Saturn‘s Magnetic Environment

Highlights of the CASSINI Magnetosphere and Plasma Science Working Group MAPS

Cassini-Huygens Analysis and Results of the Mission (CHARM) telecon, July 26, 2011

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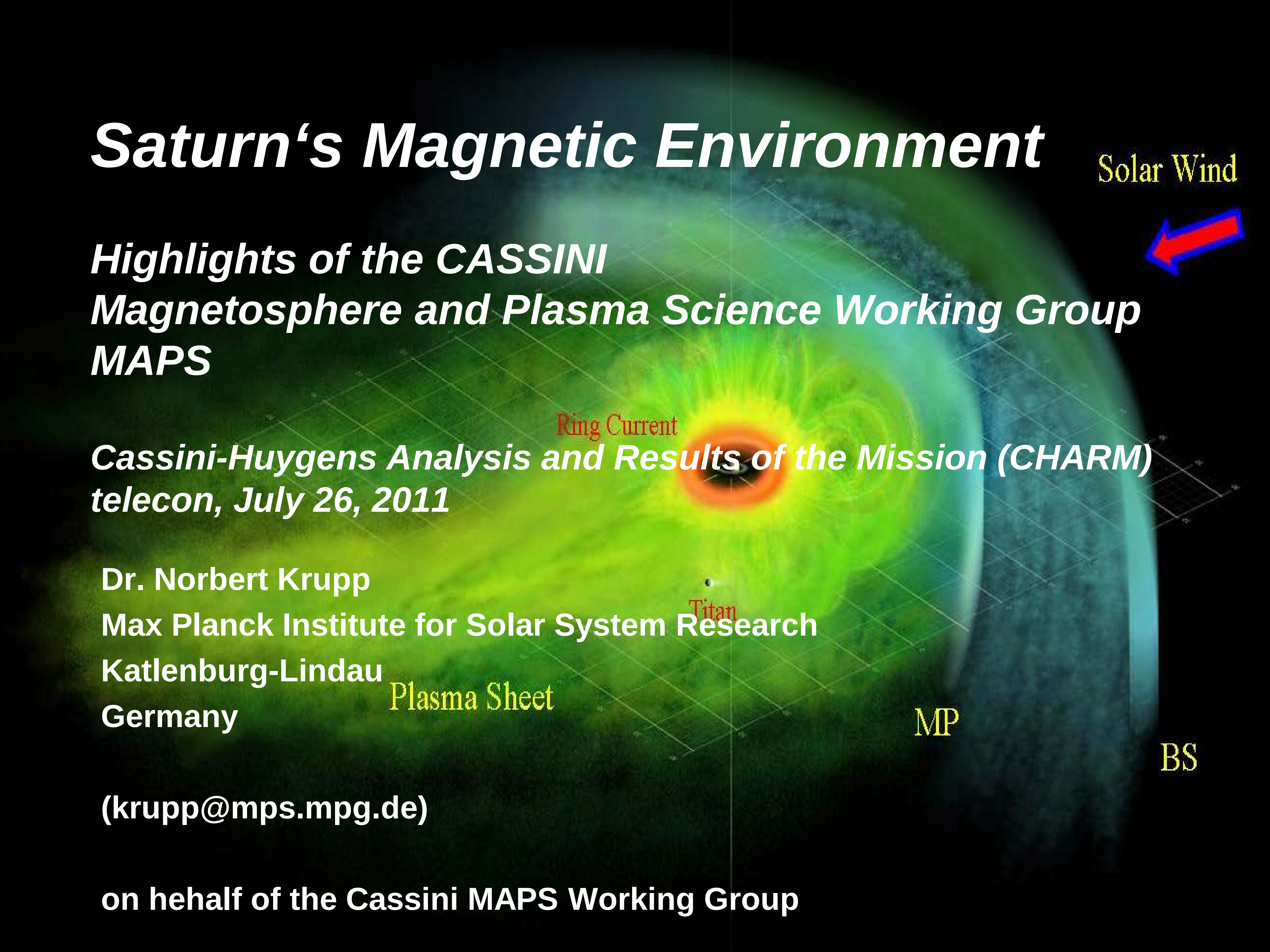

Acknowledgments

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Outline

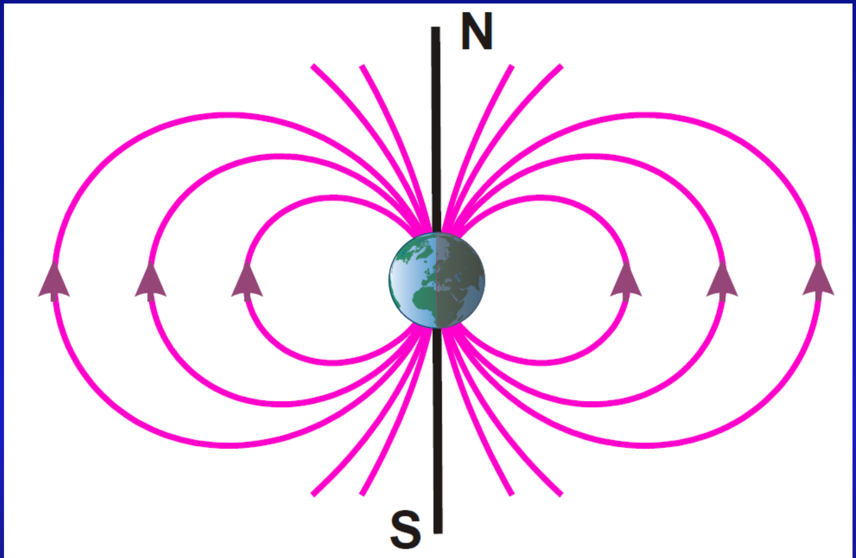
- Introduction
- Global Configuration and Dynamics of the Kronian Magnetosphere
- Interaction of the magnetospheric plasma with rings and moons
- Summary

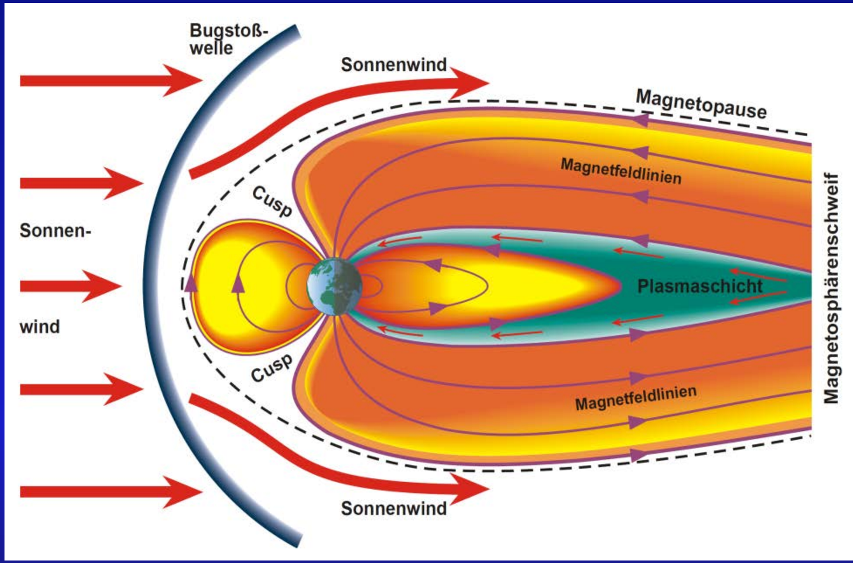
Introduction

What is a magnetosphere?

Magnetic dipole field of a planet without solar wind

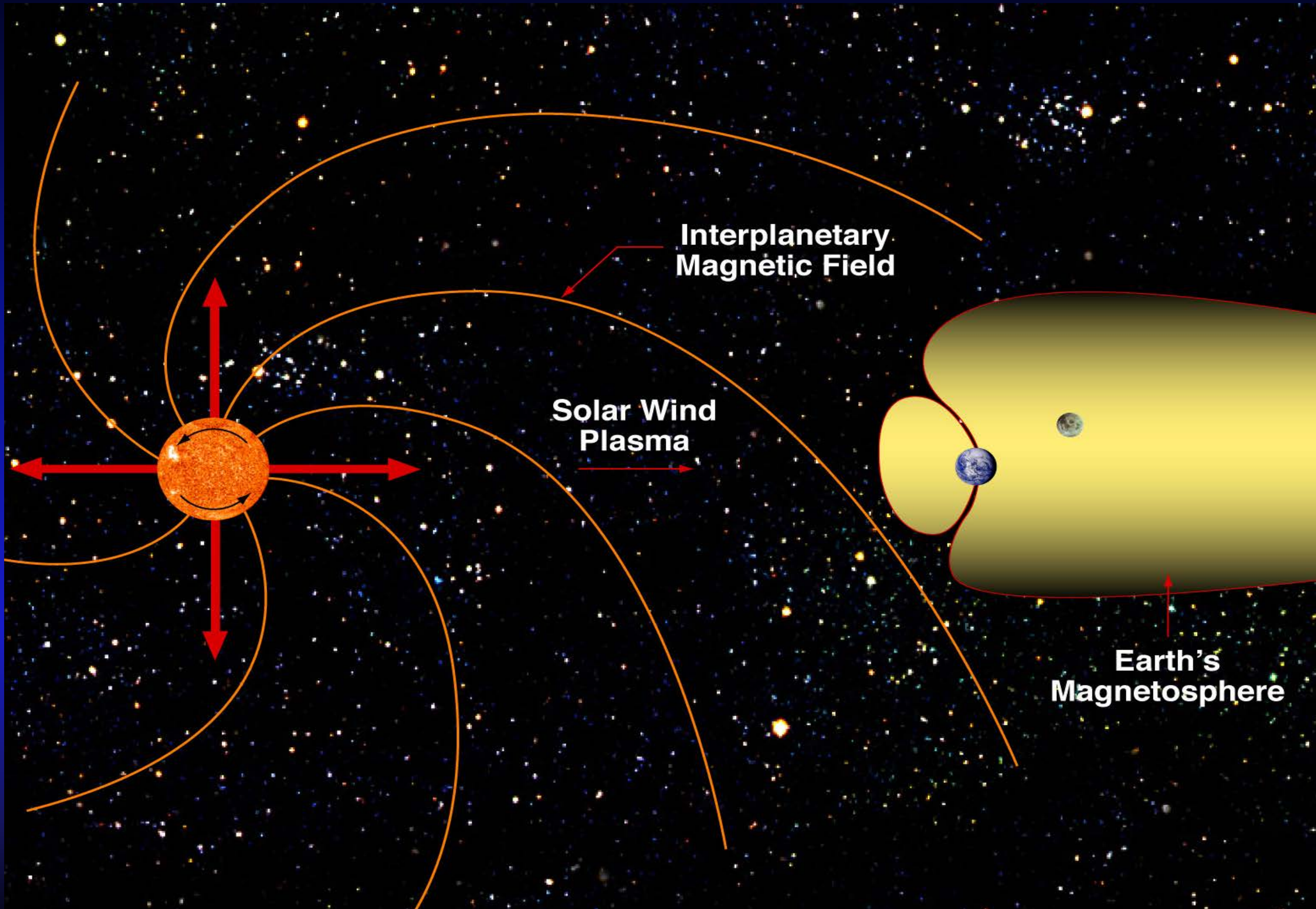
Planetary field embedded in a flowing magnetized plasma (solar wind)



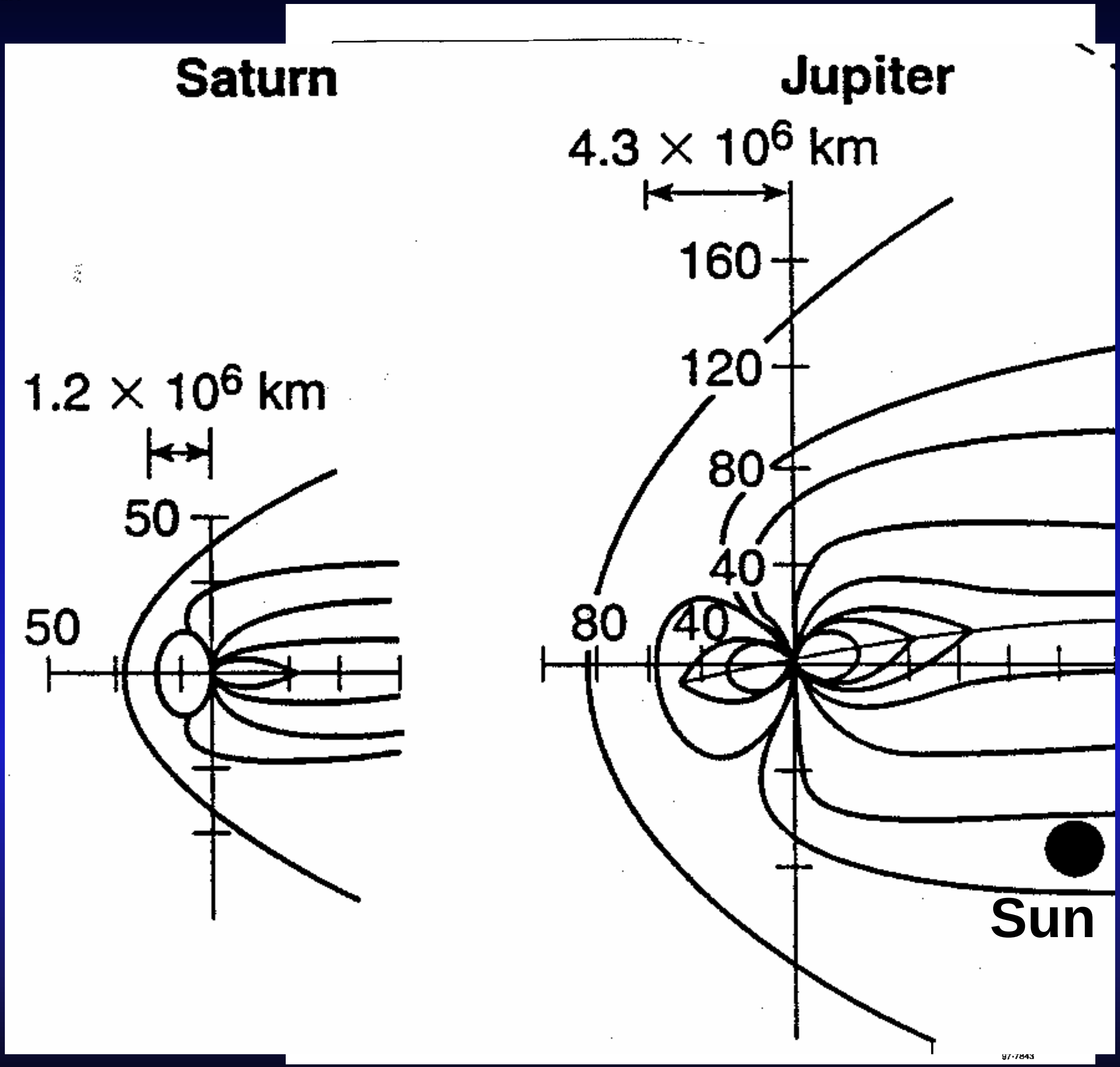


The Magnetosphere is this part of space around a planet where the planetary magnetic field dominates

Solar wind
The embedding medium



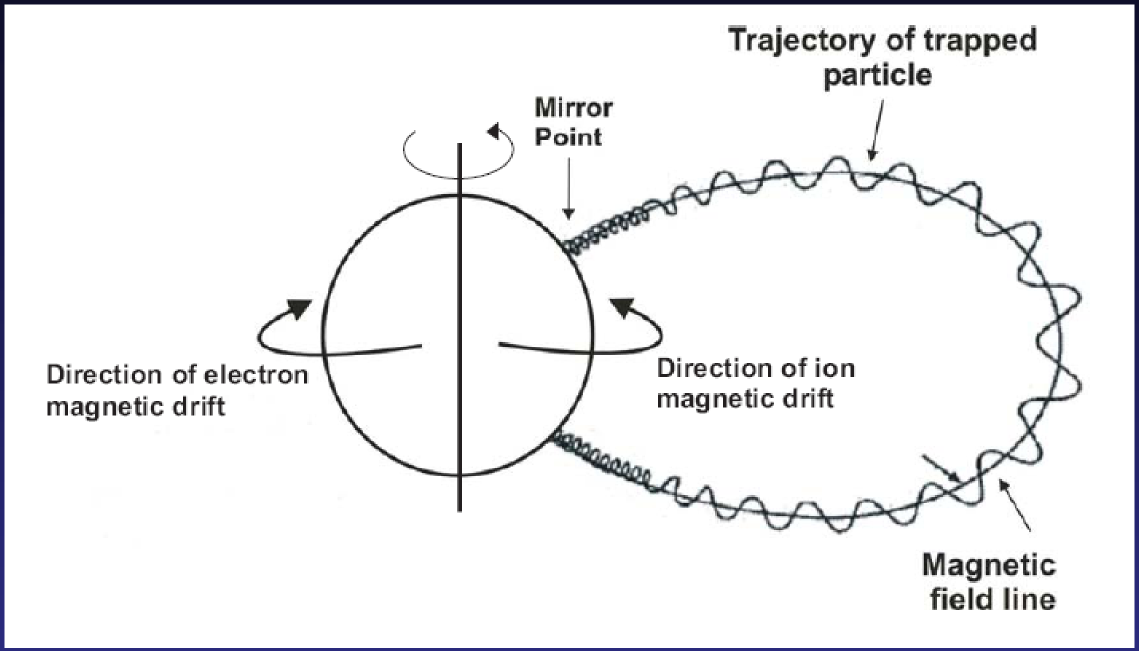
Size of magnetospheres



intermediate

huge

Charged particle motion in the magnetosphere



1. First adiabatic invariant
Gyro motion

⇩

$$\mu = \frac{p^2 \sin^2 \alpha}{B}$$

2. Second adiabatic invariant
Bounce motion

⇩

$$k = \int_{S_m}^{S'_m} \sqrt{\left[1 - \frac{B(s)}{B_m}\right]} ds$$

3. Third adiabatic invariant
Drift motion

⇩

$$J_3 = q\Phi$$

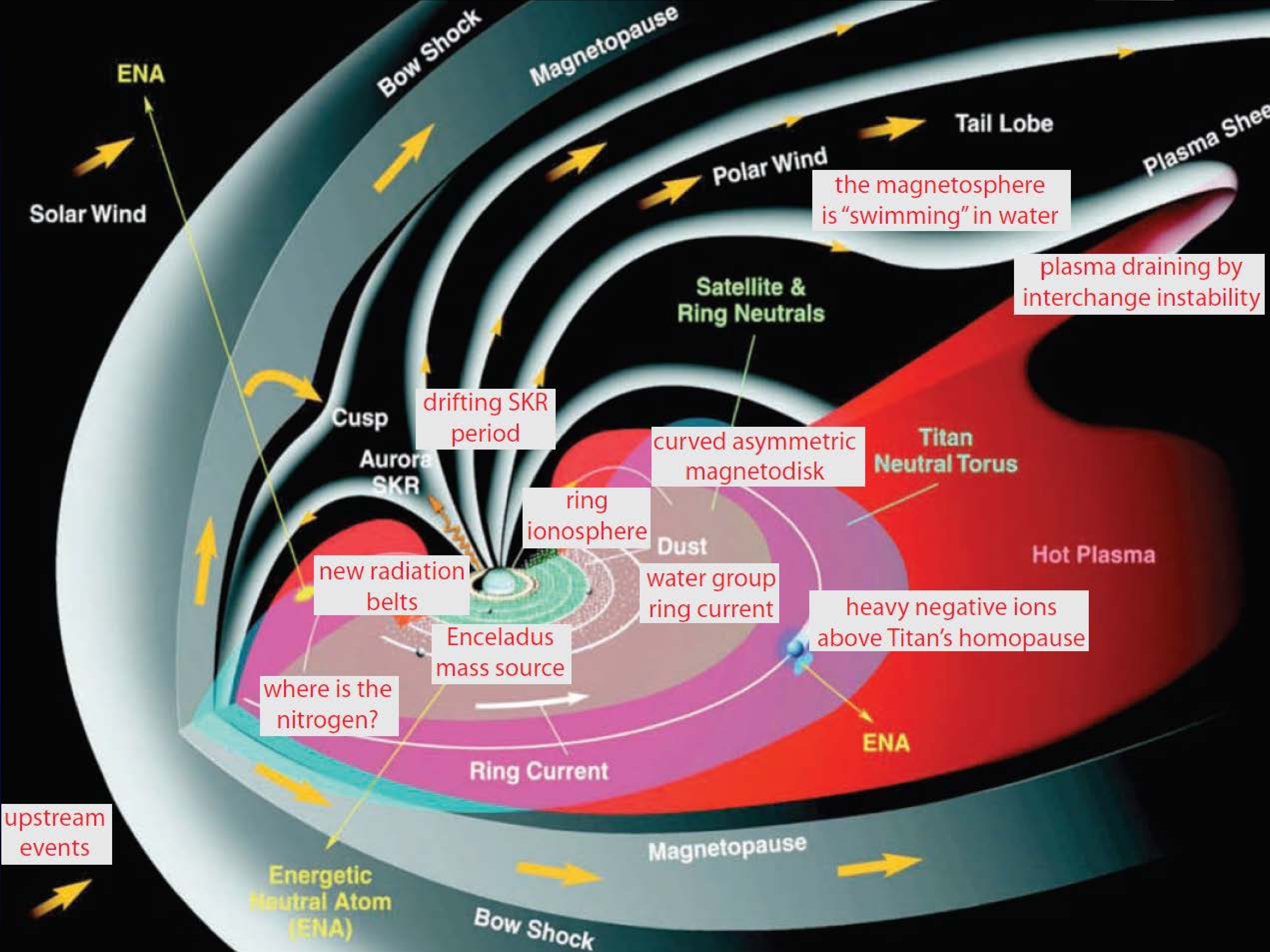
Parameters measured by particle instruments

- **particle species and charge states**
  - **ions (eventually with different charge states) and electrons**
- **differential particle intensity I:**
  - **particles / s / energy interval / cm^2 / sr**
- **energy spectrum:**
  - **differential intensity I as a function of particle energy (usually Maxwellian for lower energies and power law type for higher energies)**
- **pitch angle:**
  - **angle between the direction of the magnetic field and the direction of motion of the particle**
- **phase space density f:**
  - **Intensity / momentum^2 f=I/p^2**

CASSINI MAPS instrumentation

- Magnetometer **MAG**
- Cassini Plasma Spectrometer **CAPS**
  – low energy electrons and ions (eV-keV)
- Magnetospheric Imaging Instrument **MIMI**
  – hot electrons ions and neutrals (keV-MeV)
- Ion and Neutral Mass Spectrometer **INMS**
  – cold ions and neutrals (eV)
- Radio and Plasma Wave Spectrometer **RPWS**
- Cosmic Dust Analyzer **CDA**

- Ultraviolet Imaging Spectrometer **UVIS**

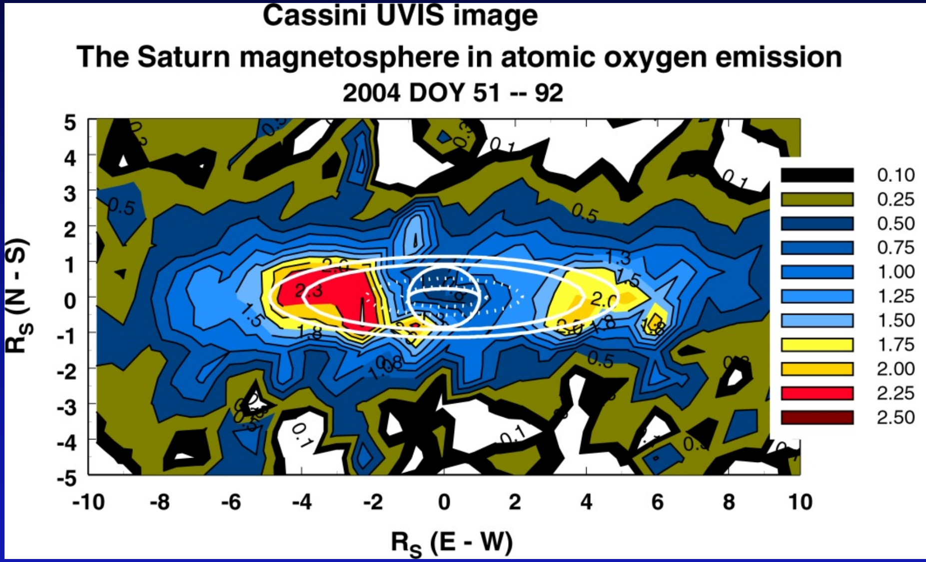


ENA
Bow Shock
Magnetopause
Tail Lobe
Plasma Shee
Polar Wind
Solar Wind
the magnetosphere is "swimming" in water
plasma draining by interchange instability
Satellite & Ring Neutrals
Cusp
drifting SKR period
Aurora SKR
curved asymmetric magnetodisk
Titan Neutral Torus
ring ionosphere
Dust
Hot Plasma
new radiation belts
water group ring current
heavy negative ions above Titan's homopause
Enceladus mass source
where is the nitrogen?
ENA
Ring Current
upstream events
Magnetopause
Energetic Neutral Atom (ENA)
Bow Shock

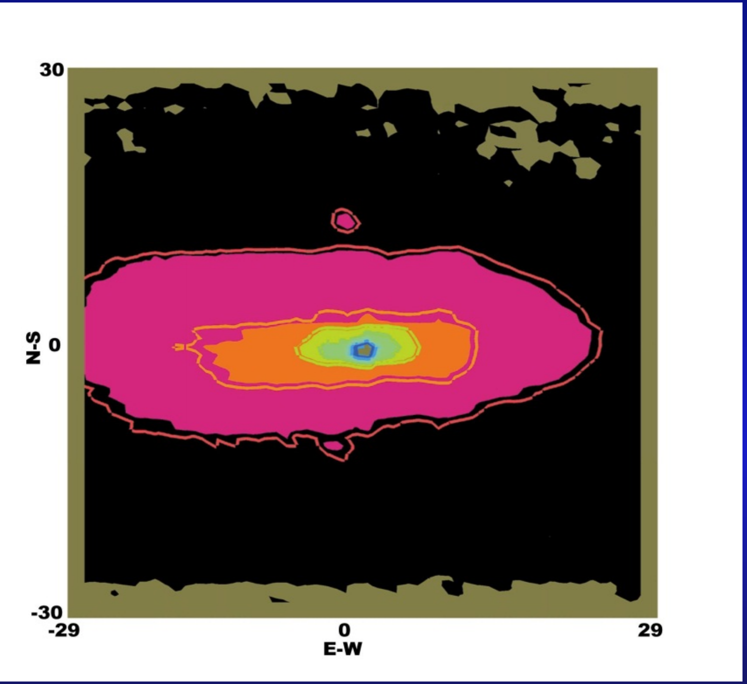
Global Configuration and Dynamics of the Kronian Magnetosphere

Norbert Krupp

Neutral gas in the Saturnian environment



…while hydrogen gas suffuses the system as far out as 45 Rs.

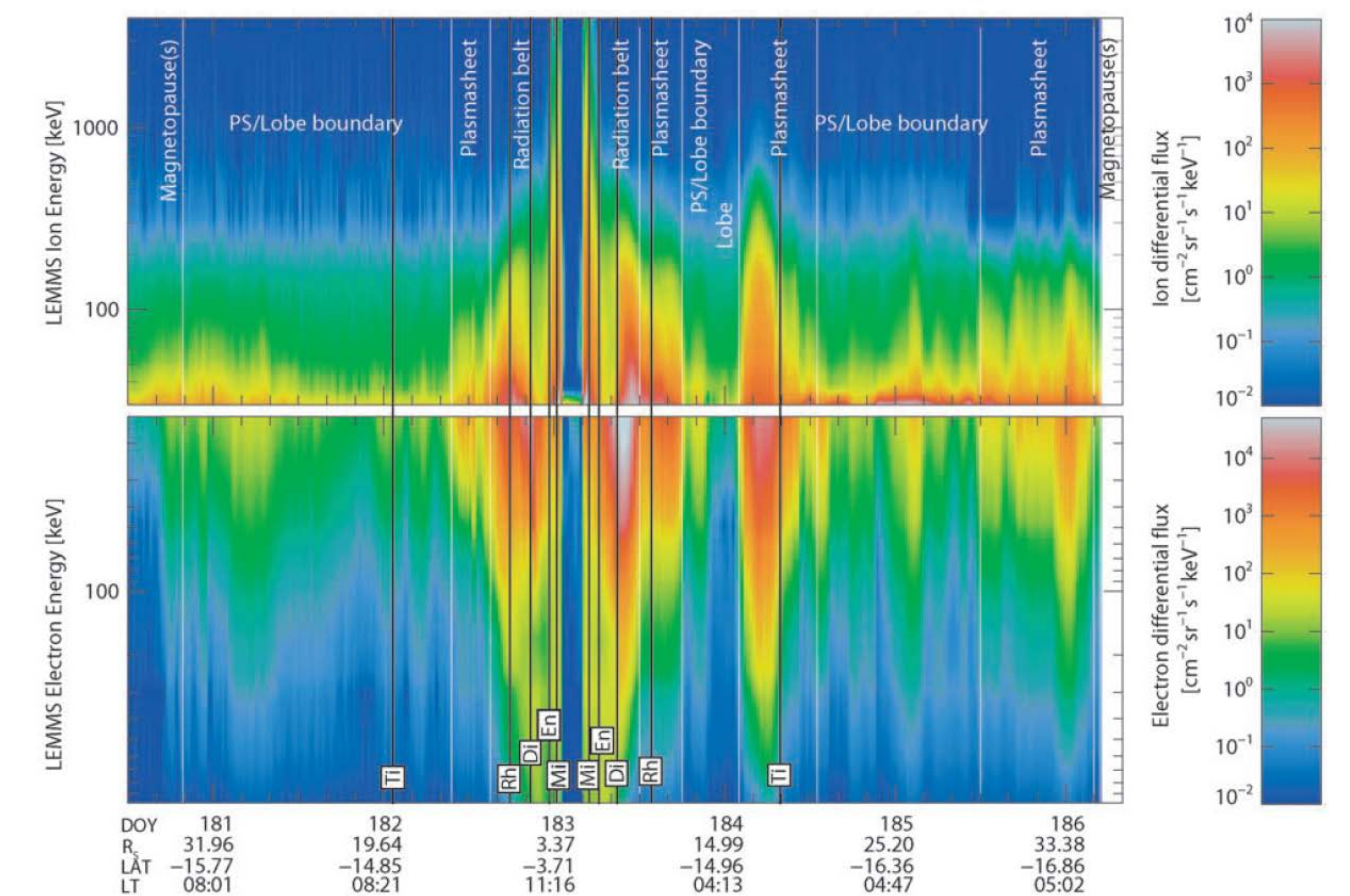


The UVIS Team (Don Shemansky, Larry Esposito et al.) have shown a high concentration of oxygen in the vicinity of the E-ring and the icy moons...

Neutral gas about 100 times more abundant at Saturn compared to Jupiter

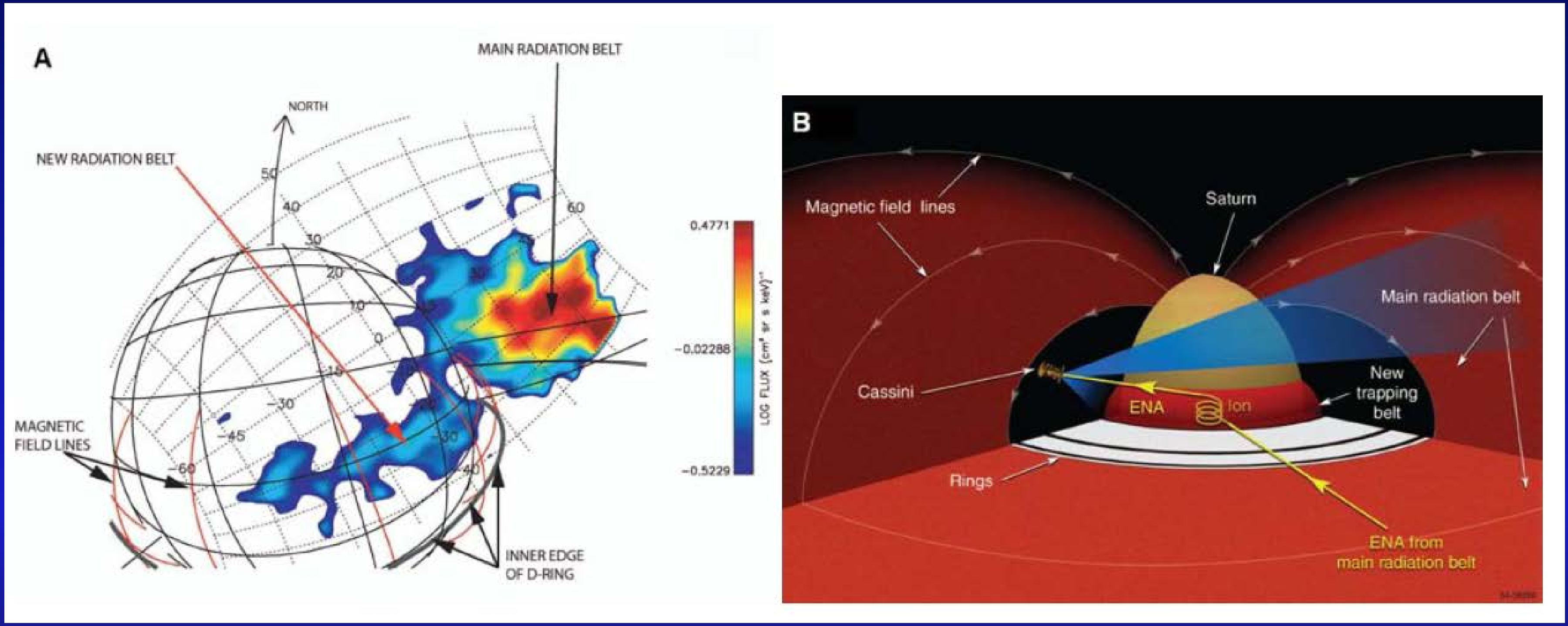
Inner magnetosphere / radiation belts

Saturn insertion orbit (SOI)
Cassini MIMI results



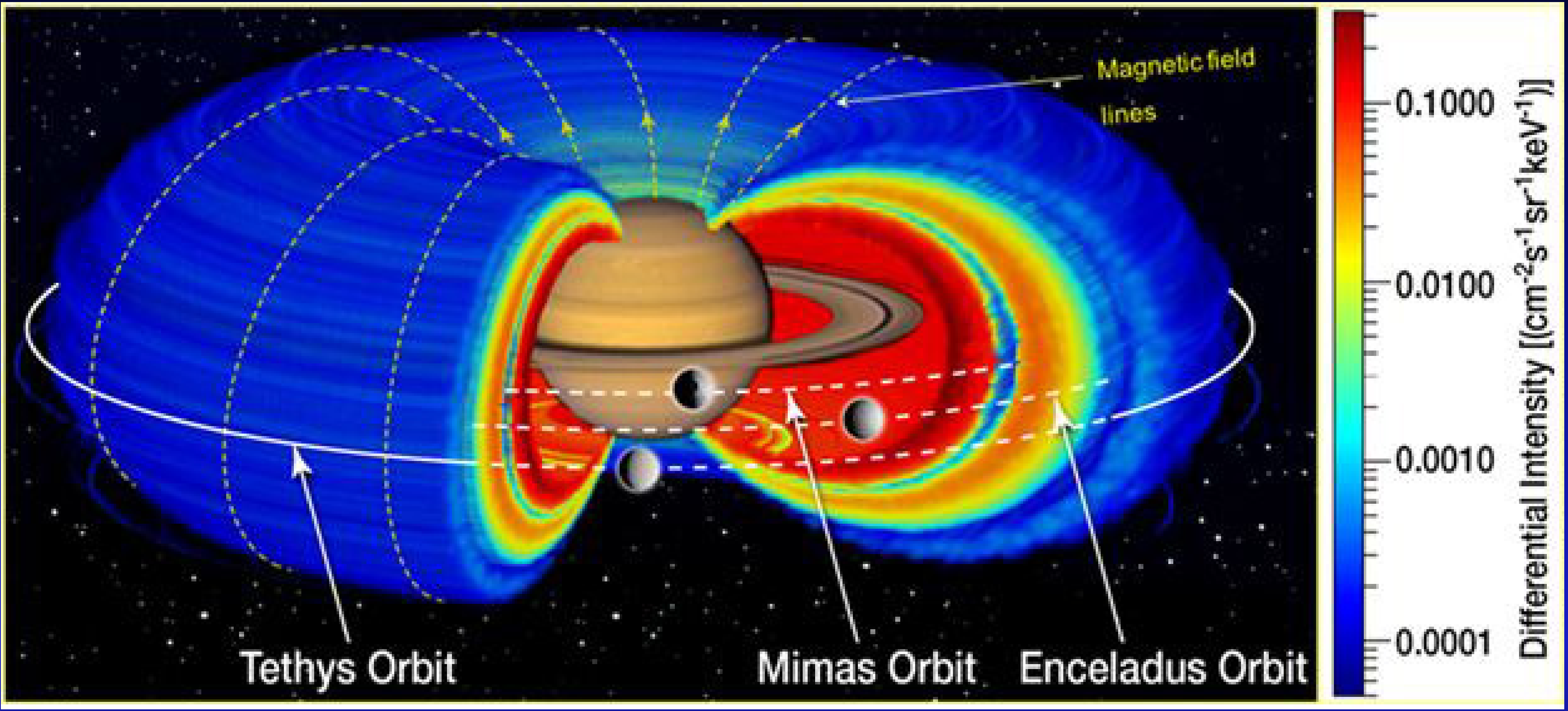
Charged particles inside the D-Ring close to the planet

Cassini MIMI results (Krimigis et al., 2005)

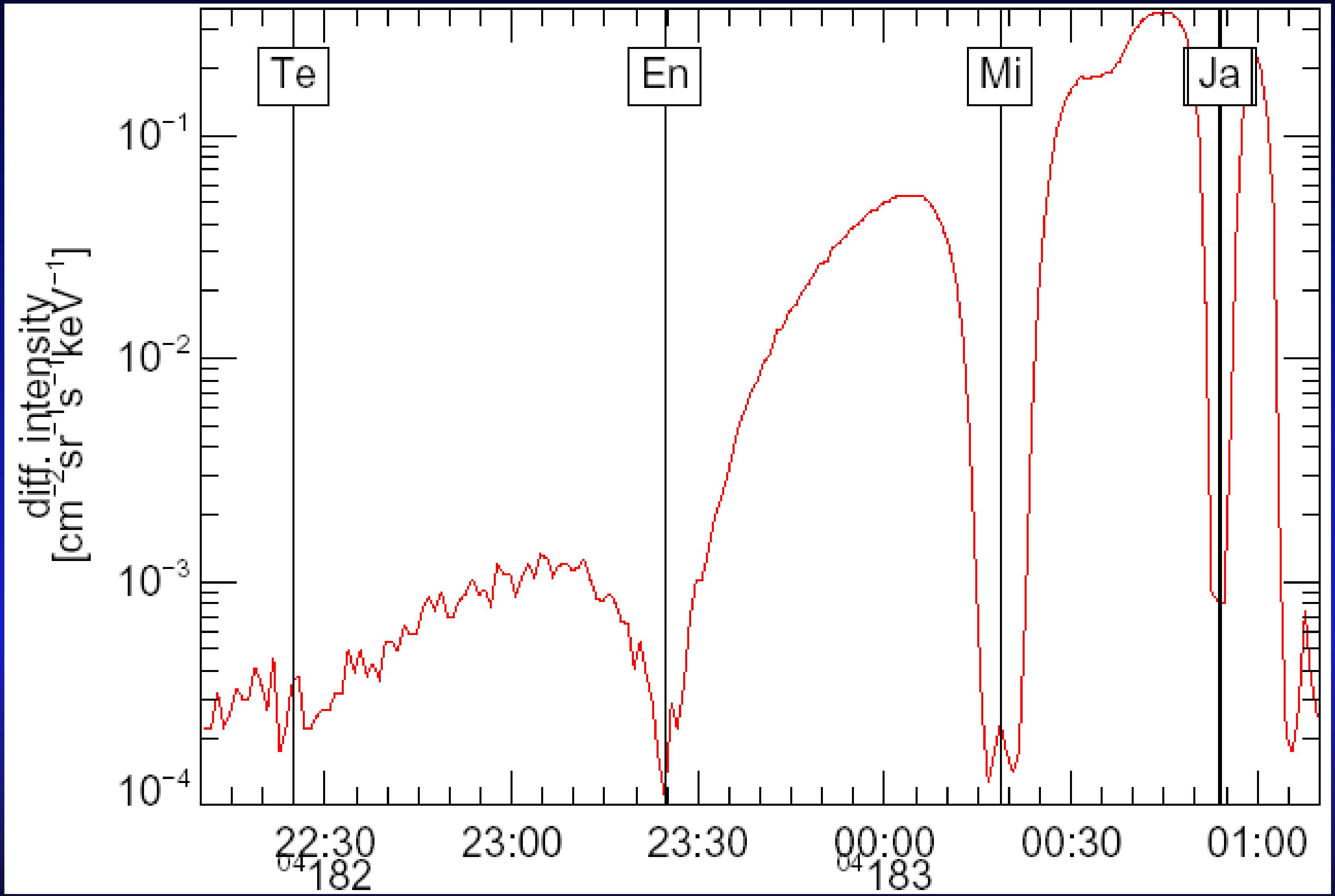


Saturn's ion radiation belts

Cassini MIMI results (Roussos et al., 2011)

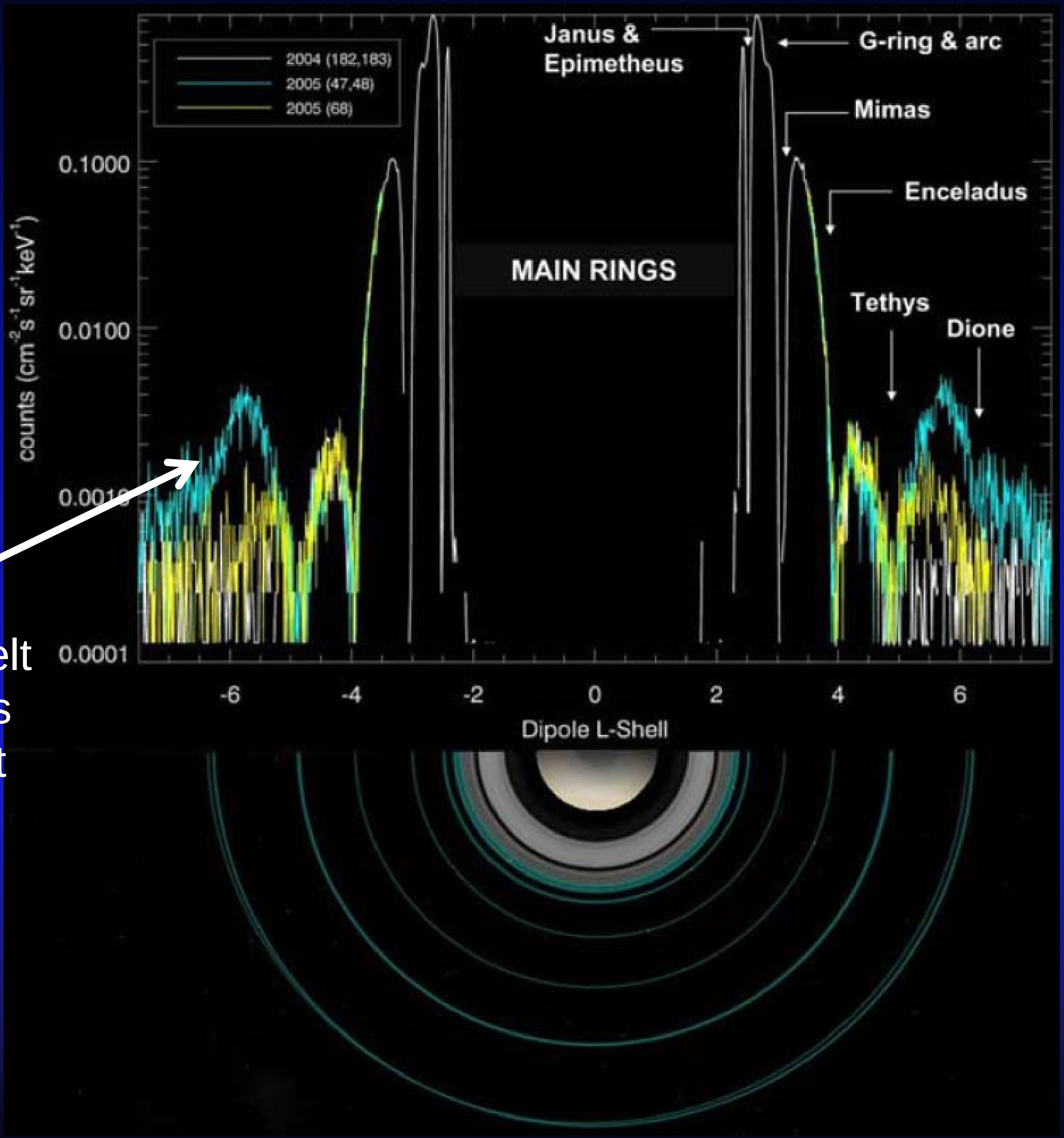


Charged particle absorption by the moons in the inner magnetosphere (Macrosignatures)



Variability of Saturn's Radiation Belts

Cassini MIMI results (Roussos et al. 2008)

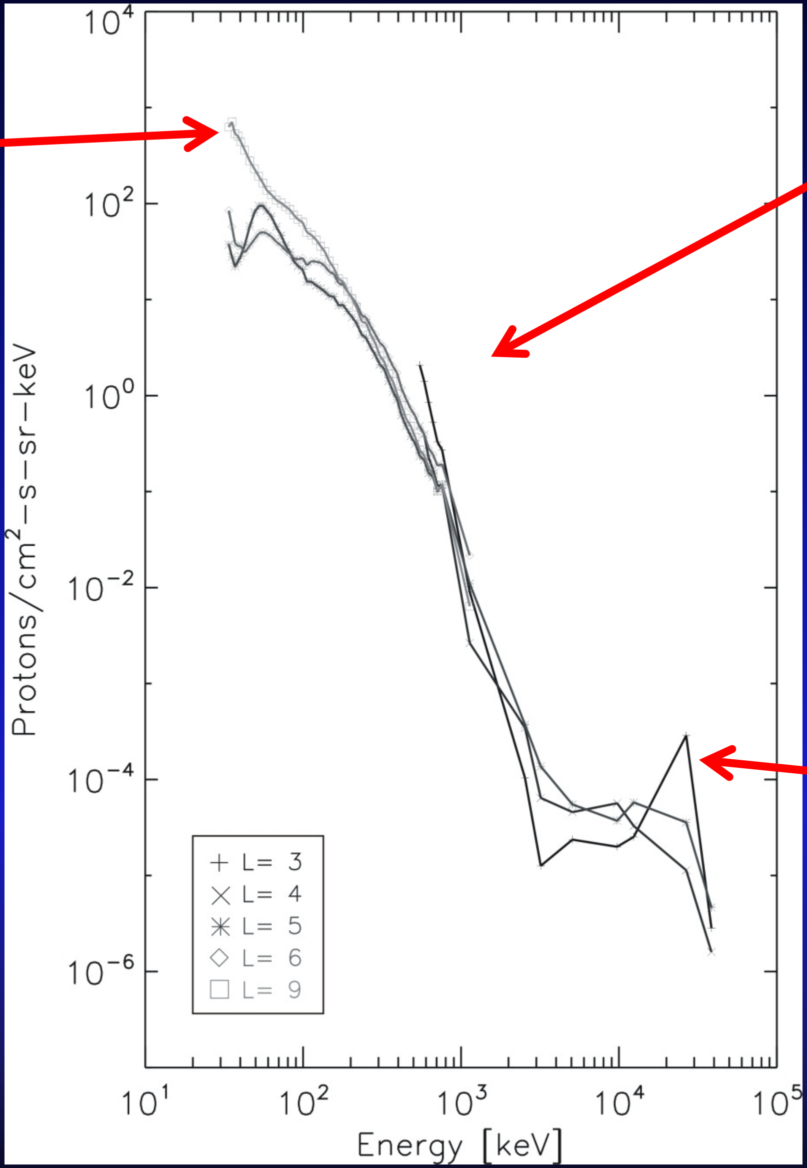


new transient belt between Dione's and Tethys' orbit

Proton Energy Spectra in Saturn's radiation Belts

Cassini MIMI results (Paranicas et al., 2011)

These 10-100 keV protons at Tethys, Dione, and Rhea, are essentially absent inward of Tethys, except within injections



The source of this part of the energy spectrum is harder to understand

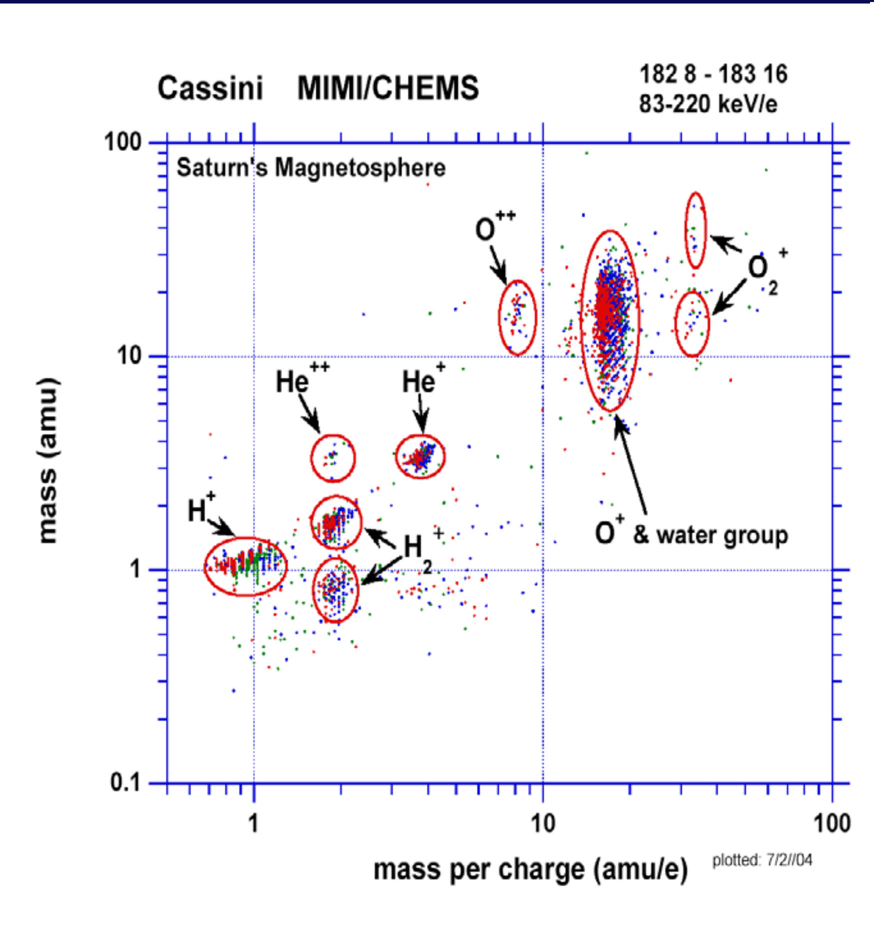
The crand peak near Mimas's orbit

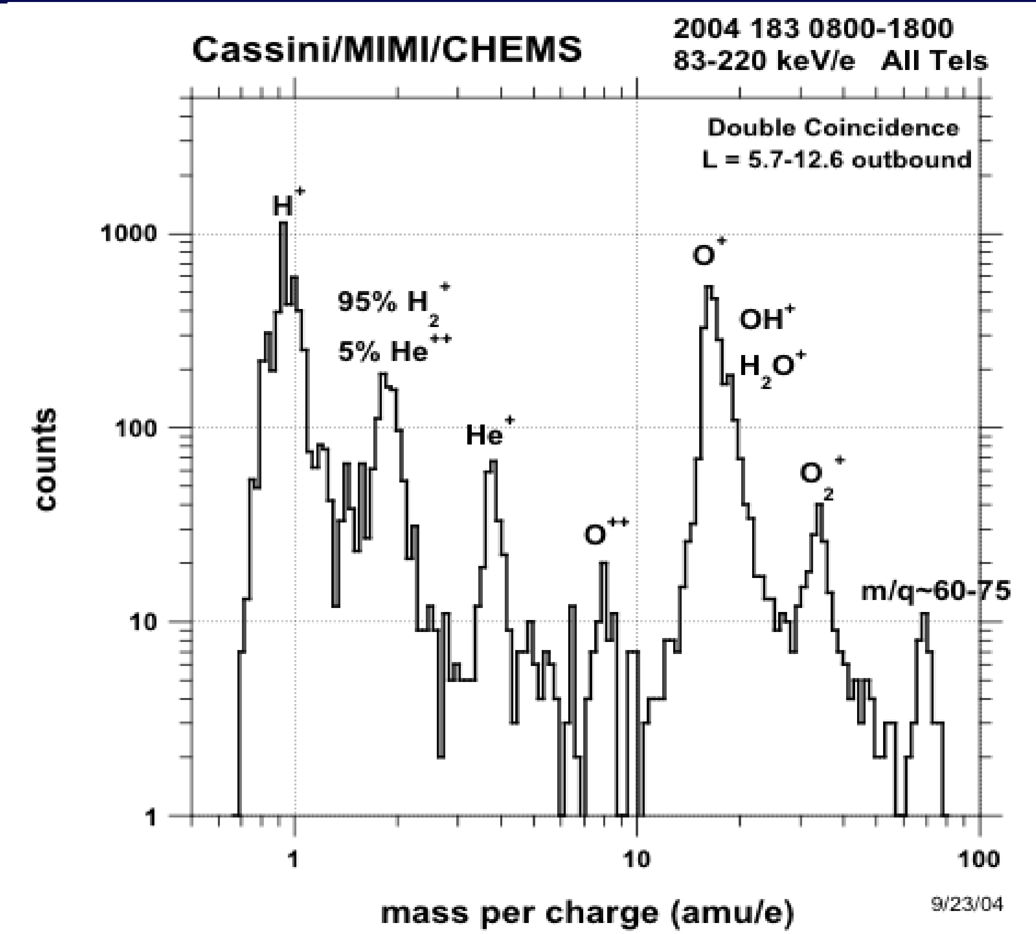
These are six-year average proton energy spectra (Paranicas et al. 2011, PSS)

particle sources / ion composition / ring current / plasma disk

Charge states of energetic ions in Saturn's magnetosphere

Cassini MIMI results (Krimigis, Science 2005)





water group ions, oygen and hydrogen most abundant

Water group ion and Hydrogen distributions
Cassini RPWS results (Persoon et al, 2009)

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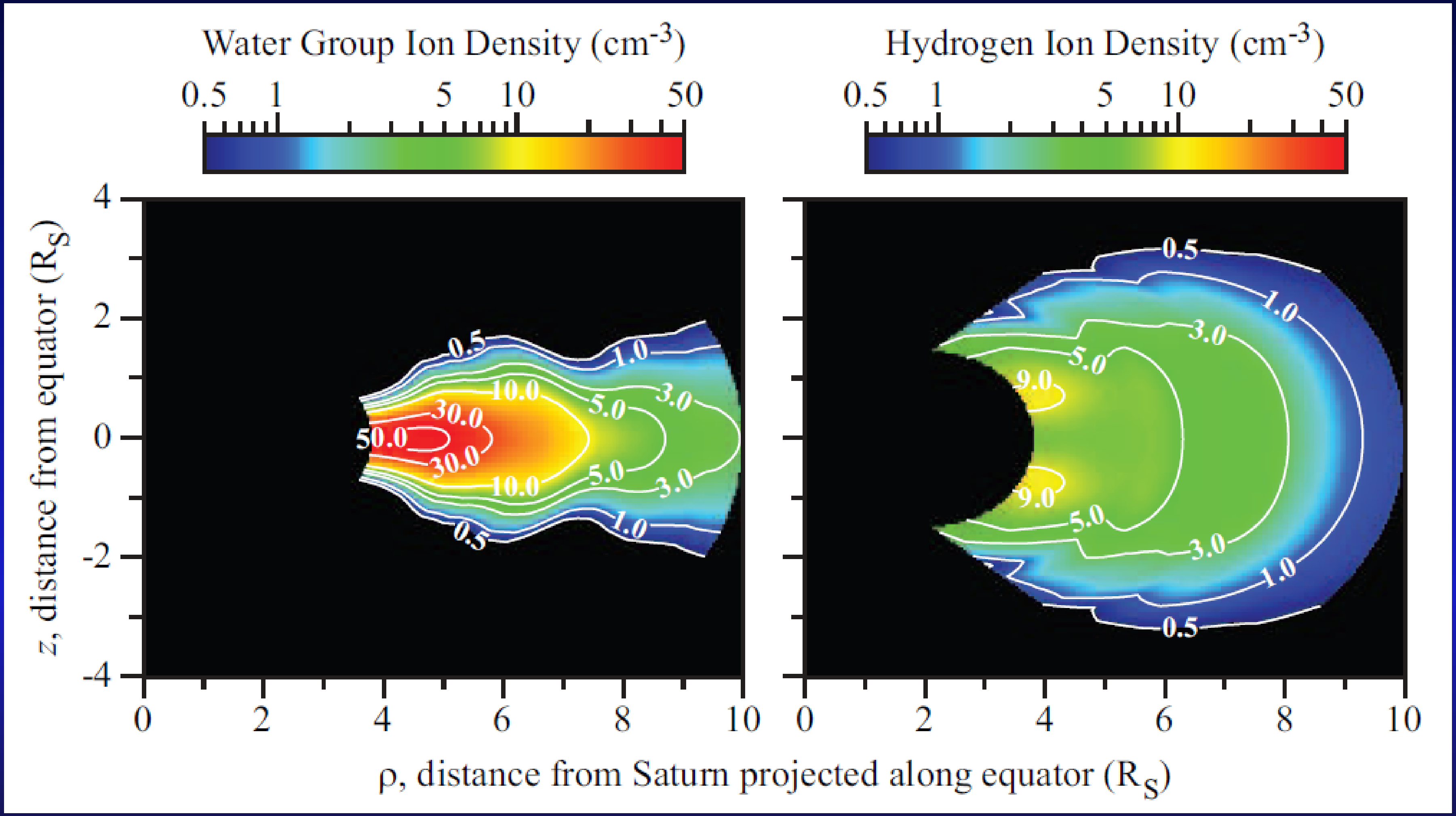
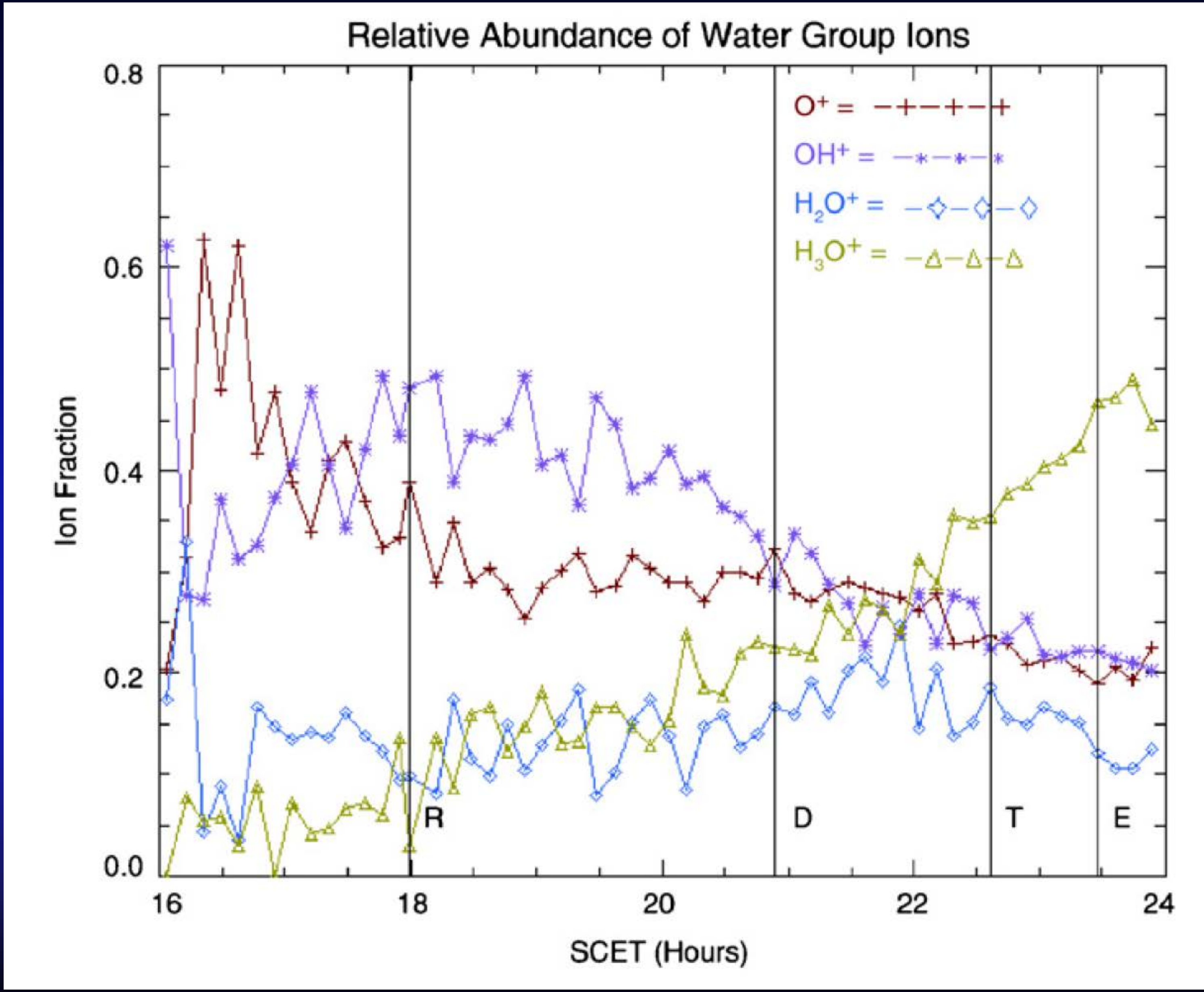
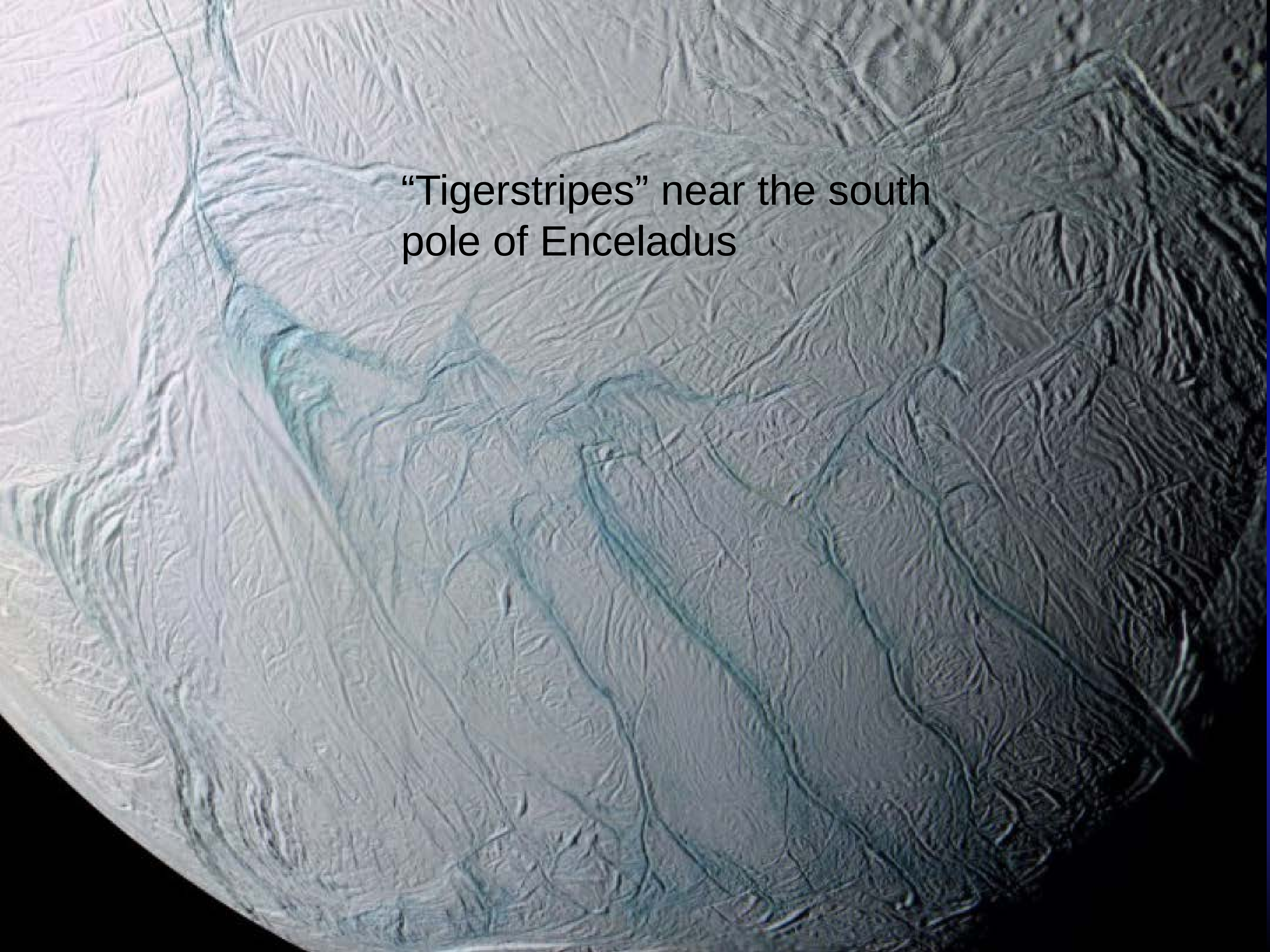


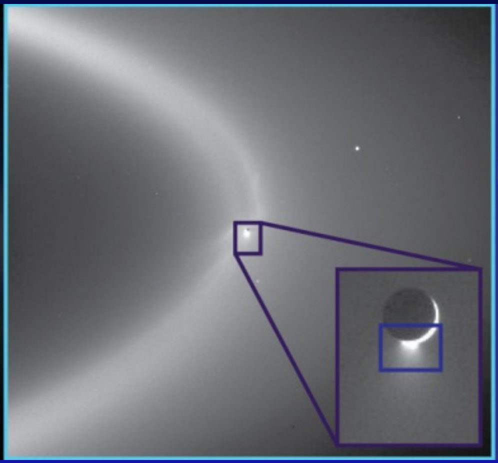
Water group ion distributions
Cassini CAPS results (Sittler et al, 2008)

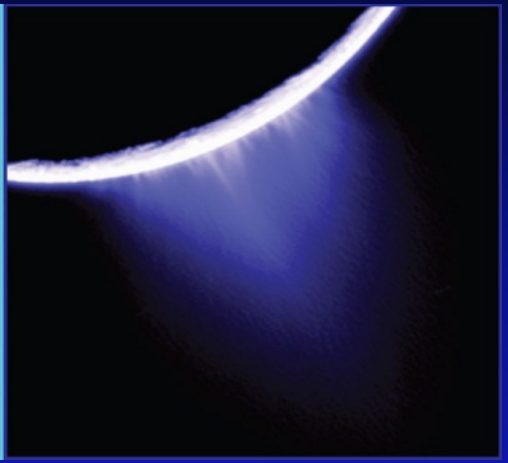




“Tigerstripes” near the south pole of Enceladus

Enceladus- Interaction with Saturn's magnetosphere





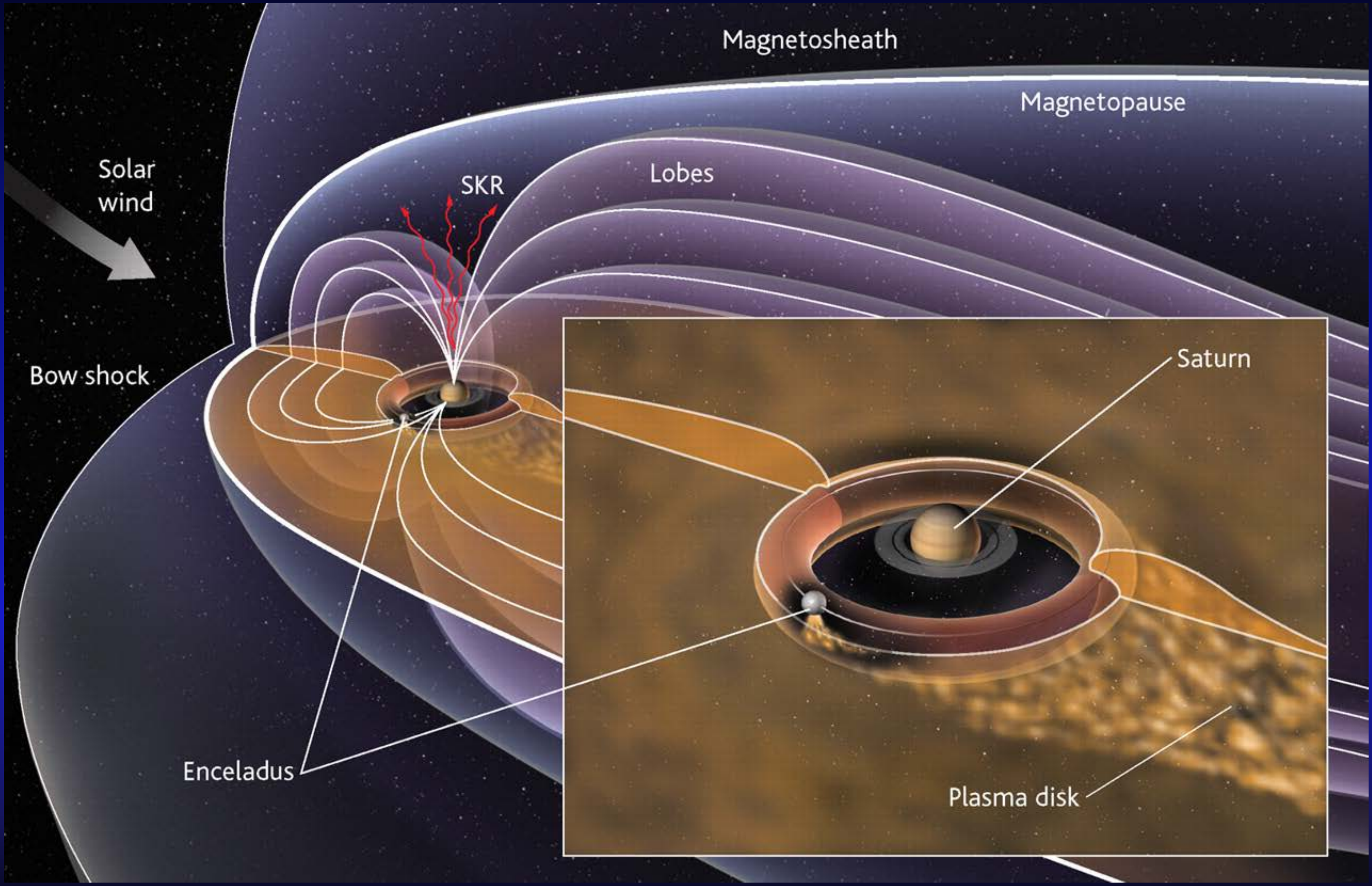
Saturn in eclipse makes the E-ring „visible“

Enceladus as the source of the E-ring and all the water in the magnetosphere

Water-ice geysirs near the south pole of Enceladus emit 100-300 kg/s into the magnetosphere

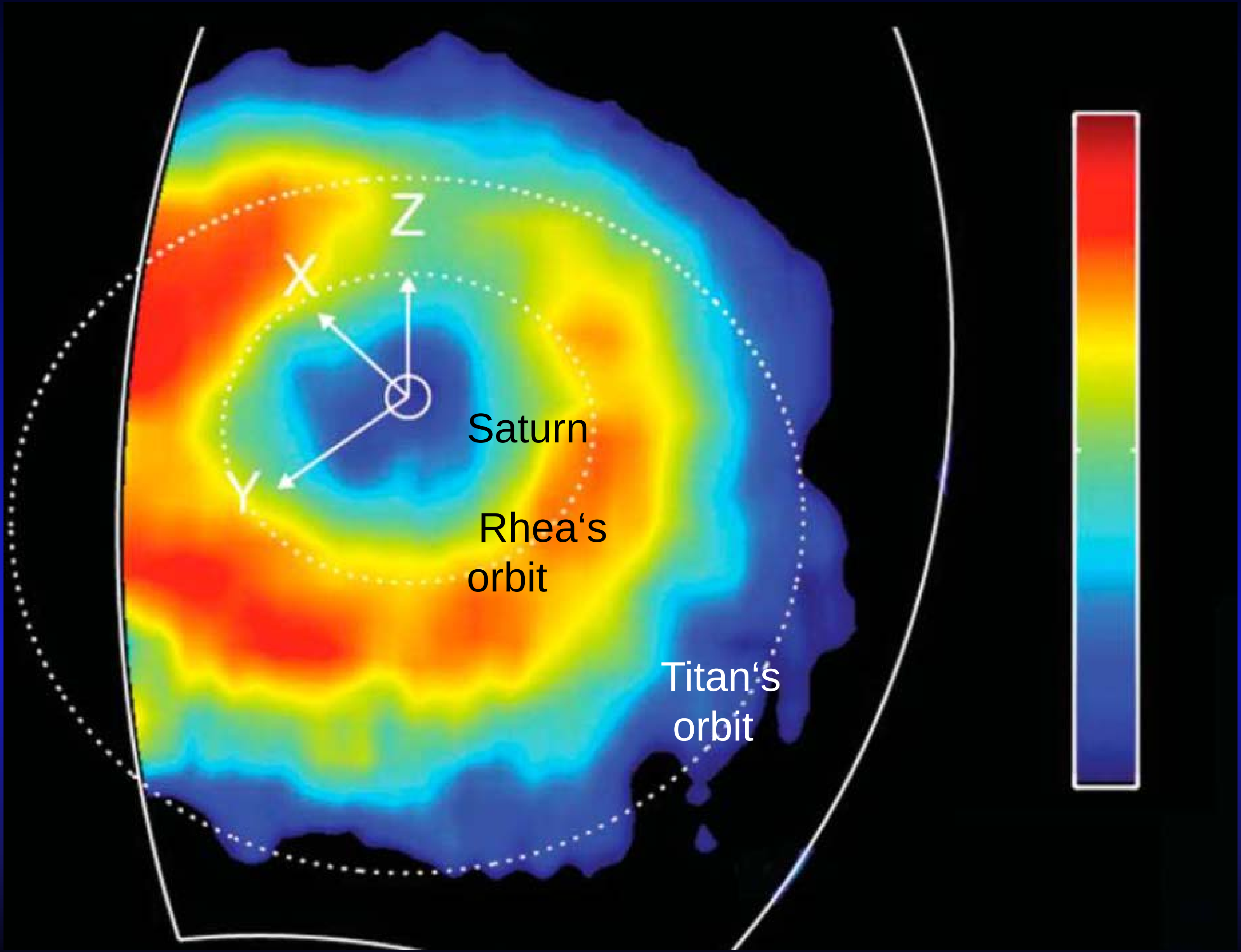
Saturn's magnetosphere and the role of Enceladus

Kivelson, Science 2006



Ring current „Image“ of ENA emission

Cassini MIMI results (Krimigis et al. 2007)



Ring current
Cassini MIMI results (Sergis et al. 2007)

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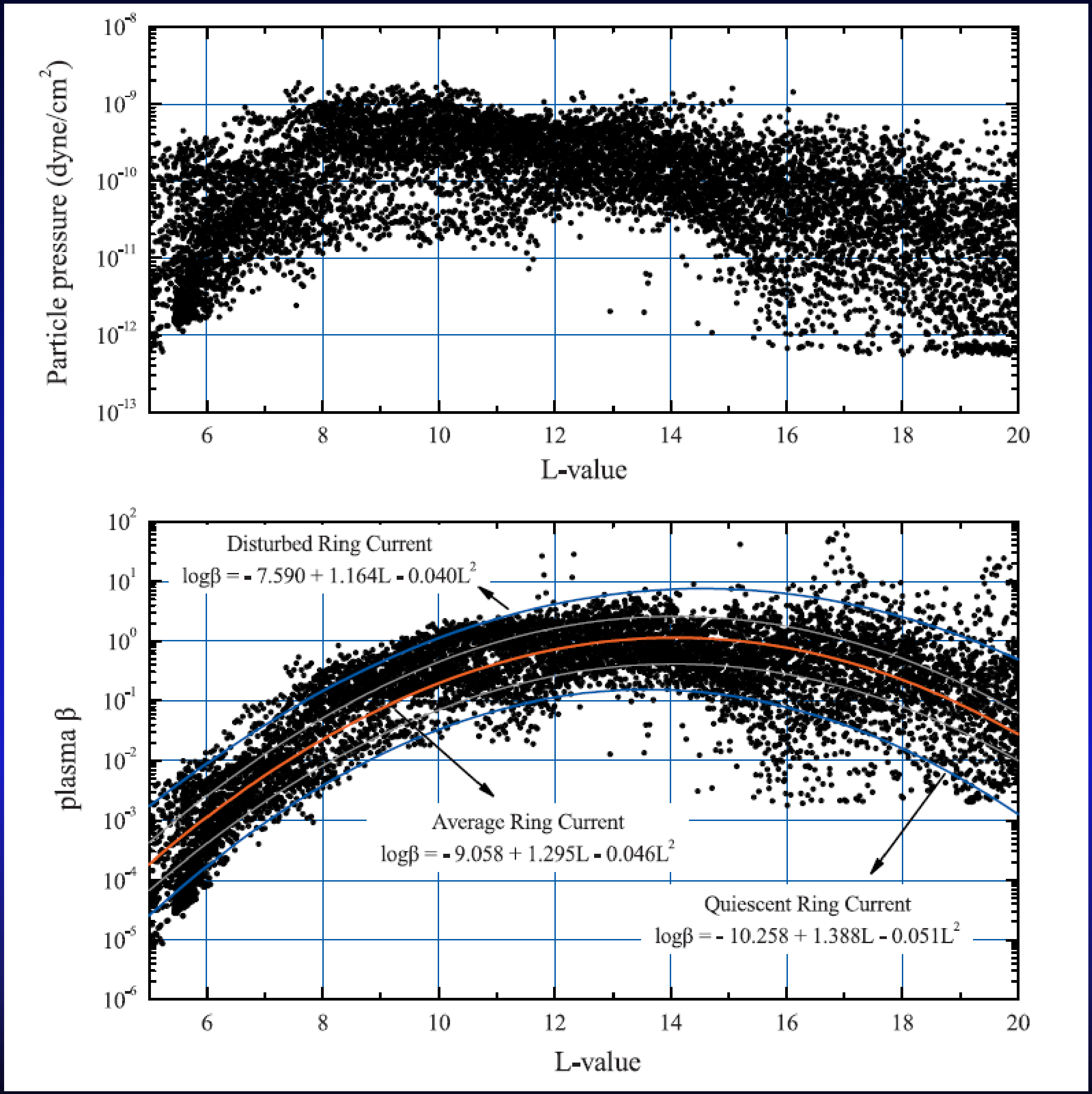
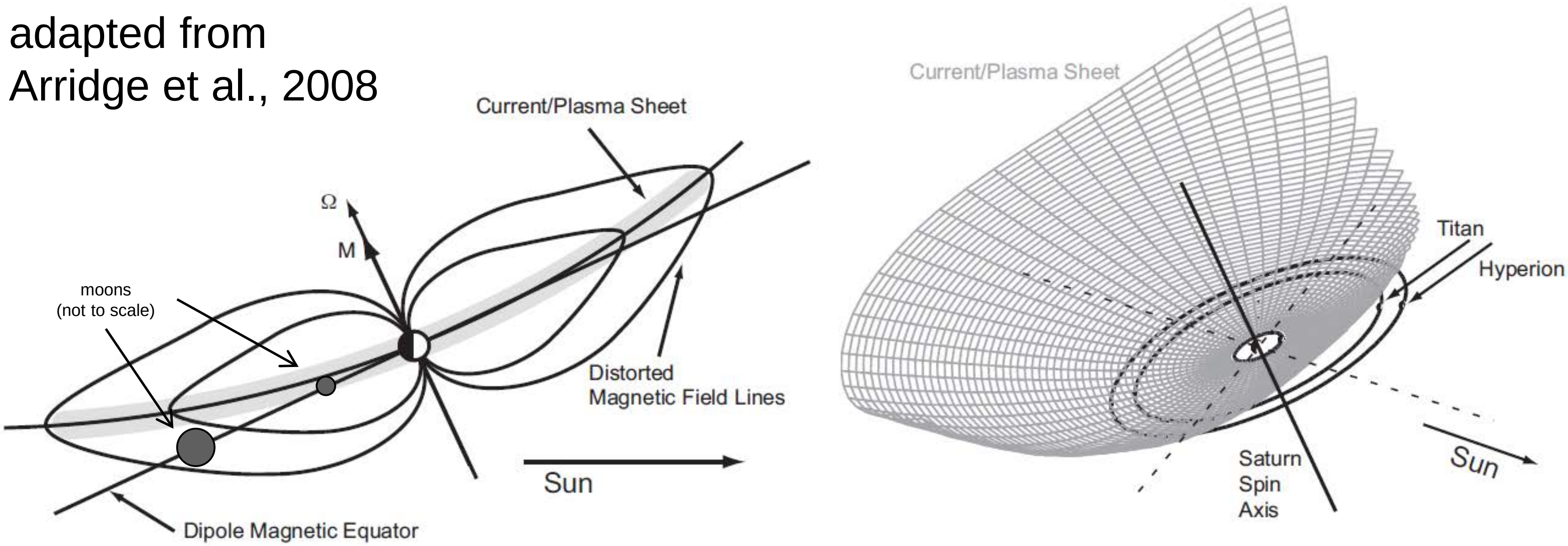


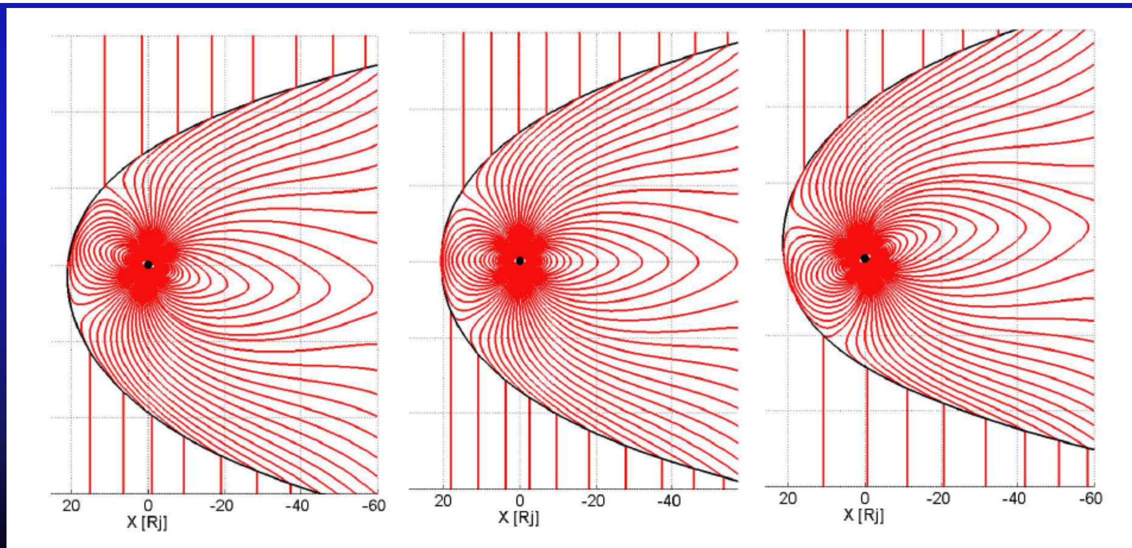
Saturn‘s middle magnetosphere is a high beta plasma
hot plasma is dominating that region

(plasma beta= particle pressure / magnetic pressure)

Shape of Saturnian plasma disk



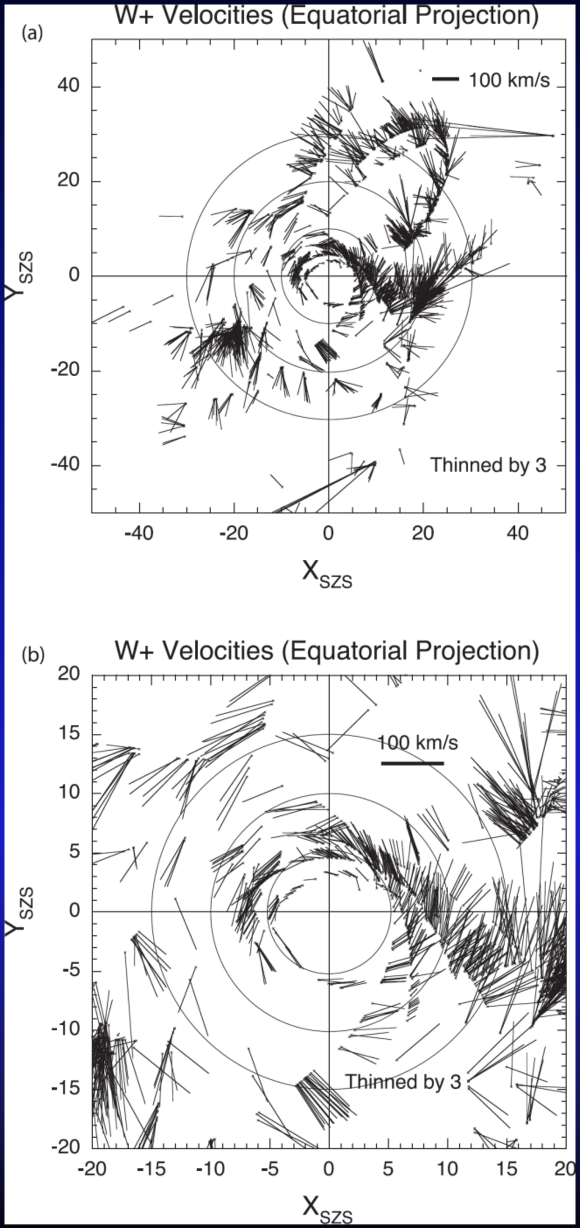
adapted from
Arridge et al., 2008



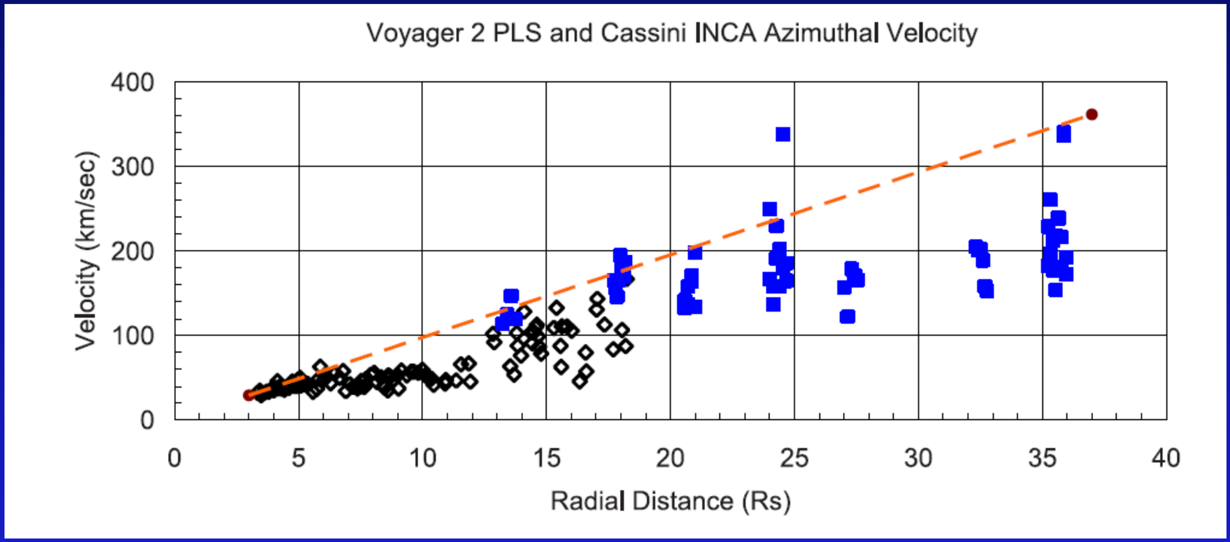
Gombosi et al., 2009

transport processes
global flow parameters,
interchange motion / particle injections
plasmoids / tail dynamics

Global flow pattern in Saturn‘s magnetosphere
Cassini CAPS + MIMI results

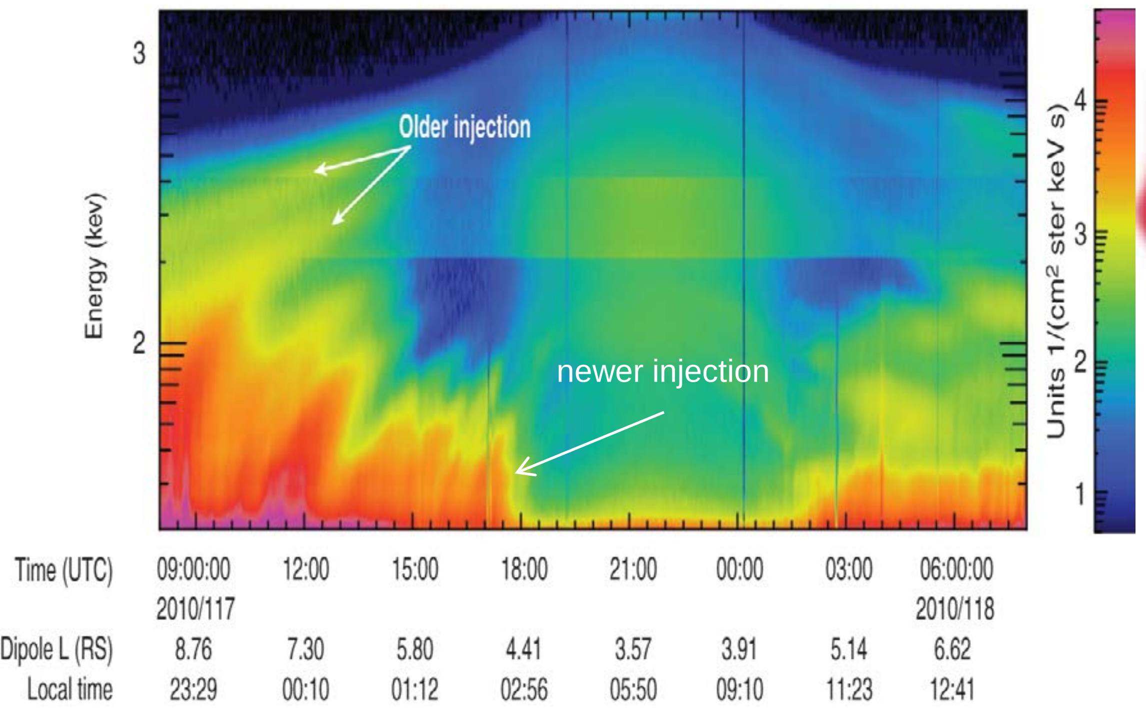


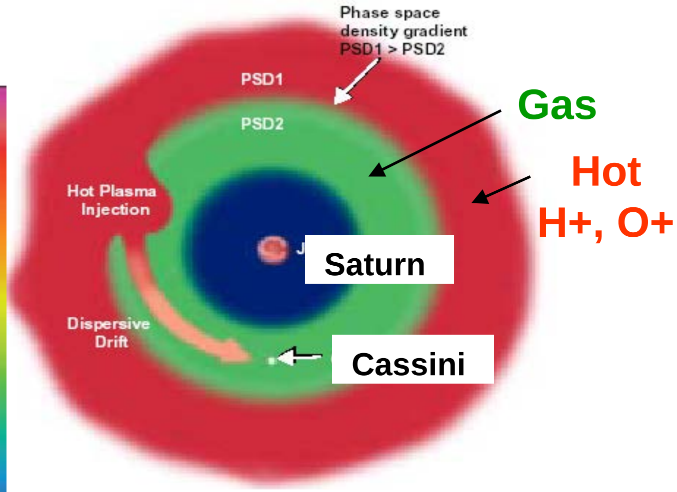
Thomsen
et al, 2010

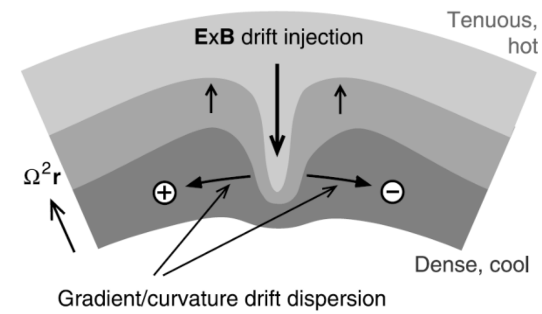


Kane et al,
2008

Saturn's dynamic magnetosphere
interchange and Injection events
(Hill et al. 2008, Mauk et al 2005)



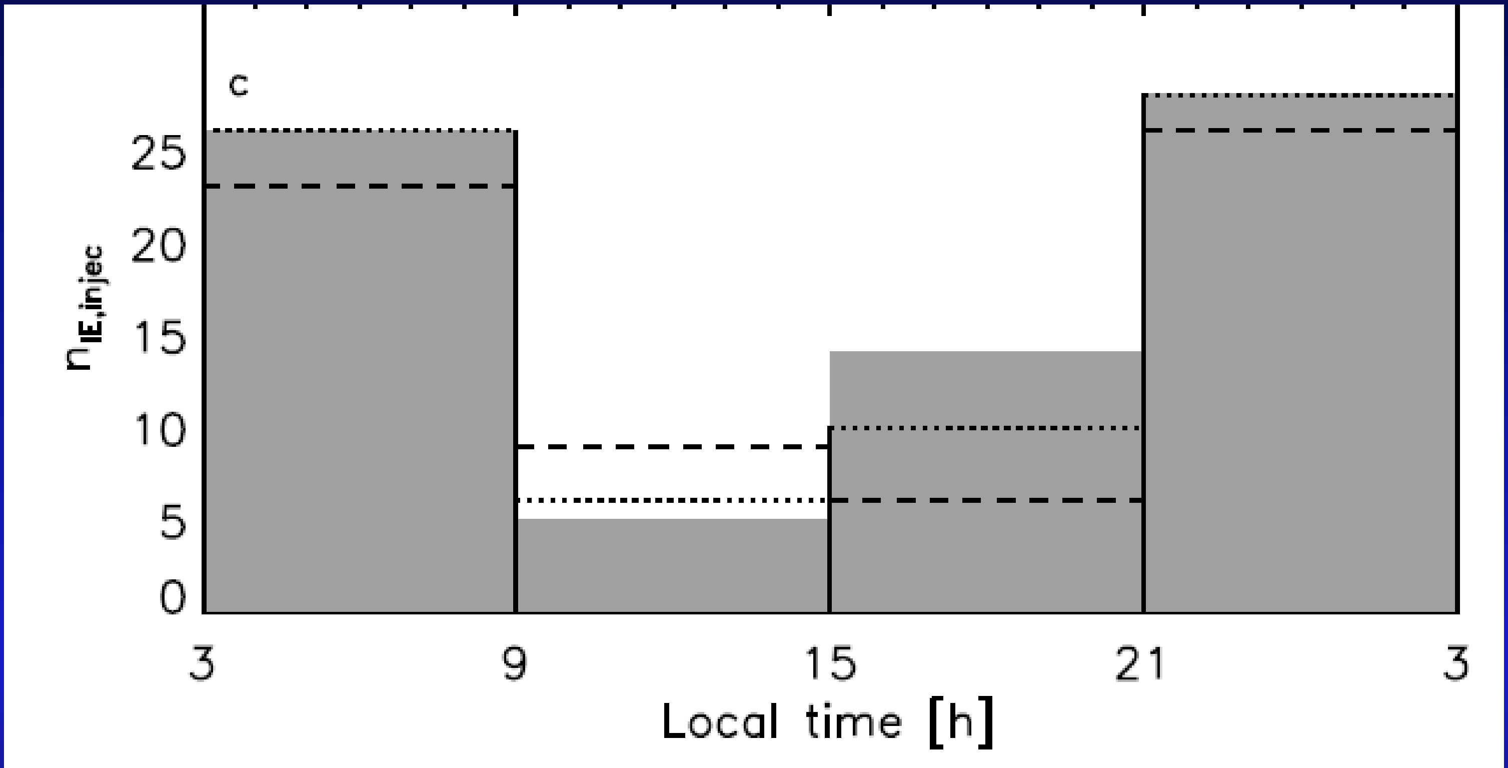




- **Charged particles are injected into neutral gas in the inner magnetosphere.**
- **Injected particles drift around the planet and show energy-time dispersion**

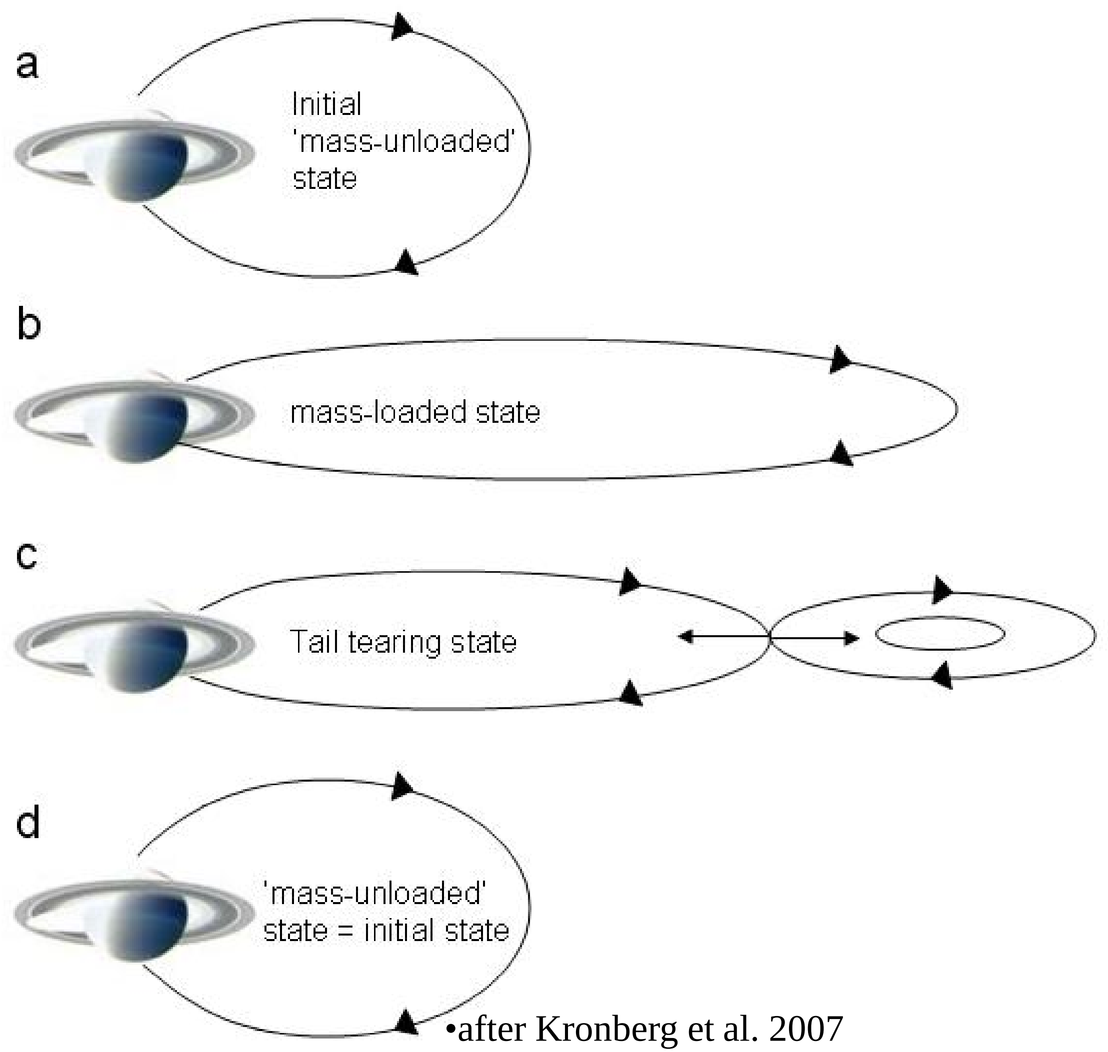
Statistical distribution of injection events

Cassini MIMI results (Müller et al, 2010)



more abundant in night sector, consistent with ENA brightening

Magnetotail dynamics



•after Kronberg et al. 2007

All loaded magnetospheres have a natural mass loading rhythm that - in the absence of external or internal variability - produce a natural clocklike behaviour

(Rymer et al, 2011)

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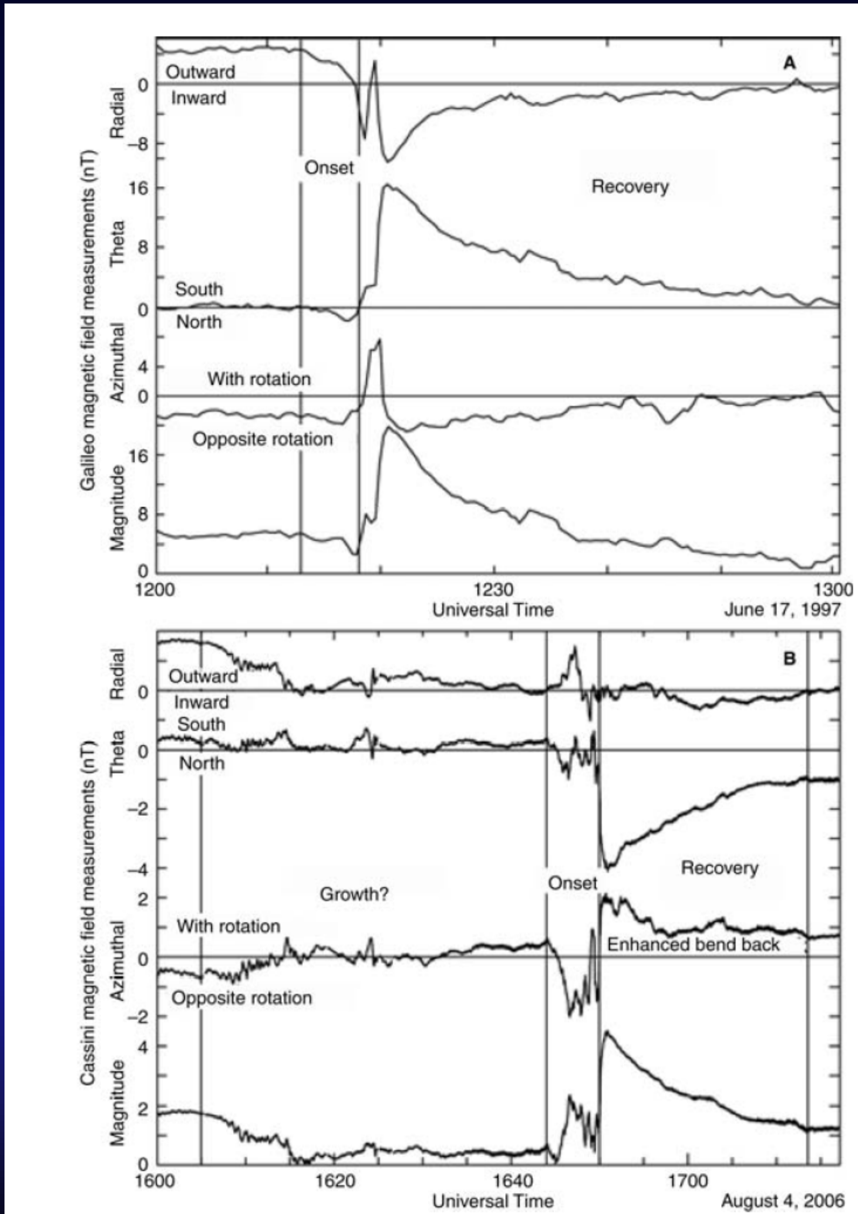
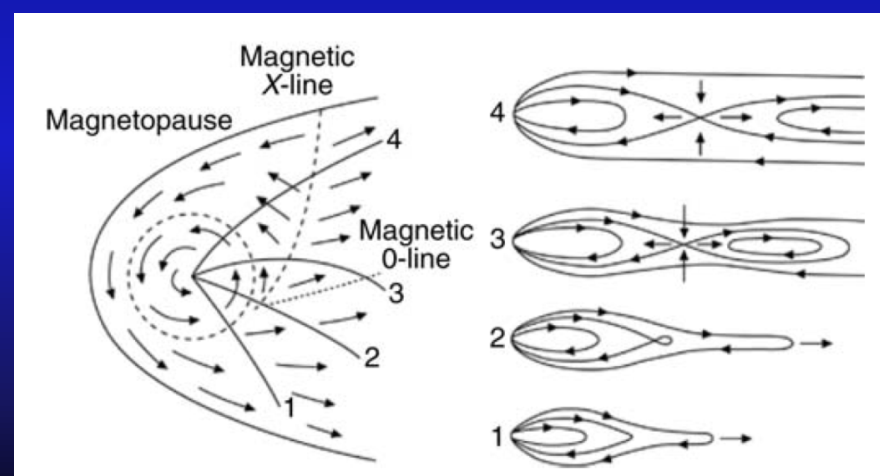
Magnetotail dynamics

Cassini MAG results (Jackman et al, 2007)



Plasmoids have been observed in bi-polar signatures of the magnetic field N-S- component

fits picture of Vasyliunas (1983)



Aurora / open-closed field line boundary

Open-closed field line boundary

Cassini RWPS+MIMI+MAG (Gurnett et al. GRL 2010)

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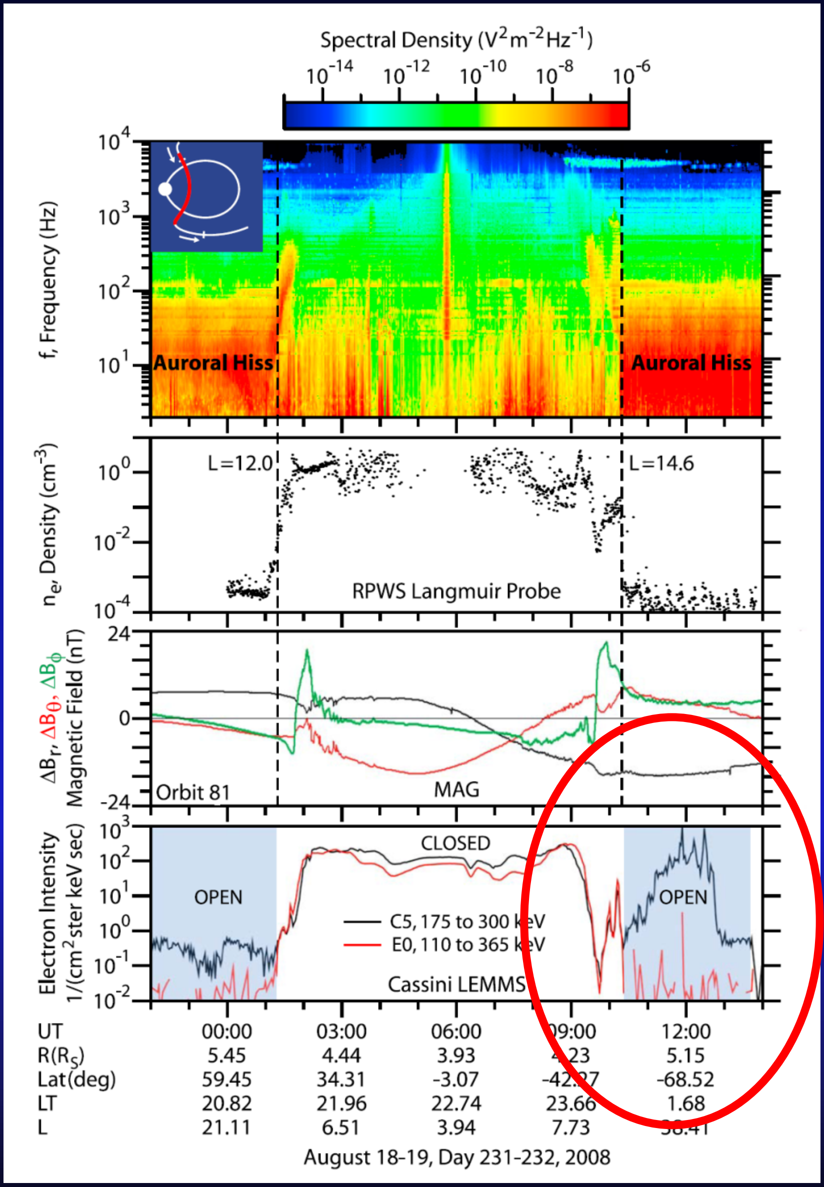


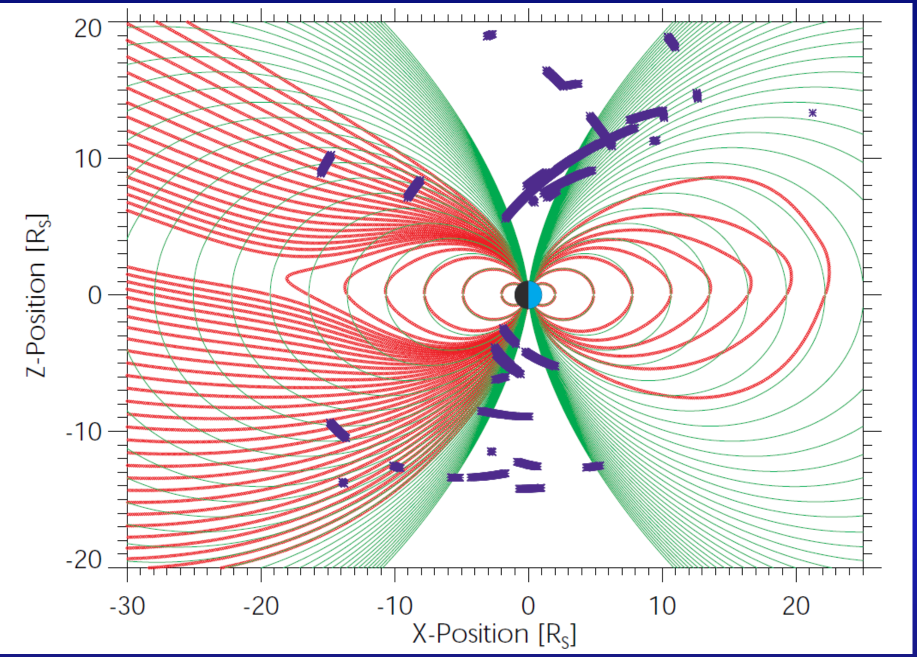
Indications for open-closed field line boundary:

- **low-energy electron density drop**
- **auroral hiss**
- **ratio of diff. intensities from field-aligned energetic electrons with the same energy but oppositie directions is a proxy of open-closed field line configuration:**

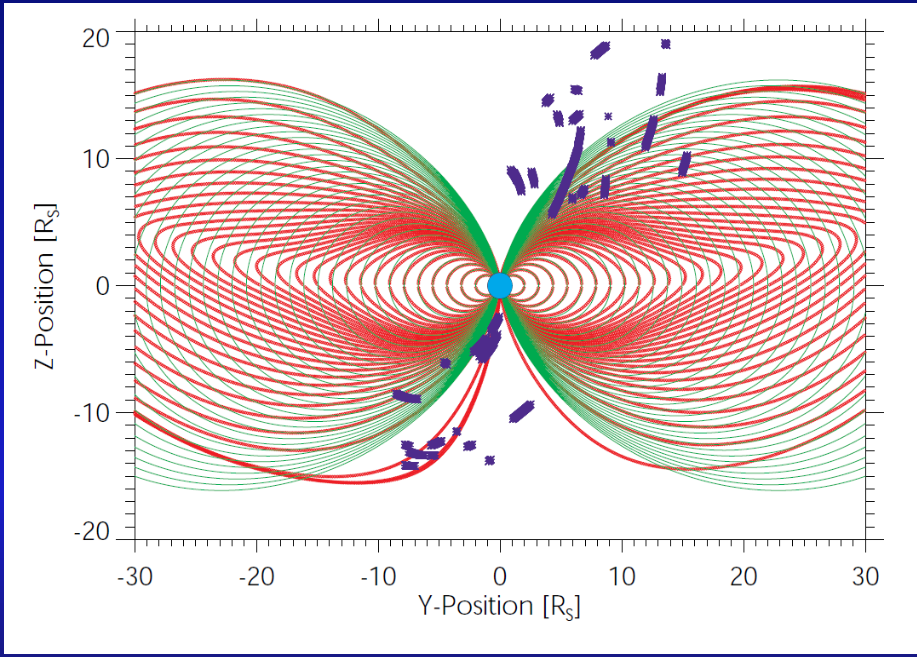
ratio = 1 (CLOSED)
ratio ≠ 1 (OPEN)

Locations of open field lines in Saturn‘s magnetosphere using offset dipole (green) or Khurana field model (red)

noon-midnight cut



dawn-dusk cut



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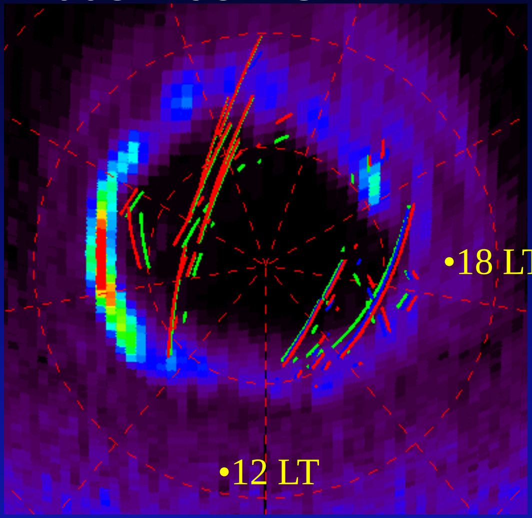
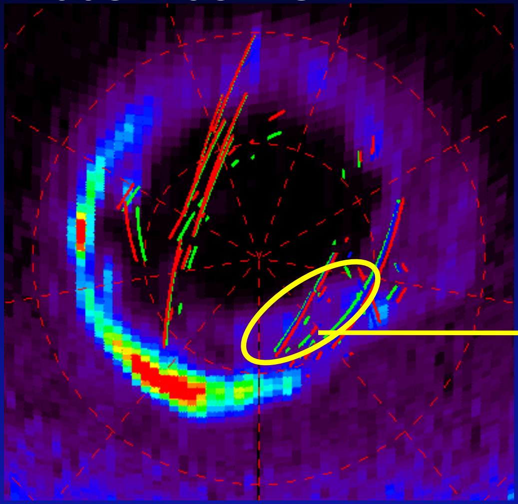
The location of the main ring of emission varies, but mainly the tracing is poleward of the emission, thus on open field lines

•2008 195 NORTH



•2008 195 NORTH

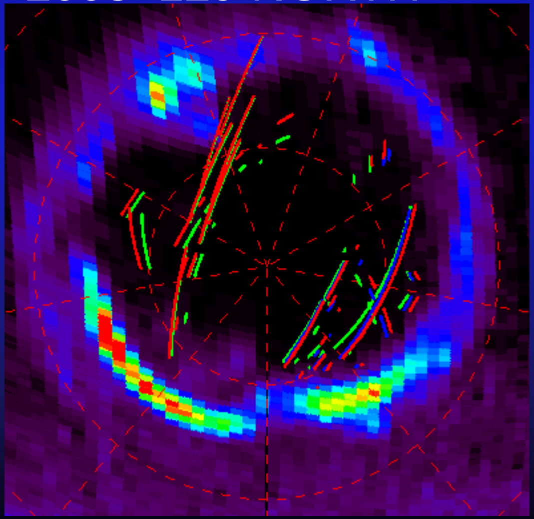


RED: Current sheet model
GREEN: dipole
BLUE: Khurana

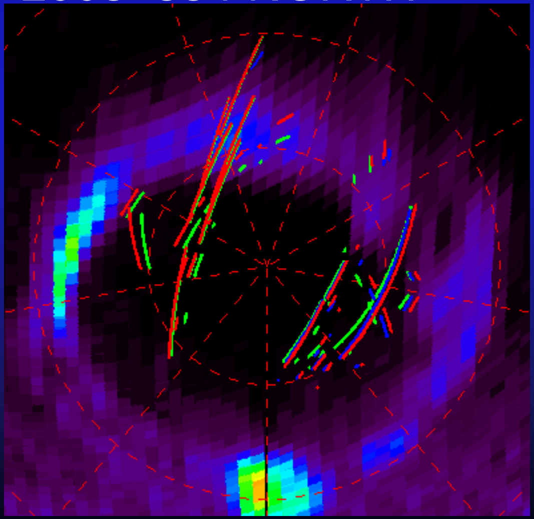
Emissions that are associated with open field lines (bifurcations: signatures of reconnection at the magnetopause, Radioti et al, submitted)

•08/07/2011

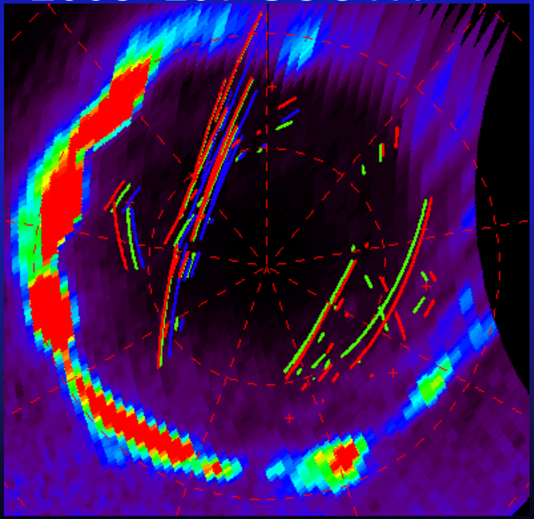
•2008 129 NORTH



•2008 334 NORTH

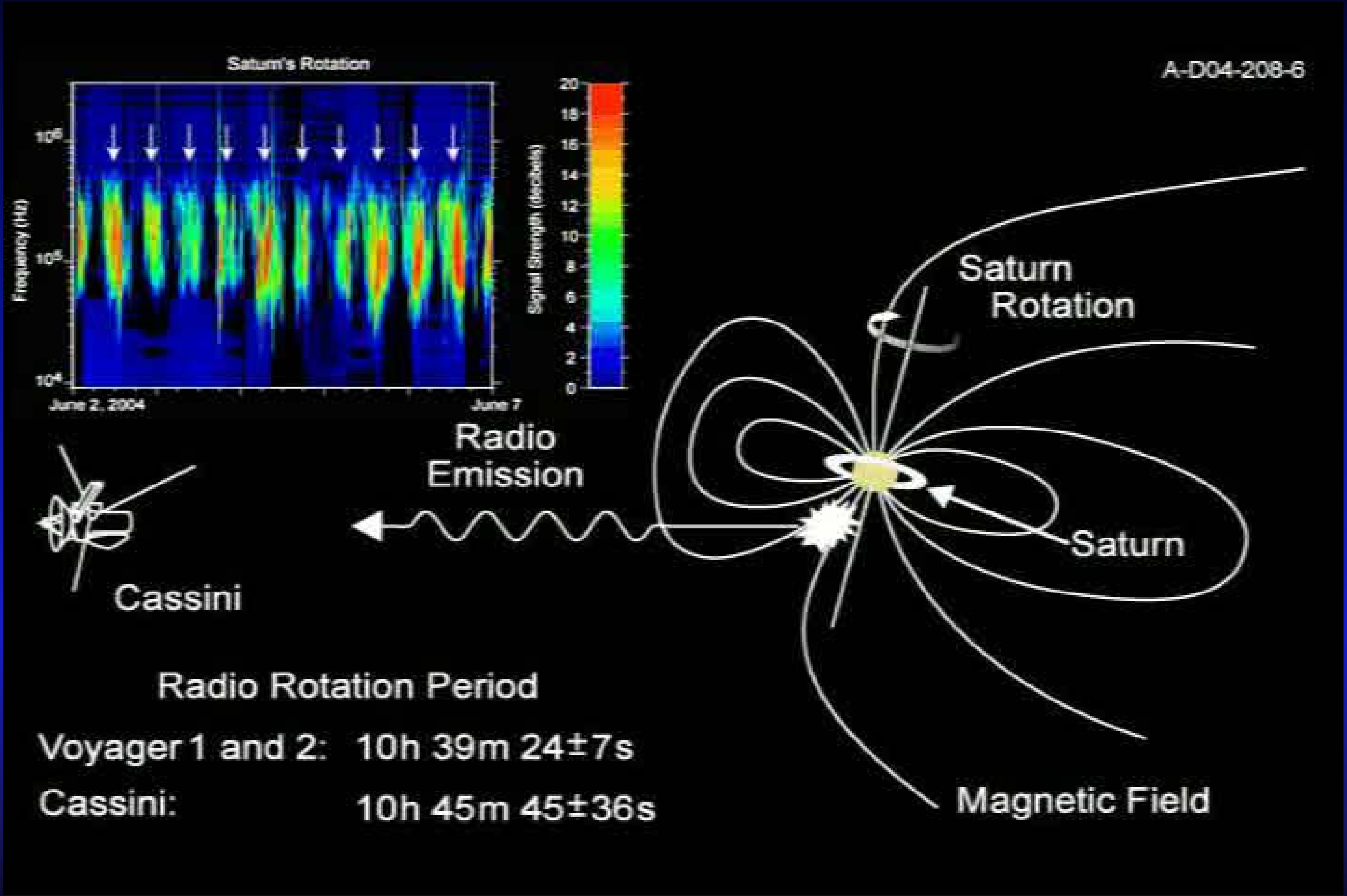


•2008 197 SOUTH



Rotational modulation / Periodicities

Periodic radio signals from Saturn's magnetosphere
Cassini RWPS results (Gurnett, et al, 2007; Kurth et al. 2008, Andrews et al. 2008)



Evidence of periodic ratational variations in the Kronian magnetosphere

* Auroral emissions:
- SKR (Gurnett et al, 05; Kurth et al, 07)
- auroral hiss (Gurnett et al, 09)
- NB emissions (Louarn et al, 07; Ye et al, 09)
- UV aurorae (Sandel et al, 81; Nichols et al, 08,10)

* Magnetic field:
- core oscillations (Espinosa & Dougherty, 00; Espinosa et al, 03; Giampieri et al, 06, Southwood & Kivelson, 07; Andrews et al, 08)
- open field lines (Provan et al, 09, Andrews et al, 10)
- magnetopause/bow shock (Clarke et al, 06,10)
- current sheet flapping (Khurana et al, 09)

* Plasma:
- cold plasma density (Gurnett et al, 07; Morooka et al, 09)
- energetic particles in the tail (Krupp et al, 05; Carbary 07a,b, Burch et al, 08; Khurana et al, 09)
- quasi-periodic plasmoid release (Burch et al, 08, Jackman et al, 09)
- energetic neutral atoms at 15-20Rs (Paranicas et al, 05; Krimigis et al, 07; Carbary et al, 08, Mitchell et al, 09)

(nicely summarized by L. Lamy at MOP 2011)

Periodic radio signals from Saturn's magnetosphere
Cassini RWPS results (Gurnett, et al, 2010)

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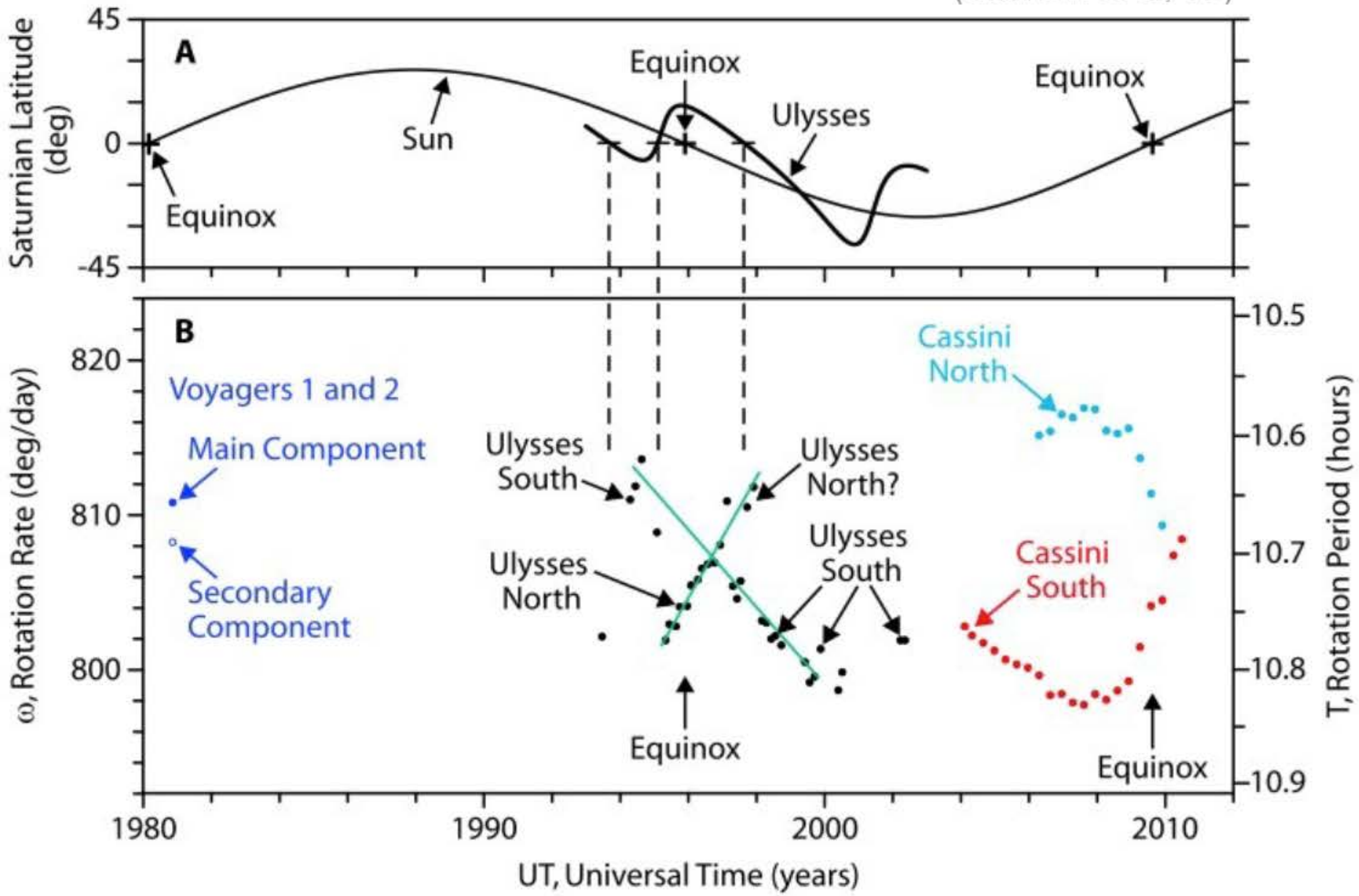
* Long-term (yearly) variability :
- S/N periods vary by ~1% over years
- S period roughly correlated with planet's inclination

(Gurnett et al, 10)



Models to explain the periodicities in Saturn‘s magnetosphere

- **Magnetic/plasma anomaly (Galopeau et al, 91; Galopeau and Zarka, 92; Carbary et al, 07; Khurana et al, 09)**
  - **corotating high latitude non-dipolar anomaly**
  - **corotating inner longitudinal plasma or pressure anomaly**
- **Camshaft model (Espinosa et al, 03)**
  - **equatorial rotating magnetic perturbation propagating via MHD waves**
- **Centrifugally-driven instability (Goldreich and Farmer, 07; Gurnett et al, 07)**
  - **outflow longitude sector**
- **Variabilities in the system (Gurnett et al, 09; Zarka et al., 07)**
  - **seasonal illumination**
  - **solar wind driven current systems**
- **Partial ring current (Mitchell et al, submitted; Brandt et al, 10)**
  - **corotating ionospheric clock enforcing cold plasma loading**
- **Ionospheric Vortex (Jia and Kivelson, submitted)**
  - **ionospheric vortical flow at southern auroral latitudes**

nicely summarized by L. Lamy at MOP 2011)

Saturn‘s Hot Plasma Explosions
(courtesy P. Brandt)
Cassini MIMI+RPWS results

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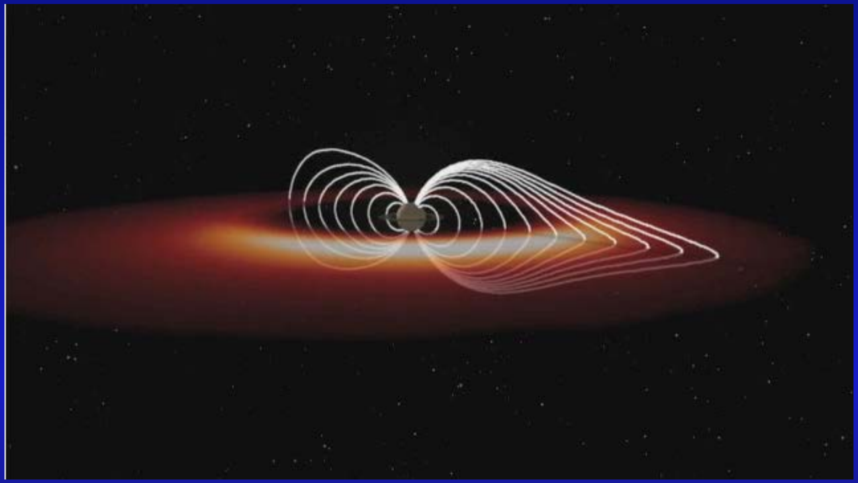
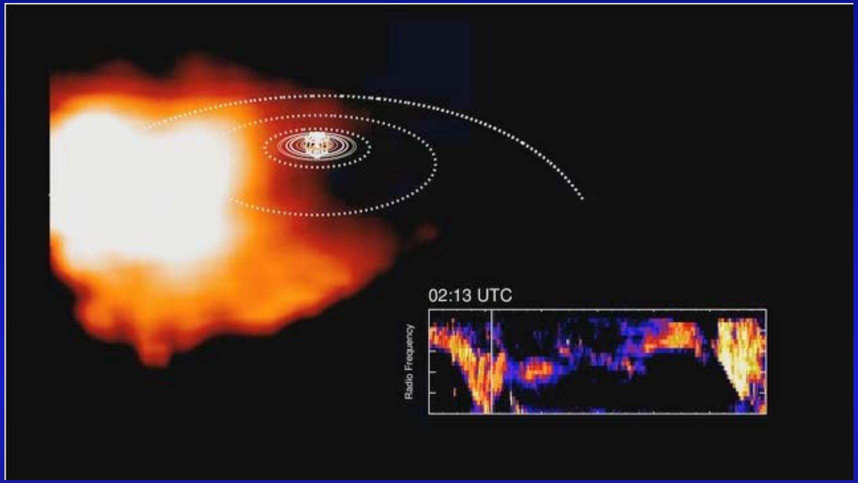
animation of plasma „explosions“

Cassini meausrements of ENA and radio emissions

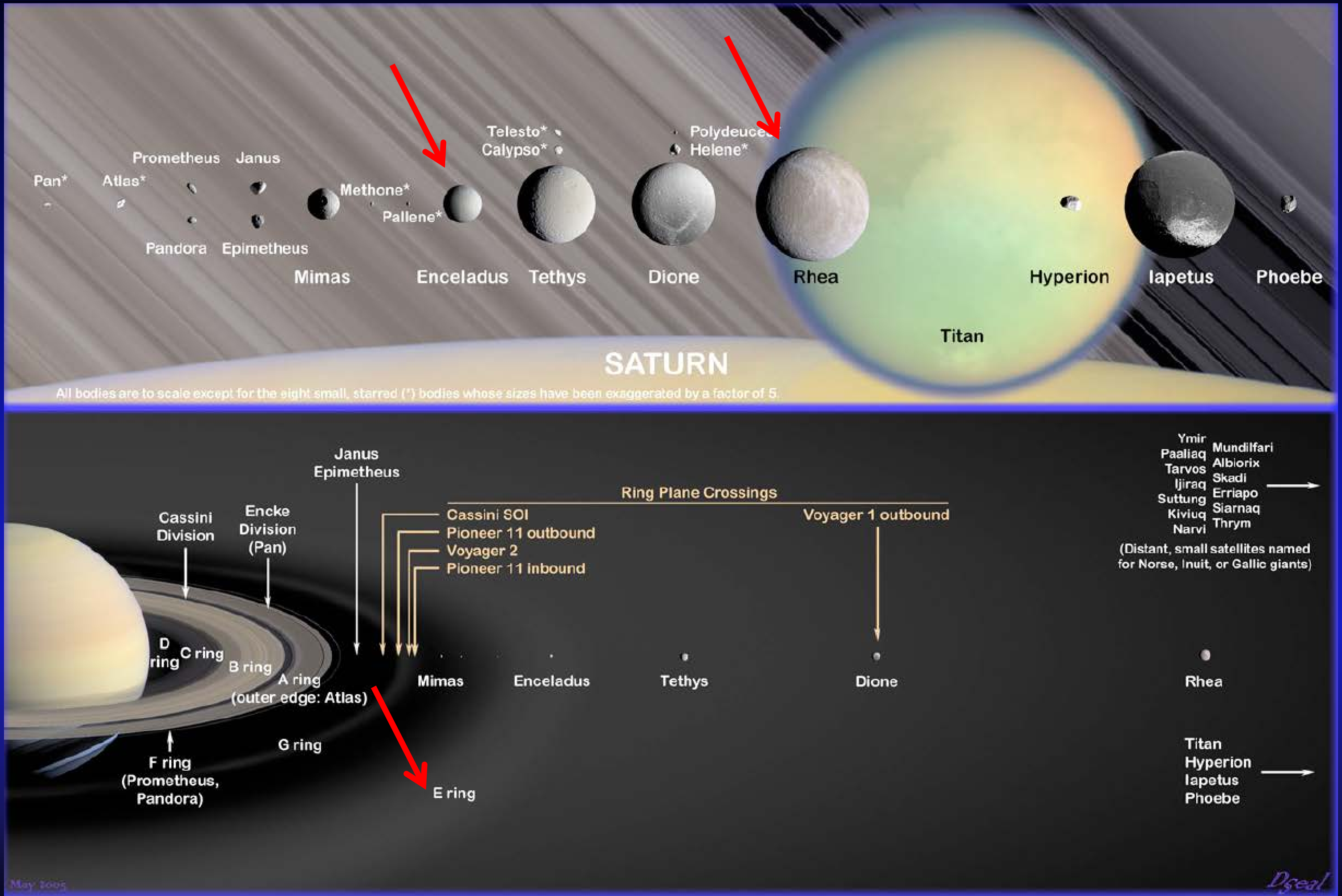




to see the movie please use the following link:
http://saturn.jpl.nasa.gov/video/videodetails/?videoID=221

Interaction of the Kronian Magnetosphere with Rings and Moons

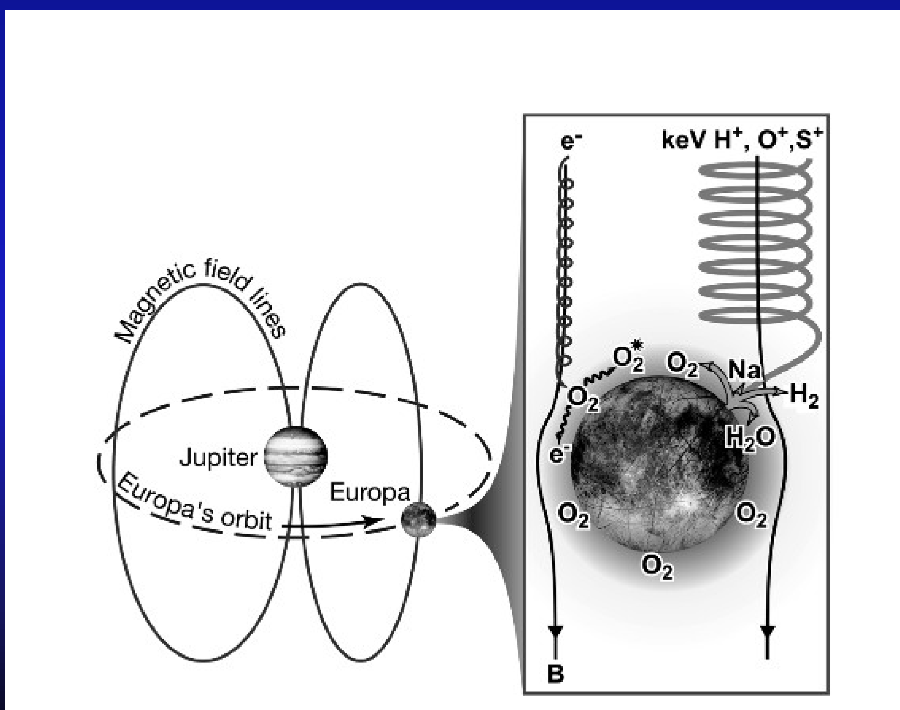
Moons and rings in the Saturnian System



Moon magnetosphere interactions

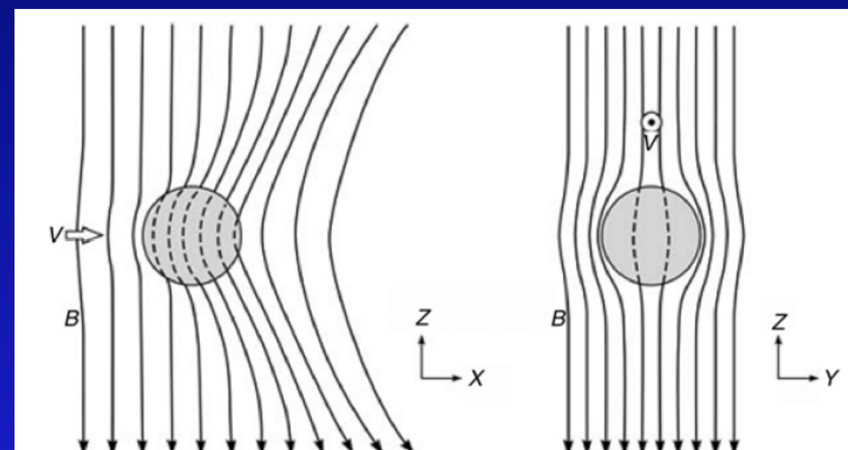
Sketch of particle trapping in a magnetosphere and the precipitation of particles onto a moon (Johnson et al. 2004)

sputtering of surface material

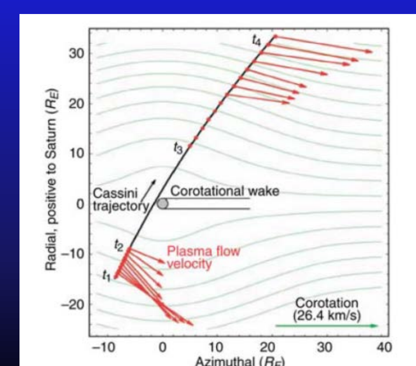


Field line draping around a conducting obstacle

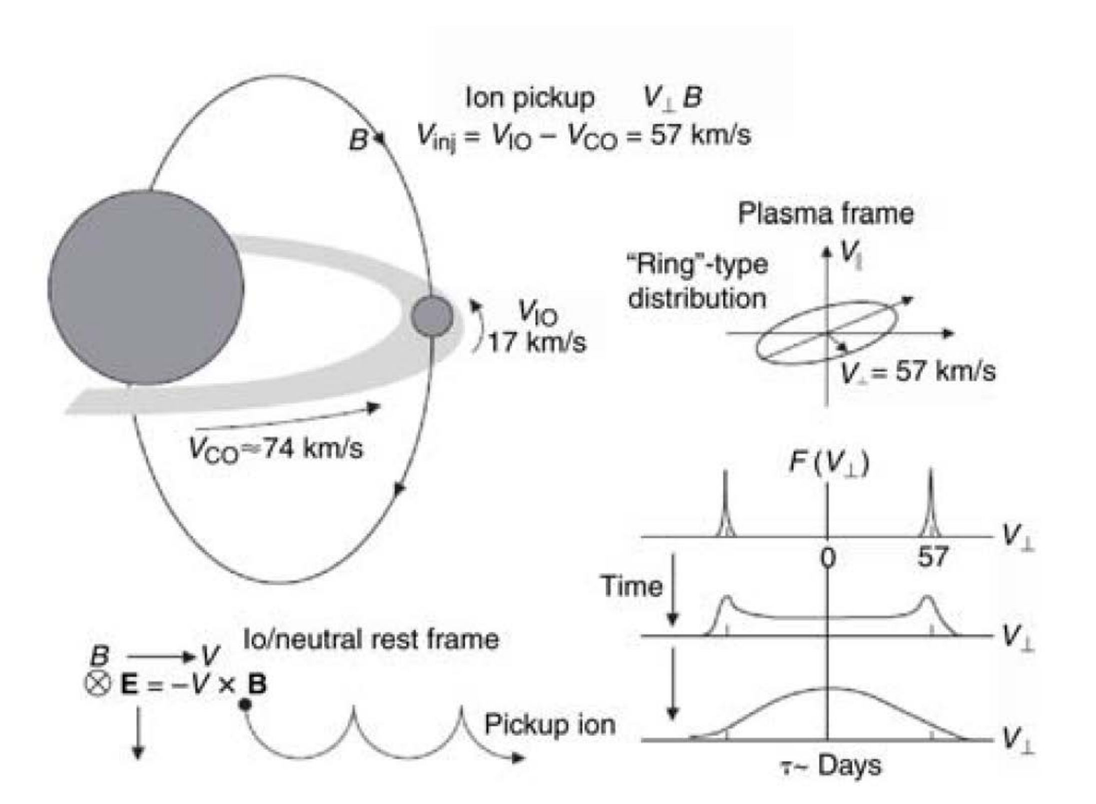
change in magnetic field direction and strength, deviation of plasma flow



Mauk et al, 2009



Moon magnetosphere interaction: Ion pick-up process (Huddleston et al., 1998)

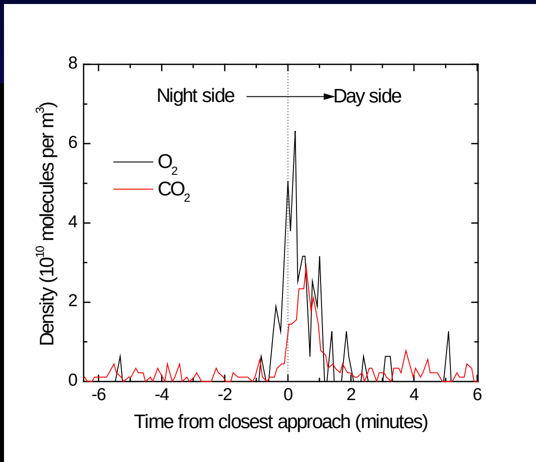


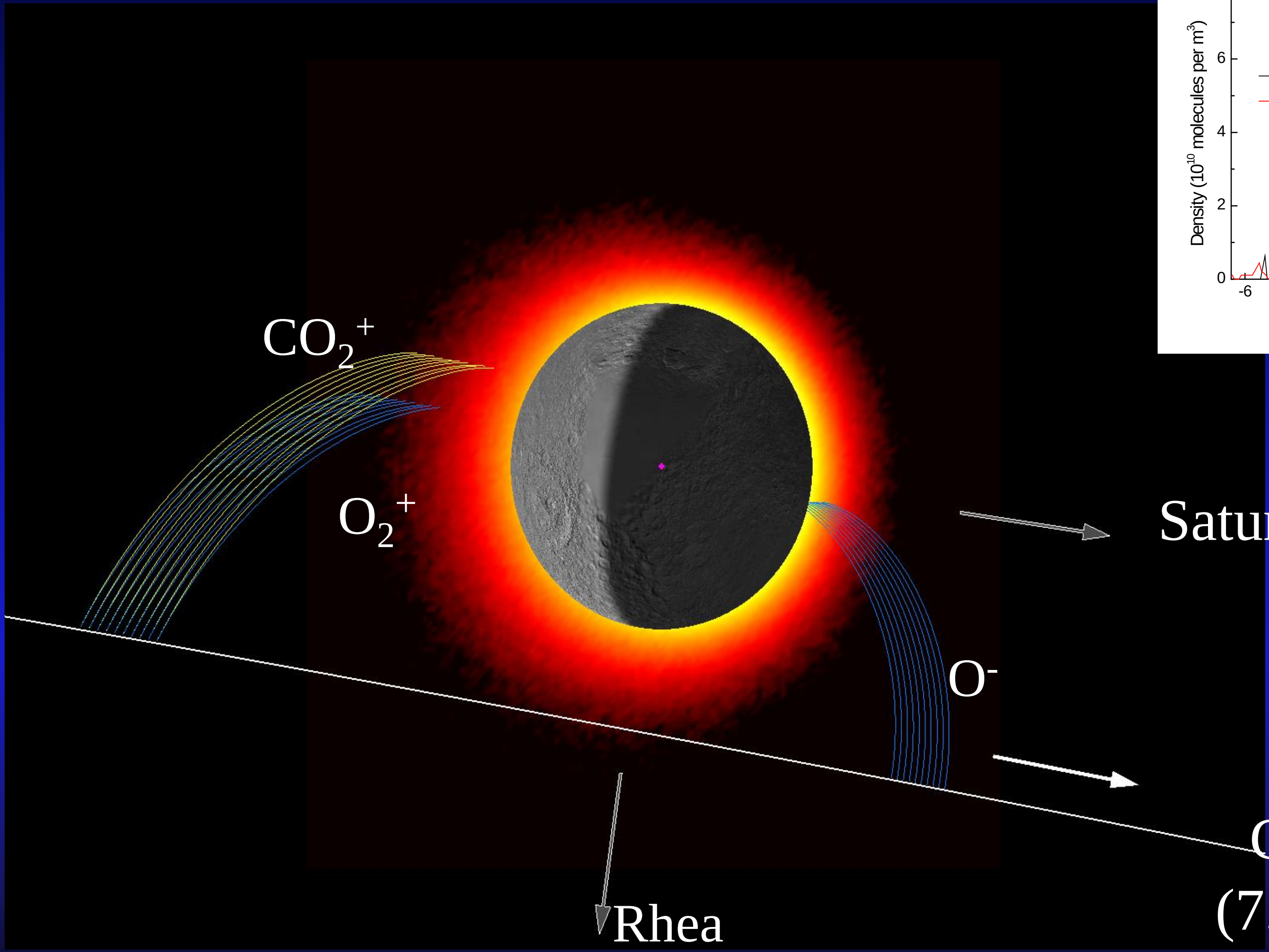
Neutrals that get suddenly ionized perform a cycloidal motion perpendicular to E and B

Accelerated Pick-up ions can be measured

Discovery of Rhea's exosphere

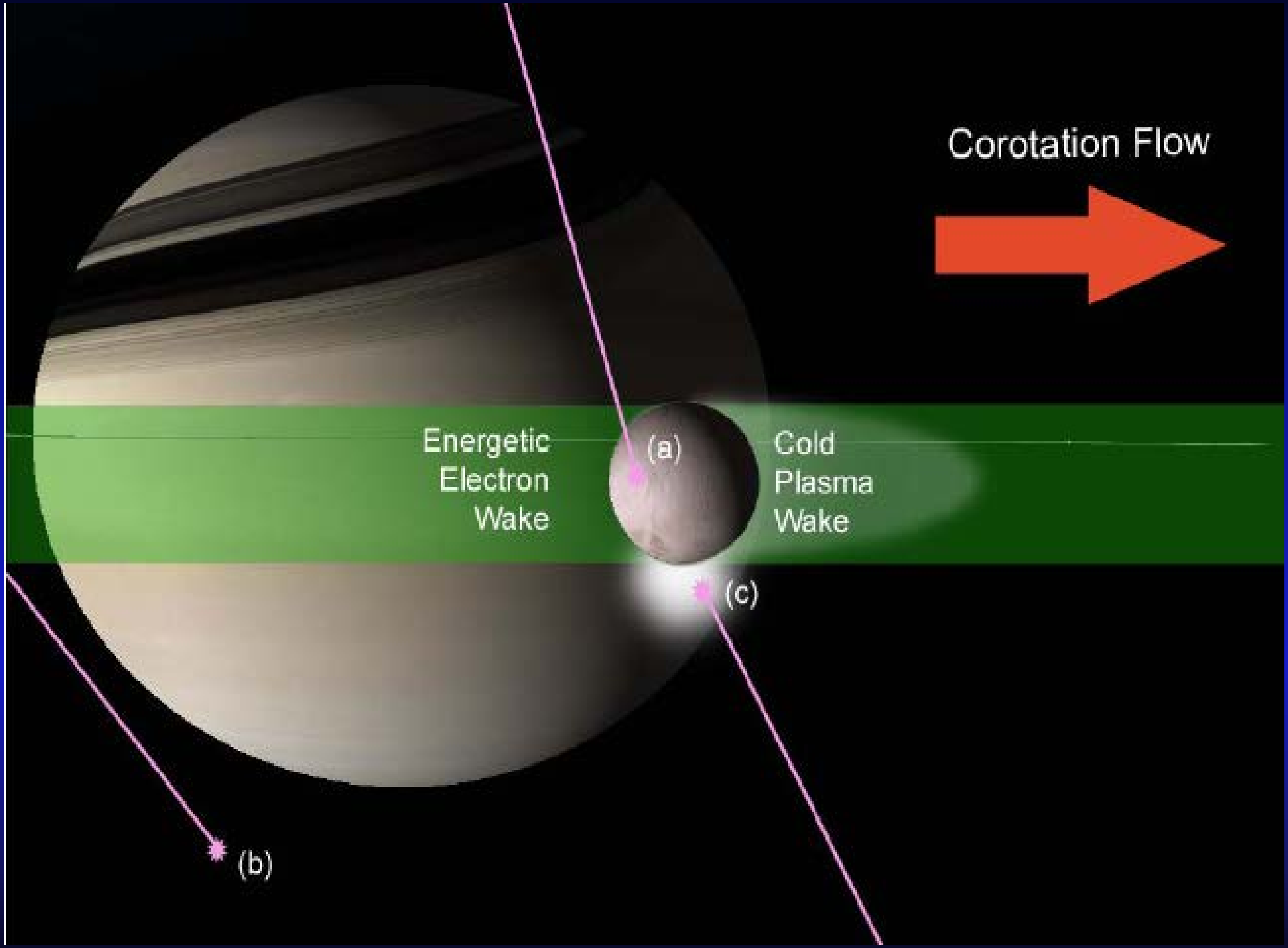
Rhea Encounter 26 November, 2005
Cassini CAPS+INMS results





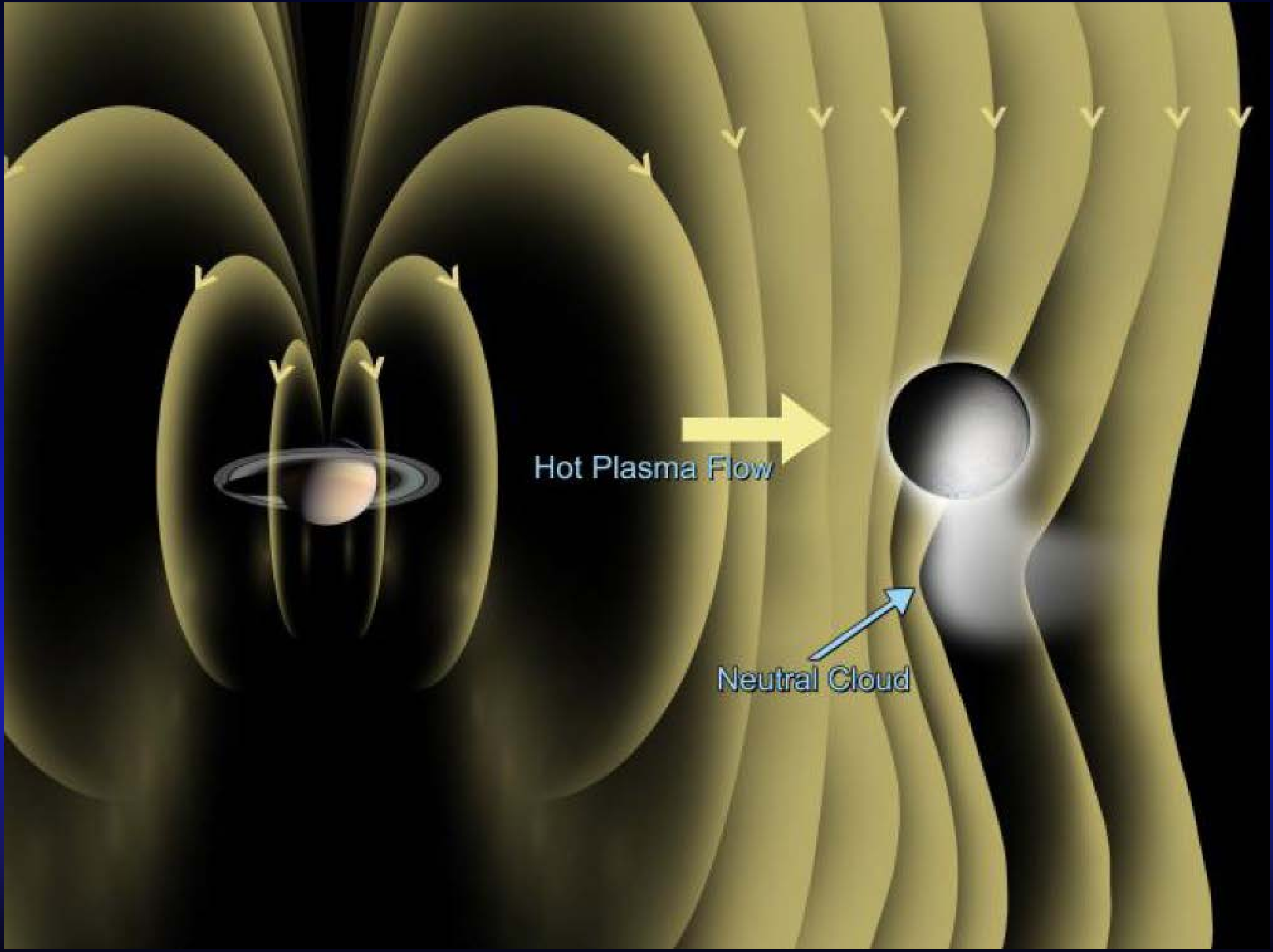
Interaction of magnetospheric plasma with the moon: loss of particles

Max-Planck-Institut für Sonnensystemforschung



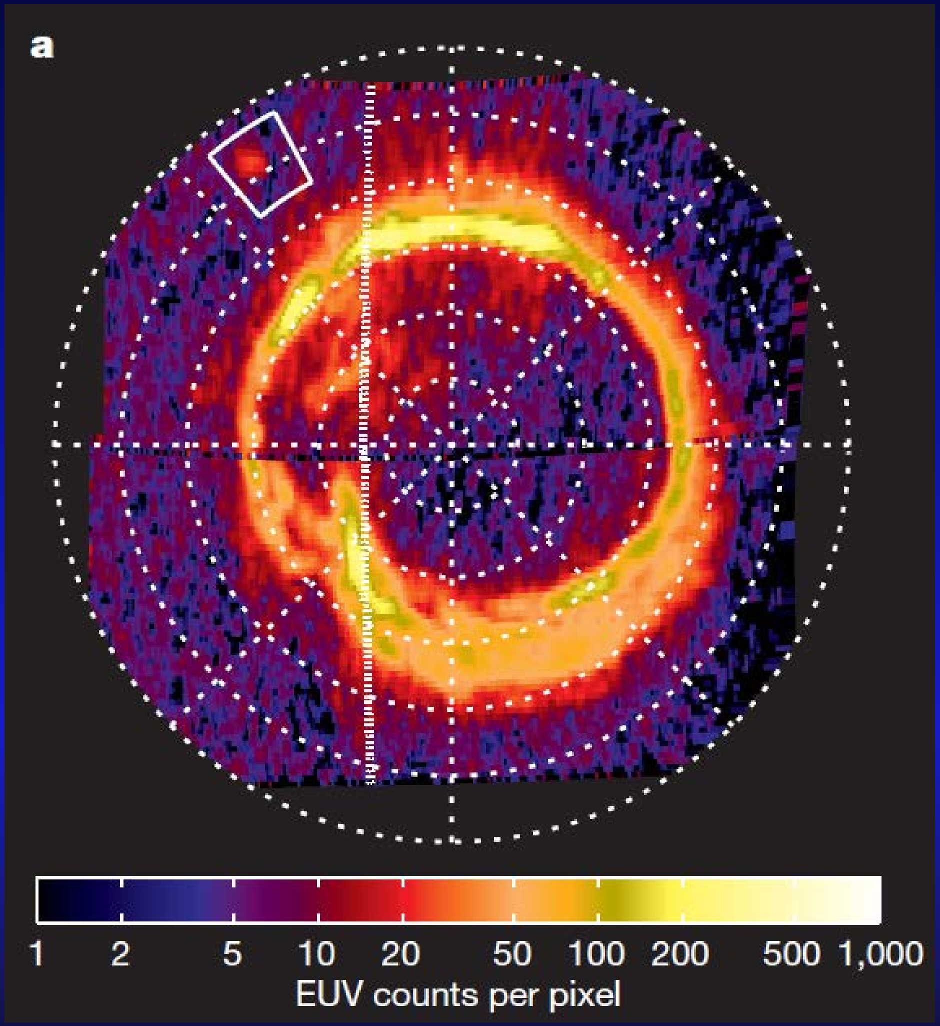
Discovery of the Enceladus plume

Cassini MAG results (Dougherty et al., 2006)



Discovery of the Enceladus footprint in Saturn's atmosphere

Max-Planck-Institut für Sonnensystemforschung



Pryor, Rymer, et al., 2011, Nature

Enceladus- Eruptions from ice volcanoes

Cassini CDA results (Postberg, 2011)

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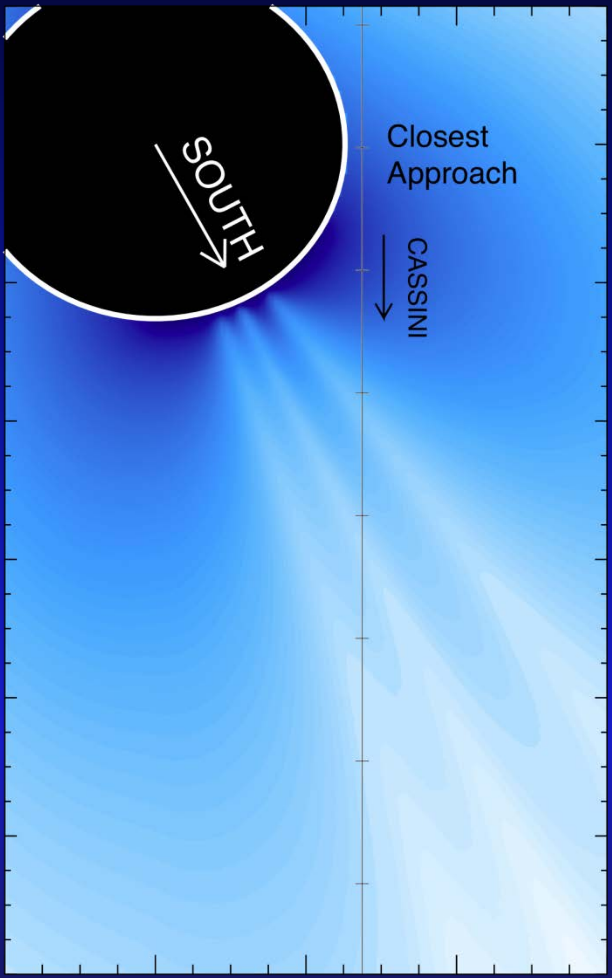


•Darker blue indicates more salt-rich grains.

• Cassini's Cosmic Dust Analyze (CDA) has made the first in-situ measurements of the composition and structure of freshly ejected ice particles from Enceladus' plume and high-speed jets

• There are two sources of ice grains from Enceladus' south pole:

- High speed jets eject mostly small pure ice grains far out into space forming the E-ring *(condensed ocean vapor)*

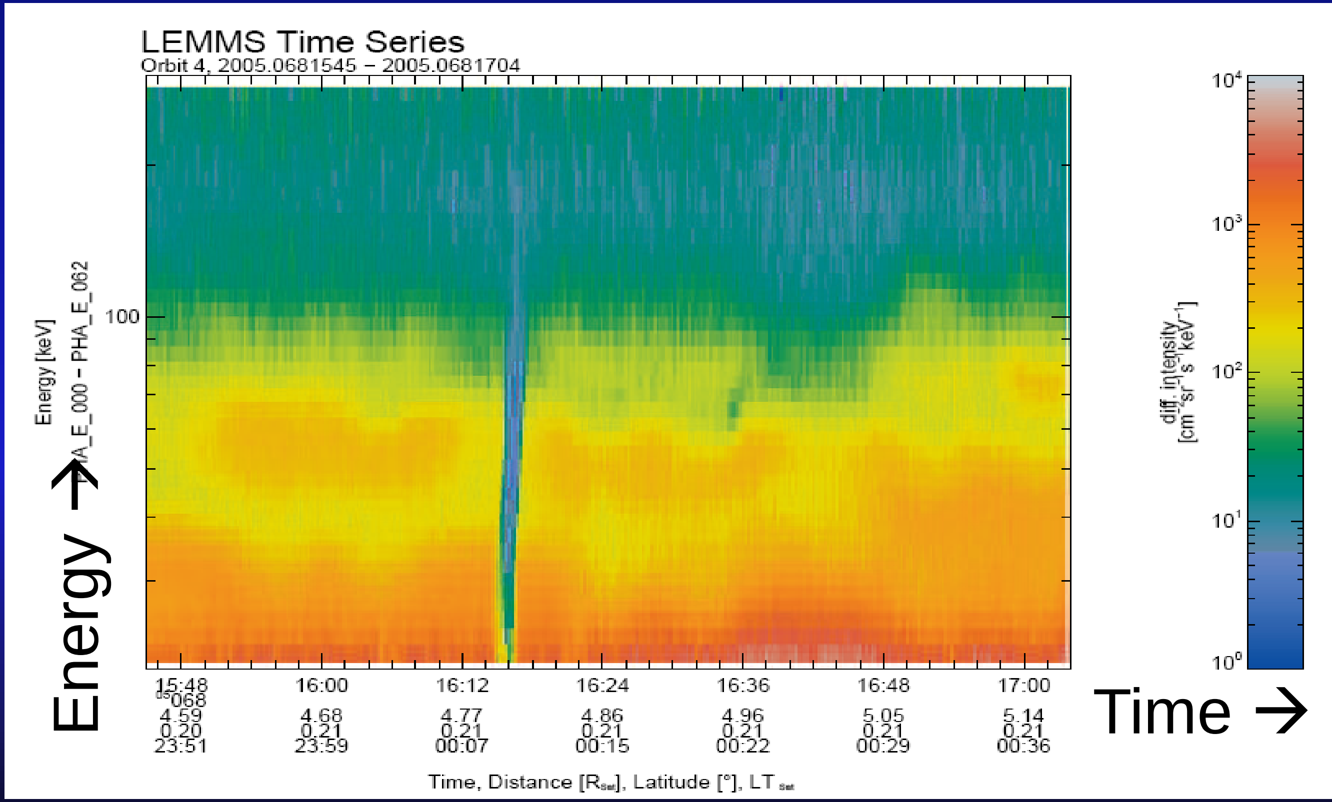
- The more diffuse plume produces bigger, mostly salt-rich ice grains with ocean-like composition *(frozen ocean spray)*

• These results are the strongest evidence to date for liquid water in Enceladus' interior.

Energetic electron microsignatures Cassini MIMI results

Andriopoulou et al, 2011; Roussos et al, 2011

- Energetic particle dropouts in the particle fluxes caused by electron absorptions from the icy moons
- Narrow profiles in the vicinity of the moon's L-shell
- Longitude-dependent depletions



Energetic electron microsignatures: G-ring arc measurements
ISS+MIMI results (Hedman et al, 2007)

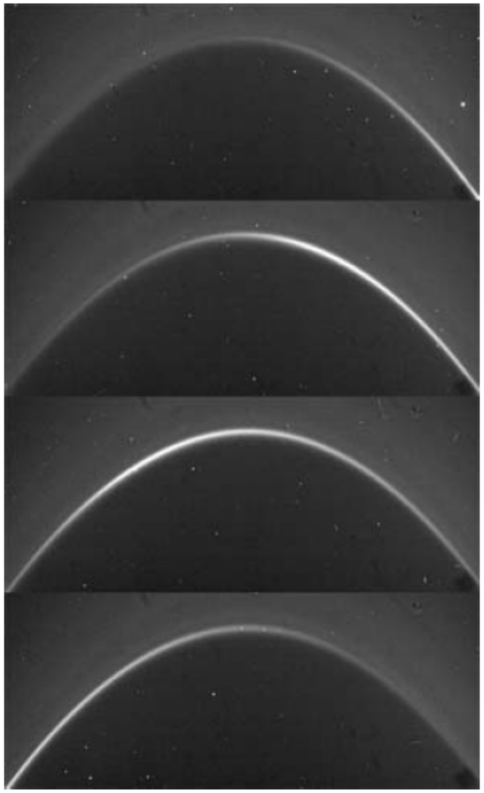


Fig. 1. Images of the G ring arc obtained on 19 September 2006 at 12:37, 13:11, 13:44, and 14:18 UTC from top to bottom. A bright arc moves from right to left through the field of view.

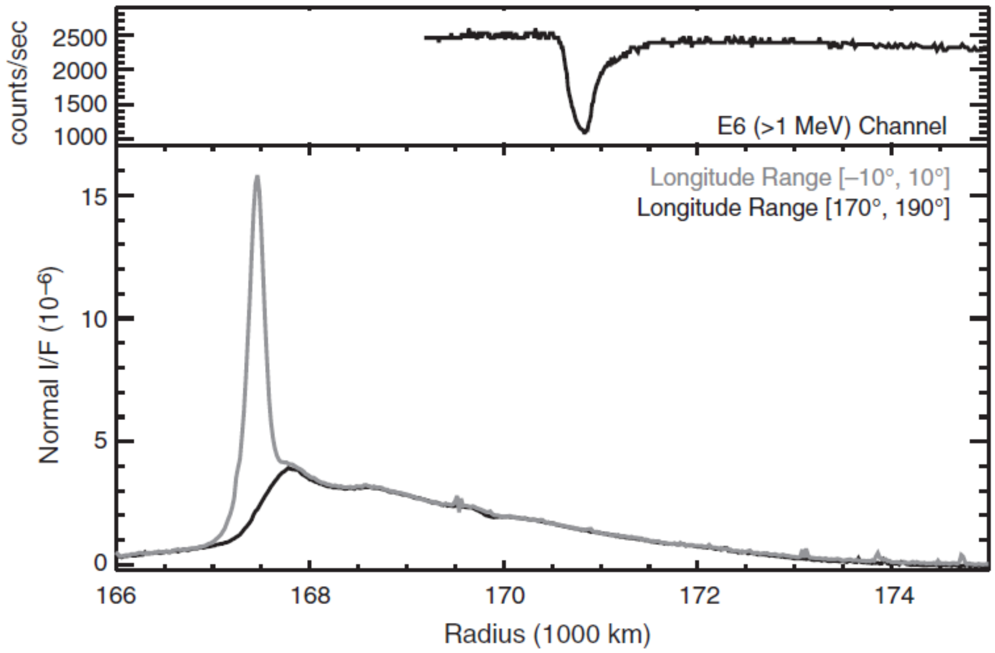


Fig. 2. (**Top**) The charged-particle flux detected by LEMMS channel E6 (*13*, *15*) during Cassini's passage over the arc region on 5 September 2005. The radial scale here corresponds to the equatorial distance of the unperturbed magnetic field lines that thread Cassini at the time of the observation. (**Bottom**) Average (offset-subtracted) radial brightness profiles of the G ring at different longitudes relative to the arc's peak based on data from 19 September 2006. The profiles through the arc (gray) and elsewhere (black) are essentially identical outside 168,000 km, whereas the arc is the sharp peak at 167,500 km in the gray profile. The absorption feature's radial width is comparable to the visible arc's. The 3000-km radial offset between the two signatures may be caused by magnetospheric effects (see SOM).

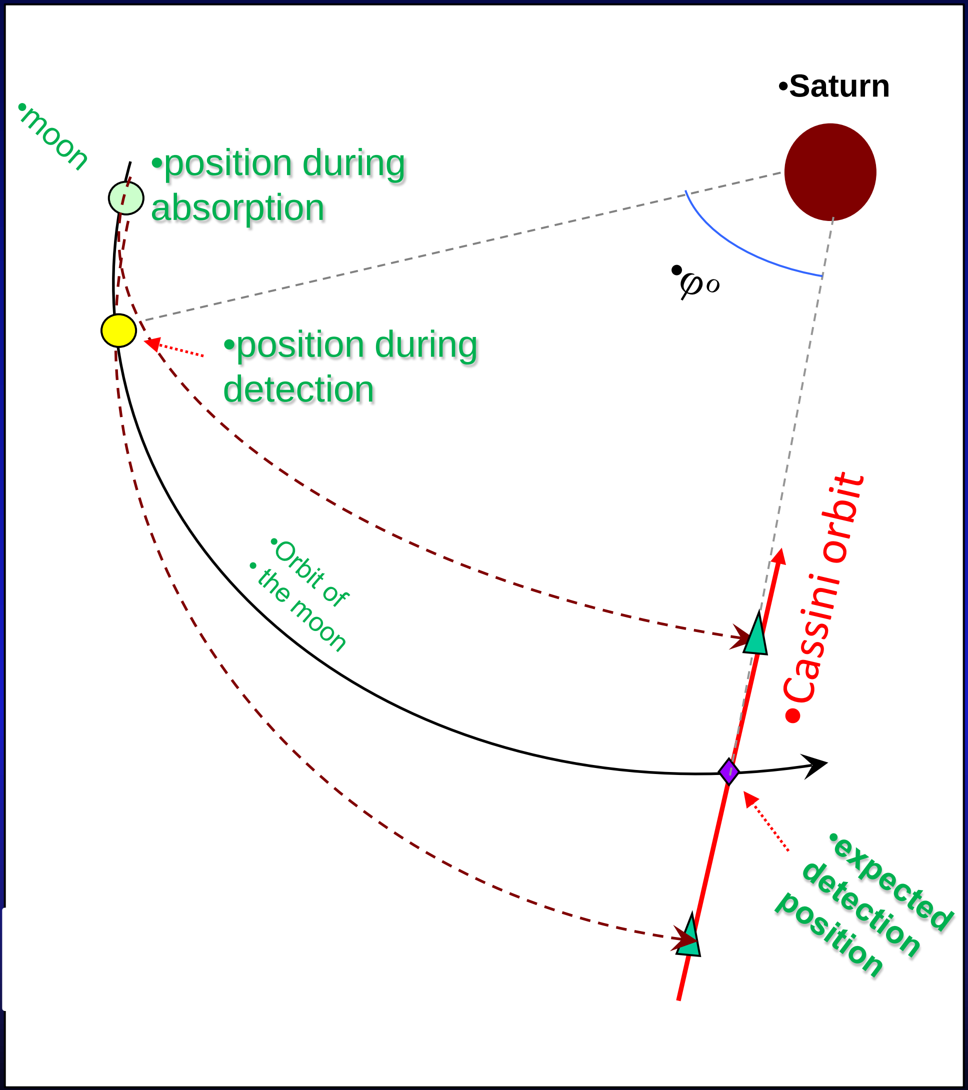
Microsignature displacements

Cassini MIMI results (Roussos et al. 2008)

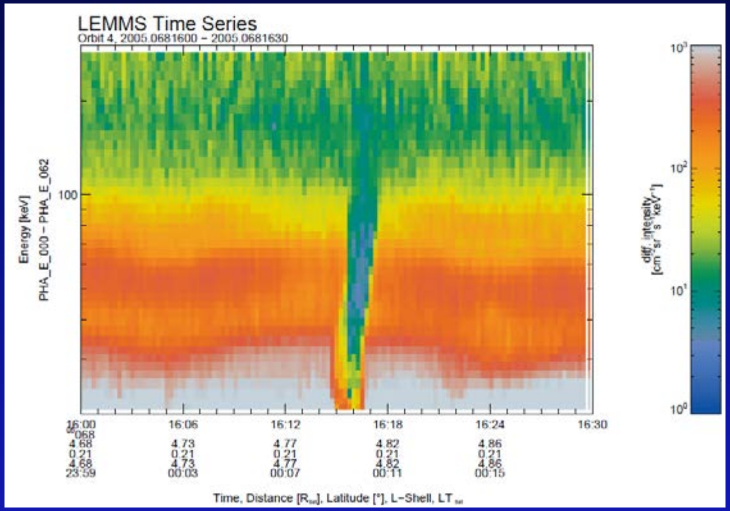
- **Sometimes offsets in the microsignature positions observed (microsignature displacements)**
- **variation in the energy dispersion of the displacements**
- **reasons of microsignature displacements could be:**

  - Insufficiency of the magnetic dipole model

  - Unidentified magnetospheric electric fields



Types of displacements

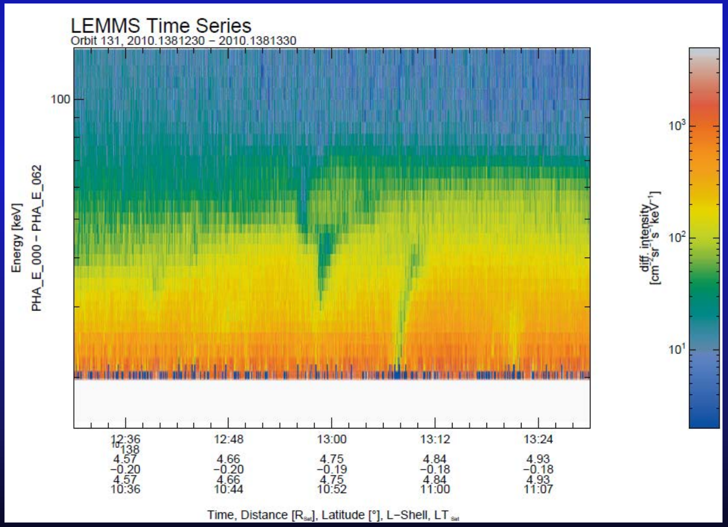


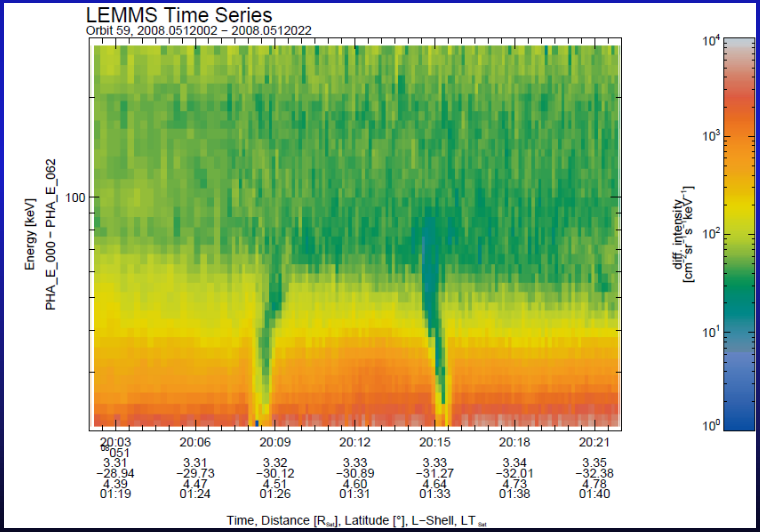
(A) ORGANIZED

(B) COMPLEX

• **Displacement origin:**

- **Dipole assumption insufficient**
- **Magnetospheric electric fields**





Summary

- Saturn‘s magnetosphere is rotationally dominated (energy source)
- The major plasma source of Saturn‘s magnetosphere is Enceladus (Enceladus plays the same role for Saturn‘s magnetosphere as Io does for Jupiter‘s magnetosphere)
- Titan does not play a major role for the magnetosphere
- Important transport mechanisms include radially outward Interchange motion of cold plasma and hot plasma injections radially inward
- Parameters from which the Saturn rotation was inferred vary in time, different models slowly merge but still differ
- Interaction of magnetospheric particles with icy moons play a more and more important role (surface weathering)
- Rhea has an tenous atmosphere
- Enceladus has a liquid ocean of water

As a reference please check:

SATURN from Cassini-Huygens
eds. Dougherty, Esposito, Krimigis
Springer Verlag, 2009

WATCH FOR NEW RESULTS !!
Thank You for your attention

Krimigis et al., Science 2005