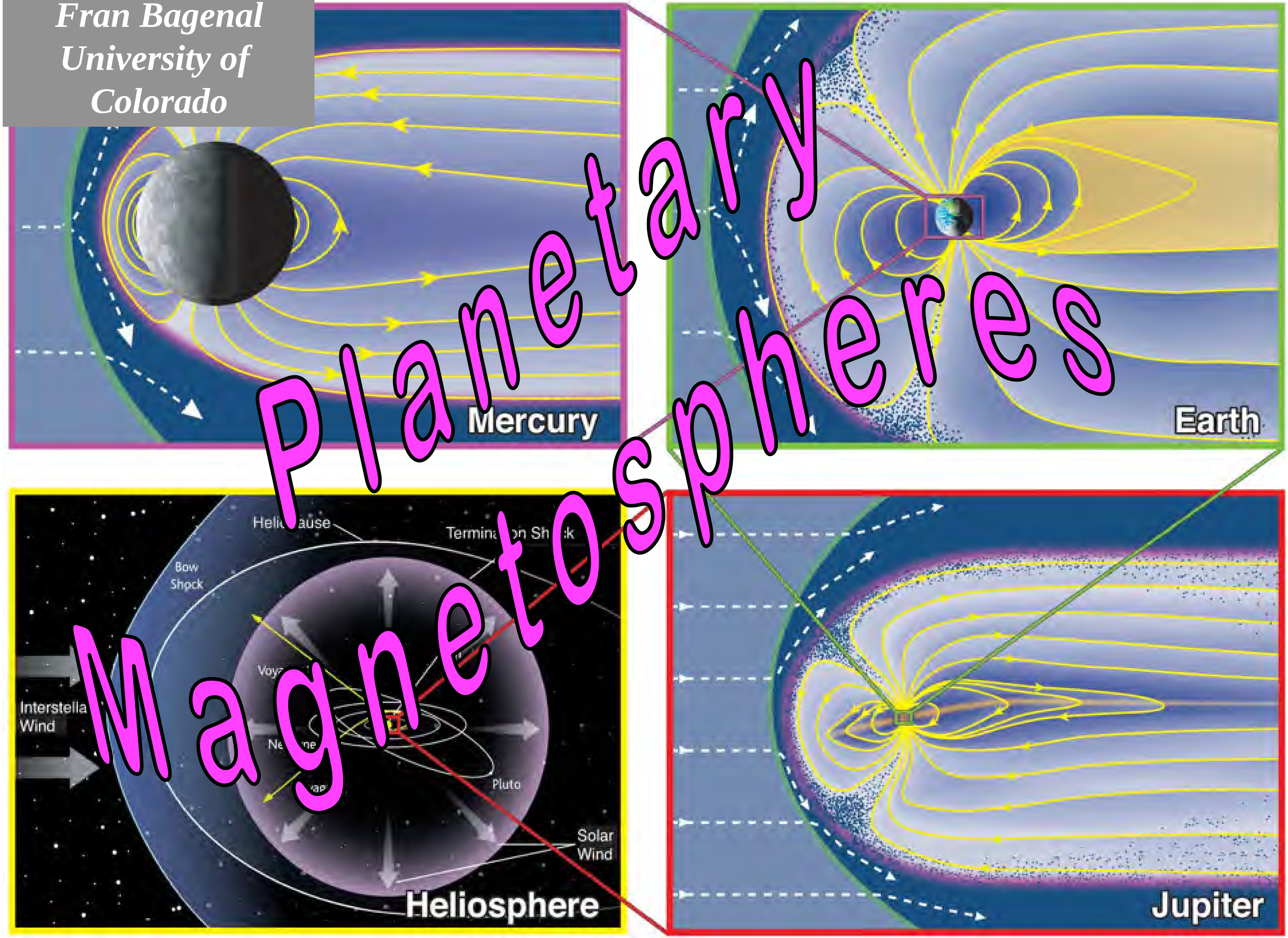
Planetary Magnetospheres

Fran Bagenal
University of Colorado



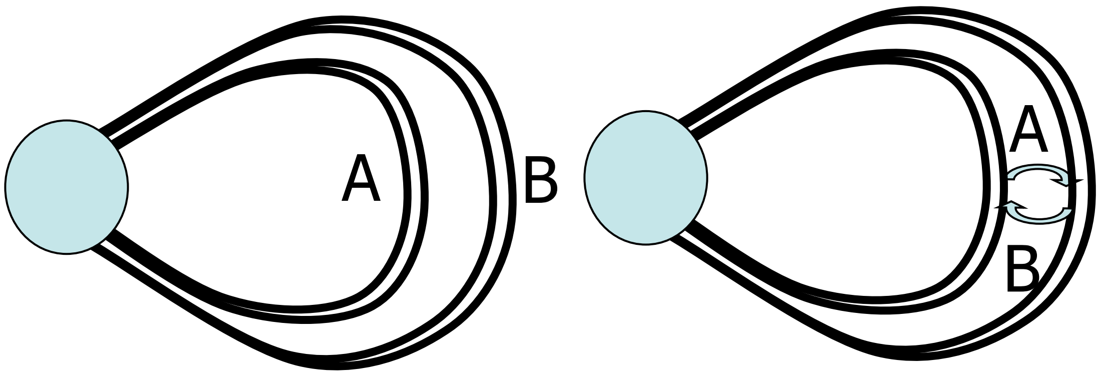
Magnetosphere Dynamics

Internal

Radial Transport

In rotating magnetosphere

If fluxtube A contains more mass than B – they interchange



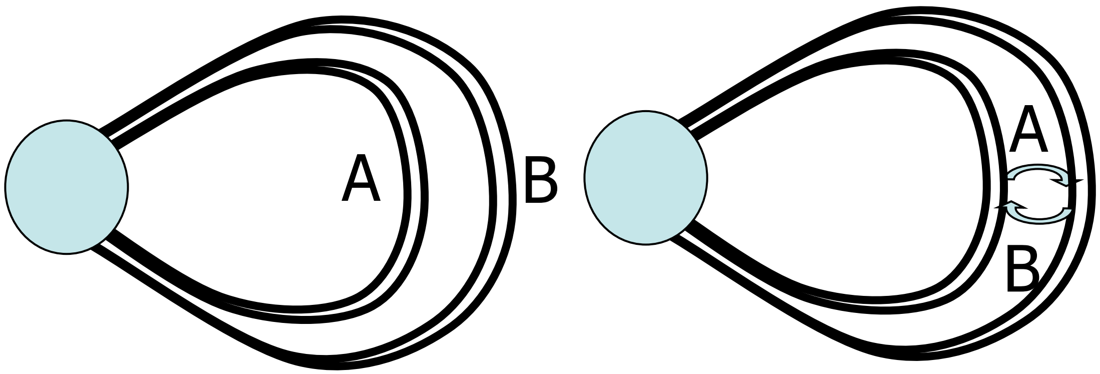
Rayleigh-Taylor instability where centrifugal potential replaces gravity

If $\beta \ll 1$,
interchange of A and B does not change field strength.

Radial Transport

In rotating magnetosphere

If fluxtube A contains more mass than B – they interchange

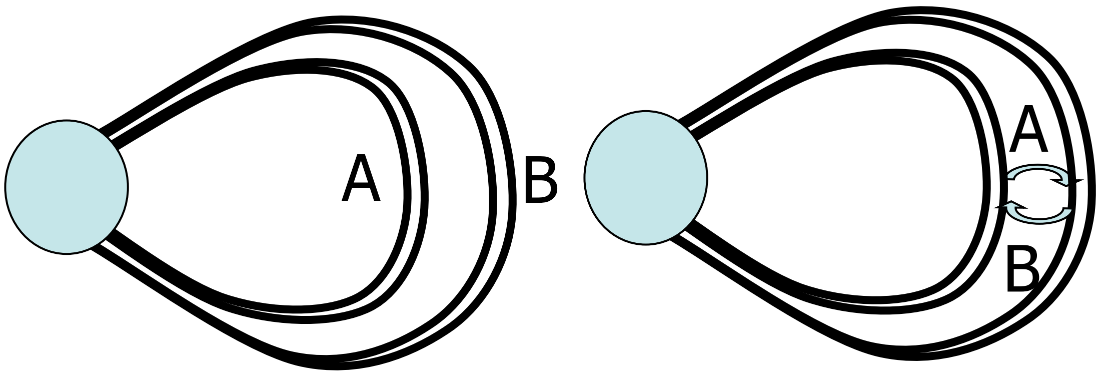


You can think of centrifugally-driven fluxtube interchange as a kind of diffusion.

- How will density vary with distance from the source?
- How will diffusion ***rate*** depend on ***gradient*** of density?

Radial Transport

Rayleigh-Taylor instability
where centrifugal potential replaces gravity



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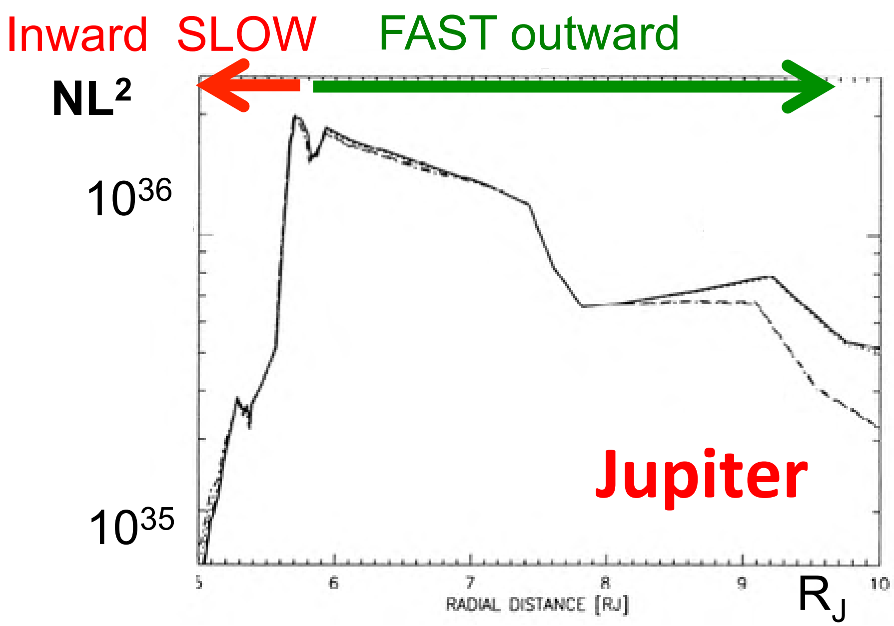
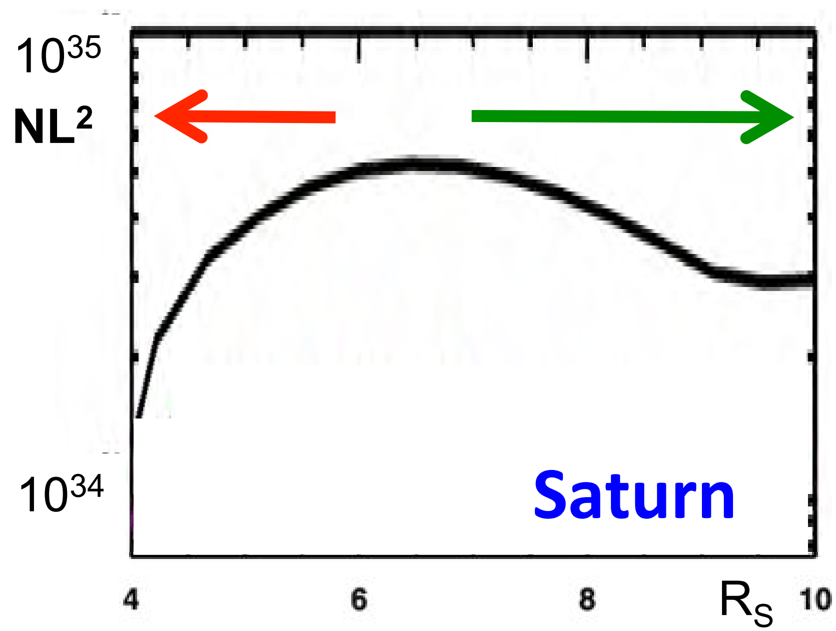




Plasmaspheres / Plasma disks

Earth's Plasmasphere

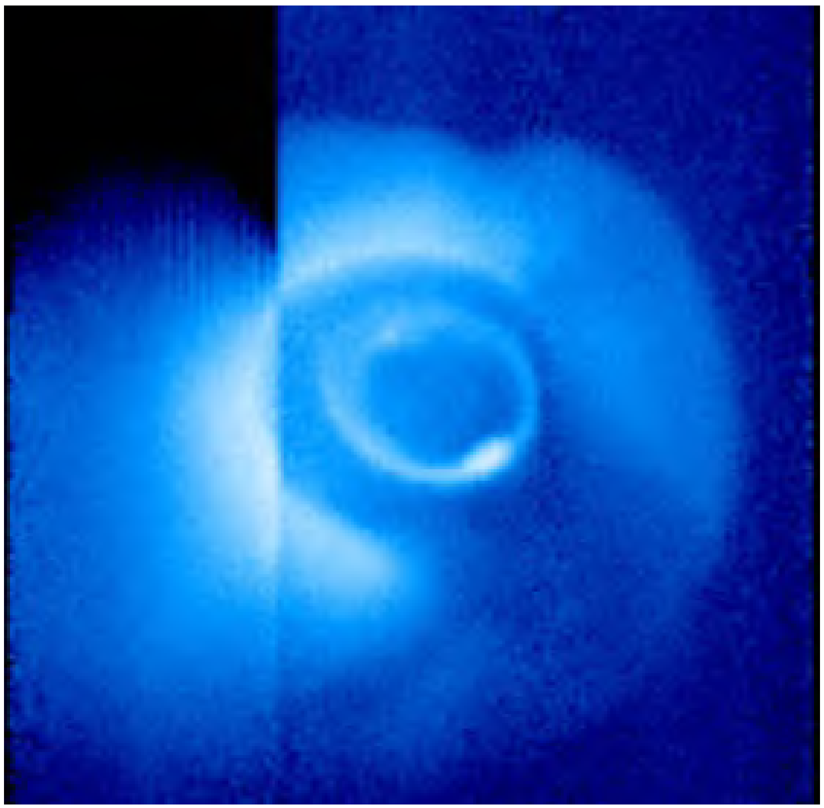
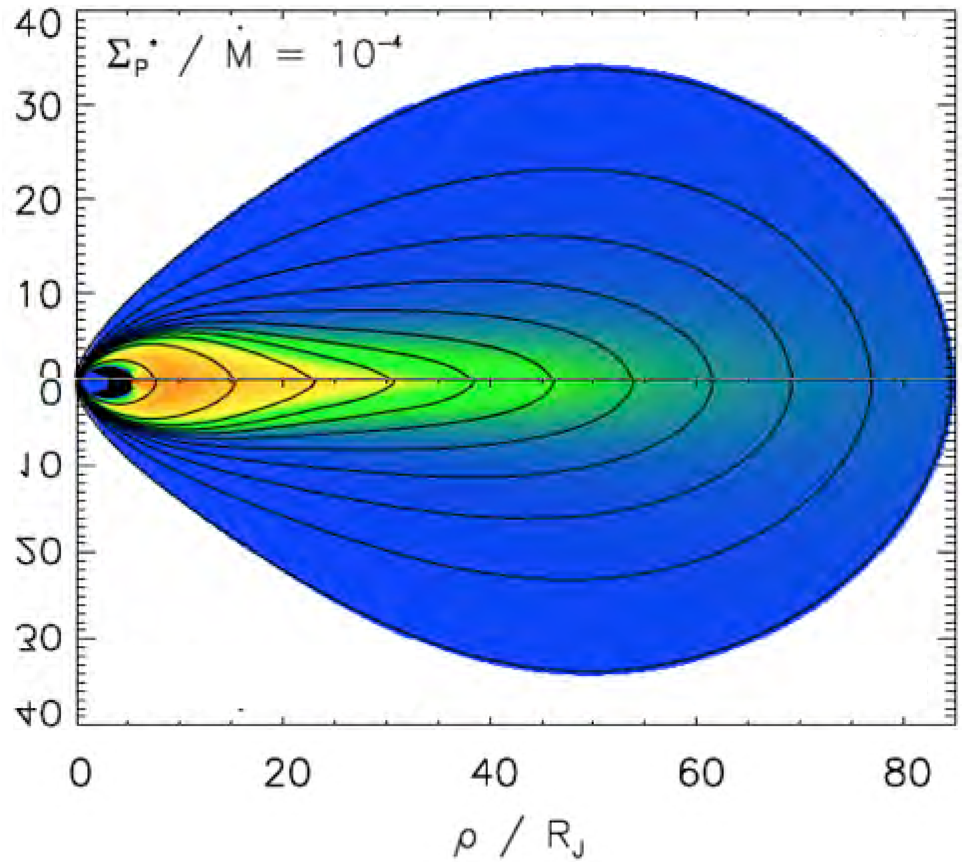


Image observations
30.4 nm He^+

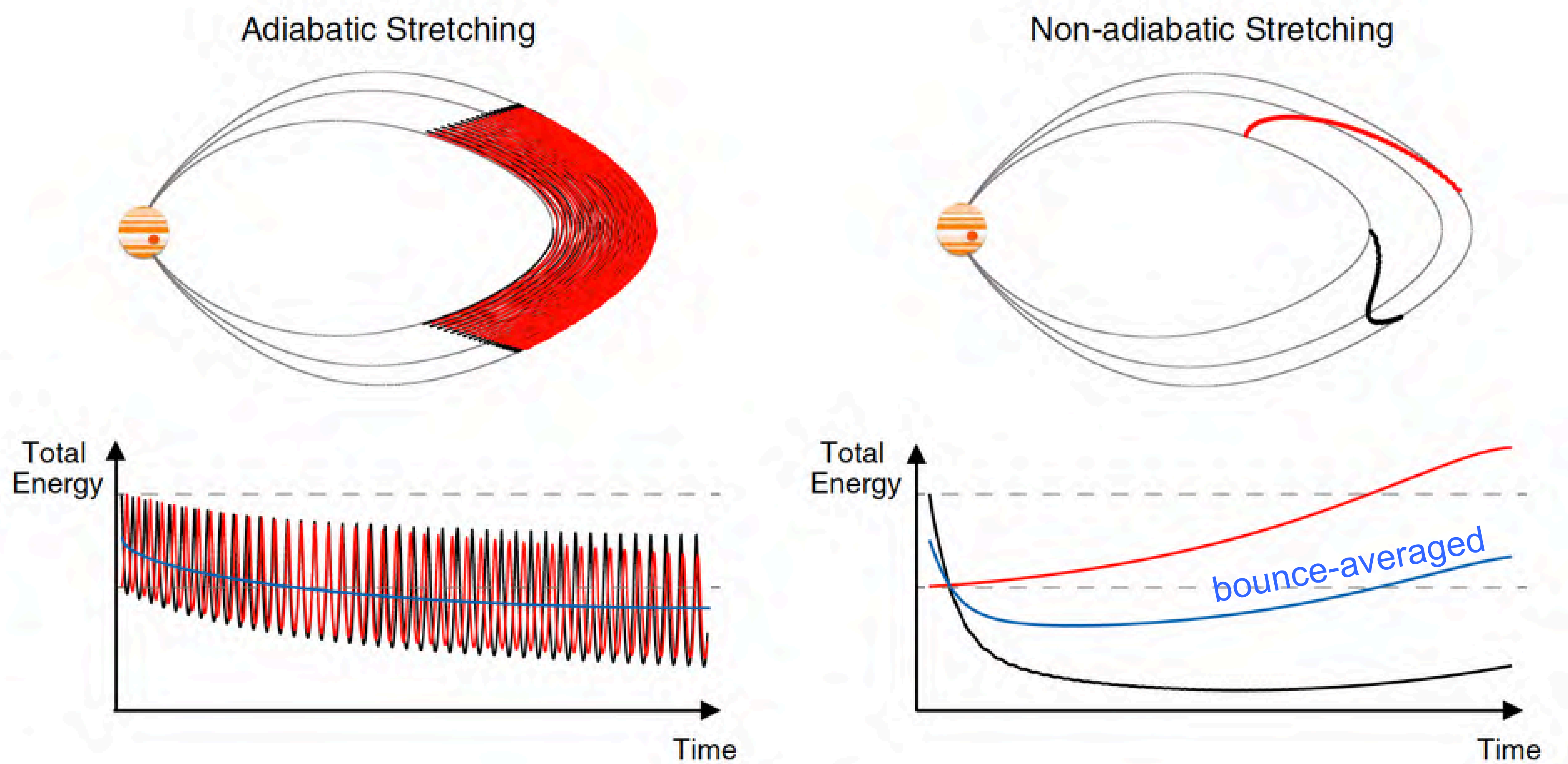


Jupiter's plasmadisk
Heats up as it moves outwards
10s keV plasma – β~10s

Plasma Heating

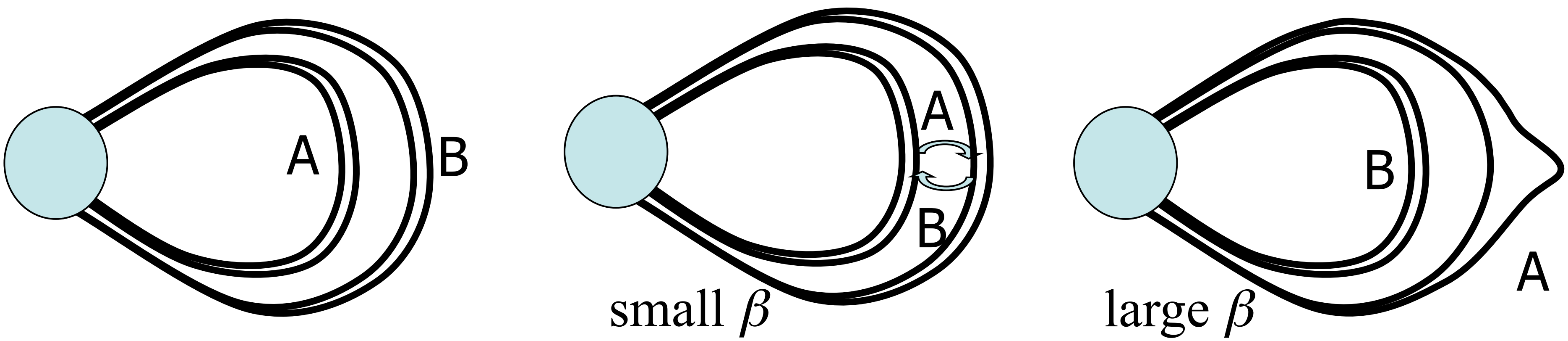
Vogt et al. (2014)

- Flux tube expands faster than bounce time
- violation of 2nd adiabatic invarient



Radial Transport – high β

Interchange transports material from inner m'sphere, but plasma β increases outward and ultimately **ballooning** replaces interchange

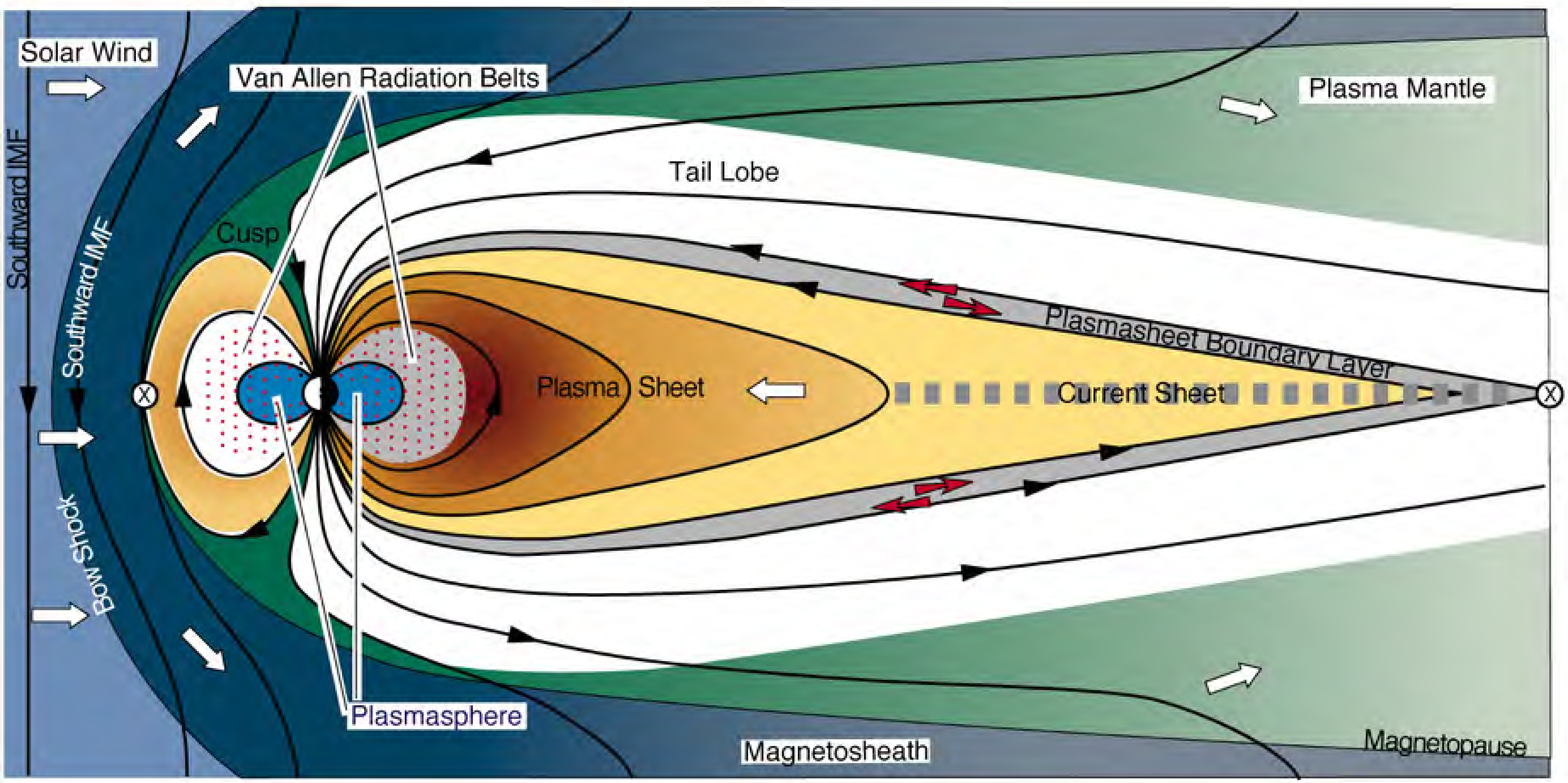


If $\beta \ll 1$, interchange of A and B does not change field strength.
- This is the 'ideal' interchange

However for finite β, if A has more plasma, pressure will increase relative to surroundings at A's new location once it is displaced.
- Now the **field pressure has to change** also to maintain quasi-equilibrium
- The motion is no longer an 'ideal' interchange
- **Once field strength changes, field must bend as well**

Magnetosphere Dynamics

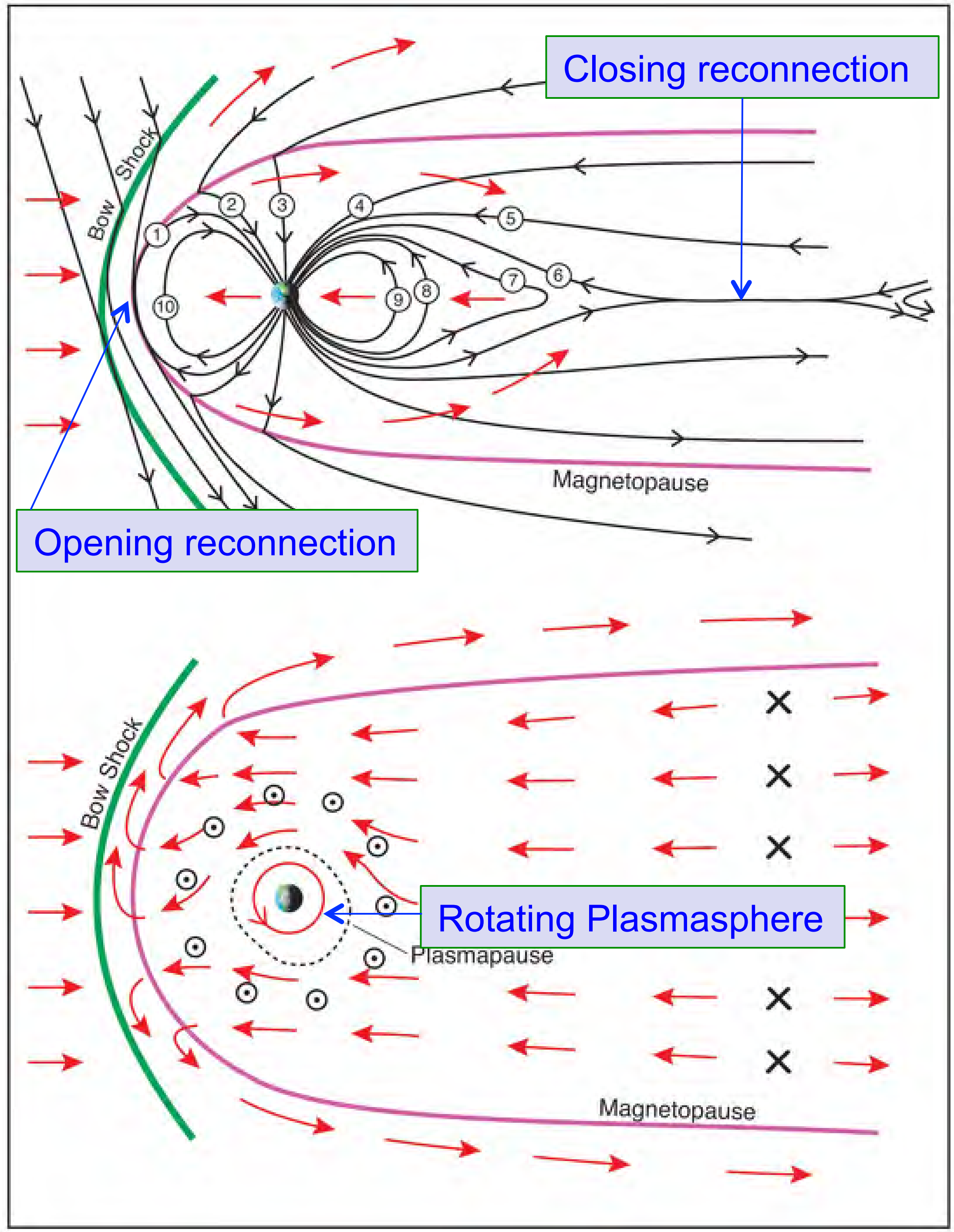
Solar-Wind-Ionosphere-Magnetosphere Coupling



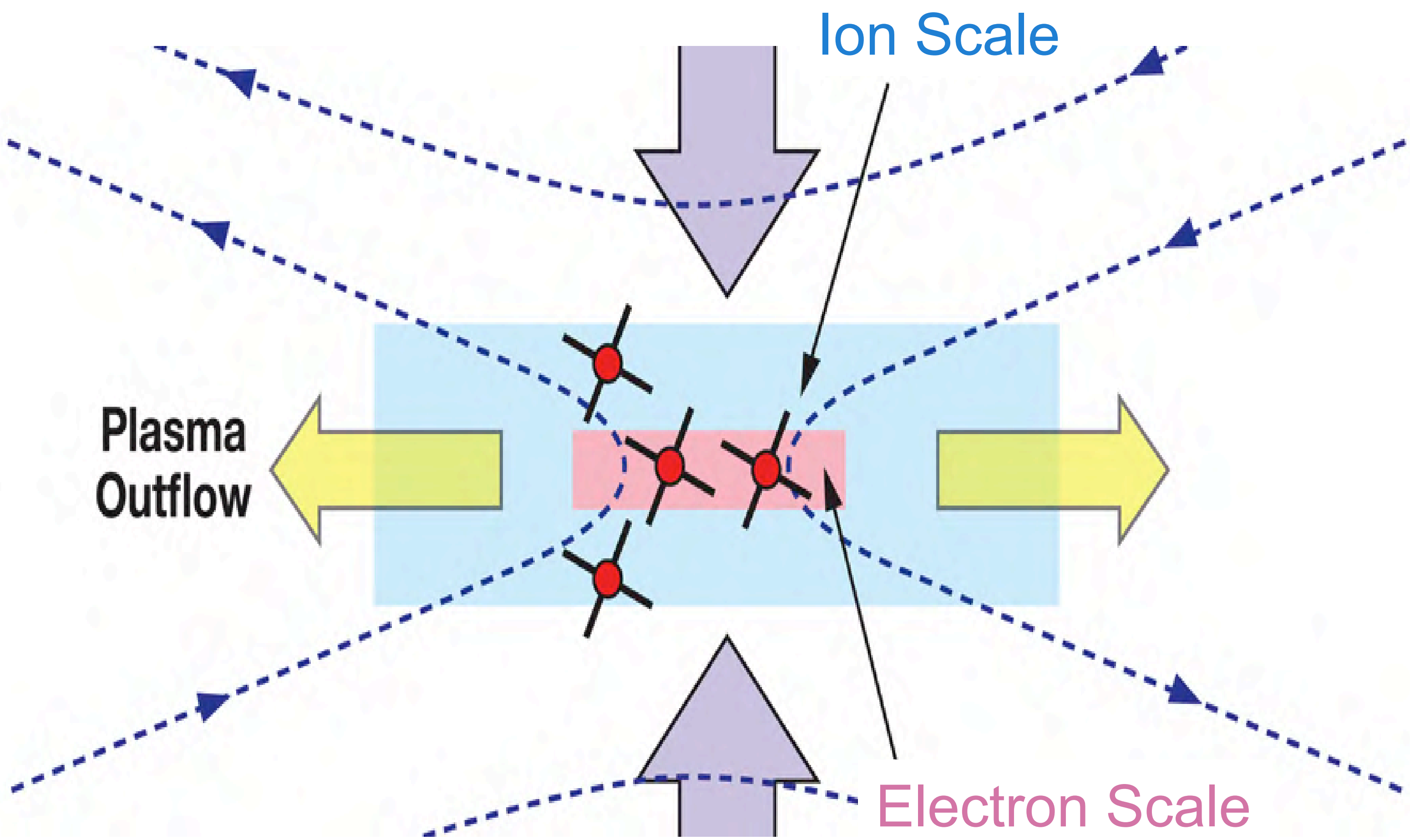
Dungey Cycle

Dynamics at Earth driven by the solar wind coupling the Sun's magnetic field to the Earth's field

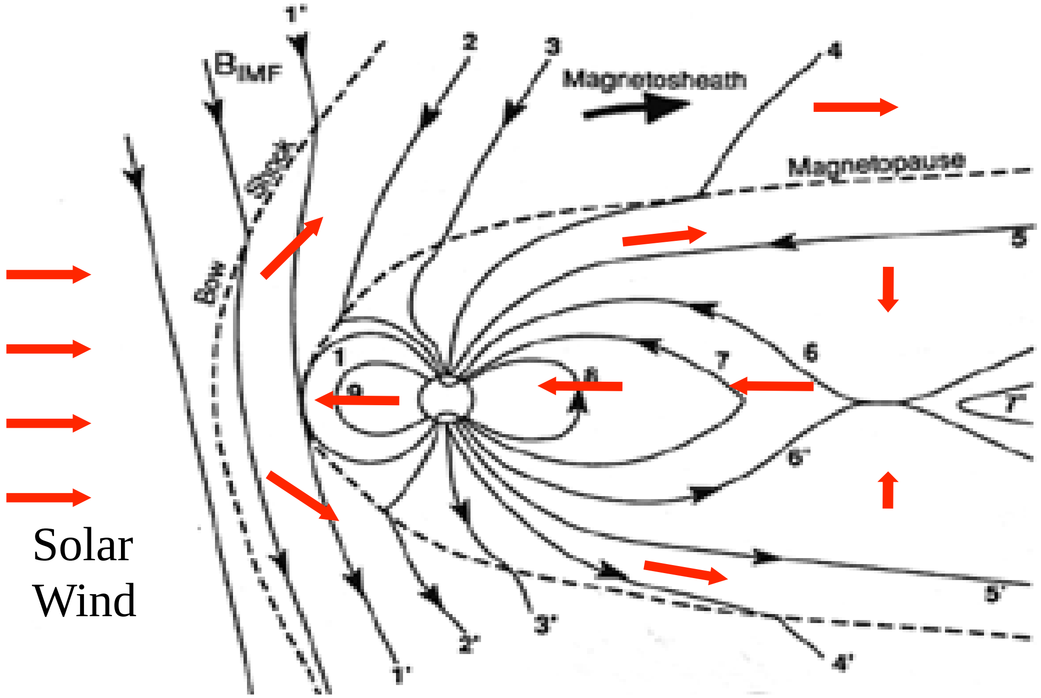
- Variable opening & closing rates
- Must be equal over time to conserve magnetic flux



Magnetic Reconnection



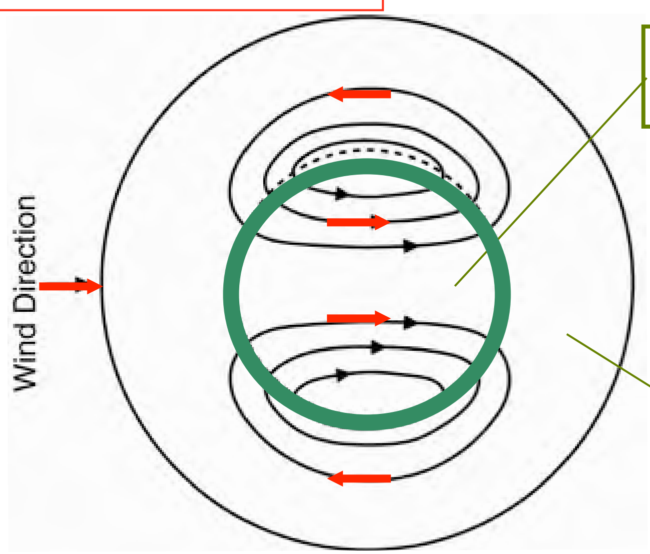
NASA Magnetospheric Multi-Scale mission – Launch spring 2015



Variable opening & closing rates

Must be equal over time to conserve magnetic flux

Polar view



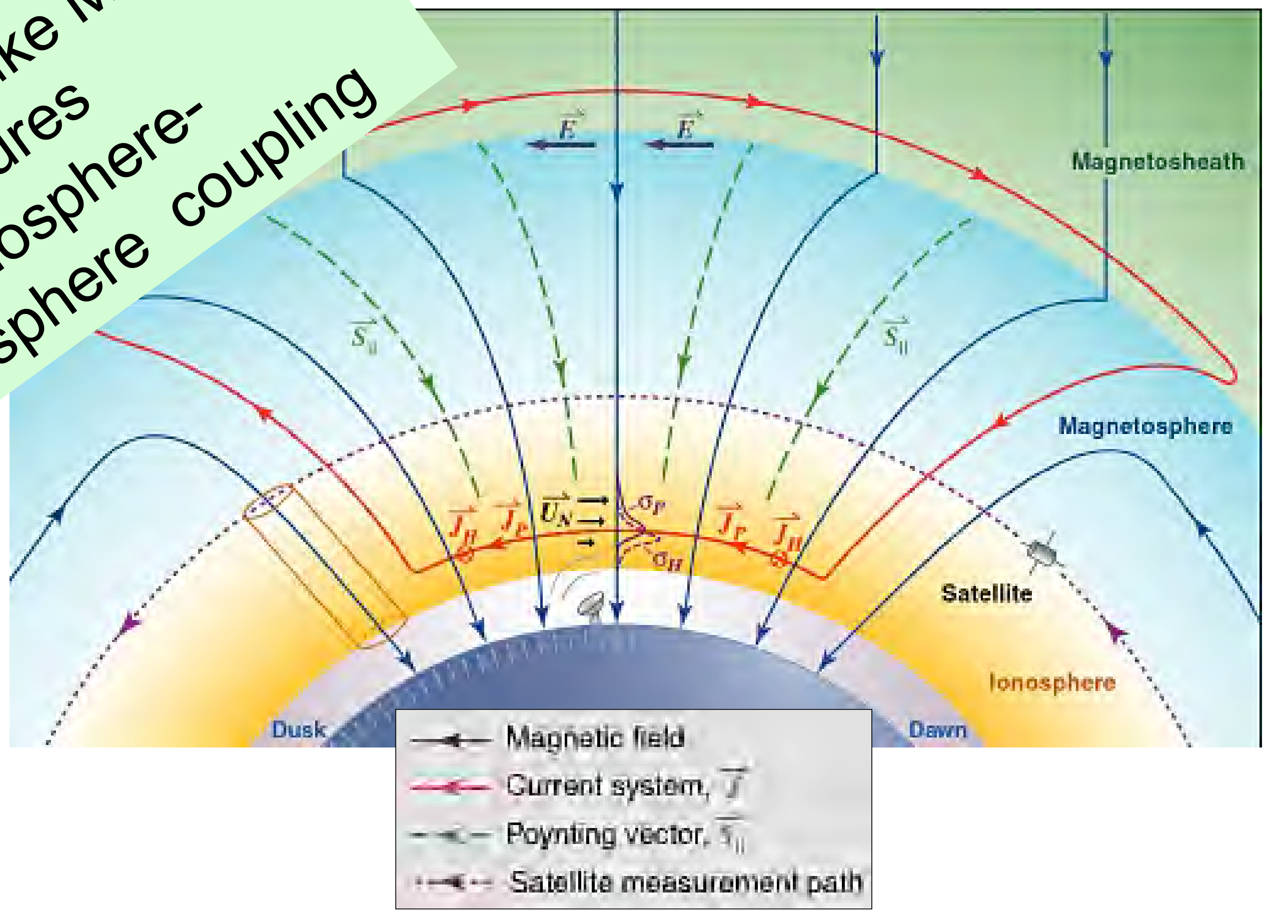
Connected to solar wind

note: ionosphere is incompressible

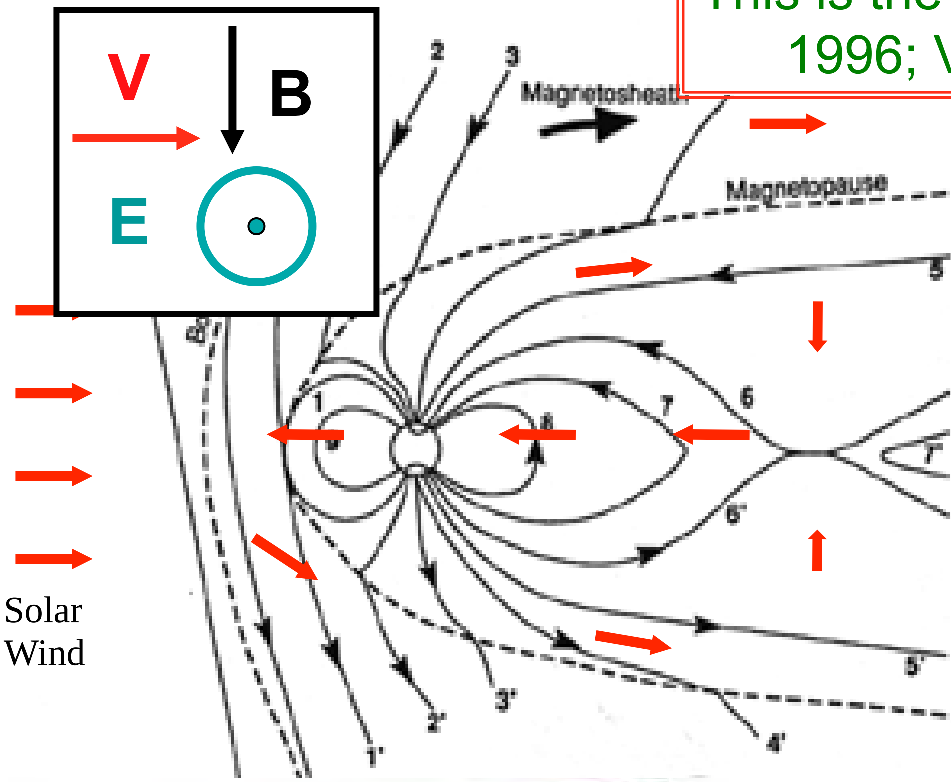
Closed magnetic field

Ionosphere - Sets boundary conditions for magnetospheric dynamics

Rod Heelis' & Luke Moore's
Lectures
On ionosphere-
magnetosphere coupling



This is the conventional E-J approach. See Parker 1996; Vasyliunas 2005,11 for B-V approach



The Dungey Cycle

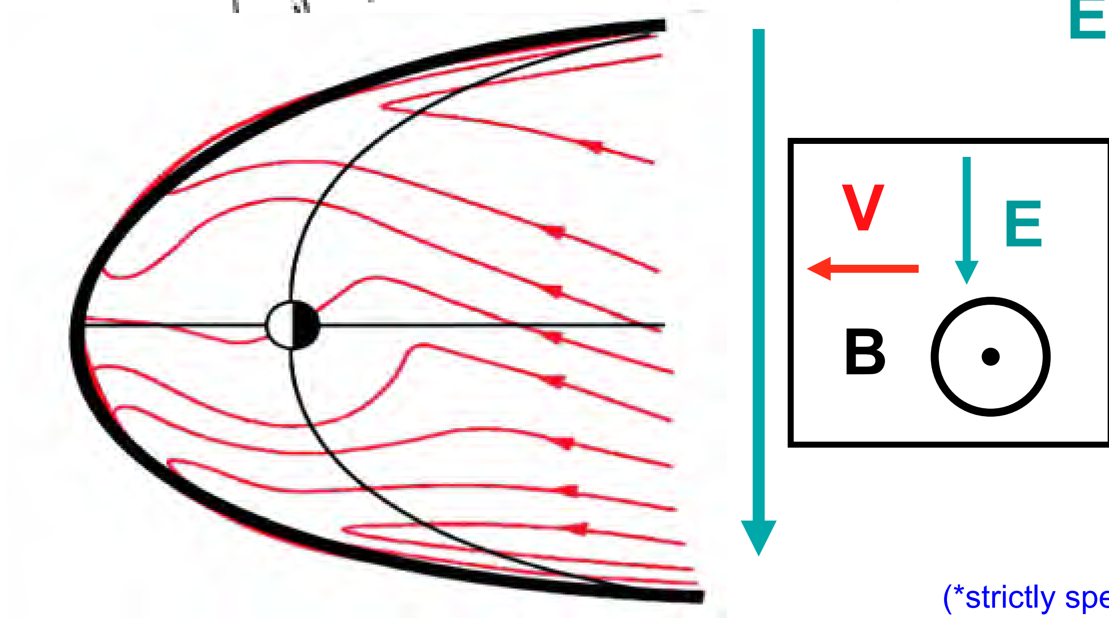
Solar wind driven magnetospheric convection*

$\mathbf{E}_{convection} = -\,\zeta\,\mathbf{V}_{SW} \times \mathbf{B}_{SW}$

ζ~ efficiency of reconnection ~10-20%

crude approximation!!

$\mathbf{E}_{conv}$~ constant in m'sphere



$\mathbf{V}_{convection}$

$\sim \zeta V_{SW}(R/R_{MP})^3$

(where 3 power assumes a dipole - in reality, the flow is not uniform and the power somewhat less)

(*strictly speaking not convection but advection or circulation)

Substorm Energy Storage

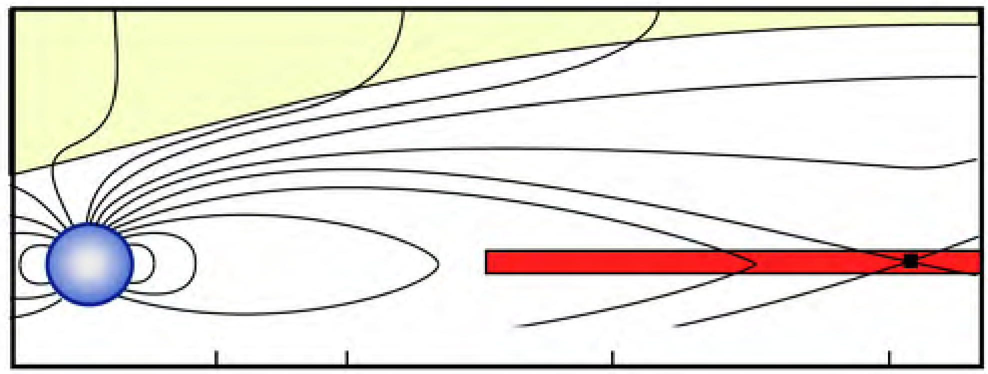
solar wind kinetic energy converted to magnetic energy

SW kinetic energy

↓

magnetic energy

growth phase

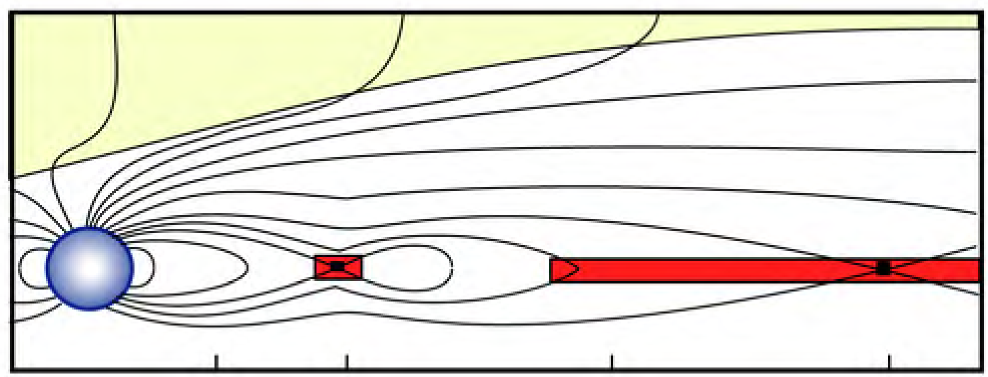


magnetic energy

↙ ↘

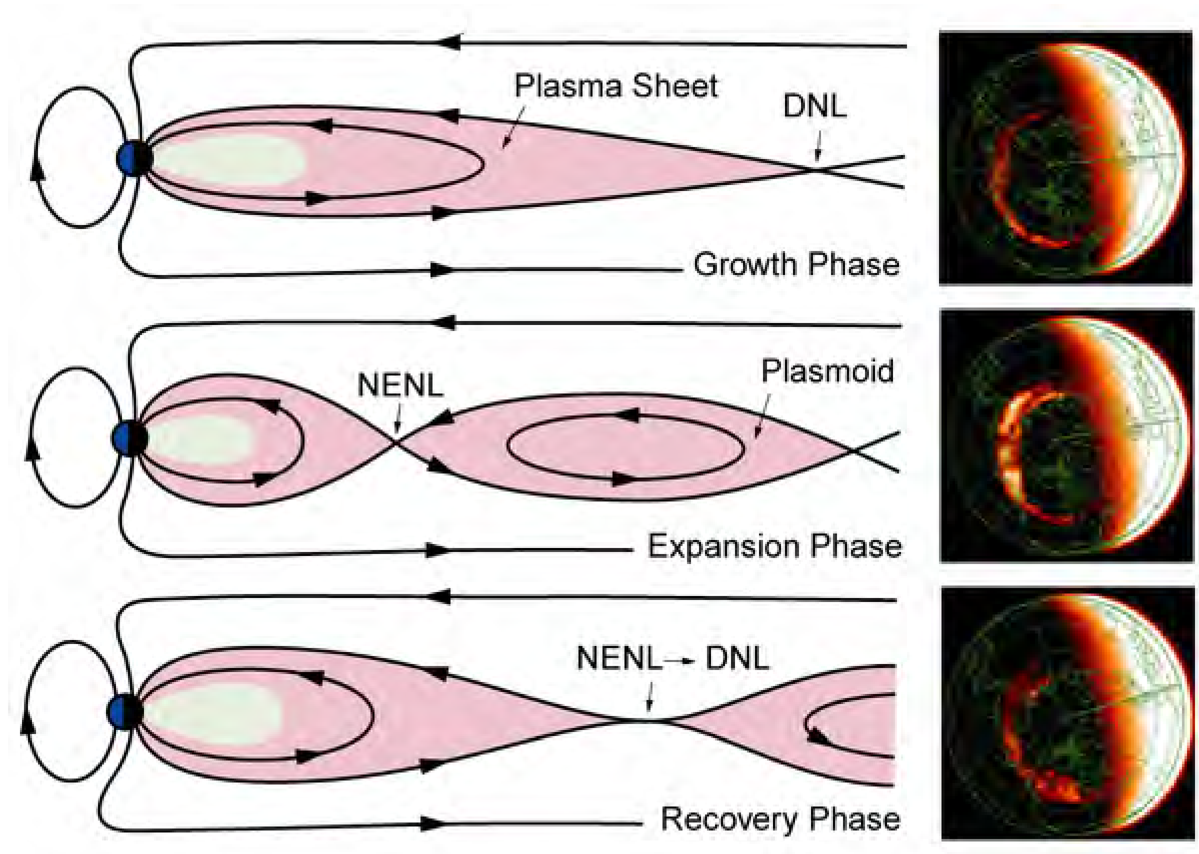
heat kinetic

substorm onset



Evolutionary Phases for Substorm Plasmoid

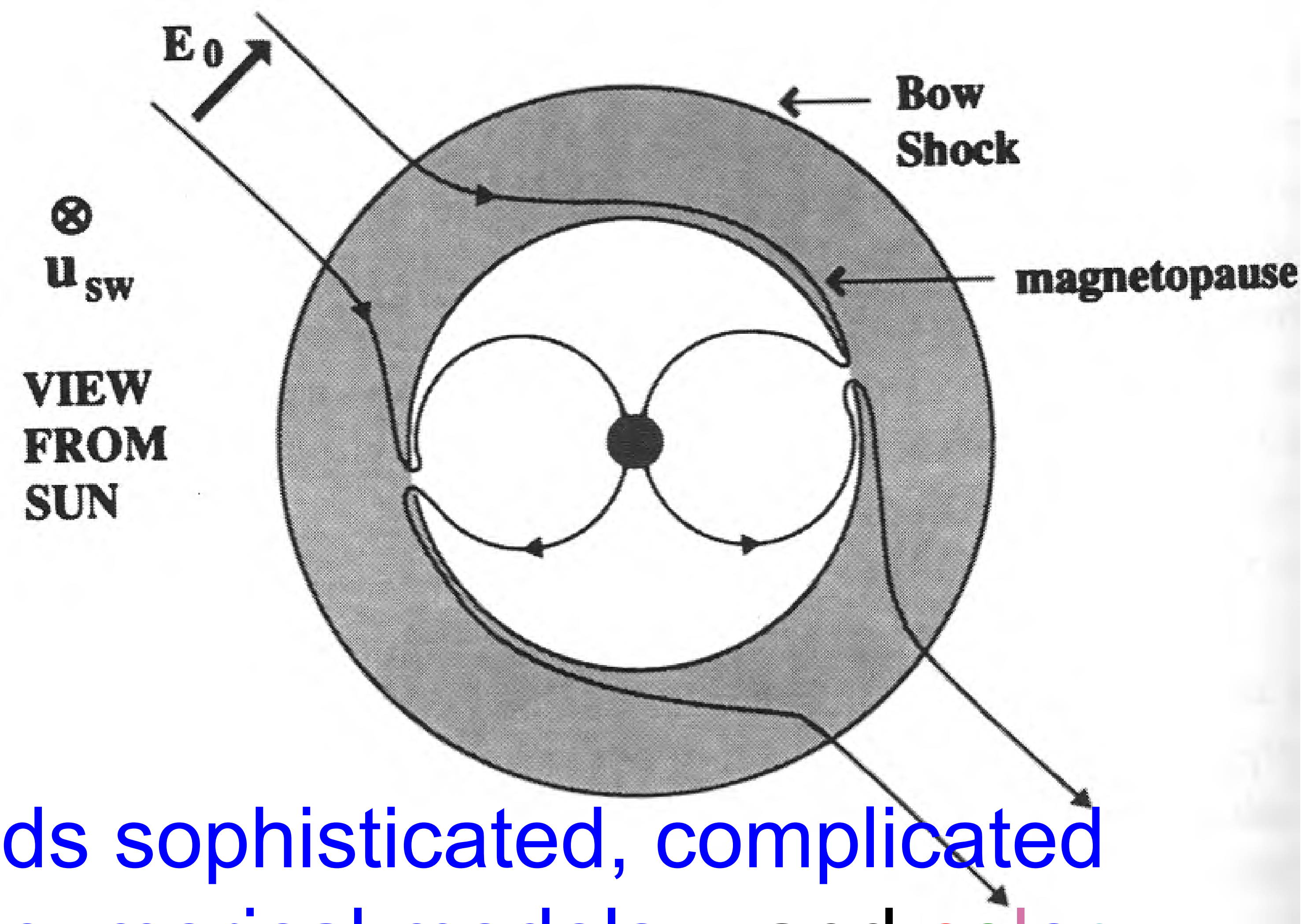
1. Energy storage:
2. Onset:
3. Recovery:



DNL=Distant Neutral Line
NENL = Near Earth Neutral Line

Aurora:
- Open-closed boundary
- Stronger on nightside
- Highly variable

Reality = Messy & 3D



Needs sophisticated, complicated numerical models – and color

Dynamics

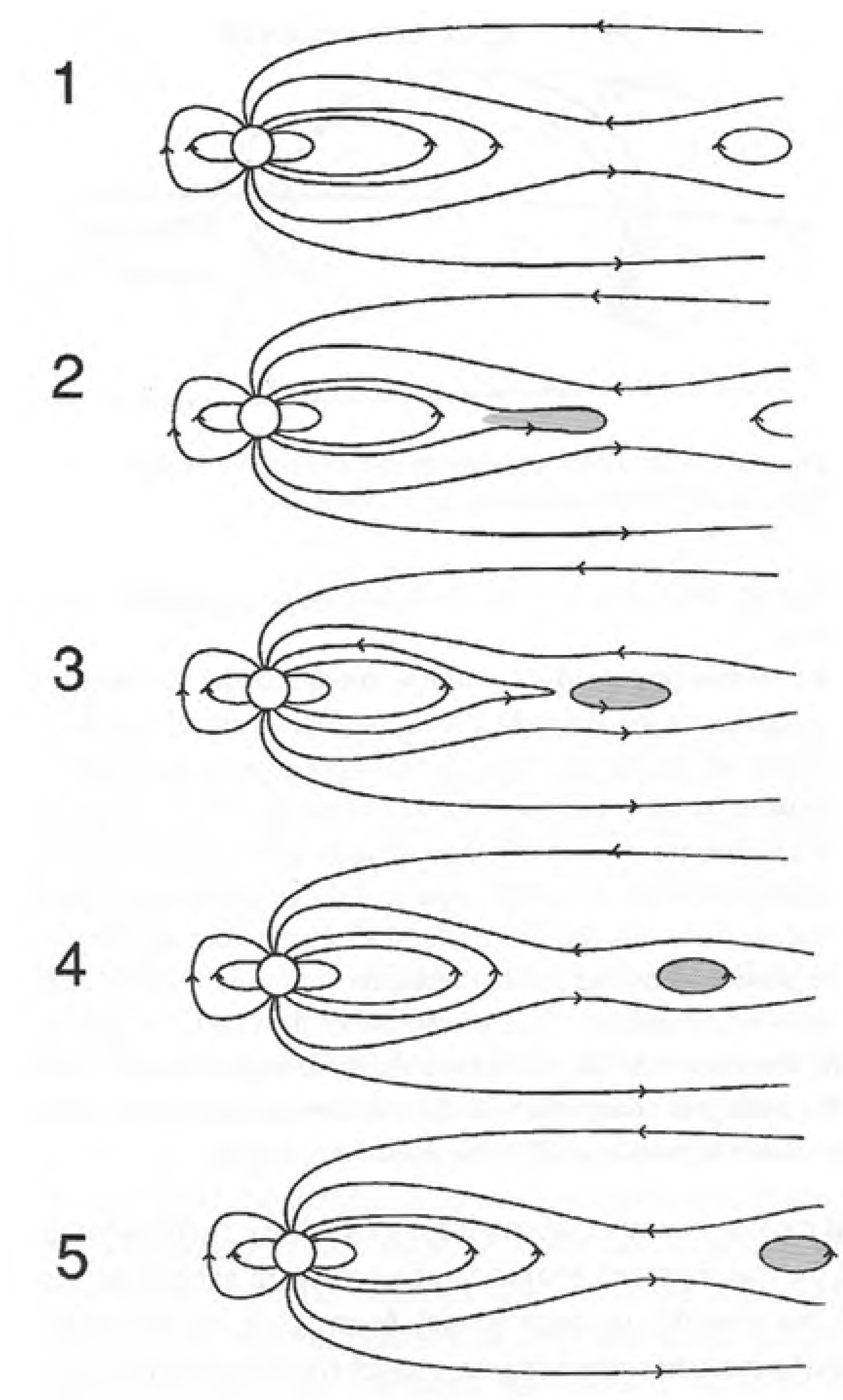
Dayside magnetopause

- Response to B_{SW} direction
- Solar wind ram pressure

Tail Reconnection

- Depends on recent history of dayside reconnection and state of plasmasheet

Space Weather!



Magnetosphere Dynamics

Solar-Wind-Ionosphere-Magnetosphere
Coupling

vs.

Ionosphere-Magnetosphere
Coupling

$$\mathbf{V}_{co} \sim \mathbf{\Omega} \times \mathbf{R}$$

$$\mathbf{V}_{convection}$$

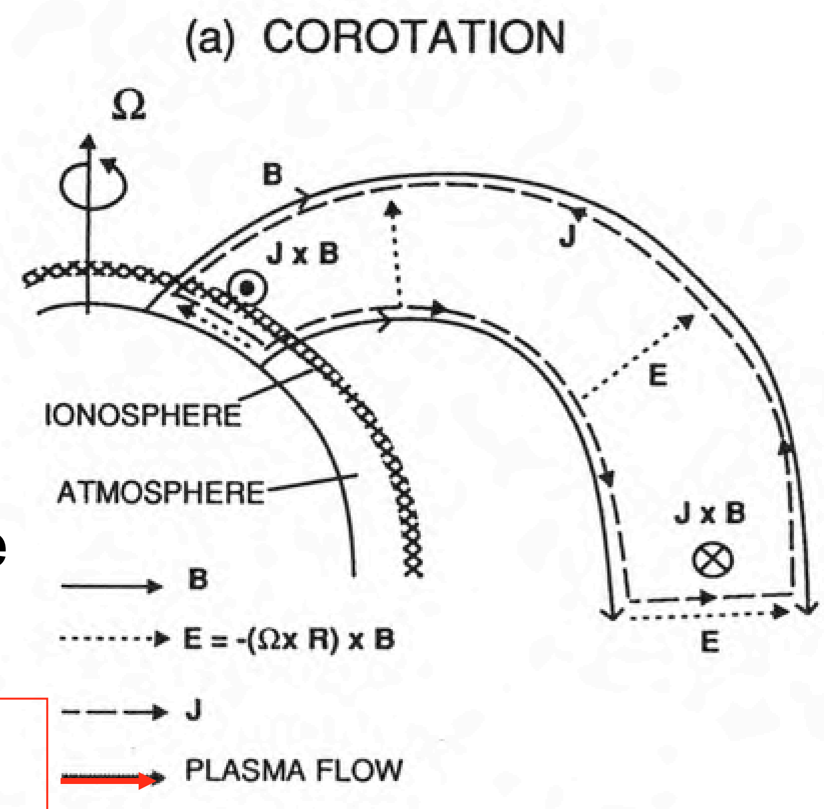
$$\sim \zeta V_{SW}(R/R_{MP})^3$$

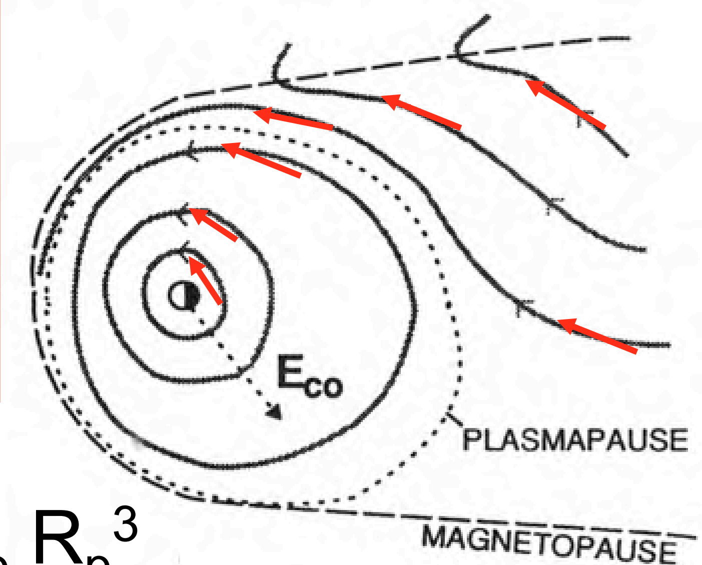
Fraction of planetary magnetosphere that is rotation dominated is…

$$R_{plasmapause}/R_{MP}$$

$$\sim [\, r_p R_{MP}\, \Omega \,/\, \zeta V_{SW}]^{1/2}$$

$$\propto \Omega^{1/2} \mu^{1/6} / (\rho_{sw})^{1/12}\, V_{sw}^{2/3}$$





r_p = planetary radius

μ = magnetic moment of planet $B_o R_p^3$

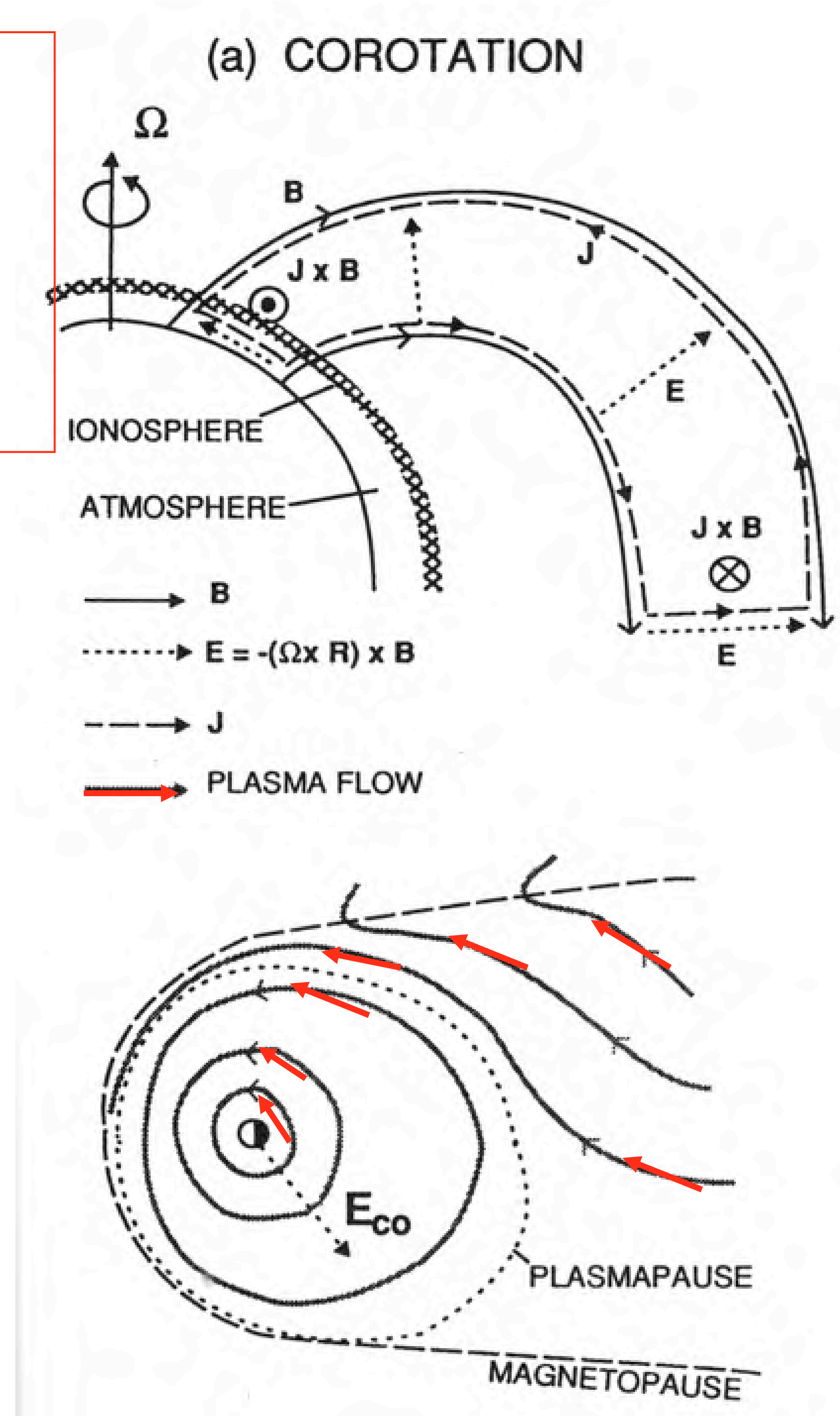
$$R_{plasmapause}/R_{MagnetoPause}$$

$$\sim [\ r_p R_{MP}\ \Omega\ /\ \zeta V_{SW}]^{1/2}$$

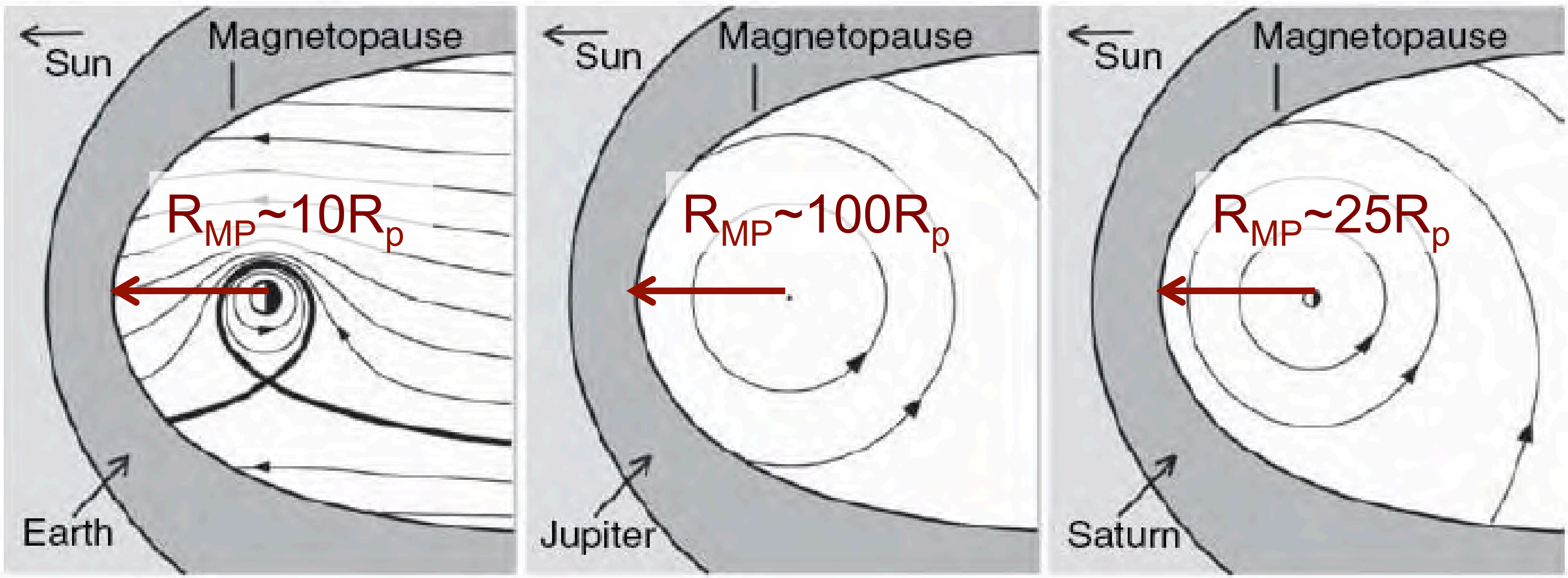
What if... How would location of plasmapause change?

1. Reconnection more/less efficient at harnessing the solar wind momentum

2. Planet's spin slows down



Solar-wind vs. Rotation-dominated magnetospheres



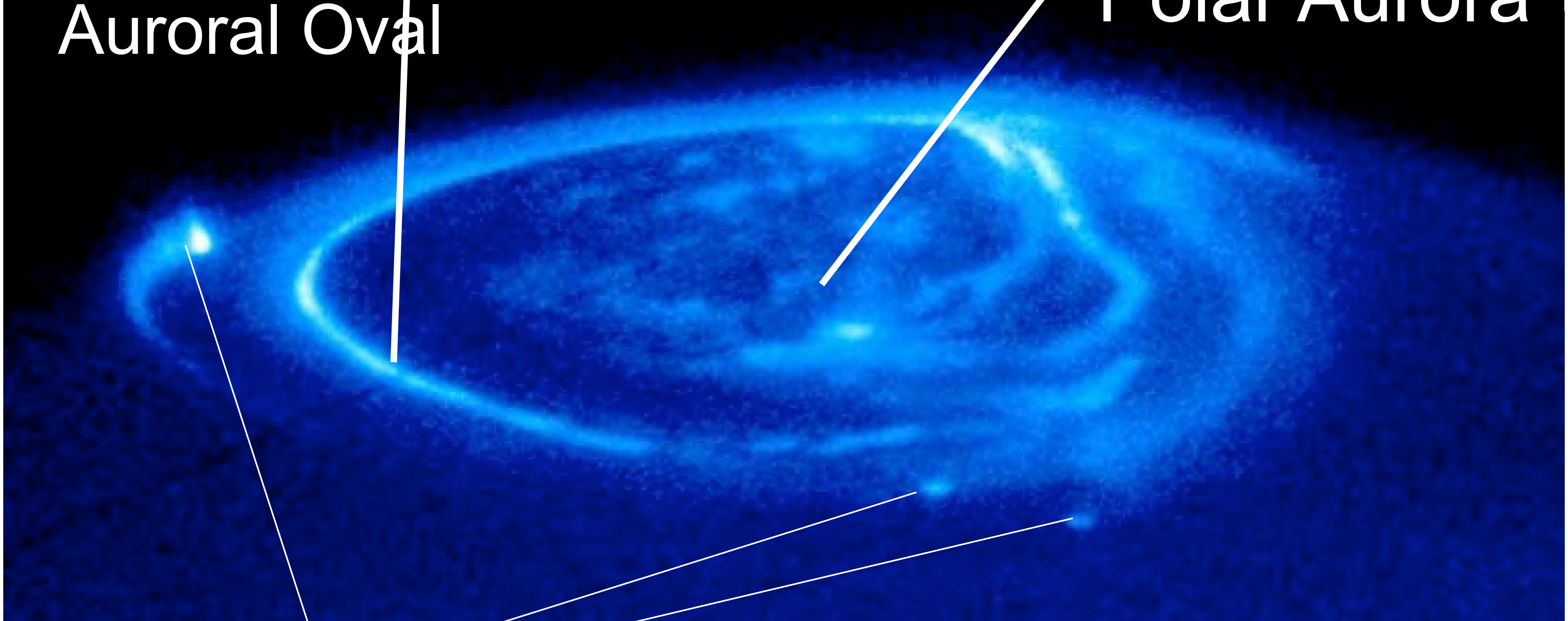
$R_{plasmapause} / R_{Planet}$ =

6.7	350	95

Assumptions:

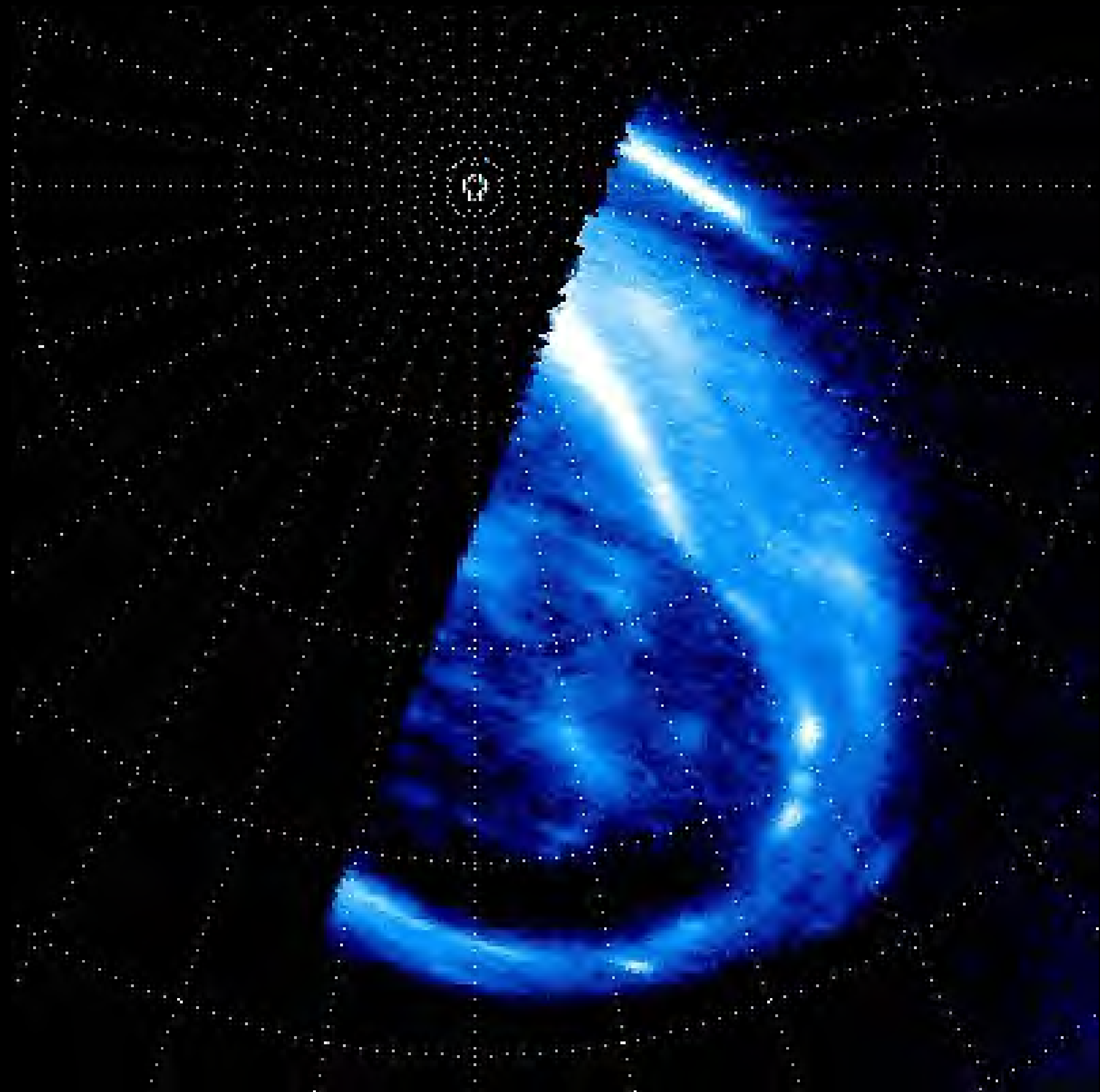
1. Planet's rotation coupled to magnetosphere
2. Reconnection drives solar wind interaction

Jupiter's 3 Types of Aurora



Jupiter's Aurora - The Movie

Fixed magnetic co-ordinates rotating with Jupiter

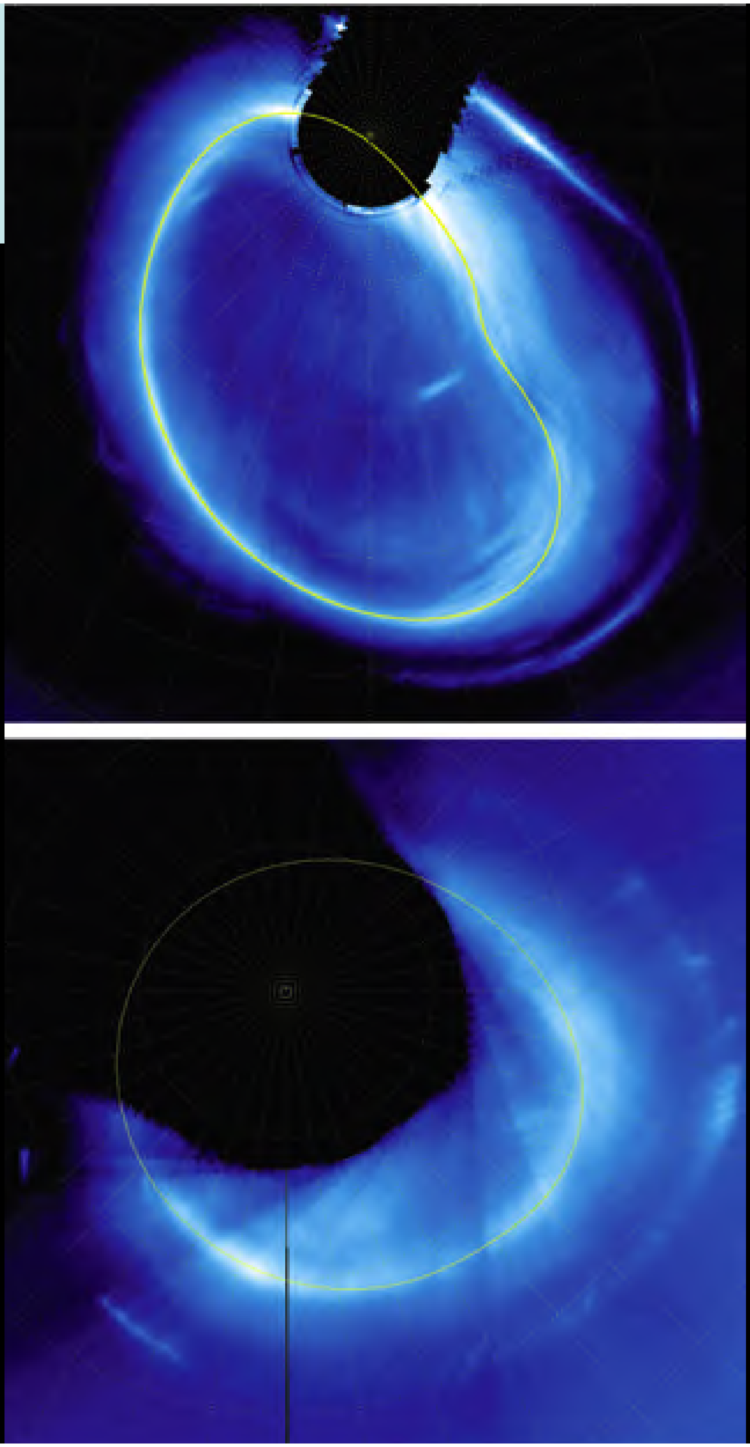


Clarke et al.
Grodent et al.
HST

Main Aurora

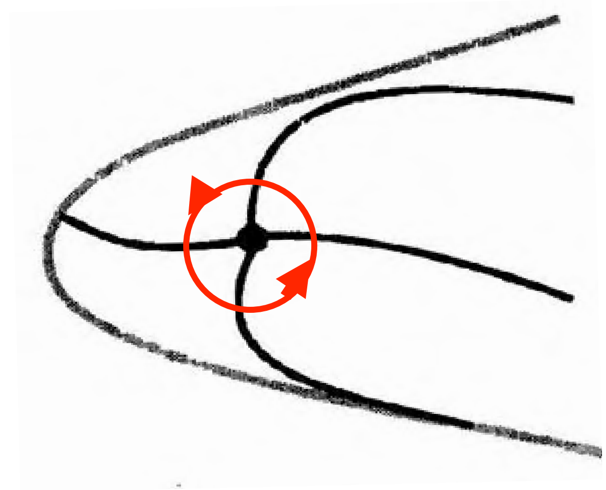
- Shape constant, fixed in magnetic co-ordinates
- Magnetic anomaly in north
- Steady intensity
- ~1° Narrow

Clarke et al., Grodent et al. HST



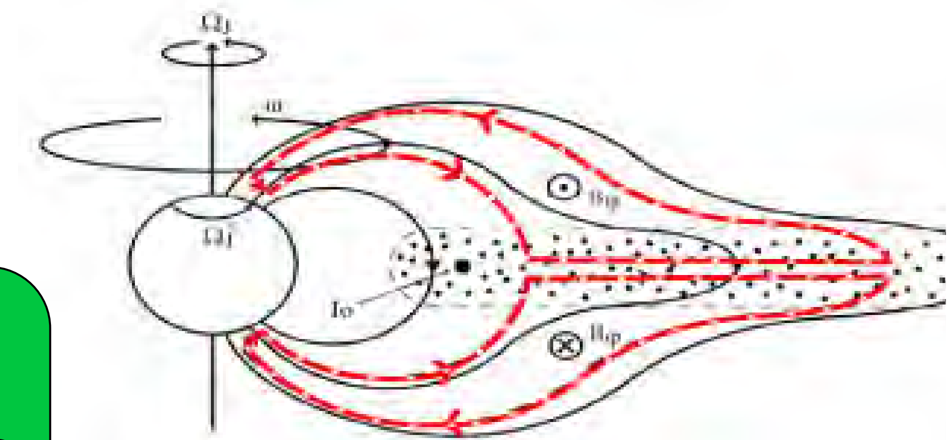
Coupling the Plasma to the Flywheel

Khurana 2001



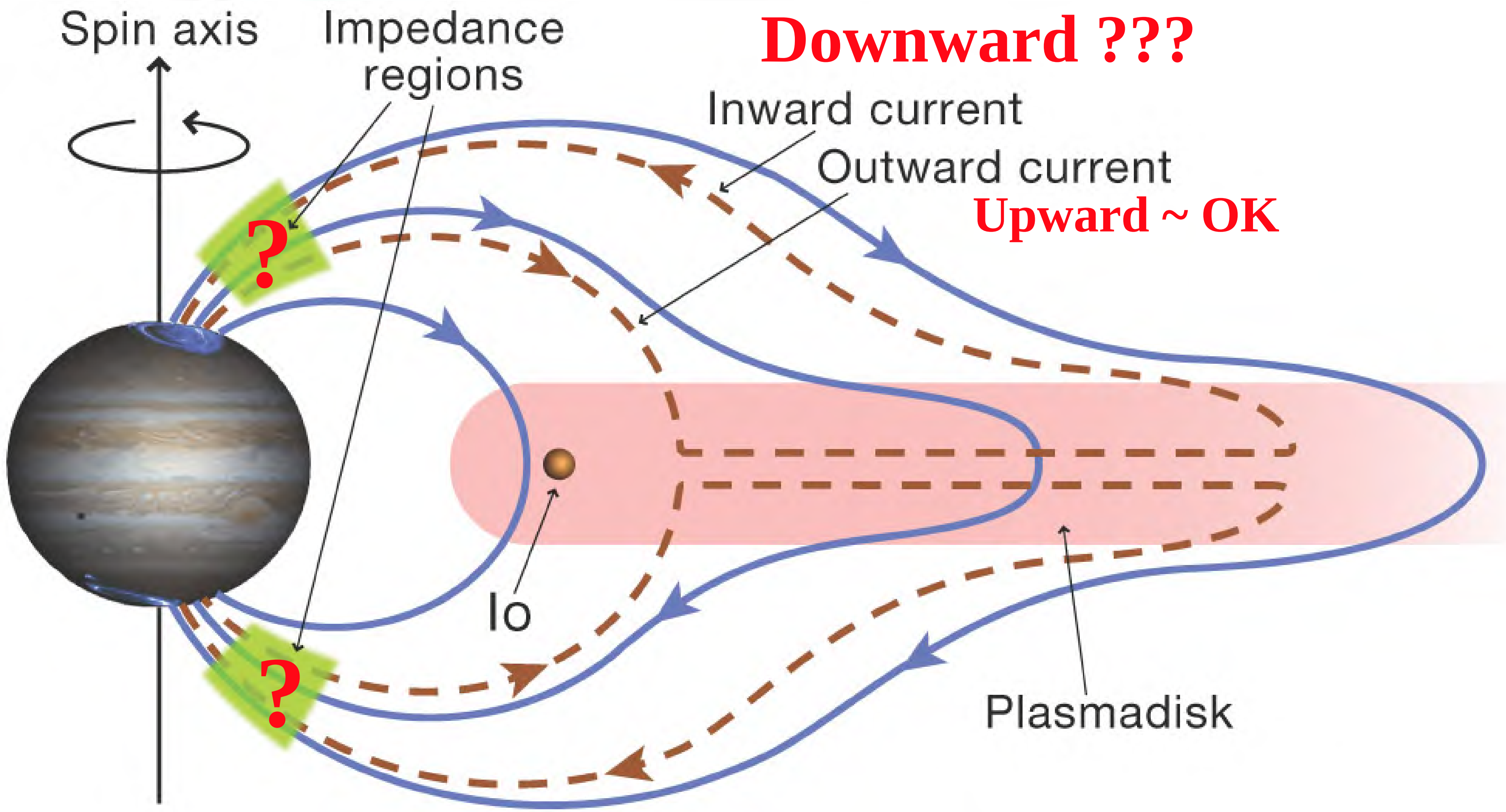
- As plasma from Io moves outwards its rotation decreases (conservation of angular momentum)
- Sub-corotating plasma pulls back the magnetic field
- Curl **B** -> radial current J_r
- J_r x **B** force enforces rotation

Field-aligned currents couple magnetosphere to Jupiter’s rotation



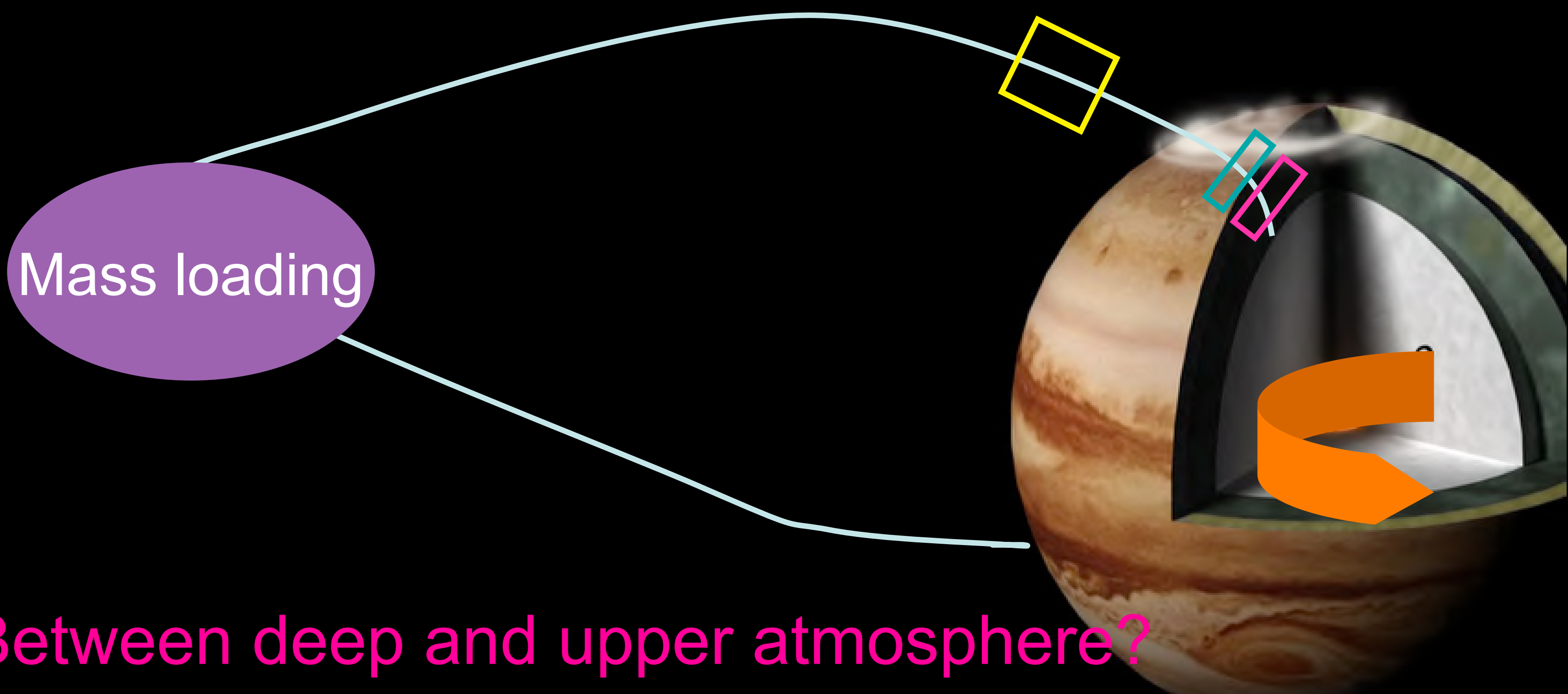
Cowley & Bunce 2001

The aurora is the signature of Jupiter's attempt to spin up its magnetosphere



Parallel electric fields: potential layers, $\phi_{||}$, "double layers"

Where is the clutch slipping?



A - Between deep and upper atmosphere?

B - Between upper atmosphere and ionosphere?

C - Lack of current-carriers in magnetosphere-> $E_{||}$?

What if there are strong thermospheric winds that drive circulation in the ionosphere – What might be the manifestation in the magnetosphere?

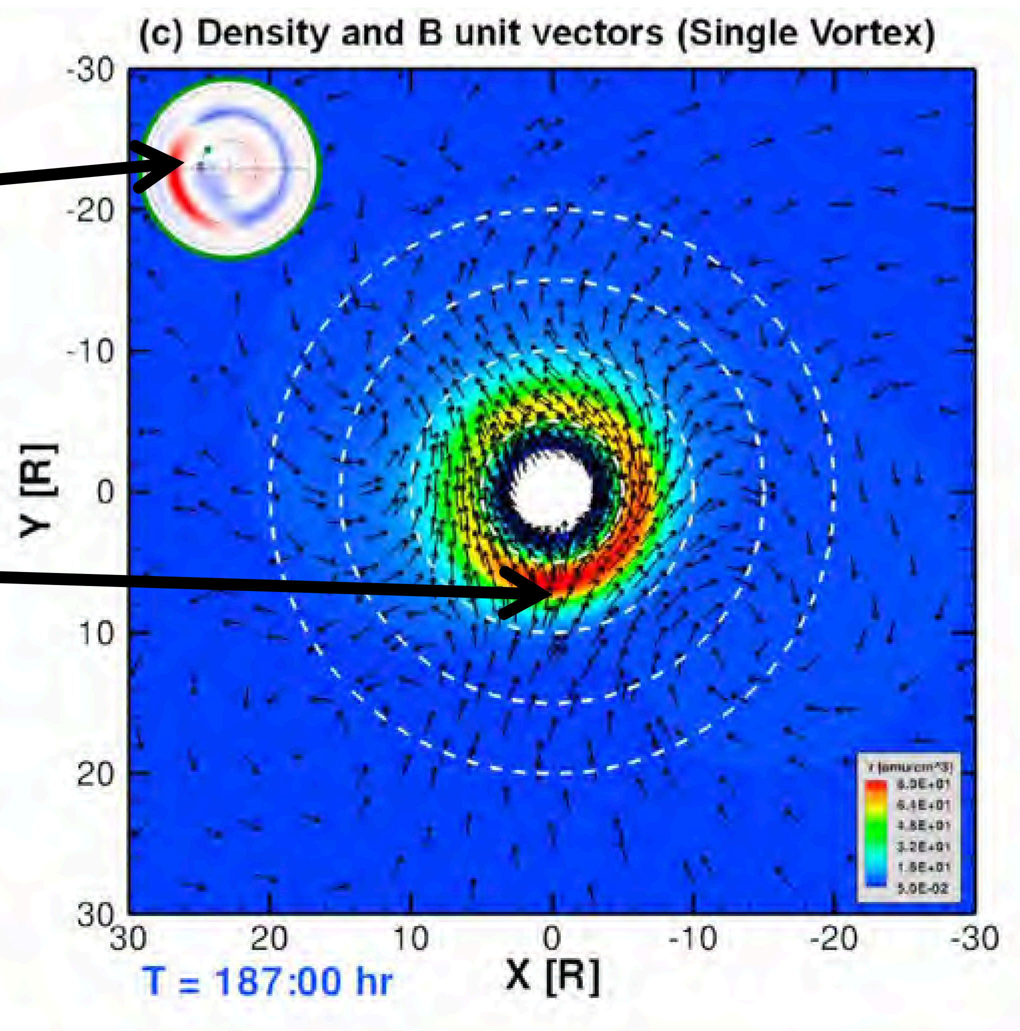
Hint: Think of a very symmetric magnetosphere – e.g. Saturn

What if there are strong thermospheric winds that drive circulation in the ionosphere – What might be the manifestation in the magnetosphere?

SATURN

Vortex in ionosphere

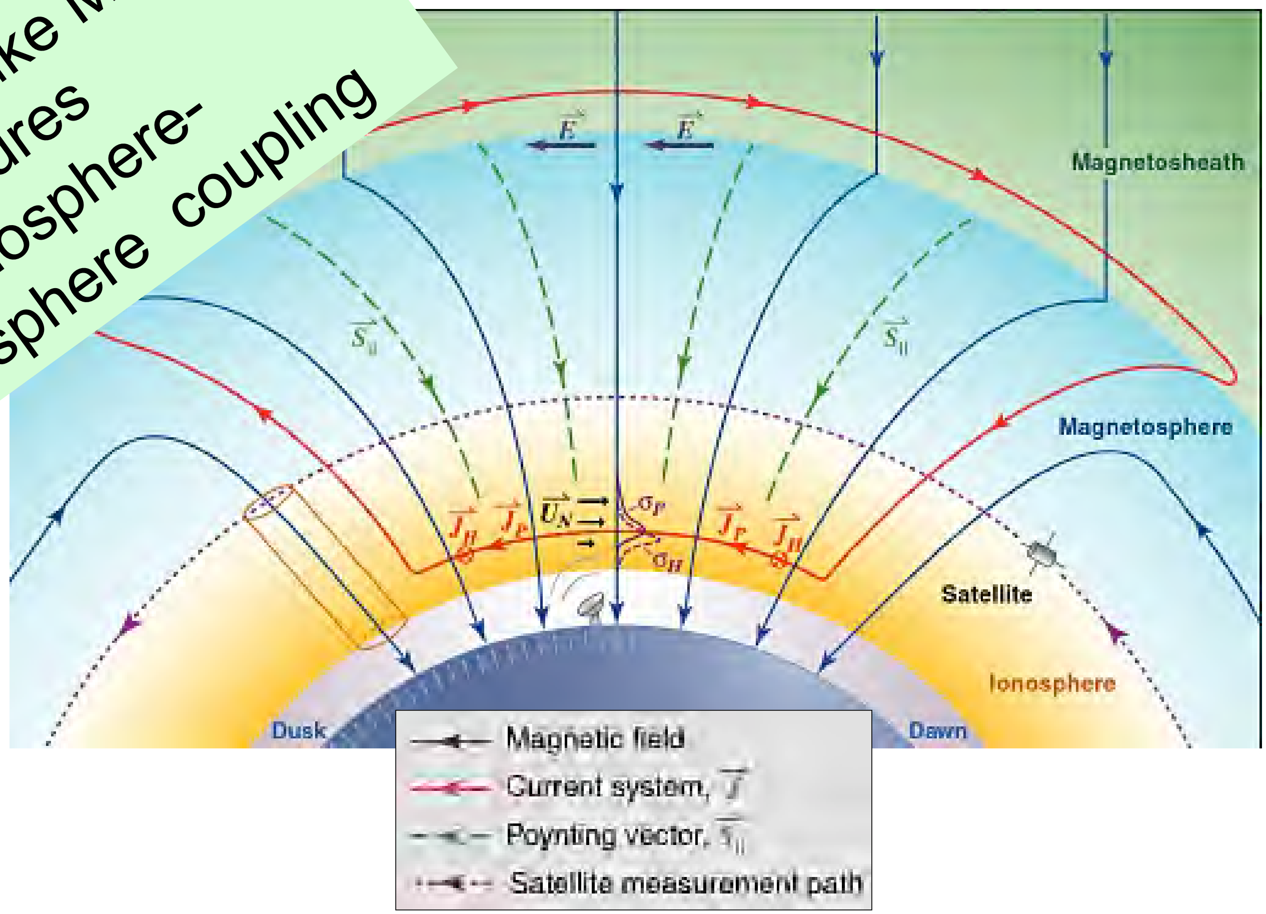
Produces longitudinal asymmetries in otherwise symmetric magnetosphere

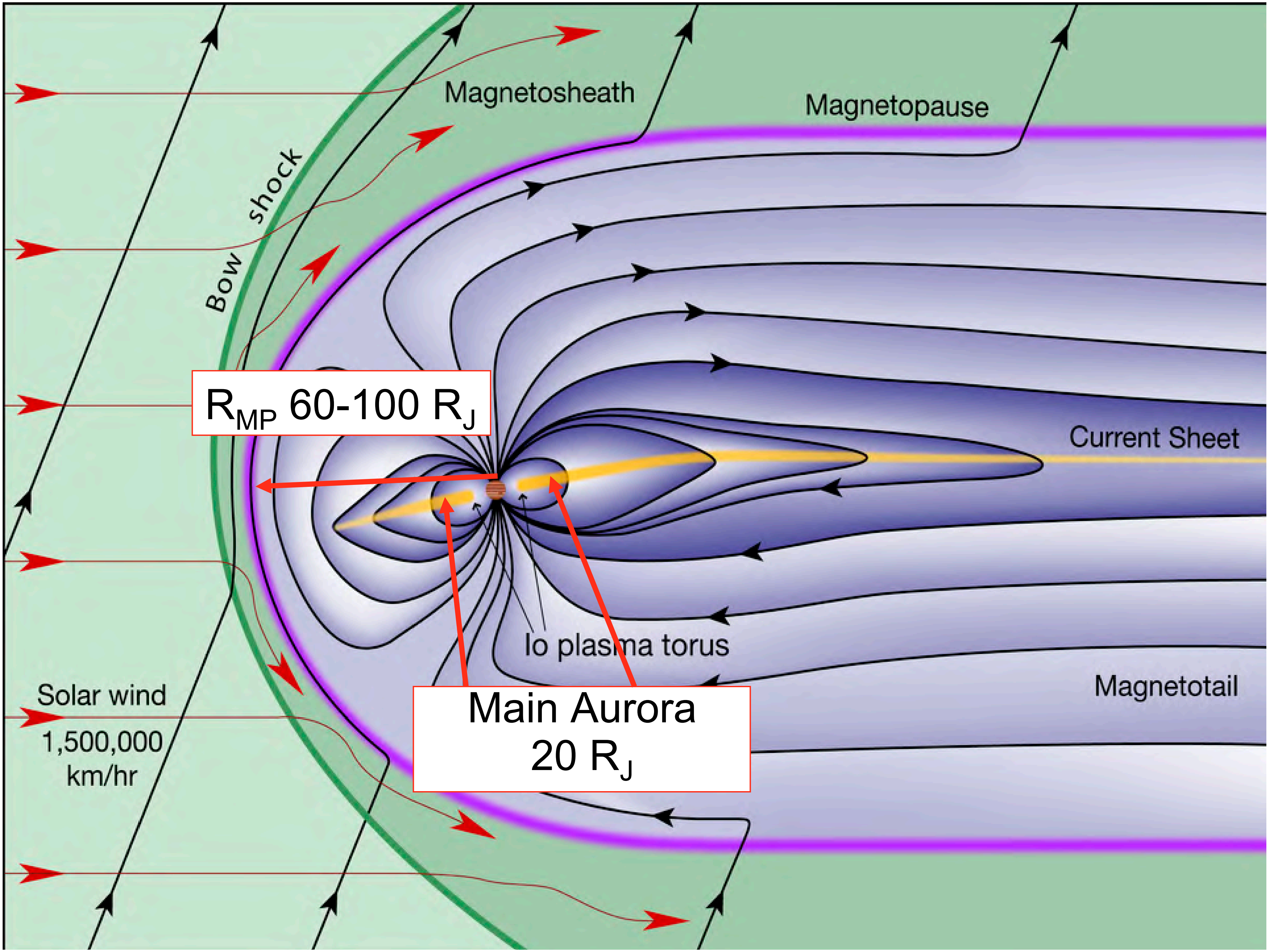


Jia, Kivelson, Gombosi (2012)

Ionosphere - Sets boundary conditions for magnetospheric dynamics

Rod Heelis' & Luke Moore's
Lectures
On ionosphere-
magnetosphere coupling

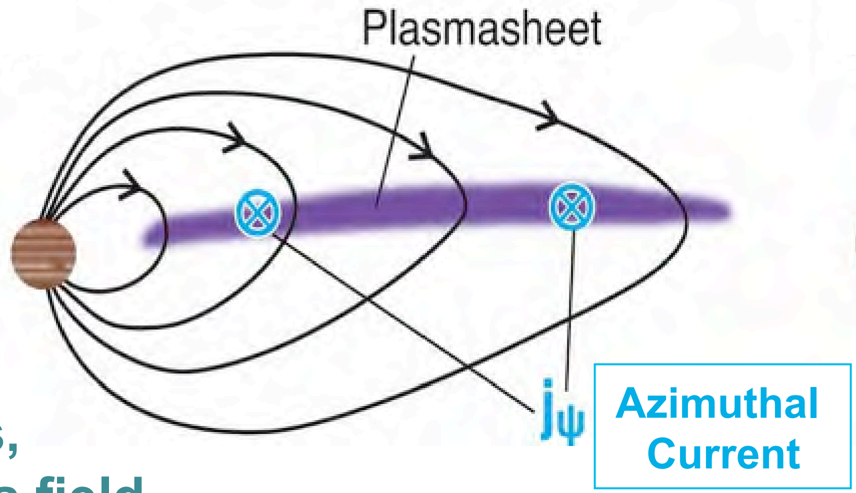


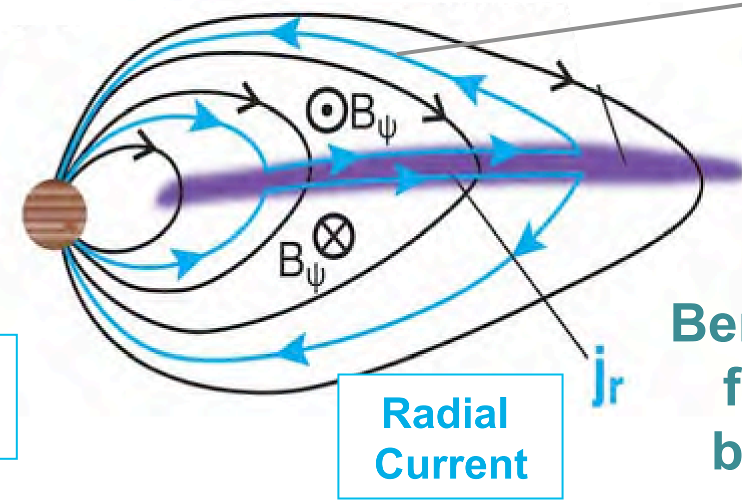

Magnetosheath
Magnetopause
Bow shock
R_{MP} 60-100 R_J
Current Sheet
Io plasma torus
Main Aurora
20 R_J
Solar wind
1,500,000
km/hr
Magnetotail

Configuration

$\nabla \times B_{observed} \rightarrow J$

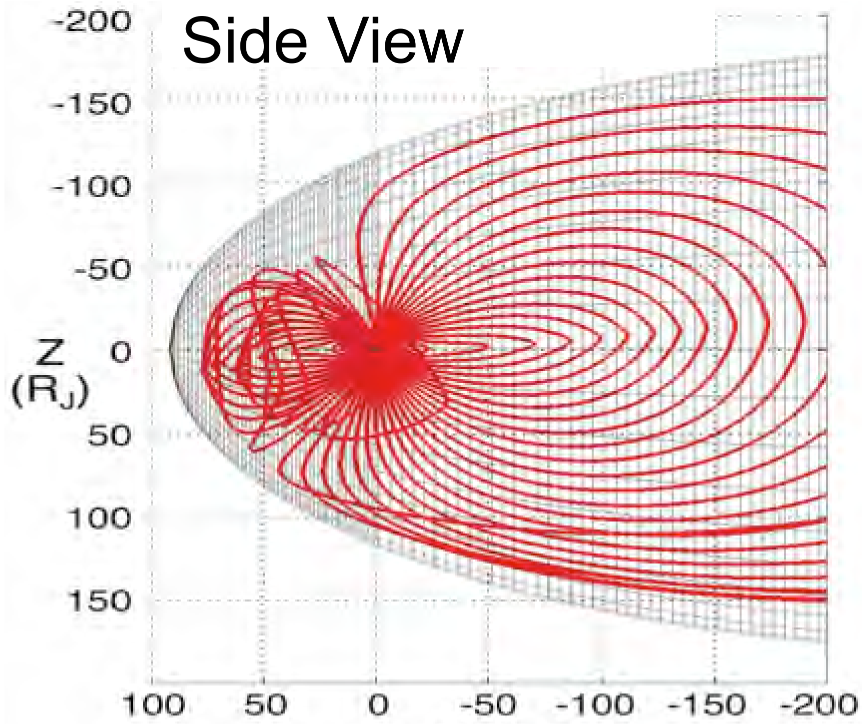
$\nabla \cdot J = 0 \rightarrow J_{||}$

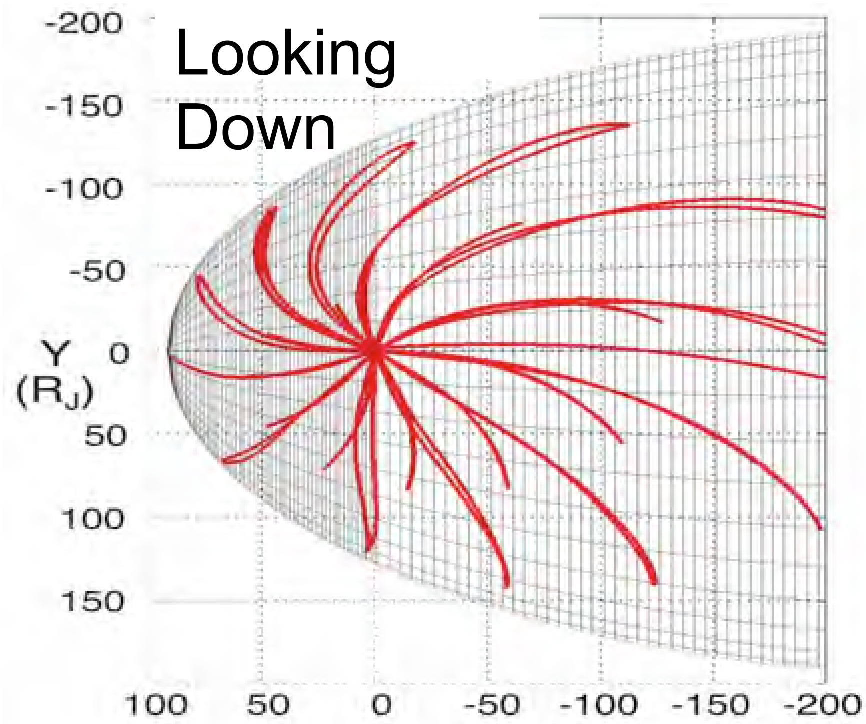




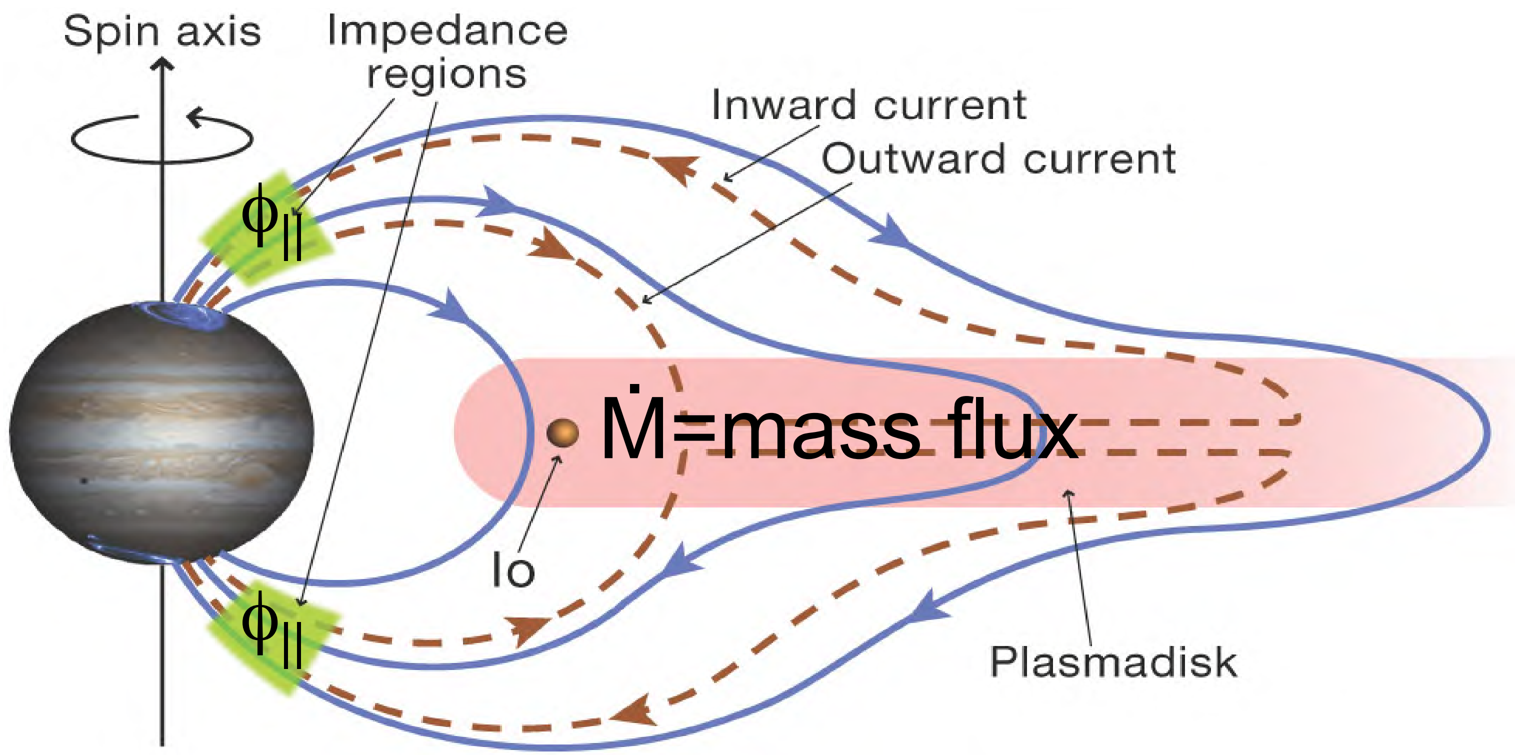
Expands, stretches field

Bends field back





(De-)Coupling - 1

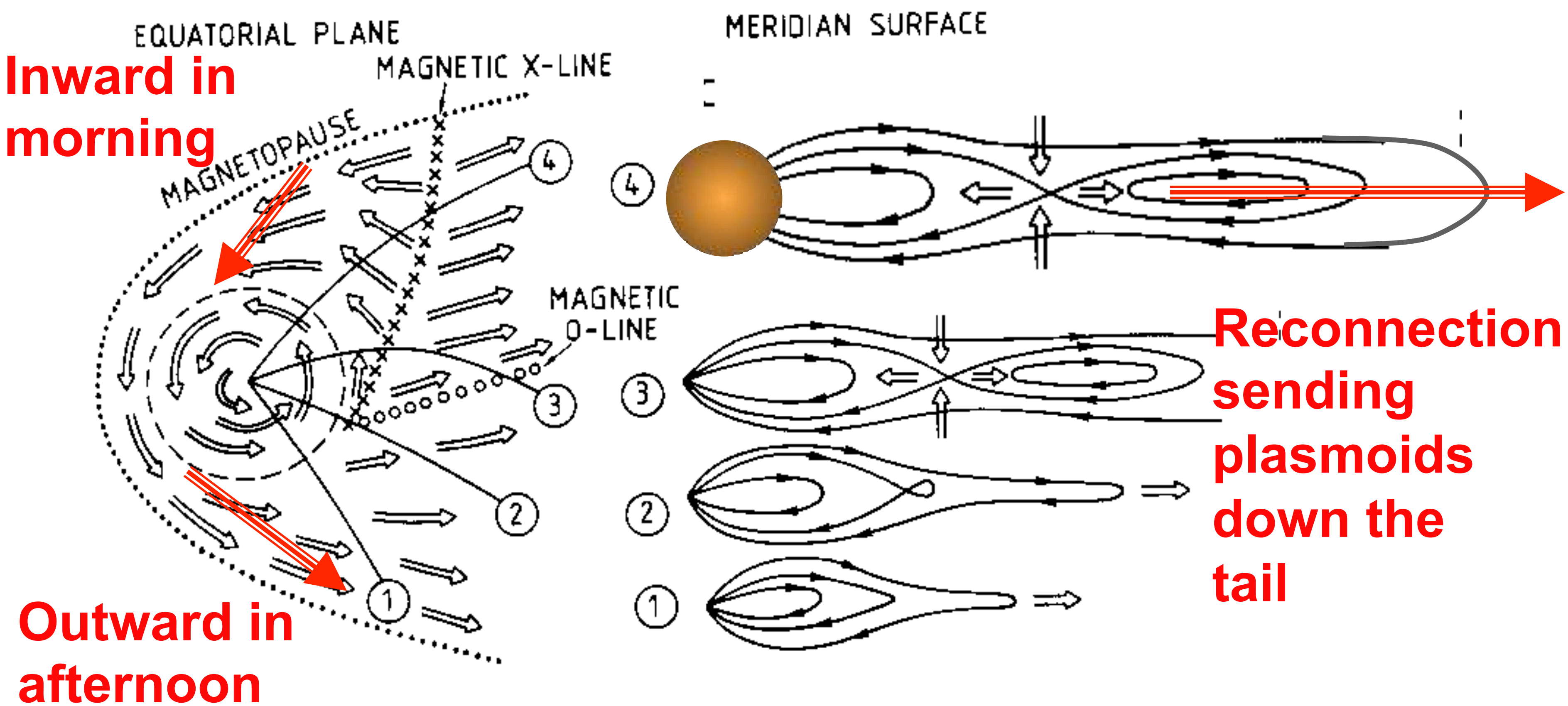


Magnetospheric Factors: $\dot{M}$, $\phi_{||}$, Alfven wave travel time
Ionosphere/Thermosphere factors: Σ_p, winds, chemistry, heating, radiation, etc;

Communication breaks down ~25R_J -> aurora
Magnetosphere & atmosphere stop talking > 60 R_J

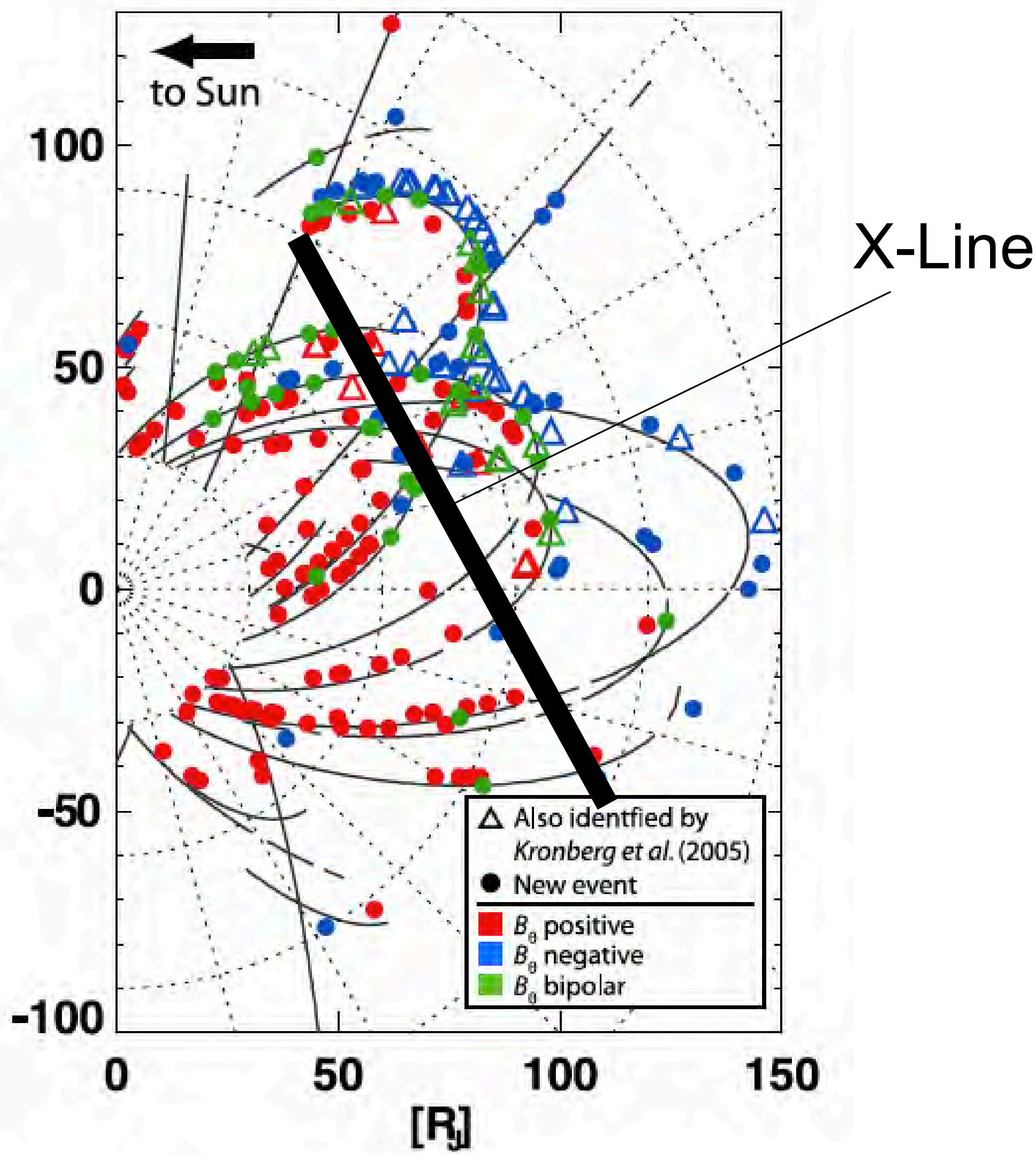
Vasyliunas Cycle

Vasyliunas
Cowley et al.
Southwood & Kivelson

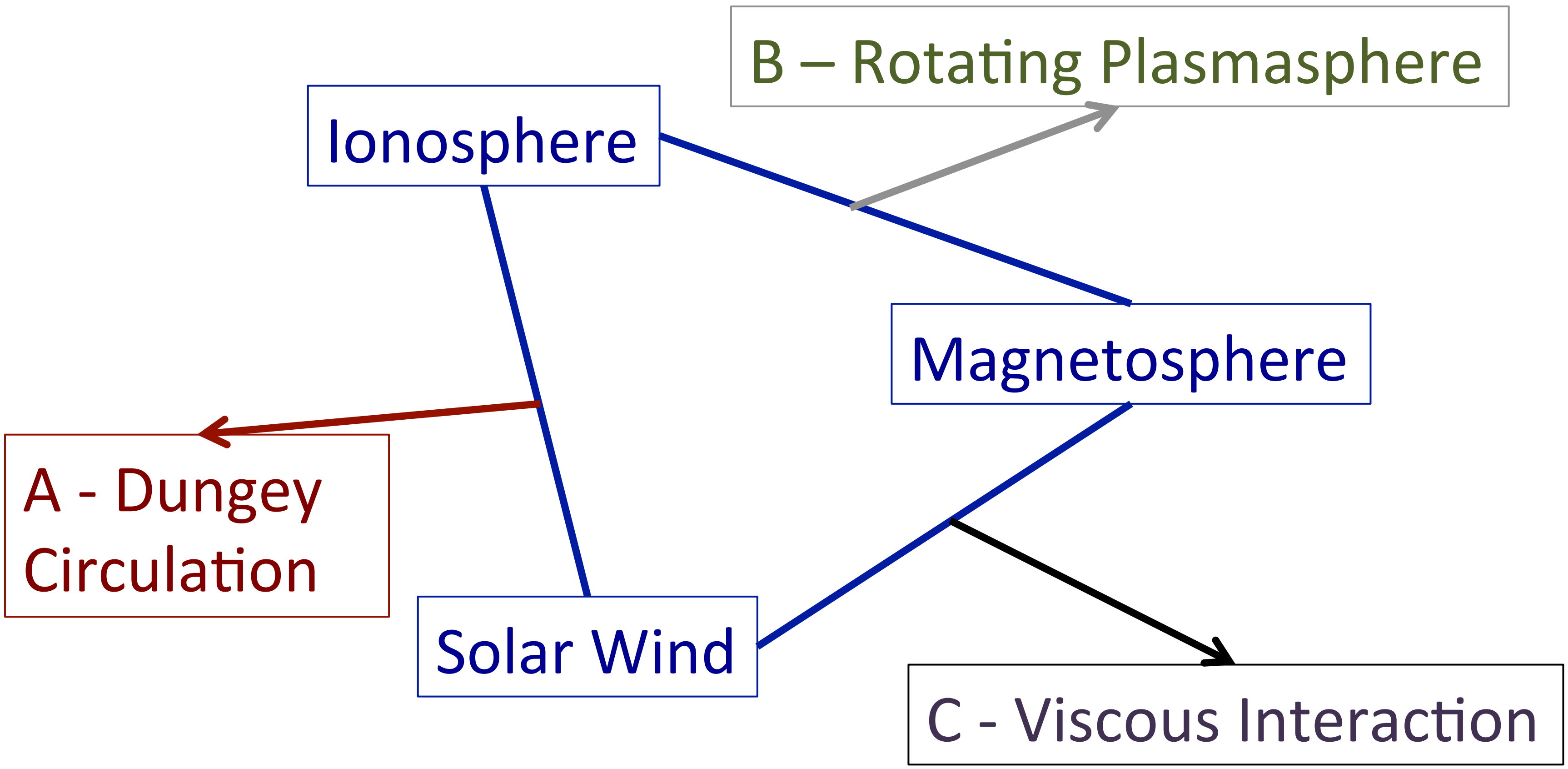


Vogt et al. 2010

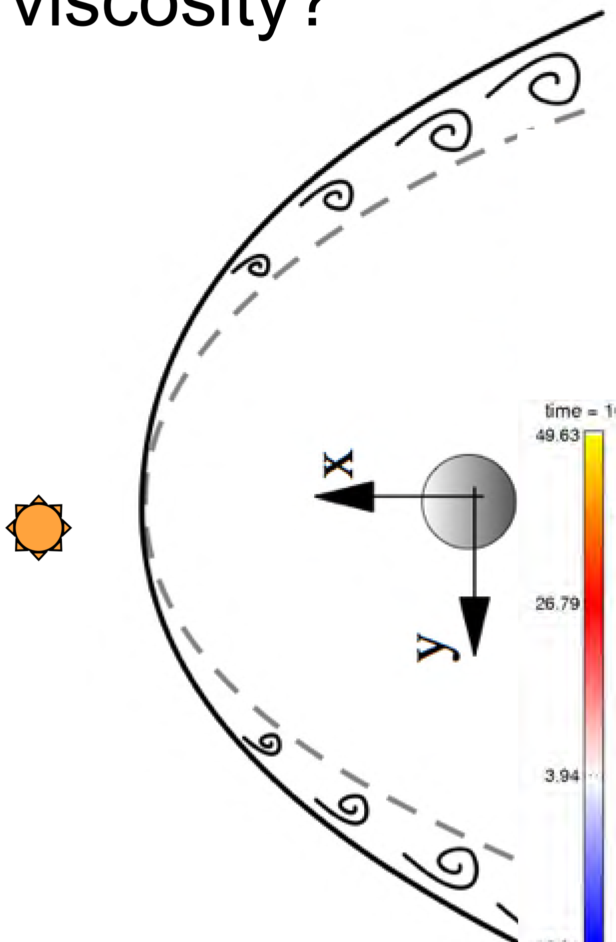
Observations of plasmoid events in *Galileo* data

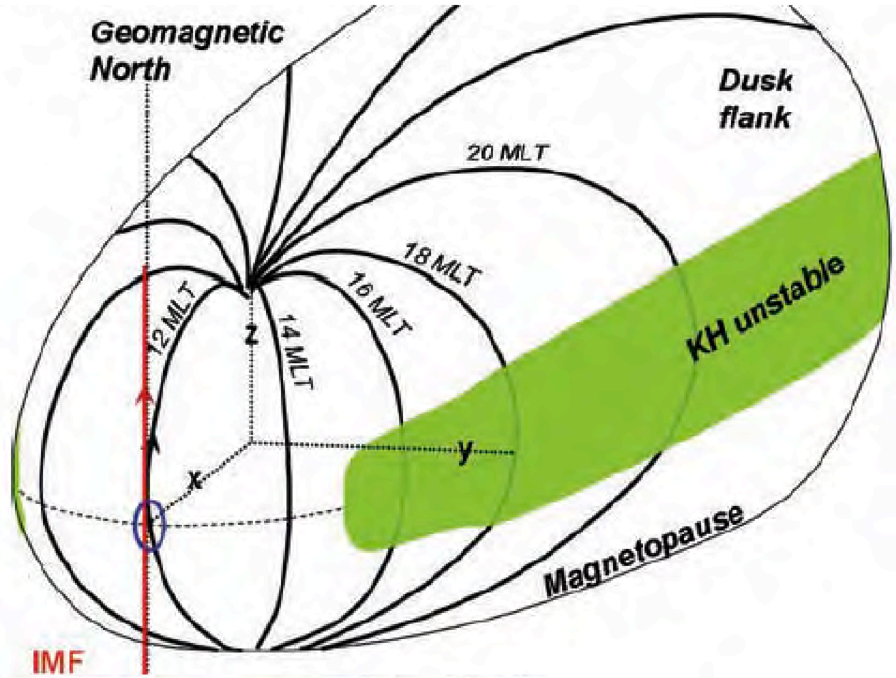


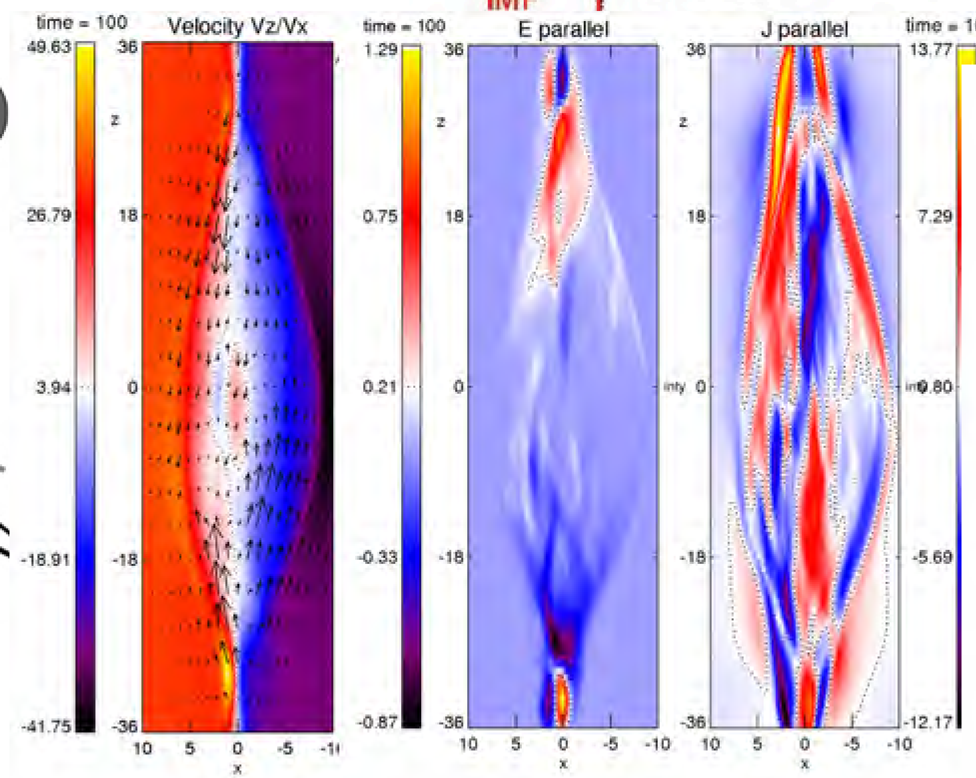
Which Form of Coupling Dominates
-> Controls Dynamics

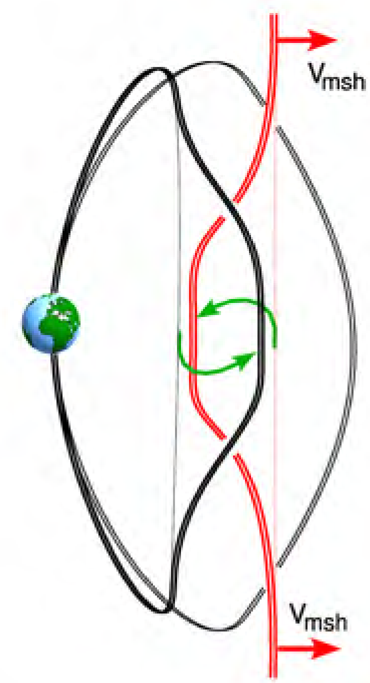


Can small-scale boundary-layer processes act like viscosity?





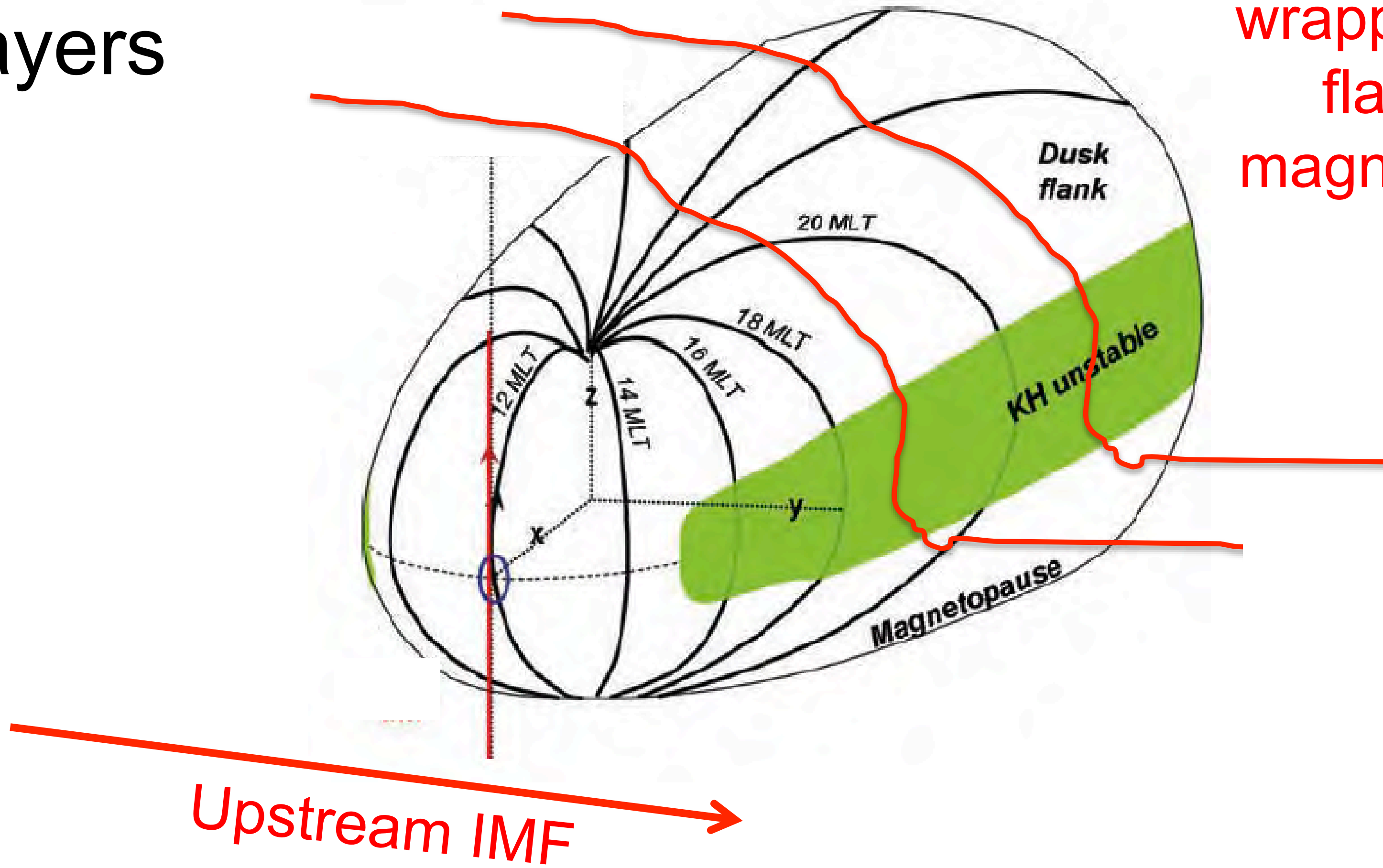


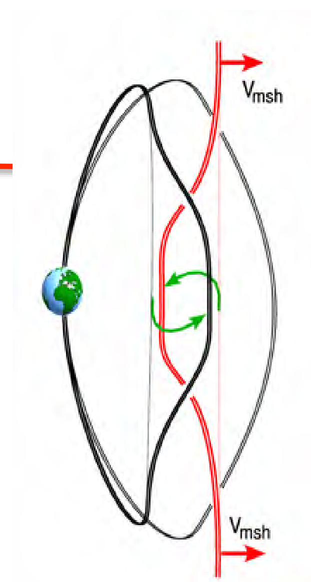


Otto & Fairfield 2001

Mass & momentum transport – boundary layers

Upstream IMF wrapped around flattened magnetospause





Small-scale, intermittant, turbulent, non-linear – reconnection

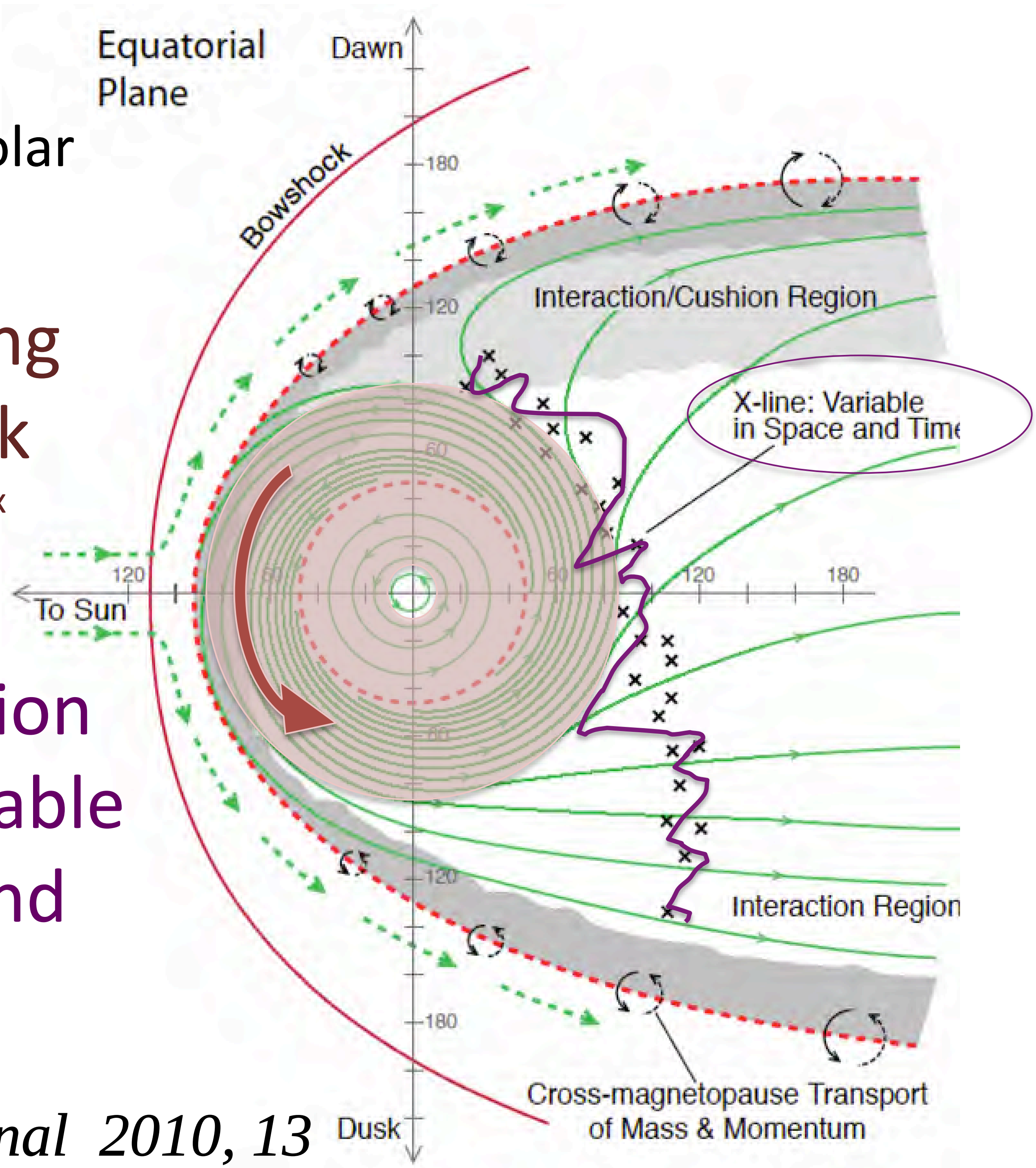
A bit like viscosity?

Combining Rotational and Solar Wind stresses

#1 Rotating plasmadisk

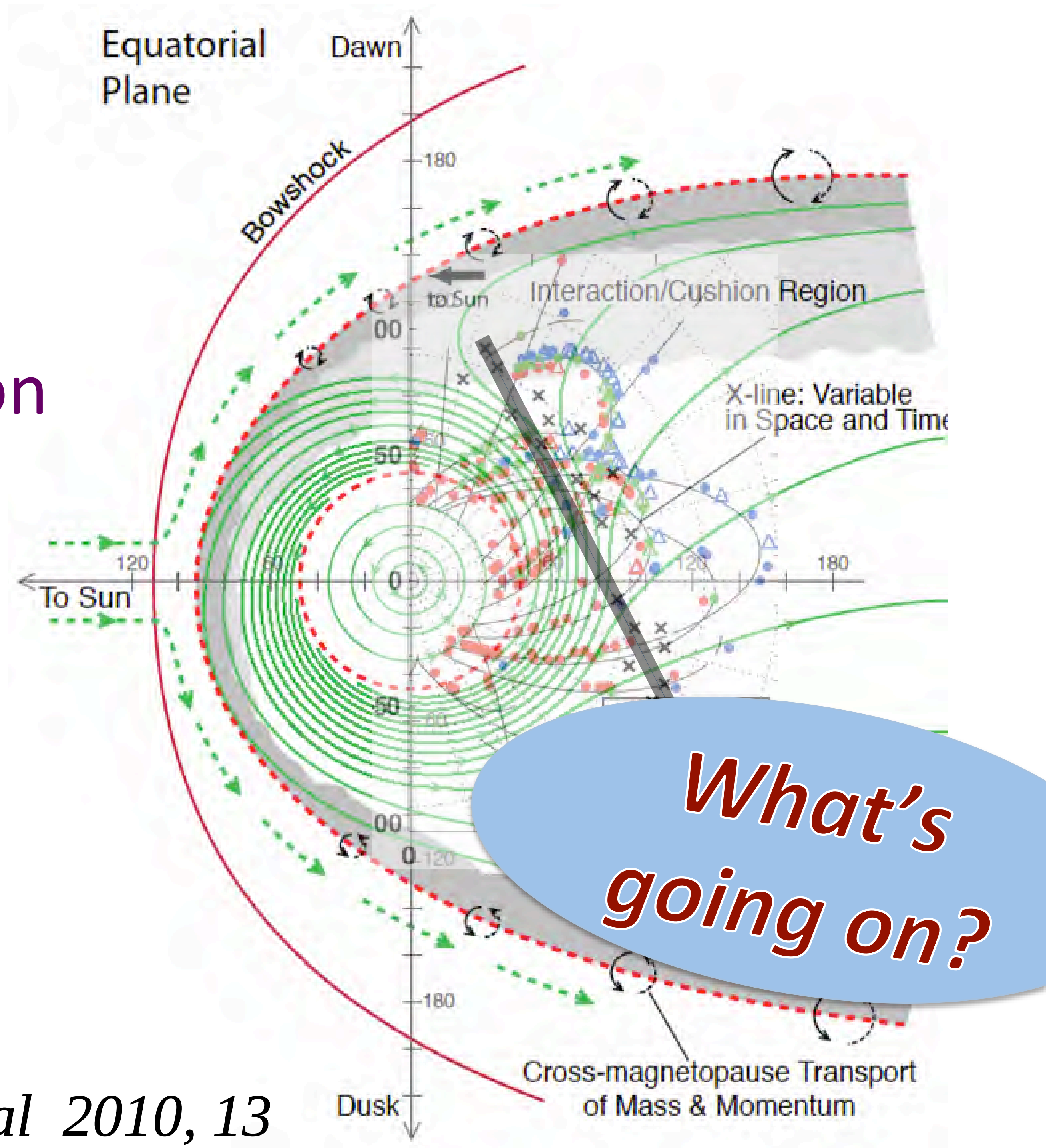
Non-uniform for flux conservation

#2 tail reconnection line is variable in space and time



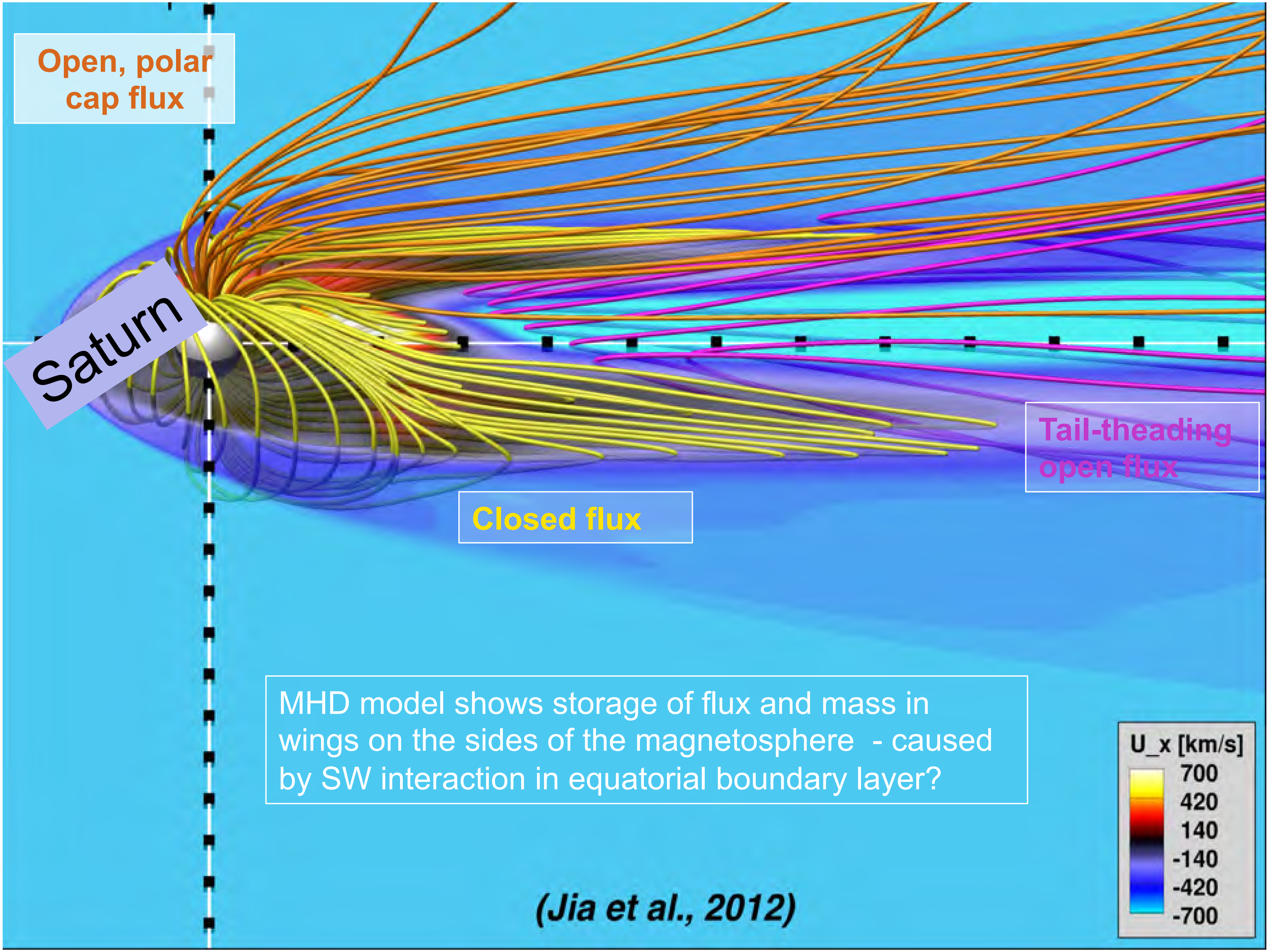
Delamere & Bagenal 2010, 13

#3 Large region on dusk flank with few observations



What's going on?

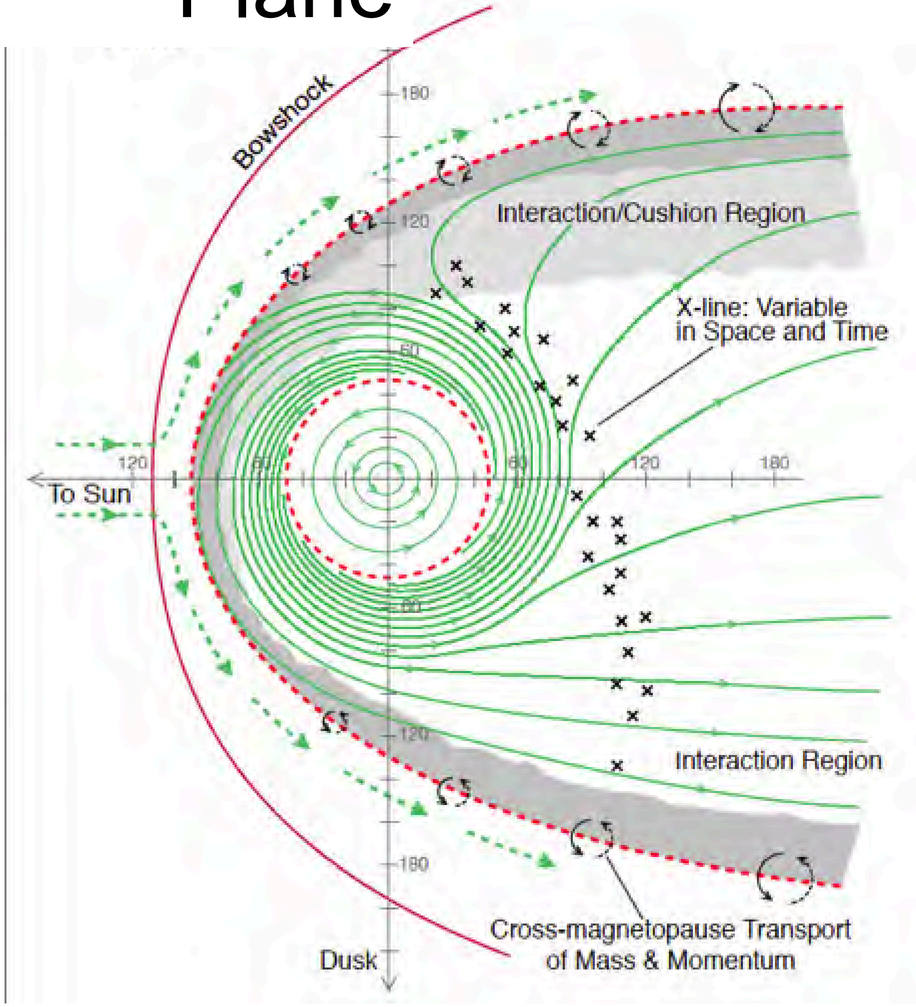
Delamere & Bagenal 2010, 13

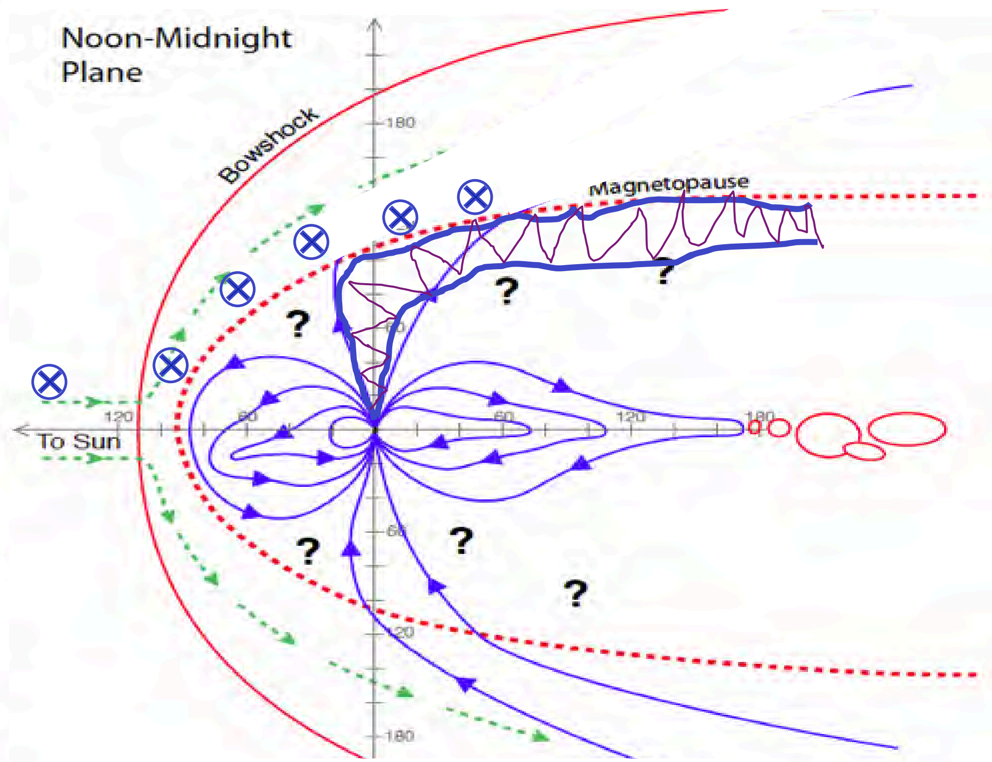

Open, polar
cap flux
Saturn
Tail-theading
open flux
Closed flux
MHD model shows storage of flux and mass in
wings on the sides of the magnetosphere - caused
by SW interaction in equatorial boundary layer?
(Jia et al., 2012)
U_x [km/s]
700
420
140
-140
-420
-700

Equatorial Plane

Noon-Midnight Plane

#4 Magnetosphere is flattened

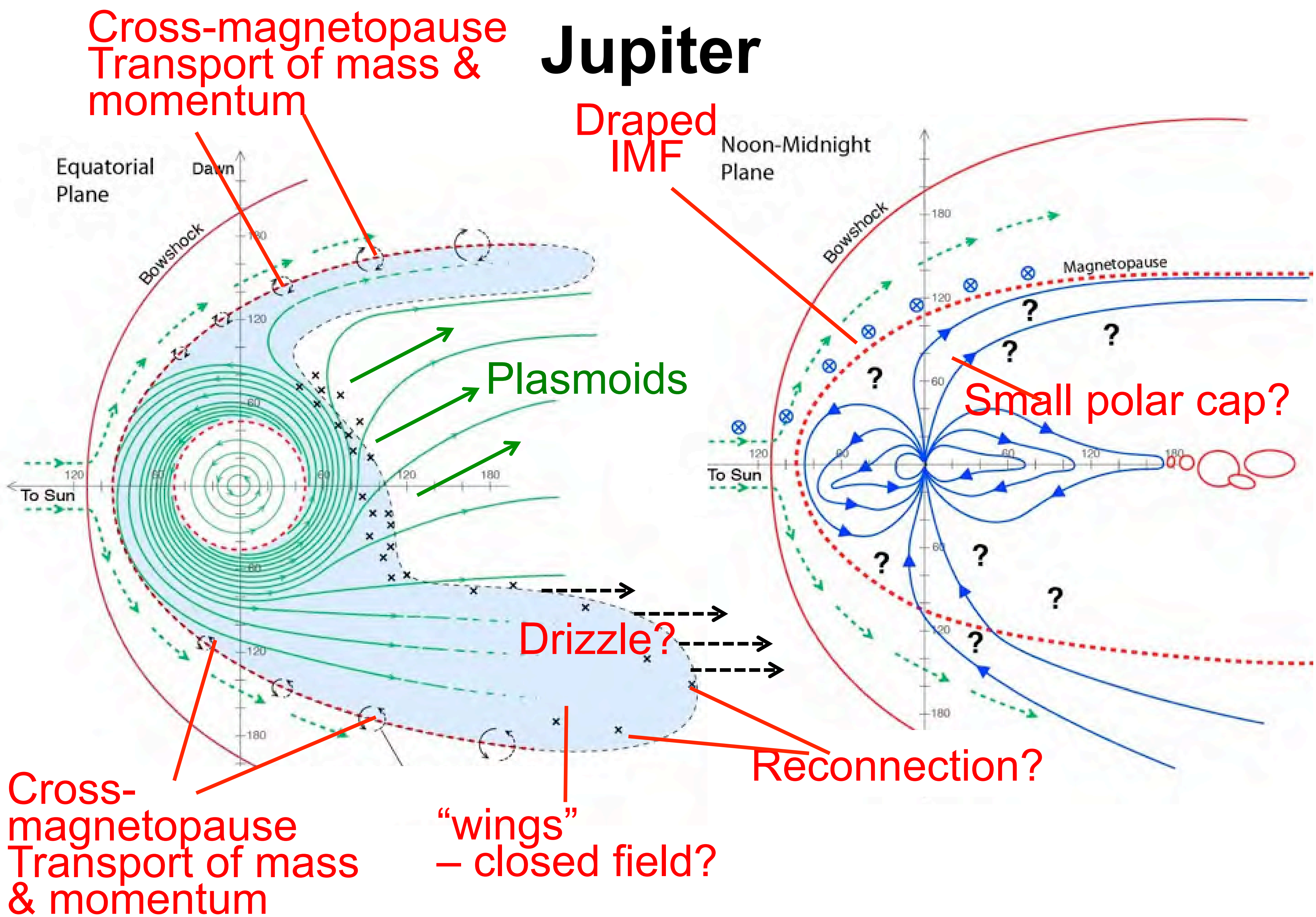




#5 Polar cap is small

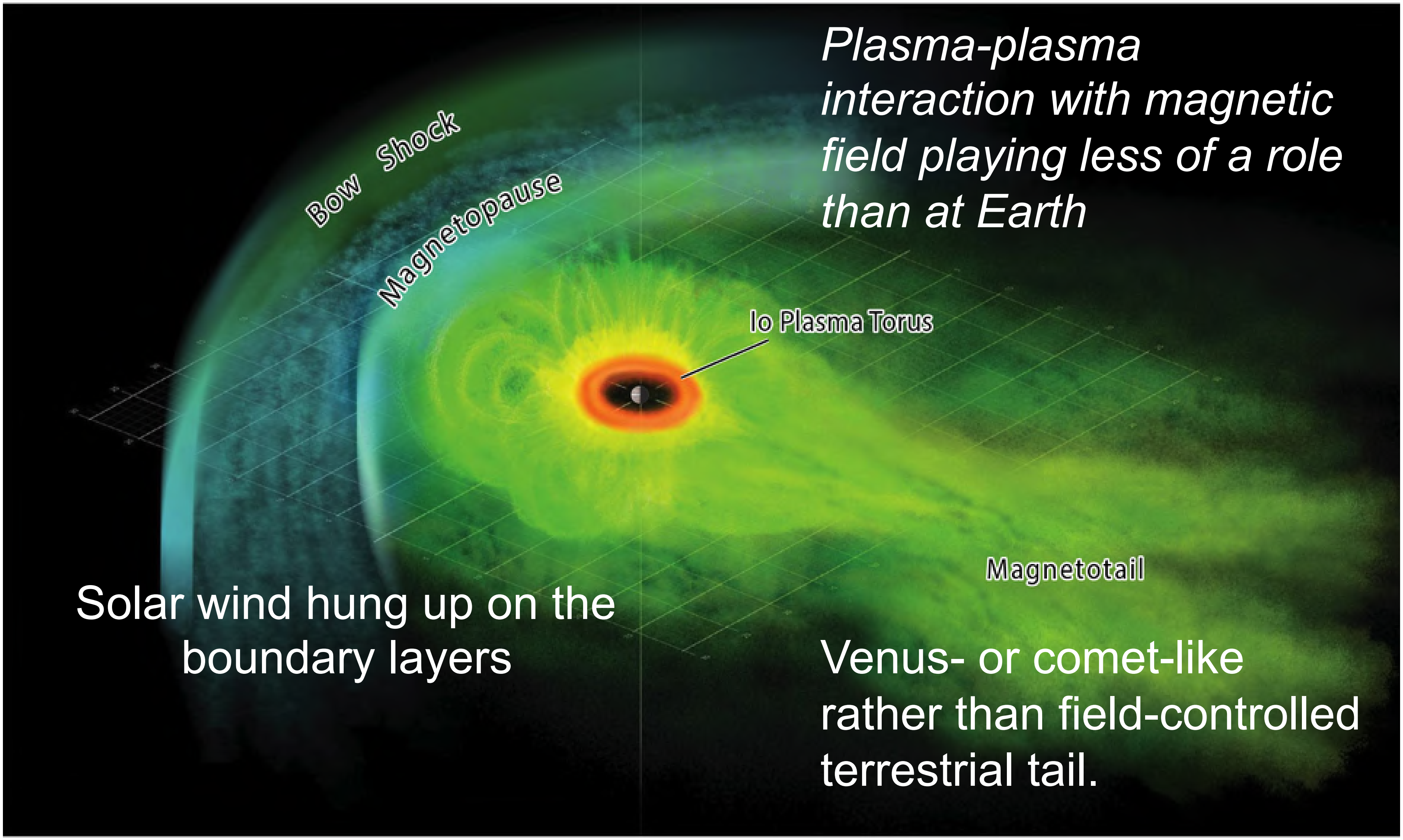
Delamere & Bagenal 2010

Jupiter



Delamere & Bagenal (2013)

Could Jupiter be a Colossal Comet?



Plasma-plasma interaction with magnetic field playing less of a role than at Earth

Solar wind hung up on the boundary layers

Venus- or comet-like rather than field-controlled terrestrial tail.

Juno

Arrives at Jupiter 2016!

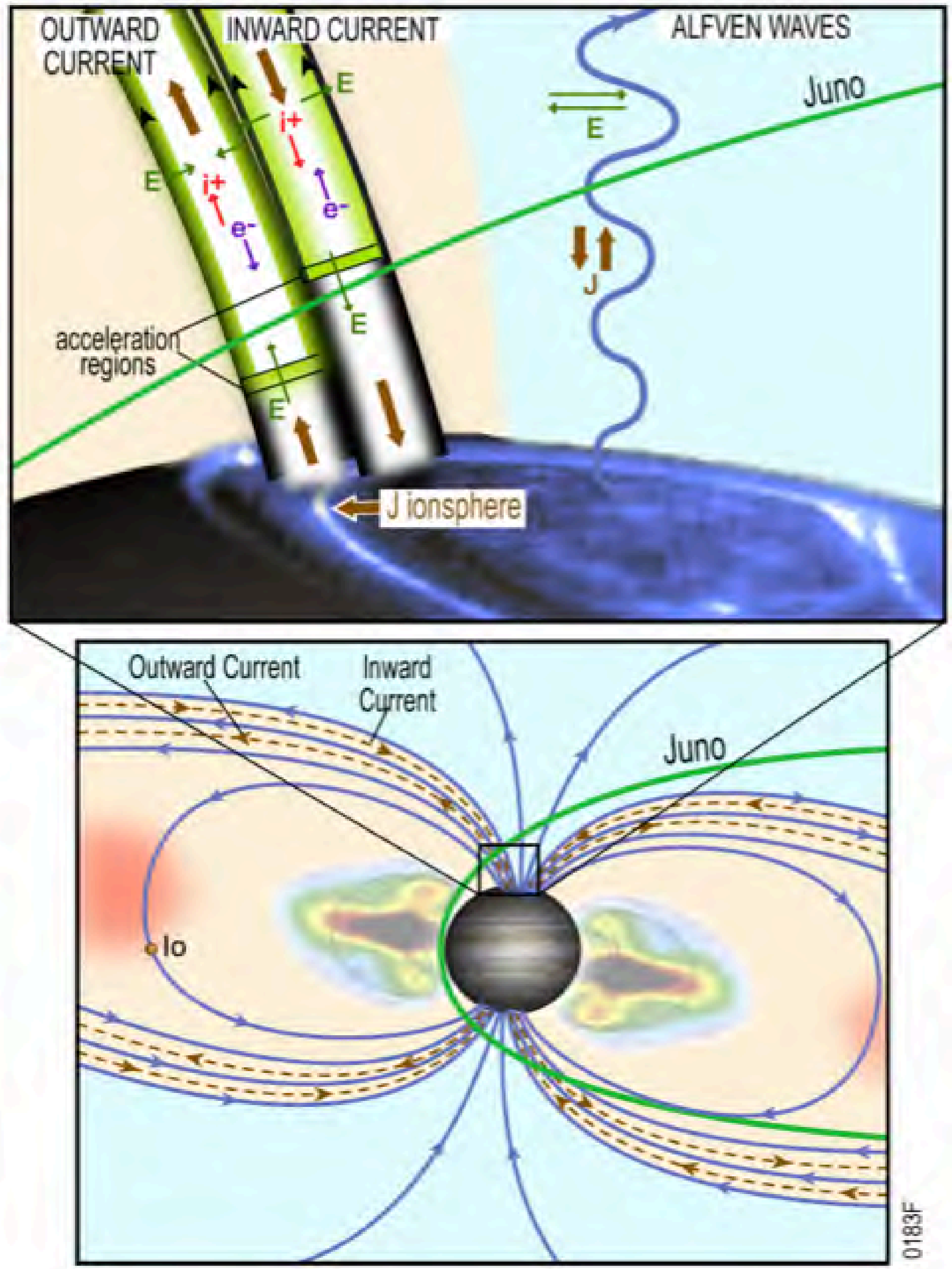
Polar Magnetosphere

Juno passes directly through auroral field lines

Measures particles precipitating into atmosphere creating aurora

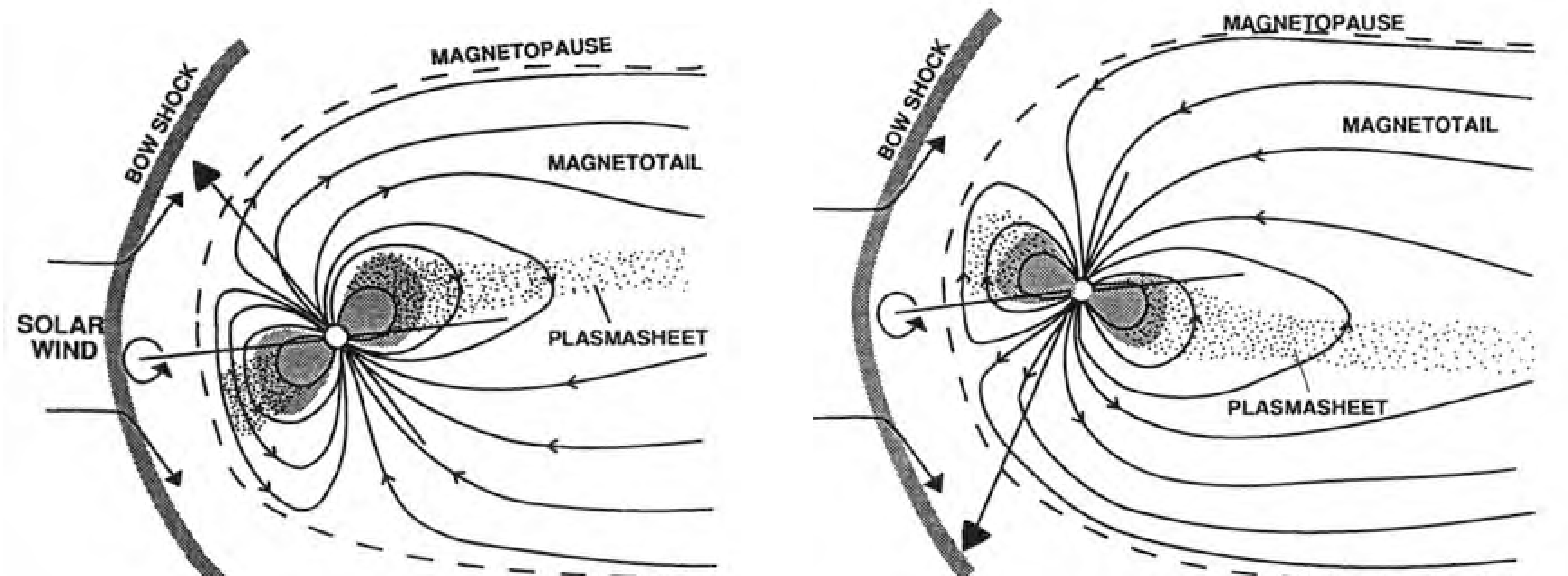
Plasma/radio waves reveal processes responsible for particle acceleration

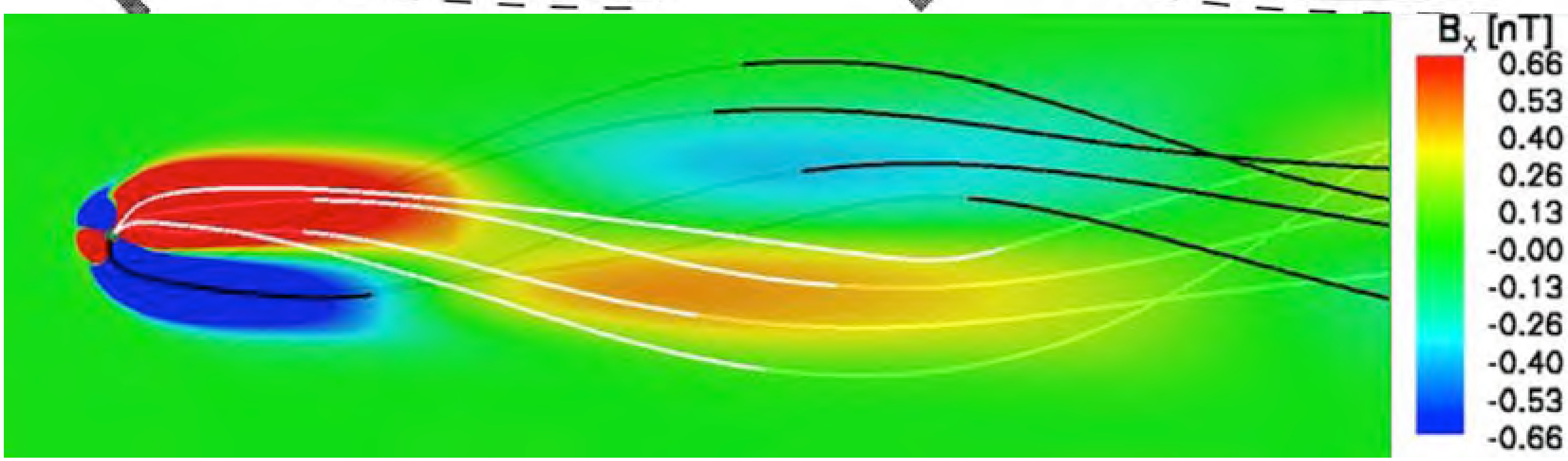
UV & IR images provides context for *in-situ* observations



Uranus

-Highly asymmetric,
-Highly non-dipolar
-Complex transport (SW + rotation)
-Multiple plasma sources (ionosphere + solar wind + satellites)

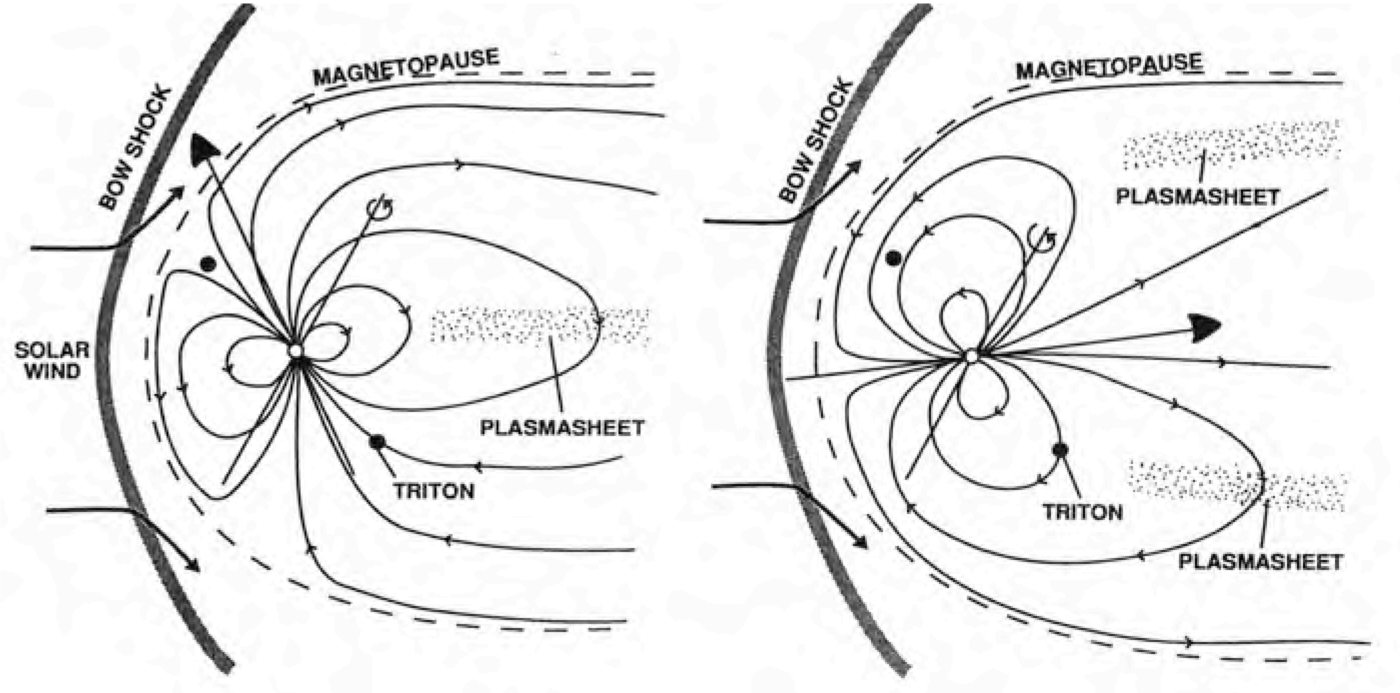


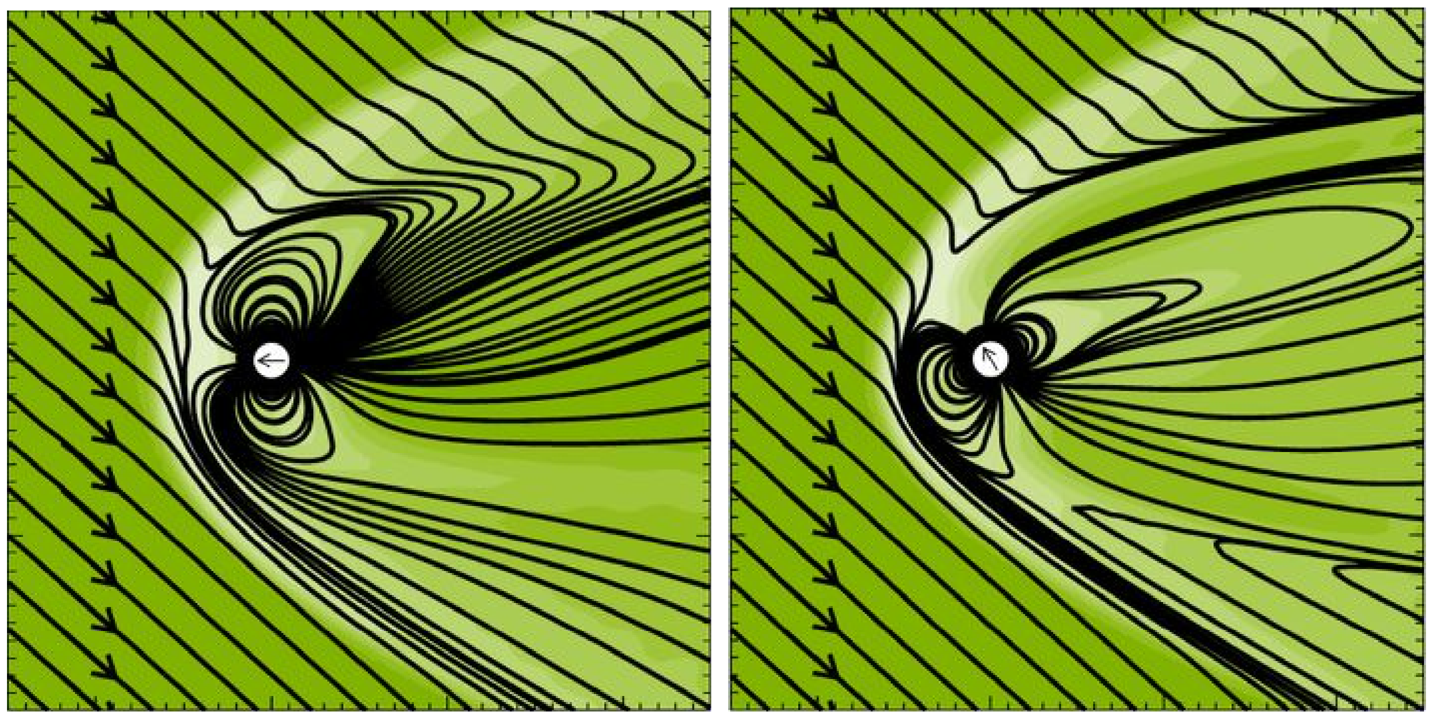


Toth et al.

Neptune

Similarly complex as Uranus



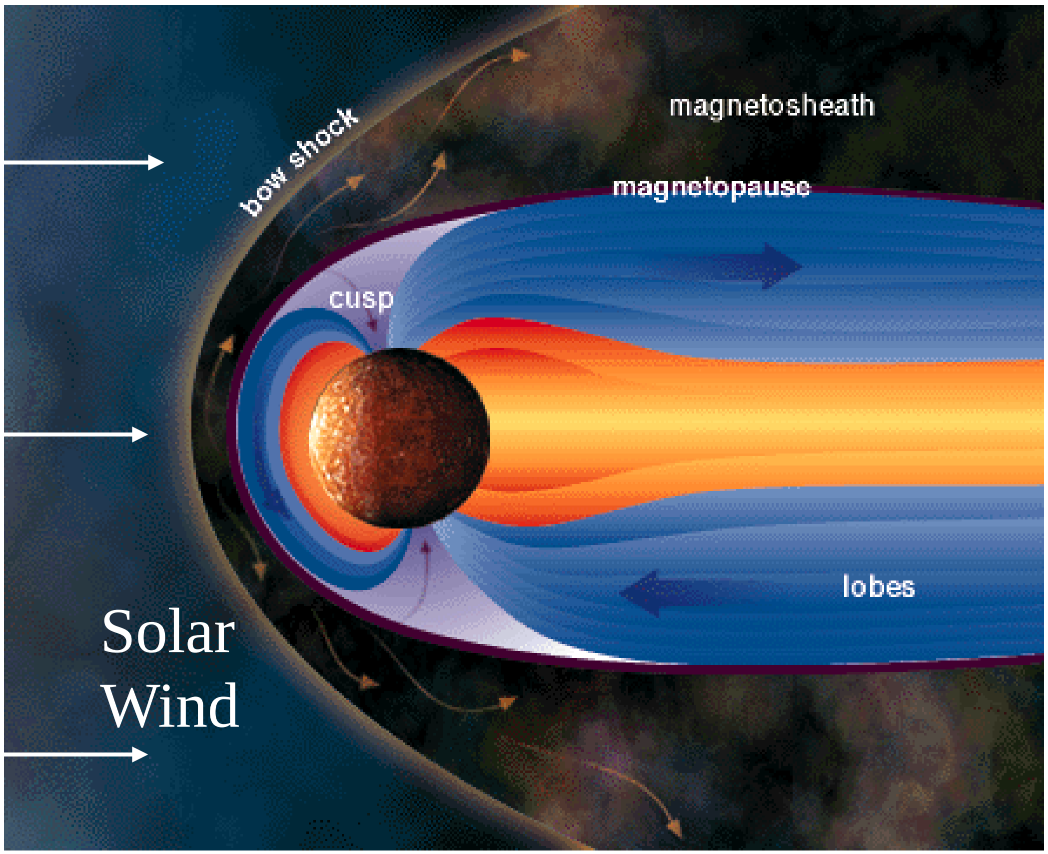


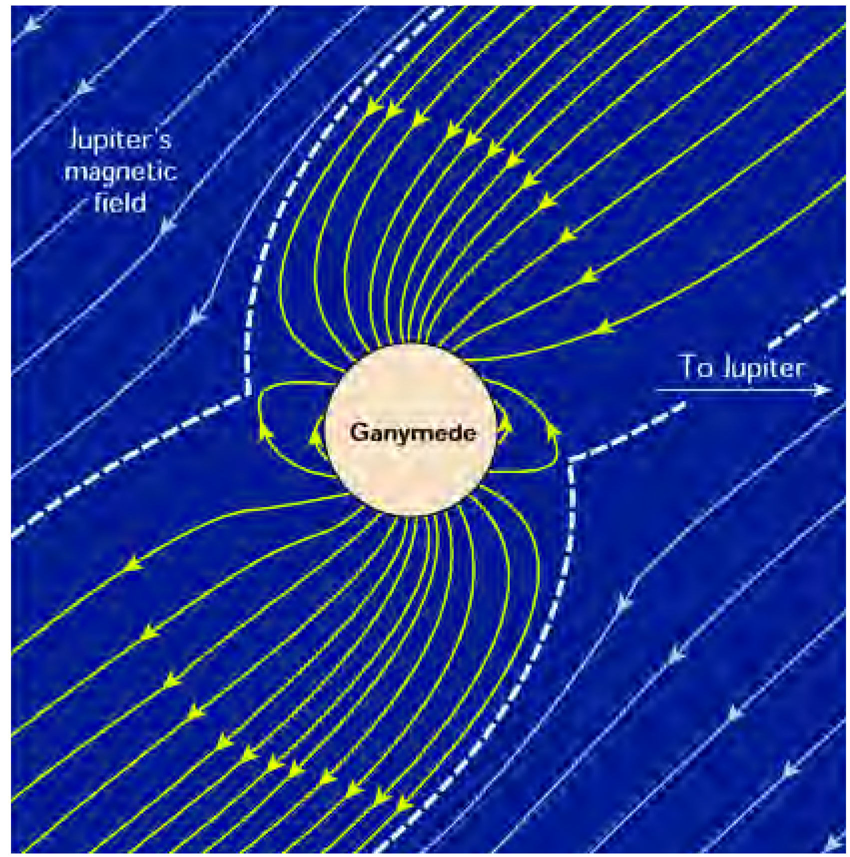
Zieger et al.

Mercury & Ganymede

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

Ganymede - Magnetic field detected by *Galileo* in 1996



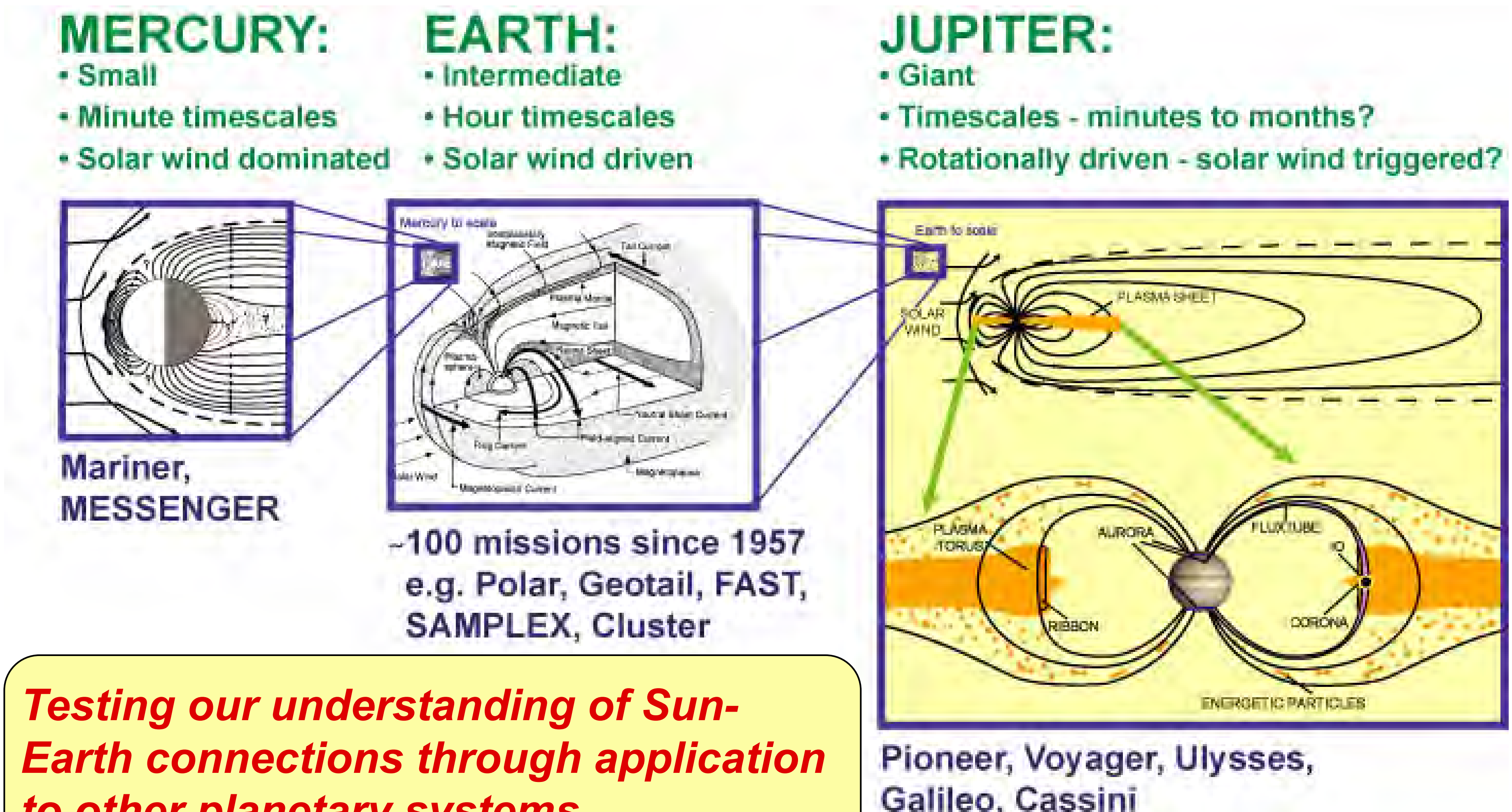


$B_{surface}$ ~ 1/100 Earth

Diameter of Earth

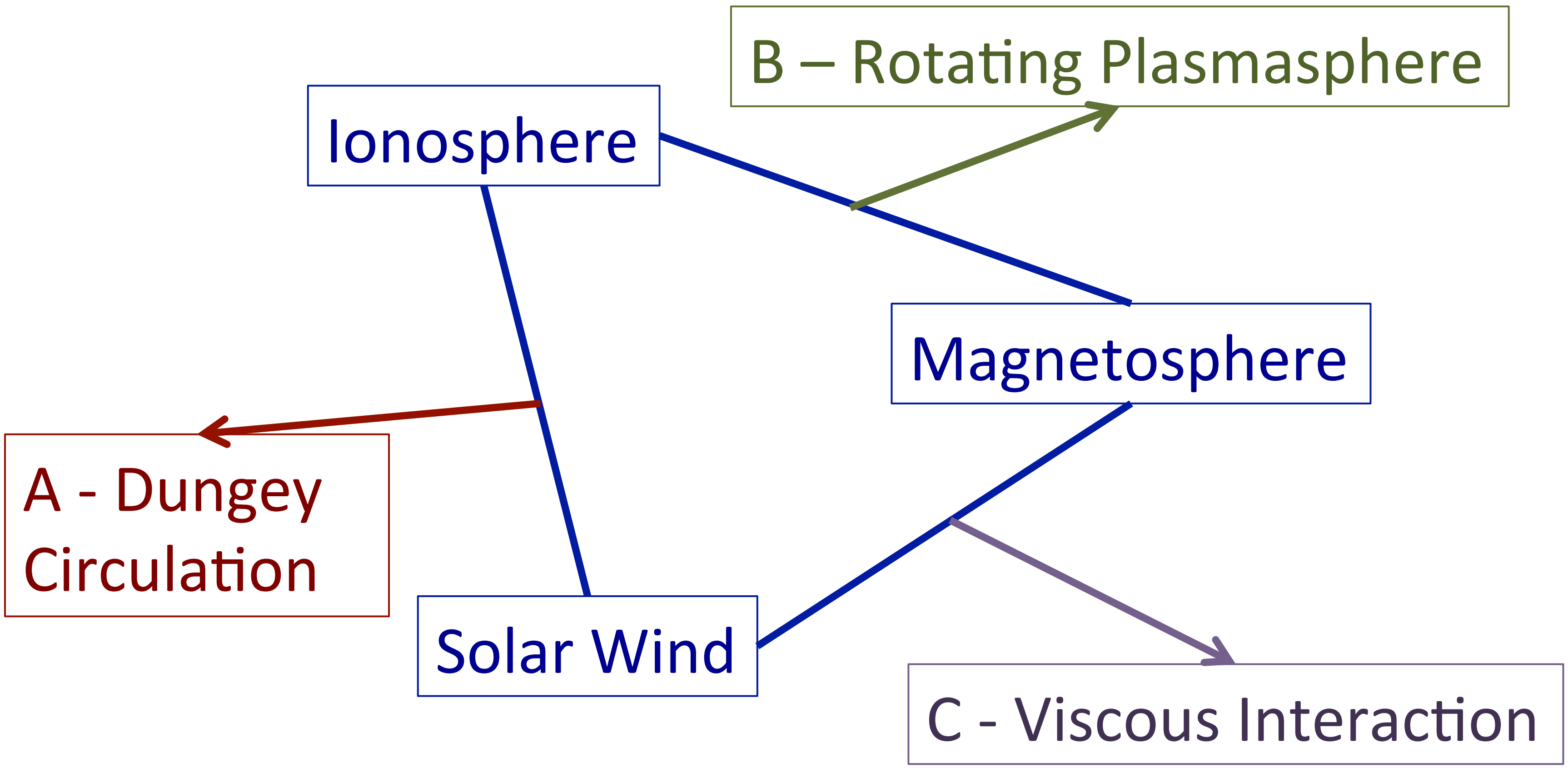
Planetary Magnetospheres

See vol. III ch. 7 & vol. I ch. 13



Testing our understanding of Sun-Earth connections through application to other planetary systems

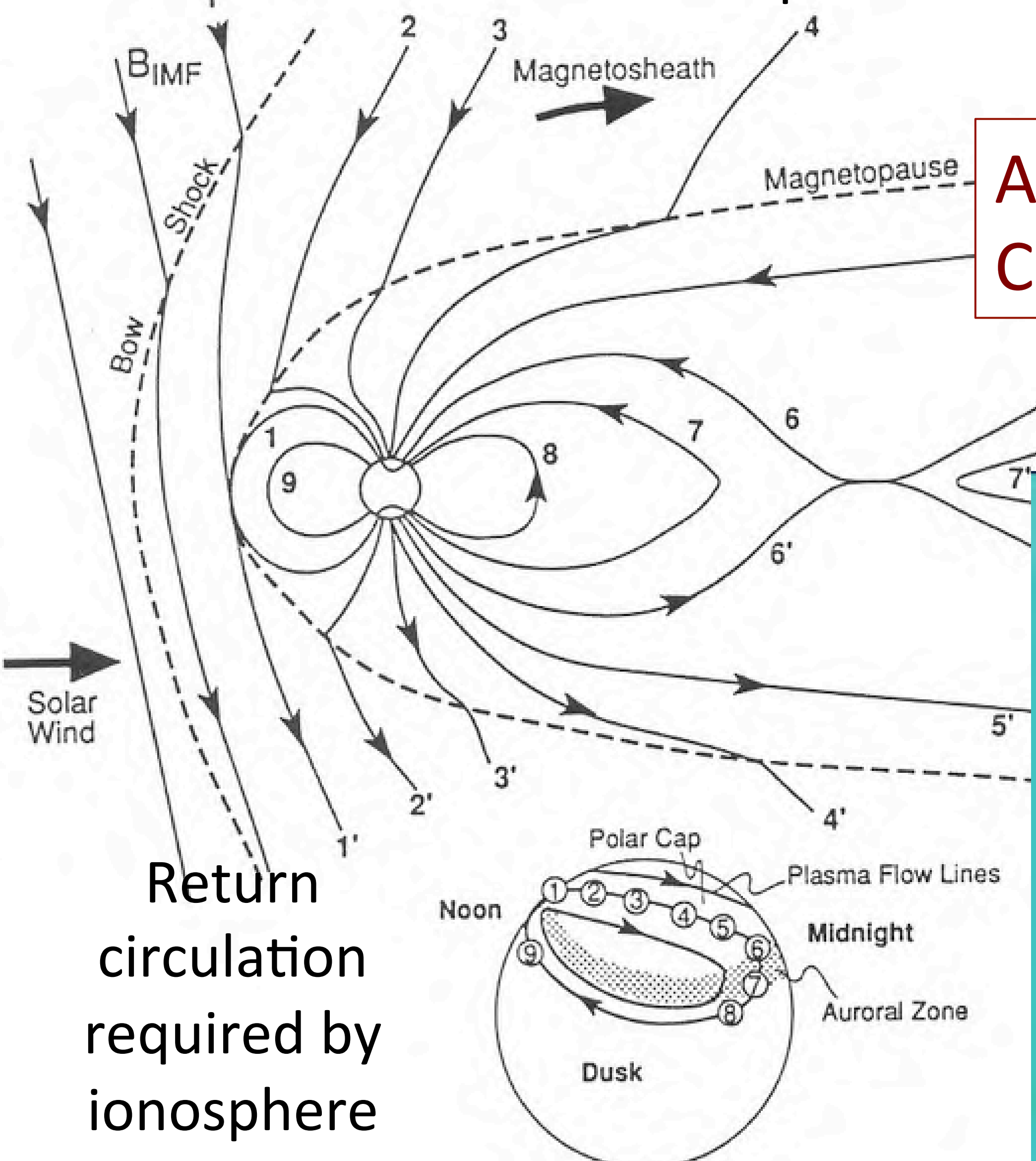
Which Form of Coupling Dominates -> Controls Dynamics



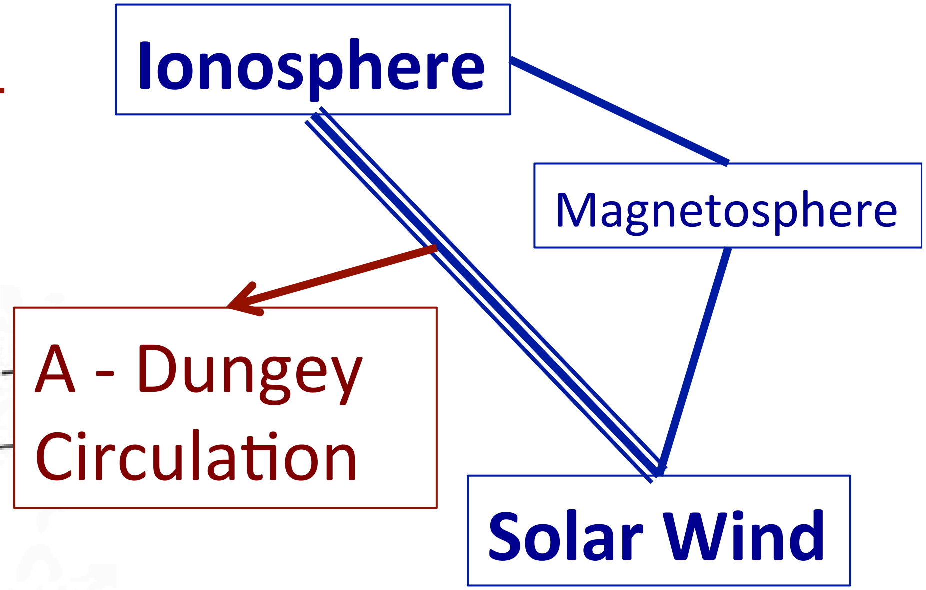
How do INTERNAL properties control a magnetosphere?
How do EXTERNAL properties control a magnetosphere?

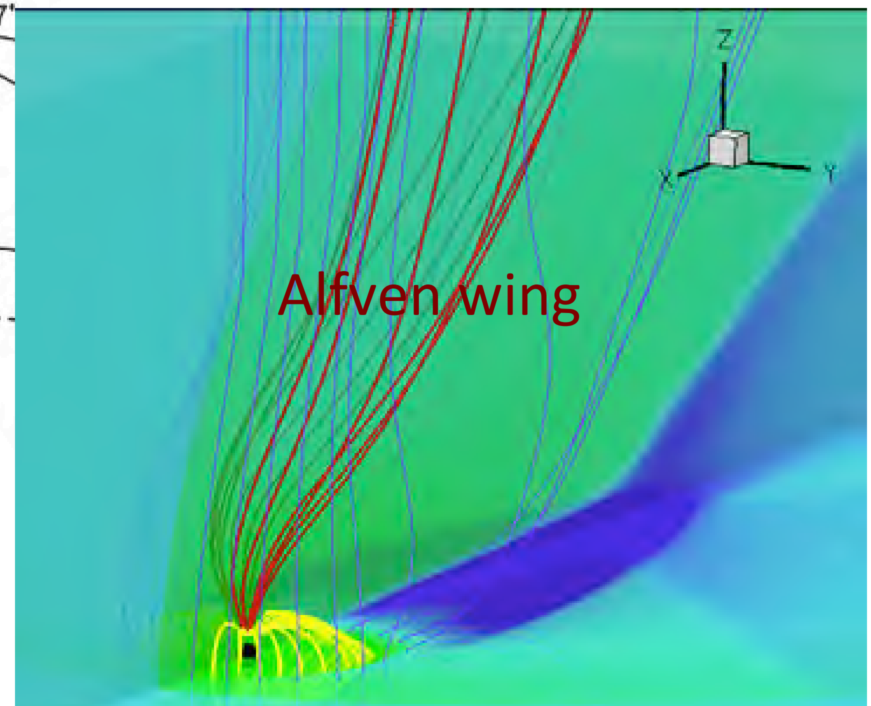
Reconnection-driven circulation

Solar wind drives flow over poles

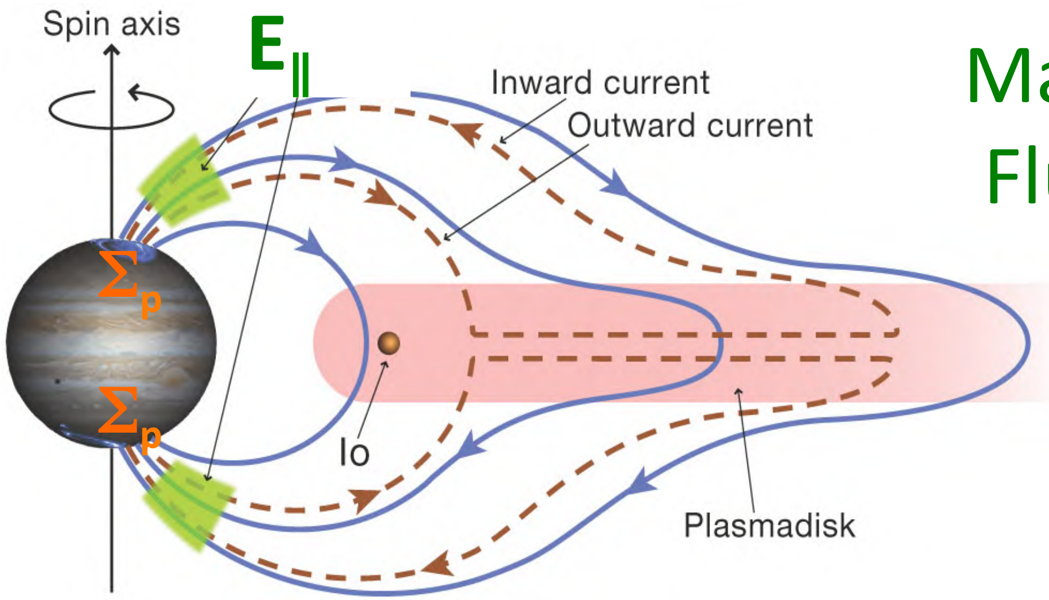


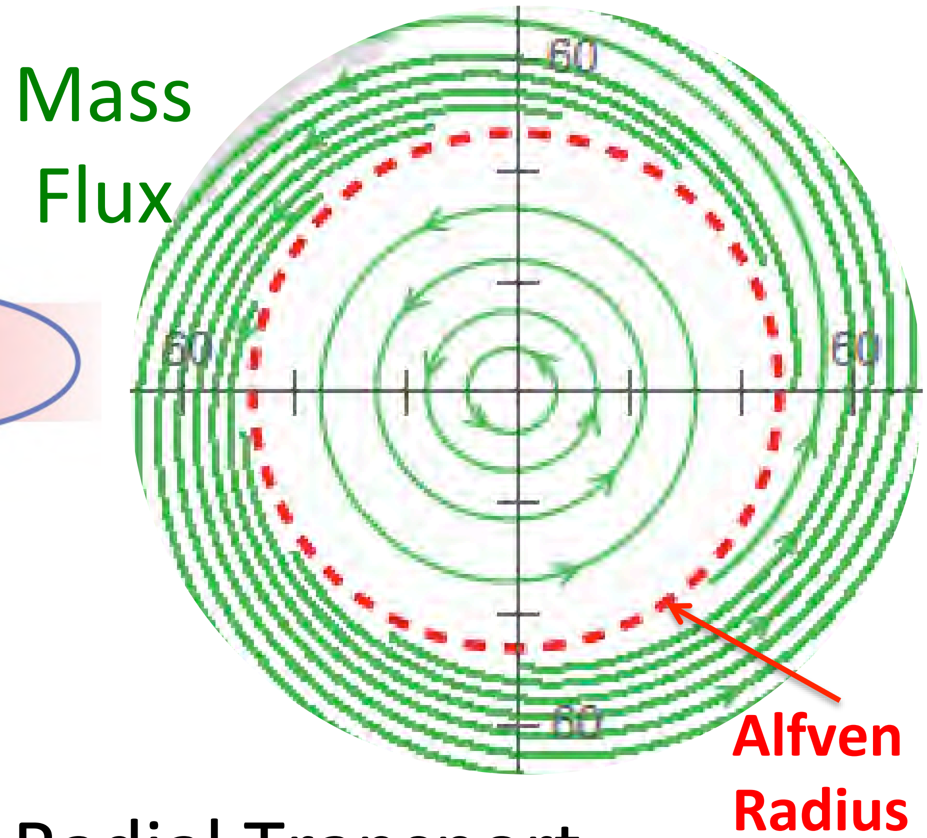
Return circulation required by ionosphere incompressibility

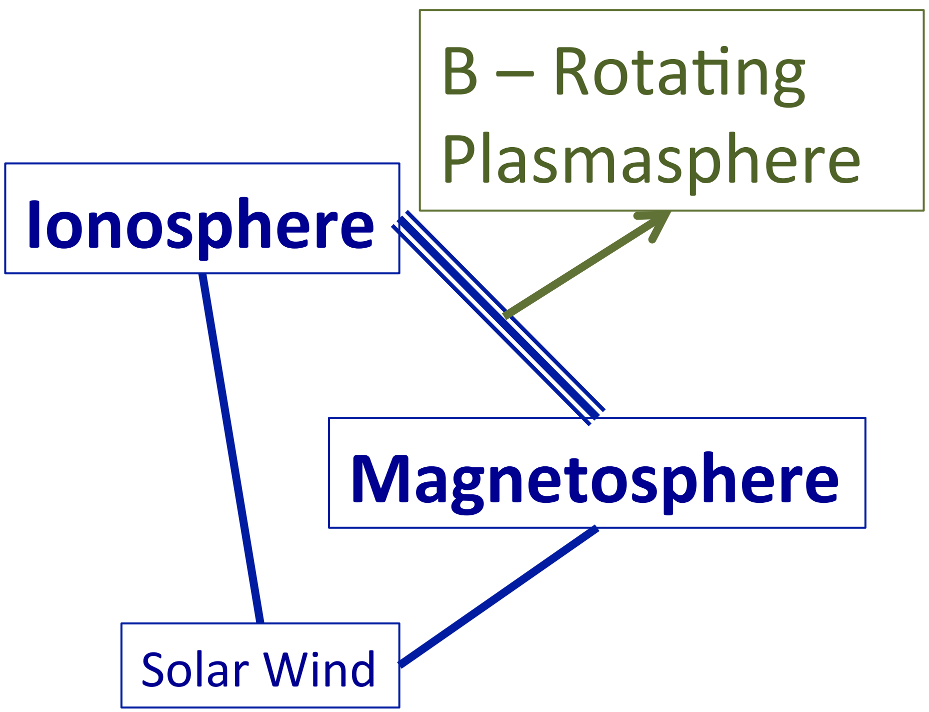




Ridley & Kivelson 2007







Radial Transport

- Fluxtube interchange
- Mass flux out
- Empty magnetic flux in
- **Decoupling**

Σ_p, $E_{\|}$ **and/or** $V_r \sim V_A$

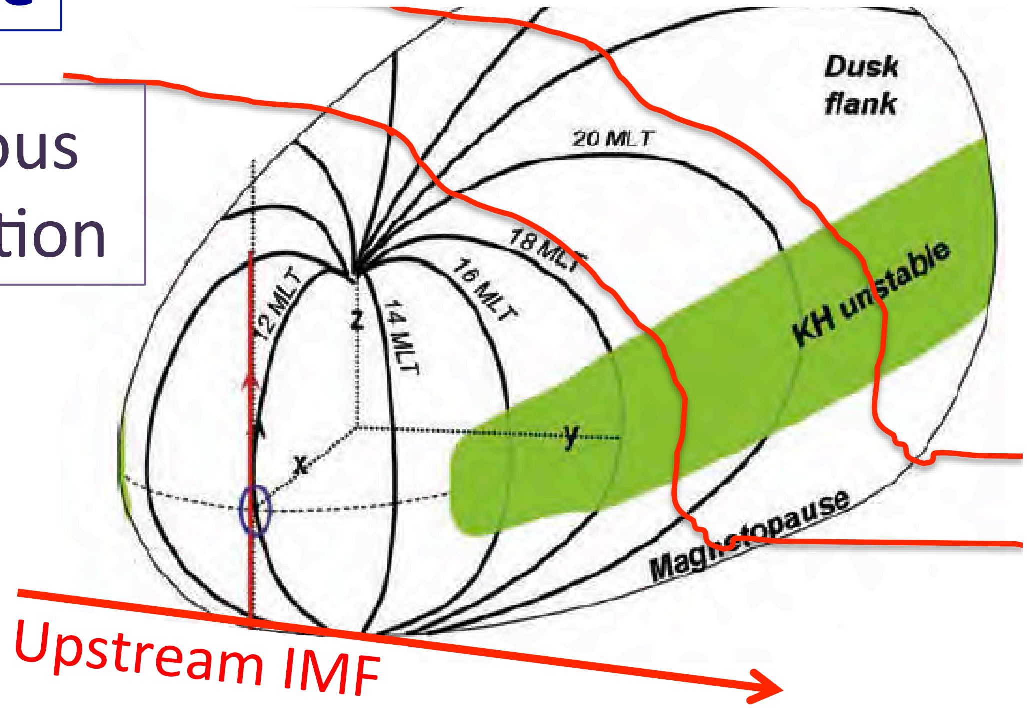
Ionosphere

Magnetosphere

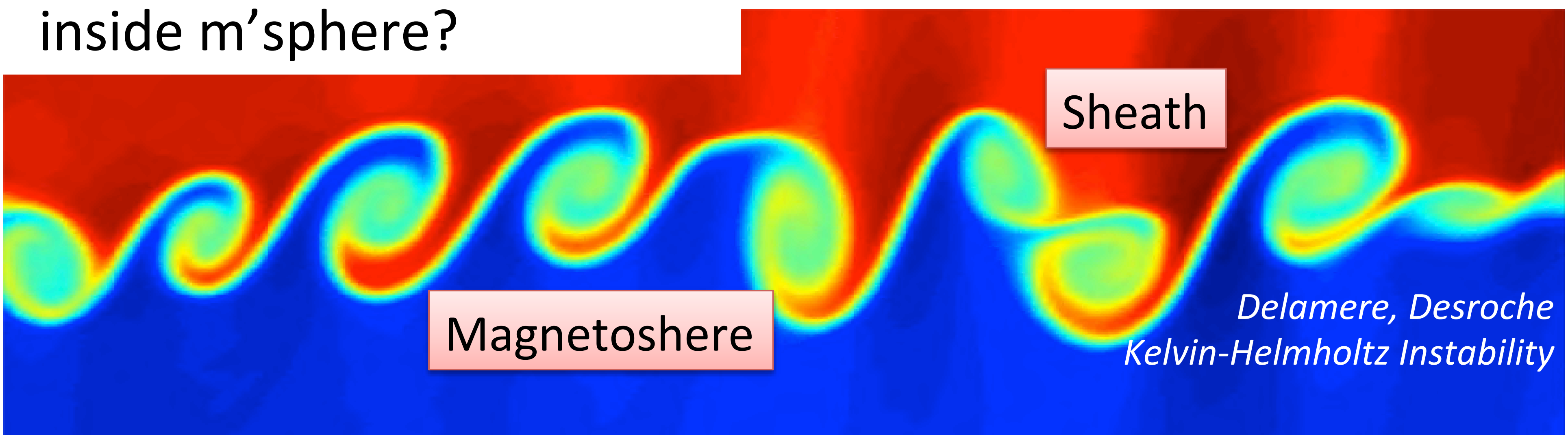
Solar Wind

C–Viscous Interaction

Upstream IMF wrapped around flattened - magnetospause



- Small-scale, intermittant reconnection
- Mixing of sheath and m'sphere plasmas
- How much IMF penetrates inside m'sphere?



Summary

- Diverse planetary magnetic fields & magnetospheres
- Earth, Mercury, Ganymede magnetospheres driven by reconnection
- Jupiter & Saturn driven by rotation & internal sources of plasma
- Uranus & Neptune are complex – *need to be explored!*

Stay tuned… Juno, JUICE missions to Jupiter

Mission(s) to Uranus?! Neptune?!