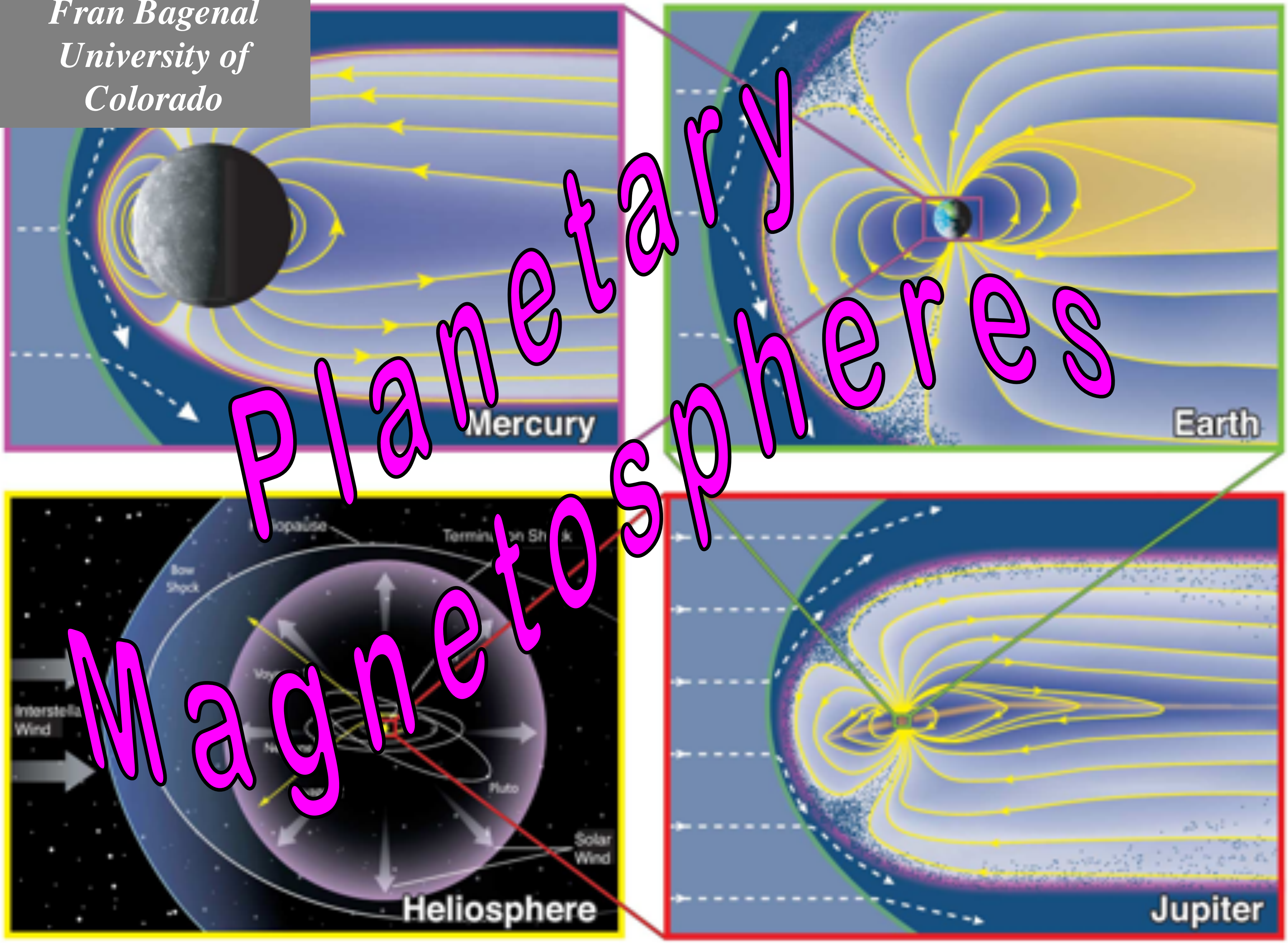
Fran Bagenal
University of Colorado

Planetary Magnetospheres



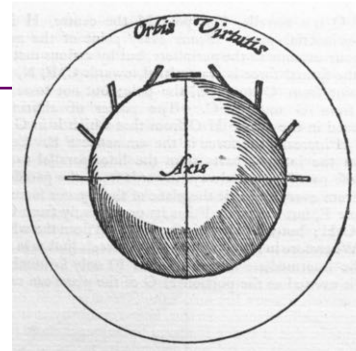
Which topic is (probably, at this point in time) your primary interest?

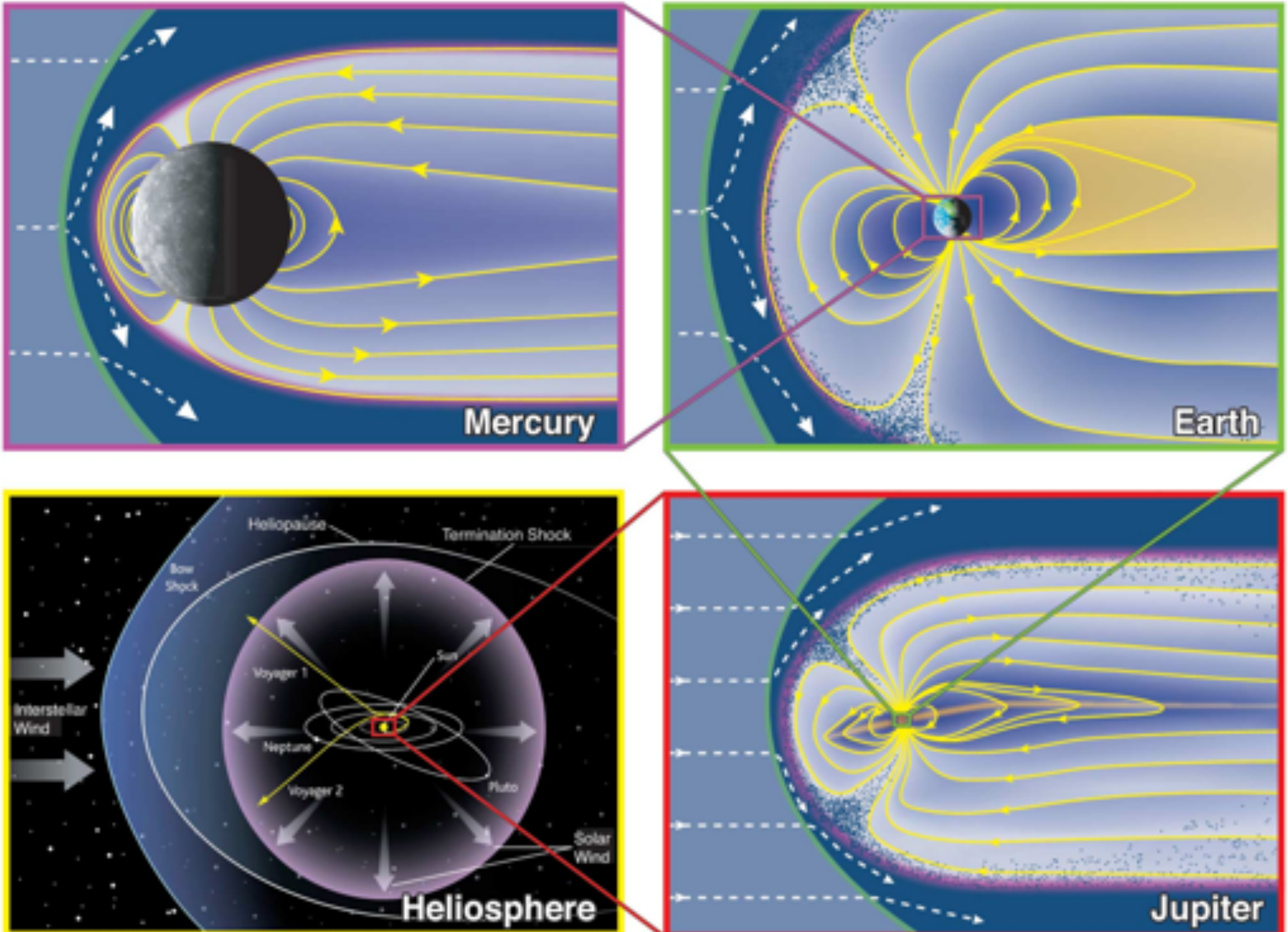
1. Solar physics – & other stars
2. Heliosphere – solar wind
3. Earth ionosphere/magnetosphere
4. Planetary space physics
5. Hummmm…. not sure

Planetary Magnetic Dynamos

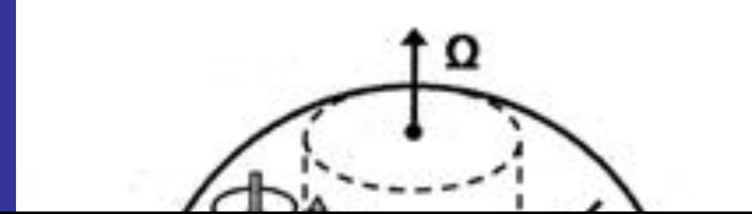
De Magnete
1600
William Gilbert

"May the gods damn all such sham, pilfered, distorted works, which do but muddle the minds of students"




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

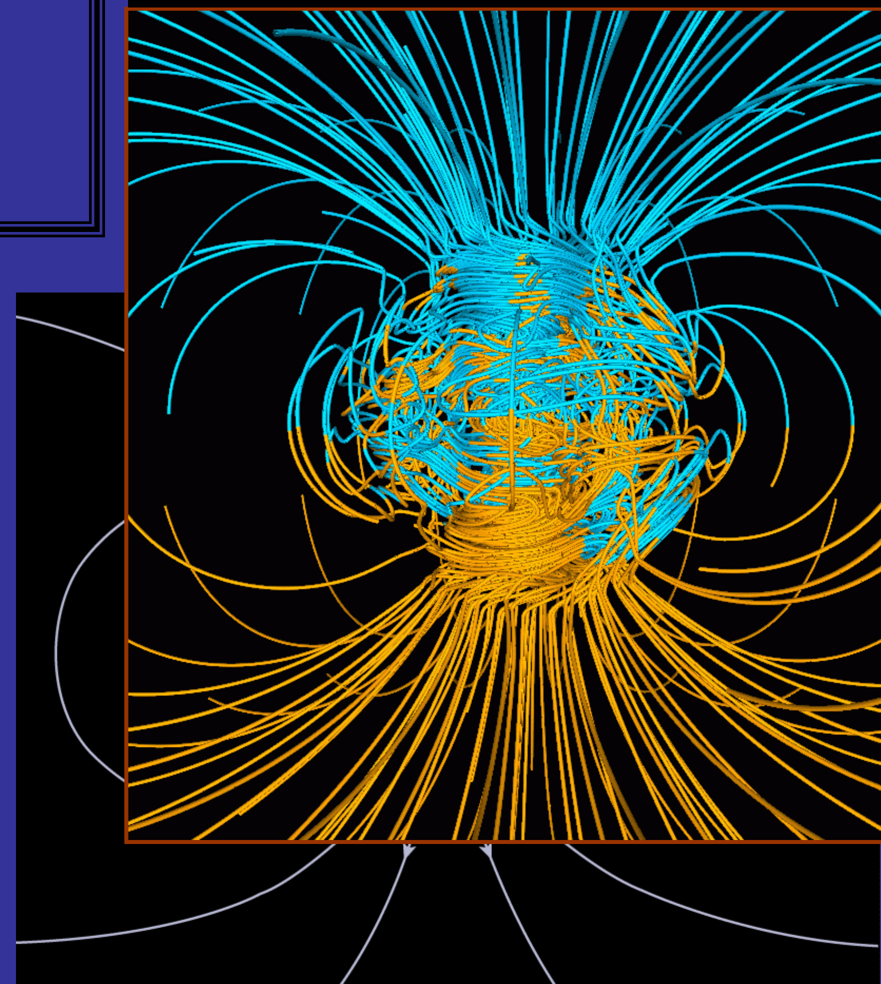
Planetary Dynamos

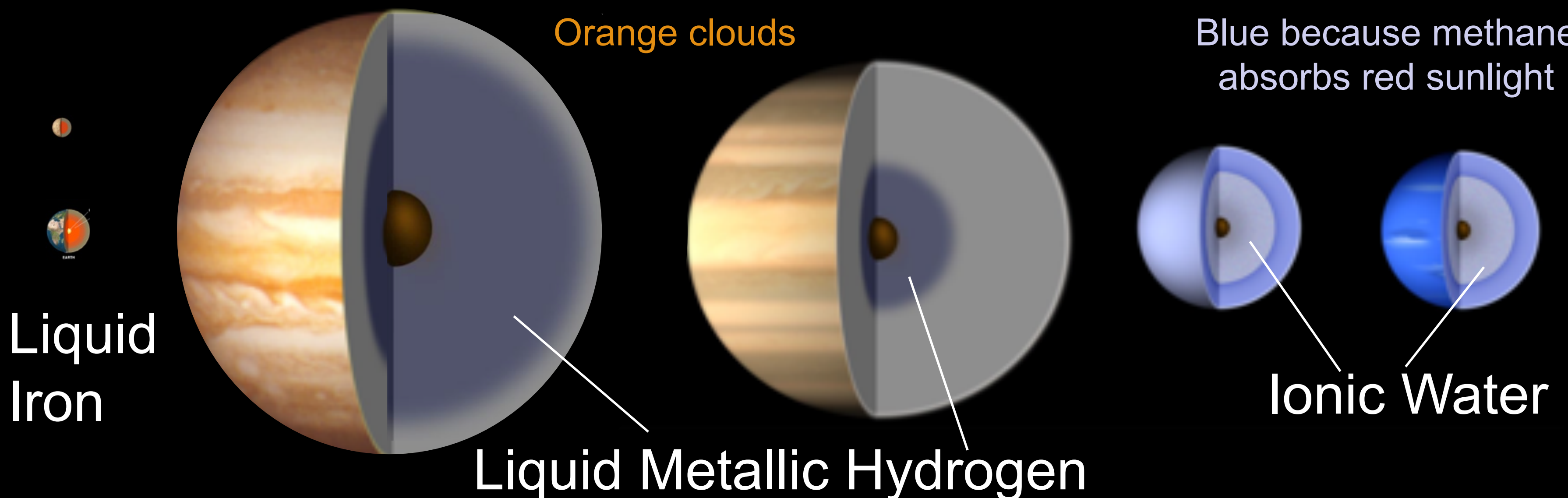


Volume of electrically conducting fluid (1) which is convecting (2) and rotating

All planetary objects probably have enough rotation - the presence (or not) of a global magnetic field tells us about (1) and (2)

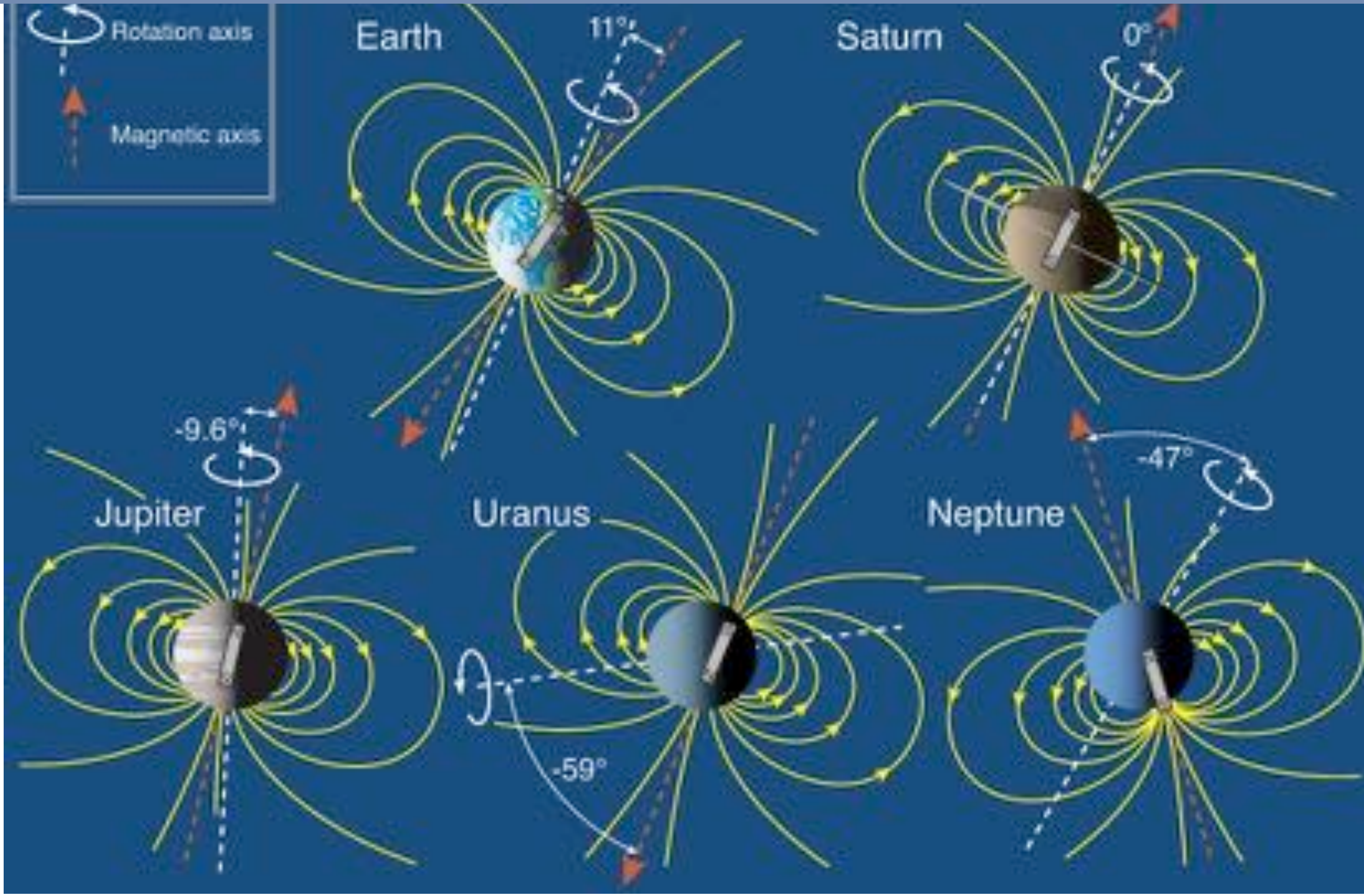
Earth dynamo model - From Glatzmeier and Roberts





	Ganymede	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
R_p/R_E	0.41	0.38	1	11	9.5	4.0	3.9
R_{core}/R_P	0.3	0.6-0.8	0.55	0.9	0.6	0.8	0.8
Magnetic Moment $/M_E$	5×10^{-4}	5×10^{-4}	1	20,000	600	50	25

Tilts and Obliquities



Offset Tilted Dipole (poor) Approximation

Magnetic Potential
3-D Spherical harmonics

$$\mathbf{B} = -grad\ V$$

$$V = R_p \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(\frac{R_p}{r}\right)^{n+1} P_n^m(\cos\theta)\left(g_n^m \cos m\lambda + h_n^m \sin m\lambda\right)$$

coefficients - constants

functions

$$P_0^0(\cos\theta) = 1$$

$$P_1^0(\cos\theta) = \cos\theta$$

$$P_1^1(\cos\theta) = -\sin\theta$$

$$P_2^0(\cos\theta) = \tfrac{1}{2}(3\cos^2\theta - 1)$$

$$P_2^1(\cos\theta) = -3\cos\theta\sin\theta$$

$$P_2^2(\cos\theta) = 3\sin^2\theta$$

$$P_3^0(\cos\theta) = \tfrac{1}{2}(5\cos^3\theta - 3\cos\theta)$$

Dipole

Quadrupole

n=0

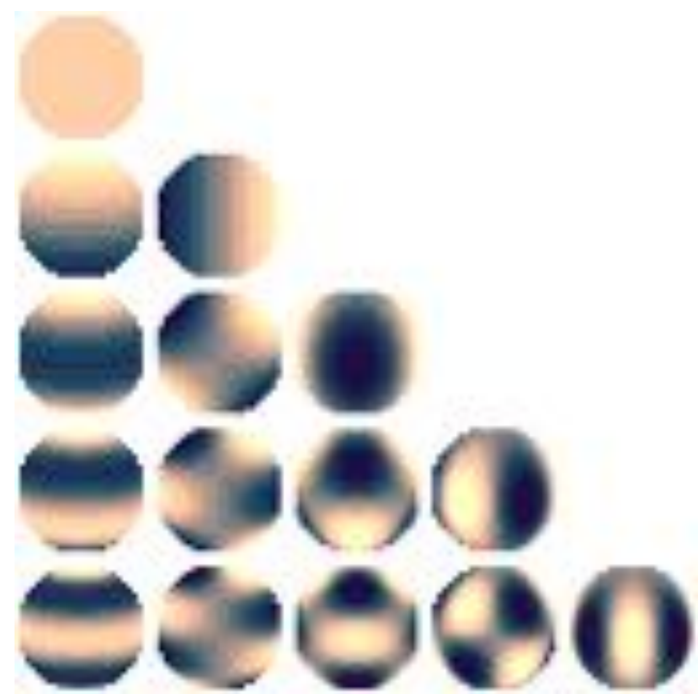
1

2

3

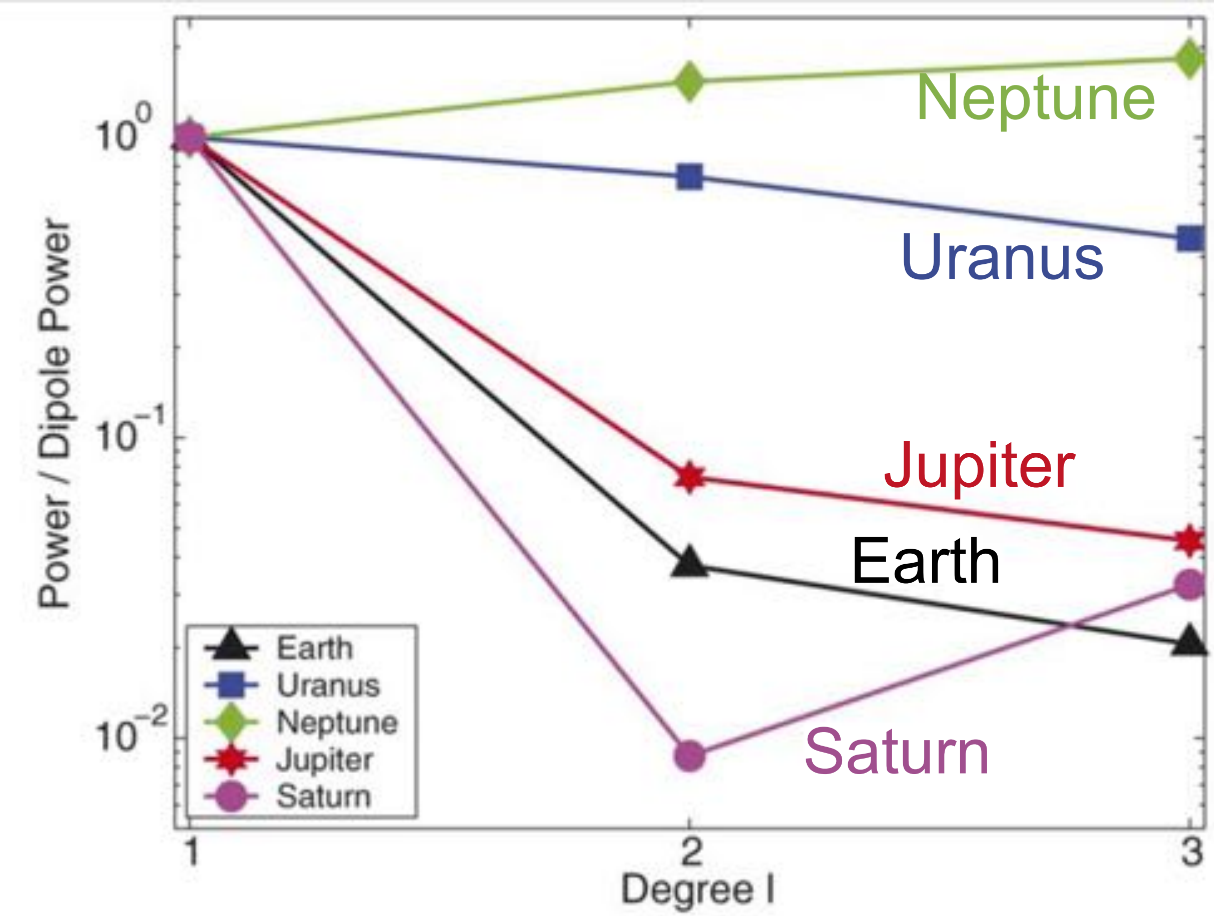
4

5

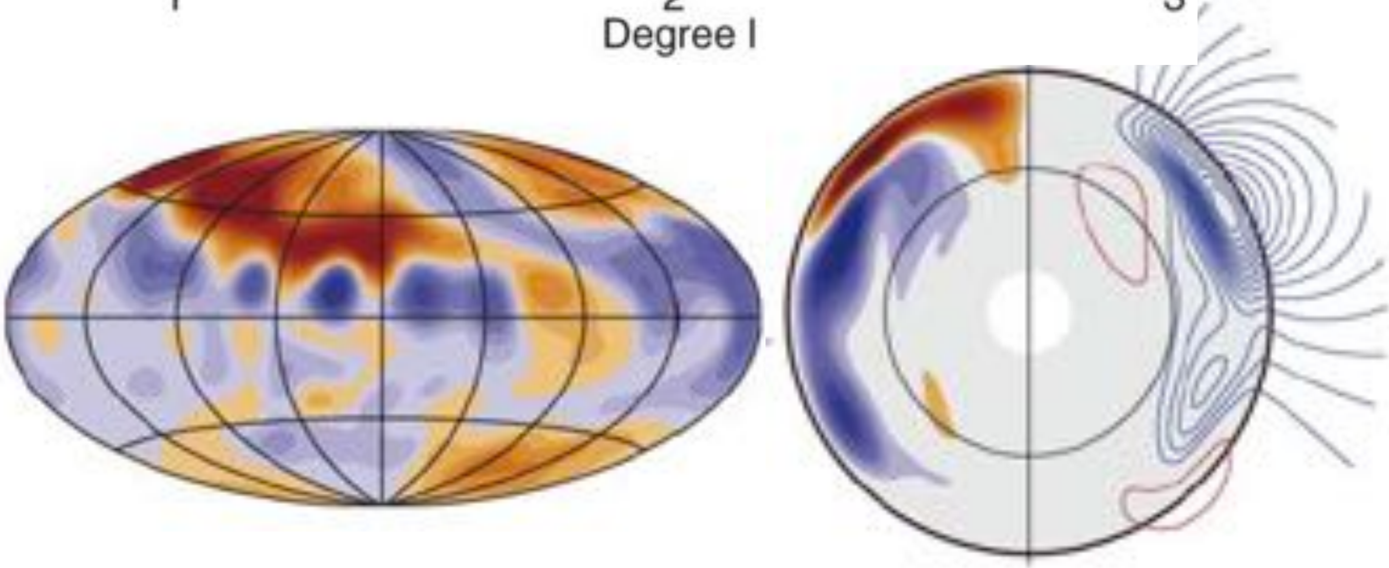


m=0 1 2 3 4 5….

Stanley & Bloxham 2006



Multipole coefficients / Dipole coefficient Indicates degree of complexity

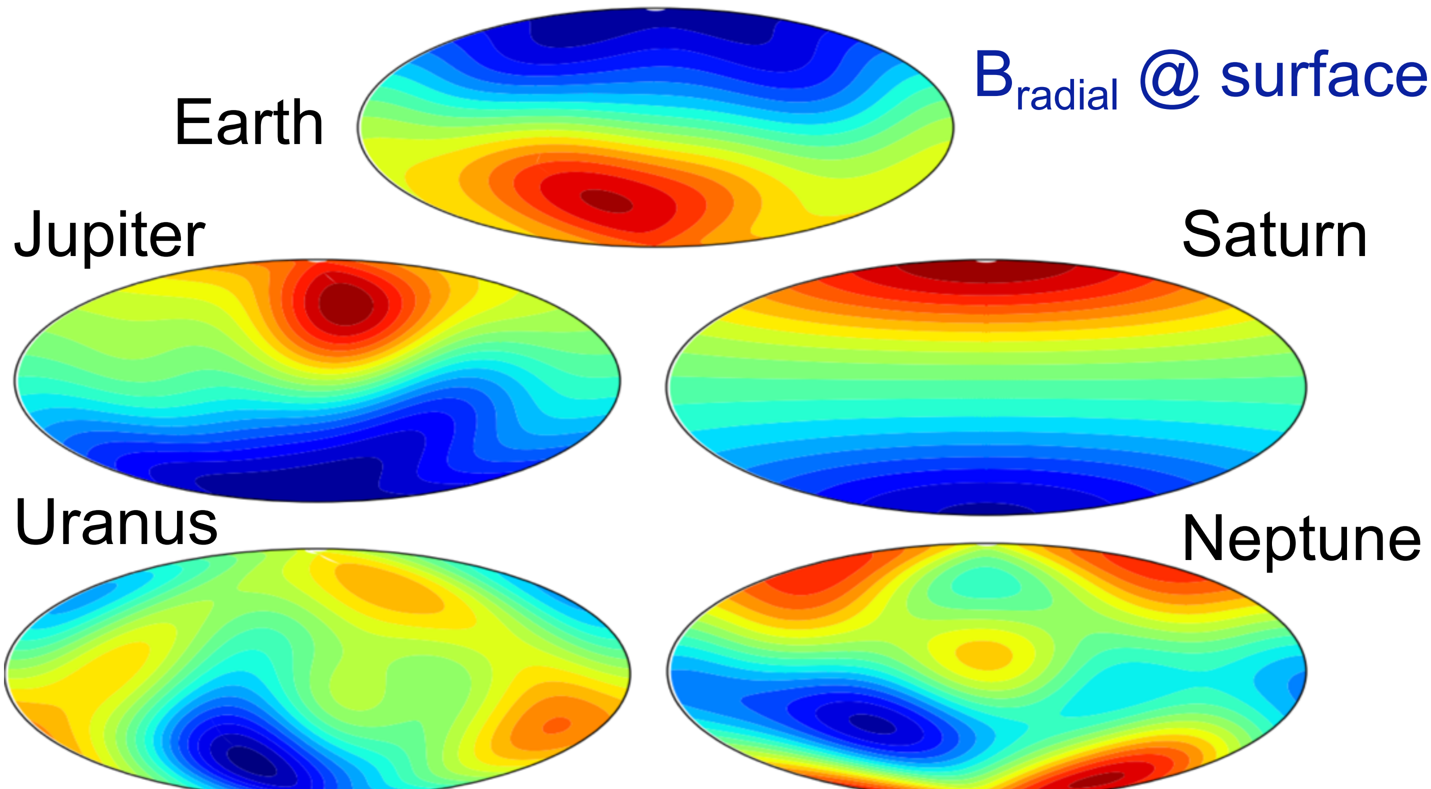


Modeling Uranus' & Neptune's non-dipolar fields with a thin-shell dynamo over a stratified core

Planet	Rcore / Rplanet	Bo [μT]	Tilt	Quad / Dipole
Earth	0.55	31	+9.92°	0.04
Jupiter	0.84	428	-9.6°	0.10
Saturn	0.6	21	<-1°	0.02
Uranus	0.7	23	-59°	1.3
Neptune	0.8	14	-47°	2.7

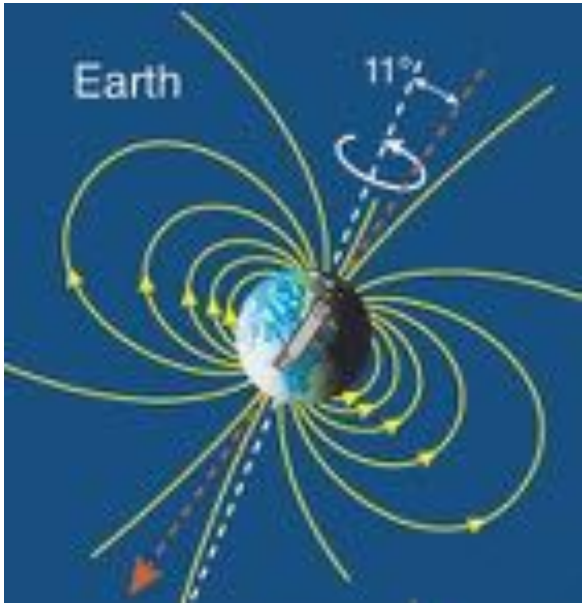
Dipolar (Earth, Saturn)

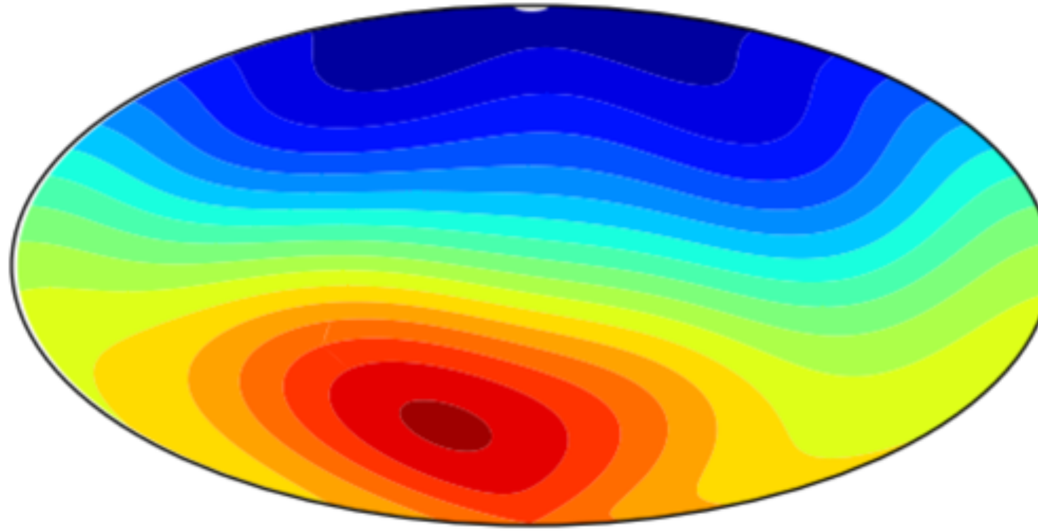
Irregular (Uranus, Neptune)



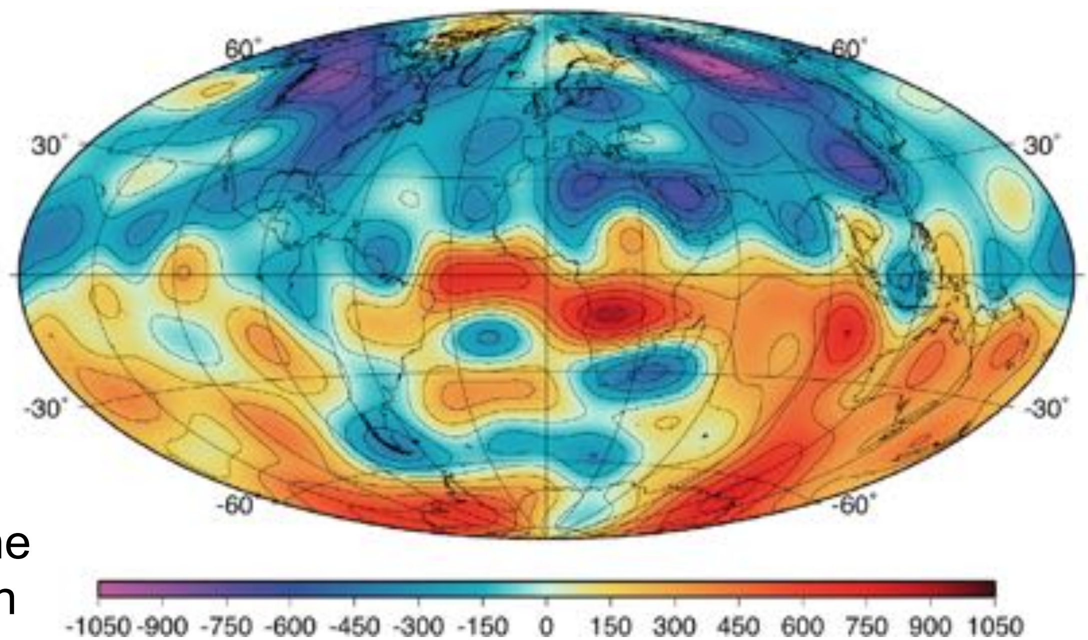
Stanley & Bloxham 2006

Earth's Magnetic Field



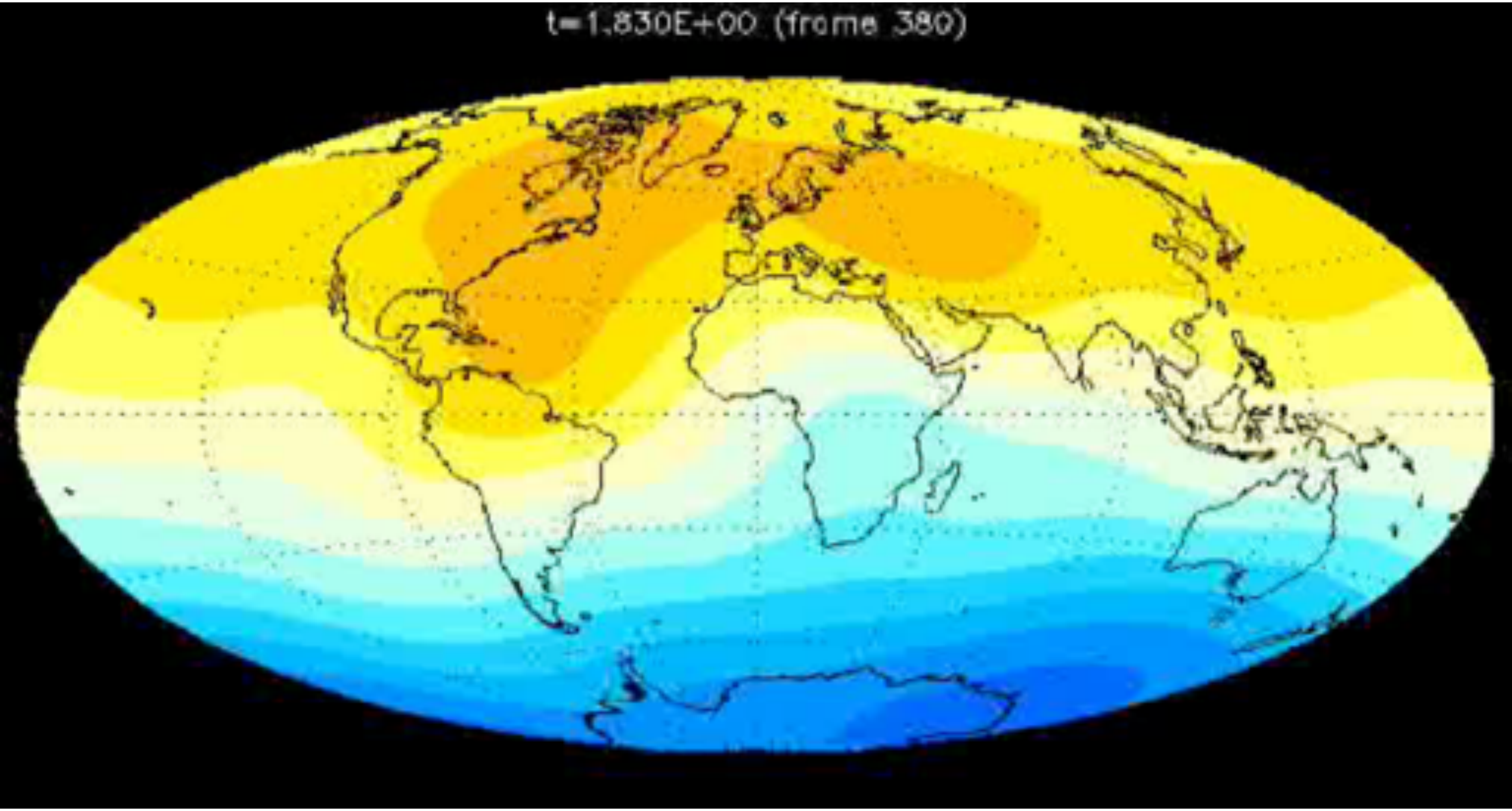


When you look closer there's more complexity



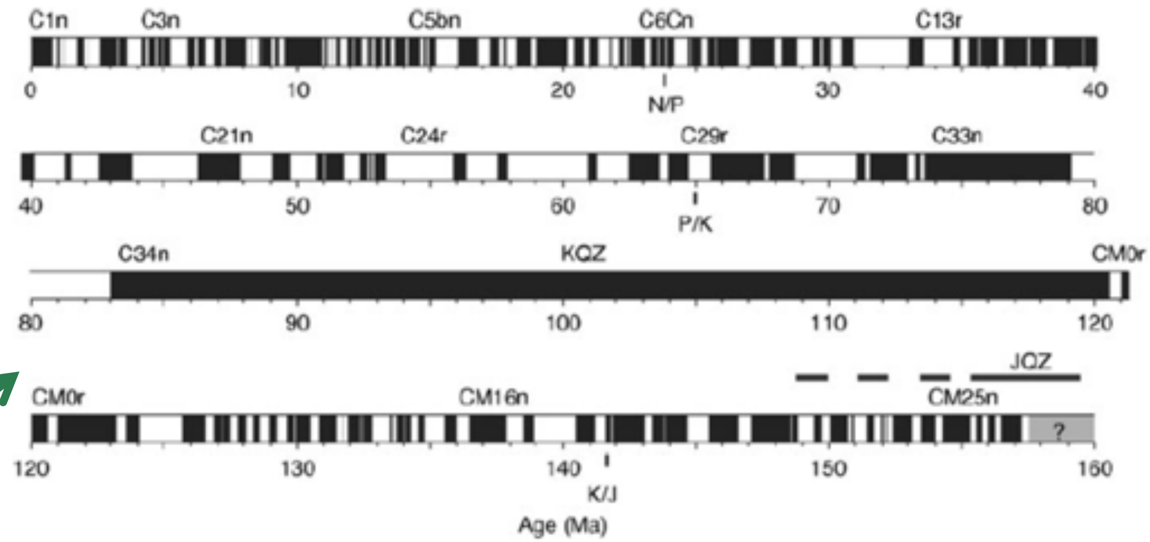
Earth's field extrapolated down to the top of the outer core dynamo region

Br through a reversal



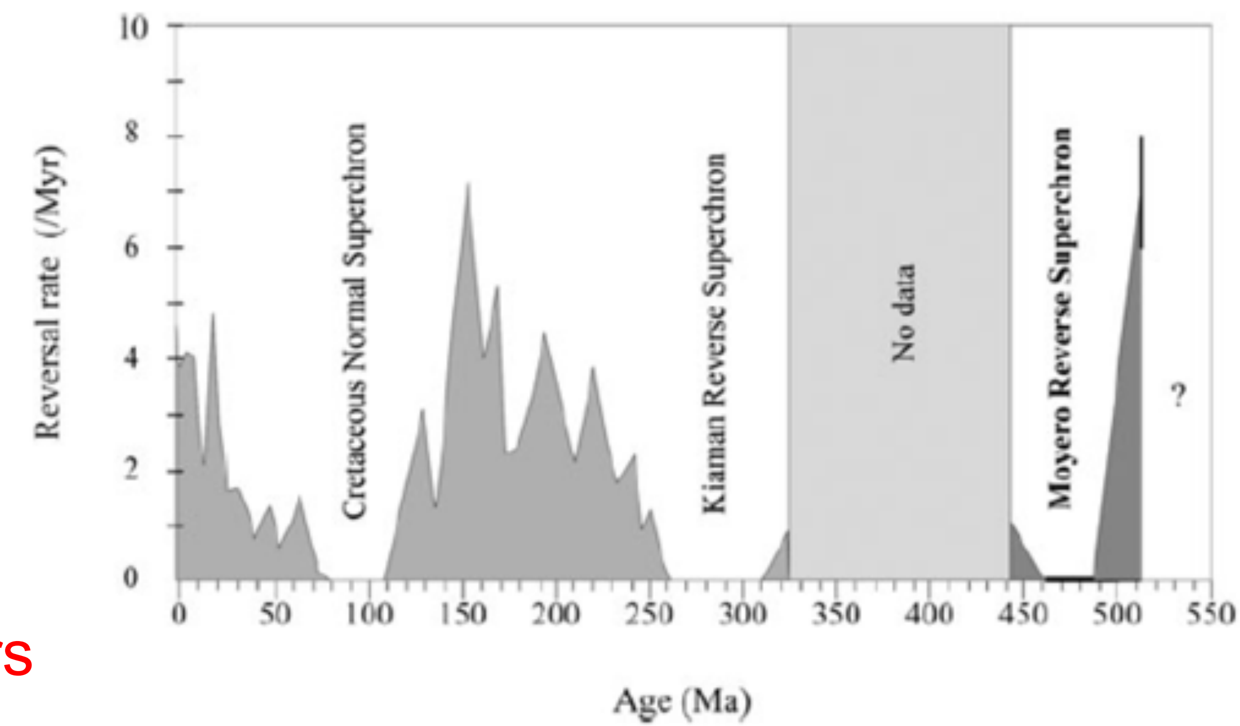
Hulot et al. 2010
Pavlov & Gallet 2005

Polarity reversals:



1. variable in duration and

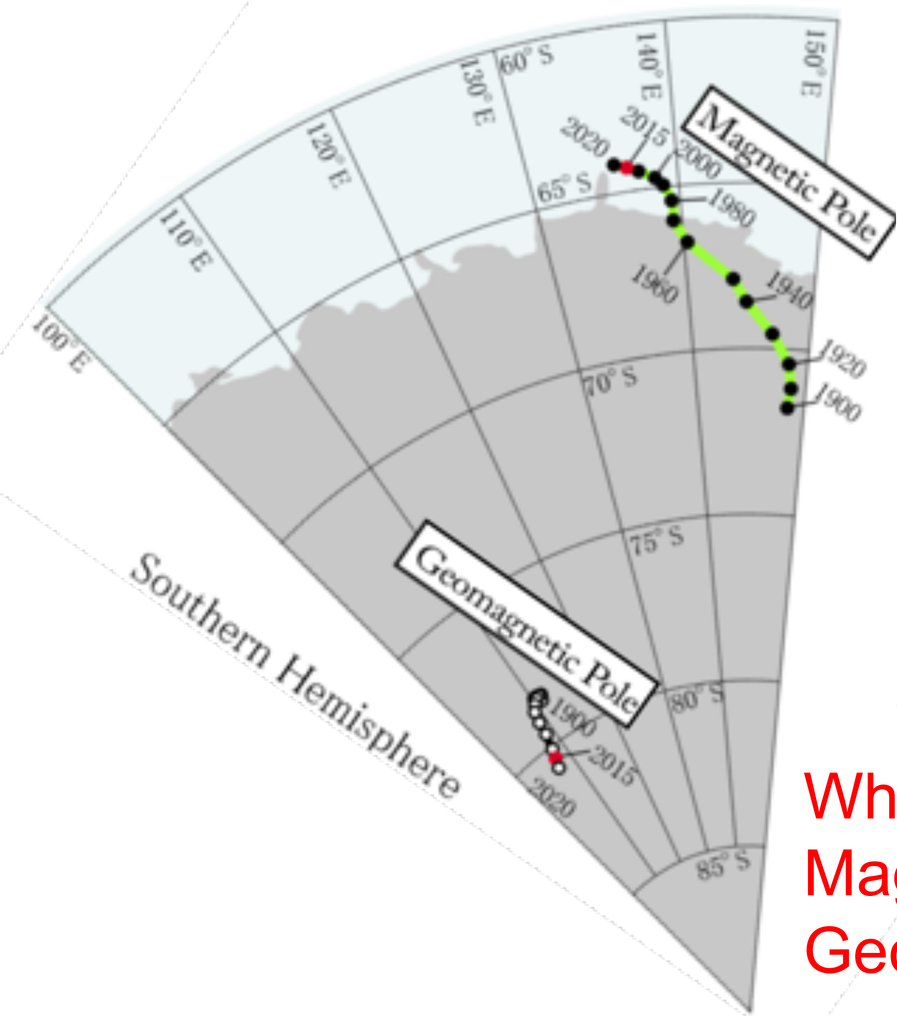
2. rate

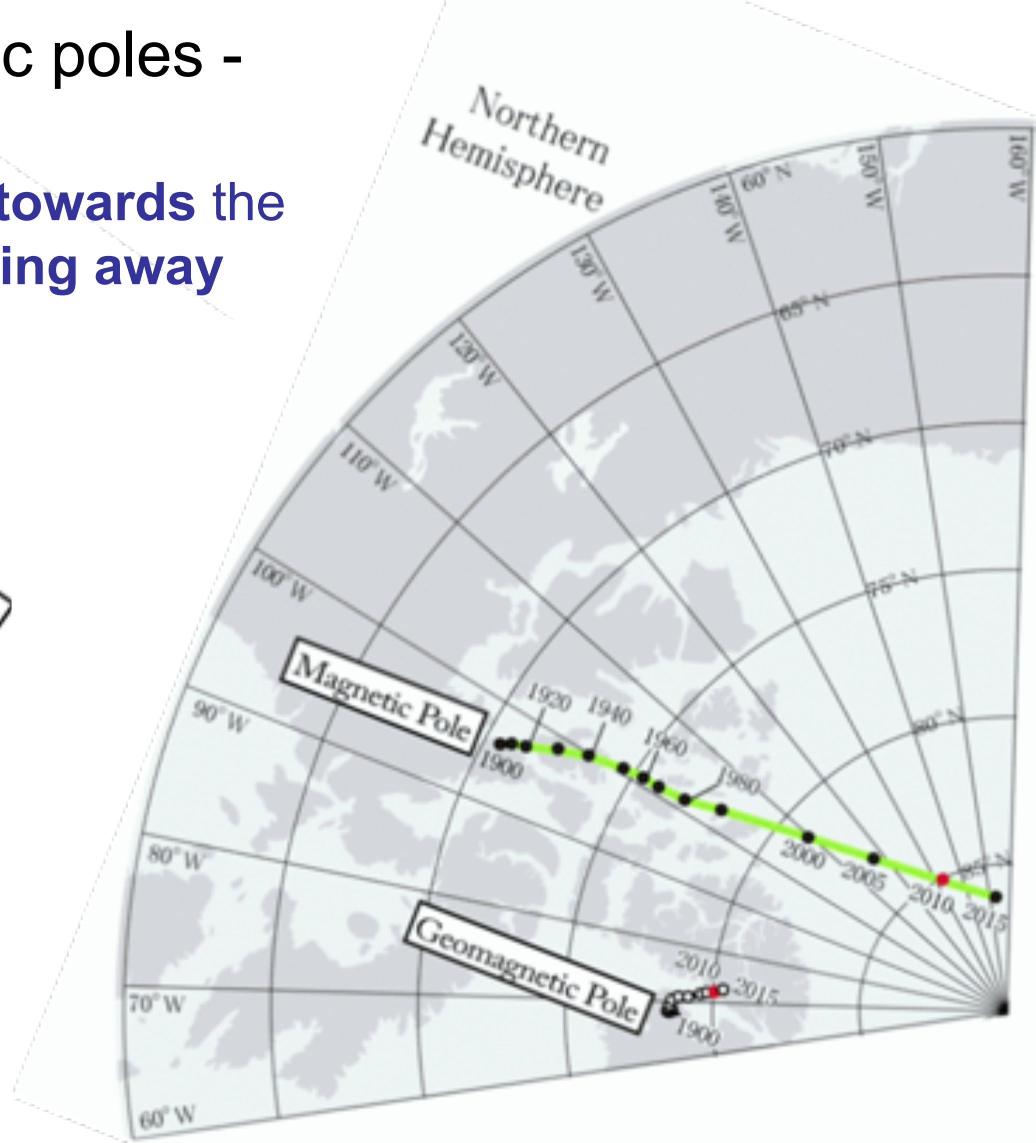


rapid rate
~ 5/million years
~ every 200,000 yrs

Where are the Earth's magnetic poles - and where are they headed?

Note that the **north pole is moving towards** the rotation pole, the **south pole is moving away** from the rotation axis…



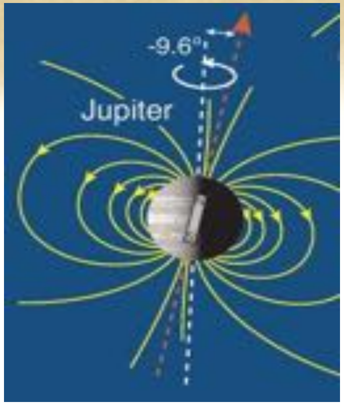


What's the difference?

Magnetic Poles = where B = Br

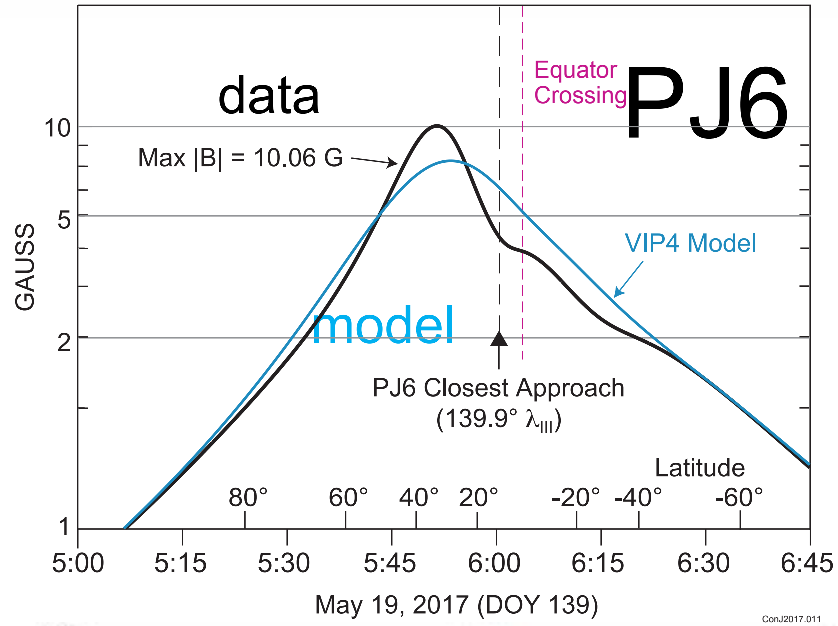
Geomagnetic Poles = best fit dipole

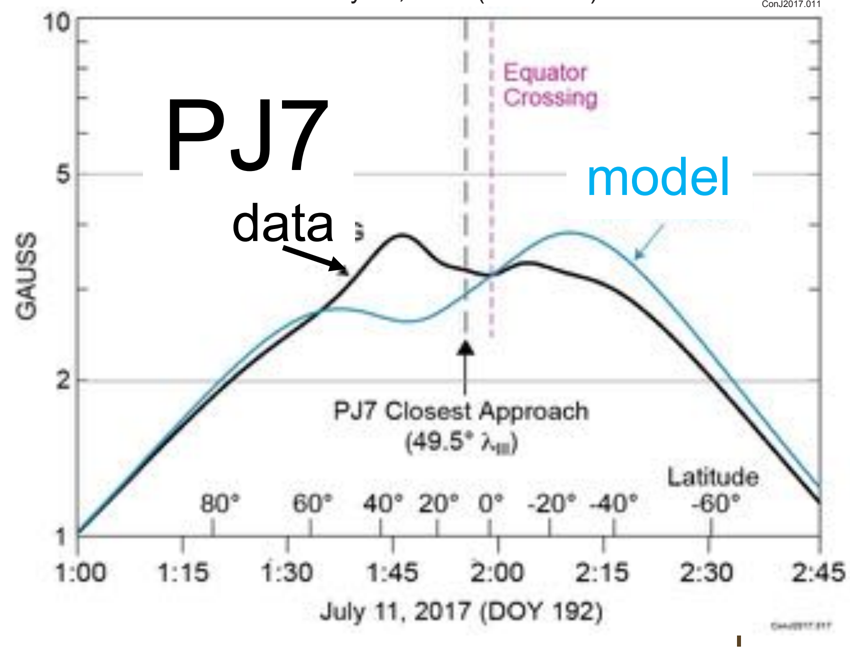
Jupiter's Magnetic Field



- Juno's first few passes are showing deviations from previous simple models

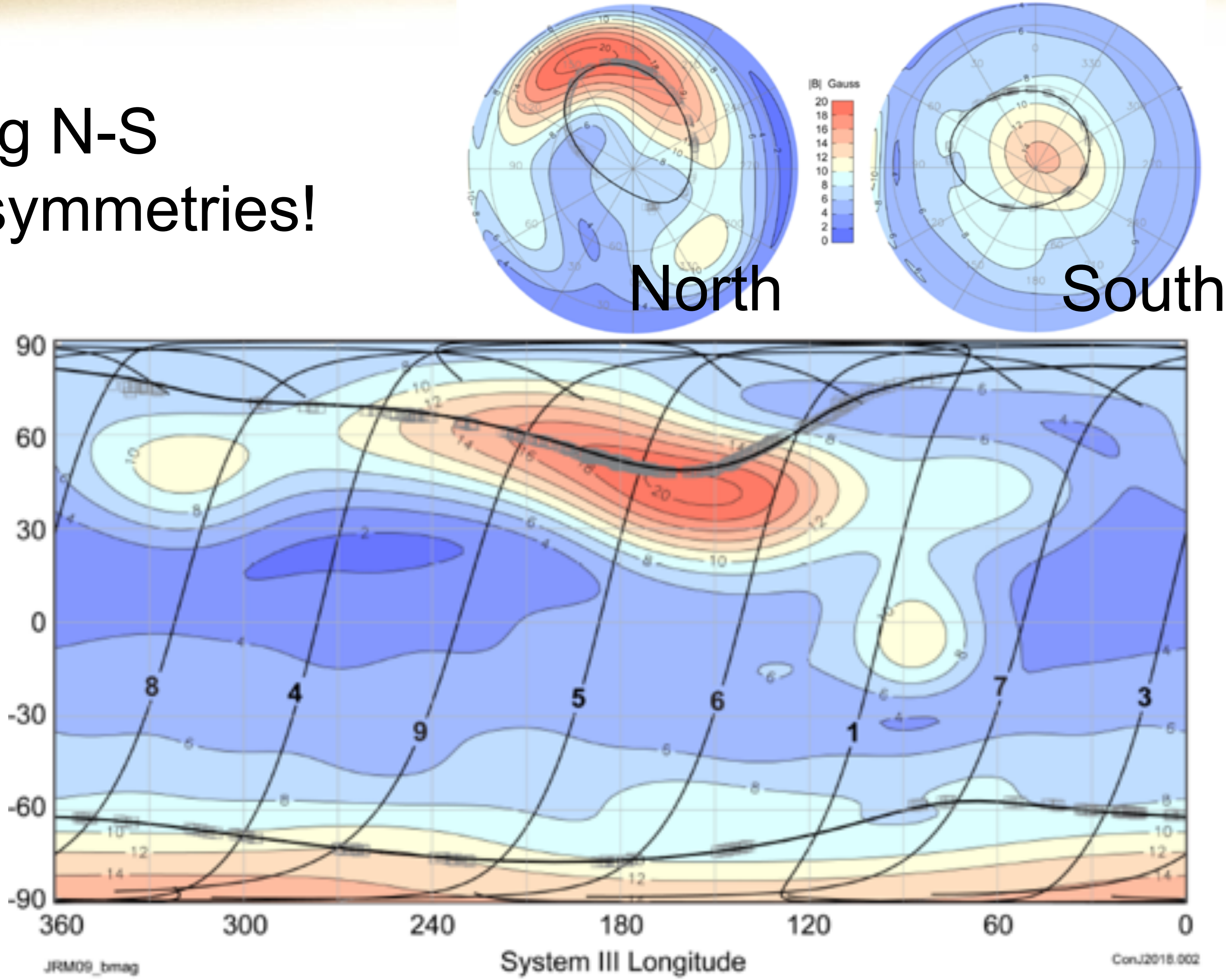
- Hints that the dynamo region is closer to the surface?





Juno - based magnetic field model

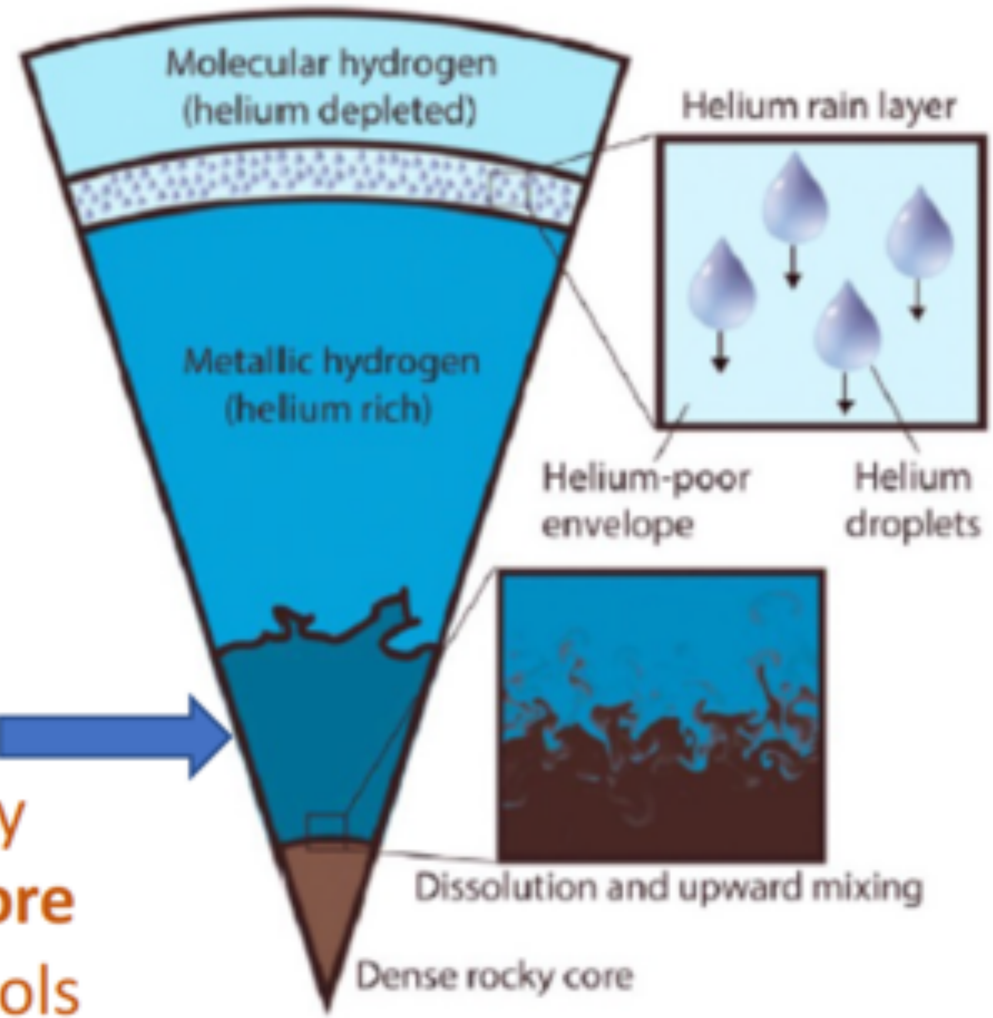
Big N-S asymmetries!



Juno

Dilute core

Heavy elements mixed with metallic H to ~40% radius



This can arise during **accretion**

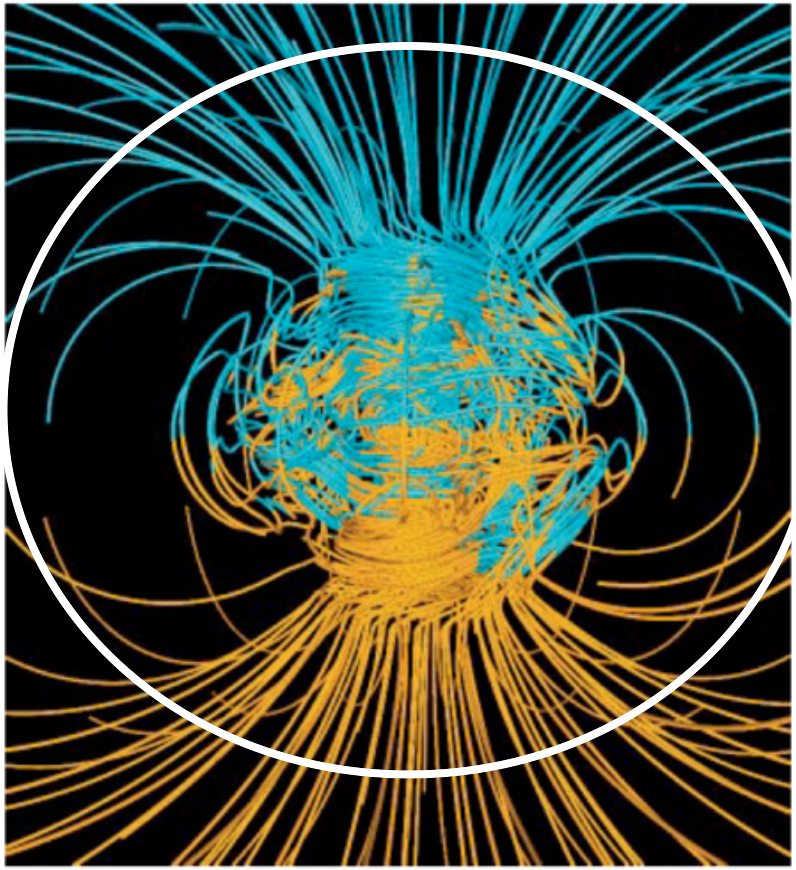
and be augmented by convective stirring -**core erosion-** as Jupiter cools over geologic time

Wahl et al. 2017

Implications for Dynamo

Earth: Dynamo deep in core – outer field ~dipole

Saturn: Deeper core, zonal flows in resistive layer makes symmetric dipolar field

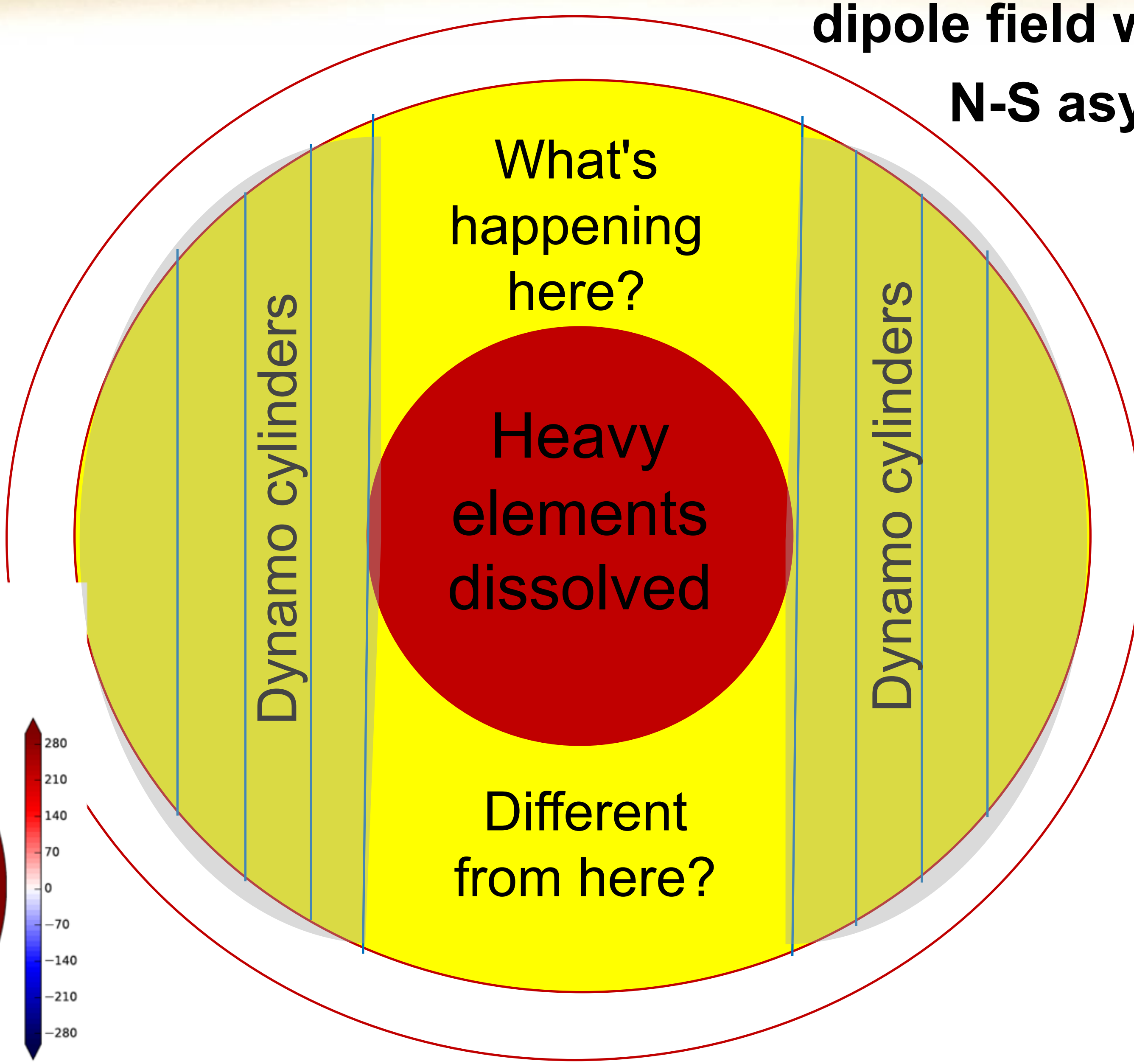


Glatzmeier 2002

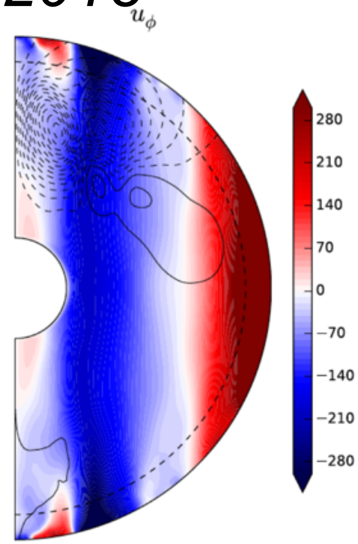
Glatzmeier 2005

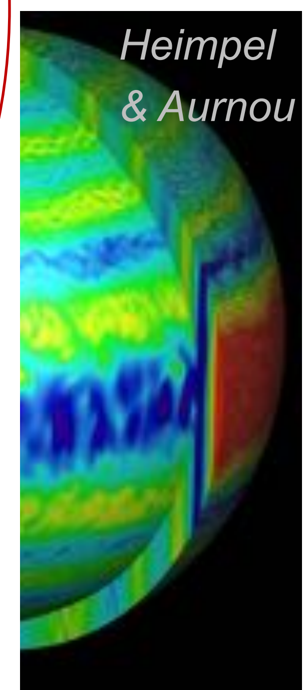
Implications for Dynamo

How to get basically dipole field with some N-S asymmetry?

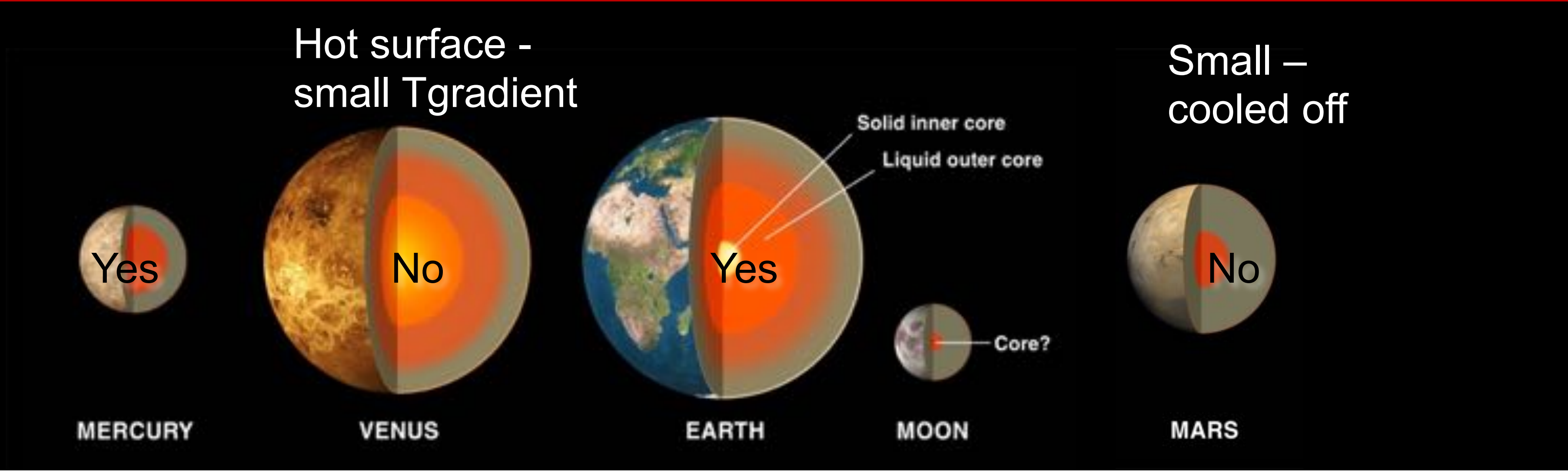


Duarte et al. 2018





WHICH HAVE ACTIVE MAGNETIC DYNAMOS?



Why Don't Venus or Mars have Dynamos?

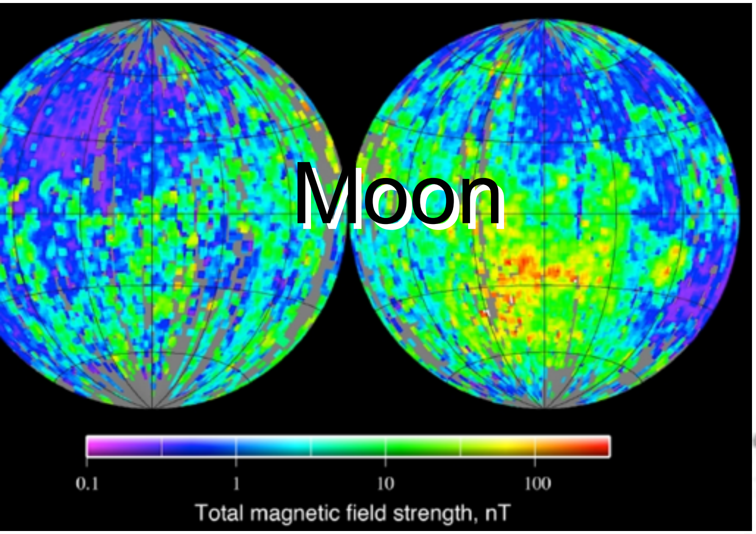
- Enough rotation – even for Venus
- Conducting fluid core – probably
- Lack of convection in core?

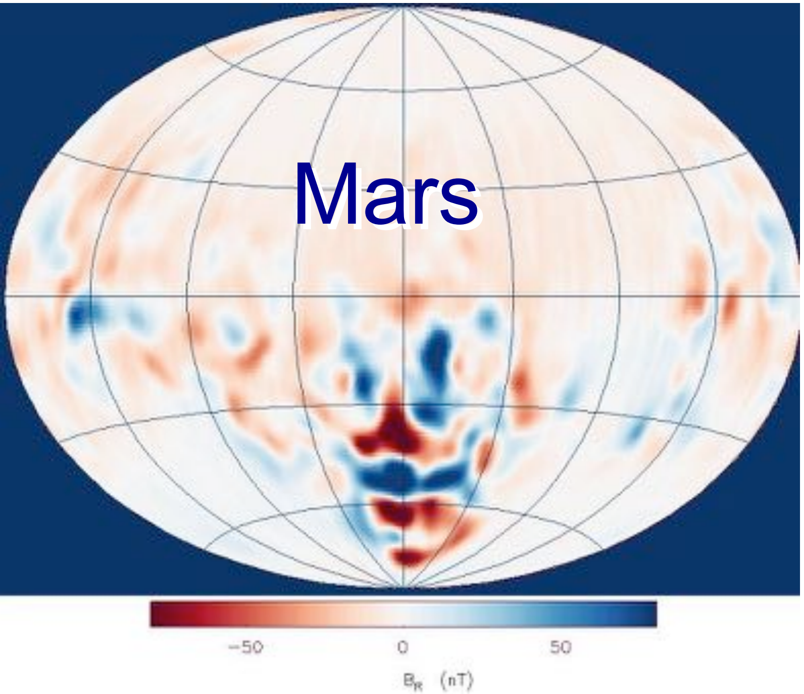
1. If....Mantle convection controls heat flow from core. Then....Lack of plate tectonics suggests less efficient cooling of interior and lower heat flux from core
2. No inner core means no latent heat of solidification and no enhancement of lighter material in the outer core

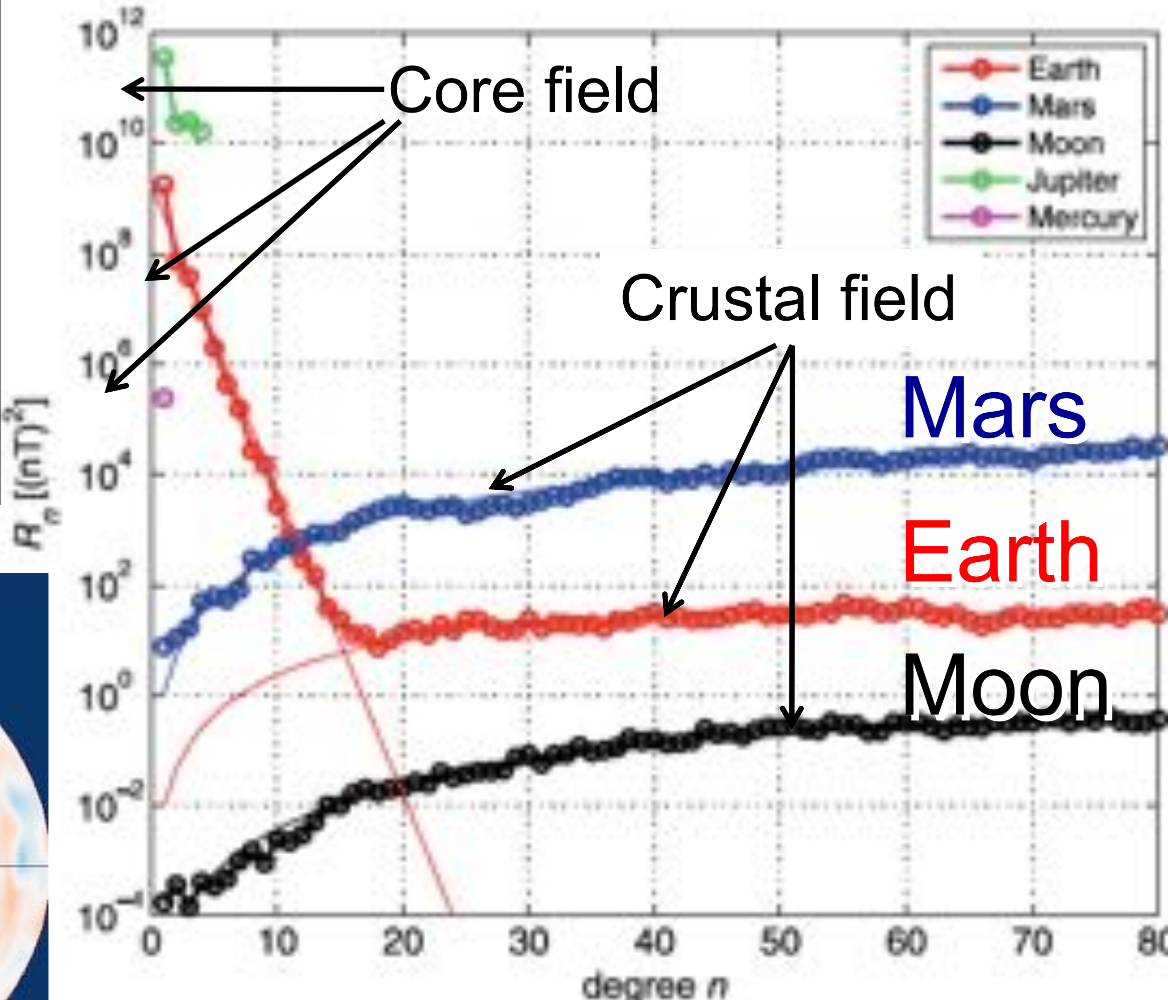
Need geophysics missions that address interior structure

Stevensen 2010

Moon & Mars: All Crustal Remanent Magnetization





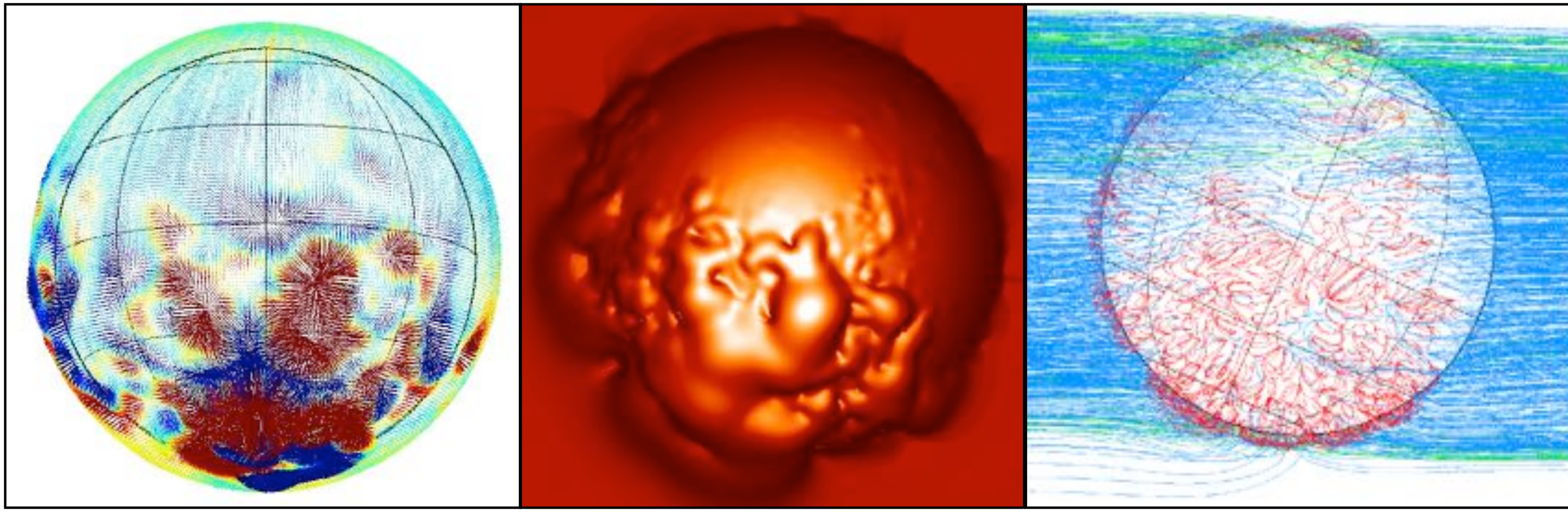


- Did Moon ever have dynamo?
- Mars' dynamo died >3.5 BYA.

Mars:

Weak, irregular field

-> bumpy surface + changing topology

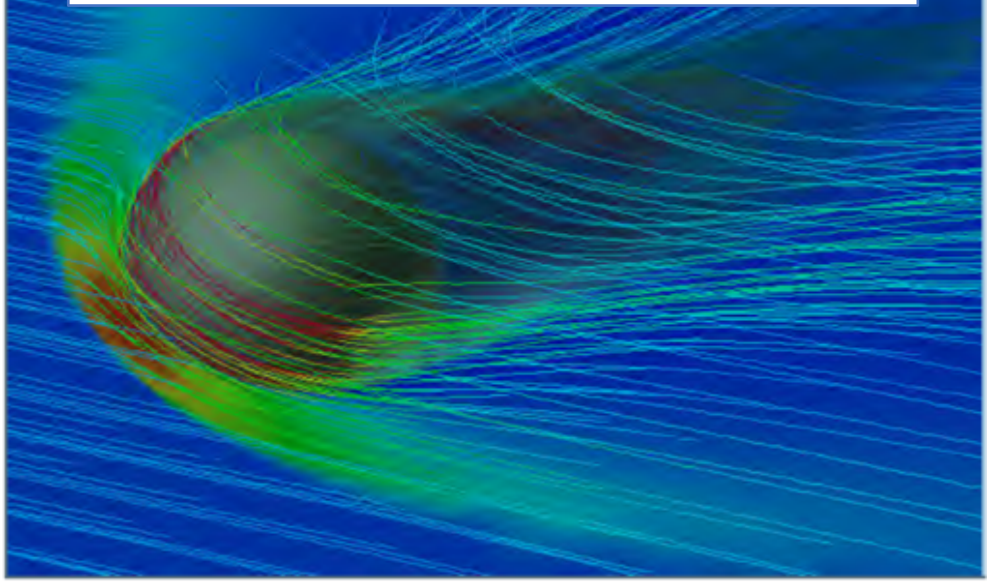


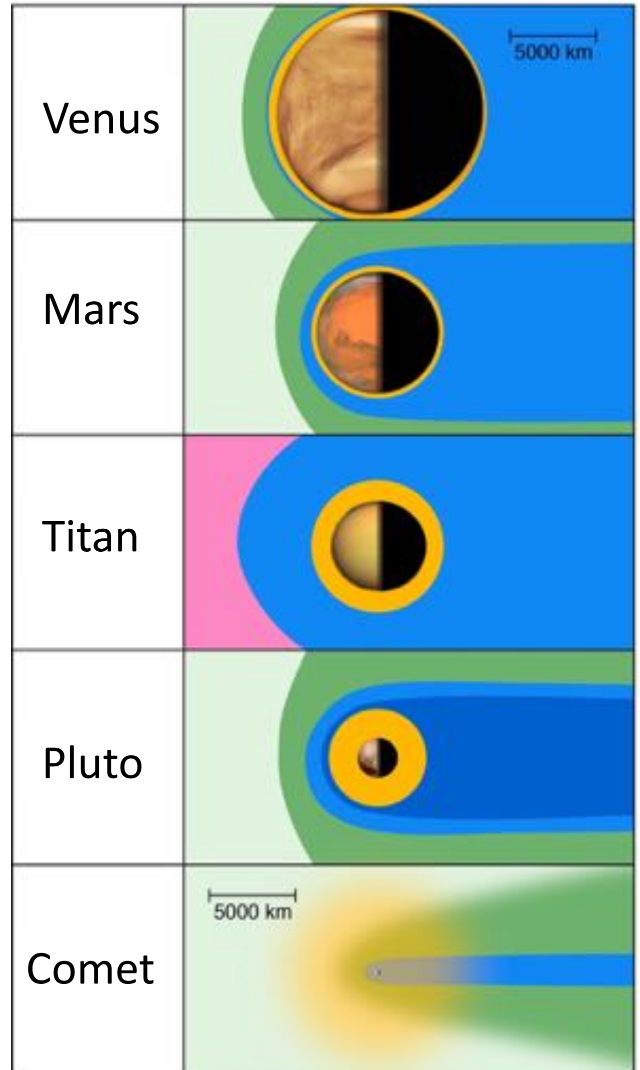
MGS mission

MAVEN mission

David Brain

Solar Wind Interaction
Atmosphere Escape





Mariner 2, 5, 10
Venera 9, 10
Pioneer Venus
Venus Express

Mariner 4
Mars 2, 3, 5
Phobos
MGS
Mars Express
MAVEN

Voyager 1
Cassini

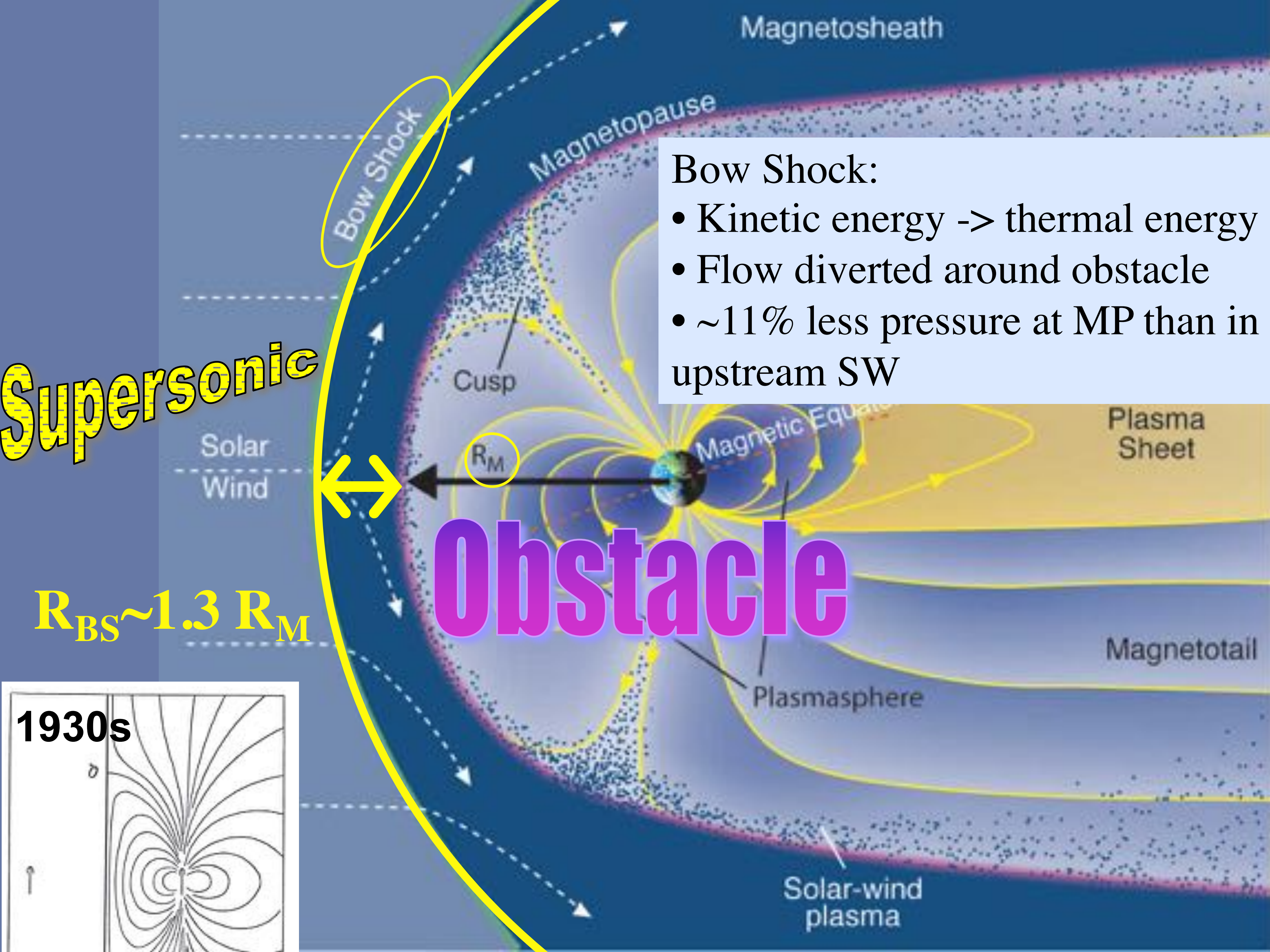
New Horizons

Vega 1, 2
Deep Space 1
Giotto
Rosetta

- Ionization of outer atmosphere
- Plasma-atmosphere interaction
- Similar scale!
- Similar loss! few kg/s
- Comets up to ton/s

Brain et al. 2016

Magnetosphere Sizes


Magnetosheath
Magnetopause
Bow Shock
Bow Shock:
• Kinetic energy -> thermal energy
• Flow diverted around obstacle
• ~11% less pressure at MP than in upstream SW
Supersonic
Cusp
Solar Wind
R_M
Magnetic Equator
Plasma Sheet
Obstacle
R_{BS}~1.3 R_M
Magnetotail
Plasmasphere
1930s
Solar-wind plasma

Small Magnetospheres

Mercury

Mariner 10

MESSENGER

In solar wind m'sphere

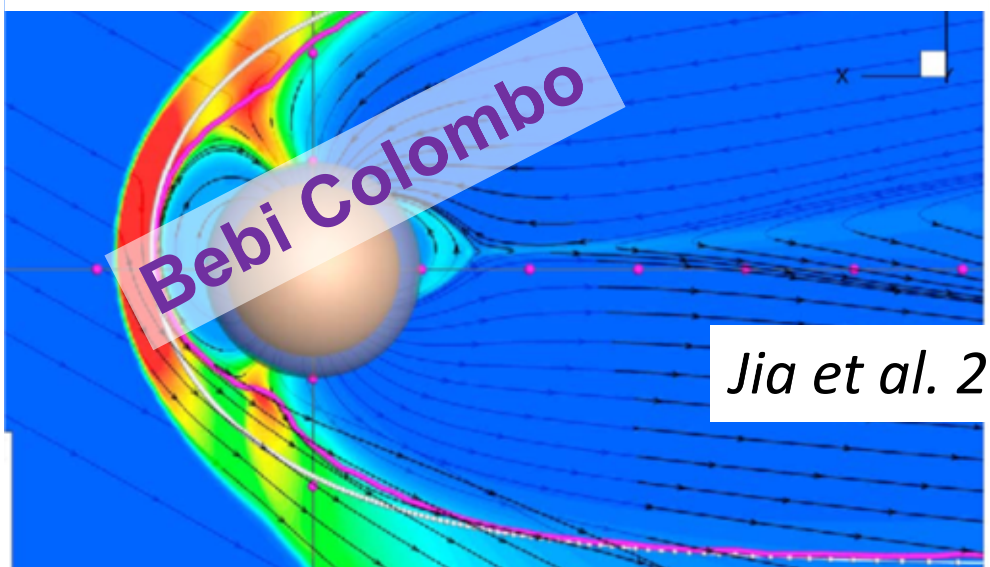
No atmosphere aurora

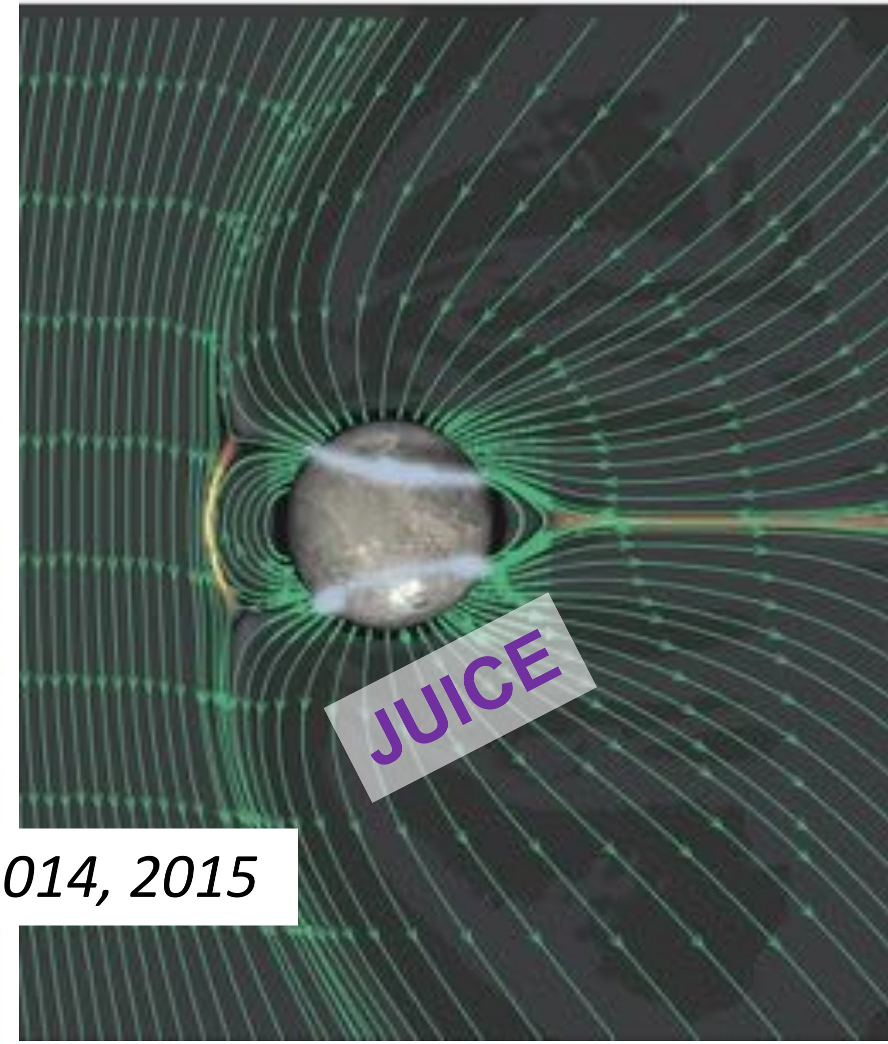
Ganymede

Galileo

In Jupiter

Atmospheric





Jia et al. 2014, 2015

$B_{surface}$ ~ 1/100 Earth

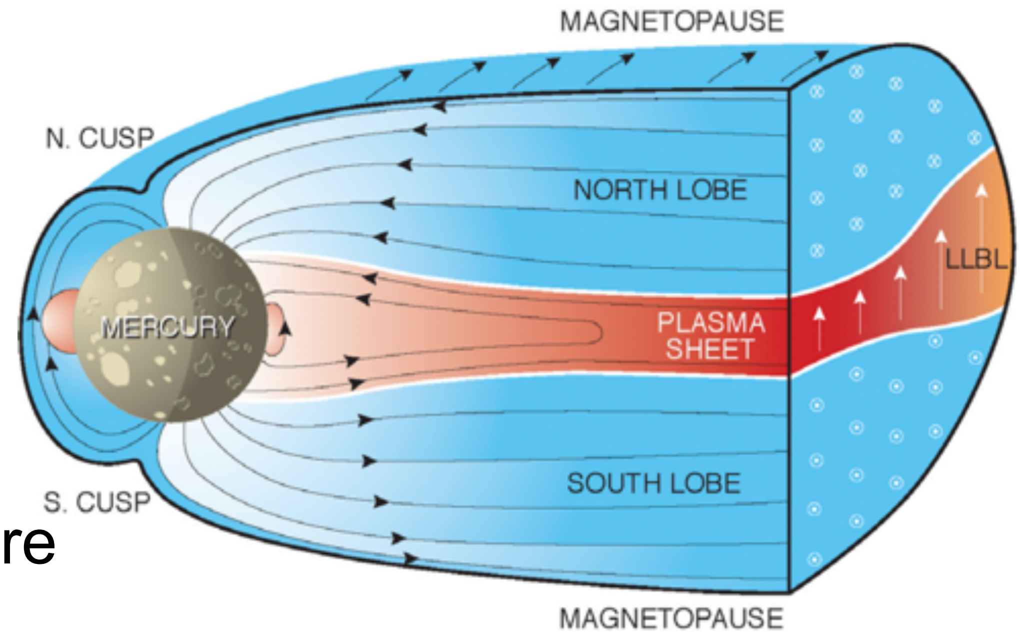
Earth Diameter

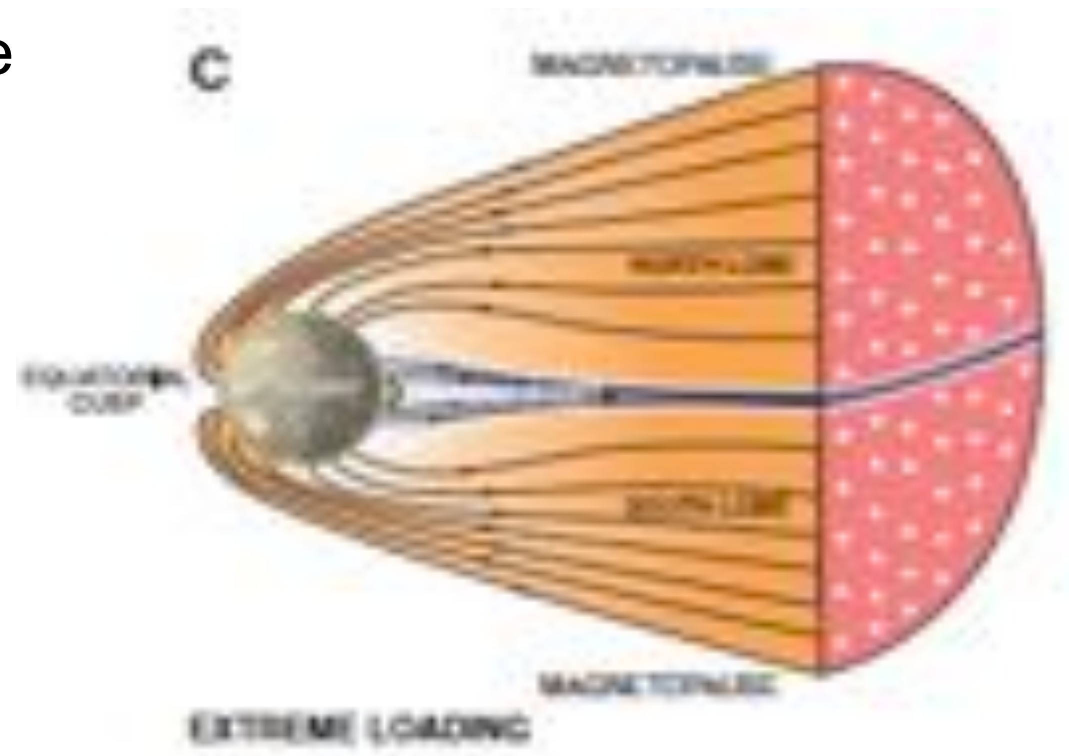
Mercury

- Small magnetosphere
- No atmosphere/ionosphere
- Currently close via crust
- Very rapid Dungey cycle
- Sputtered Na^+ escape

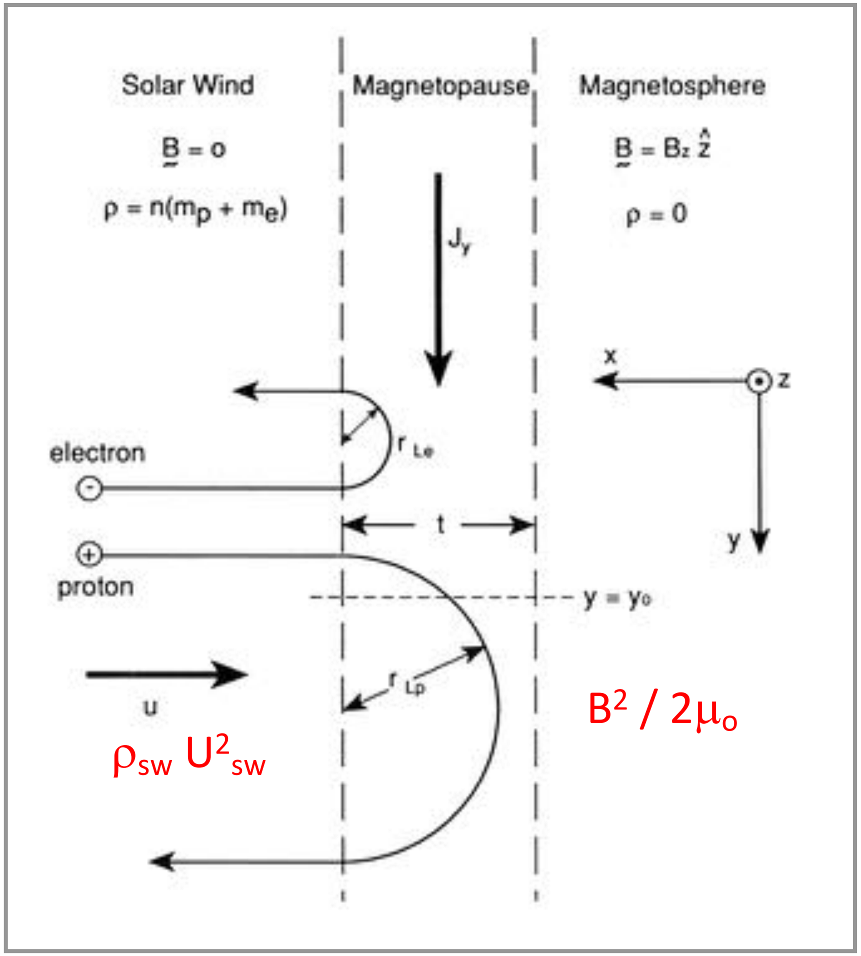
Extreme solar wind conditions -> exposed planet

Slavin et al.



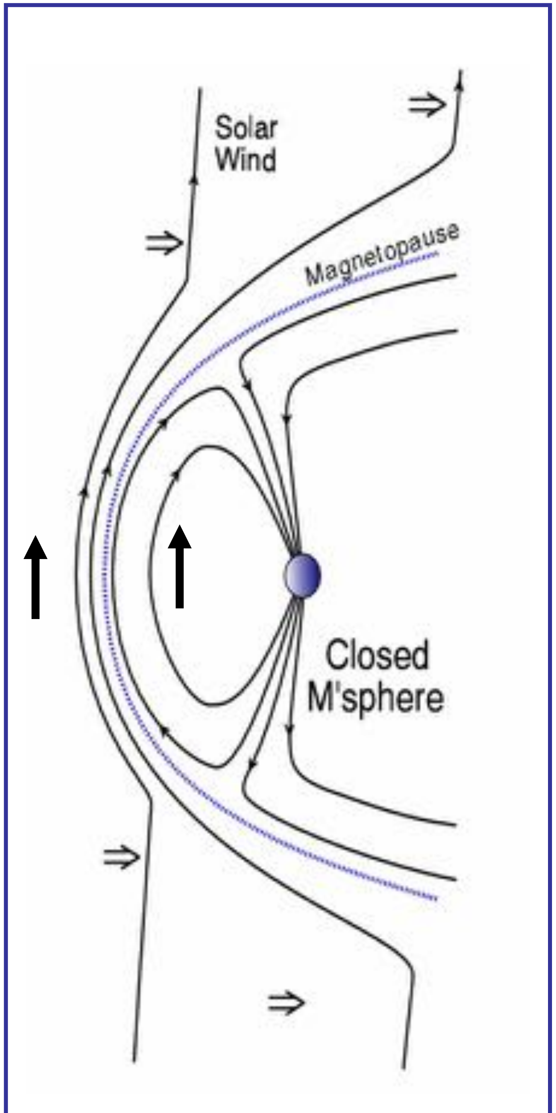


Chapman-Ferraro Current

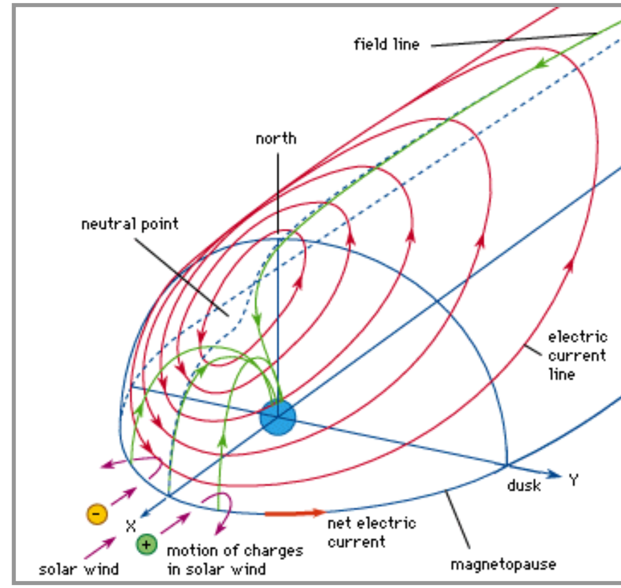


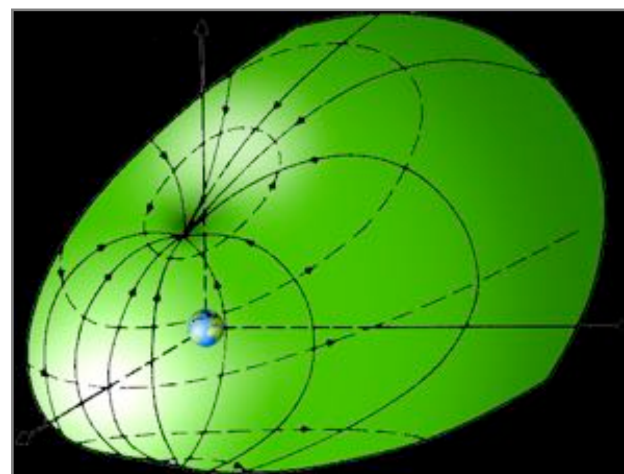
- Internal magnetic field pressure $B^2 / 2\mu_o$
- Balances the solar wind dynamic pressure $\rho_{sw} U^2_{sw}$
- Assumes northward Interplanetary Magnetic Field – IMF
- Chapman-Ferraro current must provide **j** x **B** force integrated across magnetopause

Chapman-Ferraro Current



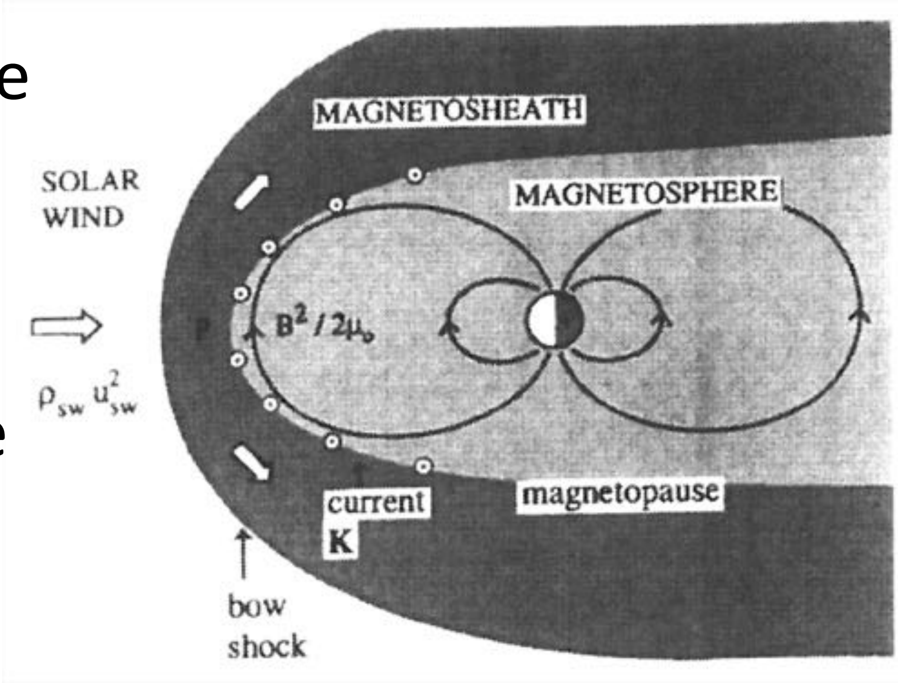
- Creates closed magnetosphere
- Limits size of magnetosphere
- Current pattern over the whole magnetopause.





$B_{dipole} = B_o \ (R_p/r)^3$

SW ram pressure <=>
internal magnetic field pressure



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

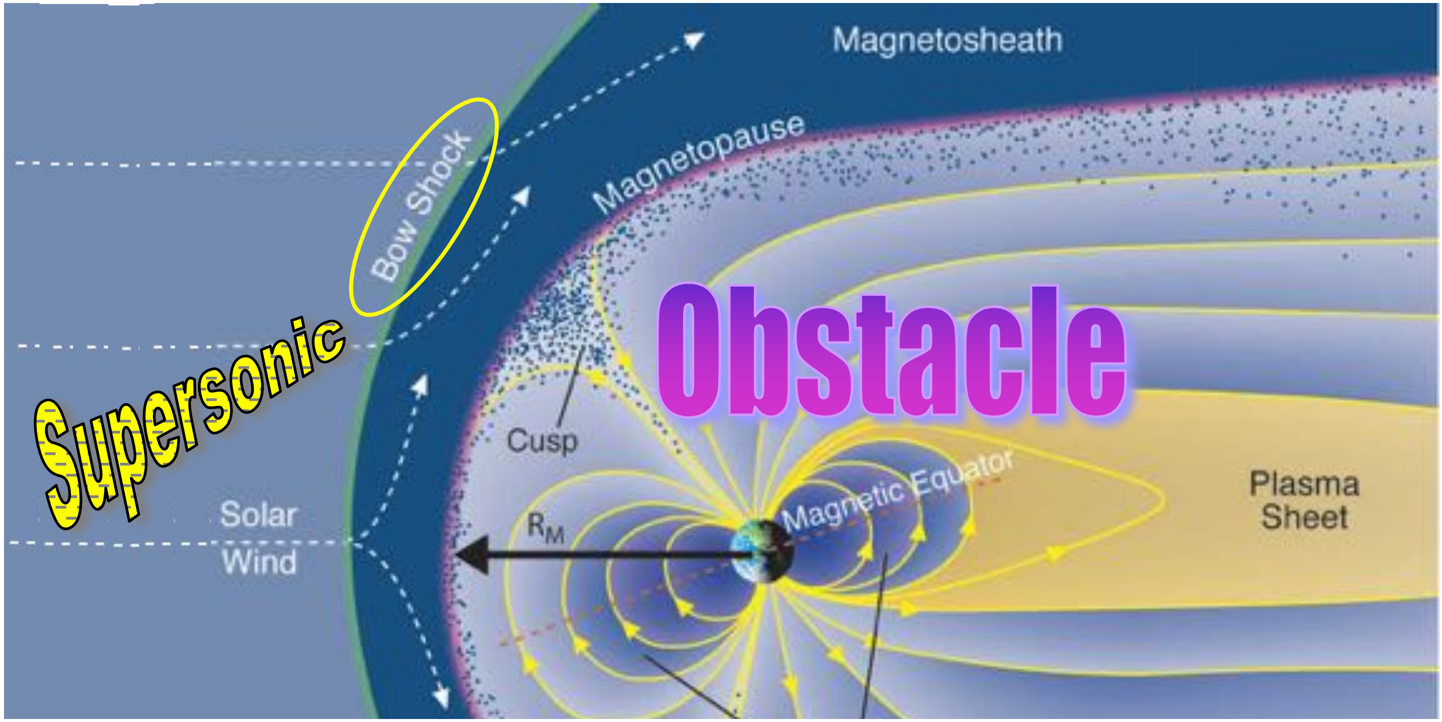
BUT what about currents at the magnetopause? -> $2B_{dipole}$

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

Solve for r=> R_{MP}

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

Dipole Magnetic Field in Solar Wind



Chapman-Ferraro Distance

SW Ram Pressure ⟷ Magnetic Pressure

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

Walker & Russell 1995

$$R_{CF}/R_p \sim 1.2\,\{\mathbf{B_o}^2 / (2\,\mu_o\,\rho_{sw}\,U^2_{sw})\}^{1/6}$$

Quick chat with your neighbors….

- How does ρ_{sw} vary with distance D from Sun?

  $\sim 1/D^2$

- How does U_{SW} vary with distance D from Sun?

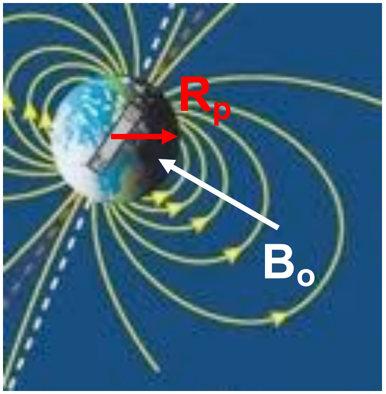
  ~ constant

- How does $\{1/\rho_{sw}\,U^2_{sw}\}^{1/6}$ vary with distance?

  $\sim D^{1/3}$

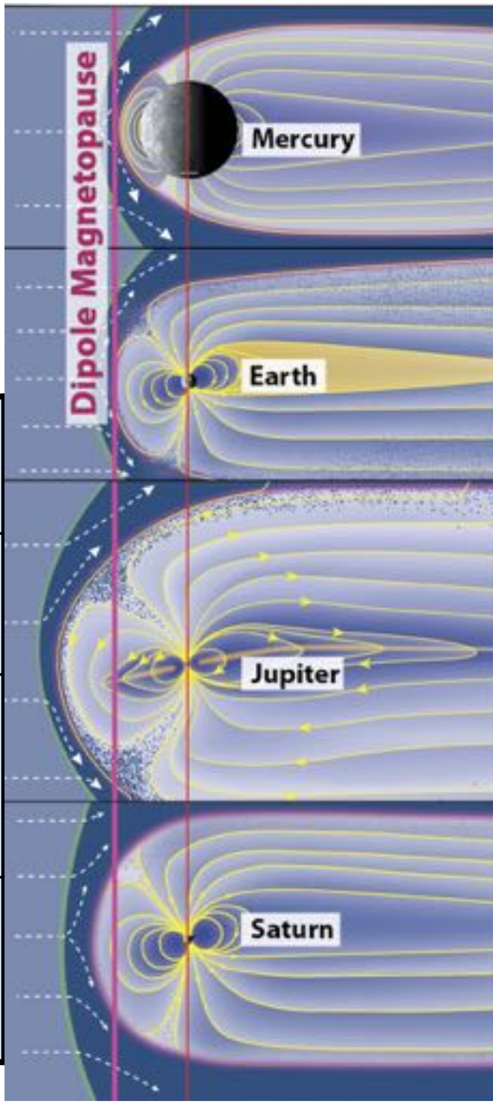
- Move Earth from 1 AU to 8 AU – How big is the magnetosphere?

  x 2

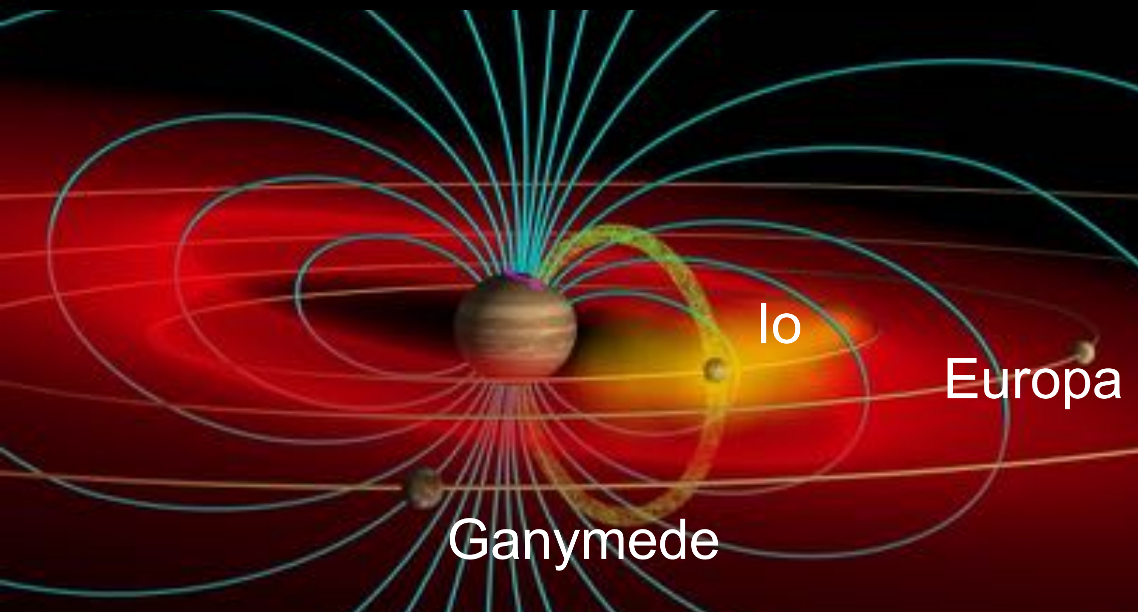


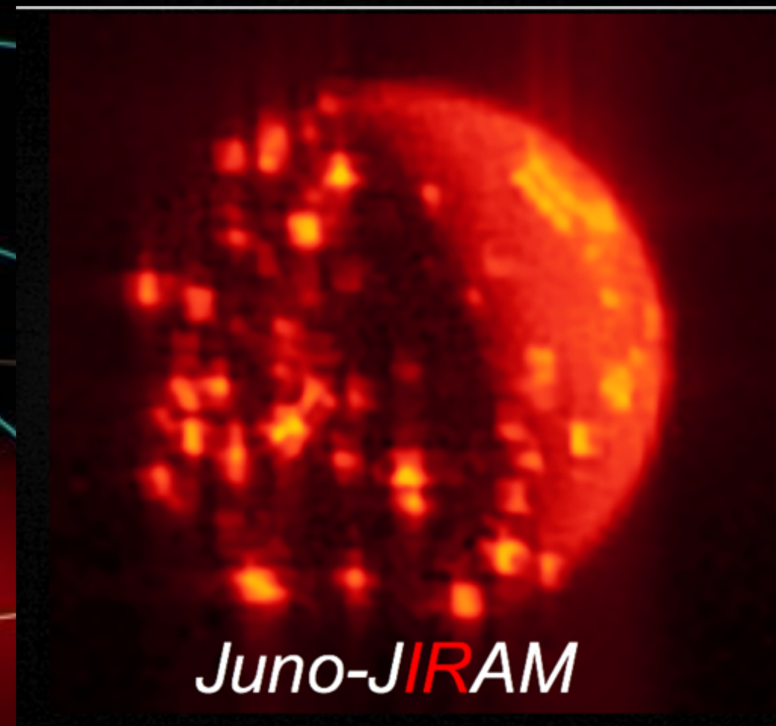
$$R_{CF}/R_p \sim 1.4\ \{B_o^2 / 2\mu_o \rho_{sw} V^2_{sw}\}^{1/6}$$

	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
B_o surface	0.3 μT	31 μT	430 μT	22 μT	23 μT	14 μT
R_{CF} Calculated	1.4 R_M	10 R_E	46 R_J	20 R_S	25 R_U	24 R_N
R_M Observed	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



Jupiter's magnetic field extends beyond 4 big moons



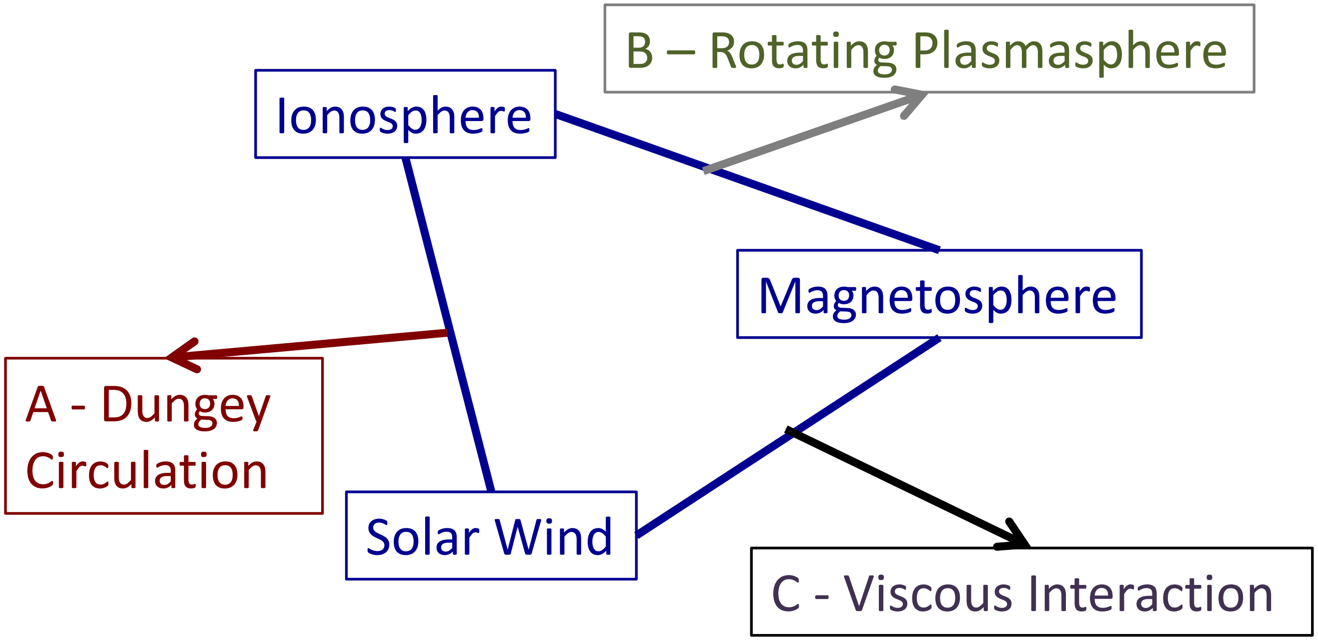


John Spencer (SwRI)

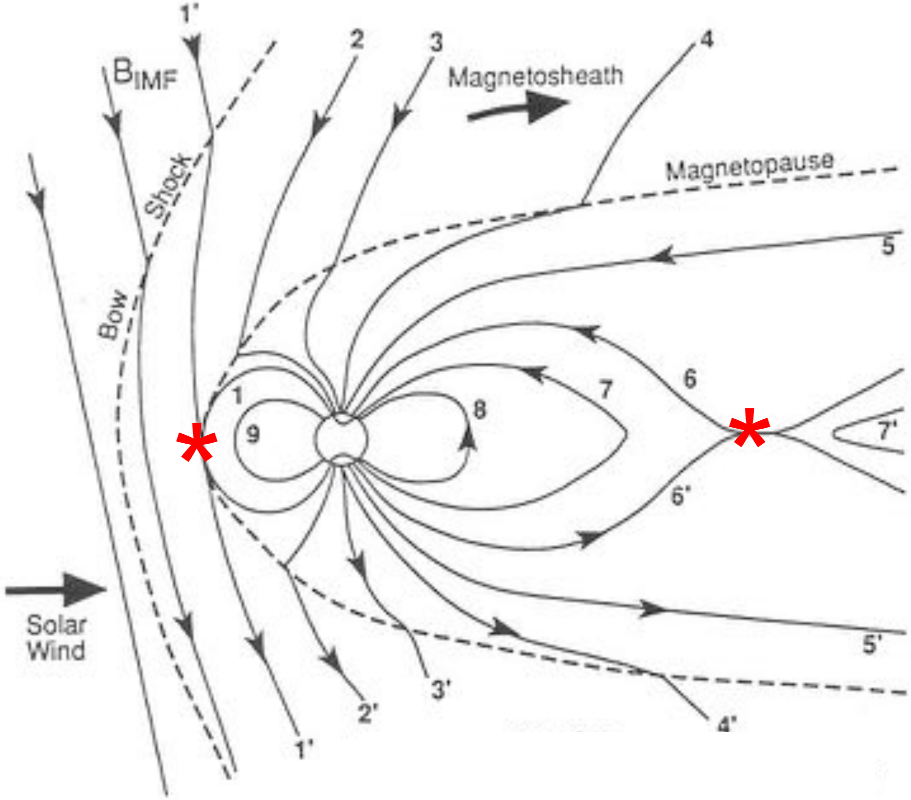
Io ejects 1 ton/s volcanic gases
Mega-Amp currents couple Io to Jupiter

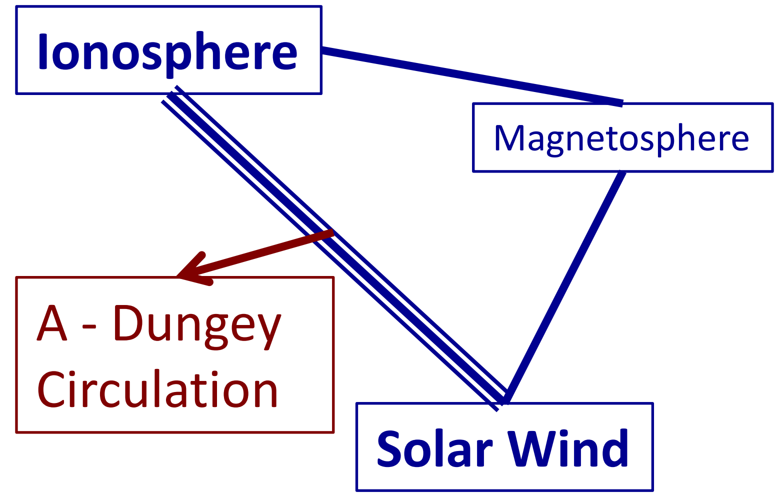
Dynamics

Which Form of Coupling Dominates -> Controls Dynamics



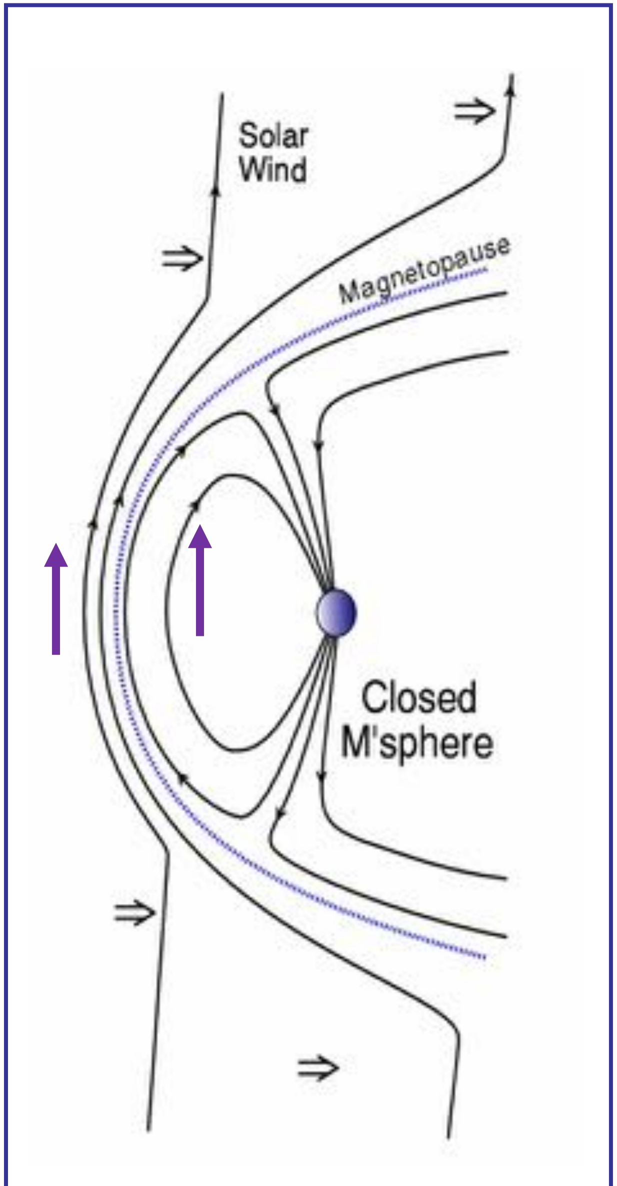
Earth





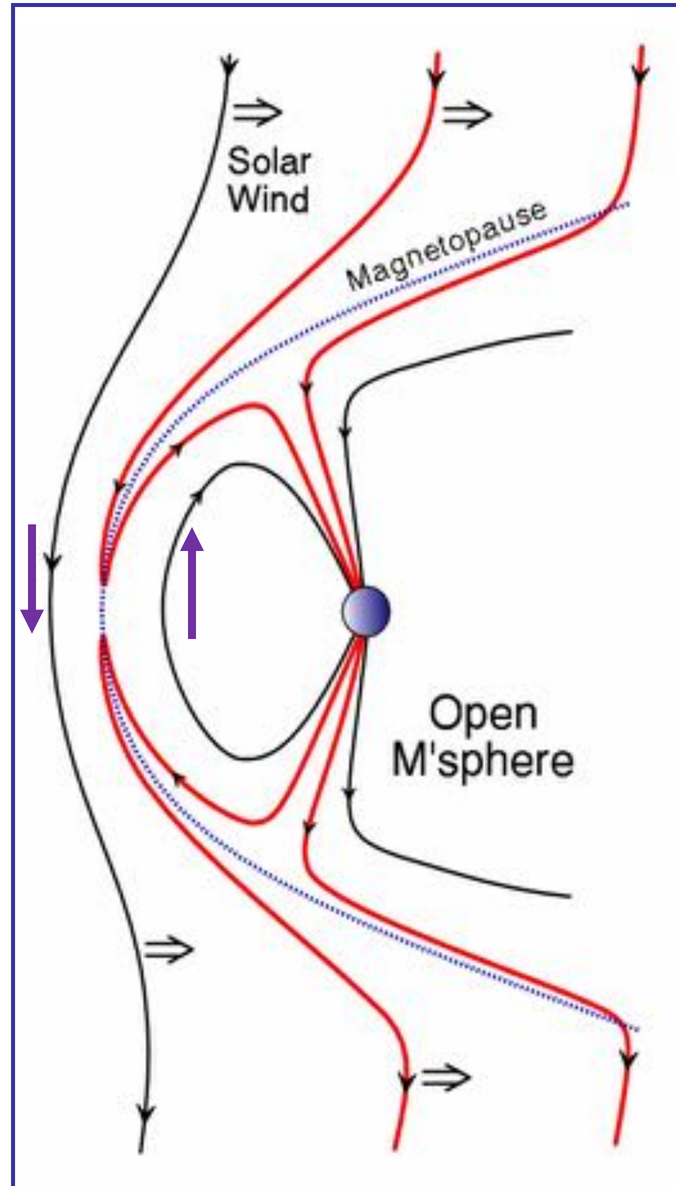
*Reconnection-Driven Global Circulation

Open Magnetosphere



Now flip Interplanetary Magnetic Field direction

Reconnection

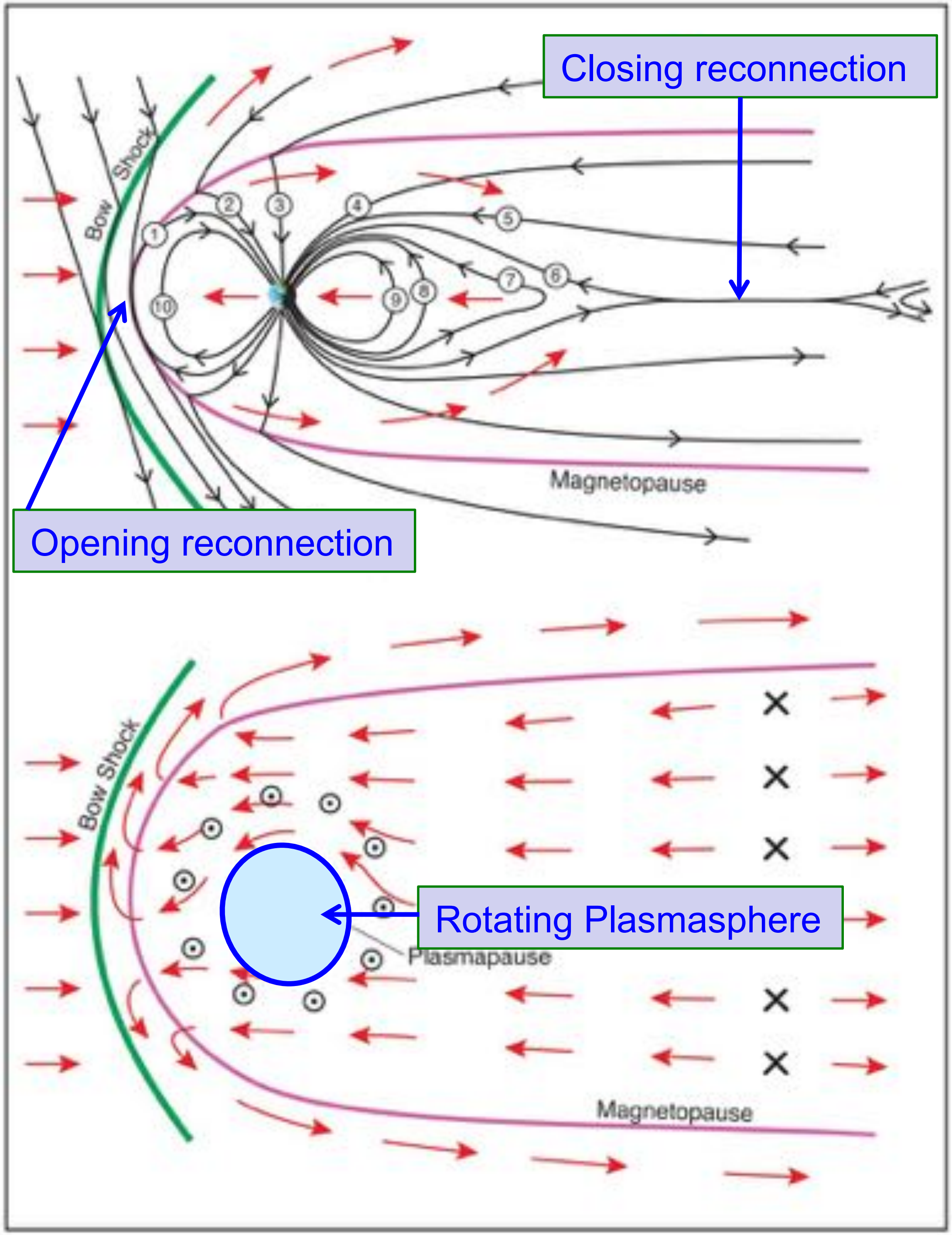


Dungey Cycle

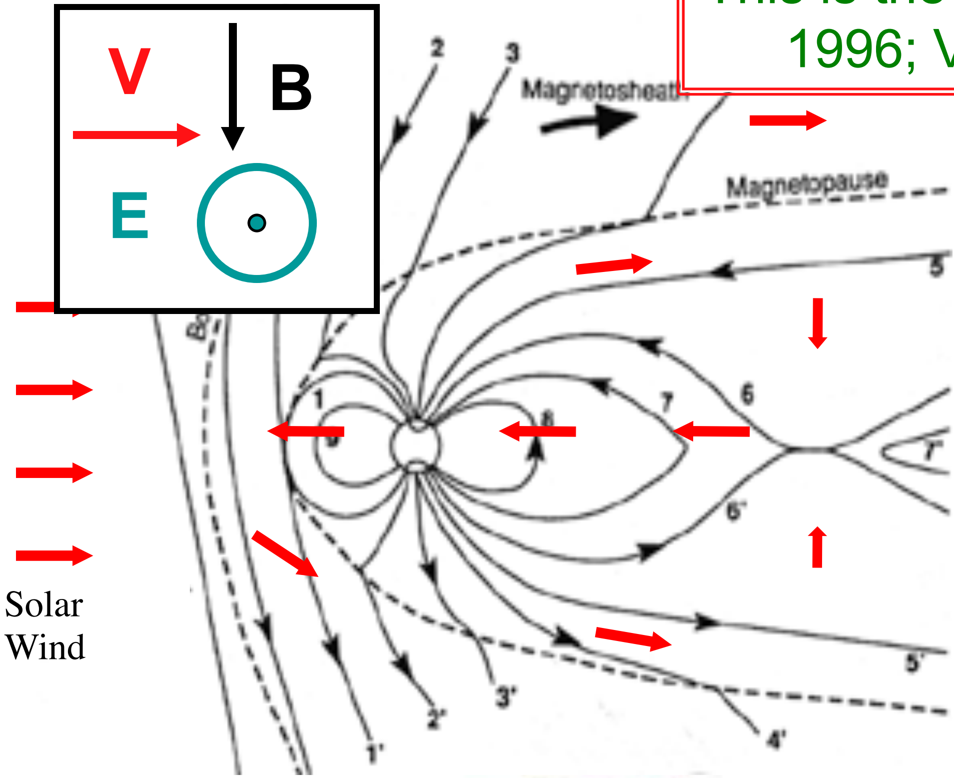
Dynamics at Earth driven by the solar wind coupling the Sun's magnetic field to the Earth's field

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

Plasmapause = boundary between corotation and convection



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



The Dungey Cycle

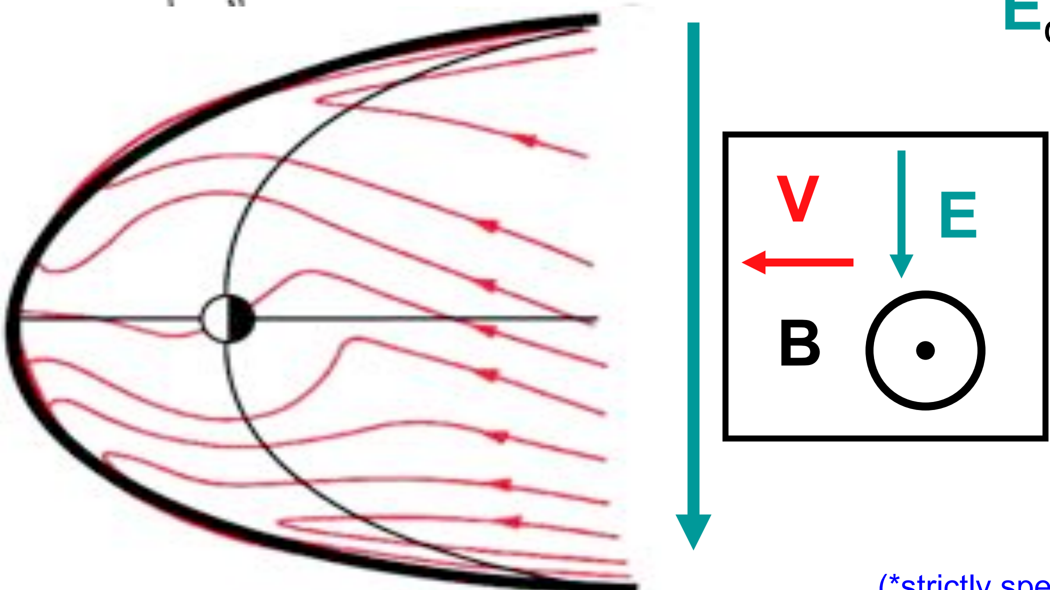
Solar wind driven magnetospheric convection*

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

ζ~ efficiency of reconnection ~10-20%

crude approximation!!

E_{conv}~ constant in m'sphere

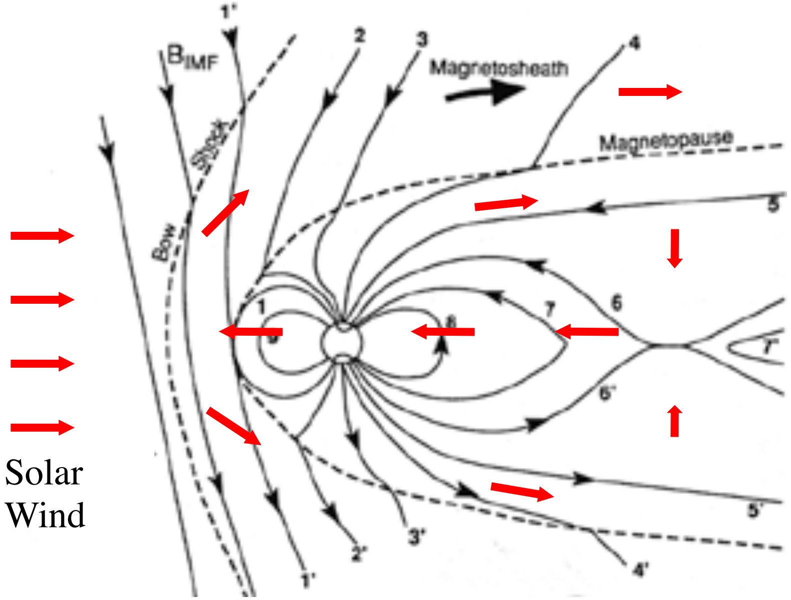


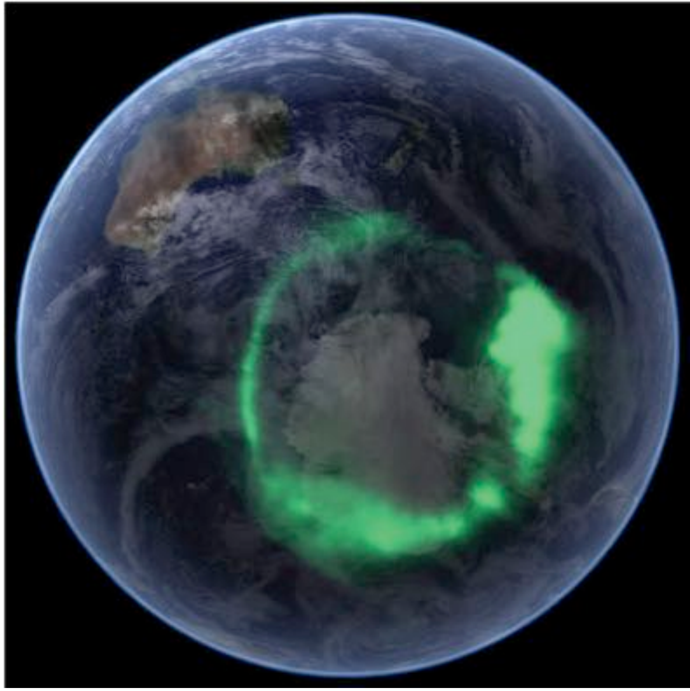
$V_{convection}$

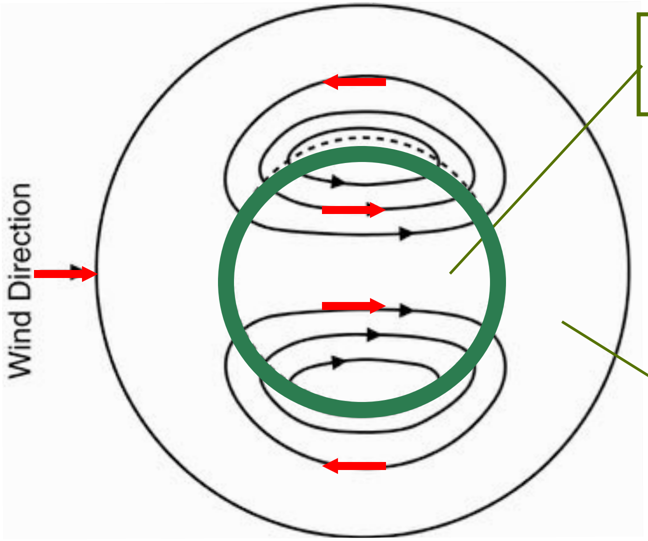
$\sim \zeta V_{SW}(R/R_{MP})^3$

(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)



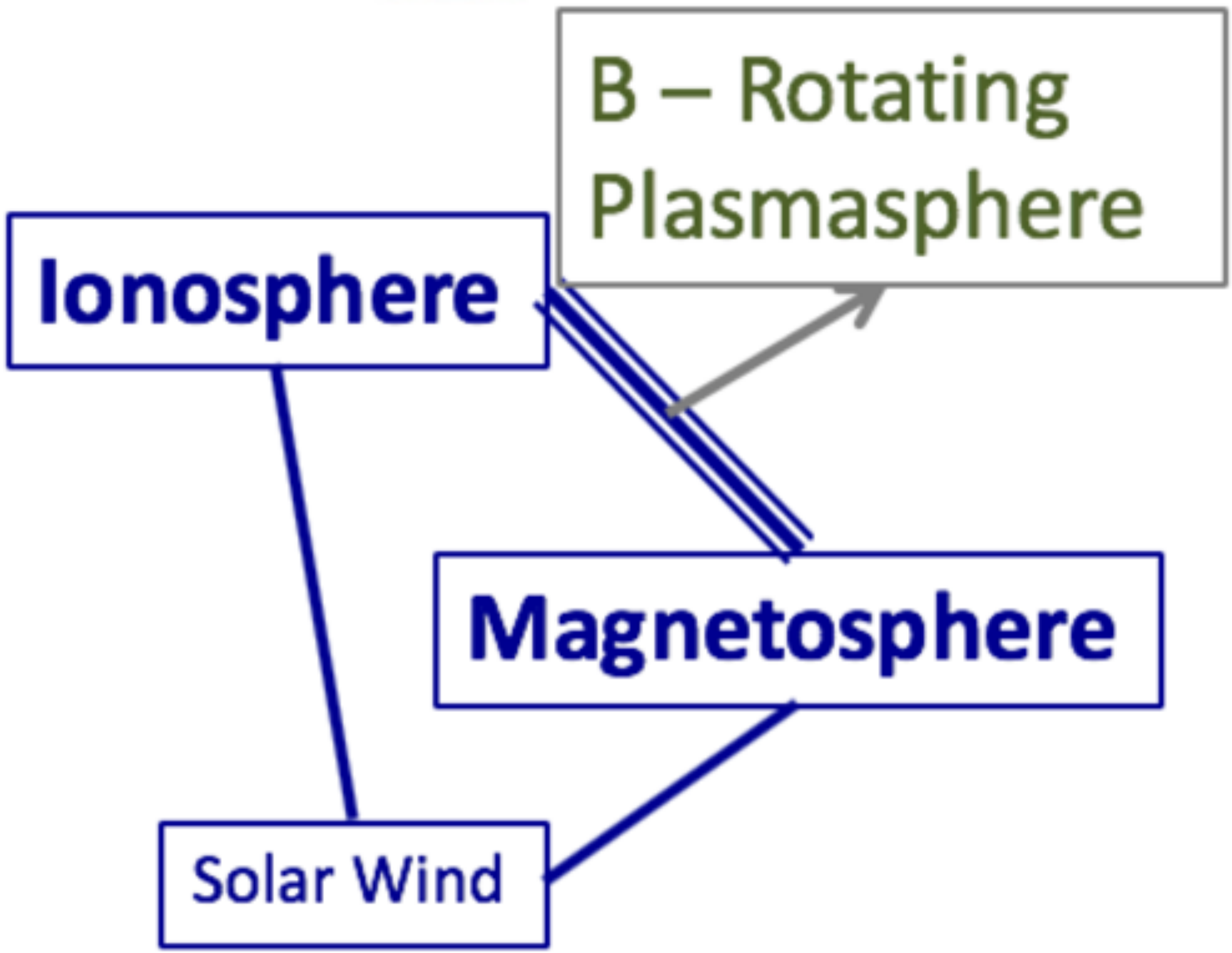




Connected to solar wind

Closed magnetic field

Polar view



B – Rotating Plasmasphere
Ionosphere
Magnetosphere
Solar Wind

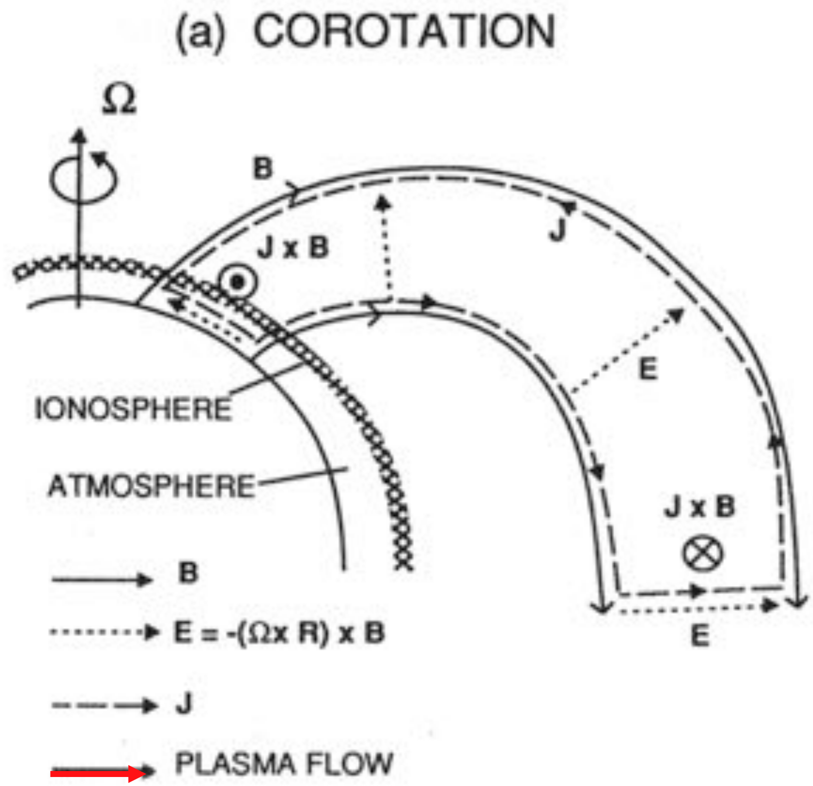
$$\mathbf{V}_{co} \sim \Omega \times \mathbf{R}$$

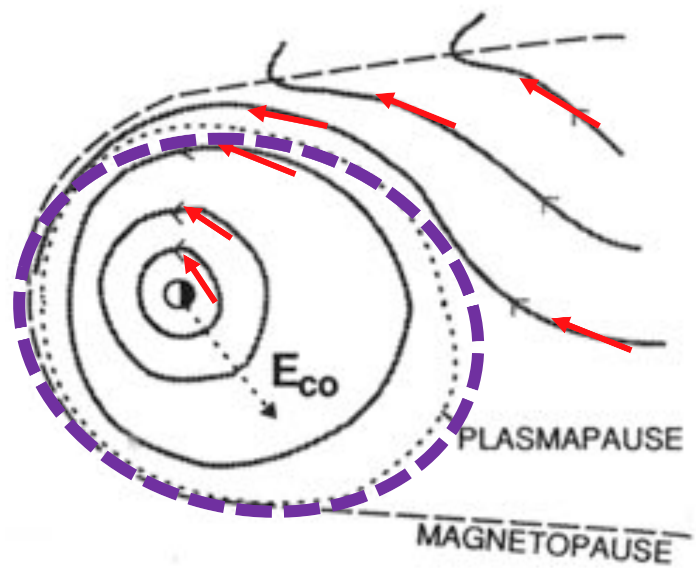
$$\mathbf{V}_{convection}$$

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

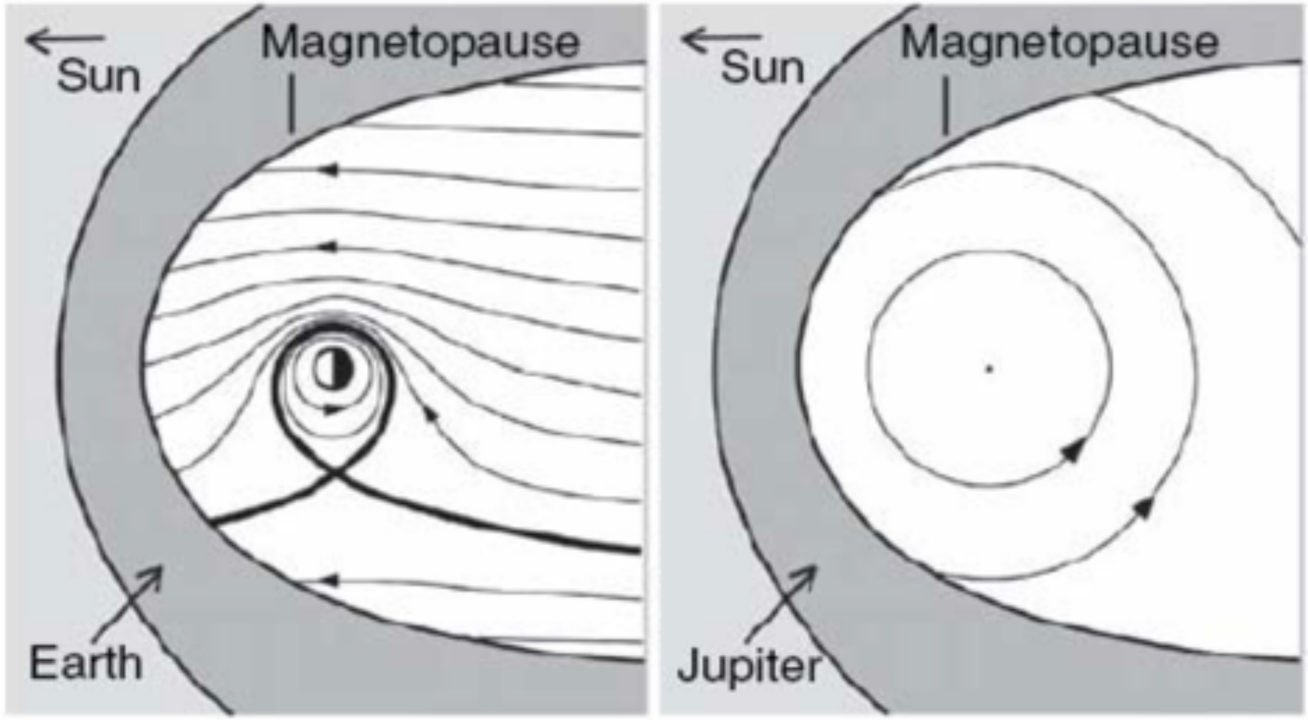
Fraction of planetary magnetosphere that is rotation dominated....

- increases with planetary spin
- increases with field strength
- decreases with solar wind strength





Solar-wind vs. Rotation-dominated magnetospheres

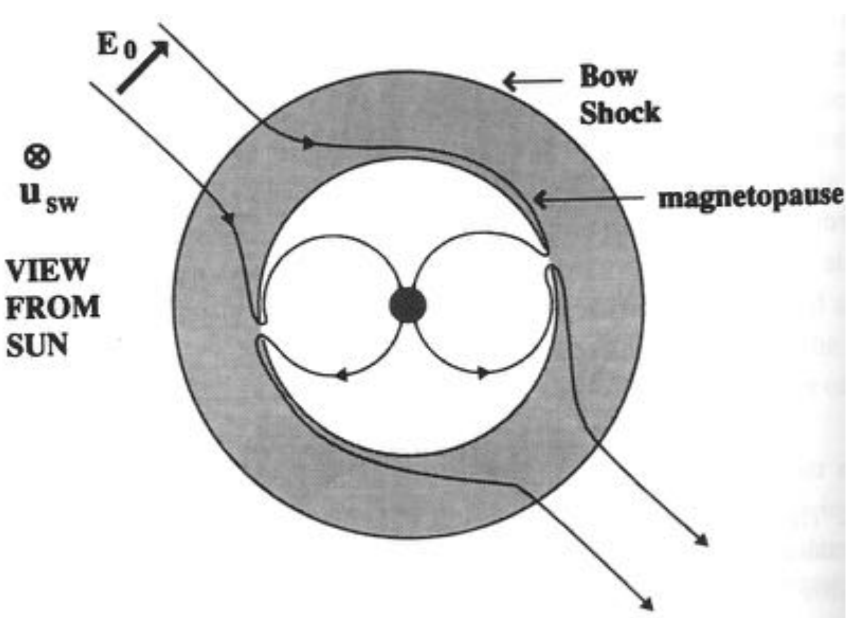


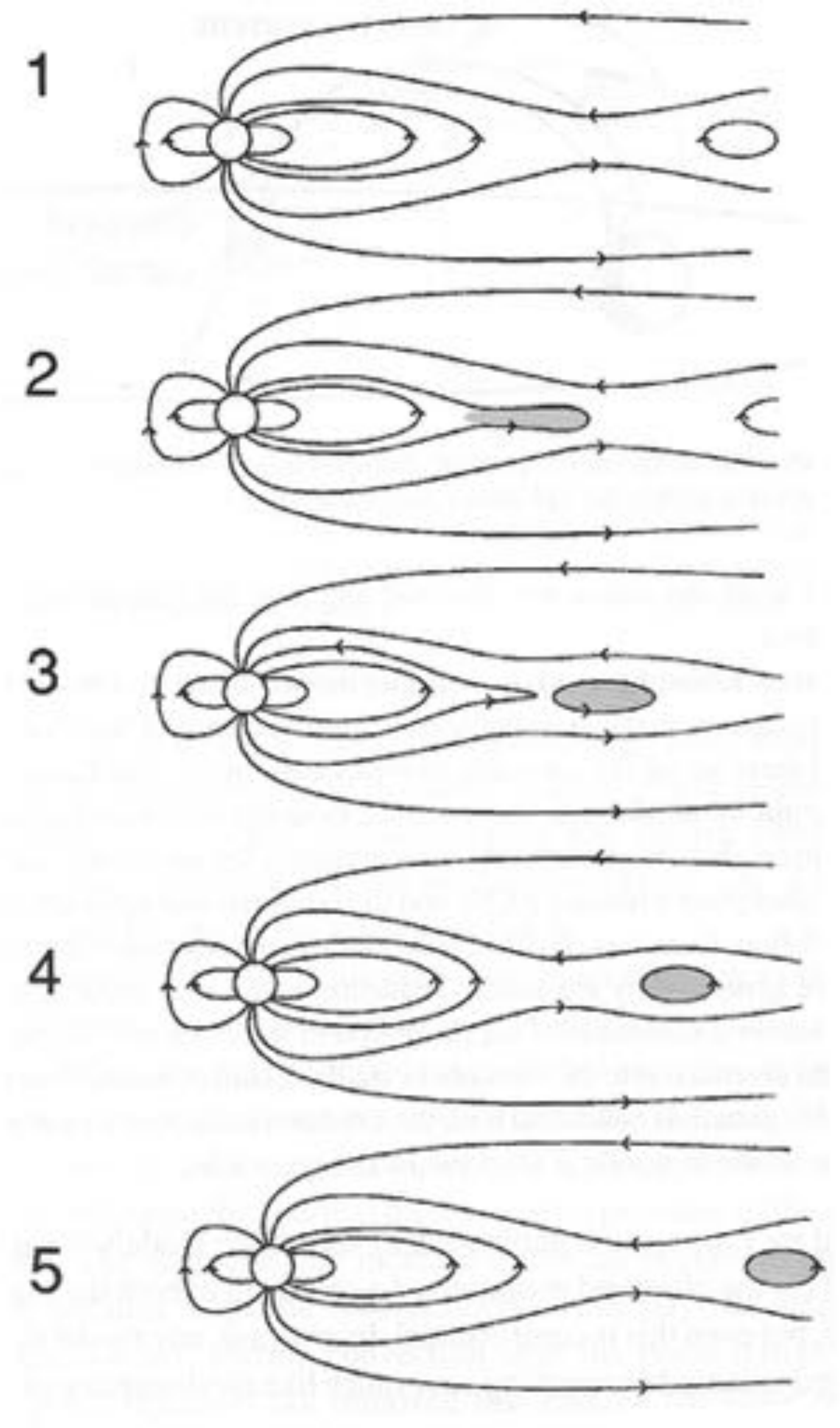
$R_{plasmapause} / R_{Planet} =$

6.7 350

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

Reality = Messy & 3D



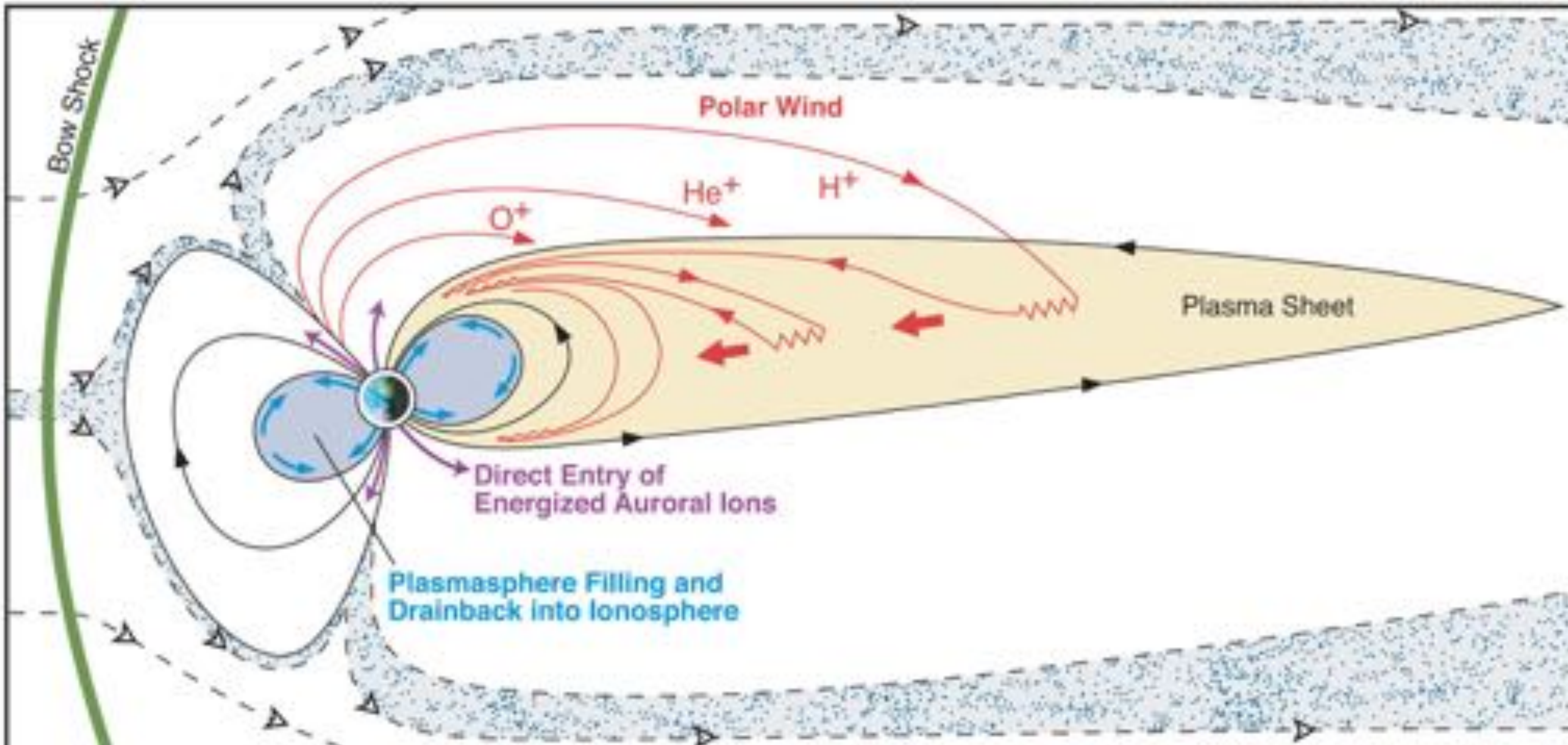


Plasma Sources

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^+ Iono-sphere	O^{n+} S^{n+} Io	O^+ H_2O^+ H^+ Enceladus	H^+ Iono-sphere	H^+ N^+ Triton Iono-sphere
Source kg / s	?	5	700-1200	70-200	~0.02	~0.2

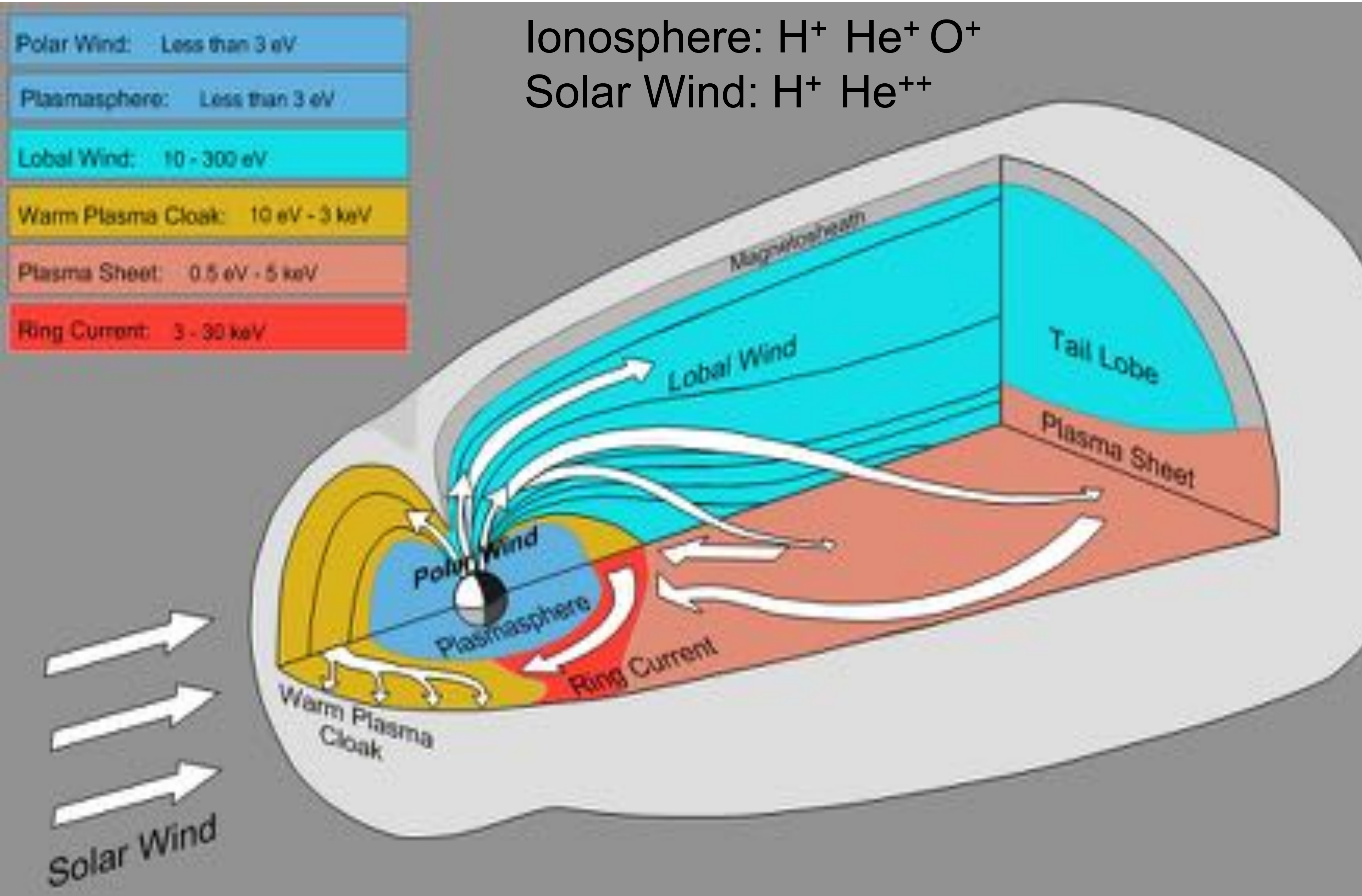
Earth Sources of Plasma (5 kg/s): Solar Wind + ionosphere mixed (over the poles) into magnetotail and convected sunward

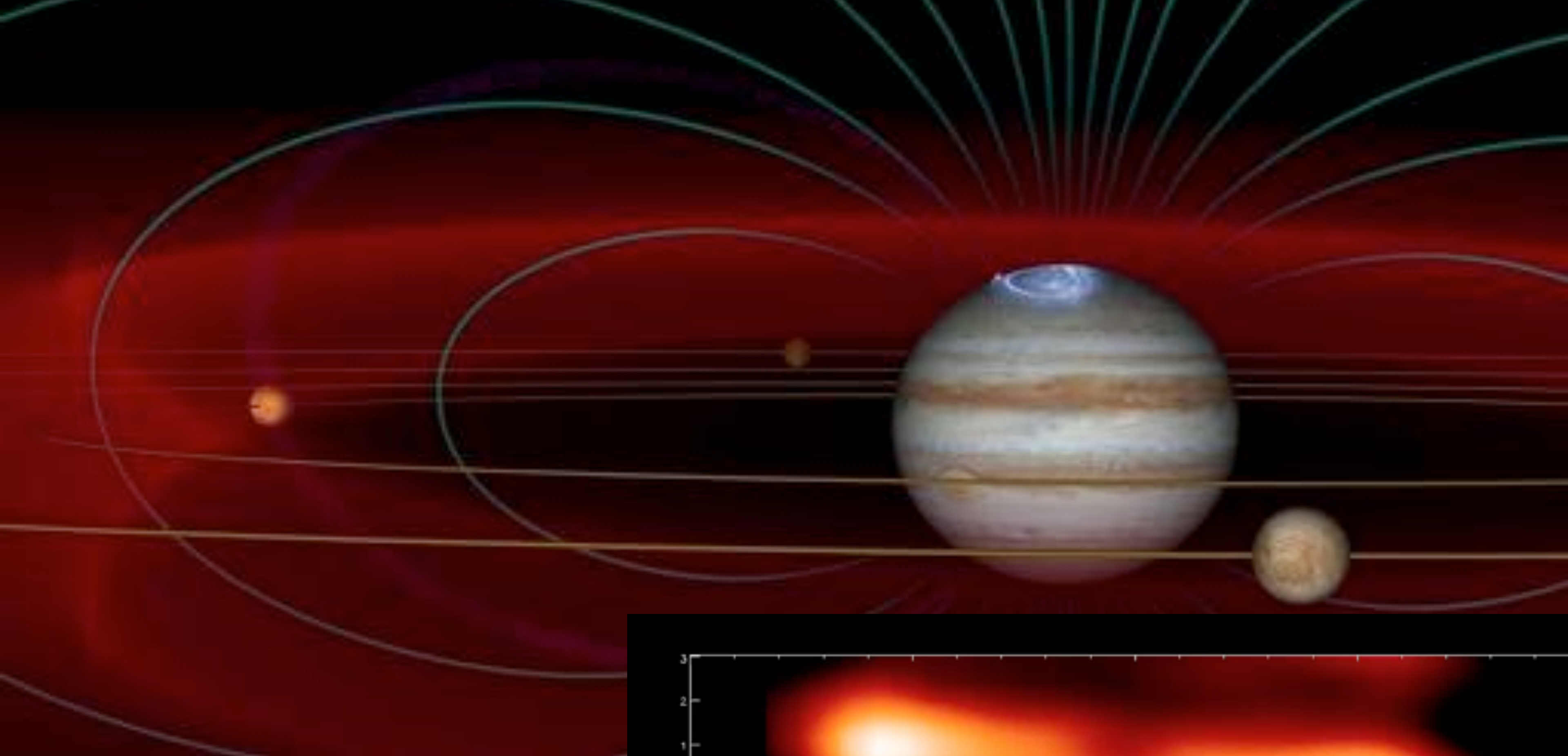


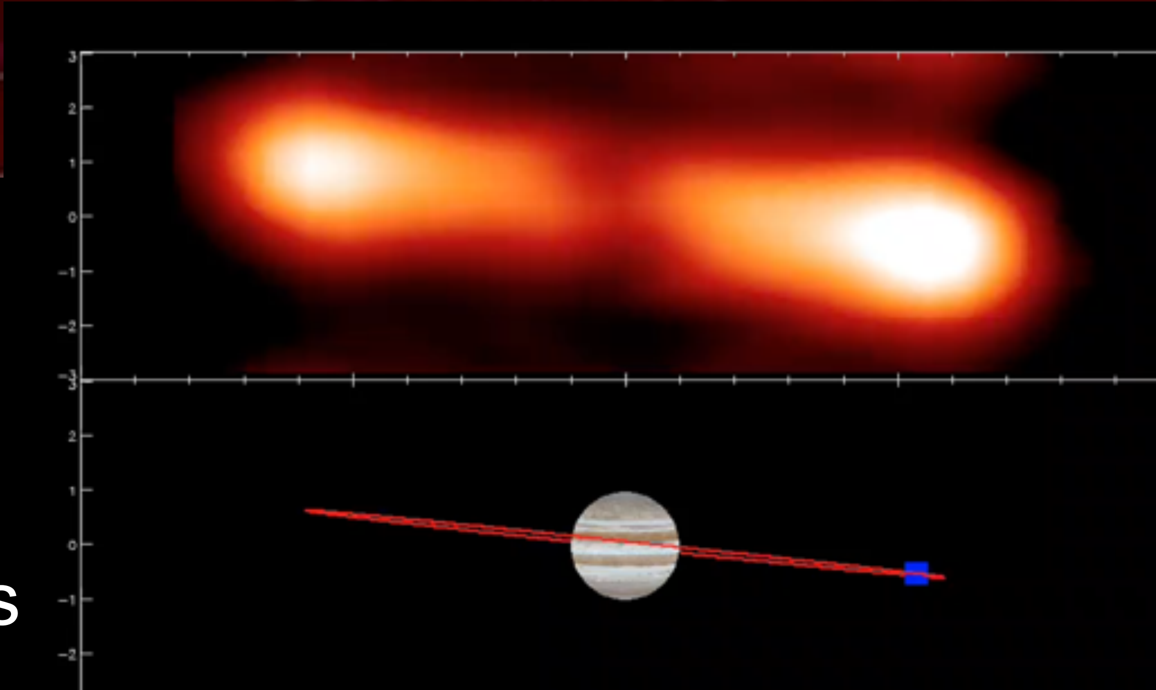
Earth Plasma Flux   5 kg/s

Ionosphere: H^+ He^+ O^+

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

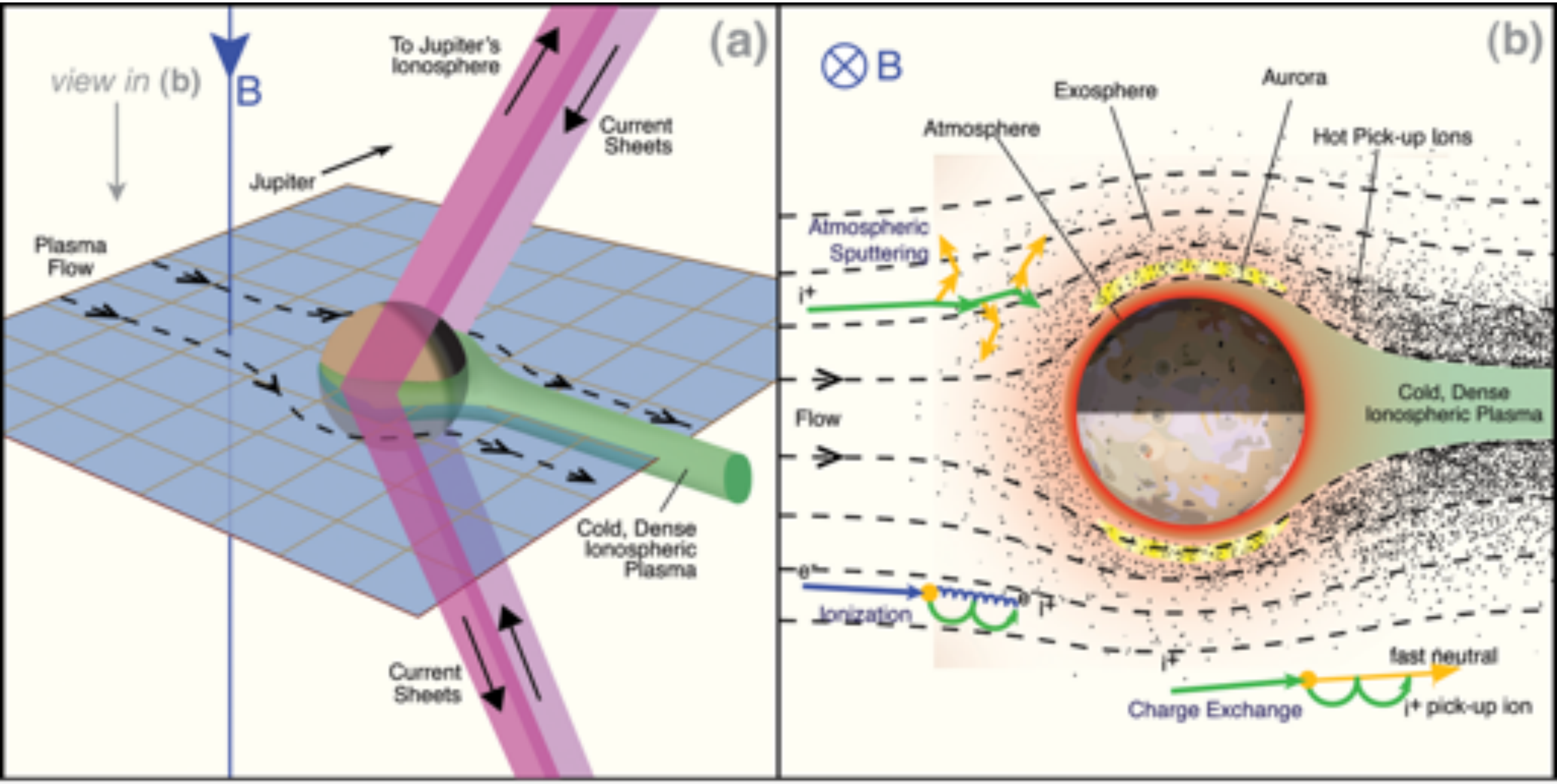






Io Plasma torus

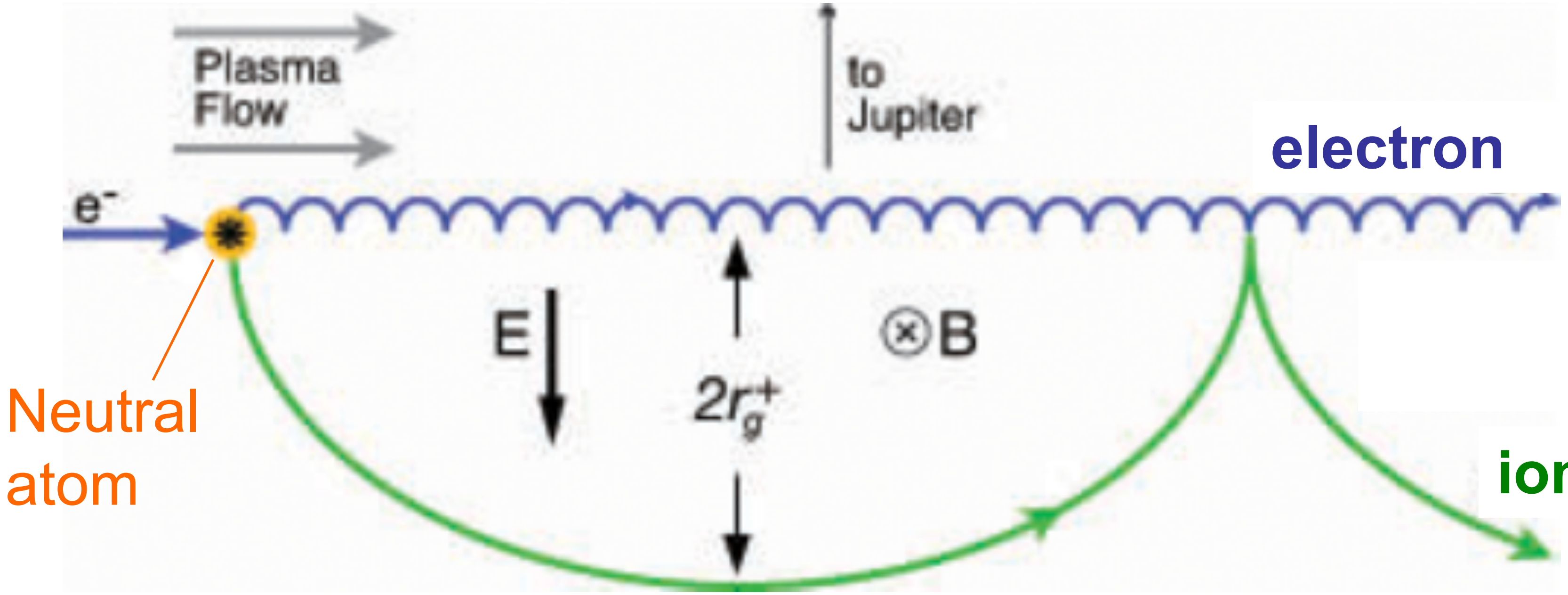
- Total mass 2 Mton
- Source 1 ton/s
- Replaced in 50 days



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

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

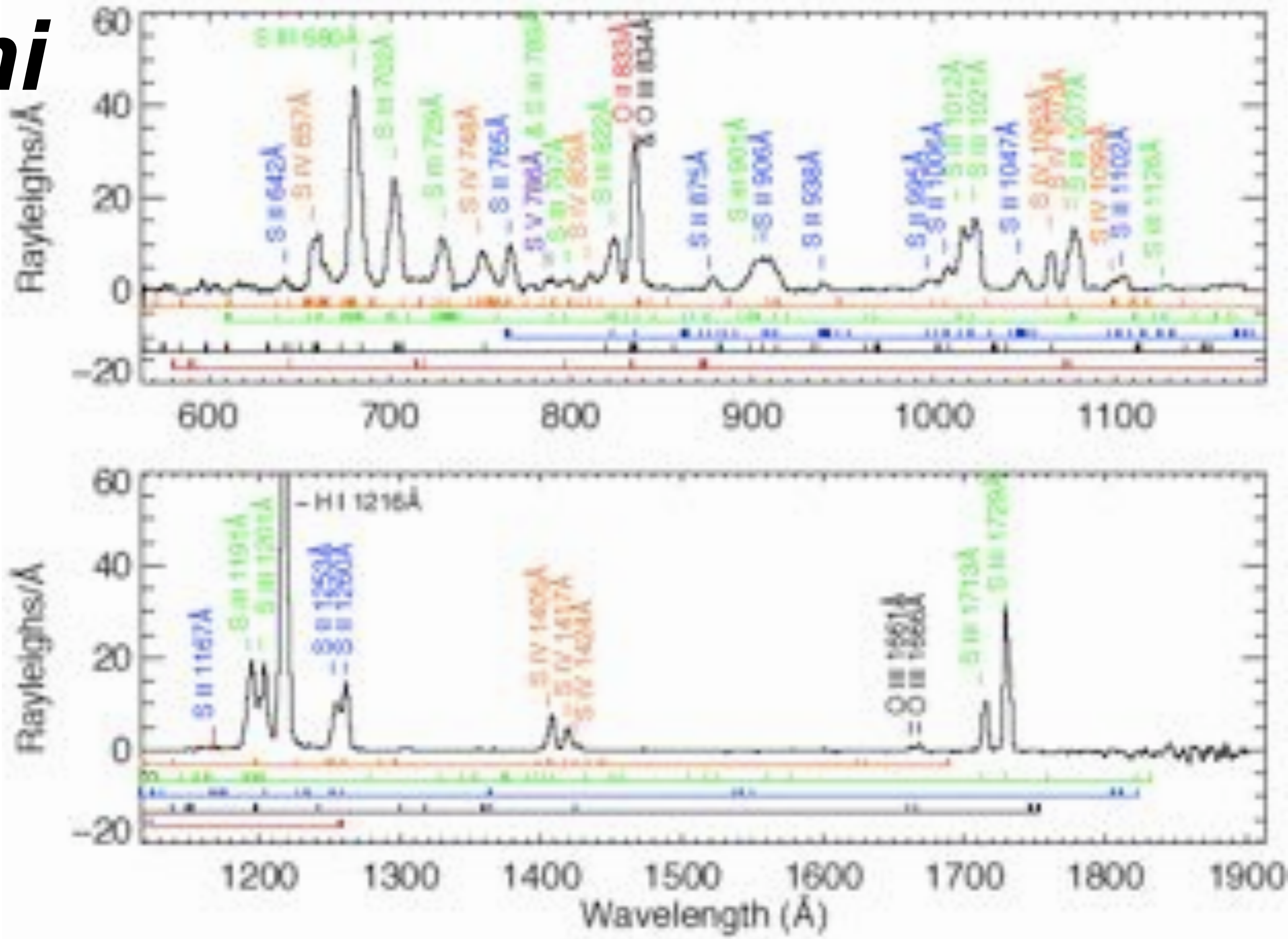
Ion Pick Up



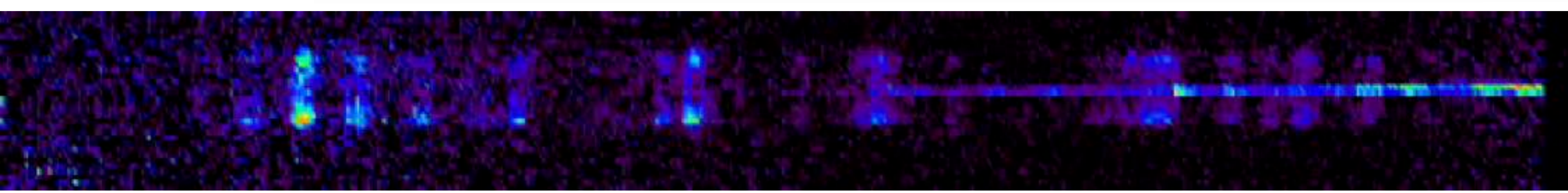
- The magnetic field couples the plasma to the spinning planet
- Ion gains large gyromotion -> heat

Cassini UVIS

Andrew Steffl



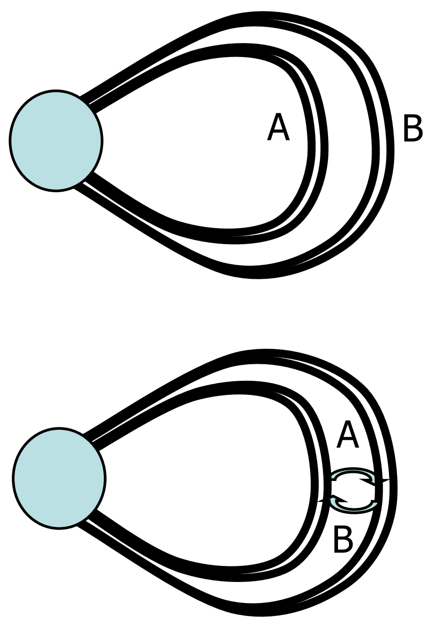
Spectral diagnosis of plasma conditions
Ni, Ne, Te

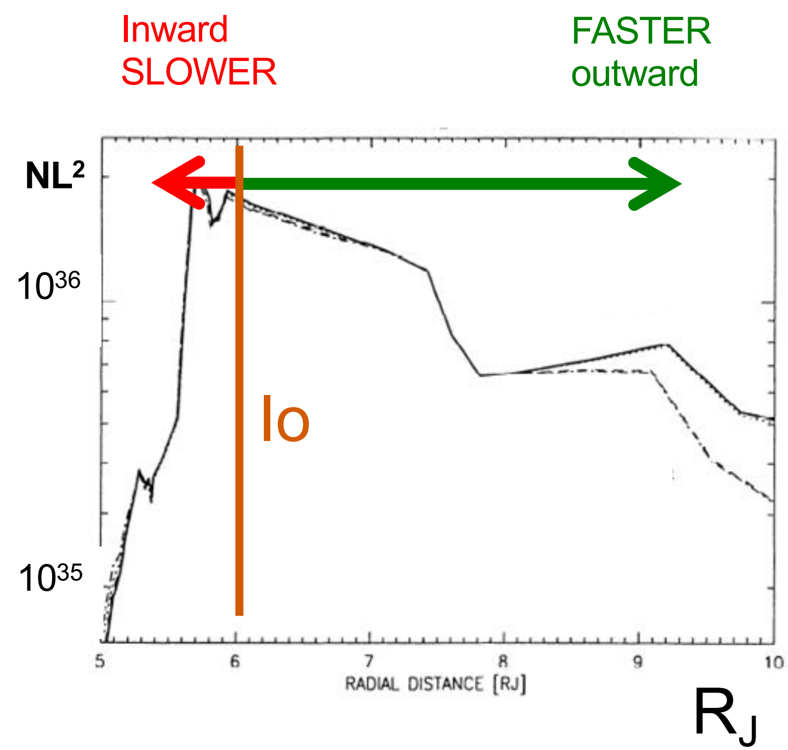


Radial Transport

In rotating magnetosphere: If fluxtube A contains more mass than B – they interchange

Interchange of A and B does not change field strength for $\beta \ll 1$



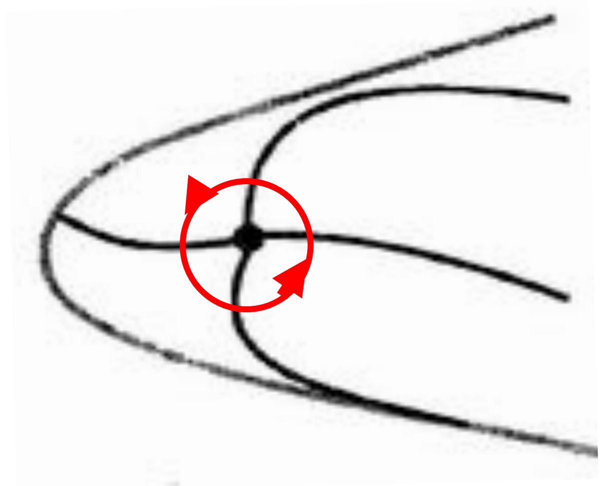


Margy Kivelson

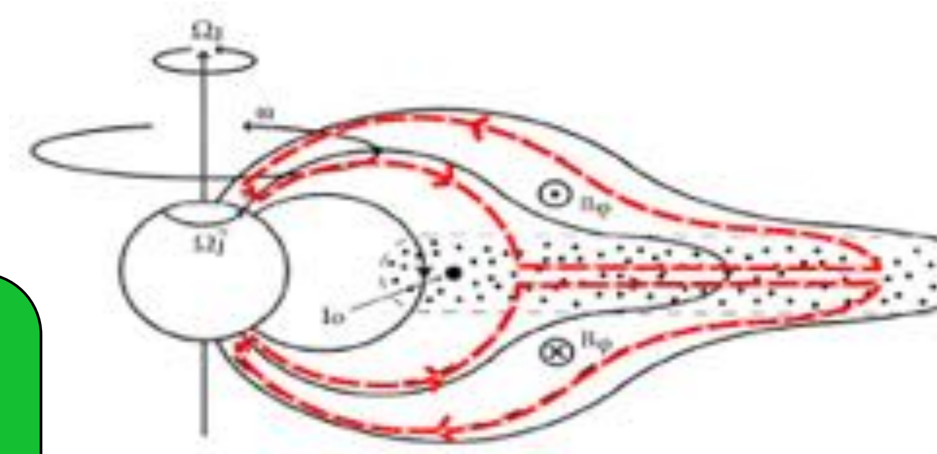
Bagenal 1994

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



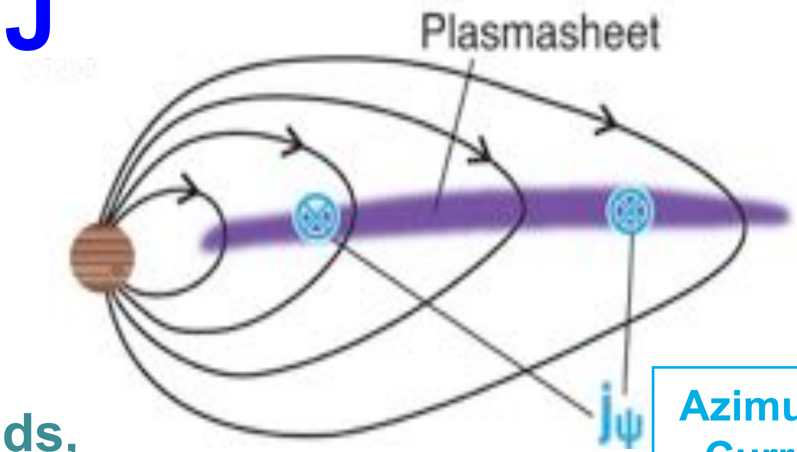
Field-aligned currents couple magnetosphere to Jupiter's rotation

Cowley & Bunce 2001

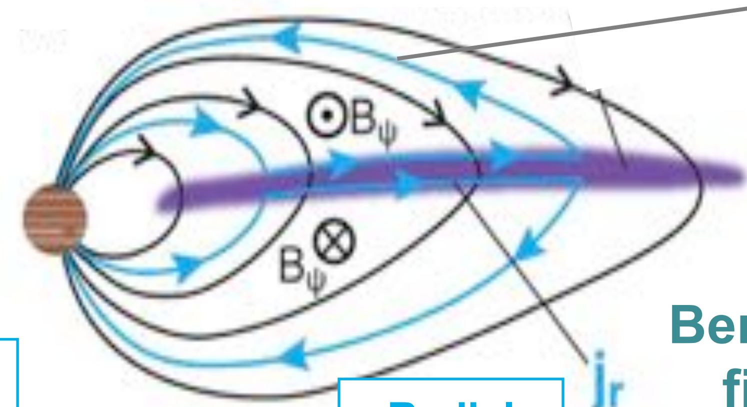
Configuration

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

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



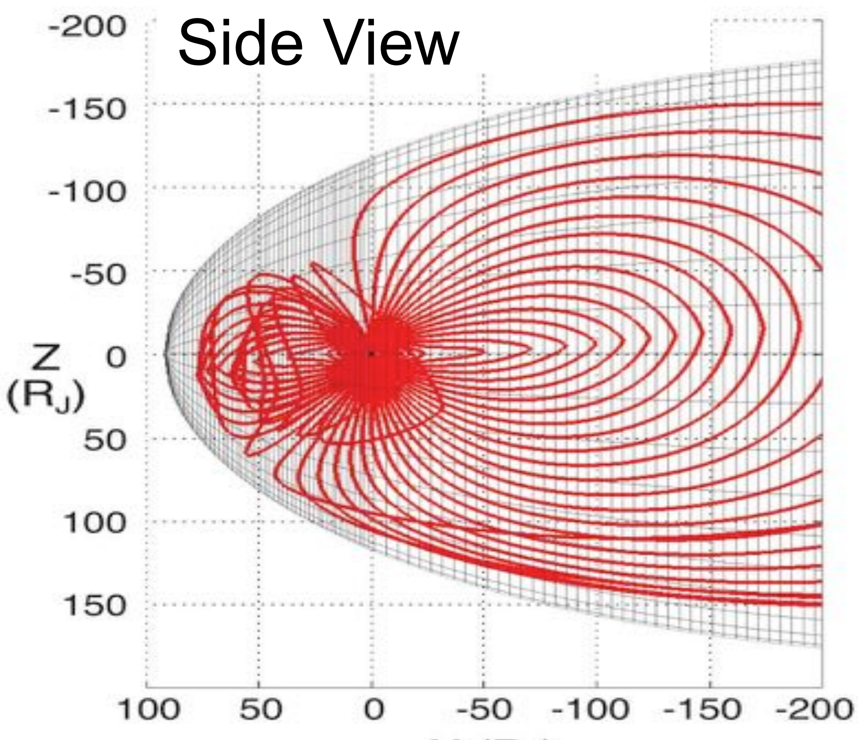
Azimuthal Current

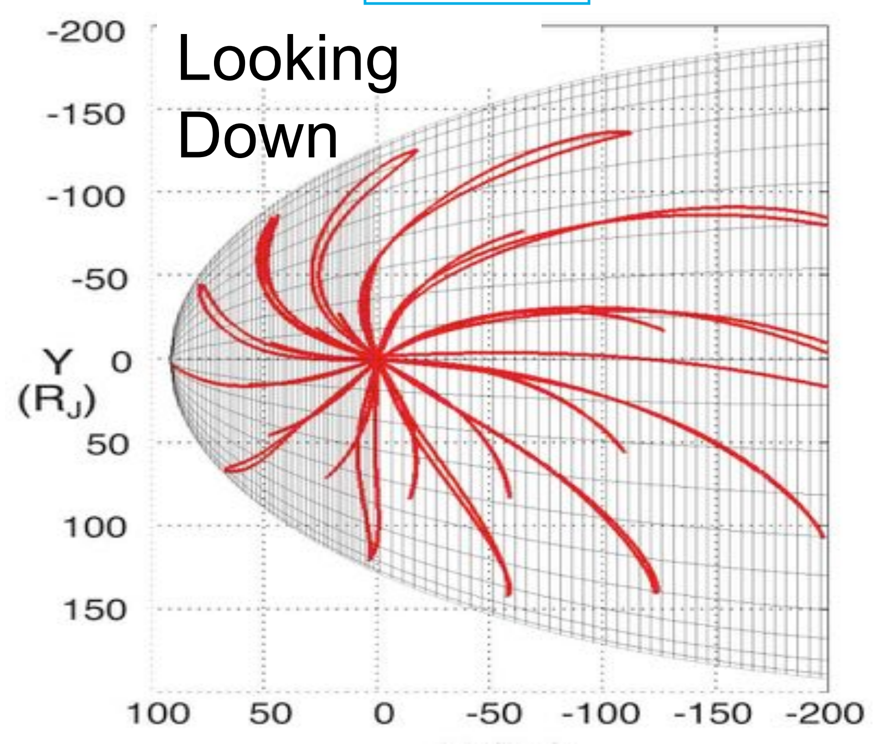


Radial Current

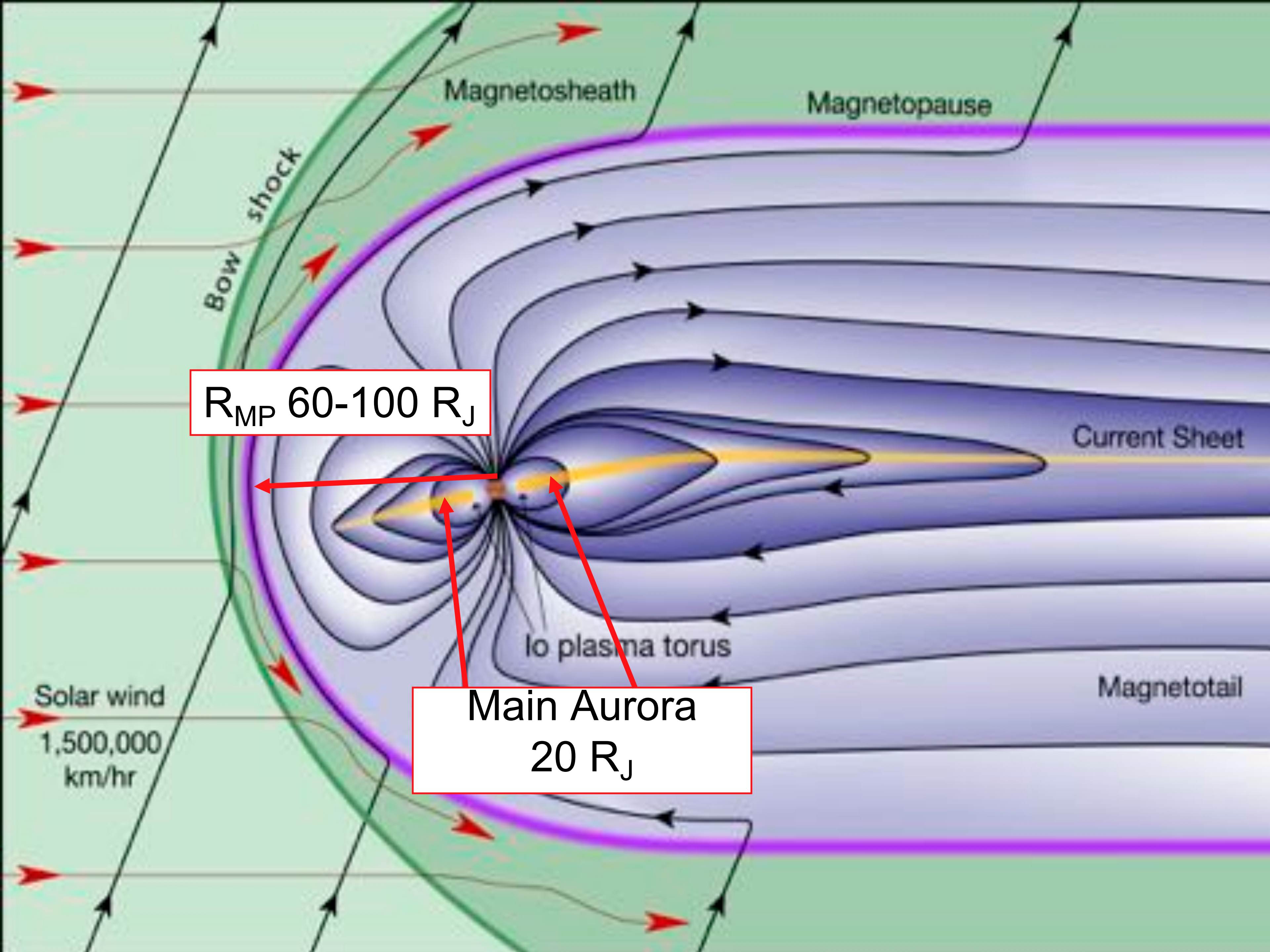
Expands, stretches field

Bends field back

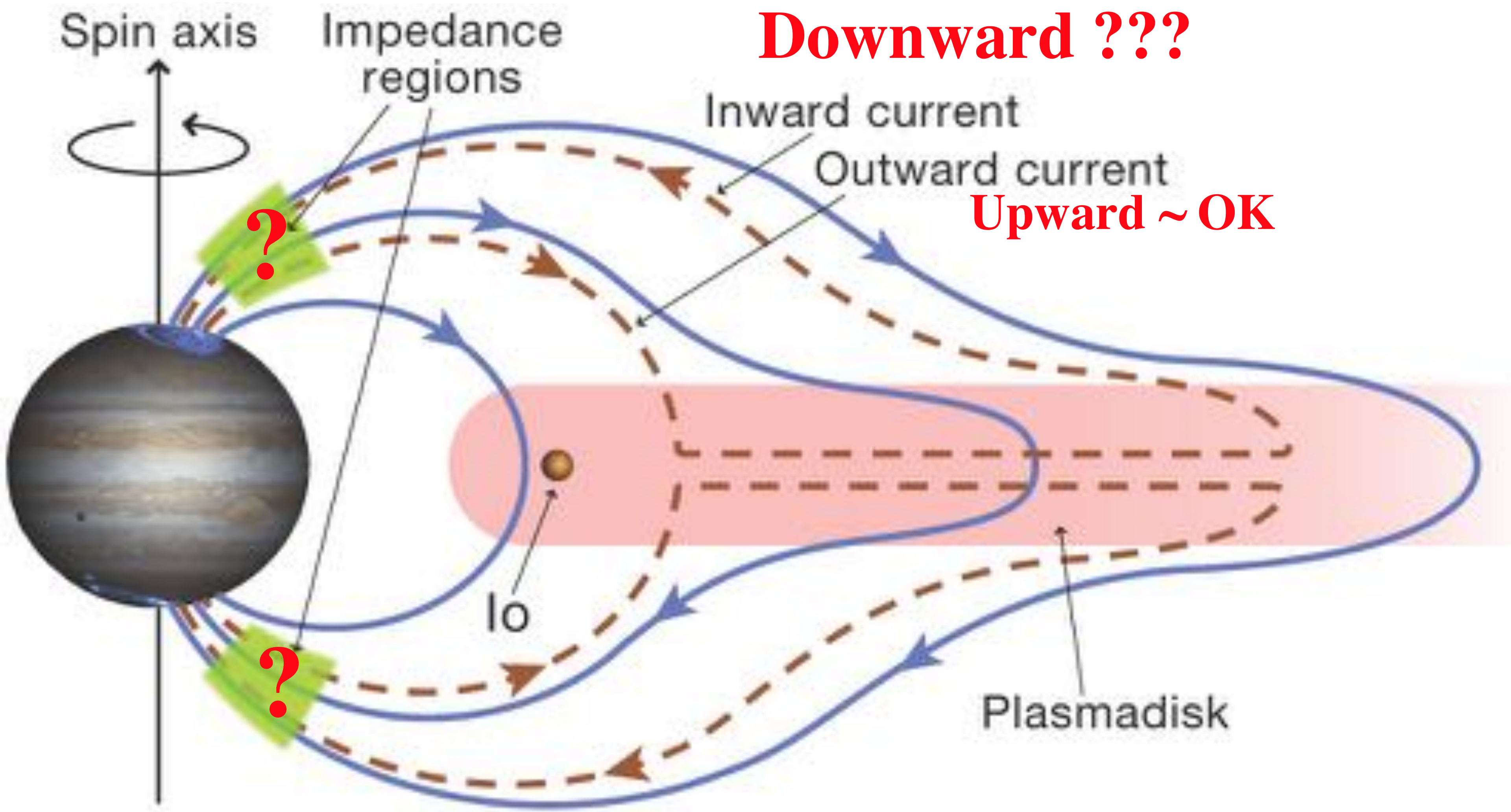




Aurora


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

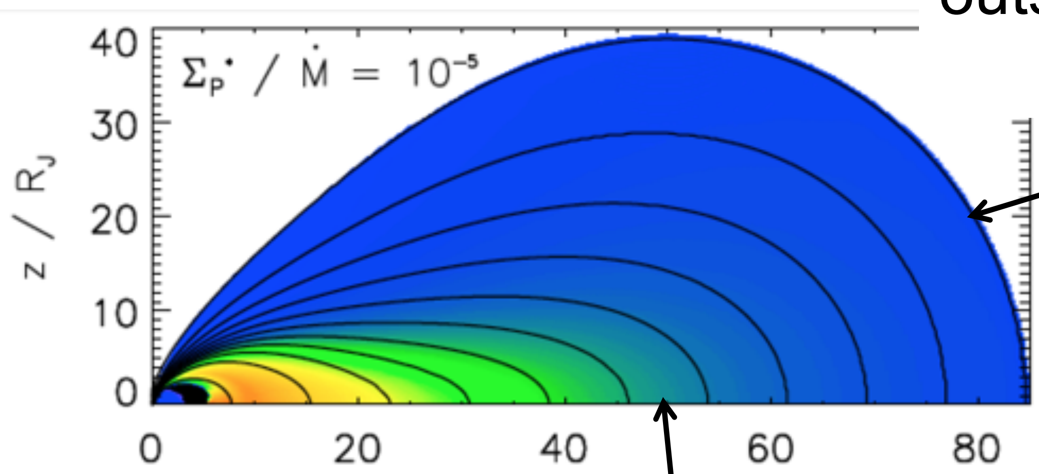
The aurora is the signature of Jupiter's attempt to spin up its magnetosphere



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

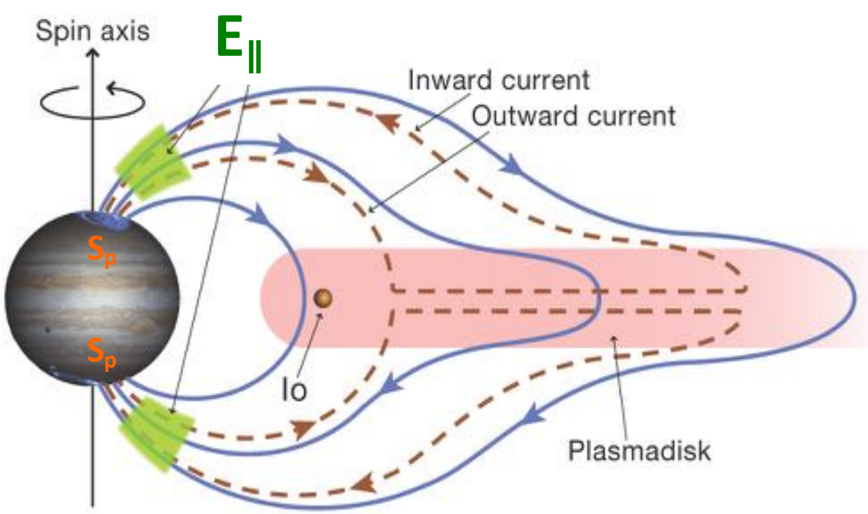
How is information transmitted along magnetic field lines?

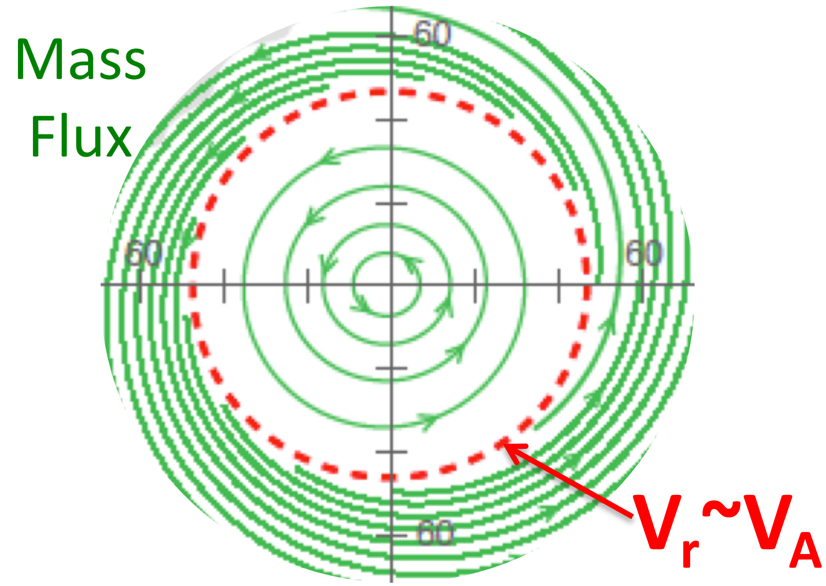
How is a stress from the outside communicated to the planet?



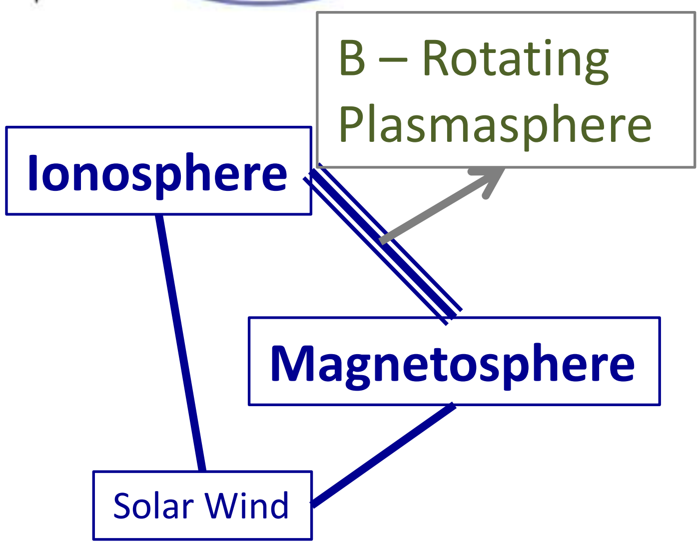
How does a blob of plasma here communicate with the planet?

Alfven waves!





Alfven Radius



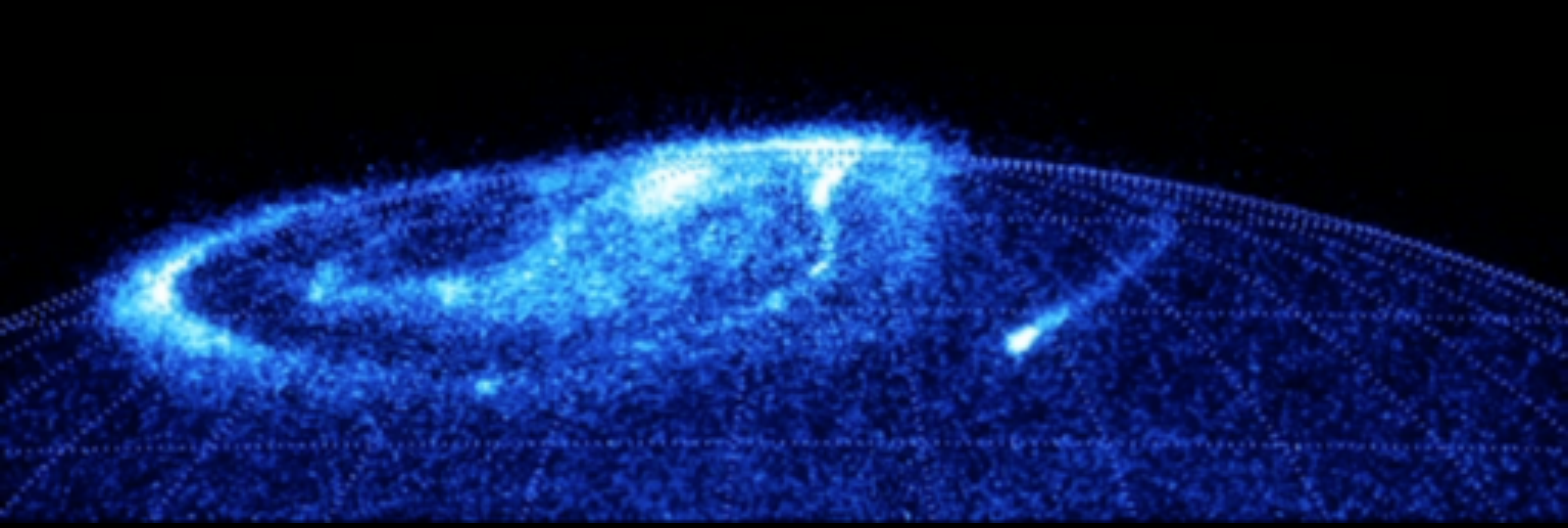
Radial Transport

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

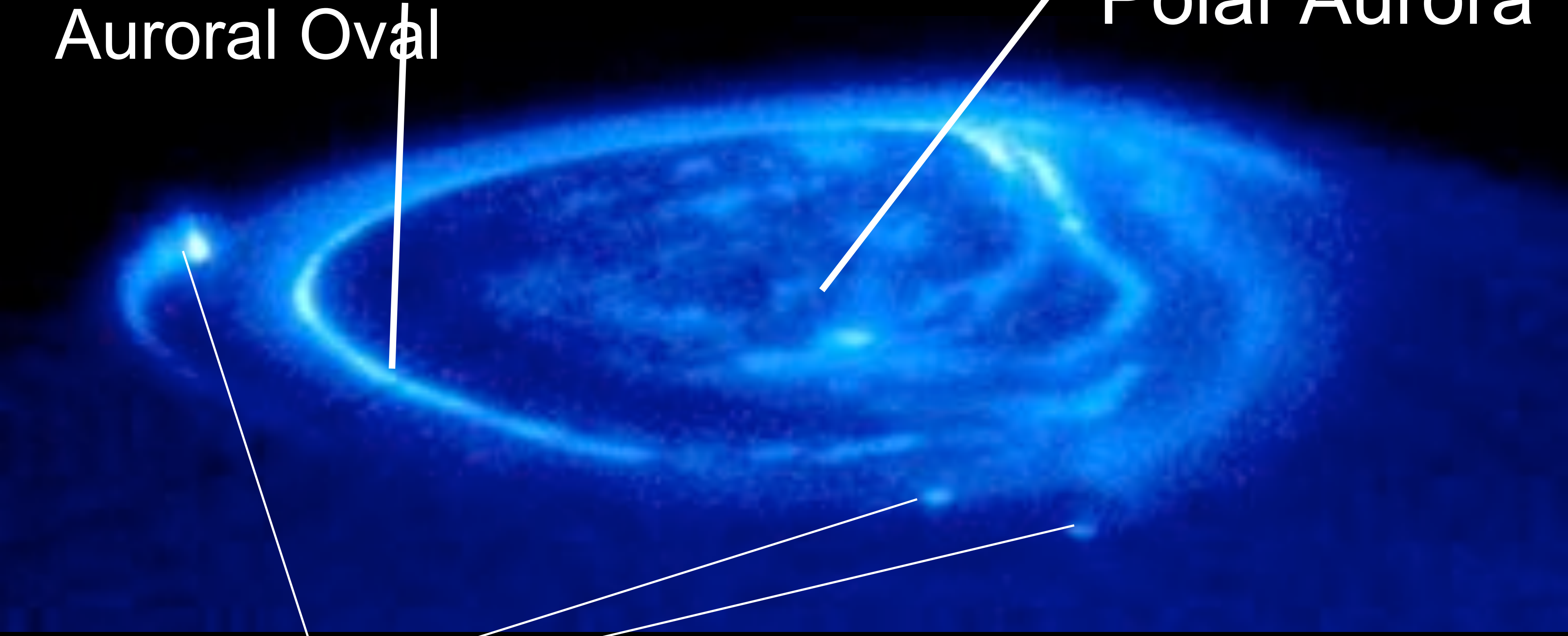
S_p, $E_{\parallel}$ and/or V_r~V_A

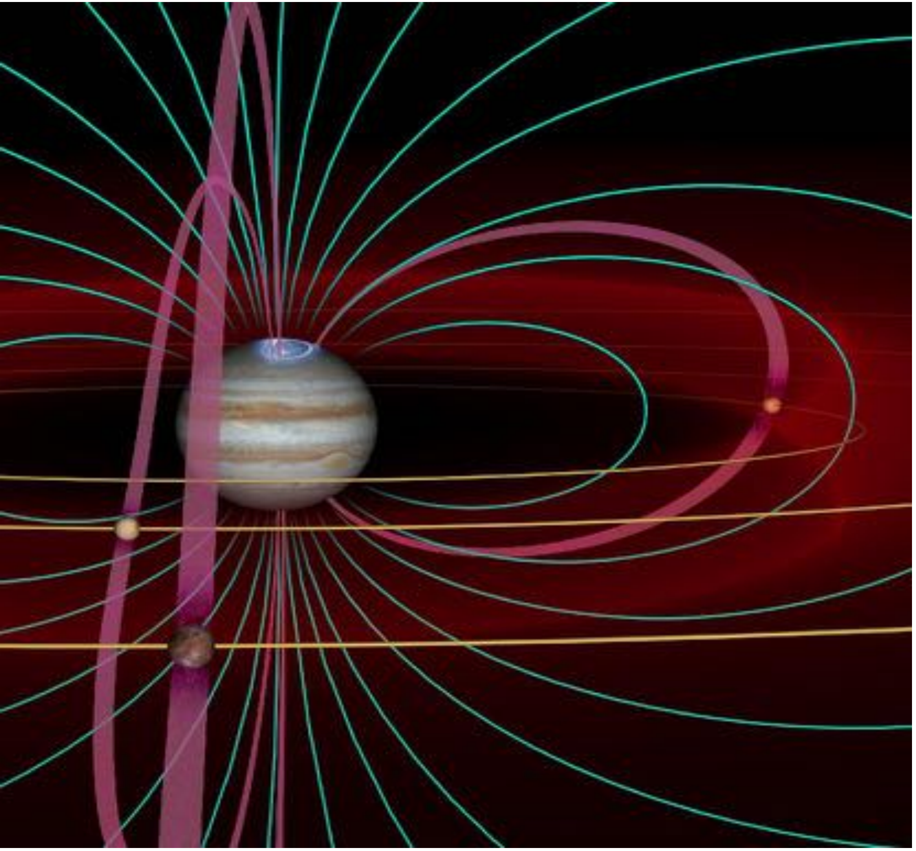
Communication breaks down ~25R_J.
Magnetosphere & atmosphere stop talking > 60 R_J

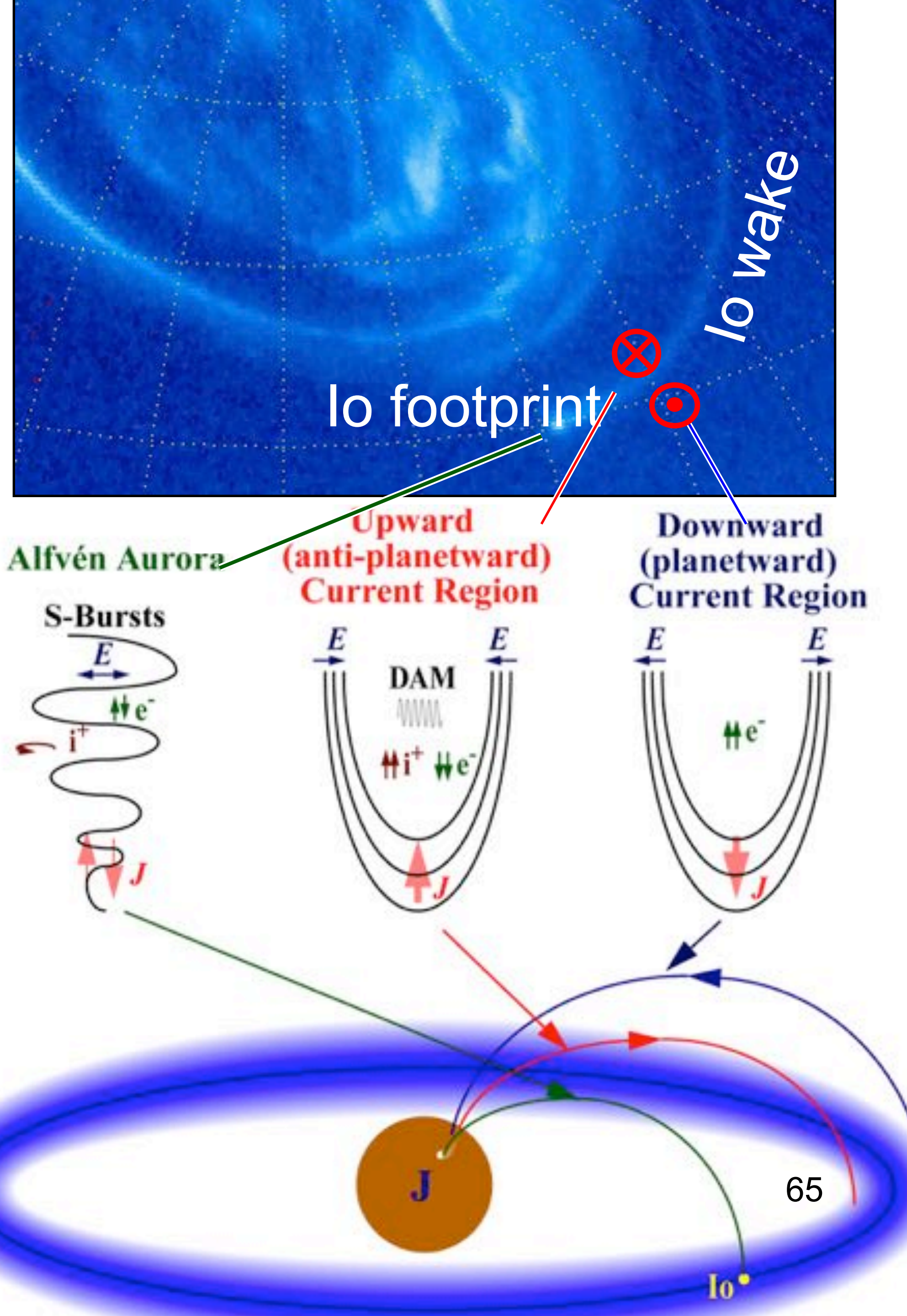
Hubble Space Telescope – *Jon Nichols*



Jupiter's 3 Types of Aurora







Satellite auroral emissions

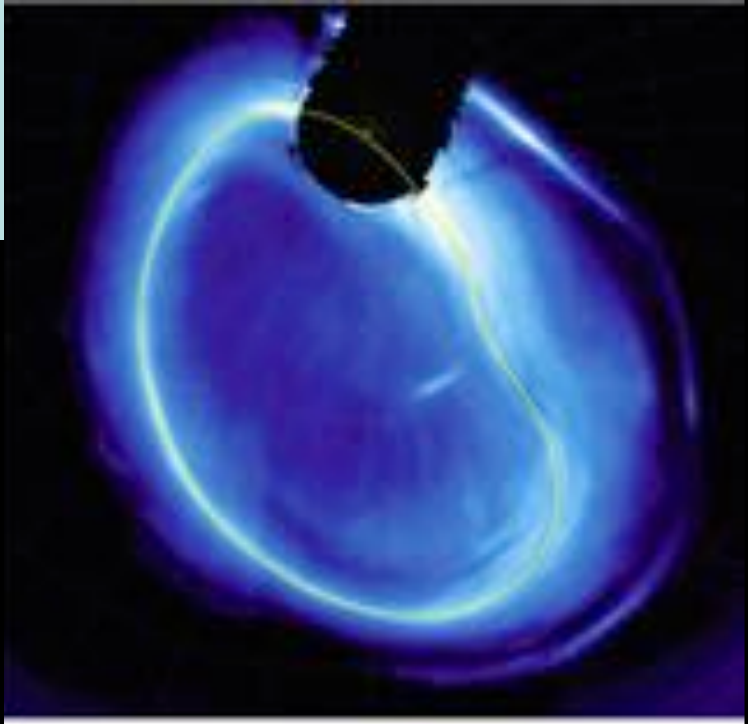
- Plasma-moon electrodynamic interaction
- Mega-amp current systems
- Analogous to Earth auroral processes

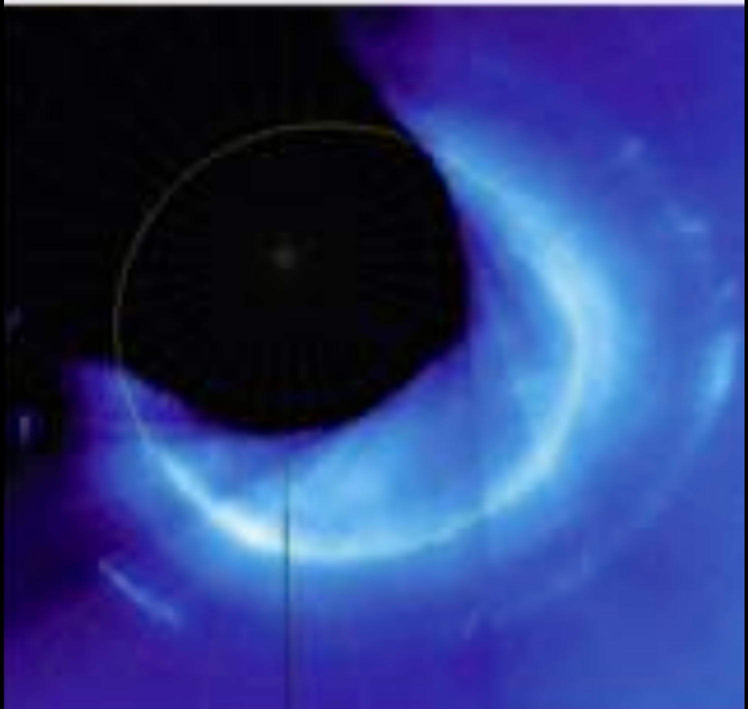
Papers by Su, Ergun, Lysak, Hess, Bonfond

Main Aurora

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

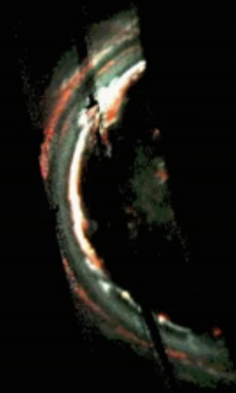
Clarke et al., Grodent et al. HST



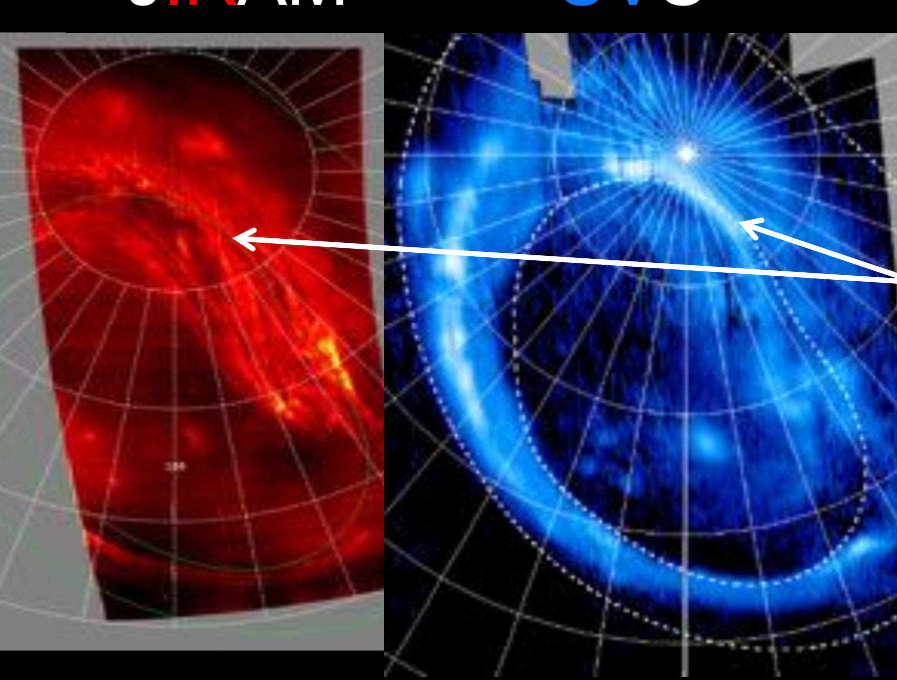


Jupiter's Aurora: Structured & Dynamic

Juno UVS



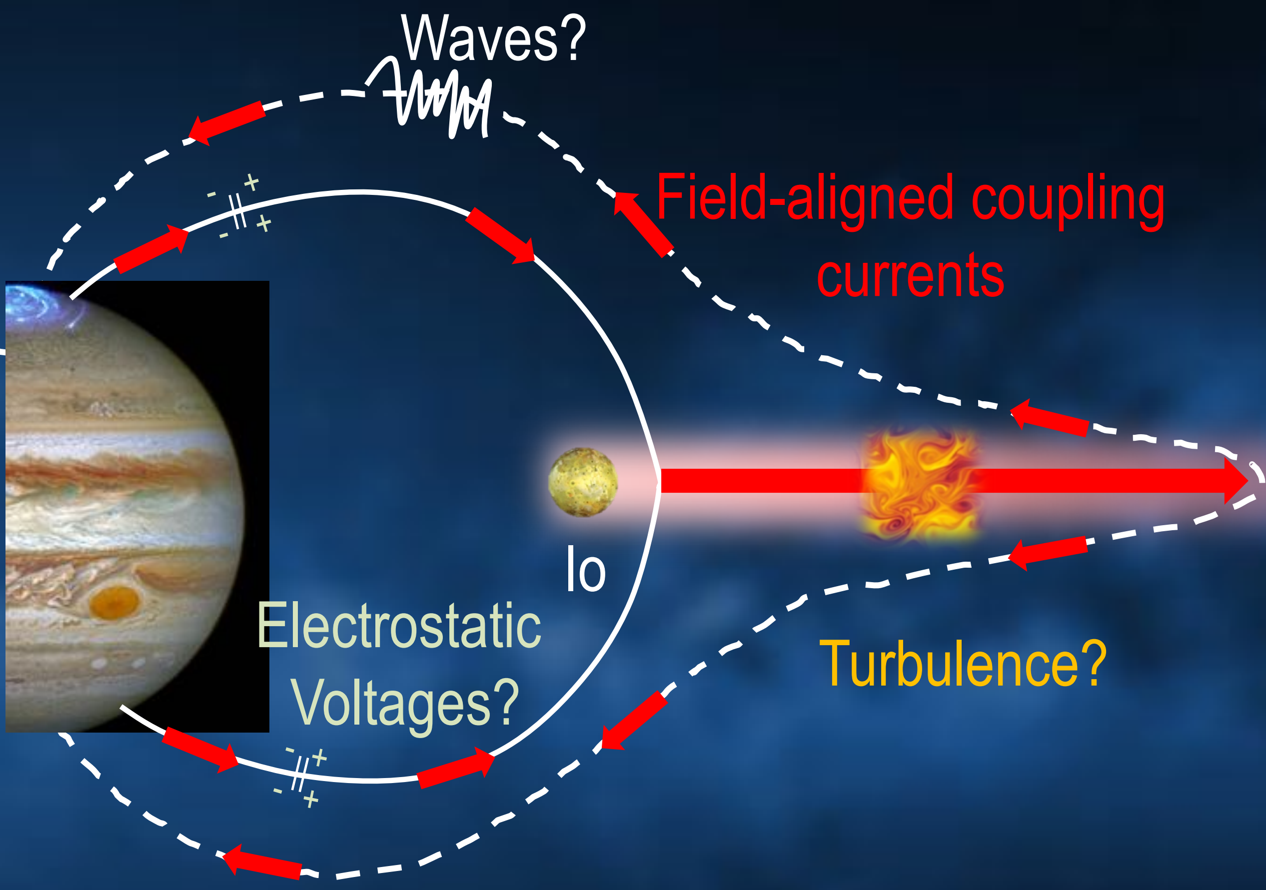
JIRAM UVS



Same region – very different structure in UV vs. IR

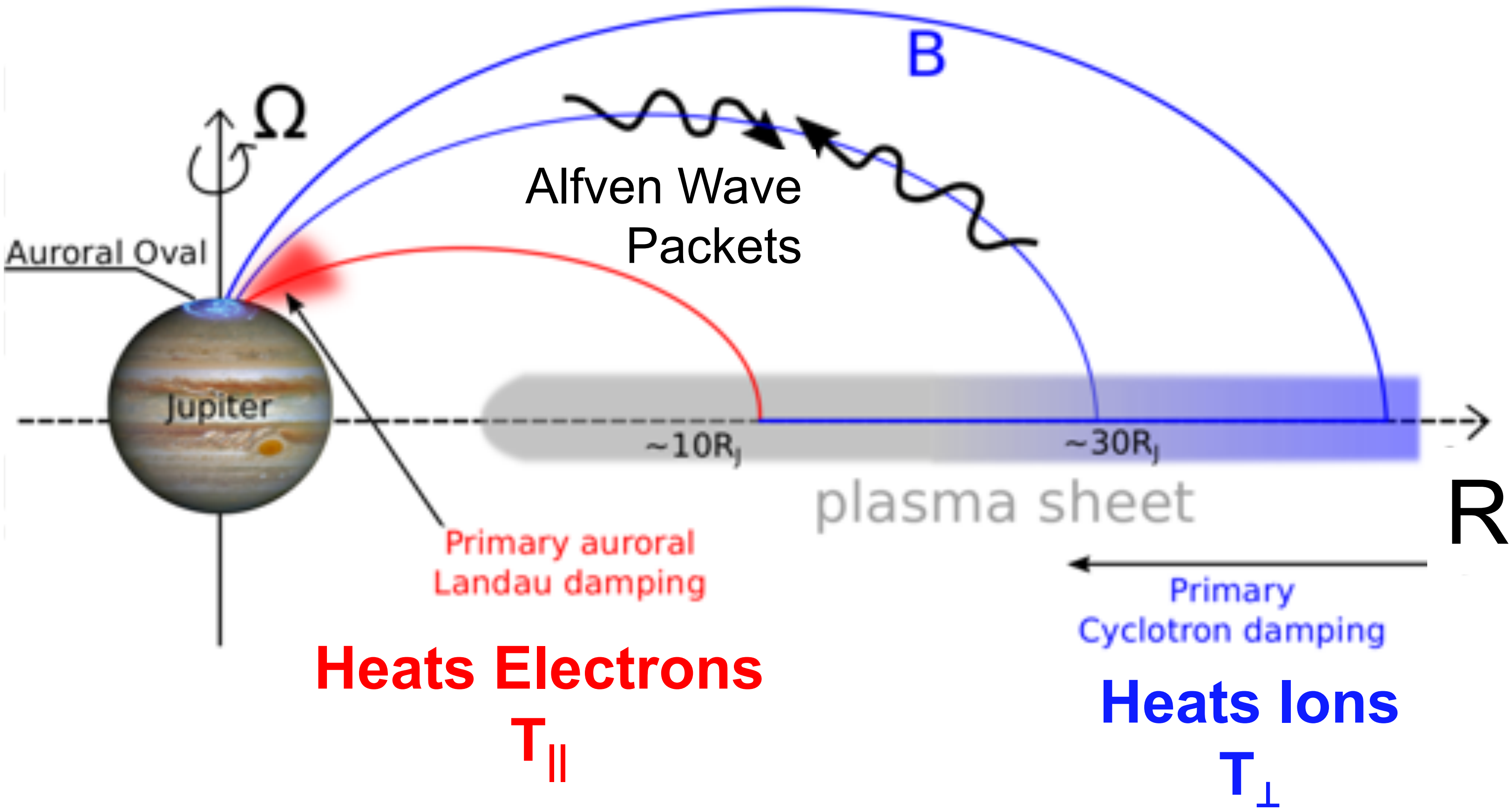
Reveals energy of bombarding electrons & atmospheric chemistry

Gerard et al. 2018



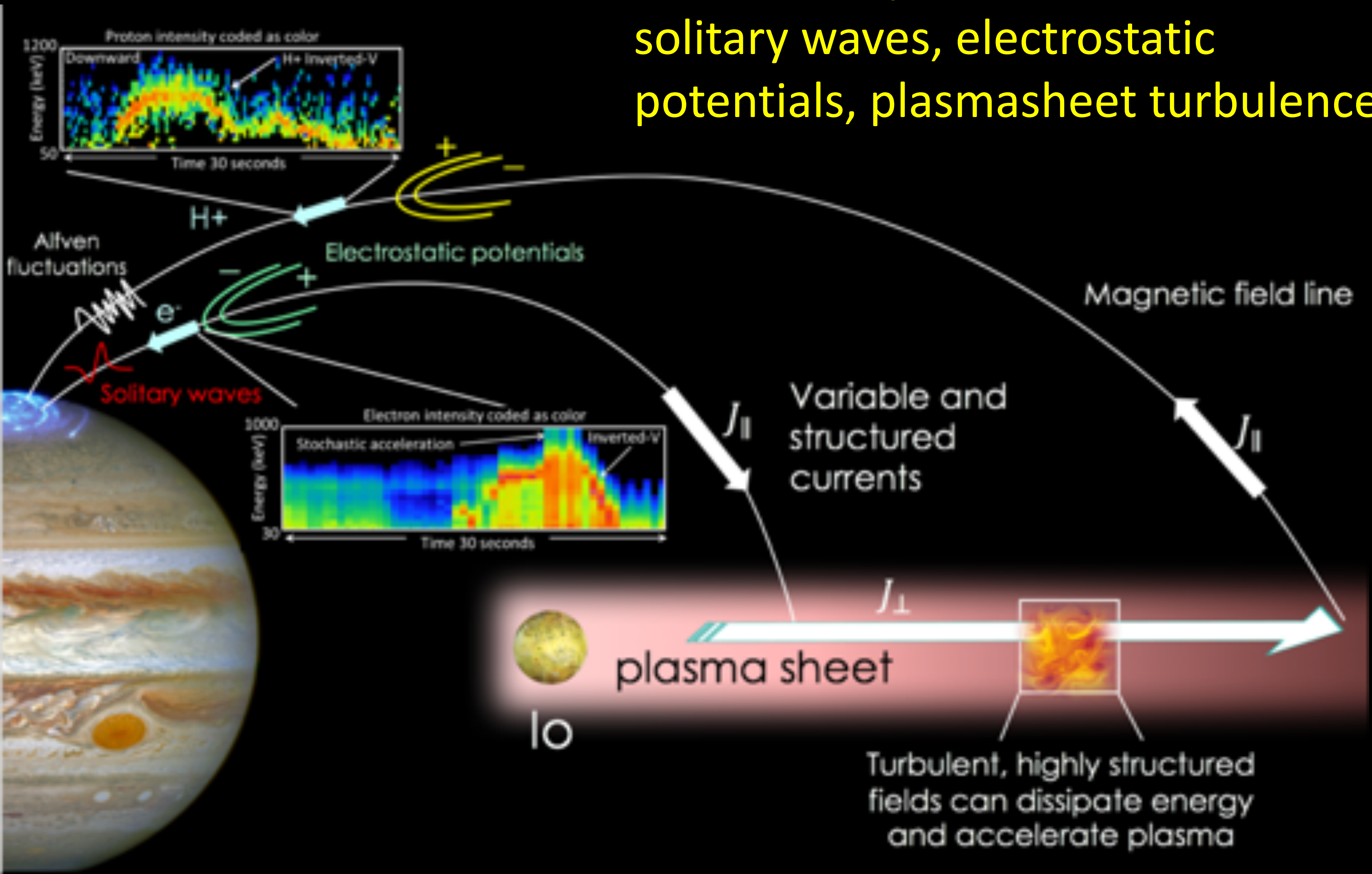
Juno is testing ideas of how charged particles that bombard Jupiter's atmosphere are accelerated

Alfven Wave Heating – Both Ions and Electrons

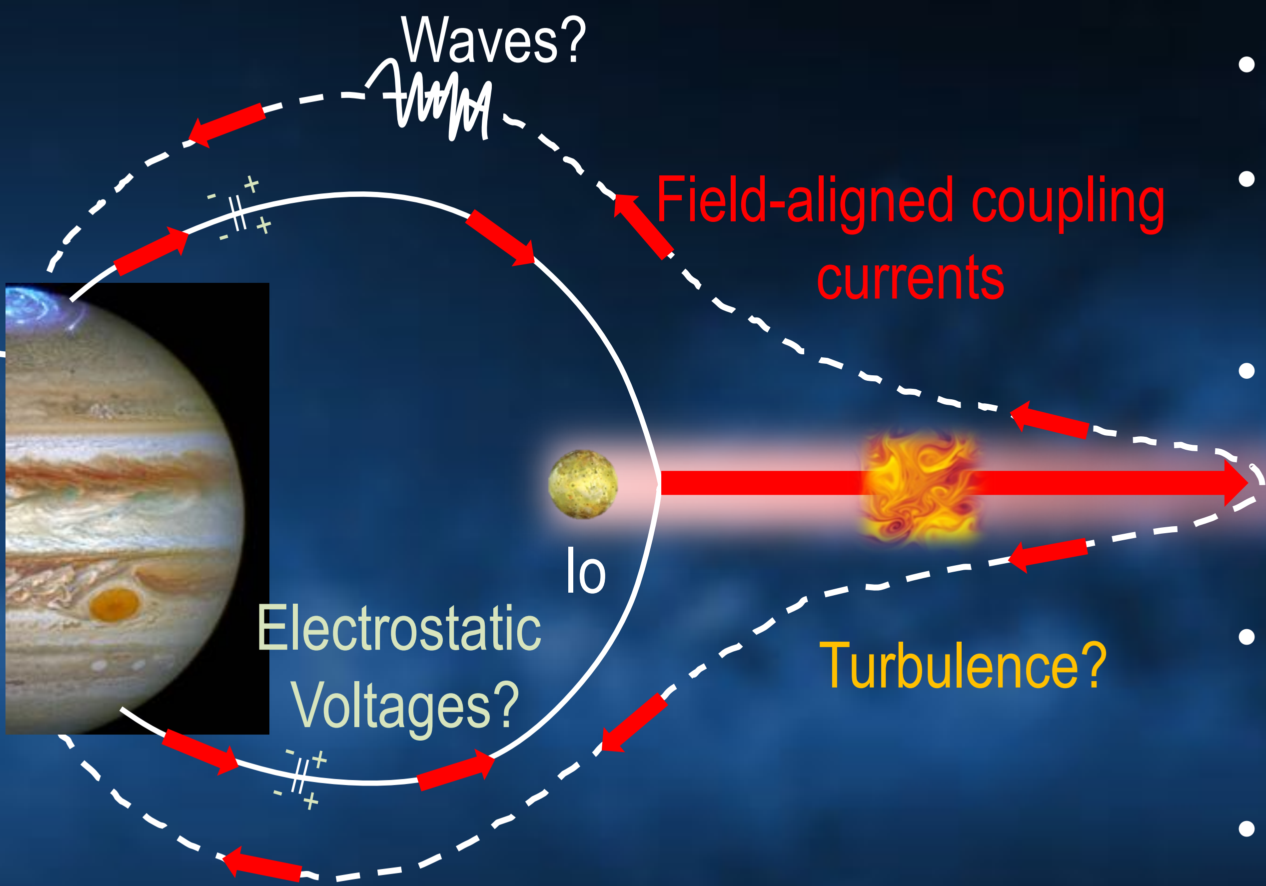


Saur et al. 2018

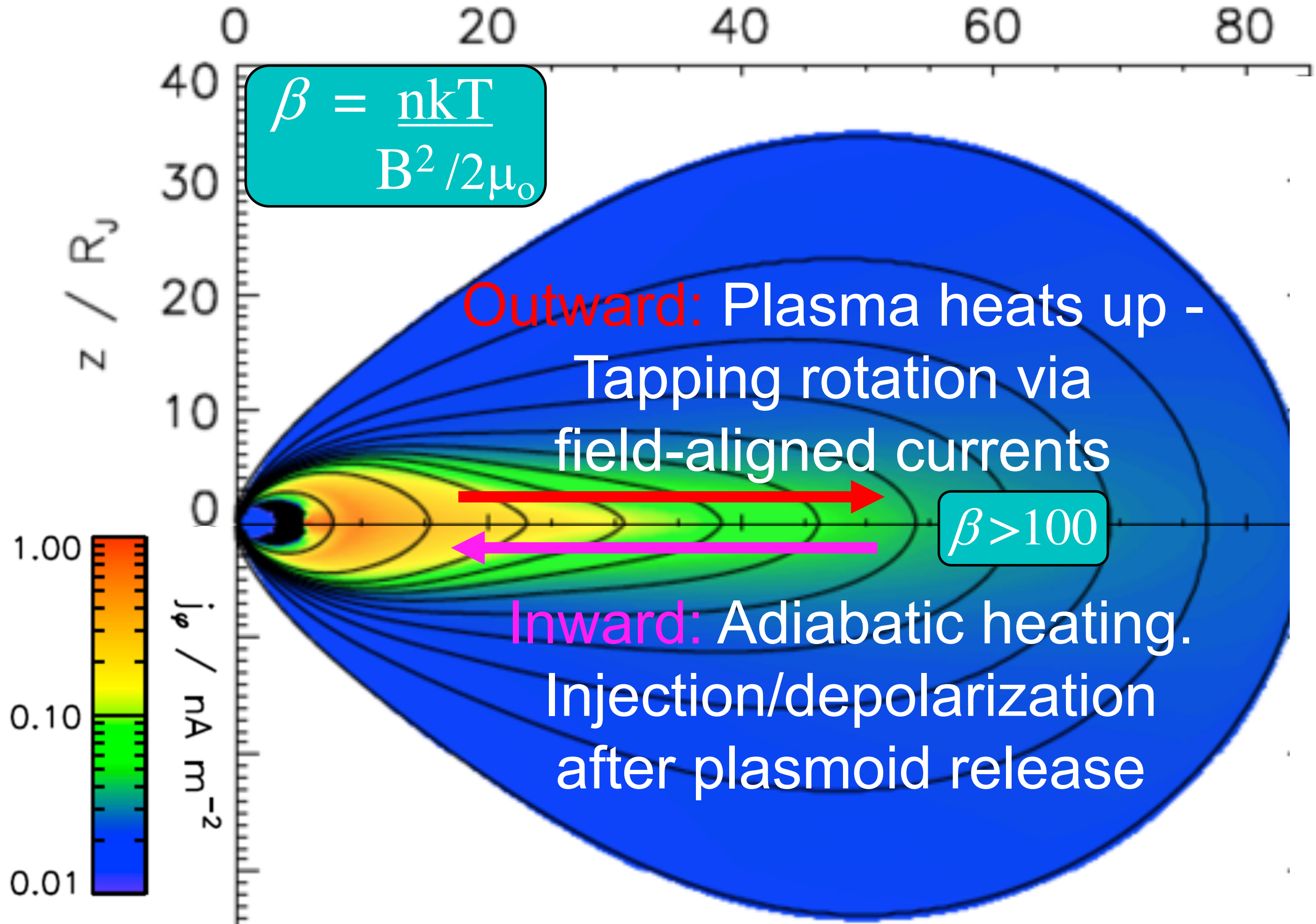
- Electrons reach >1 MeV
- Acceleration processes unclear: solitary waves, electrostatic potentials, plasmasheet turbulence



Mauk et al. 2018



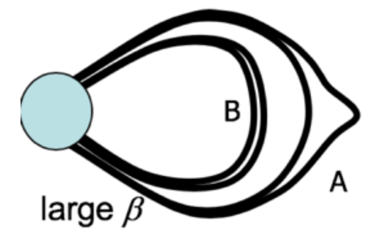
- System quasi-stable?
- Strong coupling currents unstable?
- Fluxtube interchange non-continuous – local force imbalance
- Turbulence cascades to small scales?
- Stochastic accelerations



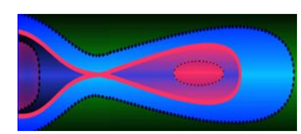
Nichols 2011

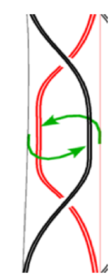
Transport:

Plasma β increases
ballooning replaces interchange

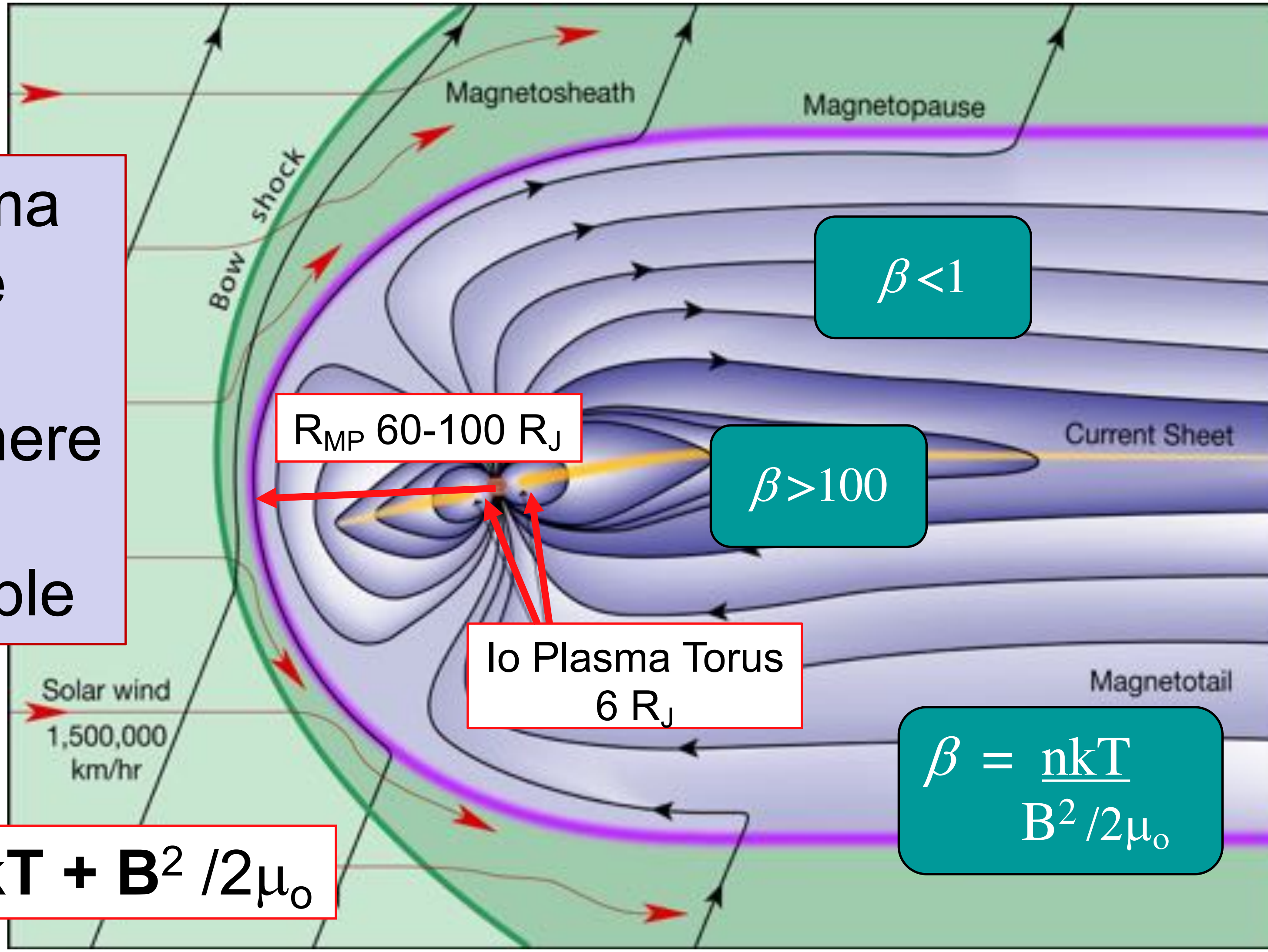


"Drizzle"
Small-scale, local
Kinetic transport?
Reconnection?
Plasmoids?





High Plasma Pressure Makes Magnetosphere Larger & Compressible



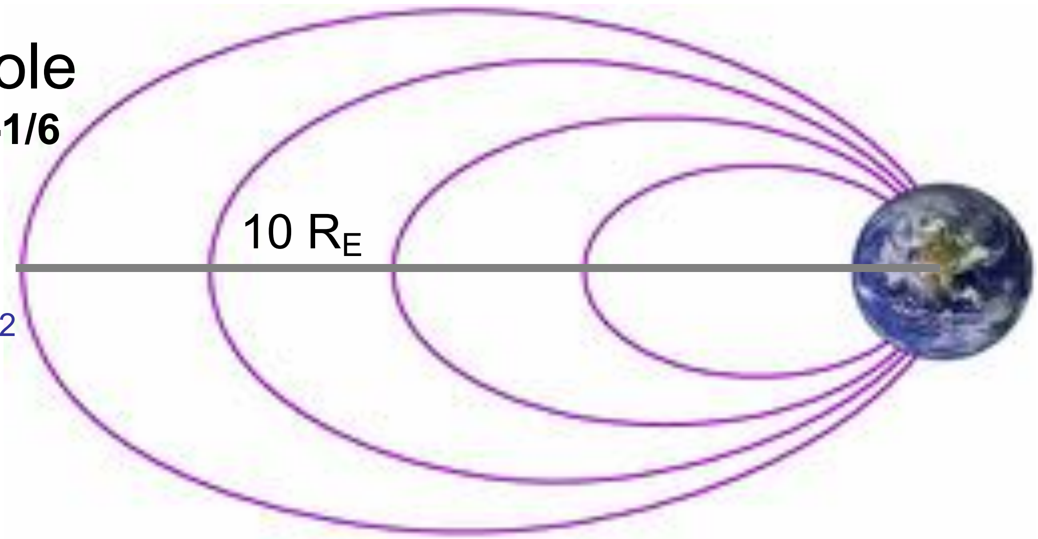
$$\rho_{sw} V^2_{sw} = nkT + B^2/2\mu_o$$

How Compressible with Solar Wind Pressure?

Earth ~ Dipole

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

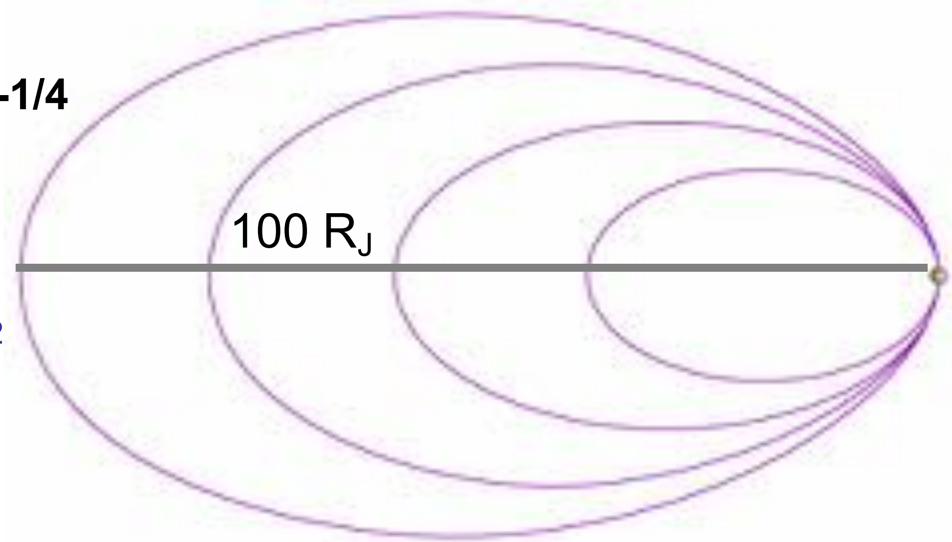
solar wind ρV^2



Jupiter

$$\mathbf{R_{mp} \sim (\rho V^2)^{-1/4}}$$

solar wind ρV^2



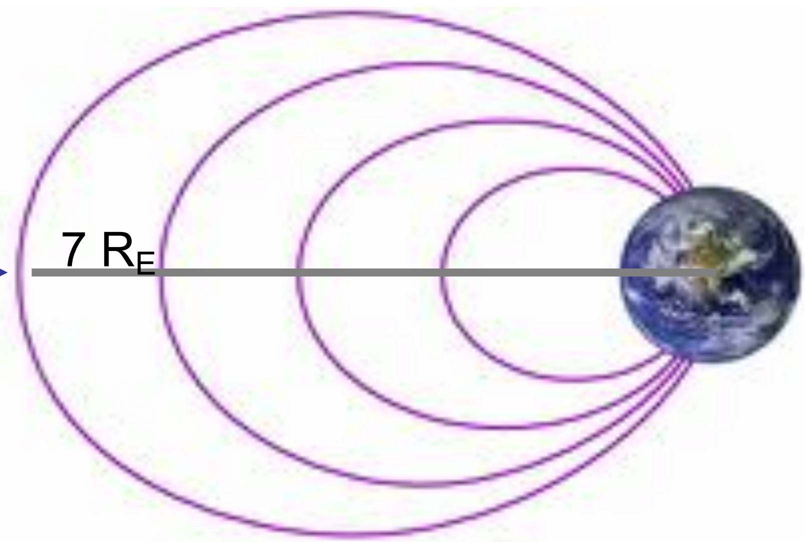
Slavin 1985
Huddleston et al. 1998
Joy et al. 2002

x10 Solar wind pressure

Earth ~ Dipole

R_{mp} -> 0.7 R_{mp}

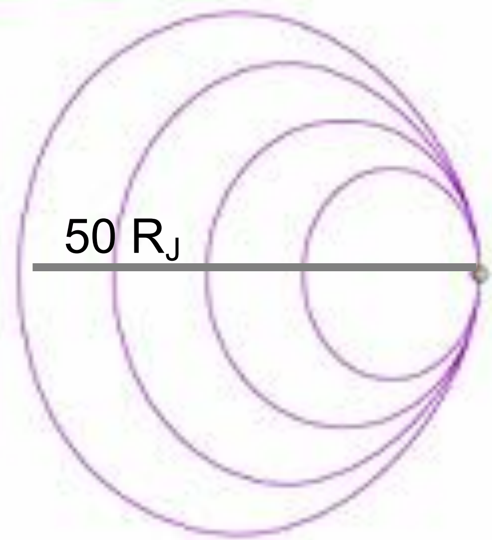
solar wind ρV^2



Jupiter

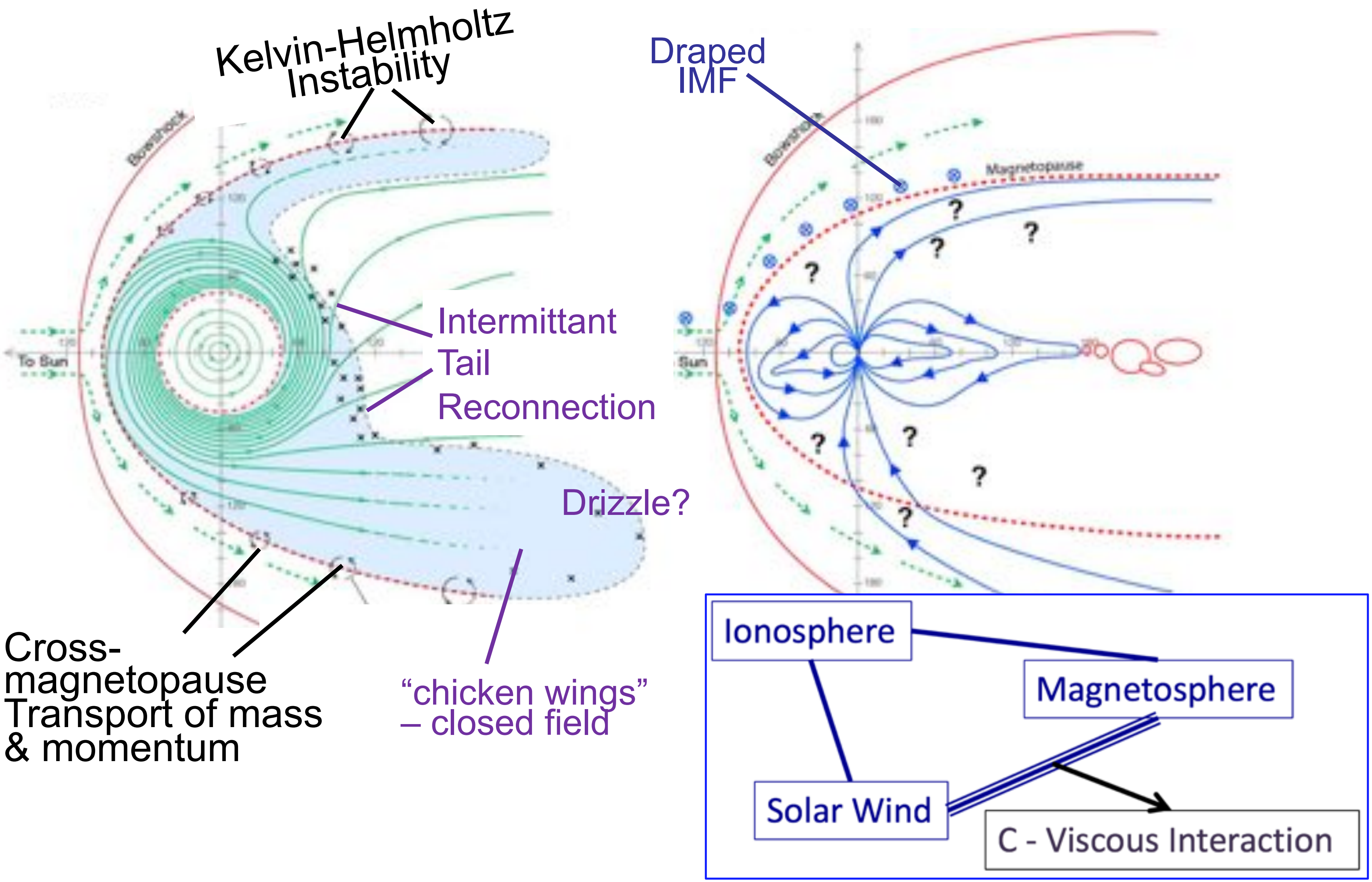
R_{mp} -> 0.5 R_{mp}

solar wind ρV^2

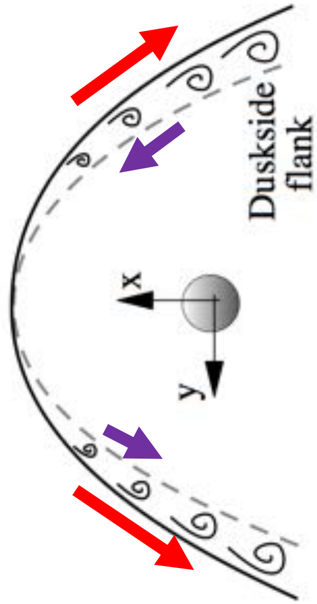


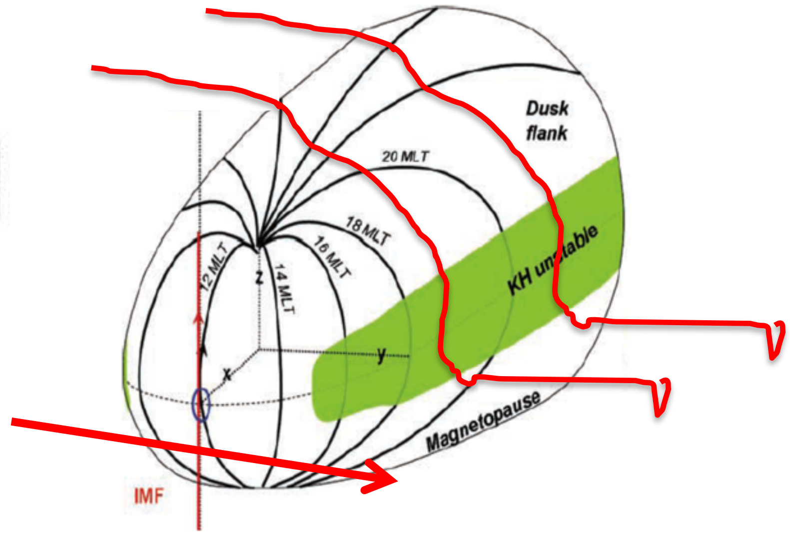
observed 100-50 R_J dayside magnetosphere

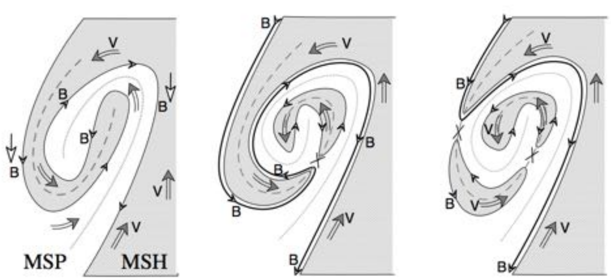
Delamere & Bagenal 2013
Masters 2017



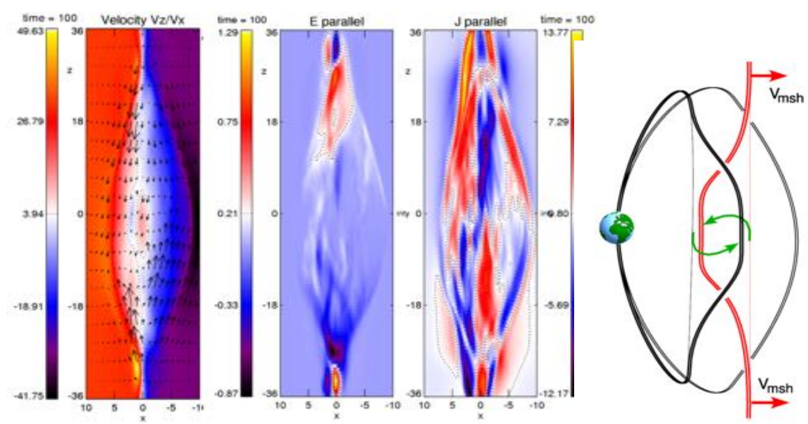
- Not open Dungey cycle
- Viscous interaction
- Shear instabilities
- Small-scale, intermittant reconnection
- Boundary layers



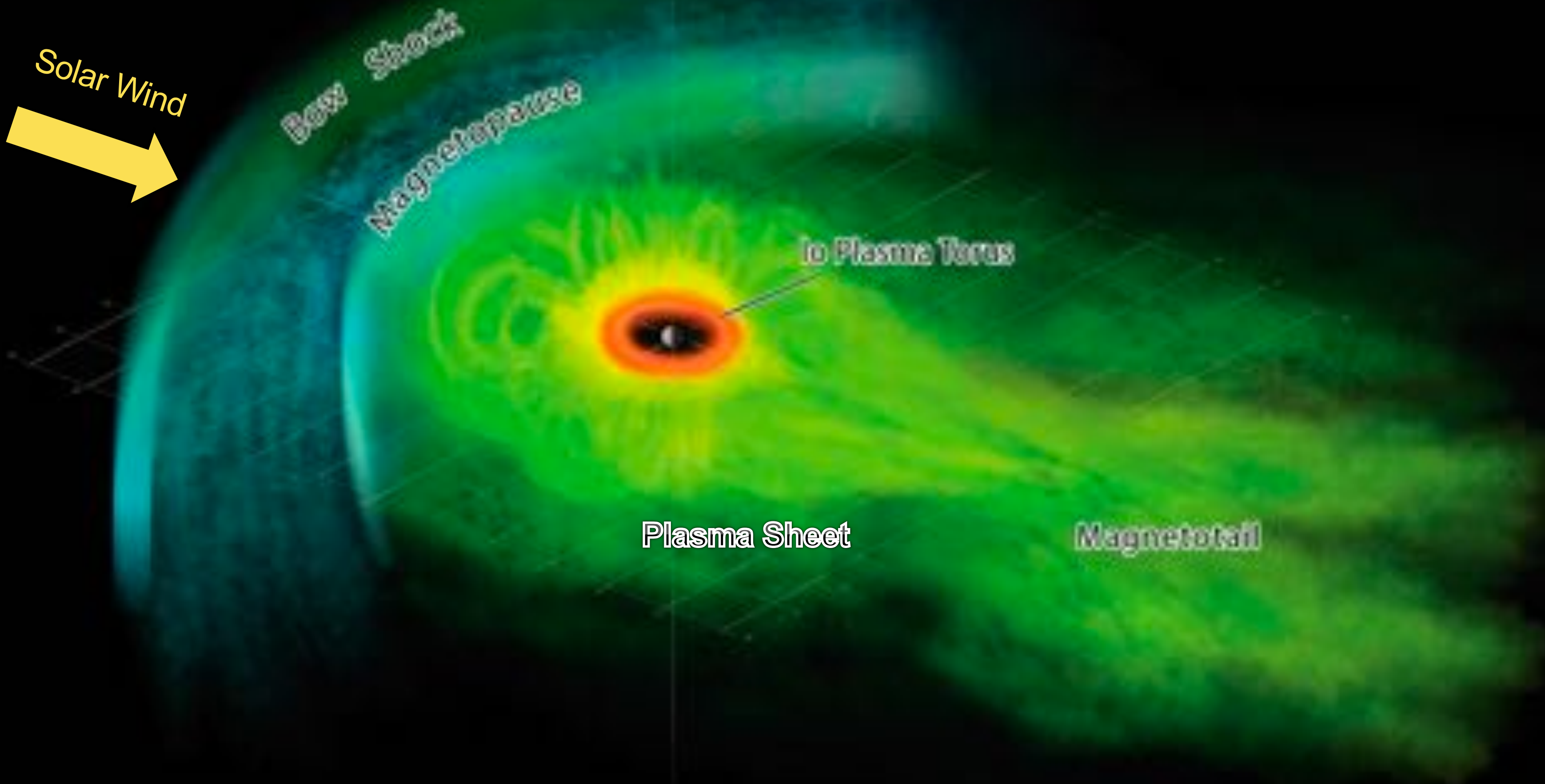




“Candy wrapper”



Is Jupiter Really Just a Colossal Comet?

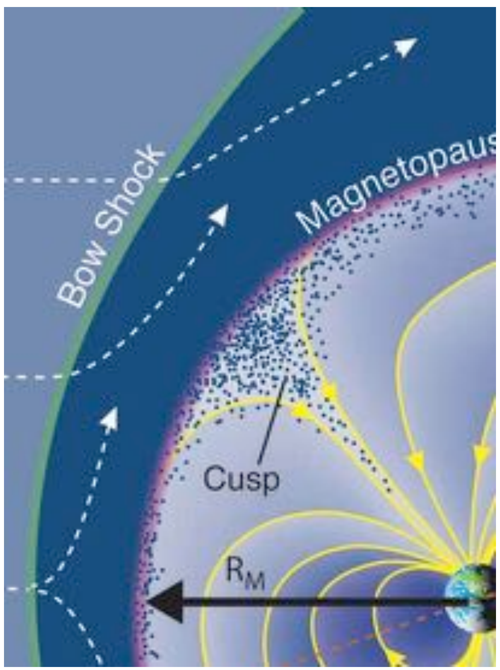


Delamere & Bagenal 2013

JHU/APL

Earth *vs.* *Jupiter*

10 R_E <3 minutes



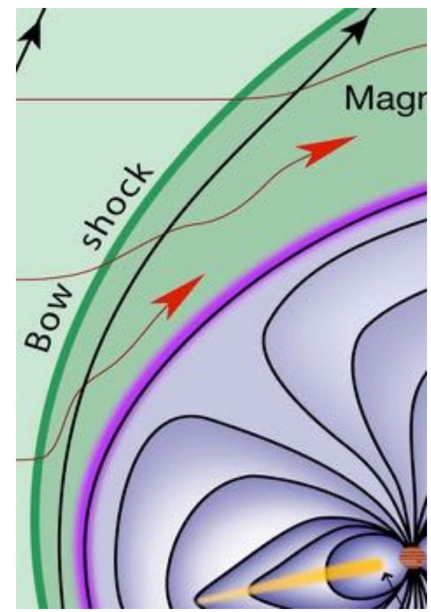
Bob McPherron
Margy Kivelson

Time for Solar Wind to Flow Nose-Terminator

$V_{solar\ wind}$ ~ 400 km/s

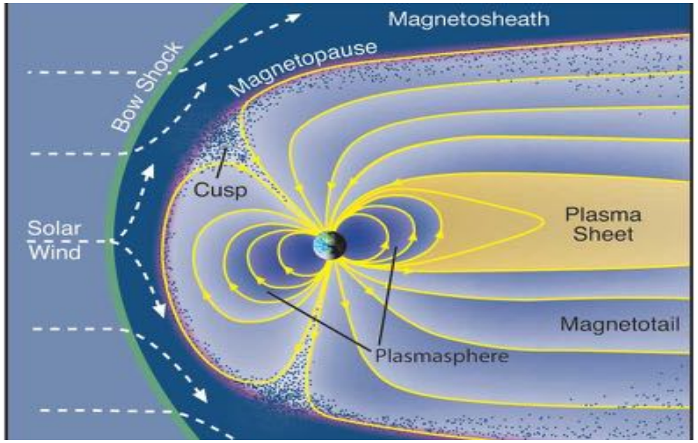
Probability of B_{IMF} staying $B_z>0$ or $B_z<0$ (i.e. N or S) for 5 hours is $\sim 10^{-3}$

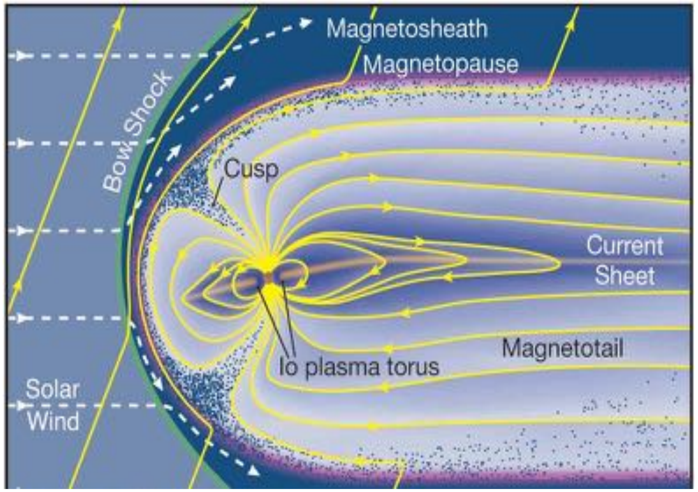
100 R_J
~ 5 hours



McComas & Bagenal 2007

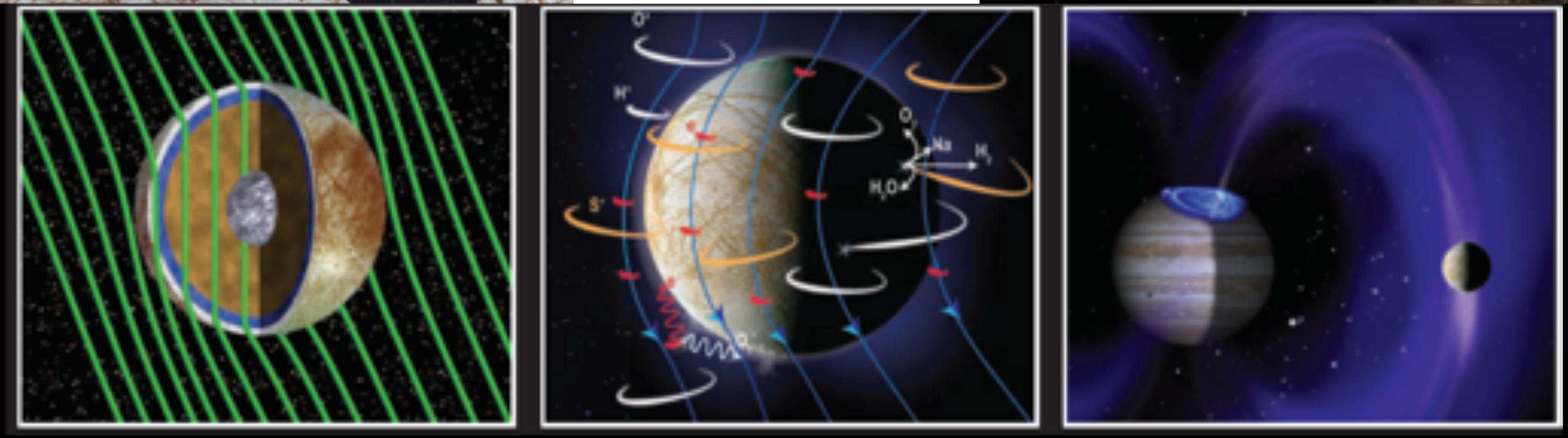
Earth	*Jupiter*
Modest plasma source	Strong plasma source
Residence time ~hours	Residence time ~weeks
Taps solar wind	Taps rotation
Global convection	Local dynamics
Small, dynamic magnetosphere	**Large, hot plasma disk**





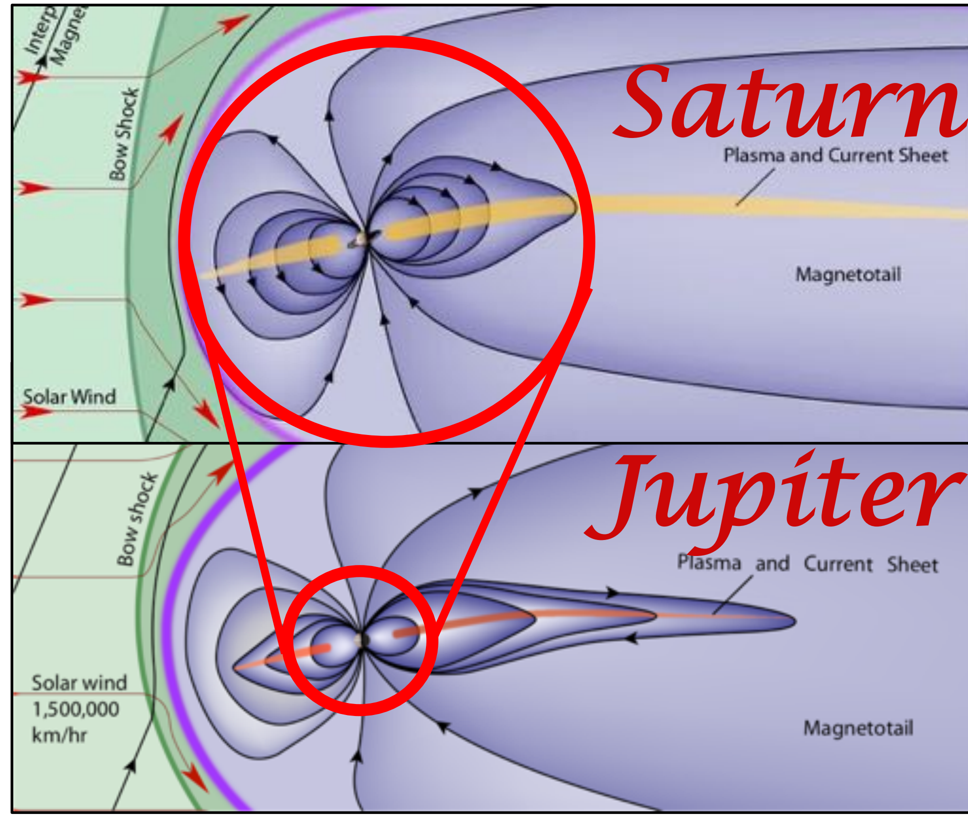
Future at Jupiter: Clipper & JUICE

Particle & field measurements key for science goals



Why so different?

	Jupiter	*Saturn*
Planet Radius	70,000 km	58,000 km
M'pause Distance	63-92* R_J	22-27# R_S

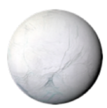


Note: Both bimodal

* Joy et al. 2002 # Achilleos et al. 2008

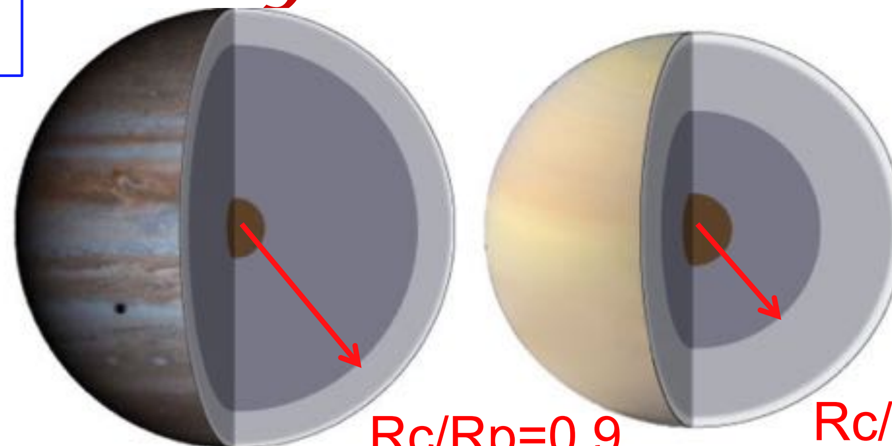
Why so different?

1. Weaker Magnetic Field
2. Weaker Plasma Source



Enceladus
50 kg/s

Jupiter *Saturn*



Mass: Saturn = 1/3 Jupiter

- lower pressures
- smaller region metallic hydroge
- 1/30 weaker magnetic field

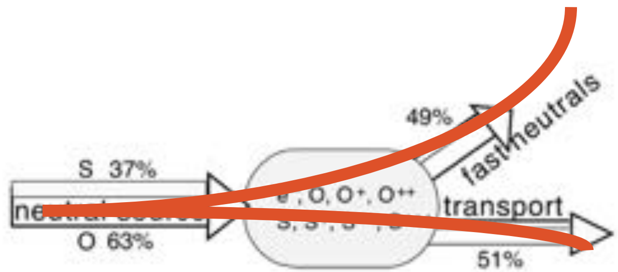
270 eV

58 eV

O^+ pickup energy

Plasma Torus Mass Flux

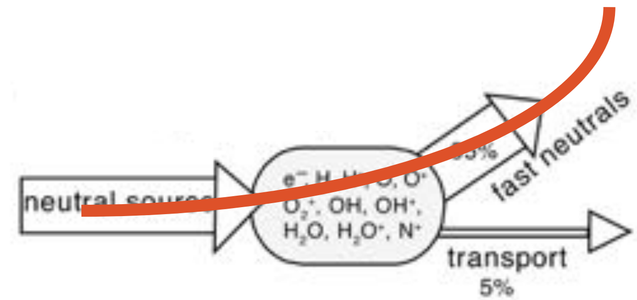
Jupiter



Half lost as fast neutrals
-> extended neutral cloud

Half transported out to plasma disk

Saturn



MOST lost as fast neutrals
-> extended neutral cloud

Few% transported out to plasma disk

Delamere et al. 2007

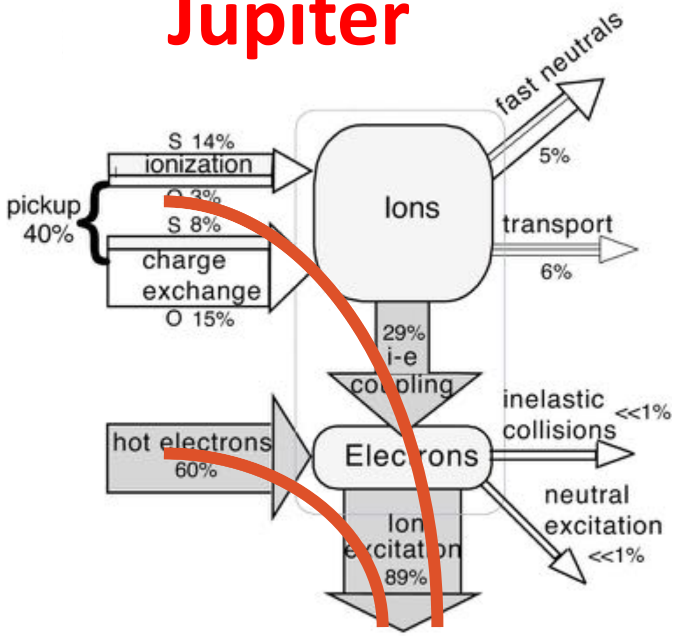
Charge Exchange = CHEX

$O^+ + O \rightarrow O^* + O^+$

rotating, stationary, Energetic Neutral Atom, Pickup Ion

Plasma Torus Energy Flux

Jupiter

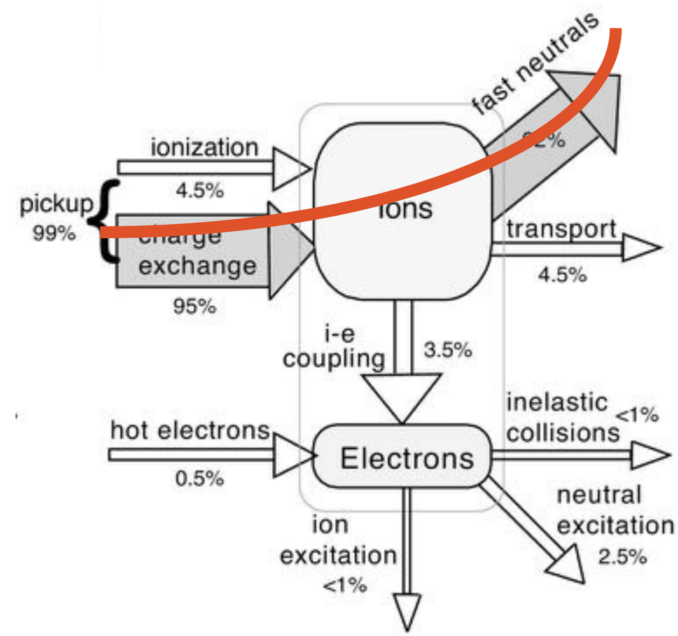


UV emission

Heating: Half pick-up,
Half hot electrons

Cooling: UV emissions

Saturn



Heating: Charge exchange pick-up

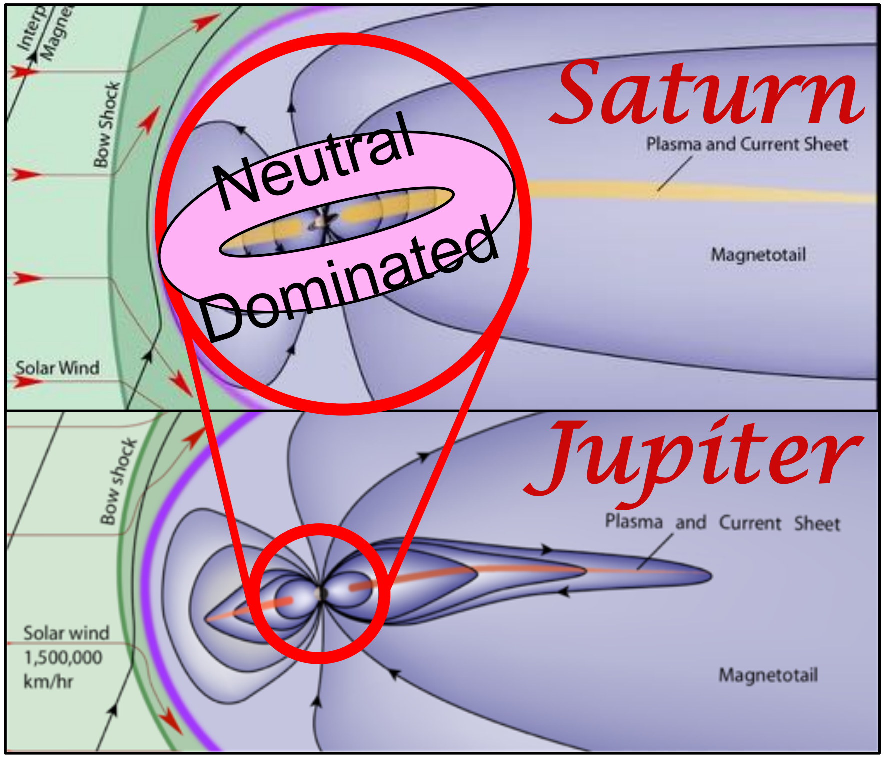
Cooling: Charge exchange escape

Delamere et al. 2007

Why so different?

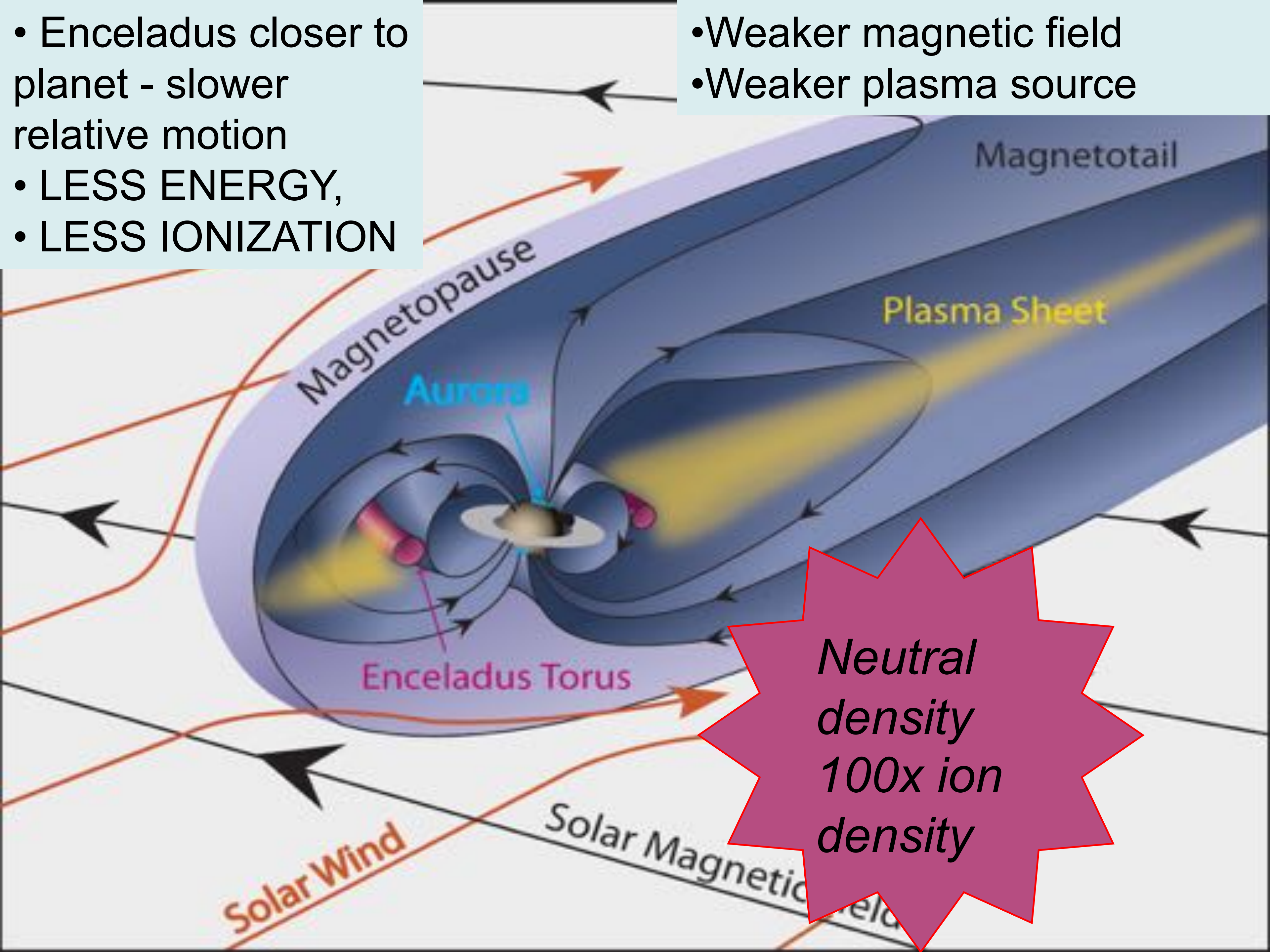
- Plasma source less, cooler
- Less heating
- More CHEX

	Jupiter	*Saturn*
Neutrals	70 kton	1 Mton
Plasma	1.5 Mton	85 kton
Disk Heating	10,000 GW	300 GW
Auroral Power	500 GW	20 GW



- Enceladus closer to planet - slower relative motion
- LESS ENERGY,
- LESS IONIZATION

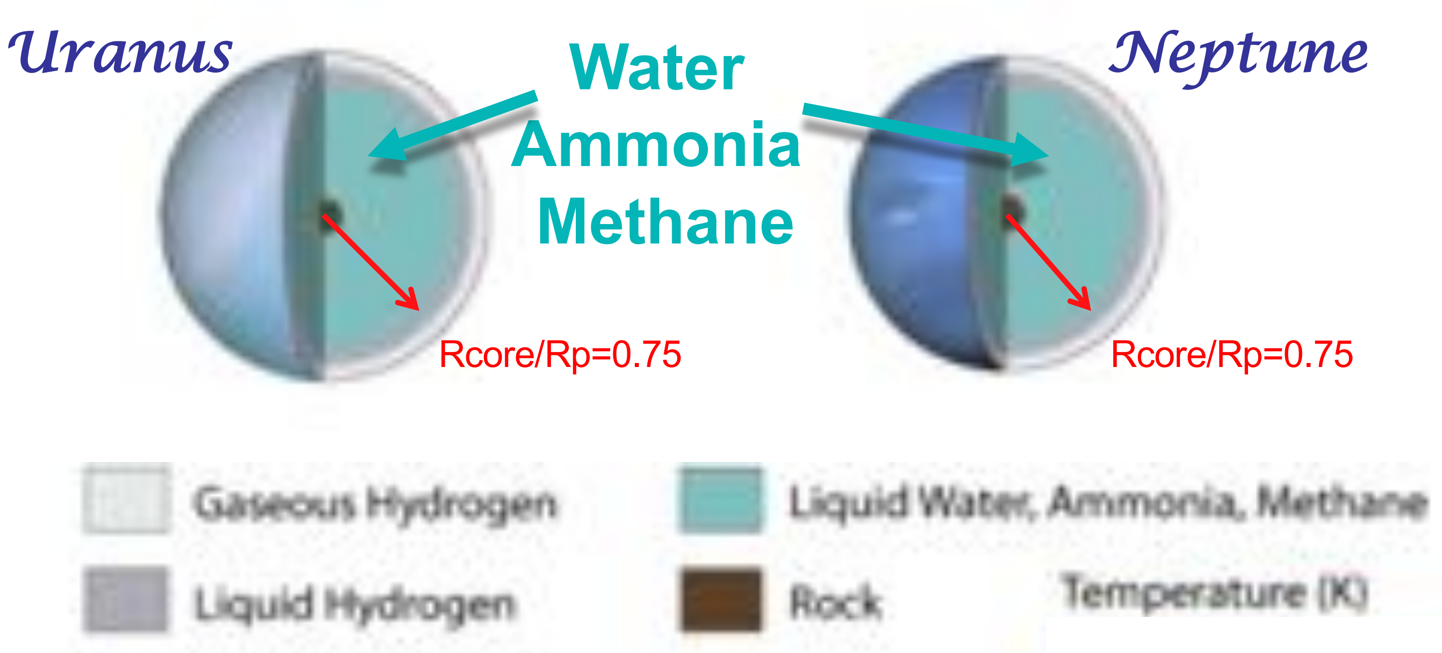
- Weaker magnetic field
- Weaker plasma source



Neutral density 100x ion density

Uranus & Neptune

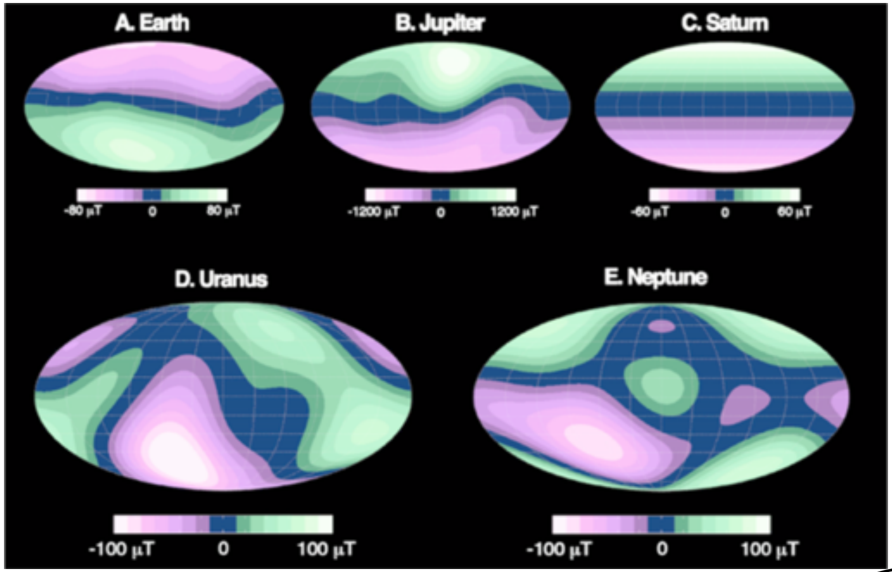
They're Totally Weird!

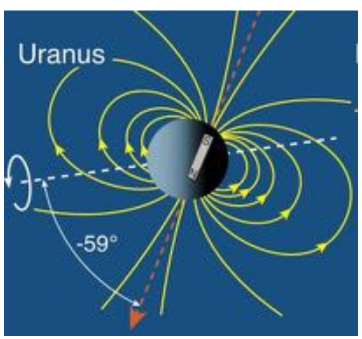


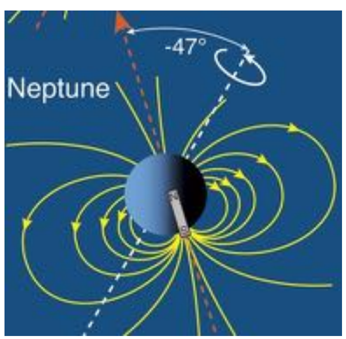
Uranus and Neptune have much less mass

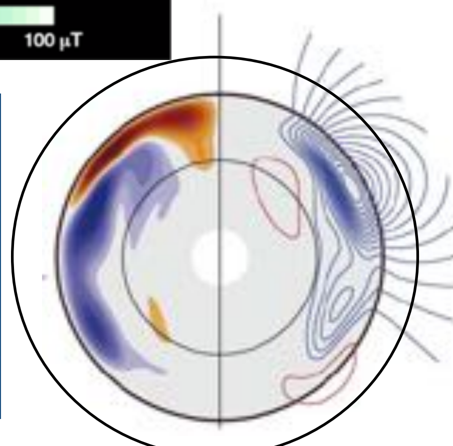
- Lower pressures
- No metallic hydrogen
- Weak & irregular magnetic fields produced in **water layer,** deep below gas envelope

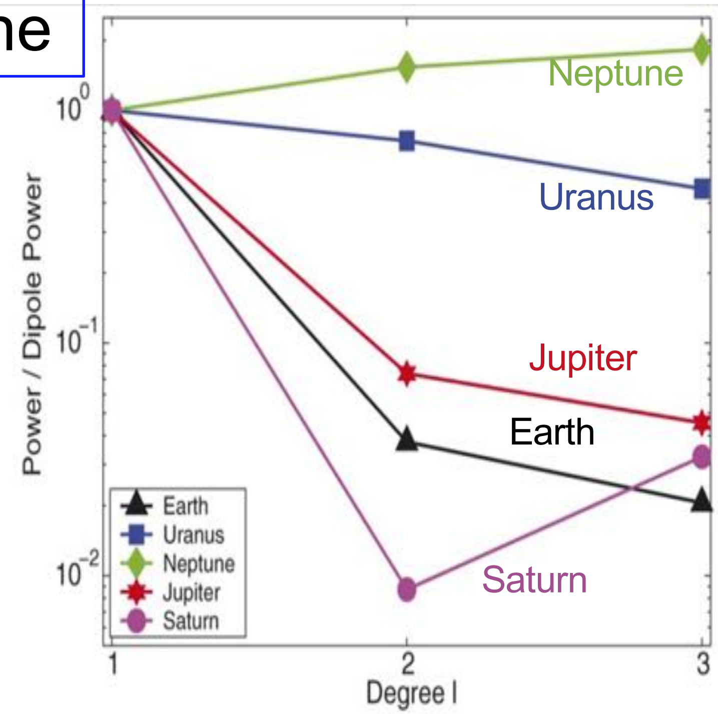
Weird Magnetospheres Uranus & Neptune







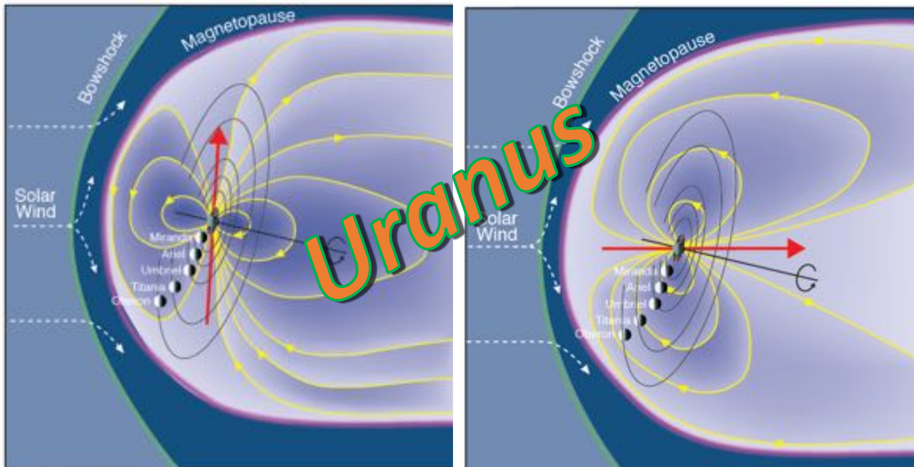




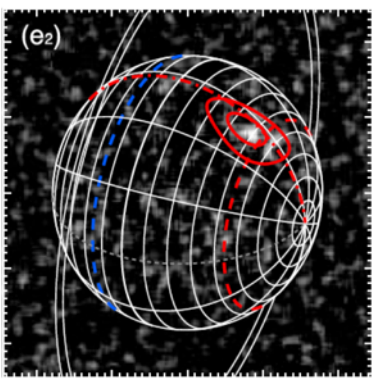
Modeling Uranus & Neptune non-dipolar fields with thin-shell dynamo over a stratified core

Stanley & Bloxham 2006

Need to go back to Uranus & Neptune

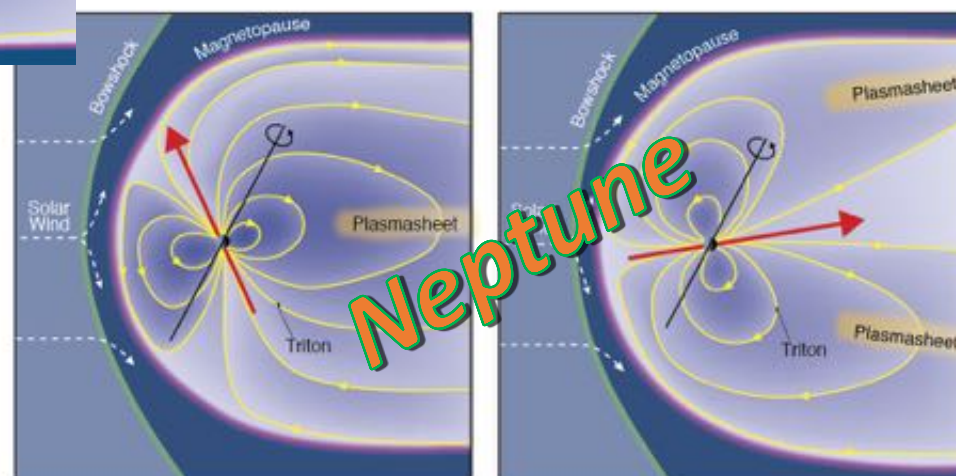


- Voyager got quick glipse!
- Saw irregular, changing field
- How do m'spheres respond to solar wind?



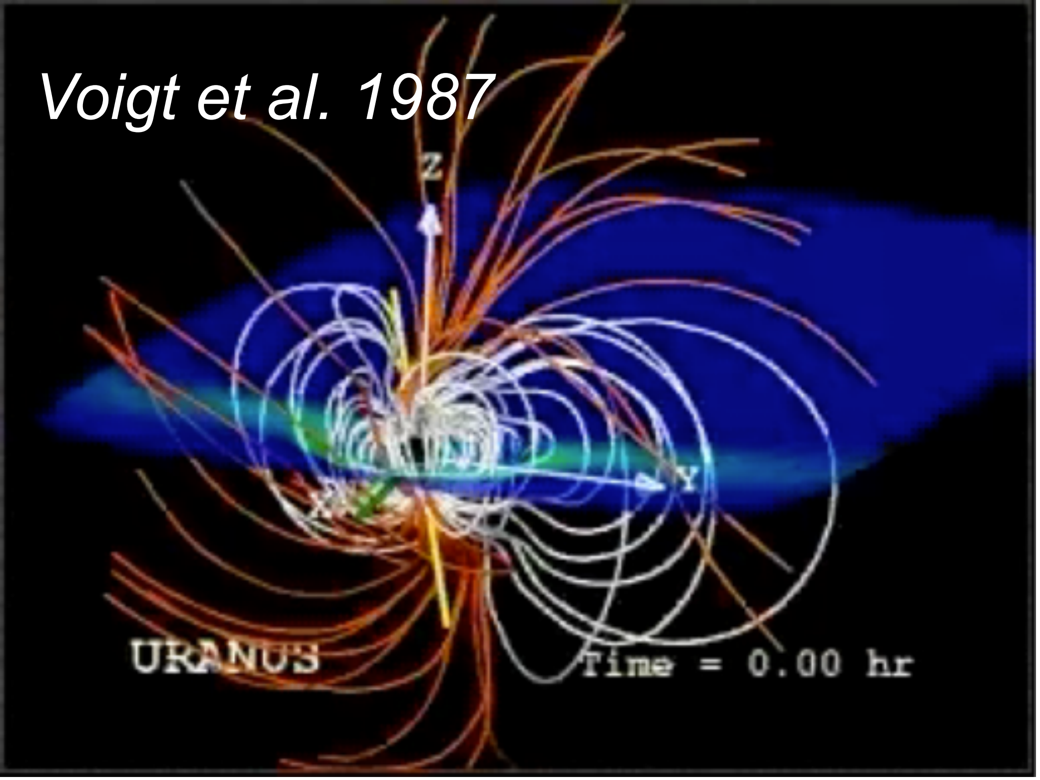
Lamy et al. 2017

Hints of aurora with HST

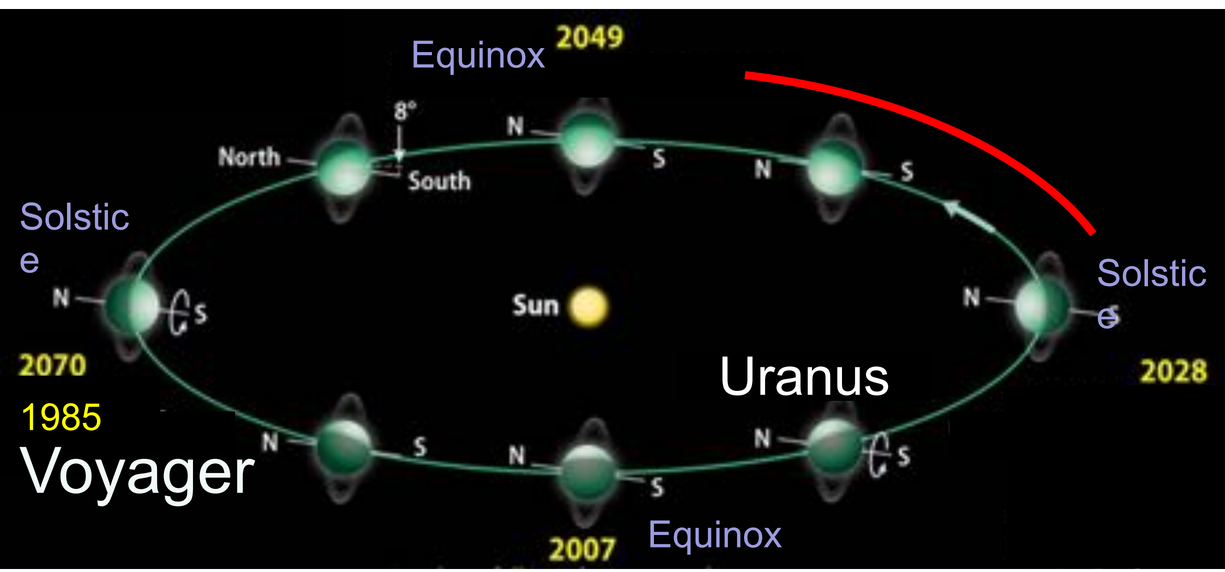


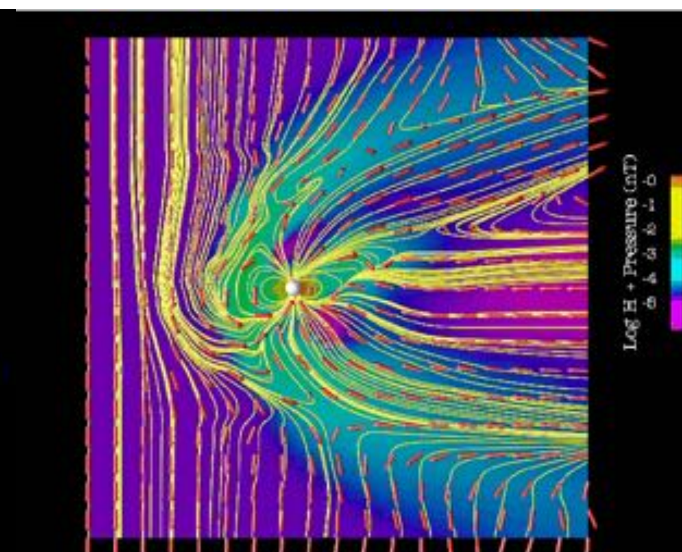
Explore weird configurations at different seasons

- Full coverage from orbit
- Modern instrumentation
- Onboard data-processing



Voigt et al. 1987



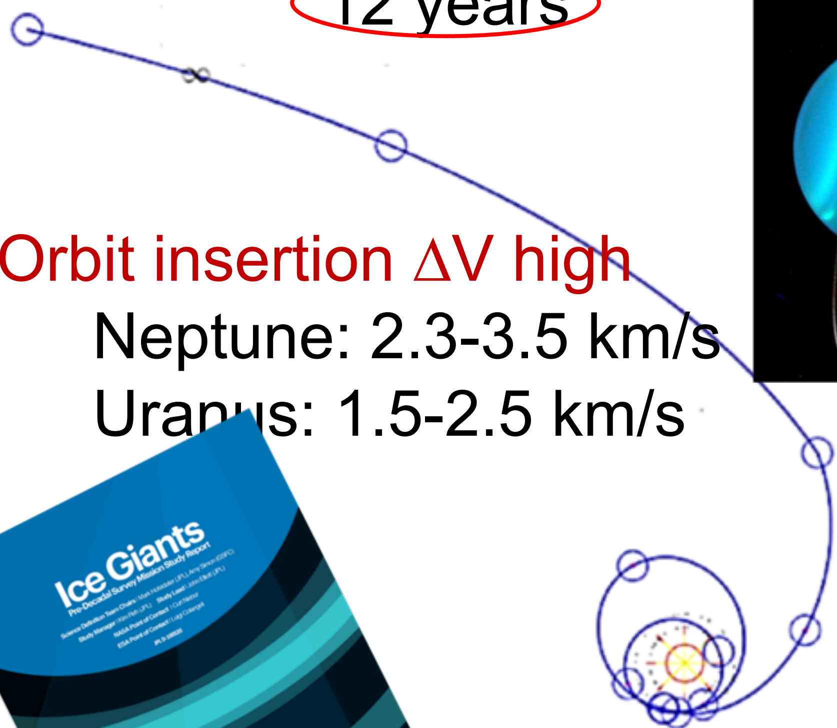


Cao & Paty 2017

Long Cruise

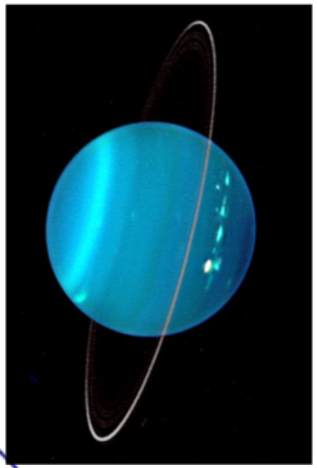
Sample Trajectory to Uranus:
Earth-Venus-Earth-Earth-Jupiter
Gravity Assist

May 2031 – May 2043
12 years

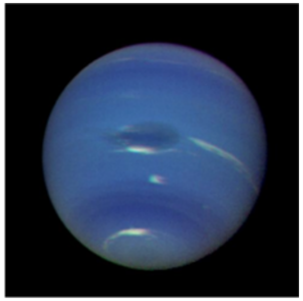


Orbit insertion ΔV high
Neptune: 2.3-3.5 km/s
Uranus: 1.5-2.5 km/s

Uranus

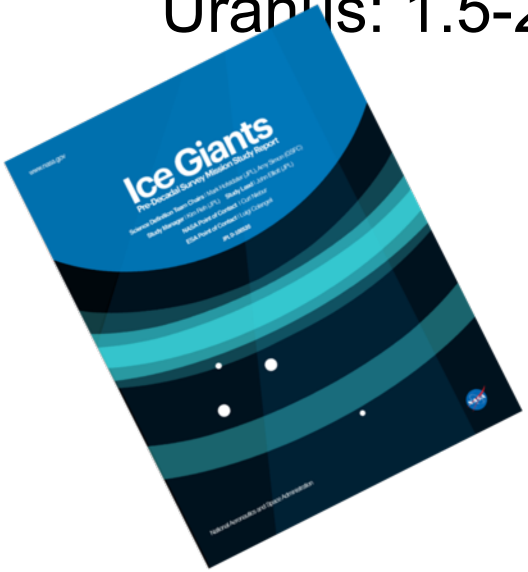


Neptune



SLS

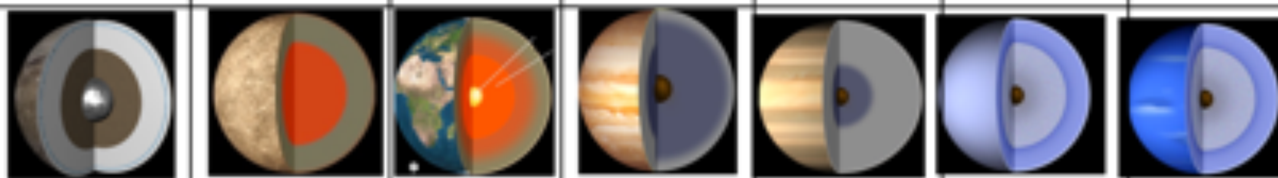
Falcon

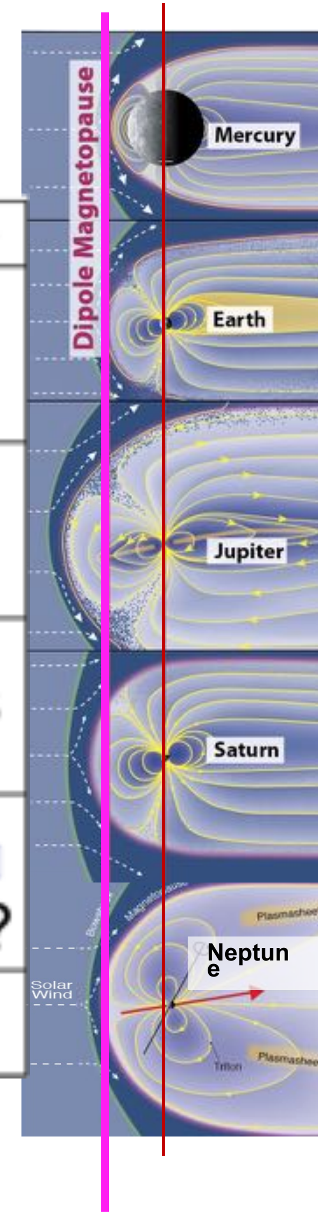


We'll have the Pu-238

Plus aerocapture capability, enables very lowers flight times
Uranus < 5 yr
Neptune < 7 yr
Delivers more mass....

Comparative Planetary Magnetospheres

	Ganymede	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
							
Moment $/M_E$	5×10^{-4}	5×10^{-4}	1	20,000	600	50	25
$R_{M'pause}/R_P$	1.8	1.5	8-12	63-92	22-27	18	23-26
Coupling Process	Ionosphere, M'sphere, Jup. M'Sphere	Ionosphere, Magnetosphere, Solar Wind	Ionosphere, Magnetosphere, Solar Wind	Ionosphere, Magnetosphere, Solar Wind	Ionosphere, Magnetosphere, Solar Wind	Ionosphere, Magnetosphere, Solar Wind ??	Ionosphere, Magnetosphere, Solar Wind ??
Timescale	mins	mins	hrs	wks	days	??	??



Summary

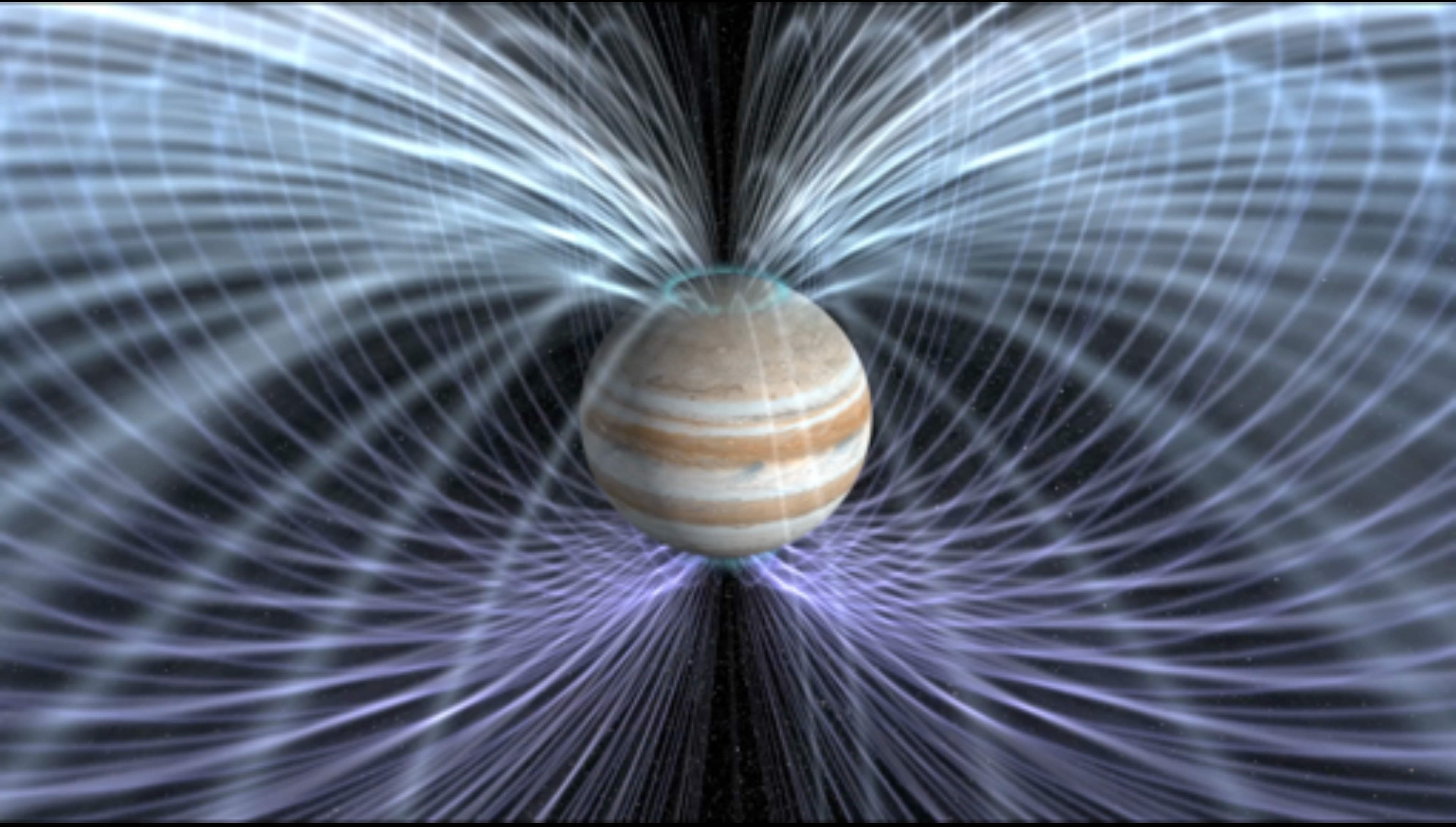
- Diverse planetary magnetic fields & magnetospheres
- Earth, Mercury, Ganymede magnetospheres driven by reconnection
- Jupiter & Saturn driven by rotation & internal sources of plasma
- Uranus & Neptune are complex – *need to be explored!*

Stay tuned…. MAVEN mission to Mars

Juno mission to Jupiter

Bebi-Columbo to Mercury

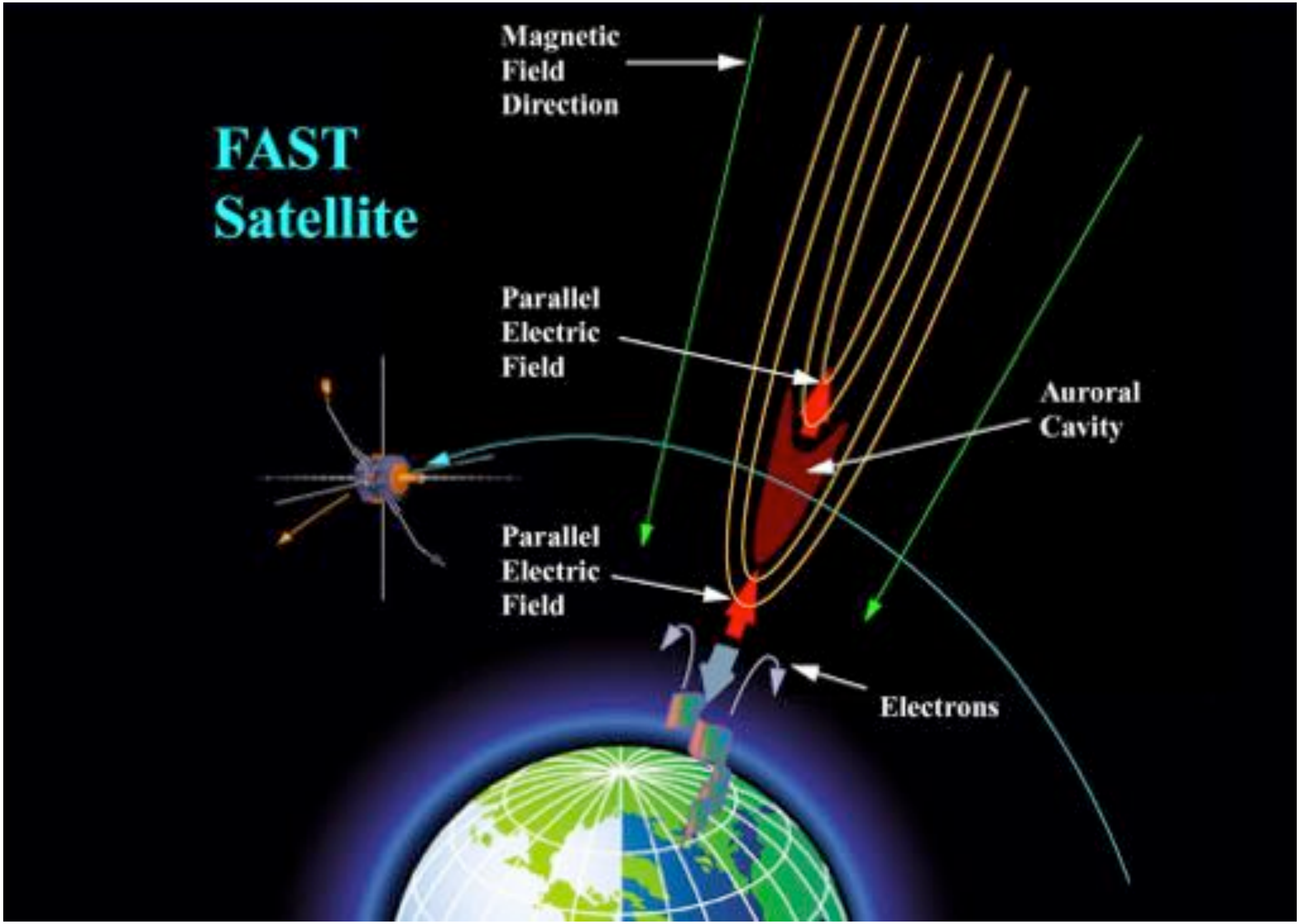
Go Juno!



Planetary Magnetic Dynamos – Questions:

A. What controls amount of non-dipole field?
B. Are dynamos of Earth, Jupiter, Sun similar – or completely different?
C. What controls variation in time?
D. Why do some dynamos die out?

Earth Auroral Current Region
Does same physics apply at Jupiter?

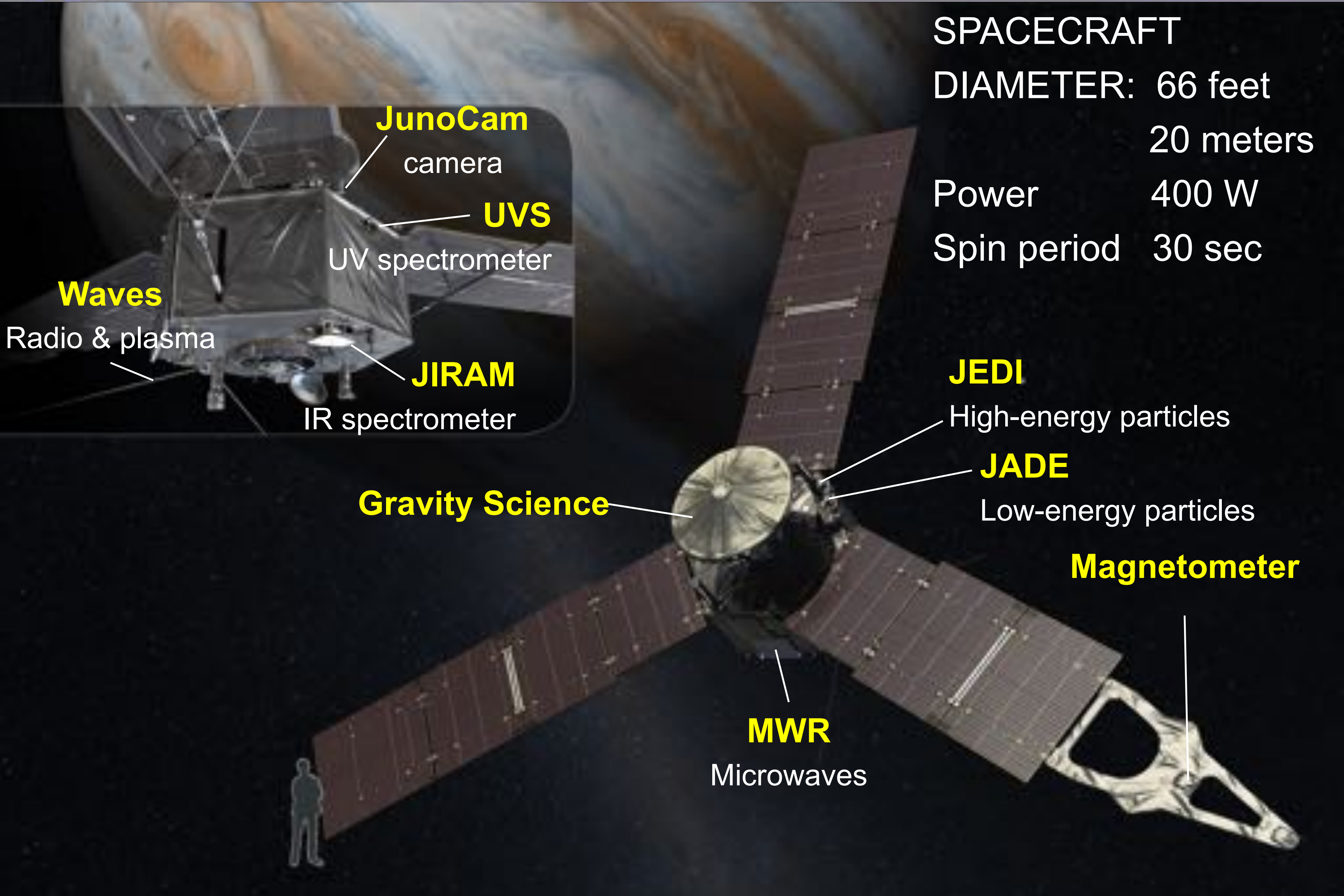


Spacecraft & Payload

Orbit Insertion
4th July 2016

SPACECRAFT

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



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