



# ***Planetary Magnetospheres***

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- **...**

## Literature

- Kivelson and Russell, *Introduction to Space Physics*, Cambridge Univ. Press, 1995.
- Roederer, *Dynamics of geomagnetically trapped radiation*, Springer, 1970
- Walt, *Introduction to Geomagnetical Trapped radiation*, Cambridge Univ. Press, 1994.
- Chapman, Matthews, Vilas, *Mercury*, University of Arizona Press, 1989.
- Colin, Donahue, Hunten, *Venus*, University of Arizona Press, 1983.
- Jakosky, Snyder, Kieffer, Matthews, *Mars*, University of Arizona Press, 1993
- Dessler, *The magnetosphere of Jupiter*, Cambridge Univ. Press, 1983
- Bagenal, Dowling and McKinnon, *Jupiter*, 2007
- Gehrels and Matthews, *Saturn*, University of Arizona Press, 1984
- A new book about Saturn in preparation

## Outline

### Introduction

Basic concepts of magnetospheric physics

### The Magnetosphere of the Earth – the prototype

Regions

Current systems

### Planetary Magnetospheres

Overview

Mercury and Ganymede

Uranus and Neptune

Jupiter and Saturn

### Future missions

# The Magnetosphere

## Introduction and definitions

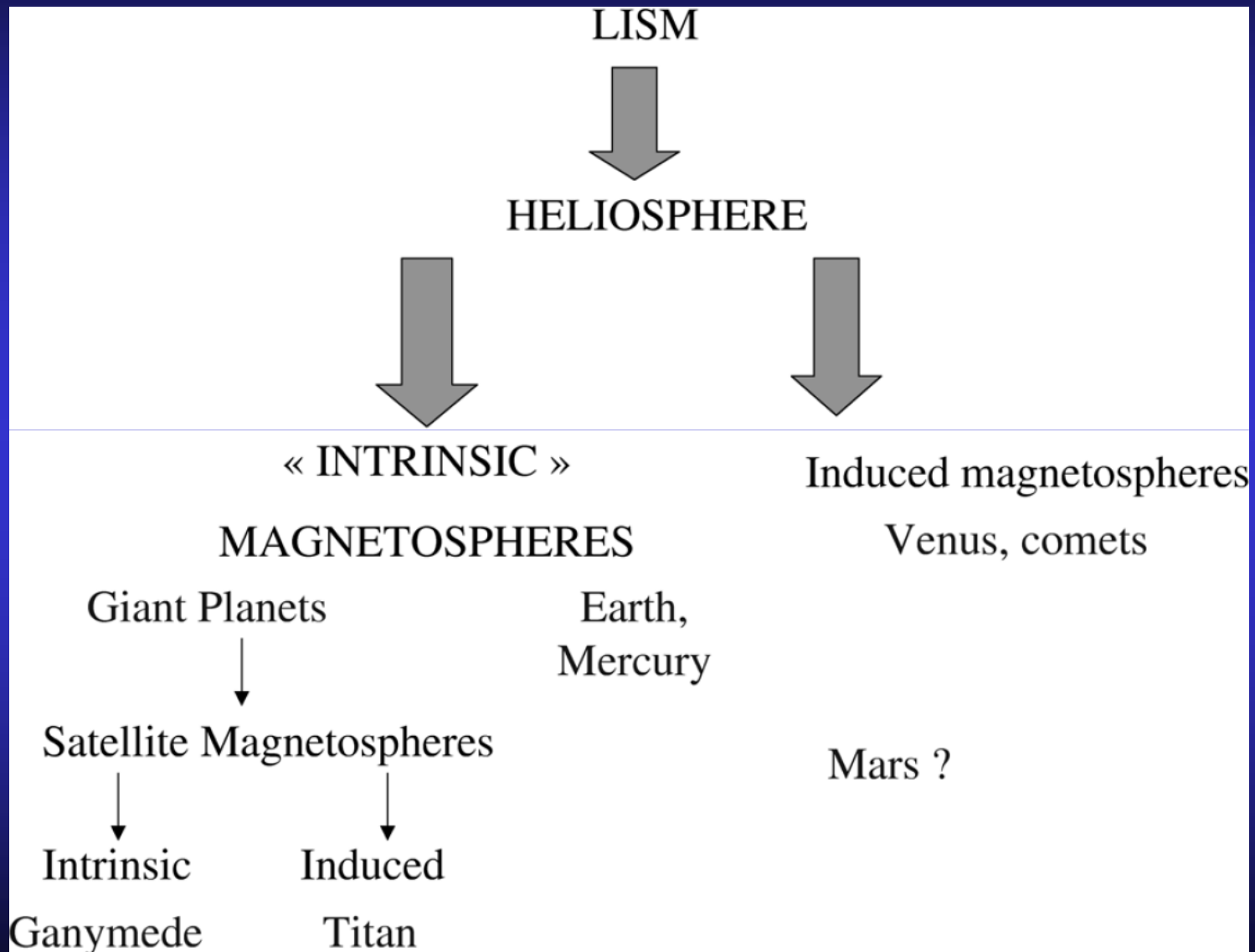
- A magnetosphere may form when a magnetized planetary object is embedded in a flowing plasma
- The magnetic pressure of the planet must be large enough to stand off the incident flow over at least some parts of the surface
- magnetospheres are surrounded by a magnetized plasma- the solar wind:
  - hot tenuous magnetized plasma whose source is the solar corona
  - flows radially outward from the Sun at supersonic speed (~400 km/s)
- the structure of a planetary magnetic field is modified by interaction with the solar wind
- a magnetized planet deflects the solar wind forming a cavity from which the solar wind is excluded -> the magnetosphere

# The Magnetosphere

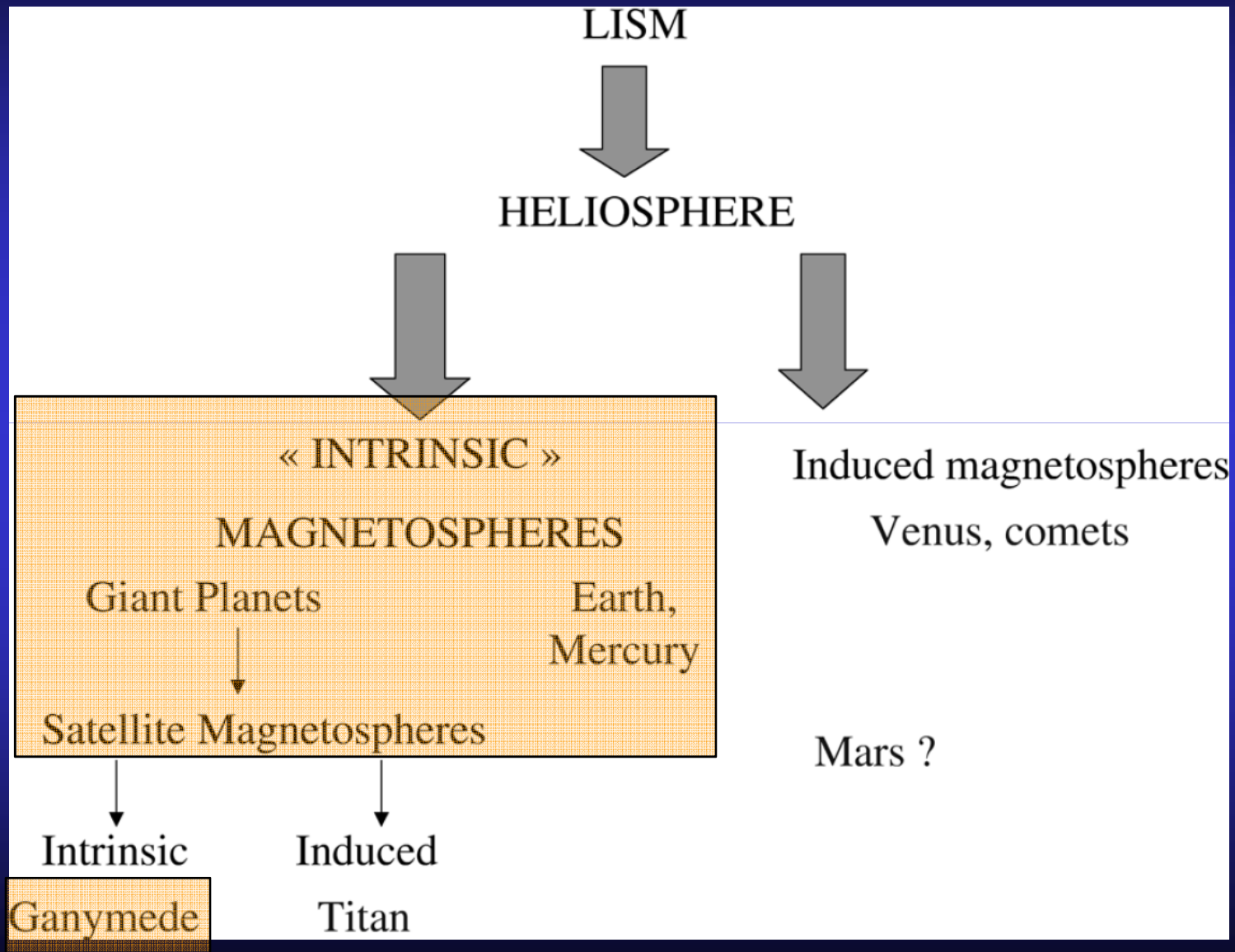
## Definitions

- **Term introduced by Thomas Gold in 1959**
- **Earth's magnetic field determines the motion of the charged particles**
- **Not a "sphere"- solar wind deforms the shape of the magnetosphere**
- **Proper magnetospheres (planets with internal B)**
  - Mercury, Earth, Jupiter, Saturn, Uranus, Neptune
  - neutron stars, pulsars, ...
  - magnetized moons (Ganymede) and asteroids (Gaspra?)
- **Solar wind induced magnetospheres**
  - Venus, Mars, Comets

# Planetary magnetospheres



# Planetary magnetospheres

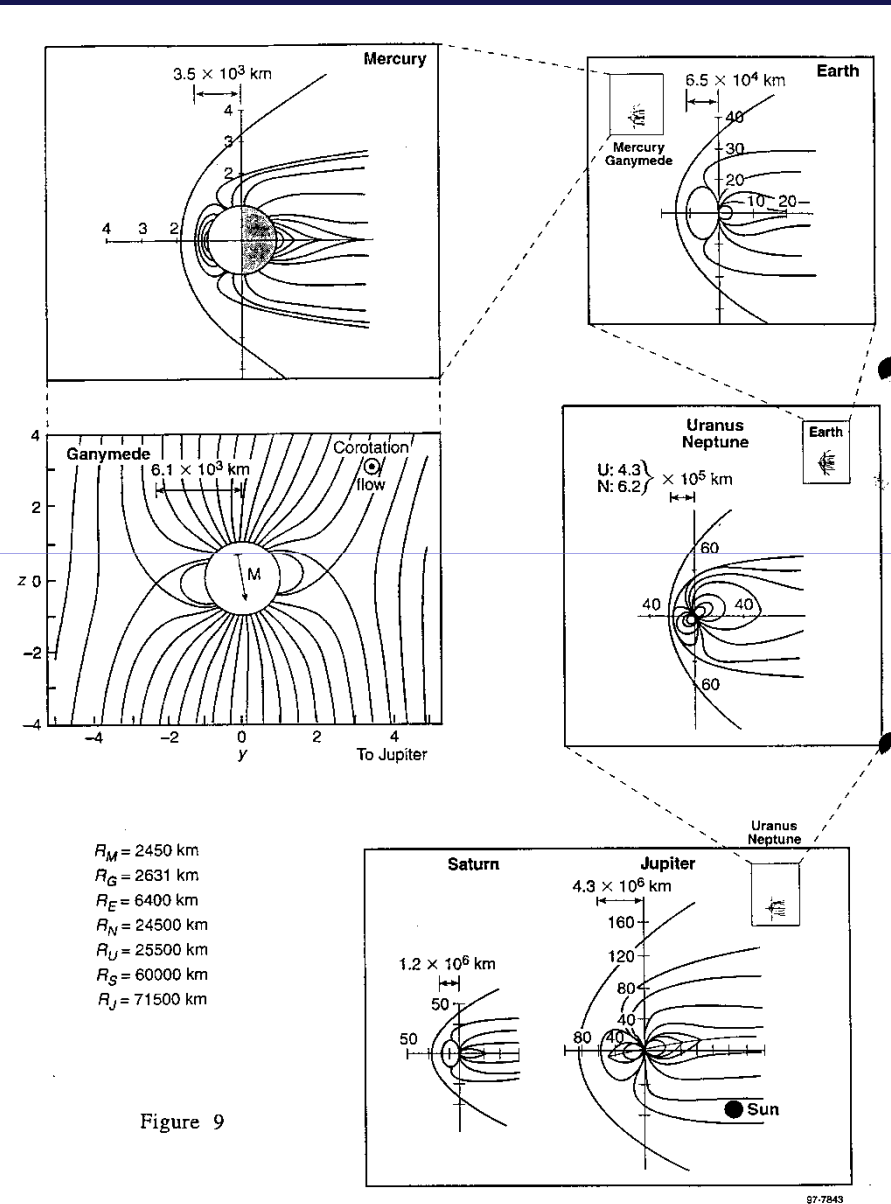


# Intrinsic planetary magnetospheres

small

intermediate

huge



## Sizes and shape

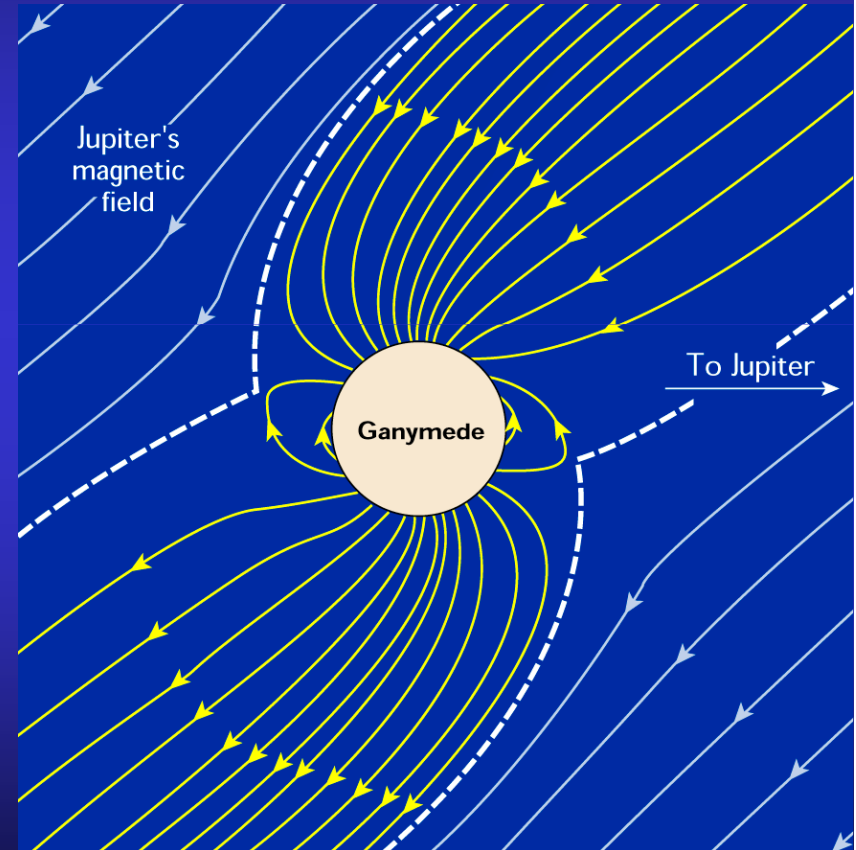
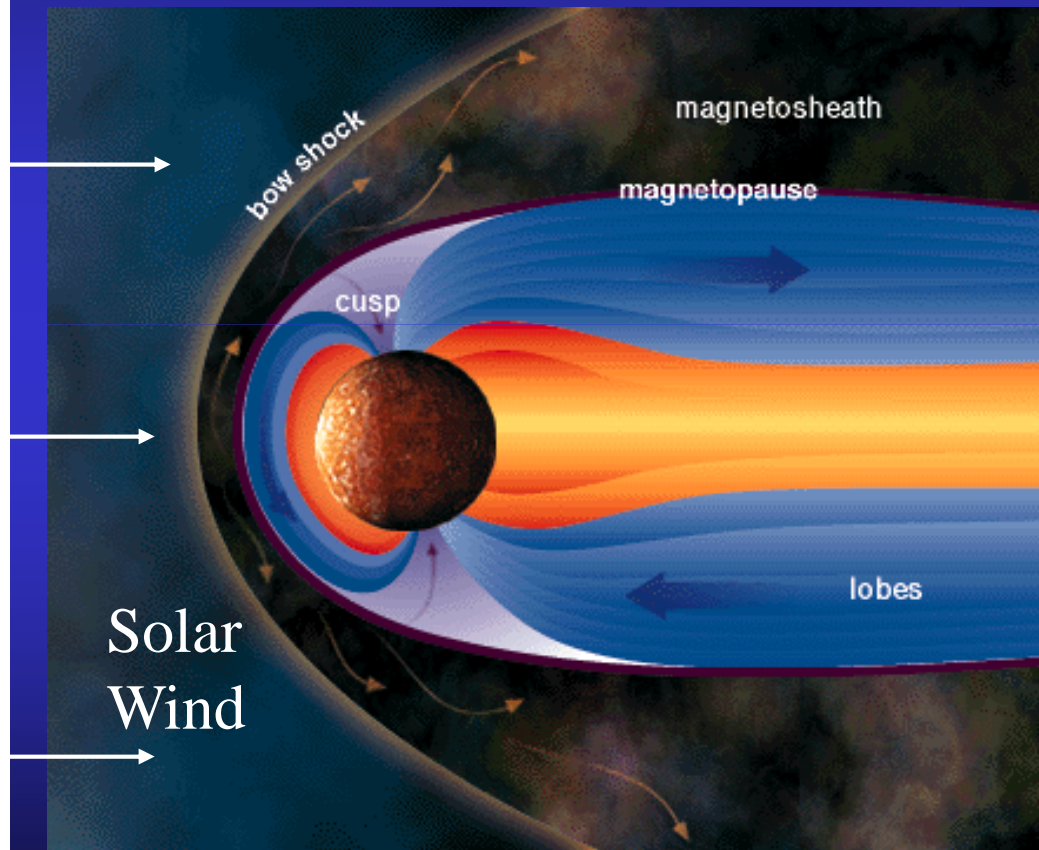
$$R_M/R_p \sim 1.2 \{B_o^2 / \rho_{sw} V_{sw}\}^{1/6}$$

	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
$B_o$	.003	.31	4.28	.22	.23	.14
$R_M$ Calc.	1.4 $R_M$	10 $R_E$	42 $R_J$	19 $R_S$	25 $R_U$	24 $R_N$
$R_M$ Obs.	1.4-1.6 $R_M$	8-12 $R_E$	50-100 $R_J$	16-22 $R_S$	18 $R_U$	23-26 $R_N$

## Small magnetospheres Mercury and Ganymede

Mercury - Magnetic field  
detected by *Mariner 10* in 1974

Ganymede - Magnetic field  
detected by *Galileo* in 1996

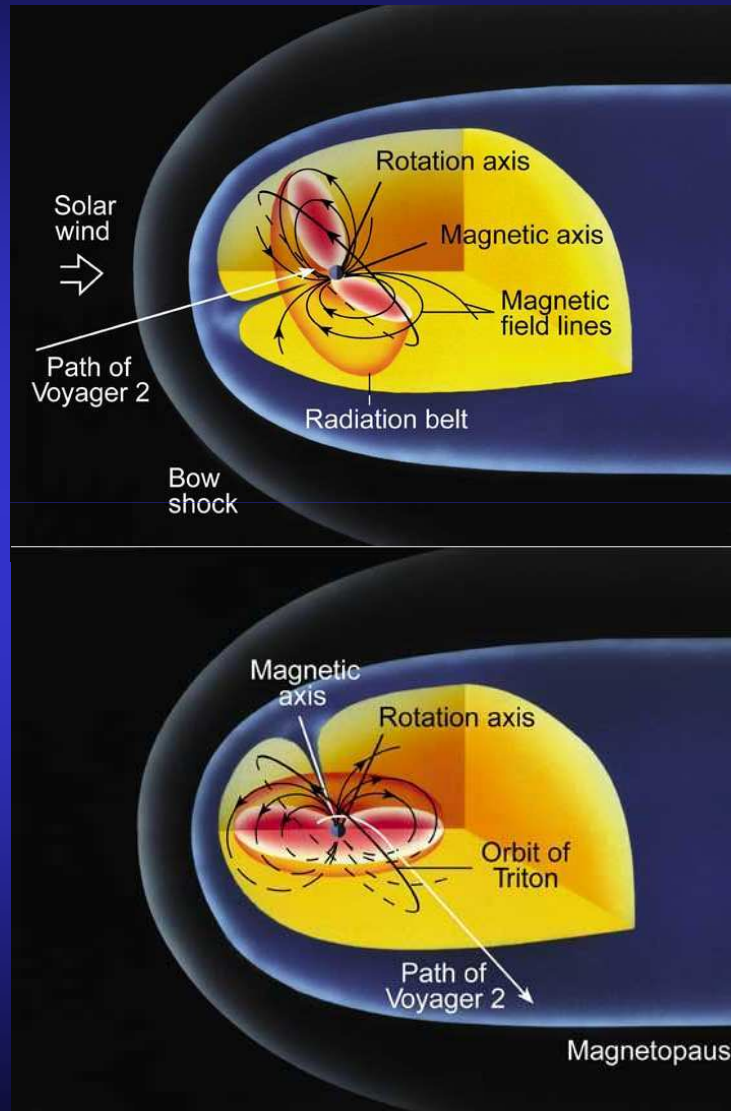


$B_{\text{surface}} \sim 1/100 \text{ Earth}$

————— | Diameter of Earth

# Huge magnetospheres

## Giant Planet Magnetospheres



- **Rotation Dominated**
- **Satellite plasma sources**
  
- **Jupiter and Saturn**
  - **Symmetric**
  - **~Dipolar**
  - **Strong plasma production**
  - **Limited solar wind influence**
  
- **Uranus and Neptune**
  - **Highly asymmetric,**
  - **Highly non-dipolar**
  - **Complex transport (SW + rotation)**
  - **Multiple plasma sources (ionosphere + solar wind + satellites)**

## Solar wind conditions

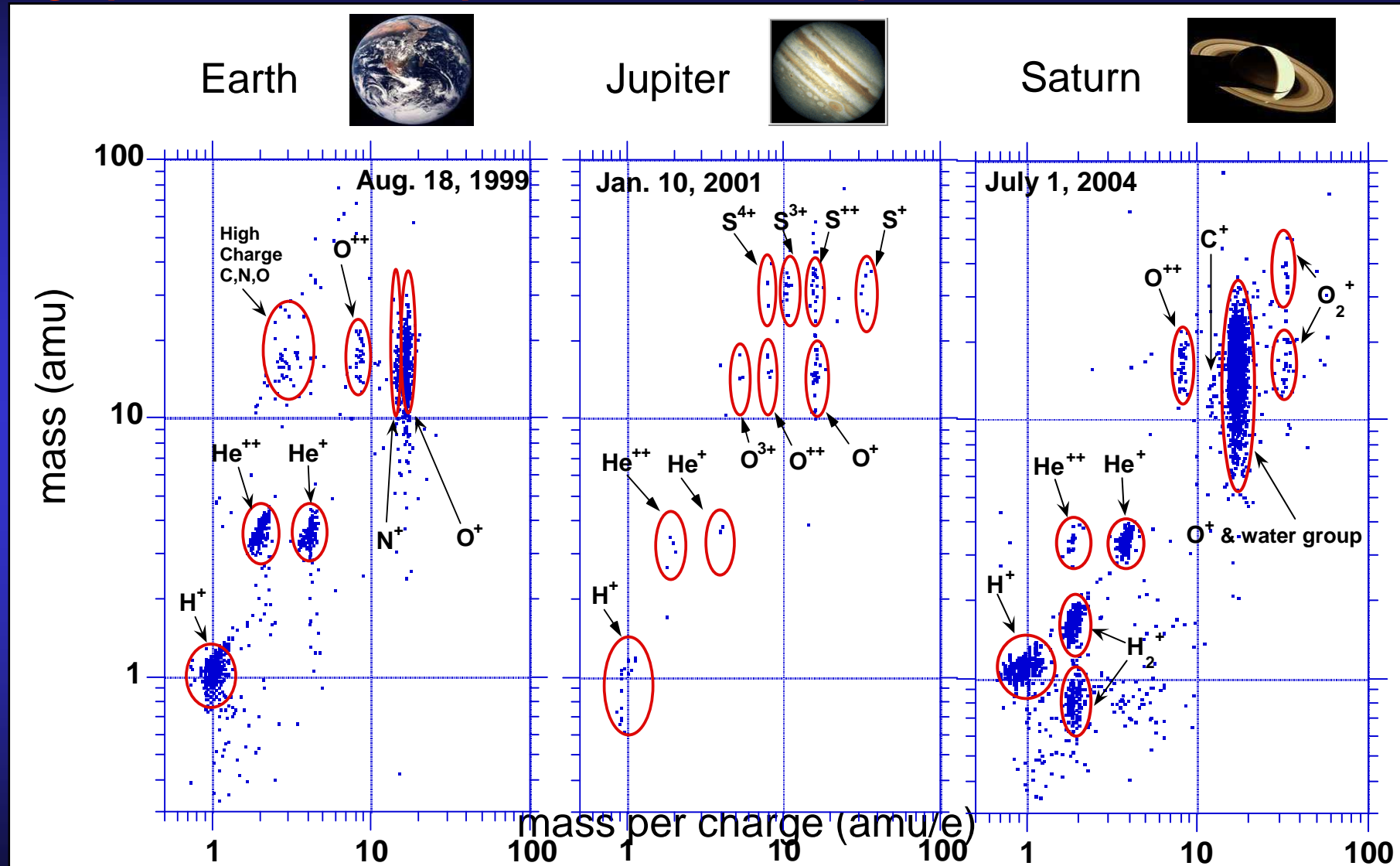
	Magnetic field	plasma density
• Mercury:	46 - 21 nT	73 - 33 cm <sup>-1</sup>
• Earth:	8 nT	5 cm <sup>-1</sup>
• Jupiter:	1 nT	0.2 cm <sup>-1</sup>
• Saturn:	0.6 nT	0.06 cm <sup>-1</sup>
• Uranus:	0.3 nT	0.01 cm <sup>-1</sup>
• Neptune:	0.005 nT	0.005 cm <sup>-1</sup>

The velocity is almost constant in the inner part of the heliosphere and ranges between 400 and 800 km/s

## Plasma sources

	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
$N_{\max}$ $\text{cm}^{-3}$	~1	1-4000	>3000	~100	~3	~2
Compo sition	$\text{H}^+$  Solar wind Exosphere	$\text{O}^+$ $\text{N}^+$ $\text{H}^+$ Iono- sphere Solar wind	$\text{O}^{n+}$ $\text{S}^{n+}$ $\text{H}^+$ Io Iono- sphere Solar wind	$\text{O}^+$ $\text{H}_2\text{O}^+$ $\text{H}^+$ Rings, Enceladus  Moons Solar wind	$\text{H}^+$  Iono- sphere	$\text{H}^+$ $\text{N}^+$ Triton, Iono- sphere
Source kg / s	?	5	700- 1200	~2-100	~0.02	~0.2

# Charge Energy Mass Spectrometer (CHEMS) on Cassini records “fingerprints” of ion composition at Earth, Jupiter, and Saturn



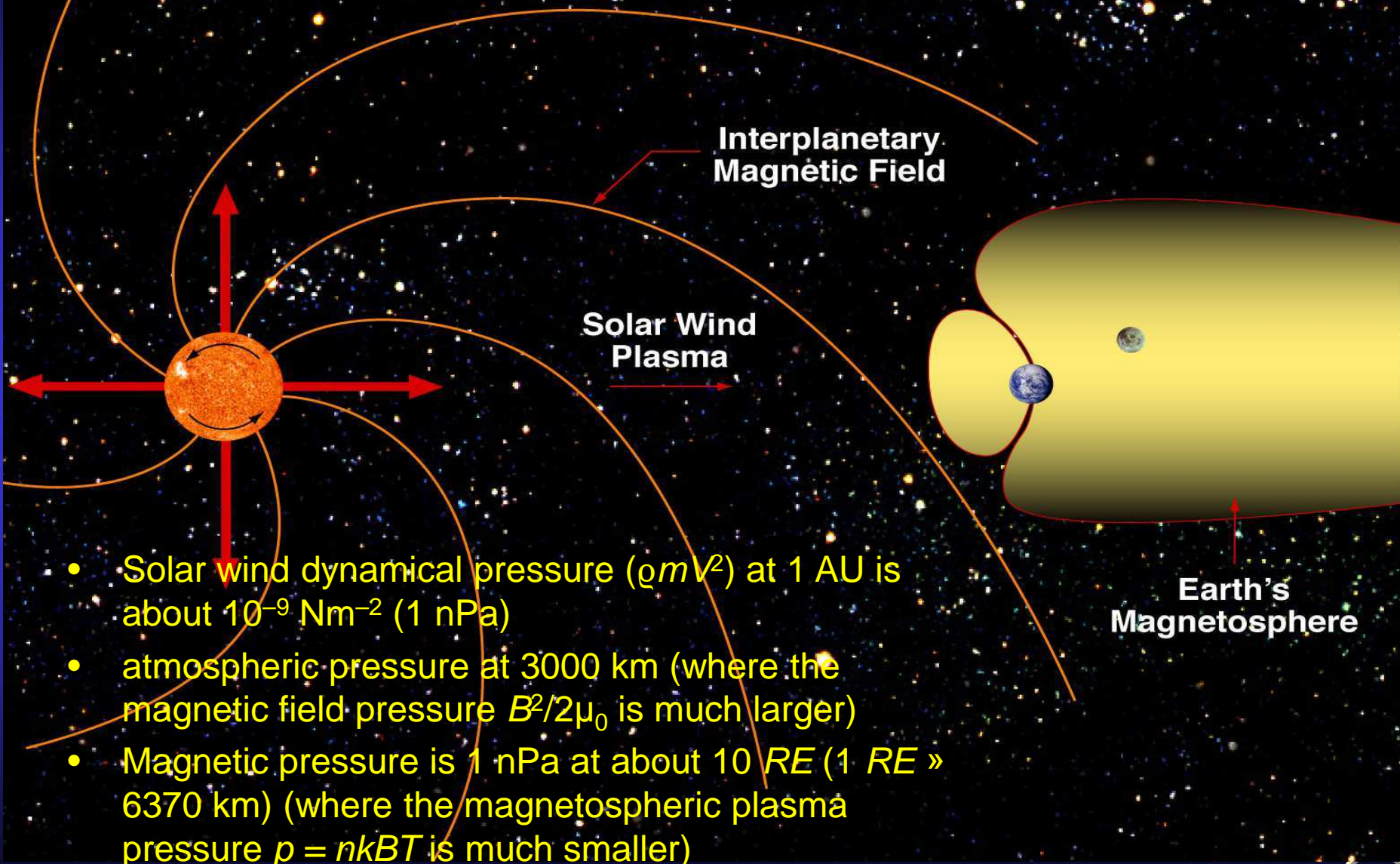


***The Magnetosphere of the Earth  
– the prototype***

***Environment  
Regions  
Plasma Sources***

## Solar wind

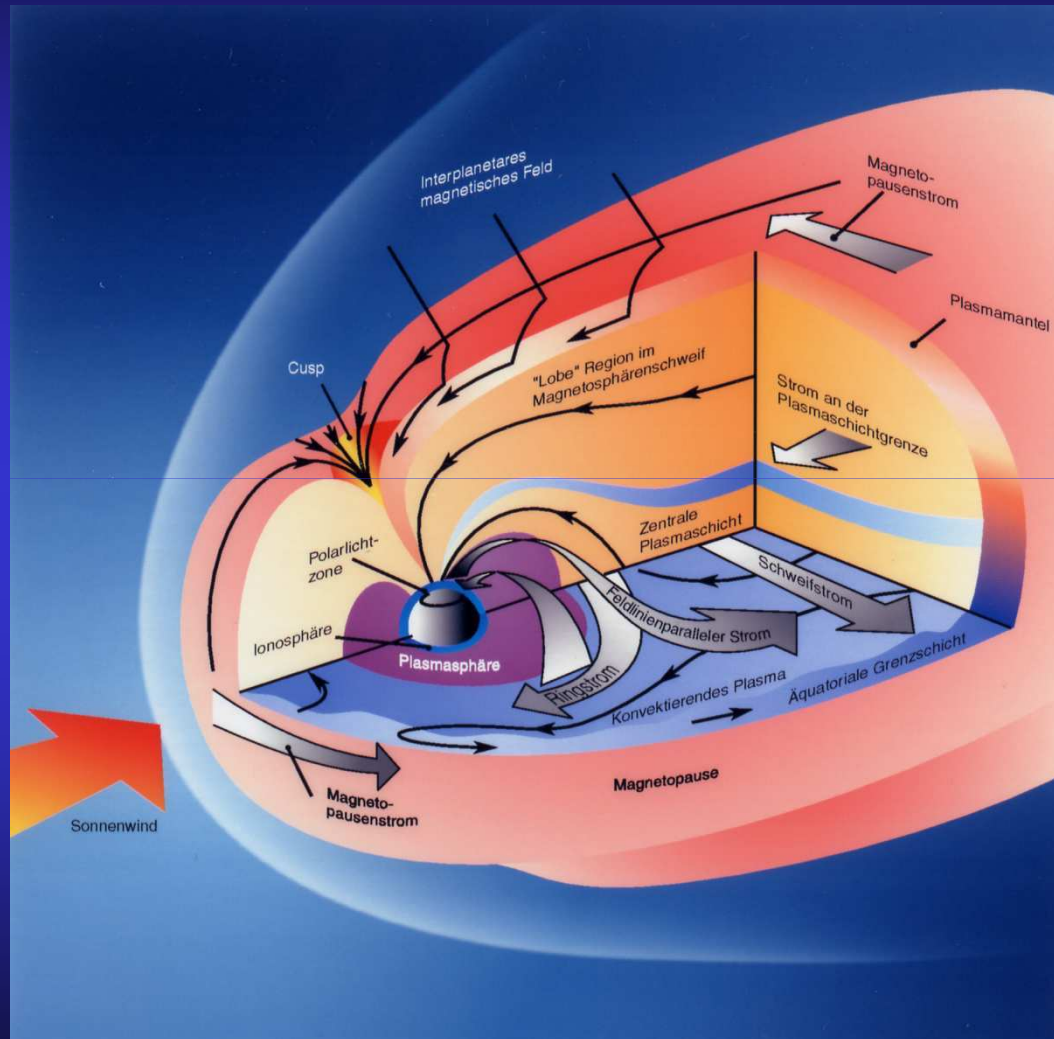
The embedding medium



- Solar wind dynamical pressure ( $\rho m V^2$ ) at 1 AU is about  $10^{-9} \text{ Nm}^{-2}$  (1 nPa)
- atmospheric pressure at 3000 km (where the magnetic field pressure  $B^2/2\mu_0$  is much larger)
- Magnetic pressure is 1 nPa at about 10  $RE$  (1  $RE$  » 6370 km) (where the magnetospheric plasma pressure  $p = nkBT$  is much smaller)

# The magnetosphere of the Earth

## The prototype magnetosphere



- **Regions:**
  - **Bow shock**
  - **Magnetosheath**
  - **Magnetopause and polar cusp**
  - **Plasmasphere and Plasmopause**
  - **Magnetotail Plasma sheet / Current sheet**
  - **Polar cap and Auroral Zone**

# **The magnetosphere of the Earth**

## **Regions**

- **Bow shock**
  - if incident flow is supersonic
- **Magnetosheath**
- **Magnetopause**
  - Separatrix surface between external and internal plasmas
- **Plasmapause**
  - Separatrix surface between plasma trapped over multiple rotations and plasma lost within a day
- **Magnetotail Plasma sheet / Current sheet**
- **Polar cap**
  - Surface linked to field lines with two ends on planet and those with one

## Plasma parameters for various regions in the magnetosphere

### 1. Solar wind

Outside Earth's magnetosphere.

$$n_e = [3 \dots 9] \text{ cm}^{-3}, kT_e = [100 \dots 10]$$

### 2. Plasma sheet/magnetotail

Outside about 10 RE to about 15 RE (Sunward) or several 100 RE tailward.

The configuration depends strongly on solar wind conditions (pressure).

$$n_e = [0.8 \dots 0.5] \text{ cm}^{-3}, kT_e = [1.7e3 \dots 2.5e4] \text{ eV}$$

### 3. Geosynchronous plasma environment

Outside plasmasphere out to approx. 10 RE.

$$n_e = [10 \dots 0.5] \text{ cm}^{-3}, kT_e = [1.e3 \dots 3.e3] \text{ eV}$$

### 4. Plasmasphere

Inside 4 to 5 RE. Outer boundary has local time variations.

$$n_e = [1.e4 \dots 1.e3] \text{ cm}^{-3}, kT_e = [0.2 \dots 1.2] \text{ eV}$$

## Magnetopause formation

The magnetopause is a surface where the dynamic pressure of the solar wind and the magnetic pressure of the magnetospheric plasma are in equilibrium:

$$p_{dyn} = 2n_{sw} m_p v_{sw}^2 = \frac{B^2}{2\mu_0}$$

The dynamic pressure of solar wind particles is transferred to the magnetospheric plasma by specular reflection of the particles at the boundary.

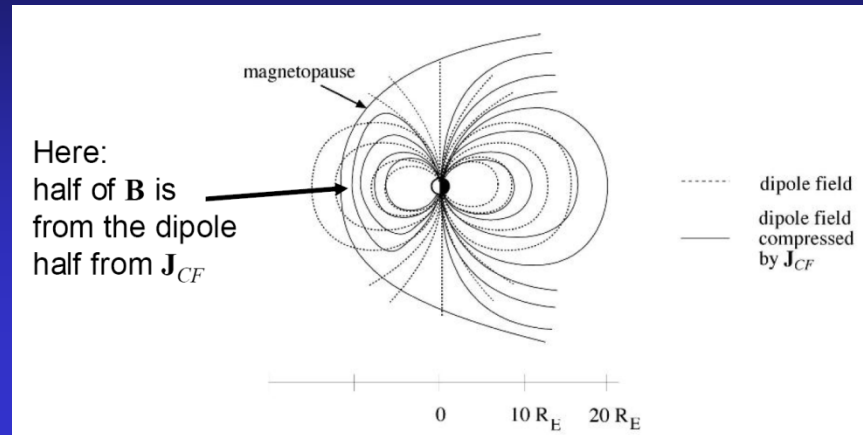
## Magnetopause position

The magnetopause stand-off distance along the Sun-Earth line is given by

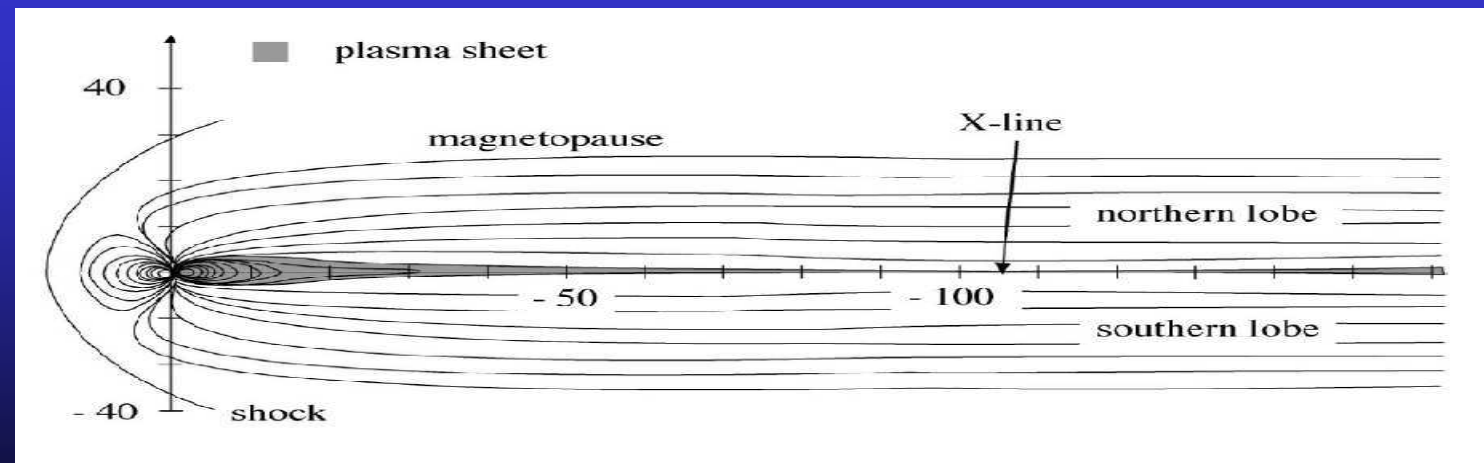
$$R_{MP} = \left( \frac{4B_{Surface}^2}{2\mu_0 k n_{sw} m_p v_{sw}^2} \right)^{1/6}$$

where  $k$  is a correction factor resulting from gasdynamic approximations to the magnetosheath flow.

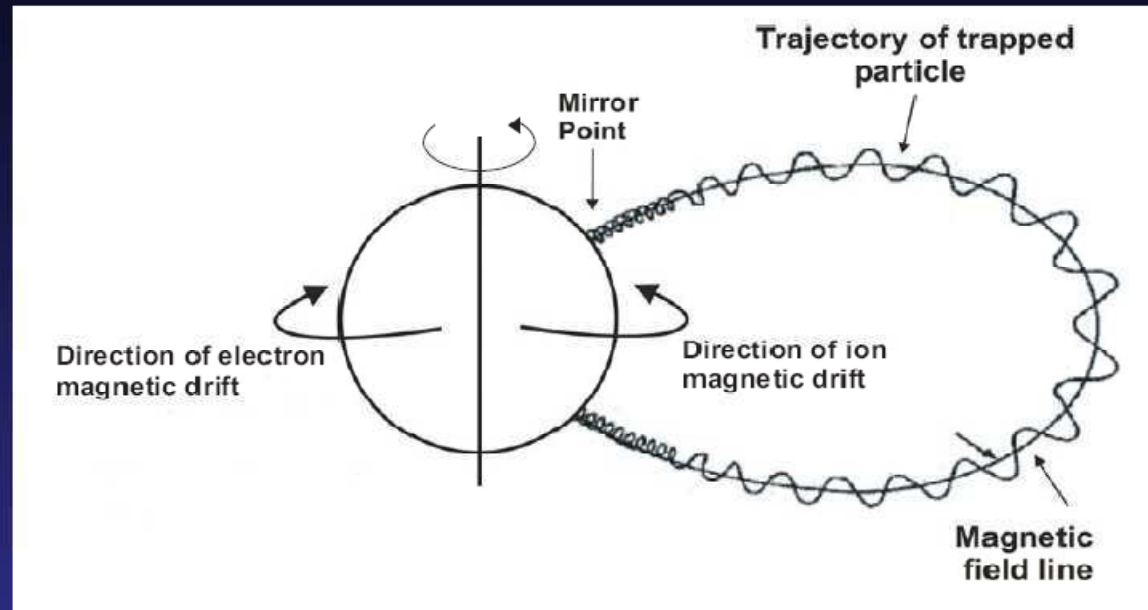
## Deformation of the Dipole magnetic field



- Note: the pressure balance predicts a raindropshaped magnetosphere
- The real magnetosphere has a long tail
- solar wind energy powers a current system to sustain the tail



# 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



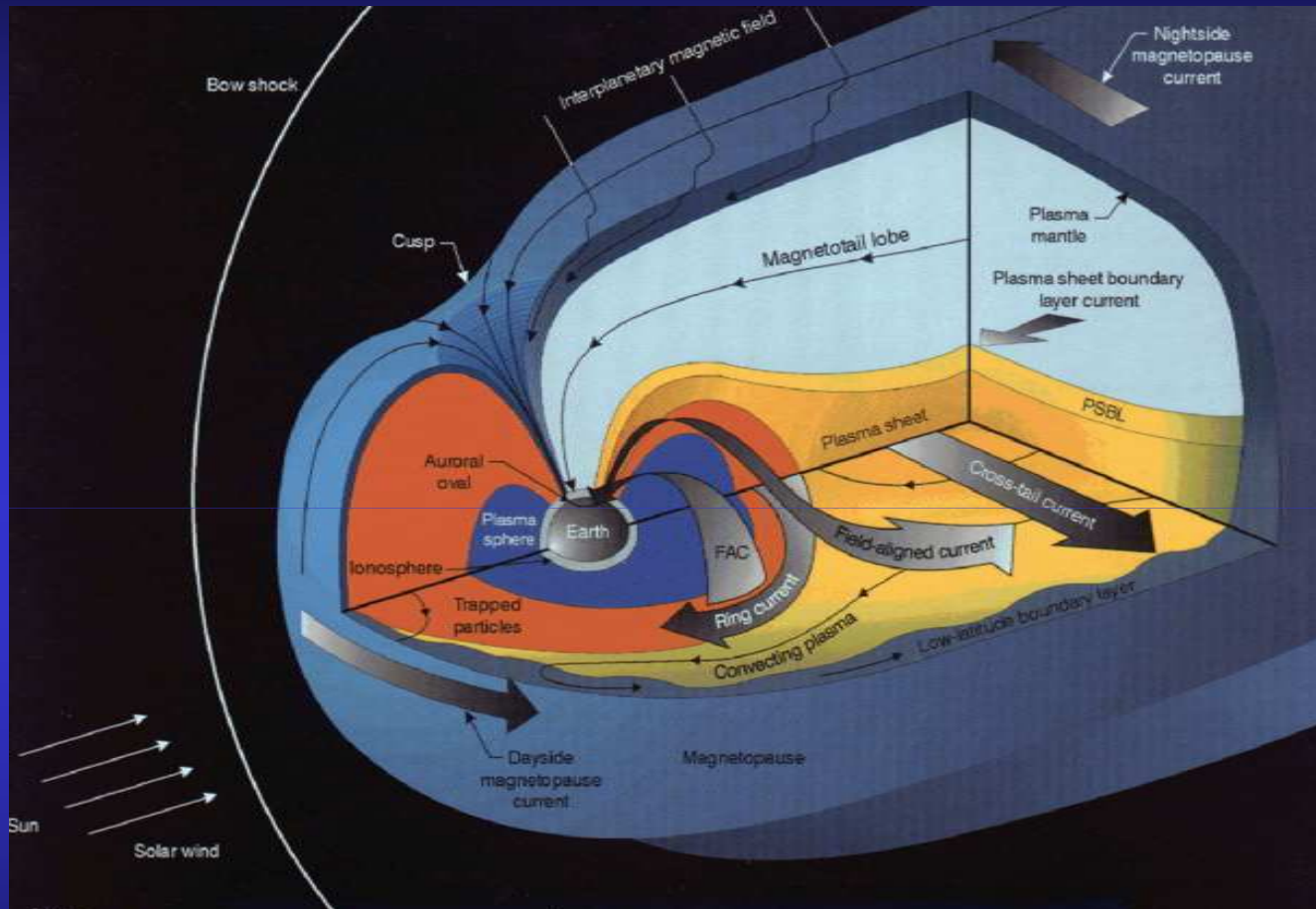
$$k = \int_{s_m}^{s'_m} \sqrt{1 - \frac{B(s)}{B_m}} ds$$

3. Third adiabatic invariant  
Drift motion



$$J_3 = q\Phi$$

# Electric current systems in the magnetosphere



**Magnetopause currents**

**Ring current**

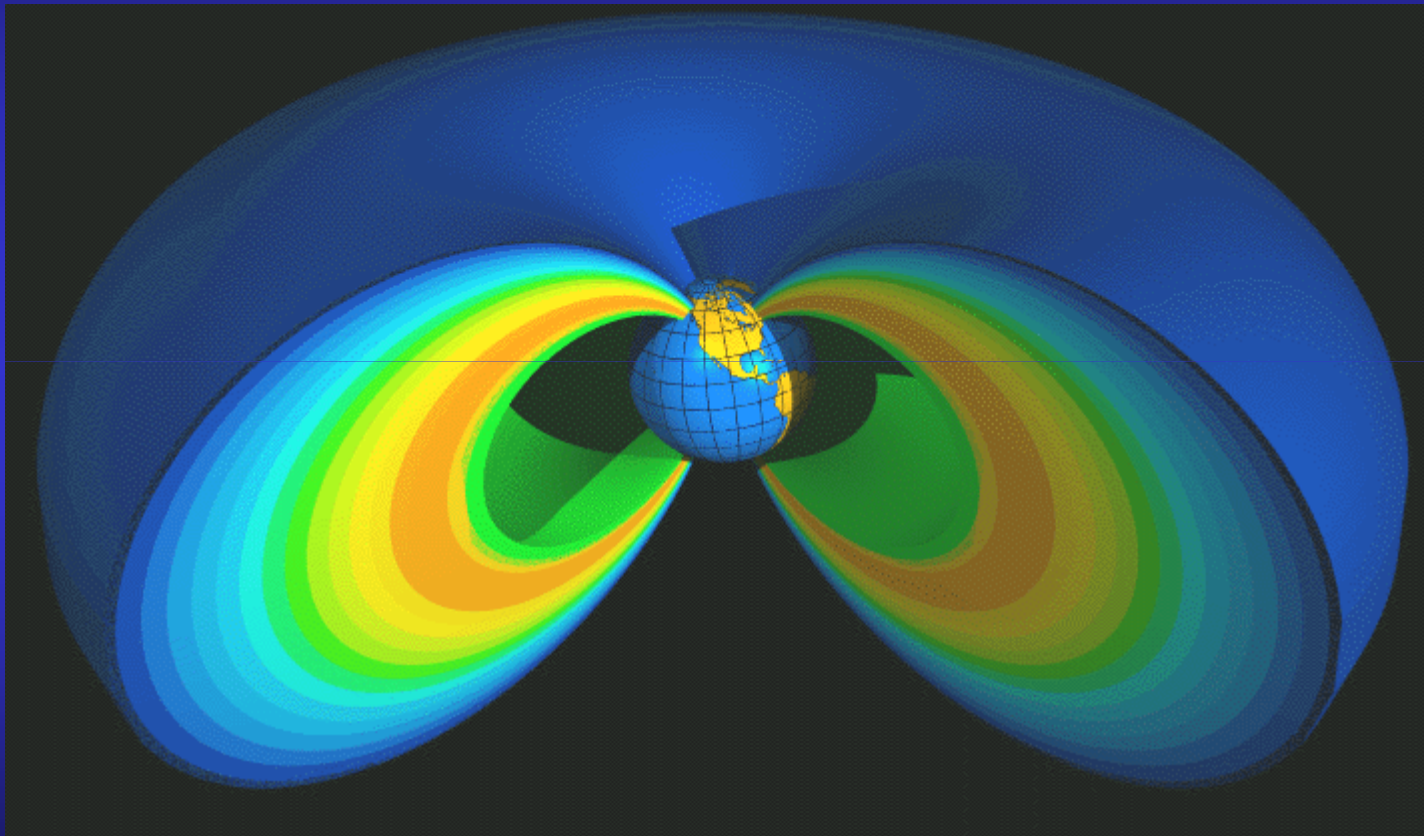
**Neutral sheet current**

**Tail current**

**Field-aligned currents**

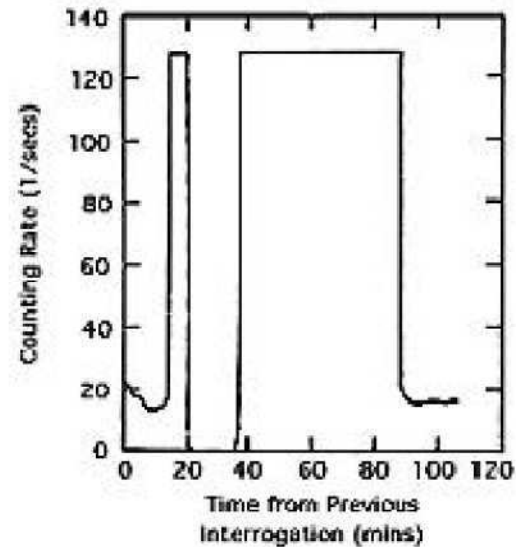
**Polar electrojet currents**

## Radiation belts



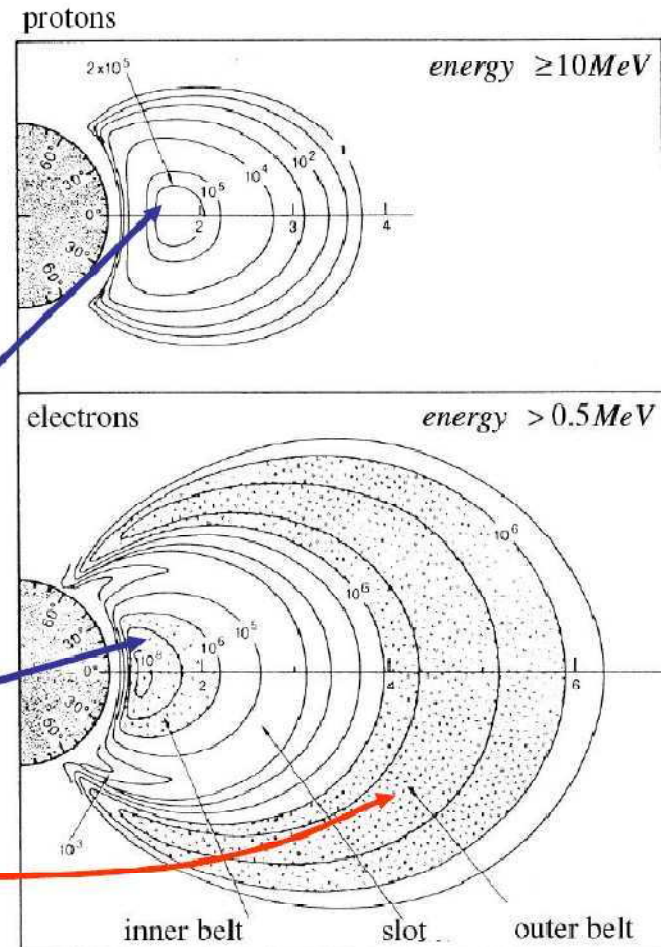
# Radiation belts

First observations  
James Van Allen, Explorer 1, 1958



Geiger counter saturated  
when crossing the inner  
and outer belts

Inner belt: mostly protons 0.1 – 40 MeV  
Outer belt: electrons keV's – MeV's



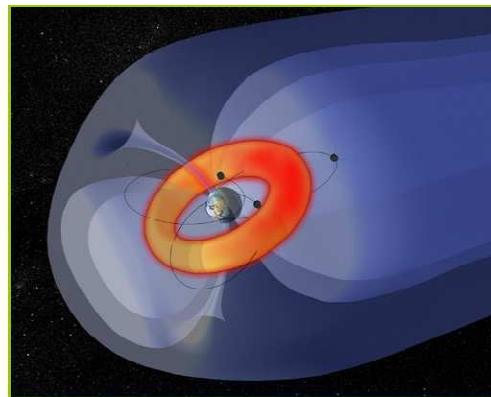
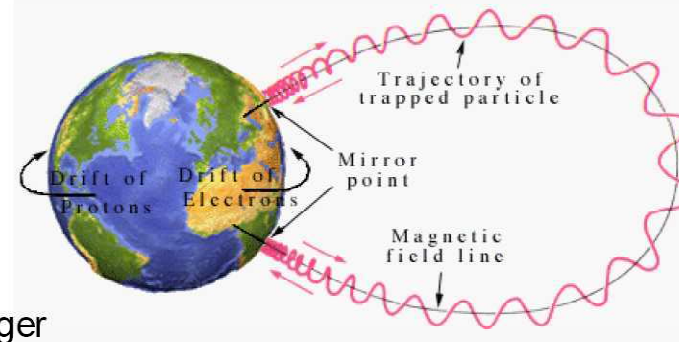
## Ring current

Drift motion causes  
a westward current

$$\mathbf{J}_{RC} = \mathbf{J}_M + \mathbf{J}_G + \mathbf{J}_C$$

Total current 1 – 10 MA

During strong storms even larger



The number densities of radiation belt particles (high energies) is low  
→ they carry very small current !

The main carriers of the ring current  
are ions

- at energies 20 – 300 keV

- centered at  $\approx L = 4$

(co-located with the outer electron belt)

- Because positive ions and negative electrons drift in opposite directions (see drawing), that motion will create an electric current that circulates clockwise around the Earth when viewed from north. The current is aptly named the ring current.

## Magnetospheric convection and corotation

Corotation implies plasma motion and via the frozen-in theorem

$$\vec{E} + \vec{v} \times \vec{B} = 0$$

electric fields, that is the corotational electric field is given as

$$\vec{E}_{cor} = - \frac{\Omega_{Earth} B_{surface} R_E^3}{r^2} \vec{e}_r$$

and corotation driven plasma motion is ExB-drift convection

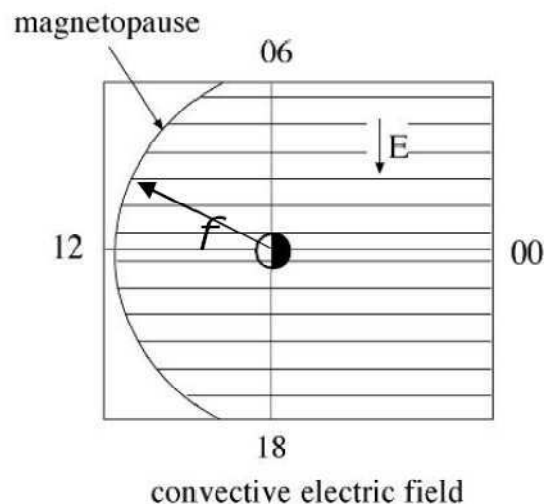
$$\vec{v}_{cor} = \frac{\vec{E}_{cor} \times \vec{B}}{B^2}$$

## Convection and corotational fields

Let the sunward convection correspond to a simple  $\mathbf{E}_0 \mathbf{e}_y$  :

$$\mathbf{E}_{conv} = -\nabla(-E_0 r \sin \phi)$$

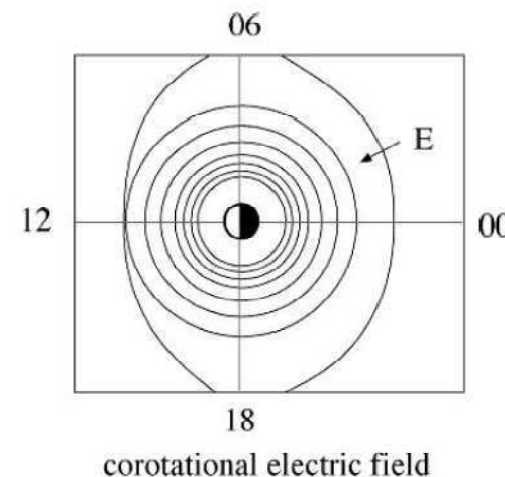
$$\phi_{conv} = -E_0 r \sin \phi$$



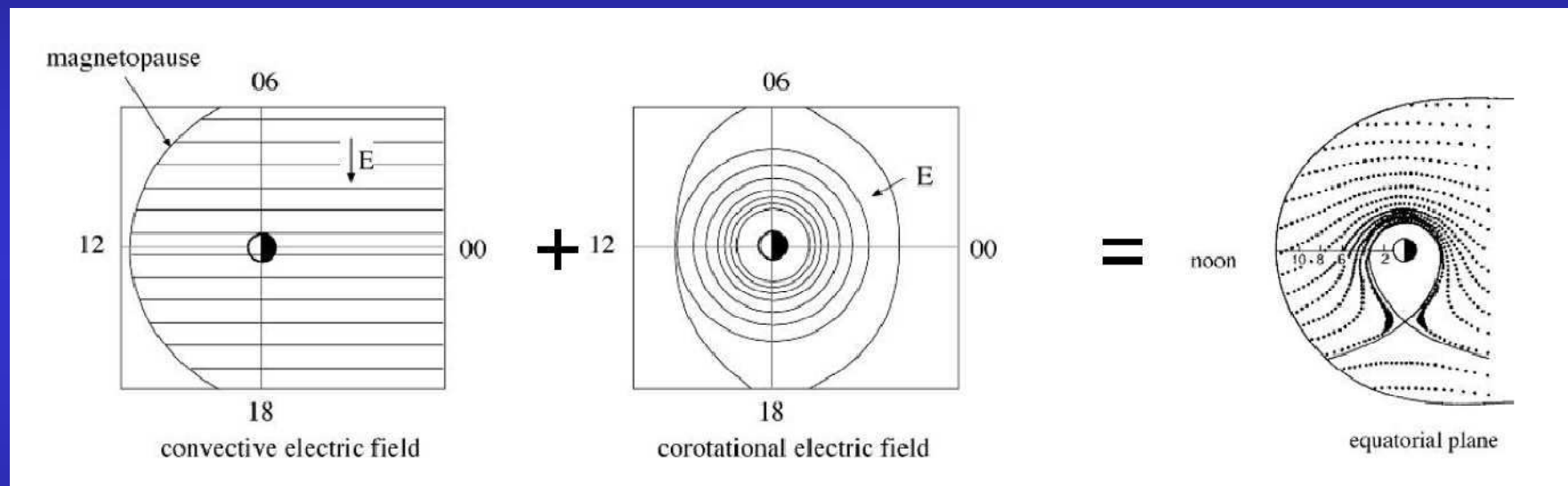
The Earth with its atmosphere (up to the plasmopause) rotates in this frame:  $W_E = 2\text{p} / 24 \text{ h}$

$$\mathbf{V}_{rot} = \Omega_E r \mathbf{e}_\phi = \mathbf{E}_{rot} \times \mathbf{B} / B^2$$

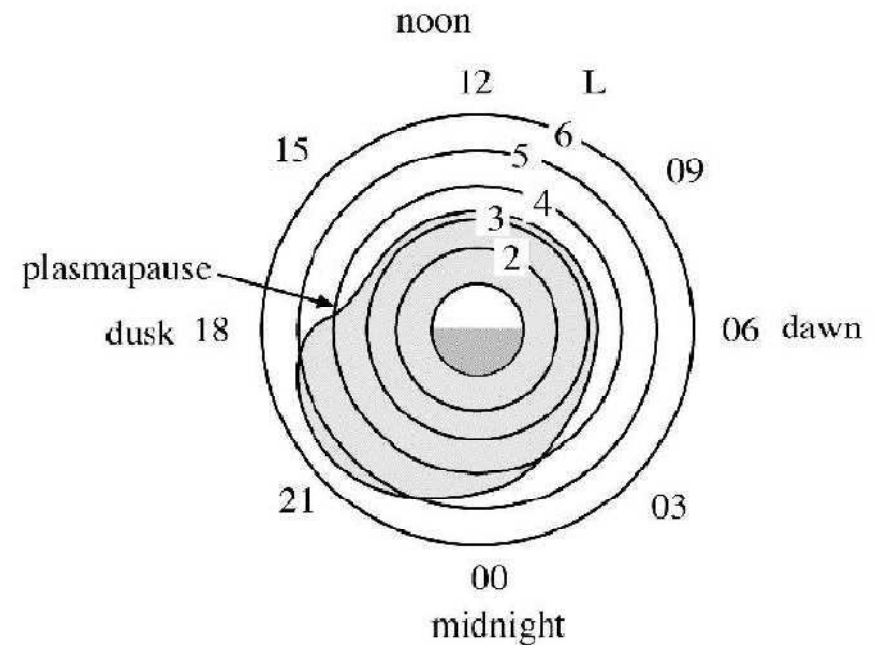
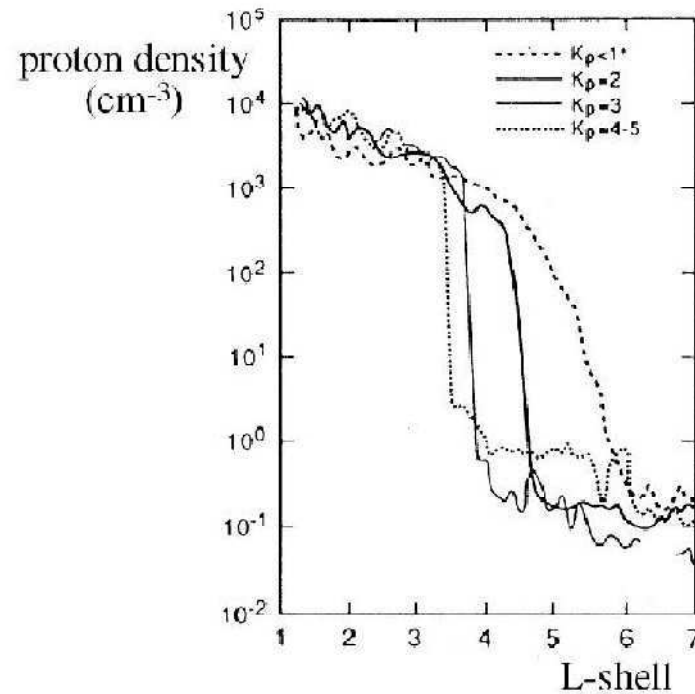
$$\text{D} \quad \phi_{rot} = \frac{-\Omega_E k_0}{r} = \frac{-\Omega_E B_0 R_E^3}{r}$$



# Sum of corotational and convection electric fields



# Plasmasphere

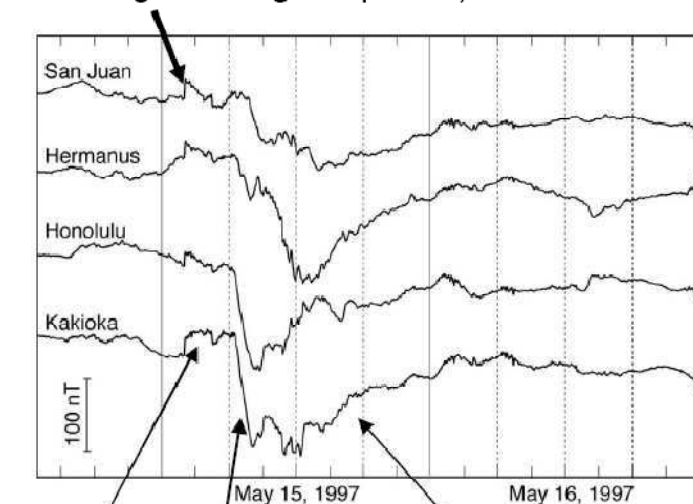


- Expansion of cool ( $\leq 1$  eV) ionospheric plasma
- within quasi-dipolar field lines (small  $L$ )
  - co-rotates with the Earth

# Magnetic storms

Magnetic storm: World-wide depression of magnetic horizontal ( $H$ ,  $\sim$  north) component mostly due to enhanced westward ring current

storm sudden commencement (SSC)  
(shock hitting the magnetopause)

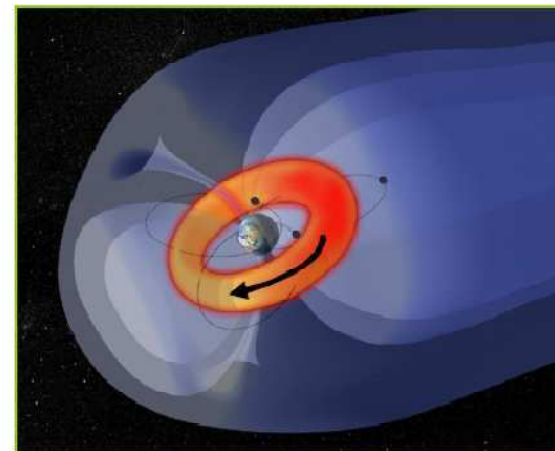


initial phase

main phase

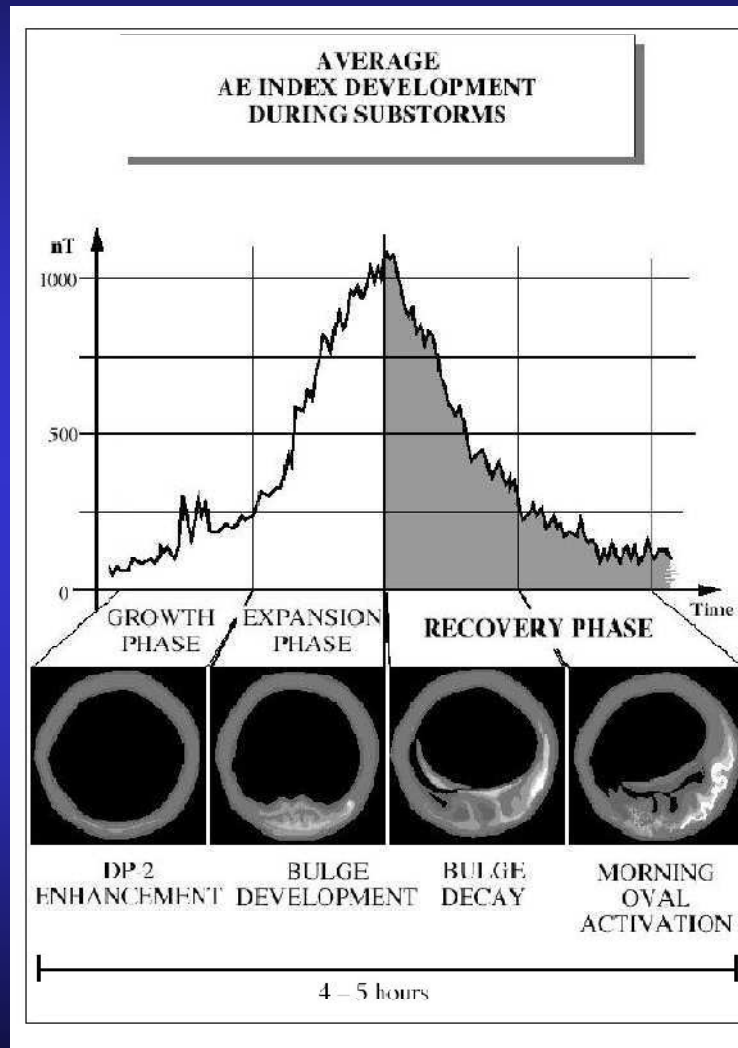
strong southward IMF  
in the shocked flow  
or in the CME

recovery phase

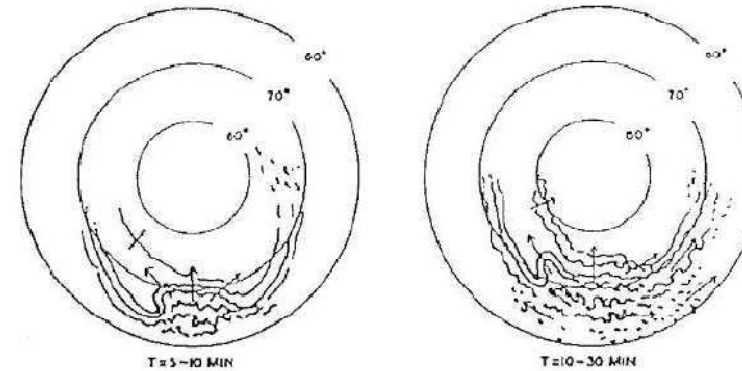


Substorms (Akasofu and Chapman, 1961) are magnetic and auroral activations at high latitudes (auroral zone). They occur both during storms and other times.

# Substorm phases



## Auroral development in the expansion phase



### Growth phase

- oval expands equatorward

### Substorm onset

- auroral breakup (possibly multiple)

### Expansion phase

- eastward, westward and poleward

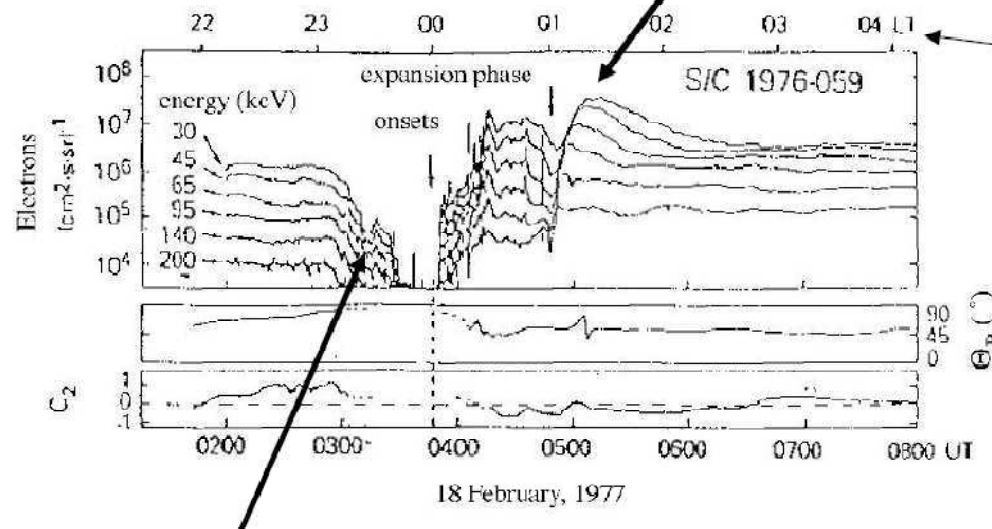
### Recovery phase

- most activity after past-midnight sector

## Particle injections to the inner magnetosphere

Data from geostationary satellite S/C 1976-059  
(a secret military S/C)

Dispersion due to energy dependent GC drift  
→ the spacecraft is toward the dawn  
of the injection point

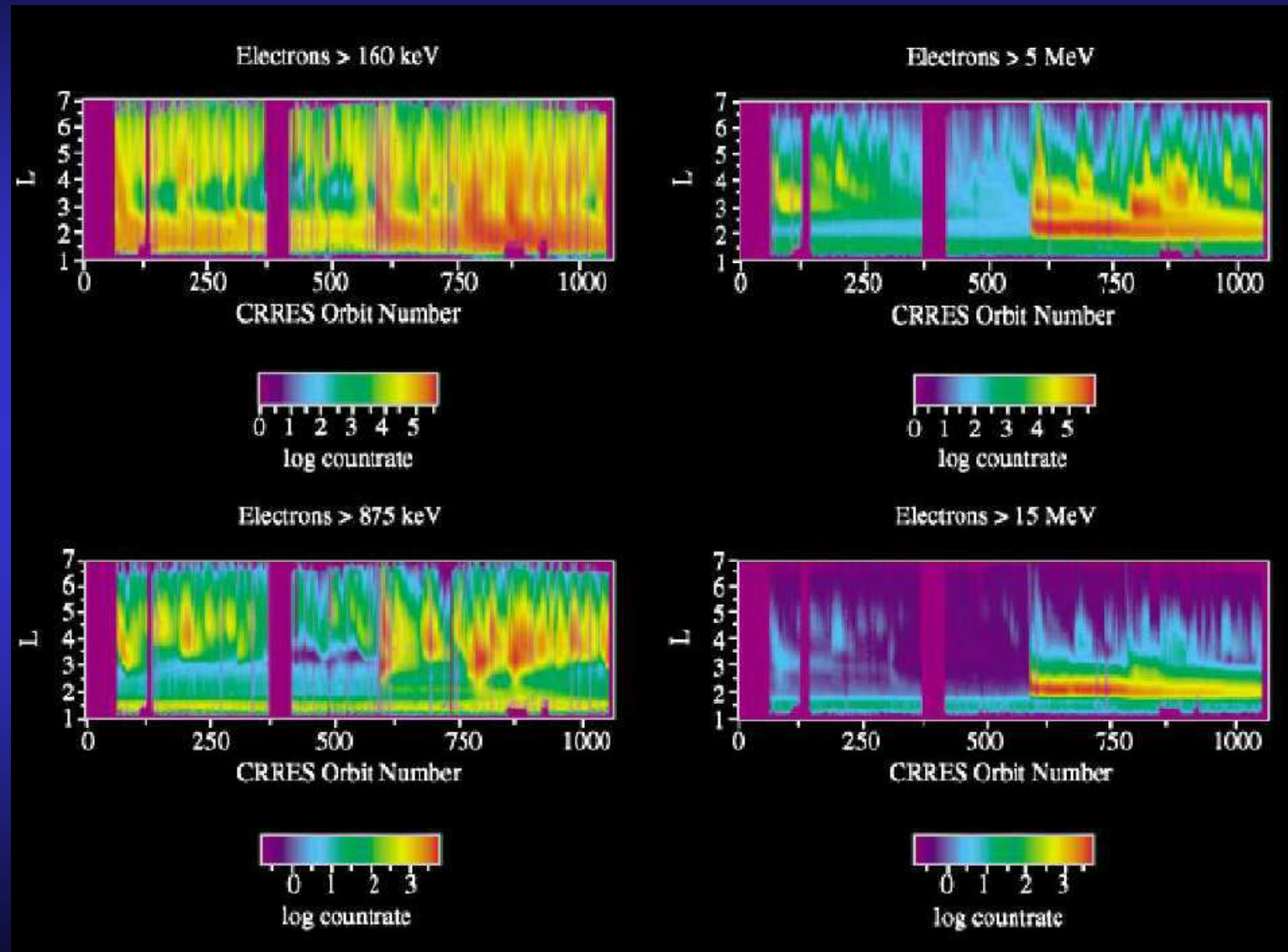


Magnetic local time  
at the location of the S/C

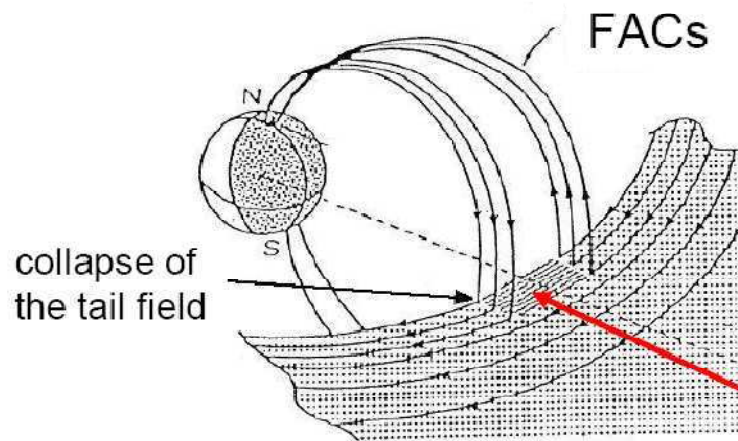
The injections are due  
to processes associated  
with the tail current sheet  
collapse (X-line formation)

Plasma sheet thinning during the growth phase:  
the satellite “moves” from the plasma sheet  
to the tail lobe

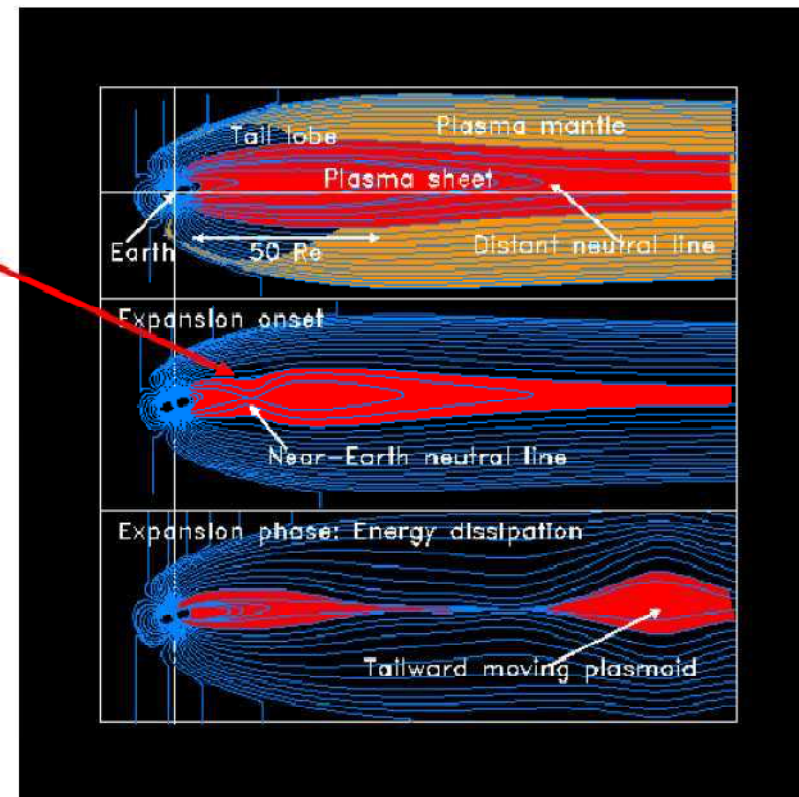
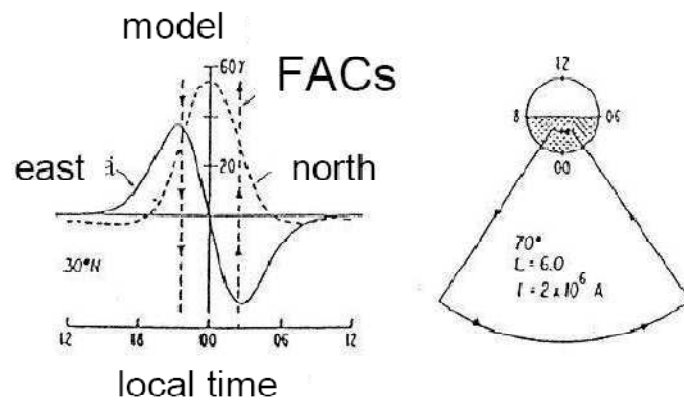
# Particle injections to the inner magnetosphere



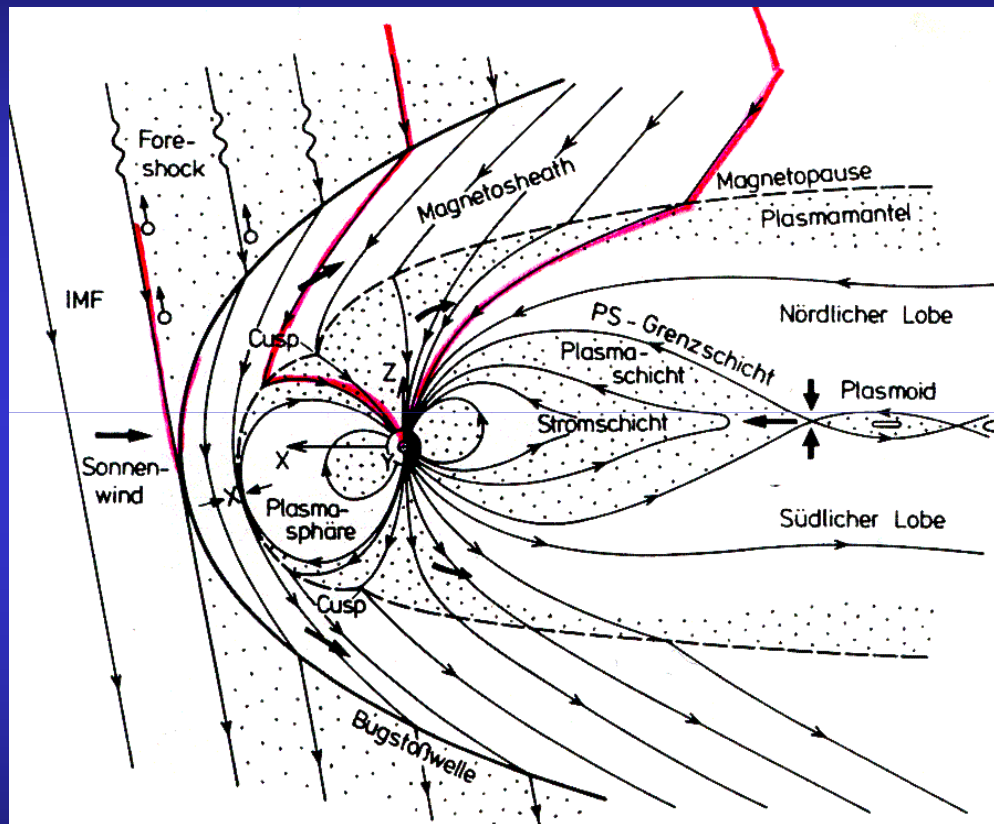
# Substorm current wedge



Something inhibits cross-tail current flow → current closes via the ionosphere

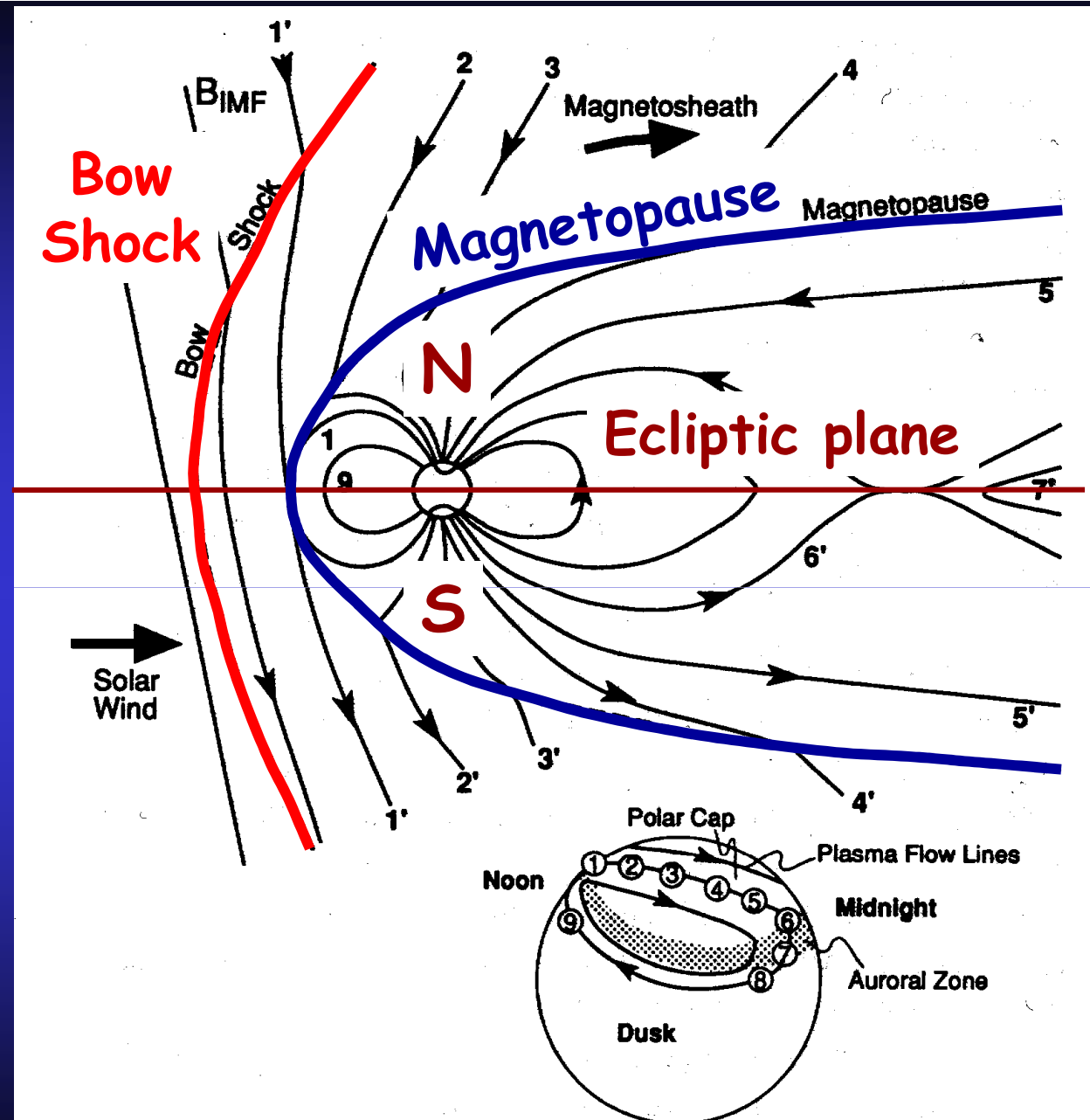


## A magnetosphere at work



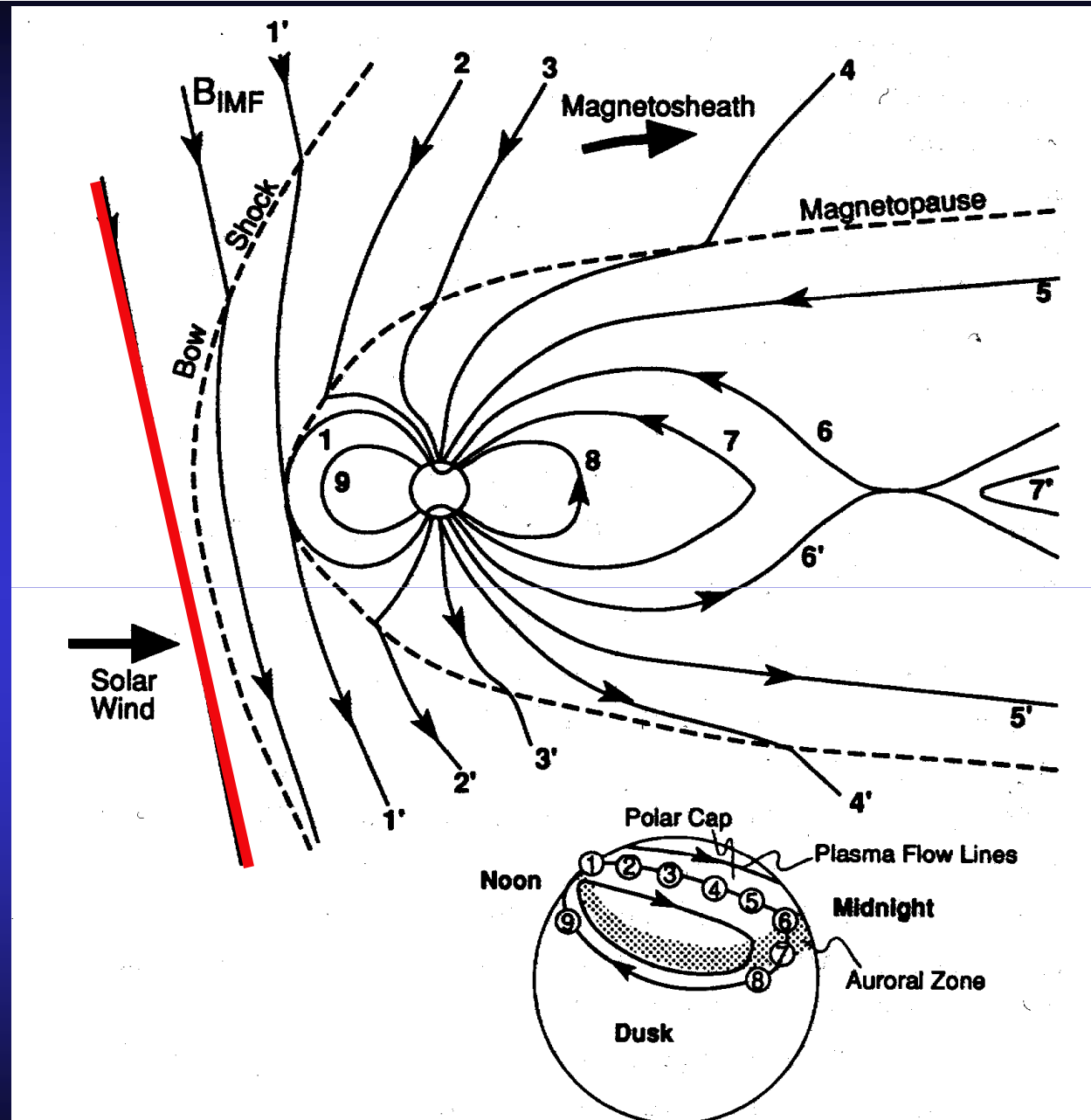
- Magnetic reconnection at the front side of the magnetosphere occurs, when the interplanetary  $B_z$  turns south, i.e. anti-parallel to the Earth's intrinsic field.
- Charged particles can now penetrate from outer space way down into the polar ionosphere.
- Reconnection in the tail causes ejection of plasmoids away from the Earth and injection of lobe plasma into the polar caps.

# A magnetosphere at work



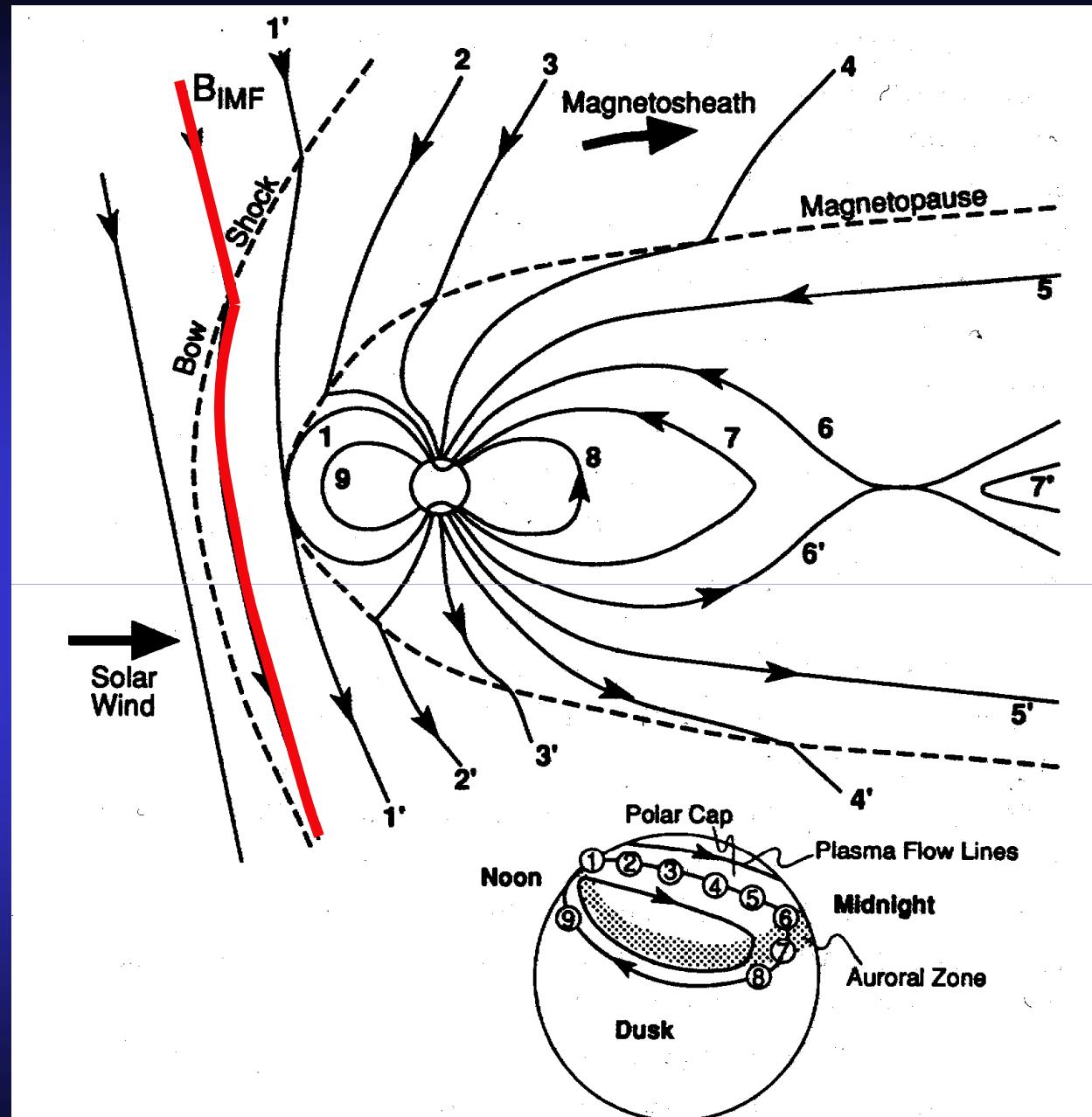
Hughes, 1995

# A magnetosphere at work



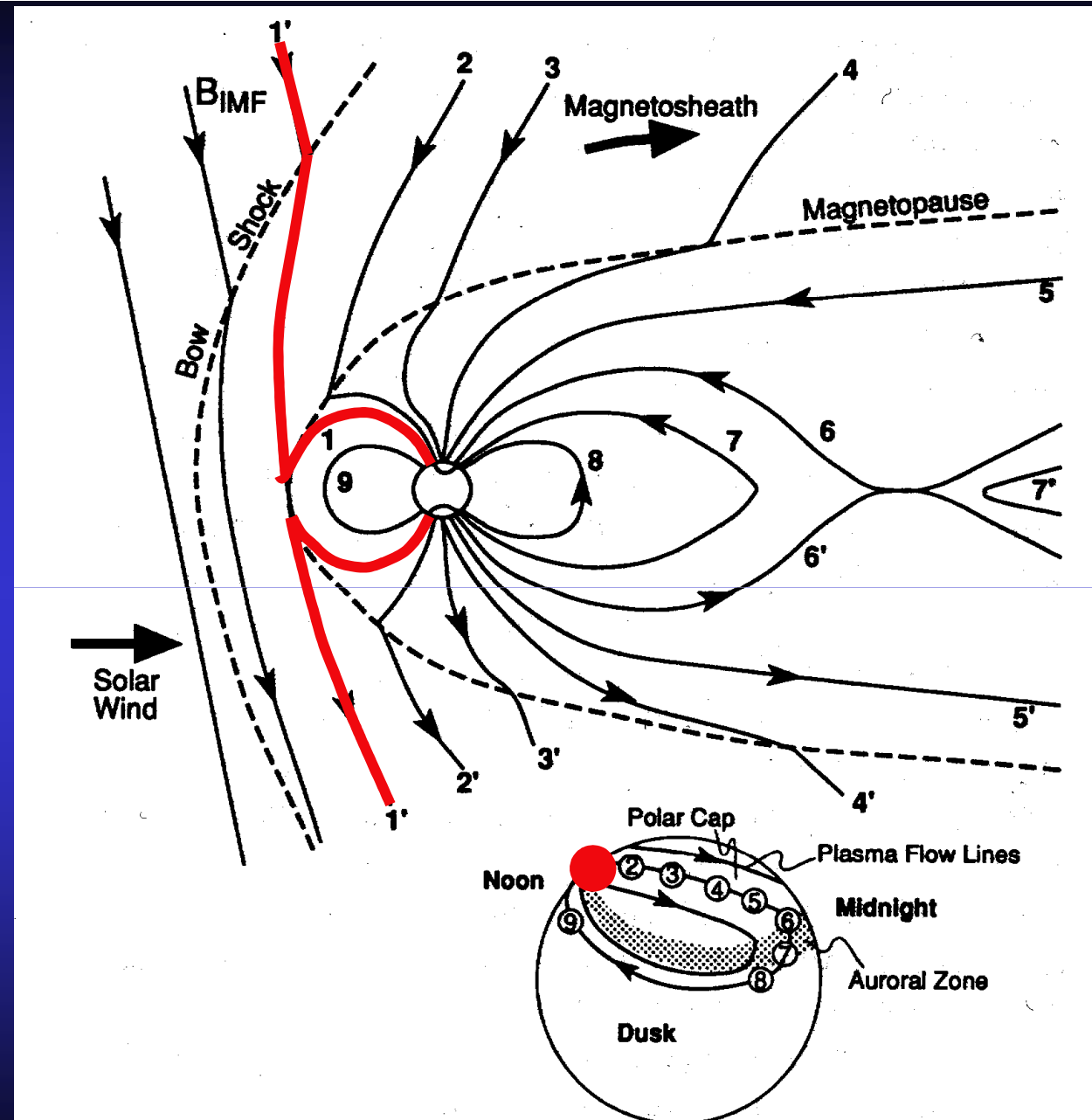
In case of  $B_z$  south:

# A magnetosphere at work



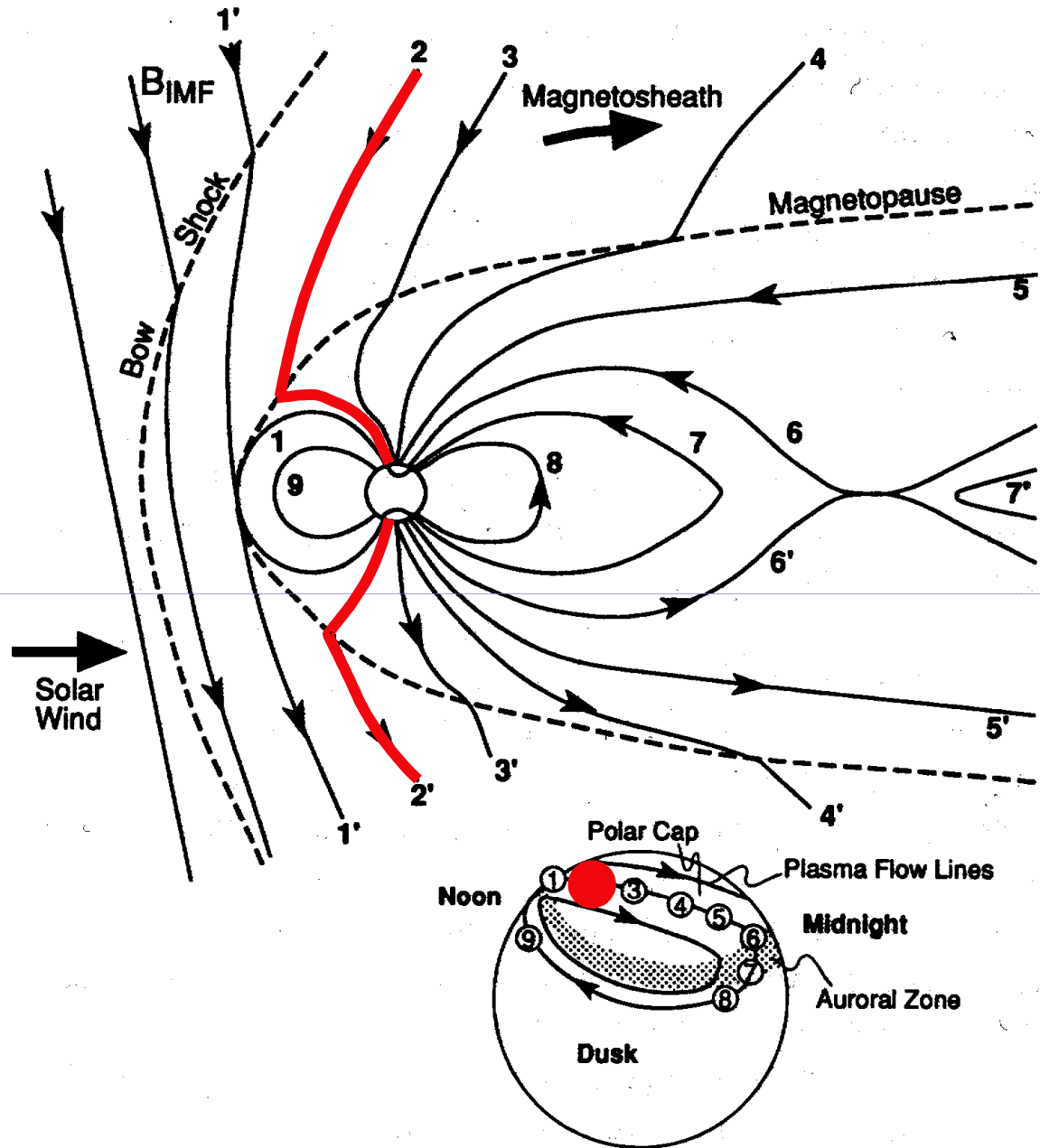
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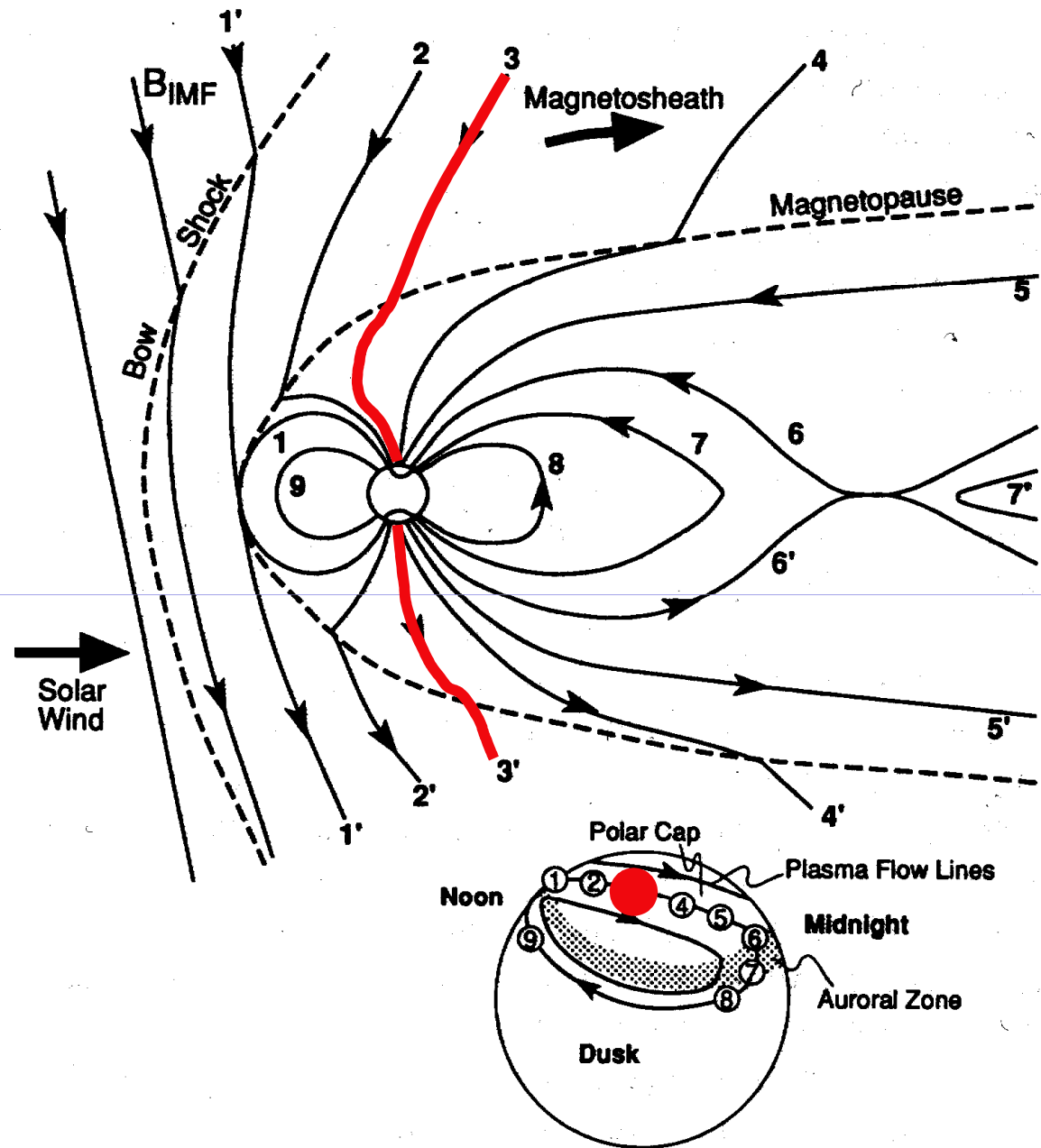
In case of  $B_z$  south:  
reconnection at the  
magnetopause!

# A magnetosphere at work



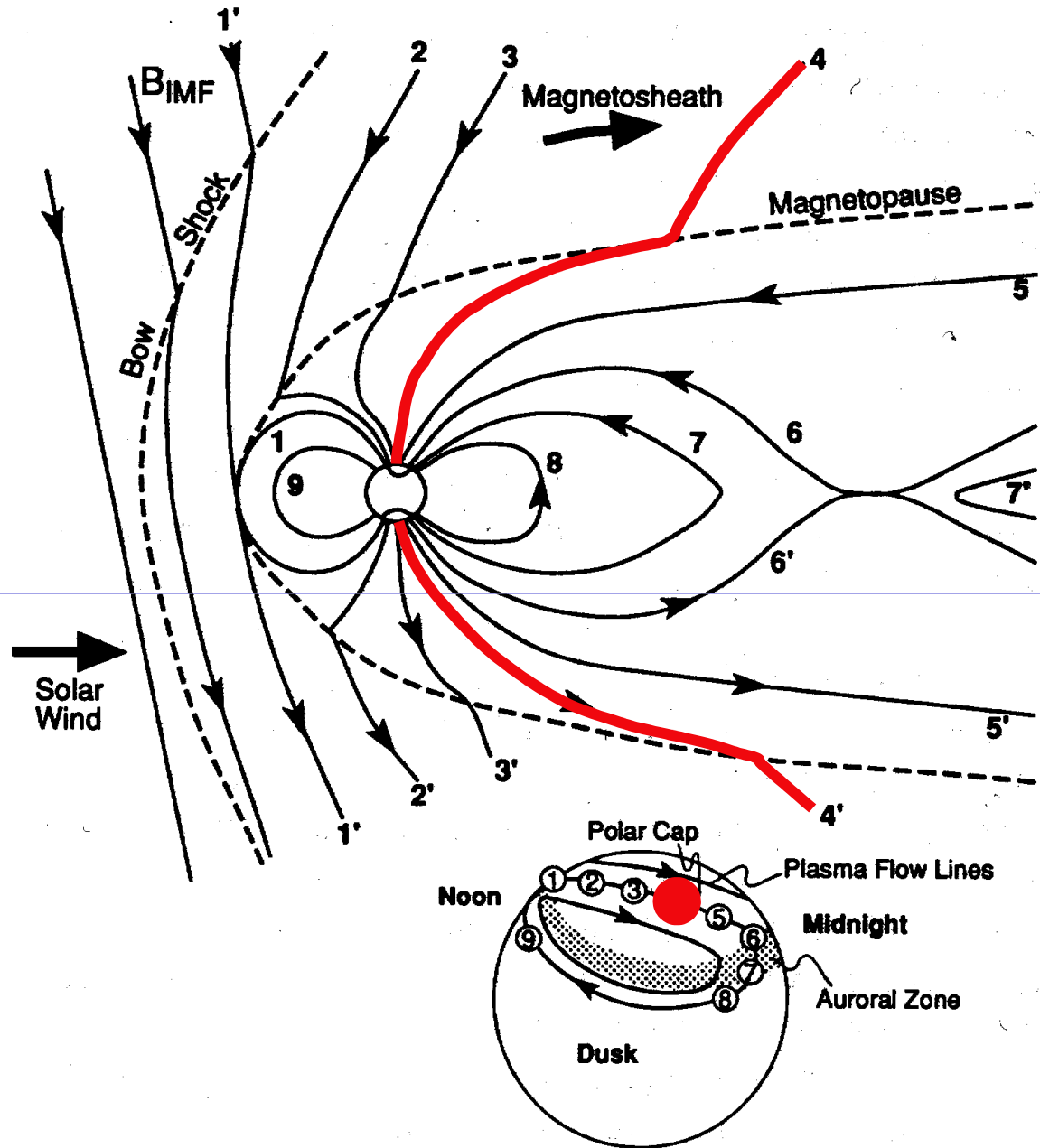
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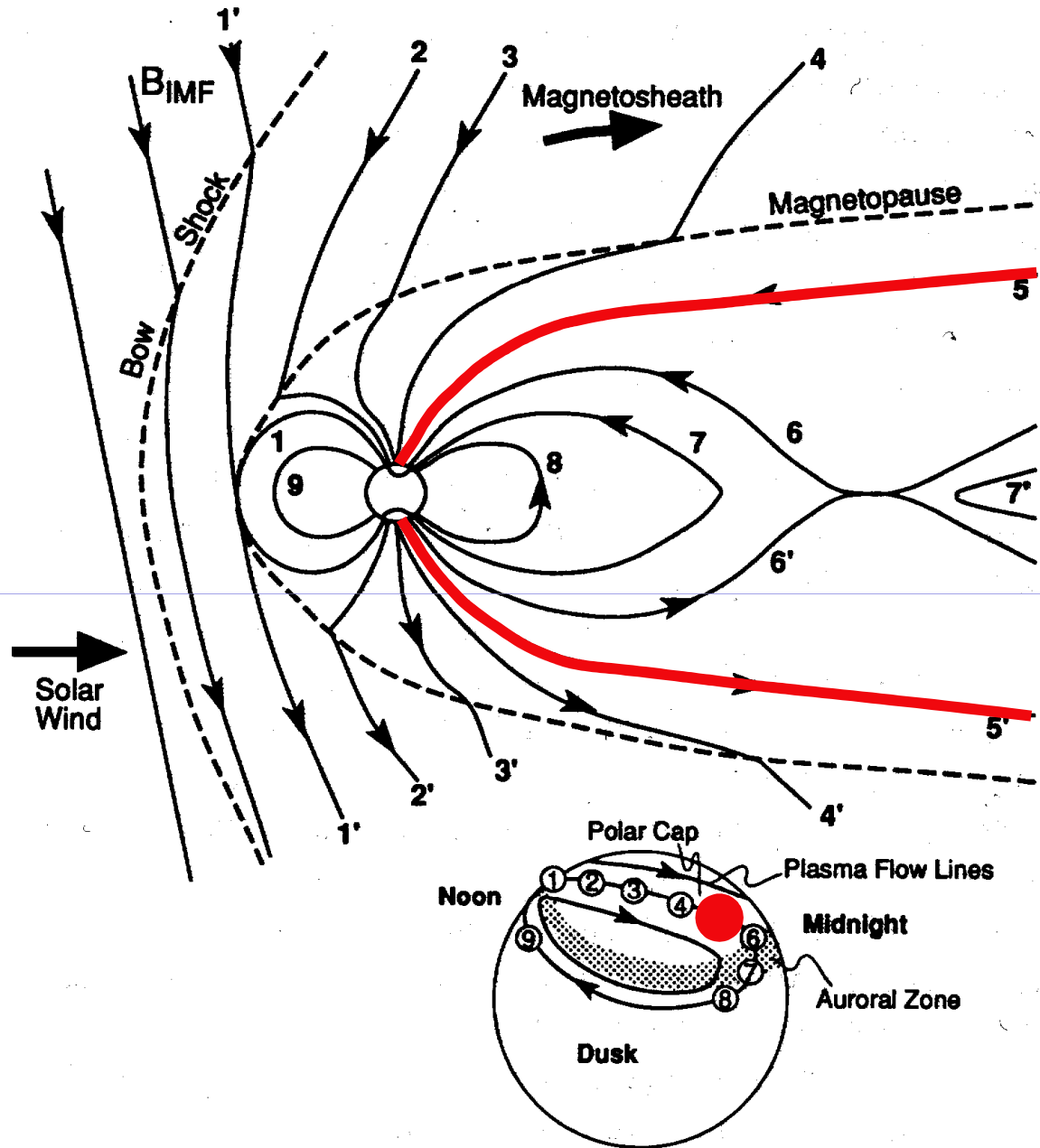
In case of  $B_z$  south:  
reconnection at the  
magnetopause!

# A magnetosphere at work



In case of  $B_z$  south:  
reconnection at the  
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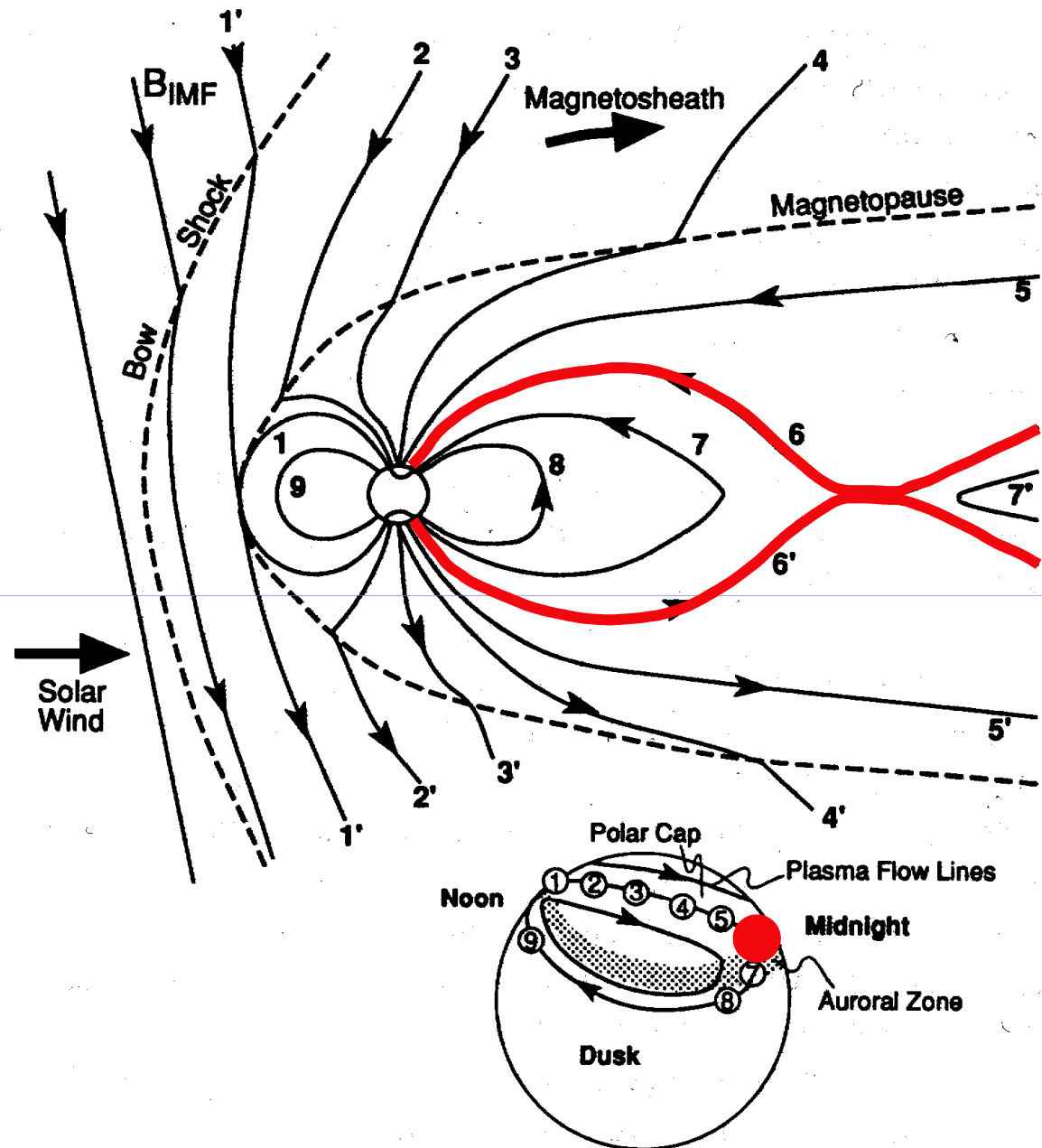
# A magnetosphere at work



In case of  $B_z$  south:  
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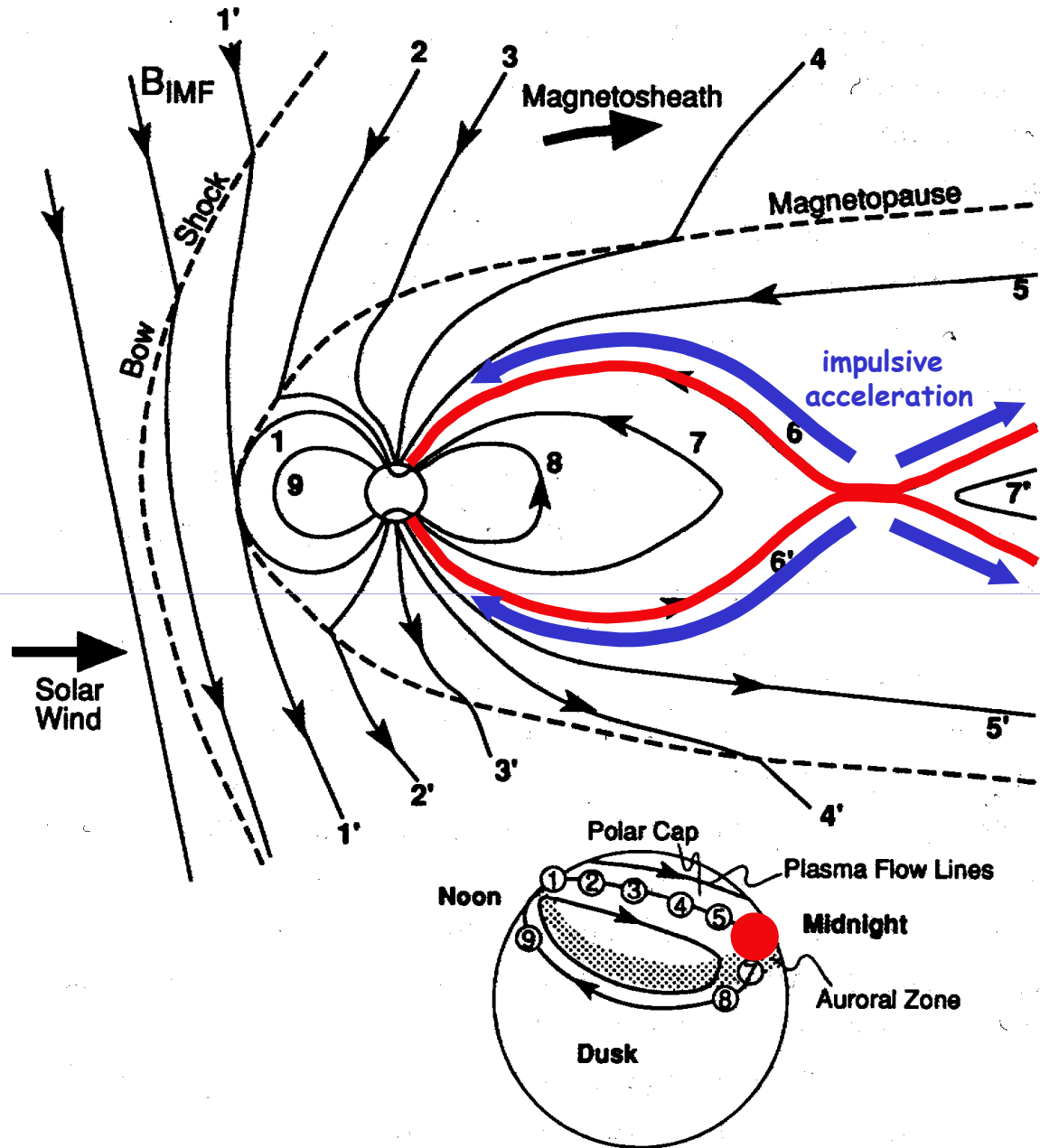
# A magnetosphere at work

In case of  $B_z$  south: reconnection at the magnetopause, and reconnection in the magnetotail!



# A magnetosphere at work

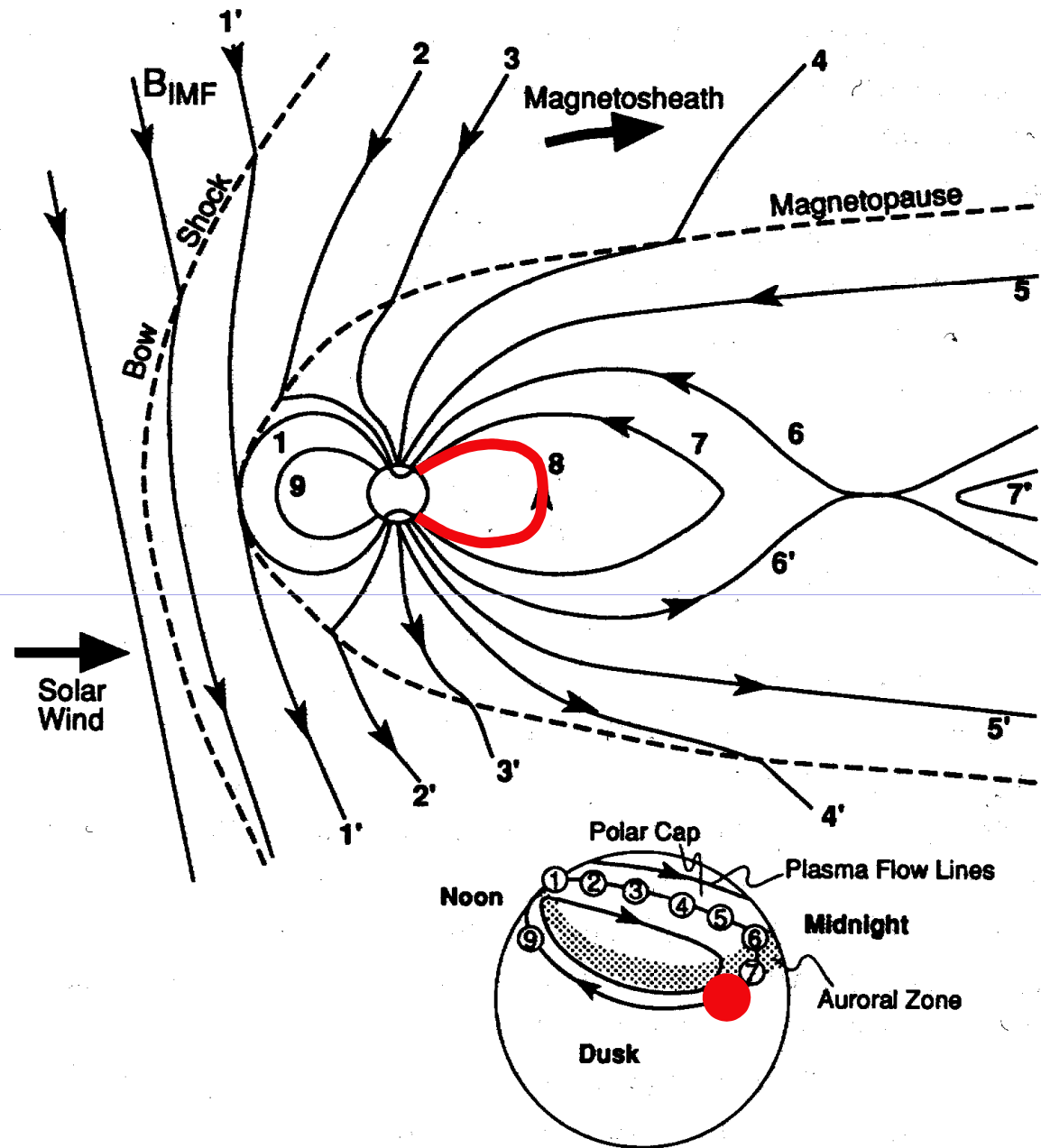
In case of  $B_z$  south: reconnection at the magnetopause, and reconnection in the magnetotail!





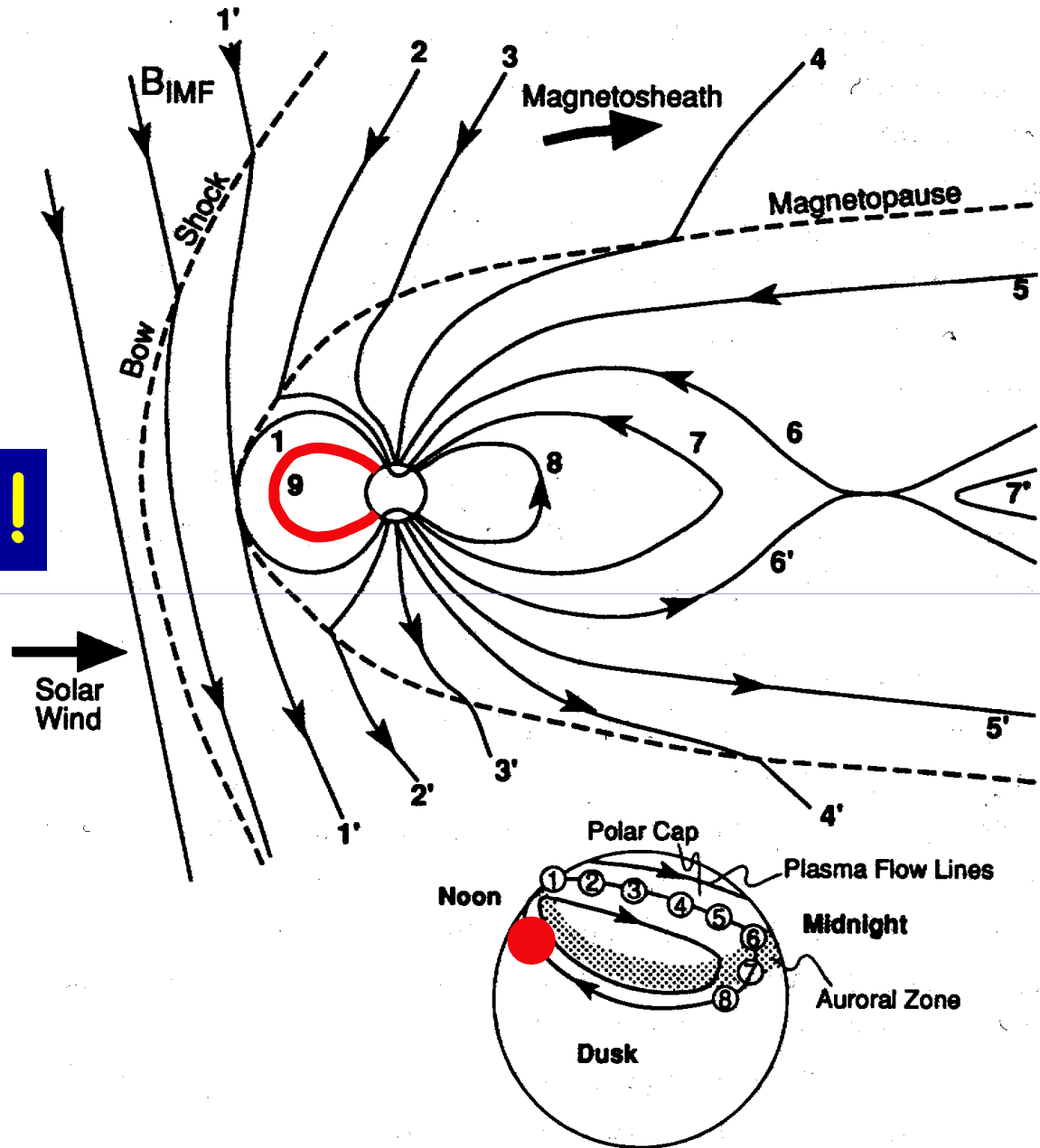
# A magnetosphere at work

In case of  $B_z$  south: reconnection at the magnetopause, and reconnection in the magnetotail!



A magnetosphere at work

A substorm !



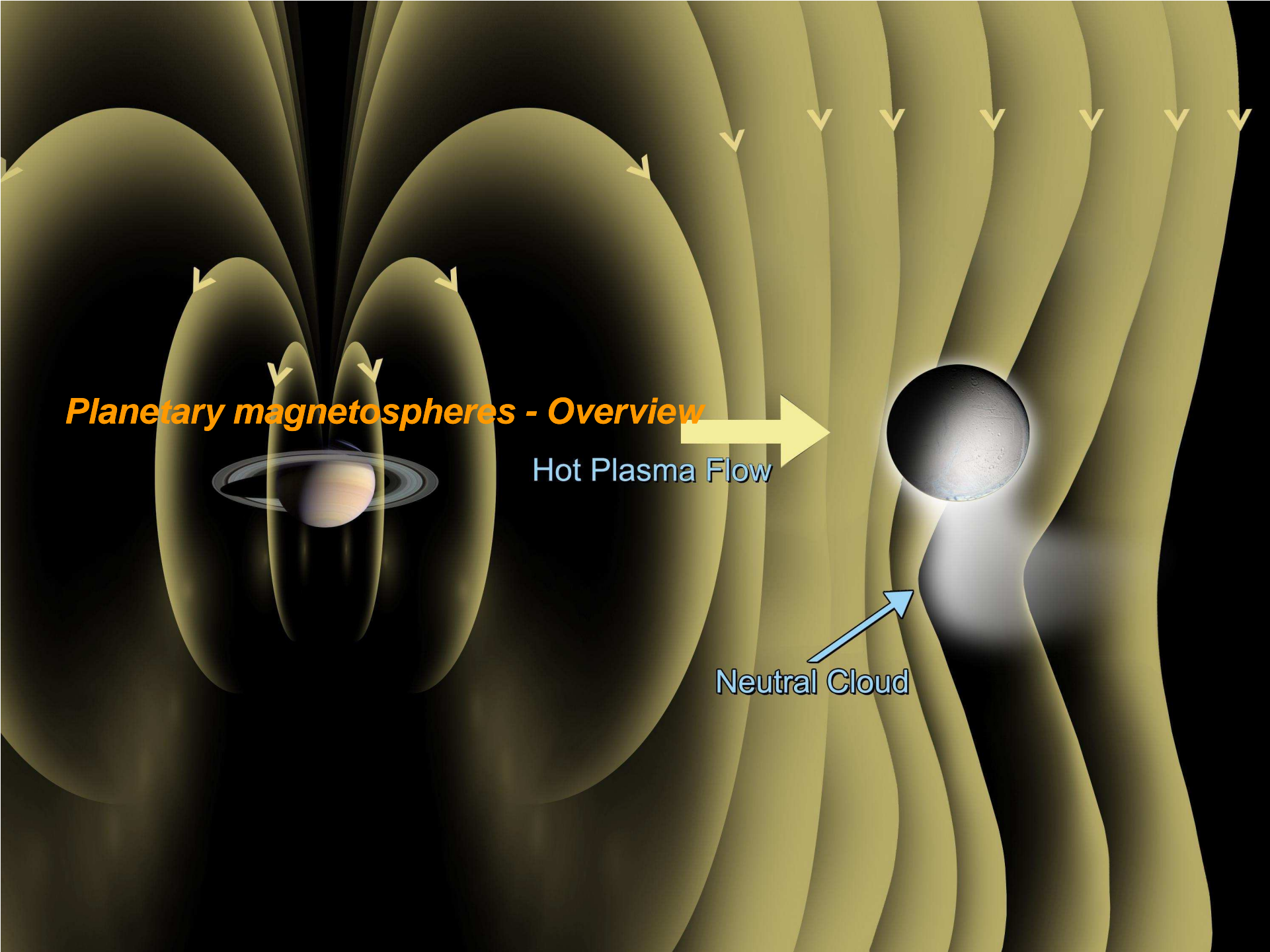
## *Dynamics*

- major instability of the terrestrial magnetosphere is referred to as a **SUBSTORM**
- magnetic reconnection on the day side opens flux tubes which are dragged to the magnetotail and increase tail flux
- Compression by the solar wind stresses the tail and increases current in the current sheet
- magnetic reconnection in tail current sheet produces plasmoid configuration that relaxes stress and allows plasma to flow down the tail

**Planetary magnetospheres - Overview**

Hot Plasma Flow

Neutral Cloud



# The magnetosphere of Mercury

*J.A. Slavin / Advances in Space Research 33 (2004) 1859–1874*

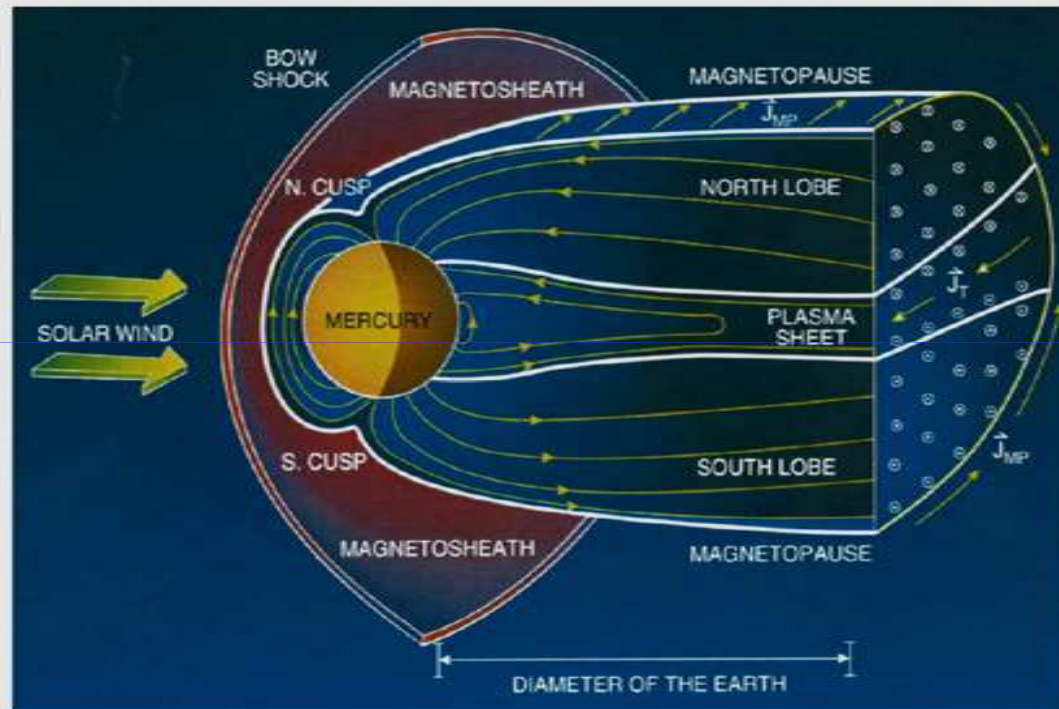


Fig. 2. Schematic view of the bow shock and magnetosphere of Mercury.

No atmosphere

thus no ionosphere

but exosphere

No plasmasphere

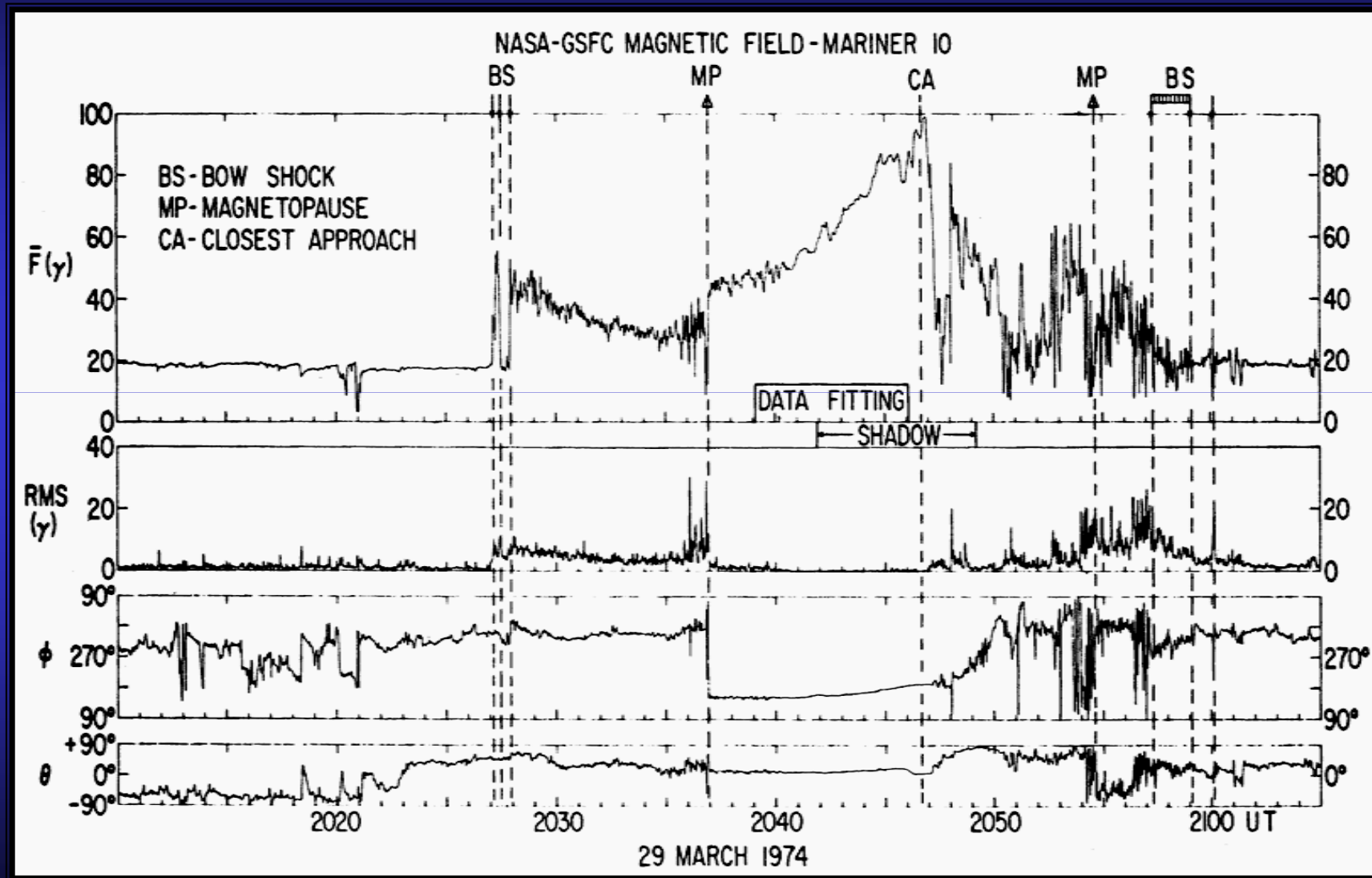
Weak magnetic field

Multi-ion plasma

Small magnetosphere

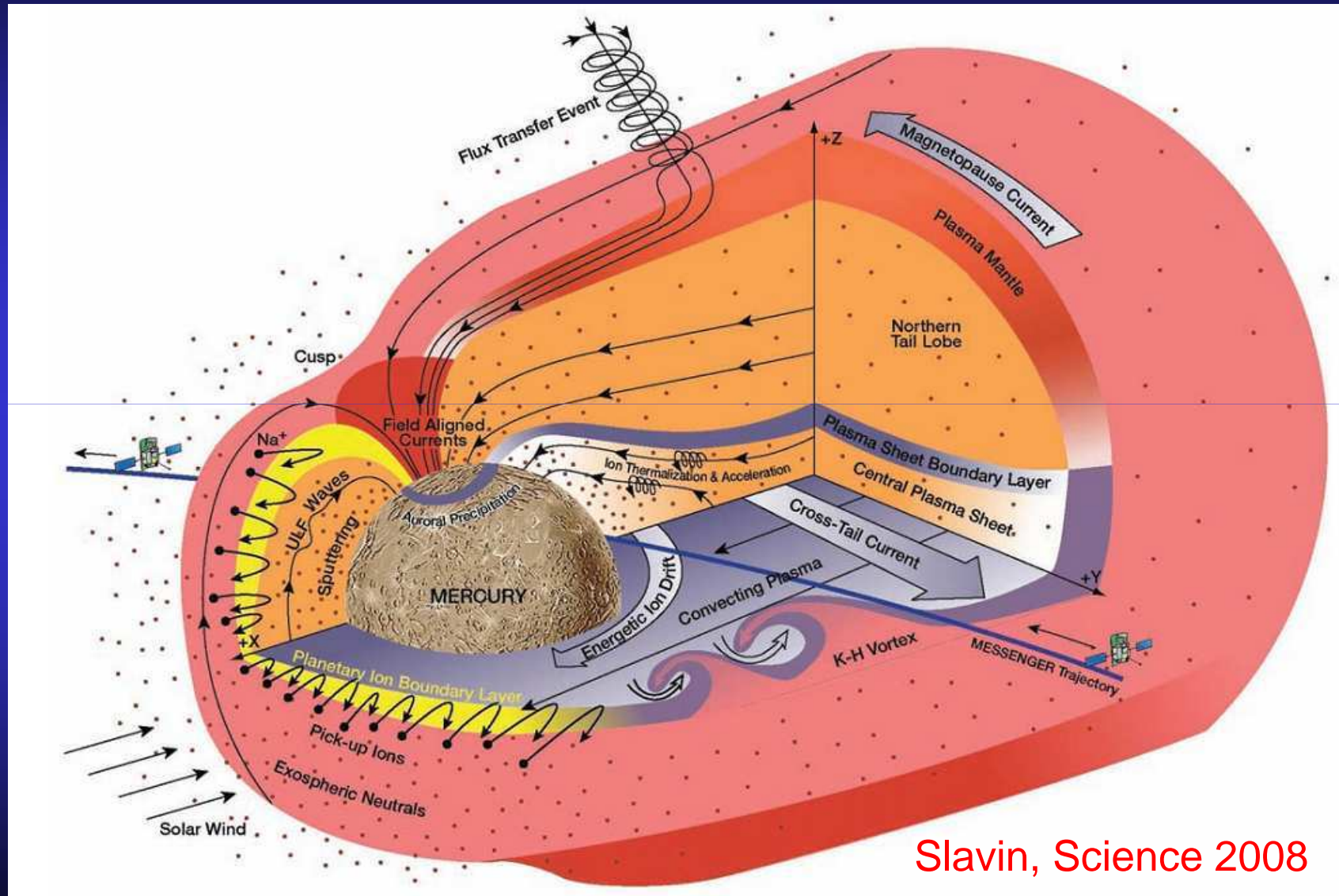
# Planetary magnetic field of Mercury

## Mariner 10 results 1974



Ness et al., 1978

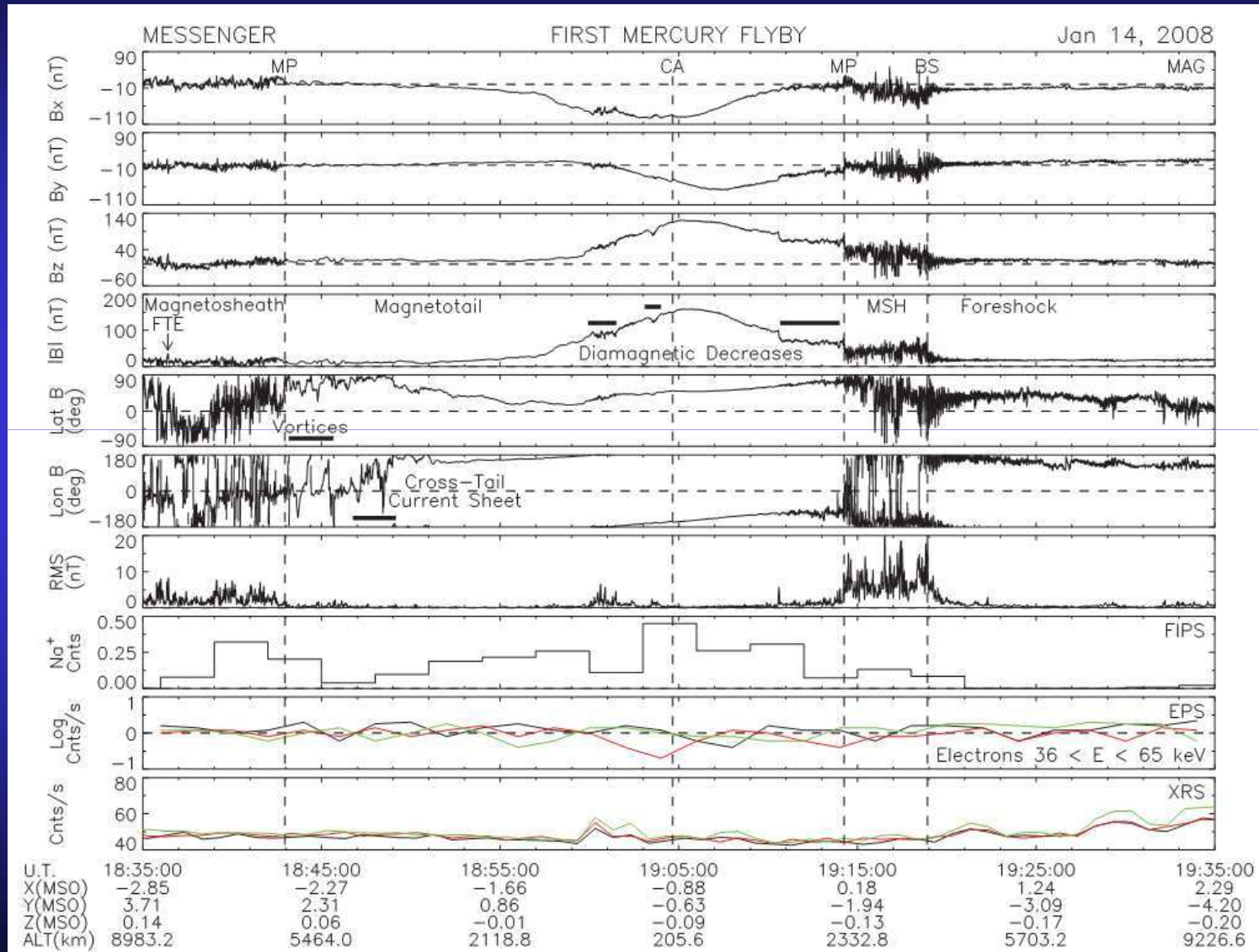
# Mercury's magnetosphere after Messenger flyby 1, Jan 2008



Slavin, Science 2008

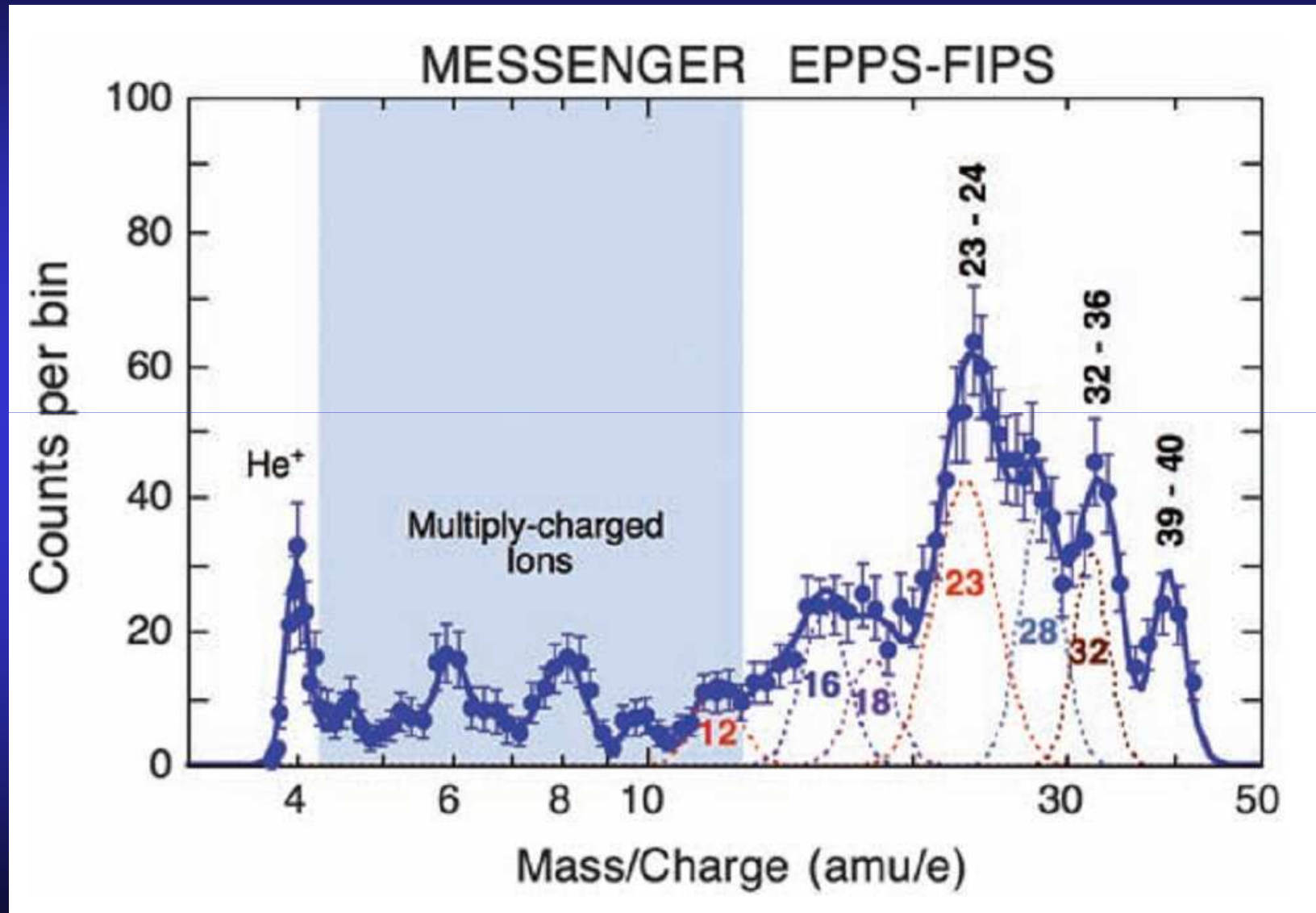
# Mercury's magnetosphere

## Messenger flyby 1, Jan 2008



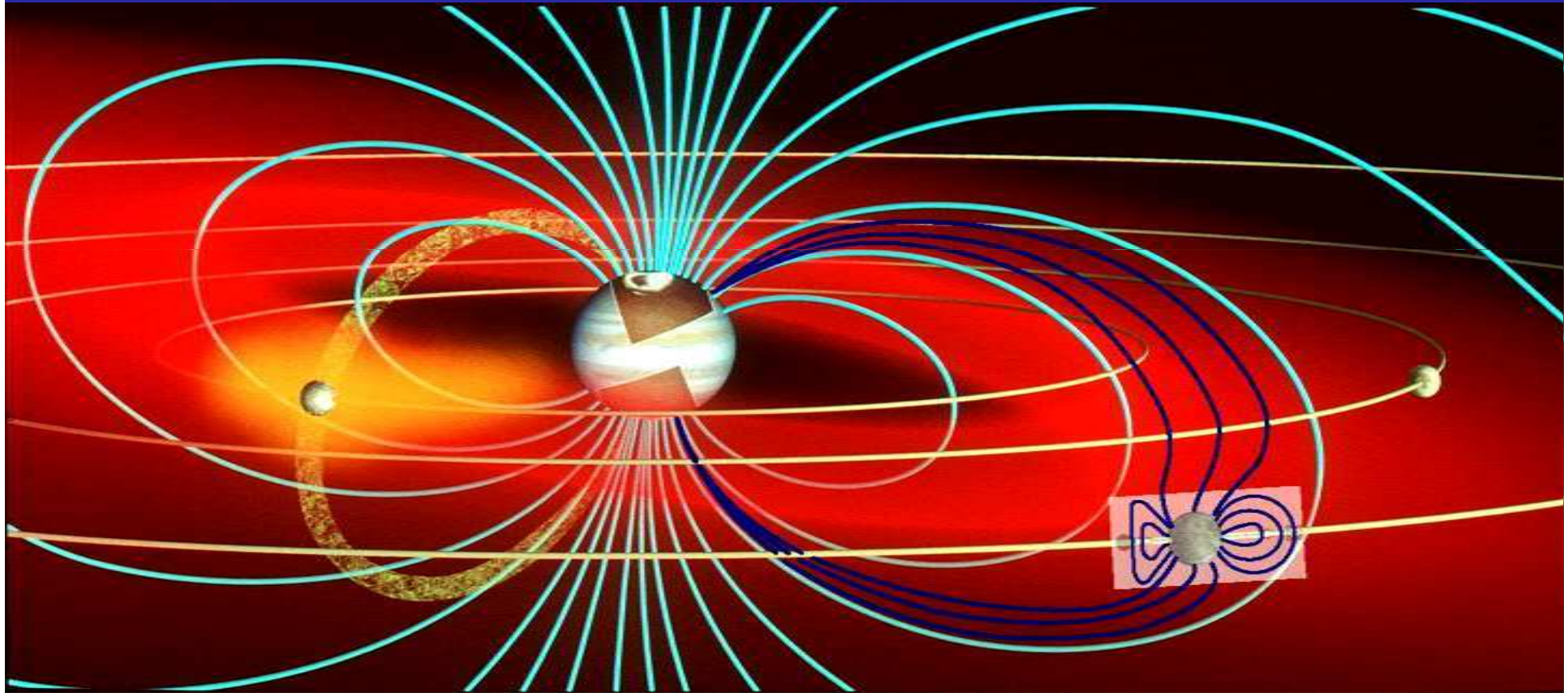
# Mercury's magnetosphere

## Messenger flyby 1, Jan 2008



# Ganymede magnetosphere

*A magnetosphere within a magnetosphere*

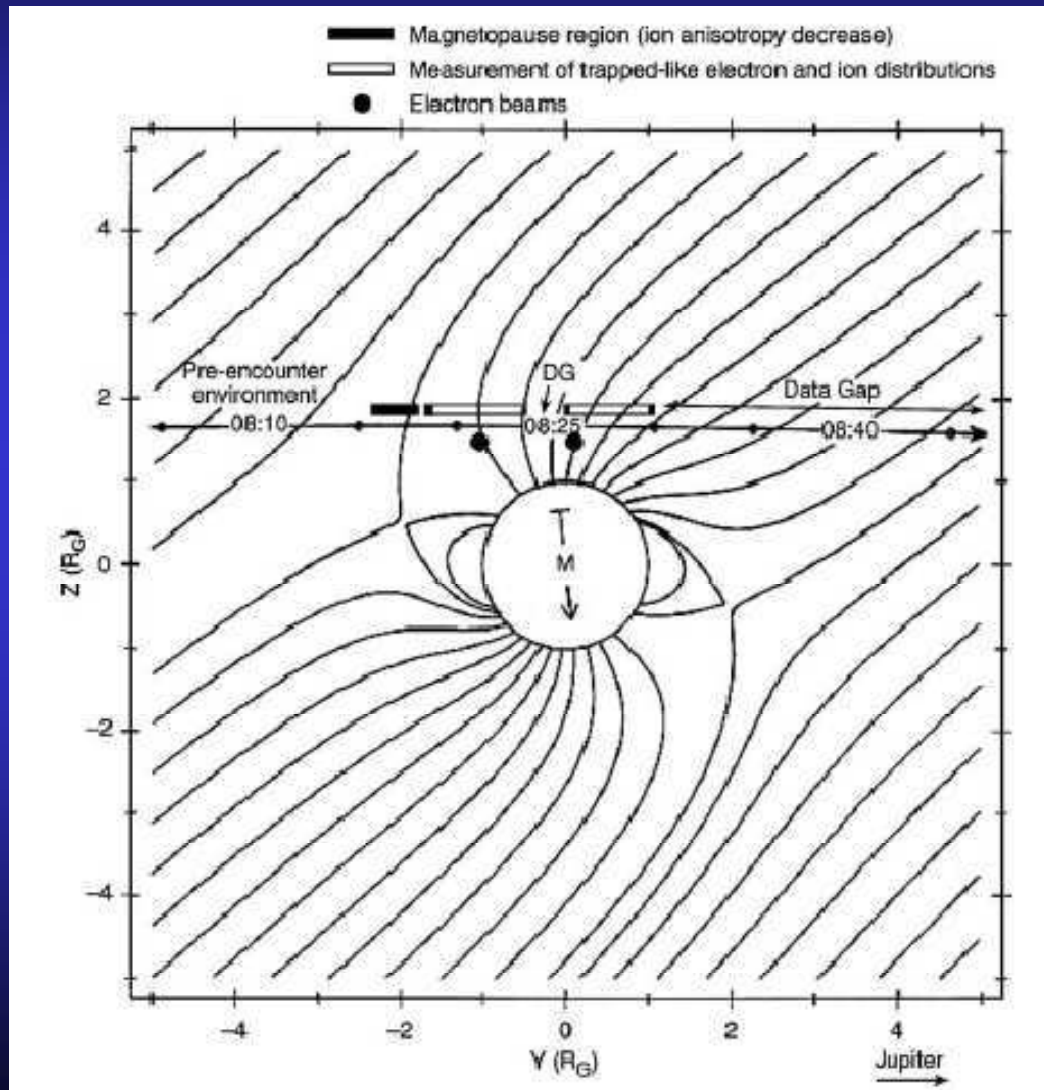


# Ganymede:

## Electron beams in Ganymede's magnetosphere

Williams, JGR, 2004

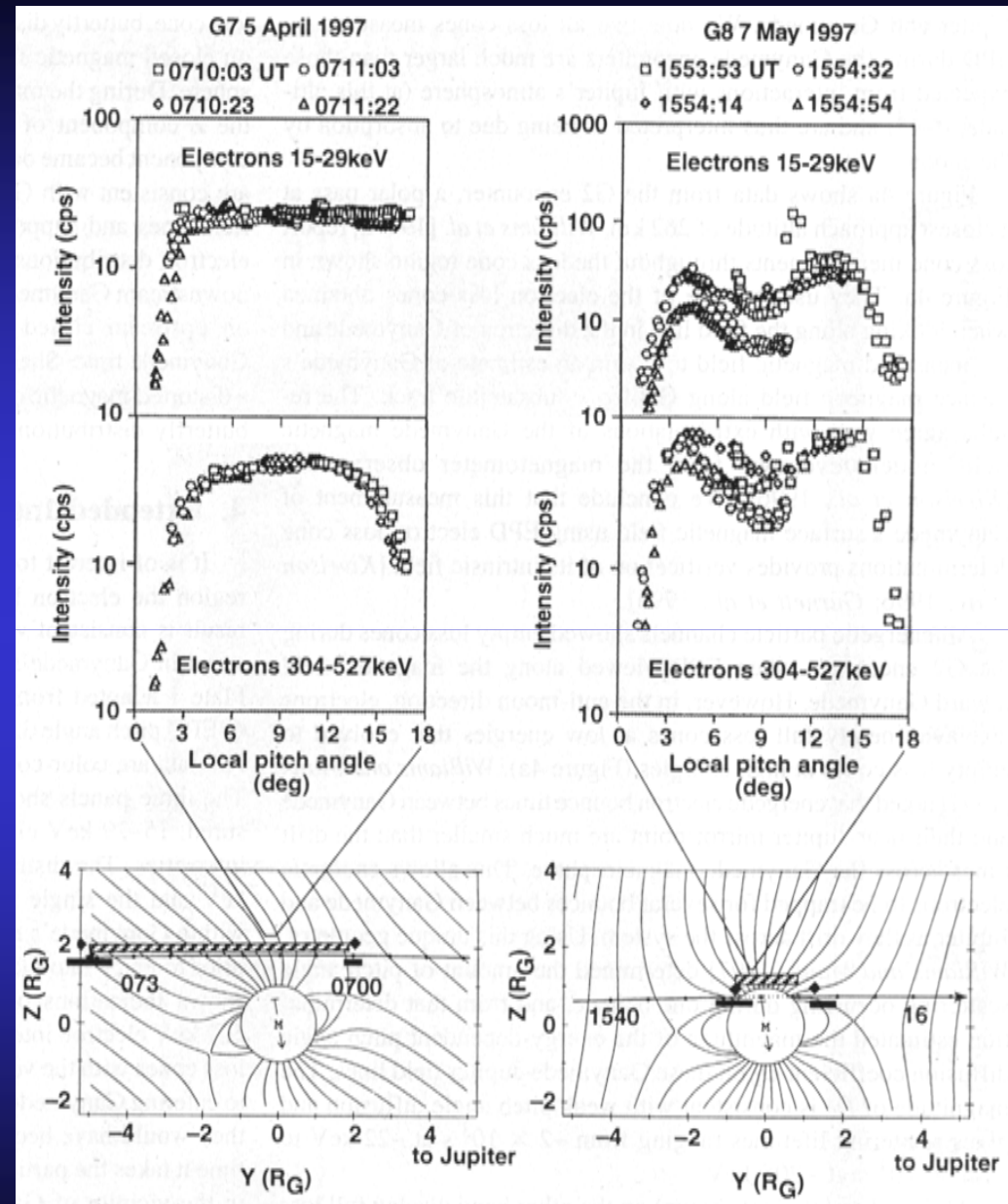
EPD results from Galileo's orbit 29



- Ganymede's magnetosphere more complex
- Electron beams may be formed by the entry and subsequent quasi-chaotic drift of ambient Jovian electrons

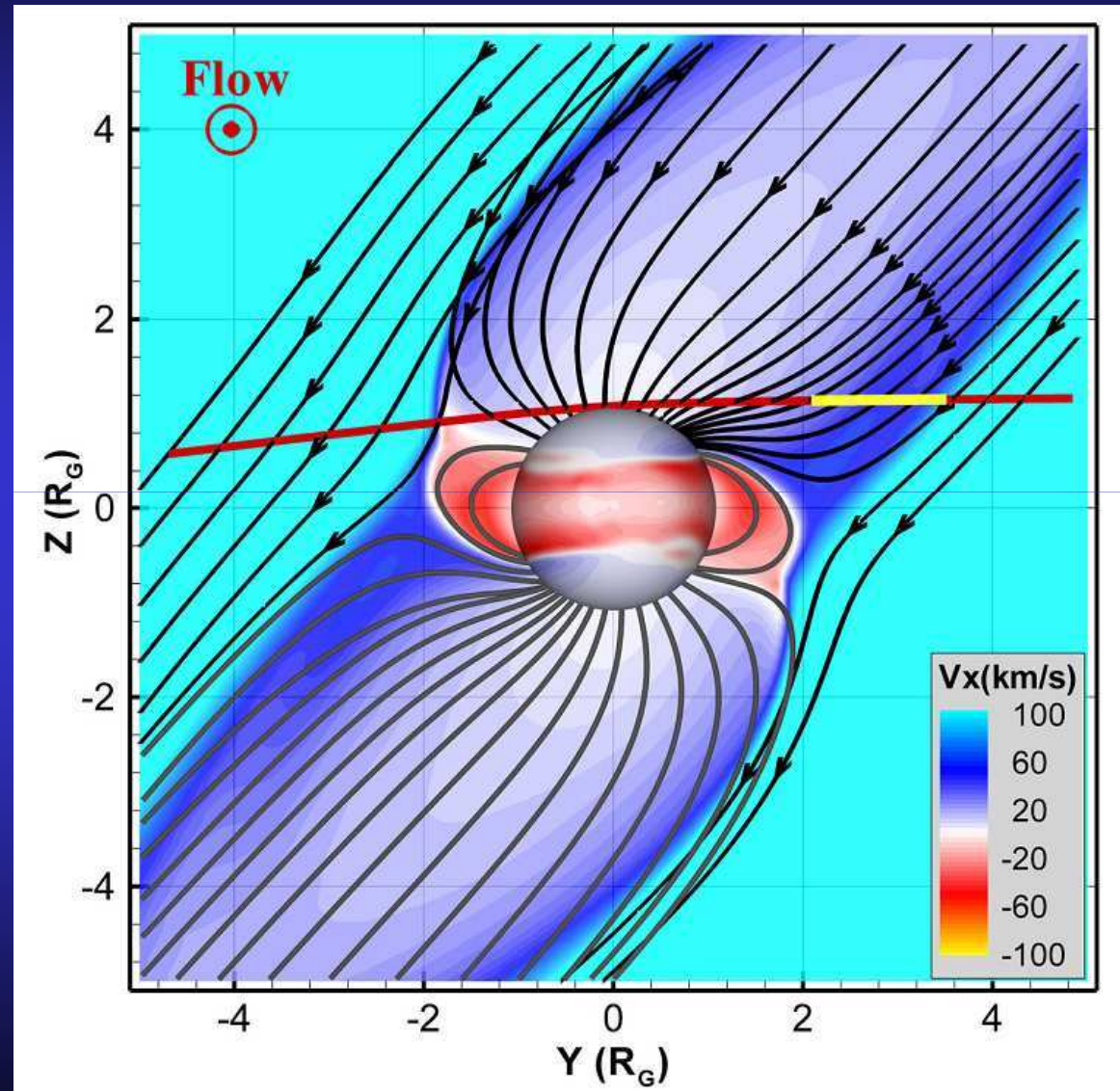
# Magnetosphere of Ganymede

Energetic electron measurements remotely diagnose magnetic topology, boundary geometry and surface magnetic field strengths of icy moons.



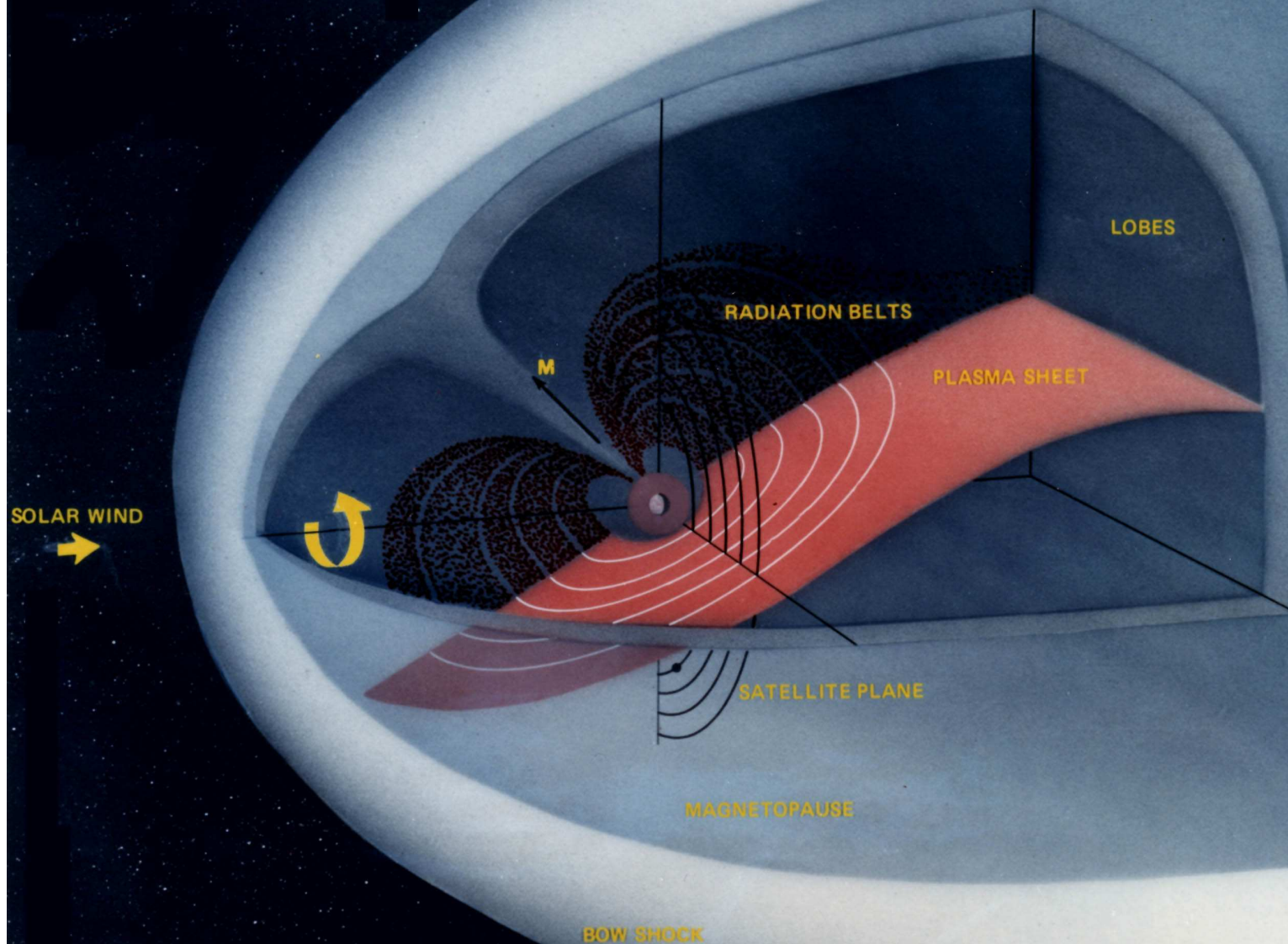
Williams et al., GRL, 1998

# Ganymede magnetosphere simulation



Jia 2009

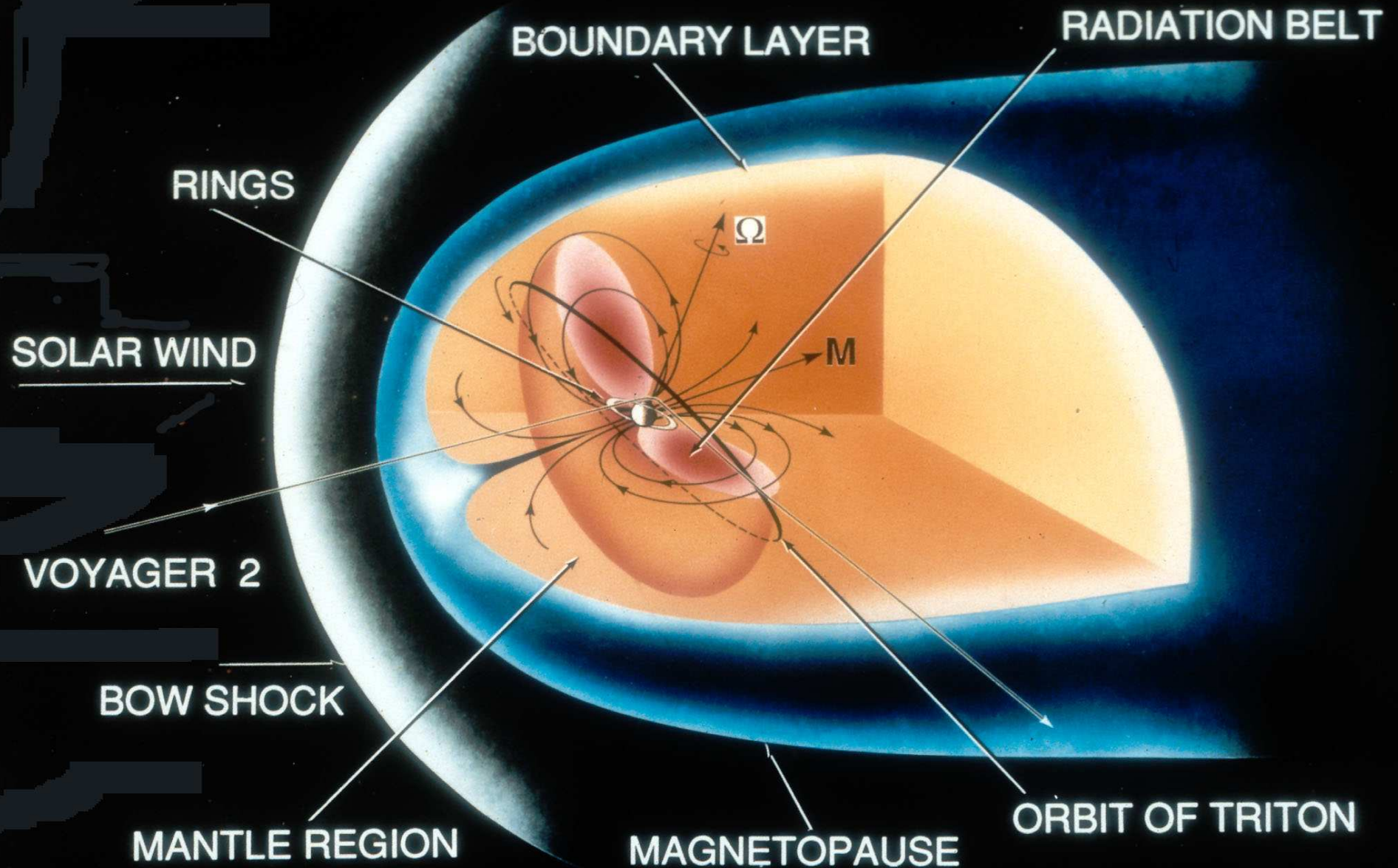
# URANUS MAGNETOSPHERE



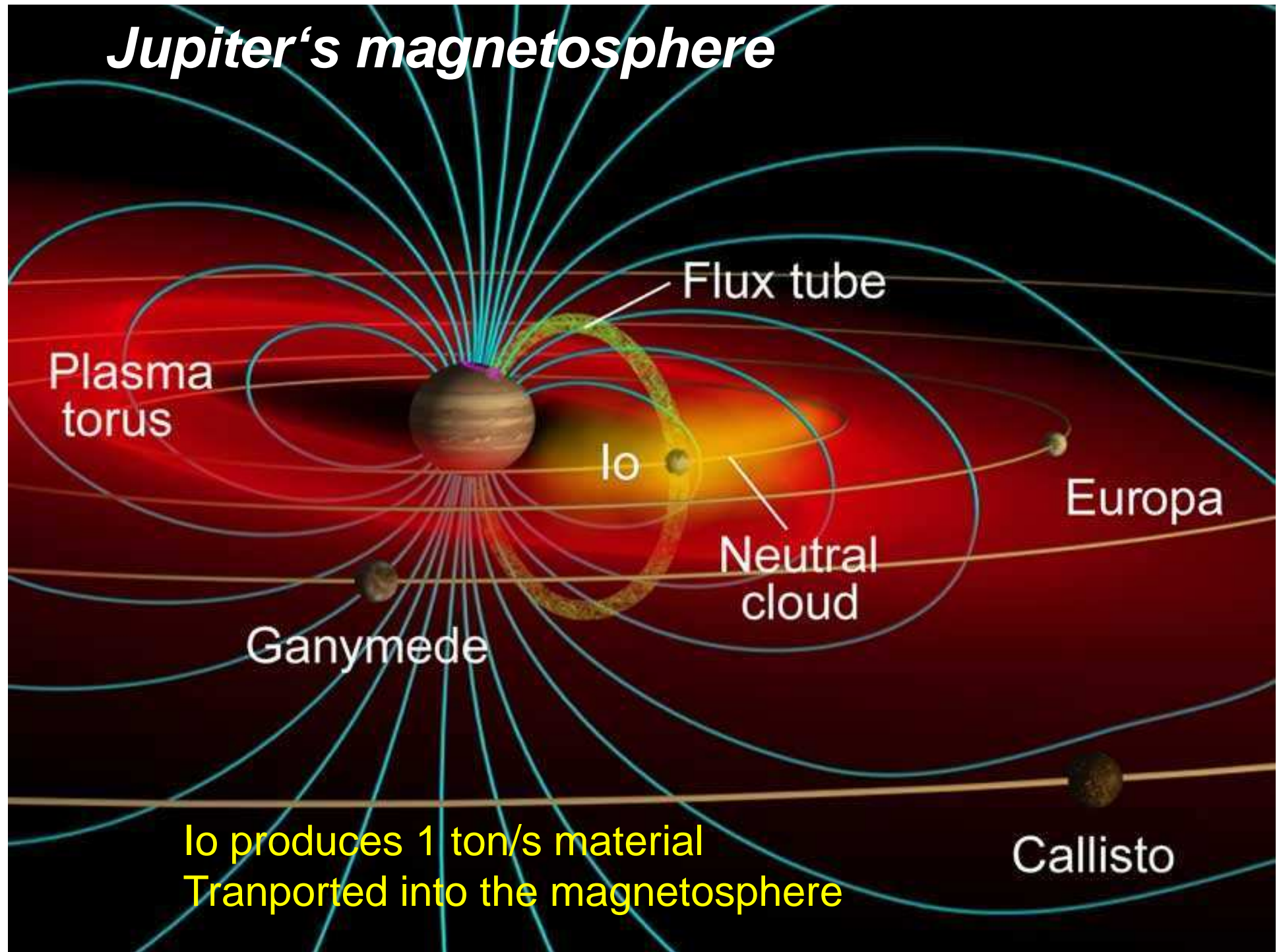
Krimigis et al, *Science*, 233, 97-102, 1986

Krimigis et al, *Science*, 246,  
1483-1494, 1989

# NEPTUNE'S MAGNETOSPHERE



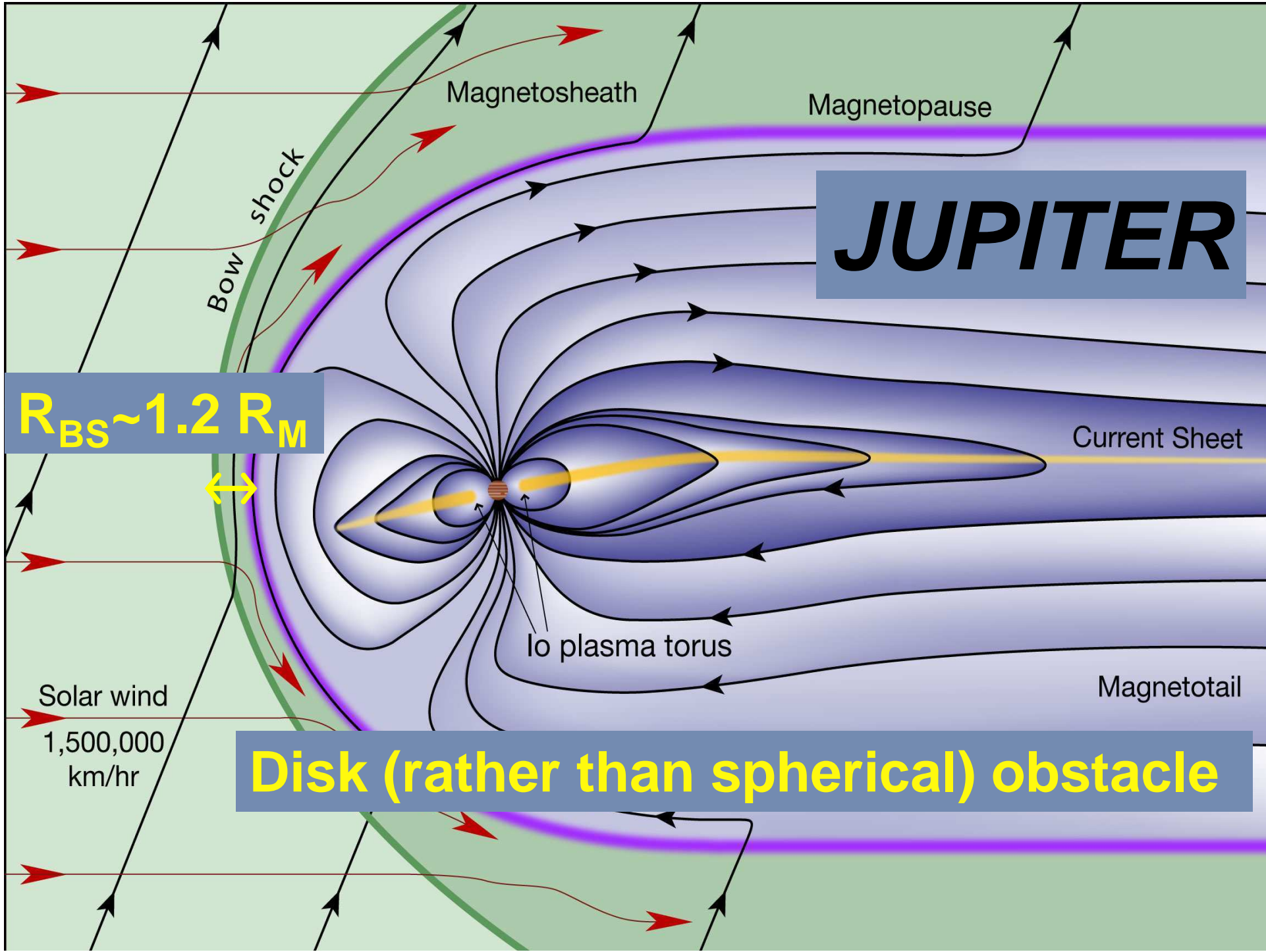
# *Jupiter's magnetosphere*



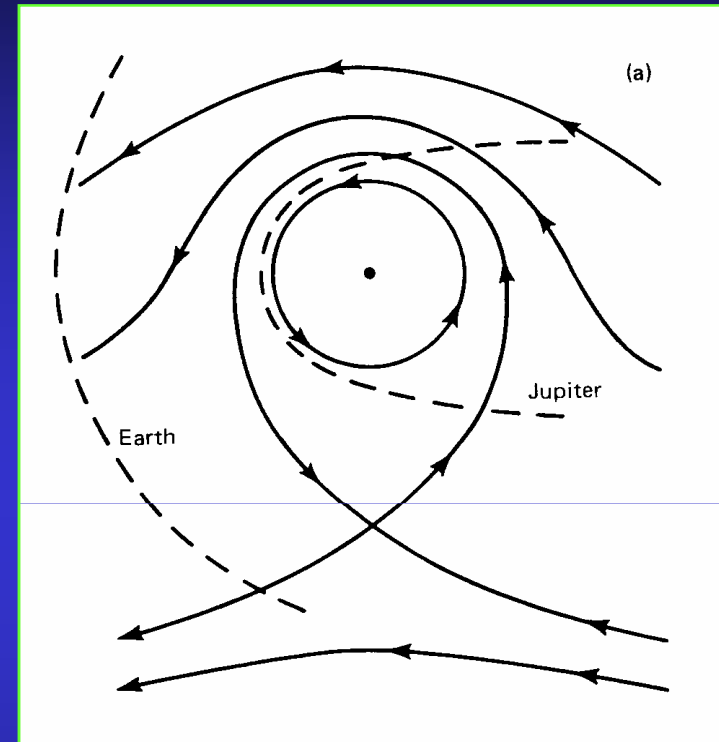
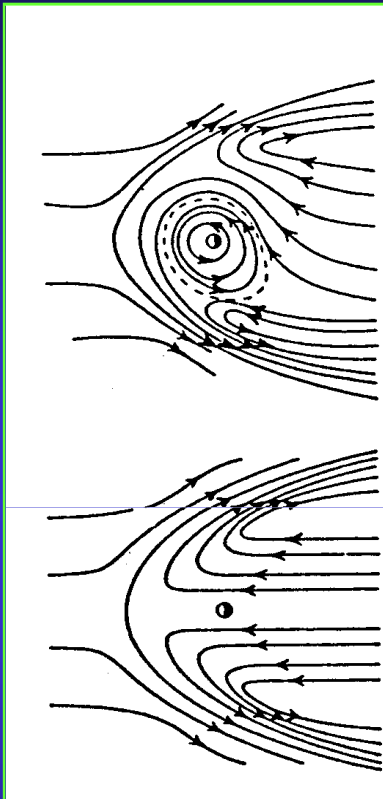
# JUPITER

$$R_{BS} \sim 1.2 R_M$$

**Disk (rather than spherical) obstacle**

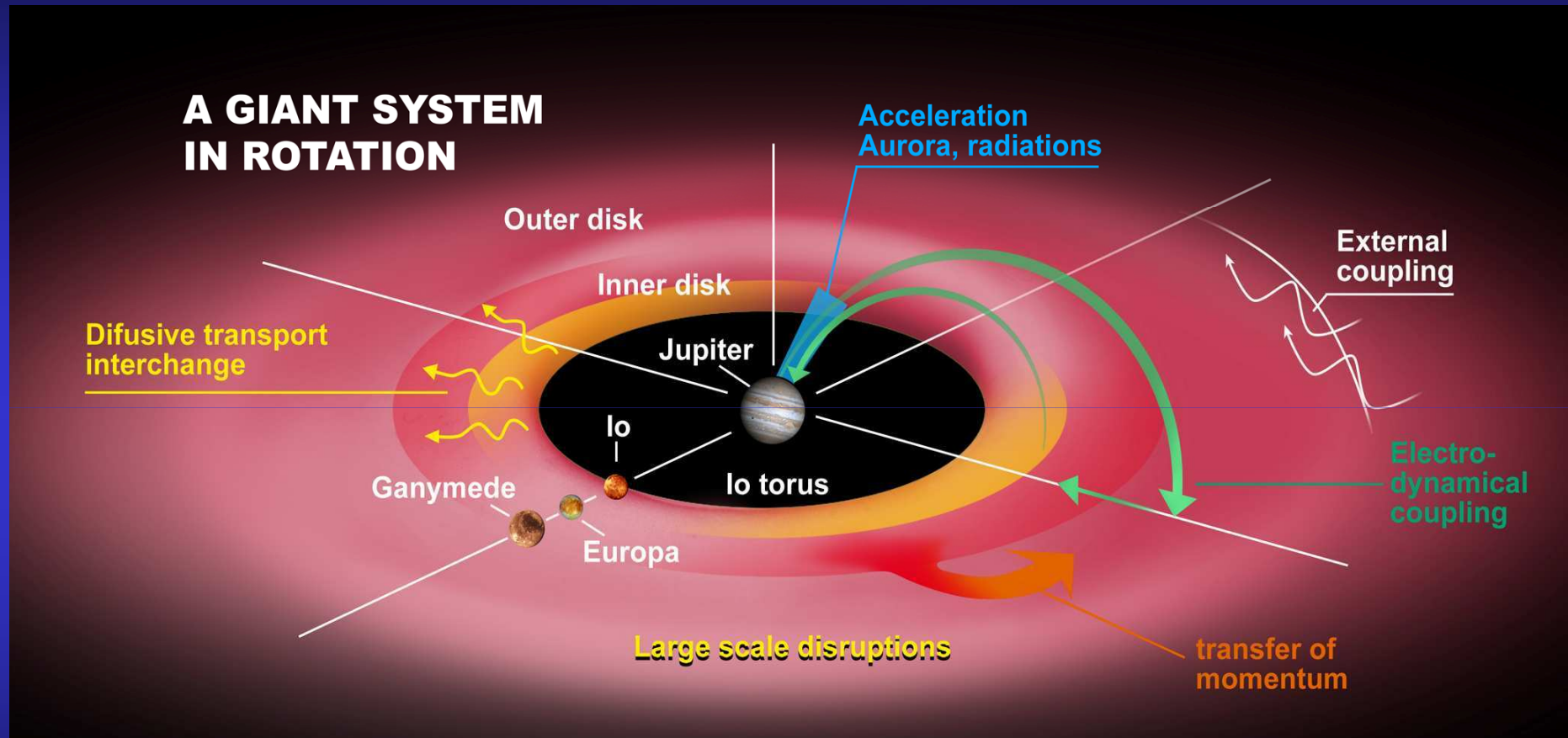


## Earth's-like magnetosphere



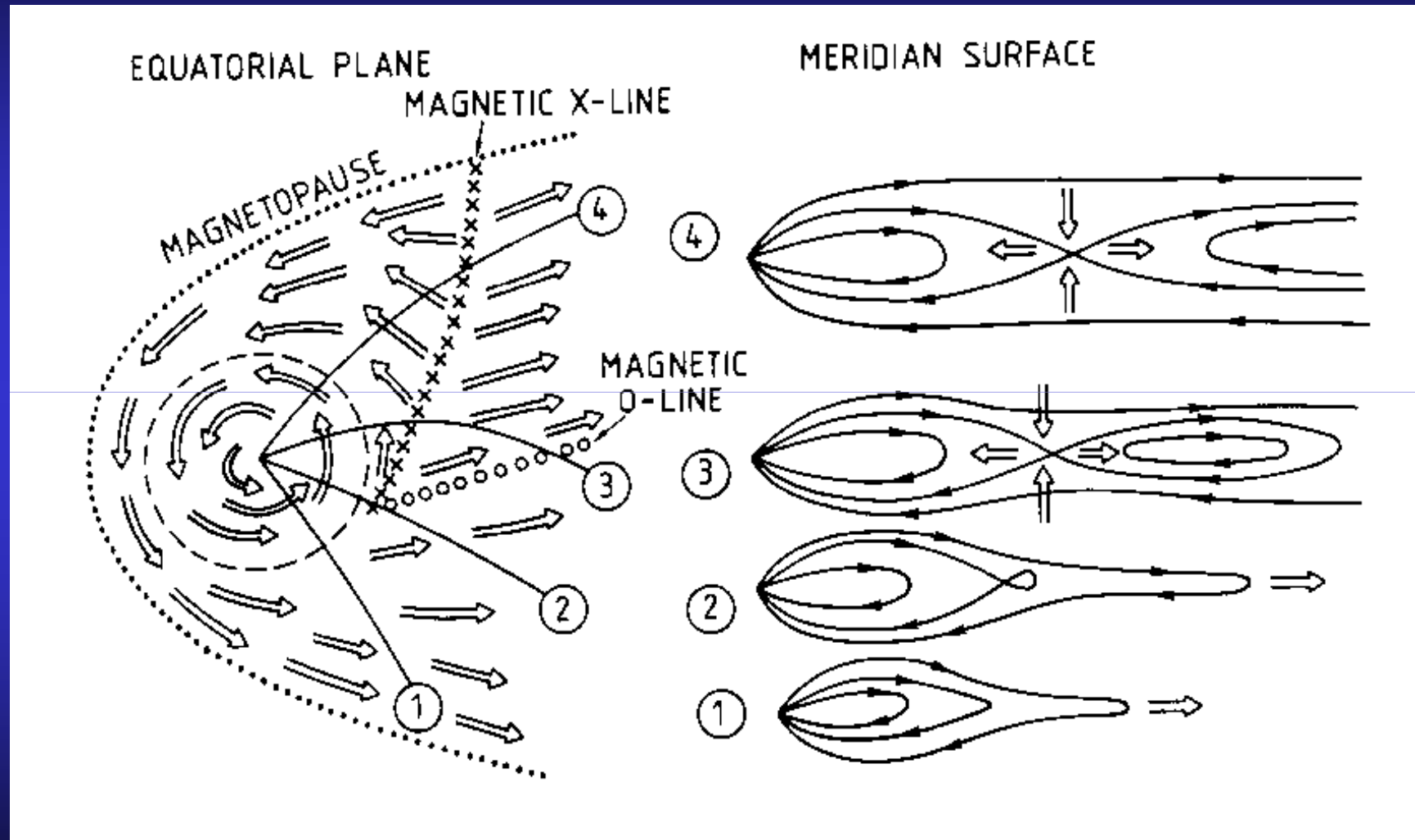
- **plasmasphere in the inner magnetosphere with closed flow lines**
- **if scaled to Jupiter: closed flow lines outside the magnetosphere**

# Jupiter's magnetosphere



# Jupiter

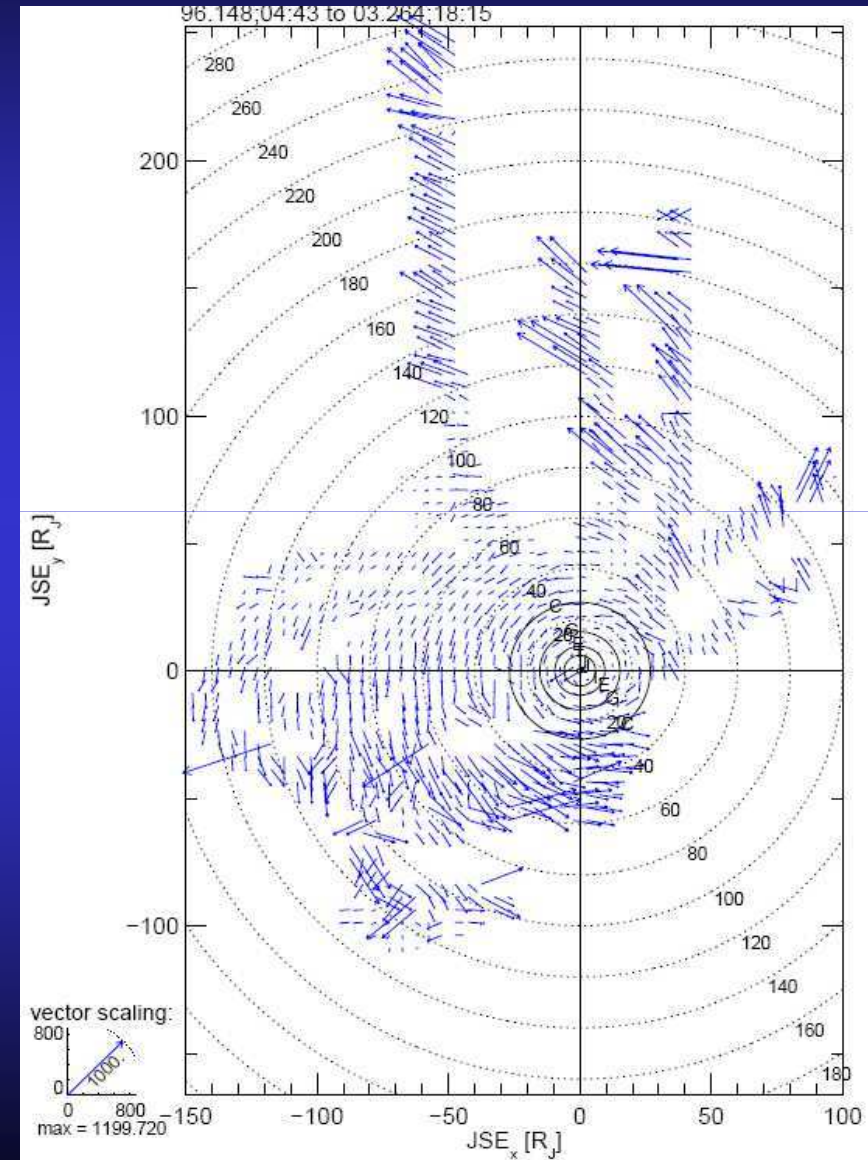
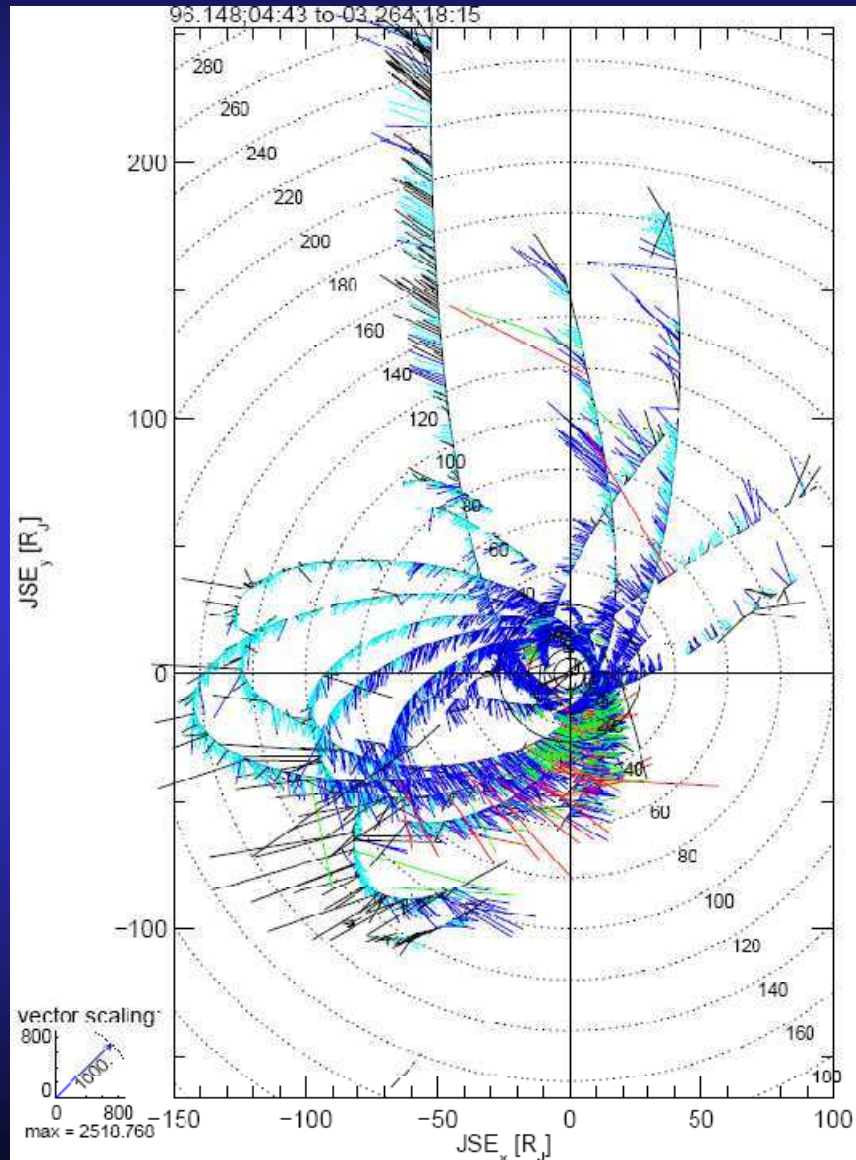
## Structure and dynamics of the outer magnetosphere



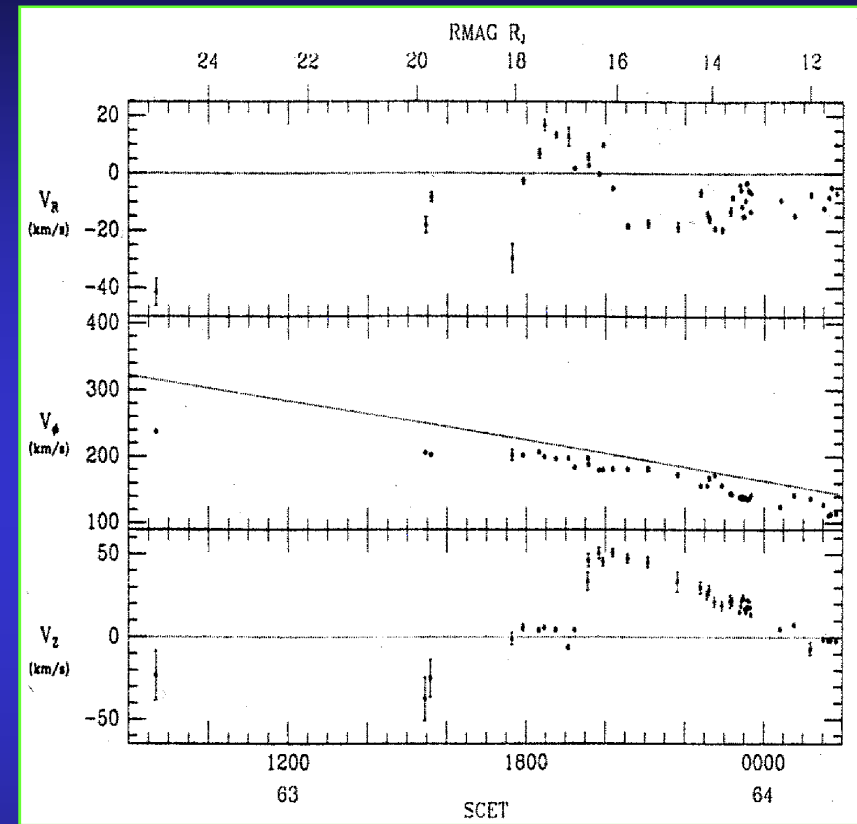
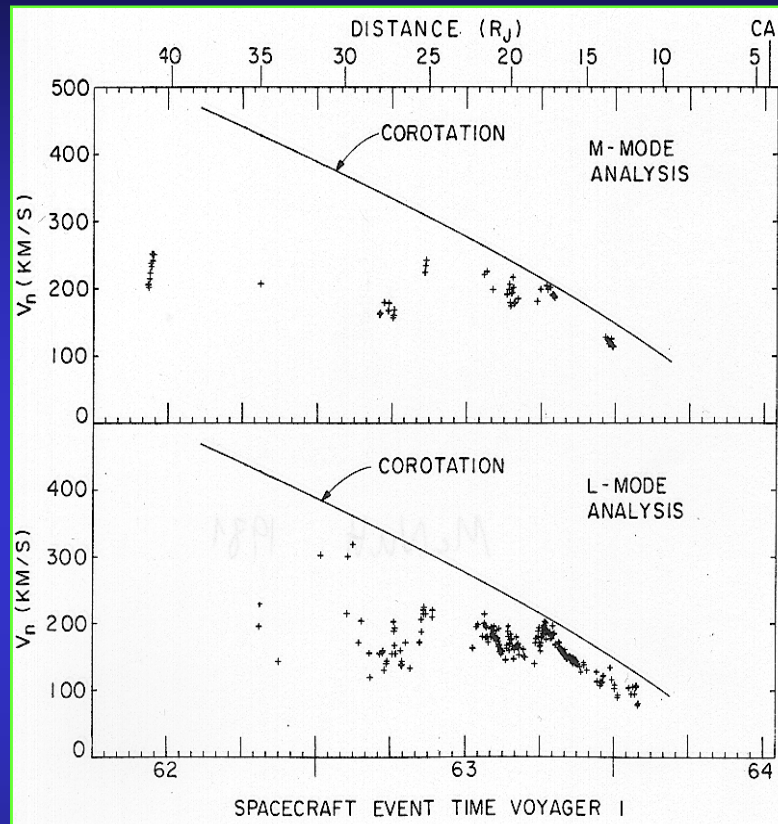
Vasyliunas 1983

# Jupiter: Global particle flow pattern in Jupiter's magnetosphere

## Galileo/EPD measurements in the equatorial plane



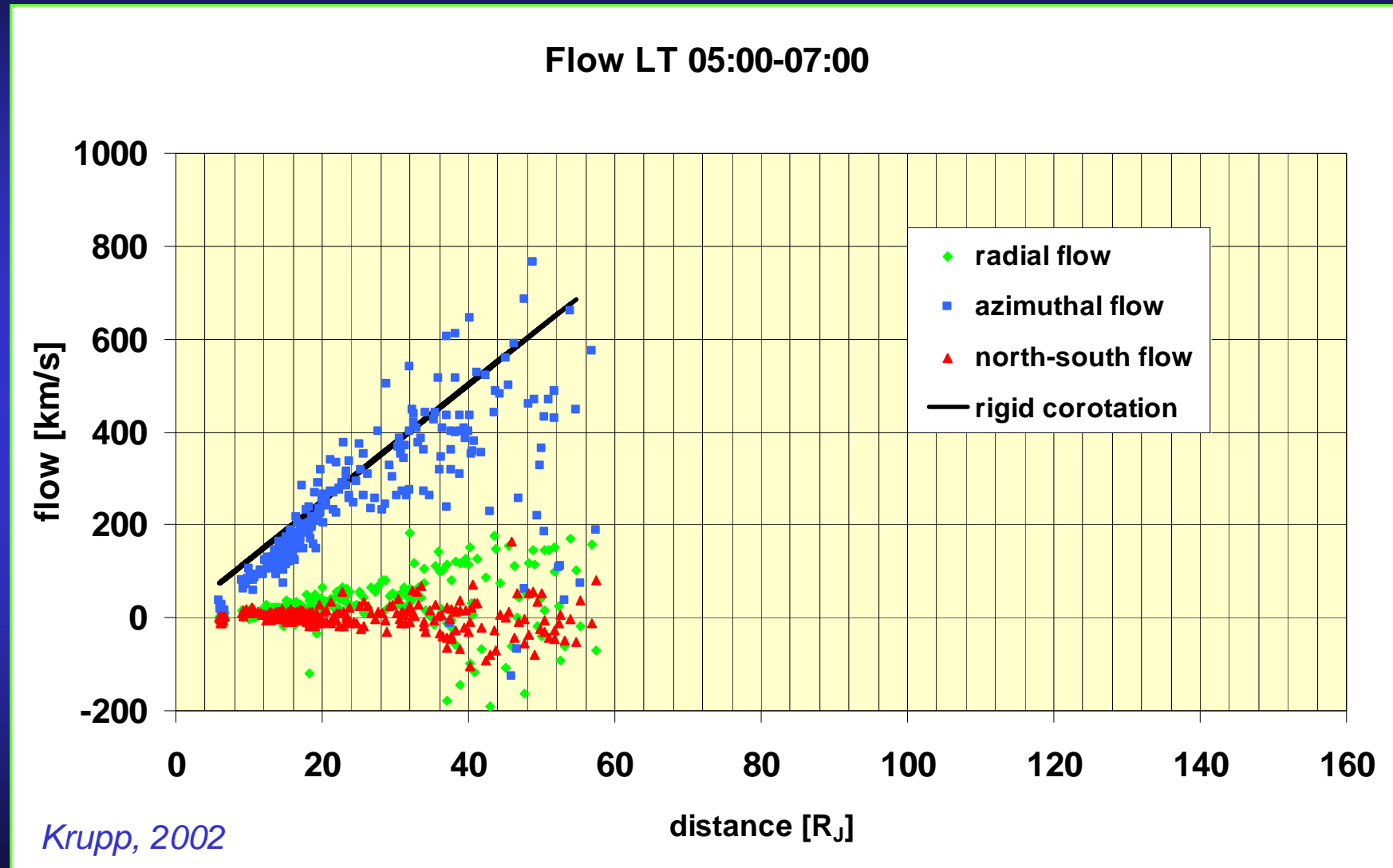
# Flow measurements in Jupiter's magnetosphere



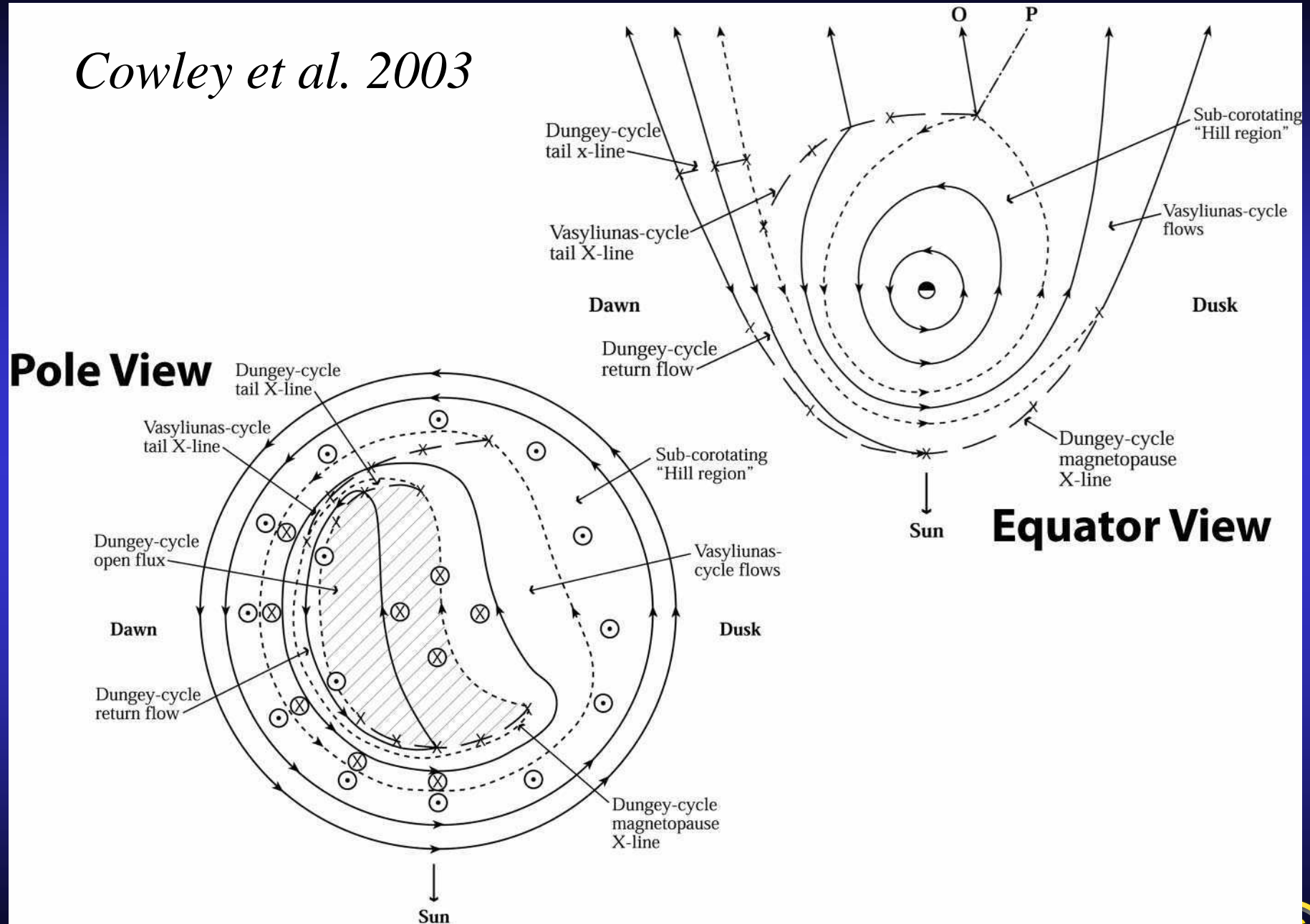
- **Voyager 1 PLS results**
  - McNutt et al., JGR, 86, 8319, 1981
  - Sands and McNutt, JGR, 93, 8502, 1988
- **Velocity lags rigid corotation trend to “constant” velocity outside 20 R<sub>J</sub>**

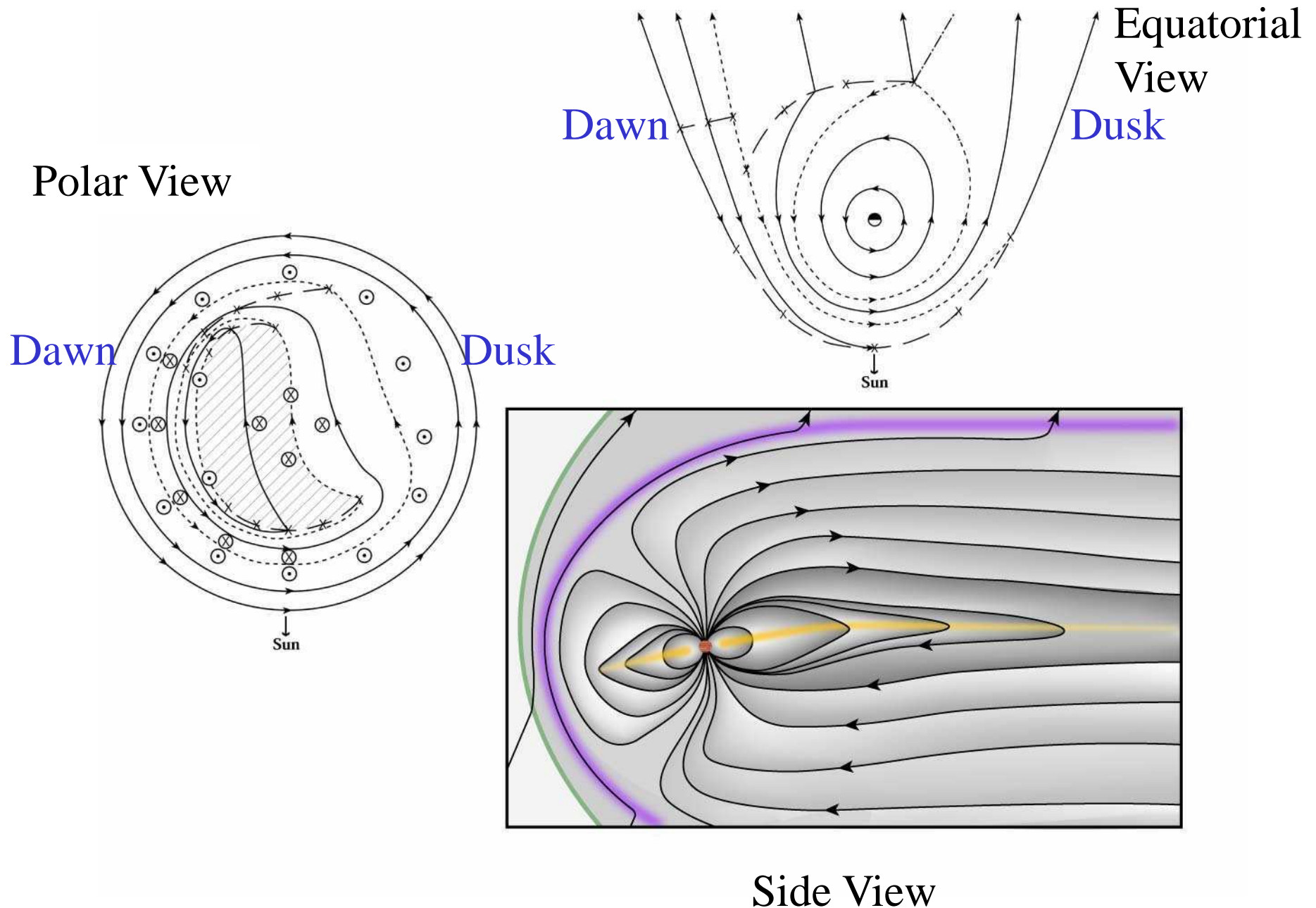
# Global Flow Pattern in Jupiter's equatorial plane

strong local time asymmetry between dawn and dusk

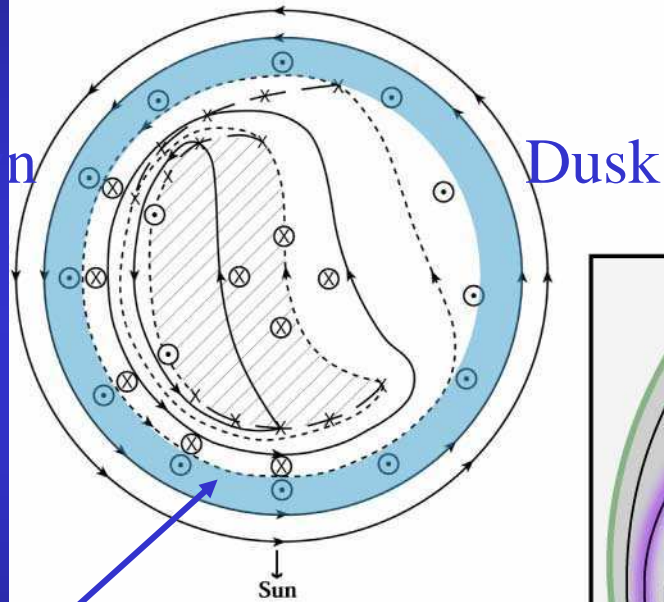


*Cowley et al. 2003*

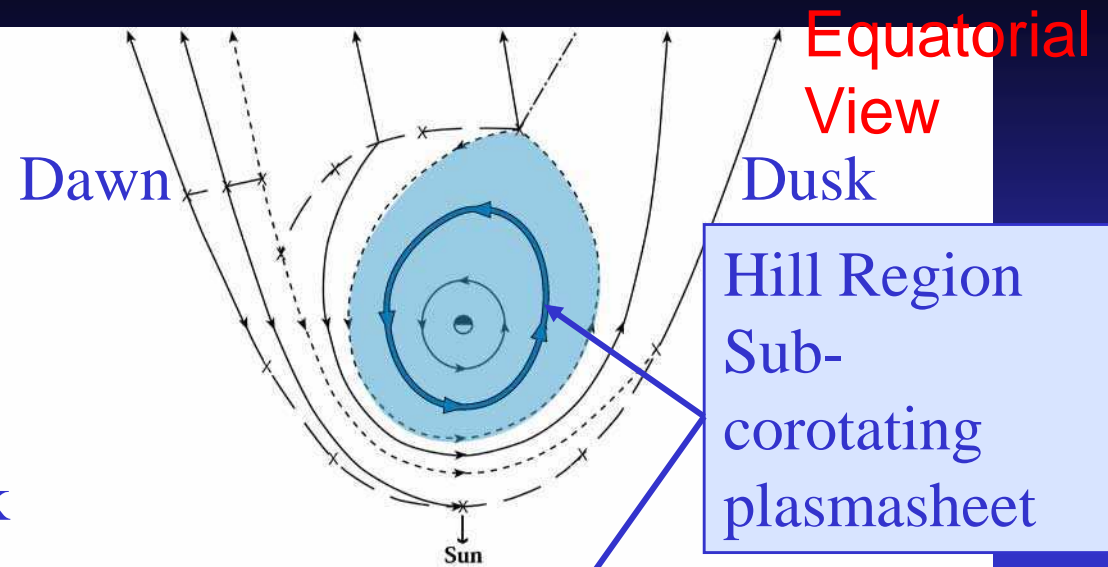




Polar View

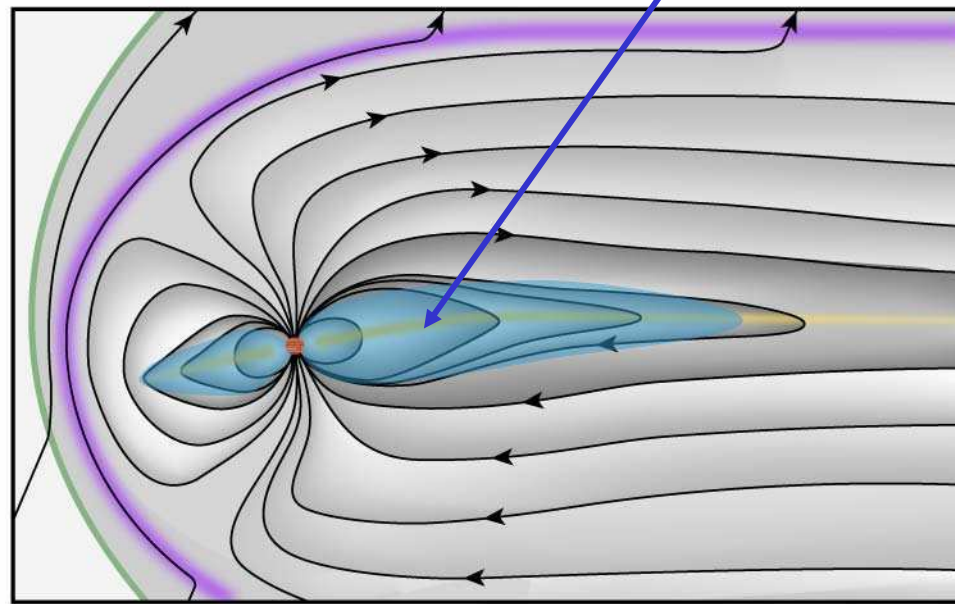


Main Auroral Oval



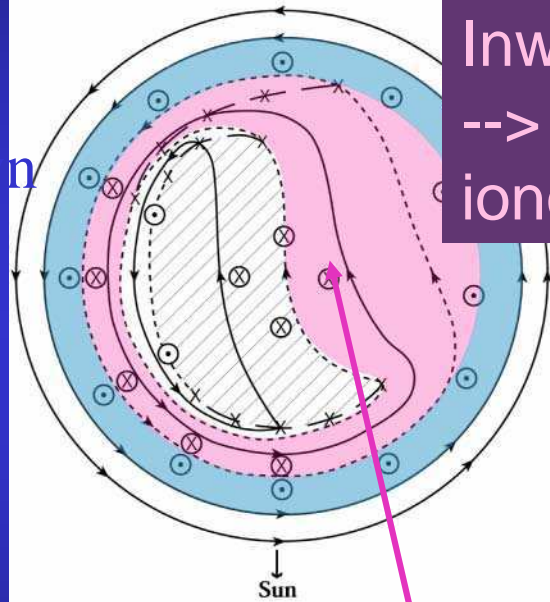
Equatorial View

Hill Region  
Sub-corotating  
plasmasheet



Side View

Polar View



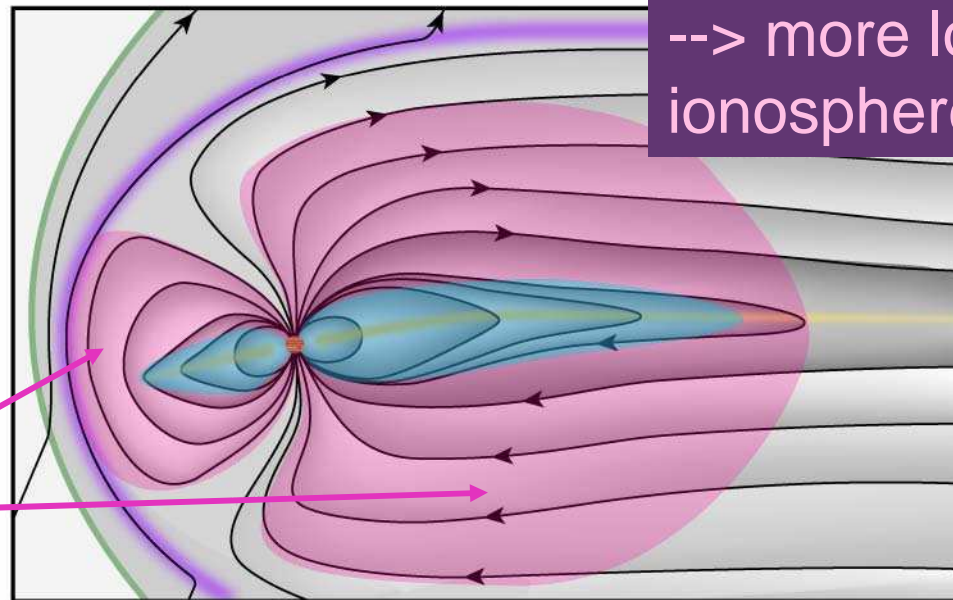
Dawn

Equatorial View  
Dusk

Inward motion  
--> less load on ionosphere

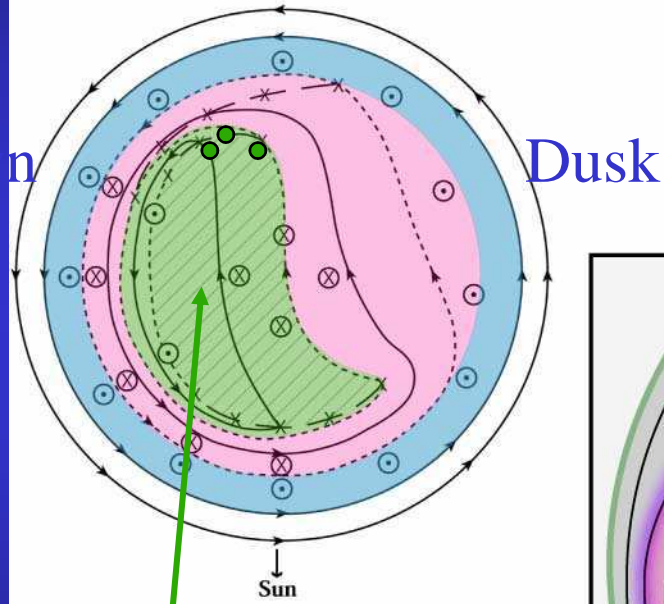
Outward motion  
--> more load on ionosphere

Outer Magnetosphere  
"Cushion Region"

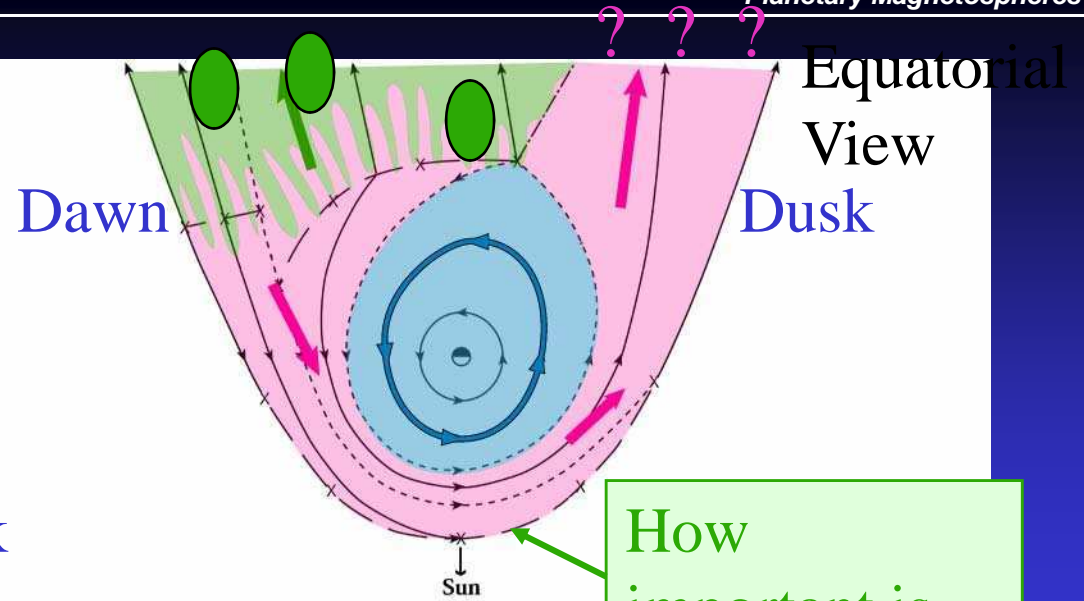


Side View

Polar View

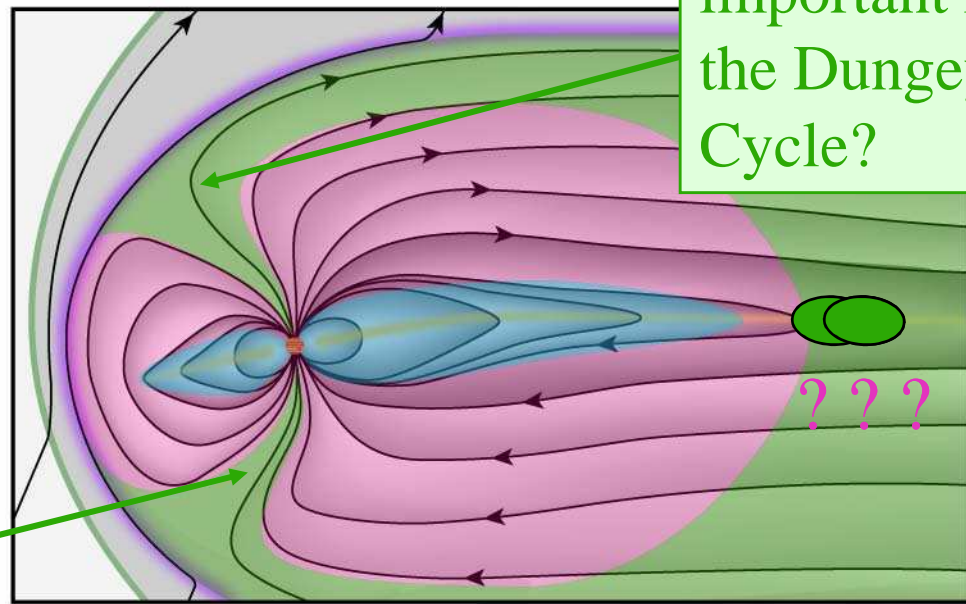


How Much of Polar Flux is Open?



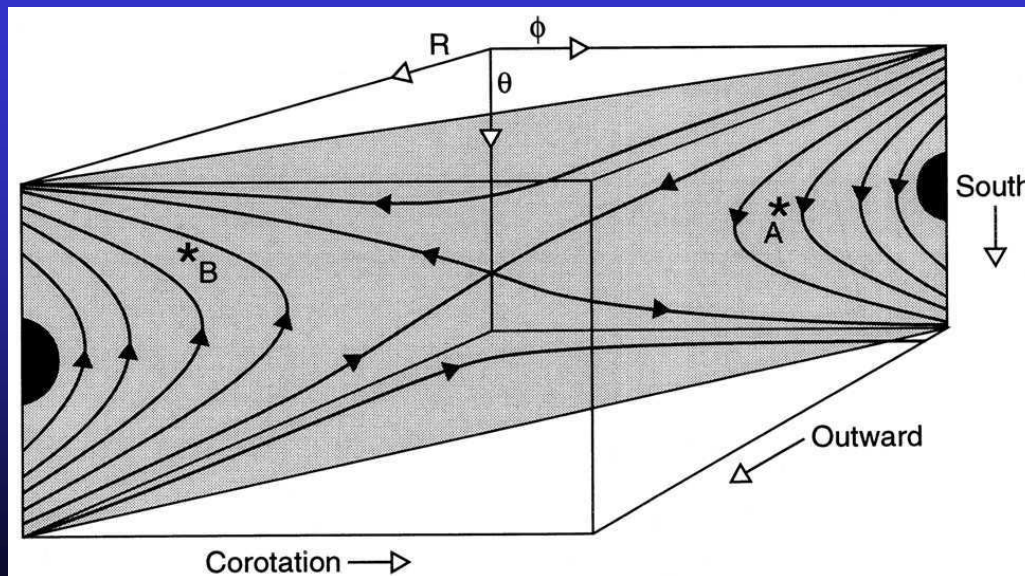
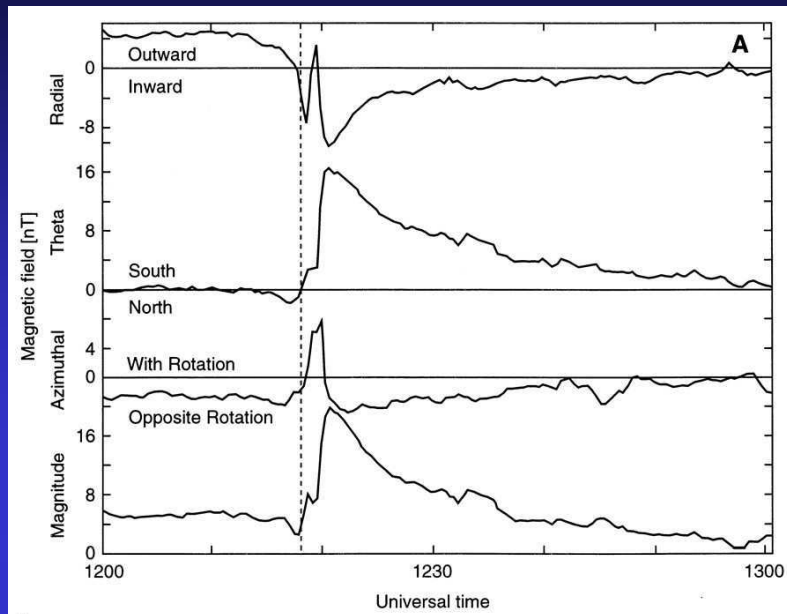
Equatorial View

How important is the Dungey Cycle?



Side View

## Are there substorms in Jupiter's m'sphere?



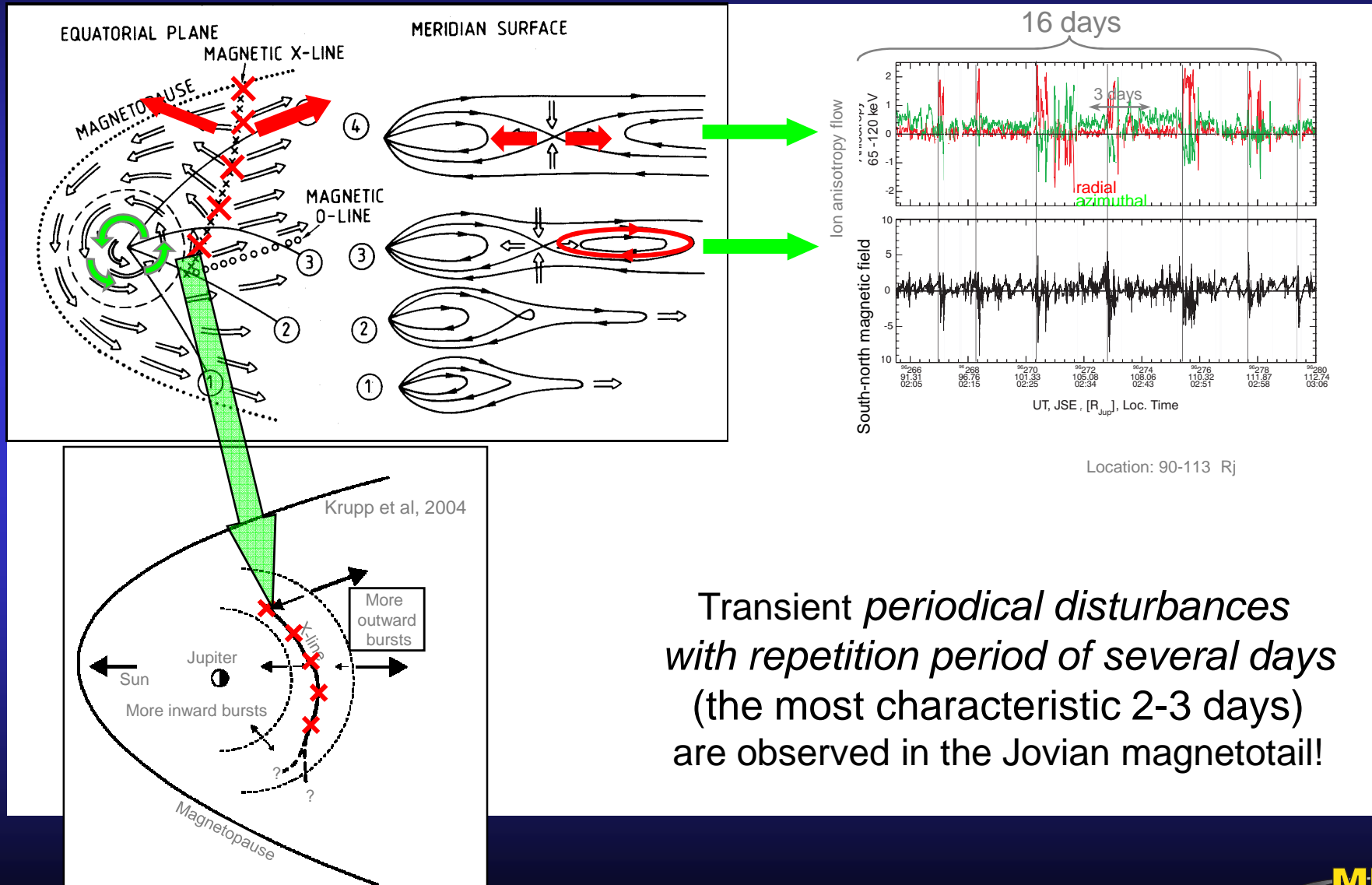
–Russell [Adv. Space Res., 2000, 2002] provides evidence for reconnection in the magnetotail.

–The enhanced southward field accompanied by Jupiter ward flows and enhanced northward field accompanied by tailward flow.

–Most of the reconnection events were seen in the dawn sector.

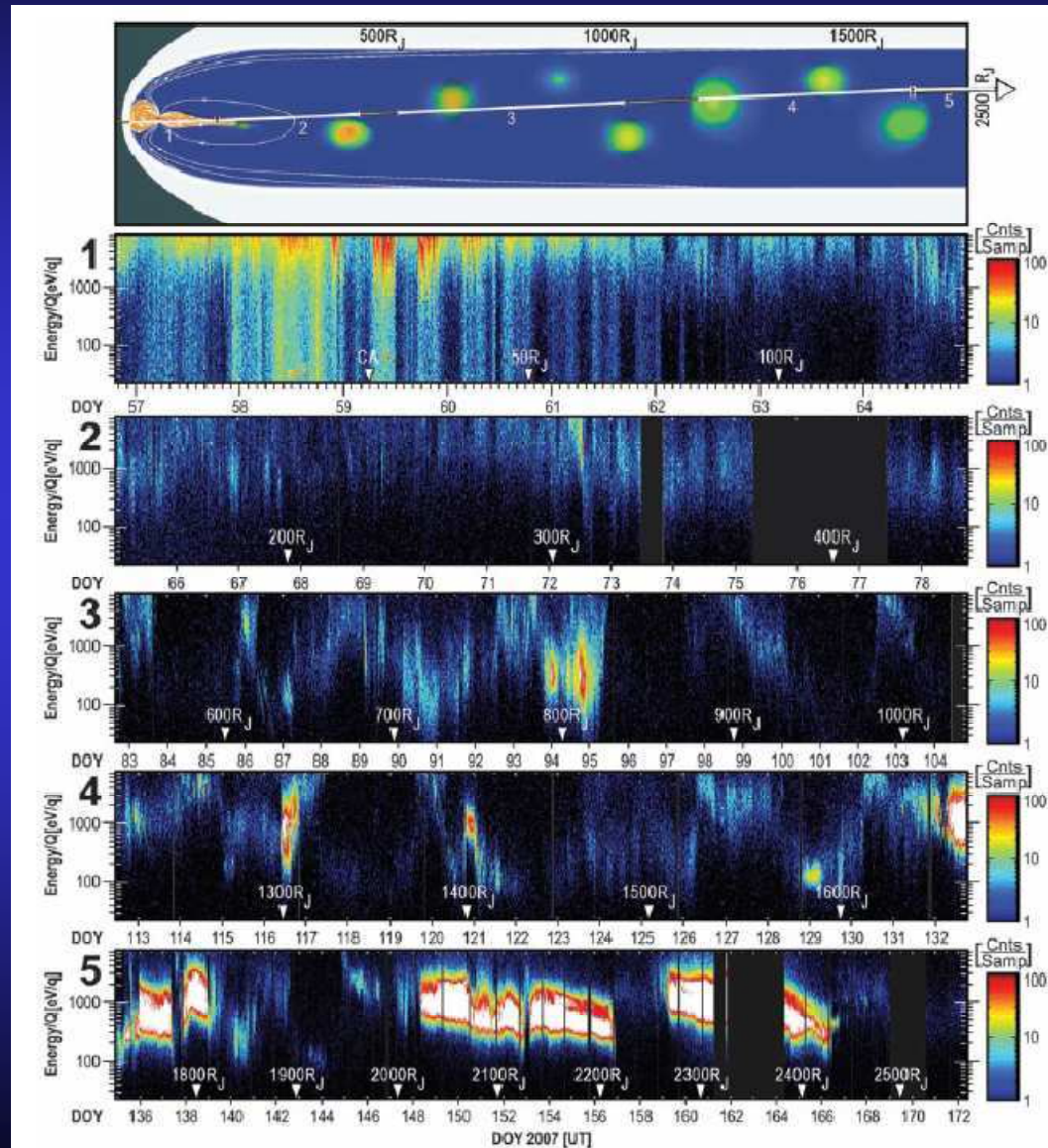
–In accord with the study of Krupp et al. [2001] who saw flow bursts mostly in the dawn sector.

# Dynamics of the Jovian magnetotail



Transient *periodical disturbances* with repetition period of several days (the most characteristic 2-3 days) are observed in the Jovian magnetotail!

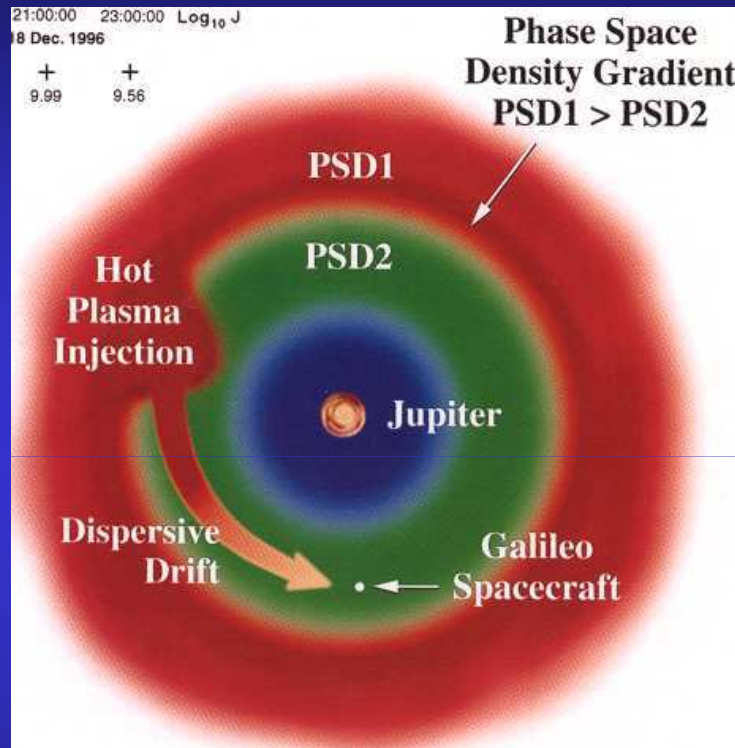
# Jupiter: Particle observations in the deep Jovian magnetotail (New Horizons)



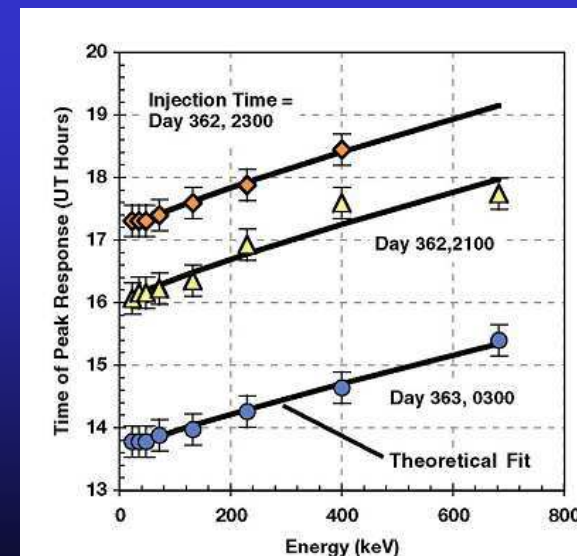
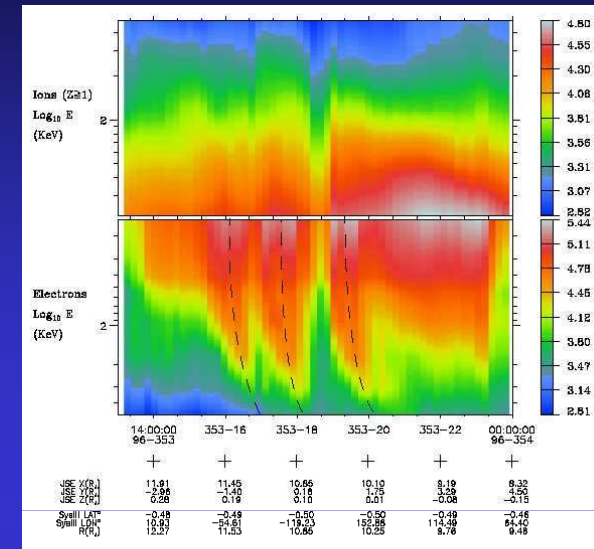
McComas, 2007

# Dynamics in Jupiter's magnetosphere

## Particle injections



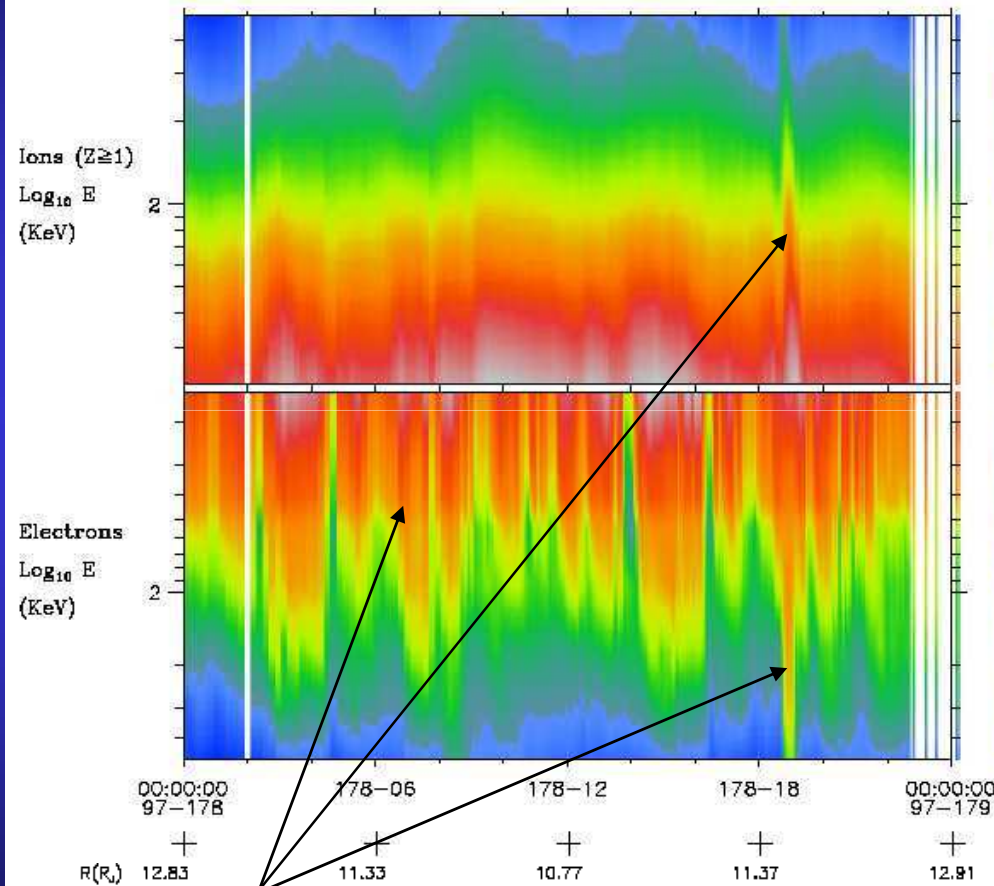
The behaviors of Jupiter magnetosphere injections were understood by invoking sudden radial injections over confined regions in azimuth followed by slow, dispersive, azimuthal drifts.



# Dynamics in Jupiter's magnetosphere

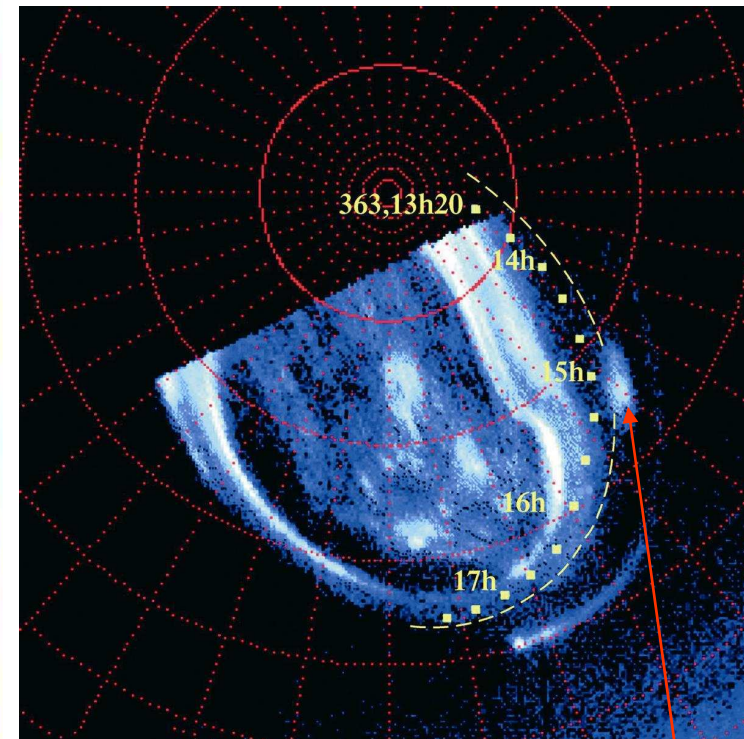
## Energetic Particle Injections & correlation to auroral emissions

24 hour Galileo Energetic Particle Spectrogram



Extreme "storm-time" dynamics  
 observed in the vicinity of Europa's  
 orbit

HST Image of Jupiter's UV aurora

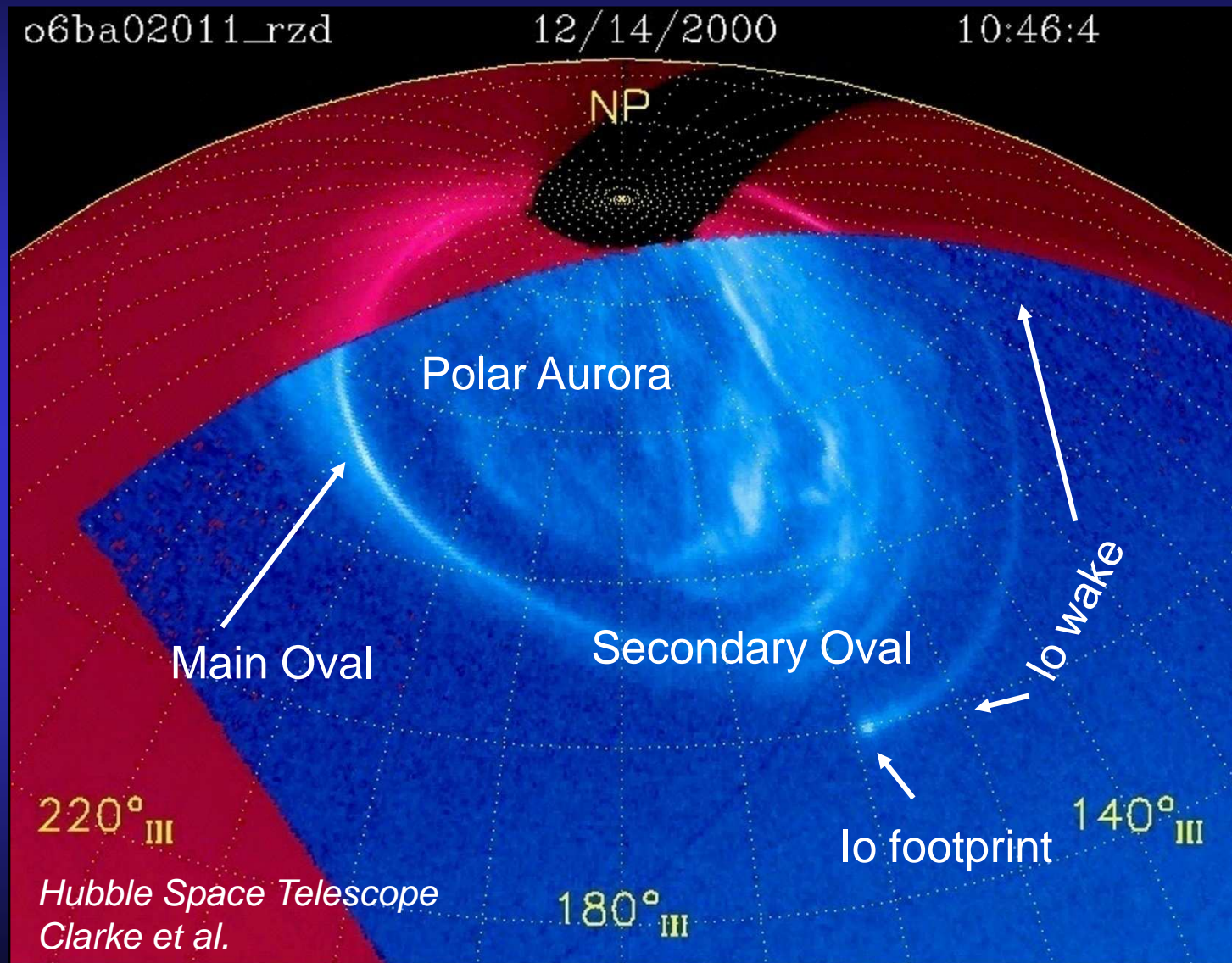


Mauk et al., 1997; 1999, 2000

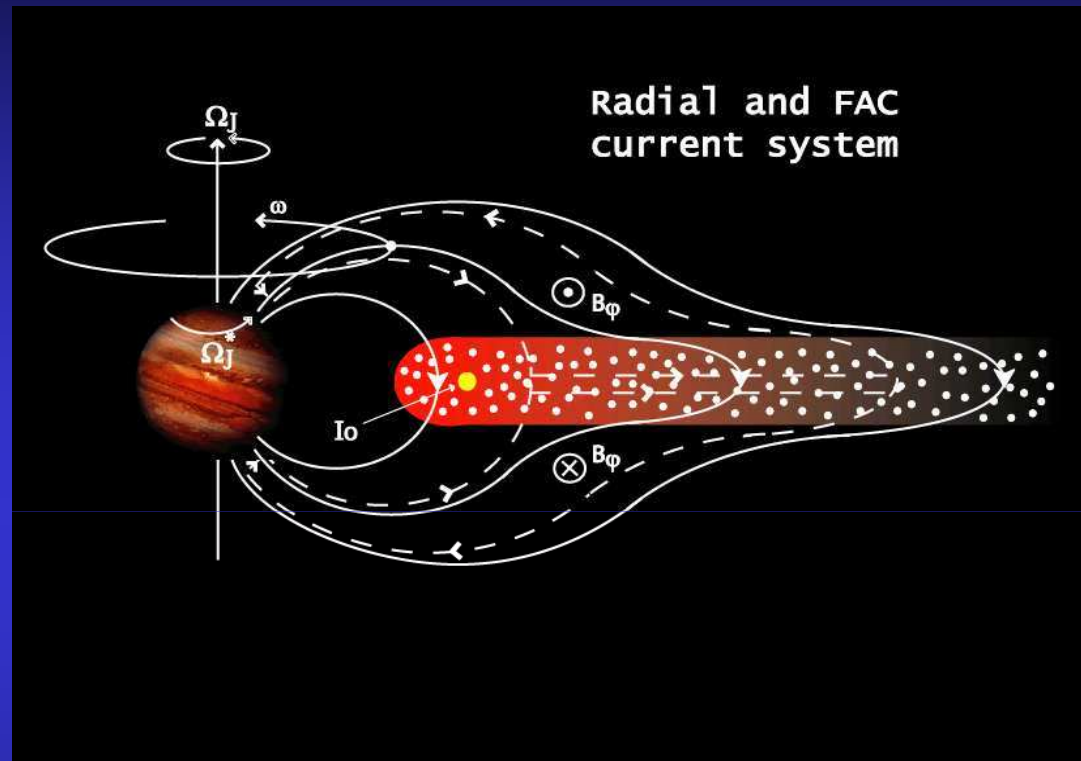
Auroral manifestation of near-  
 Europa storm dynamics

# Jupiter

## Different types of aurora



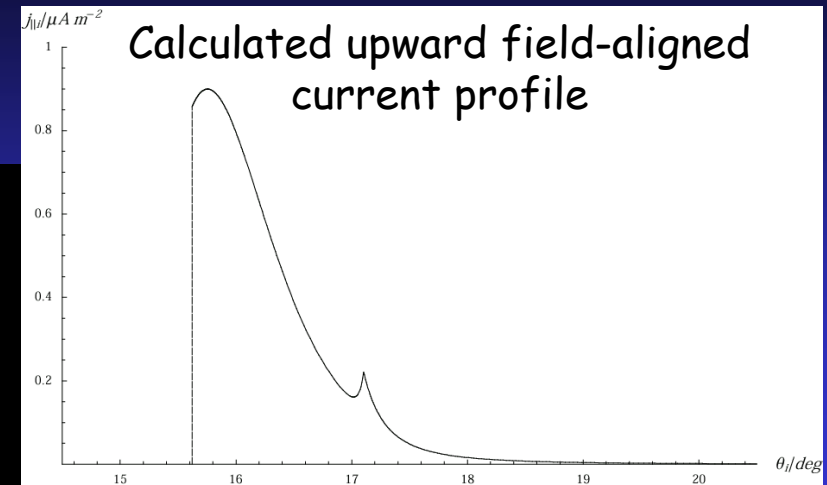
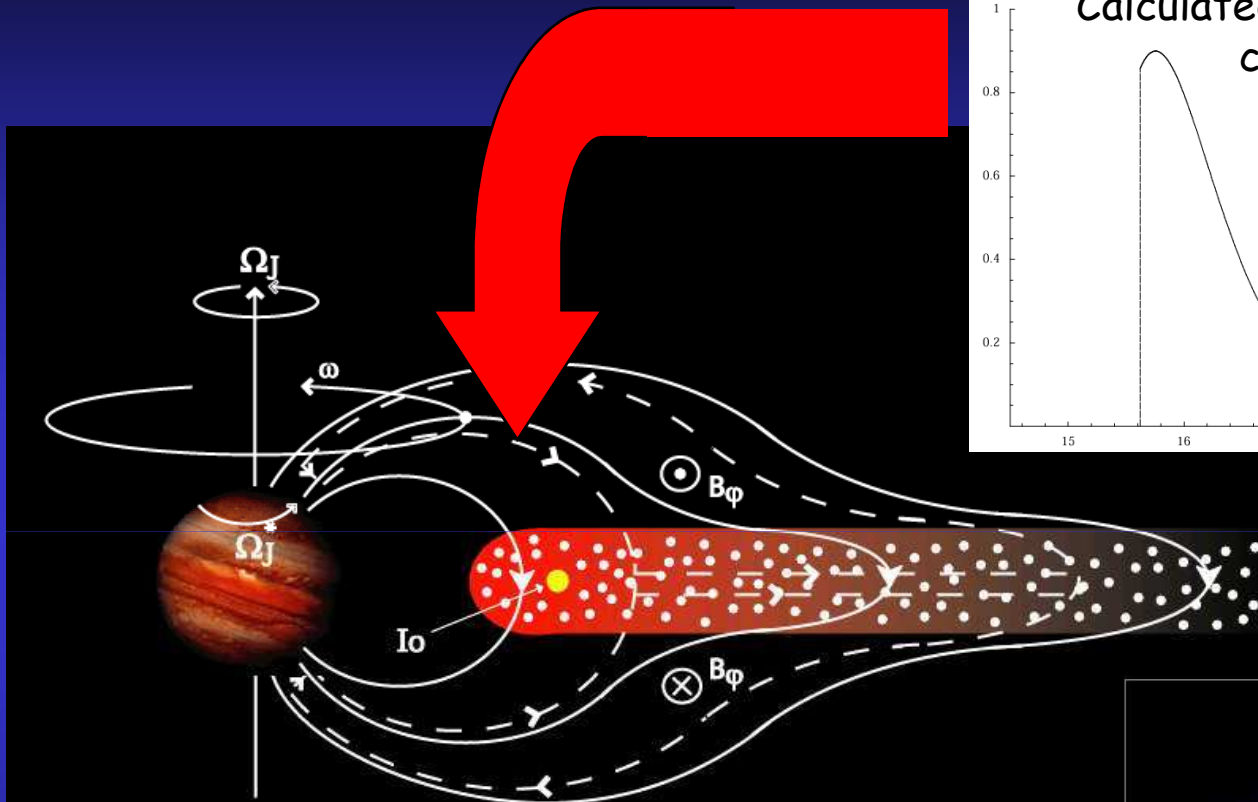
## Large-scale current system in the Jovian magnetosphere



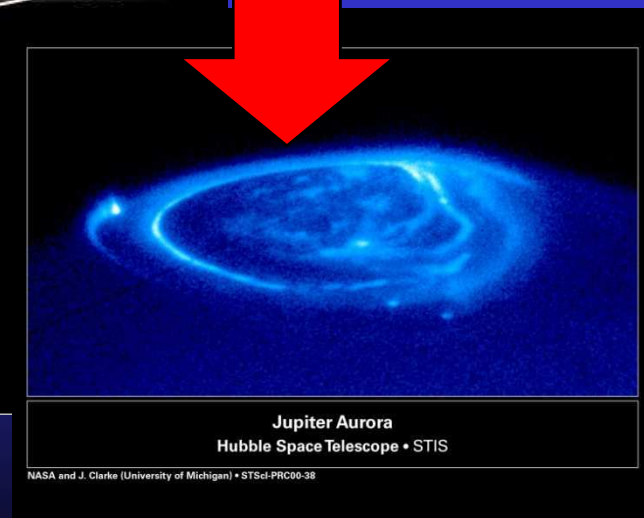
After Hill (1979)  
and Vasyliunas (1983)

- Discovery of a local time asymmetry in the system of azimuthal currents which distend the field lines away from the planet (Bunce and Cowley, 2001a; Khurana, 2001)
- Investigations of field-aligned currents associated with magnetosphere-ionosphere coupling currents found to be  $\sim 1 \mu\text{Am}^{-2}$  (Bunce and Cowley, 2001b; Khurana, 2001)

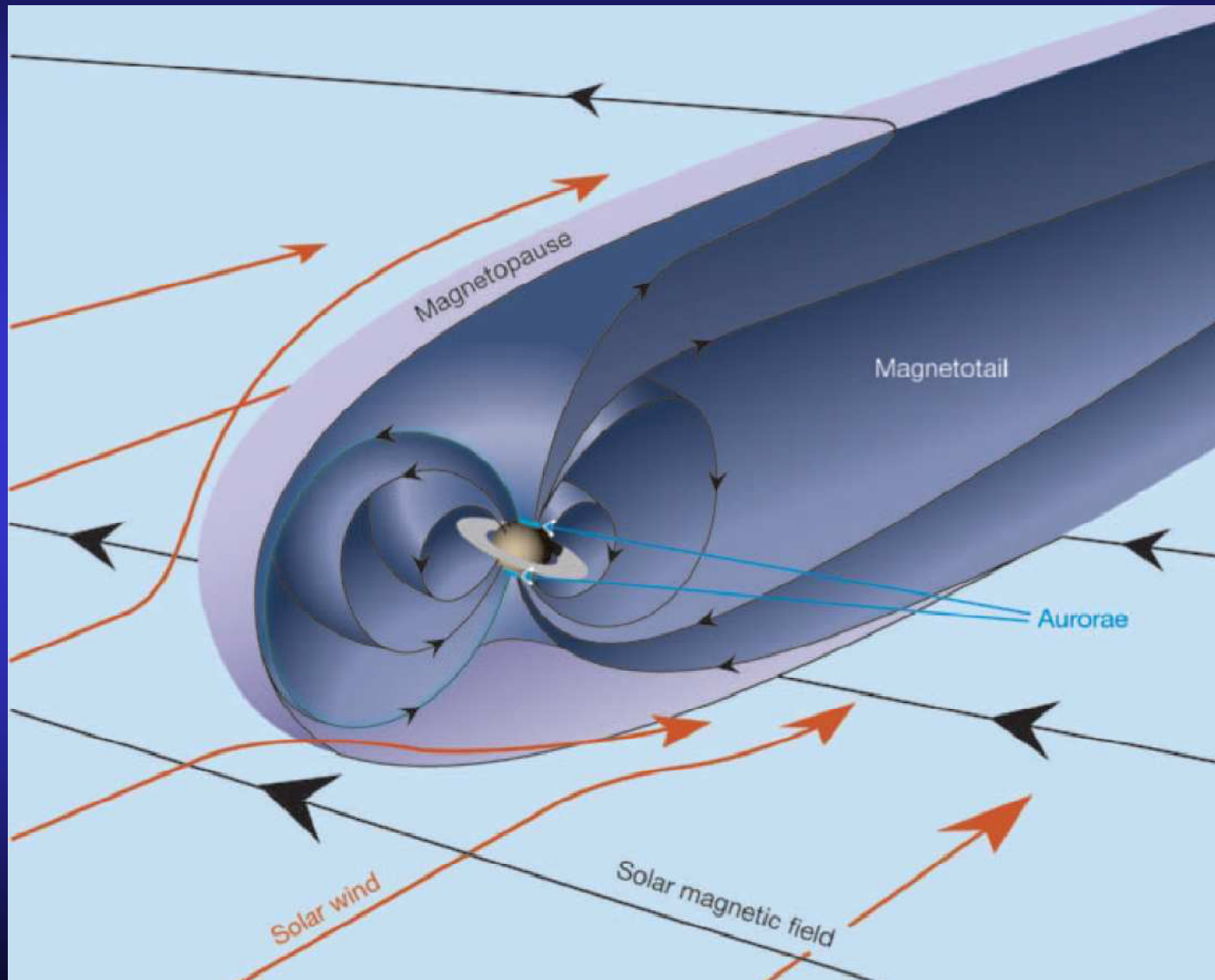
# Origin of the Jovian main aurora



- Bunce and Cowley (2001b), Cowley and Bunce (2001), Hill (2001) and Southwood and Kivelson (2001) suggest the main auroral oval is due to the breakdown of corotation of the equatorial plasma
- Modulation of the oval in anti-correlation with solar wind dynamic pressure (C&B, 2001, 2003a&b; S&K, 2001)

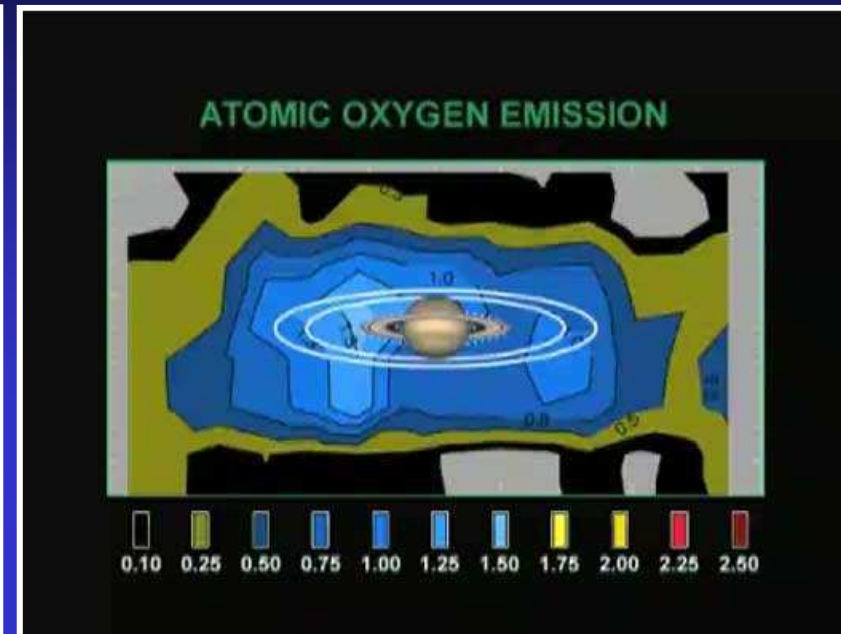
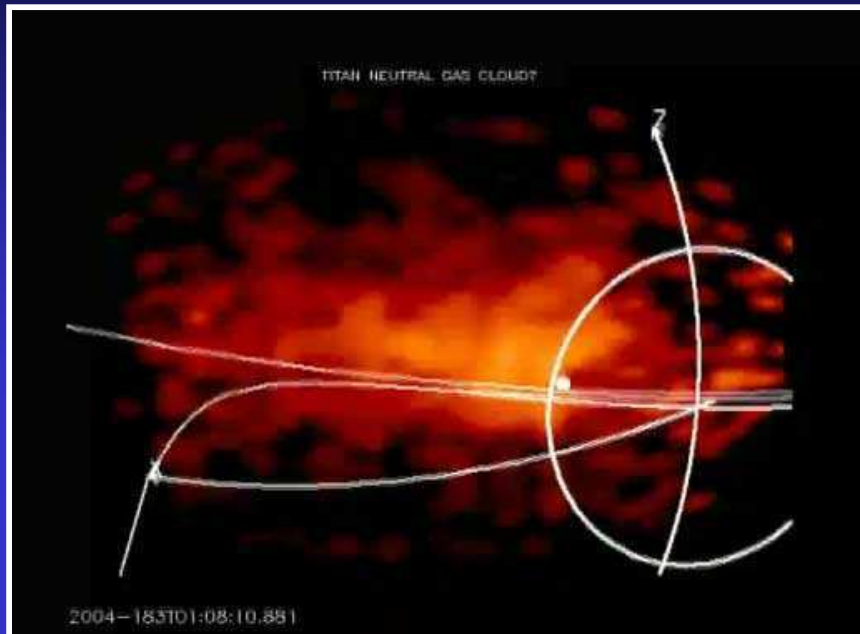


# Saturn: Mixed magnetosphere



Bagenal,  
Nature 2005

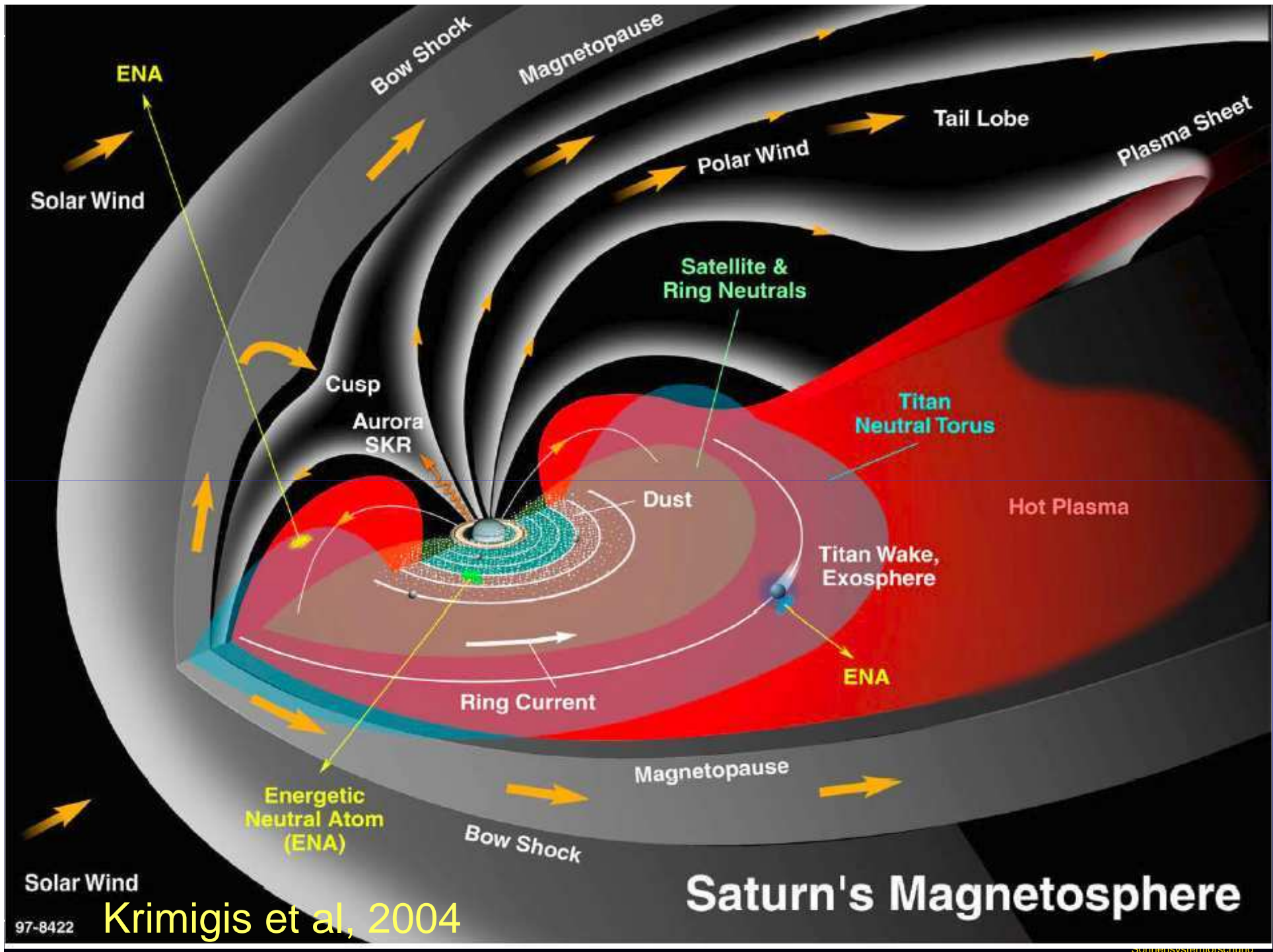
## Saturn's magnetosphere Cassini results



Hot neutral gas emissions:  
MIMI/INCA measurements

cold neutral gas:  
UVIS measurements

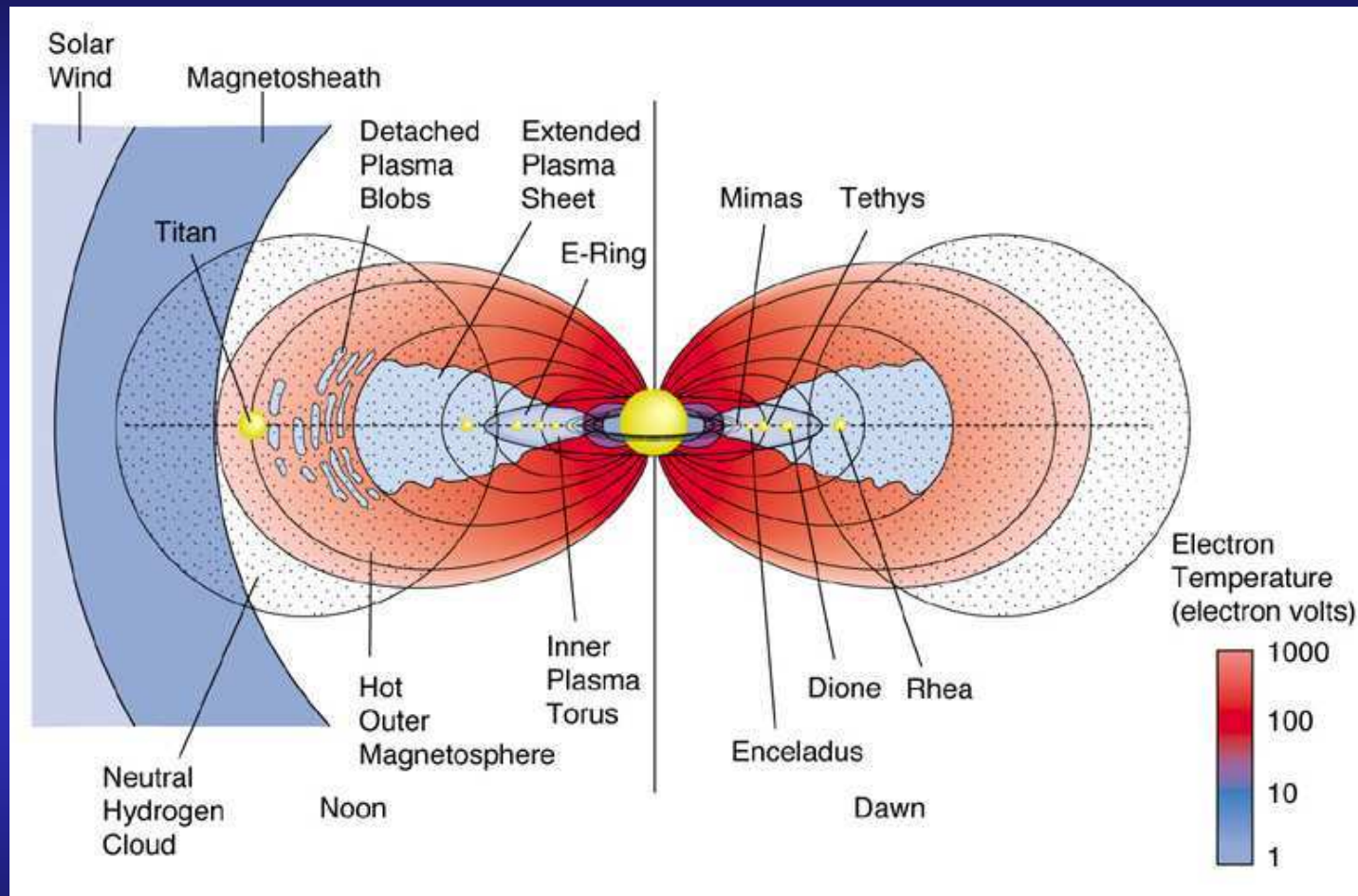
- Neutral gas cloud surrounds Saturn as far out as 45 RS = 2.7 Mio km
- Neutrals play a more important role than at Jupiter



97-8422

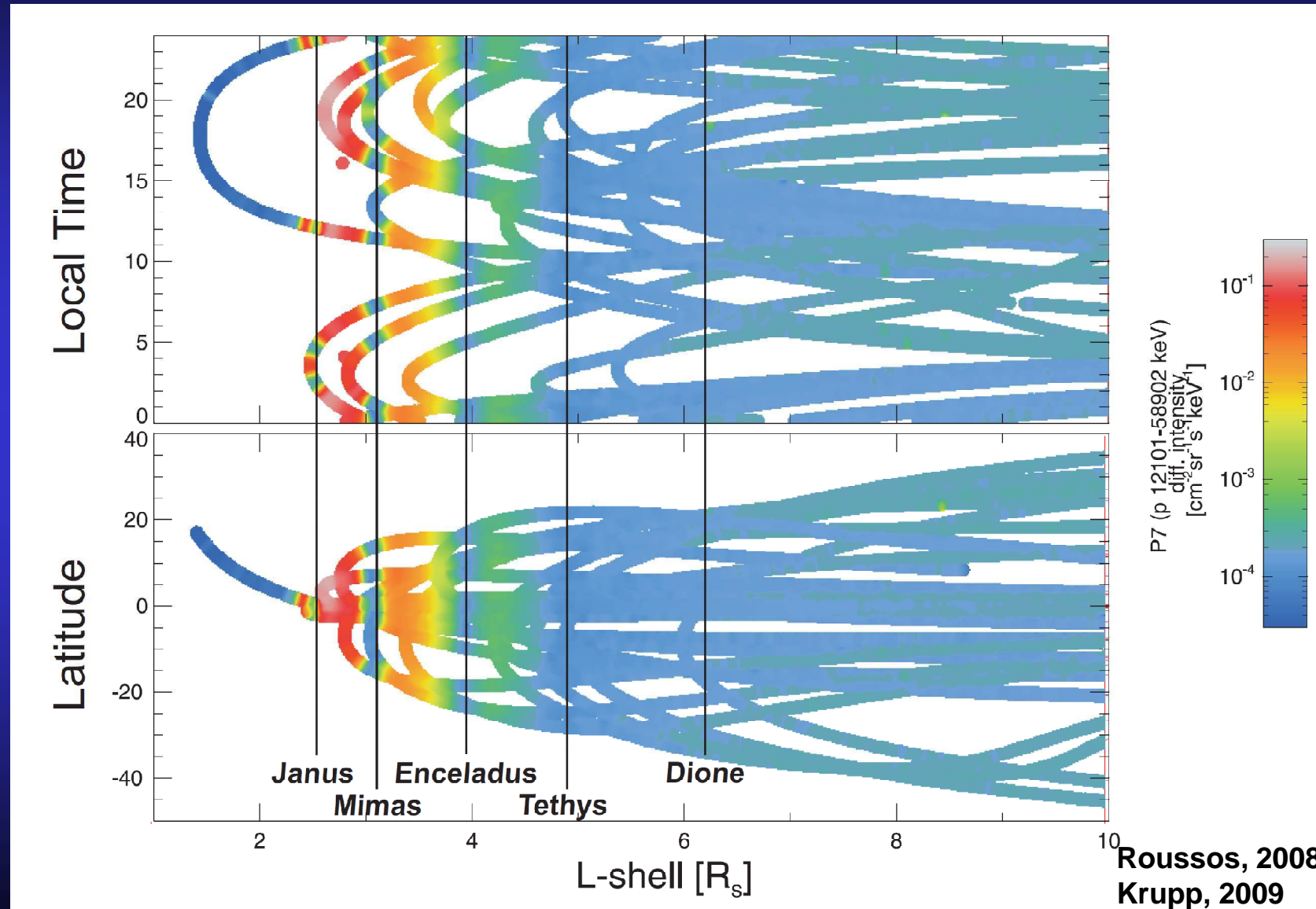
Krimigis et al, 2004

## Plasma regions and sources at Saturn



- Strong satellite & ring sputtering, weak ionization
- $N_{\text{neutrals}} \sim 100 \times N_{\text{ions}}$

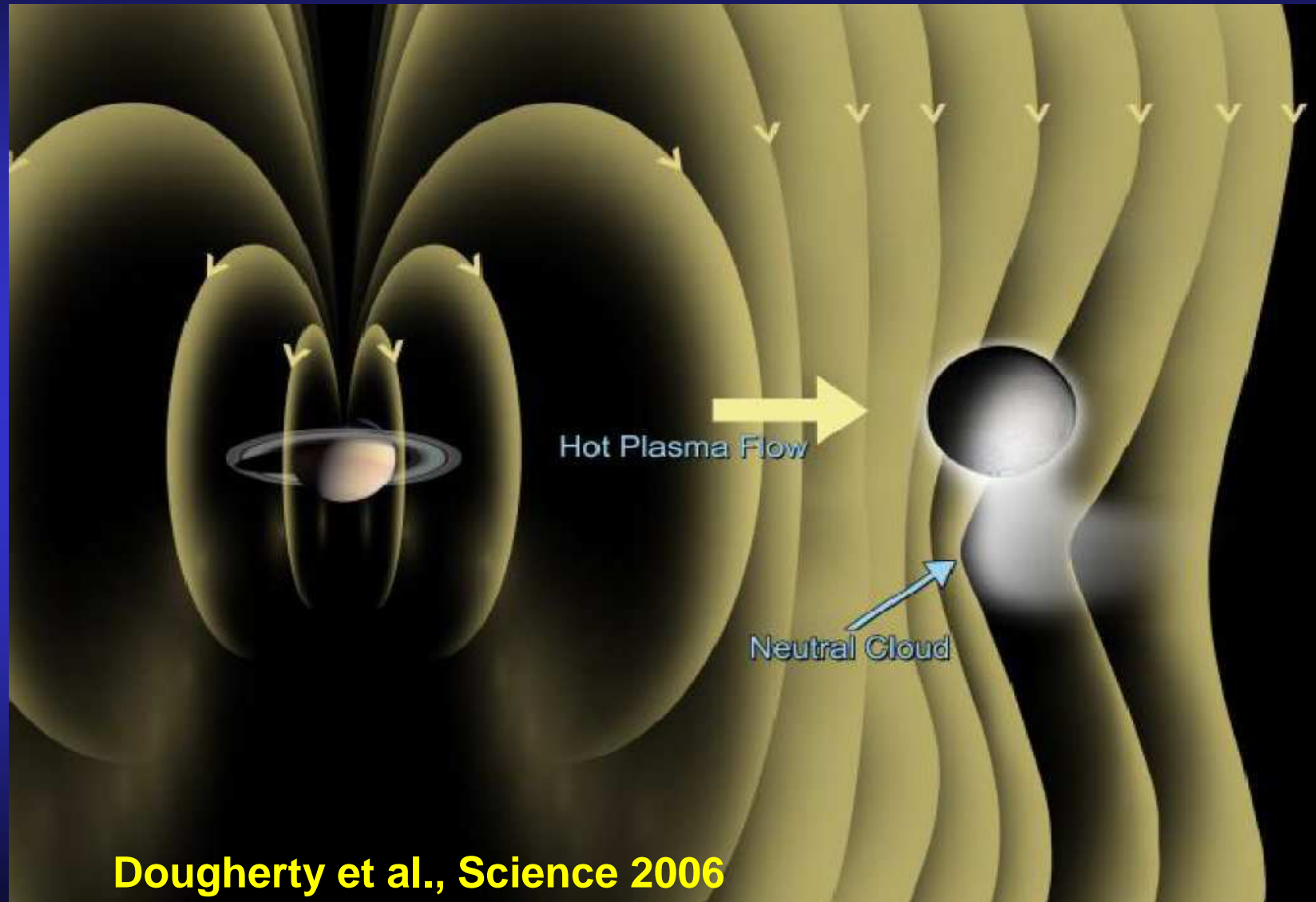
# Saturn: Macrosignatures in the energetic particle intensities from moons



Roussos, 2008  
Krupp, 2009

# Saturn:

## Enceladus- Imprint on the magnetosphere



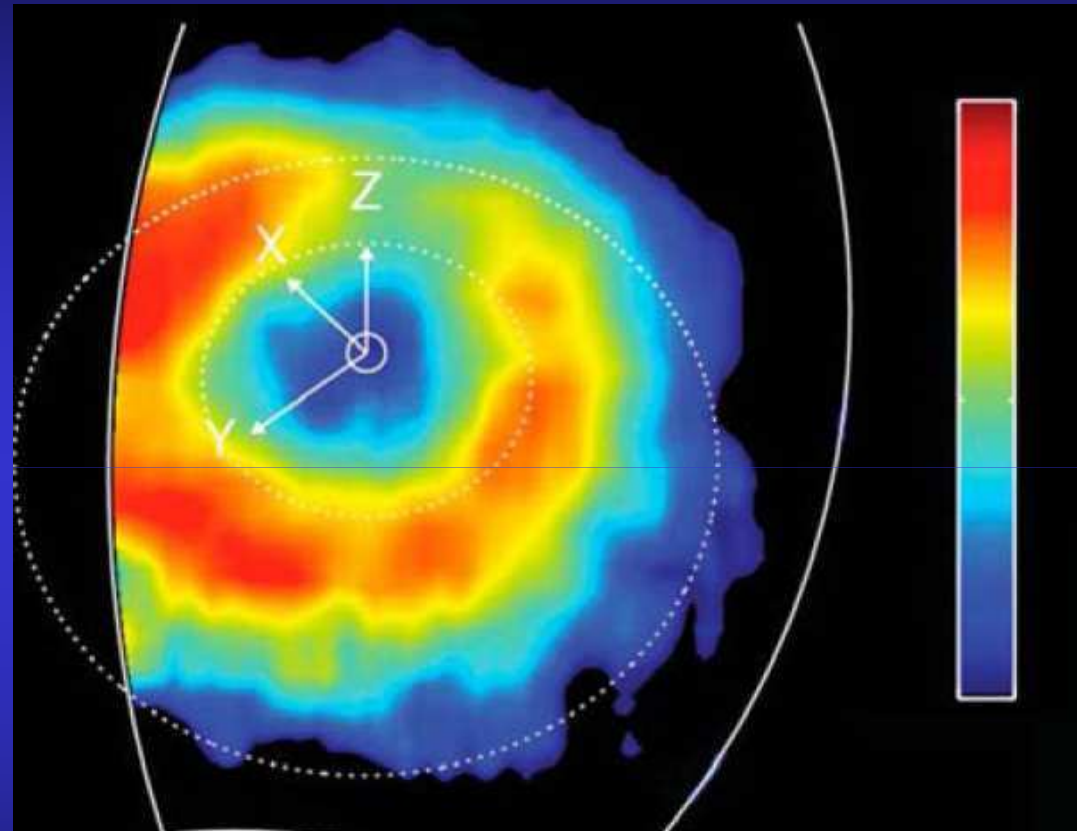
Dougherty et al., Science 2006

## *Ring current at Saturn*

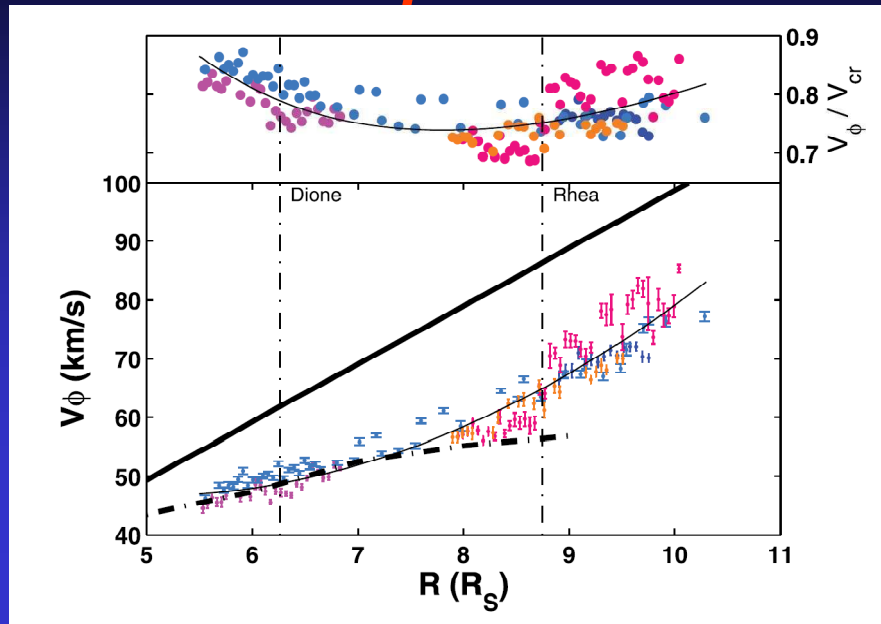
### *ENA image of Cassini MIMI/INCA*

**View from above  
Saturn's north pole  
down to the equatorial  
plane**

**Energetic neutral atom  
emissions in color as a  
result of charge  
exchange reaction  
between cold neutrals  
and hot ions**

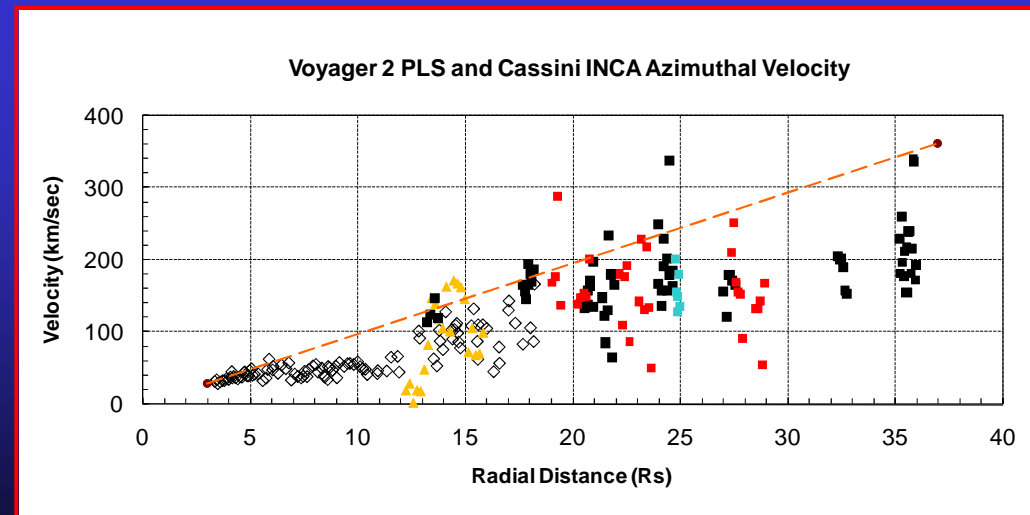


# Saturn: Flow pattern



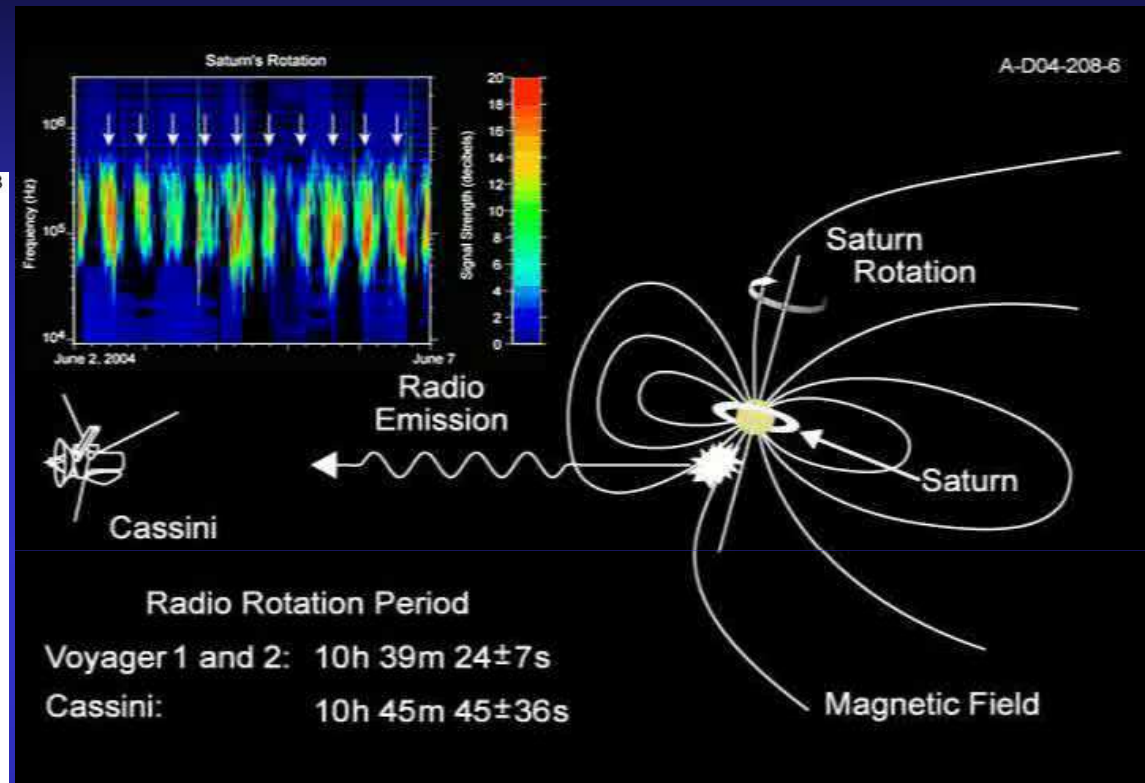
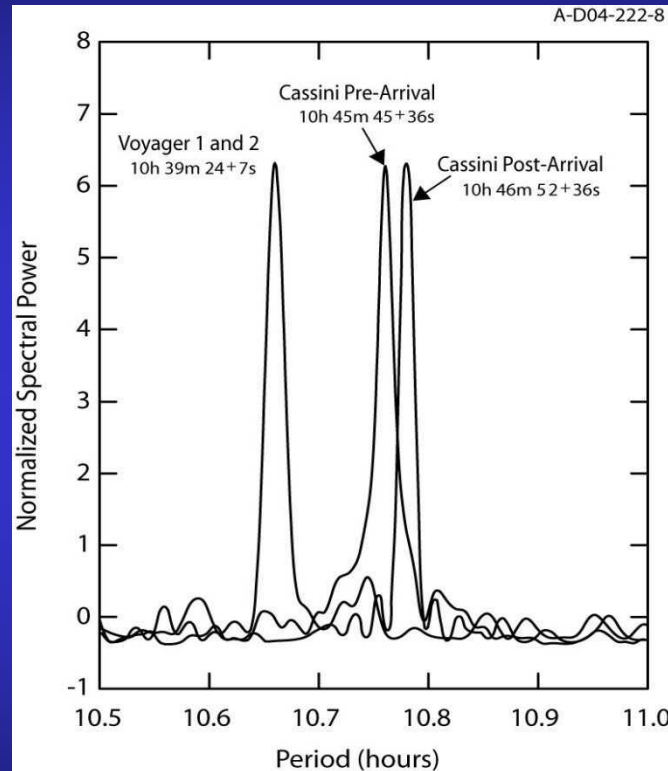
Wilson, 2008

Kane, 2008



# Saturn:

## Periodicity of SKR



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

## Saturn:

### Plasmoids and Tail Reconnection

- 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.

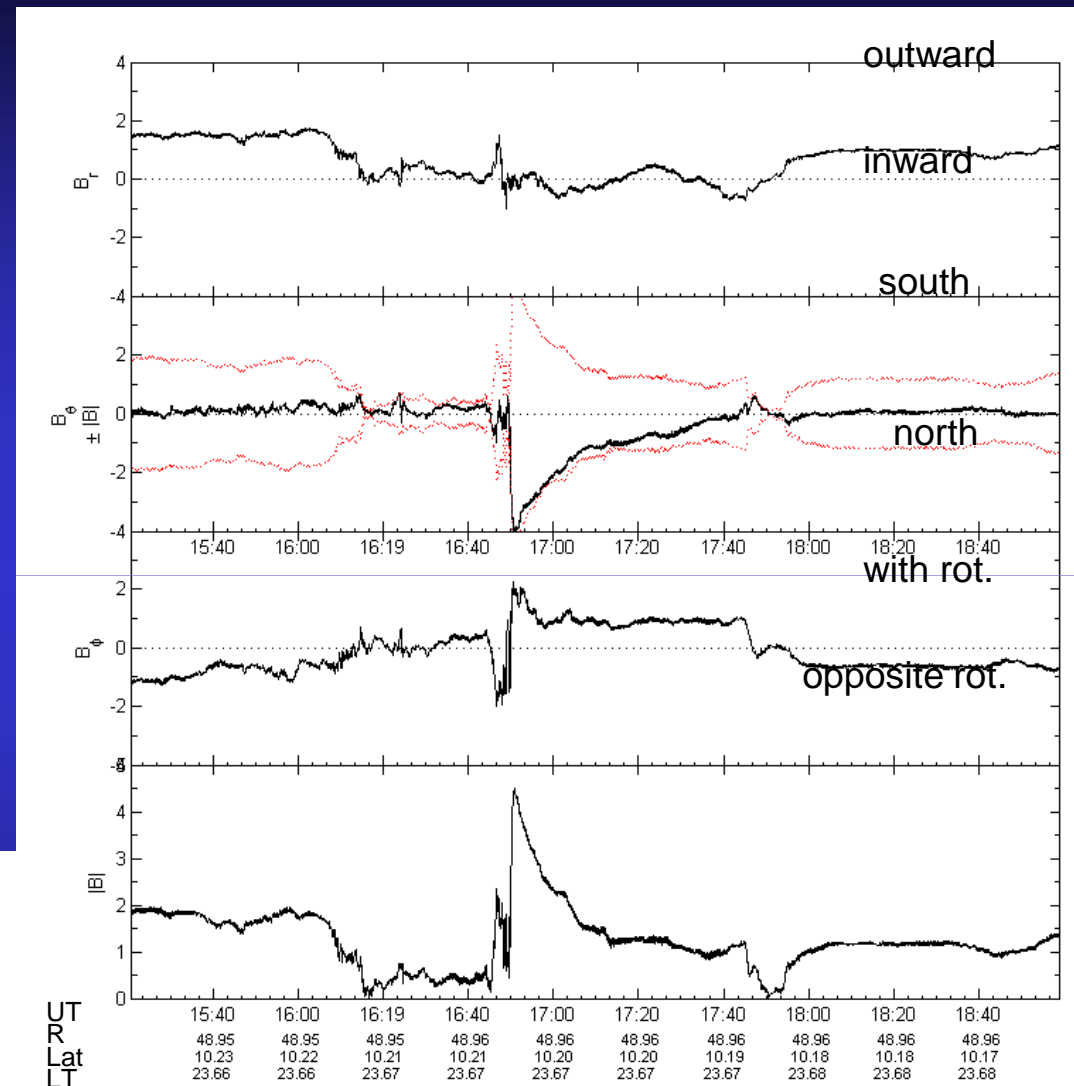
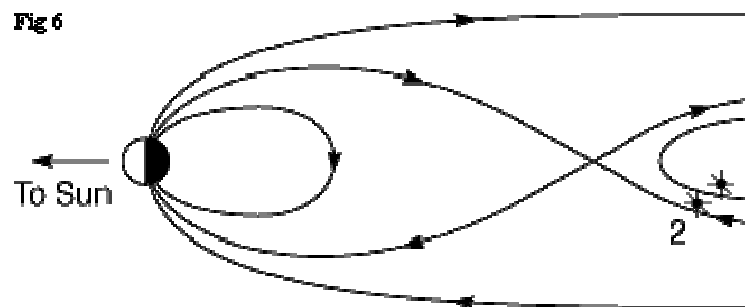
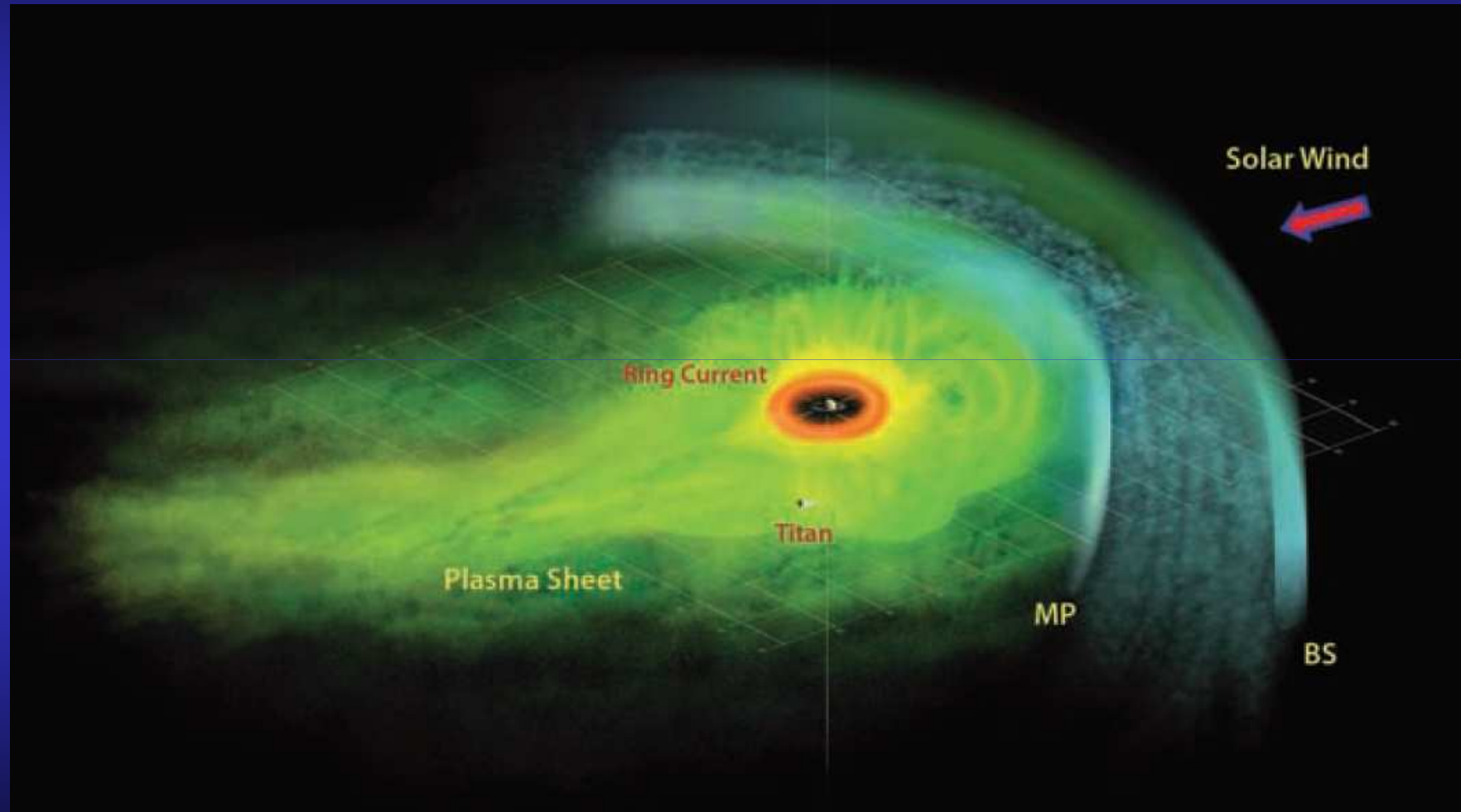


Fig 6



Jackman et al., 2007

# Saturn's magnetosphere



## Summary

- Planetary magnetospheres are the largest plasma laboratories in our solar system
- Each magnetosphere in our solar system is unique
- The magnetospheres of Earth and Mercury are essentially solar wind driven, only minor internal plasma sources
- The magnetospheres of the giant planets are rotationally driven, major plasma sources inside the magnetosphere (Io, Enceladus, Triton,...)
- Ganymede's magnetosphere is the only magnetosphere of a moon so far
- Saturn's magnetosphere is a mixed magnetosphere (sometimes like Earth, most of the time like Jupiter)

## Future missions

- **Mercury**
  - Messenger: 3rd flyby 2010, in orbit around Mercury: 2011
  - Bepi Colombo: 2 spacecraft in orbit around Mercury, launch 2014, arrival 2018
- **Jupiter**
  - Juno: highly inclined orbit around Jupiter, launch 2011, arrival 2016
  - EJSM (Europa Jupiter System Mission): 2 spacecraft around Europa and Ganymede, to be selected in 2011, possible launch 2020, arrival 2025
- **Saturn**
  - Cassini: in orbit around Saturn until 2010 (hopefully 2017)
  - TSSM (Titan Saturn System Mission): proposed but not preselected