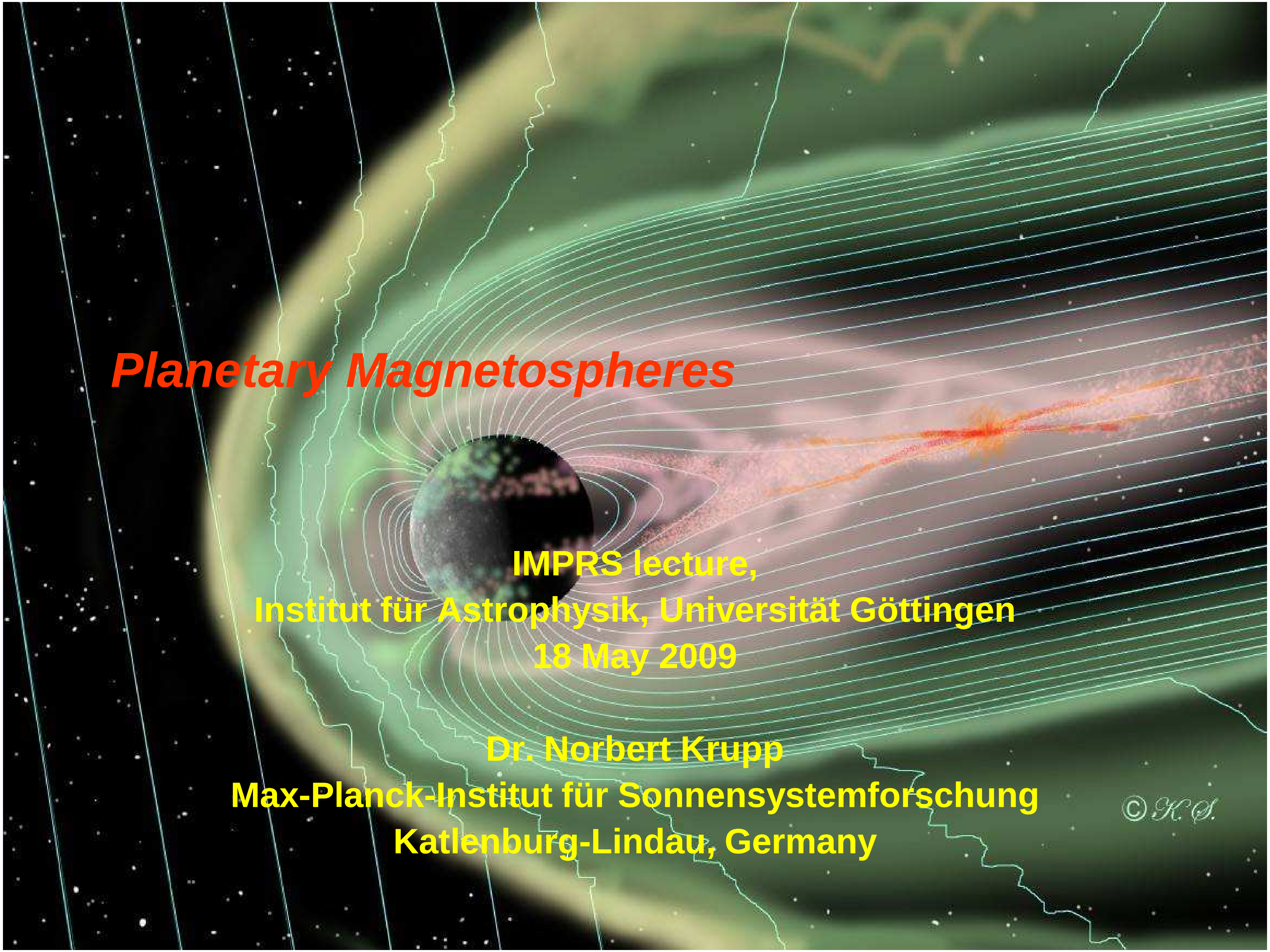

Planetary Magnetospheres

IMPRS lecture,
Institut für Astrophysik, Universität Göttingen
18 May 2009

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- ...

Literature

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- Roederer, *Dynamics of geomagnetically trapped radiation*, Springer, 1970
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- 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

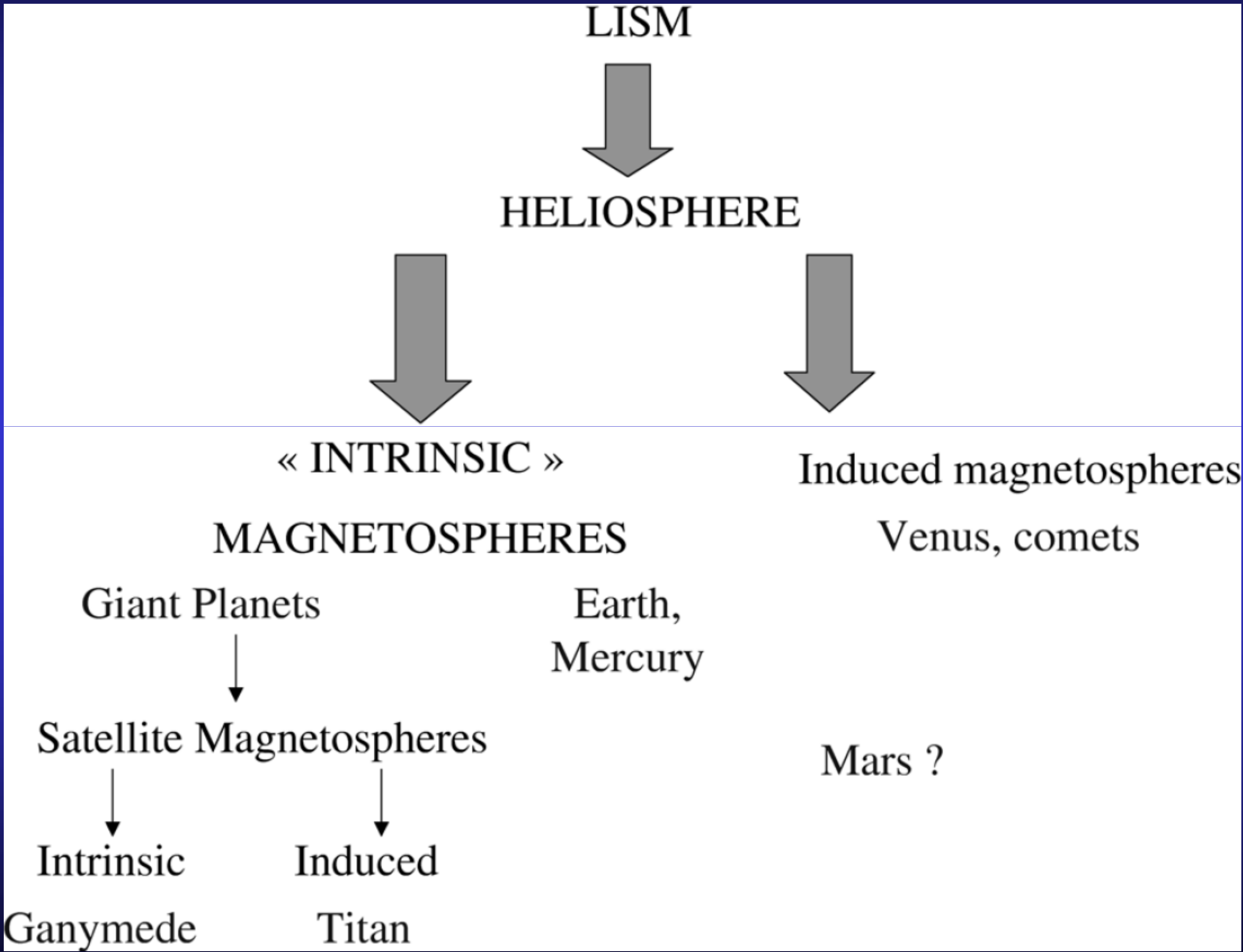
The Magnetosphere
Introduction and definitions

- 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



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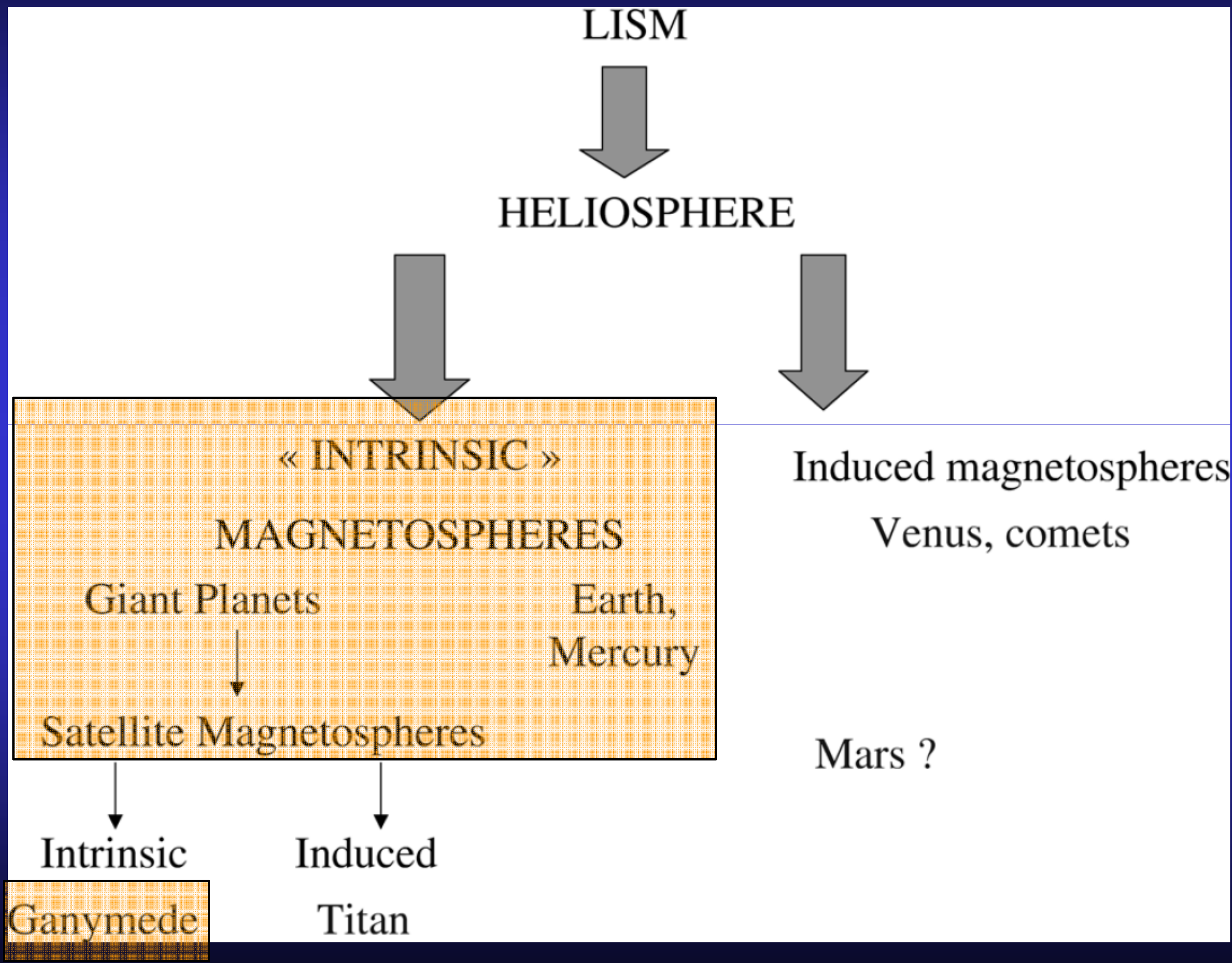
Planetary magnetospheres



Intrinsic planetary magnetospheres

small

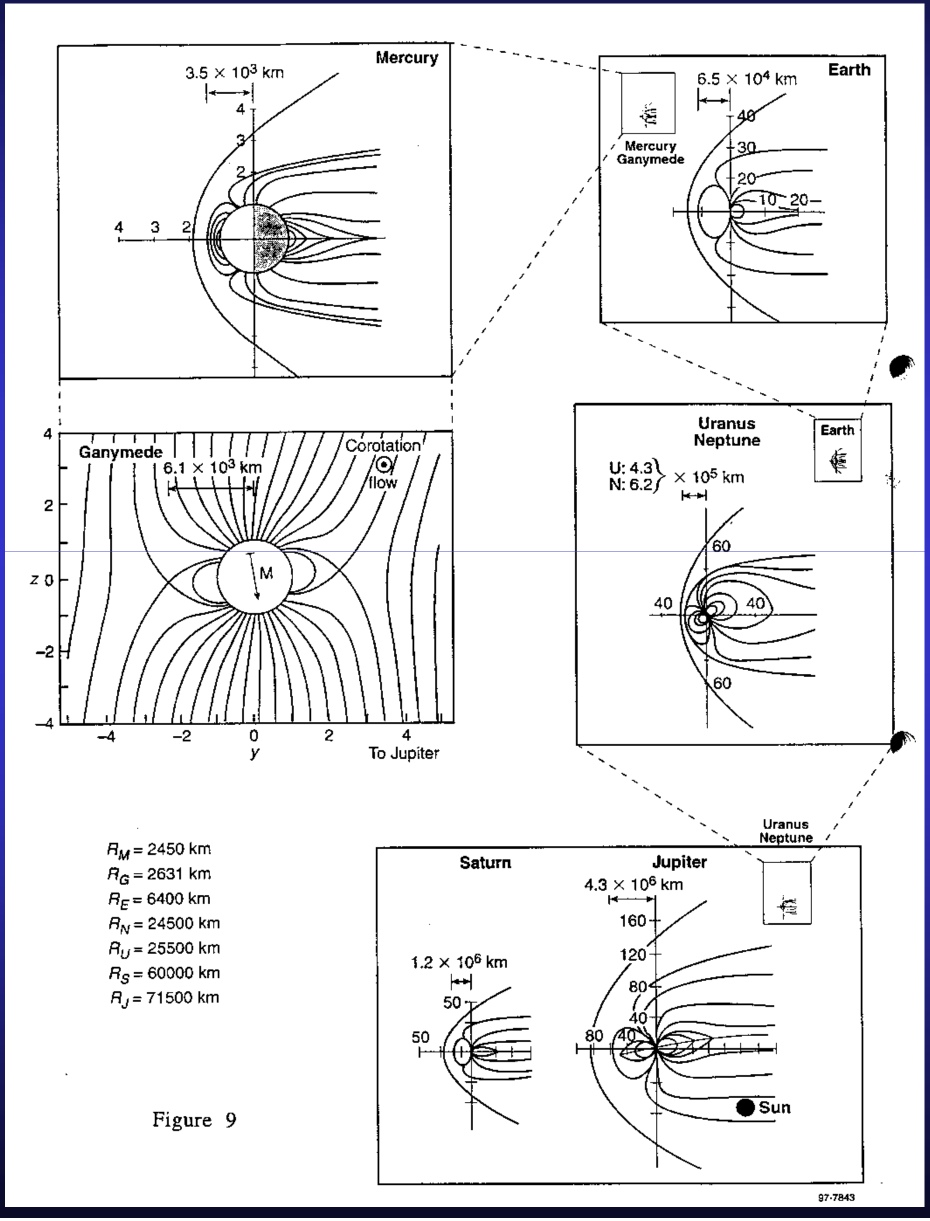


Figure 9

intermediate

huge

Sizes and shape

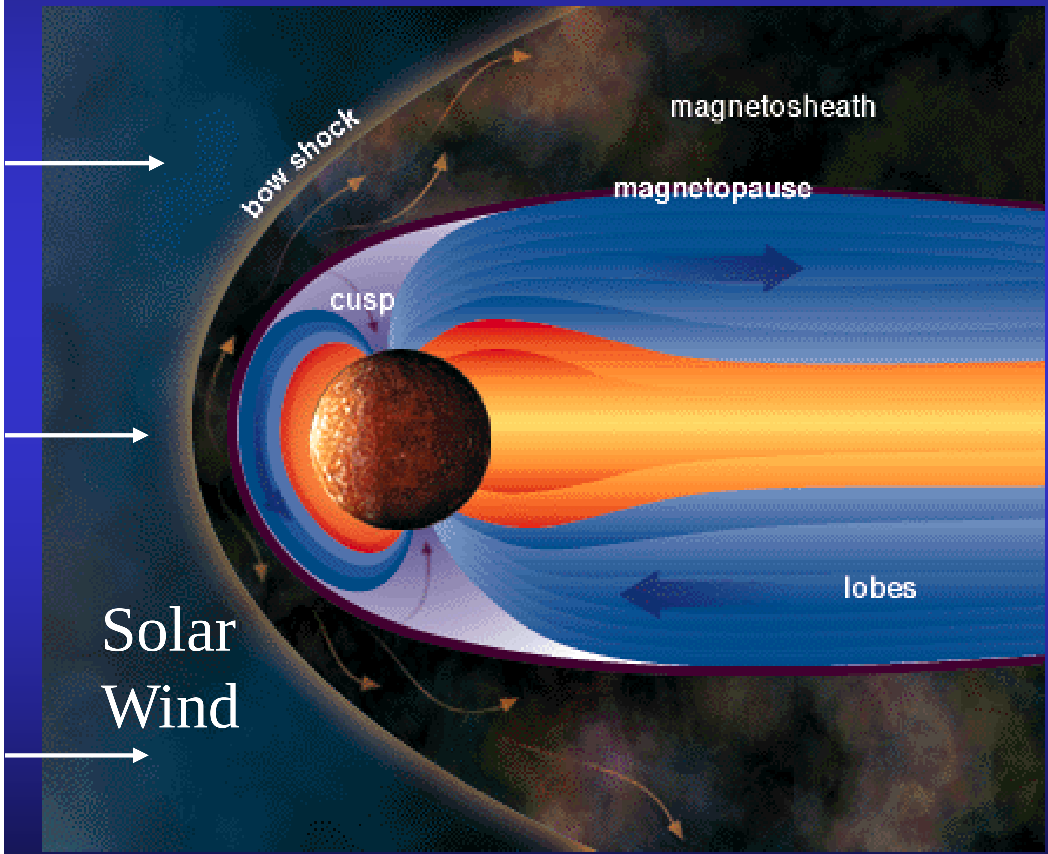
$R_M/R_p \sim 1.2\{B_o^2/\rho_{sw} V_{sw}\}^{1/6}$

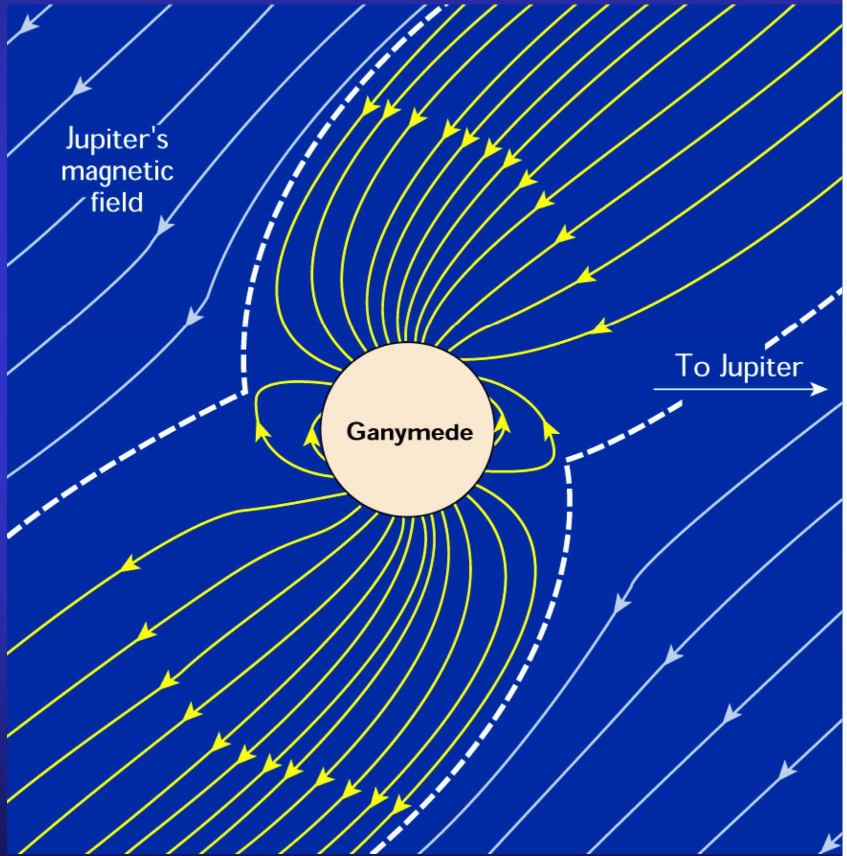
	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
B_o	.003	.31	4.28	.22	.23	.14
R_M Calc.	1.4 R_M	10 R_E	42 R_J	19 R_S	25 R_U	24 R_N
R_M Obs.	1.4-1.6 R_M	8-12 R_E	50-100 R_J	16-22 R_S	18 R_U	23-26 R_N

Small magnetospheres
Mercury and Ganymede

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

Ganymede - Magnetic field detected by *Galileo* in 1996

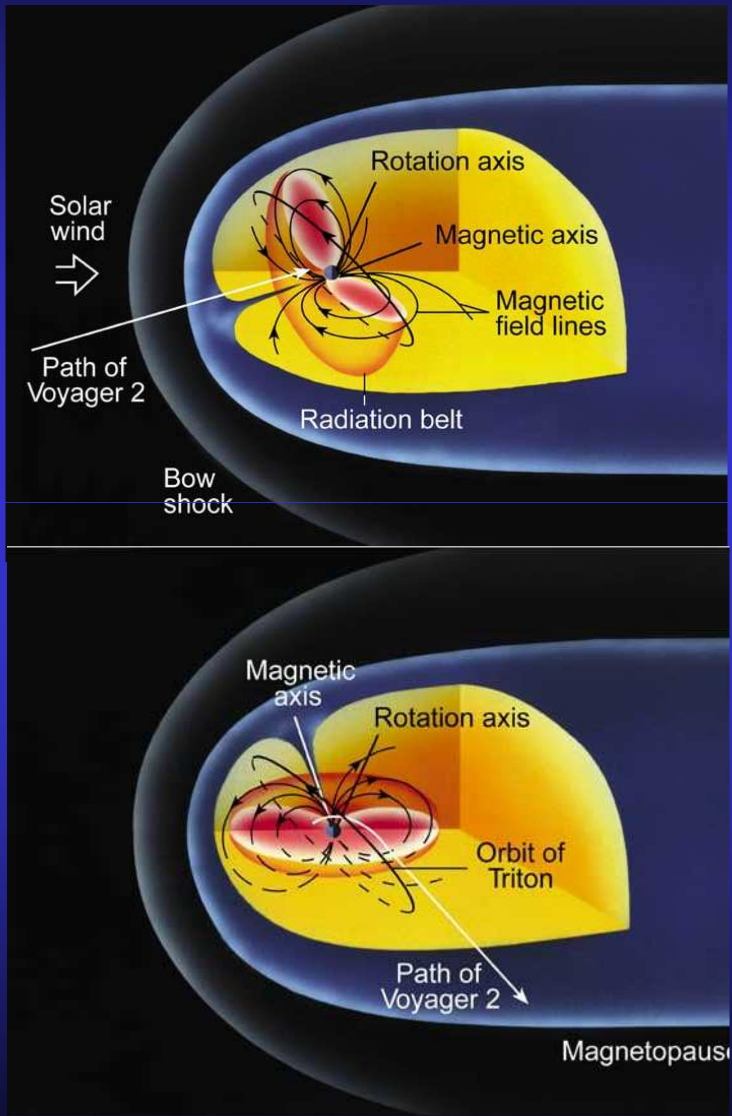




$B_{surface}$ ~ 1/100 Earth

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

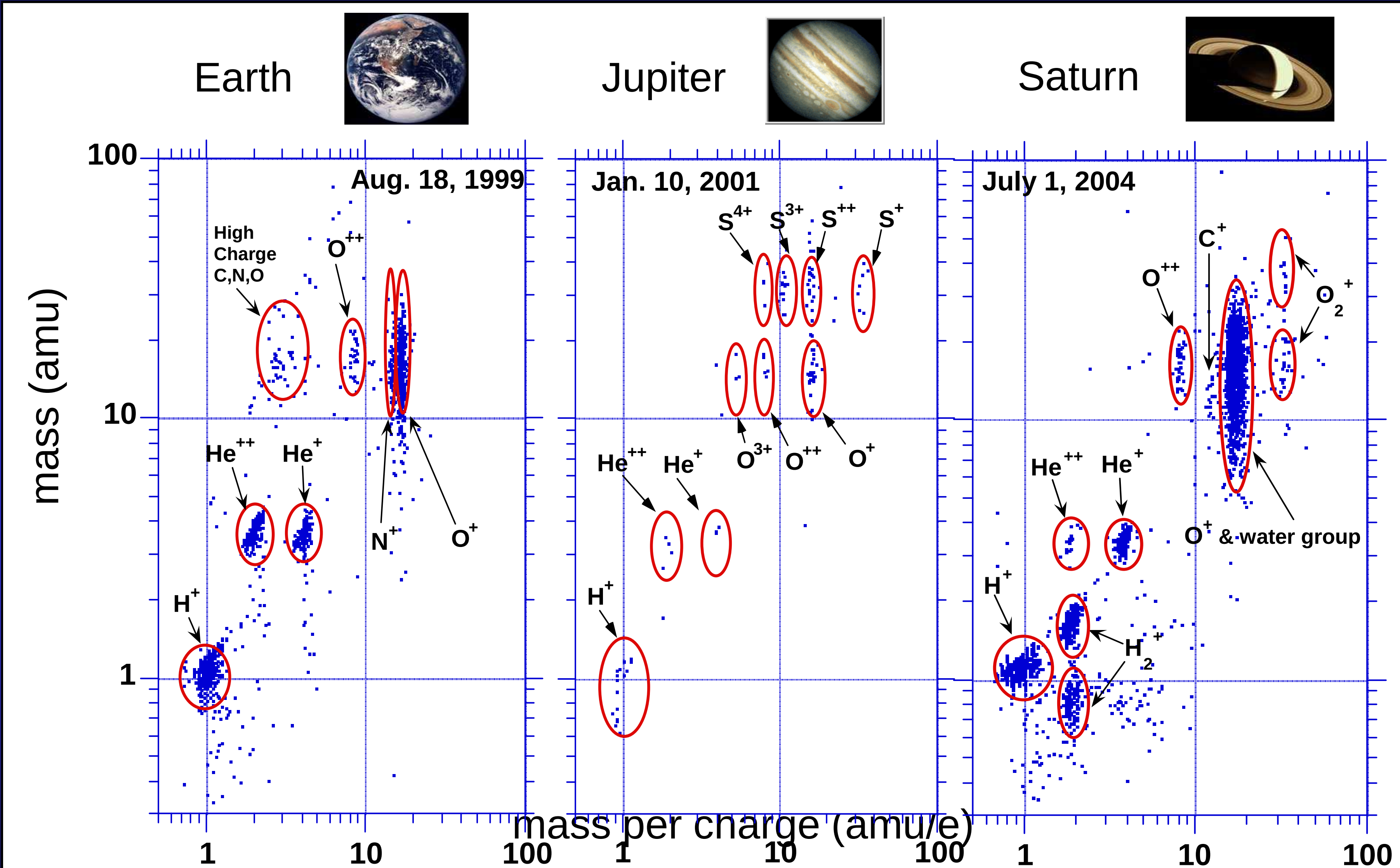
	Magnetic field	plasma density
• Mercury:	46 - 21 nT	73 - 33 cm-1
• Earth:	8 nT	5 cm-1
• Jupiter:	1 nT	0.2 cm-1
• Saturn:	0.6 nT	0.06 cm-1
• Uranus:	0.3 nT	0.01 cm-1
• Neptune:	0.005 nT	0.005 cm-1

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} cm^{-3}	~1	1-4000	>3000	~100	~3	~2
Compo sition	H^+ Solar wind Exosphere	O^+ N^+ H^+ Iono-sphere Solar wind	O^{n+} S^{n+} H^+ Io Iono-sphere Solar wind	O^+ H_2O^+ H^+ Rings, Enceladus Moons Solar wind	H^+ Iono-sphere	H^+ N^+ Triton, Iono-sphere
Source kg / s	?	5	700-1200	~2-100	~0.02	~0.2

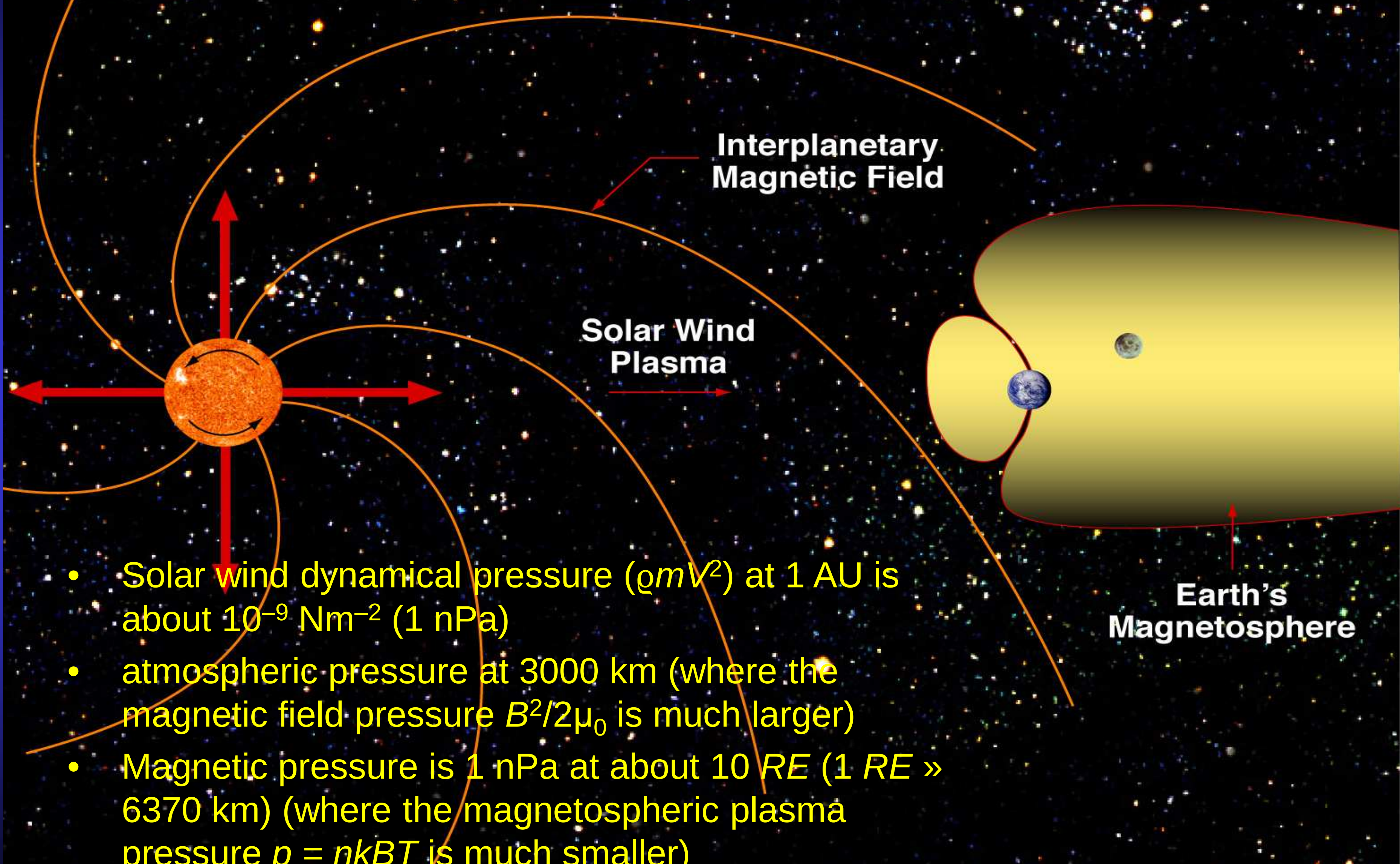
Charge Energy Mass Spectrometer (CHEMS) on Cassini records "fingerprints" of ion composition at Earth, Jupiter, and Saturn



The Magnetosphere of the Earth – the prototype

- Environment
- Regions
- Plasma Sources

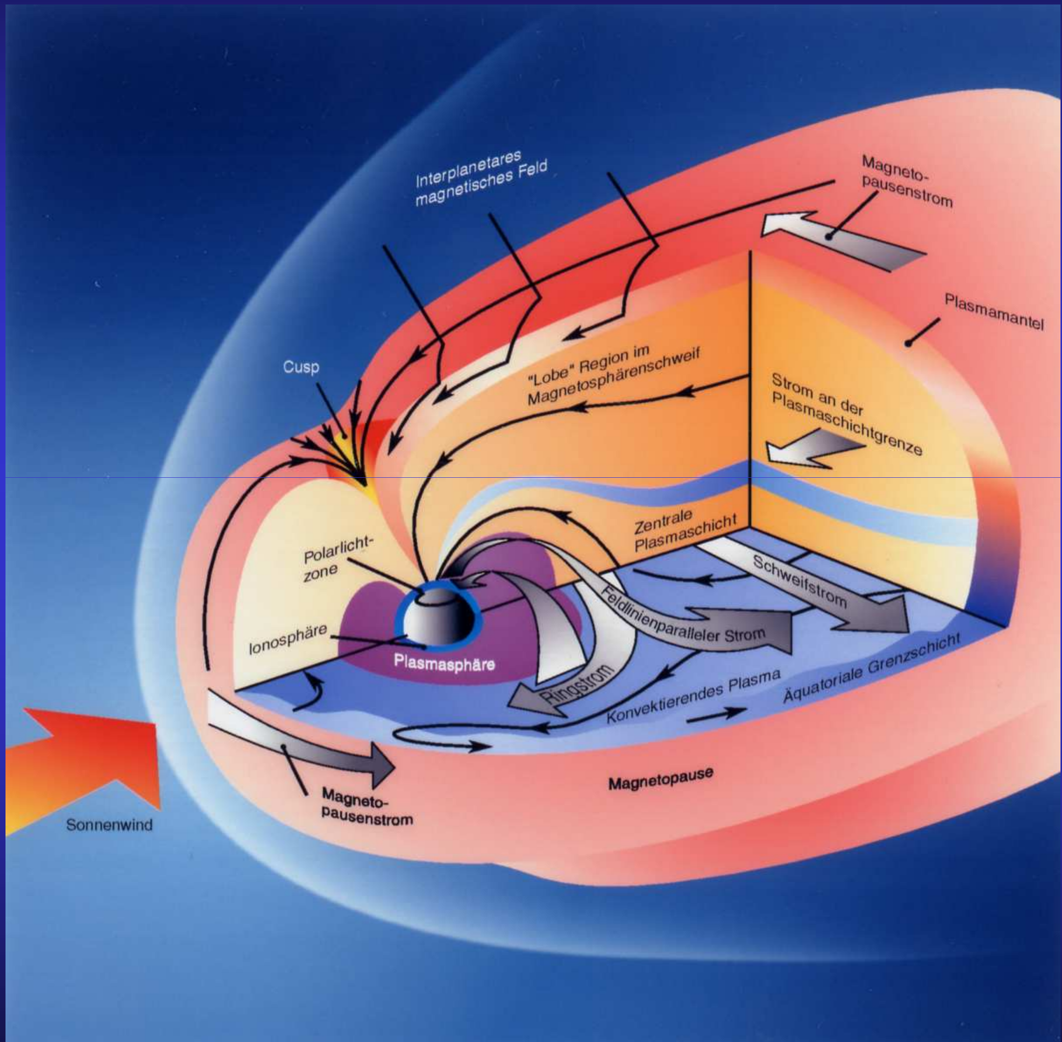
Solar wind
The embedding medium



- Solar wind dynamical pressure ($\varrho m V^2$) at 1 AU is about 10^{-9} 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 Plasmapause**
  - **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.
   ***ne* =[3 ... 9] cm-3, *kTe* =[100 ... 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).
   ***ne* = [0.8 ... 0.5] cm-3, *kTe* =[1.7e3 ... 2.5e4] eV**

3. **Geosynchronous plasma environment**
   Outside plasmasphere out to approx. 10 RE.
   ***ne* = [10 ... 0.5] cm-3, *kTe* =[1.e3 ... 3.e3] eV**

4. **Plasmasphere**
   Inside 4 to 5 RE. Outer boundary has local time variations.
   ***ne* = [1.e4 ... 1.e3] cm-3, *kTe* = [0.2 ... 1.2] 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:

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

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

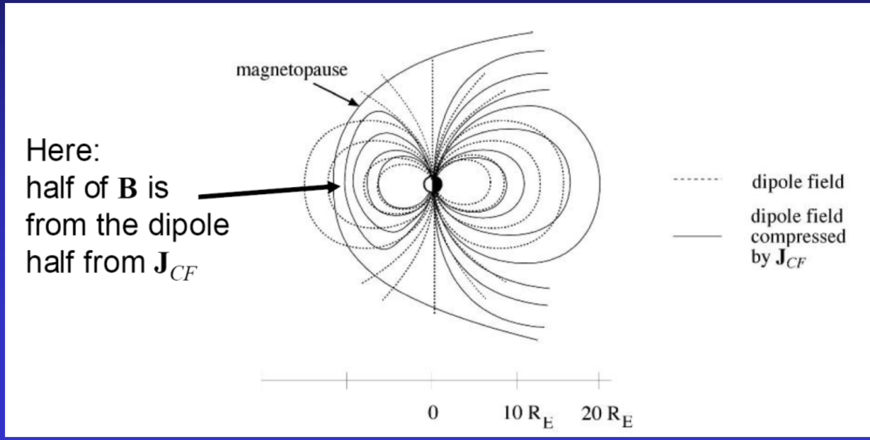
Magnetopause position

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

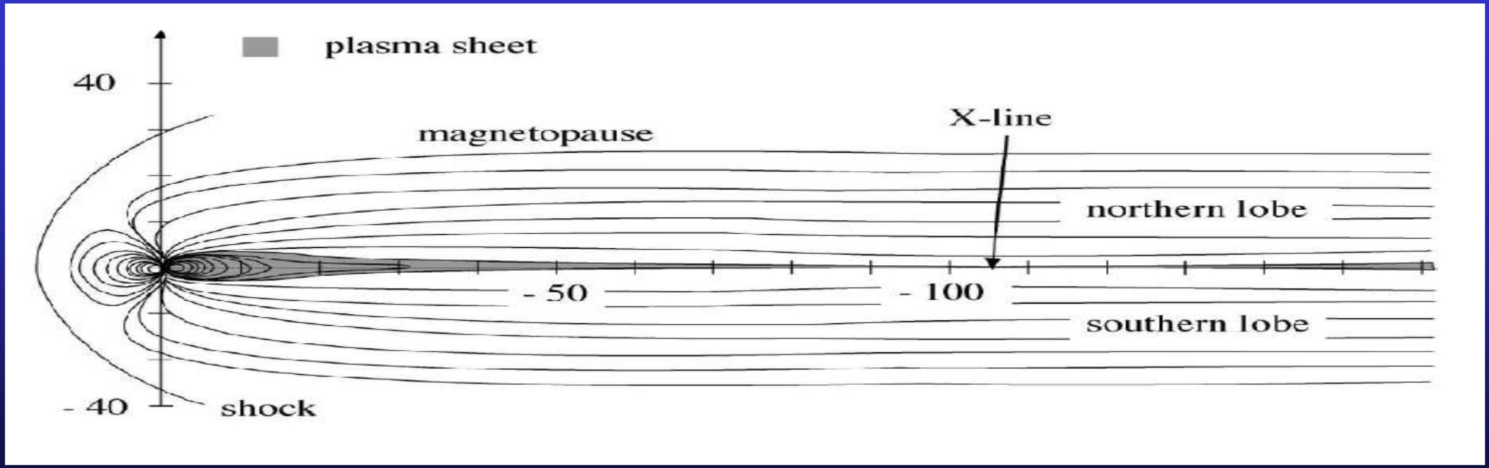
$$R_{MP} = \left(\frac{4B_{Surface}^2}{2\mu_0 k\, n_{sw} m_p v_{sw}^2}\right)^{1/6}$$

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

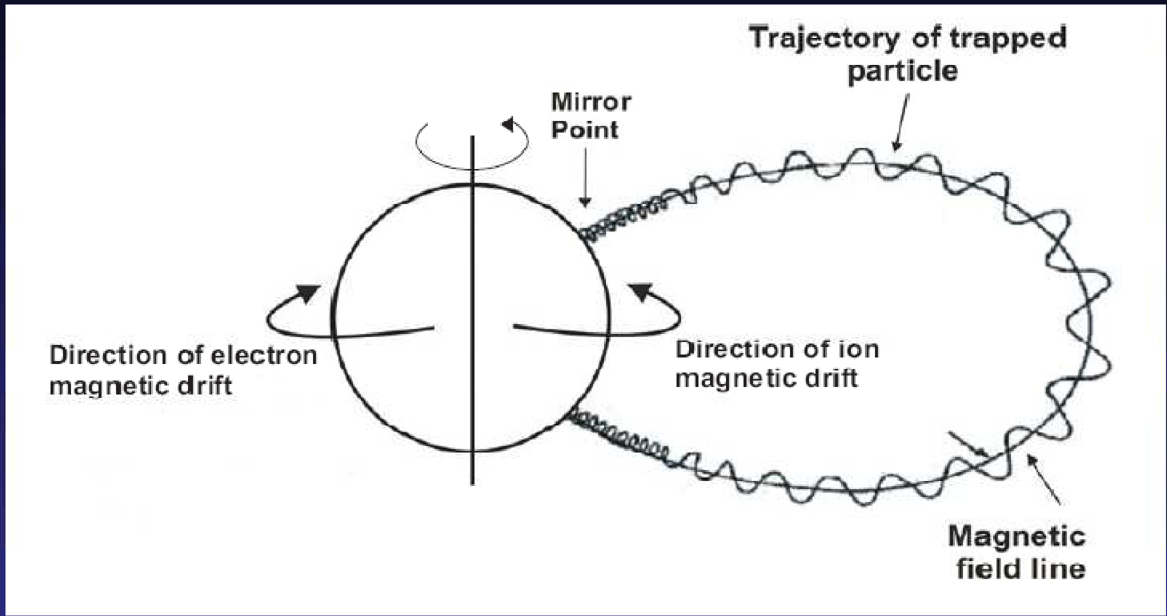
Deformation of the Dipole magnetic field



- 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

⇩

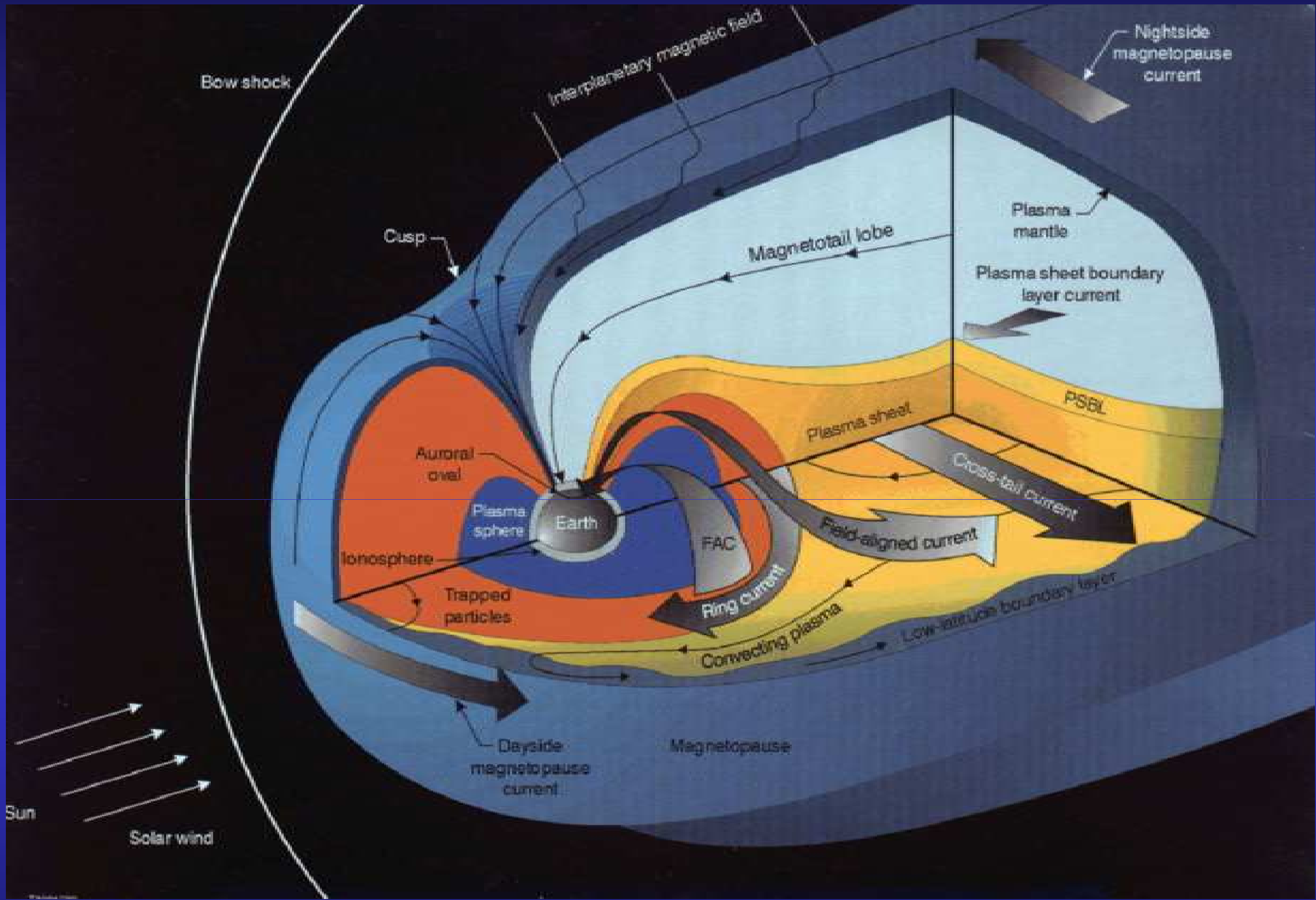
$$k = \int_{S_m}^{S'_m} \sqrt{\left[1 - \frac{B(s)}{B_m}\right]} ds$$

3. Third adiabatic invariant
Drift motion

⇩

$$J_3 = q\Phi$$

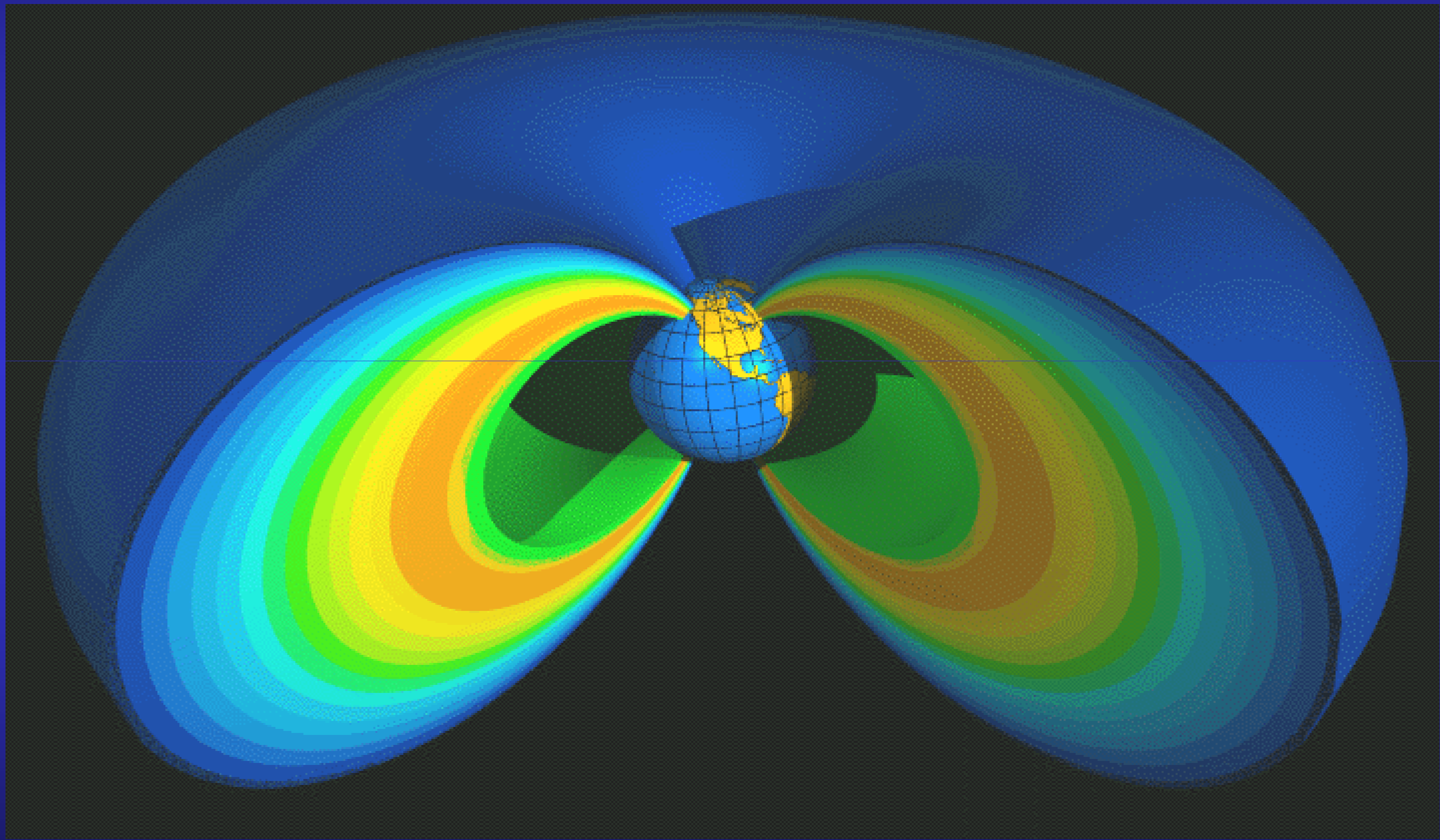
Electric current systems in the magnetosphere



Magnetopause currents
Ring current
Neutral sheet current

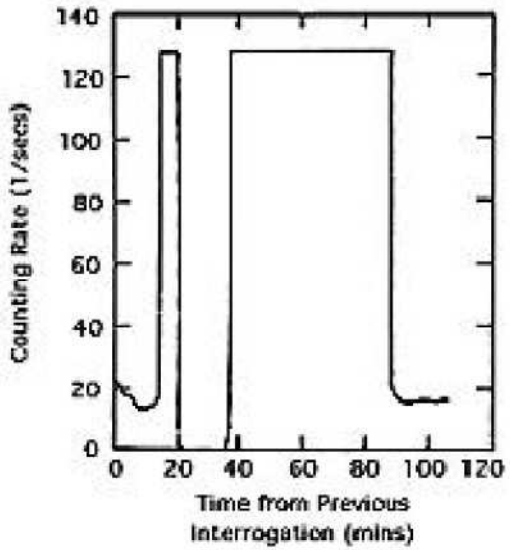
Tail current
Field-aligned currents
Polar electrojet currents

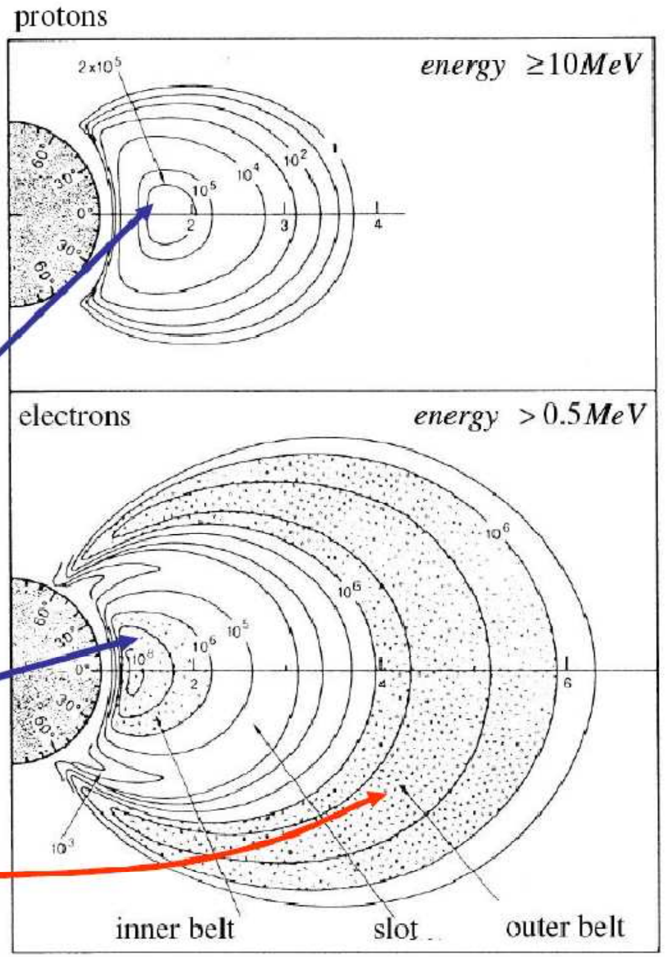
Radiation belts



Radiation belts

First observations
James Van Allen, Explorer 1, 1958





Geiger counter saturated when crossing the inner and outer belts

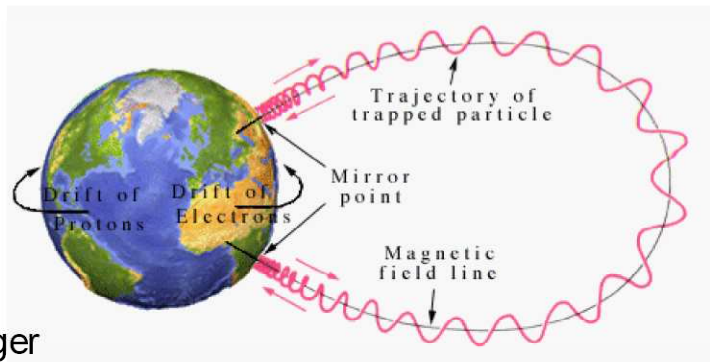
Inner belt: mostly protons 0.1 – 40 MeV
Outer belt: electrons keV's – MeV's

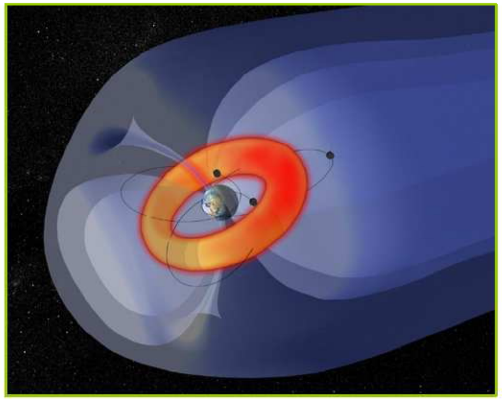
Ring current

Drift motion causes
a westward current

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

Total current $1-10\ \mathrm{MA}$
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

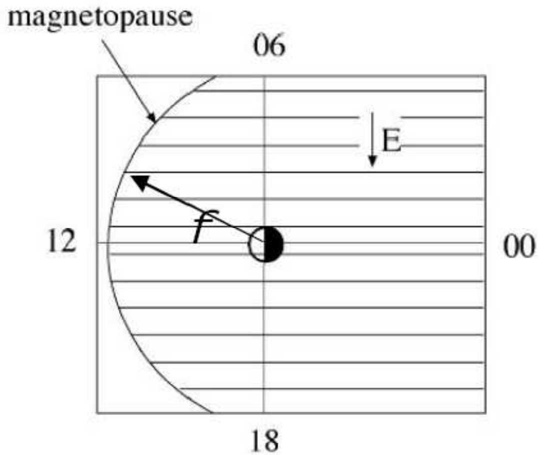
$$\vec{v}_{cor} = \frac{\vec{E}_{cor} \times \vec{B}}{B^2}$$

Convection and corotational fields

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

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

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

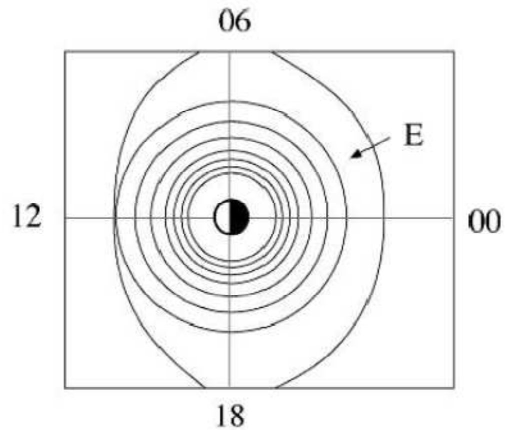


convective electric field

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

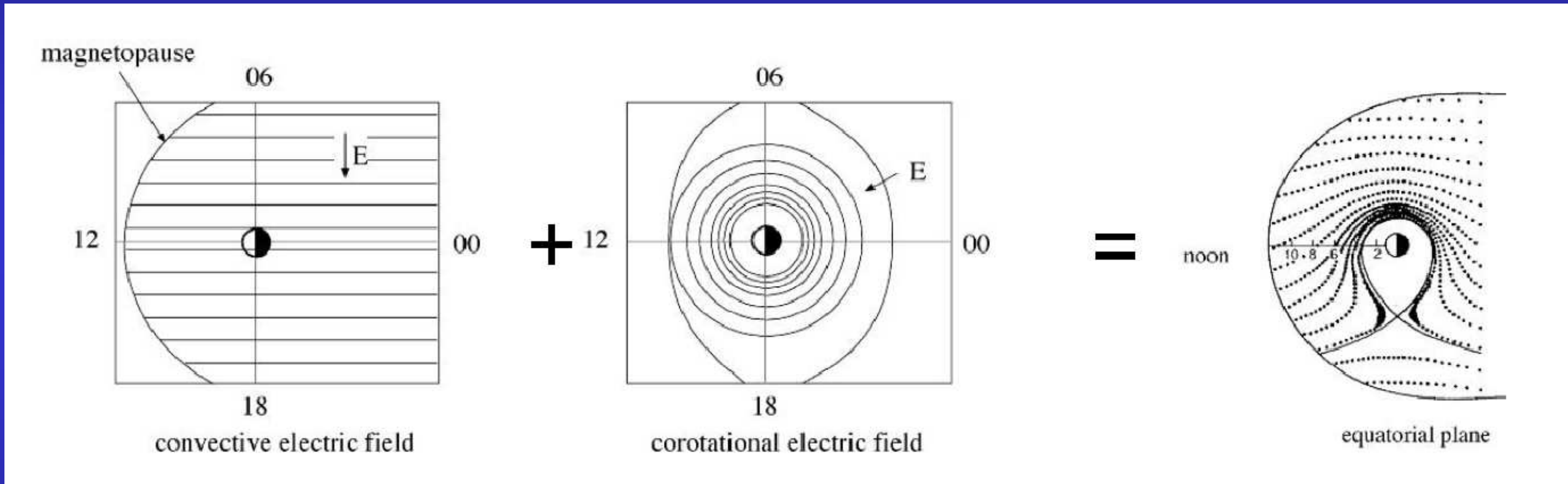
$$\mathbf{V}_{rot} = \Omega_E r \mathbf{e}_\phi = \mathbf{E}_{rot} \times \mathbf{B} / B^2$$

$$Þ \quad \varphi_{rot} = \frac{-\Omega_E k_0}{r} = \frac{-\Omega_E B_0 R_E^3}{r}$$

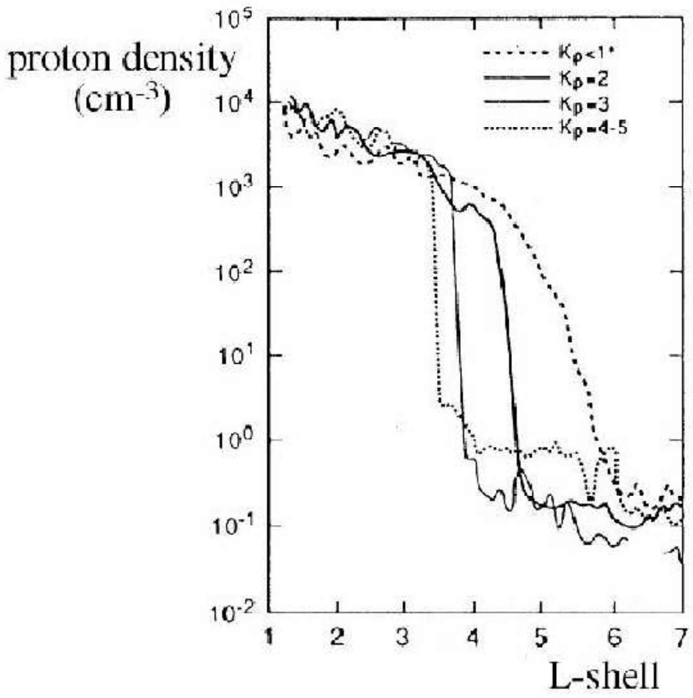


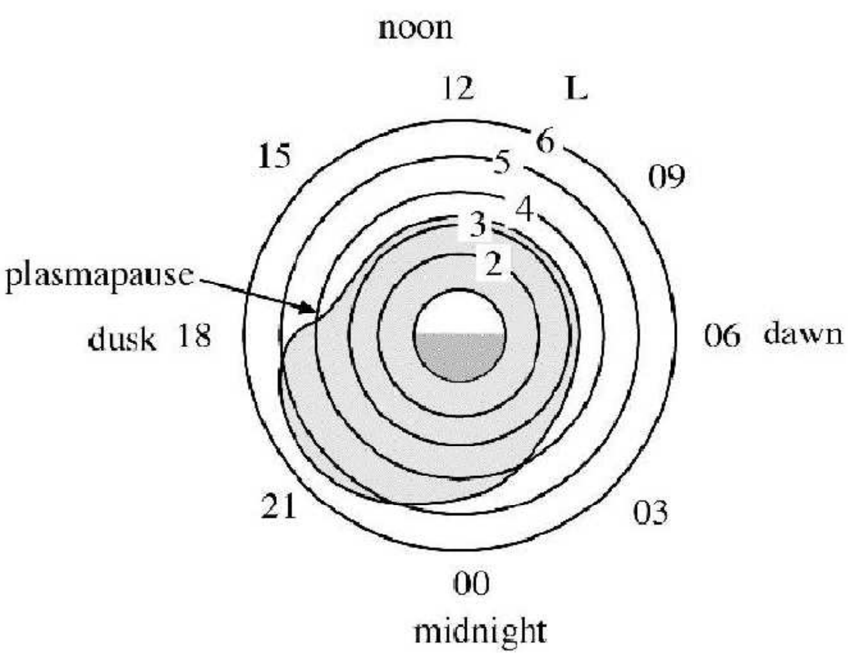
corotational electric field

Sum of corotational and convection electric fields



Plasmasphere



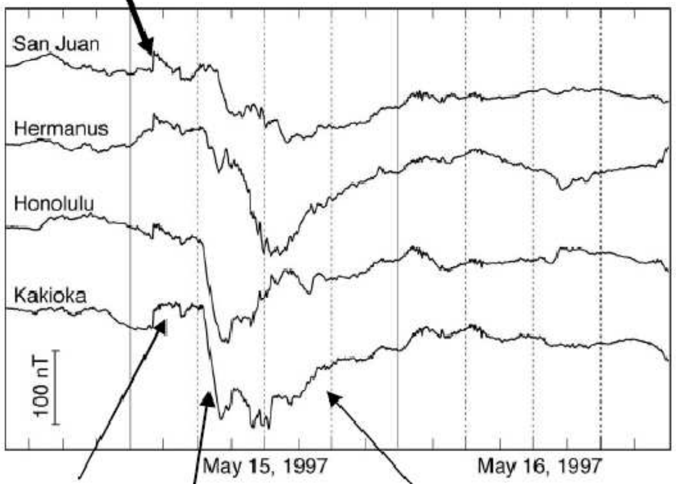


Expansion of cool (≤ 1 eV) ionospheric plasma
- within quasi-dipolar field lines (small L)
- co-rotates with the Earth

Magnetic storms

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

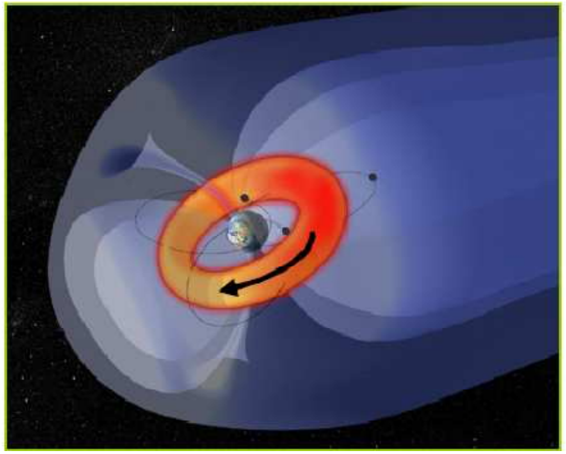
storm sudden commencement (SSC)
(shock hitting the magnetopause)



initial phase

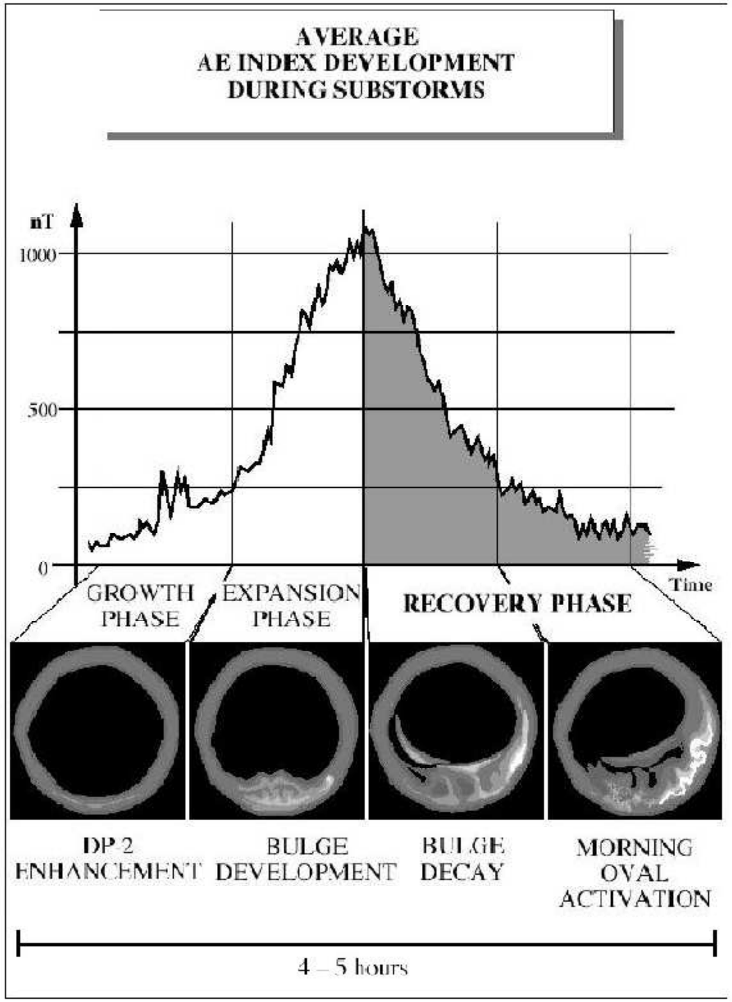
main phase
strong southward IMF
in the shocked flow
or in the CME

recovery phase

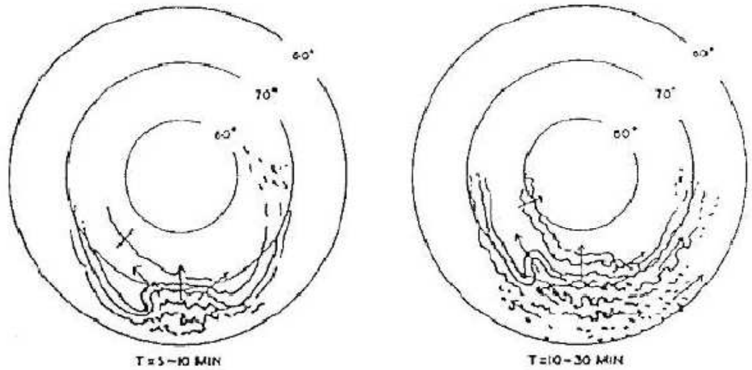


Substorms (Akasofu and Chapman, 1961) are magnetic and auroral activations at high latitudes (auroral zone). They occur both during storms and other times.

Substorm phases



Auroral development in the expansion phase



Growth phase
- oval expands equatorward

Substorm onset
- auroral breakup (possibly multiple)

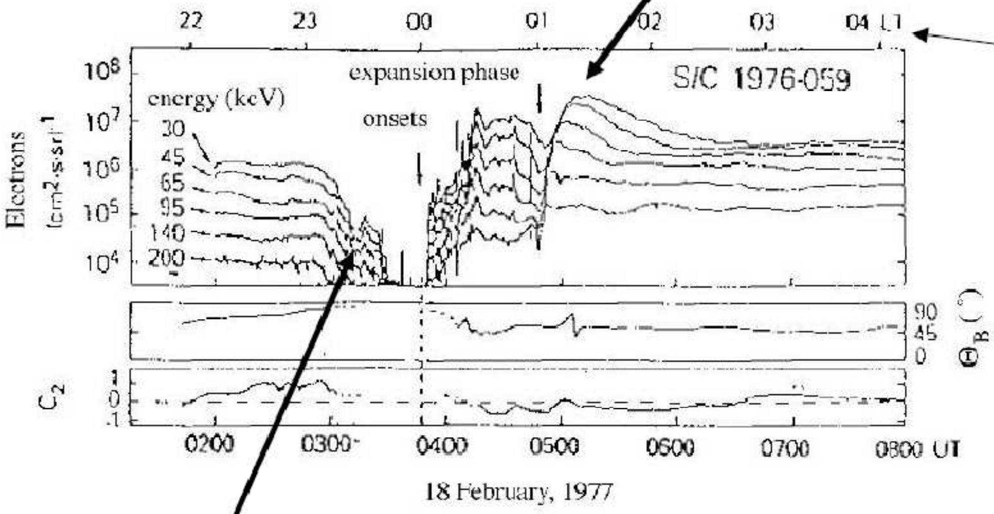
Expansion phase
- eastward, westward and poleward

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

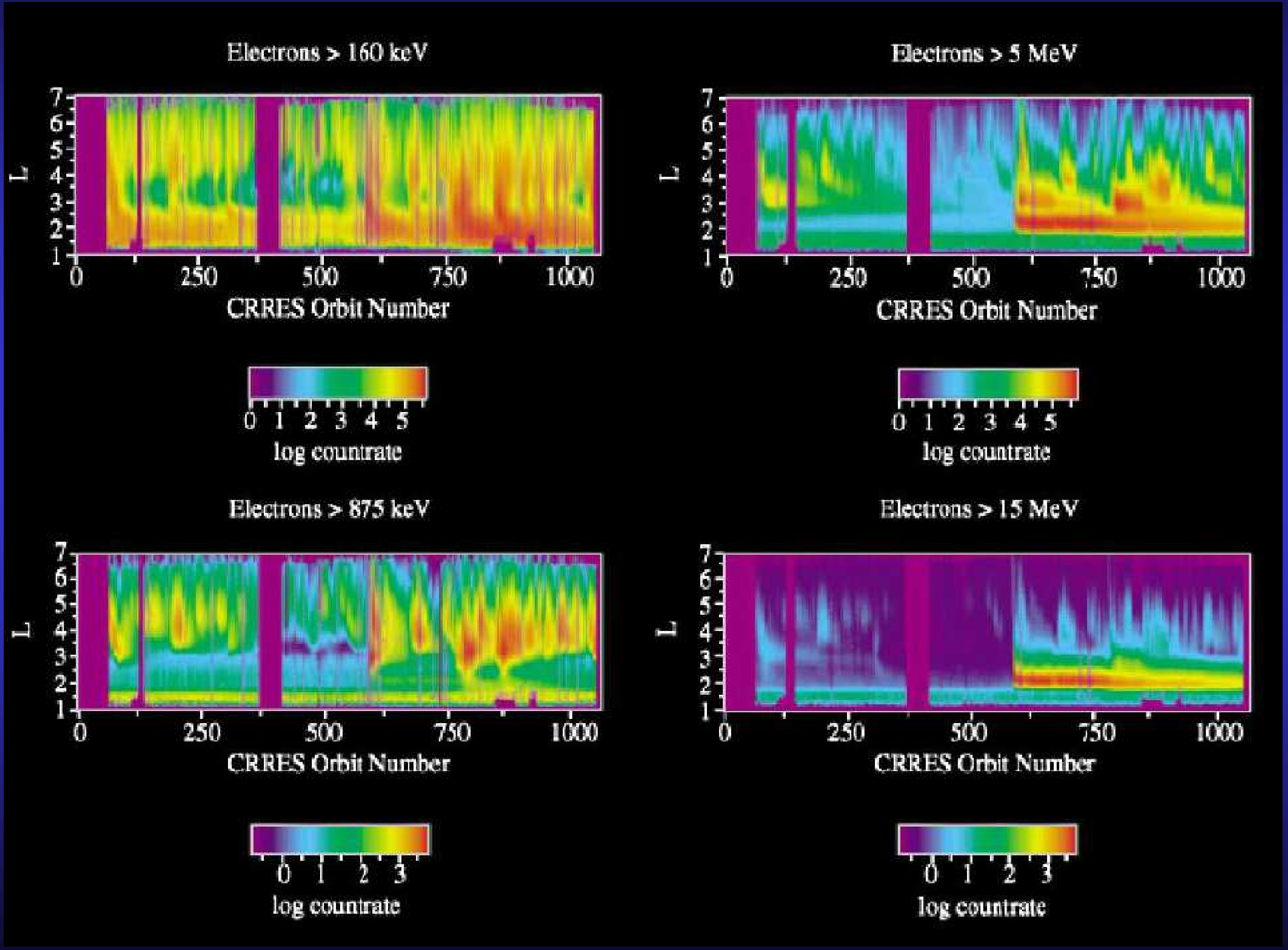


Magnetic local time at the location of the S/C

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



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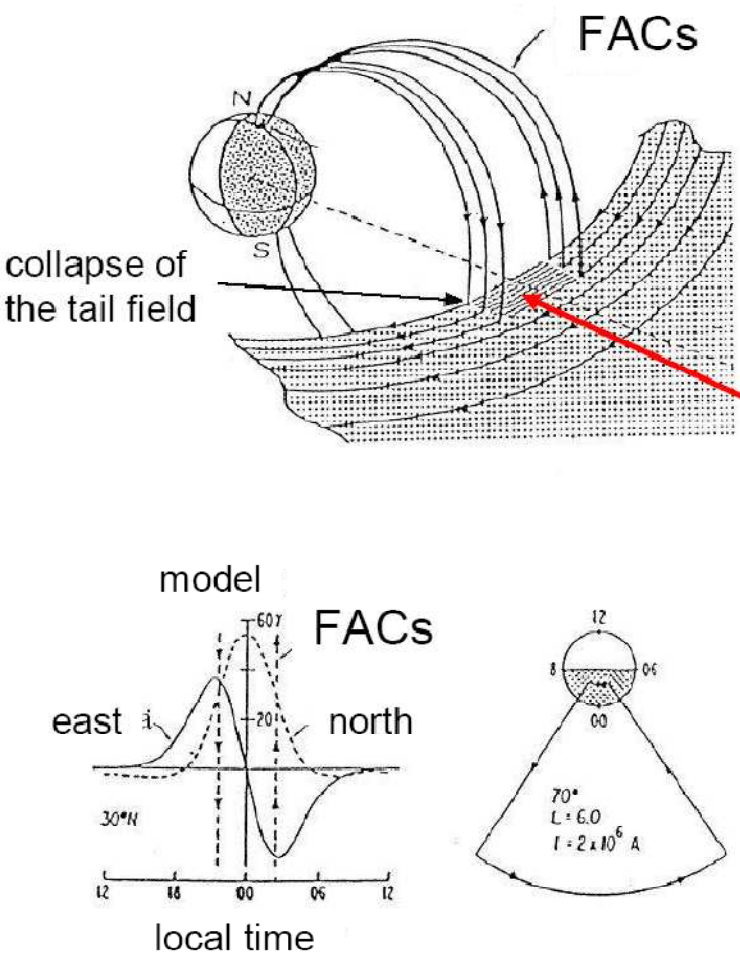
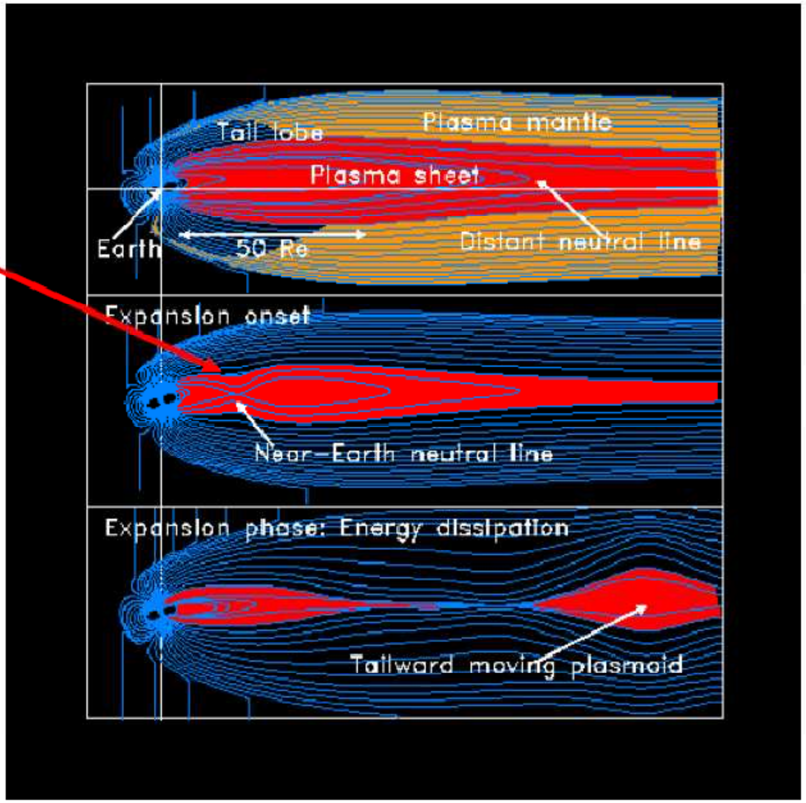
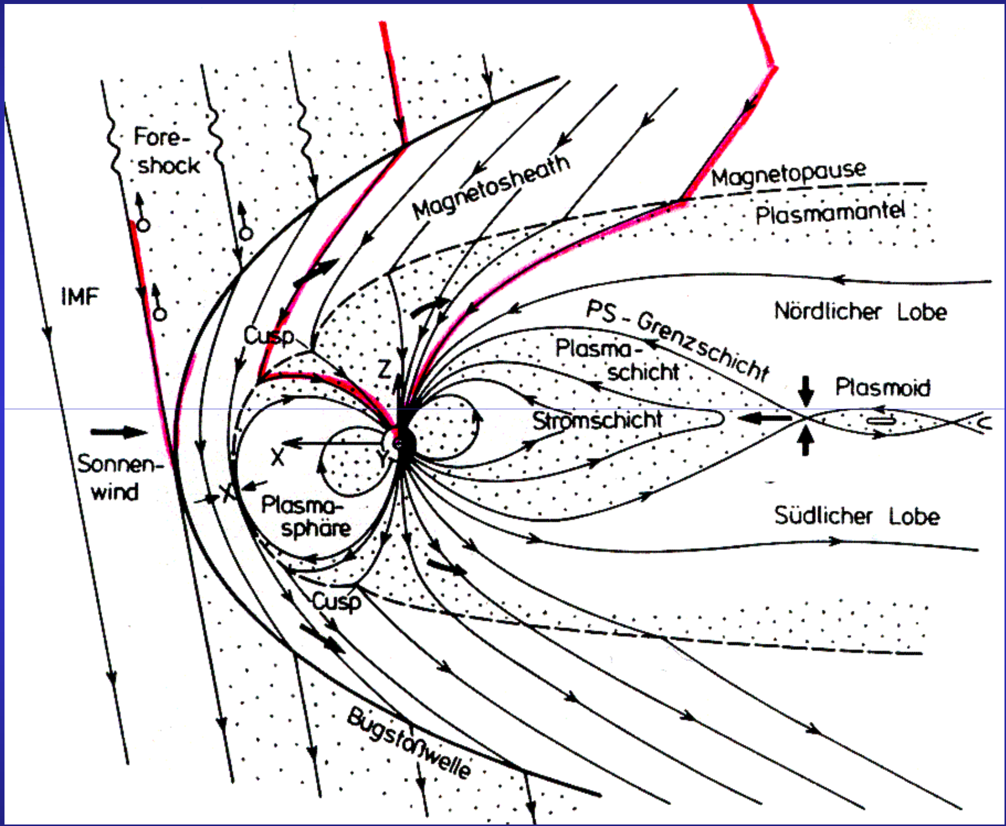
Substorm current wedge



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

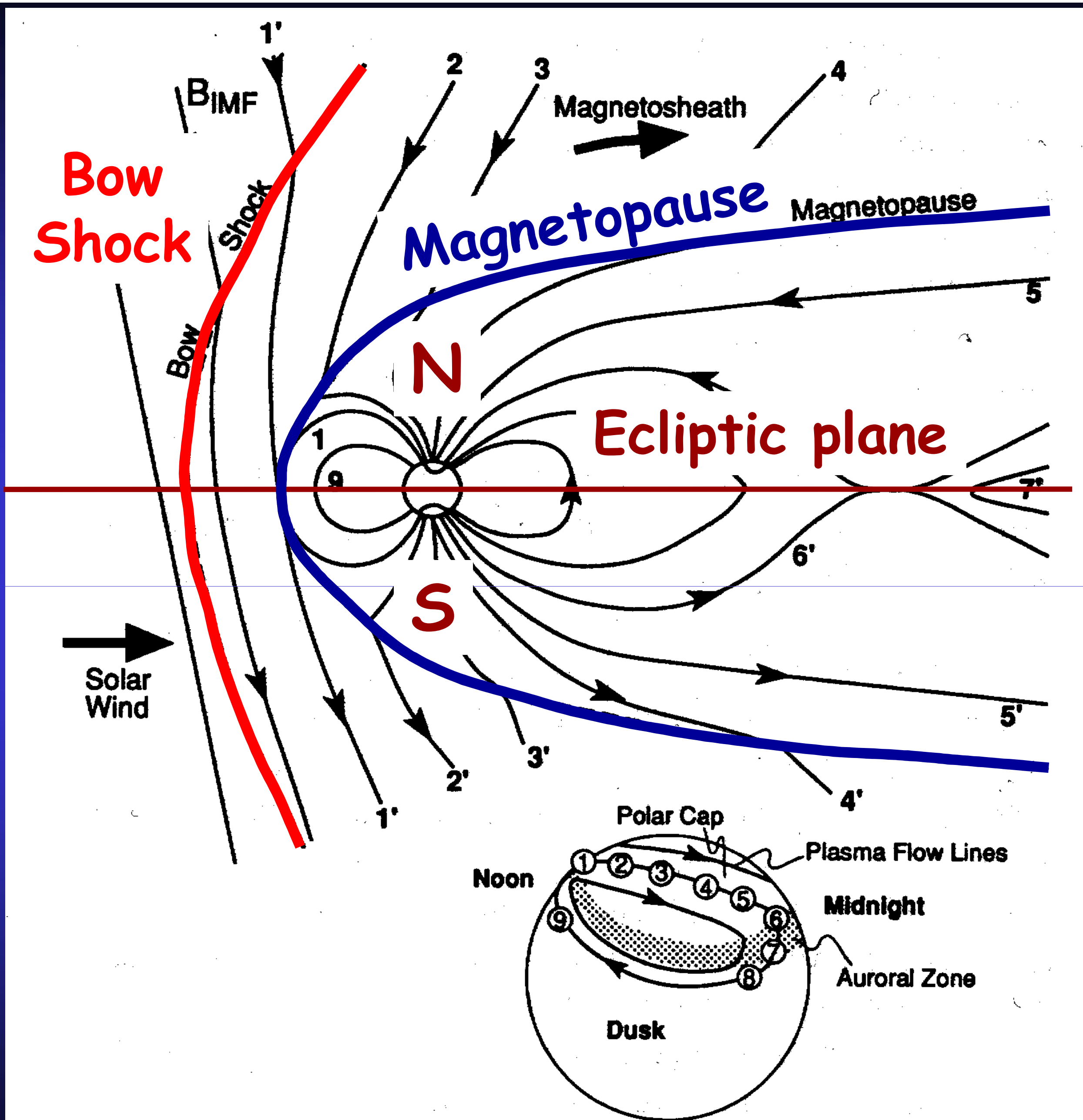


A magnetosphere at work



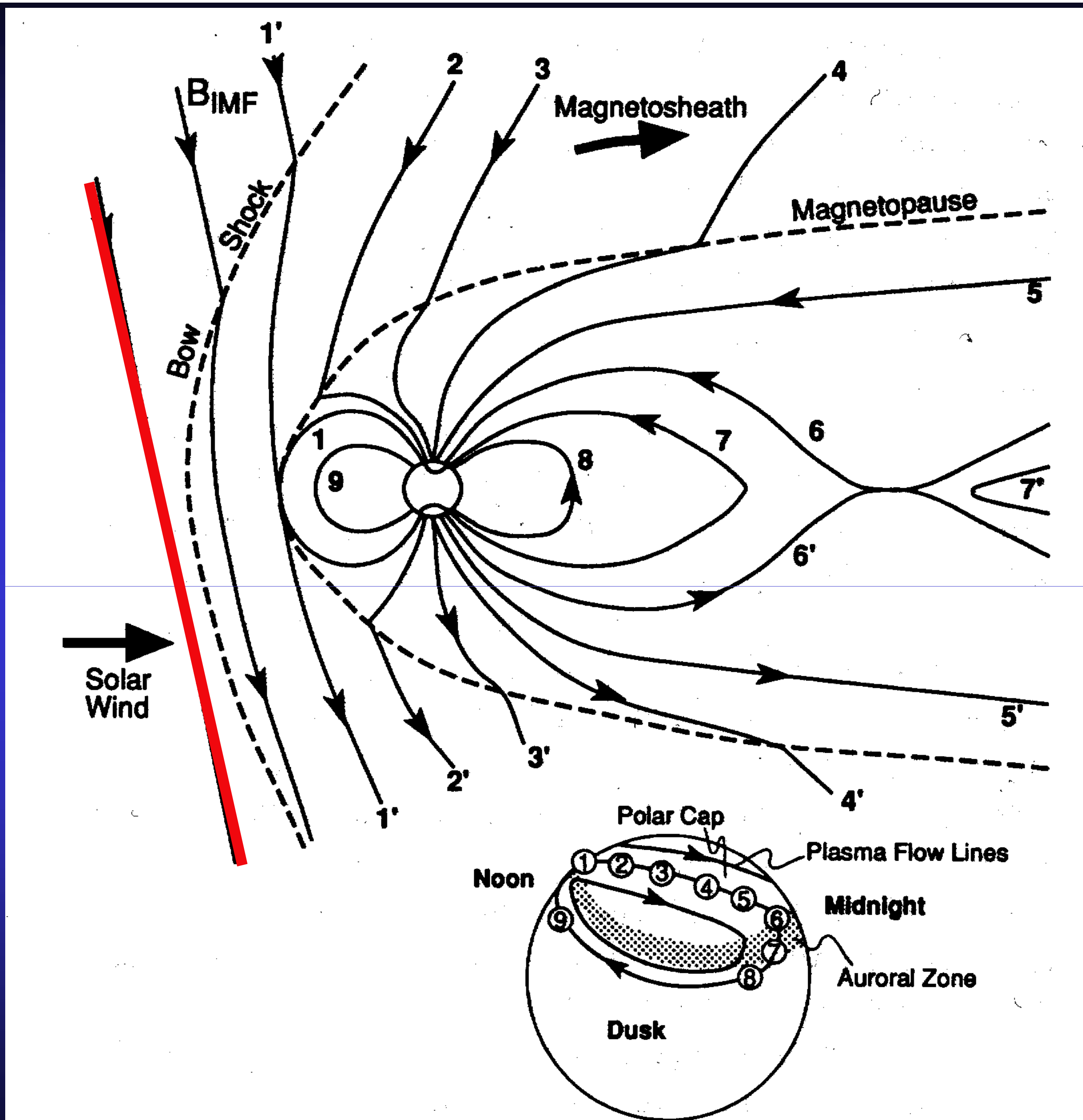
- Magnetic reconnection at the front side of the magnetosphere occurs, when the interplanetary Bz turns south, i.e. anti-parallel to the Earth's intrinsic field.
- Charged particles can now penetrate from outer space way down into the polar ionosphere.
- Reconnection in the tail causes ejection of plasmoids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

A magnetosphere at work



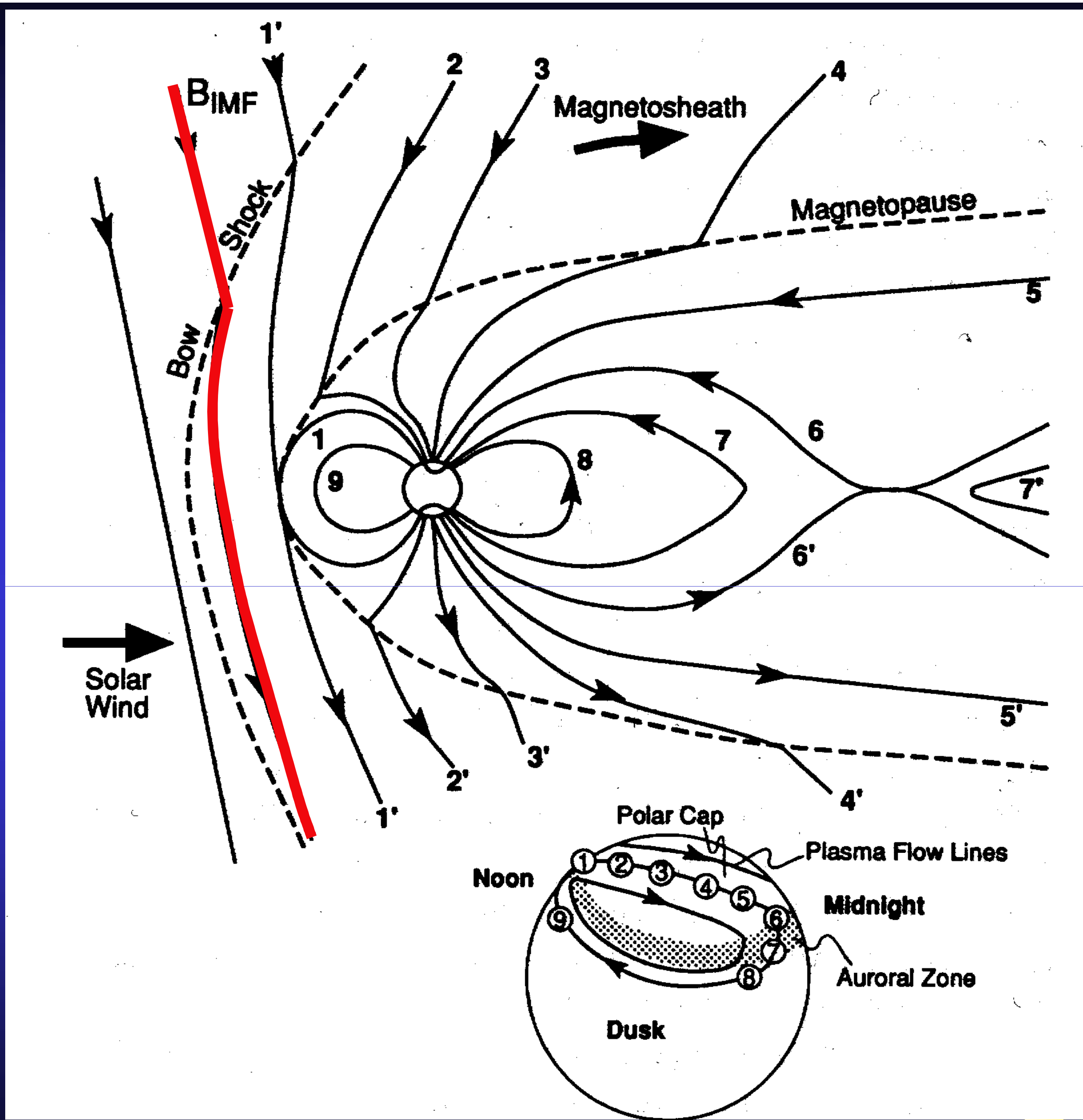
Hughes, 1995

A magnetosphere at work



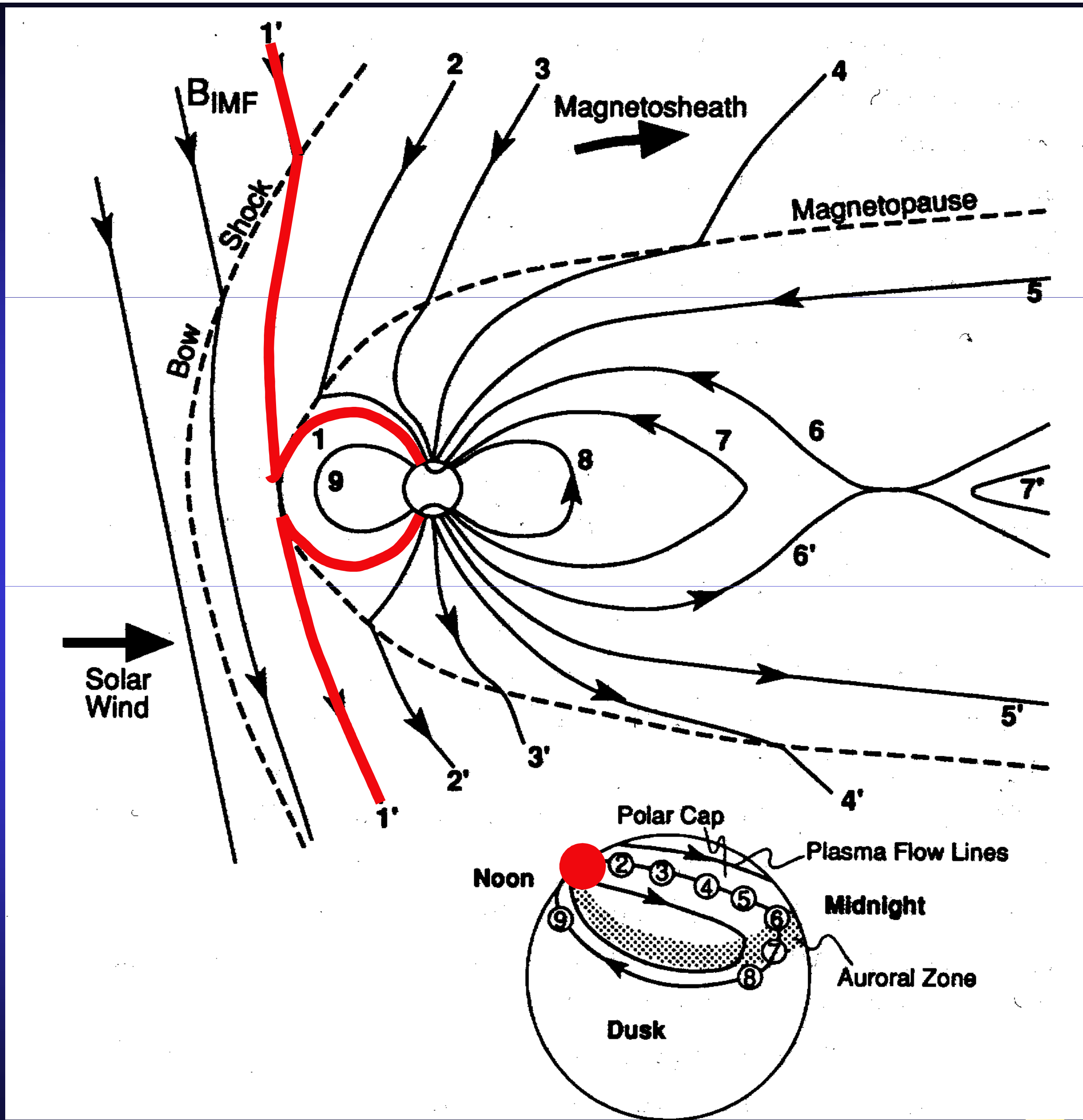
In case of B_z south:

A magnetosphere at work



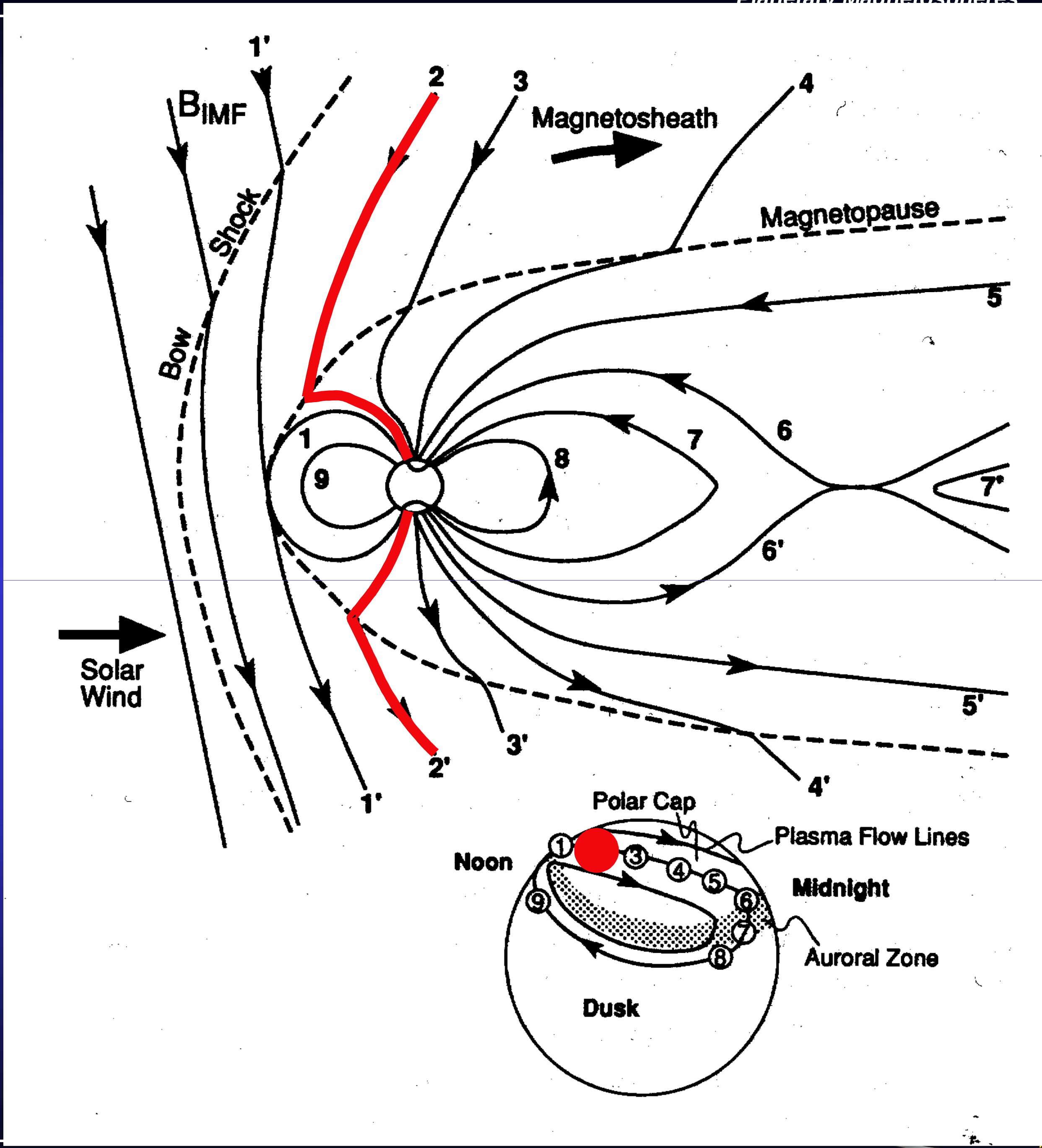
In case of B_z south:

A magnetosphere at work



In case of B_z south: reconnection at the magnetopause!

A magnetosphere at work



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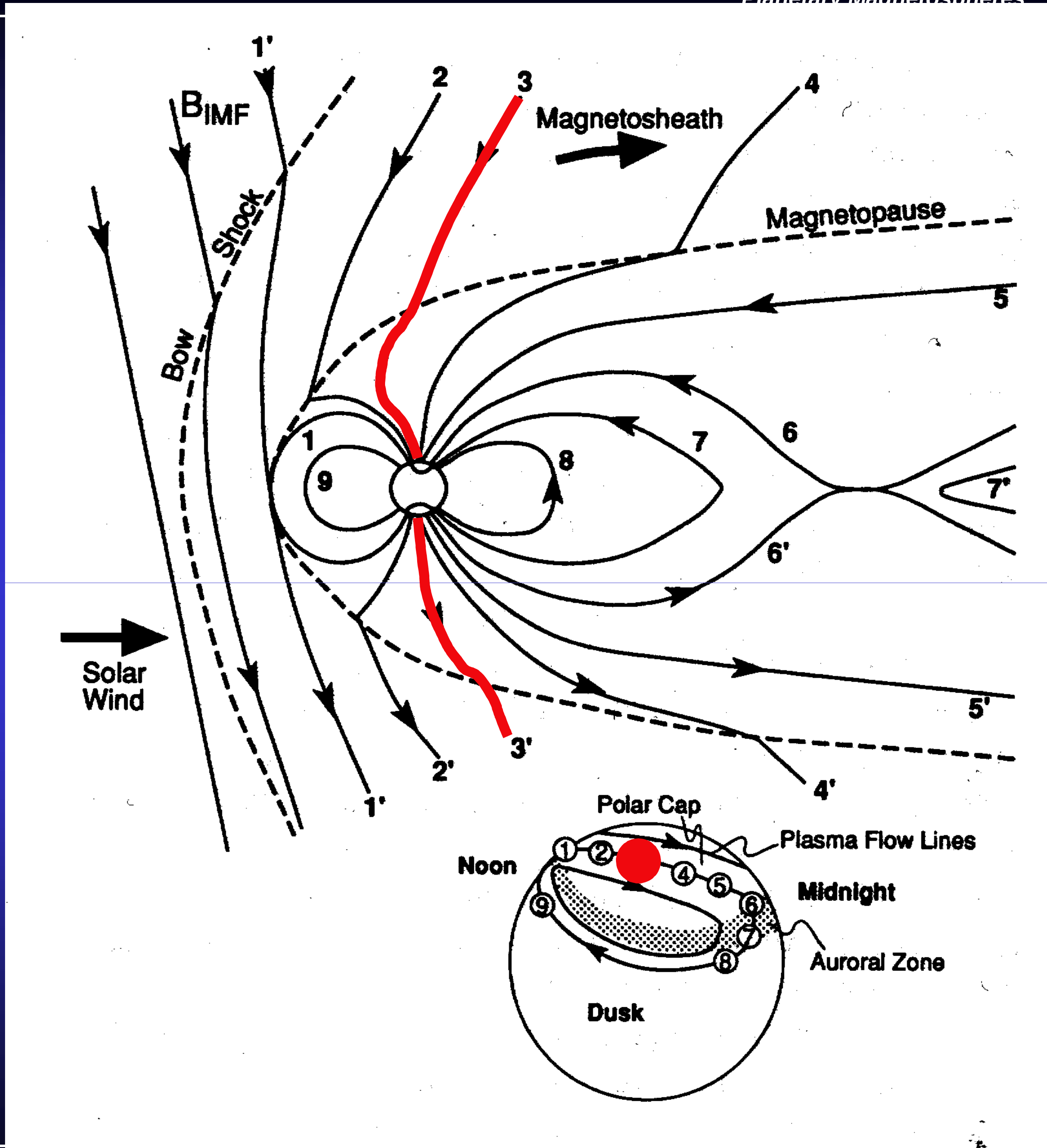

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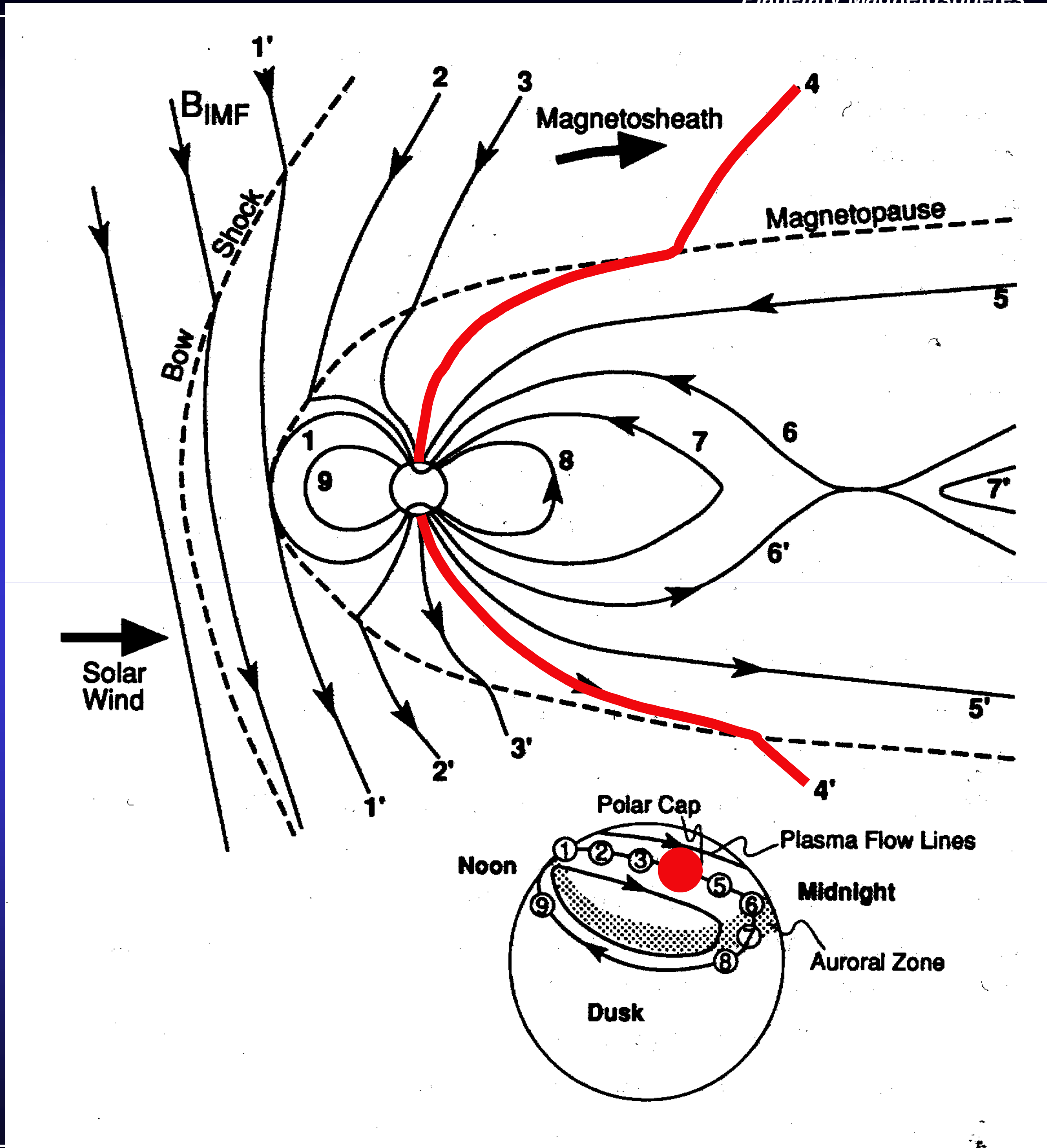
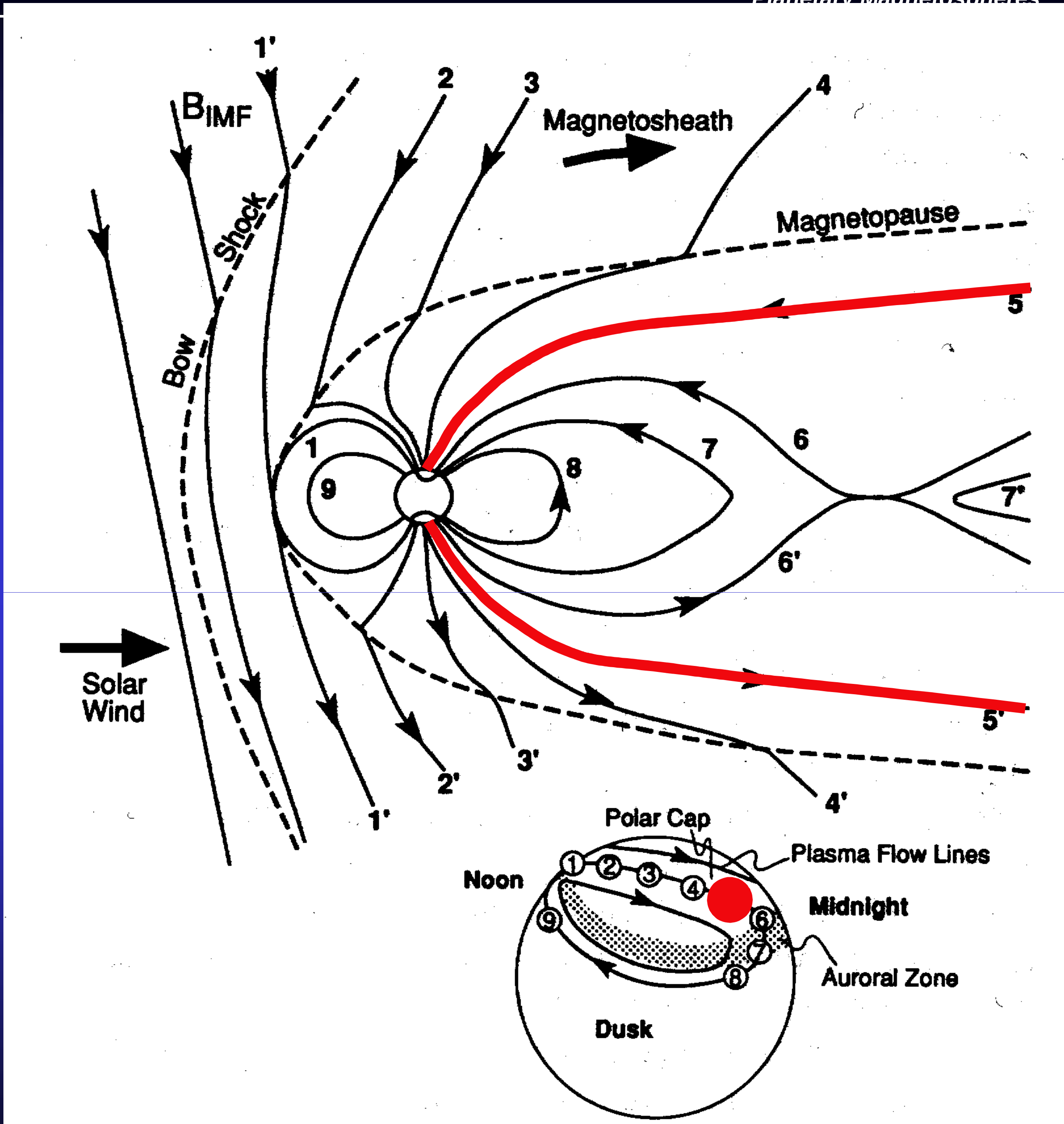
A magnetosphere at work



In case of B_z south: reconnection at the magnetopause!

A magnetosphere at work



In case of B_z south: reconnection at the magnetopause!

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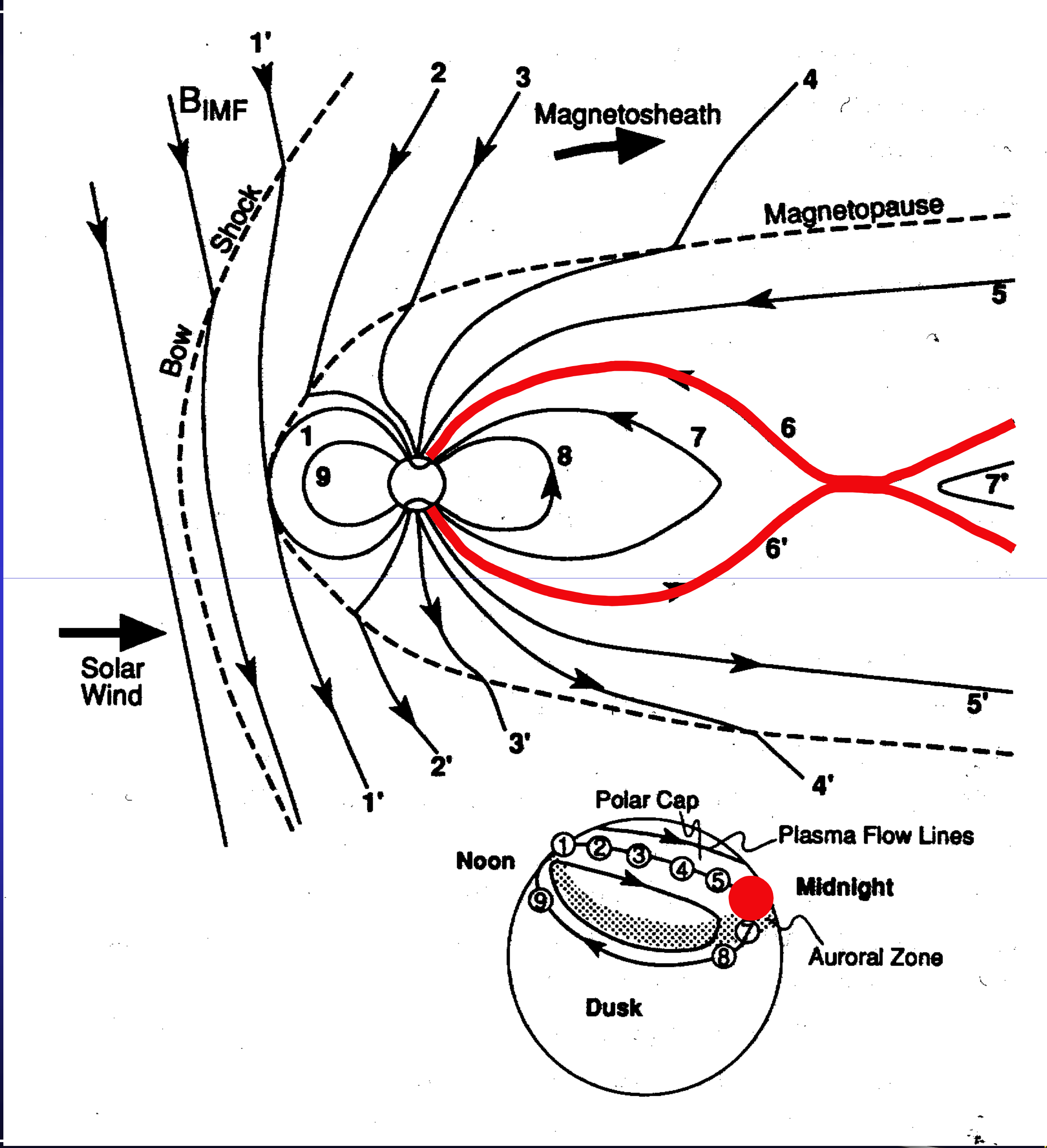
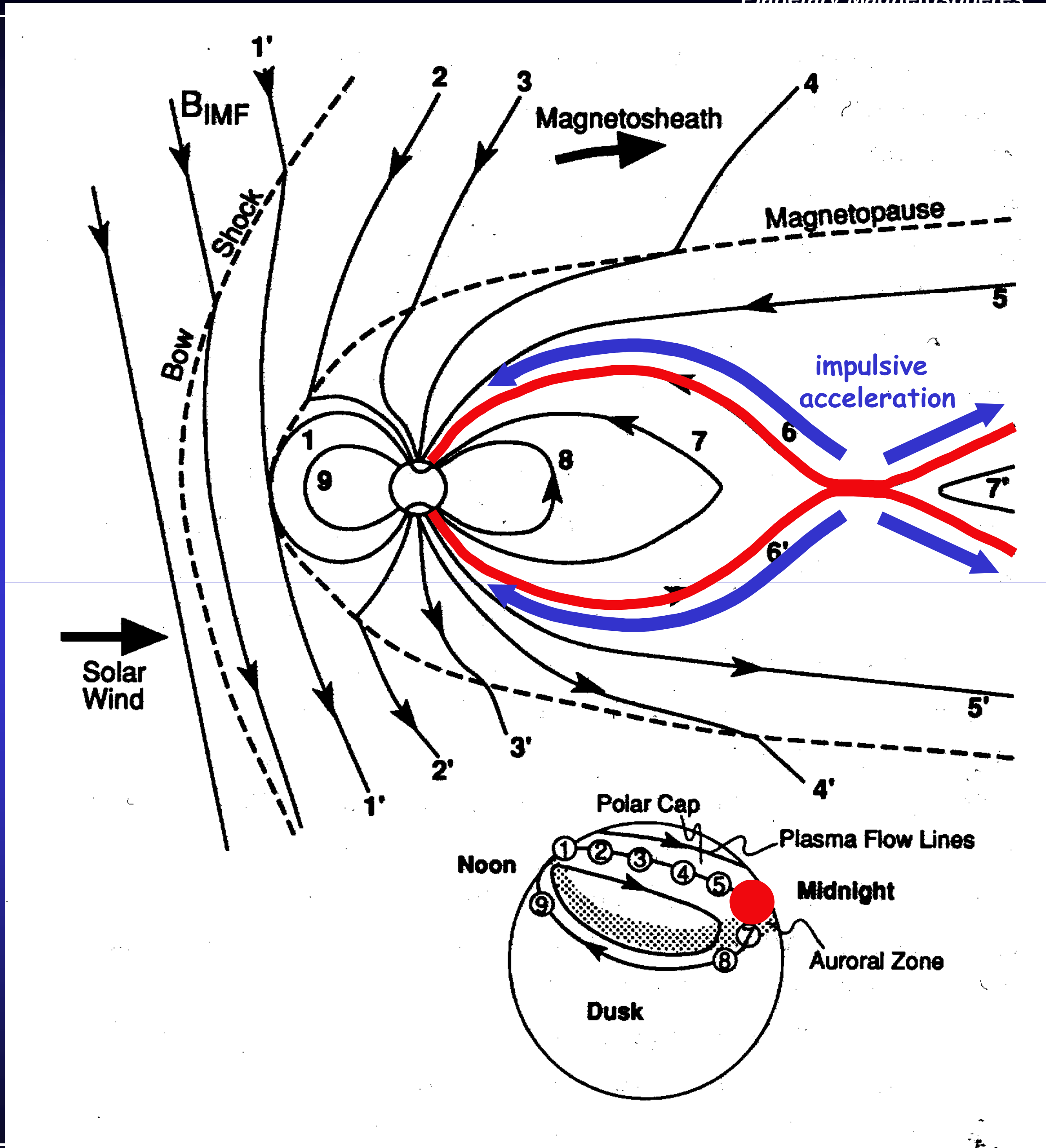


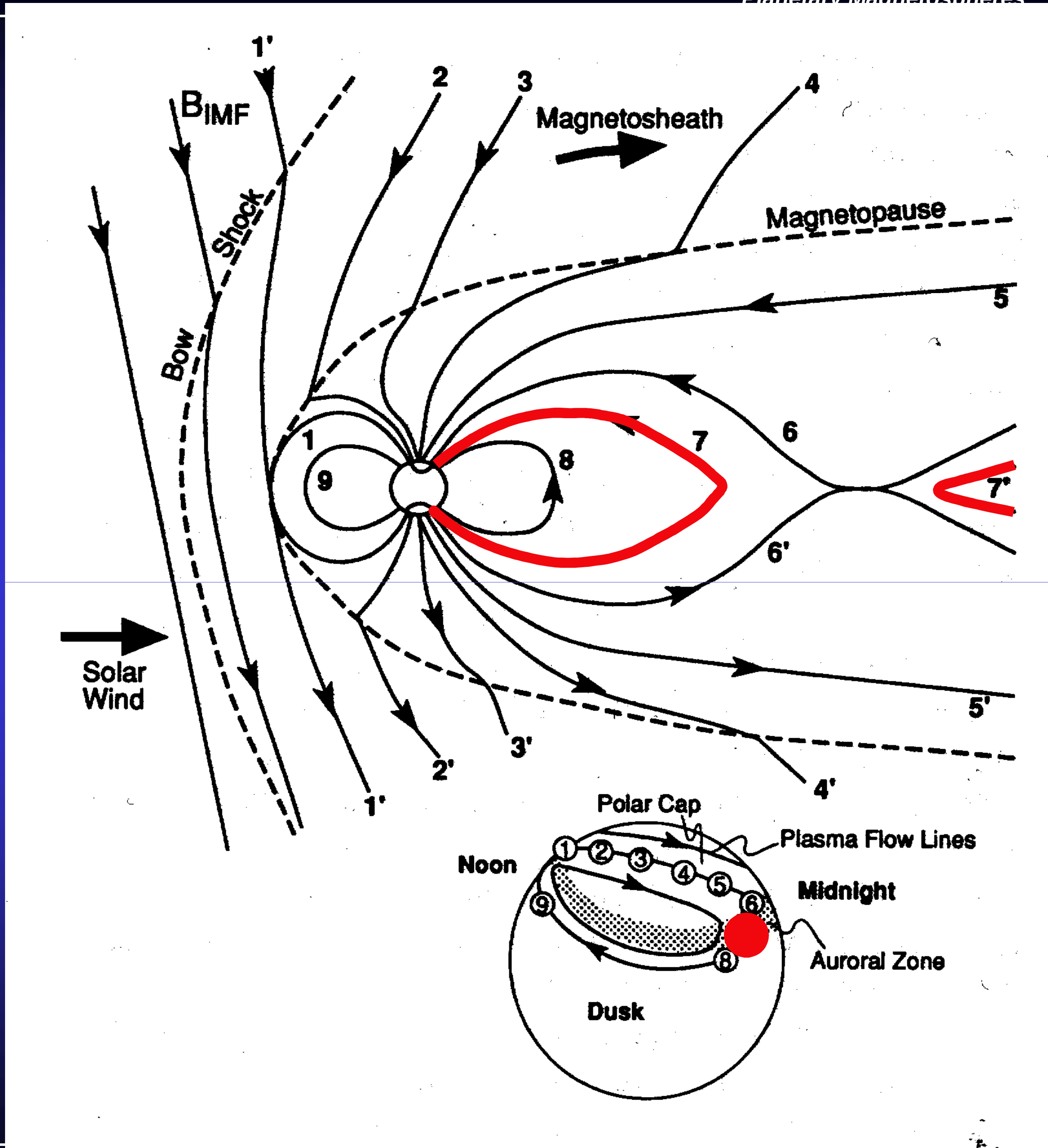
In case of B_z south: reconnection at the magnetopause, and reconnection in the magnetotail!

A magnetosphere at work



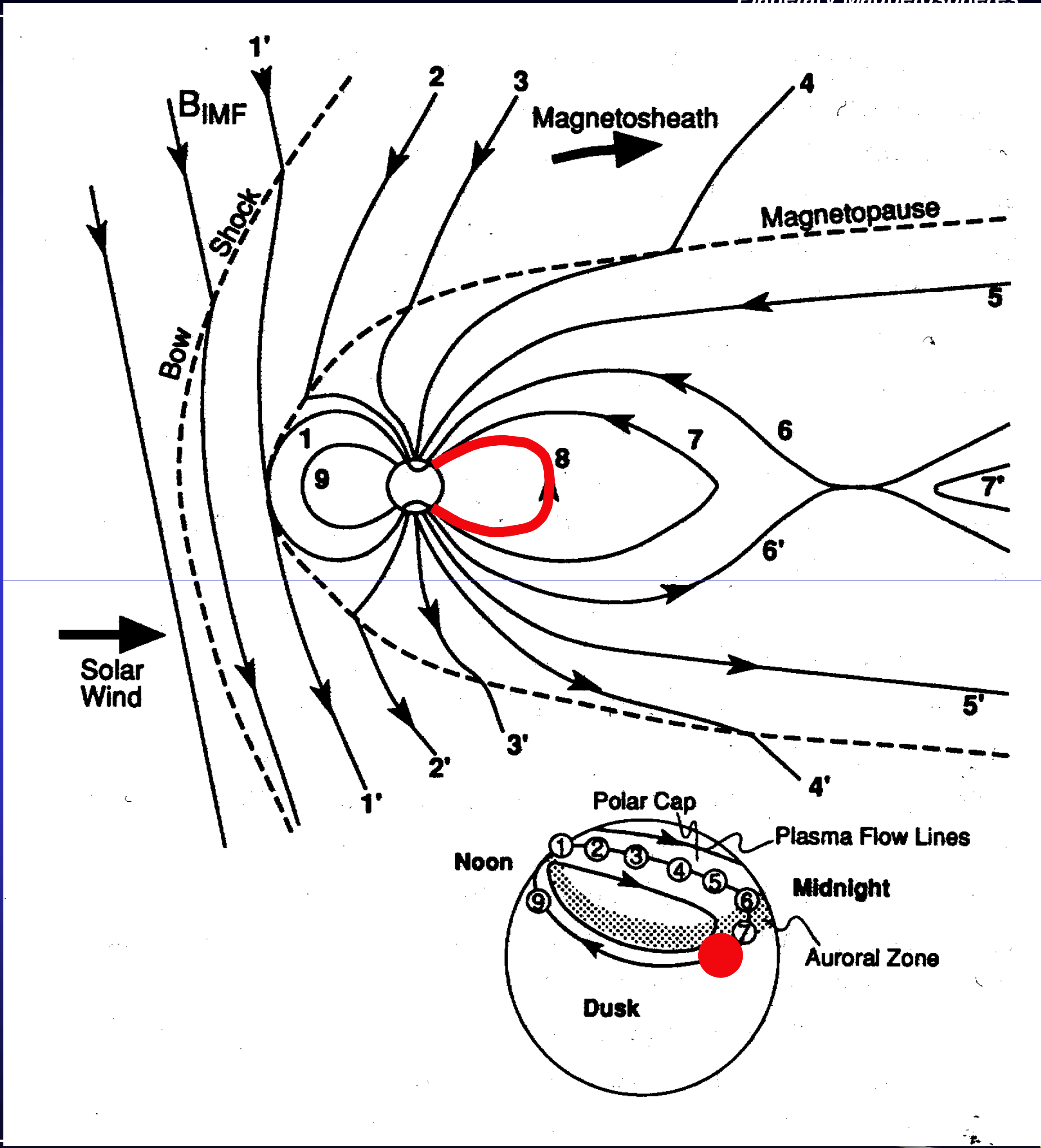
In case of B_z south: reconnection at the magnetopause, and reconnection in the magnetotail!

A magnetosphere at work



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

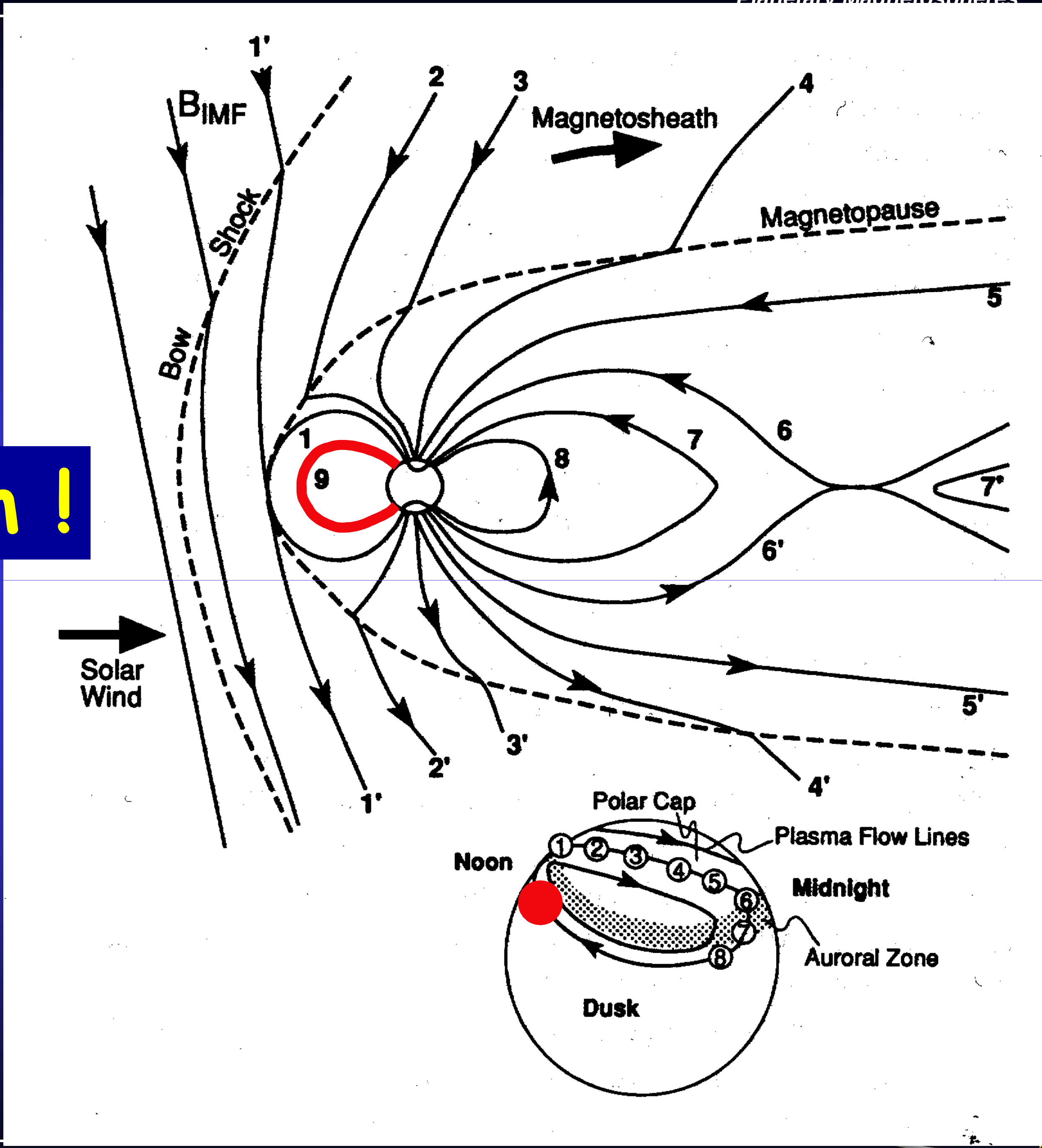
A magnetosphere at work



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

A magnetosphere at work

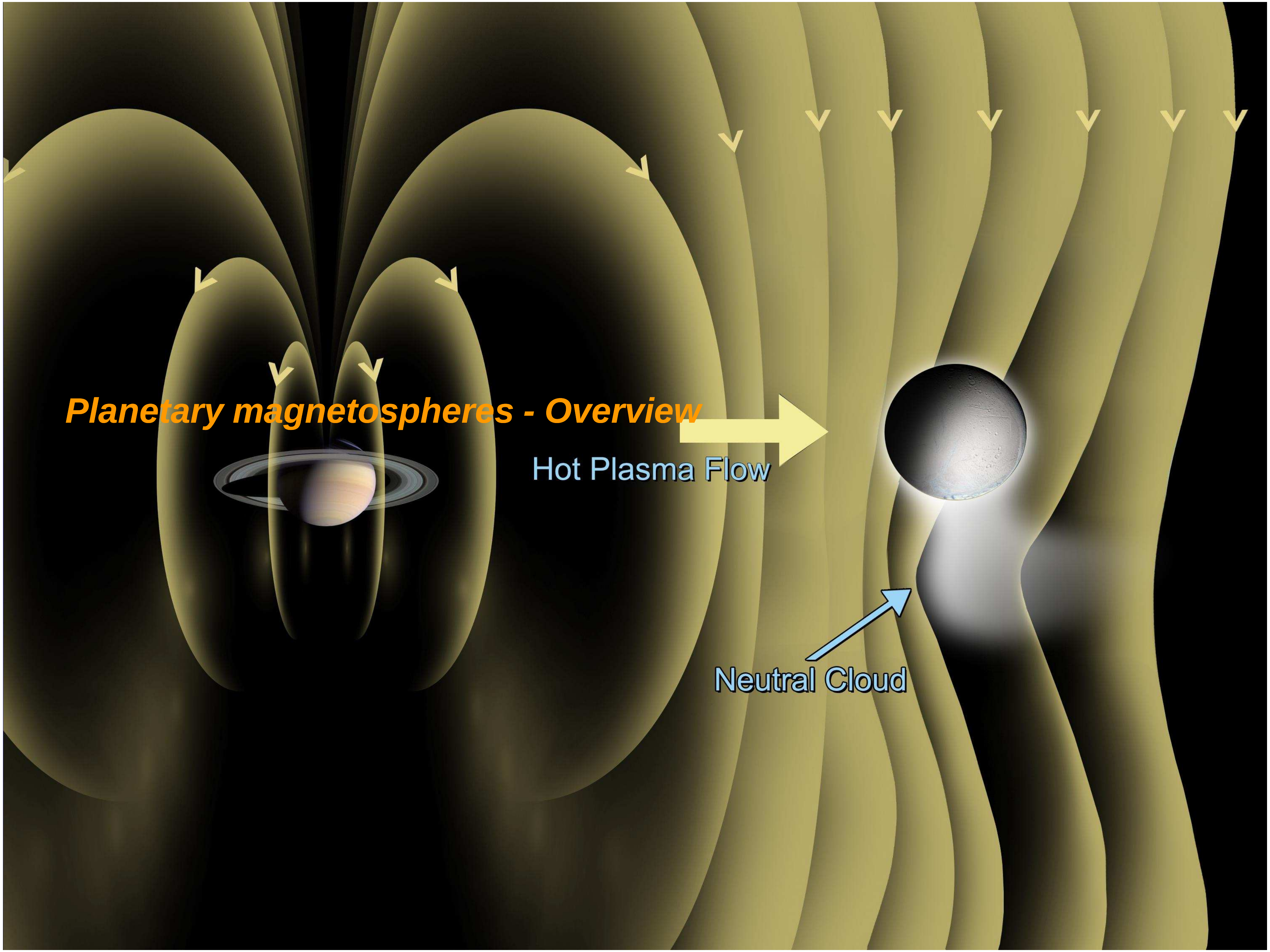
A substorm !



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



The magnetosphere of Mercury

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

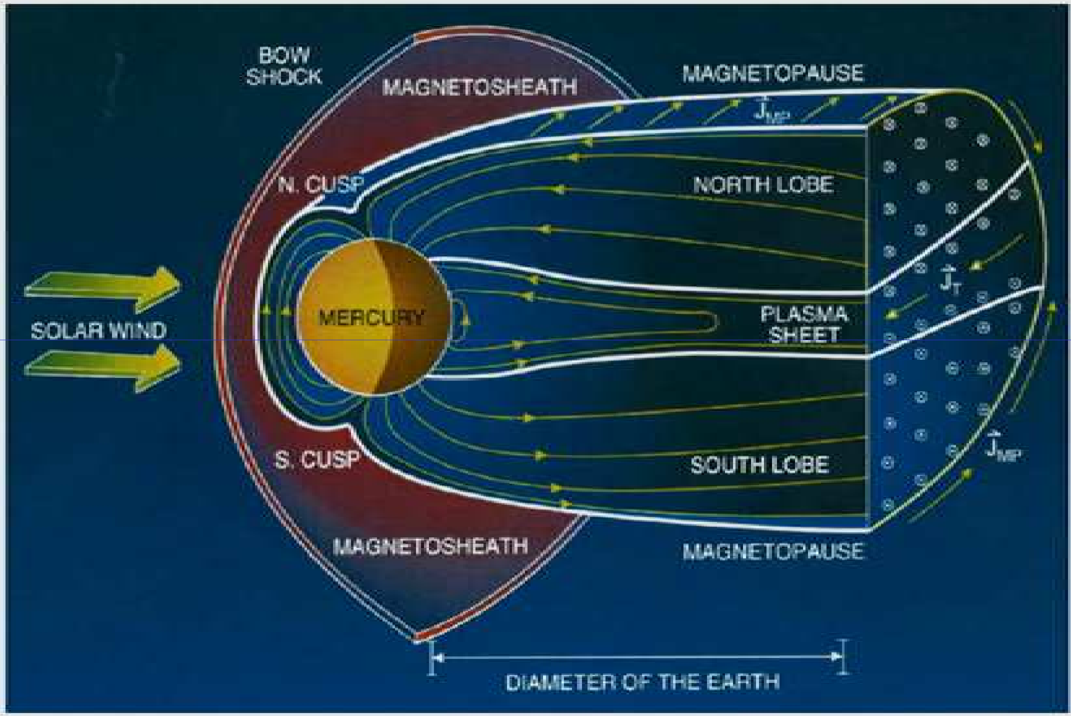


Fig. 2. Schematic view of the bow shock and magnetosphere of Mercury.

No atmosphere

thus no ionosphere

but exosphere

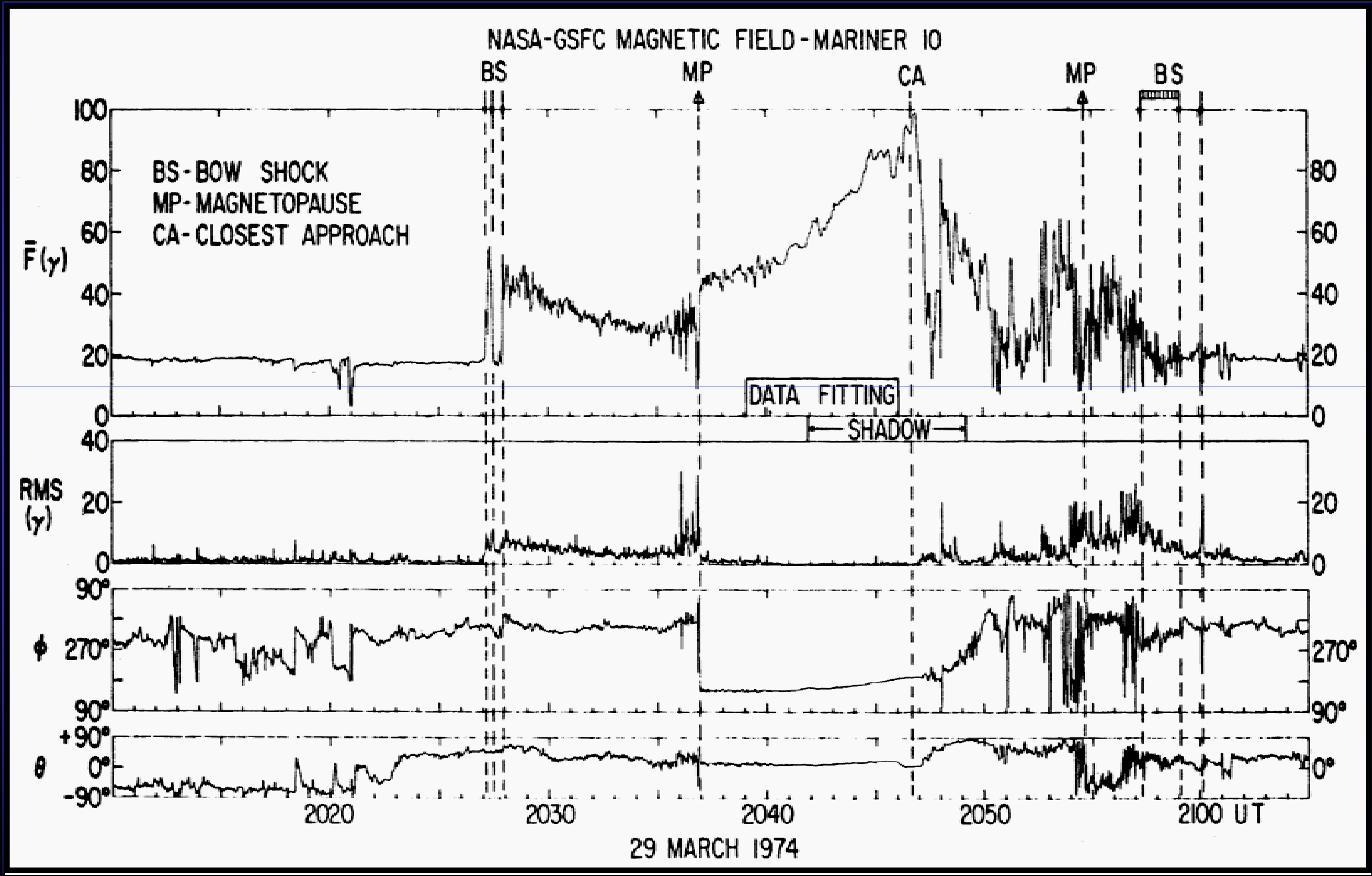
No plasmasphere

Weak magnetic field

Multi-ion plasma

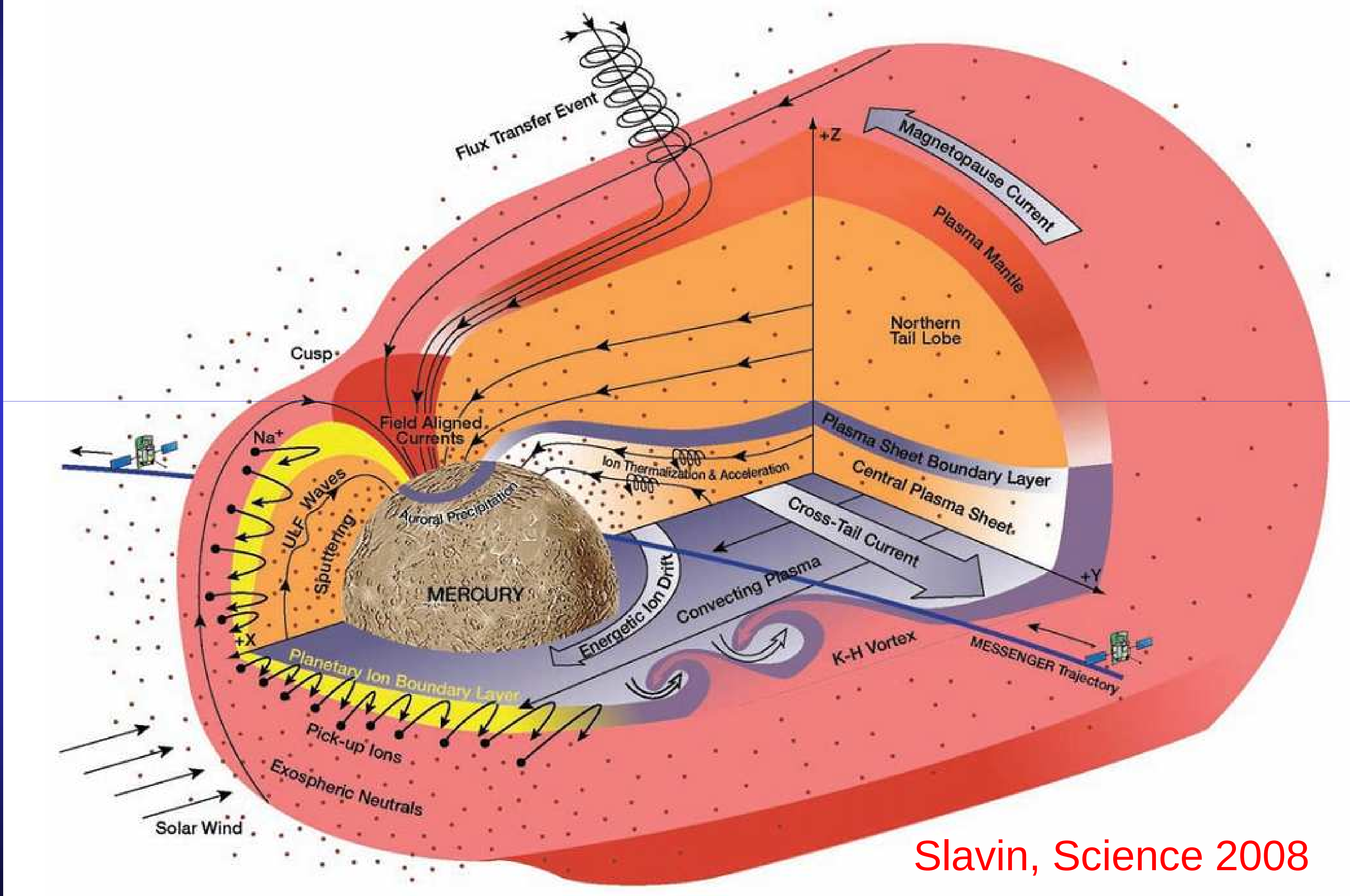
Small magnetosphere

Planetary magnetic field of Mercury
Mariner 10 results 1974



Ness et al., 1975

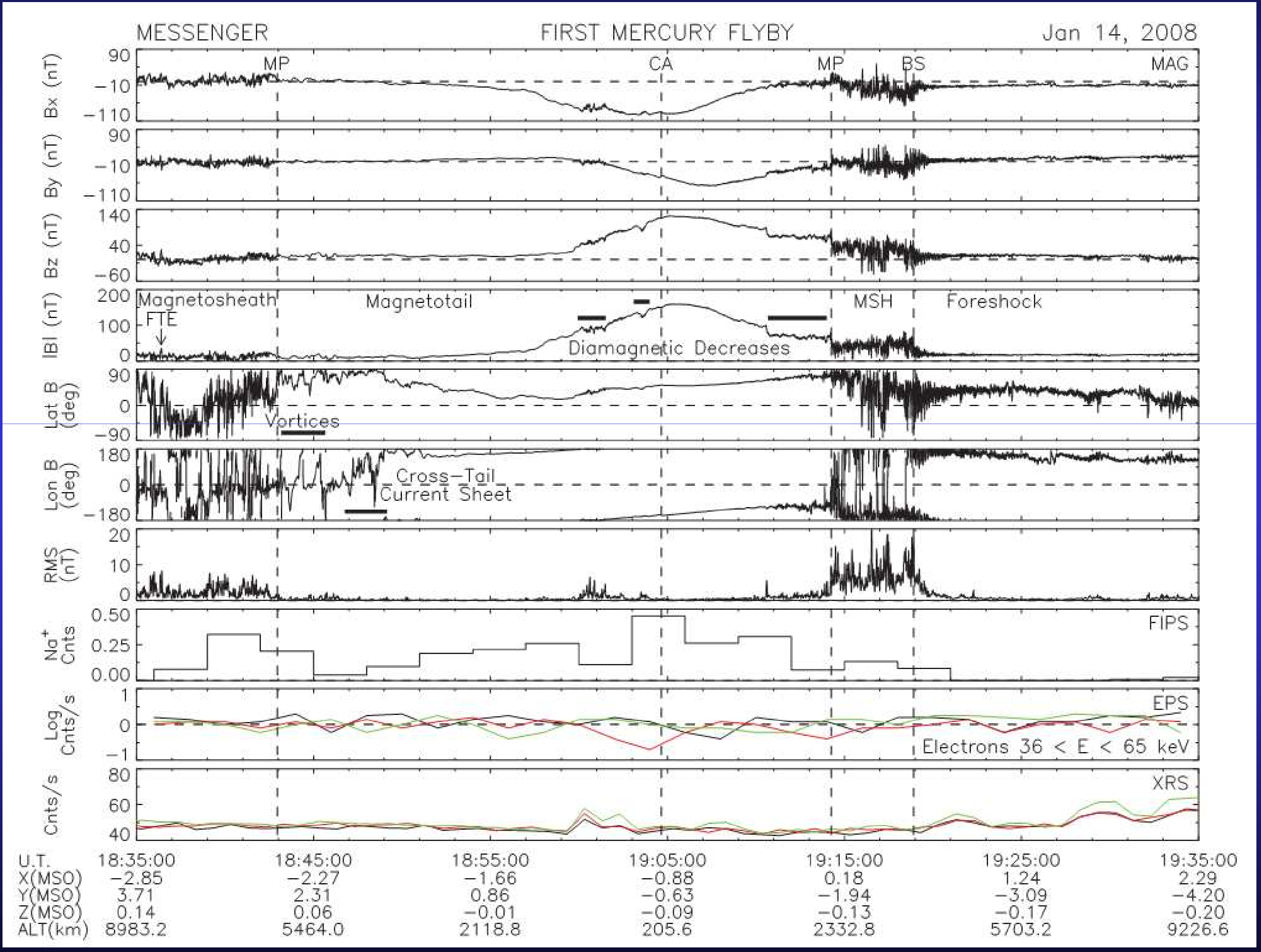
Mercury's magnetosphere
after Messenger flyby 1, Jan 2008



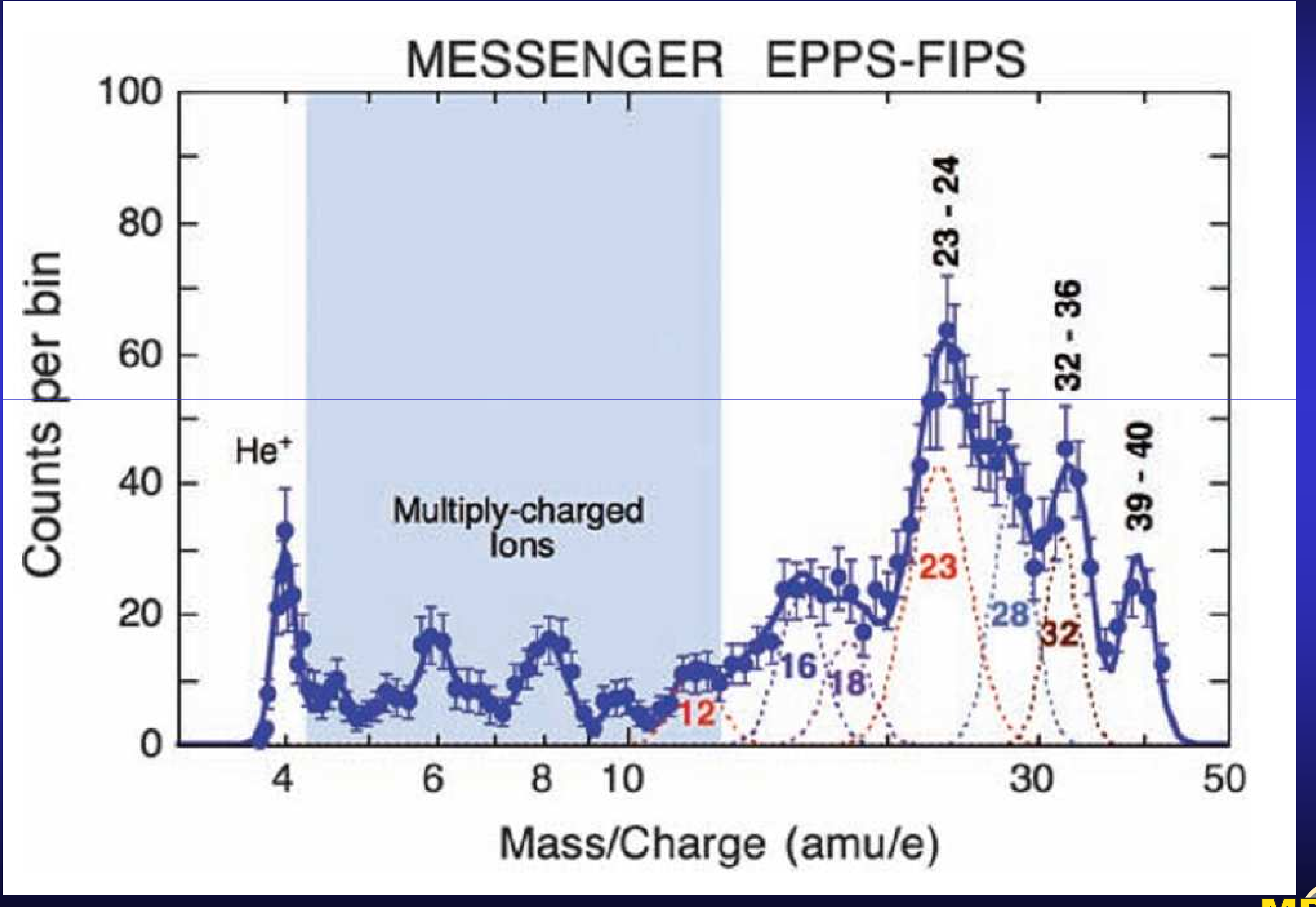
Slavin, Science 2008

Max-Planck-Institut für Sonnensystemforschung

Mercury's magnetosphere
Messenger flyby 1, Jan 2008

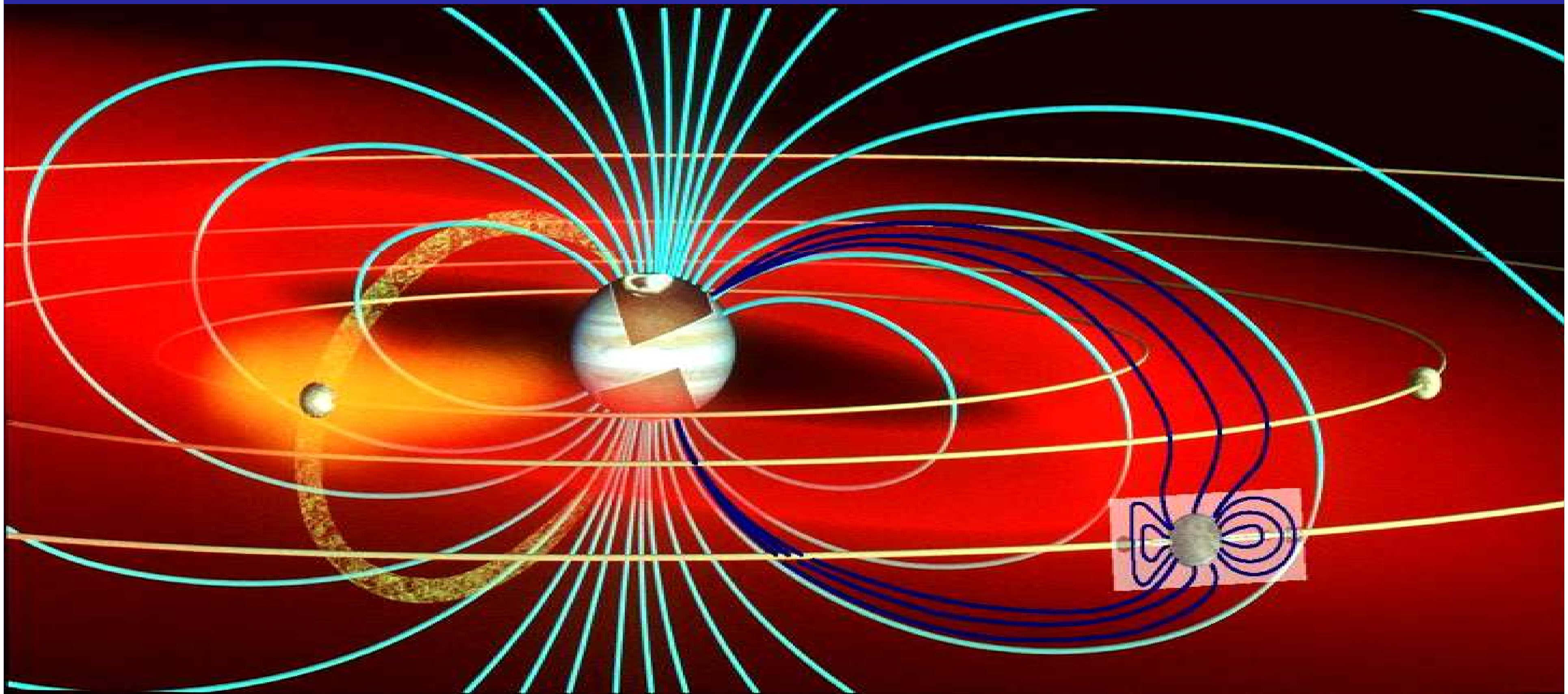


Mercury's magnetosphere
Messenger flyby 1, Jan 2008

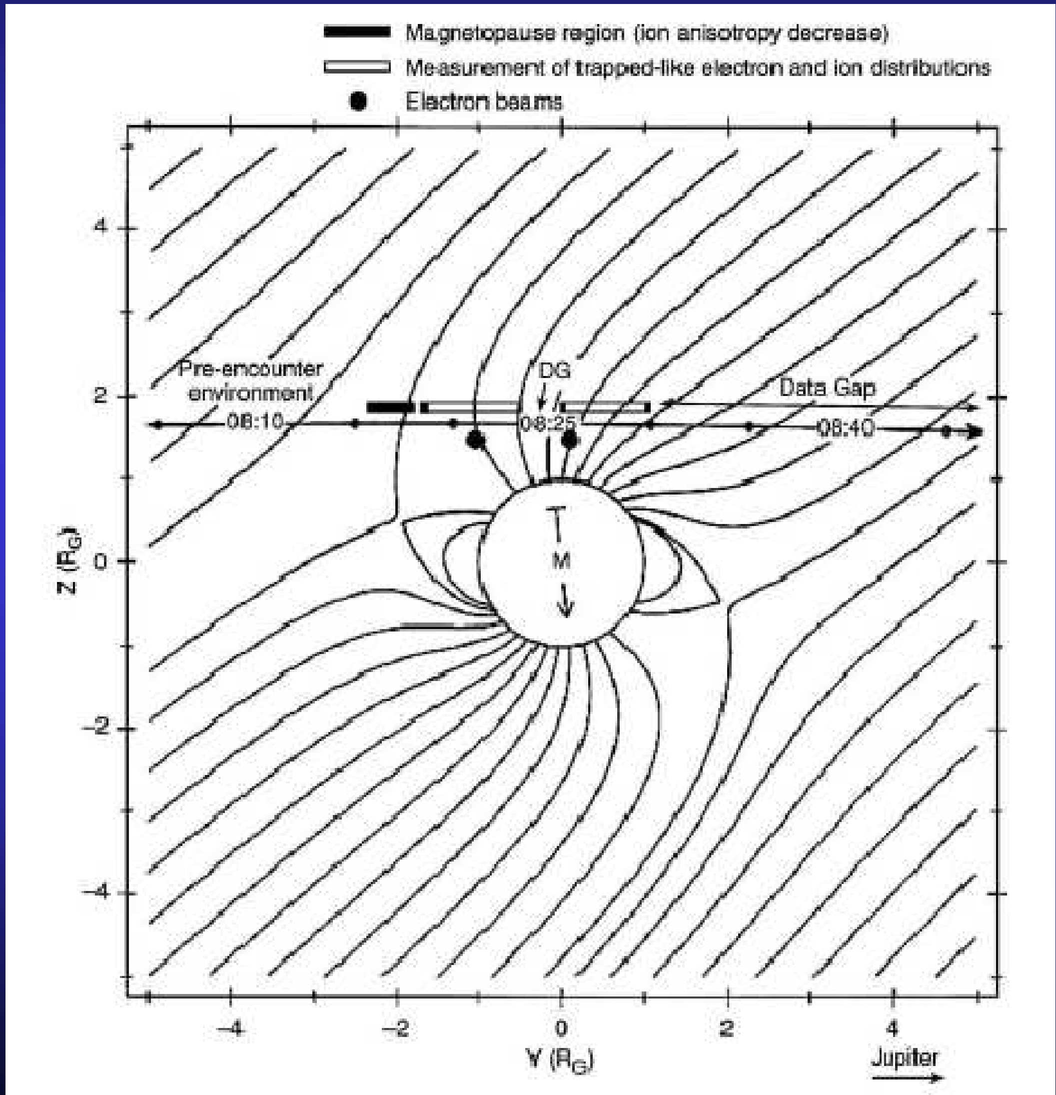


Ganymede magnetosphere

A magnetosphere within a magnetosphere



Ganymede:
Electron beams in Ganymede's magnetosphere



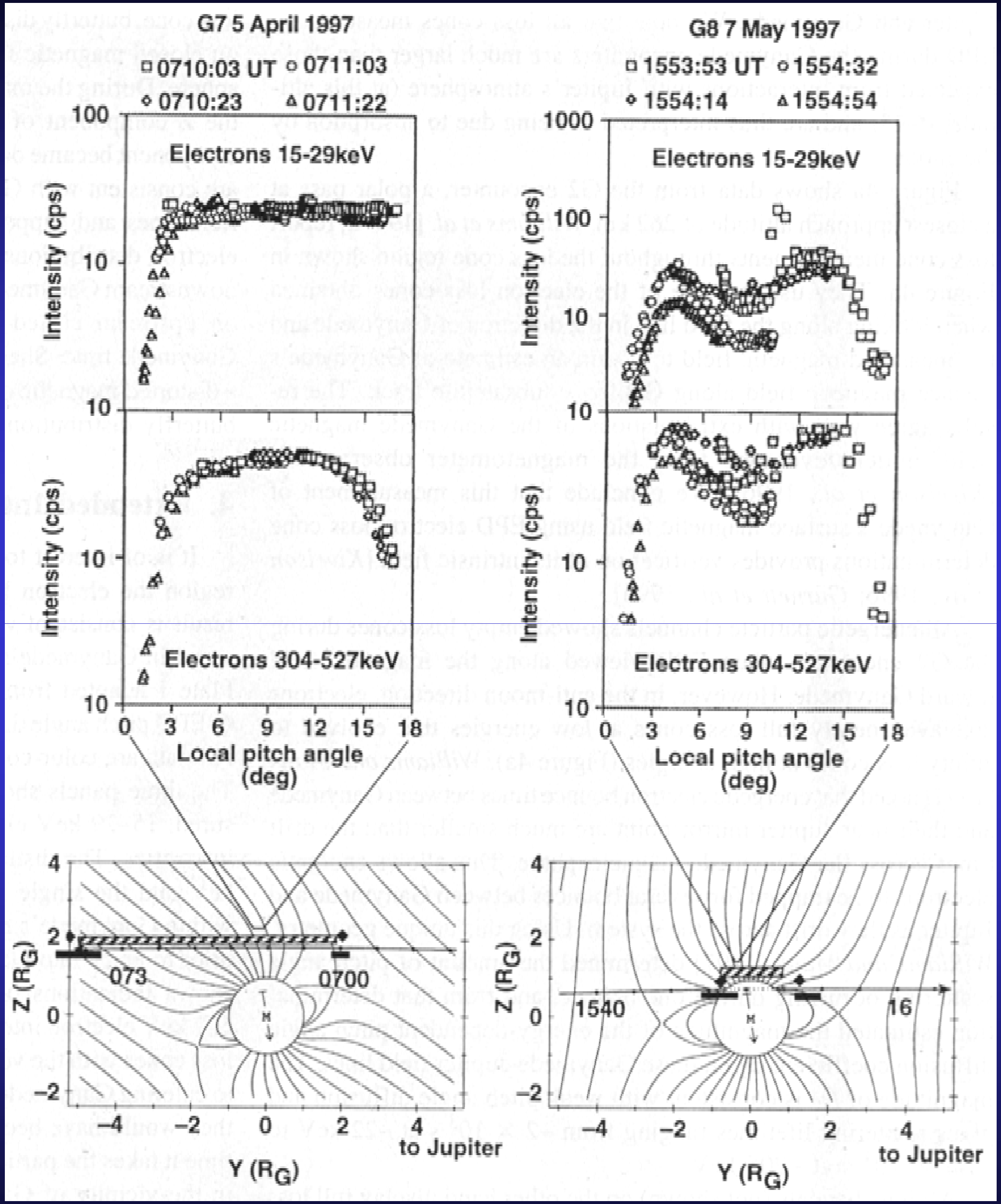
Williams, JGR, 2004

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

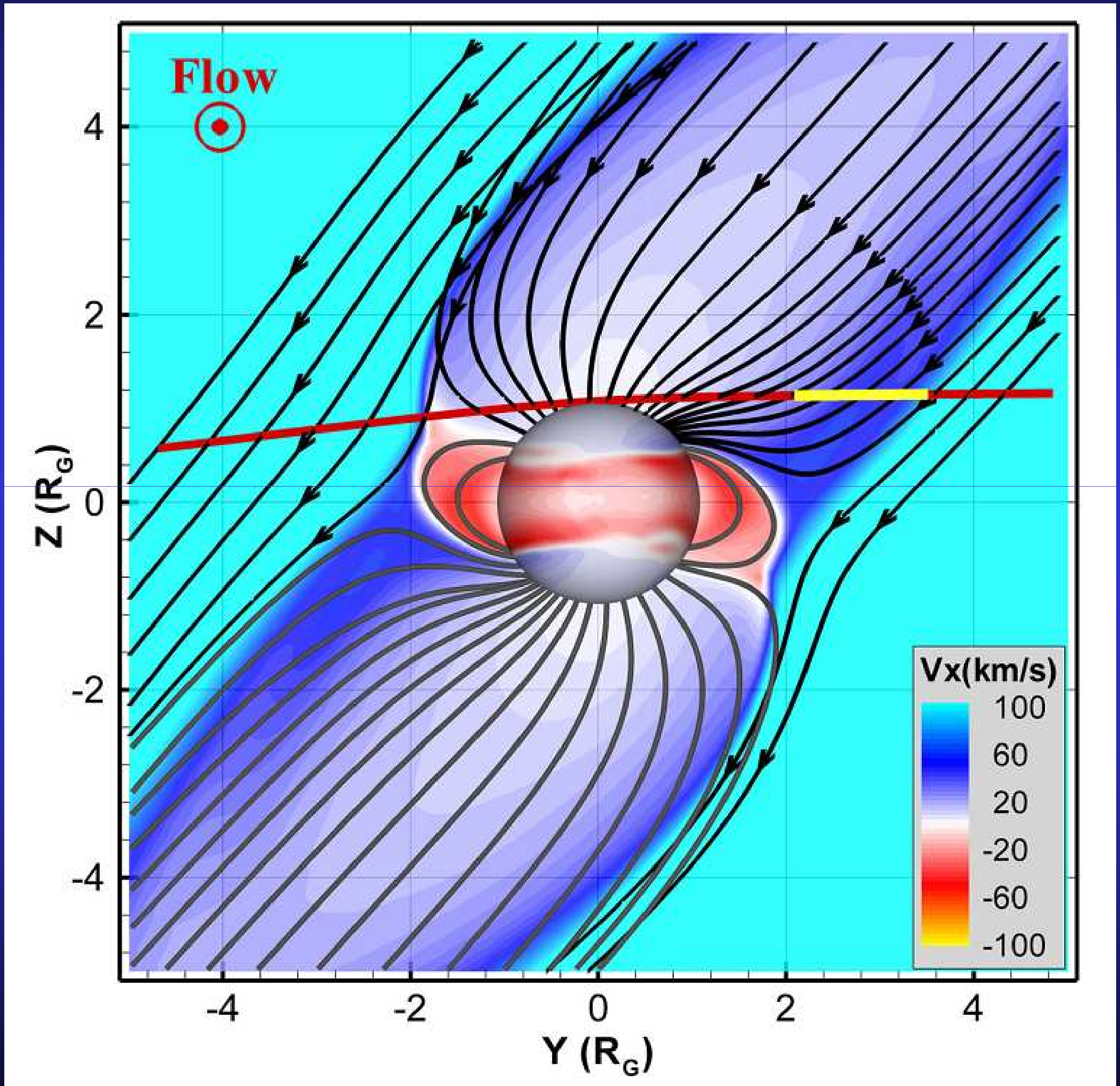
Energetic electron measurements remotely diagnose magnetic topology, boundary geometry and surface magnetic field strengths of icy moons.

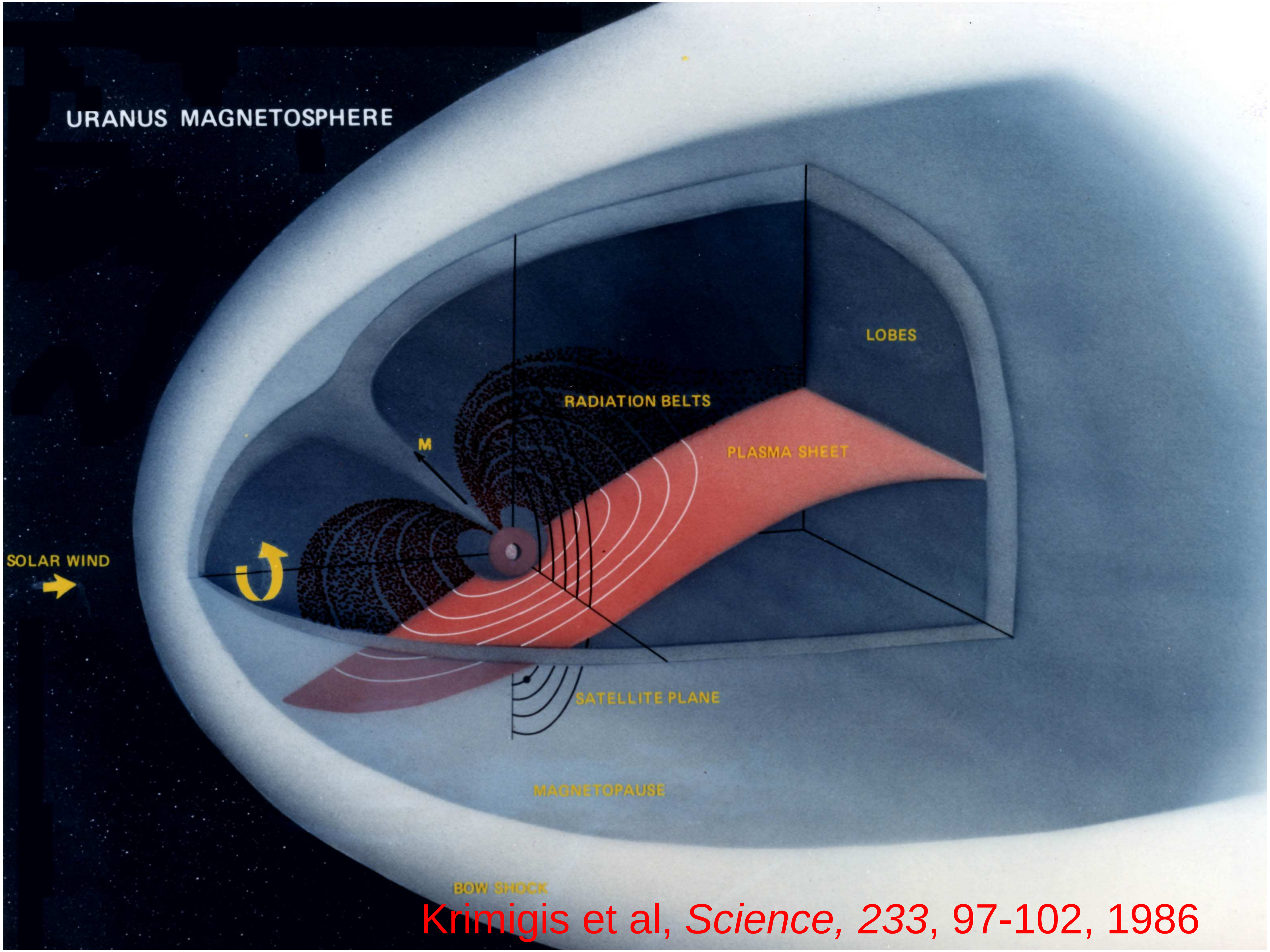


Williams et al., GRL, 1998

Ganymede magnetosphere simulation

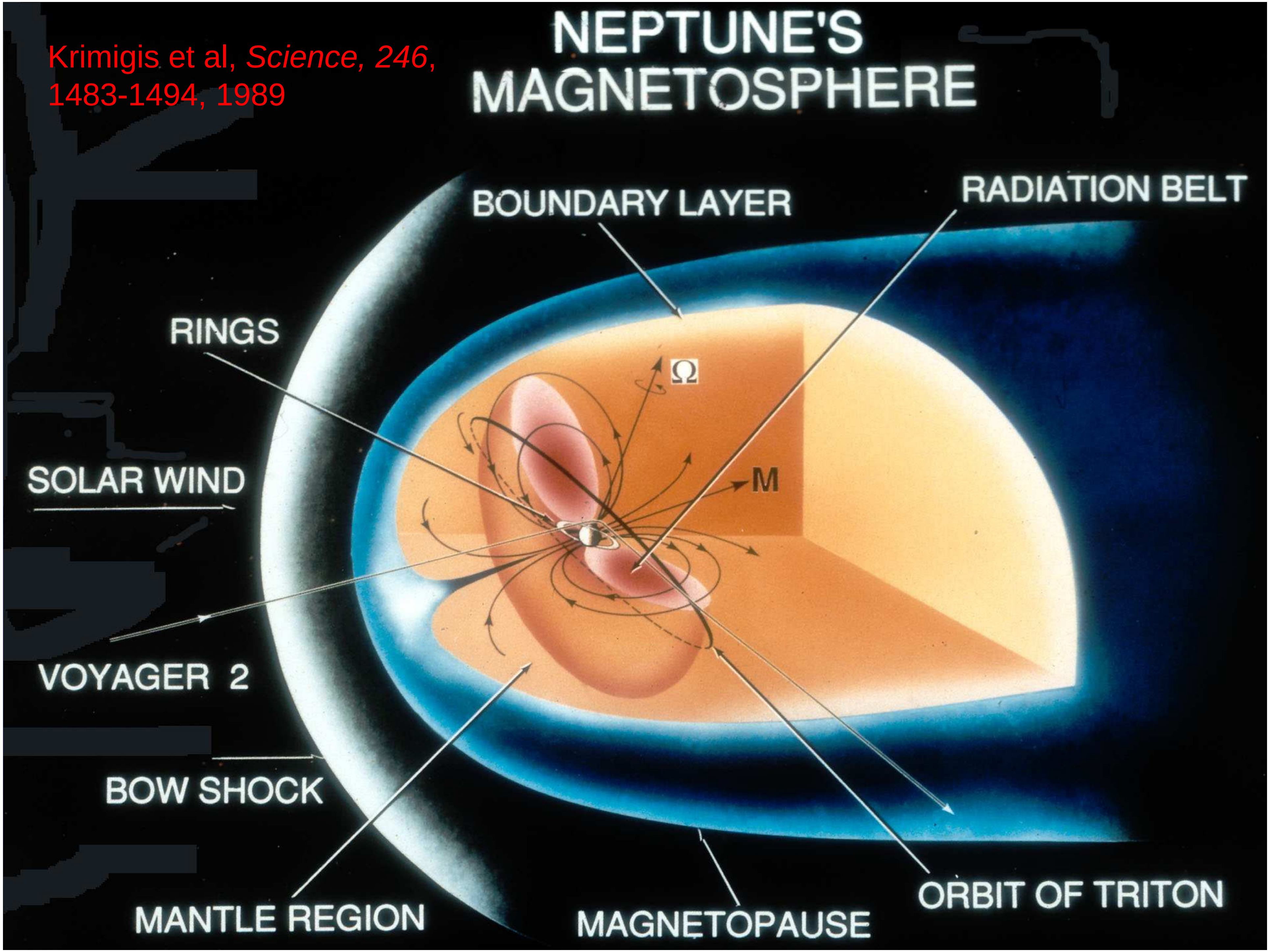
Jia 2009



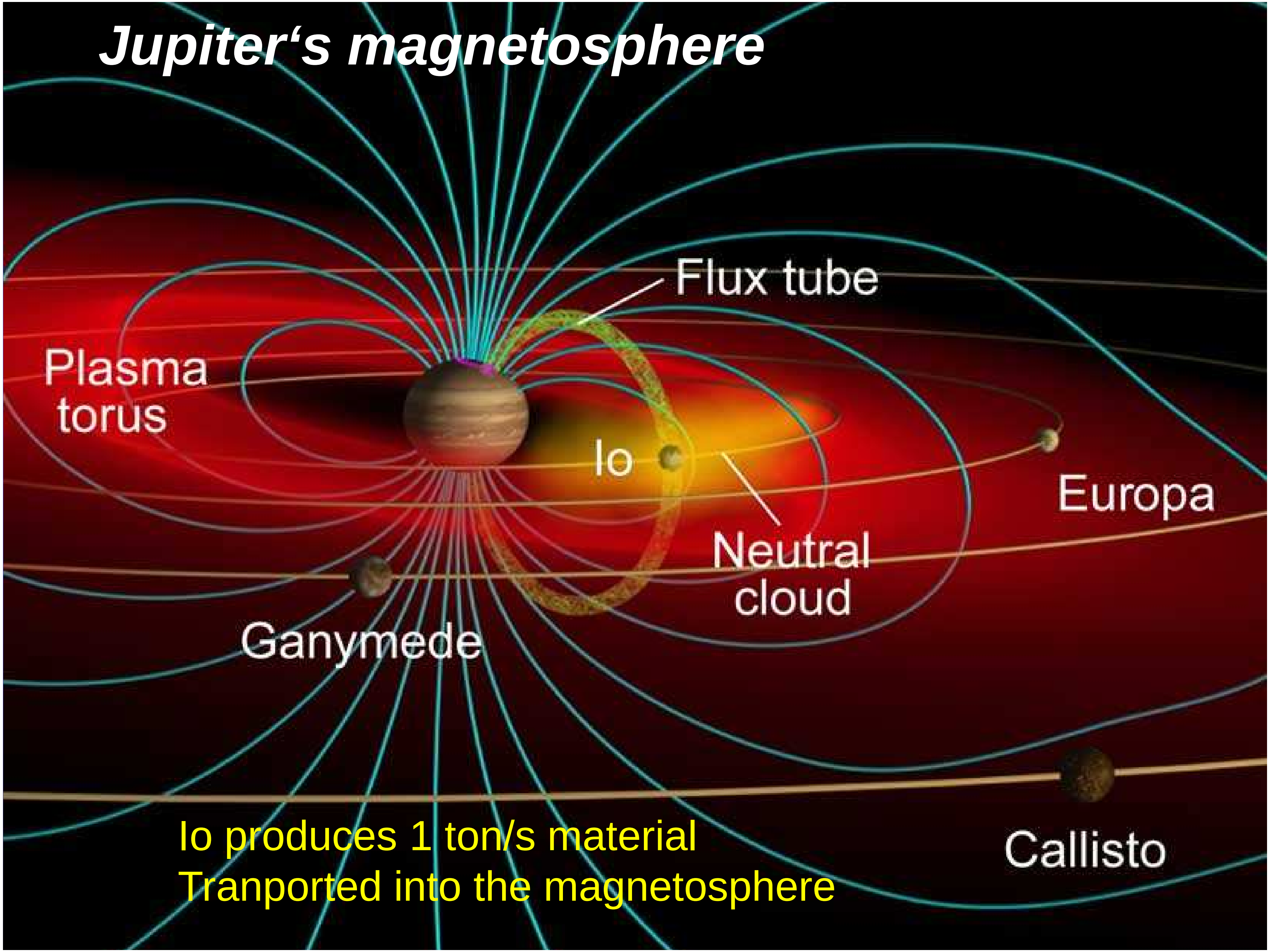


Krimigis et al, *Science, 233*, 97-102, 1986

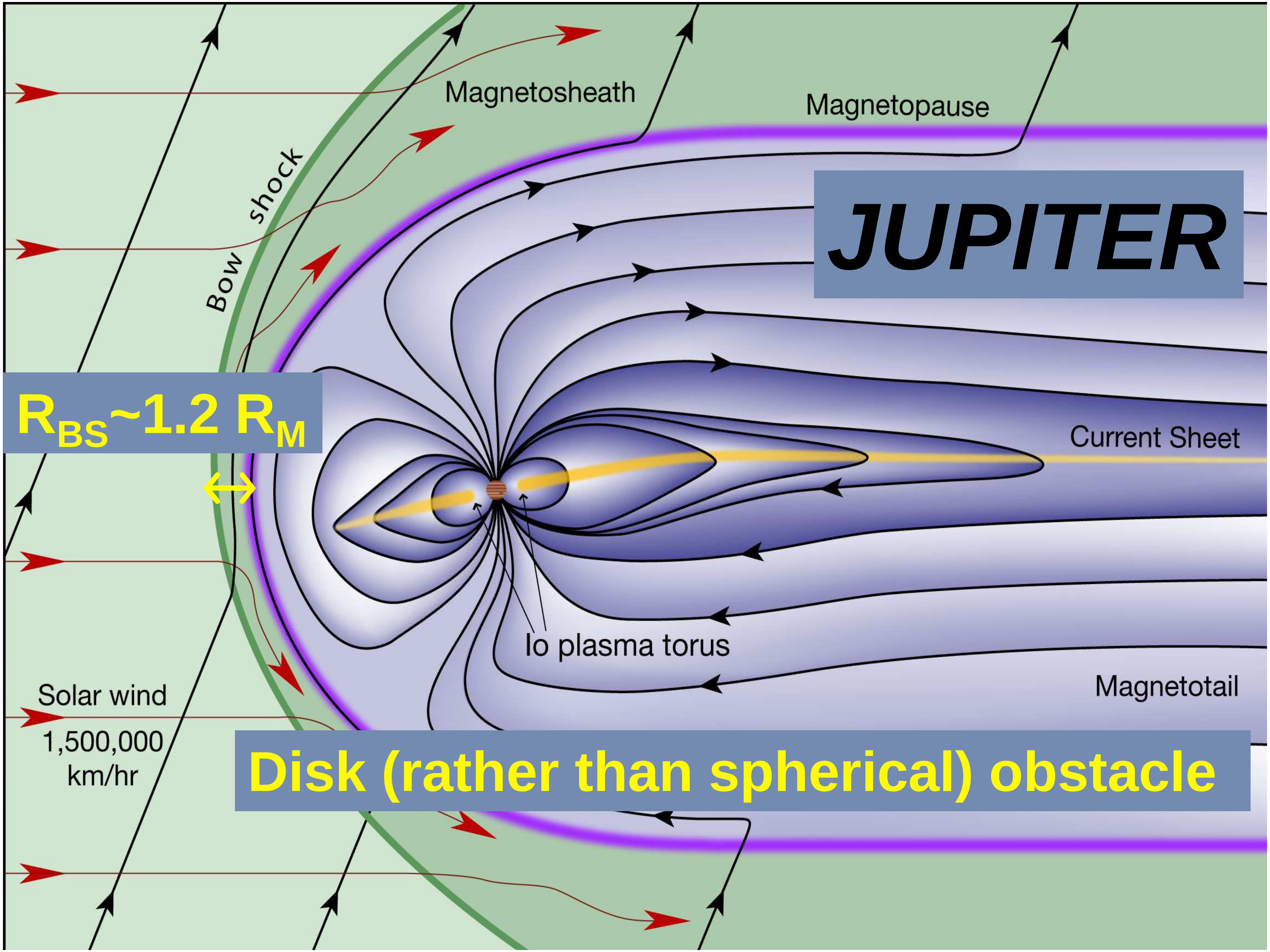
Krimigis et al, *Science, 246*, 1483-1494, 1989



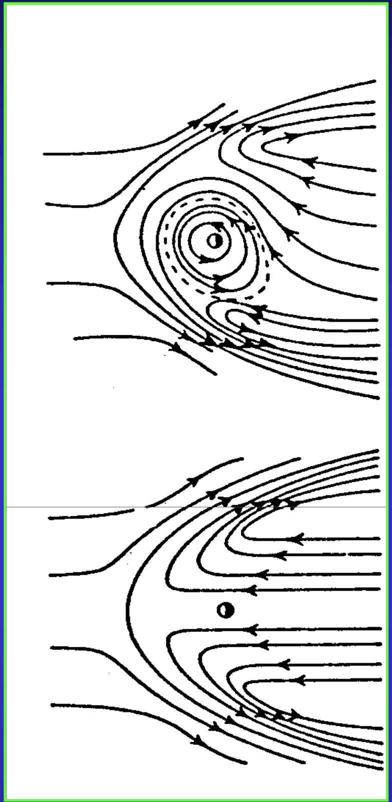
Jupiter's magnetosphere

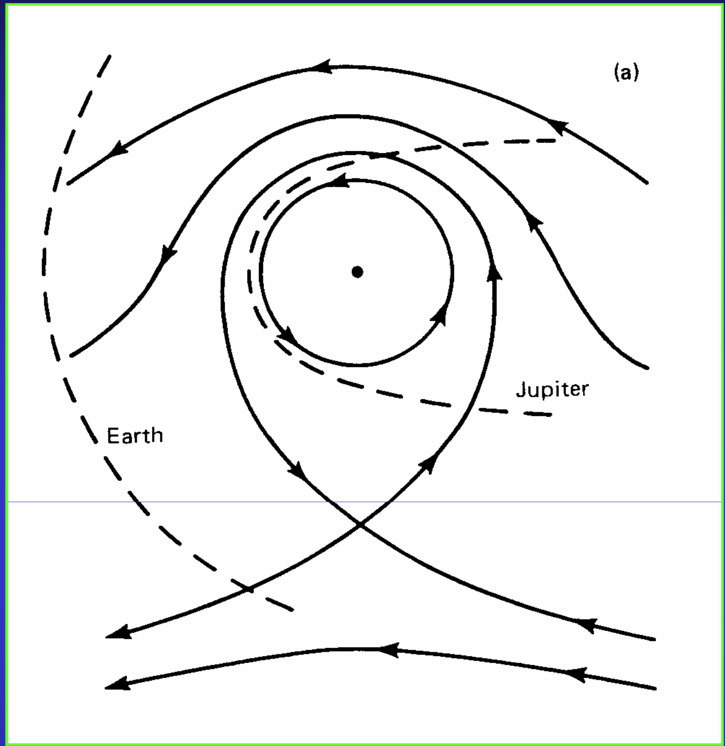


Io produces 1 ton/s material
Tranported into the magnetosphere


JUPITER
R_{BS}~1.2 R_M
Disk (rather than spherical) obstacle
Magnetosheath
Magnetopause
Bow shock
Current Sheet
Io plasma torus
Magnetotail
Solar wind
1,500,000
km/hr

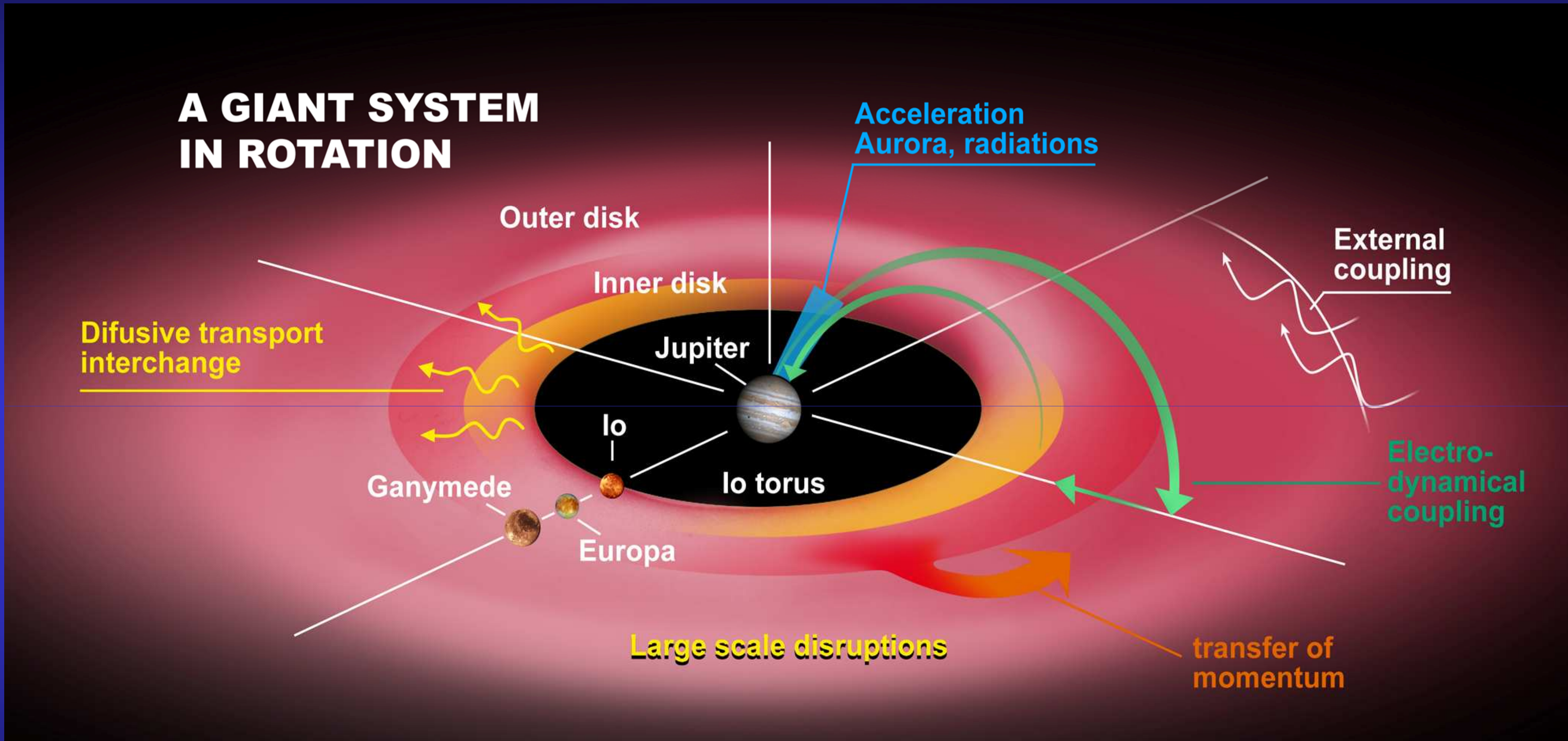
Earth's-like magnetosphere





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

Jupiter’s magnetosphere



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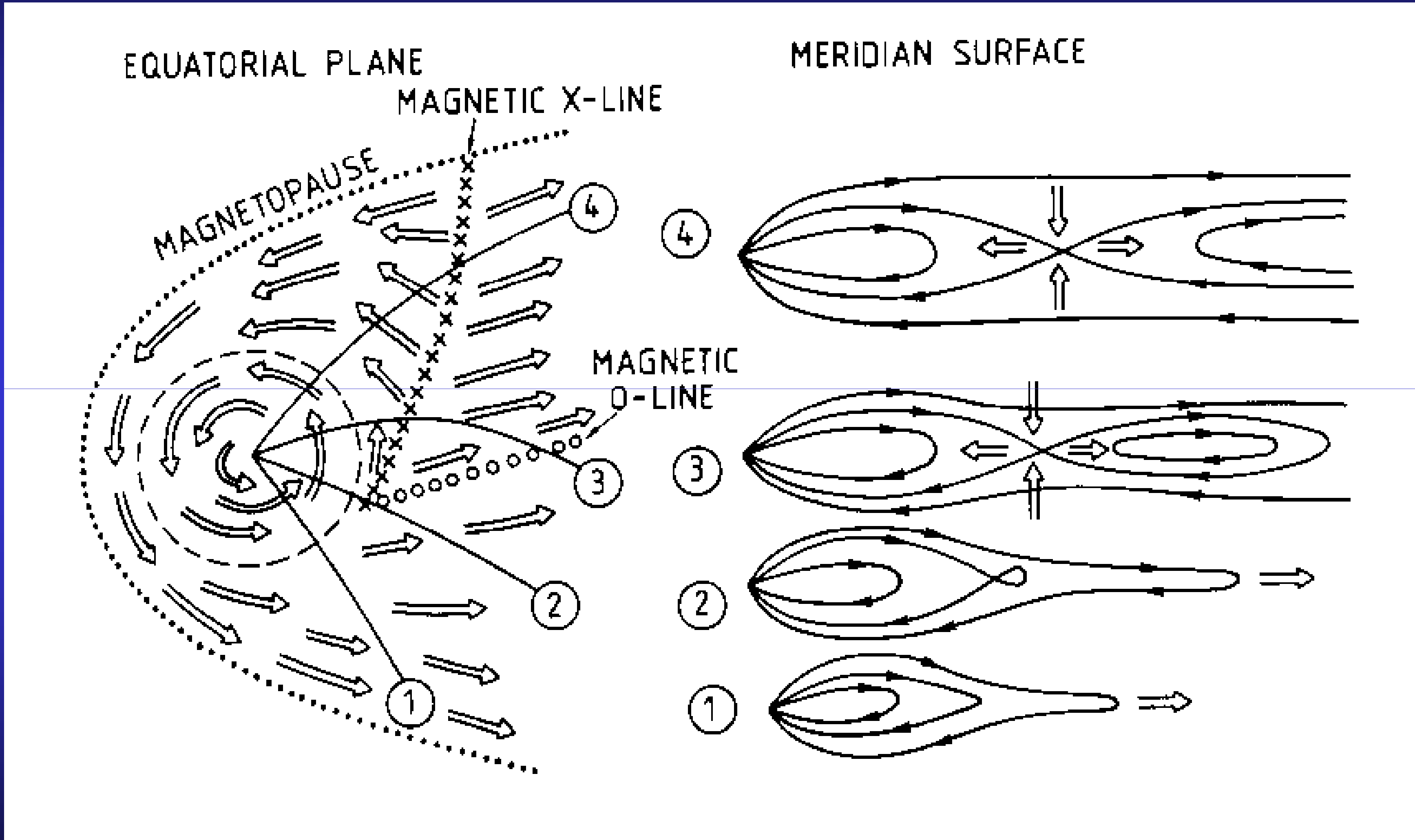
Sonnensystemforschung

Jupiter

Structure and dynamics of the outer magnetosphere



Vasyliunas 1983

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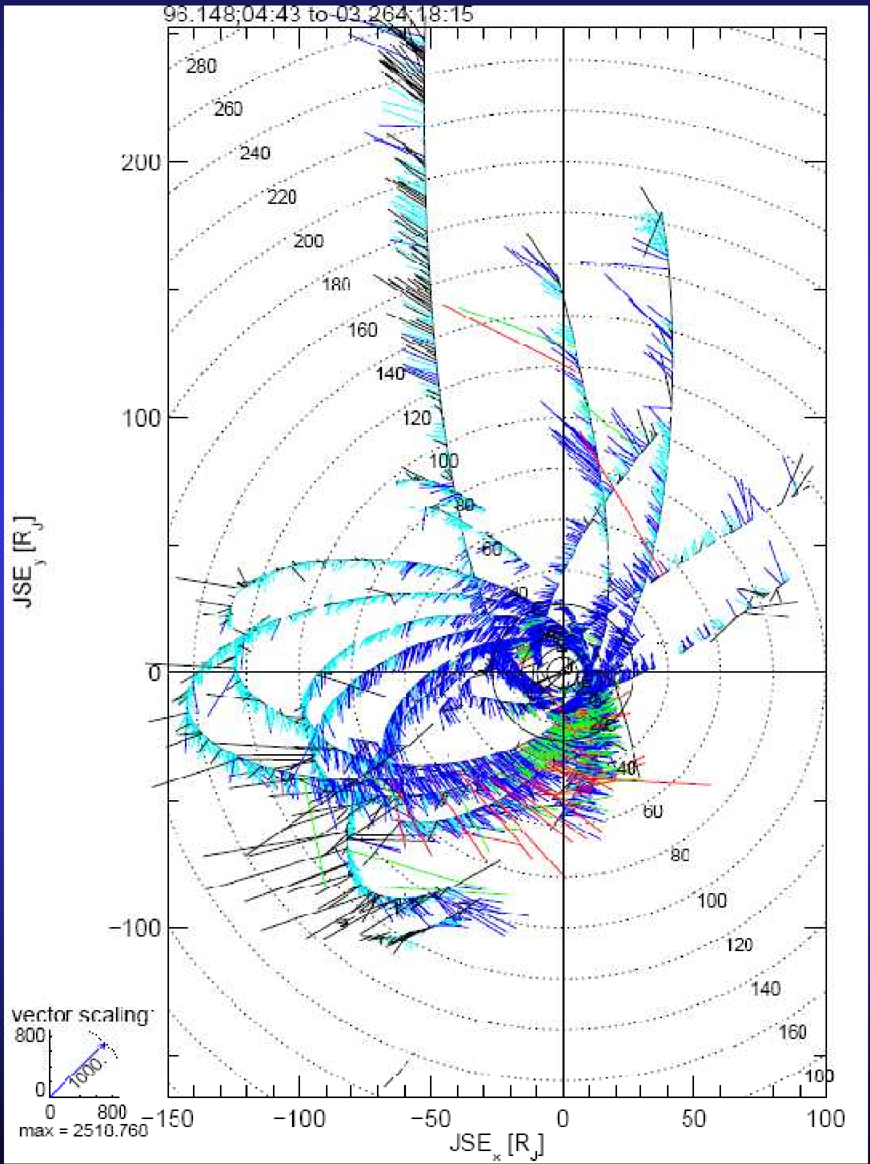
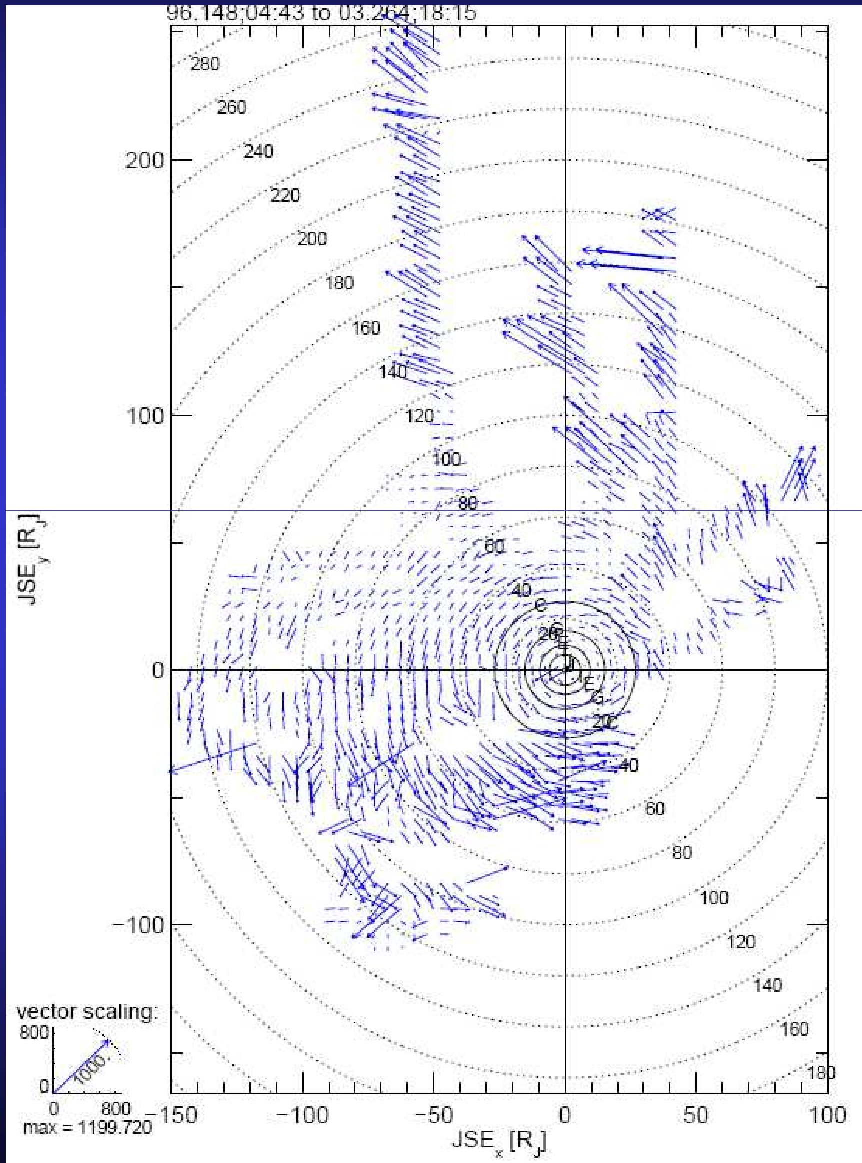
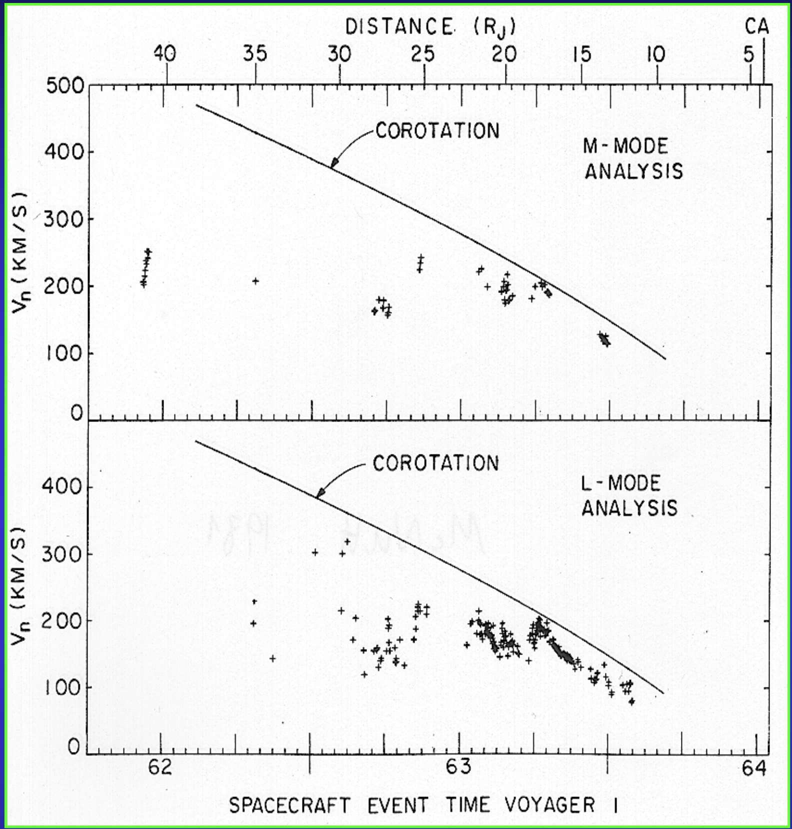
Jupiter: Global particle flow pattern in Jupiter's magnetosphere

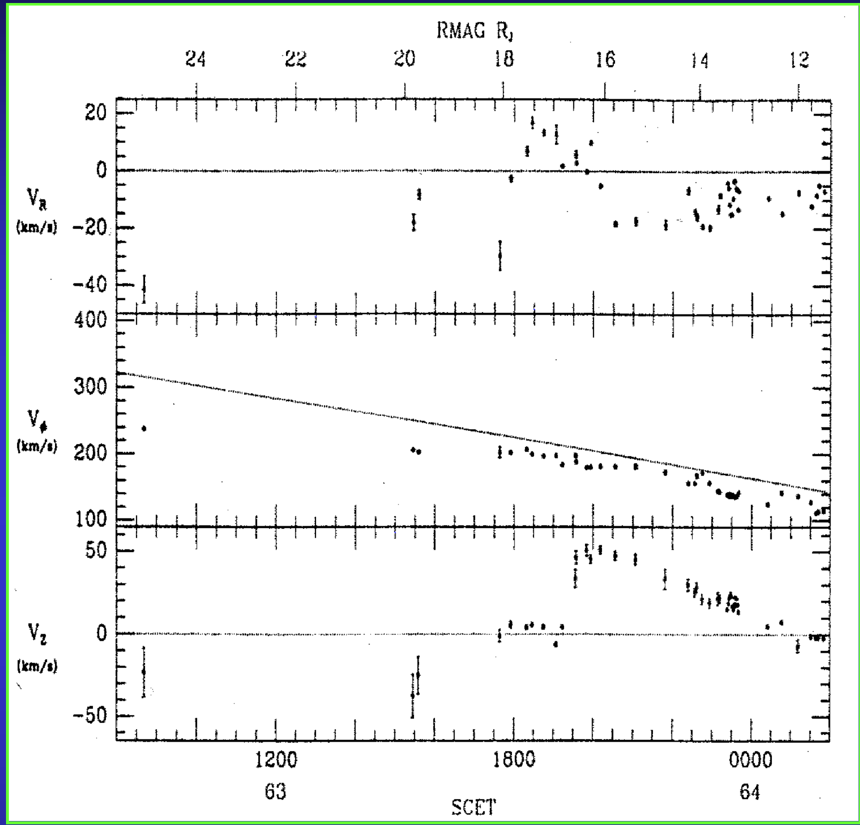
Galileo/EPD measurements in the equatorial plane





Flow measurements in Jupiter’s magnetosphere

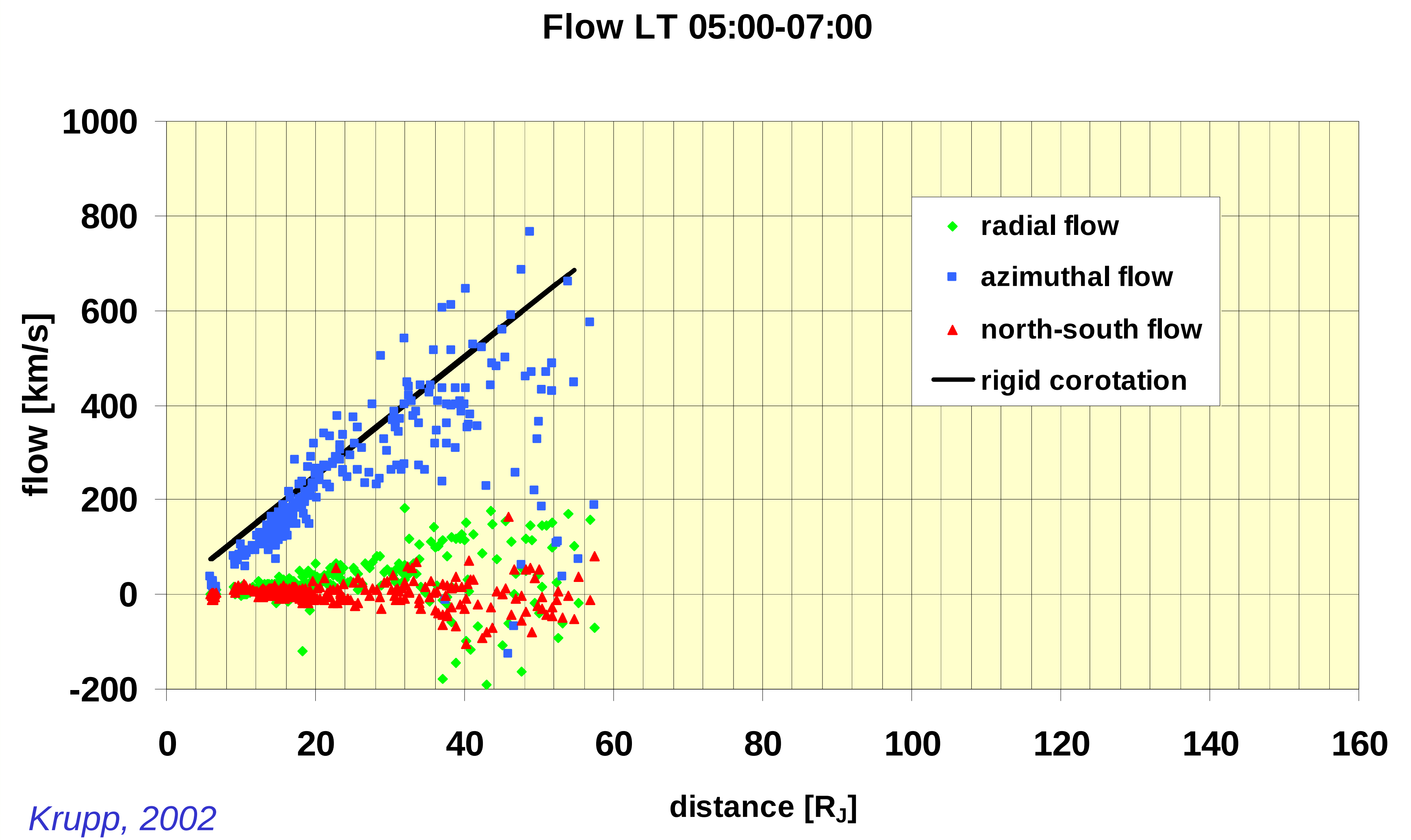




- Voyager 1 PLS results
  - McNutt et al., JGR, 86, 8319, 1981
  - Sands and McNutt, JGR, 93, 8502, 1988
- Velocity lags rigid corotation trend to “constant” velocity outside 20 RJ

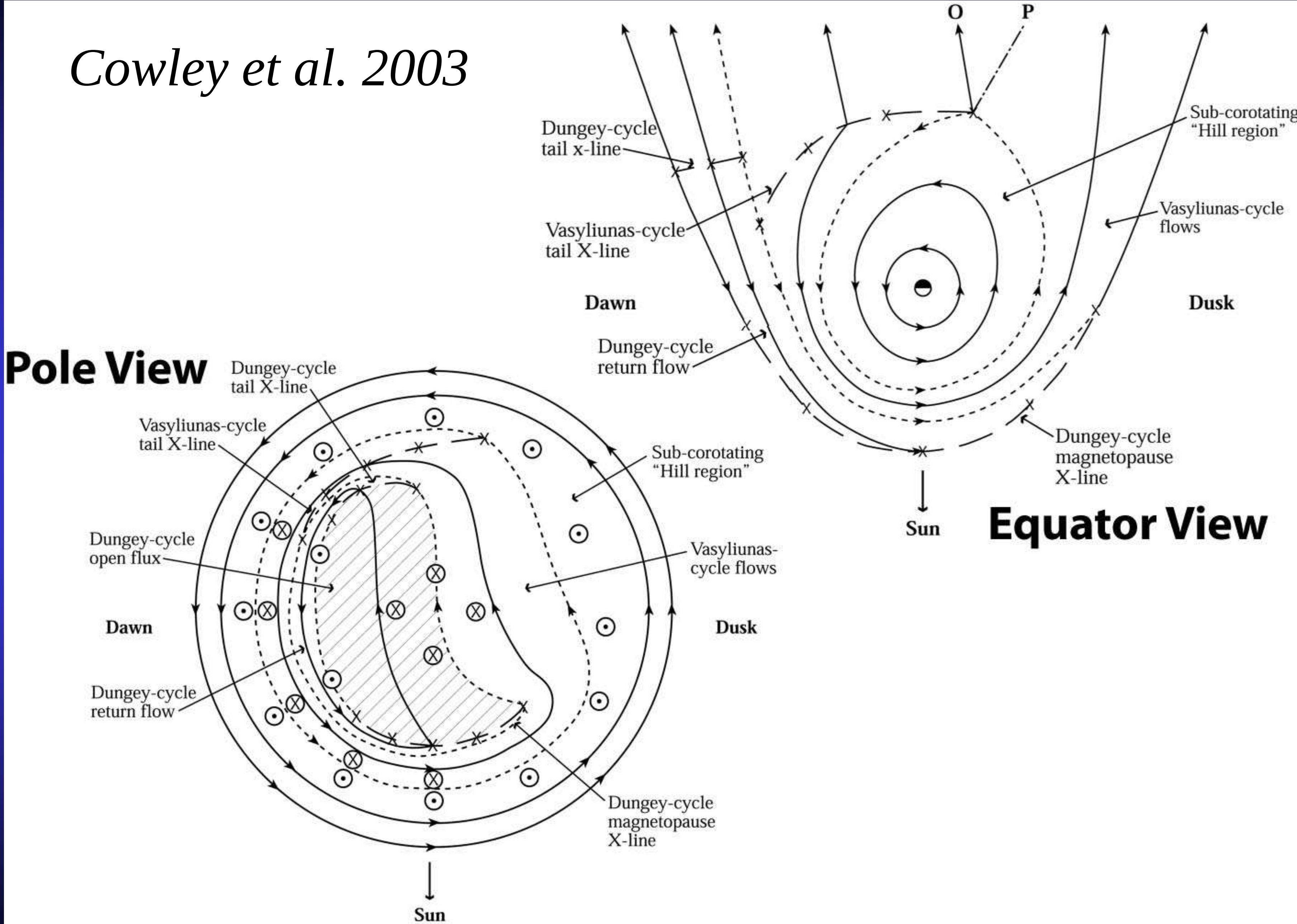
Global Flow Pattern in Jupiter's equatorial plane

strong local time asymmetry between dawn and dusk



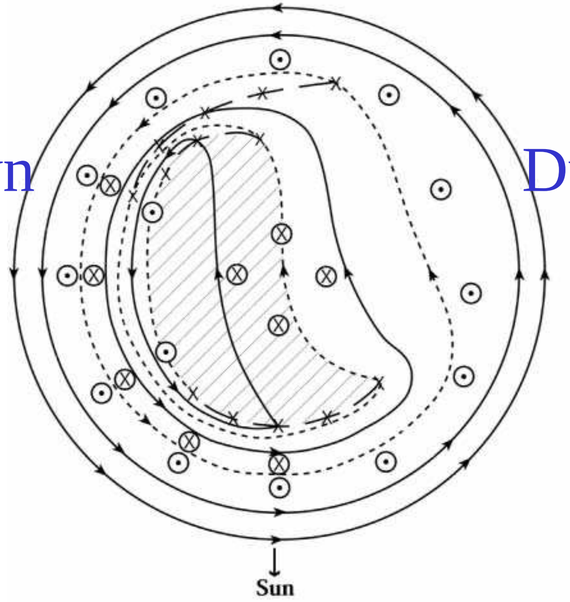
Krupp, 2002

Cowley et al. 2003



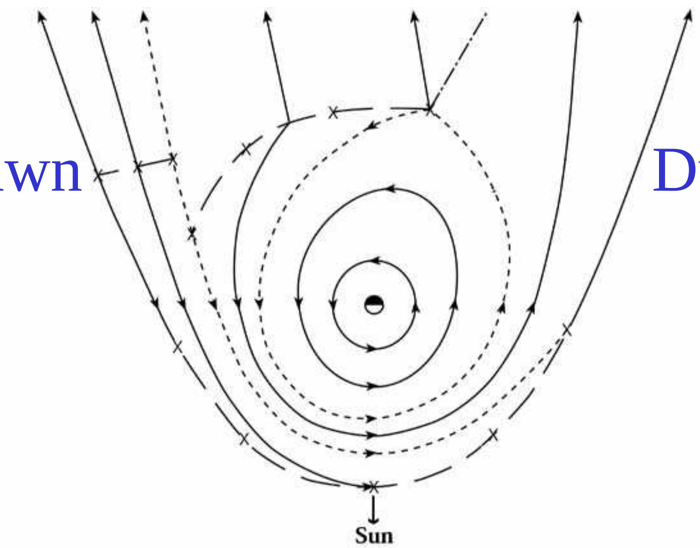
Polar View

Dawn



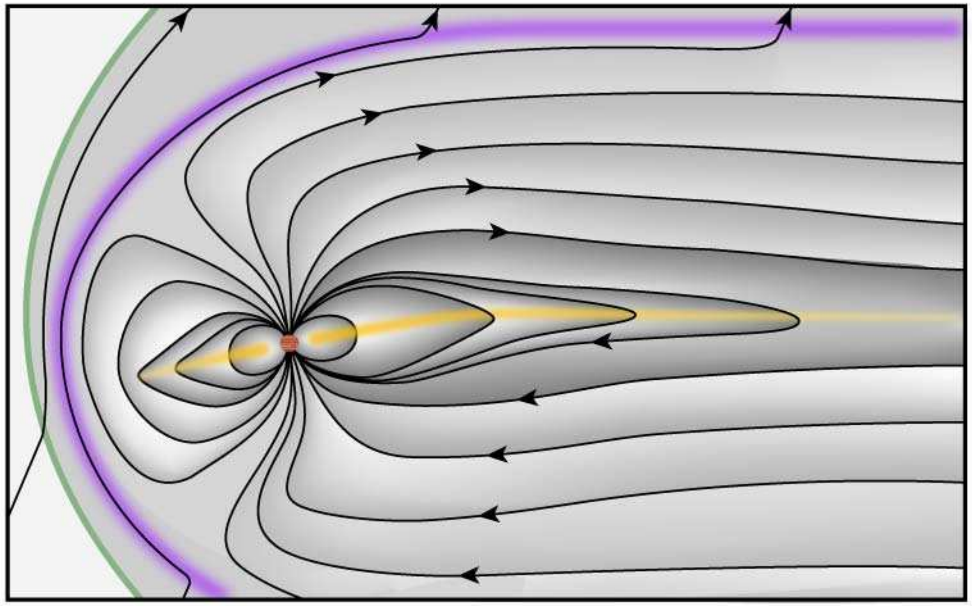
Dusk

Dawn



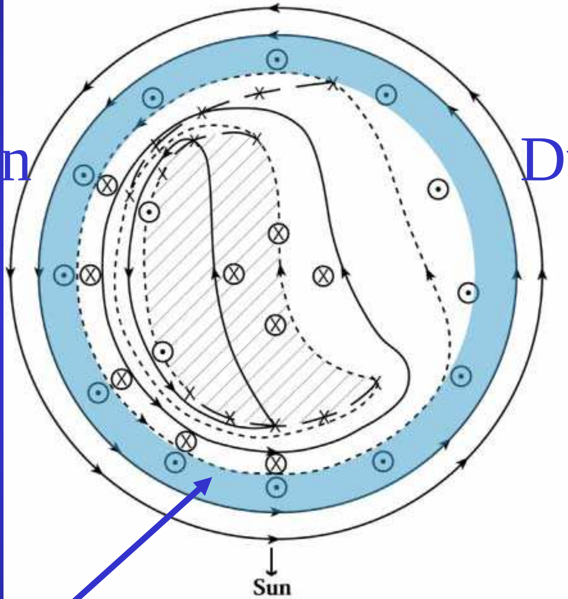
Equatorial View

Dusk



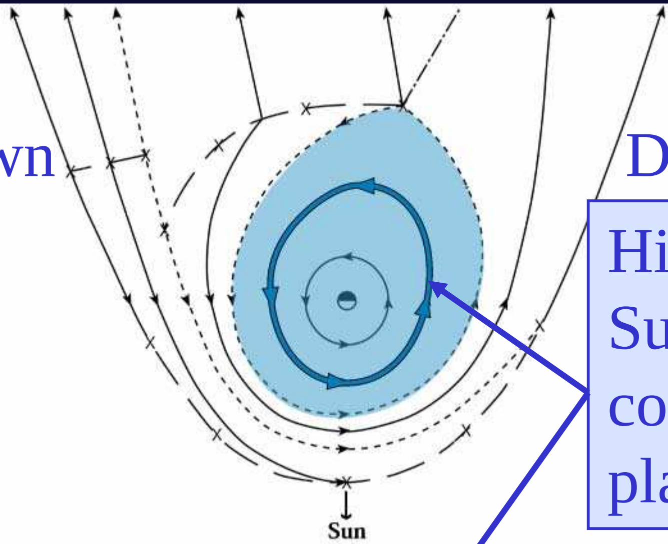
Side View

Polar View

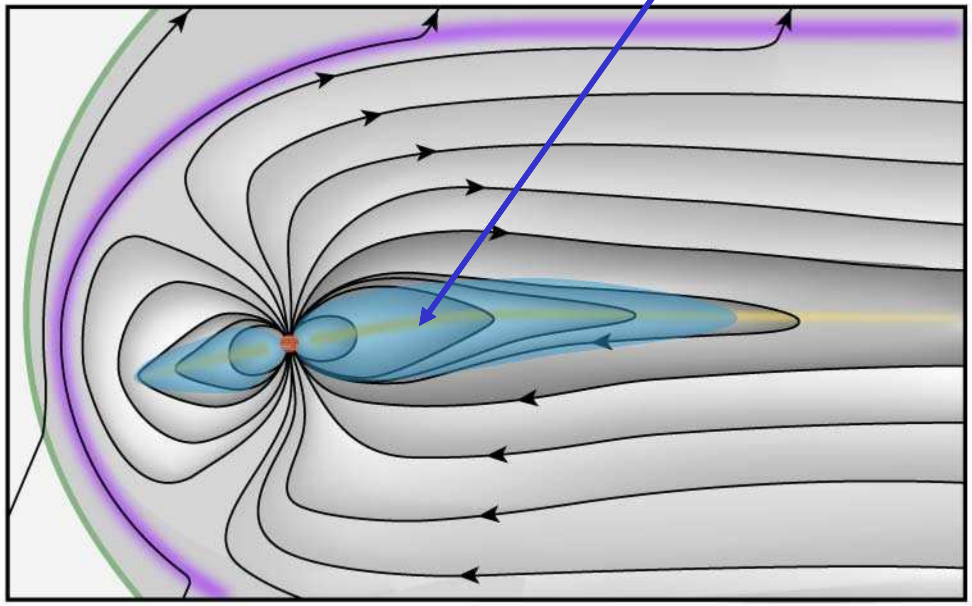


Main Auroral Oval

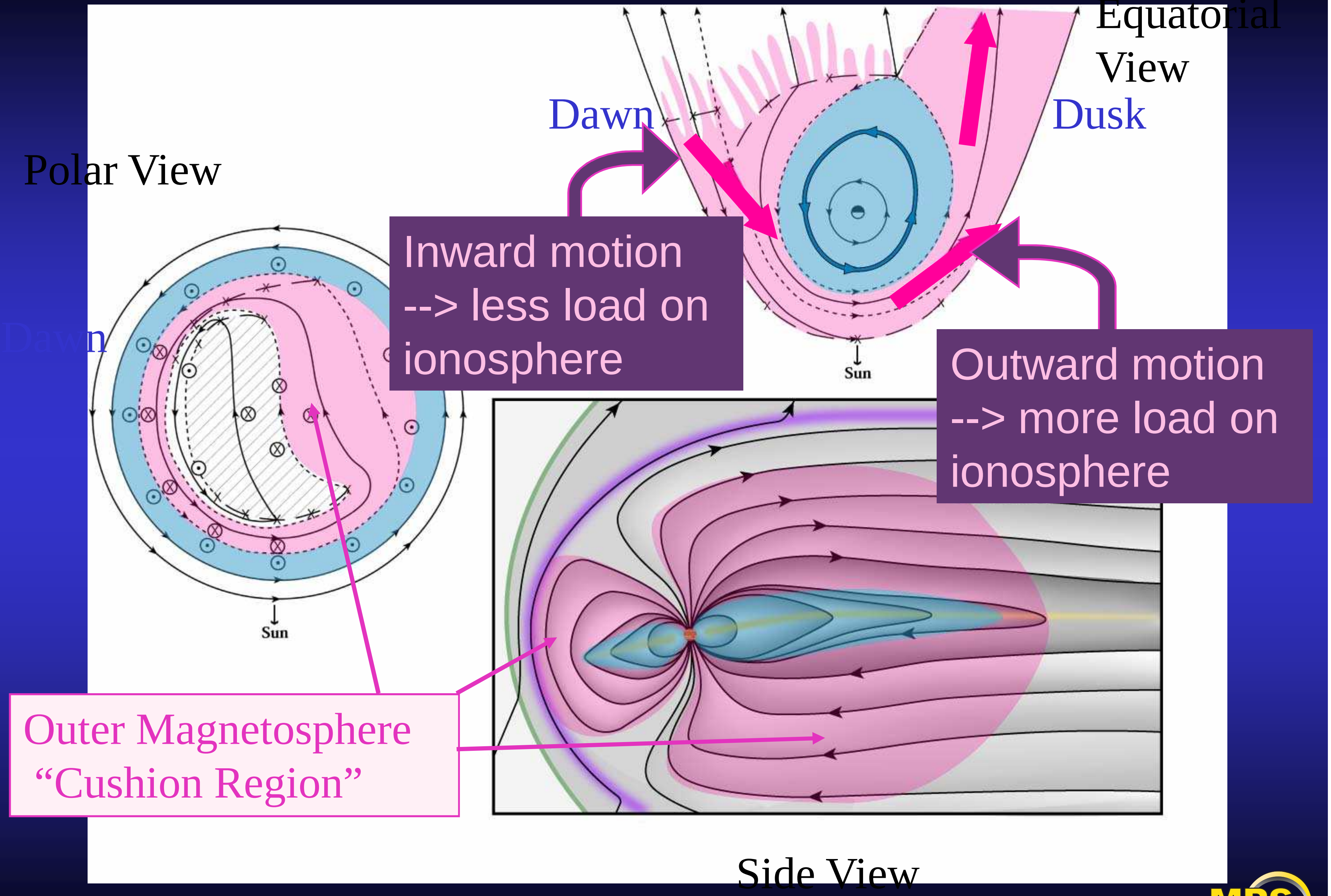
Equatorial View



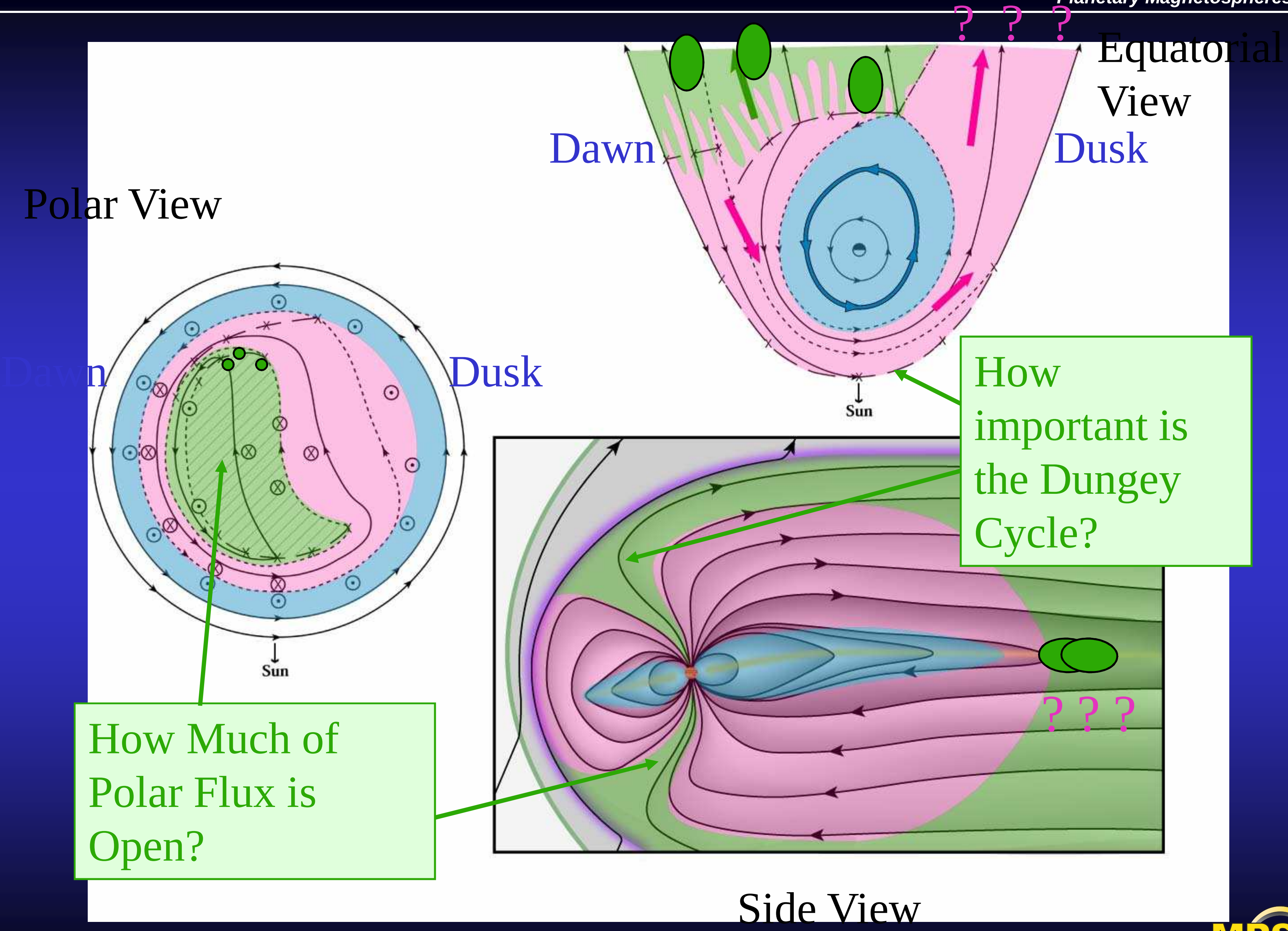
Hill Region Sub-corotating plasmasheet



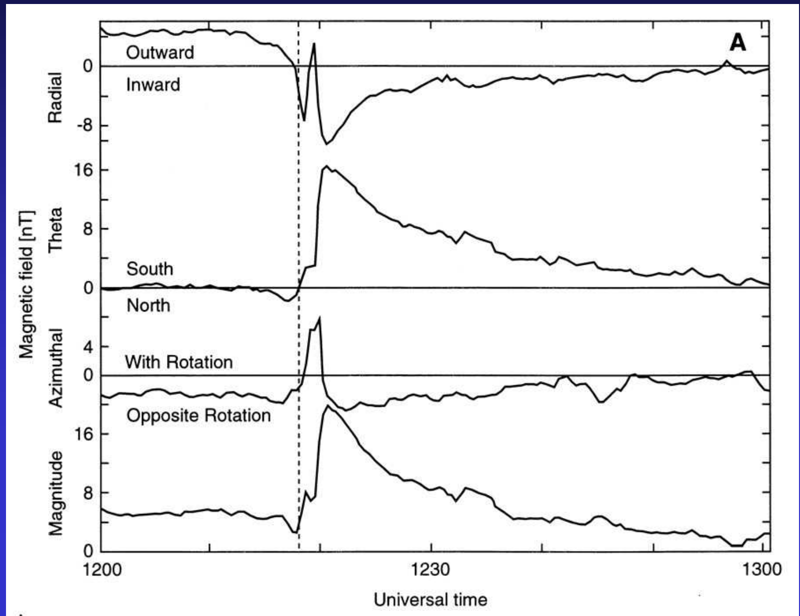
Side View

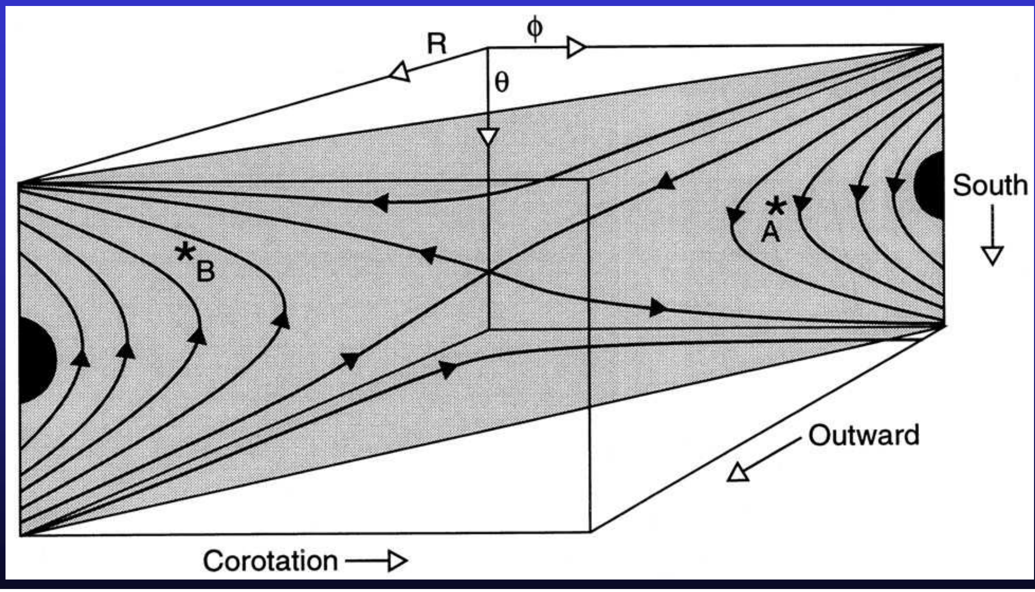


Equatorial View
Dawn
Dusk
Sun
Polar View
Dawn
Sun
Inward motion --> less load on ionosphere
Outward motion --> more load on ionosphere
Outer Magnetosphere "Cushion Region"
Side View


? ? ?
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

Are there substorms in Jupiter's m'sphere?





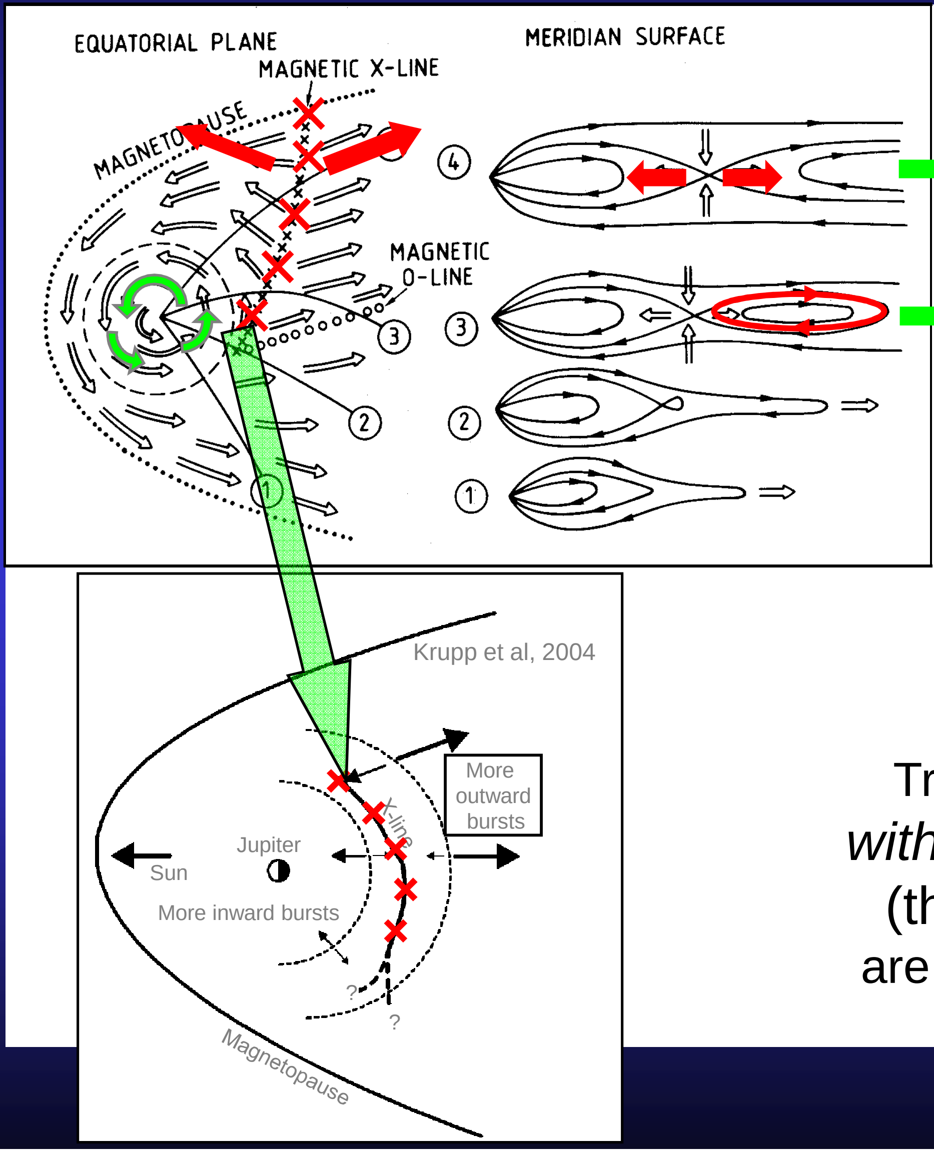
–**Russell [Adv. Space Res., 2000, 2002] provides evidence for reconnection in the magnetotail.**

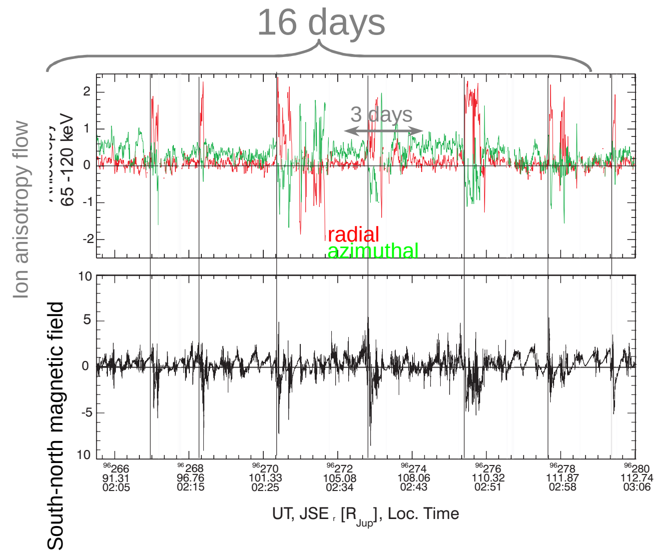
–**The enhanced southward field accompanied by Jupiter ward flows and enhanced northward field accompanied by tailward flow.**

–**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

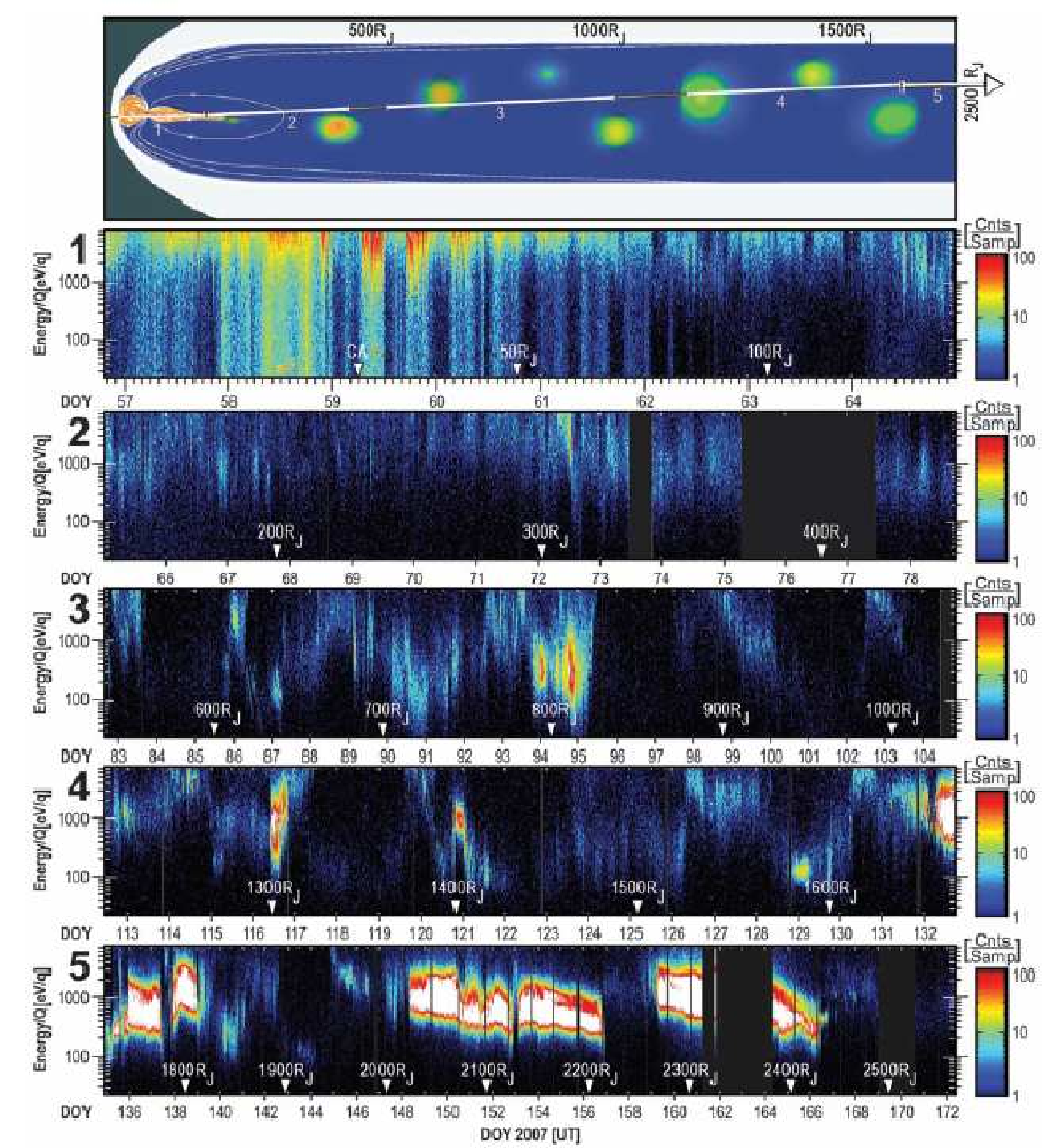




Location: 90-113 Rj

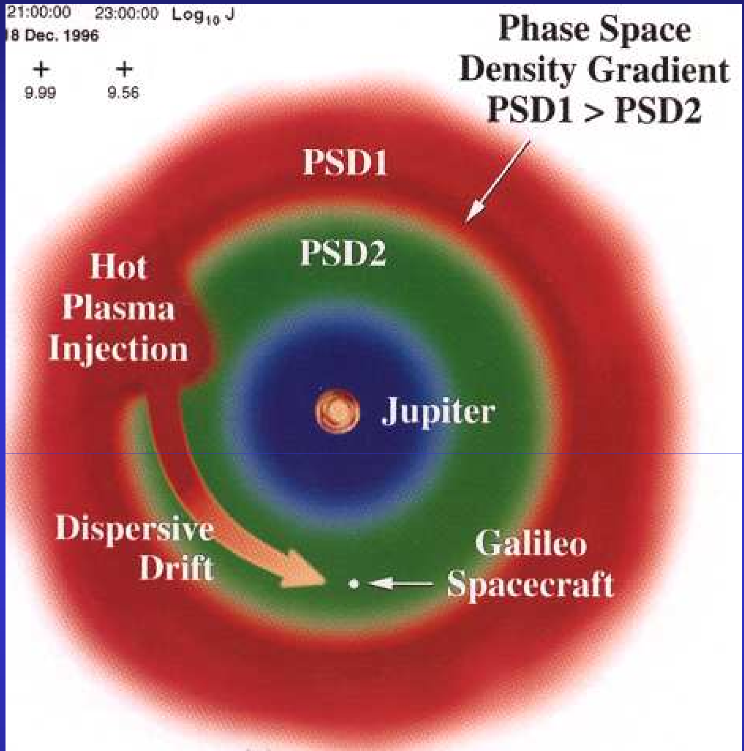
Transient *periodical disturbances*
with repetition period of several days
(the most characteristic 2-3 days)
are observed in the Jovian magnetotail!

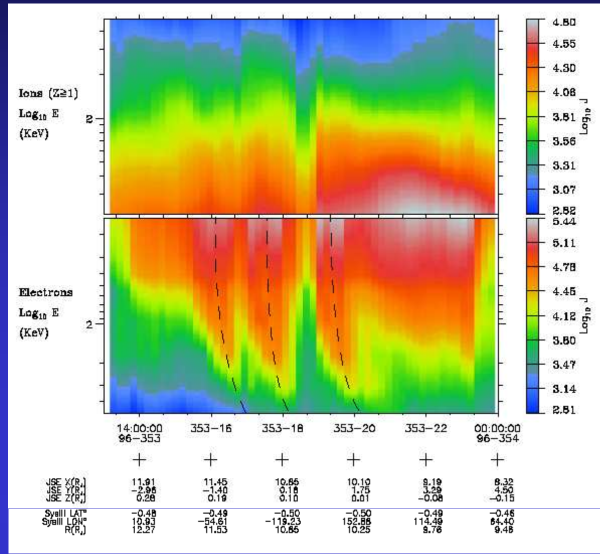
Jupiter: Particle observations in the deep Jovian magnetotail (New Horizons)

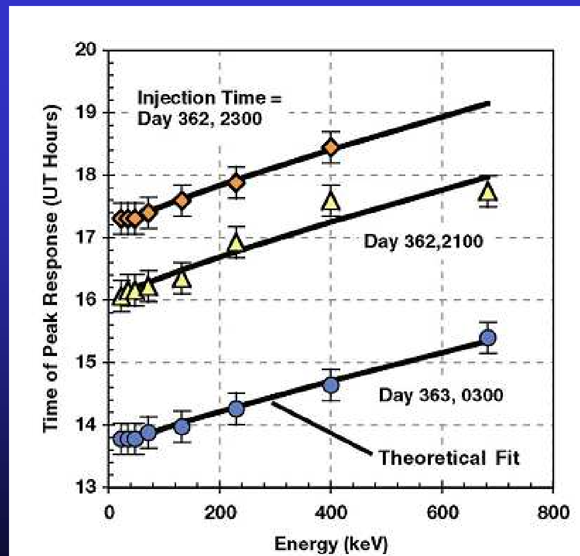


McComas, 2007

Dynamics in Jupiter's magnetosphere
Particle injections





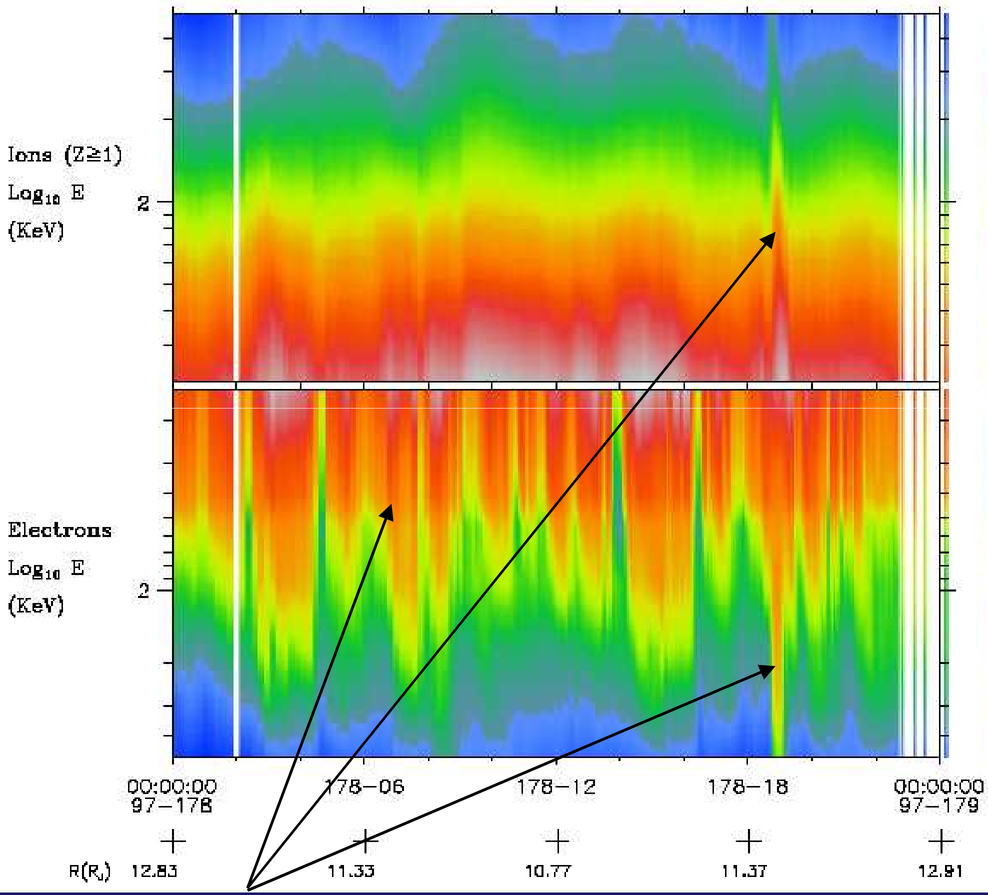


The behaviors of Jupiter magnetosphere injections were understood by invoking sudden radial injections over confined regions in azimuth followed by slow, dispersive, azimuthal drifts.

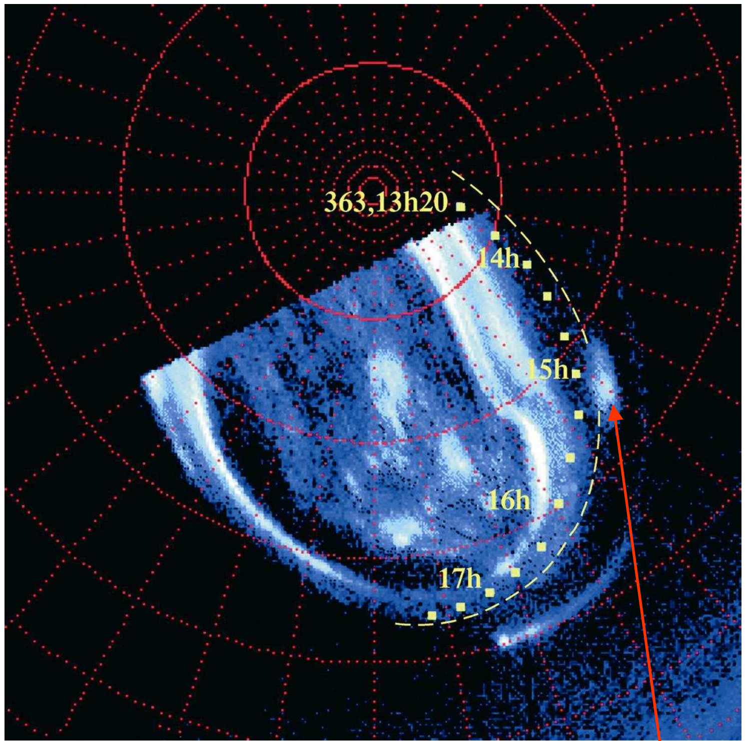
Dynamics in Jupiter's magnetosphere

Energetic Particle Injections & correlation to auroral emissions

24 hour Galileo Energetic Particle Spectrogram



HST Image of Jupiter's UV aurora

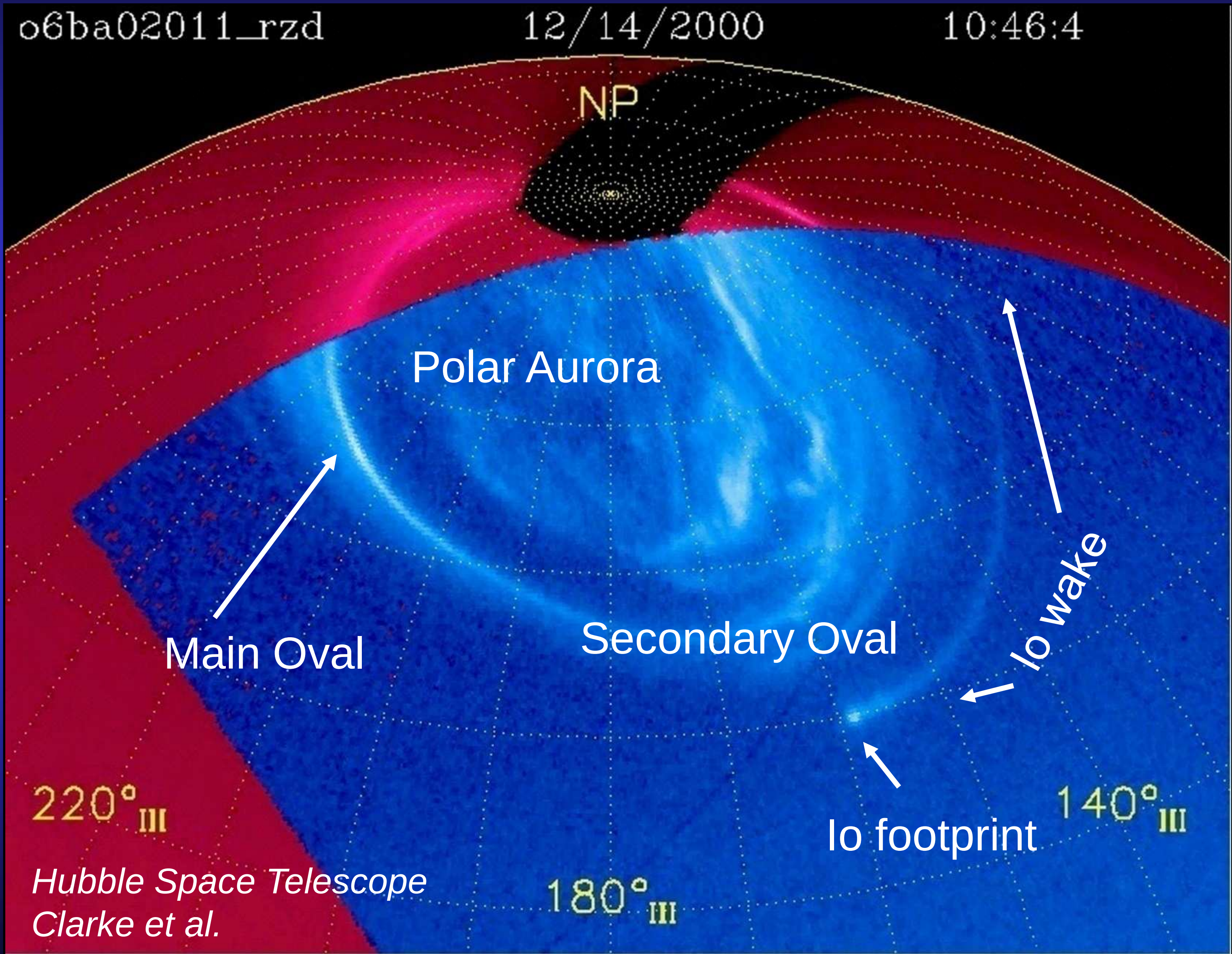


Mauk et al., 1997; 1999, 2000

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

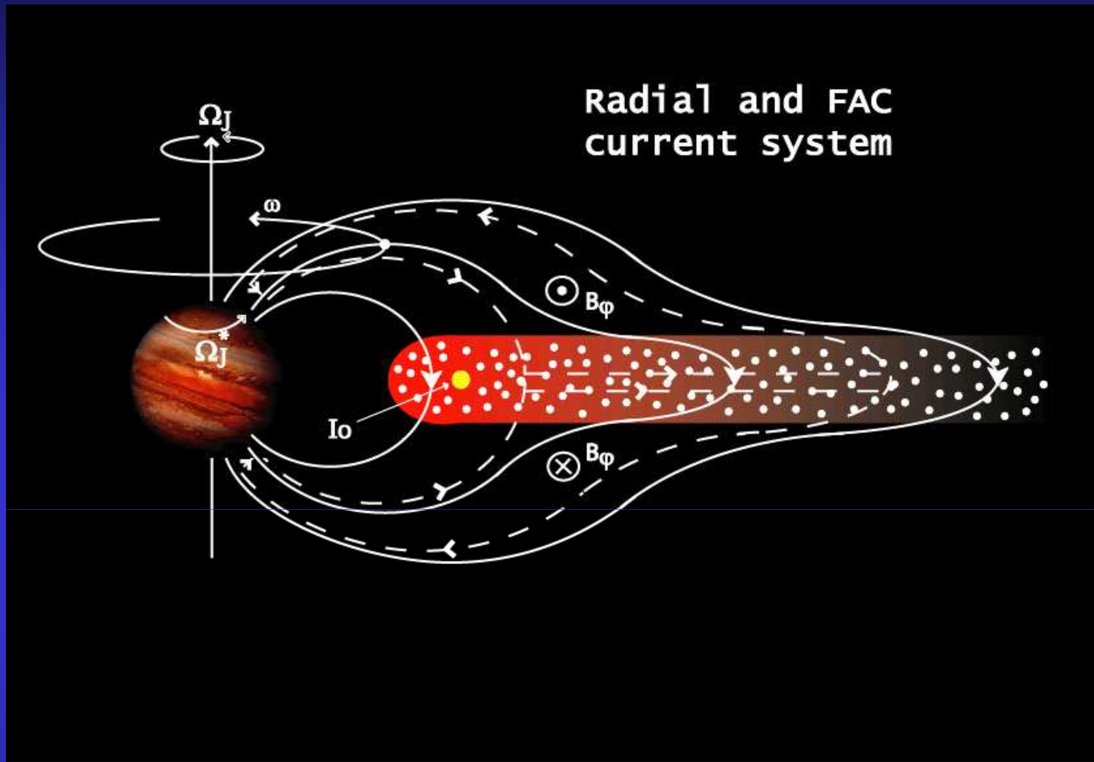
Auroral manifestation of near-Europa storm dynamics

Jupiter
Different types of aurora



Hubble Space Telescope
Clarke et al.

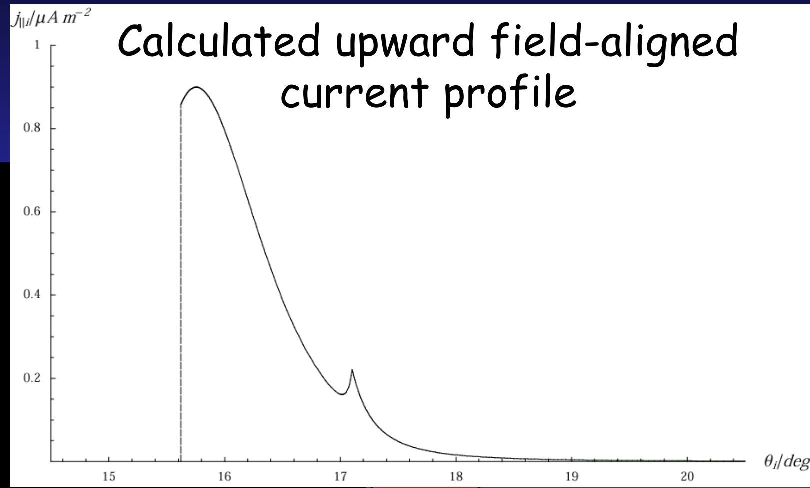
Large-scale current system in the Jovian magnetosphere

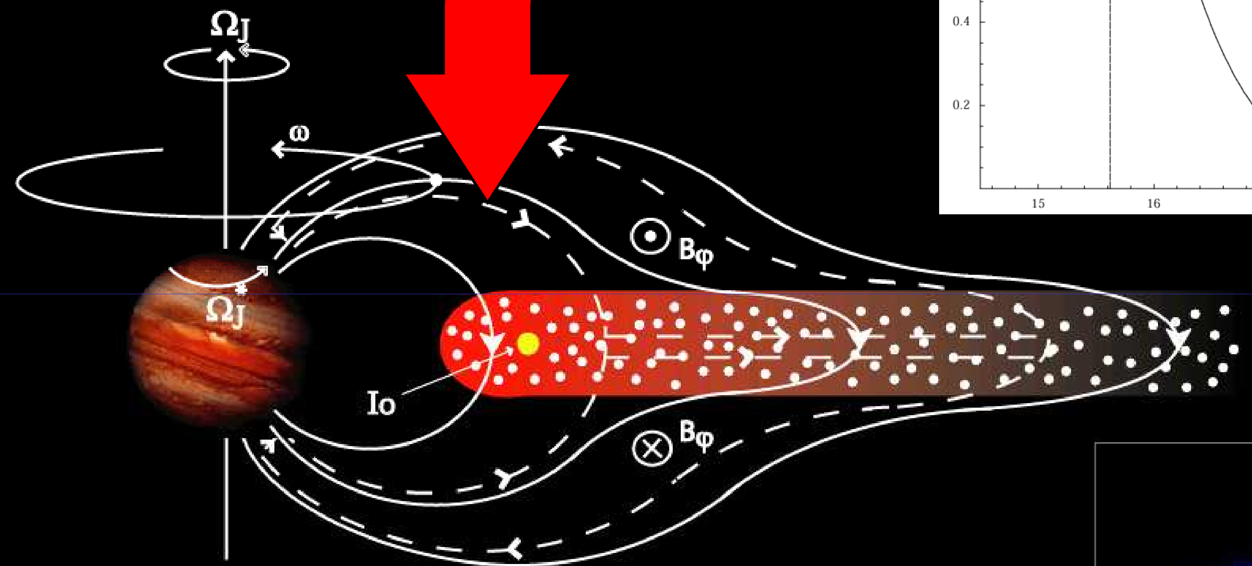


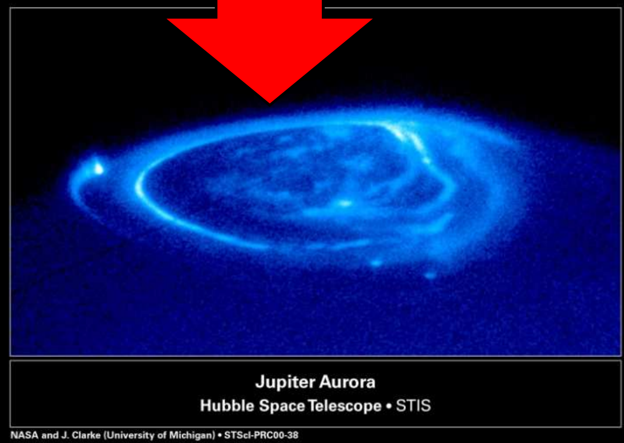
After Hill (1979)
and Vasyliunas (1983)

- 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 ~1μAm-2 (Bunce and Cowley, 2001b; Khurana, 2001)

Origin of the Jovian main aurora

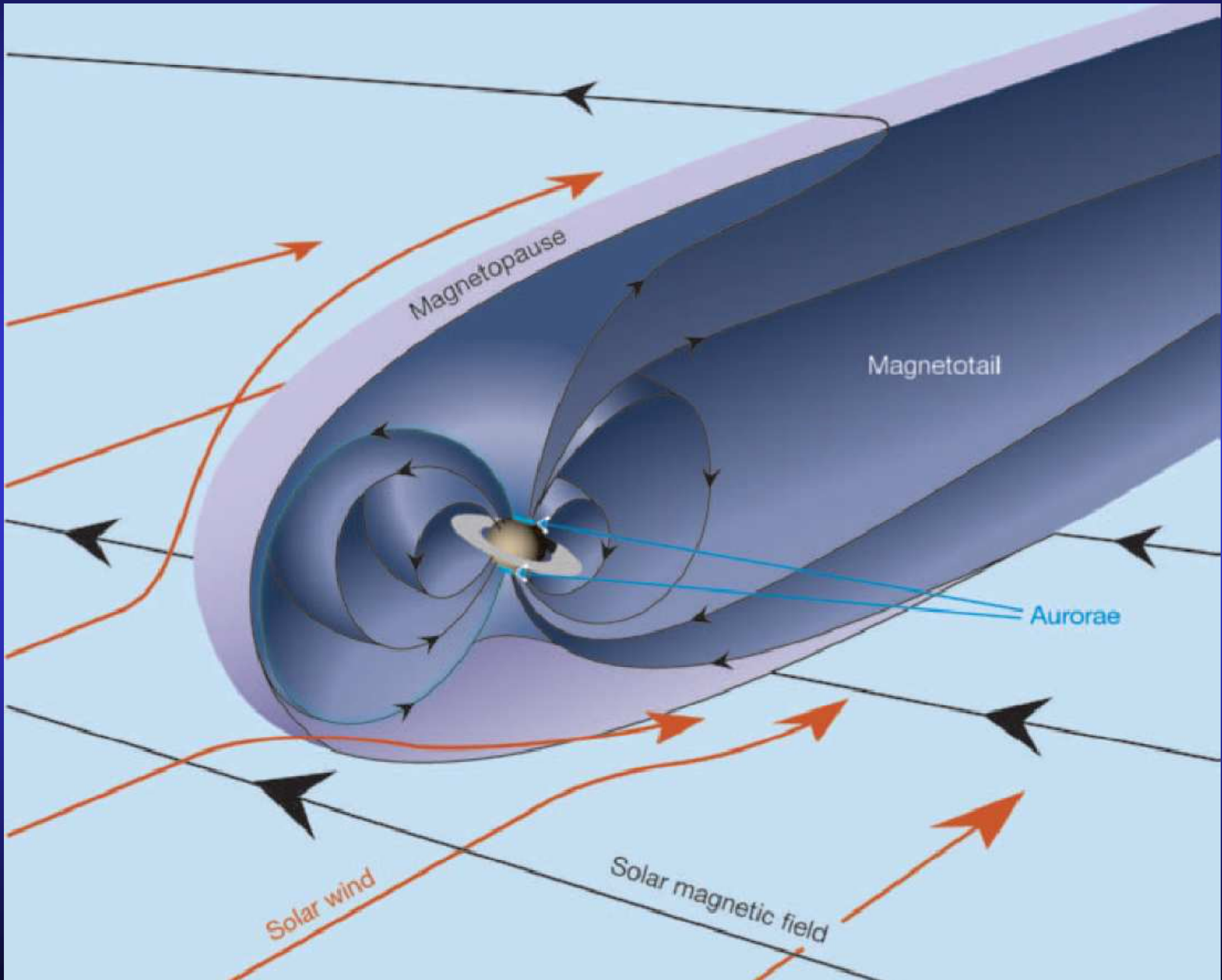






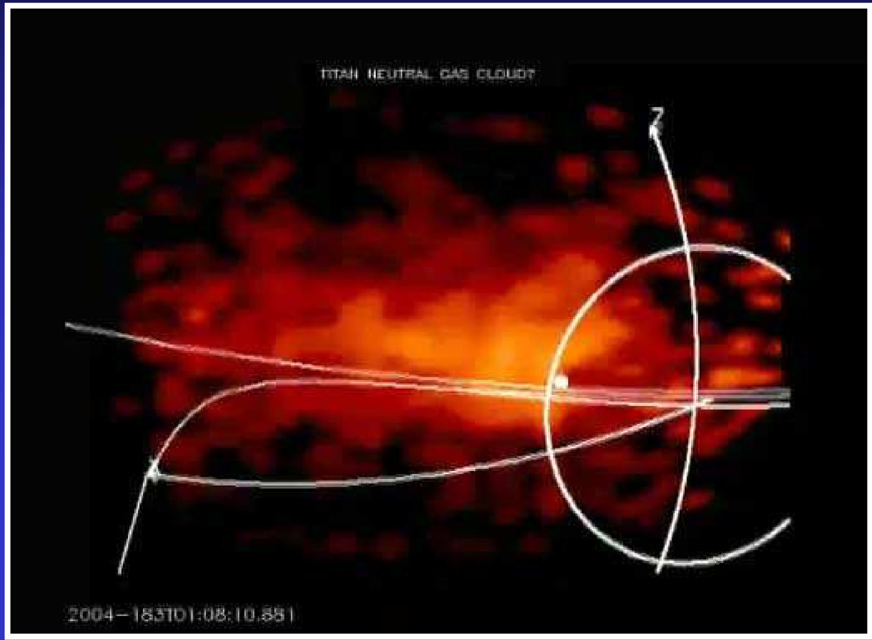
- Bunce and Cowley (2001b), Cowley and Bunce (2001), Hill (2001) and Southwood and Kivelson (2001) suggest the main auroral oval is due to the breakdown of corotation of the equatorial plasma
- Modulation of the oval in anti-correlation with solar wind dynamic pressure (C&B, 2001, 2003a&b; S&K, 2001)

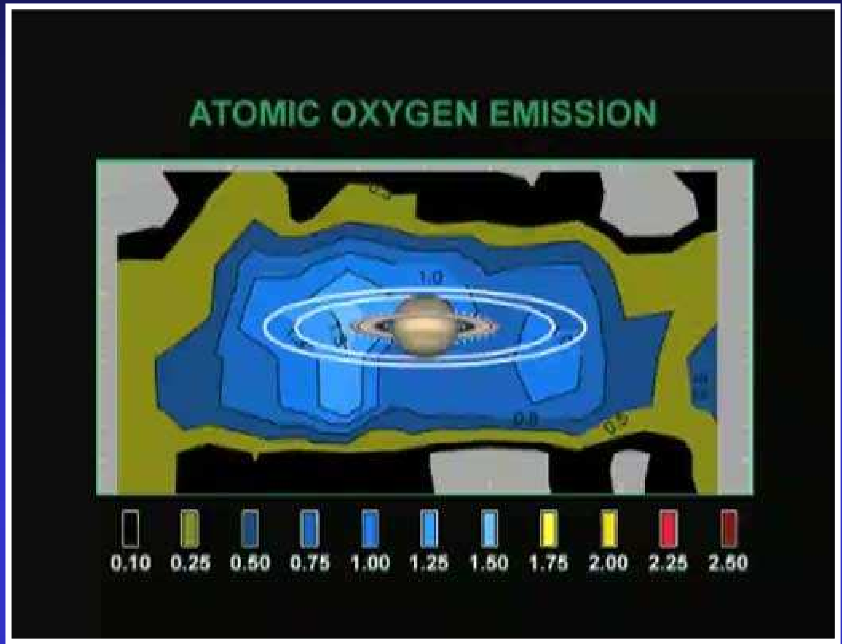
Saturn:
Mixed magnetosphere



Bagenal, Nature 2005

Saturn's magnetosphere
Cassini results

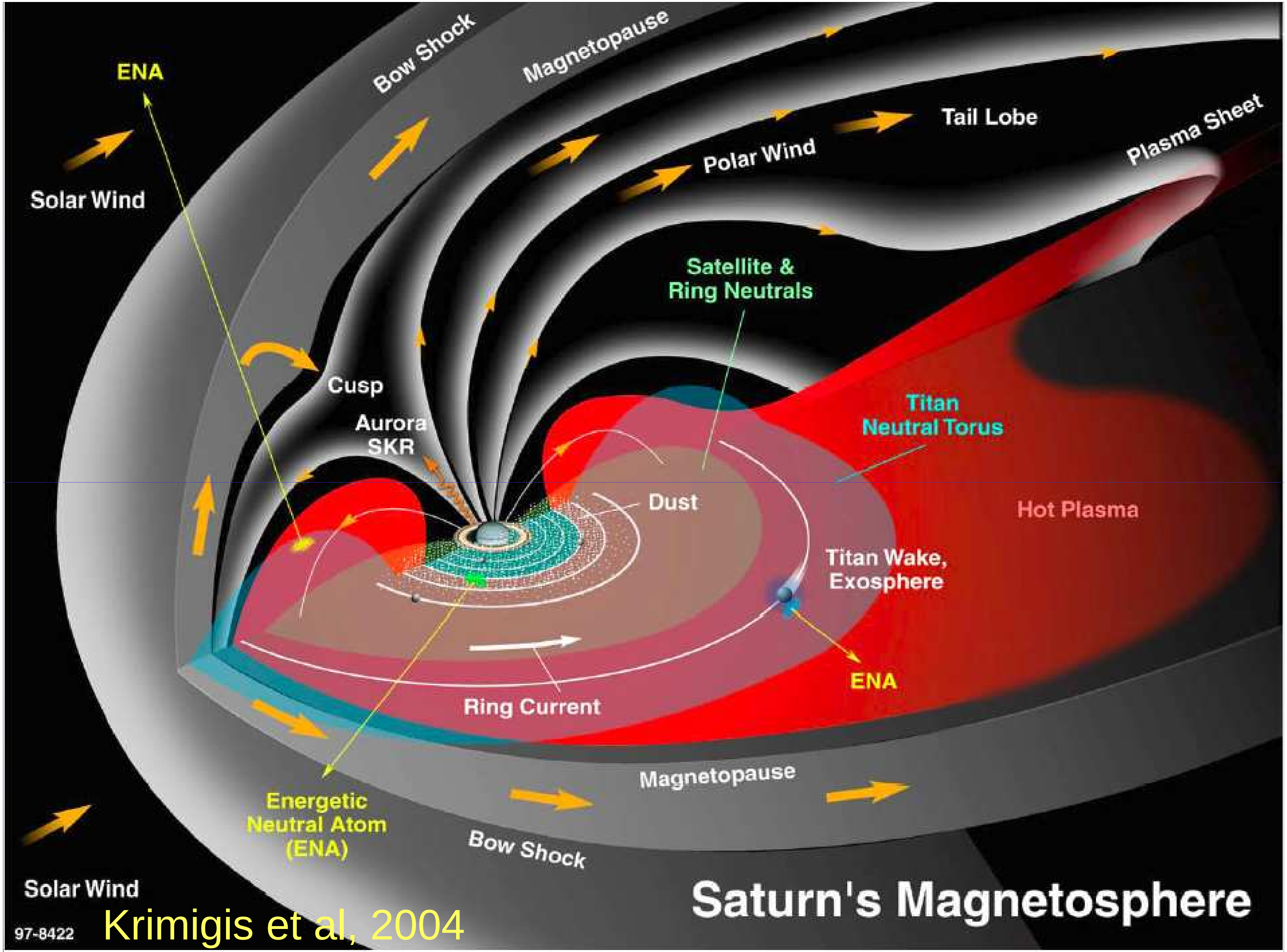




Hot neutral gas emissions:
MIMI/INCA measurements

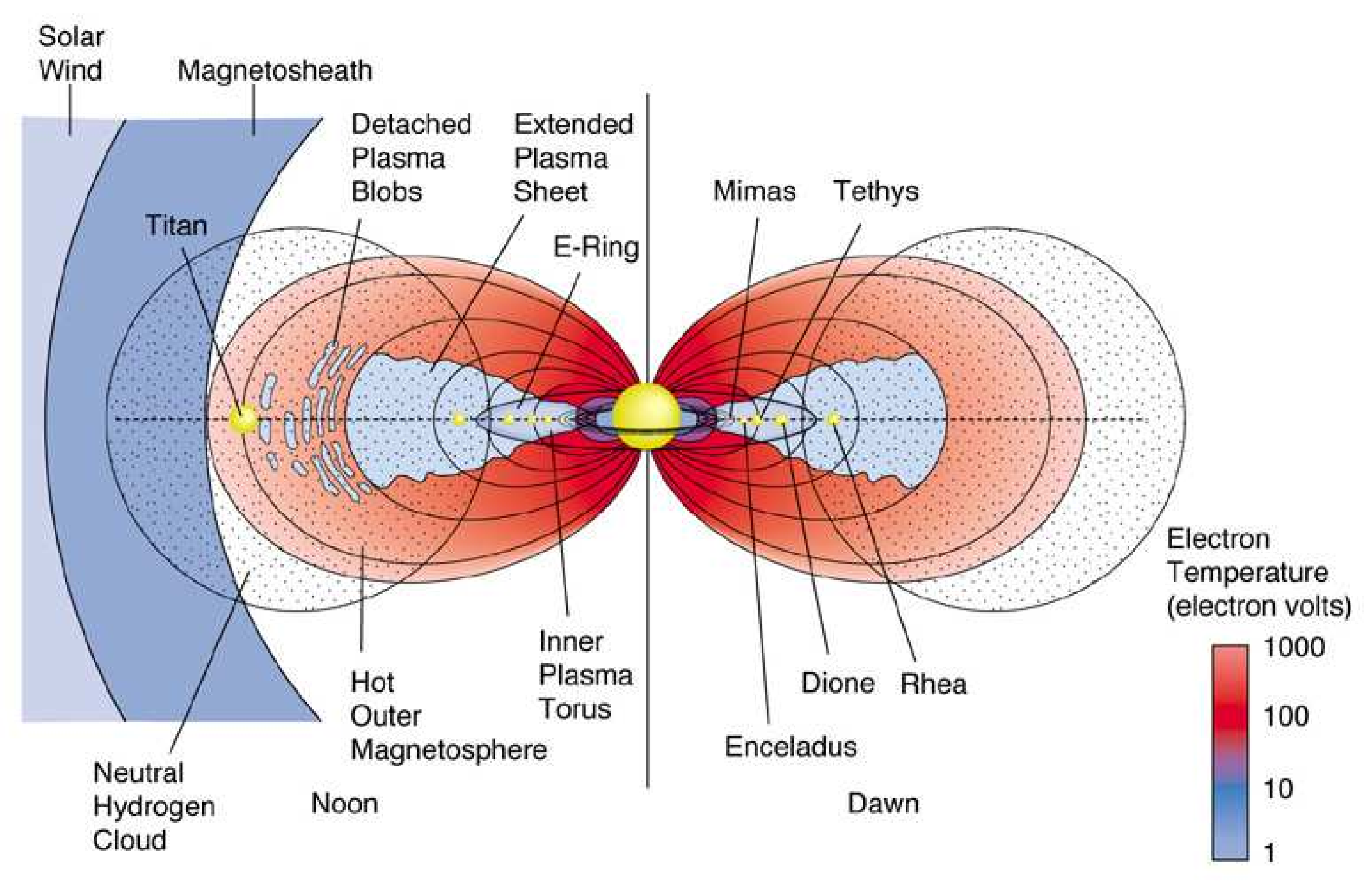
cold neutral gas:
UVIS measurements

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



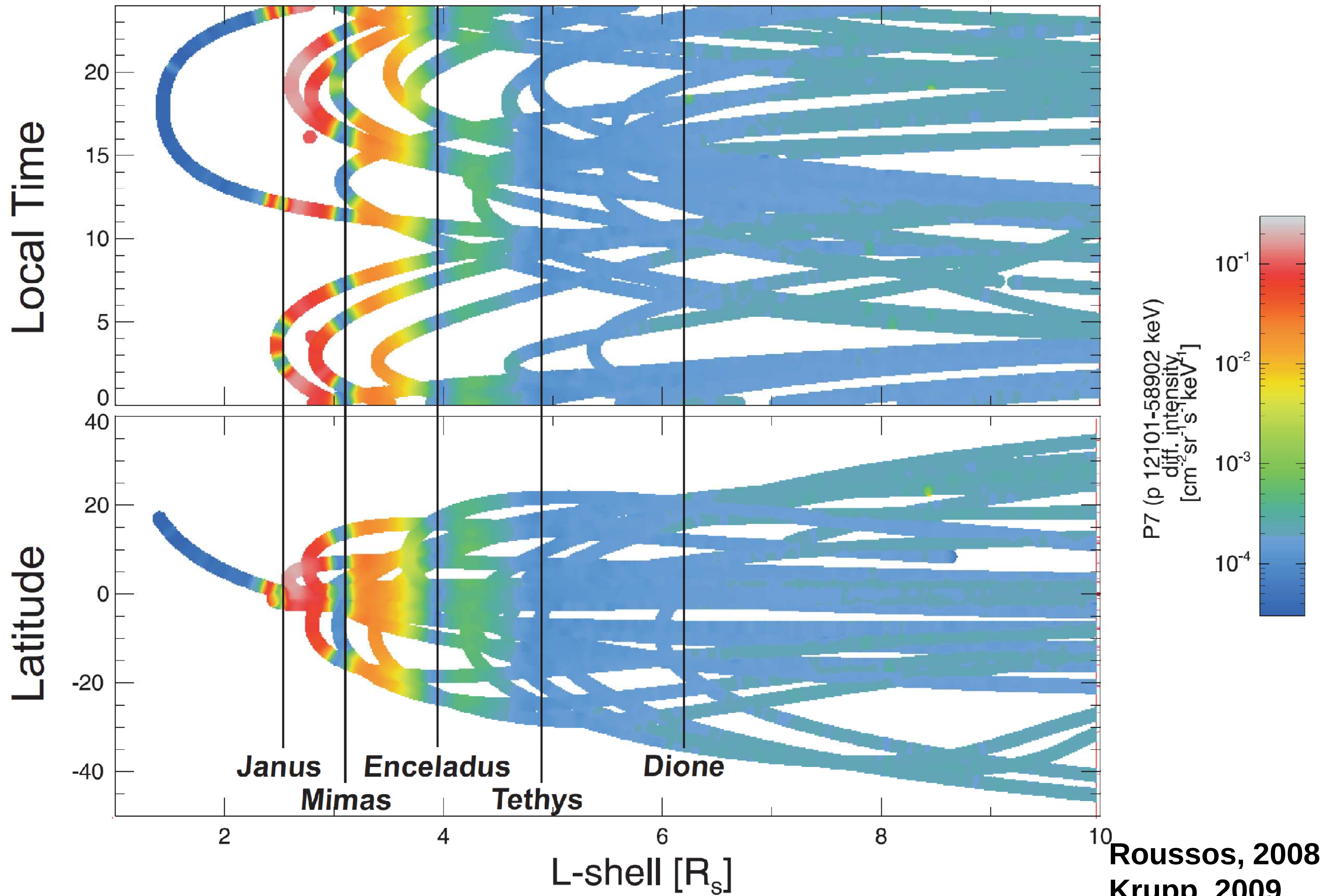
Krimigis et al, 2004

Plasma regions and sources at Saturn



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

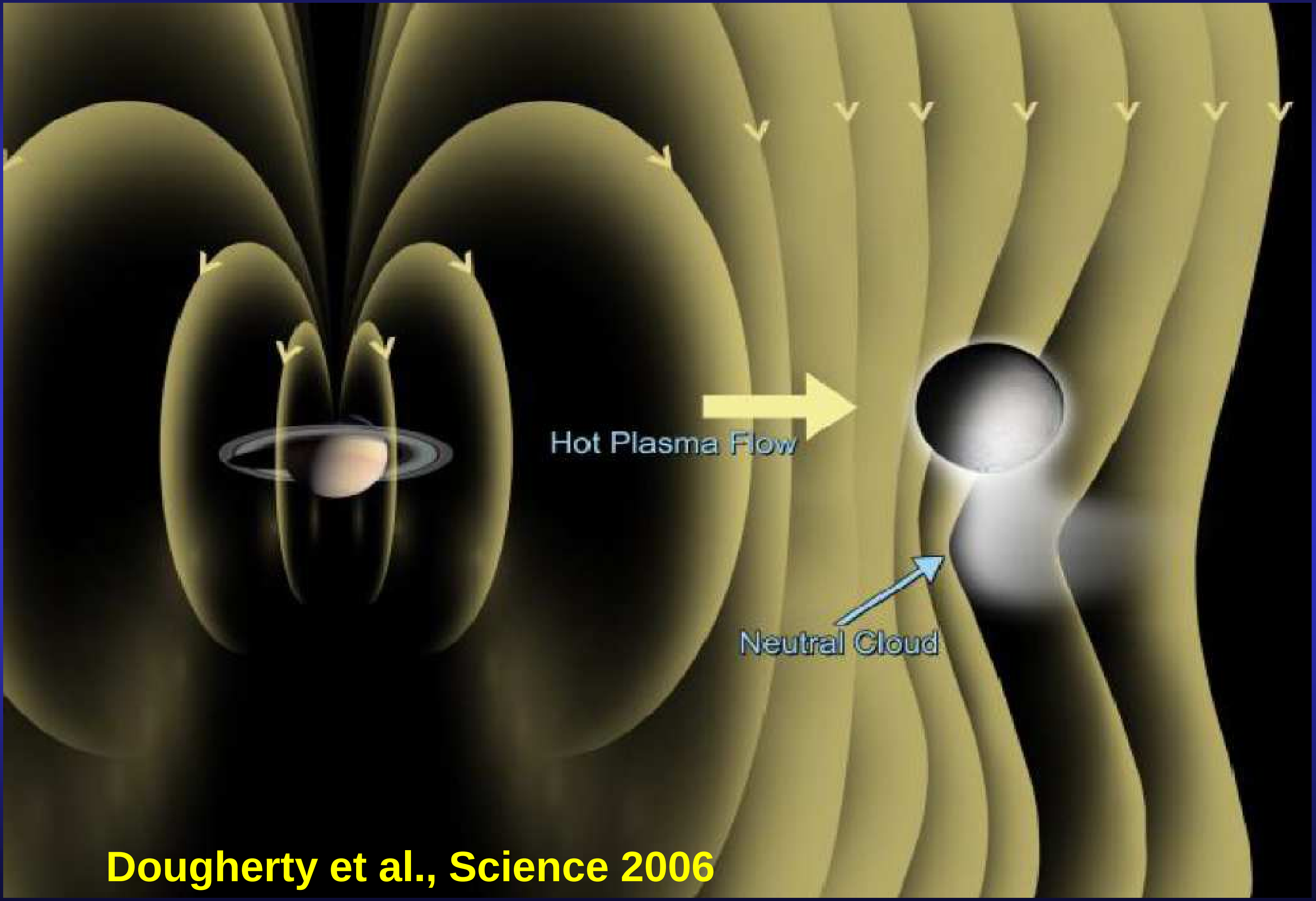
Saturn: Macrosignatures in the energetic particle intensities from moons



Roussos, 2008
Krupp, 2009

Saturn:

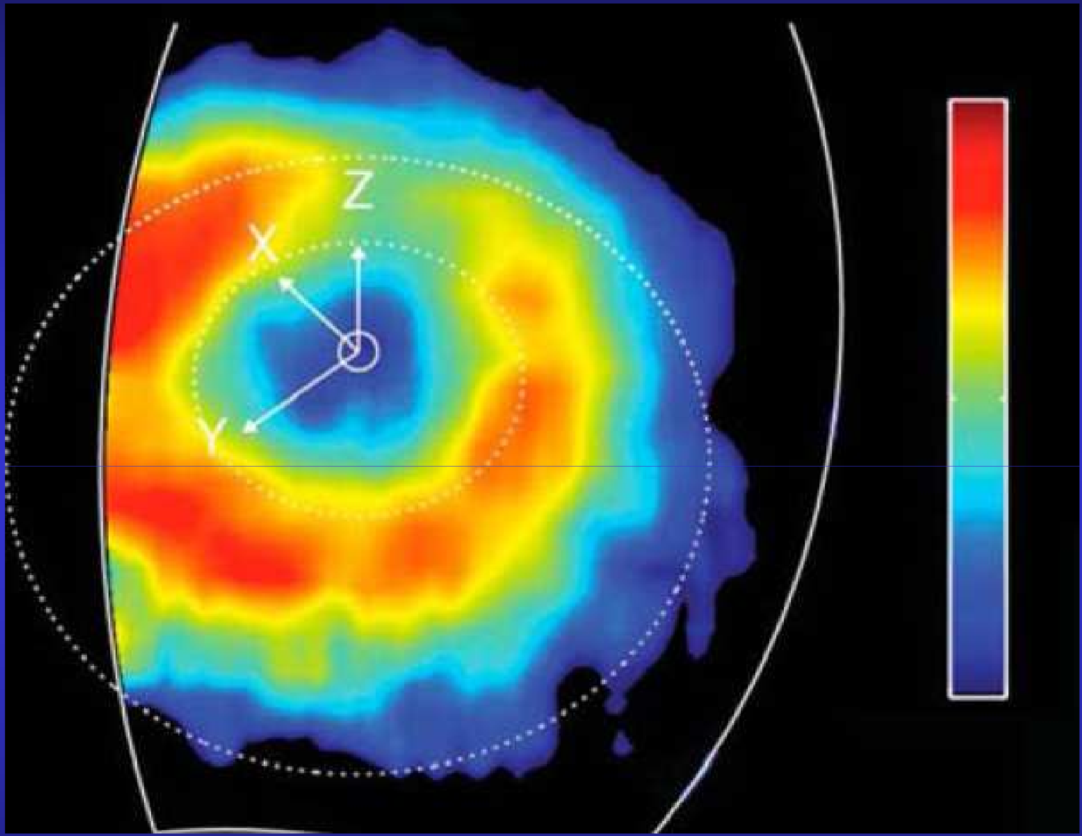
Enceladus- Imprint on the magnetosphere



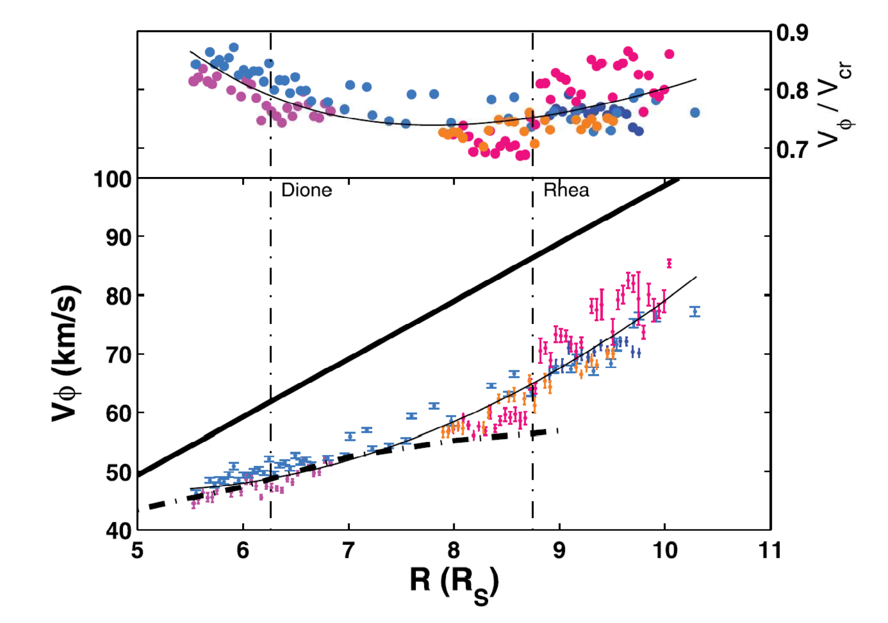
Ring current at Saturn
ENA image of Cassini MIMI/INCA

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

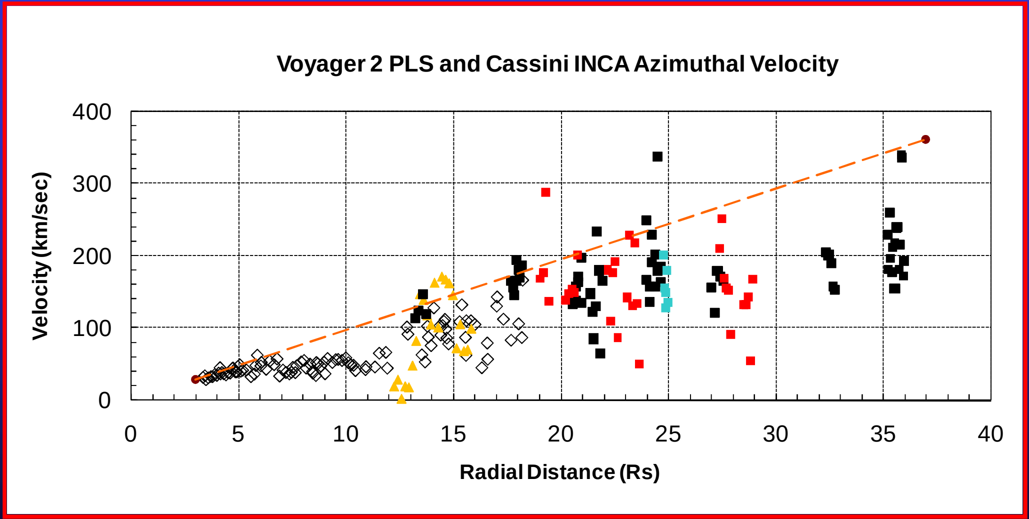


Saturn: Flow pattern

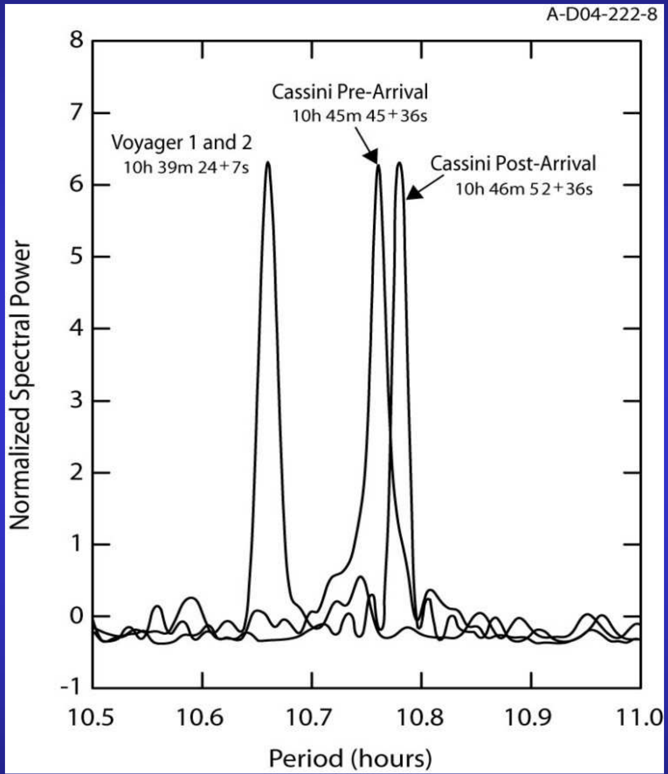


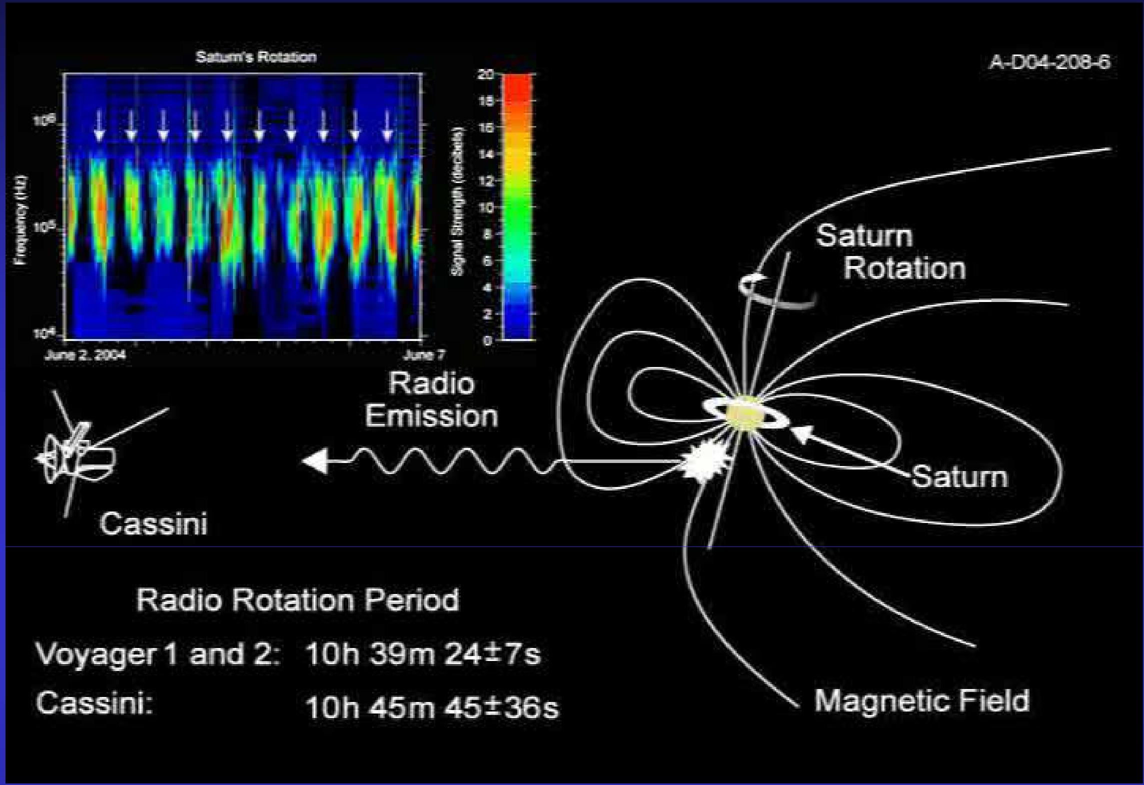
Wilson, 2008

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.

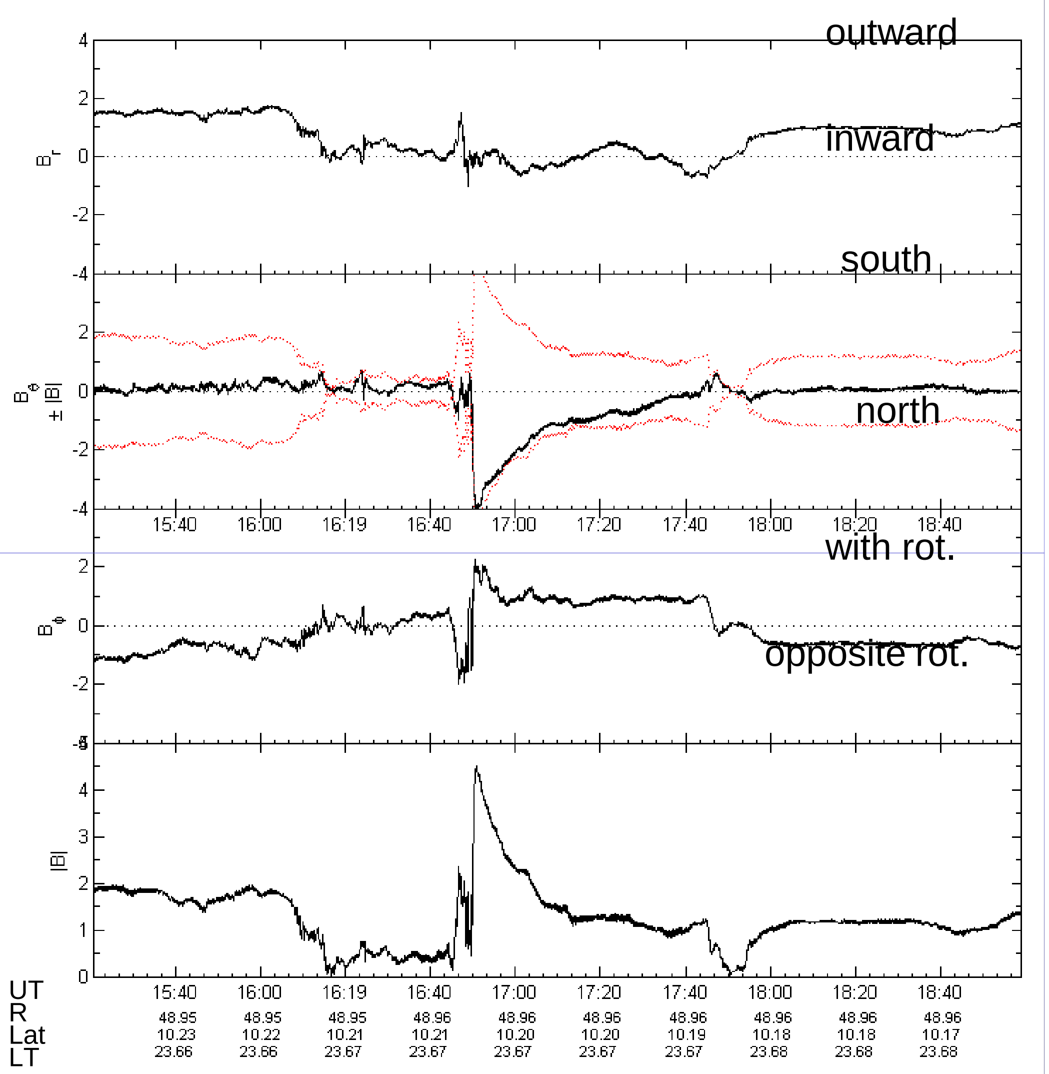
Kurth et al., 2006

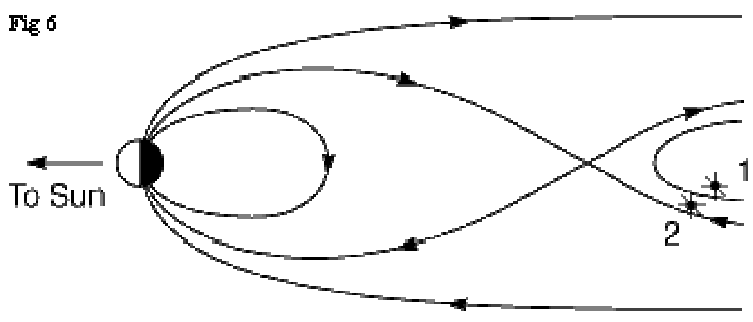
Saturn:

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.**

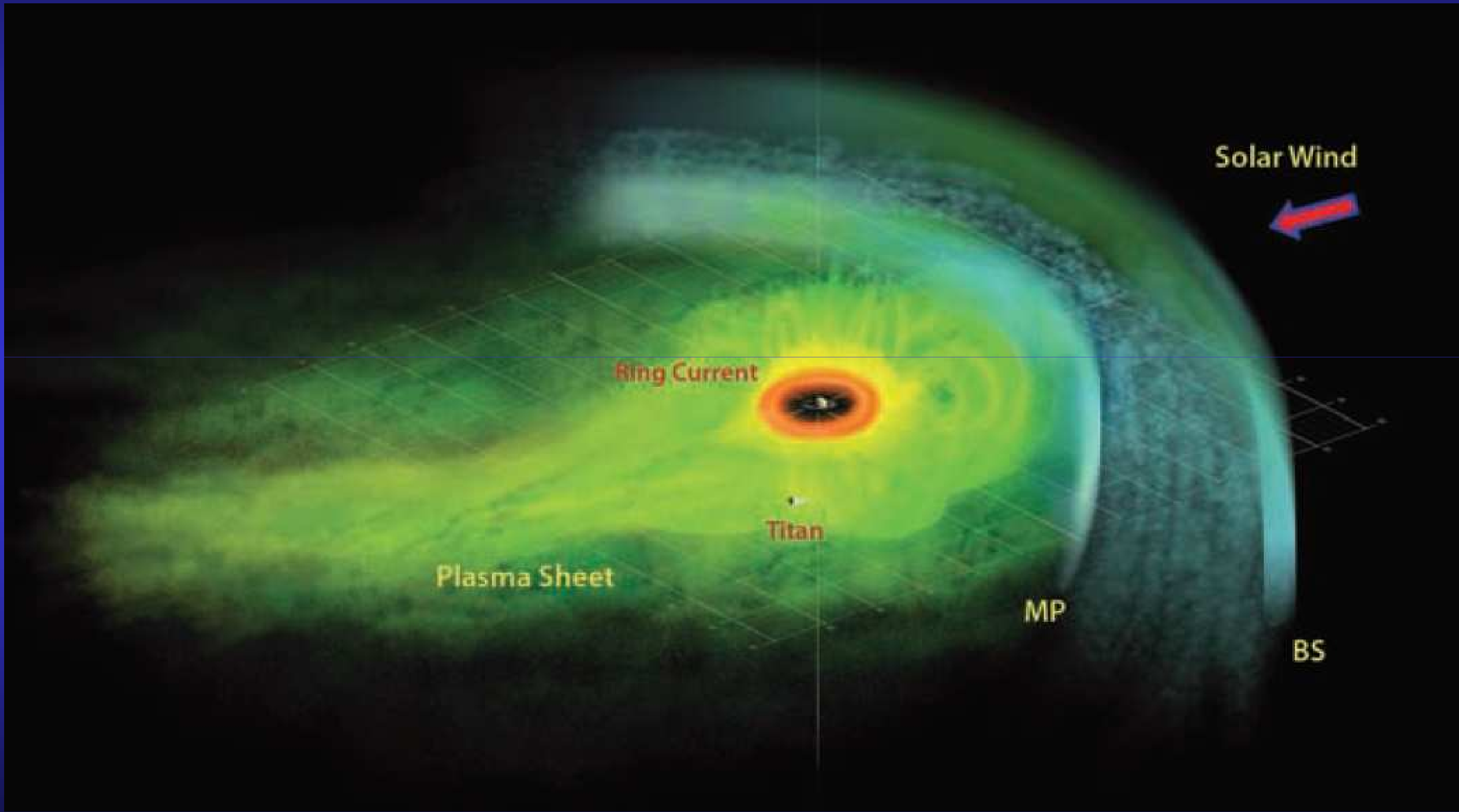
Event 1 - August 4th 2006





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 lime 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 Merury, 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**