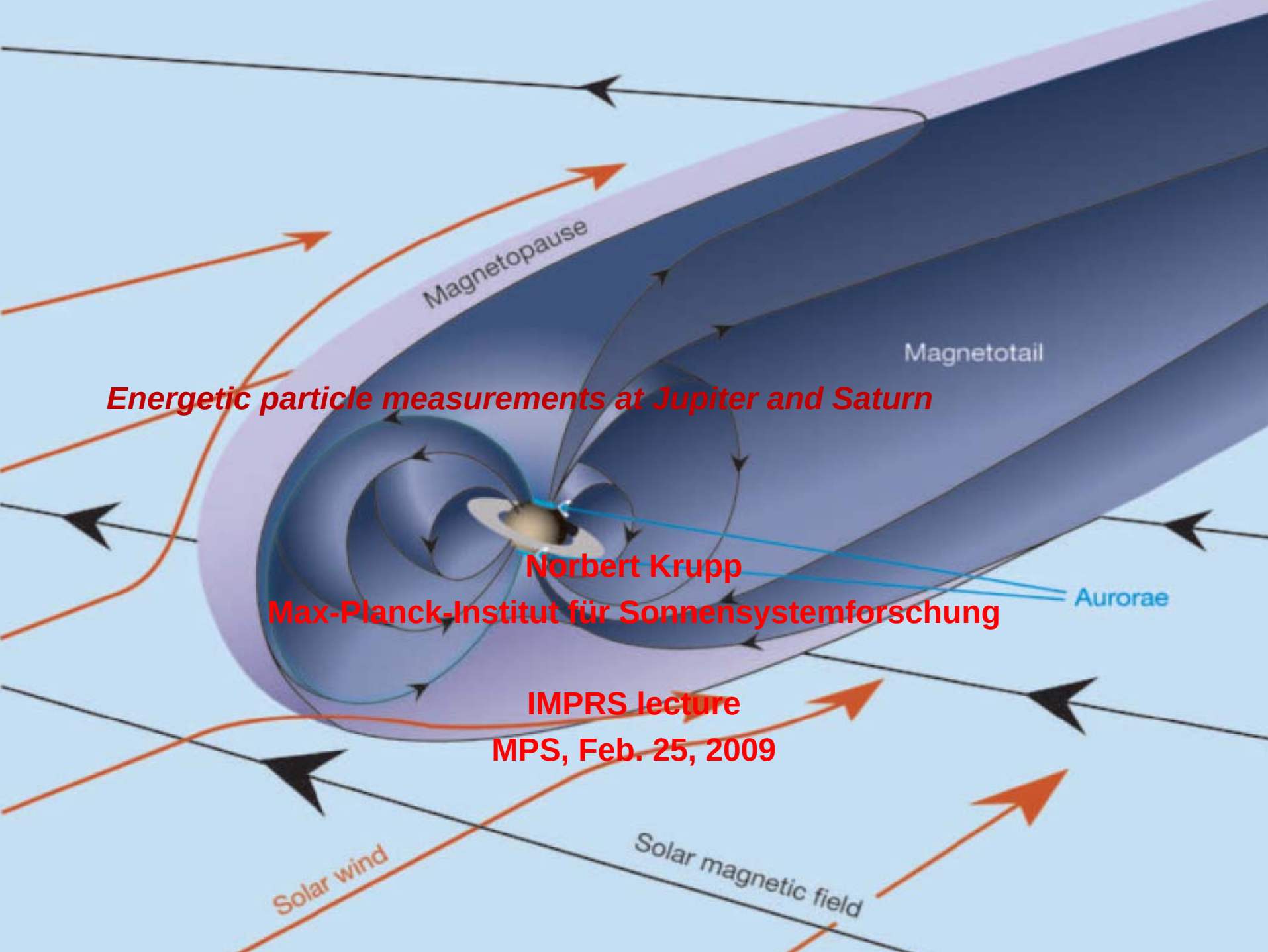
Outline

- introduction
- global configuration
  - radiation belts
  - corotational flow
  - composition
- dynamics
  - particle injections
  - reconnection in the magnetotail
  - periodicity
- magnetosphere-moon/ring material interaction
  - ring material
  - Enceladus plume
  - orbiting material around Rhea
- summary and open questions



Energetic particle measurements at Jupiter and Saturn

Norbert Krupp

Max-Planck-Institut für Sonnensystemforschung

IMPRS lecture

MPS, Feb. 25, 2009

Introduction

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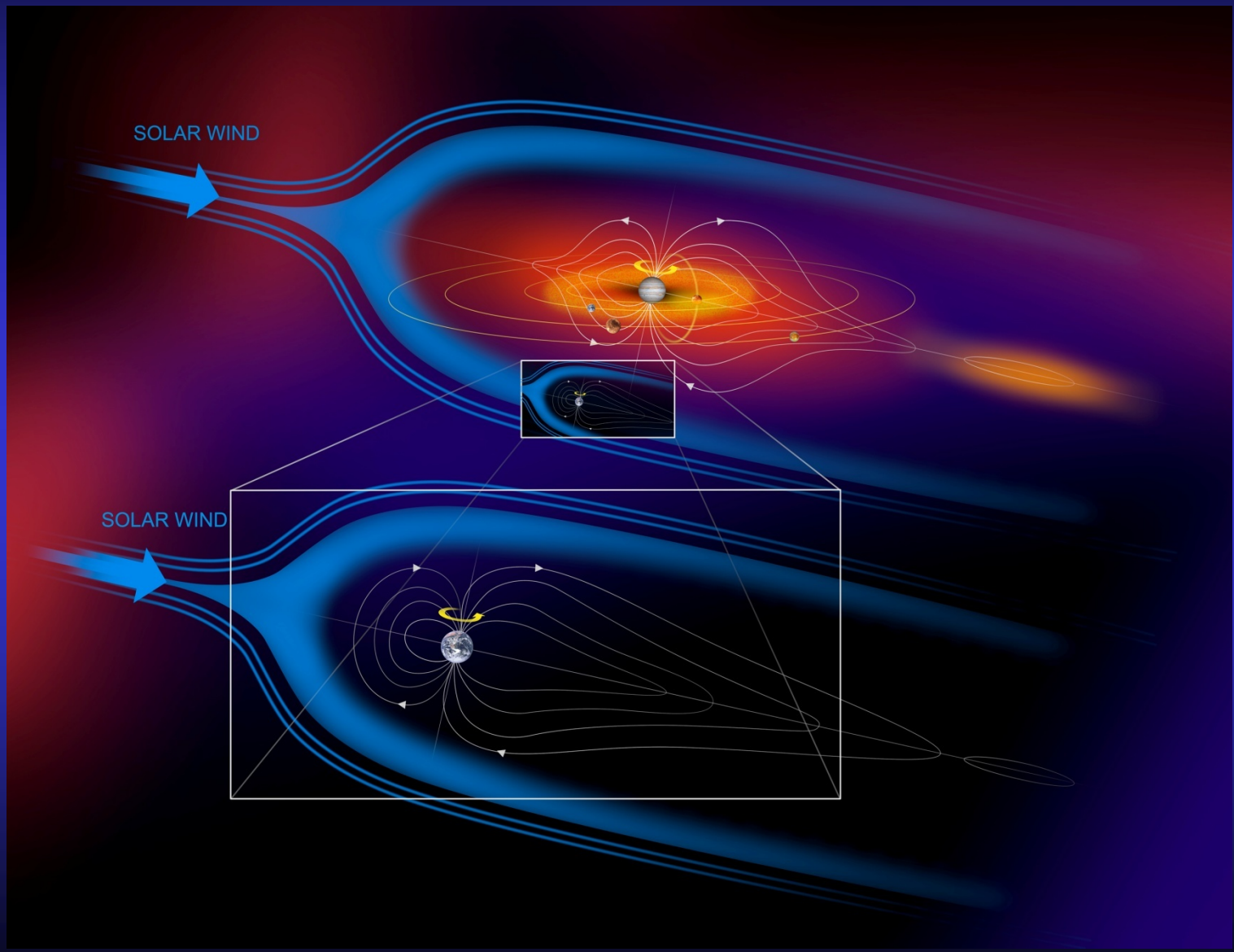
Sonnensystemforschung

Introduction:
Comparison of the magnetospheres of Jupiter and Earth

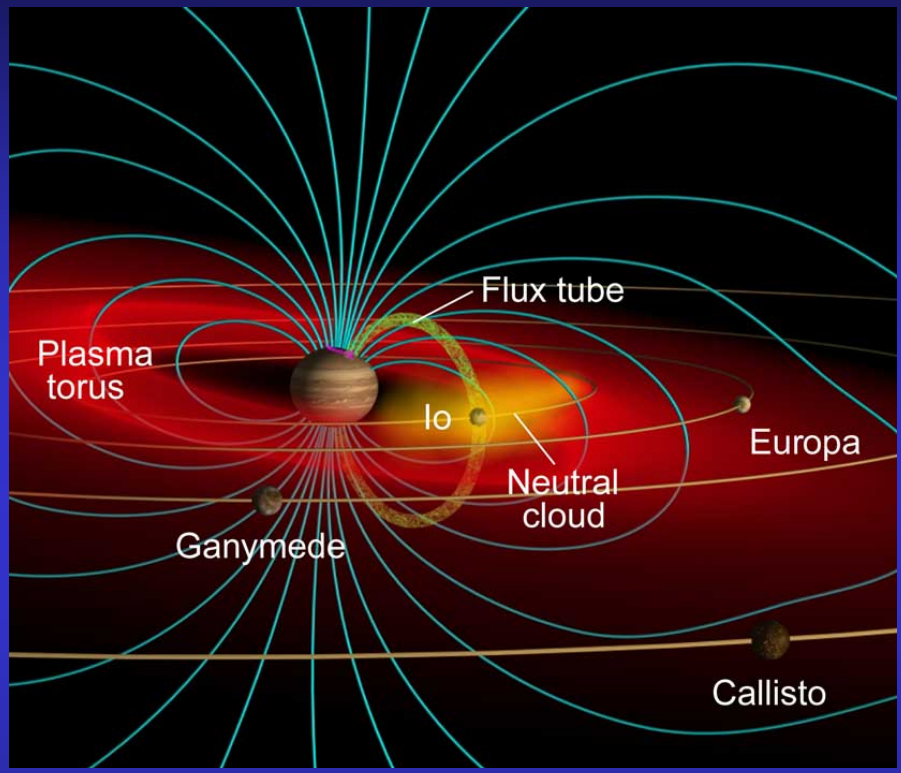


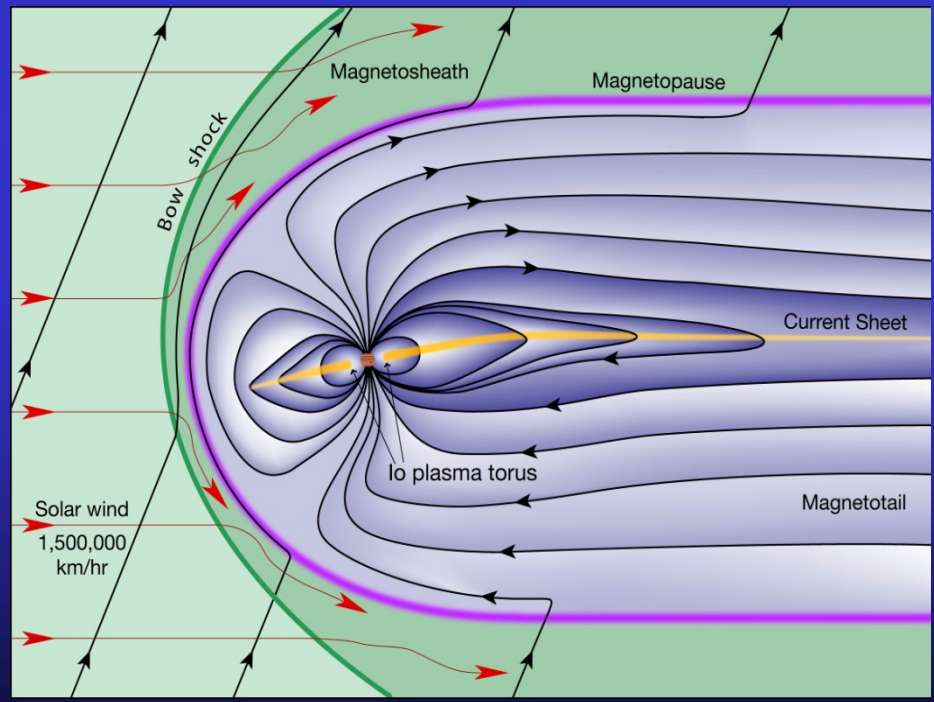
Introduction: Jupiter's magnetosphere

explored by spacecraft flybys
P10, P11, V1, V2, ULS, Cass, NH

and one orbiter
Galileo

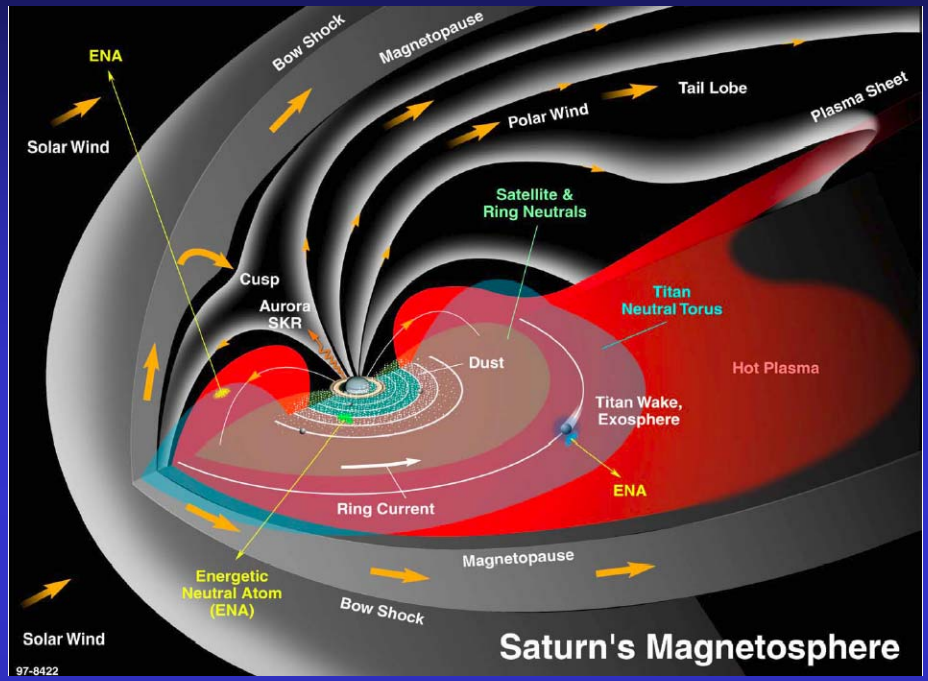
planned missions
JUNO, EJSM?





rotation-dominated, Io source

Introduction: Saturn's magnetosphere



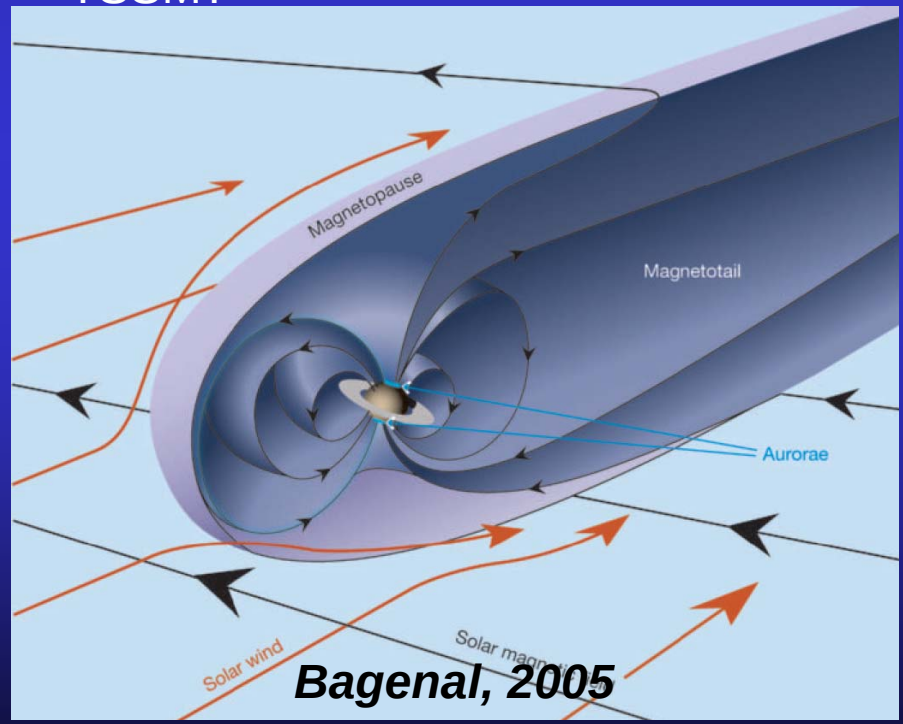
Krimigis et al, 2004

rotation-dominated, Enceladus source

explored by spacecraft flybys
P11, V1, V2

and one orbiter
Cassini

planned missions
TSSM?

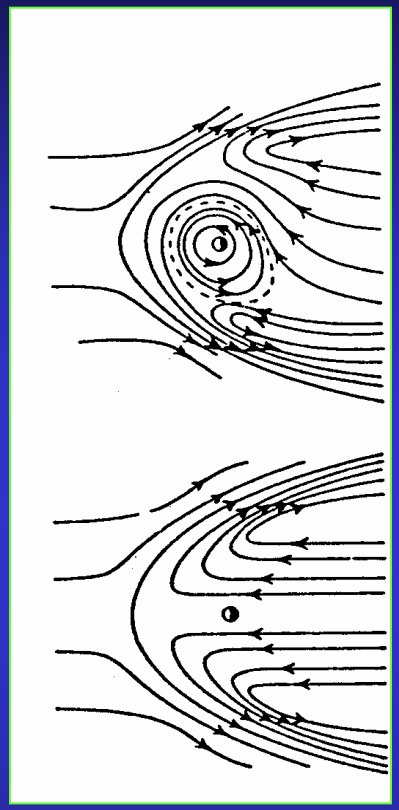


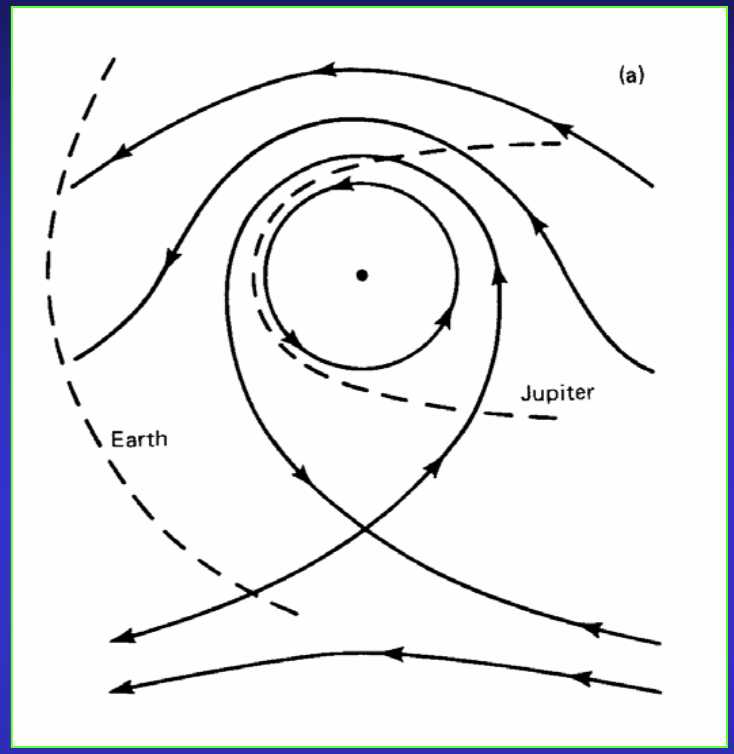
Bagenal, 2005

Introduction:
Plasma sources of planetary magnetospheres

	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
N_{max} cm^{-3}	~1	1-4000	>3000	~100	~3	~2
Composition	H^+ Solar Wind	O^+ H^+ Iono-sphere Solar wind	O^{n+} S^{n+} H^+ Io, Solar wind, ionosphere	O^+ H_2O^+ H^+ Rings, Enceladus Other icy moons Solar wind	H^+ Iono-sphere	H^+ N^+ Triton, Iono-sphere
Source kg / s	?	5	700-1200	~2-100	~0.02	~0.2

Introduction:
Rotation-dominated magnetosphere



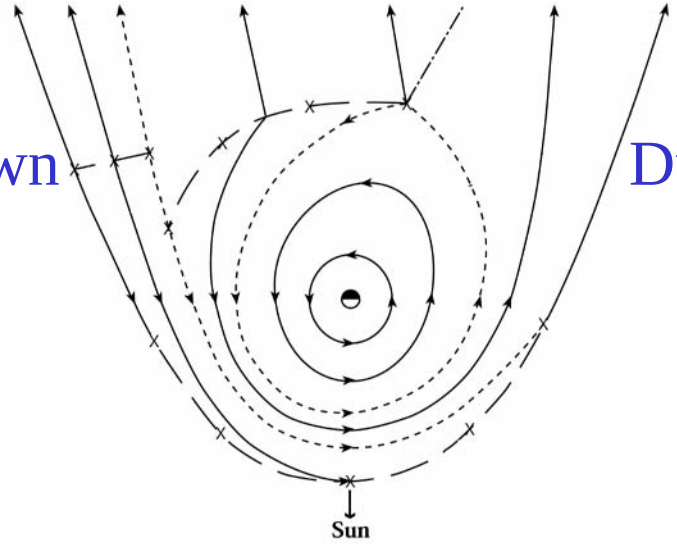


- plasmasphere in the inner magnetosphere with closed flow lines
- if scaled to Jupiter: closed flow lines outside the magnetosphere

Equatorial View

Dawn

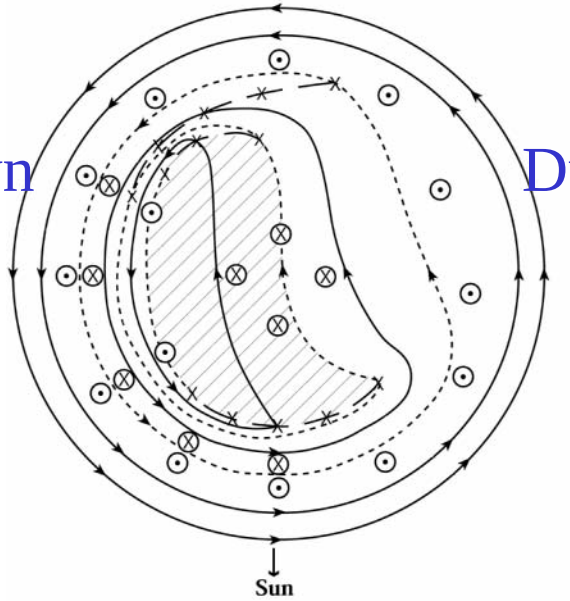
Dusk

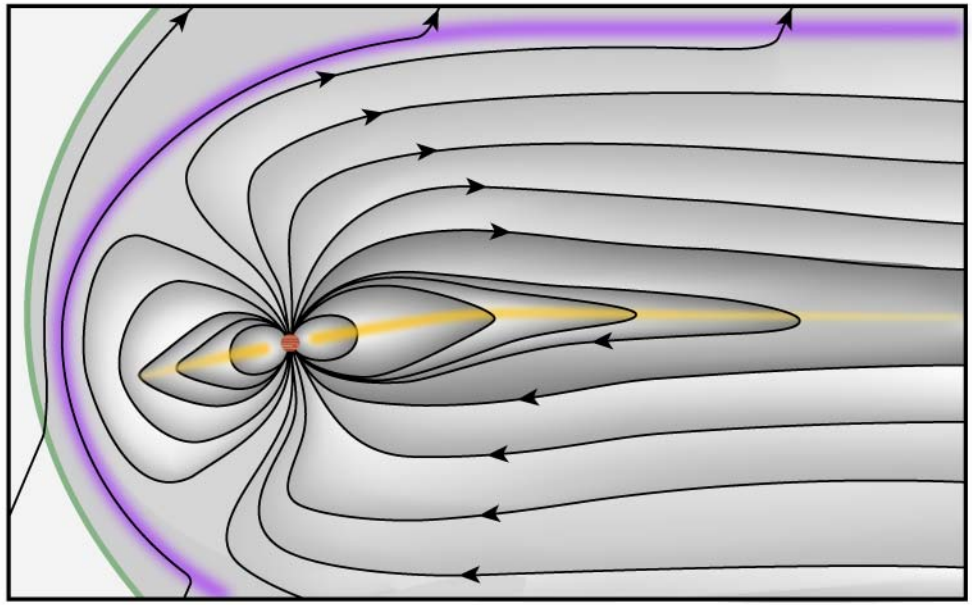


Polar View

Dawn

Dusk





Side View

Equatorial View

Dawn

Dusk

Hill Region Sub-corotating plasmasheet

Sun

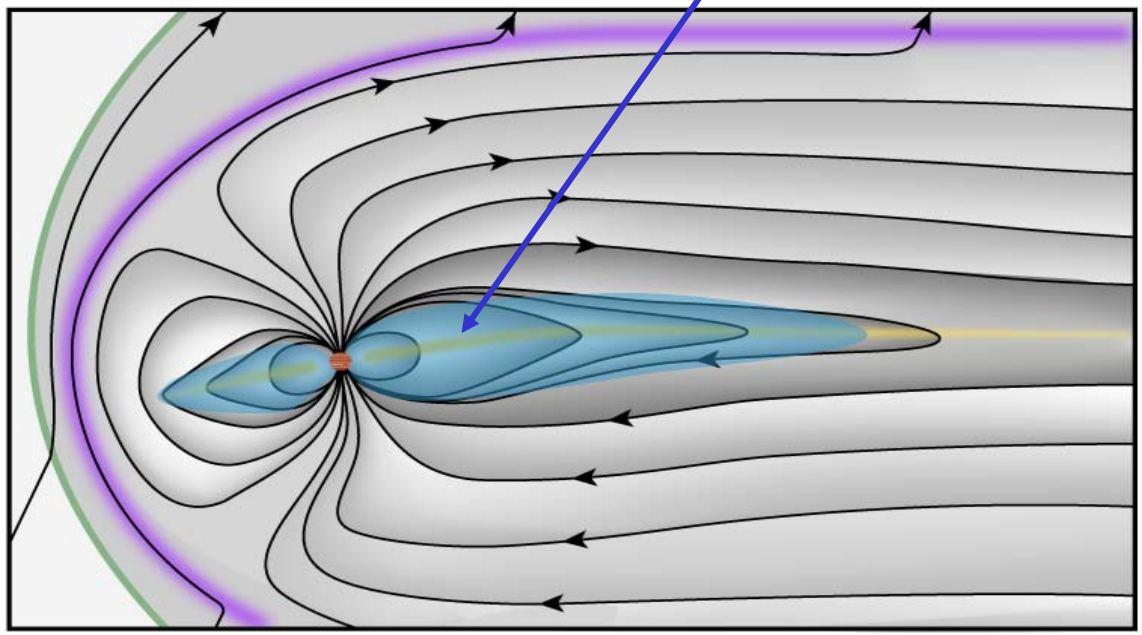
Polar View

Dawn

Dusk

Sun

Main Auroral Oval



Side View

Equatorial View

Dawn

Dusk

Sun

Polar View

Dawn

Sun

Inward motion --> less load on ionosphere

Outward motion --> more load on ionosphere

Outer Magnetosphere "Cushion Region"

Side View

Equatorial View

? ? ?

Dawn

Dusk

Sun

Polar View

Dawn

Dusk

Sun

How important is the Dungey Cycle?

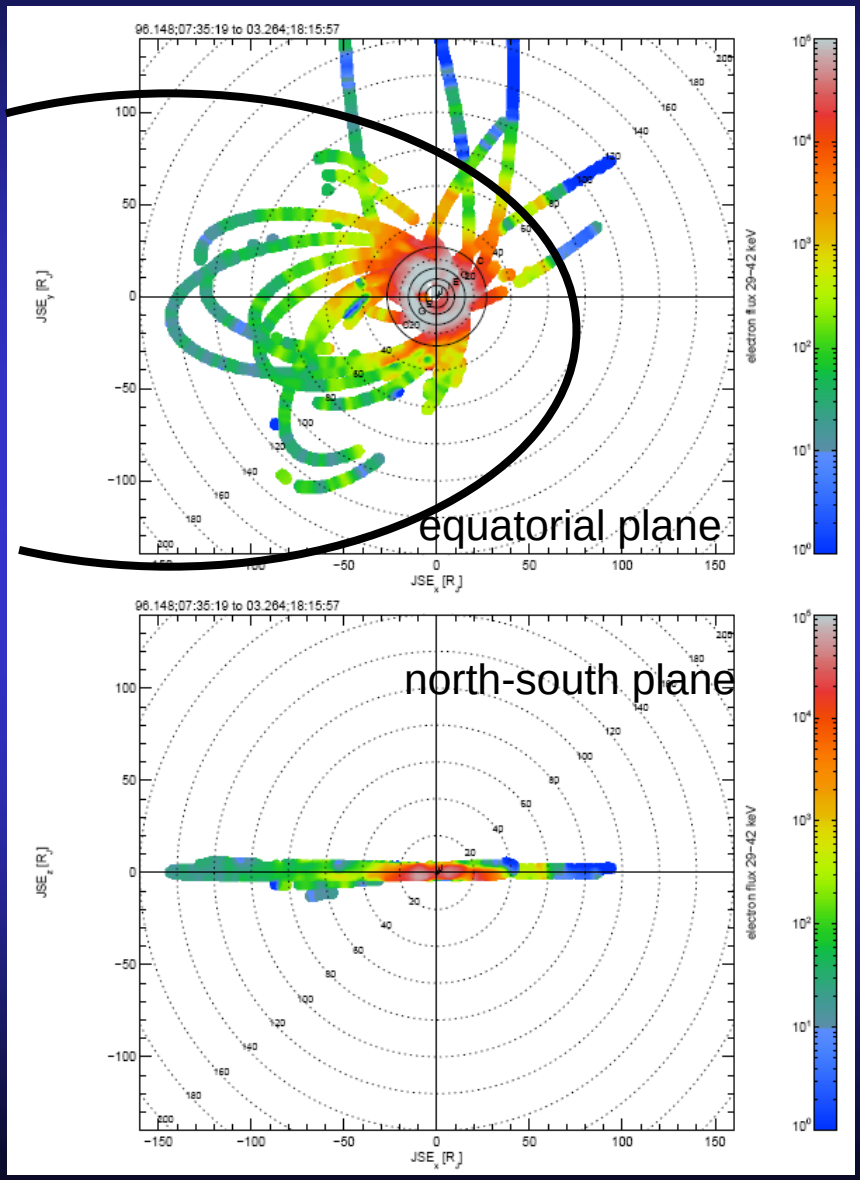
? ? ?

How Much of Polar Flux is Open?

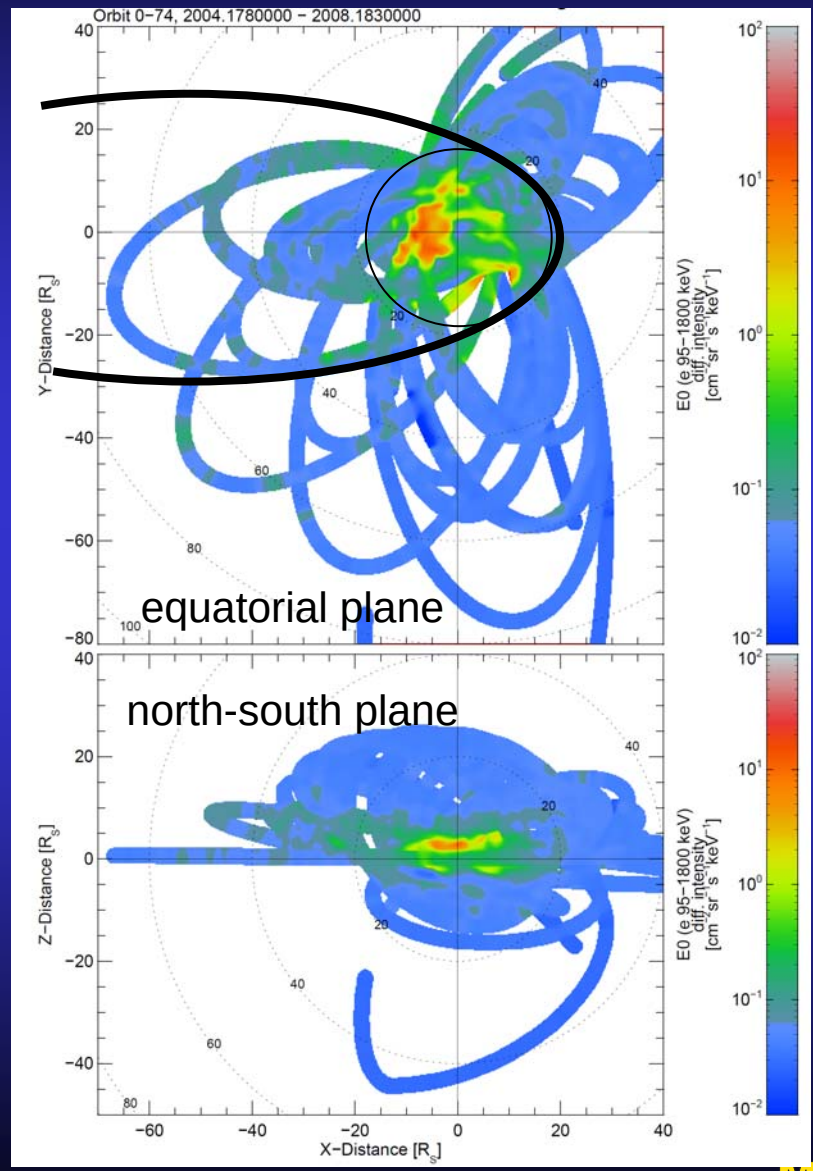
Side View

Introduction:
Magnetospheric coverage at Jupiter and Saturn

Galileo at Jupiter



Cassini at Saturn



Global configuration

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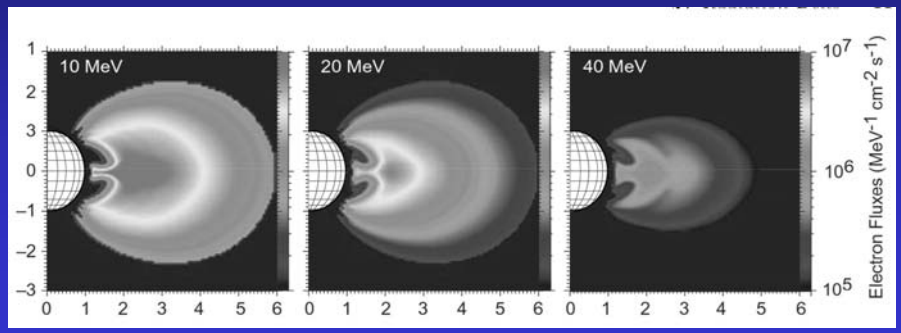
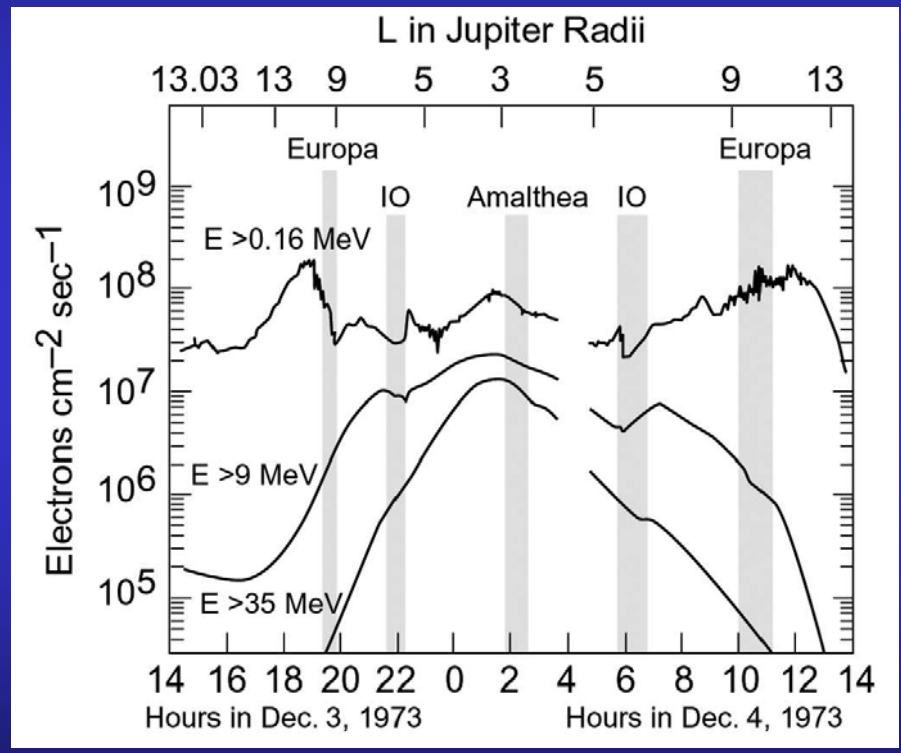
Global configuration: Jupiter's radiation belts

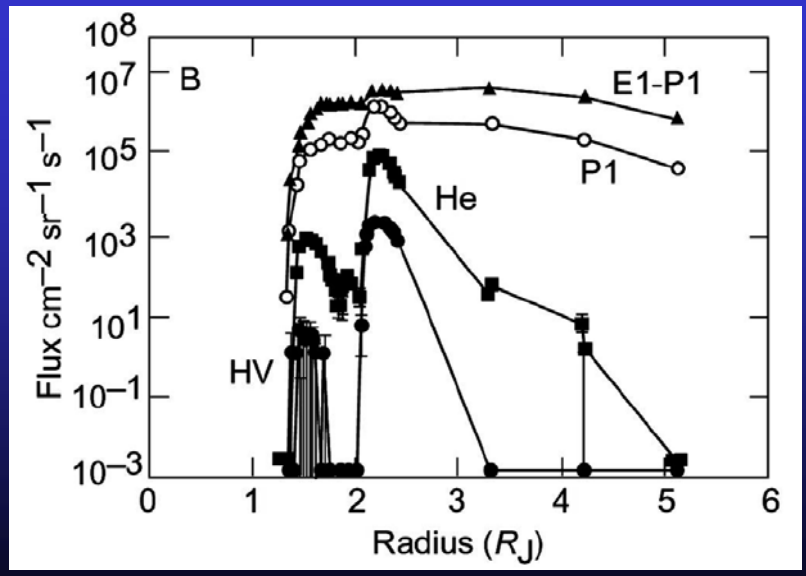
simulations



Pioneer 10 data

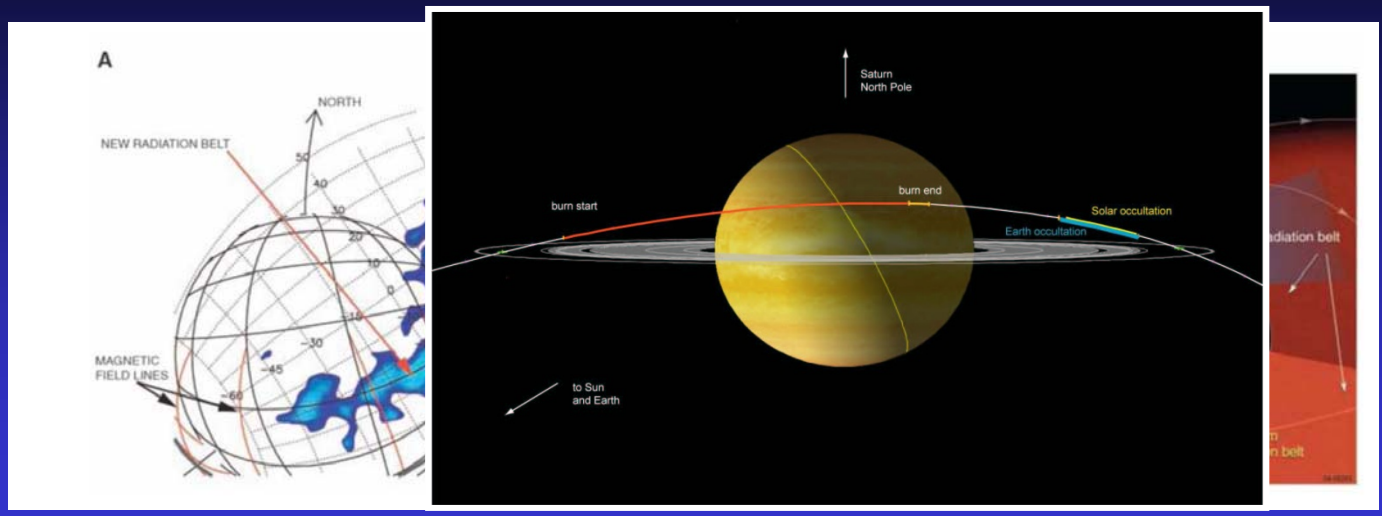


Galileo Probe data



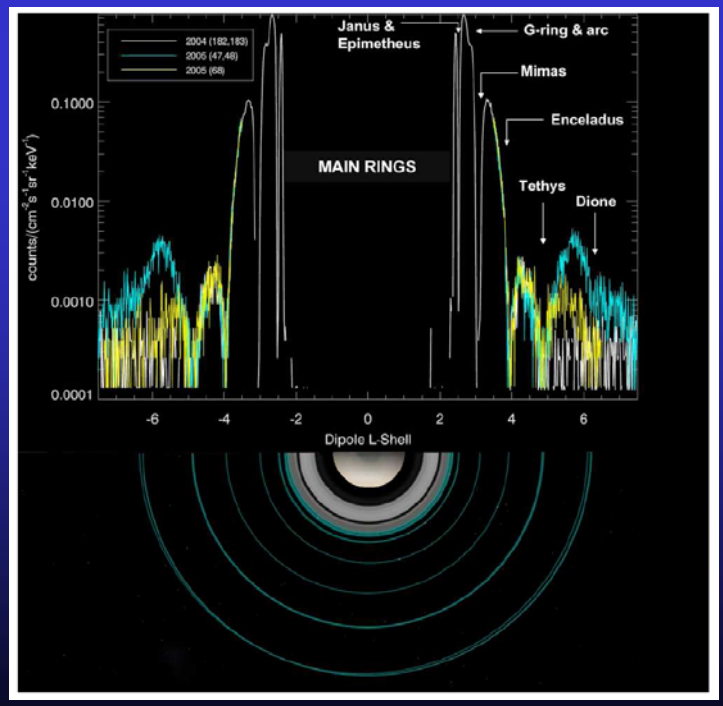
Bolton, 2004

Global configuration: Saturn's radiation belts



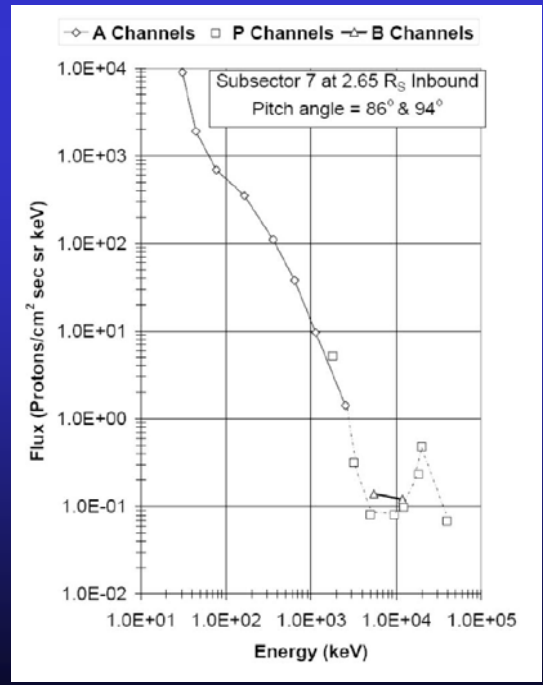
radiation belt inside the D-ring

Krimigis, 2004



main radiation belts and transient belt near Dione's orbit

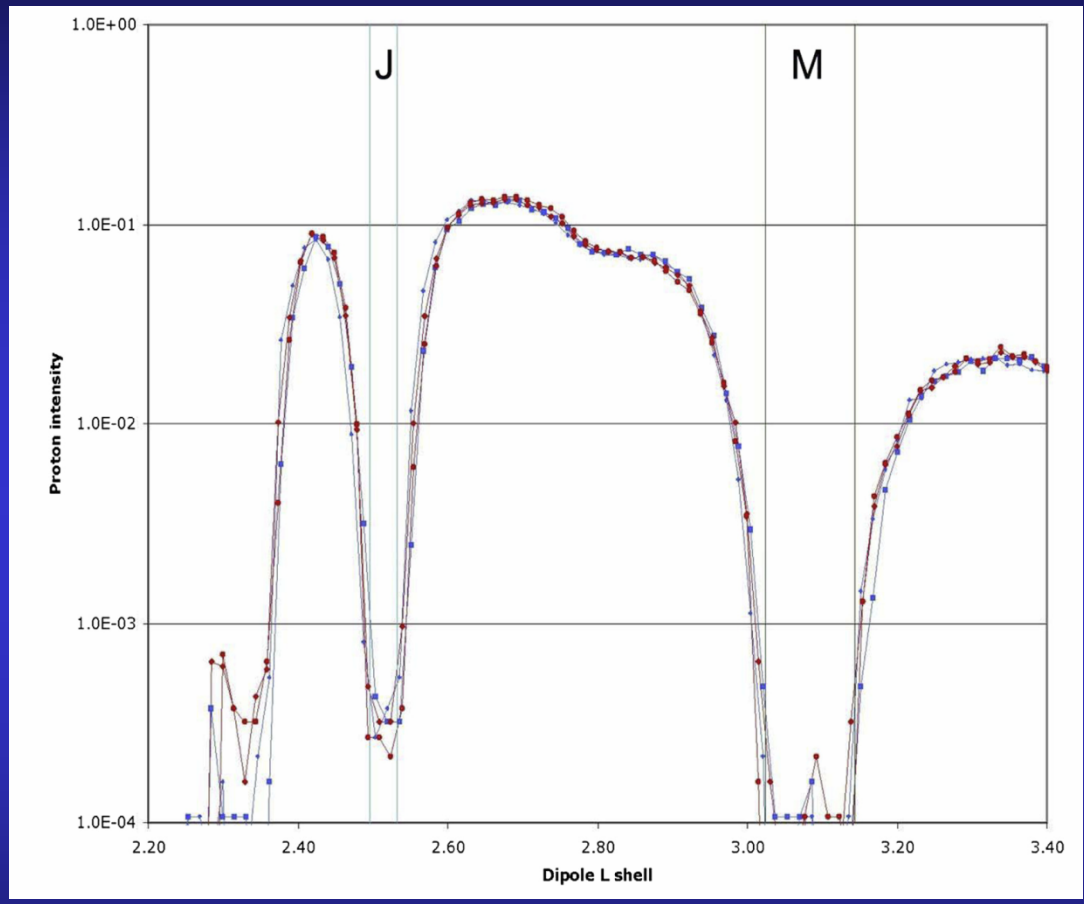
Roussos, 2008



ion energy spectrum in the main radiation belt

Armstrong, 2009

Global configuration:
Macrosignatures in Saturn's inner magnetosphere



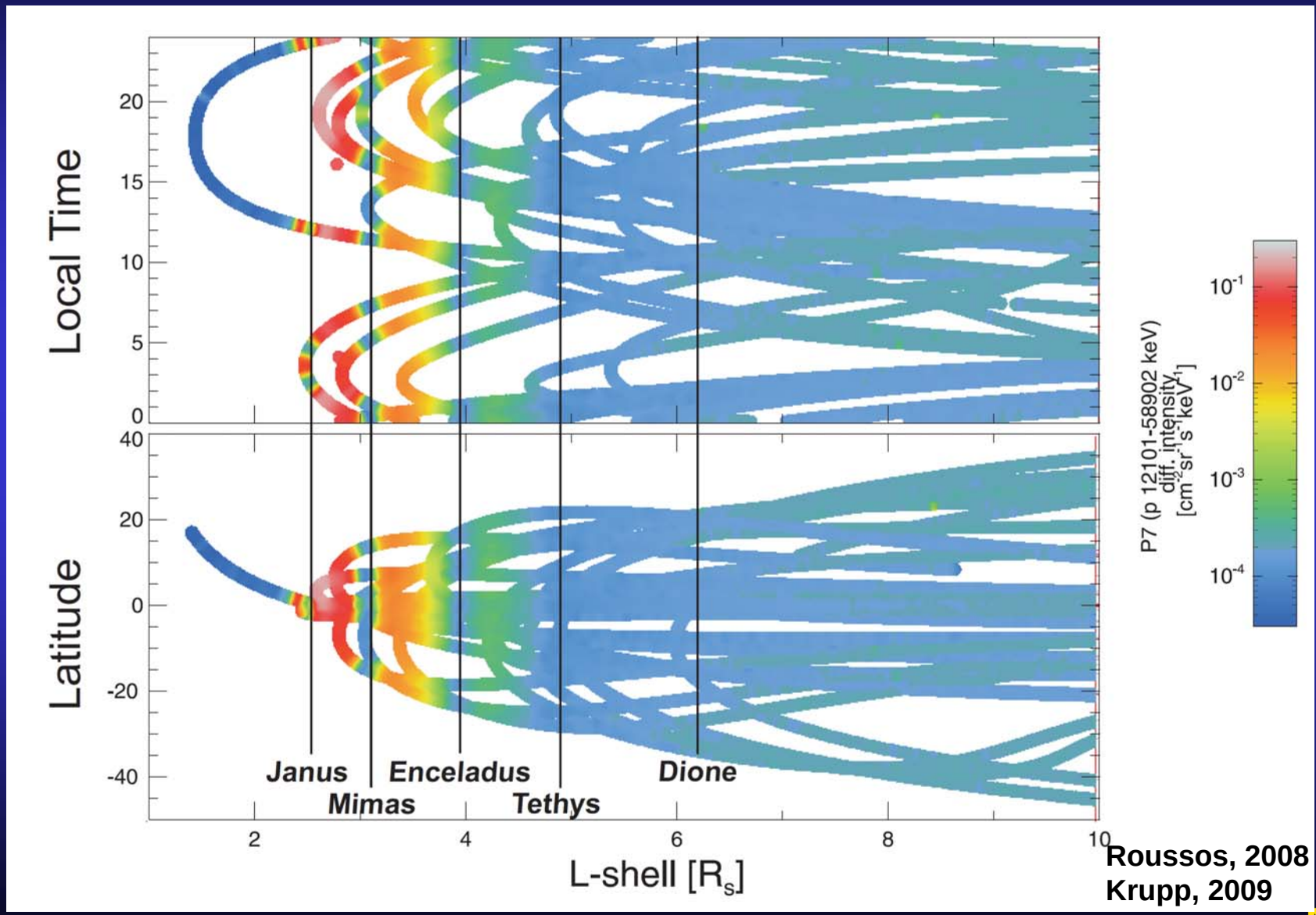
Proton intensity (protons per cm2 s sr keV) as a function of L shell during Saturn Orbit Insertion of Cassini.

Positions of the Satellites Janus *(L ~2.5) and Mimas (L ~3.1) are* shown as sweeping corridors.

Paranicas et al., Icarus, 2008

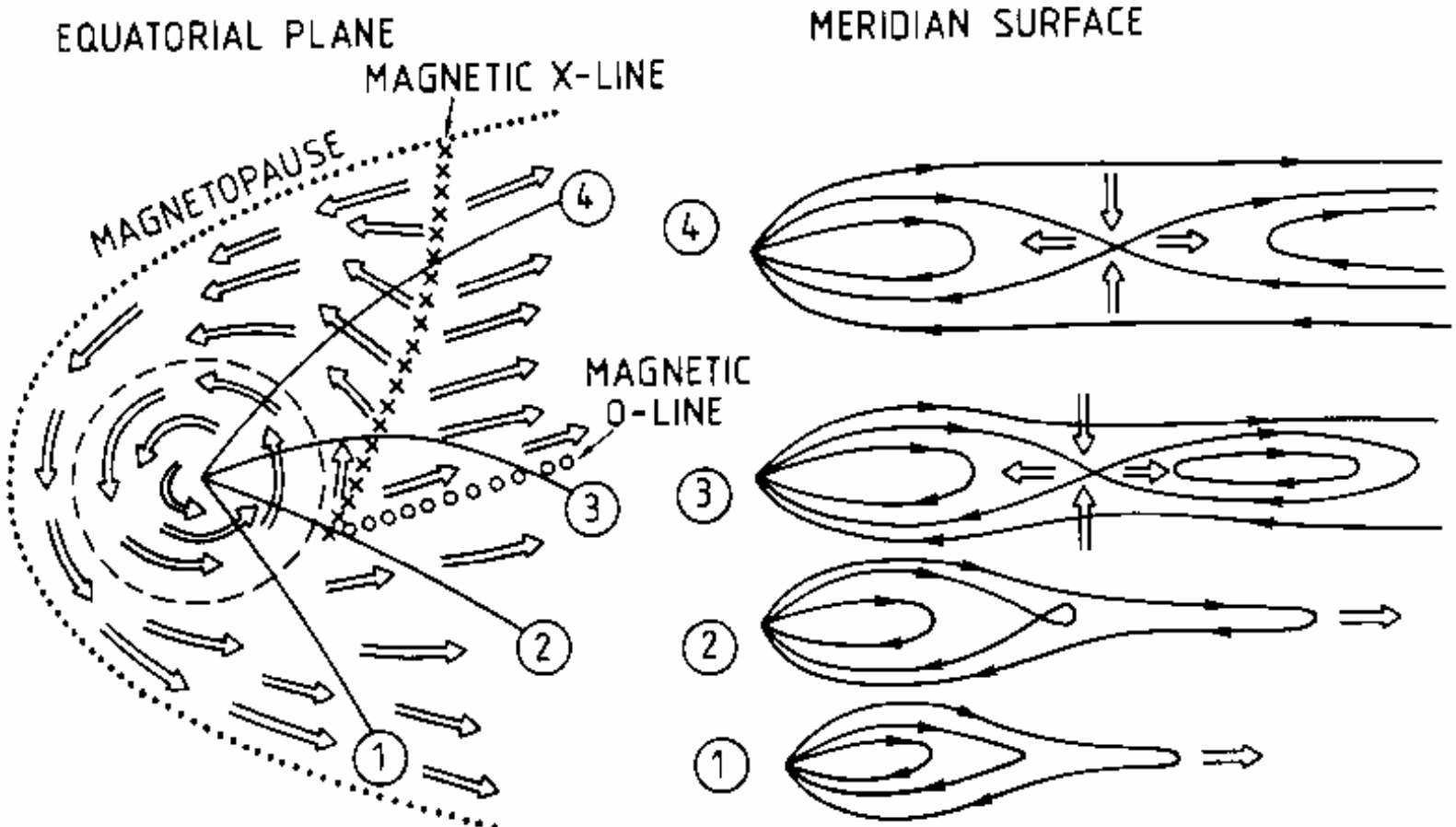
Global configuration:

Macrosignatures in the energetic particle intensities from moons in the Saturnian magnetosphere



Roussos, 2008
Krupp, 2009

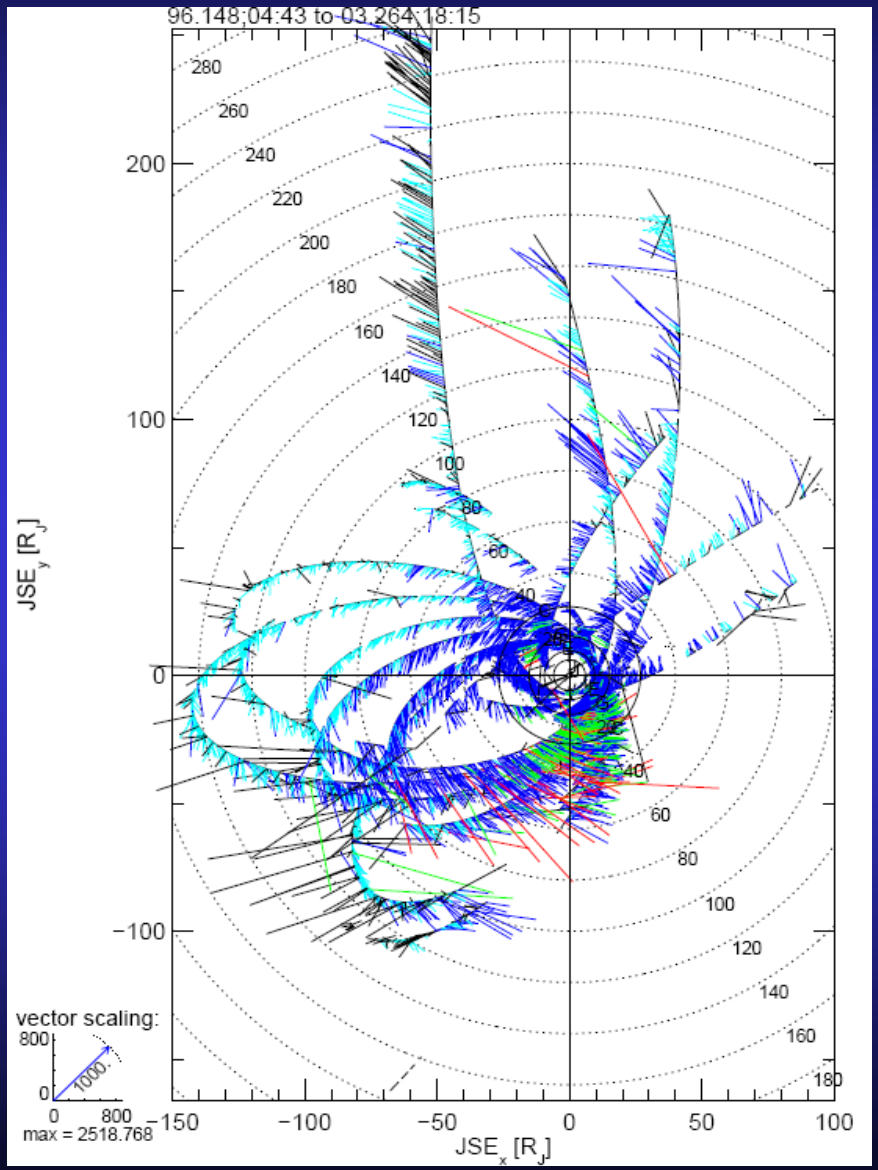
Global configuration:
Structure and dynamics of the outer Jovian magnetosphere

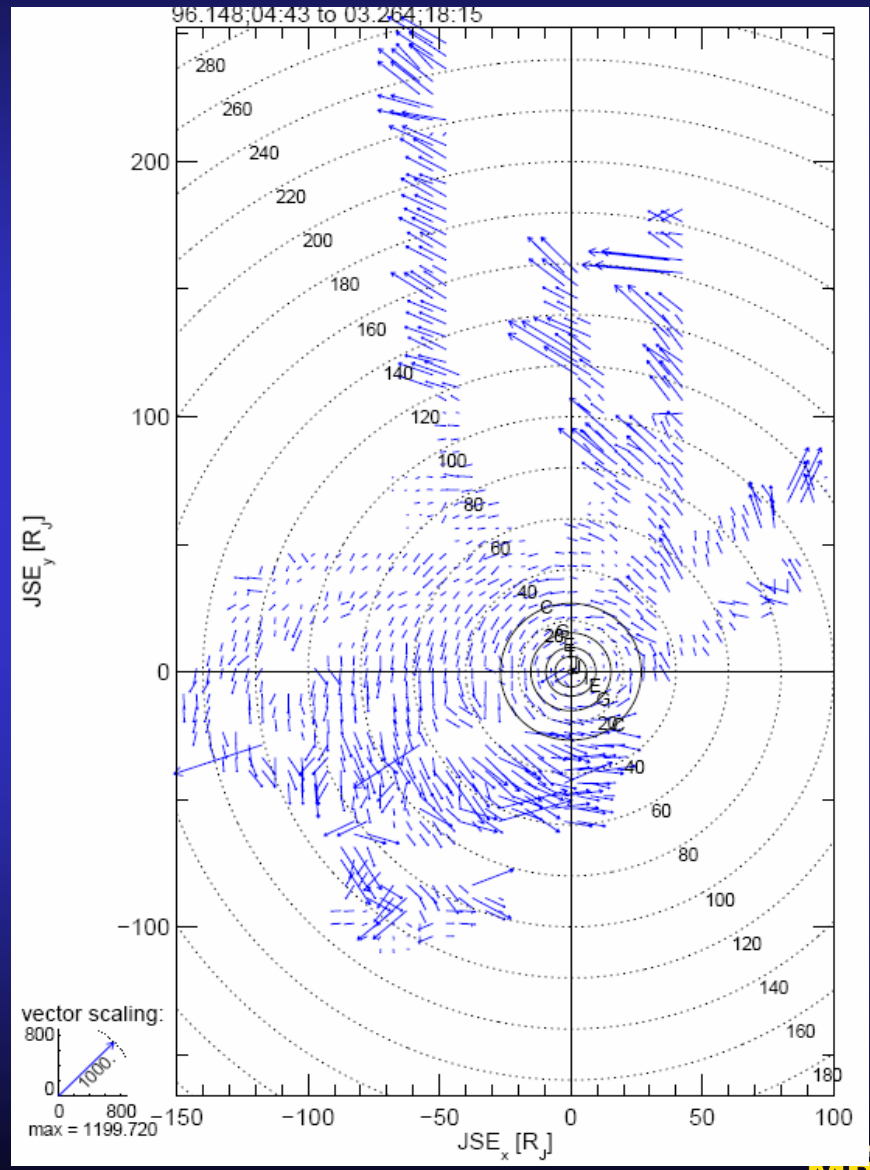


Vasyliunas 1983

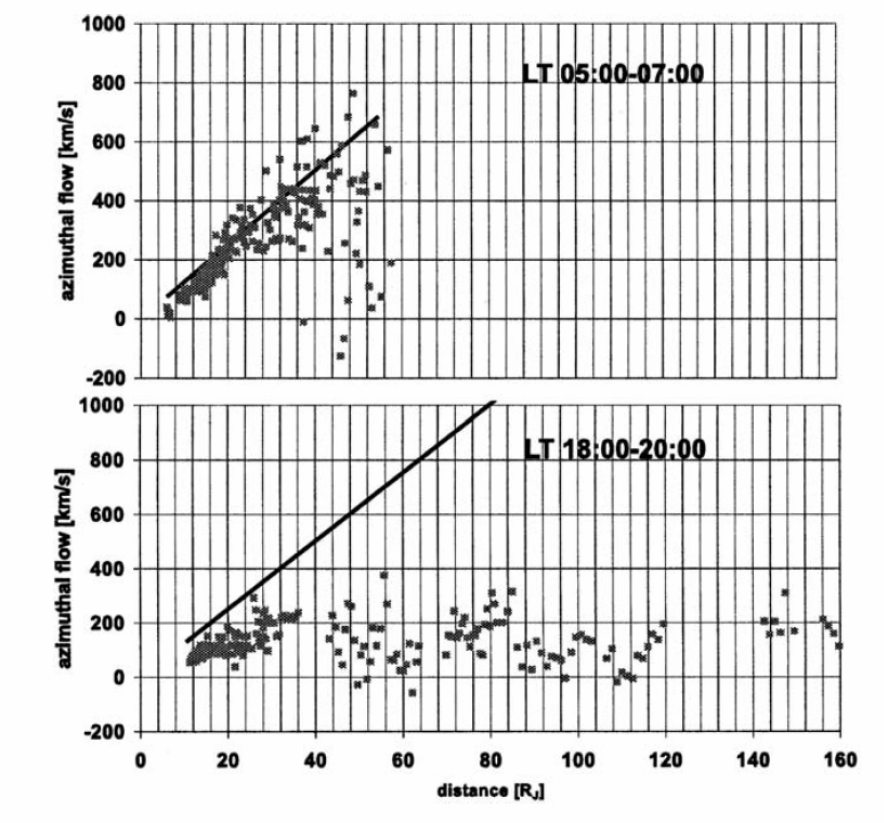
Global configuration:
Particle flow pattern in Jupiter's magnetosphere

Galileo/EPD measurements in the equatorial plane





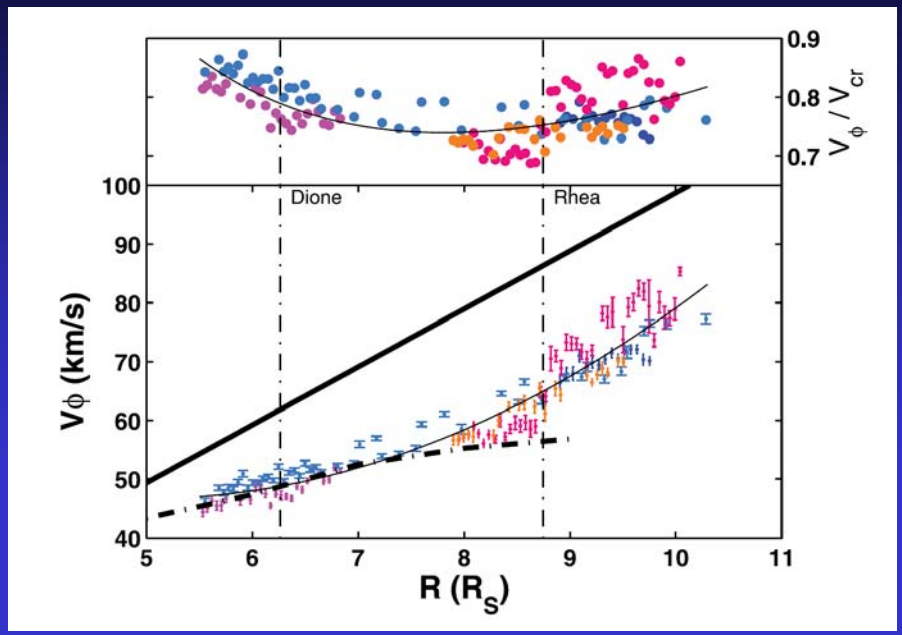
Global configuartion: Flow results from Galileo



- strong asymmetry between dawn and dusk
- corotation breakdown at 25-40 RJ dependent on local time

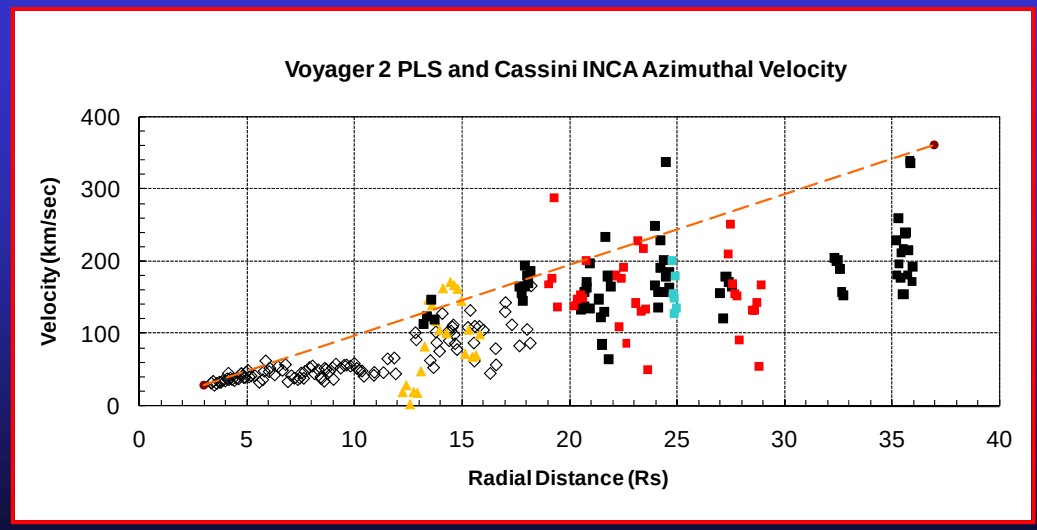
Woch et al., ASR 2004

Global configuration:
Flow results in the Saturnian magnetosphere



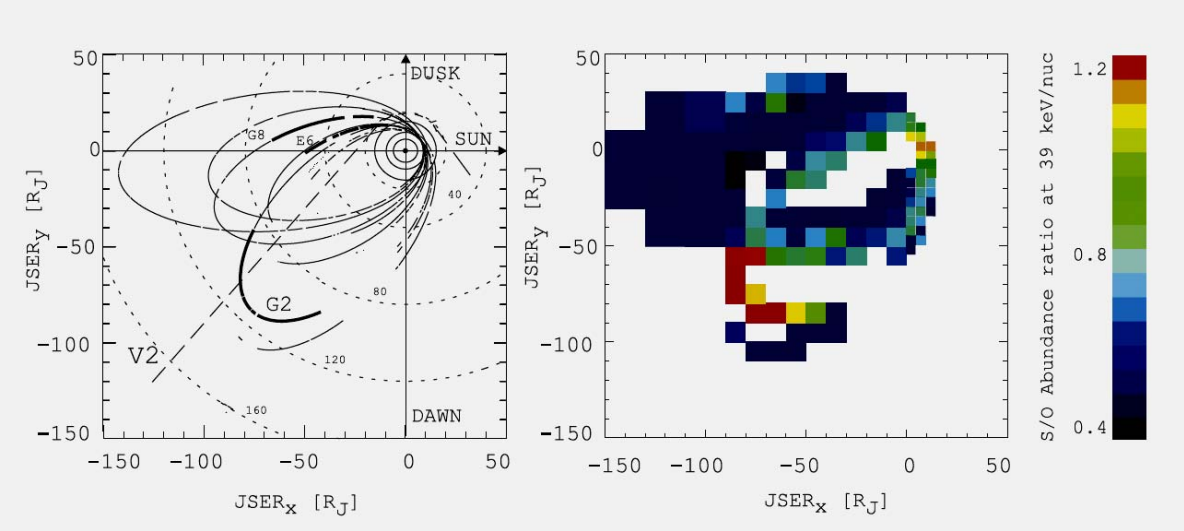
Wilson, 2008

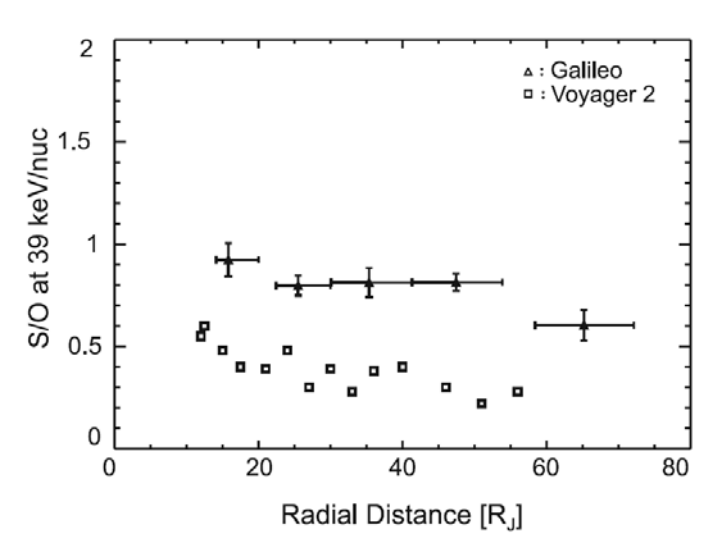
Kane, 2008



Global configuration

Energetic ion composition in Jupiter's magnetosphere



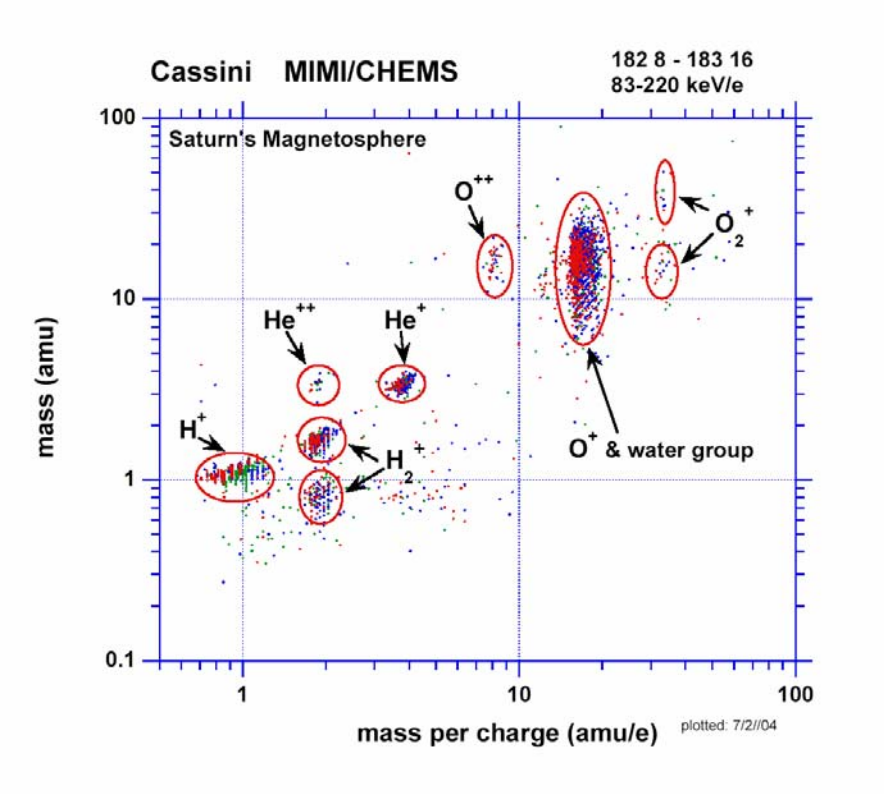


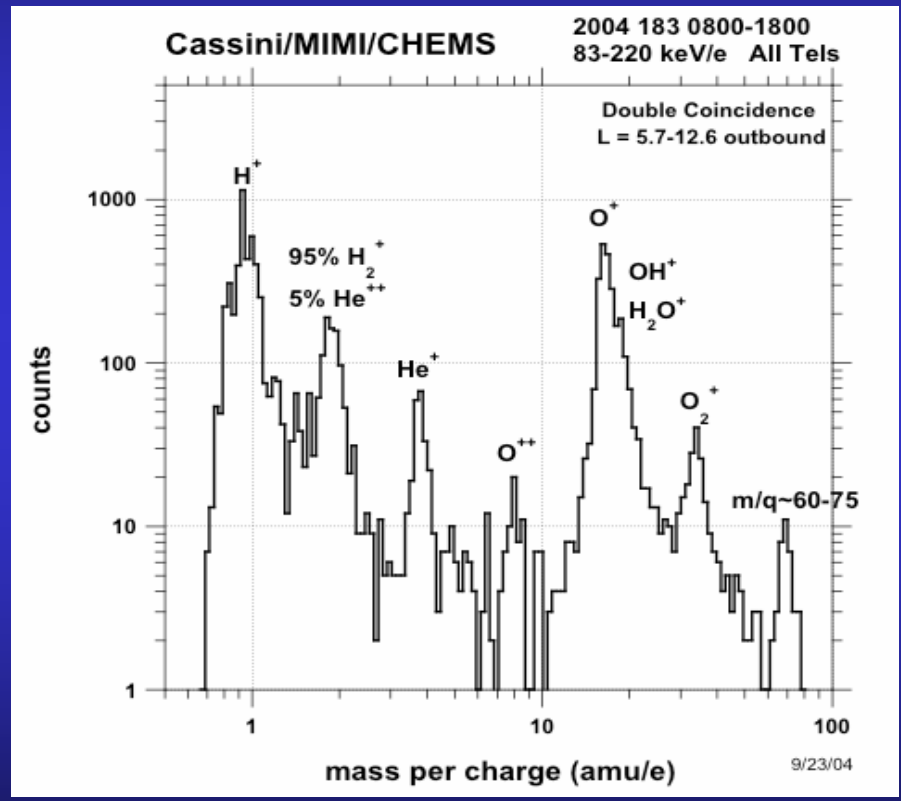
Radioti et al., JGR, 2005, 2006

S/O-ratio of Galileo in plasmoids comparable with New Horizons results in the deep tail.

Sulfur and Oxygen from Io

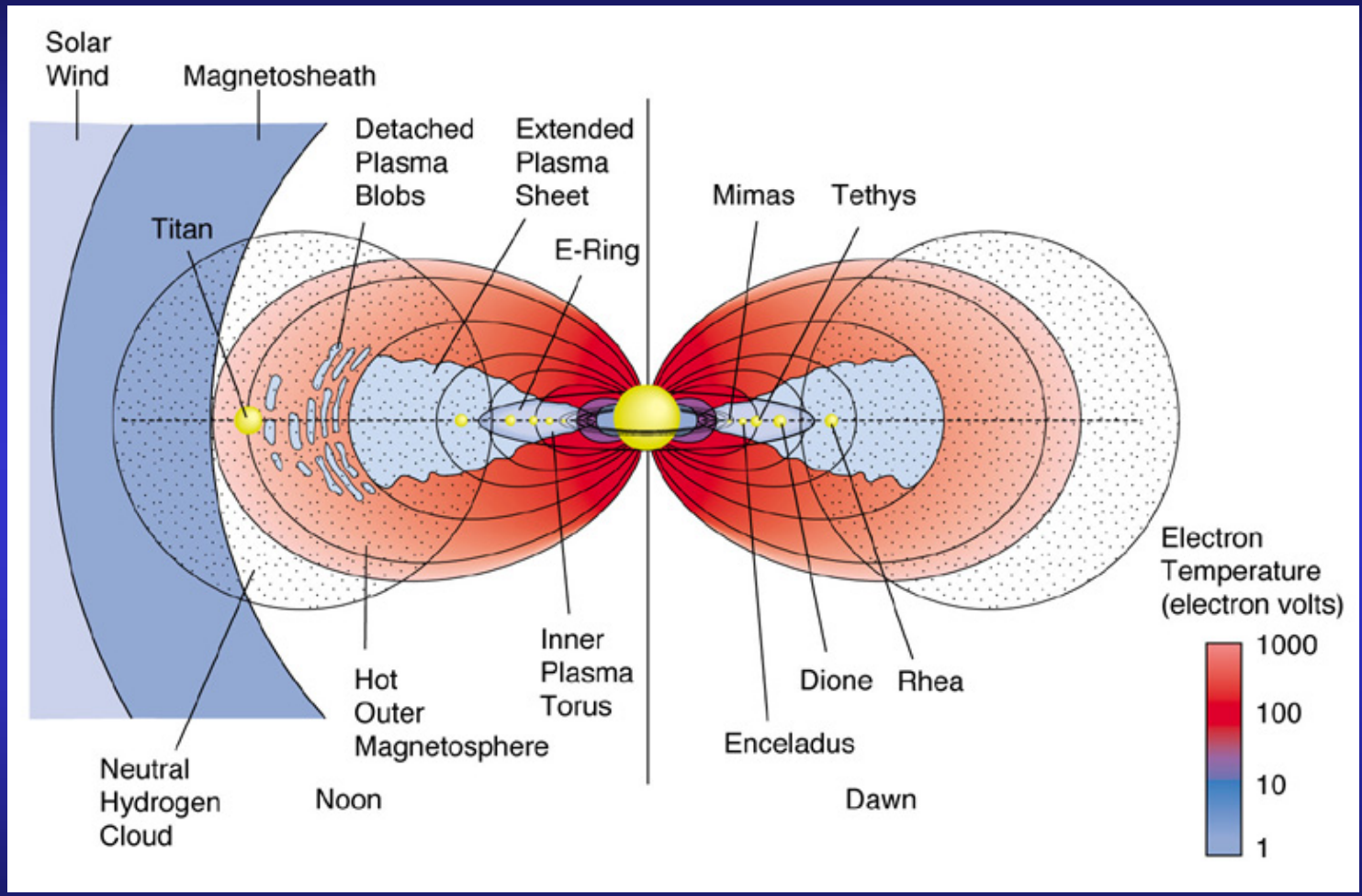
Global configuration:
Water ion products dominate Saturn‘s magnetosphere





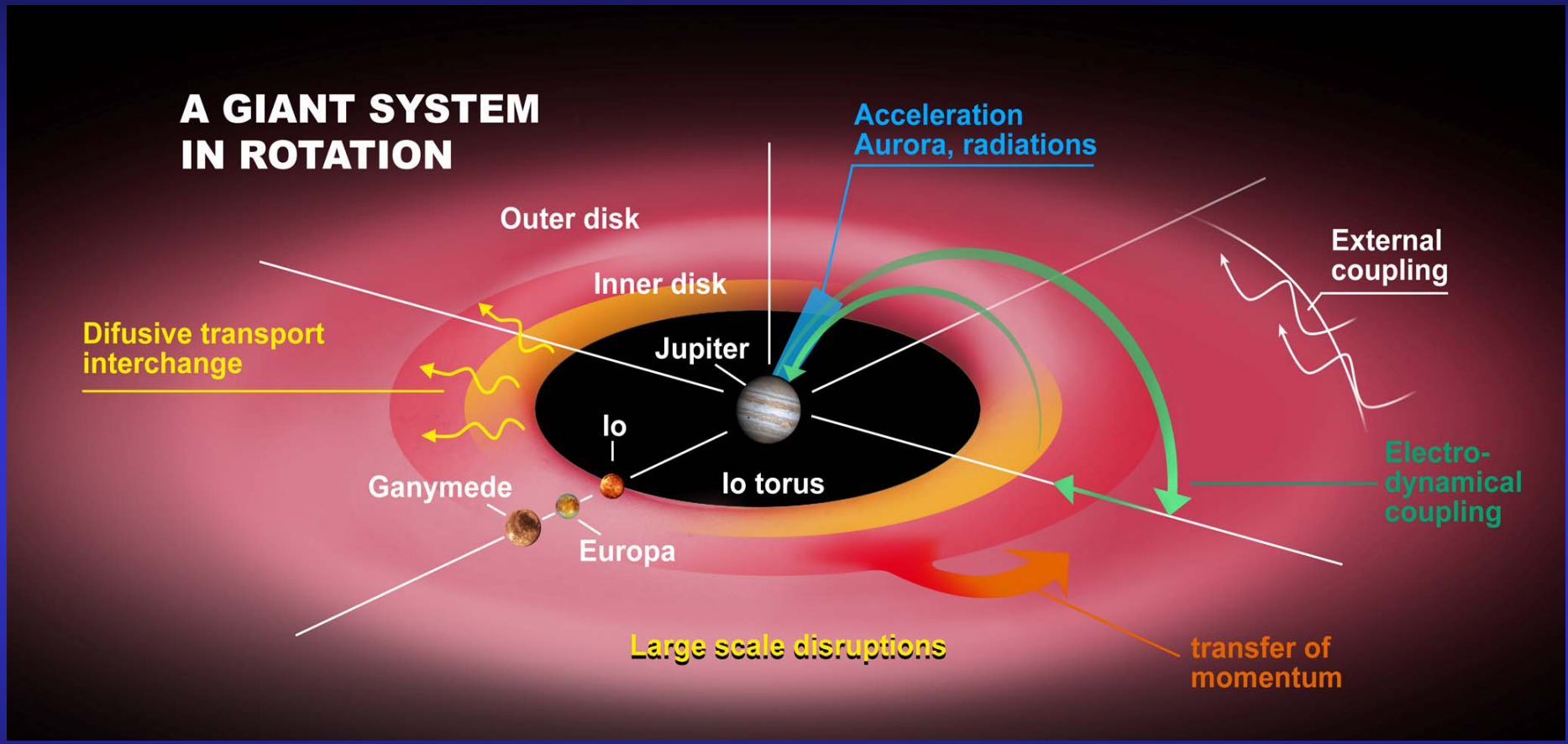
water molecules from Enceladus

Global configuration: Plasma regions and sources at Saturn



- **Strong satellite & ring sputtering, weak ionization**
- **$N_{neutrals}$~100 x N_{ions}**

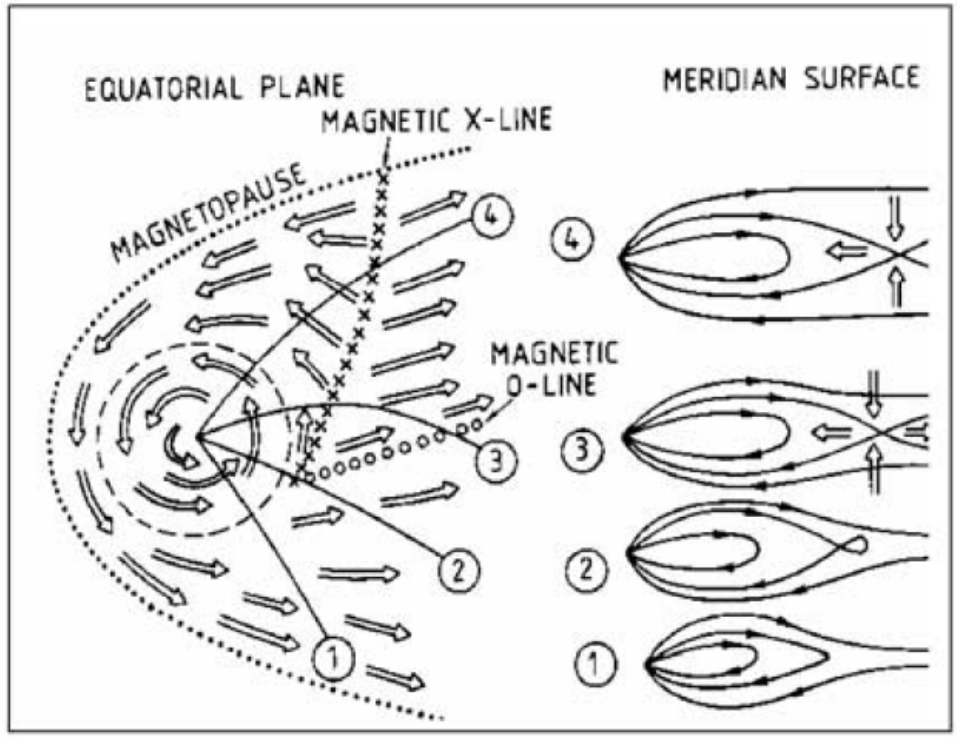
Global configuration: Jupiter's magnetosphere as a rotating system

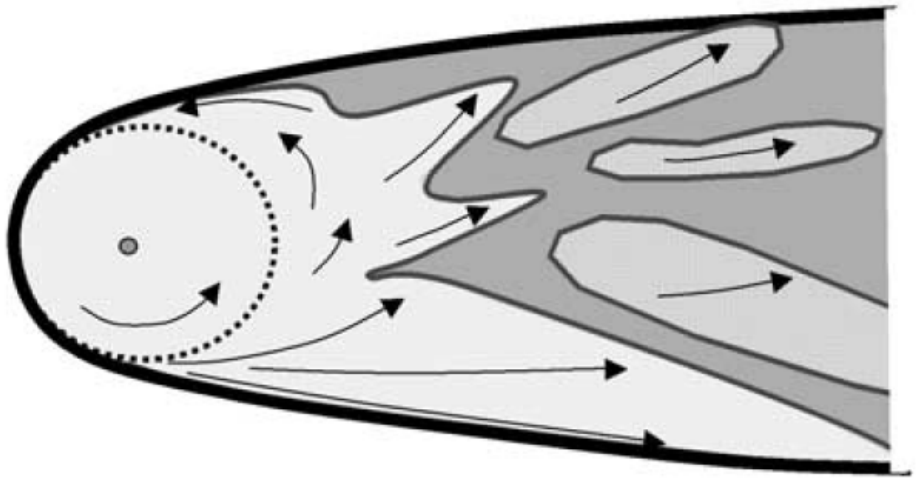


Dynamics

Dynamics:

Disturbances in the flow pattern of Jupiter's magnetosphere

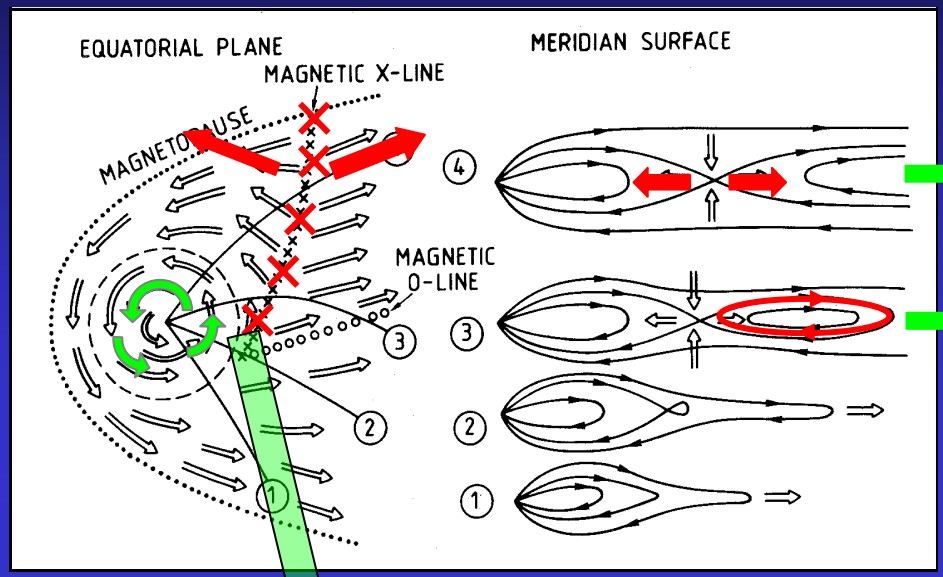


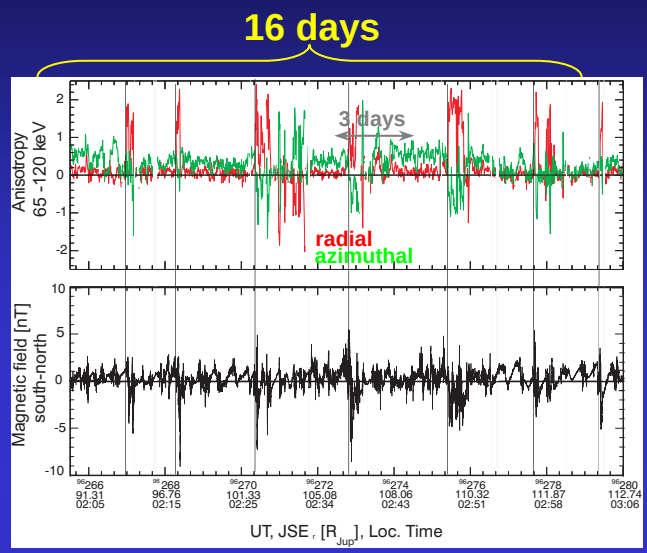


Kivelson and Southwood, 2005

Dynamics:

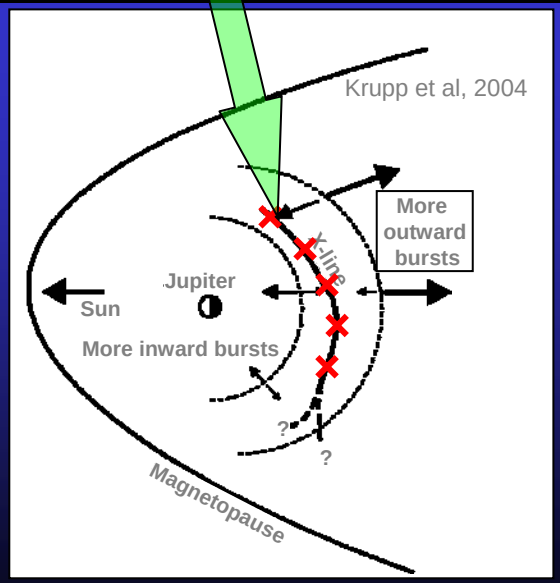
Energetic particle flow bursts and magnetospheric response in Jupiter'smagnetotail

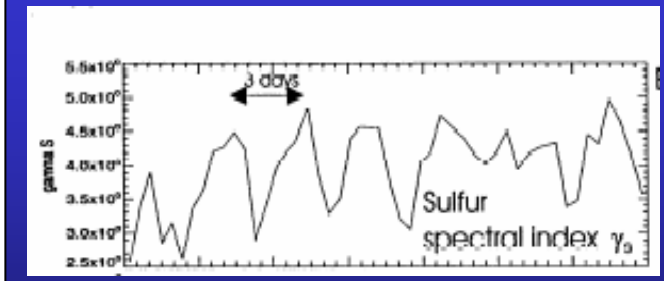




directional ion anisotropy

north-south magnetic field





Location: 90-113 Rj

energy spectra variations

Kronberg, 2007
Kronberg, 2005
Woch, 1998
Louarn, 2001
Krupp, 1998

Transient *periodical disturbances with repetition period of several days* are observed in the Jovian magnetotail!

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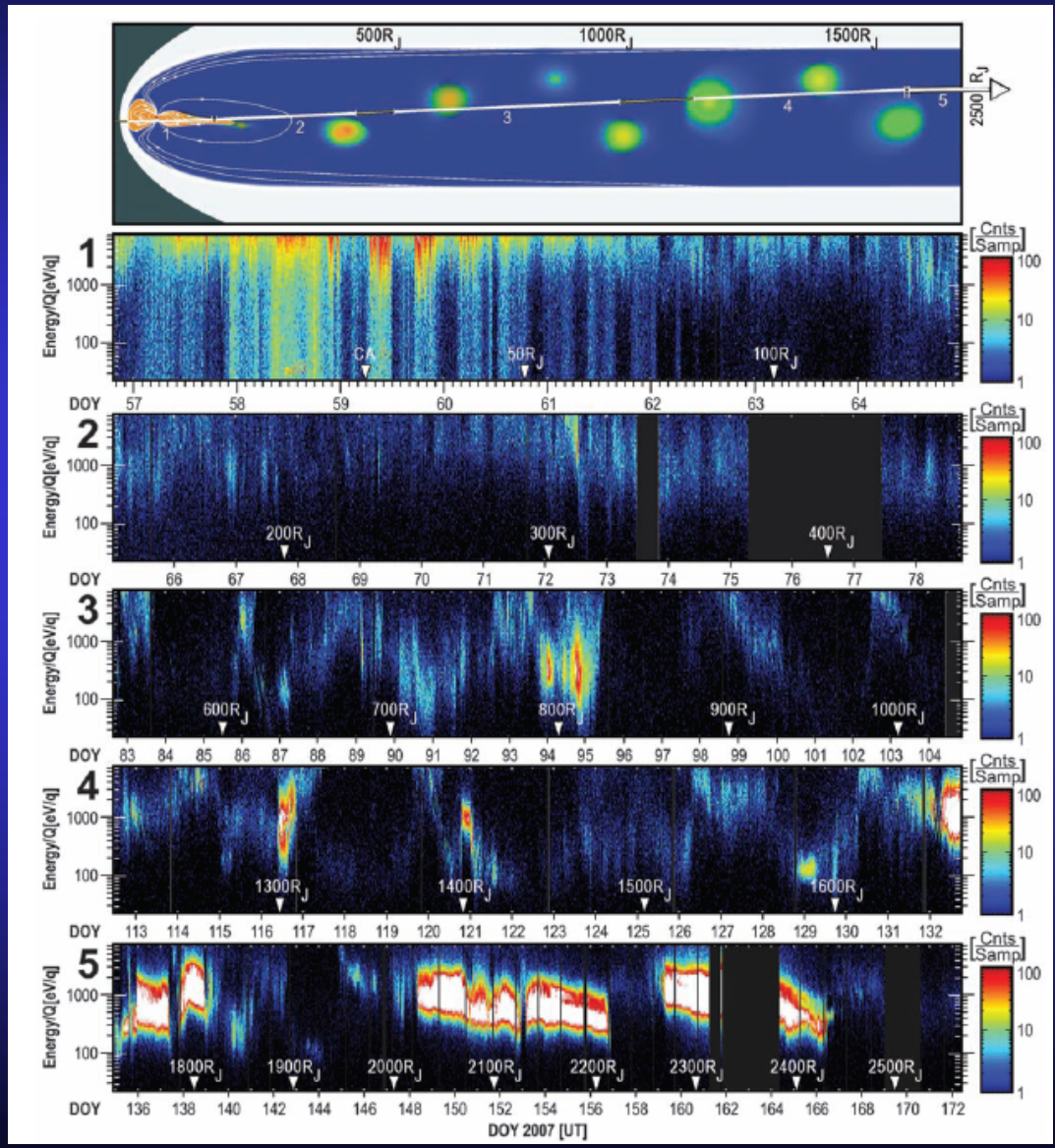
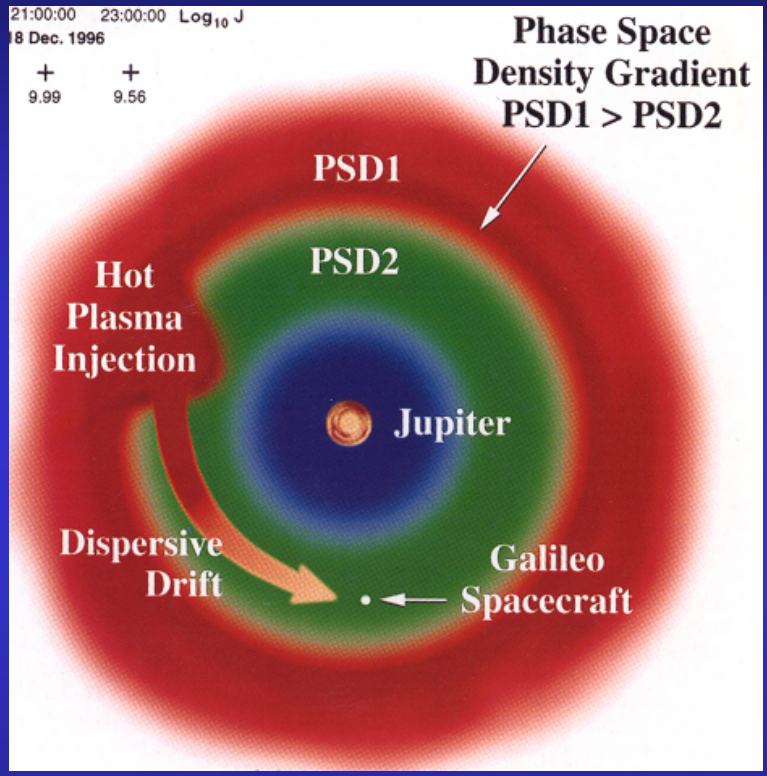
Dynamics:
Particle observations in the deep Jovian magnetotail (New Horizons)

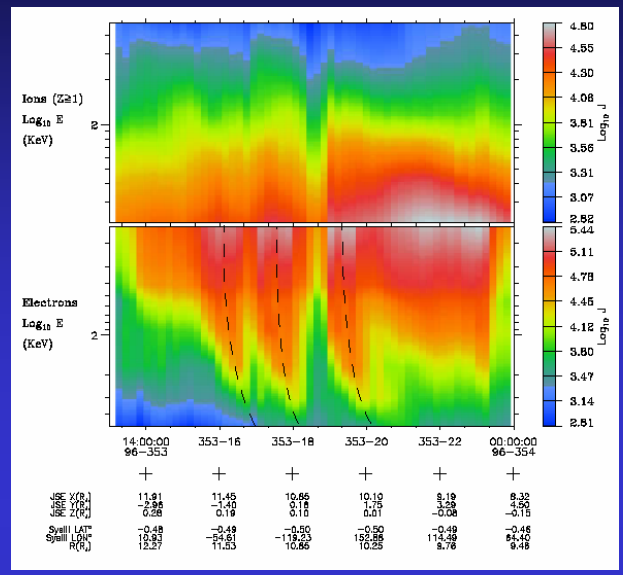


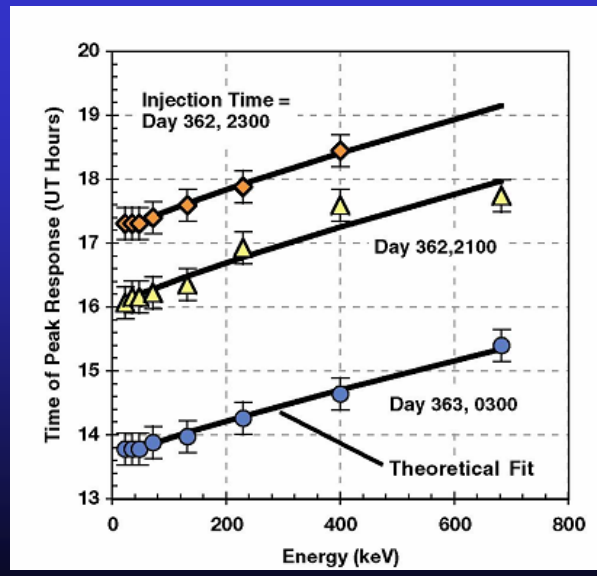
McComas, 2007

Dynamics:

Particle injections in Jupiter's and Saturn's magnetosphere

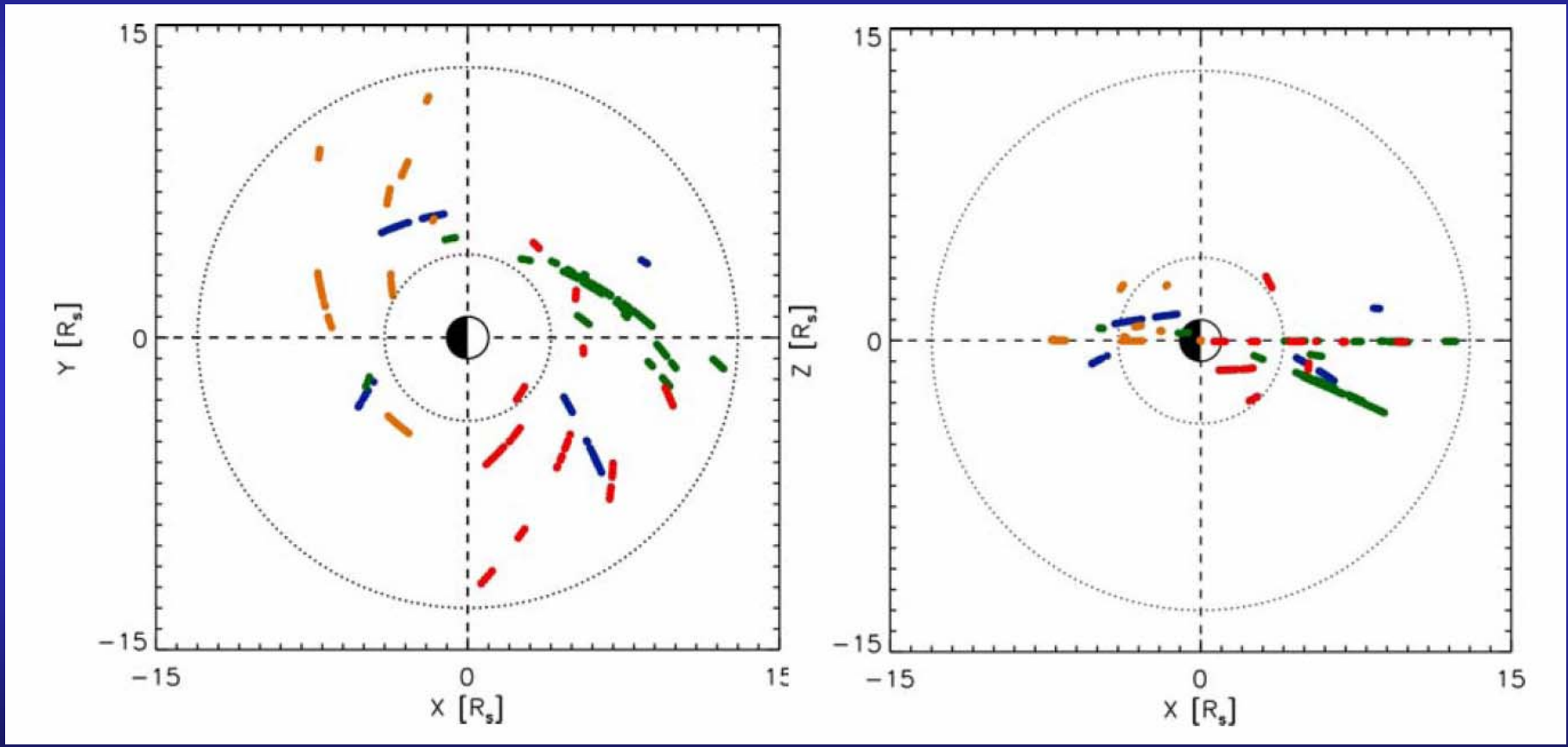






Sudden radial injections over confined regions in azimuth followed by slow, dispersive, azimuthal drifts (Mauk et al.)

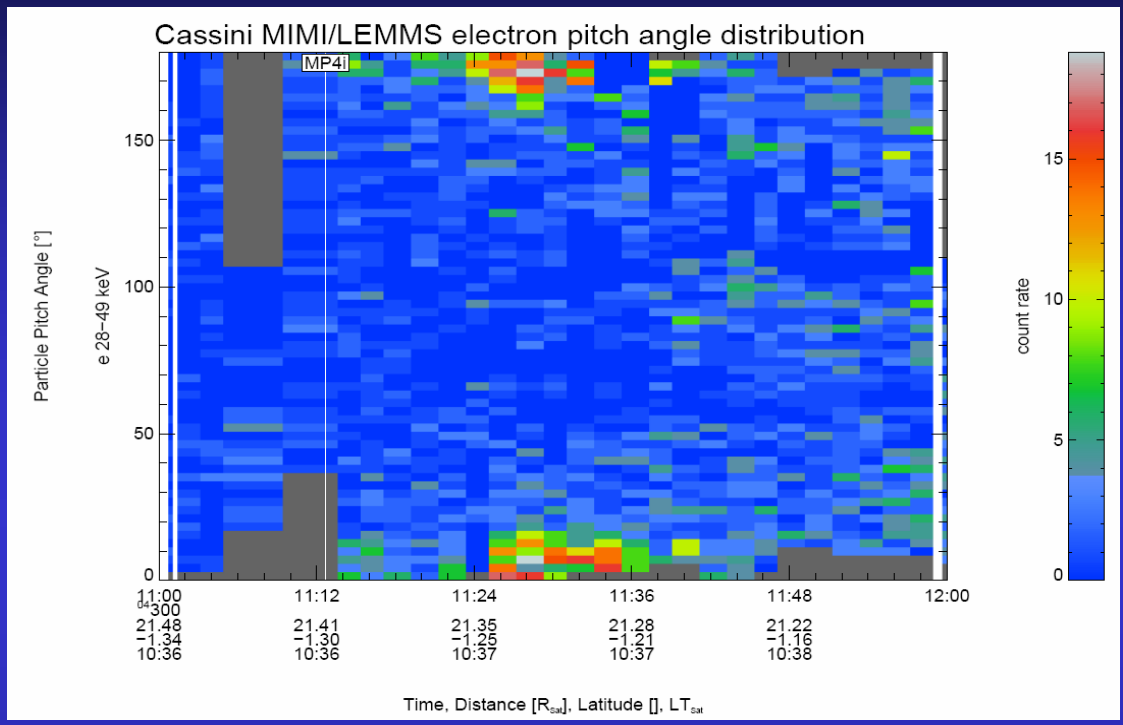
Dynamics:
Overview of observed injection events in Saturn's magnetosphere

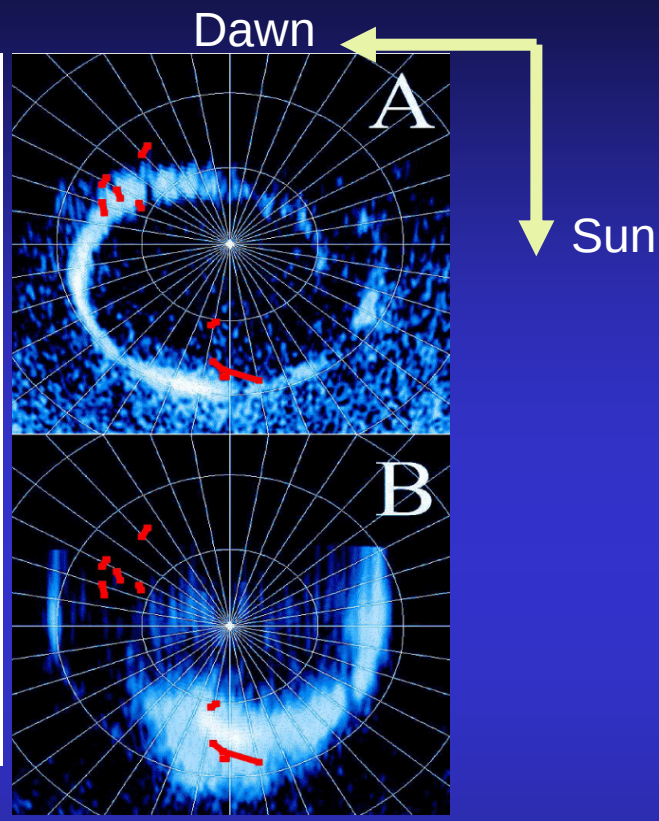


A. Müller, 2009

Dynamics

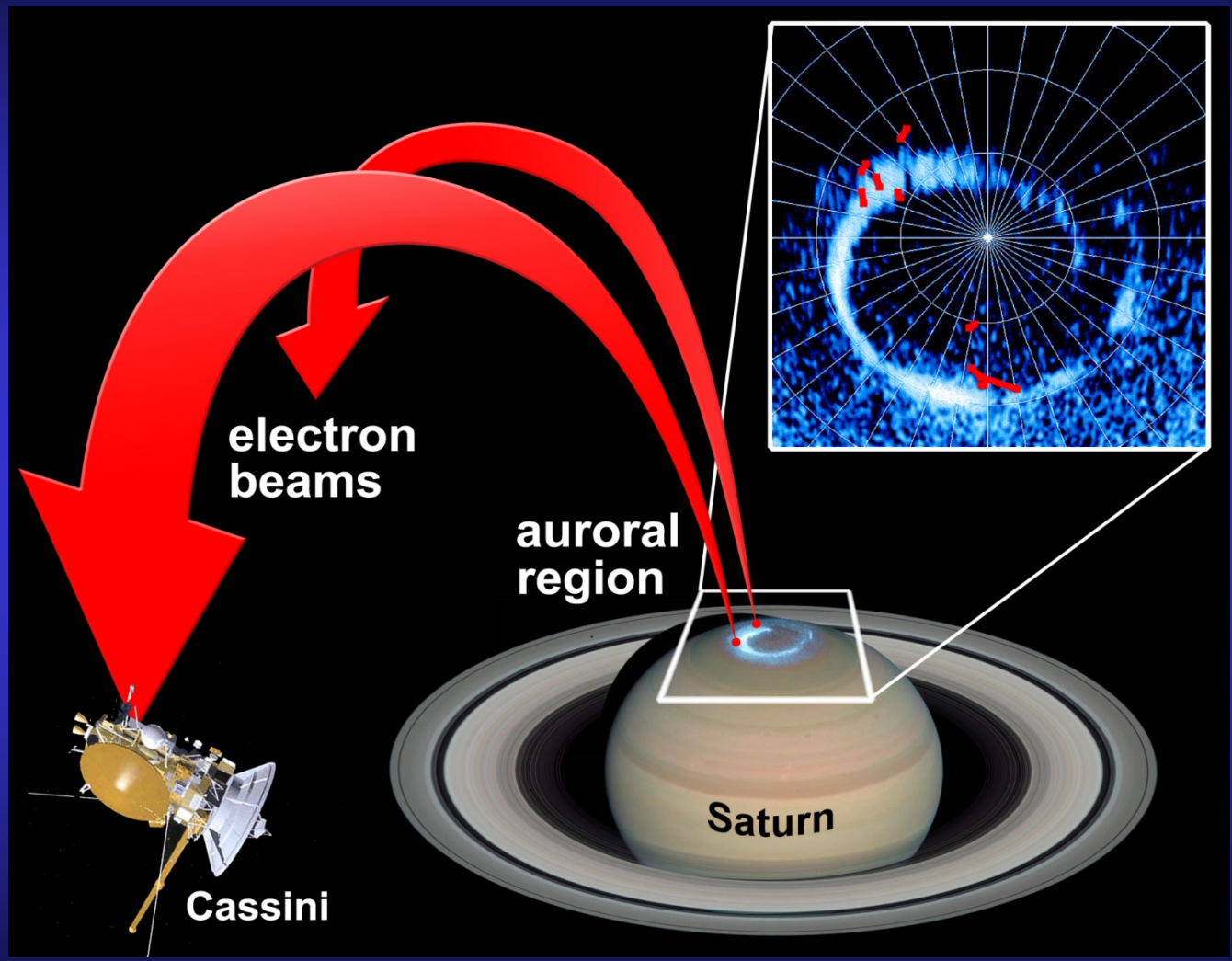
Electron beams and their relation to auroral emissions at Saturn





- FUV auroral images from HST STIS instrument (Gérard et al., JGR 2009, 2007, 2004) [no observations of the aurora during the electron beam events]
- ~80 deg latitude feature corresponds to just inside m'pause; others are from much deeper in the magnetosphere.
- Periods of electron counterstreaming map into auroral zone. Beams map well in a statistical sense into the regions of Saturn's aurora.

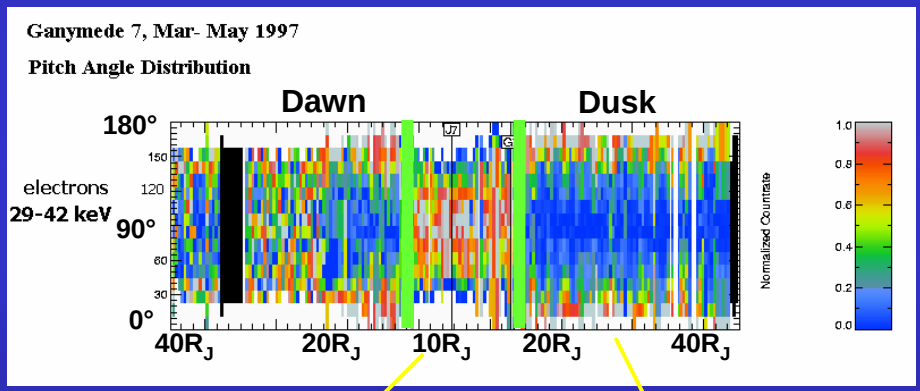
Dynamics
Electron beams and their relation to auroral emissions at Saturn

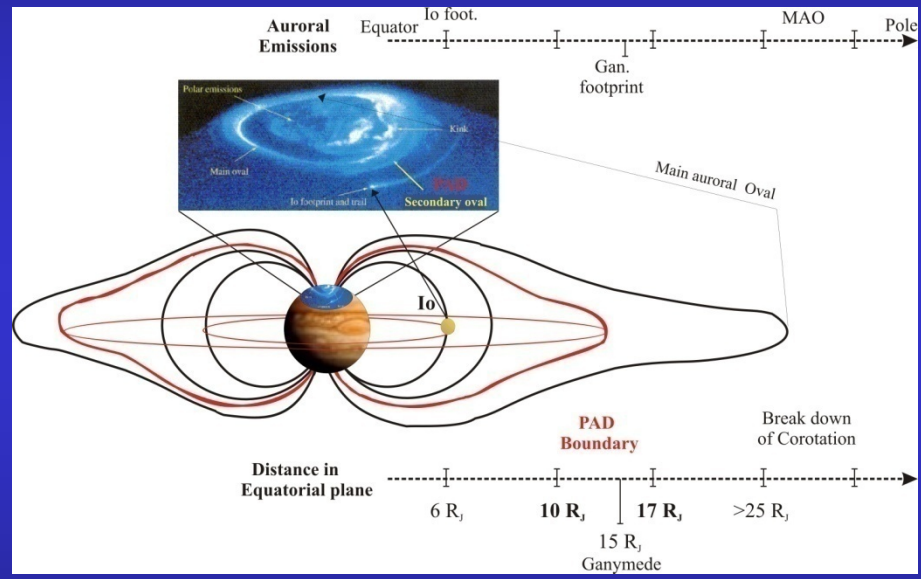


Saur et al., Nature, 2006

Dynamic:
Energetic electron measurements at Jupiter (Galileo EPD observations)

Most prominent and well defined boundary → change in the electron pitch angle distributions located between 10 and 17 R_J.





Inner Region

Pancake distribution with electrons maximum at 90^0

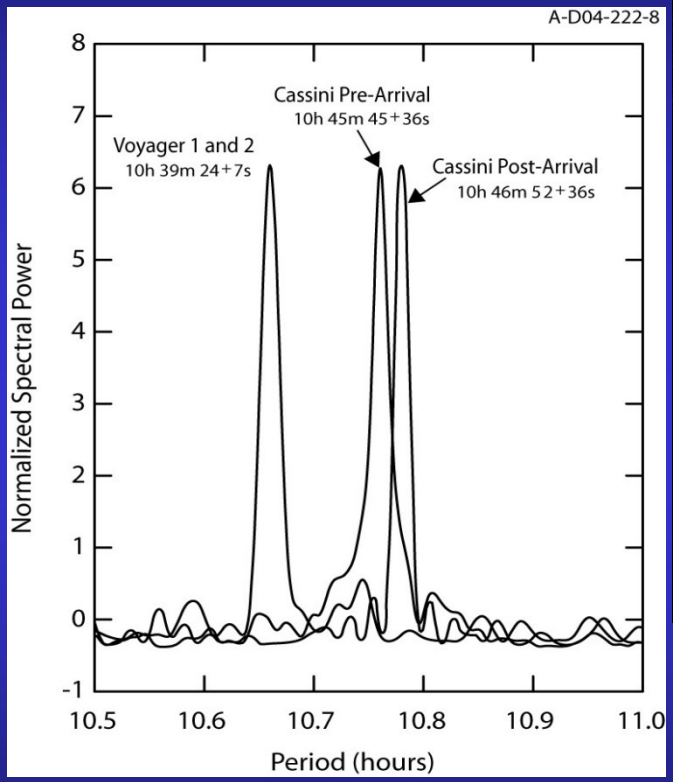
Outer Region

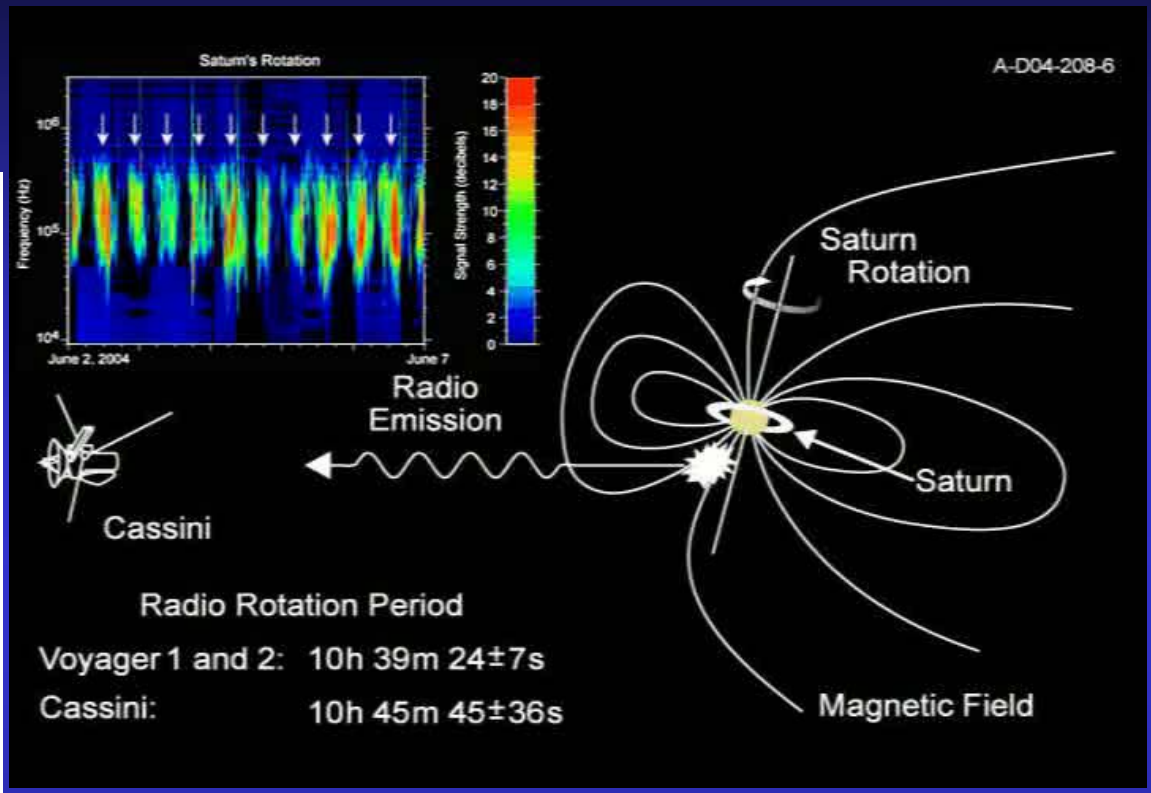
Field aligned

bi-directional electrons

Tomas, 2004

Dynamics:
Periodicity of Saturn Kilometric Radiation





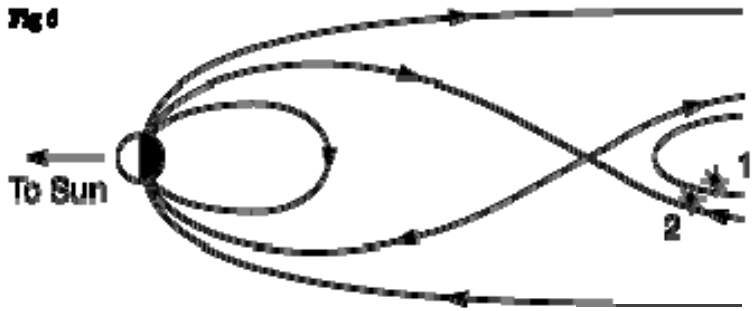
Cassini has found a different radio period than Voyager. The radio period is usually used to determine the rotation period of gas giant planets. A major mystery for Cassini to solve is the reason for the variation of the radio period.

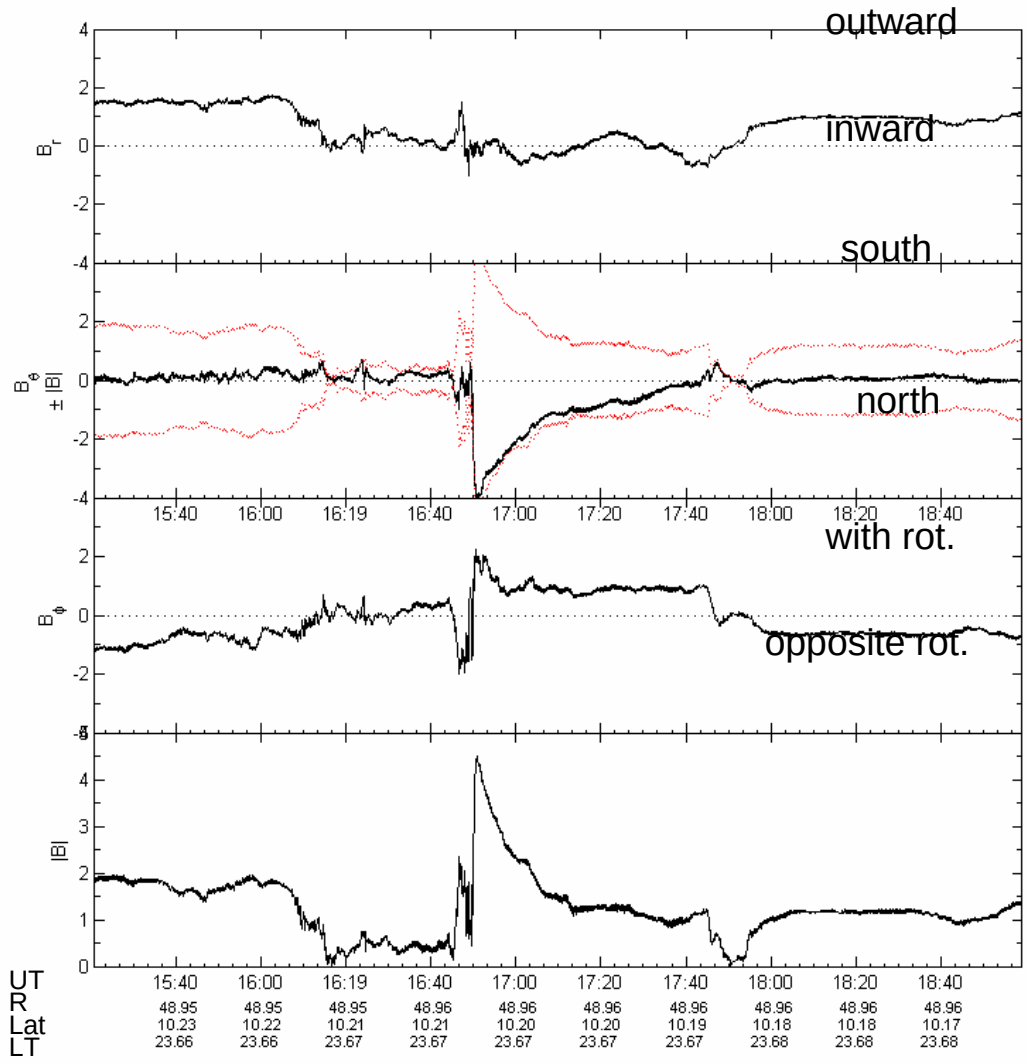
Kurth et al., 2006

Dynamics:

Plasmoids and Tail Reconnection in Saturn's magnetotail

- Surveyed all Cassini tail data – study of multiple events reveals clear rapid dipolarizations
- Events 35-55 RS downtail and midnight to post midnight sector
- Example – day 216 2006. Northward turning of the magnetic field (theta component)
- Future work will involve a full multi-instrument study including MAG,CAPS, MIMI and RPWS.





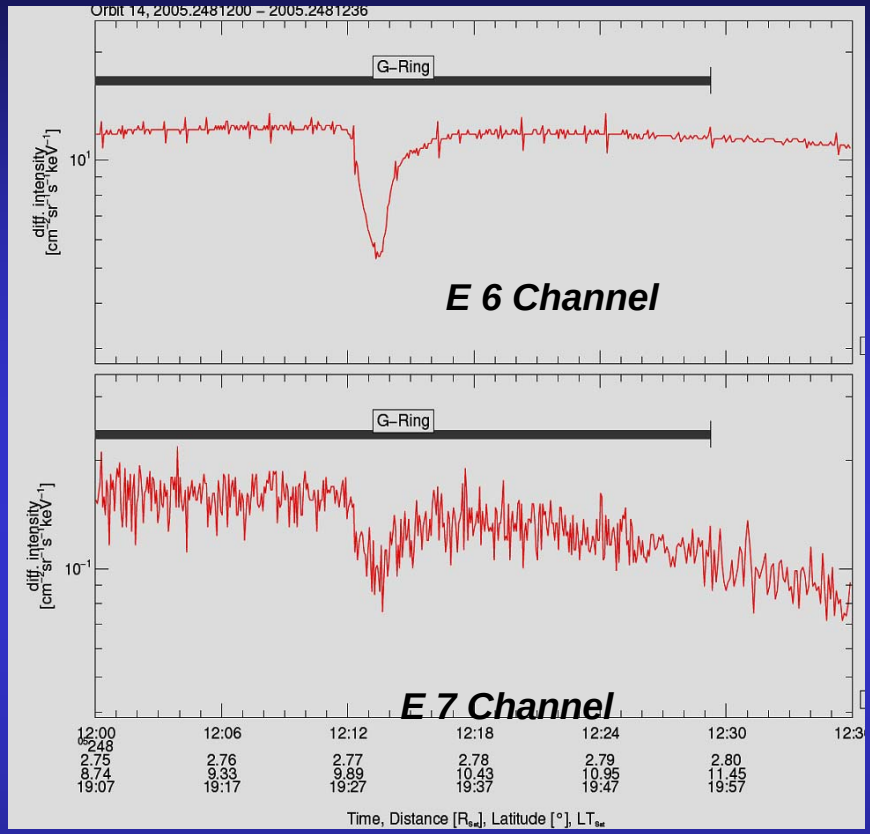
Jackman et al., 2007

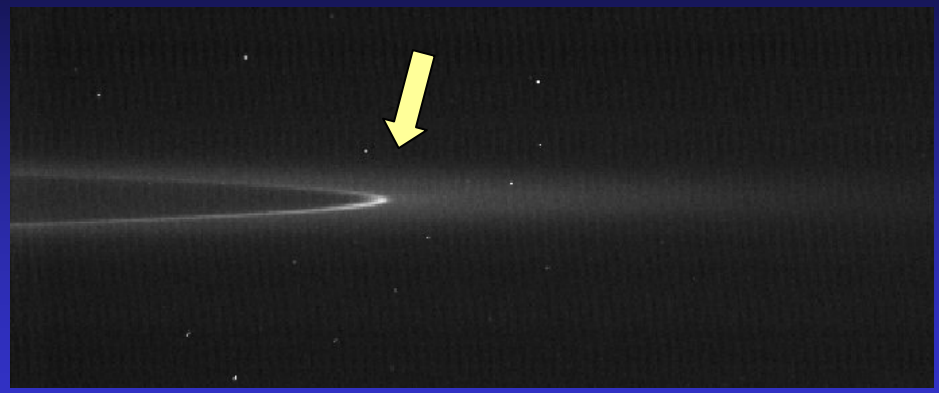
Magnetosphere-moon/ring material interaction

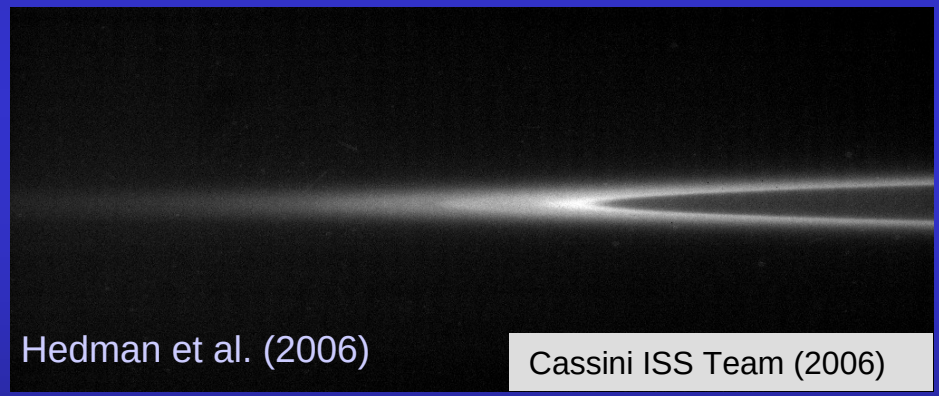
MPS
Max-Planck-Institut für Sonnensystemforschung

Magnetosphere-ring material interaction

ring material in the Saturnian G-ring arc







Hedman et al. (2006)

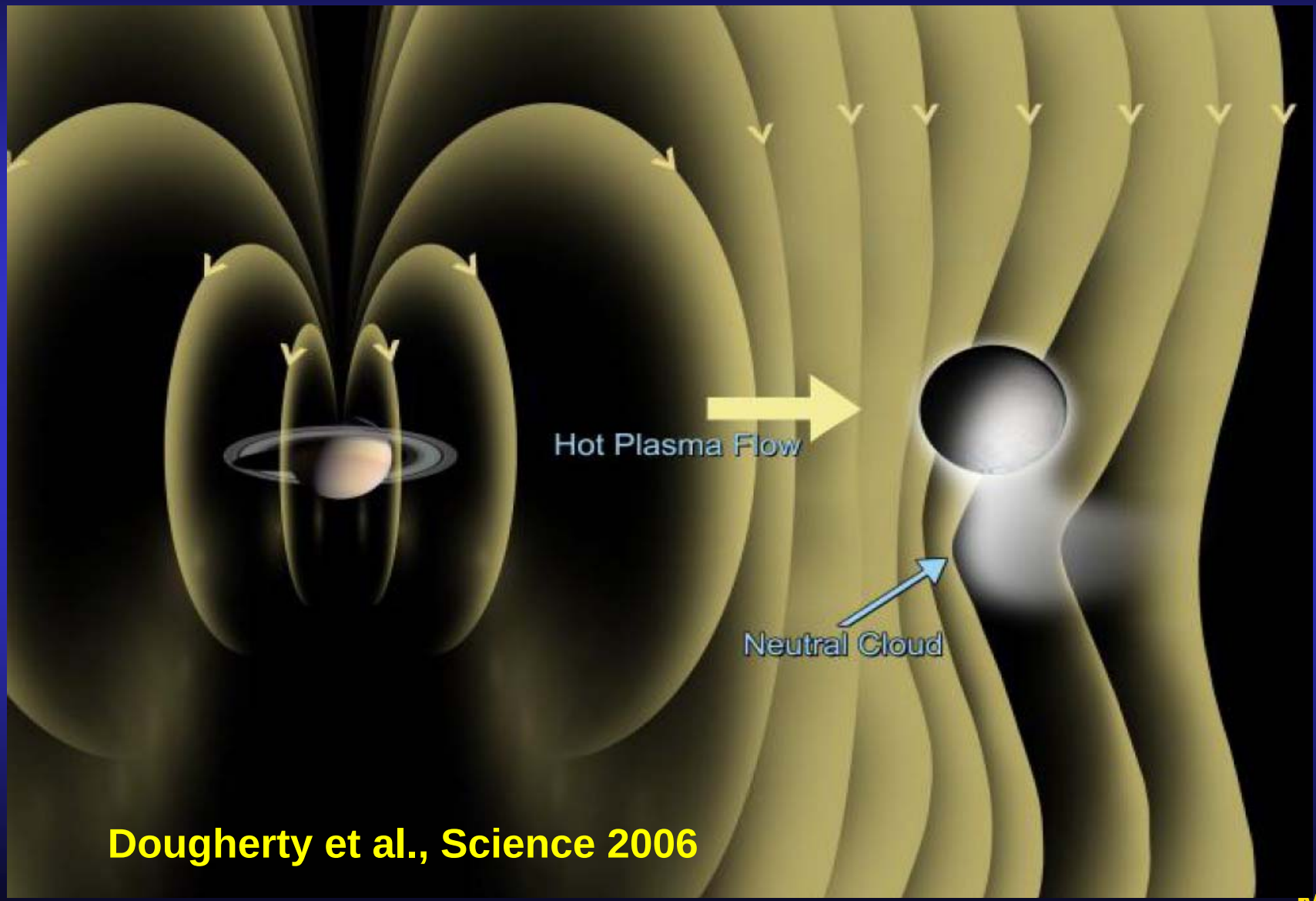
Cassini ISS Team (2006)

Hedman et al., Science 2007 ; Roussos et al., Icarus 2007

- **Cassini flew over the arc around the time the microsignature was recorded. Estimated mass of absorbers: 108 – 1010 kg (~100 m diameter sphere)**
- **Solution to the origin of the G-ring: Collisions between big particles produce micron-sized populations (visible arc); Non gravitational forces (mainly ion collisions) add momentum to the small dust grains → outward radial motion→ G-ring**

Magnetosphere-moon interaction

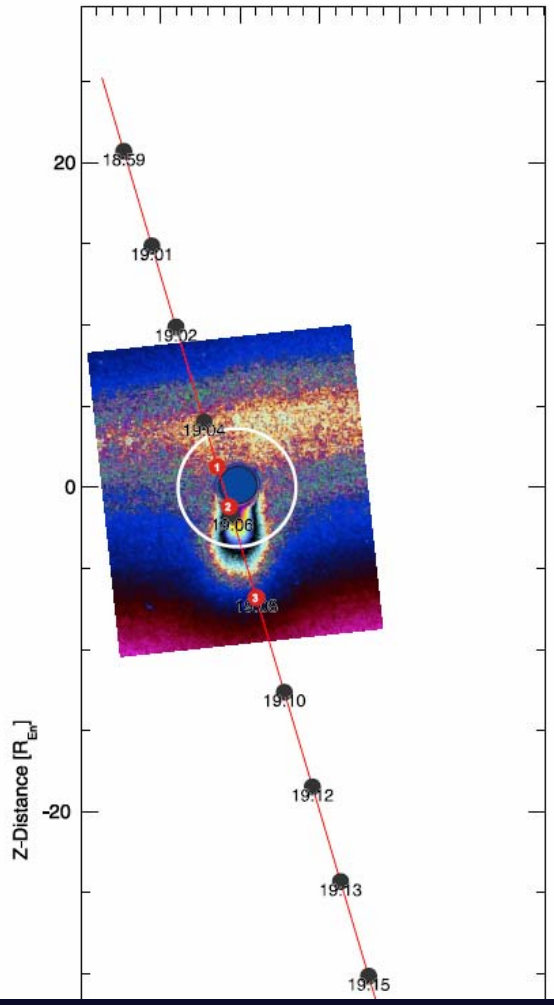
Enceladus- Imprint on the Saturnian magnetosphere



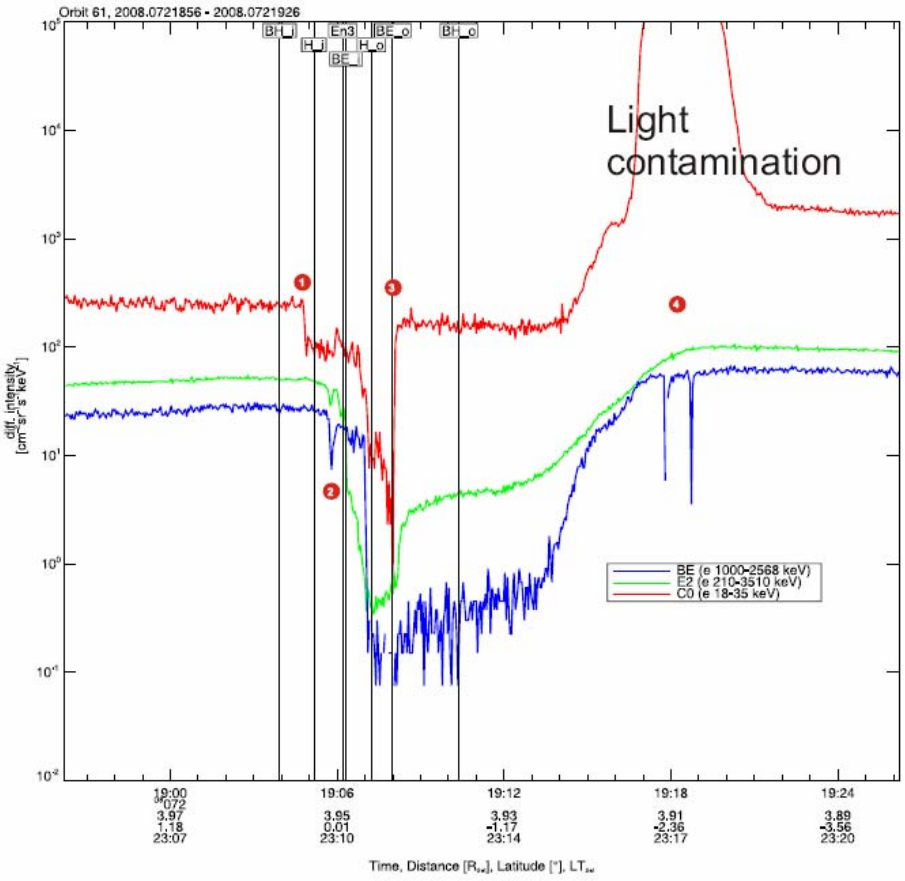
Dougherty et al., Science 2006

Magnetosphere-moon interaction
Enceladus plume

Enceladus flyby E3

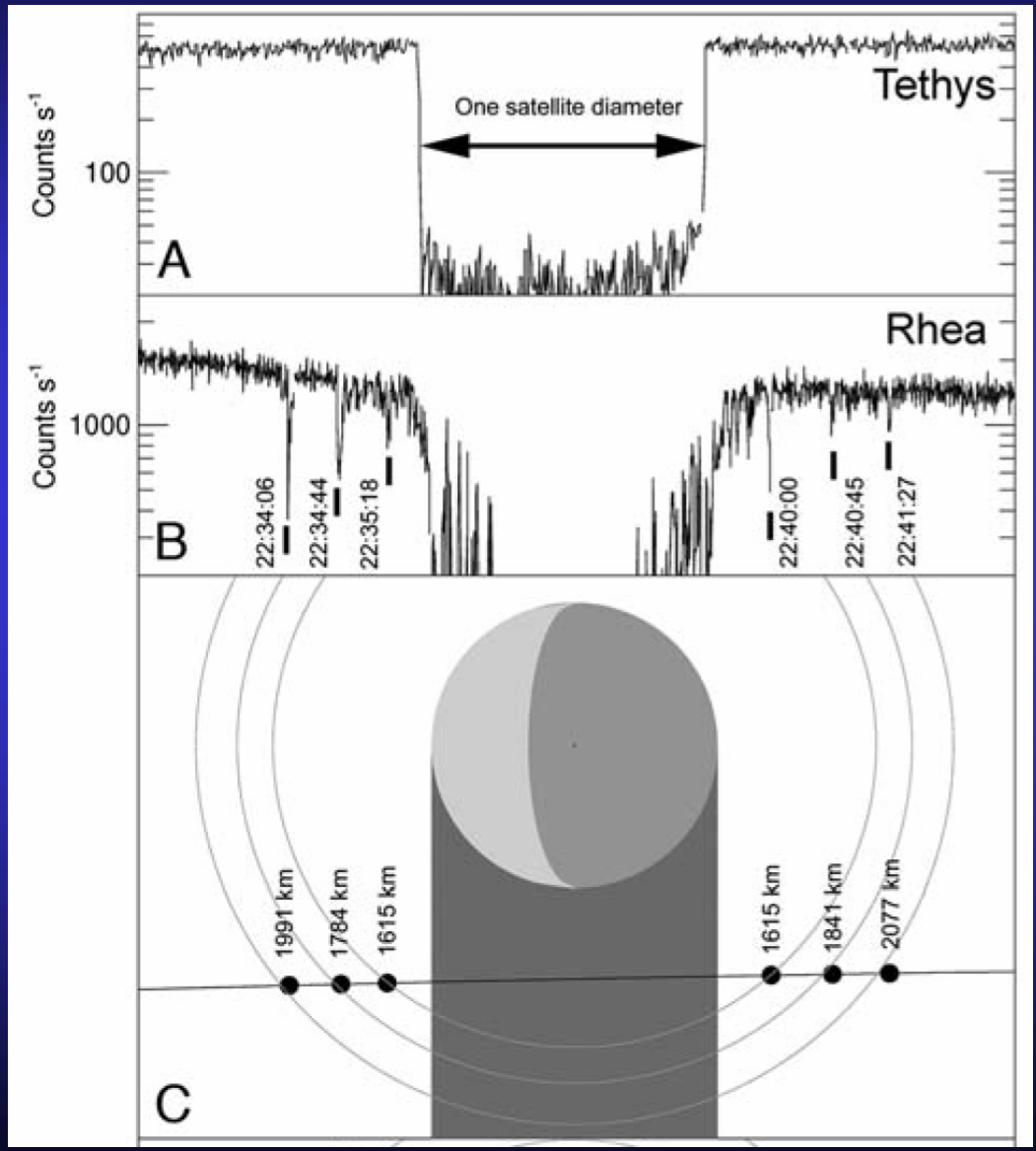


Cassini MIMI/LEMMS electron measurements



Magnetosphere-moon interaction

Evidence for orbiting material around the Saturnian moon Rhea



Jones et al, Science, 2008

Jupiter: Summary and open questions

- Jupiter's magnetosphere sub-corotates on average out to at least 150 RJ in the magnetotail
- dawn-dusk asymmetry in the flow pattern inside 40-50 RJ with smaller velocities at dusk (correlated to thickness of plasma sheet and diffuse vs. discrete aurora)
- radial (tailward) periodic disruptions of flow pattern in predawn and midnight sector. Released plasmoids observed down the magnetotail at least out to > 2500 RJ
- Stagnated flow signatures in afternoon magnetosphere
- Galileo measurements restricted to equatorial plane. How does the high-latitude magnetosphere look like? → JUNO

Saturn: Summary and open questions

- **Saturn‘s magnetosphere is rotation-dominated with Enceladus as the major internal plasma source**
- **Is there a corotation breakdown and is there a similar process responsible?**
- **What is the rate of corotation?**
- **What is the rotation rate of the Saturnian magnetosphere?**
- **Is there a steady state reconnection line in the magnetotail?**