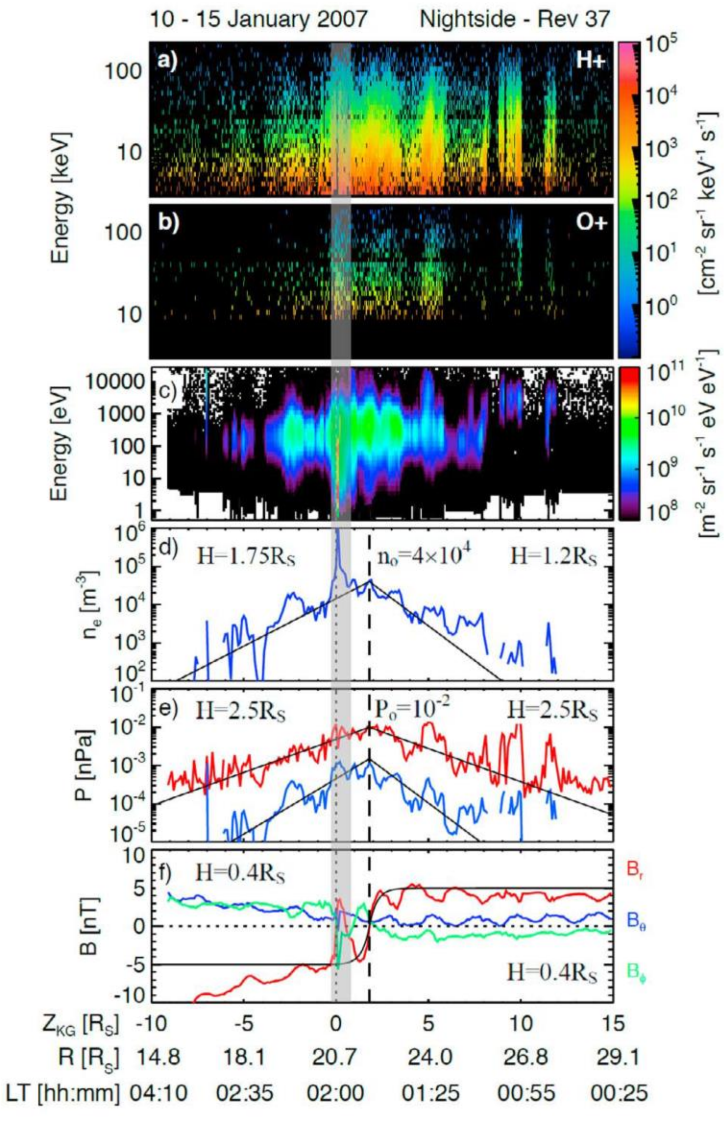
Temporal additional radiation belt between Tethys and Dione caused by interplanetary event (Roussos et al., 2008)



Variation of the electron radiation belts outer boundary (Roussos et al., 2014)



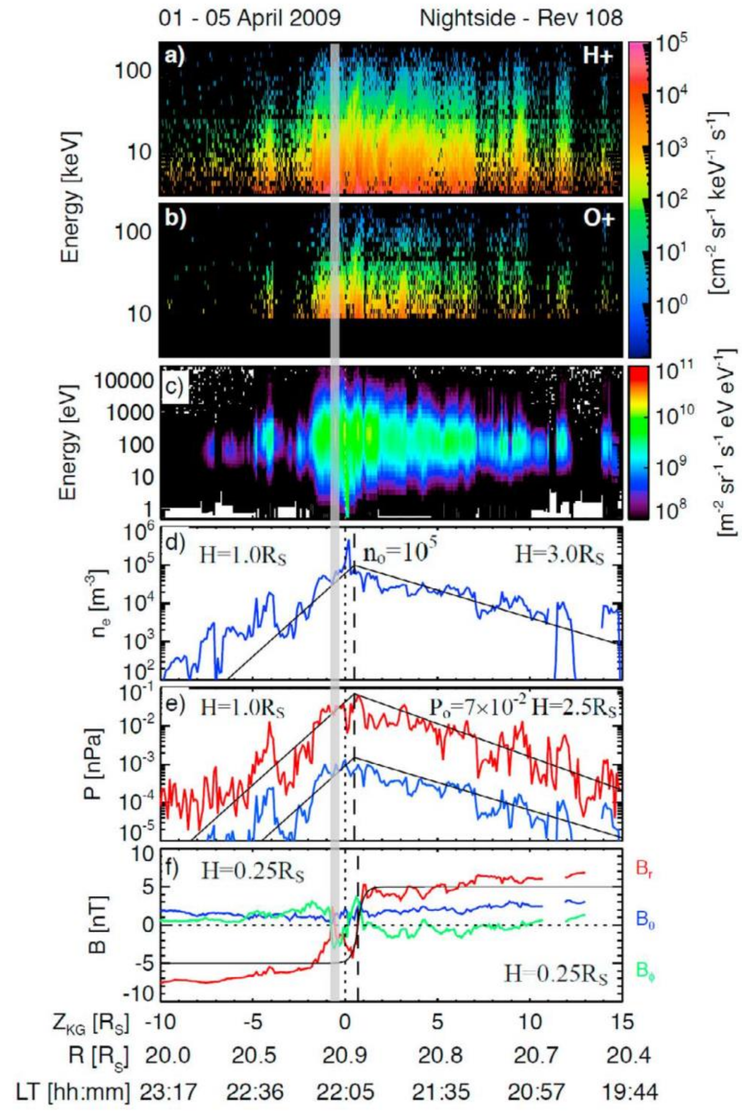
Seasonal variation of the plasma sheet warp and thickness (Sergis et al., 2010)



Before (left) and close to equinox (right)

Warping angle decrease

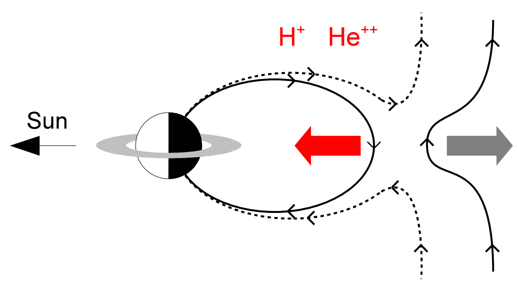
Density, pressure nearly unaffected



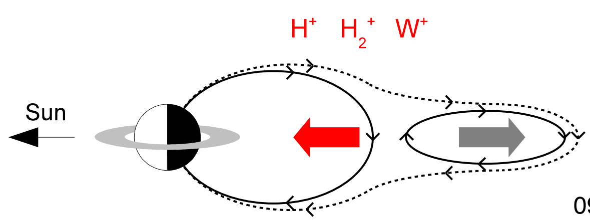
Supercorotating return flow from reconnection in Saturn's magnetotail (Masters et al. 2011)

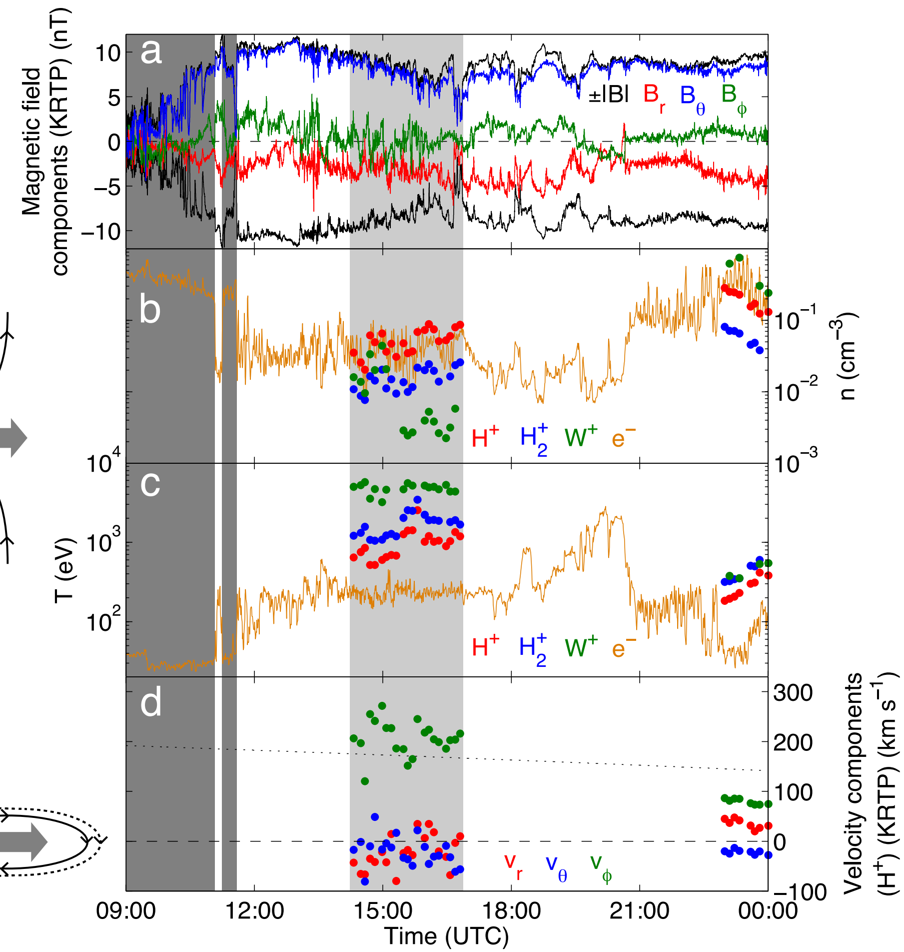
- Reconnection in Saturn's magnetotail is an important aspect of energy flow through the magnetosphere
- This process leads to hot, fast flows in the dawn magnetosphere
- Hot, supercorotating return flow has been detected by Cassini for the first time
- Such flows can have a strong effect on the magnetosphere and auroral emissions

Dungey cycle return flow



Vasyliunas cycle return flow

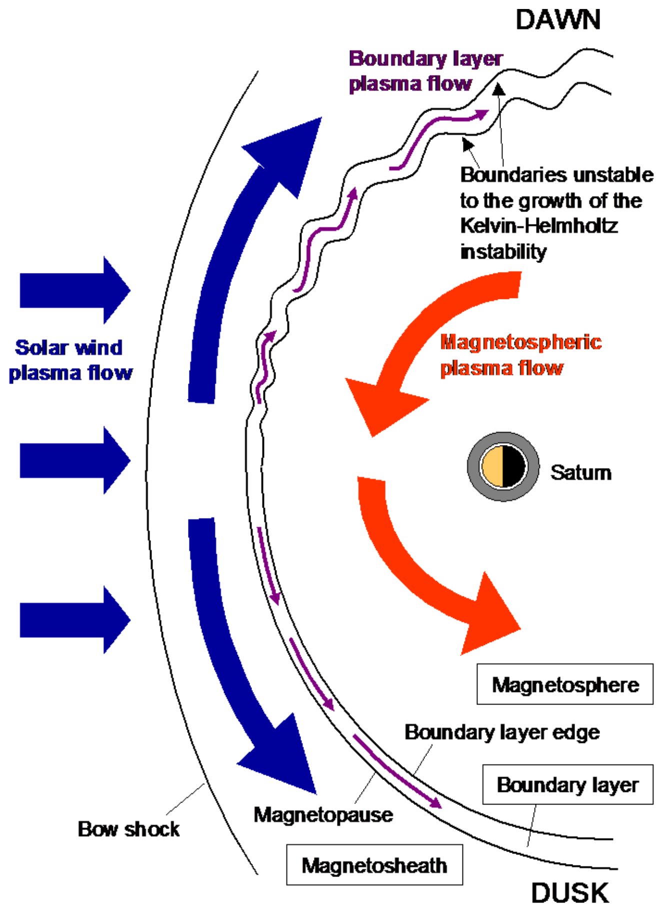


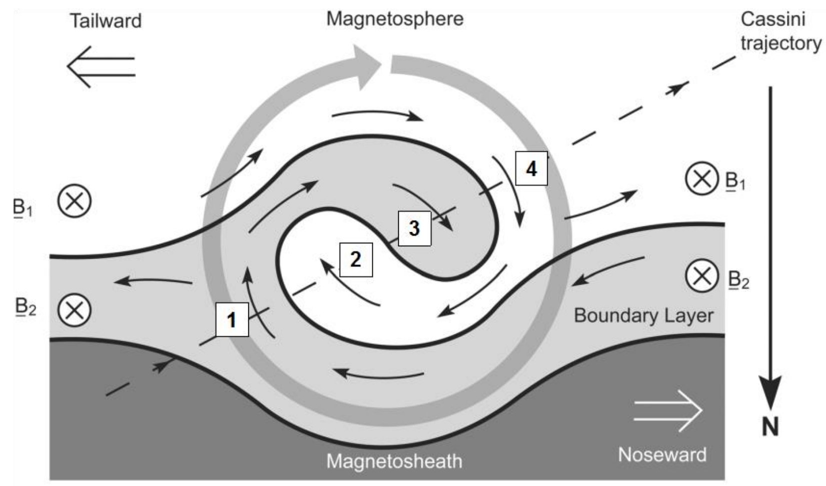


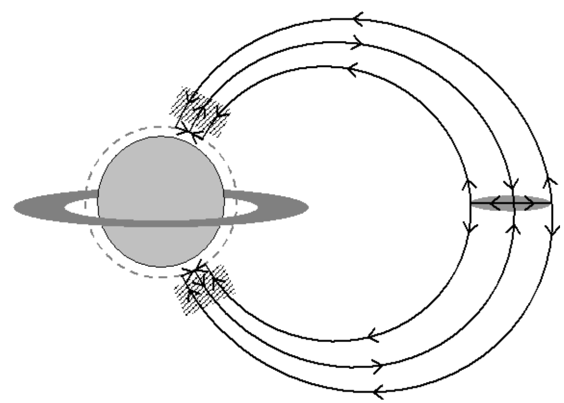
Boundary Phenomena

1. Kelvin Helmholtz [Masters et al., 2010; Delamere et al., 2013]
2. Magnetosheath plasma [Sergis et al., 2013}
3. Cusp [Jasinski et al., 2014]

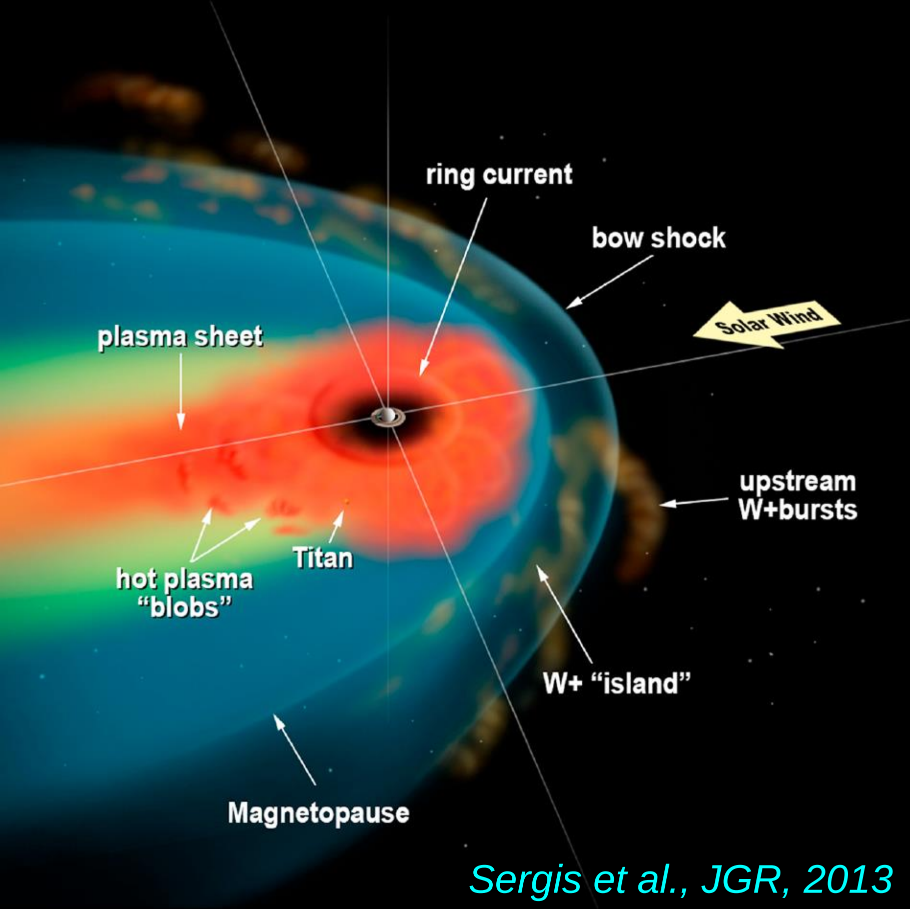
Kelvin-Helmholtz vortex observations in Saturn's outer magnetosphere (Masters et al., 2010)





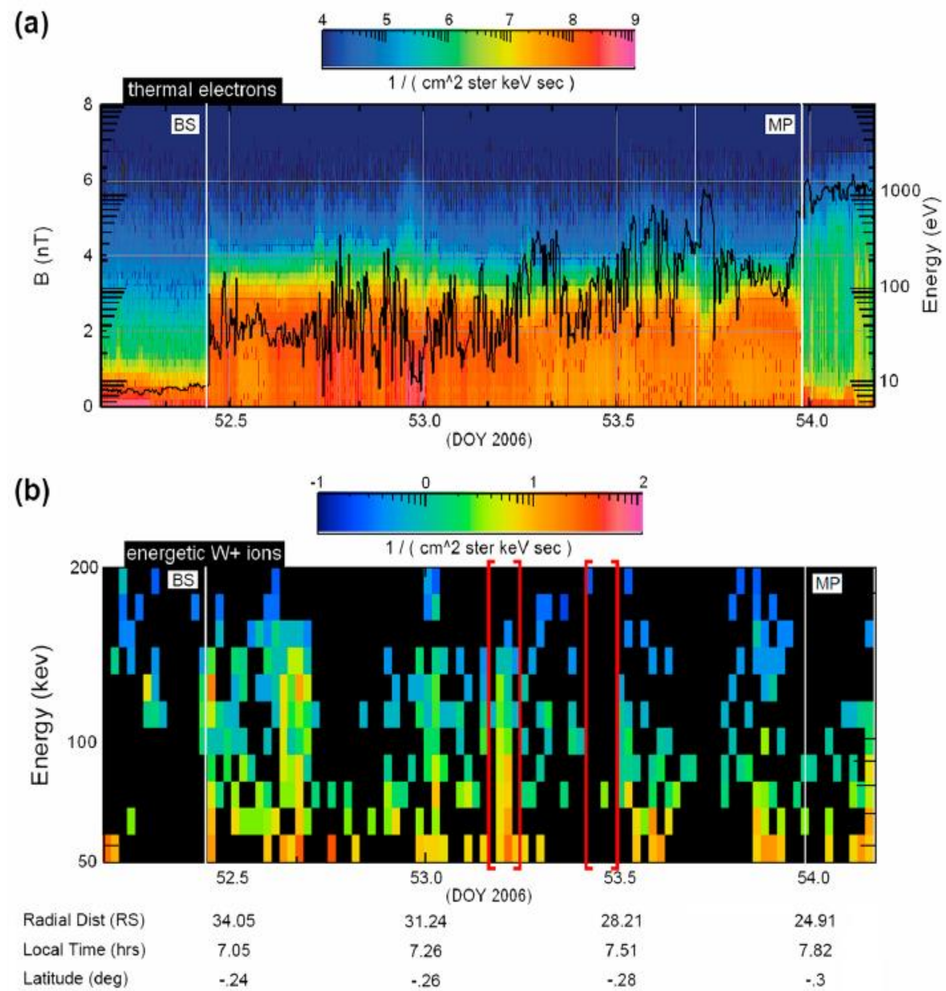


- Discovery of a vortex in Saturn's outer magnetosphere, revealing a new aspect of the solar wind-magnetosphere interaction that transports energy into the system



Cassini revealed the properties of the Saturnian magnetosheath. MIMI/CHEMS and INCA measured energetic magnetospheric W+ ions (10-500 keV) that due to their large gyroradius define the magnetopause boundary and populate the magnetosheath forming distinct W+ "islands". In addition, they also leak to the nearby solar wind in the form of upstream bursts that Cassini observes whenever the IMF connects it to the bow shock.

Saturnian Magnetosheath Properties Measured by Cassini	
Particle number density (cm^{-3})	0.05–0.25
Plasma Temperature (eV)	210–370
Plasma flow velocity (km/s)	170–240
Particle pressure (pPa)	6–30
Magnetic pressure (pPa)	0.2–1.1
Magnetic field (nT)	0.6–1.6
Plasma β (estimated)	10–100

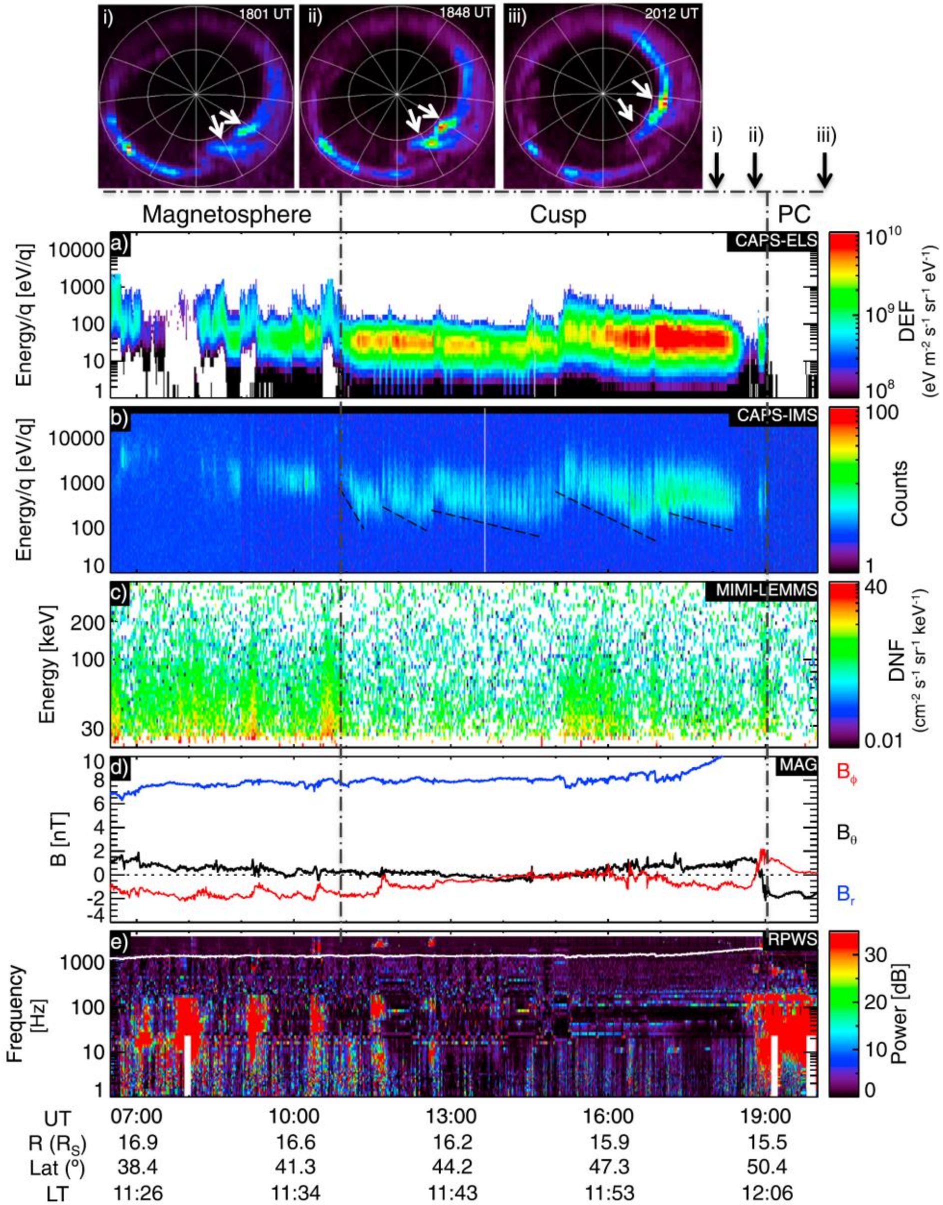


Cusp observations (Jasinski et al, 2014)

Auroral signatures of reconnection

Pulsed

Solar wind event changed conditions for more favorable reconnection conditions.



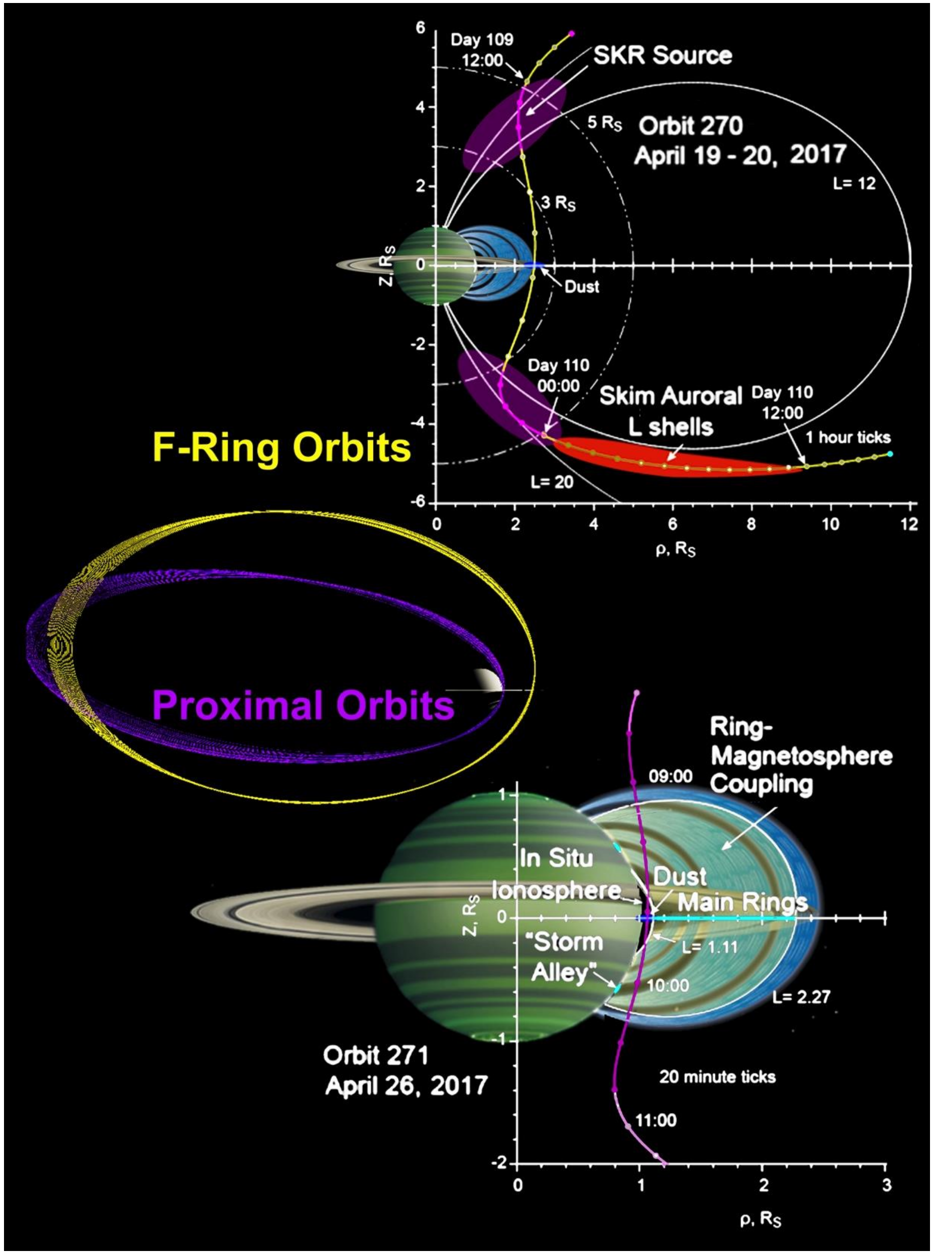
Proximal and F-ring orbit

Magnetospheric science

F-Ring and Proximal orbits, science opportunities

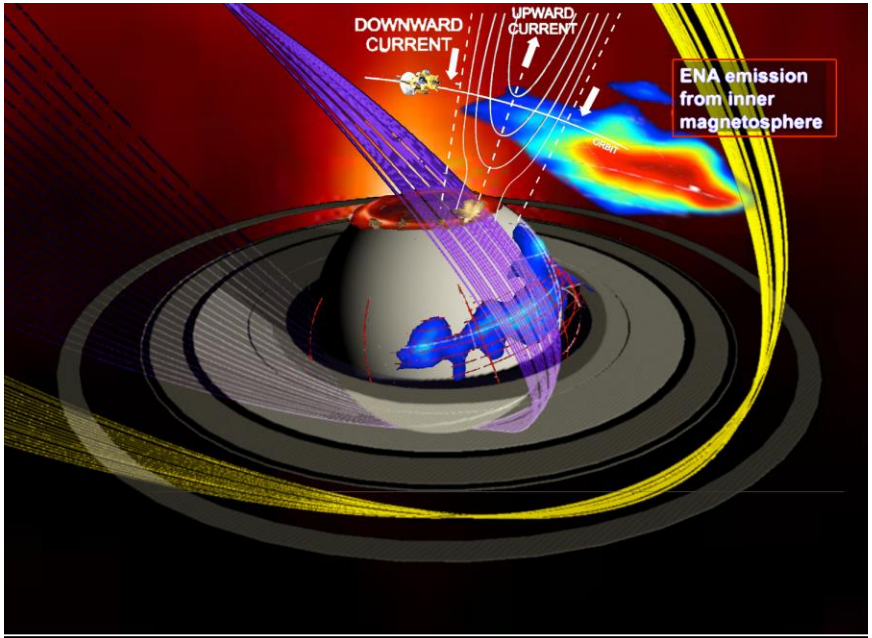
- F-Ring orbits excellent for both in situ and remote sensing (ENA imaging, UV and visible imaging, and radio).
- Auroral investigations close to Saturn where imaging can resolve small scale arcs and ENA structures and RPWS can detect weak radio emissions.
- Close up measure of open/closed magnetic field boundary

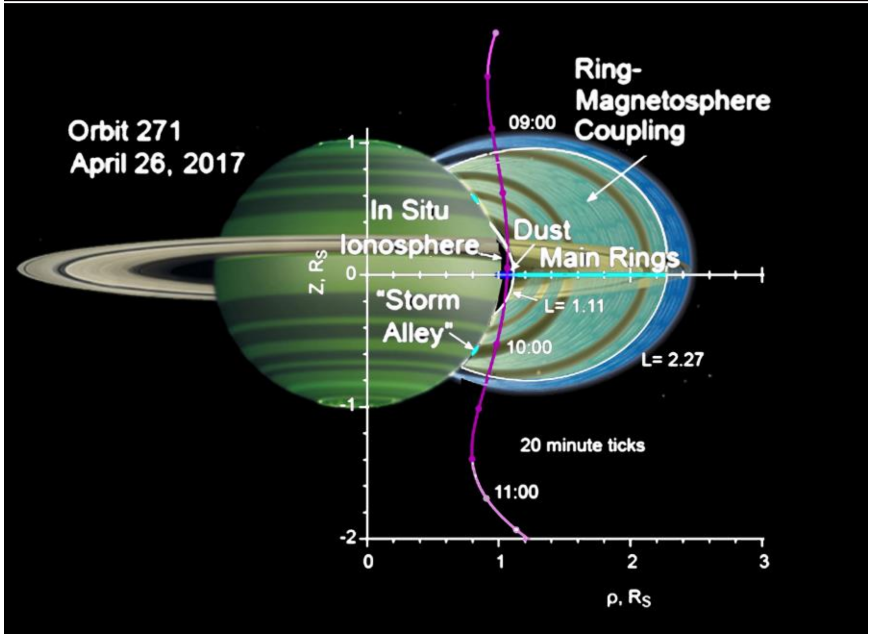
- **Proximal orbits excellent for probing the unexplored region between the D-Ring and the atmosphere.**
- **Unique place to investigate the processes on the field lines connecting the ionosphere and upper atmosphere (including storms) with the rings.**
- **Directly measure possible sprite accelerated energetic electrons, as for example in Jones et al., GRL 2006.**

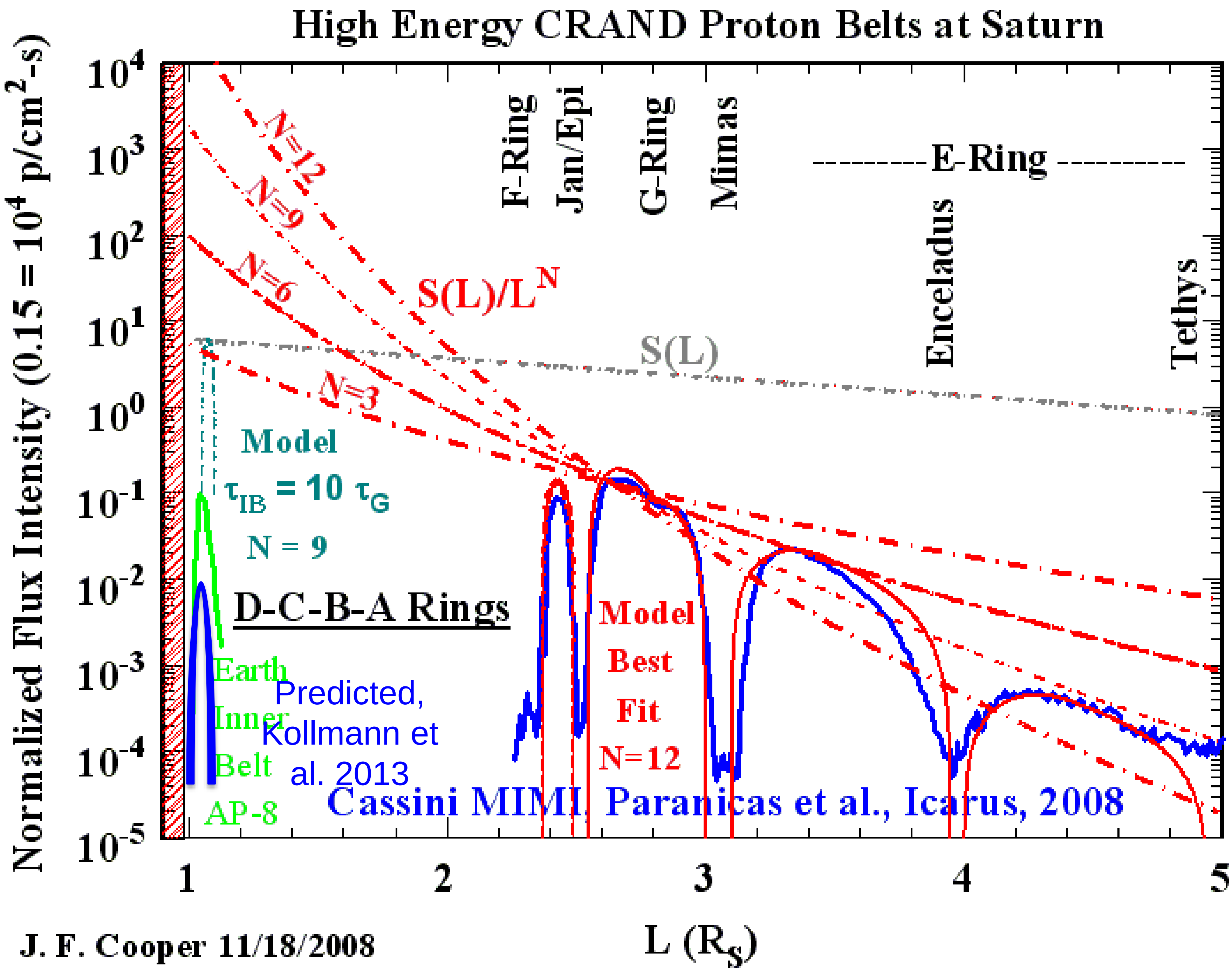


More on Proximal Orbit Science

- Image the inner belt with INCA
- Closeup view of aurora, particle acceleration
- Low noise imaging of ring current
- Very interesting region where Saturn is ‘connected’ to the rings via the planetary magnetic field
- Unexplored except for a brief period during SOI
- Direct access to field lines carrying lightning whistlers.
    - Do these accelerate electrons?
- Pass through region between Saturn and inner edge of D-ring
    - Radiation belts?
    - Accelerated ionospheric plasma?
    - Undetected material?
- Best opportunity to explore Saturn’s ionosphere
- Explore wave-particle interactions in inner radiation belt (chorus?)






High Energy CRAND Proton Belts at Saturn
Normalized Flux Intensity (0.15 = 10^4 p/cm^2-s)
L (R_S)
F-Ring
Jan/Epi
G-Ring
Mimas
E-Ring
Enceladus
Tethys
N=12
N=9
N=6
N=3
S(L)/L^N
S(L)
Model
τ_IB = 10 τ_G
N = 9
D-C-B-A Rings
Earth
Inner
Belt
AP-8
Predicted,
Kollmann et
al. 2013
Model
Best
Fit
N=12
Cassini MIMI, Paranicas et al., Icarus, 2008
J. F. Cooper 11/18/2008