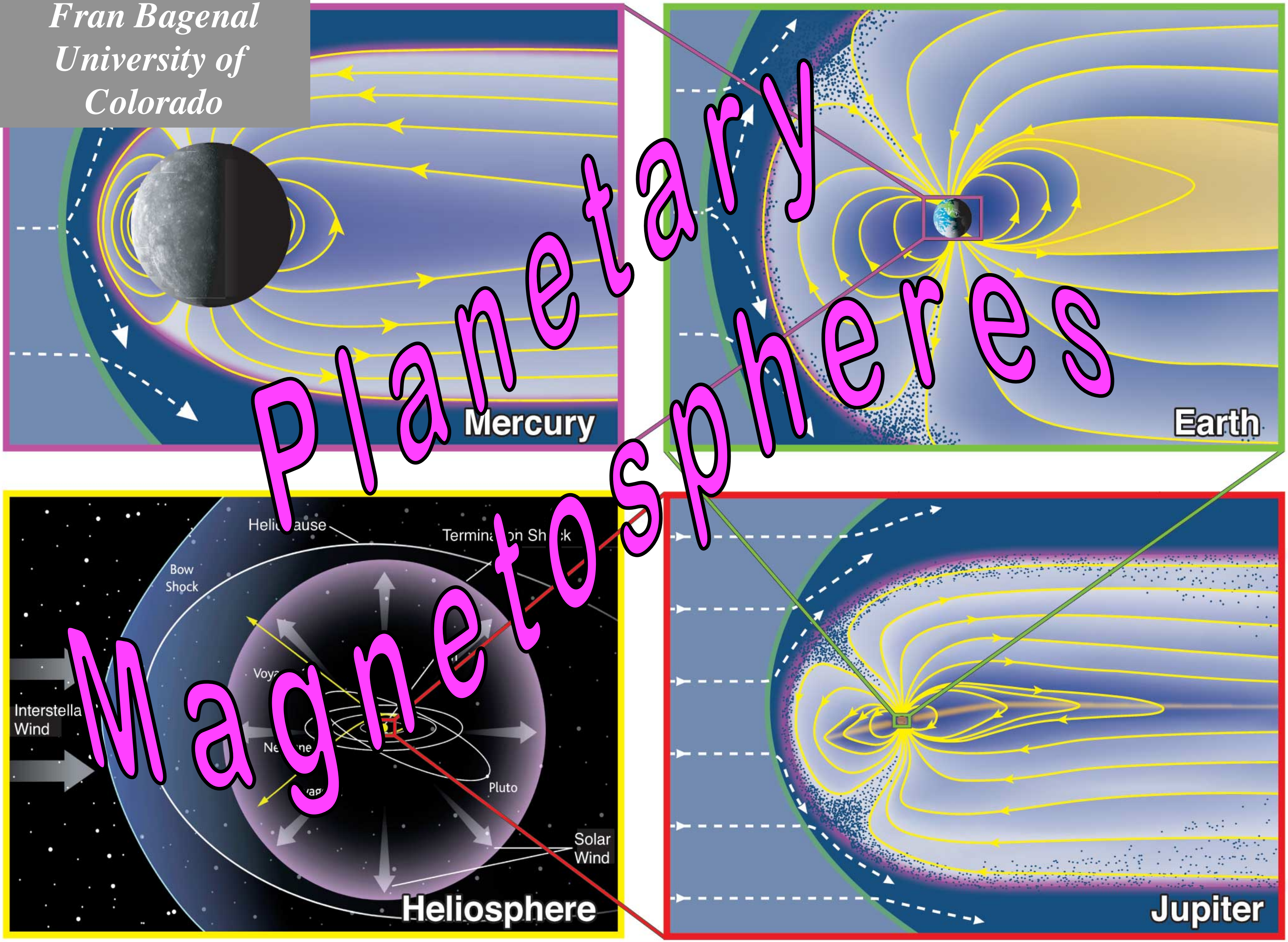
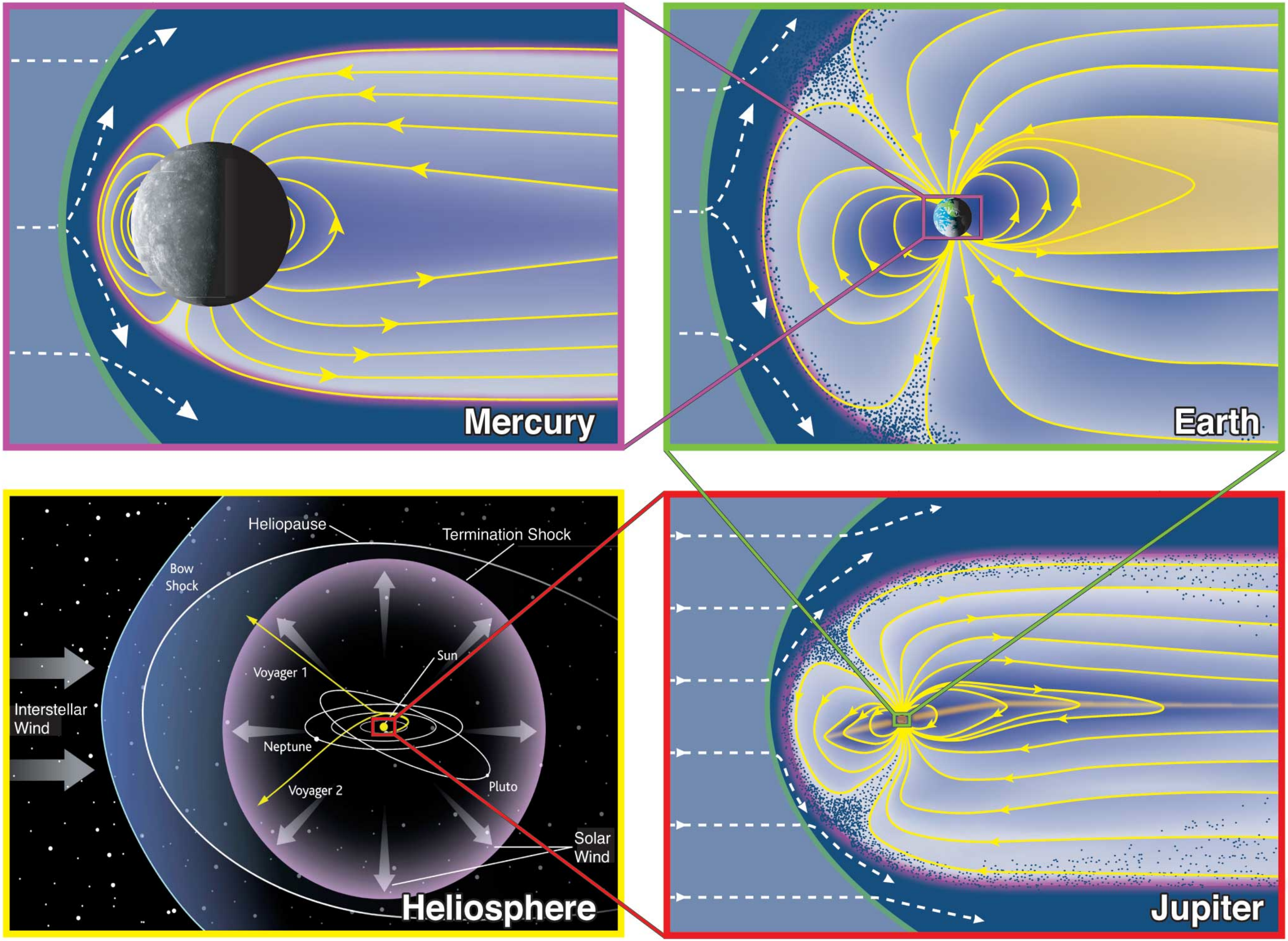
Fran Bagenal
University of Colorado

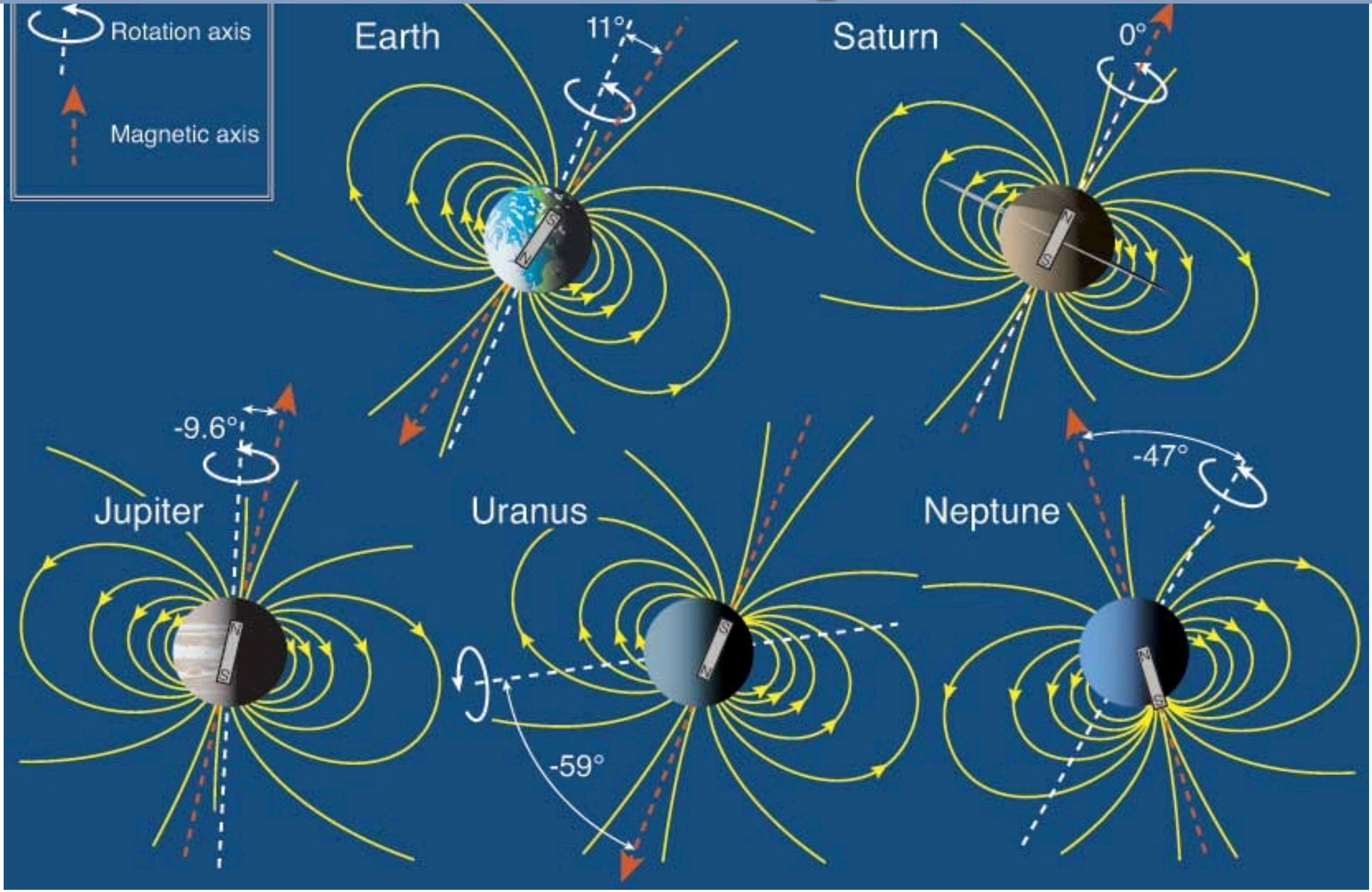
Planetary Magnetospheres



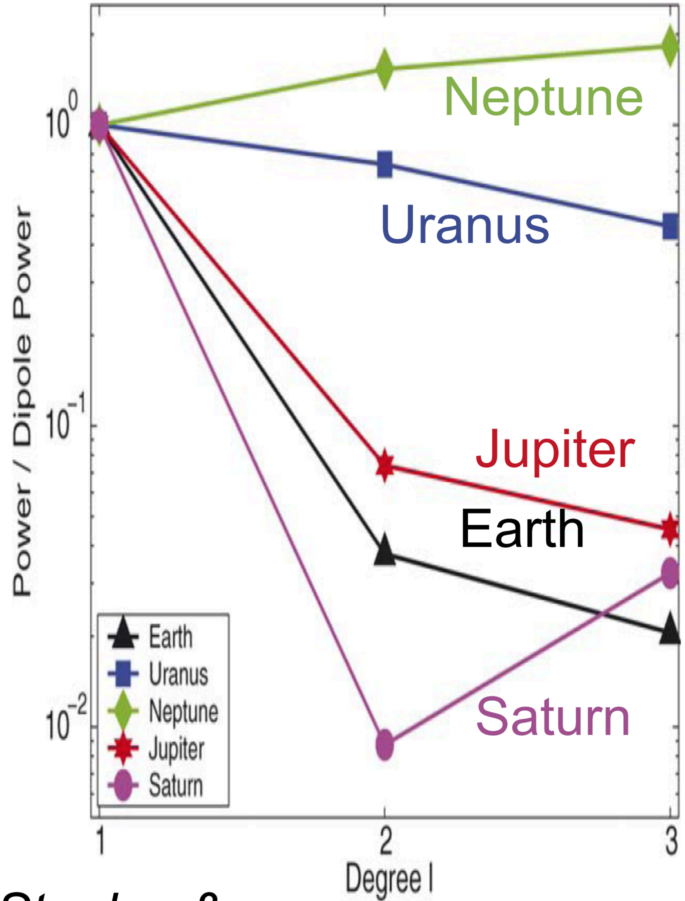
Sizes


Mercury
Earth
Heliopause
Termination Shock
Bow
Shock
Sun
Voyager 1
Interstellar
Wind
Neptune
Voyager 2
Pluto
Solar
Wind
Heliosphere
Jupiter

Tilts and Obliquities

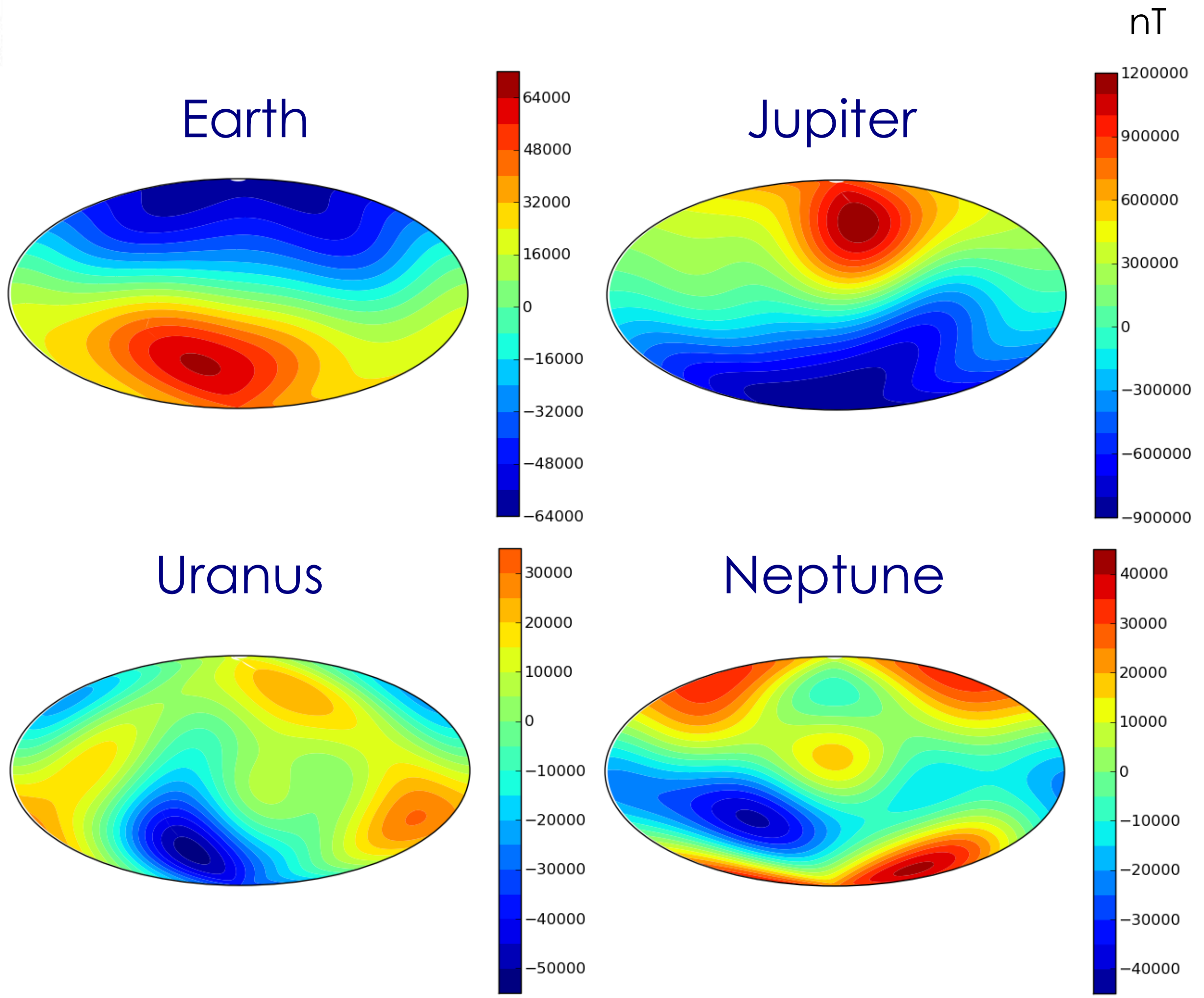


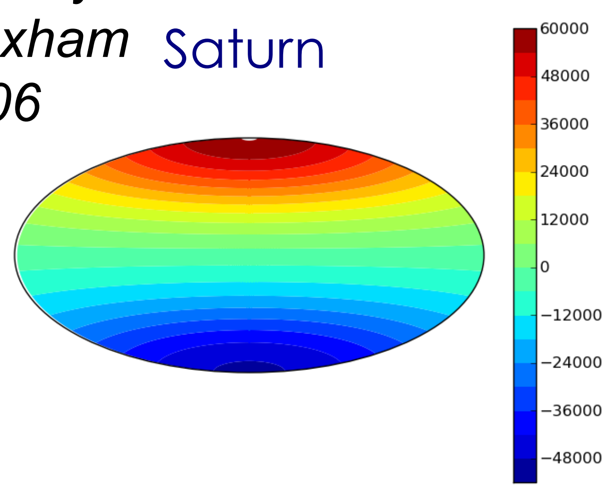
Offset Tilted Dipole (poor) Approximation



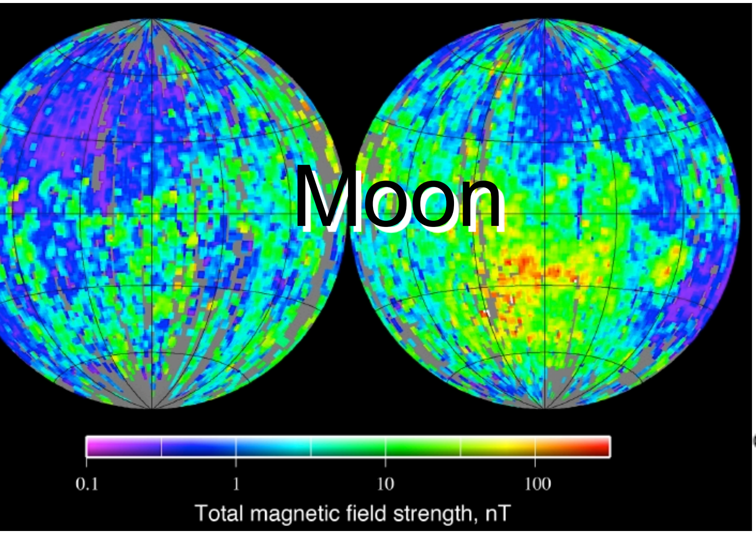
Multipole coefficients / Dipole
Indicates degree of complexity

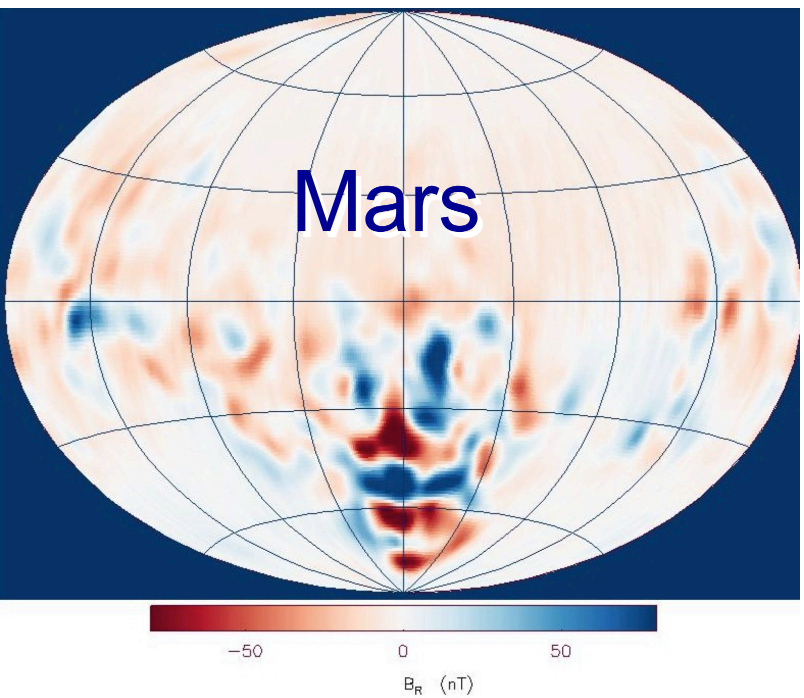
Stanley & Bloxham 2006

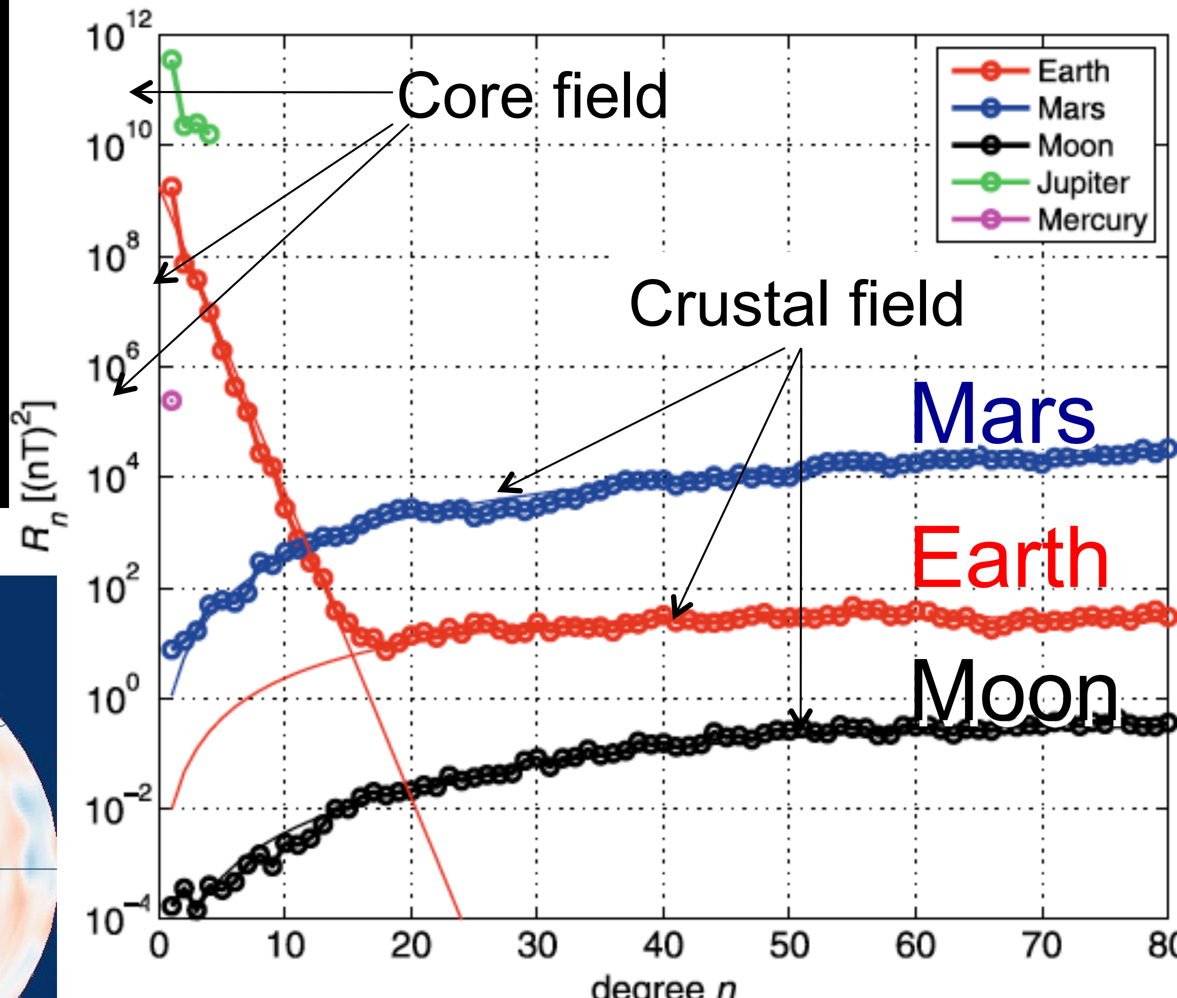




Moon & Mars: All Crustal Remanent Magnetization



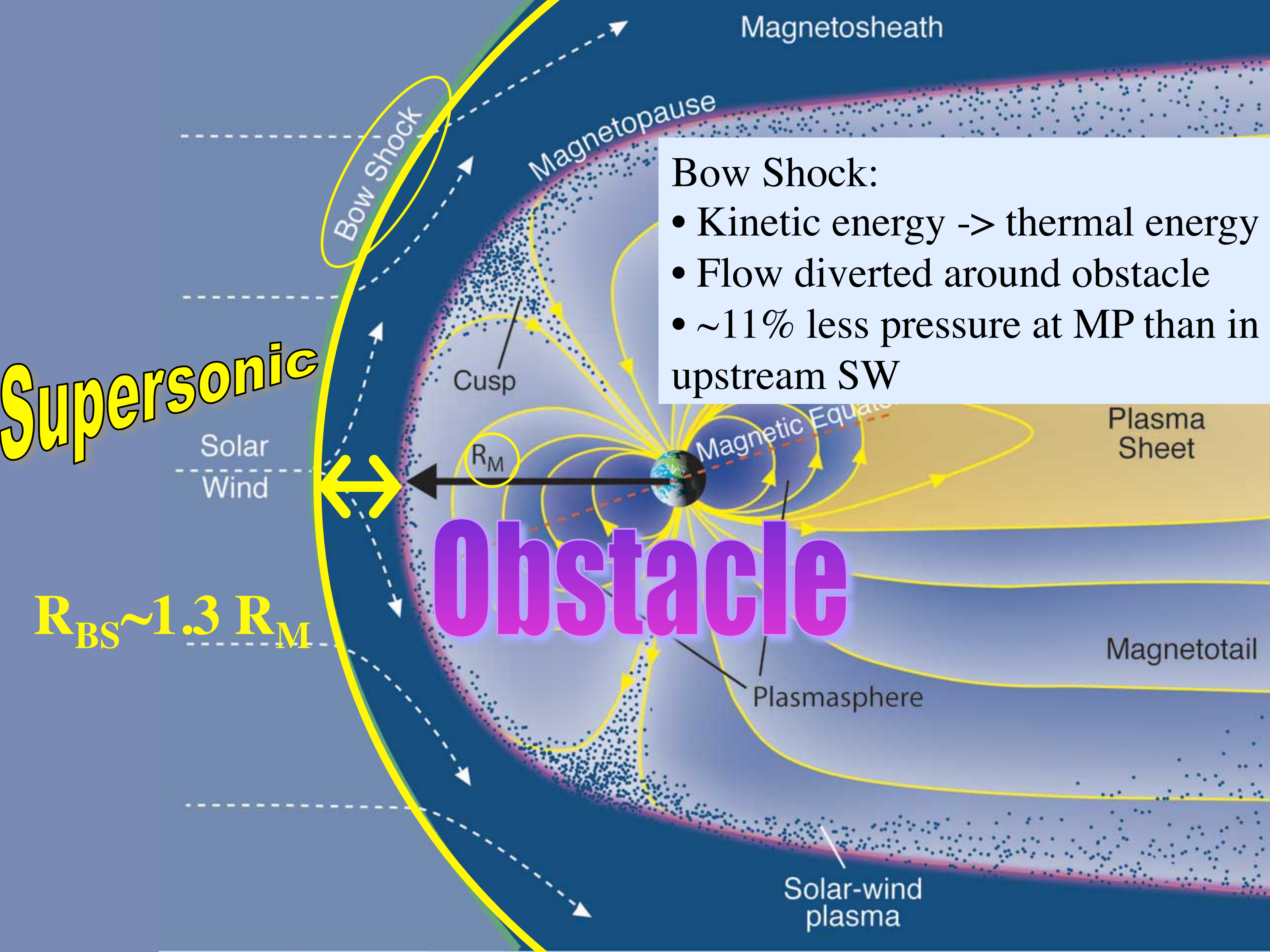




- Did Moon ever have dynamo?
- Mars' dynamo died >3.5 BYA.

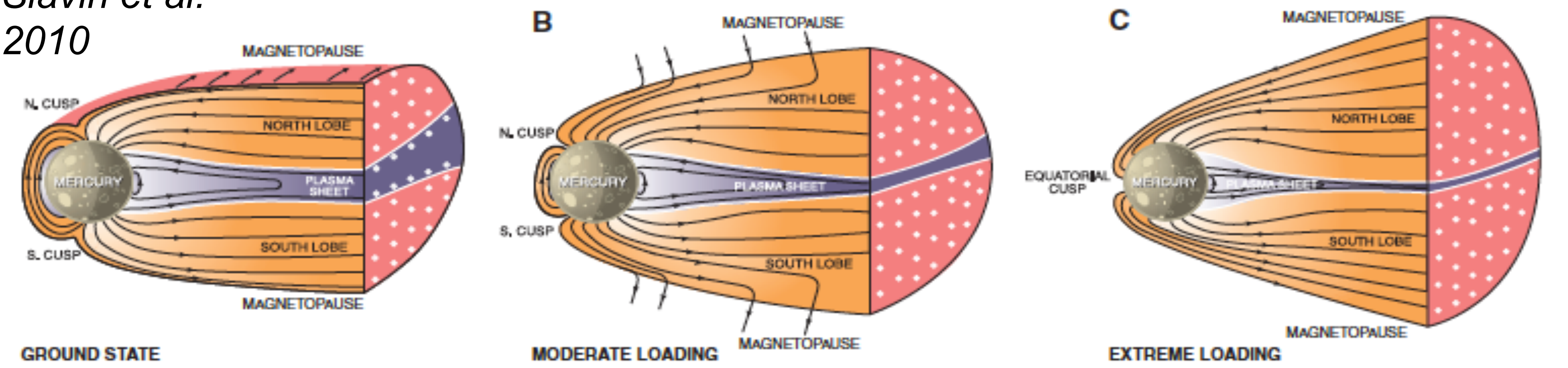
Bow Shock:

- Kinetic energy -> thermal energy
- Flow diverted around obstacle
- ~11% less pressure at MP than in upstream SW



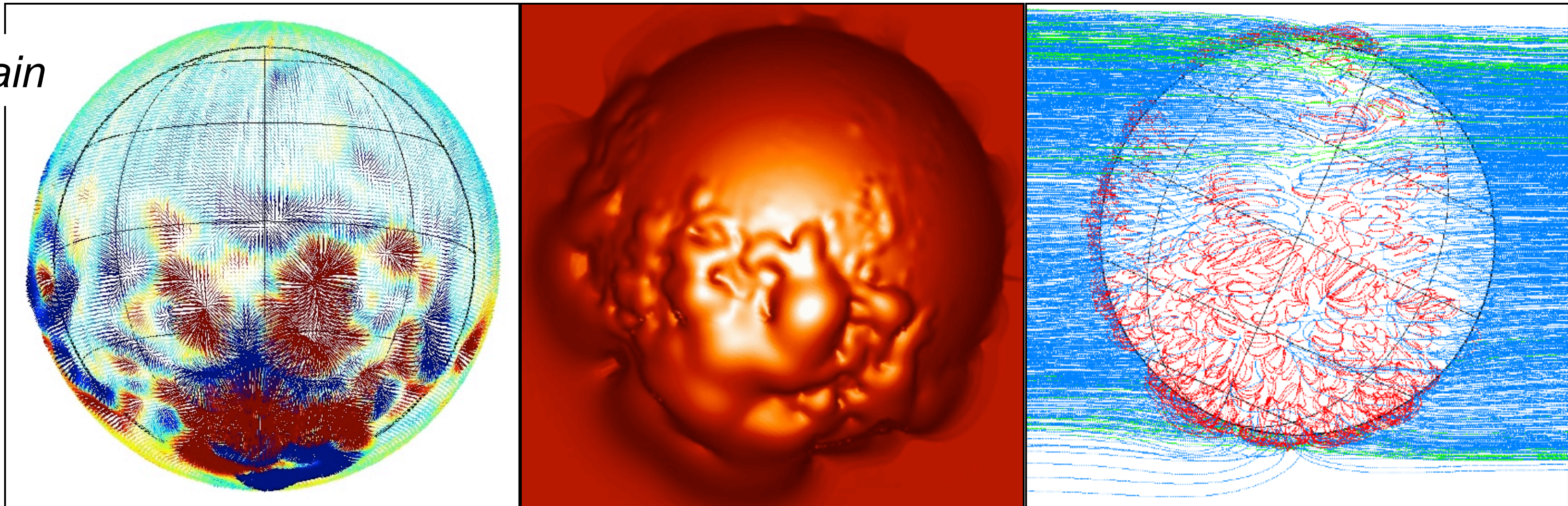
Mercury: Extreme solar wind conditions -> exposed planet

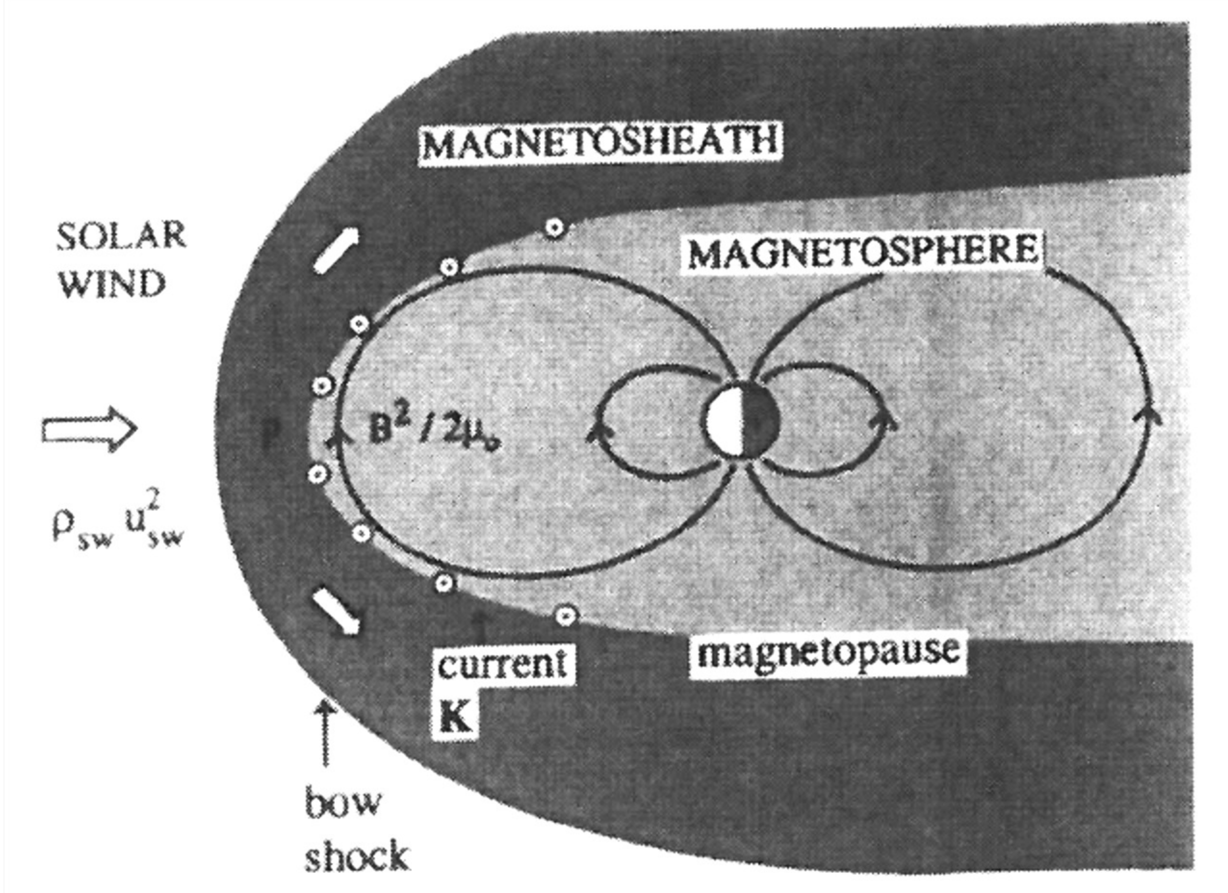
Slavin et al. 2010



Mars: Weak, irregular field -> bumpy surface + changing topology

David Brain





B_{dipole}

$= B_o \ (R_p/r)^3$

SW ram pressure <=> internal magnetic field pressure

$\rho_{sw} V^2_{sw} = B_o^2 \ (R_p/r)^6 / \ 2\mu_o$

BUT what about currents at the magnetopause? -> $2B_{dipole}$

$\rho_{sw} V^2_{sw} = (2B_o)^2 \ (R_p/r)^6 / \ 2\mu_o$

Solve for r=> R_{MP}

$$R_{MP} / R_{planet} = 2^{1/3} \left[B_o^2 \ / \ 2\mu_o \rho_{sw} V^2_{sw} \right]^{1/6}$$

Yes, I am being a bit sloppy here…

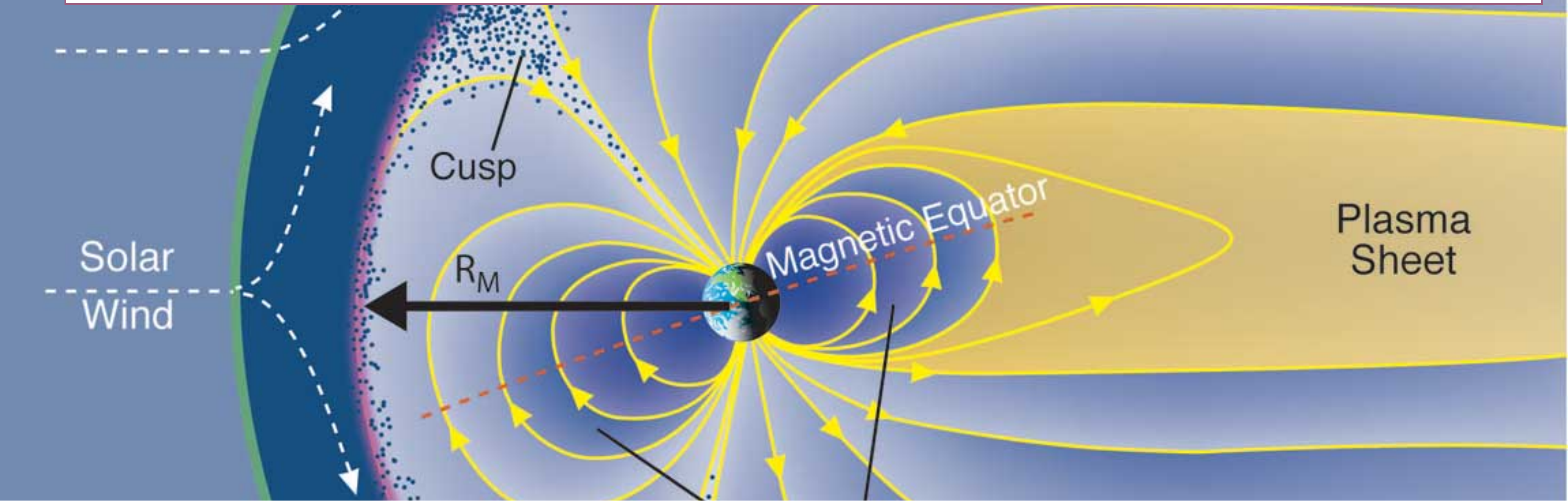
For more comprehensive treatment of magnetosheath, magnetopause (including details of the history) see 2012 HSS lecture by John Dorelli.
http://www.vsp.ucar.edu/Heliophysics/pdf/DorelliTerrestrialMagnetosphere.pdf

And lecture from 2011 from Toffoletto
http://www.vsp.ucar.edu/Heliophysics/pdf/2011_Toffoletto-lecture.pdf

I am keen to compare planetary magnetospheres – and comparison with Earth.

Dipole Magnetic Field in Solar Wind

SW Ram Pressure ⟷ Magnetic Pressure



$$R_{MP} / R_{planet} \sim 1.2 \left[B_o^2 / 2 \mu_o \rho_{sw} V^2_{sw} \right]^{1/6}$$

Chapman-Ferraro Distance

$$R_{CF}/R_p \sim 1.2\ \{\mathbf{B_o}^2 / (2\ \mu_o\ \boldsymbol{\rho}_{\mathbf{sw}}\ V^2_{\mathbf{sw}})\}^{1/6}$$

Quick chat with your neighbors….

- How does $\boldsymbol{\rho}_{\mathbf{sw}}$ vary with distance from Sun? ~$1/D^2$
- How does V_{SW} vary with distance from Sun? ~ constant
- How does $\{1/\boldsymbol{\rho}_{\mathbf{sw}}\ V^2_{\mathbf{sw}}\}^{1/6}$ vary with distance? ~$D^{1/3}$

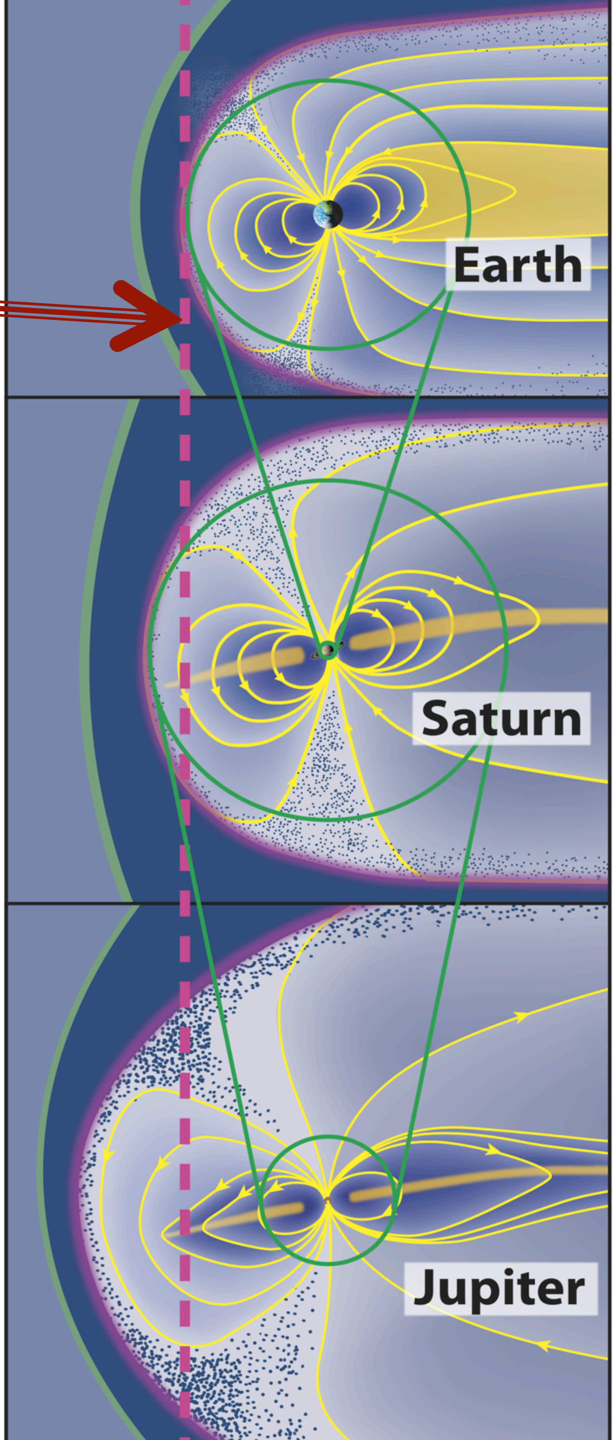
$$\mathbf{R_{CF}}/R_p \sim 1.2\, \{\mathbf{B_o}^2 / 2\, \mu_o\, \boldsymbol{\rho}_{\mathbf{sw}}\, V^2_{\mathbf{sw}}\}^{1/6}$$

	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
B_o Gauss	.003	.31	4.28	.22	.23	.14
R_{CF} Calc.	1.4 R_M	10 R_E	46 R_J	20 R_S	25 R_U	24 R_N
R_M Obs.	1.4-1.6 R_M	8-12 R_E	63-92 R_J	22-27 R_S	18 R_U	23-26 R_N

Magnetospheres scaled by stand-off distance of dipole field

	M/M_E	MP_{Dipole}	MP_{mean}	MP_{Range}
Mercury	~8×10^{-3}	1.4 R_M	1.4 R_M	
Earth	1	10 R_E	10 R_E	
Saturn	600	20 R_S	24 R_s	22-27* R_S
Jupiter	20,000	46 R_J	75 R_J	63-92# R_J

Inflated magnetospheres of Jupiter & Saturn due to HOT PLASMAS

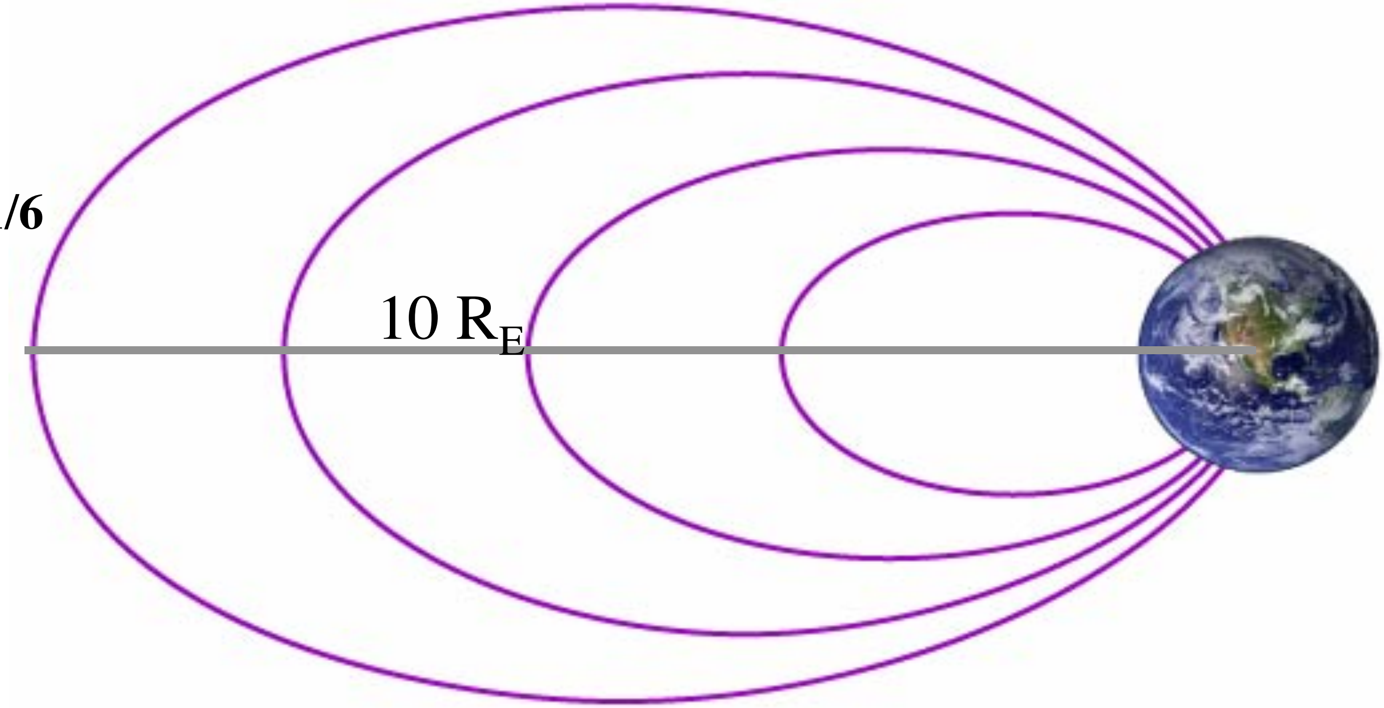


Note bimodal average locations
* *Achilleos et al. 2008* # *Joy et al. 2002*

Earth ~ Dipole

$$\mathbf{R_{mp} \sim (\rho V^2)^{-1/6}}$$

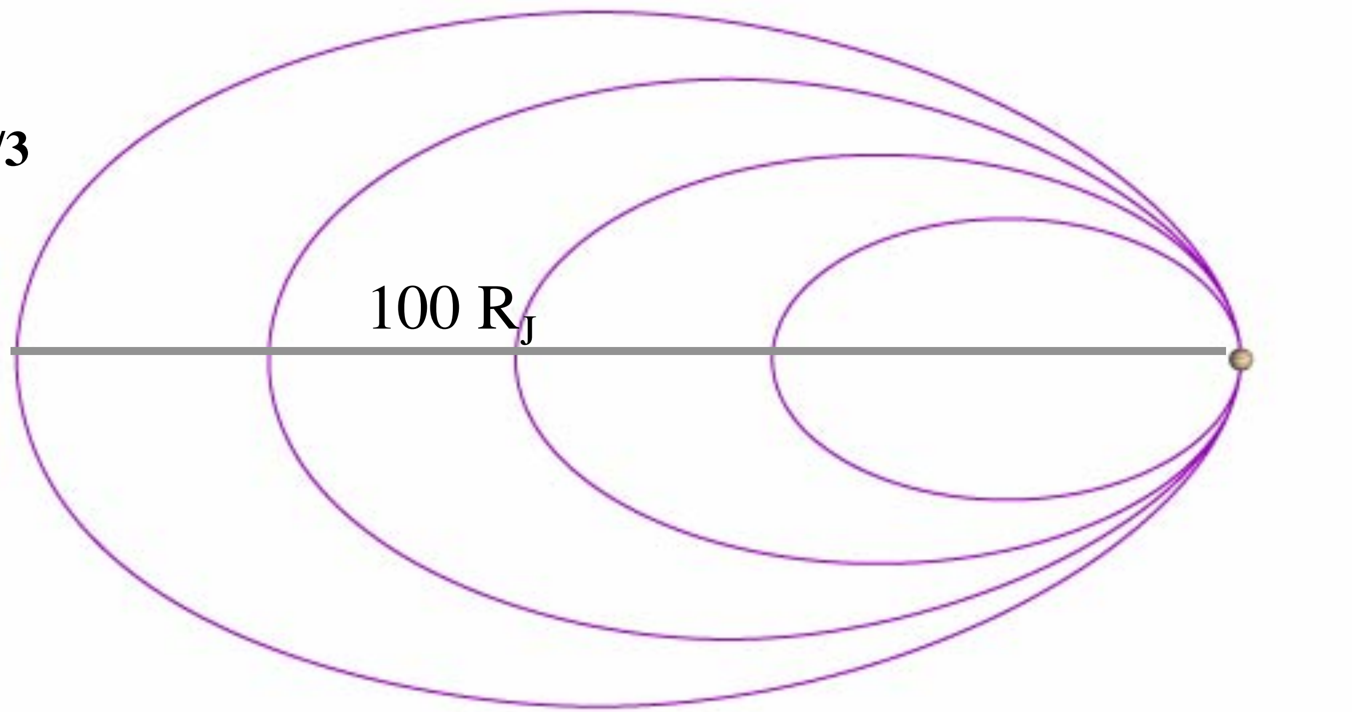
solar wind ρV^2



Jupiter

$$\mathbf{R_{mp} \sim (\rho V^2)^{-1/3}}$$

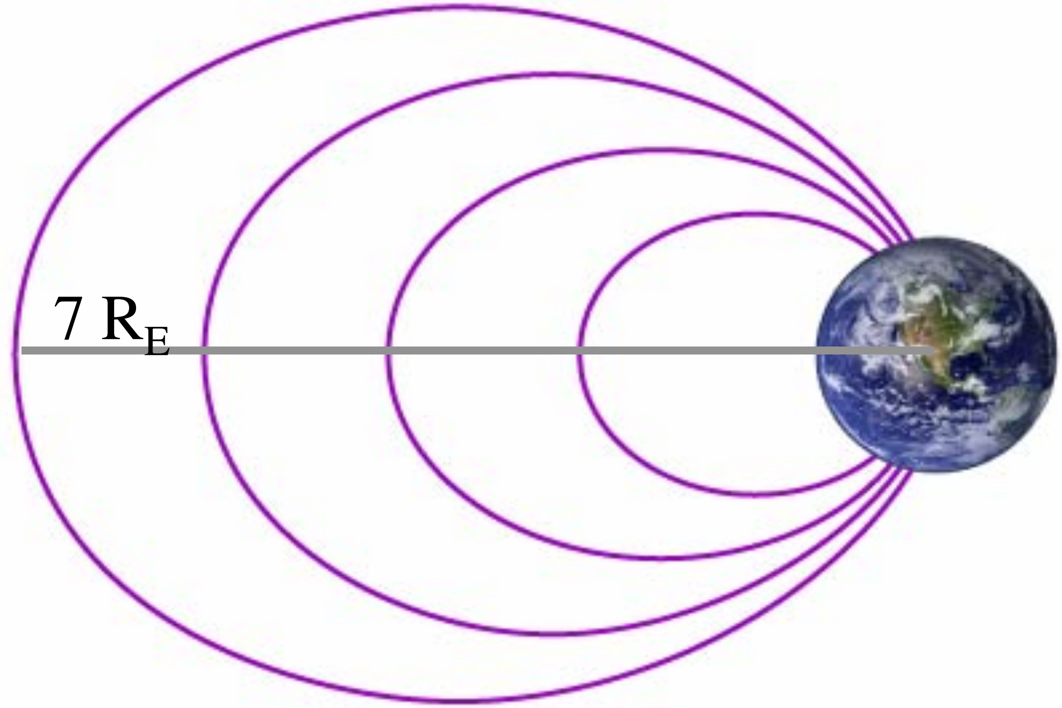
solar wind ρV^2



Earth ~ Dipole

R_{mp} -> 0.7 R_{mp}

solar wind ρV^2

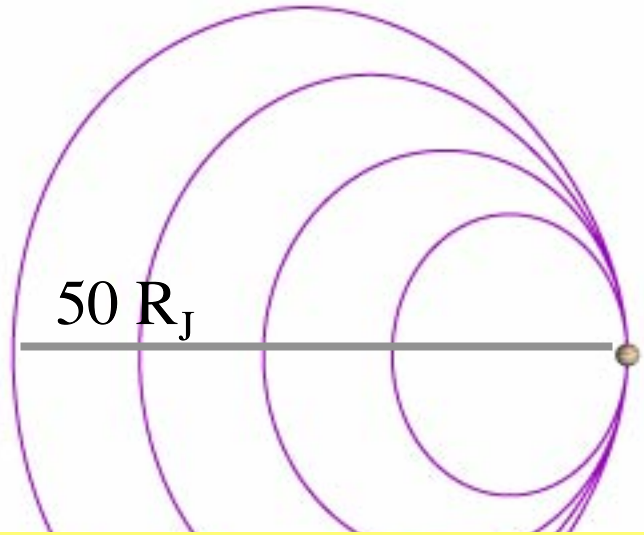


x10 Solar wind pressure

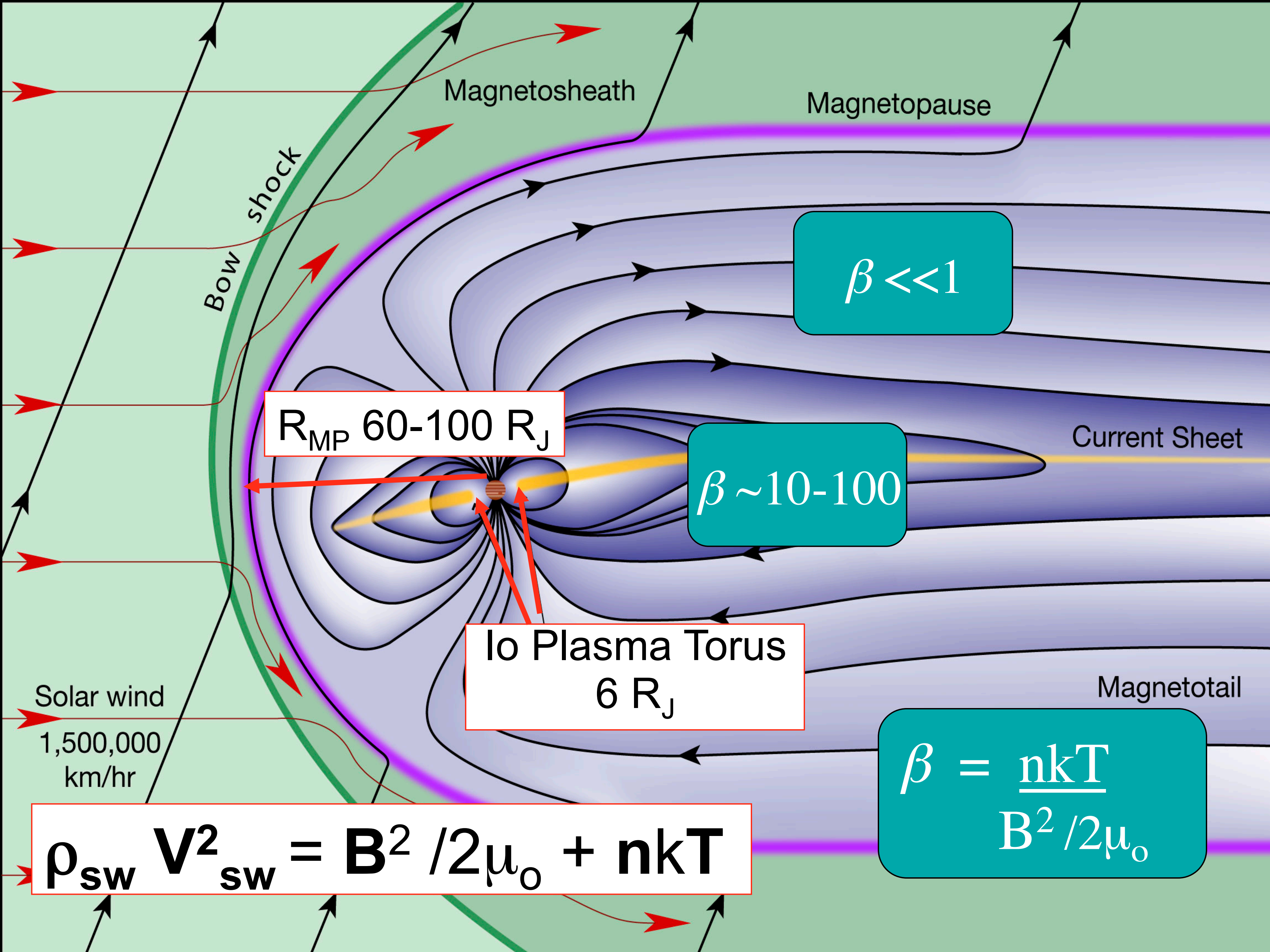
Jupiter

R_{mp} -> 0.5 R_{mp}

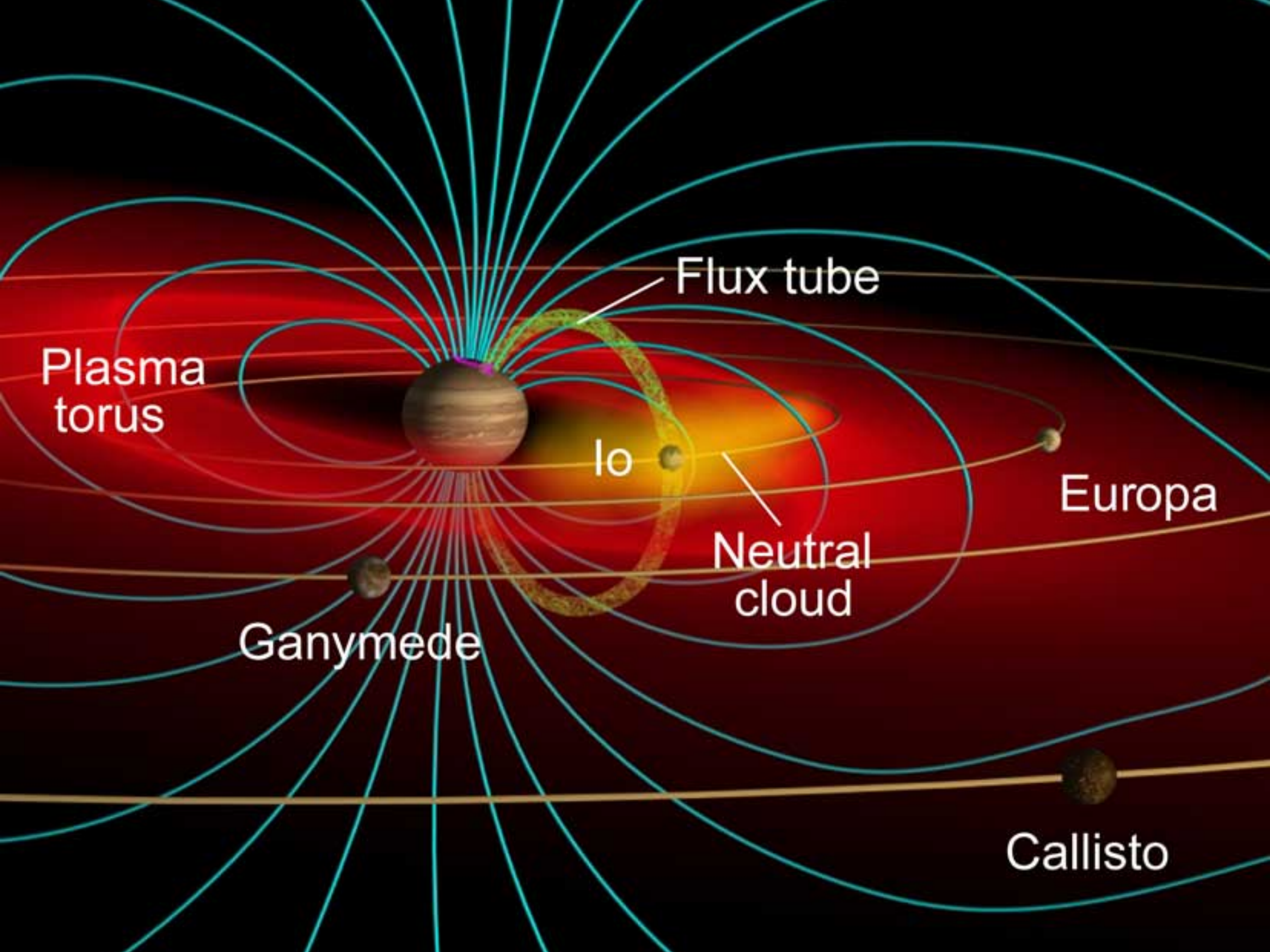
solar wind ρV^2

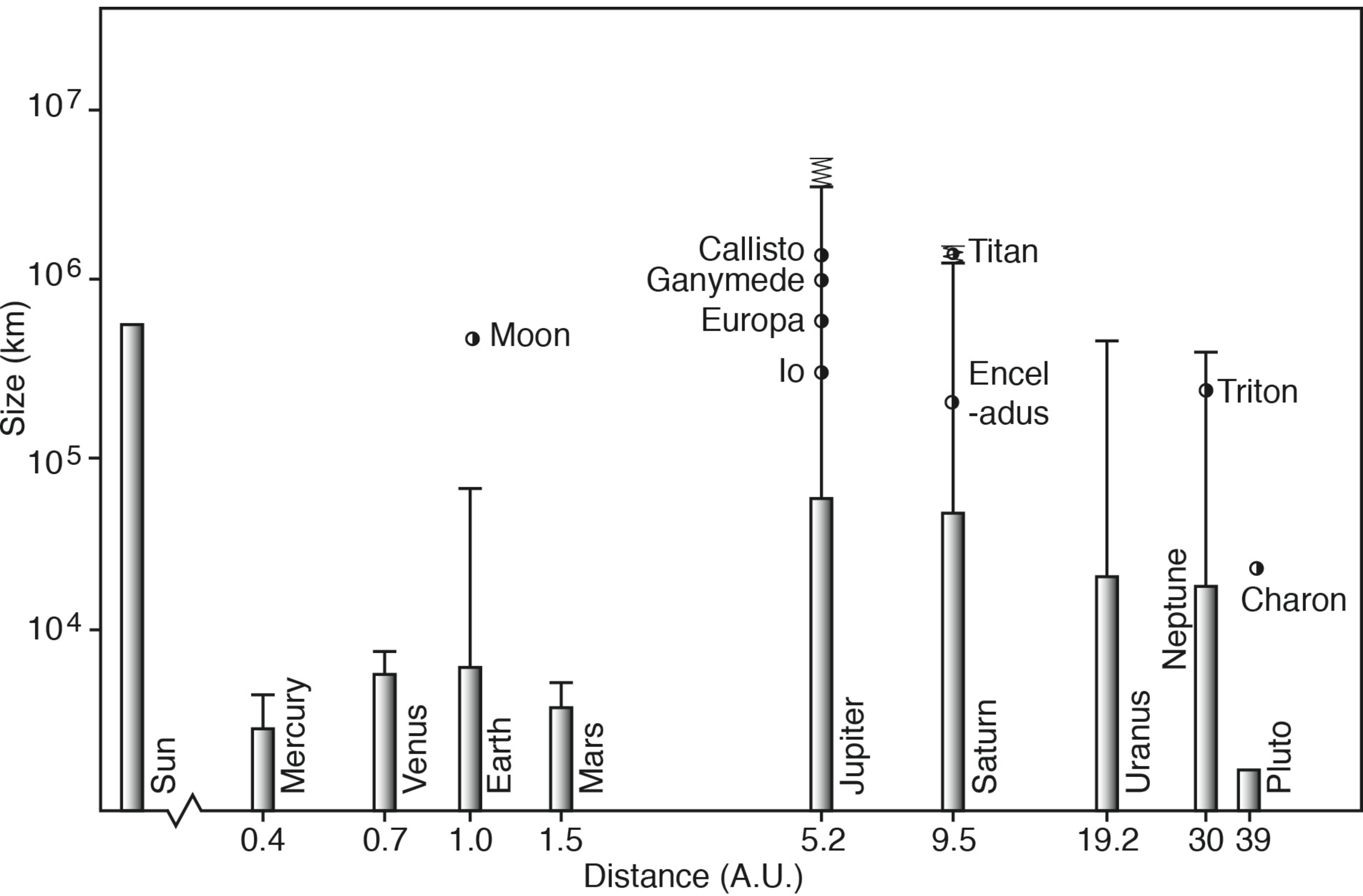


Factor ~10 variations in solar wind pressure at 5 AU
-> observed 100-50 Rj size of dayside magnetosphere



Magnetosheath
Magnetopause
Bow shock
$\beta << 1$
R_{MP} 60-100 R_J
$\beta \sim 10\text{-}100$
Current Sheet
Io Plasma Torus
6 R_J
Solar wind
1,500,000
km/hr
Magnetotail
$\beta = \frac{nkT}{B^2/2\mu_o}$
$\rho_{sw} V^2_{sw} = B^2/2\mu_o + nkT$


Flux tube
Plasma
torus
Io
Europa
Neutral
cloud
Ganymede
Callisto



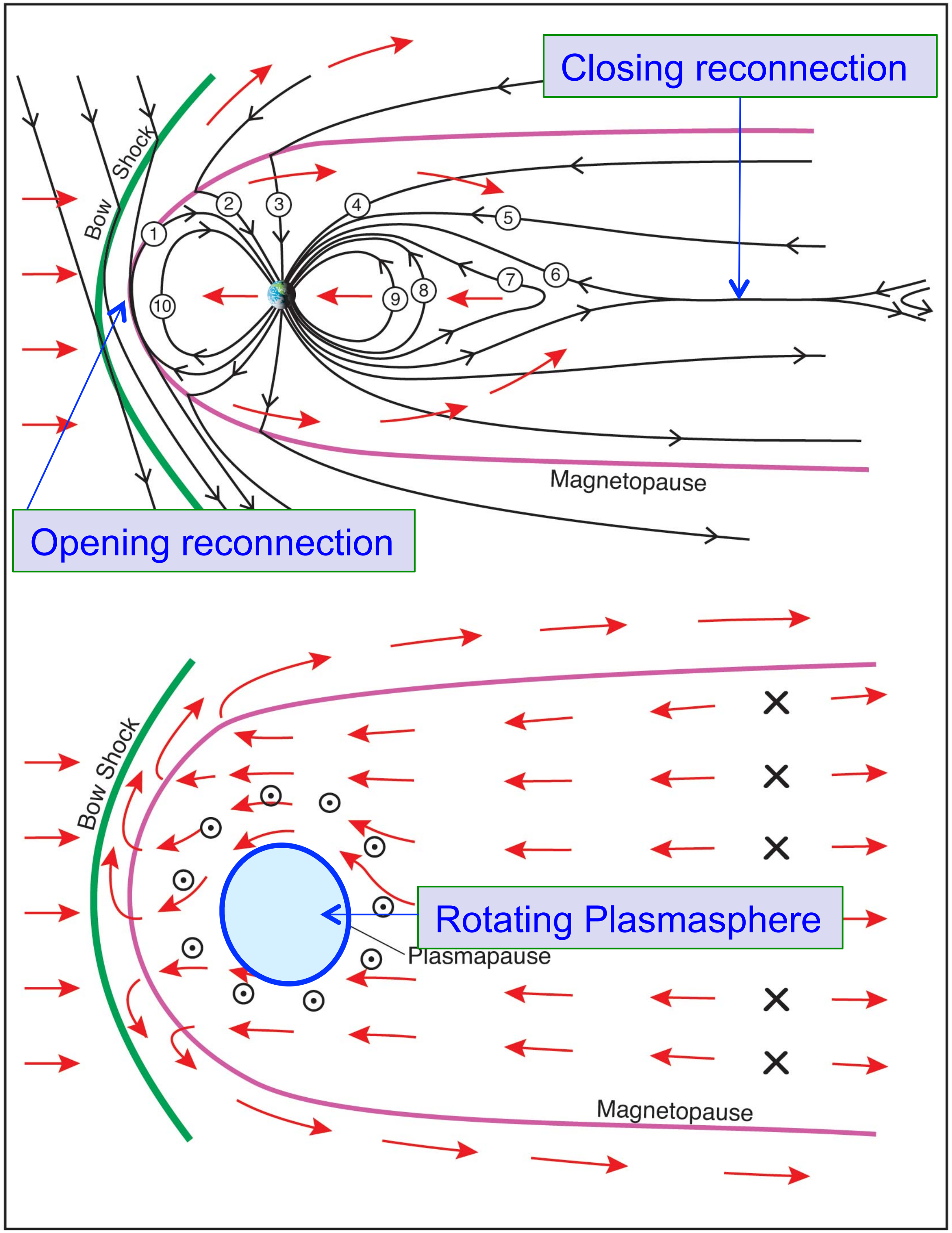
10^7
10^6
10^5
10^4
Size (km)
Moon
Callisto
Ganymede
Europa
Io
Titan
Encel
-adus
Triton
Charon
Sun
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto
0.4
0.7
1.0
1.5
5.2
9.5
19.2
30
39
Distance (A.U.)

Dynamics

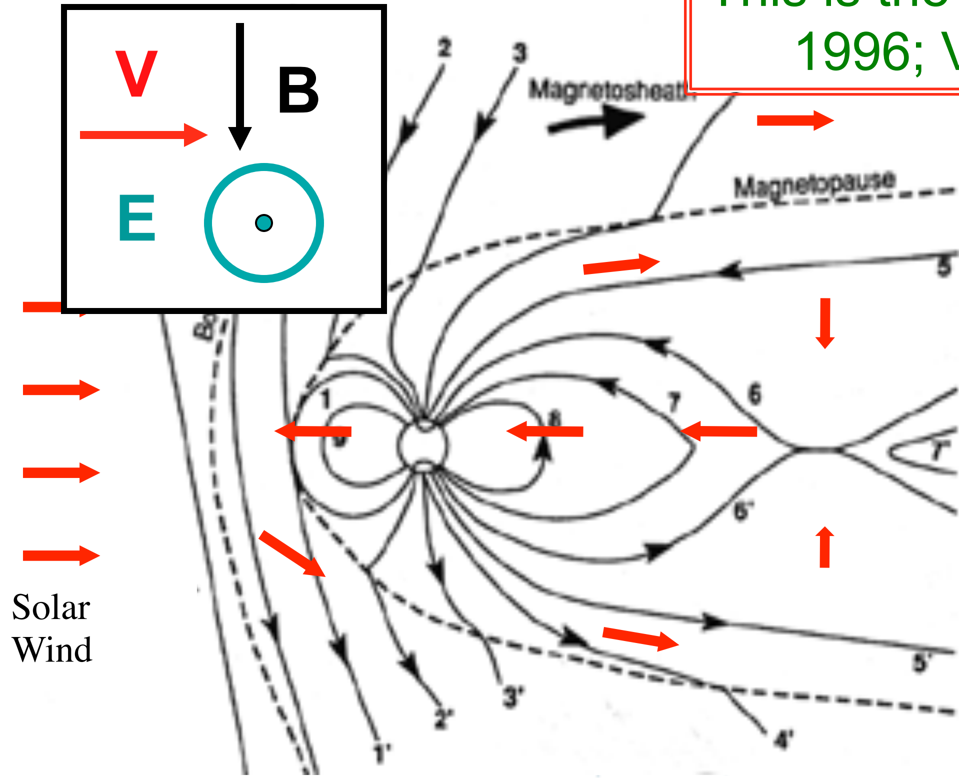
Dungey Cycle

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



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



The Dungey Cycle

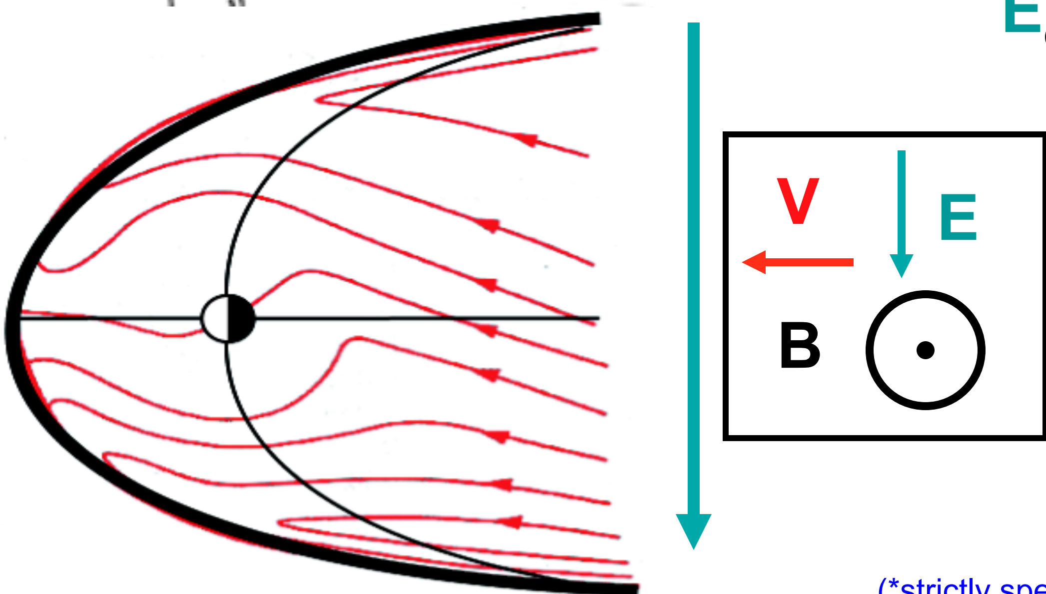
Solar wind driven magnetospheric convection*

$$E_{convection} = -\zeta\, V_{SW} \times B_{SW}$$

ζ~ efficiency of reconnection ~10-20%

crude approximation!!

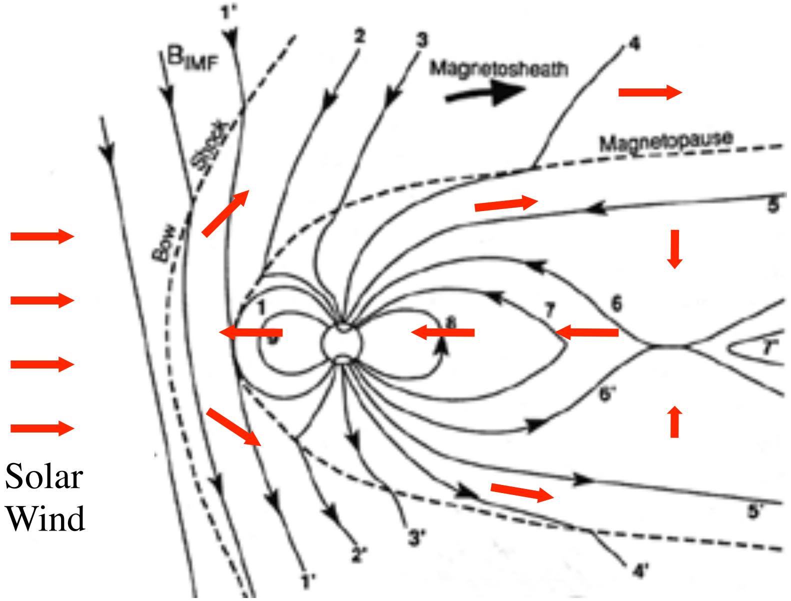
E_{conv}~ constant in m'sphere

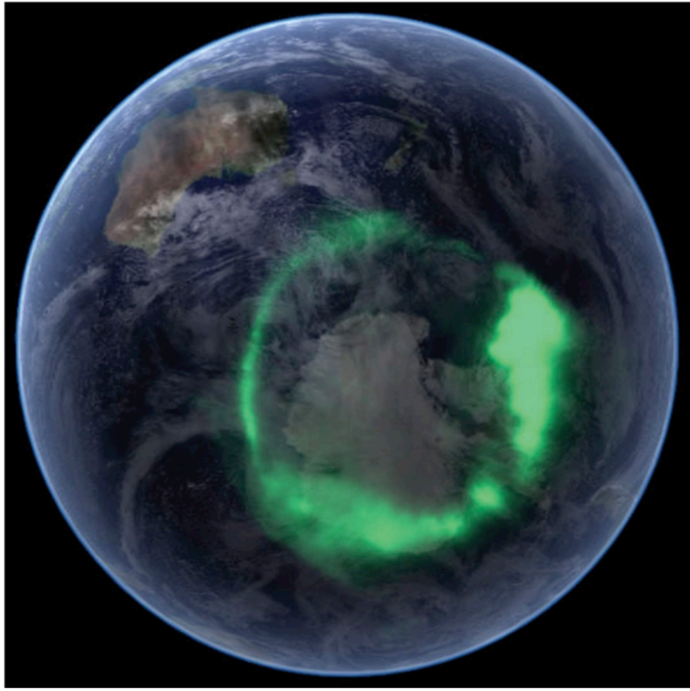


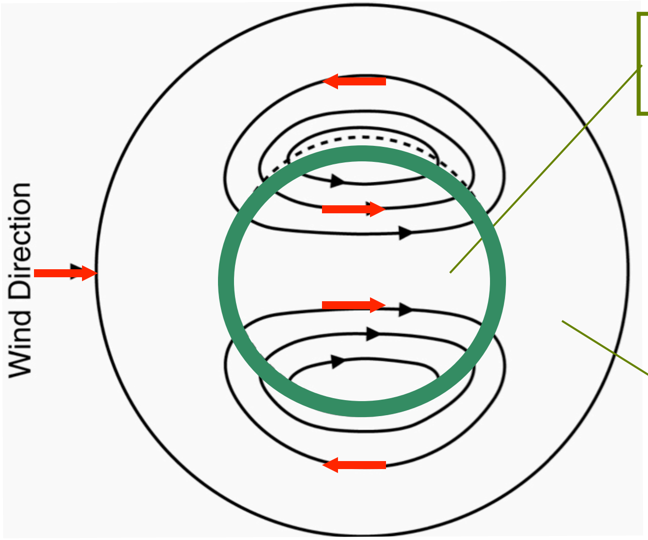
$$V_{convection} \sim \zeta V_{SW}(R/R_{MP})^3$$

(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)





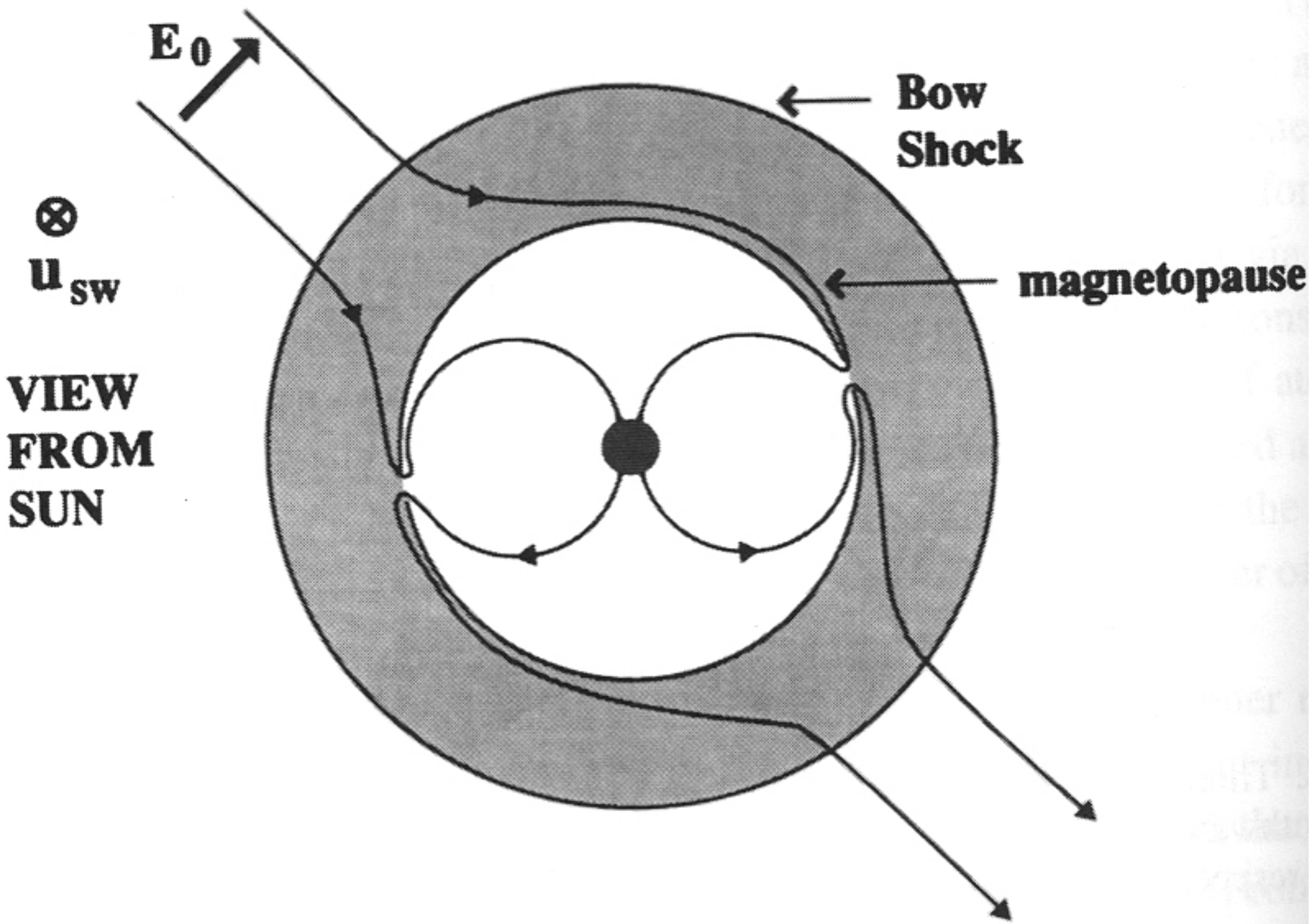


Connected to solar wind

Closed magnetic field

Polar view

Reality = Messy & 3D



Dynamics

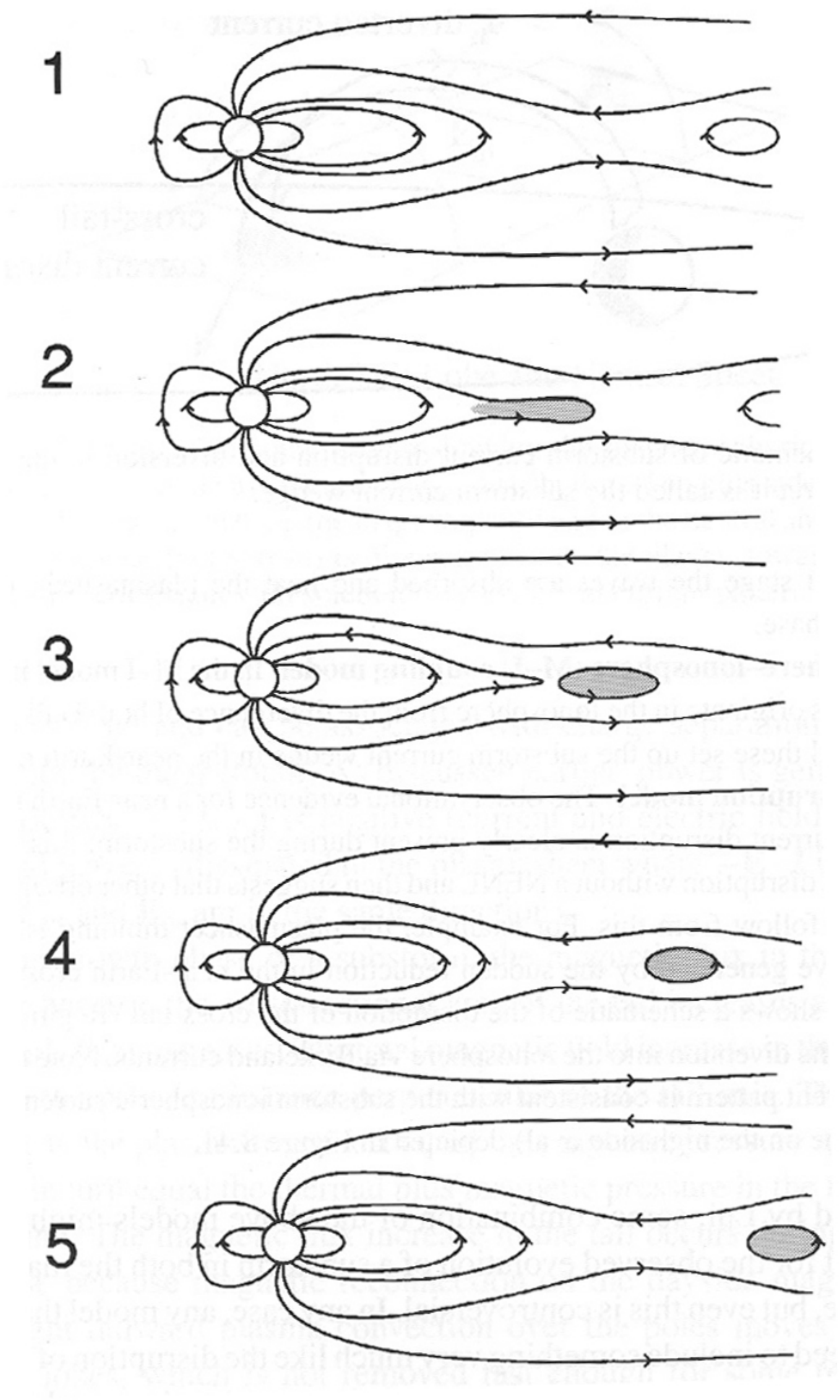
Dayside magnetopause

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

Tail Reconnection

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

Space Weather!



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

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

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

Fraction of planetary magnetosphere that is rotation dominated is…

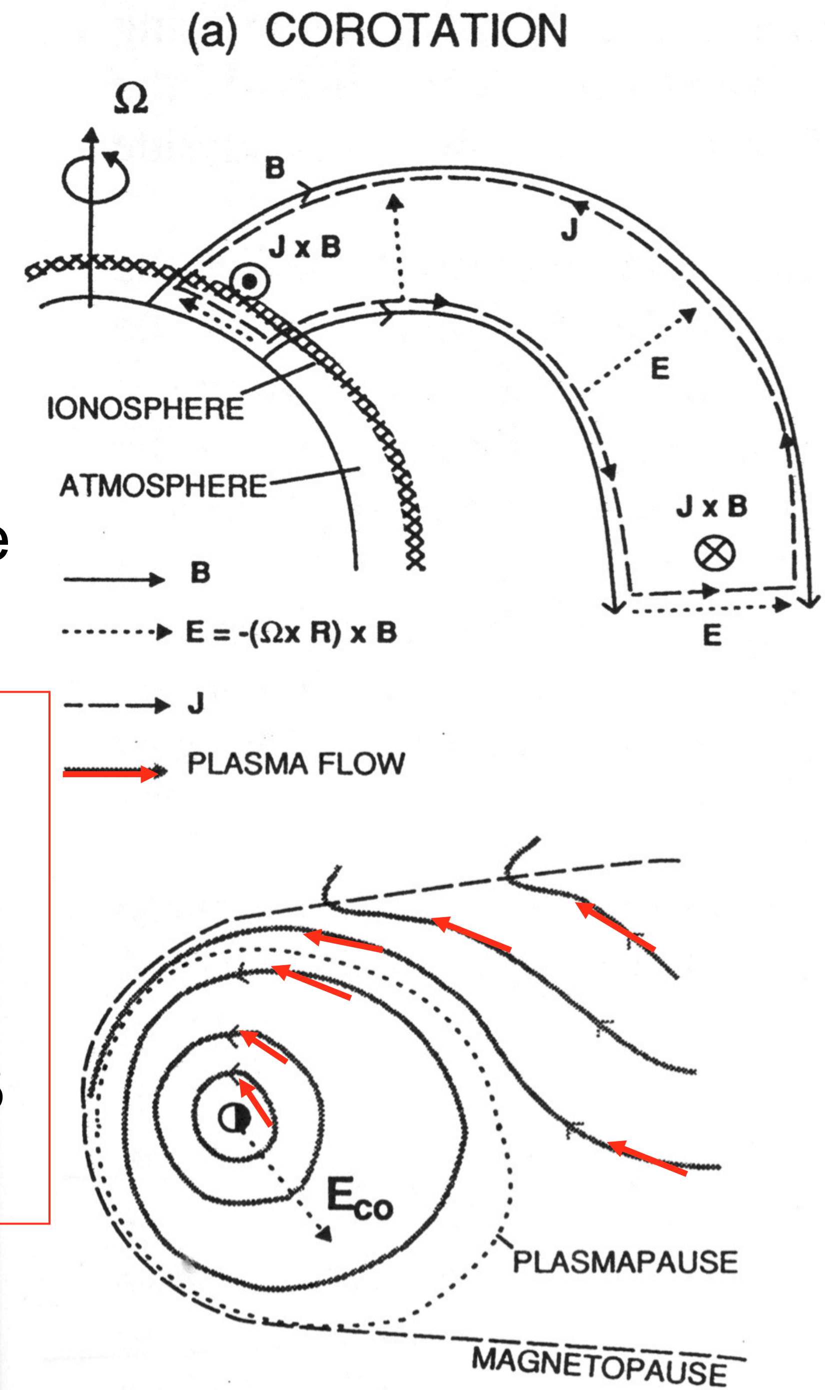
$$R_{pp}/R_{MP}$$

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

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

Where r_p=planetary radius

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



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

$\mathbf{V}_{convection}$

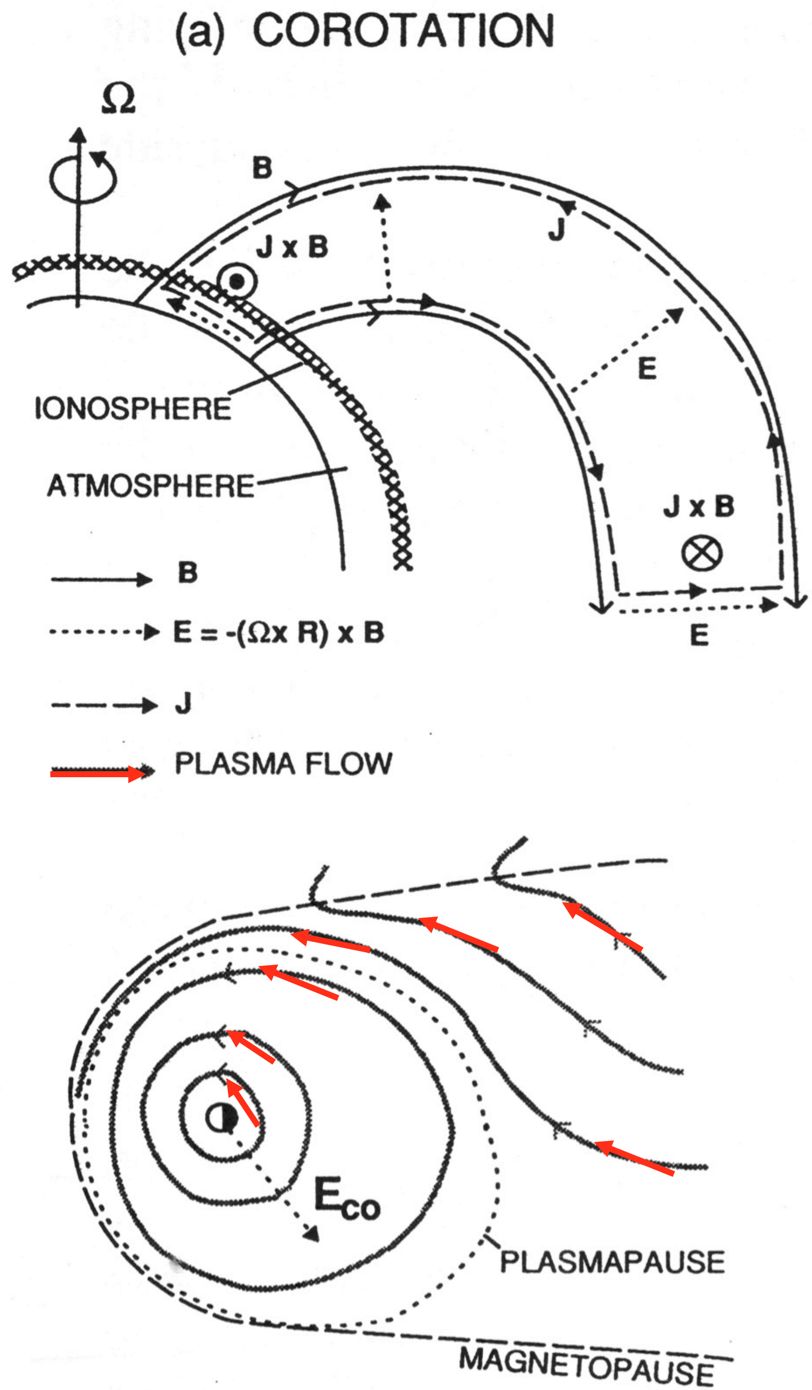
$\sim \zeta V_{SW}(R/R_{MP})^3$

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

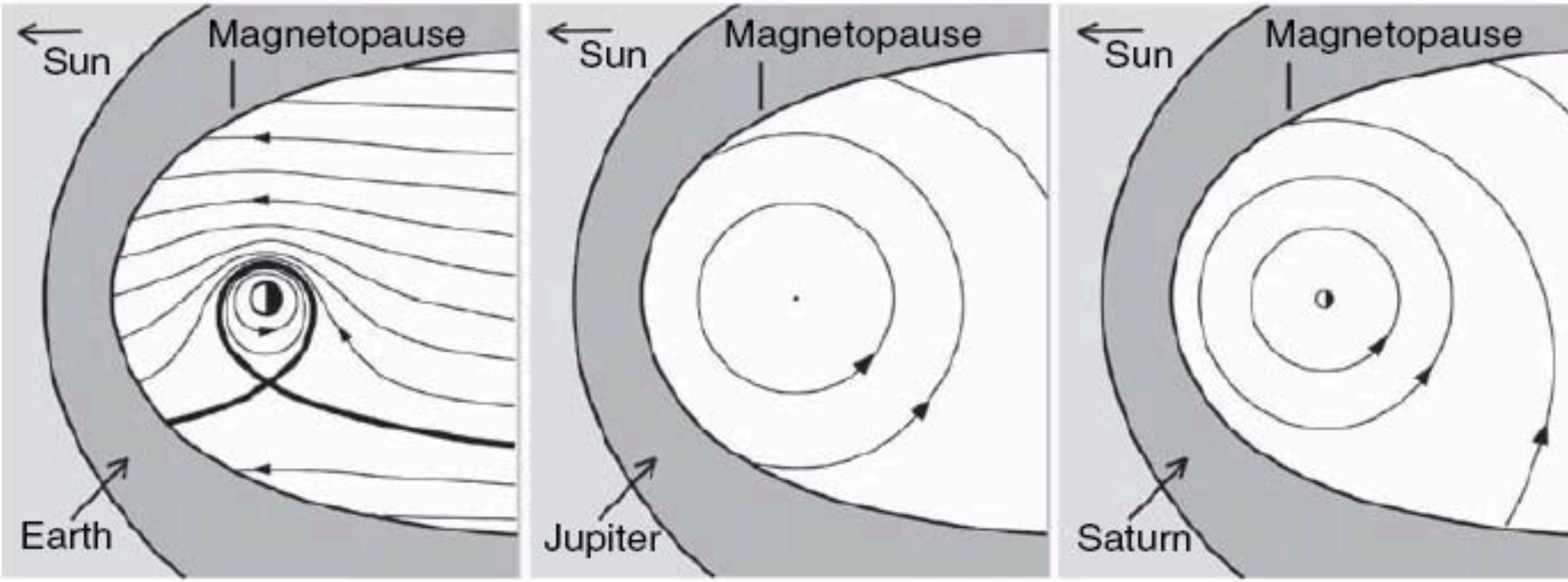
1. Reconnection more/less efficient at harnessing the solar wind momentum

2. Planet's spin slows down

3. Planet's field is stronger



Solar-wind vs. Rotation-dominated magnetospheres



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

6.7 350 95

Assumptions:

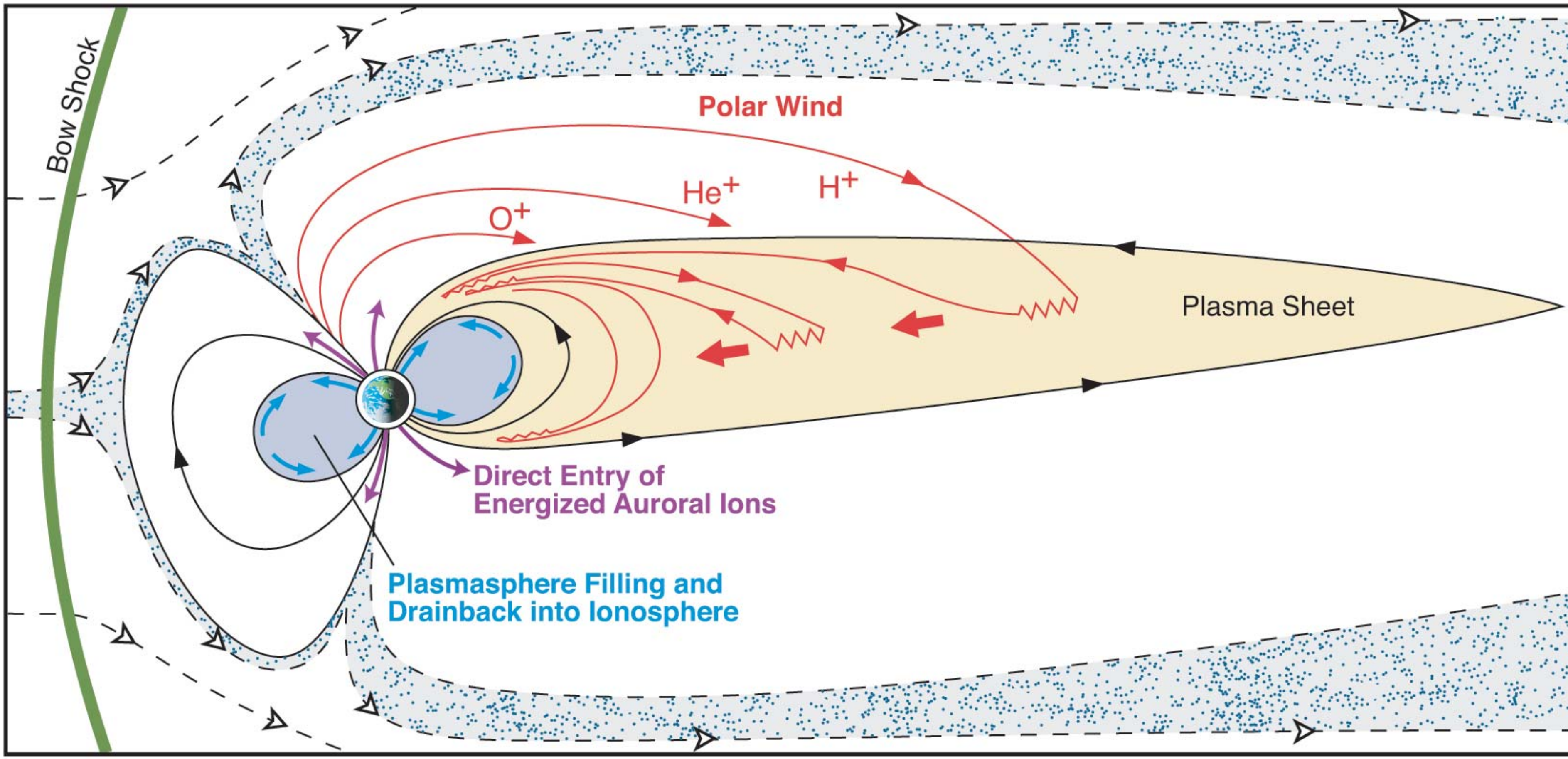
1. Planet's rotation coupled to magnetosphere
2. (Large-scale) Reconnection drives solar wind interaction

Plasma Sources

Plasma Sources

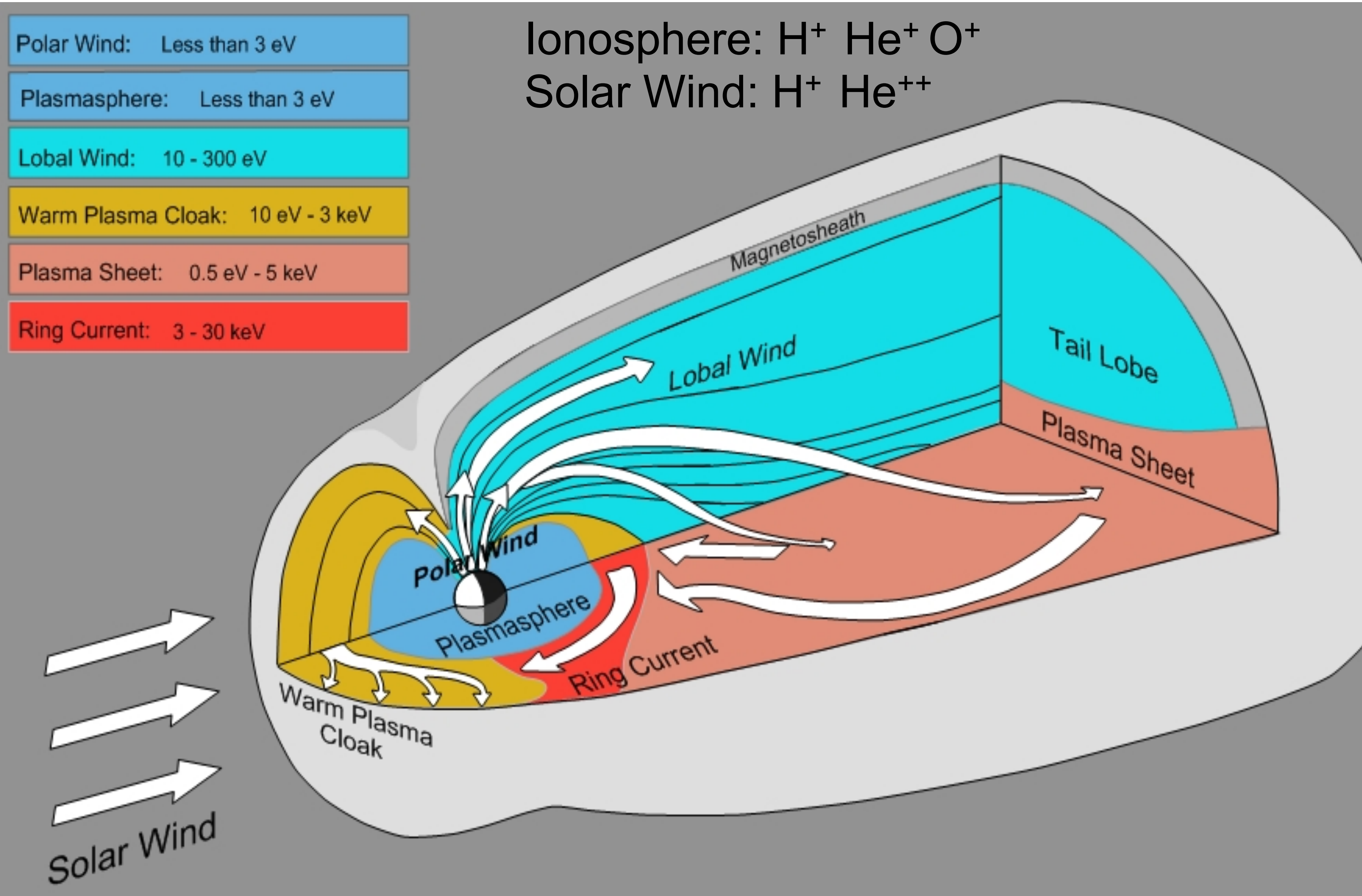
	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
N_{max} cm^{-3}	~1	1-4000	>3000	~100	~3	~2
Composition	H^+ Solar Wind	O^+ H^+ Ionosphere	O^{n+} S^{n+} Io	O^+ H_2O^+ H^+ Enceladus	H^+ Ionosphere	H^+ N^+ Triton Ionosphere
Source kg / s	?	5	700-1200	70-200	~0.02	~0.2

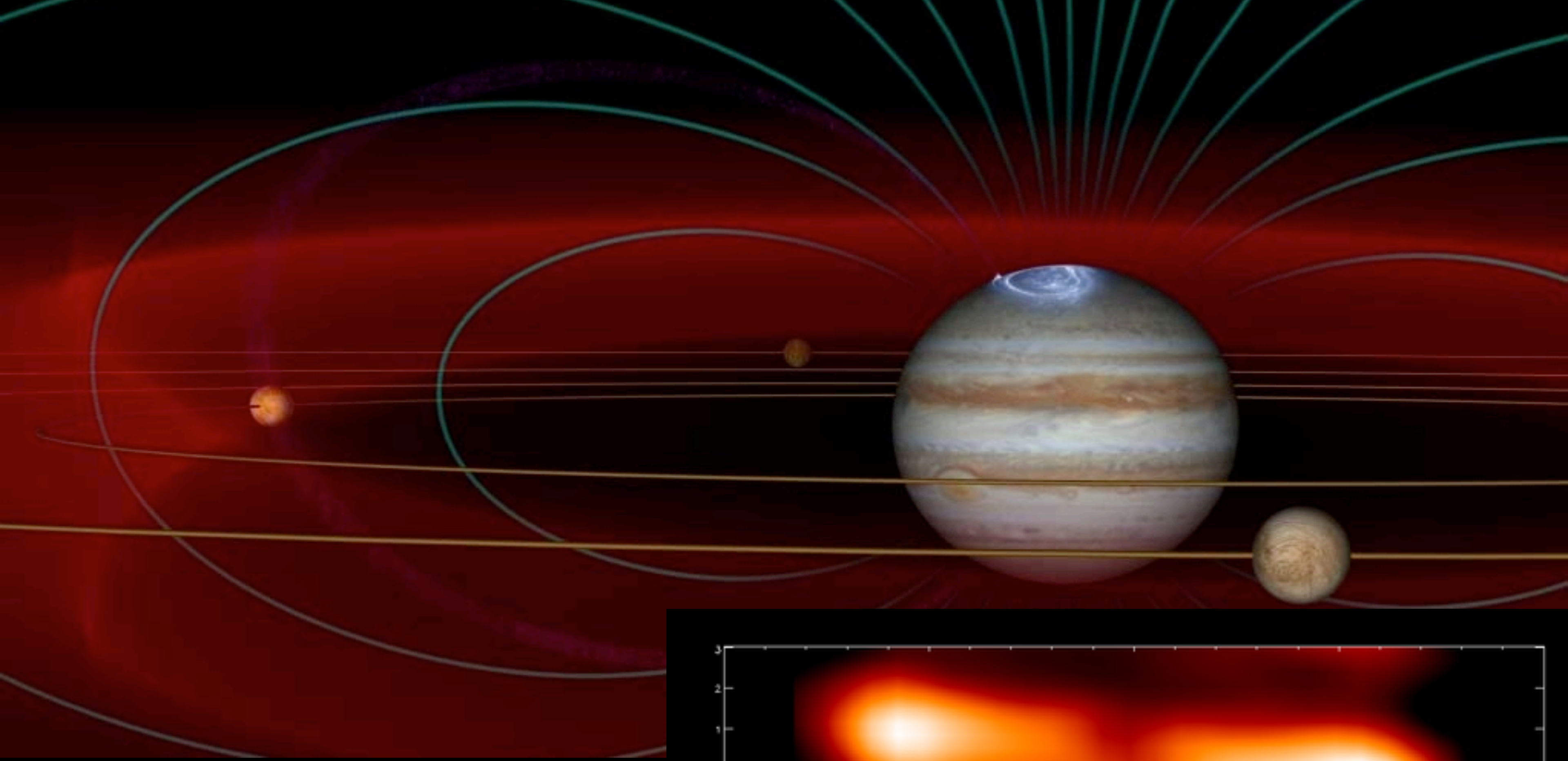
Earth Sources of Plasma (5 kg/s): Solar Wind + ionosphere mixed (over the poles) into magnetotail and convected sunward

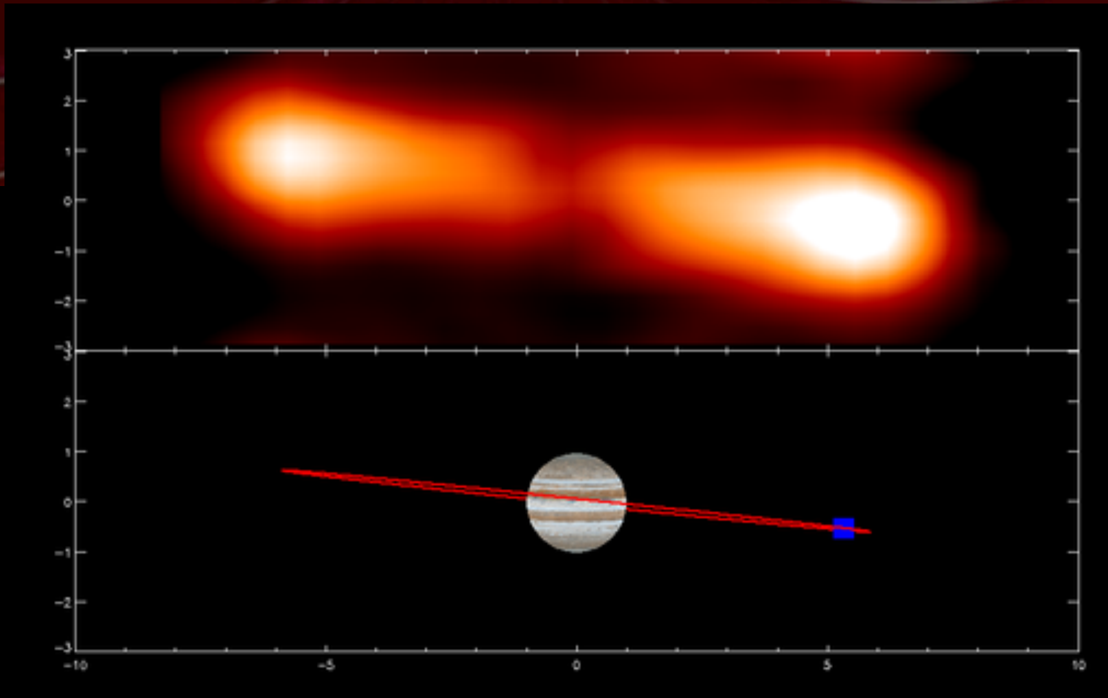


Earth Plasma Flux 5 kg/s

Ionosphere: H^+ He^+ O^+
Solar Wind: H^+ He^{++}

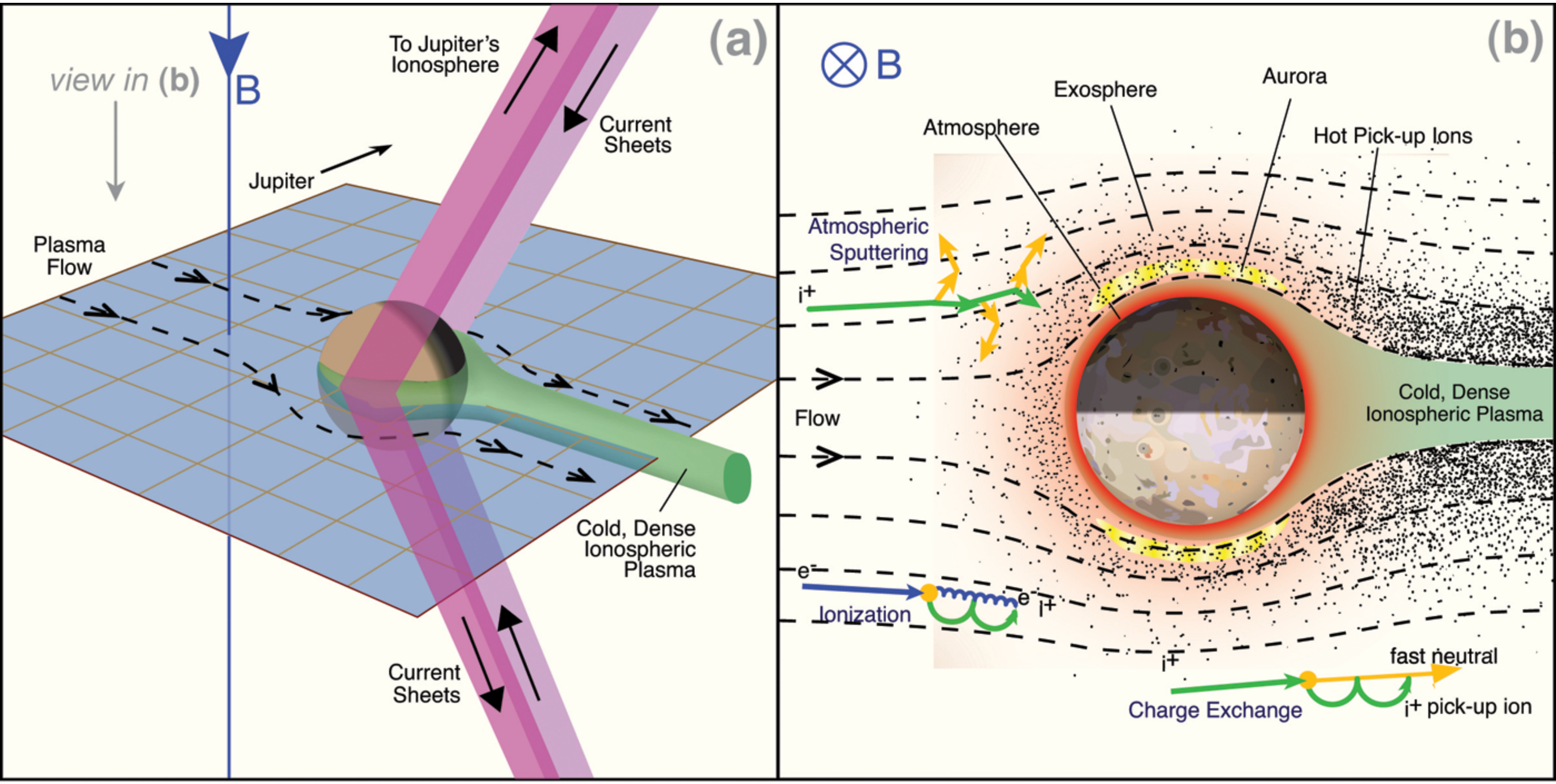






Io Plasma torus

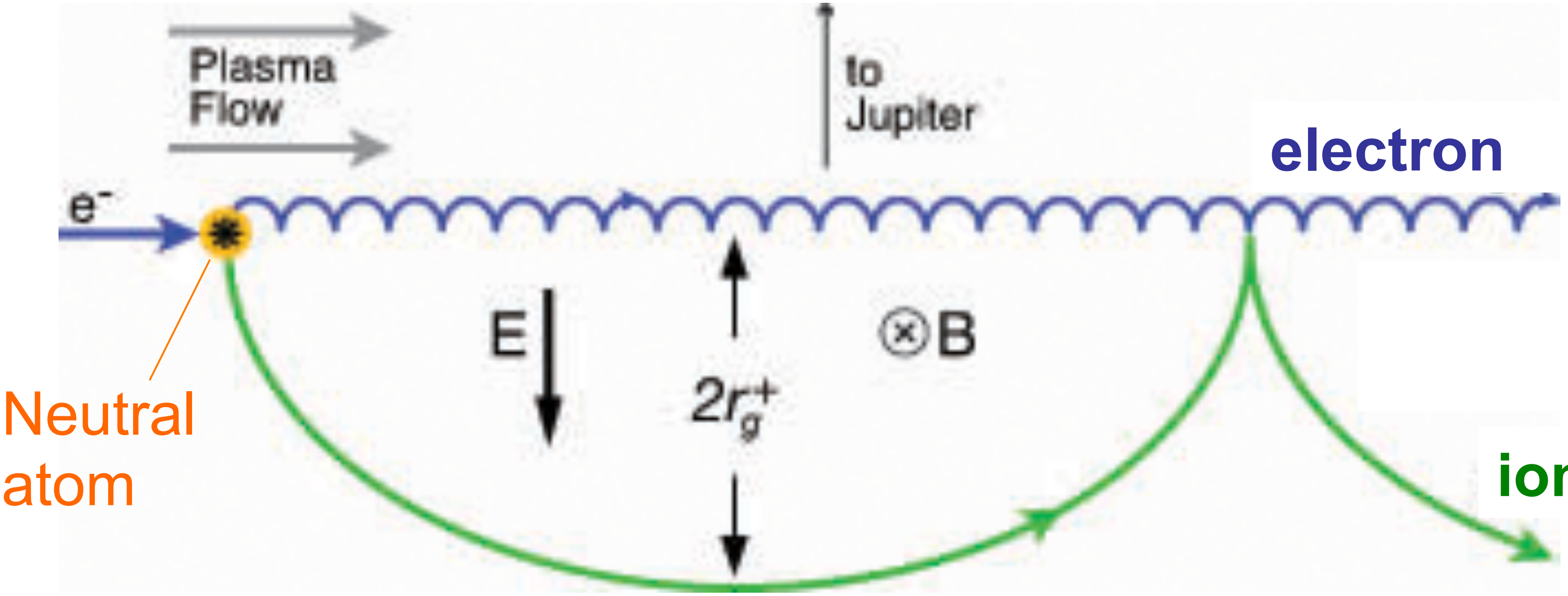
- Total mass 2 Mton
- Source 1 ton/s
- Replaced in 20-50 days



- Strong electrodynamic interaction
- Mega-amp currents between Io and Jupiter

- Plasma interaction with Io's atmosphere
- Heated atmosphere escapes
- ~20% plasma source local

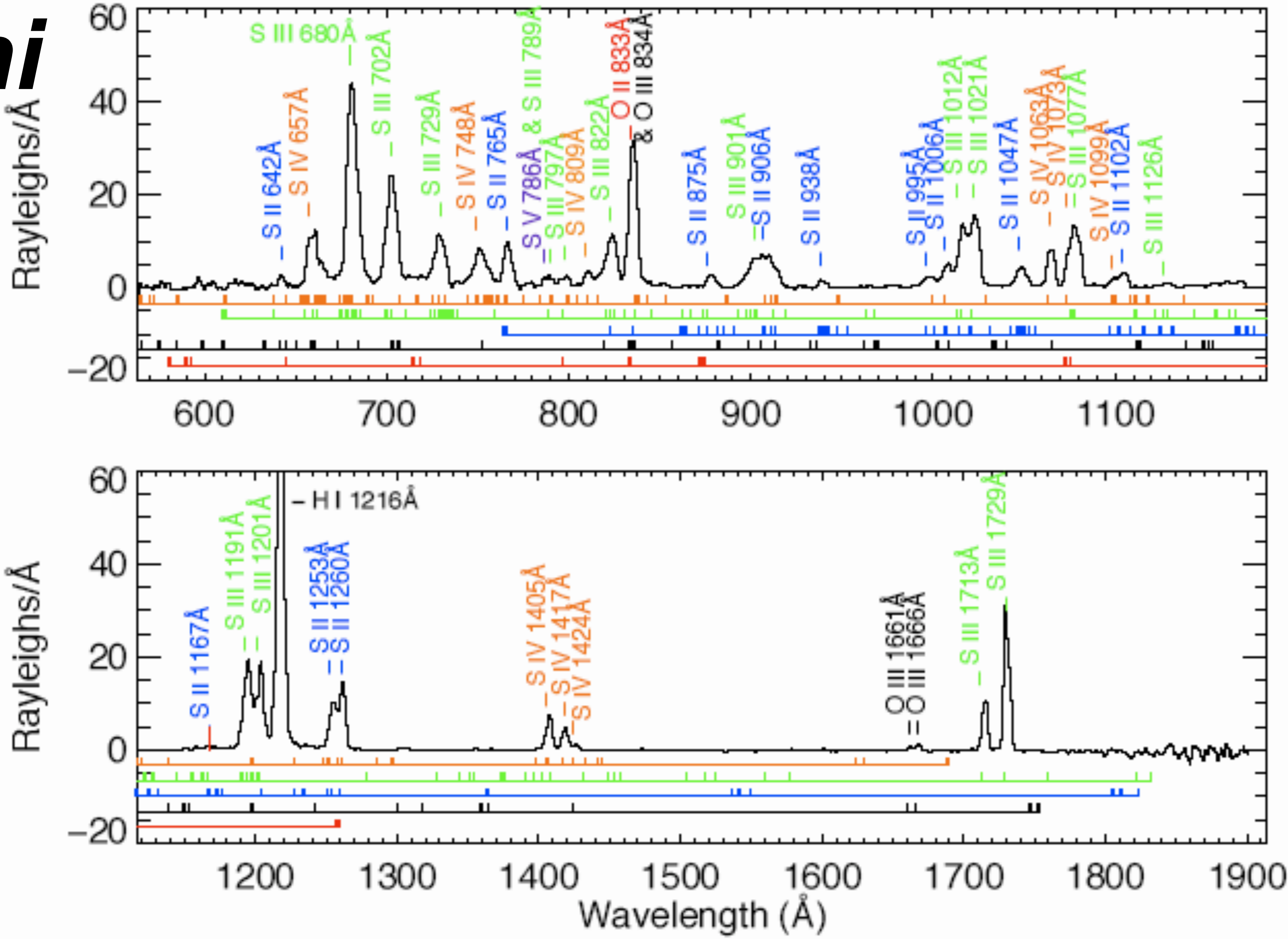
Ion Pick Up



- The magnetic field couples the plasma to the spinning planet
- Ion gains large gyromotion -> heat

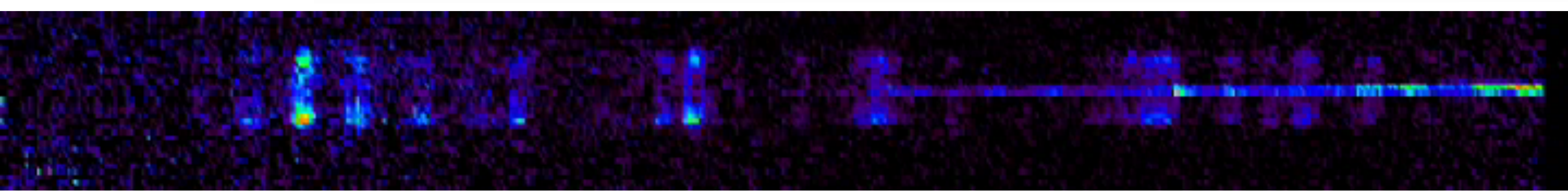
Cassini UVIS

Andrew Steffl



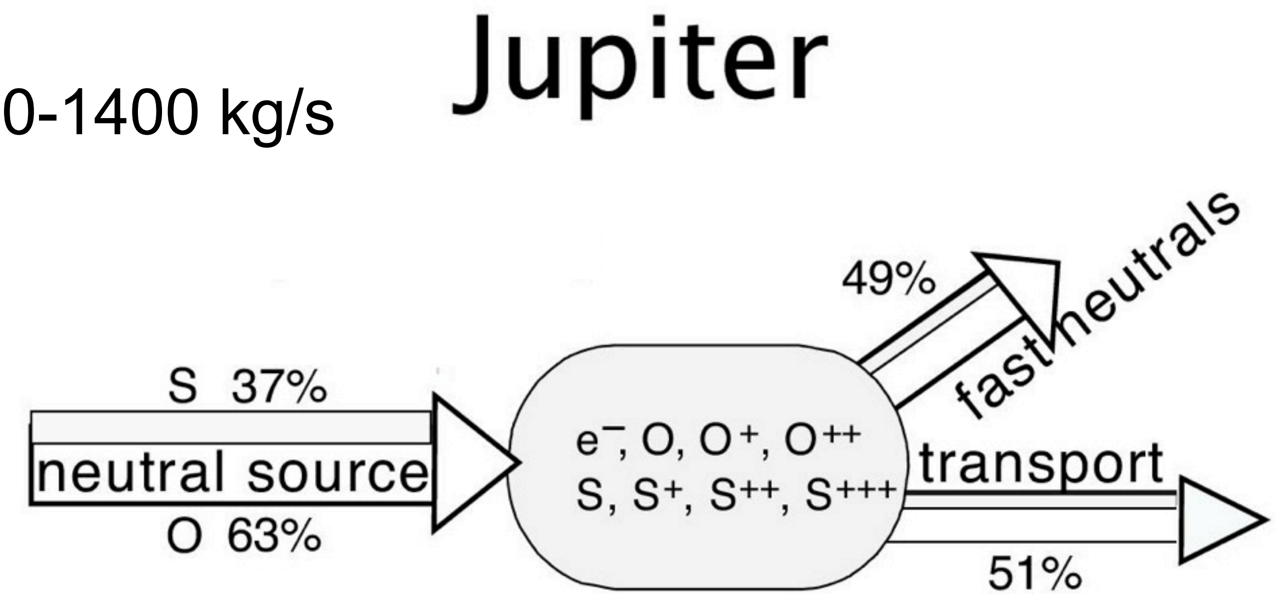
Spectral diagnosis of plasma conditions

Ni, Ne, Te



Plasma Torus   Mass Flux

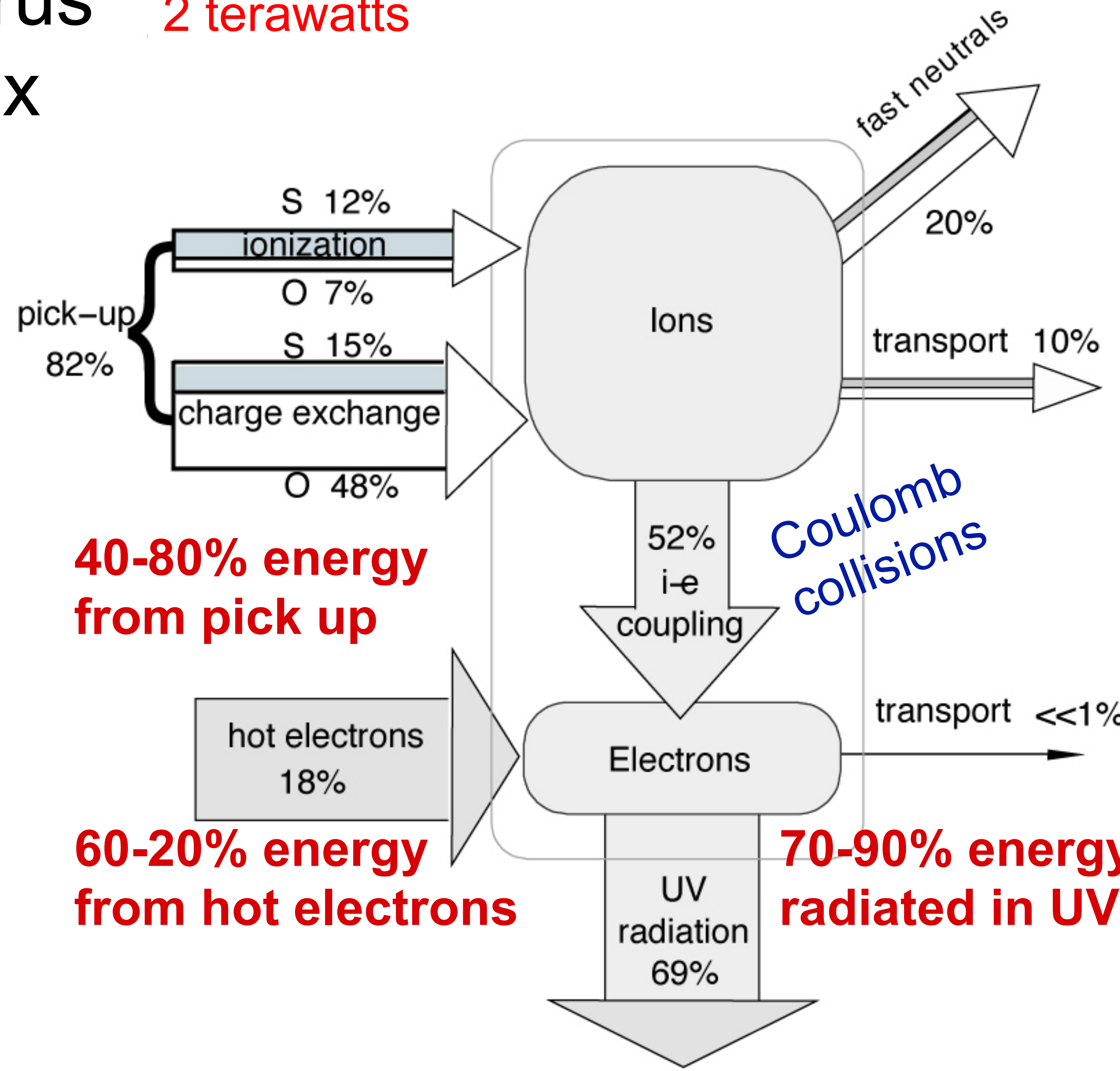
260-1400 kg/s



- Half lost as fast neutrals   -> extended neutral cloud
- Half transported out to plasma disk

Plasma Torus Energy Flux

2 terawatts



40-80% energy from pick up

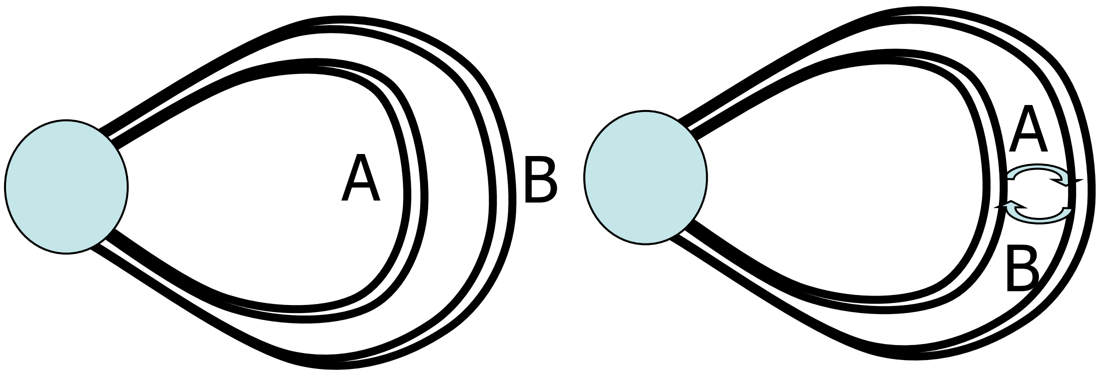
60-20% energy from hot electrons

70-90% energy radiated in UV

Radial Transport

In rotating magnetosphere

If fluxtube A contains more mass than B – they interchange



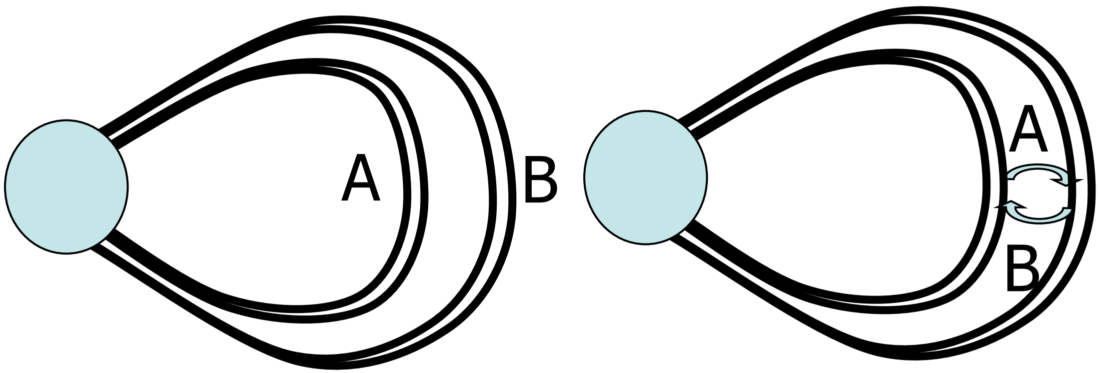
Rayleigh-Taylor instability where centrifugal potential replaces gravity

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



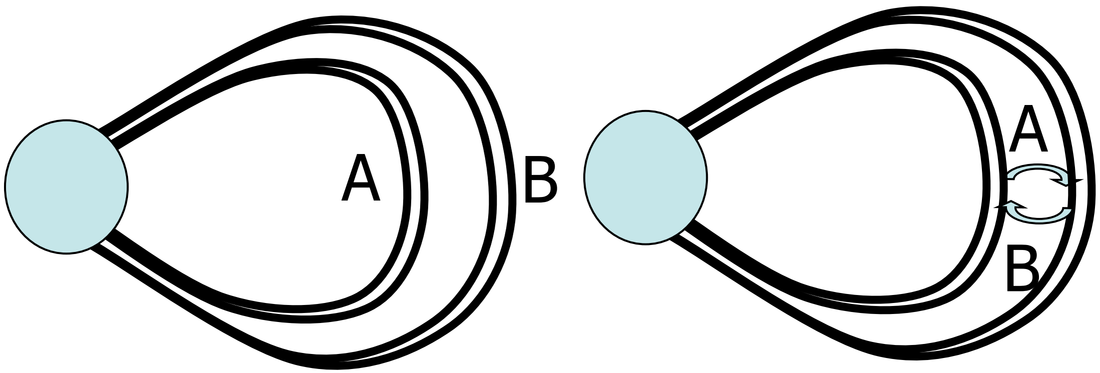
You can think of centrifugally-driven fluxtube interchange as a kind of diffusion.

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

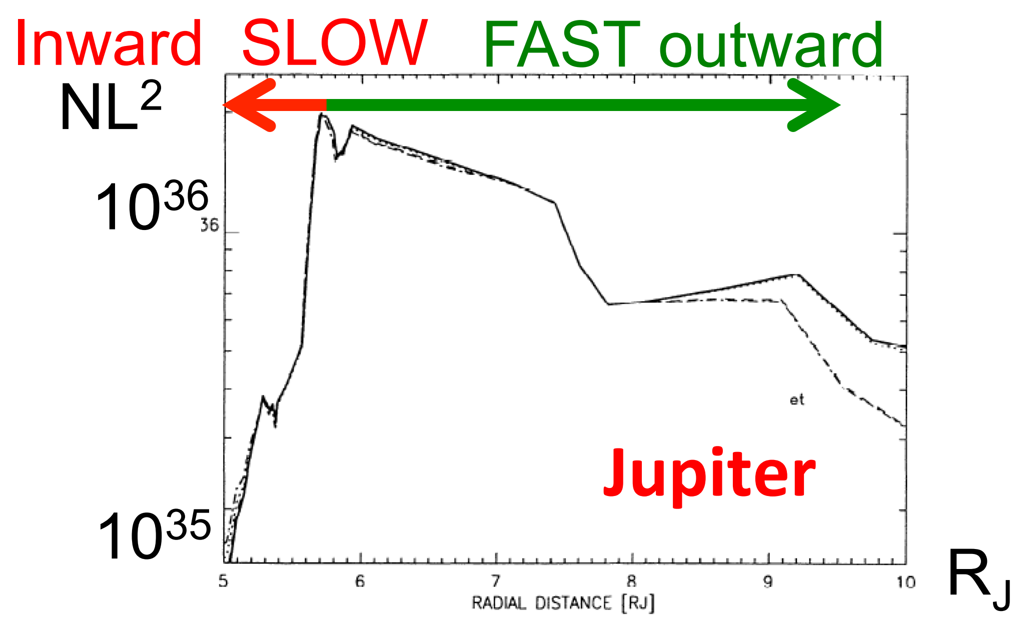
Radial Transport

In rotating magnetosphere

If fluxtube A contains more mass than B – they interchange

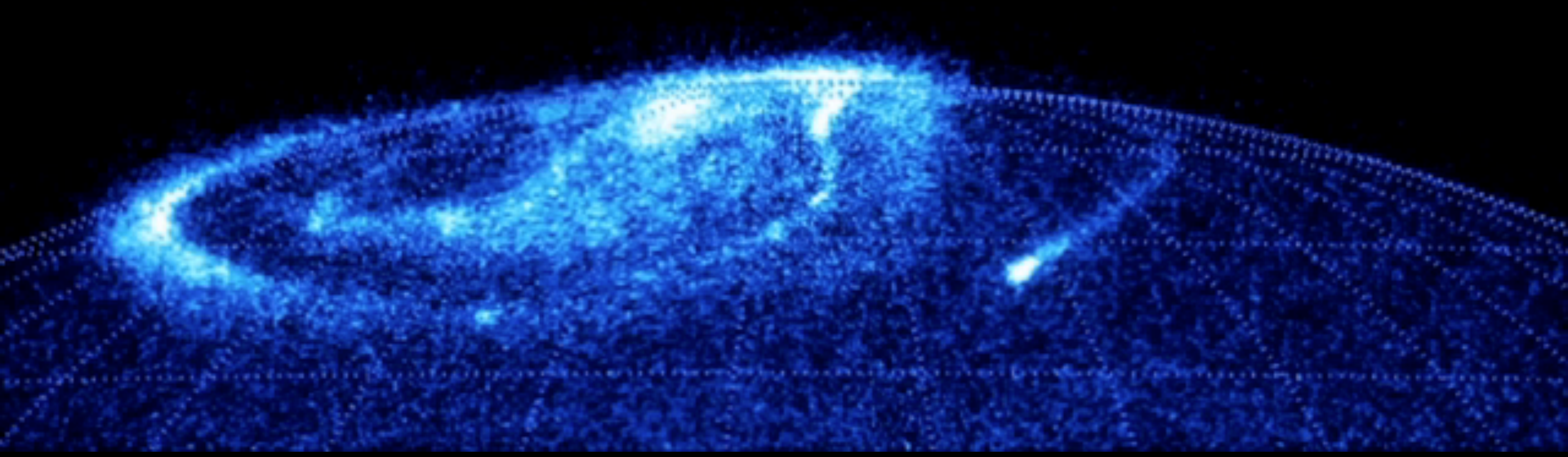


If $\beta \ll 1$,
interchange of A and B
does not change field
strength.

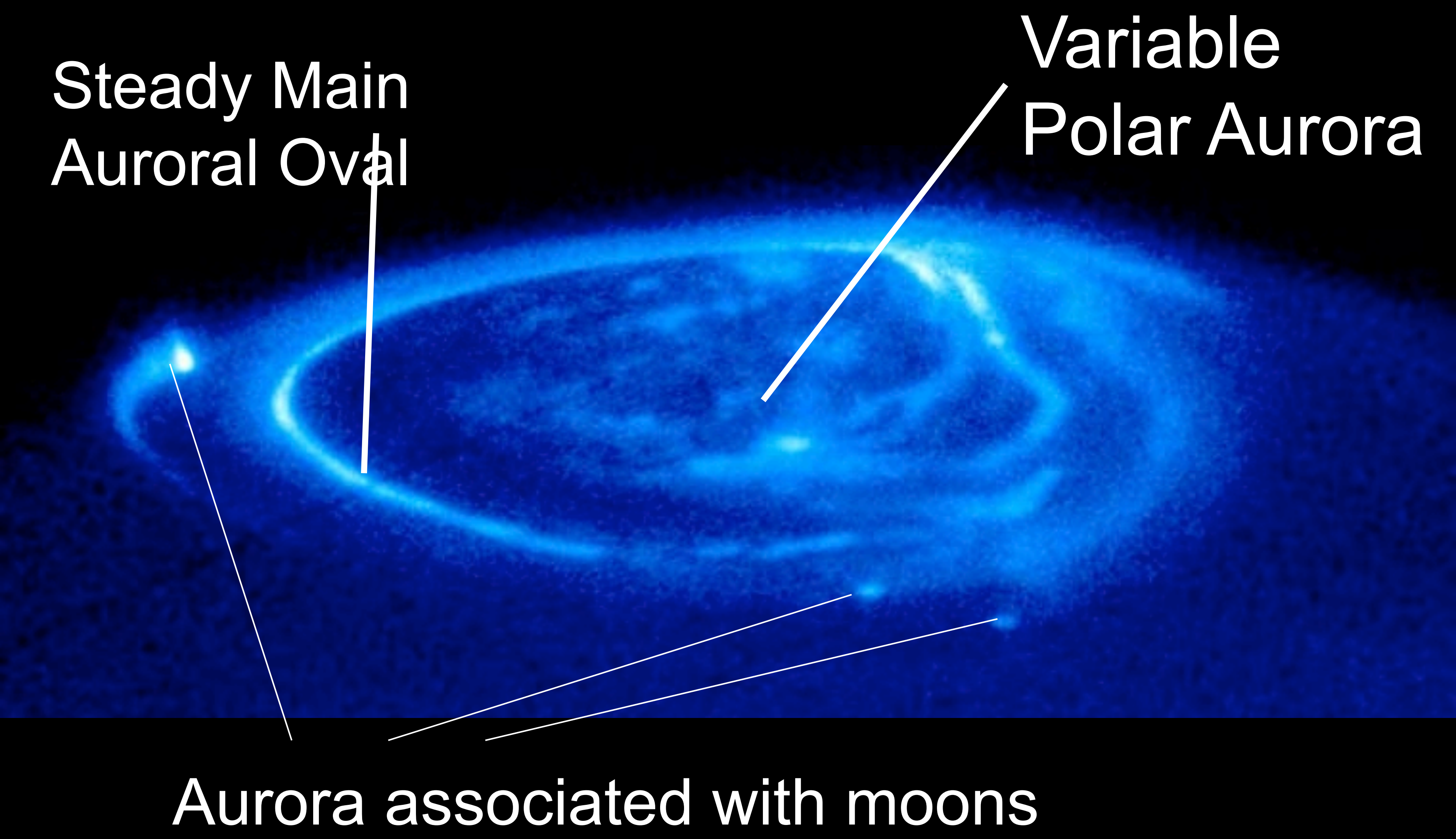


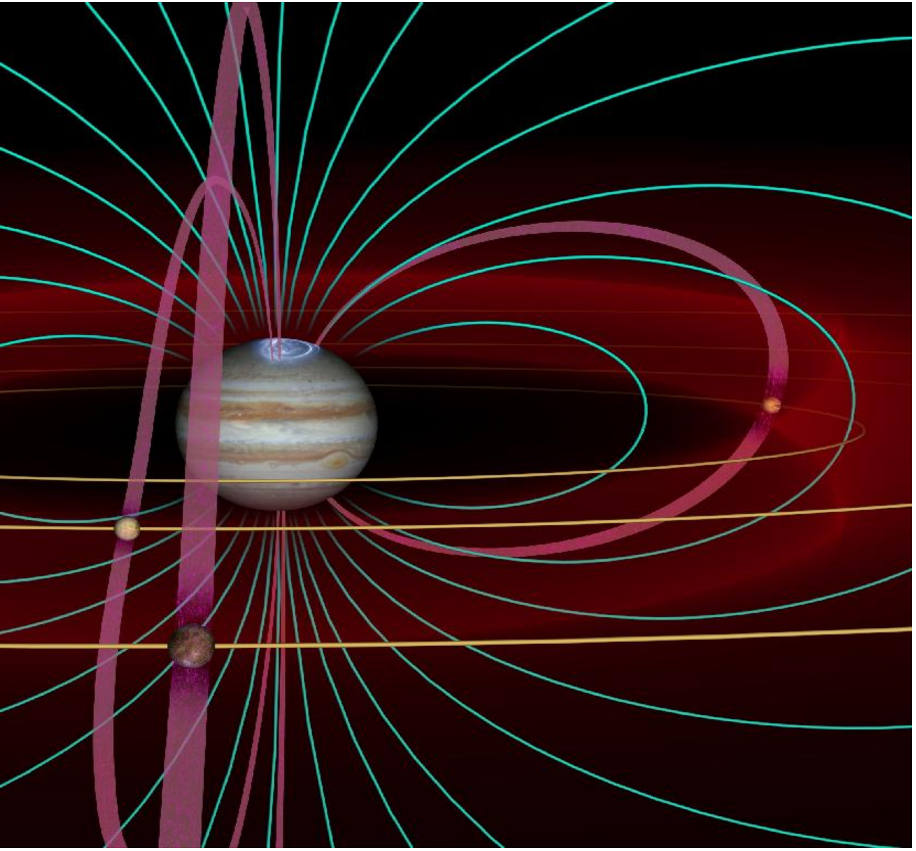
Aurora

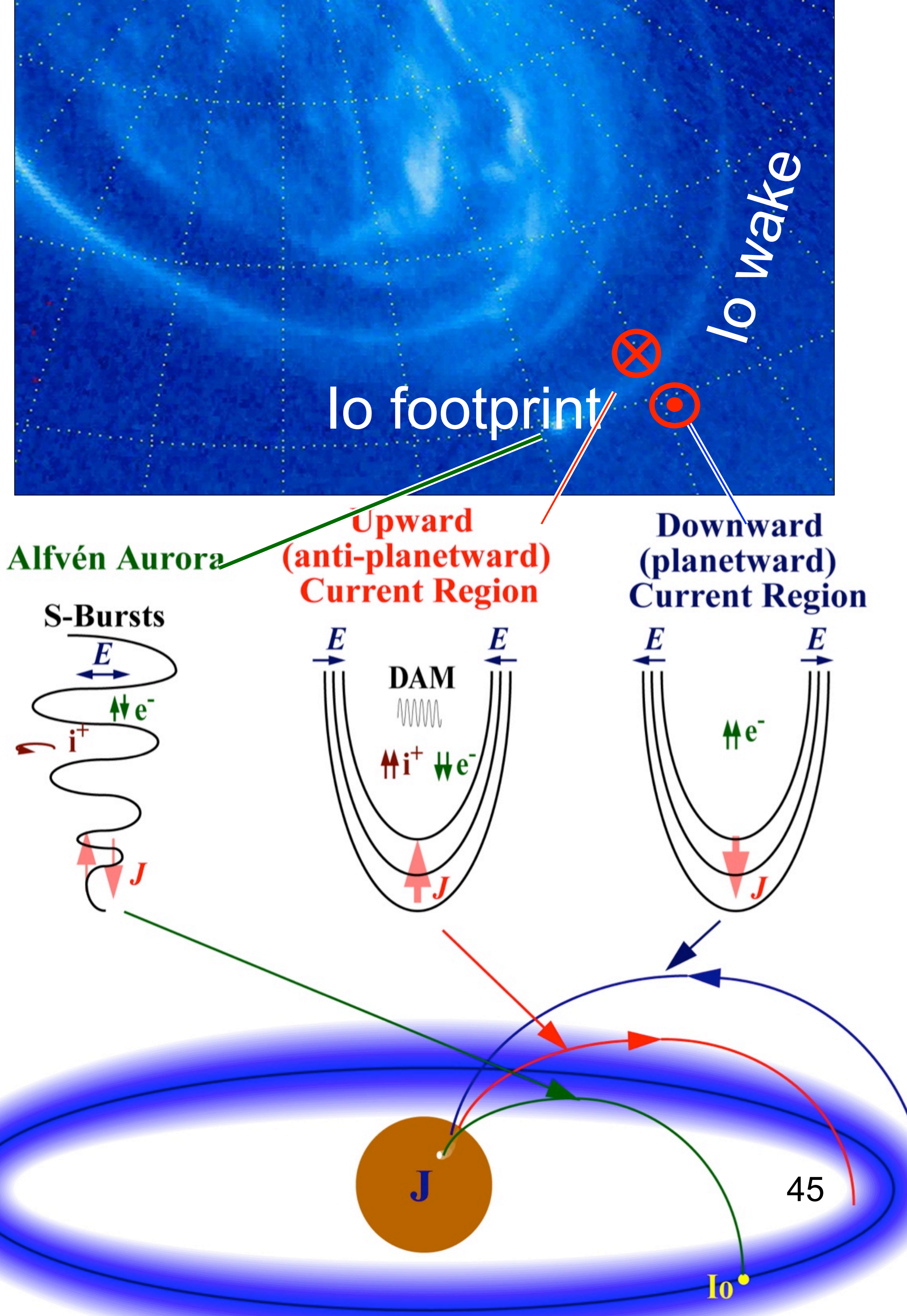
Hubble Space Telescope – *Jon Nichols*



Jupiter's 3 Types of Aurora







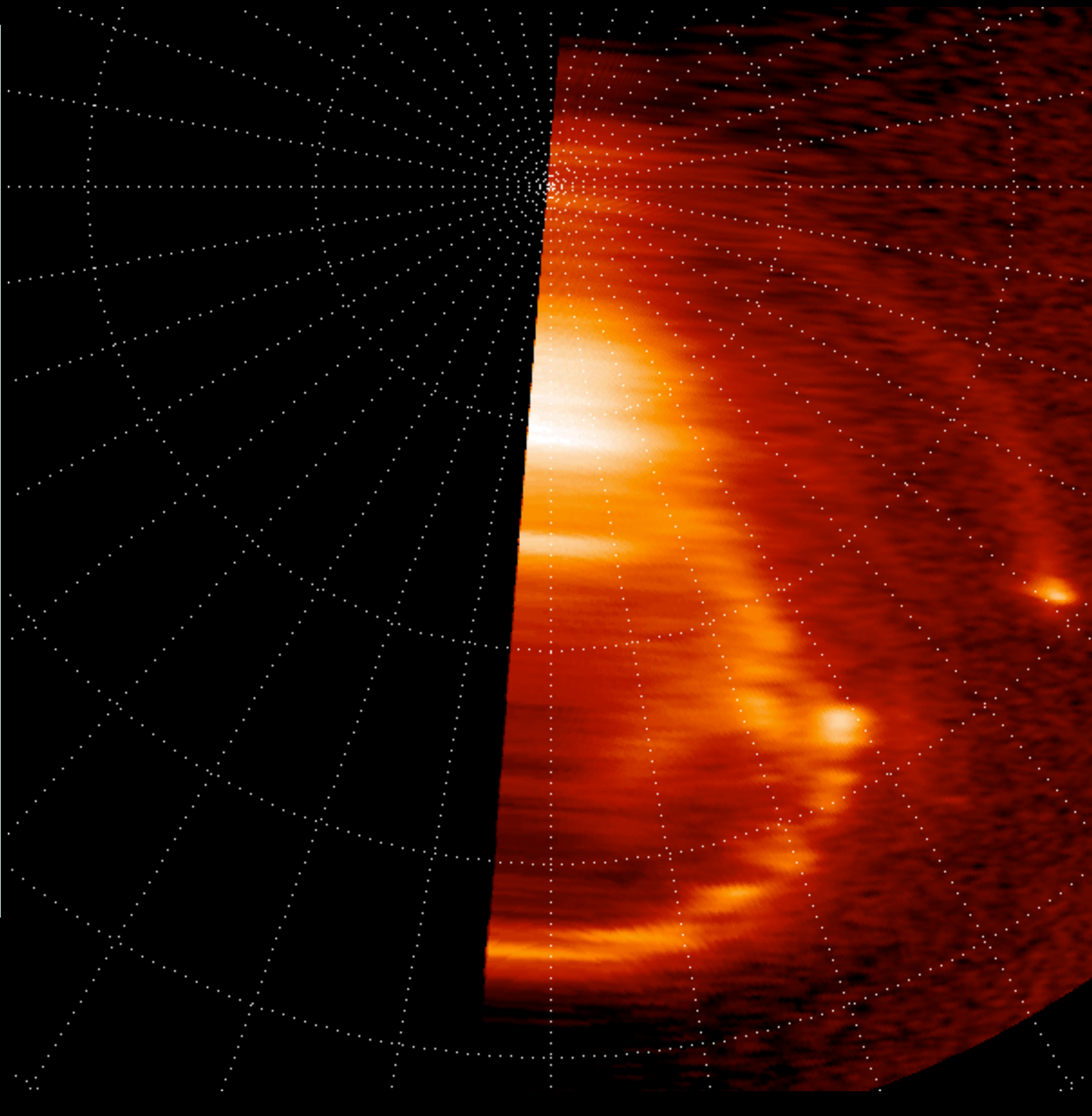
Satellite auroral emissions

- Plasma-moon electrodynamic interaction
- Mega-amp current systems
- Analogous to Earth auroral processes

Papers by Su, Ergun, Lysak, Hess, Bonfond

Jupiter's Aurora - The Movie

Fixed magnetic co-ordinates rotating with Jupiter

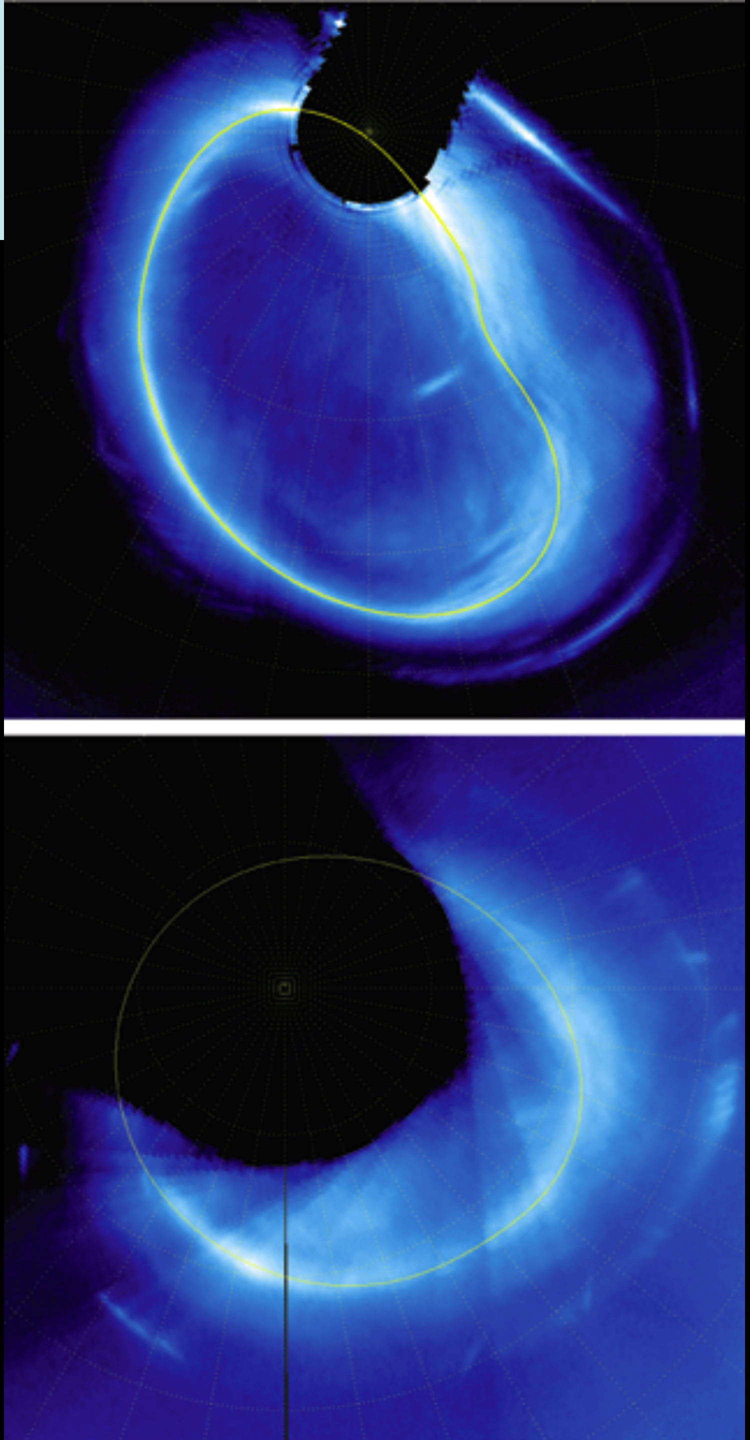


Clarke et al.
Grodent et al.
HST

Main Aurora

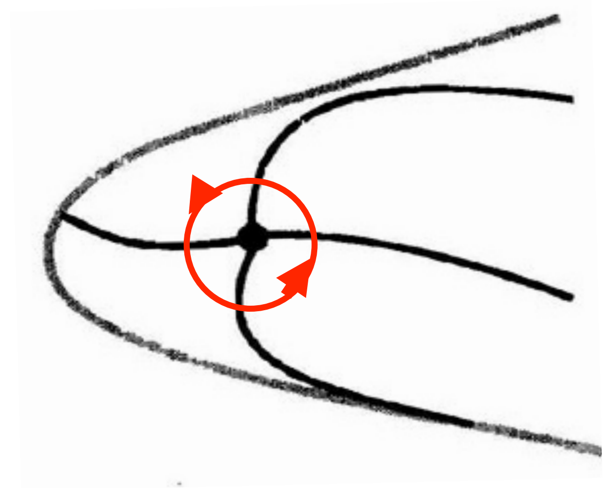
- Shape constant, fixed in magnetic co-ordinates
- Magnetic anomaly in north
- Steady intensity
- ~1° Narrow

Clarke et al., Grodent et al. HST



Coupling the Plasma to the Flywheel

Khurana 2001



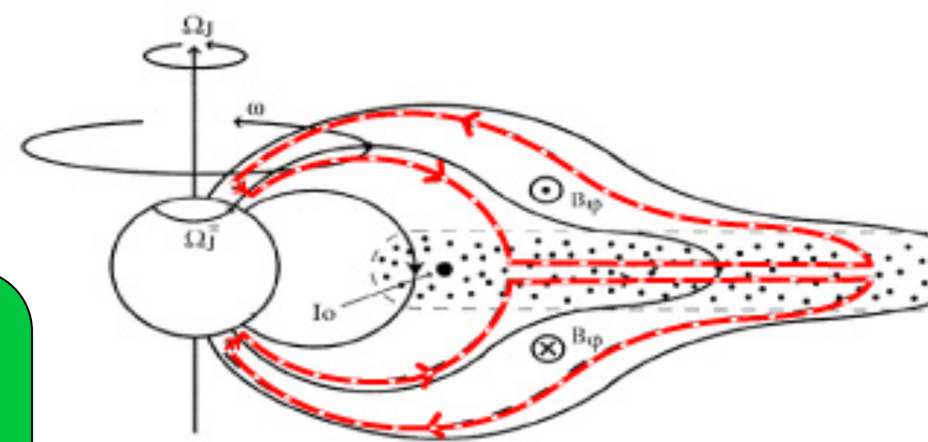
- As plasma from Io moves outwards its rotation decreases (conservation of angular momentum)

- Sub-corotating plasma pulls back the magnetic field

- Curl **B** -> radial current J_r

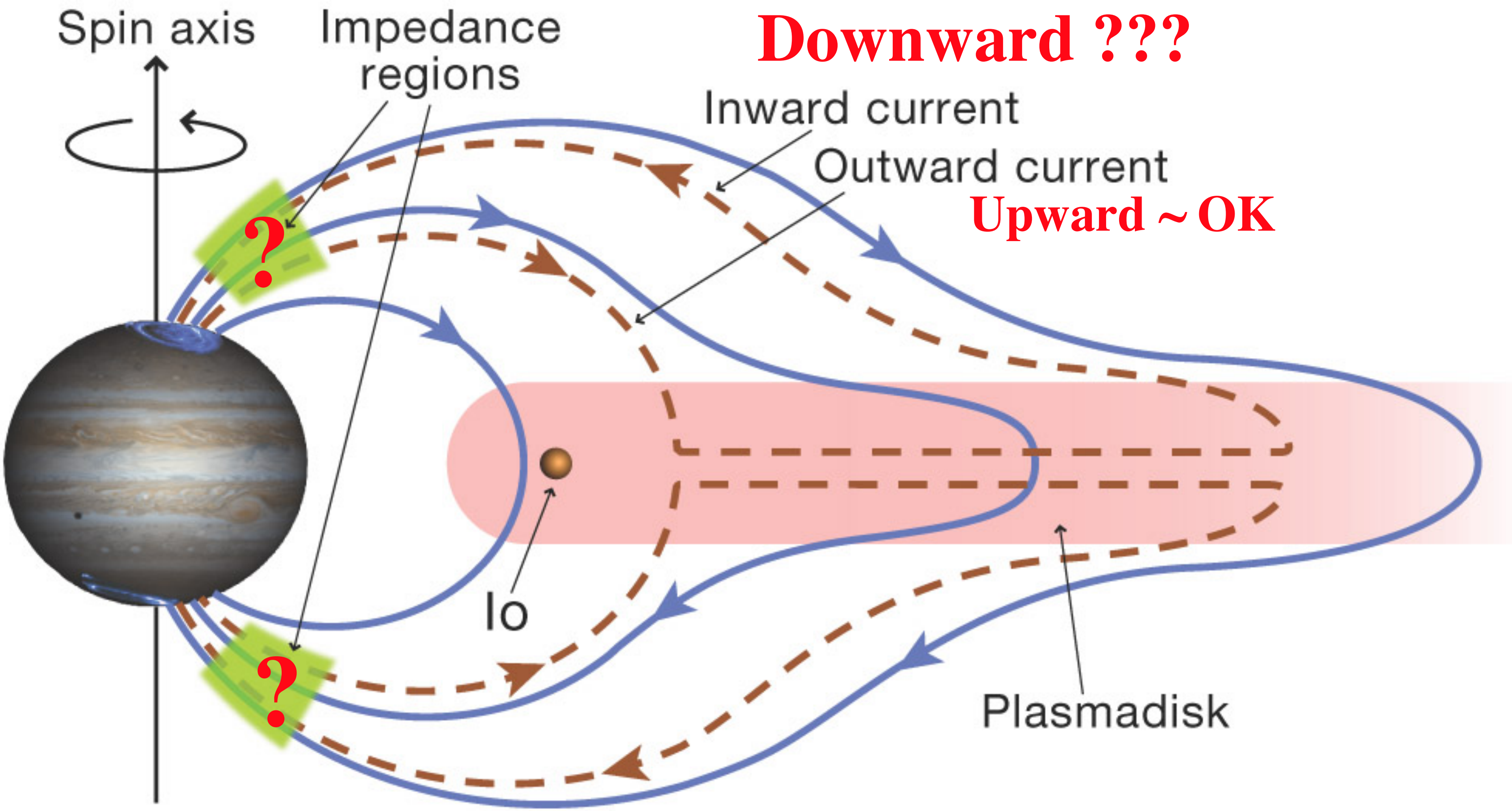
- J_r x **B** force enforces rotation

Field-aligned currents couple magnetosphere to Jupiter's rotation



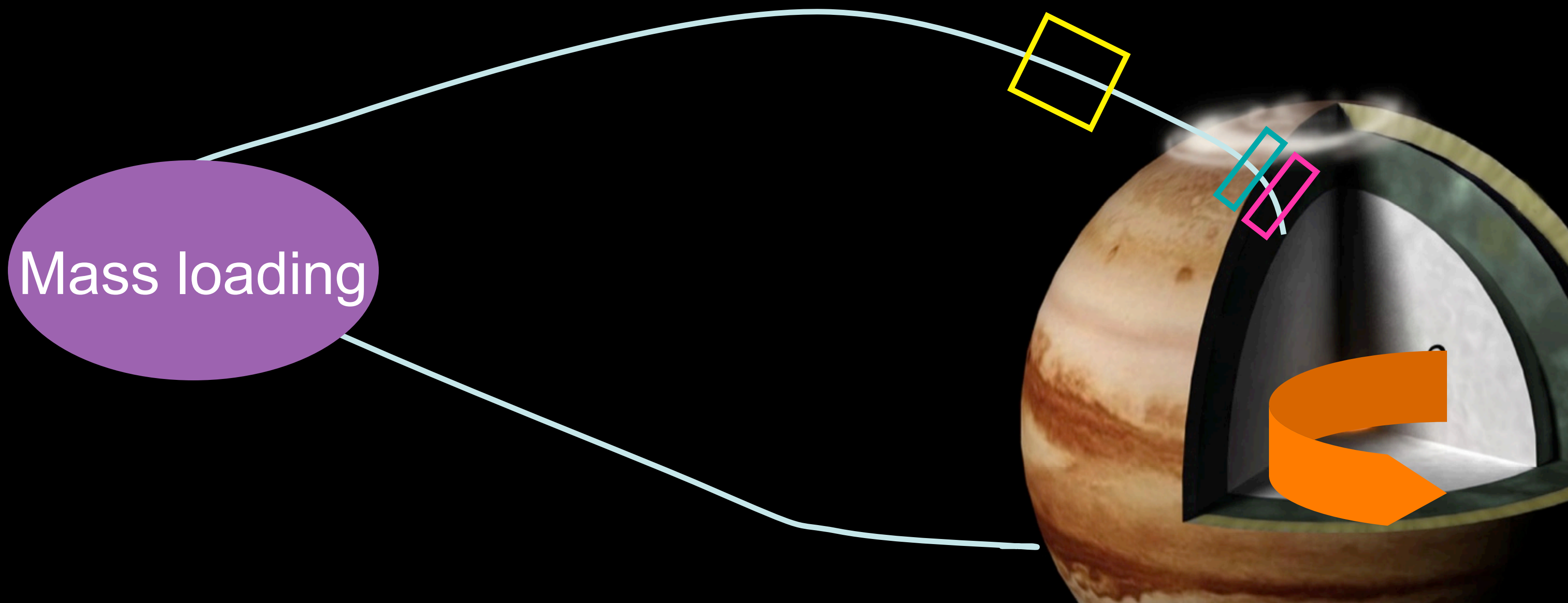
Cowley & Bunce 2001

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?



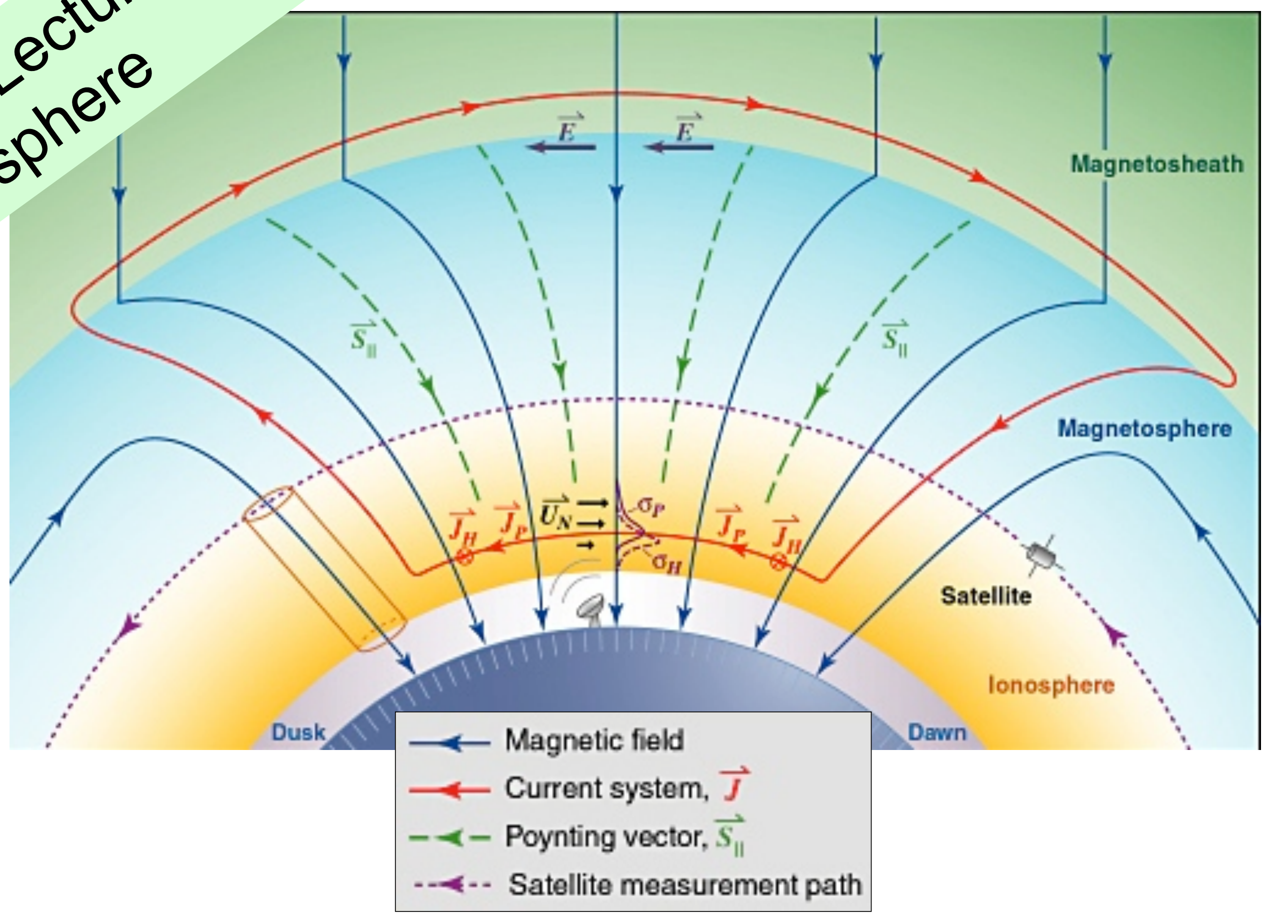
A - Between deep and upper atmosphere?

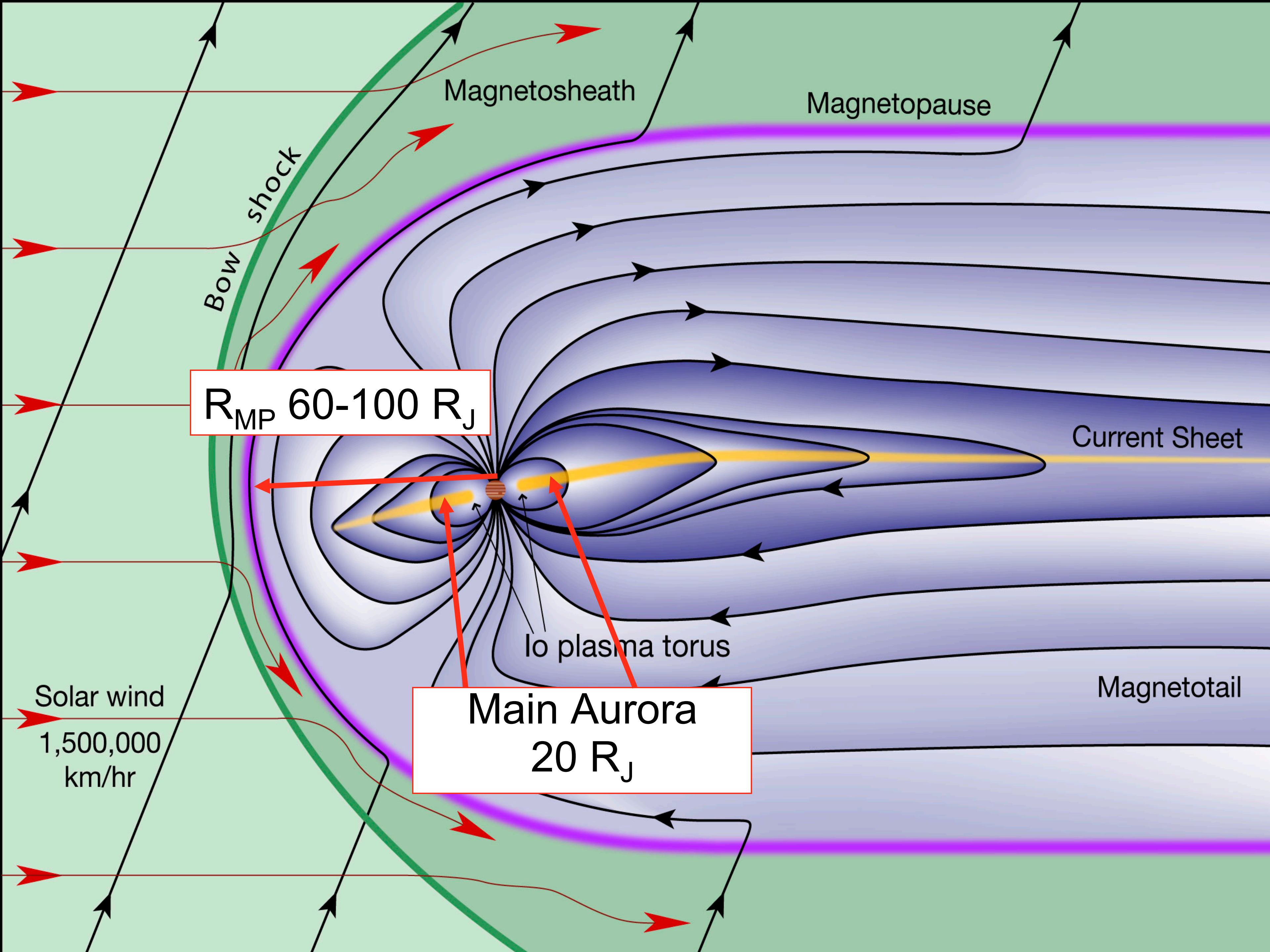
B - Between upper atmosphere and ionosphere?

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

Ionosphere - Sets boundary conditions for magnetospheric dynamics

Jan Sojka's Lecture
On ionosphere



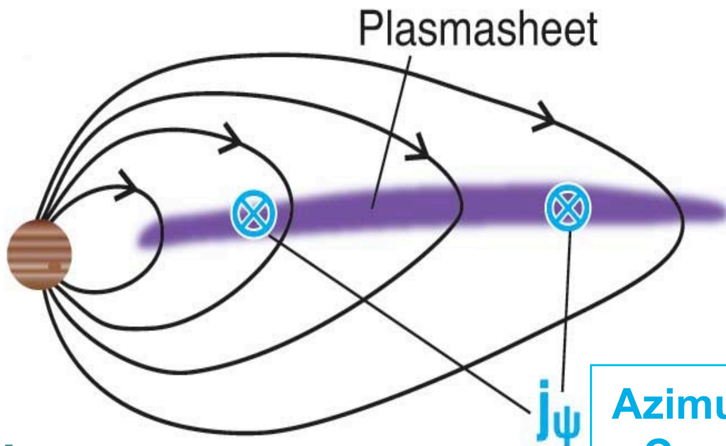


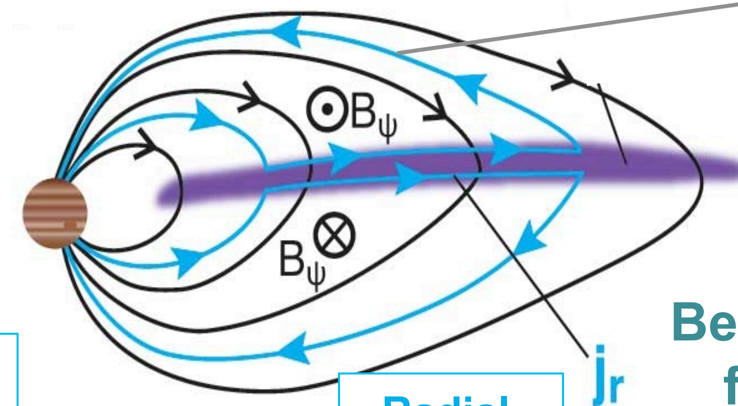
Magnetosheath
Magnetopause
Bow shock
R_MP 60-100 R_J
Current Sheet
Io plasma torus
Main Aurora
20 R_J
Magnetotail
Solar wind
1,500,000
km/hr

Configuration

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

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



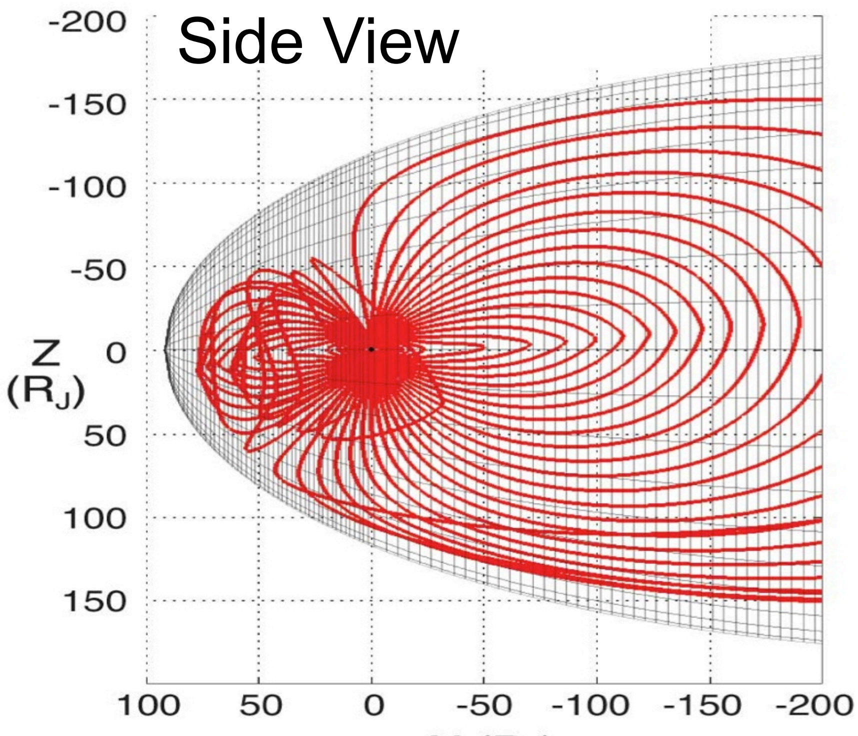


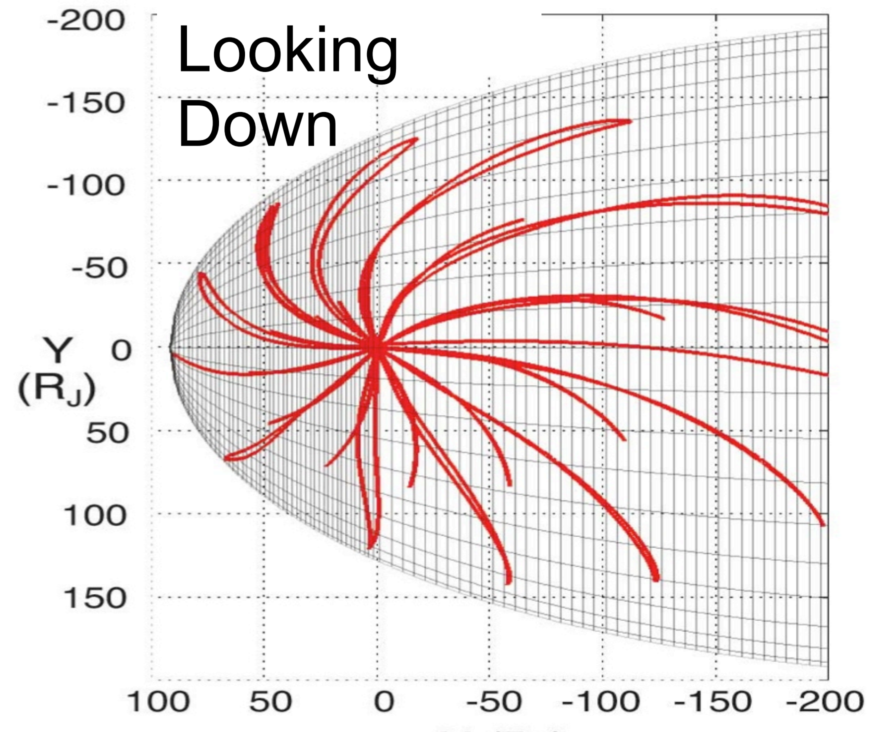
Expands, stretches field

Azimuthal Current

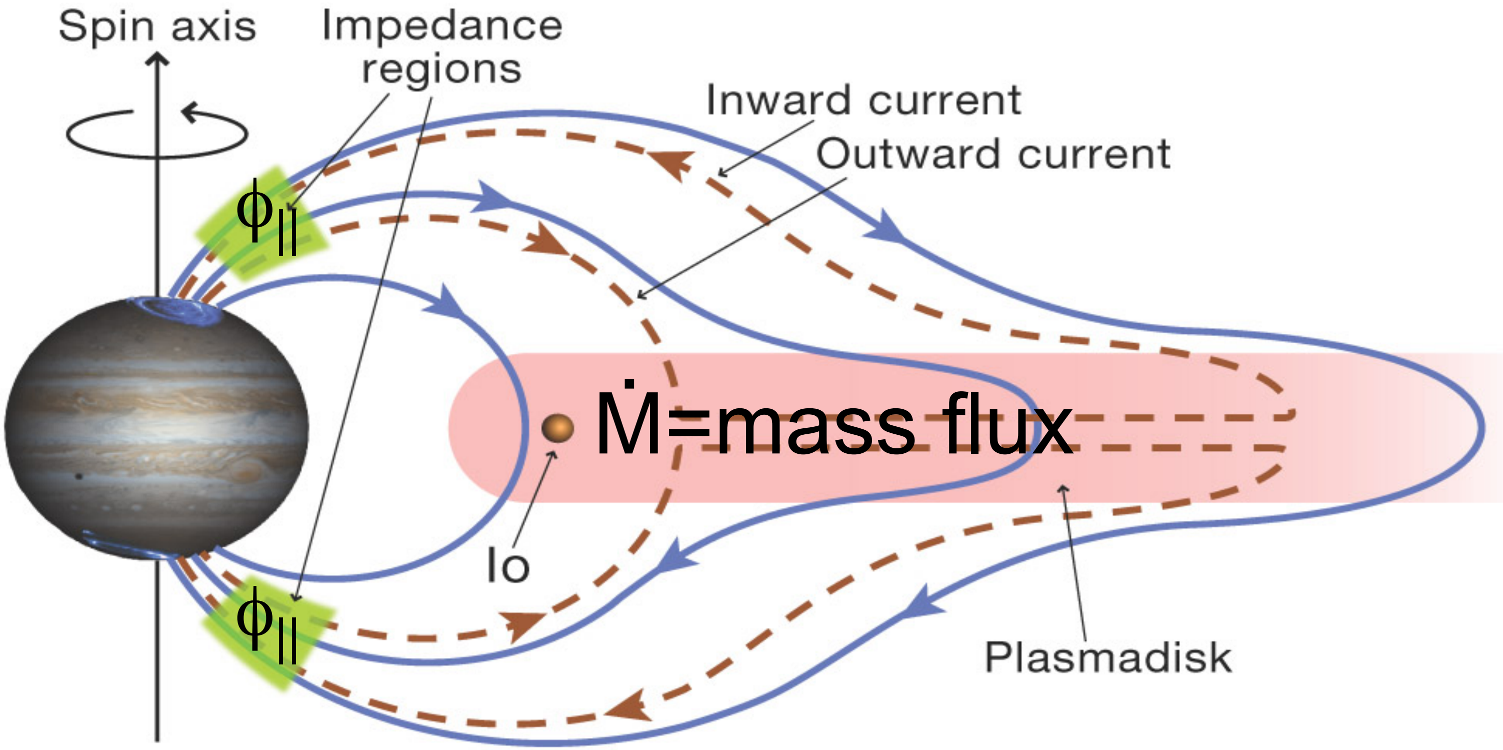
Radial Current

Bends field back





(De-)Coupling - 1

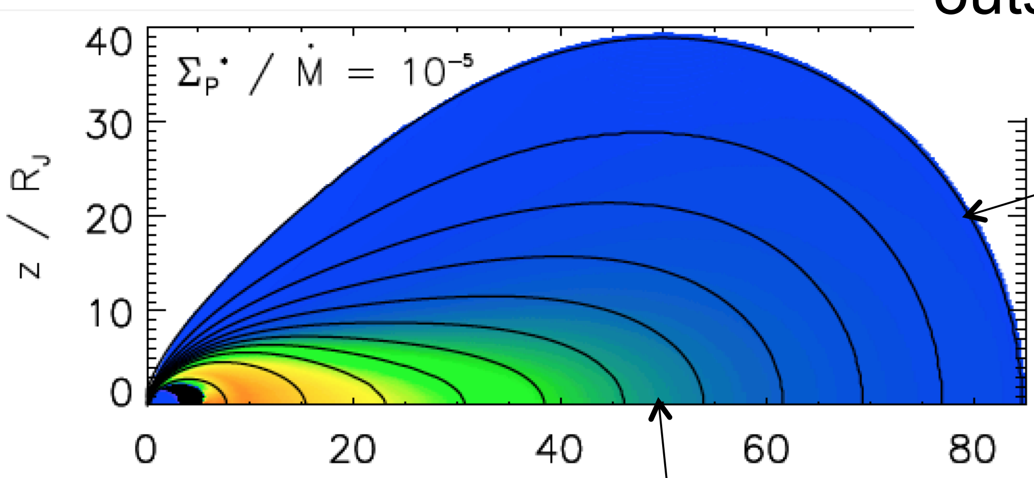


Magnetospheric Factors: $\dot{M}$ $\phi_{||}$
Ionosphere/Thermosphere factors: Σ_p winds, chemistry, heating, radiation, etc;

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

How is information transmitted along magnetic field lines?

How is a stress from the outside communicated to the planet?

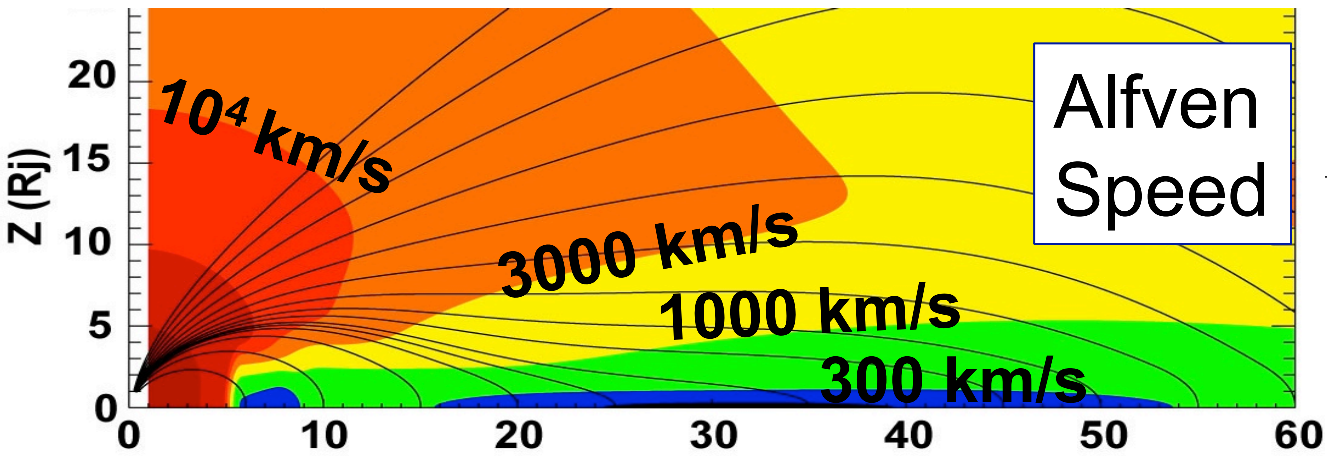


How does a blob of plasma here communicate with the planet?

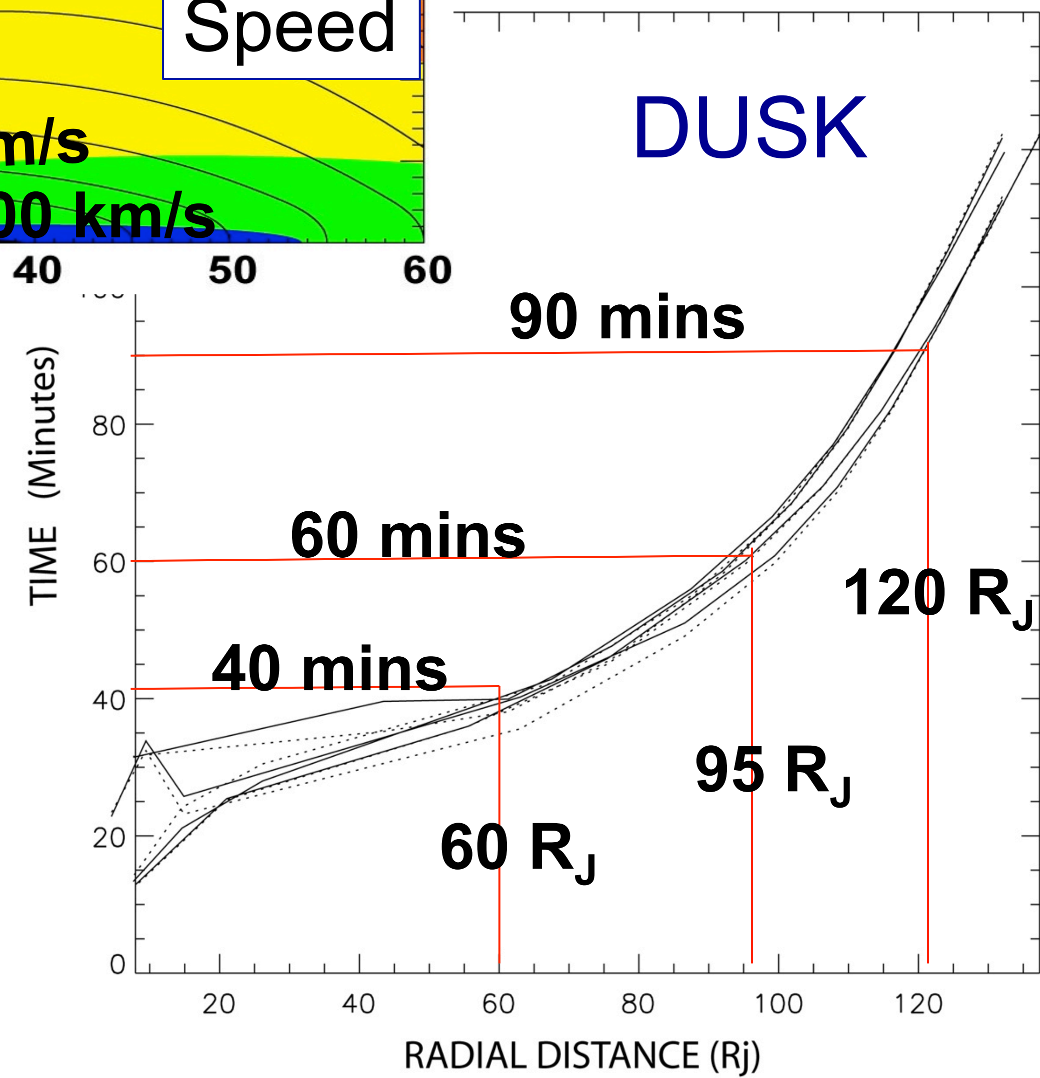
Alfven waves!

De-Coupling - 2

$$v_A = \frac{B}{\sqrt{\mu_0 \rho}}$$

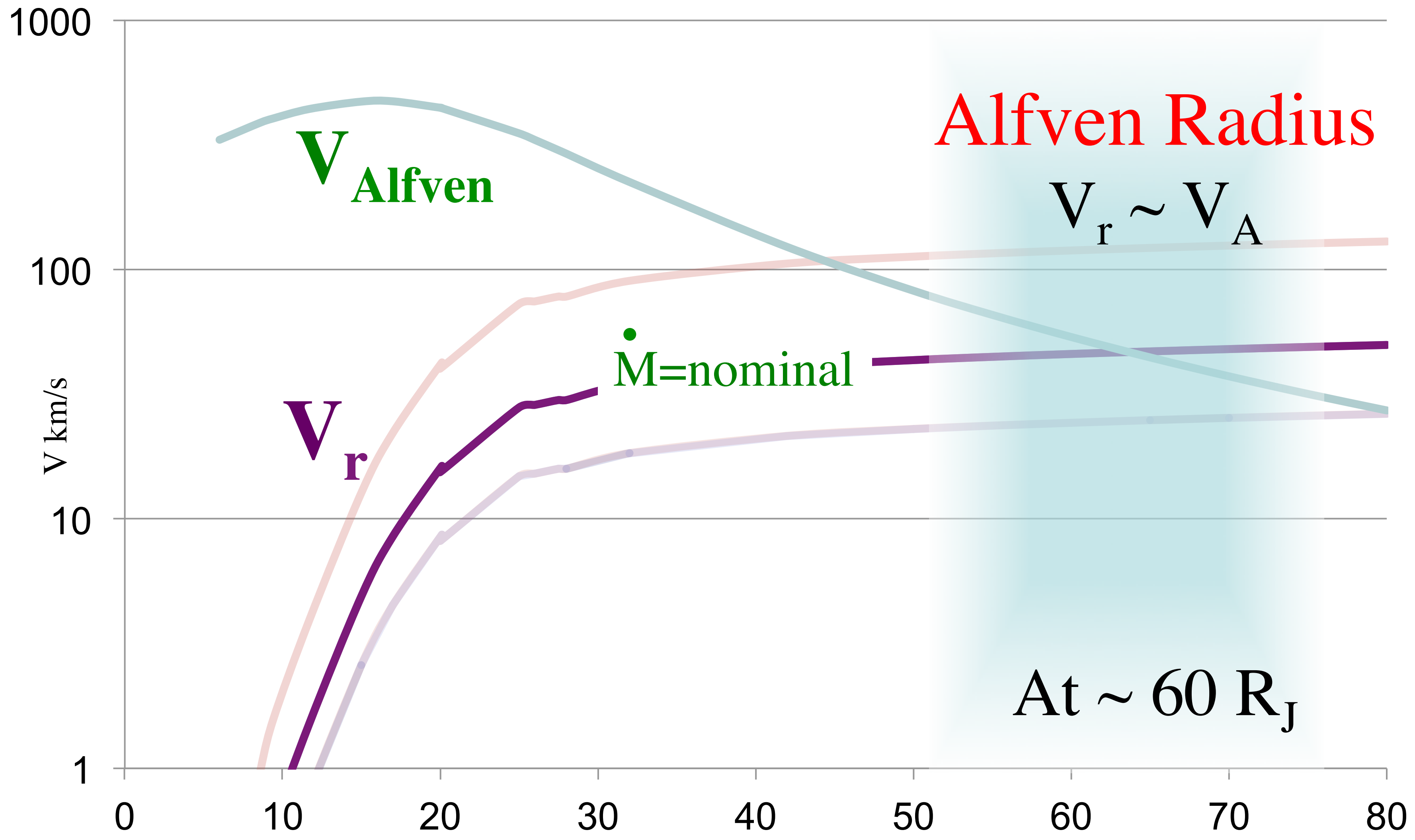


Alfven 1-way travel time

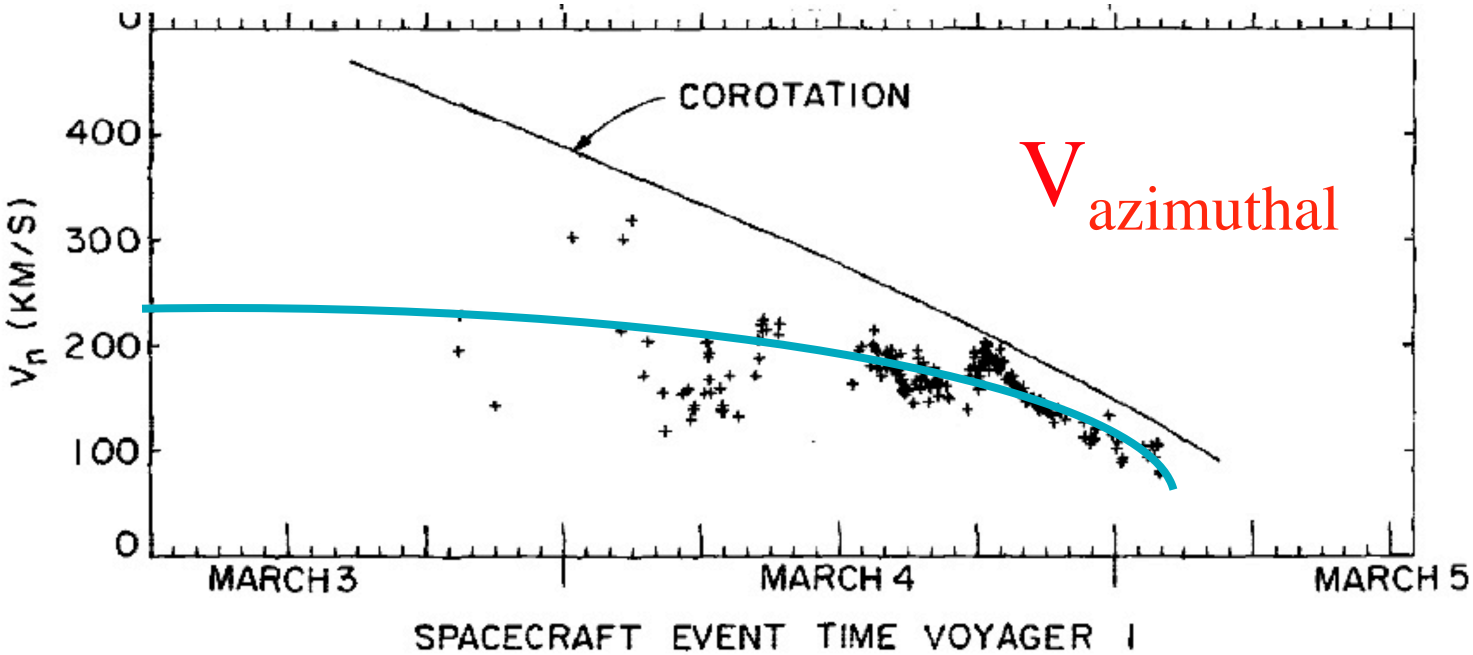


Communication breaks down between the planet and magnetosphere

De-Coupling - 3

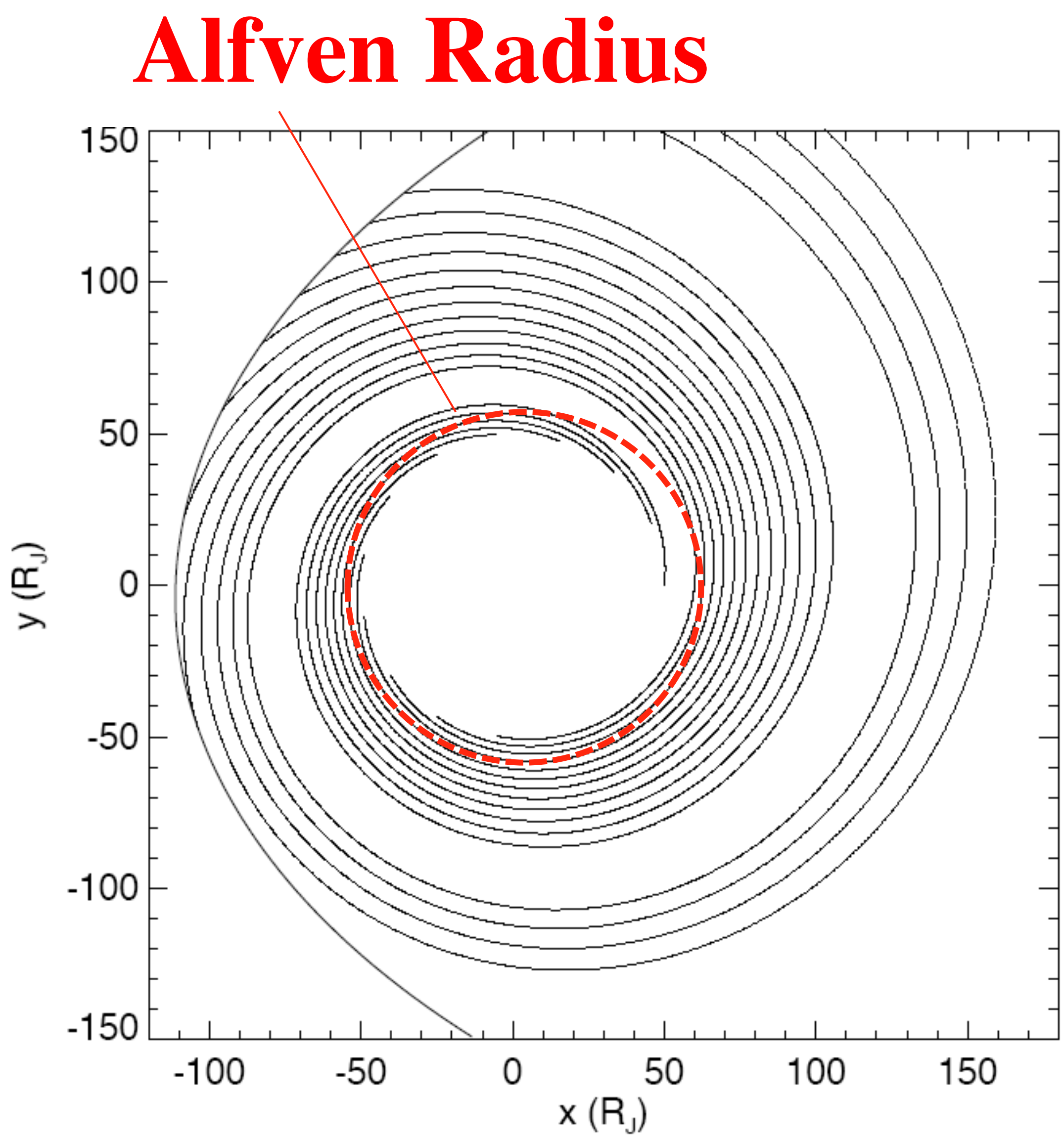


Azimuthal Flow Profile

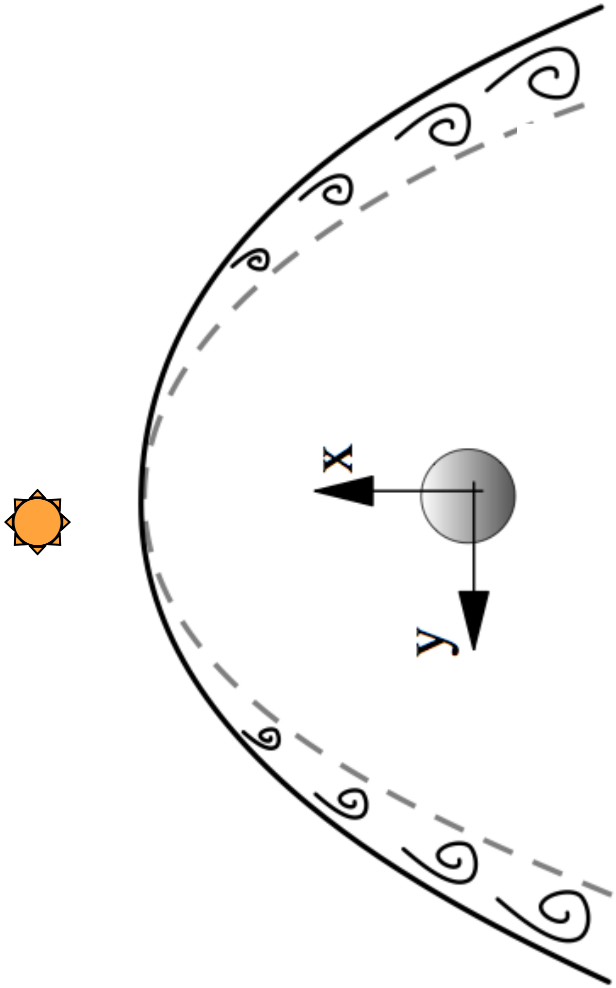


Combining V_r and $V_{azimuthal}$ we get….

Pattern of Net Momentum Flux



- Beyond ~60 R_J material spirals away from Jupiter in 10s of hours
- Radial transport is still diffusive: Centrifugally-driven fluxtube interchange



Reconnection is reduced in the outer solar system:

- weaker solar fields
- shear boundaries
- strong change in β

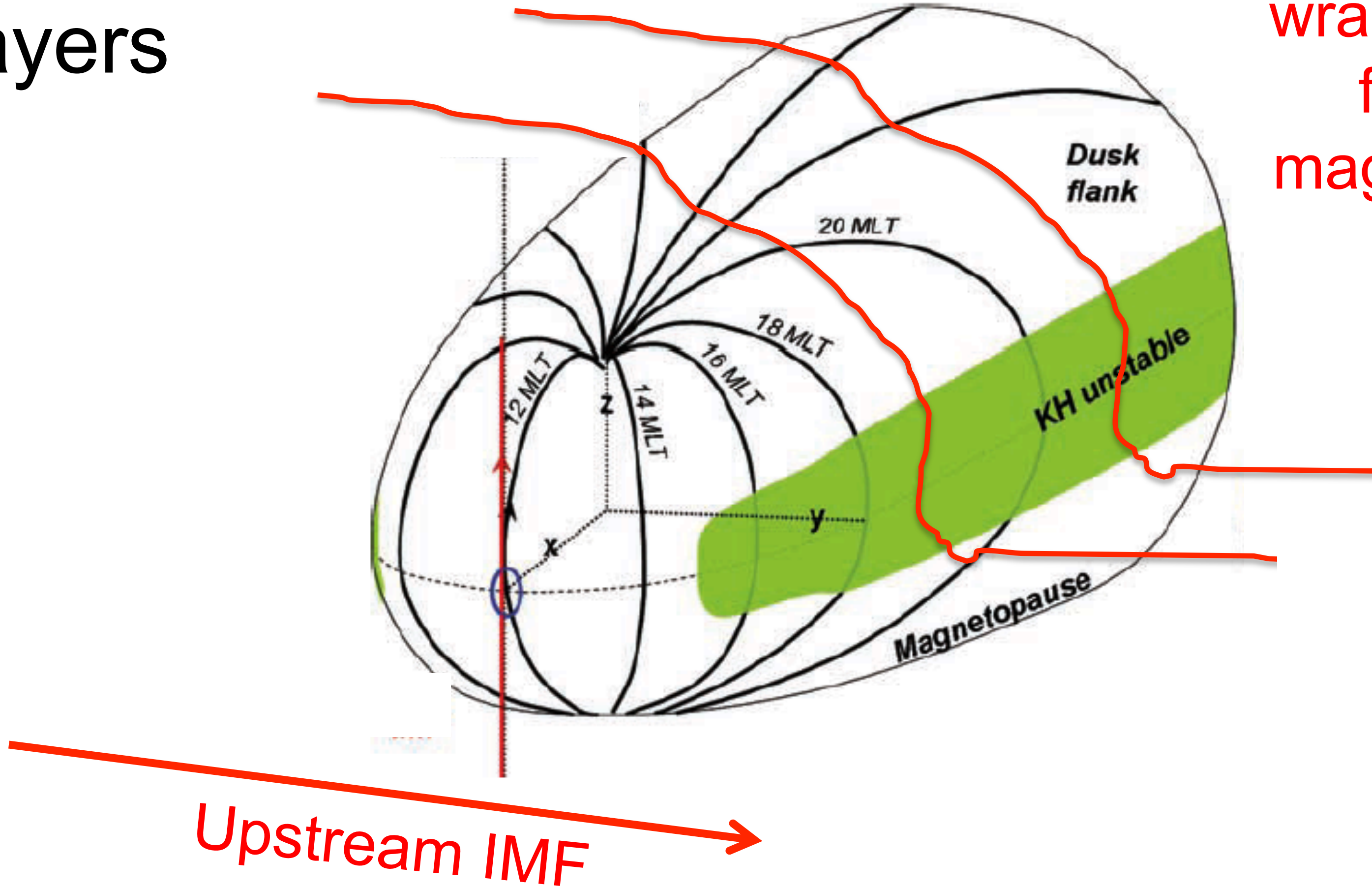
Can small-scale boundary-layer processes act like viscosity?

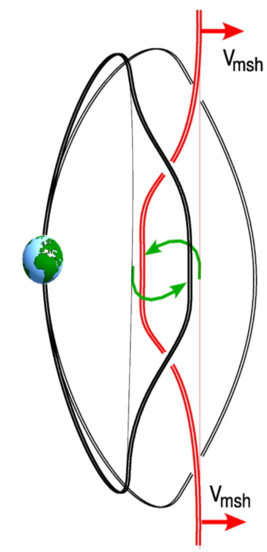
Shear-driven Kelvin-Helmholtz instability

This is **small-scale, intermittent reconnection** − as compared to **large-scale, quasi-steady reconnection** per Dungey cycle

Mass & momentum transport – boundary layers

Upstream IMF wrapped around flattened magnetospause

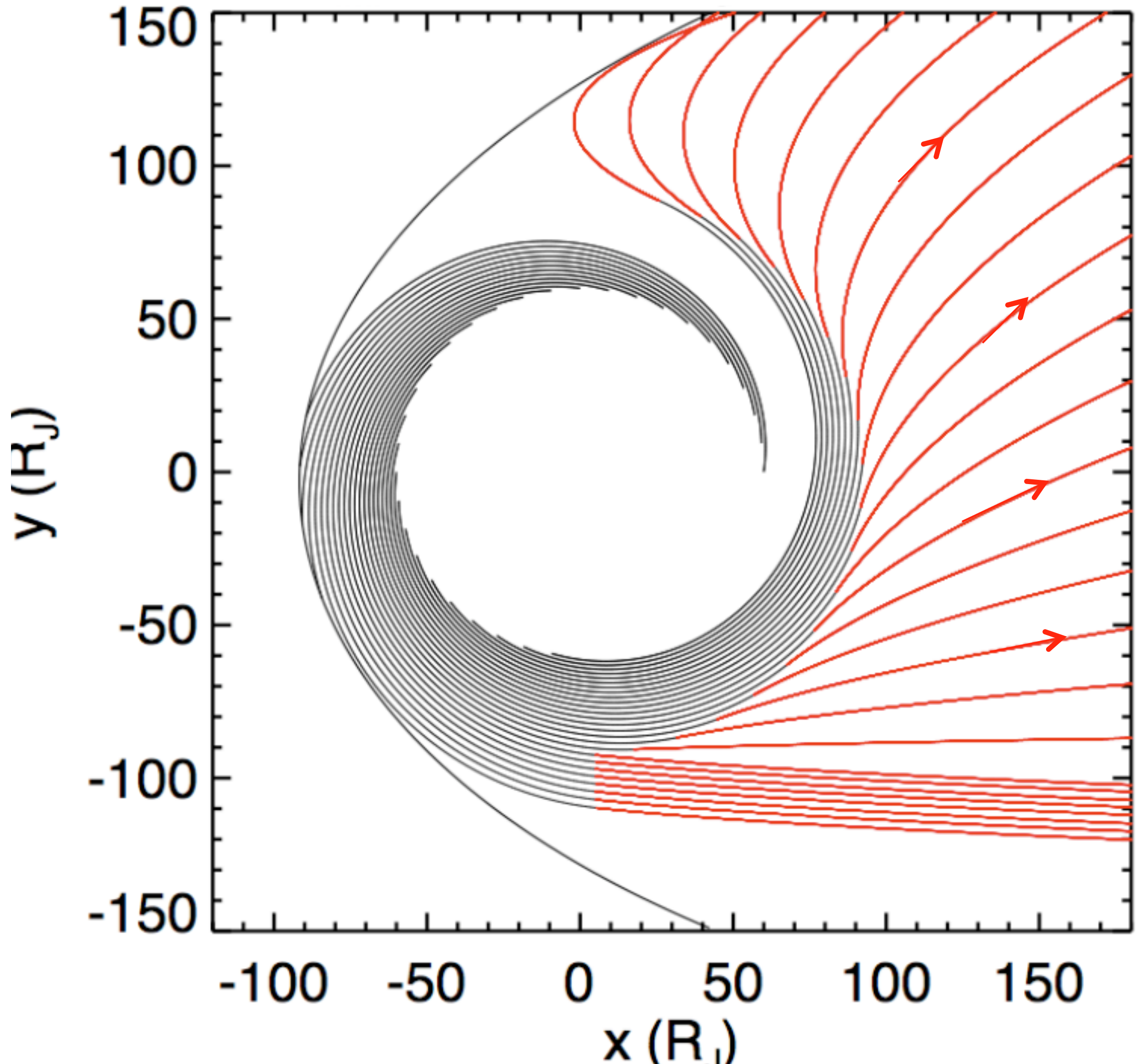




Solar Wind Stresses Overcome Rotation

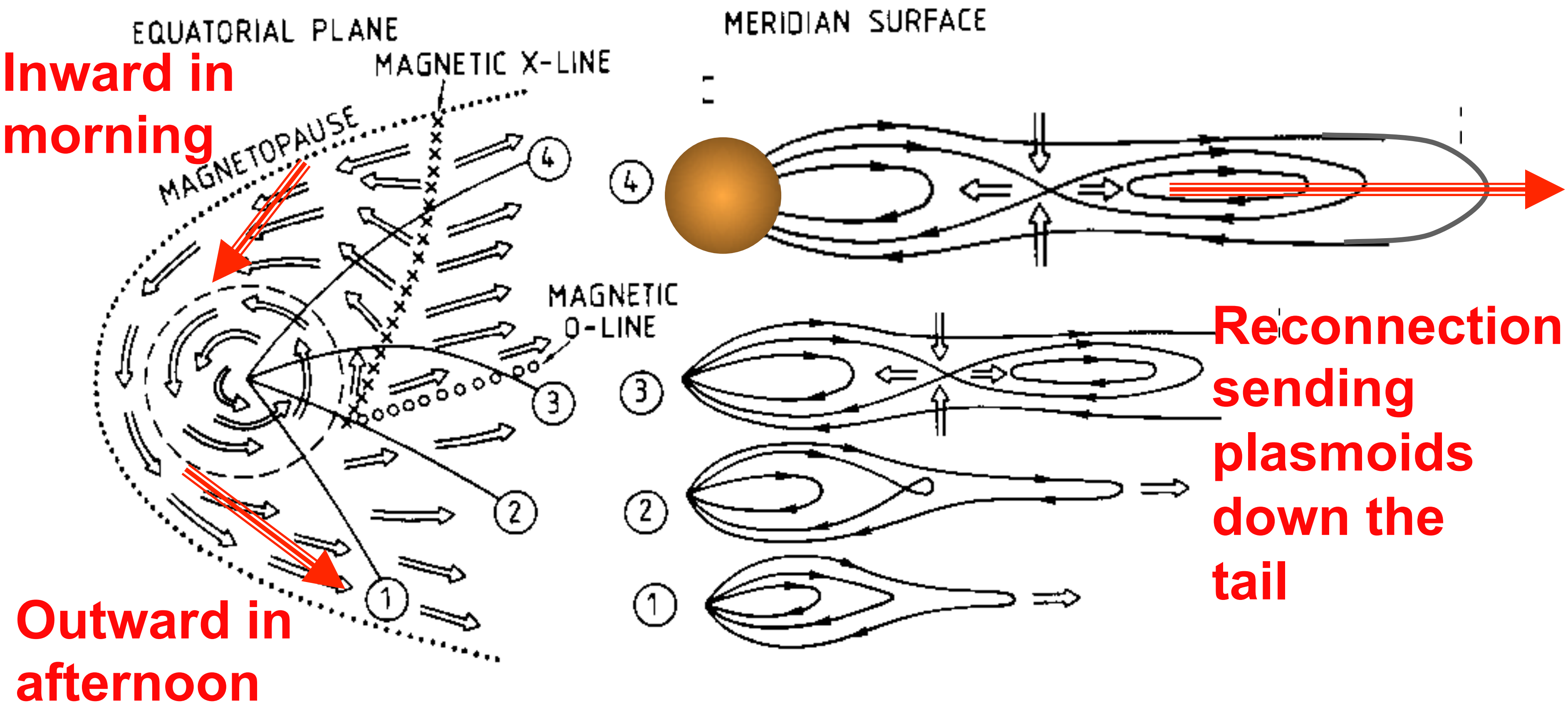
Add Maxwell stresses from solar wind interaction

Stresses from magnetic shear on boundary



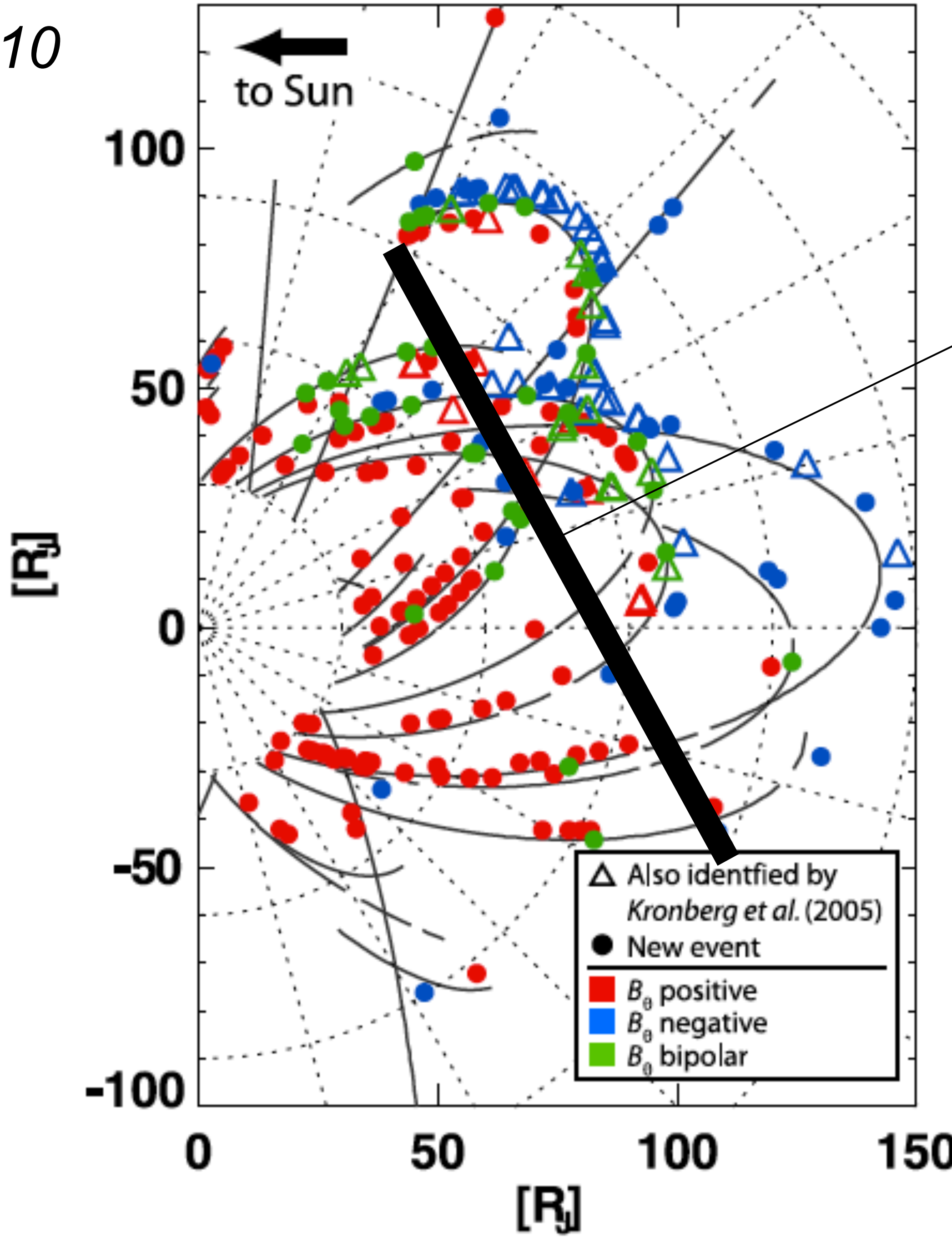
Vasyliunas Cycle

Vasyliunas
Cowley et al.
Southwood & Kivelson



Vogt et al. 2010

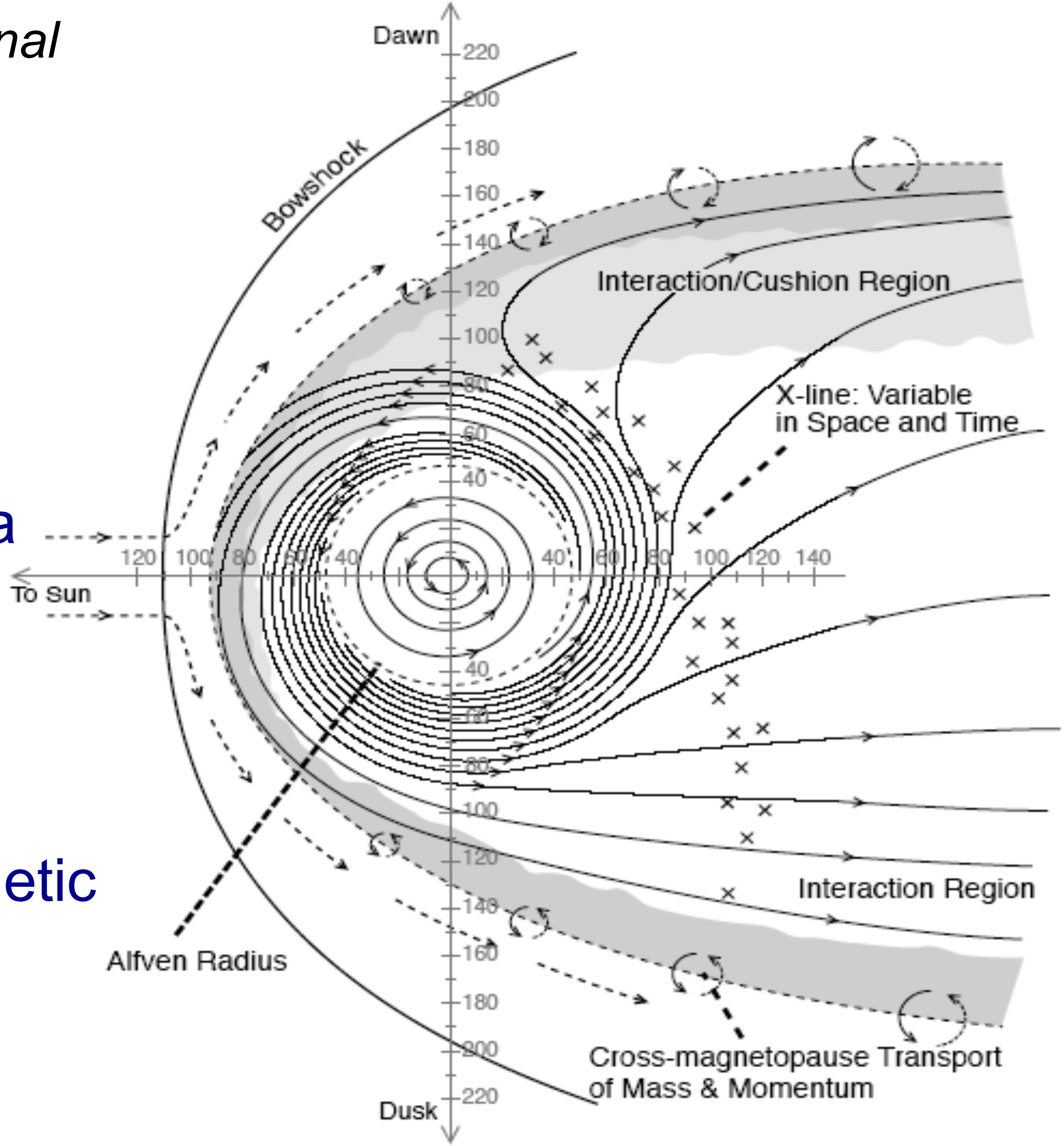
Observations of plasmoid events in *Galileo* data



Delamere & Bagenal (2011)

Solar wind interaction:

- More of a plasma-plasma interaction
- Less of an interaction between magnetic fields



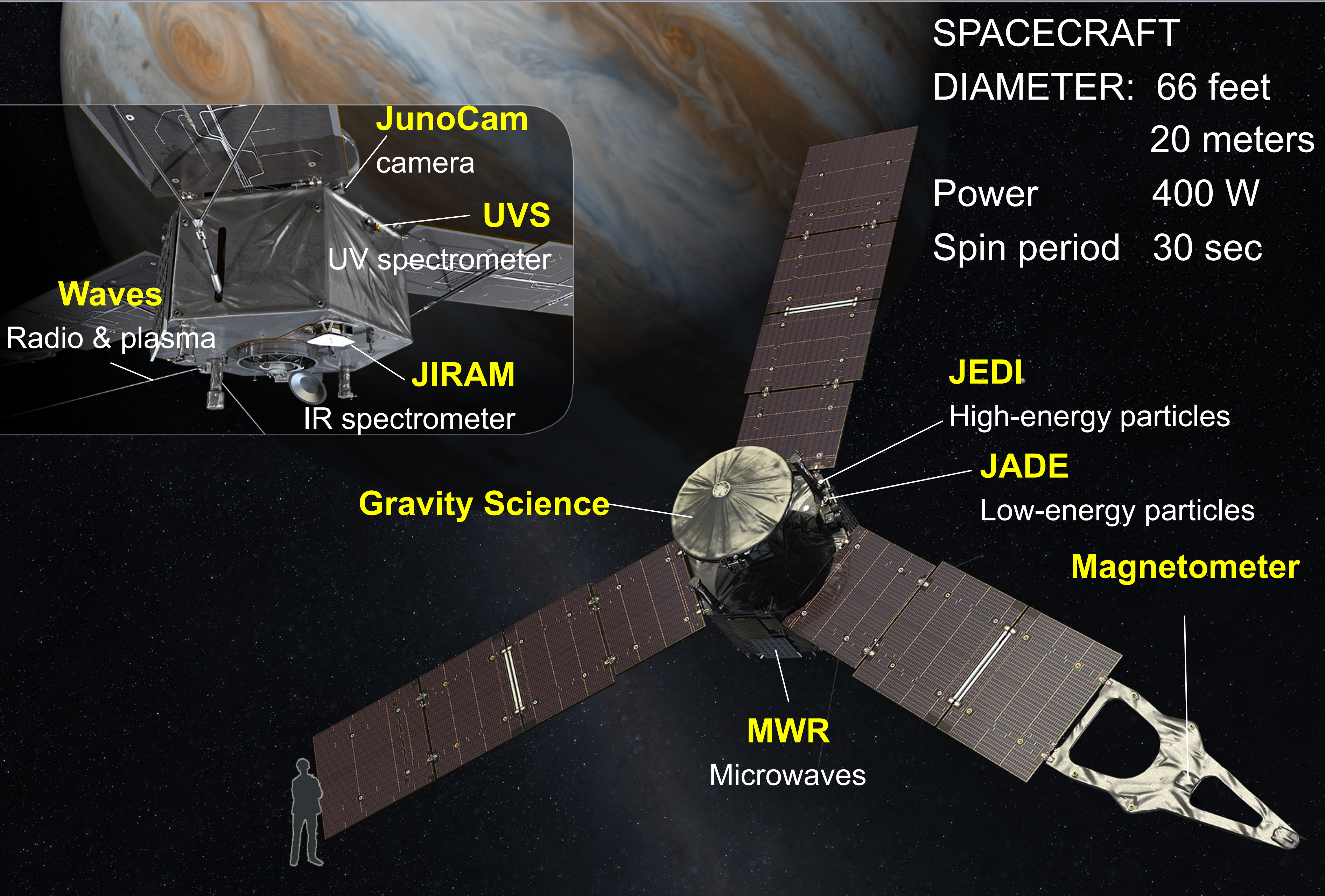
Juno

Spacecraft & Payload

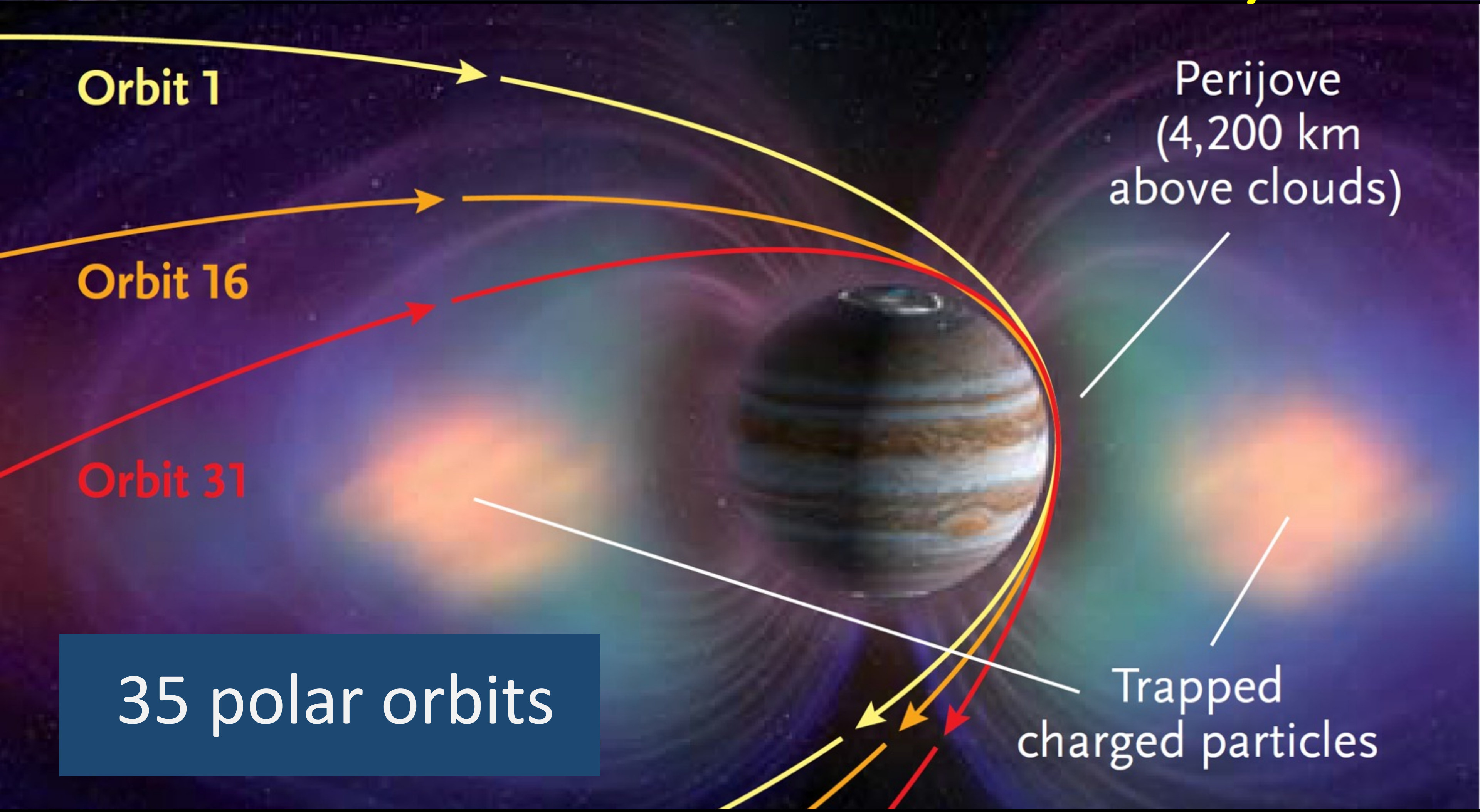
Orbit Insertion
4th July 2016

SPACECRAFT

DIAMETER:	66 feet 20 meters
Power	400 W
Spin period	30 sec



Juno: Close Polar Orbit is Key

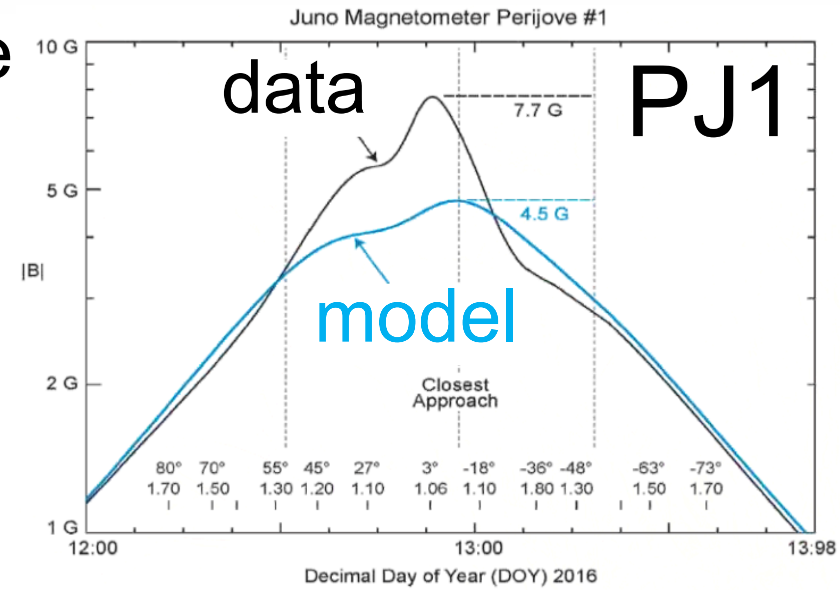


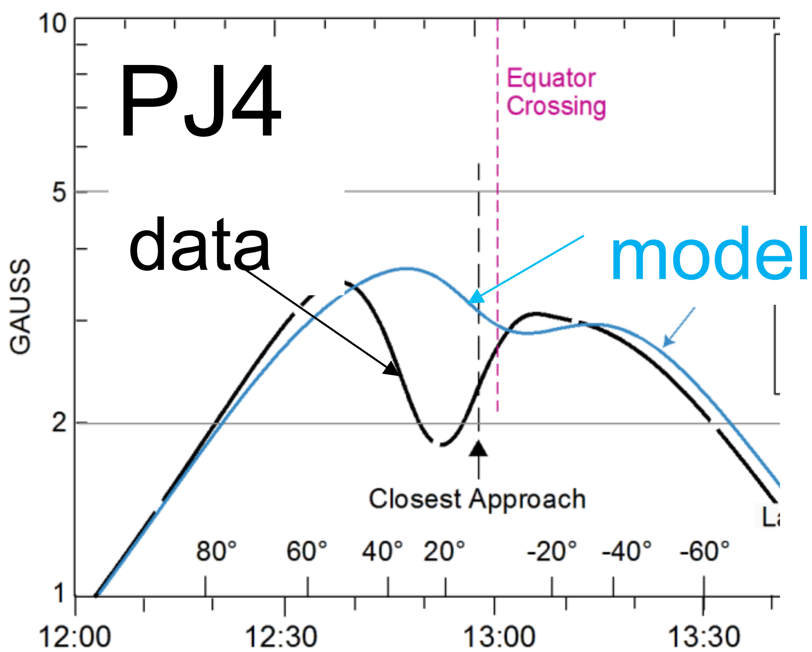
Duck under radiation belts…

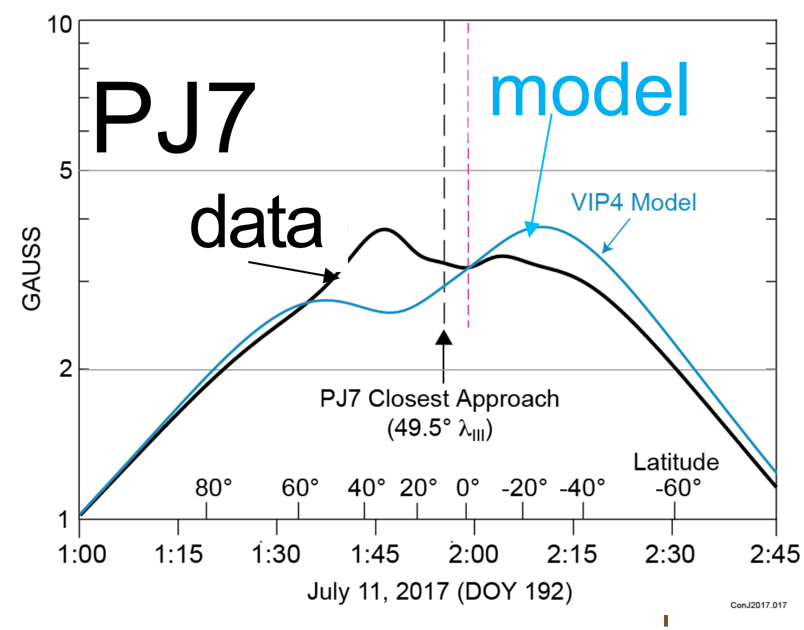
Skim above clouds…

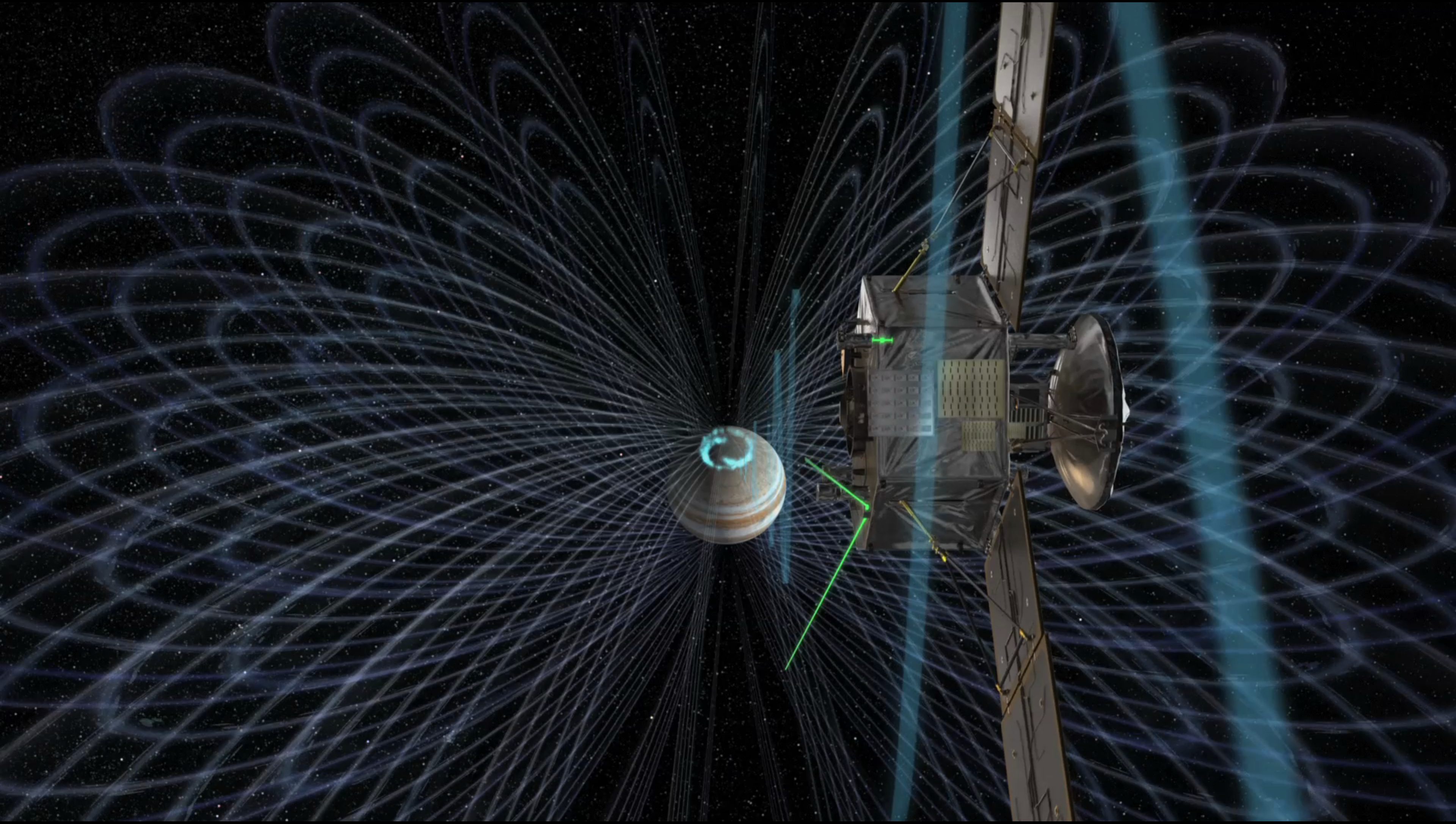
Jupiter's Magnetic Field

- Juno's first few passes are showing deviations from previous simple models
- Hints that the dynamo region is closer to the surface?









In orbit since July 2016!

Juno

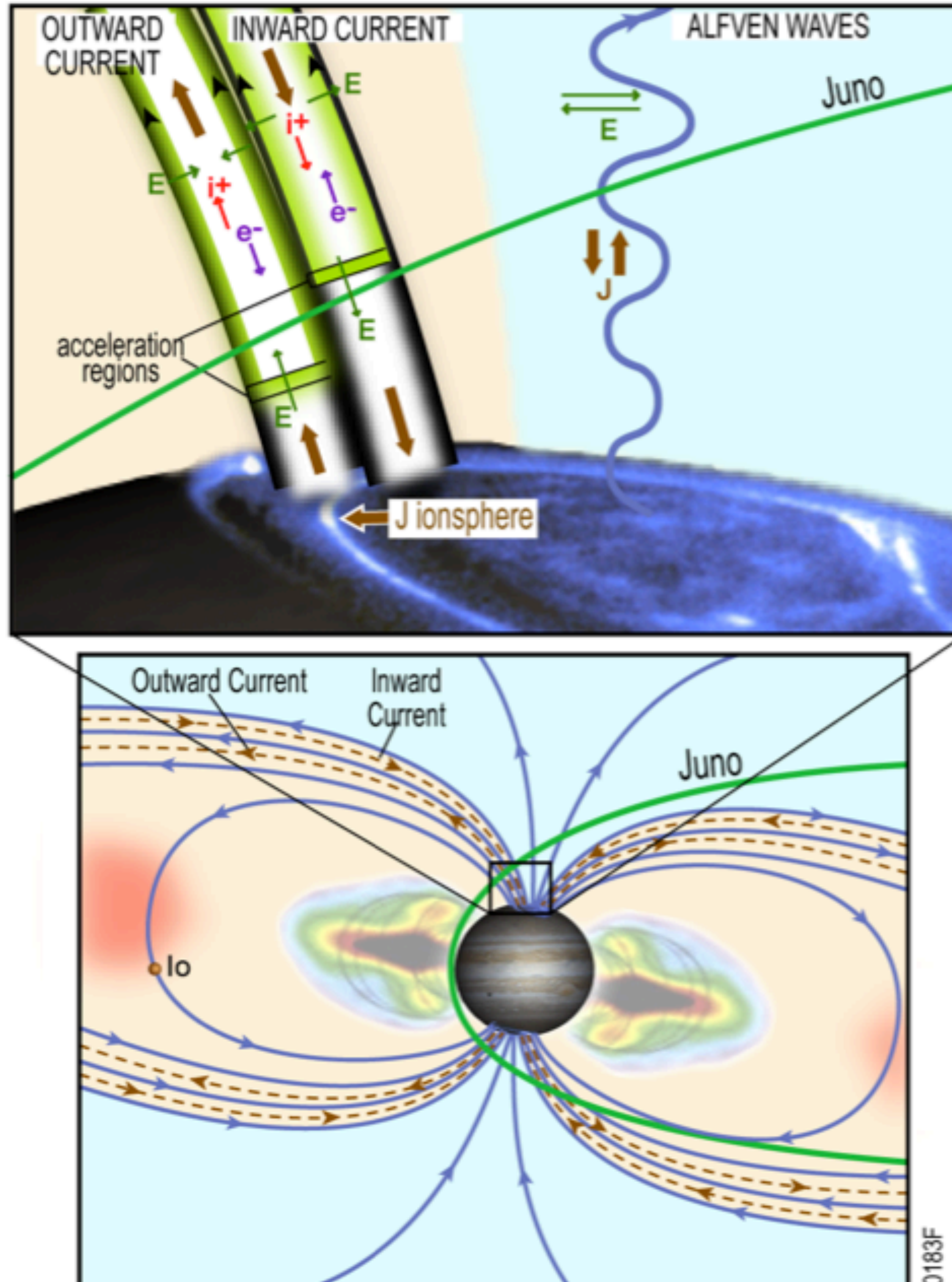
Polar Magnetosphere

Juno passes directly through auroral field lines

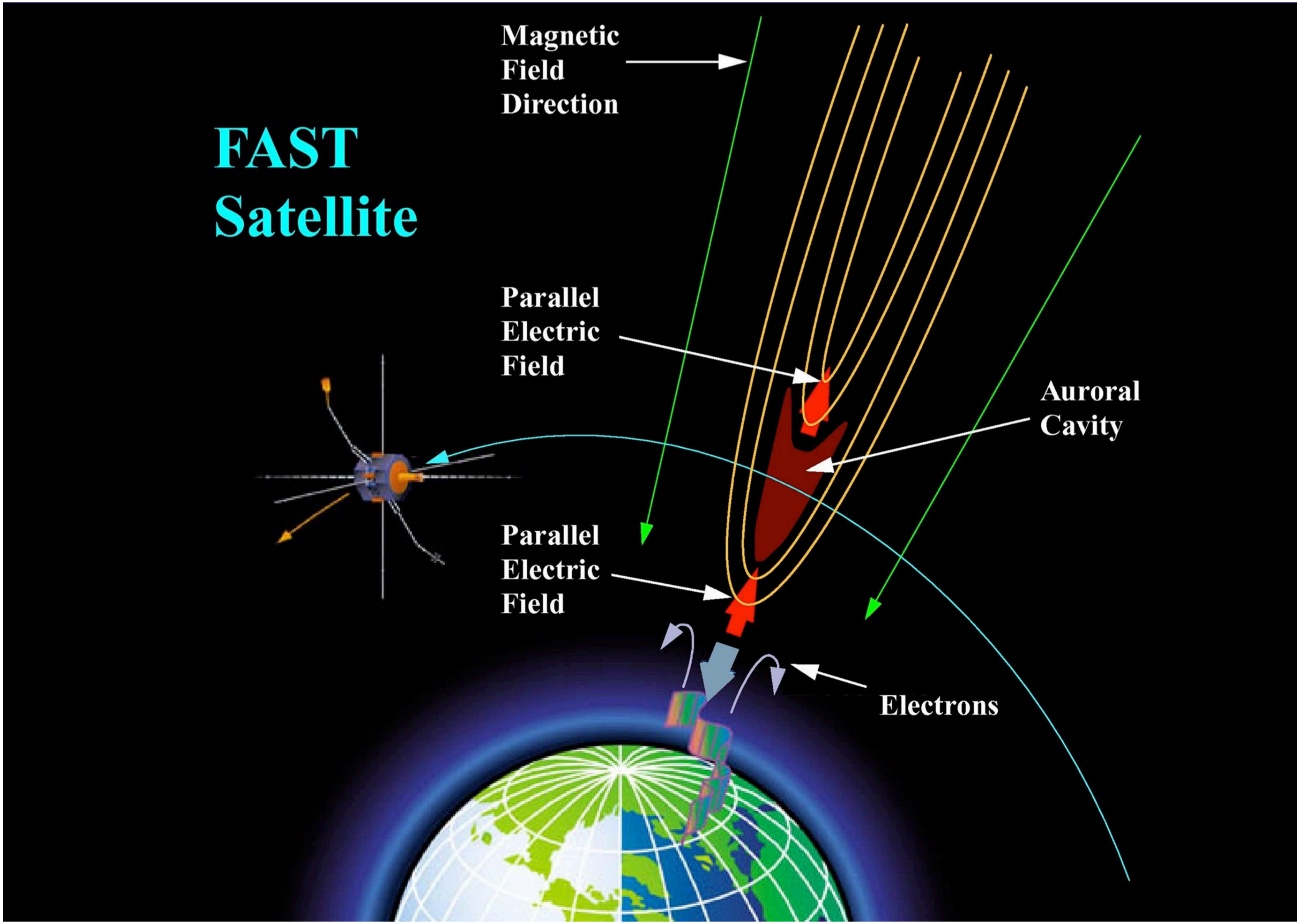
Measures particles precipitating into atmosphere creating aurora

Plasma/radio waves reveal processes responsible for particle acceleration

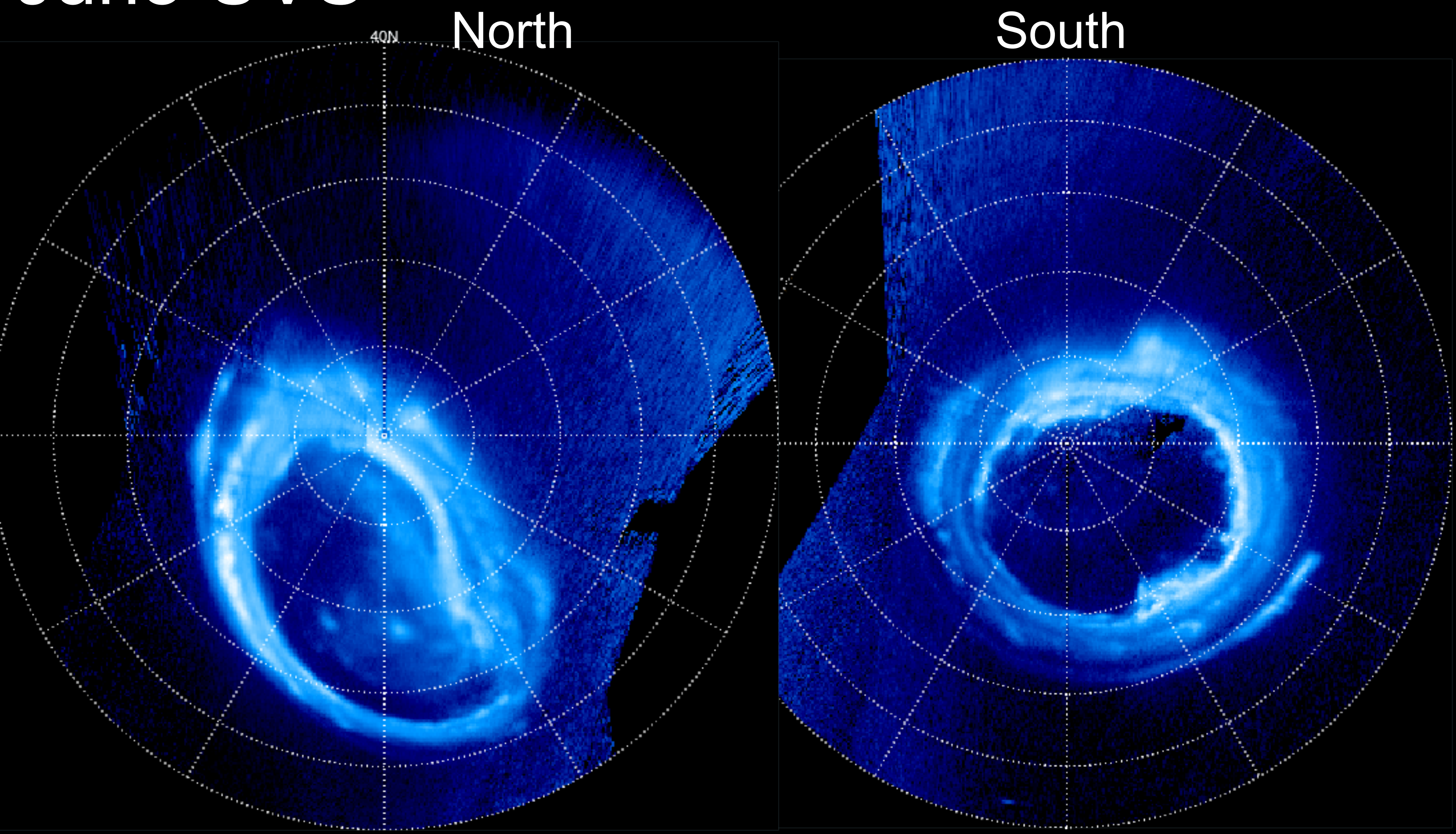
UV & IR images provides context for *in-situ* observations



Earth Auroral Current Region
Does same physics apply at Jupiter?

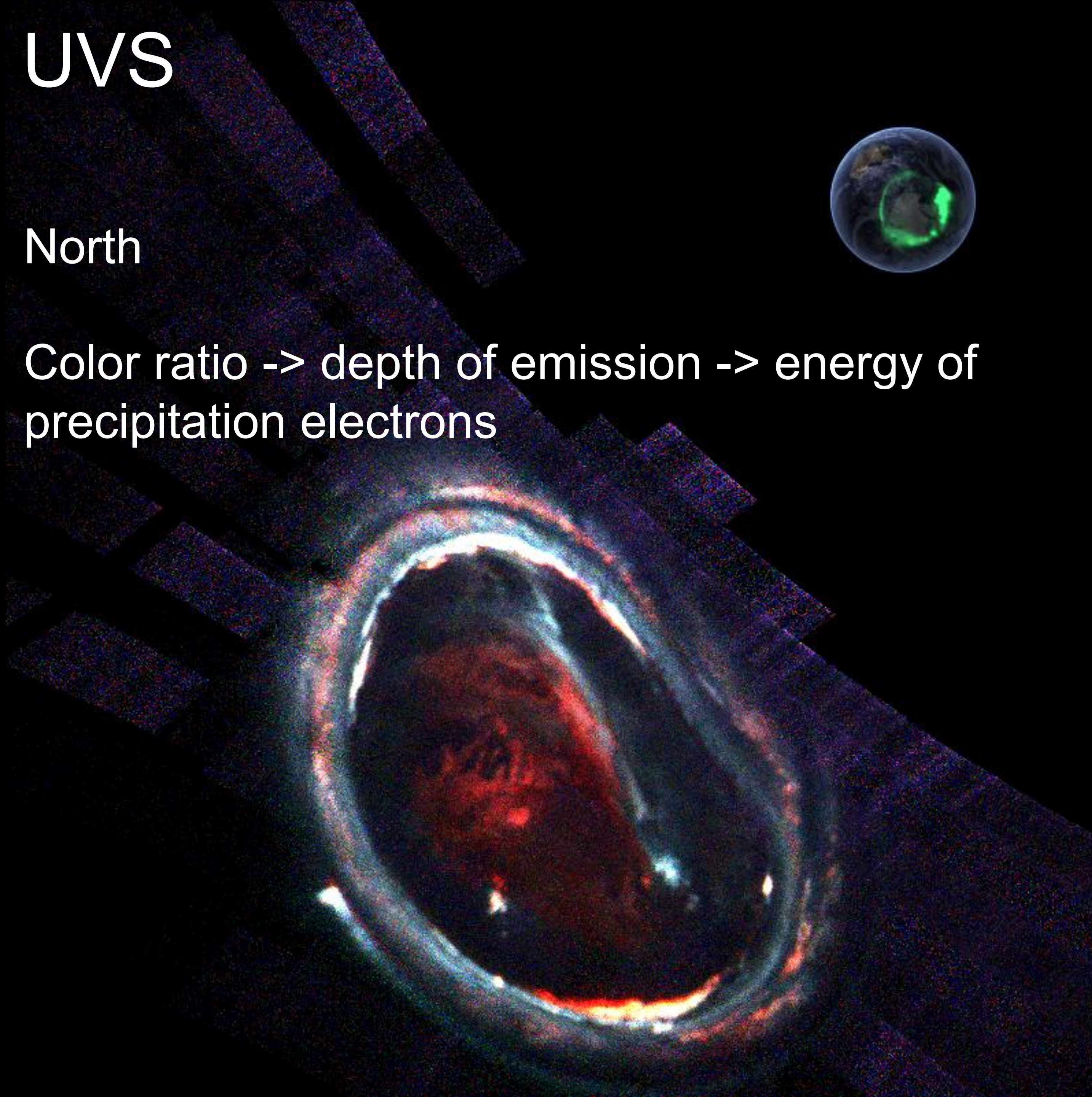


Juno UVS



Jupiter's aurora is structured & dynamic

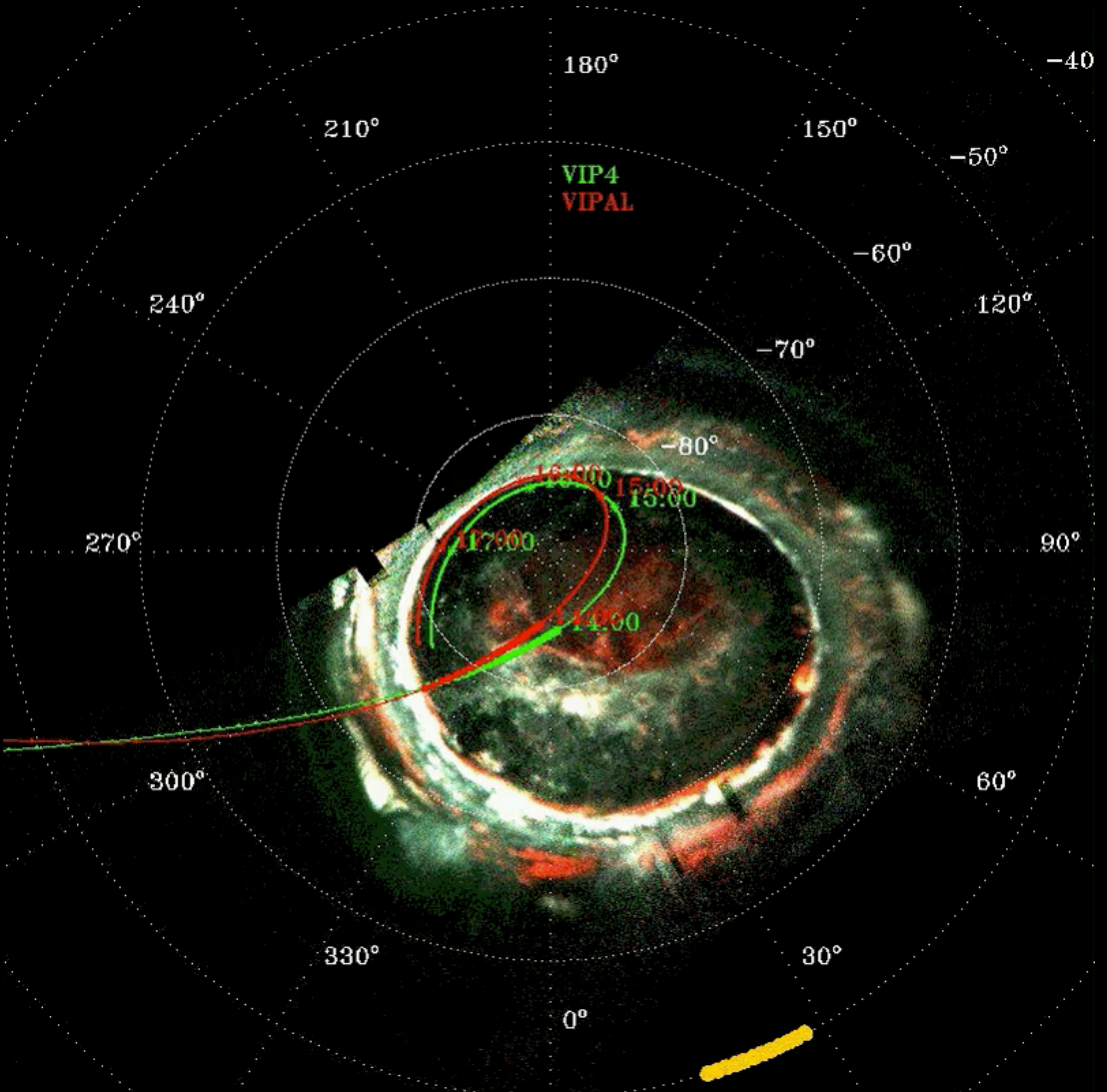
Juno UVS



North

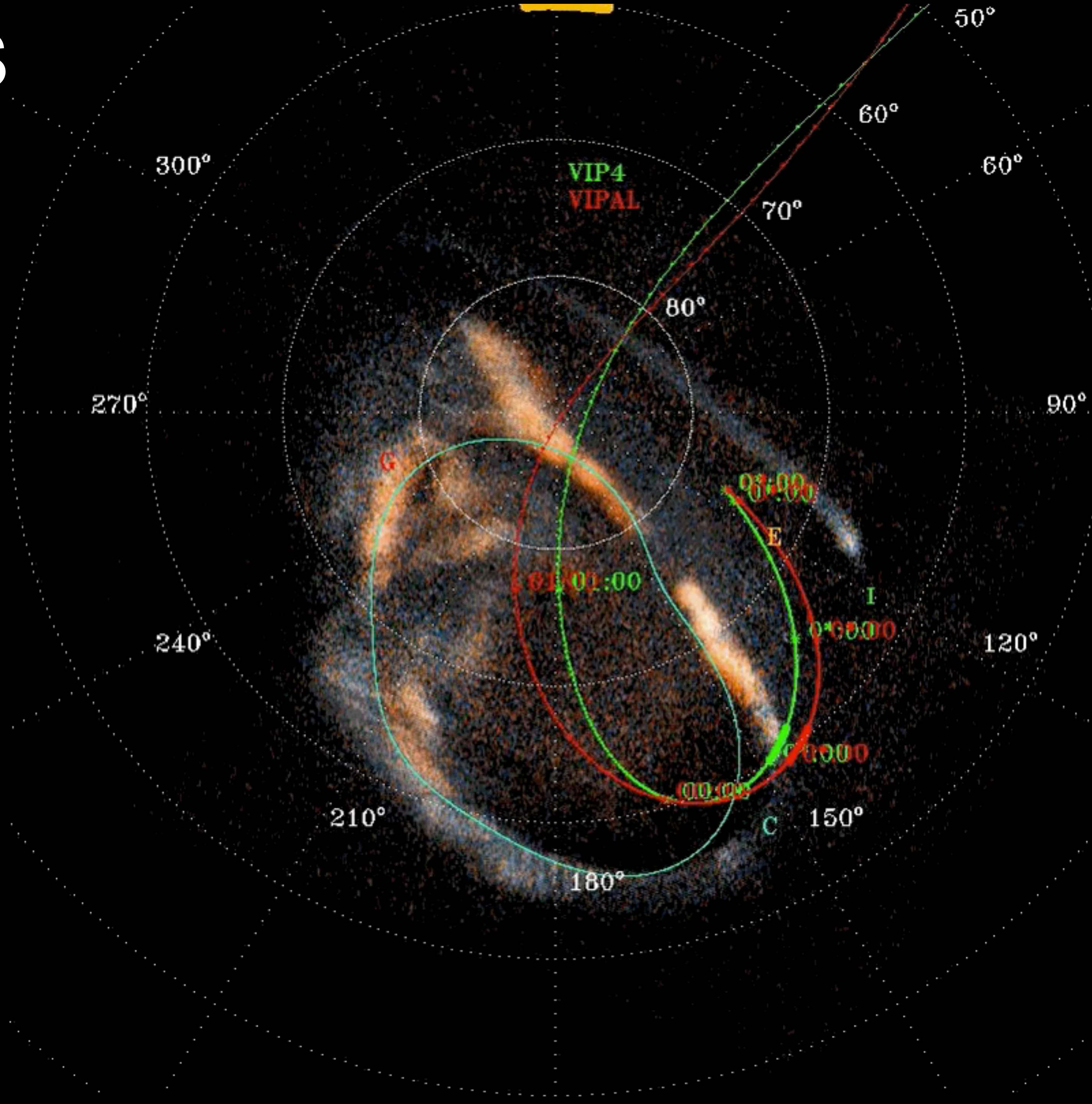
Color ratio -> depth of emission -> energy of precipitation electrons

Juno UVS



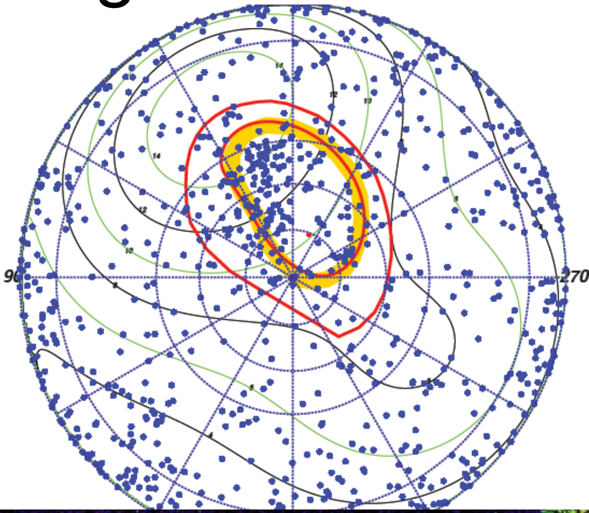
180°
210°
150°
-40
-50°
VIP4
VIPAL
-60°
240°
120°
-70°
-80°
16:00
15:00
15:00
270°
17:00
90°
14:00
300°
60°
330°
30°
0°

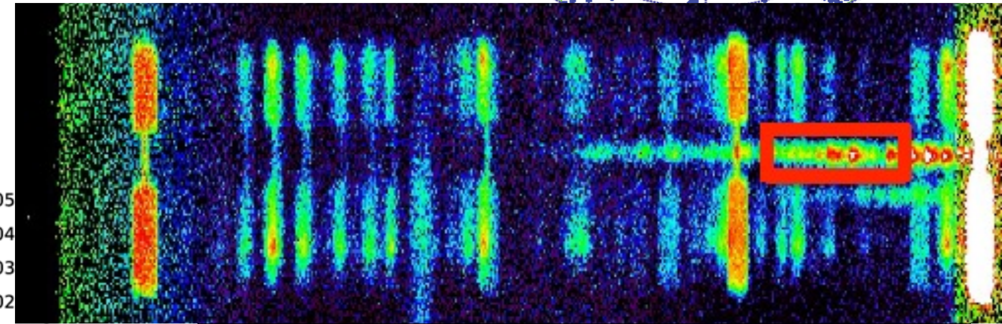
Juno UVS

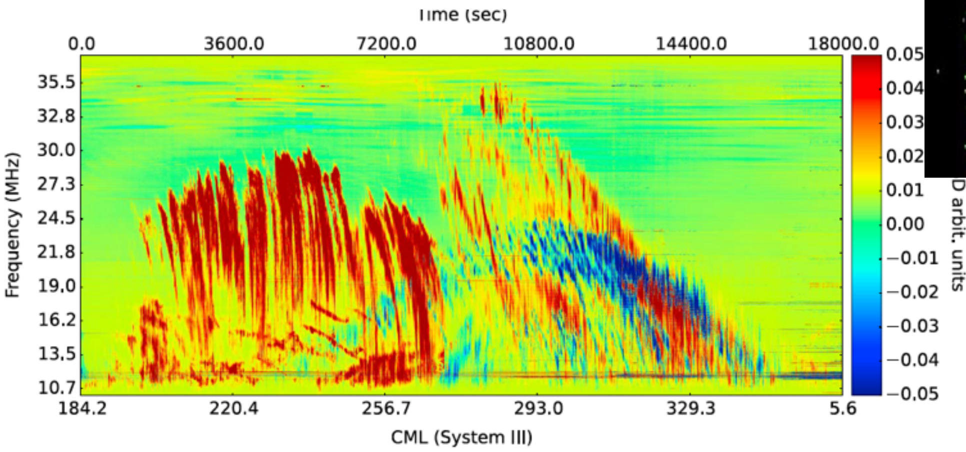


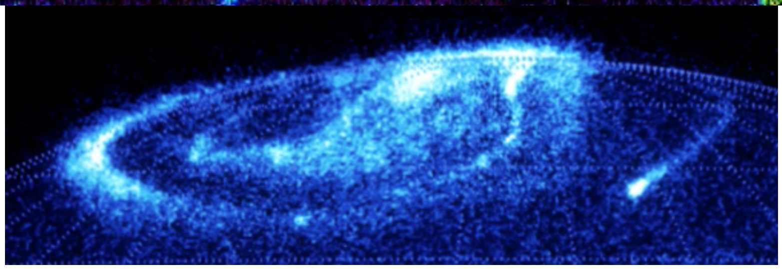
Earth Based Observing Programs

- Hubble Space Telescope
  - – Denis Grodent – Large observing program
- Hisaki UV – Torus, Aurora
- Radio Observations
- Chandra, XMM X-Rays
- Keck, IRTF H_3^+







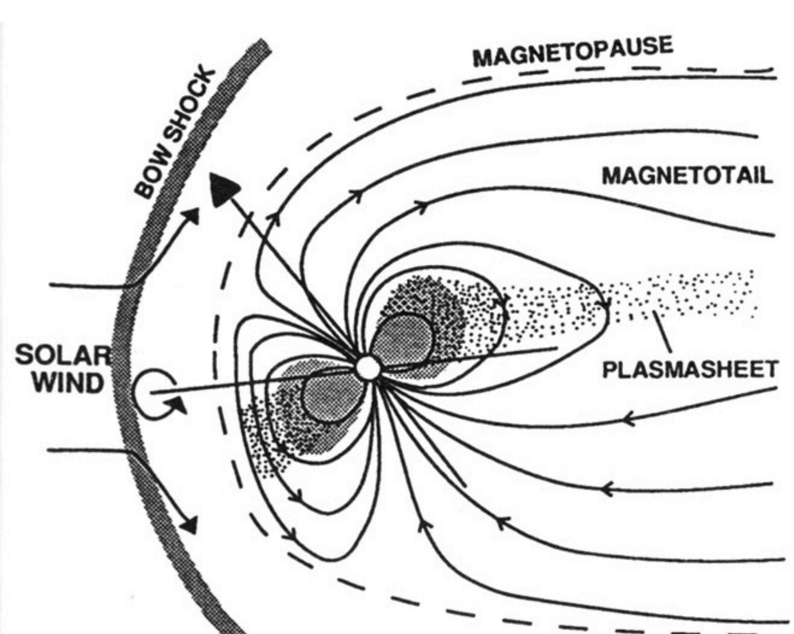


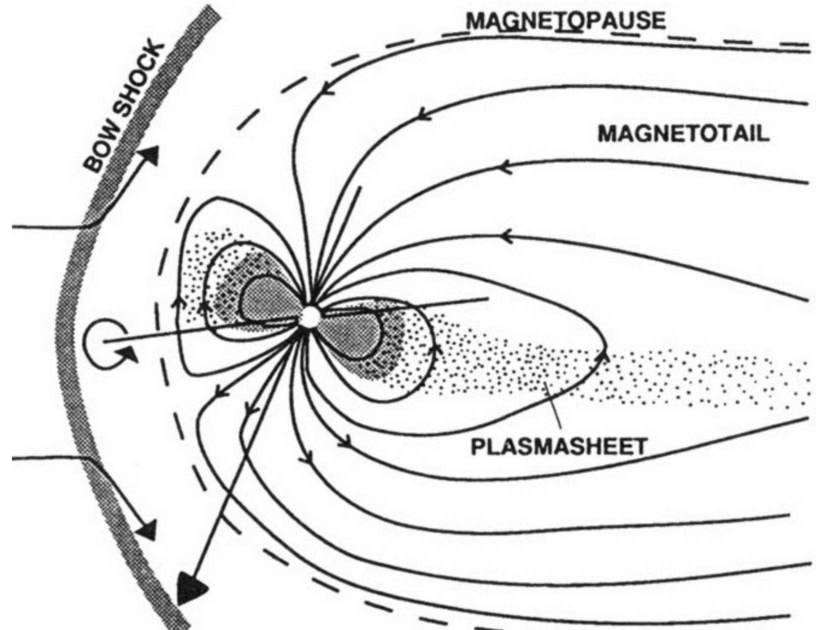
Go Juno!

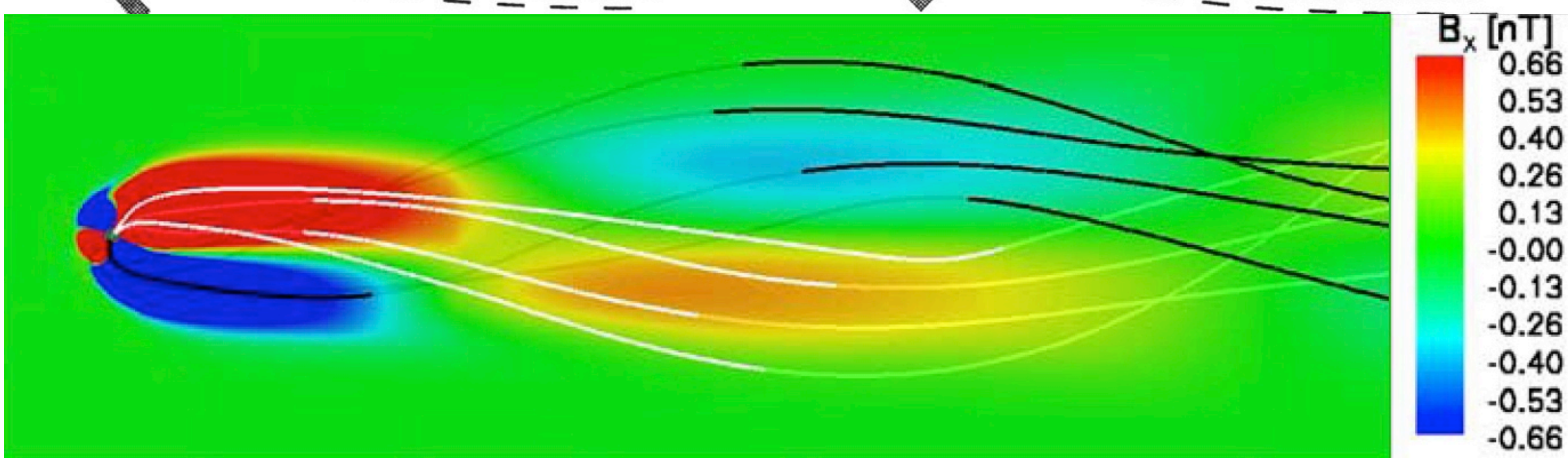
Thank you!

Uranus

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



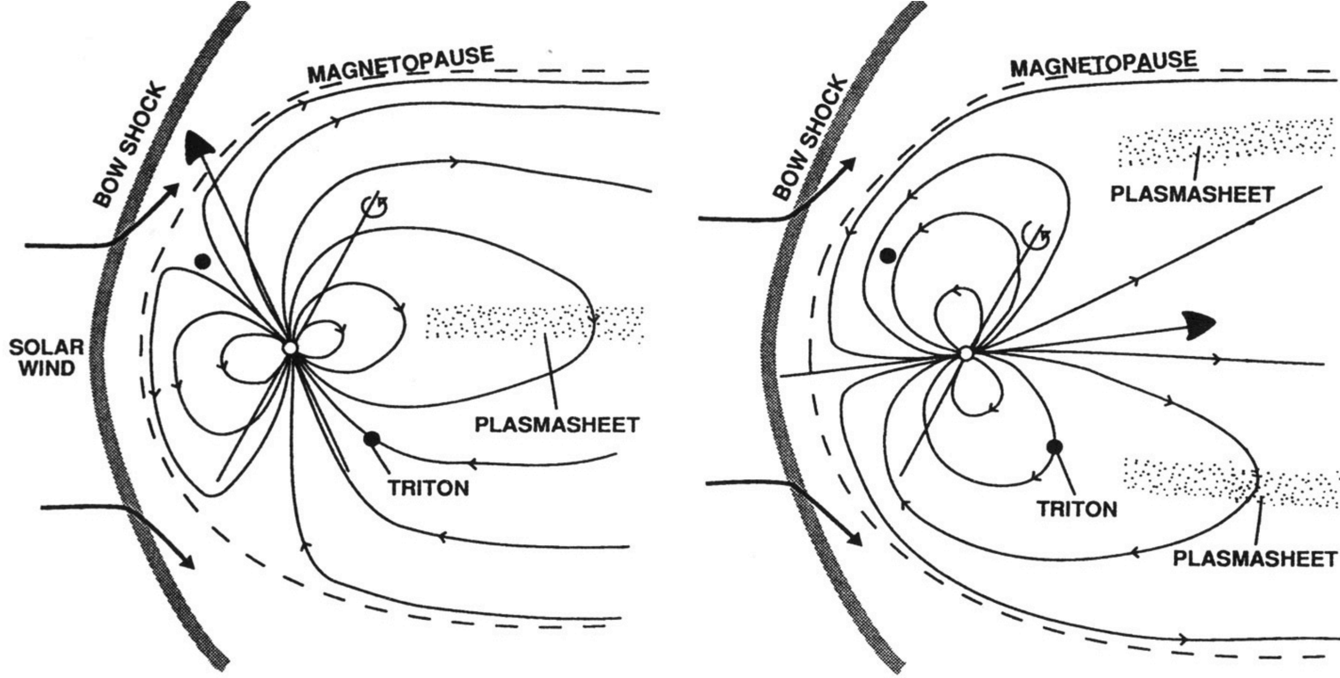


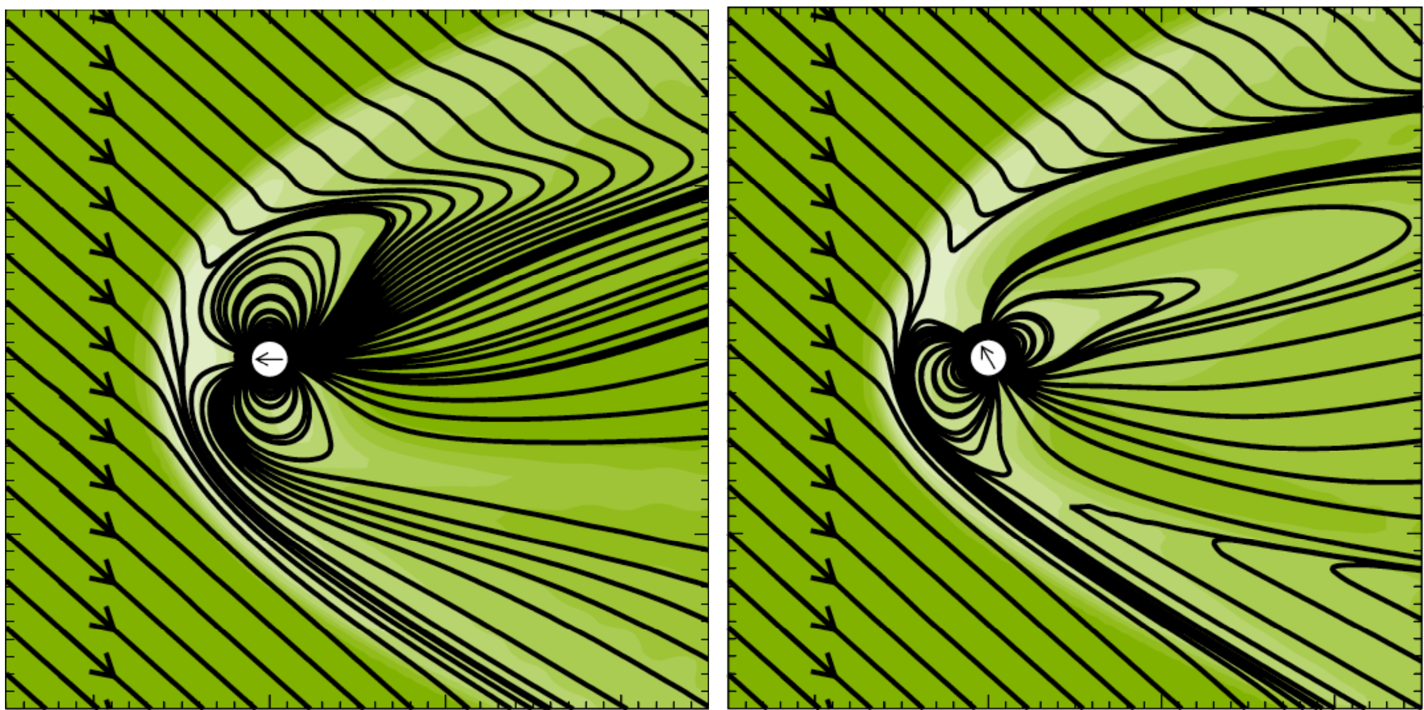


Toth et al.

Neptune

Similarly complex as Uranus



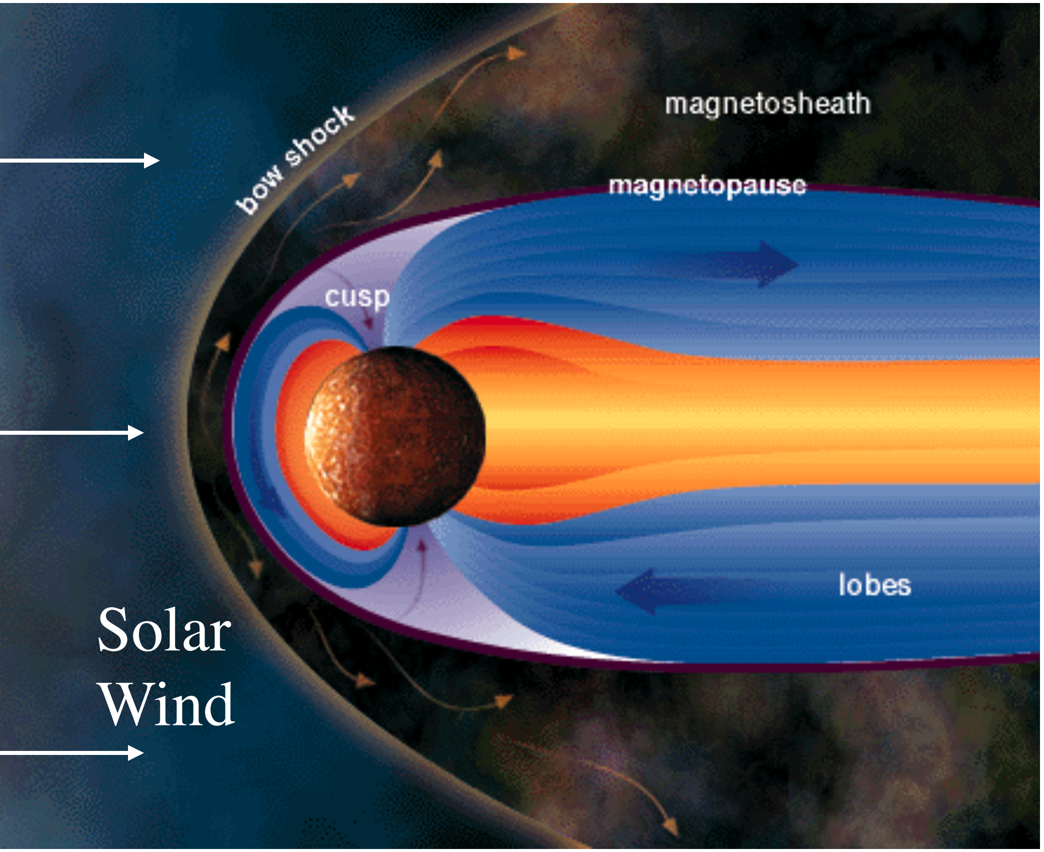


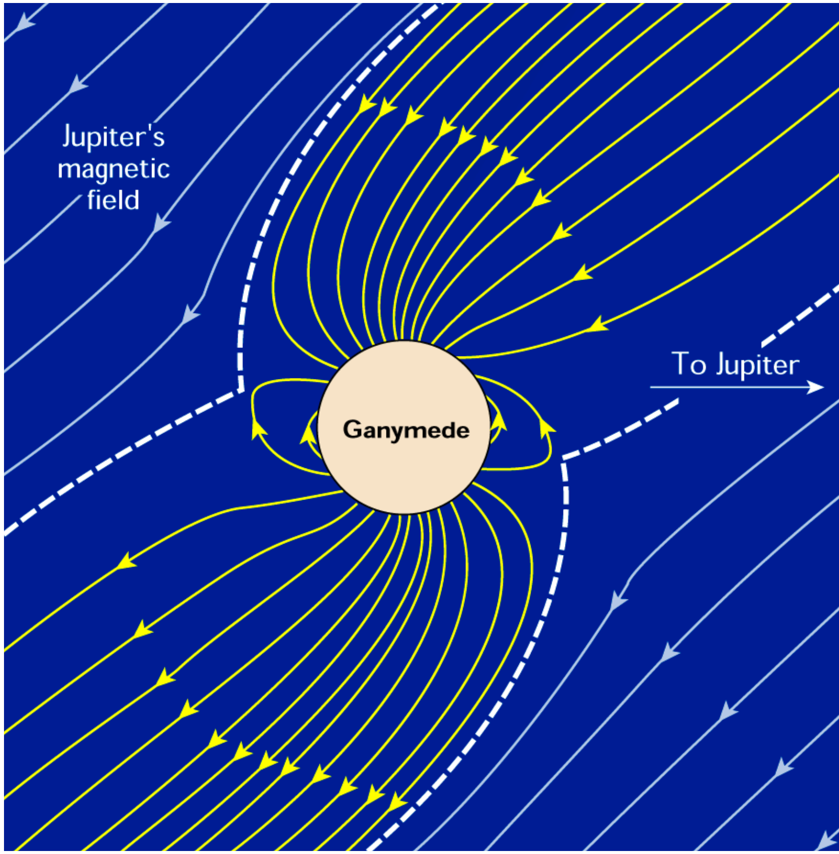
Zieger et al.

Mercury & Ganymede

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

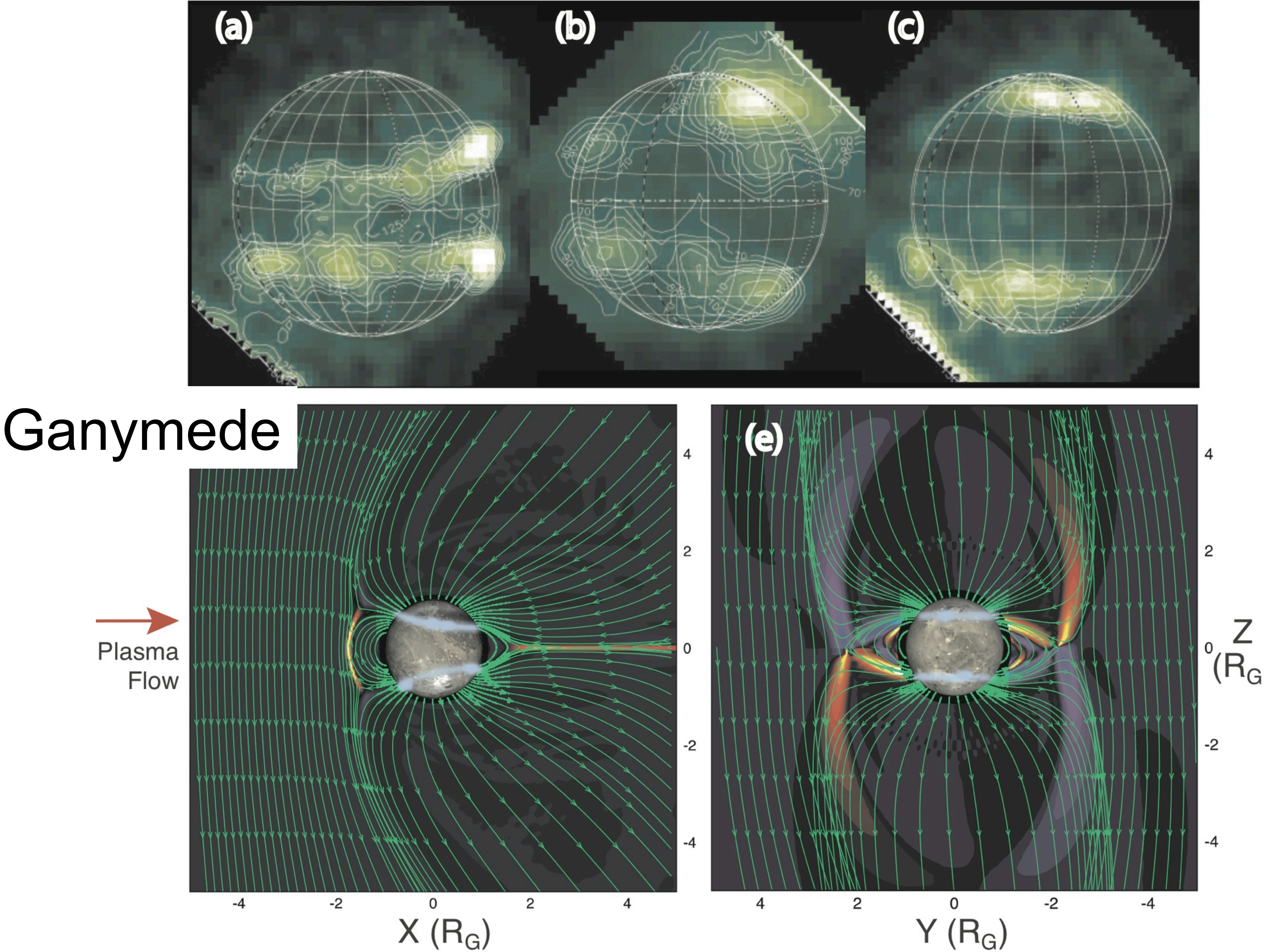
Ganymede - Magnetic field detected by *Galileo* in 1996





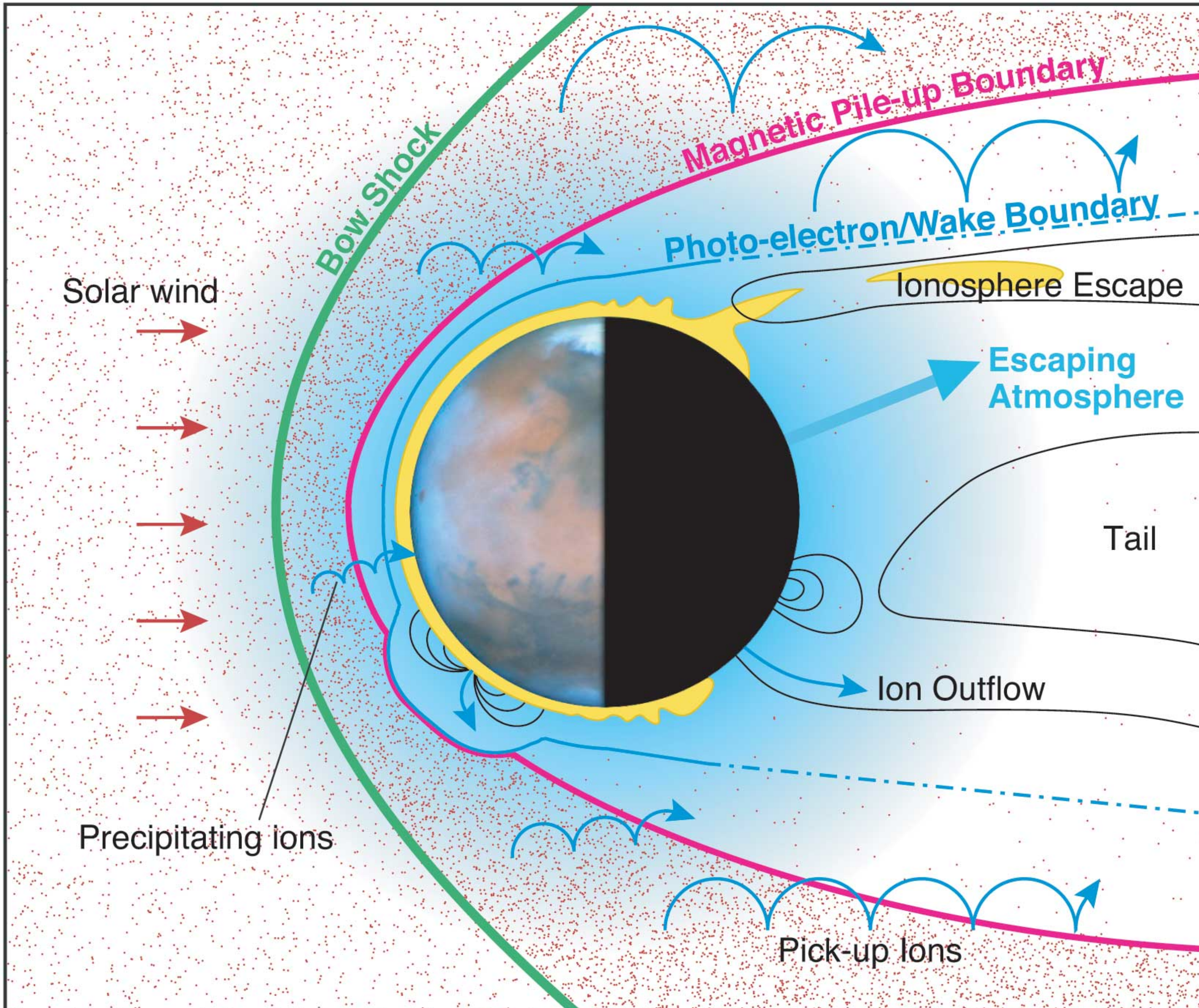
$B_{surface}$ ~ 1/100 Earth

Diameter of Earth



(a)
(b)
(c)
Ganymede
(e)
Plasma Flow
X (R_G)
Y (R_G)
Z (R_G)

Mars



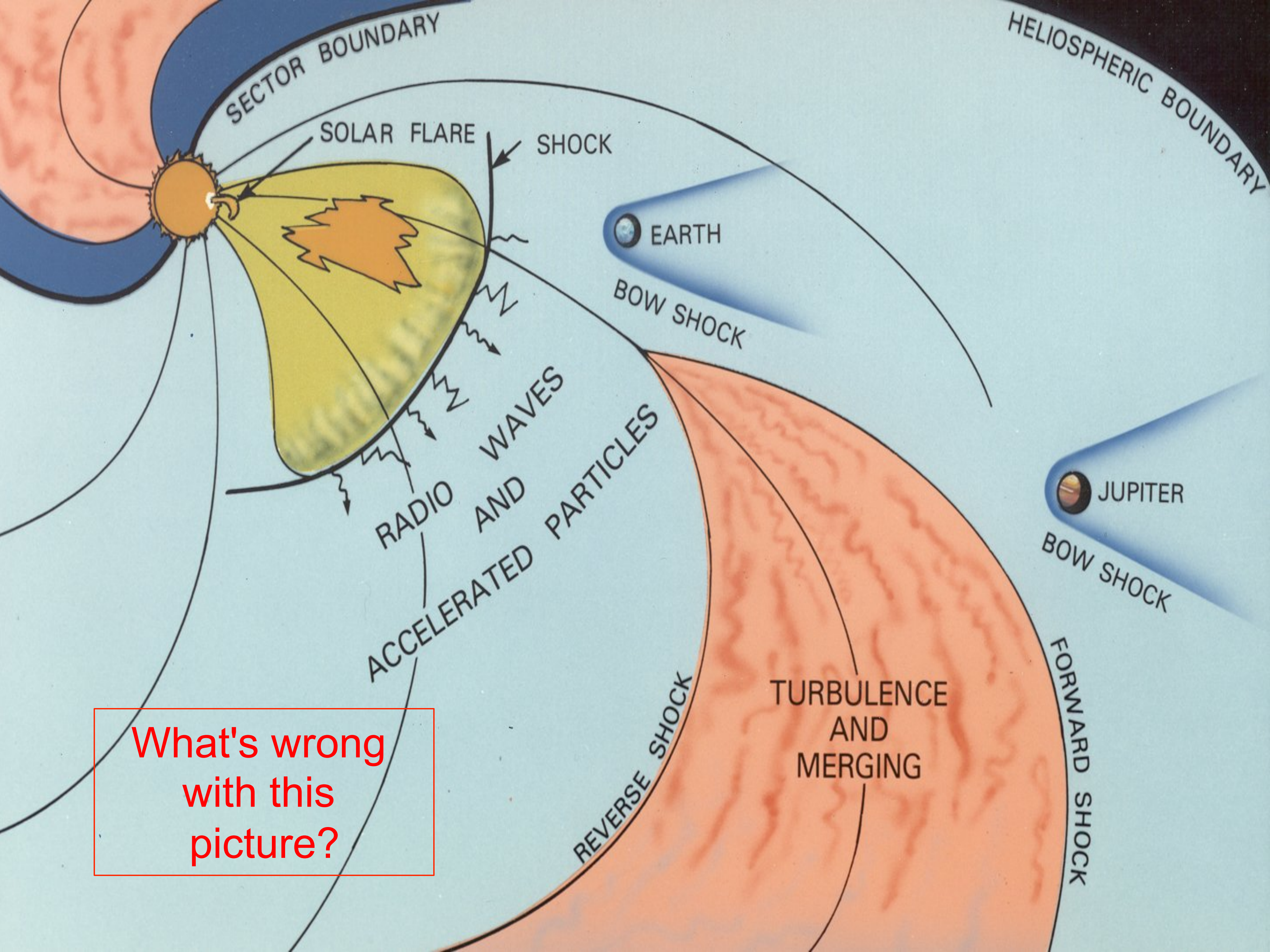
Bow Shock
Magnetic Pile-up Boundary
Photo-electron/Wake Boundary
Solar wind
Ionosphere Escape
Escaping Atmosphere
Tail
Ion Outflow
Precipitating Ions
Pick-up Ions

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…. *MAVEN mission to Mars*

Juno mission to Jupiter!


SECTOR BOUNDARY
HELIOSPHERIC BOUNDARY
SOLAR FLARE
SHOCK
EARTH
BOW SHOCK
RADIO WAVES AND ACCELERATED PARTICLES
JUPITER
BOW SHOCK
REVERSE SHOCK
TURBULENCE AND MERGING
FORWARD SHOCK
What's wrong with this picture?

Anderson, B. J., M. H. Acu~na, H. Korth, J. A. Slavin, H. Uno, C. L. Johnson, M. E. Purucker, S. C. Solomon, J. M. Raines, T. H. Zurbuchen, G. Gloeckler, and R. L. McNutt, The Magnetic Field of Mercury, Space Sci. Rev., 152, 307{339, doi:10.1007/s11214-009-9544-3, 2010.

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