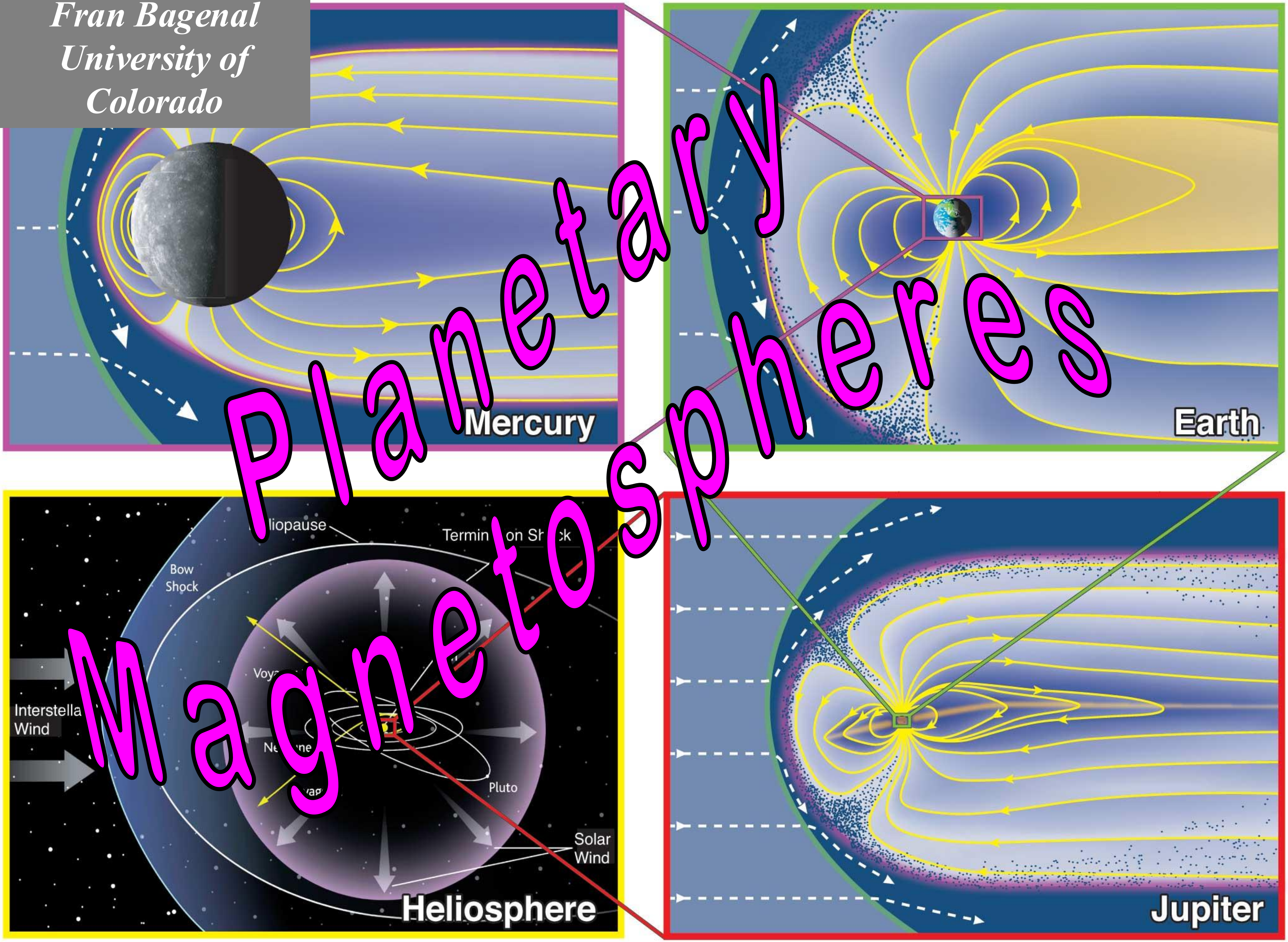
Planetary Magnetospheres

Fran Bagenal
University of Colorado

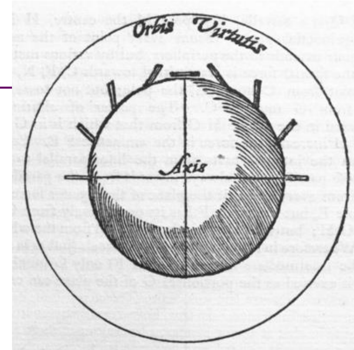


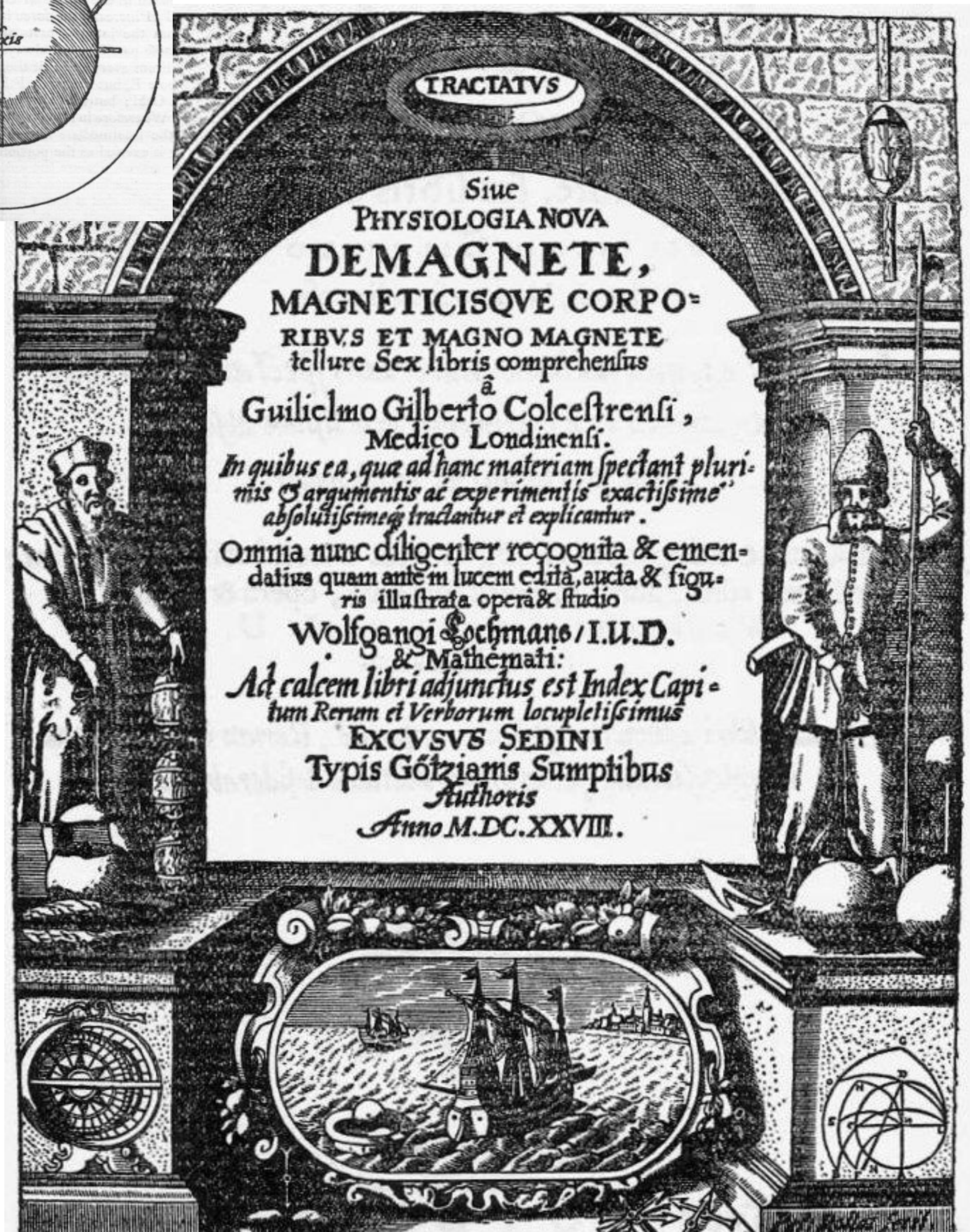
Which topic is (probably, at this point in time) your primary interest?

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

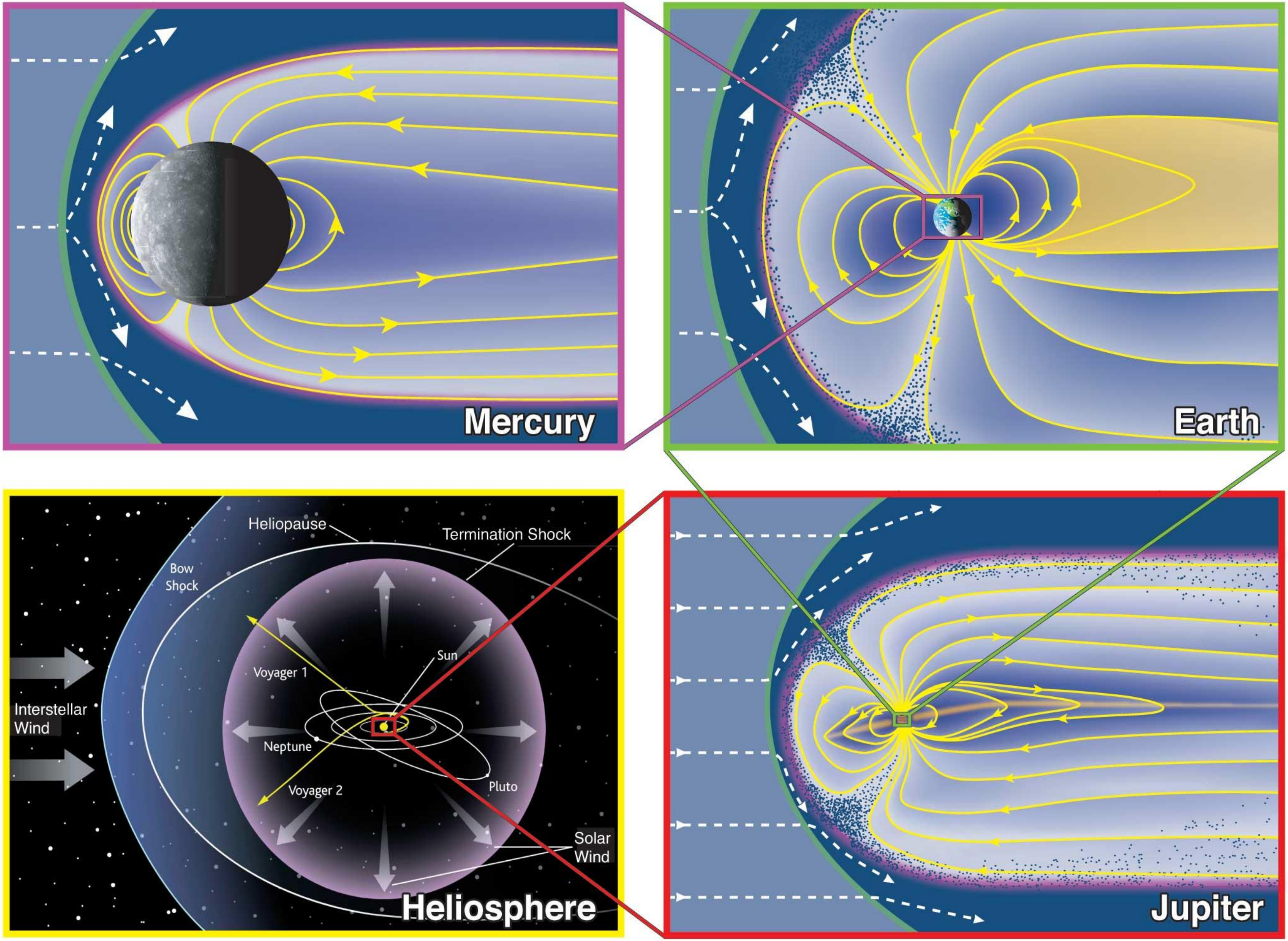
De Magnete
1600
William Gilbert

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





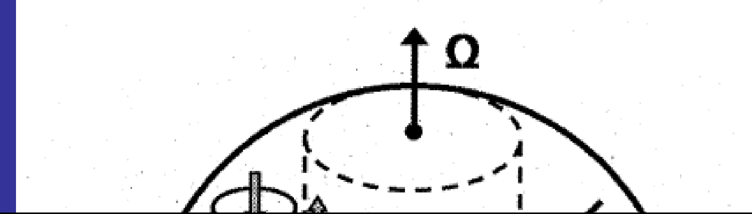
TRACTATVS
Siue
PHYSIOLOGIA NOVA
DE MAGNETE,
MAGNETICISQVE CORPORIBVS ET MAGNO MAGNETE tellure Sex libris comprehensus
à
Guilielmo Gilberto Colcestrensi,
Medico Londinensi.
In quibus ea, quæ ad hanc materiam spectant plurimis & argumentis ac experimentis exactissime absolutissimeq; tractantur et explicantur.
Omnia nunc diligenter recognita & emendatius quam ante in lucem edita, aucta & figuris illustrata operâ & studio
Wolfgangi Lochmans / I.U.D. & Mathemati:
Ad calcem libri adjunctus est Index Capitum Rerum et Verborum locupletissimus
EXCVSVS SEDINI
Typis Götzianis Sumptibus Authoris
Anno M.DC.XXVIII.


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

Planetary Magnetic Dynamos

What are the 3 main ingredients for a planetary dynamo?

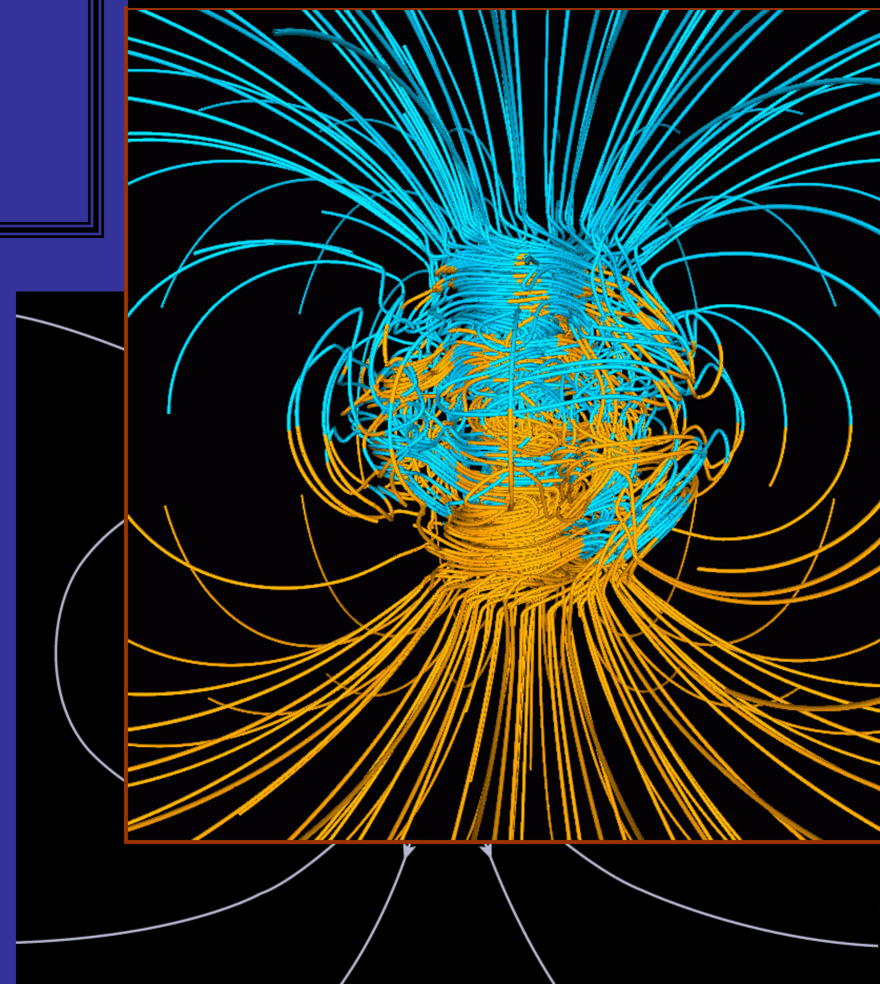
Planetary Dynamos

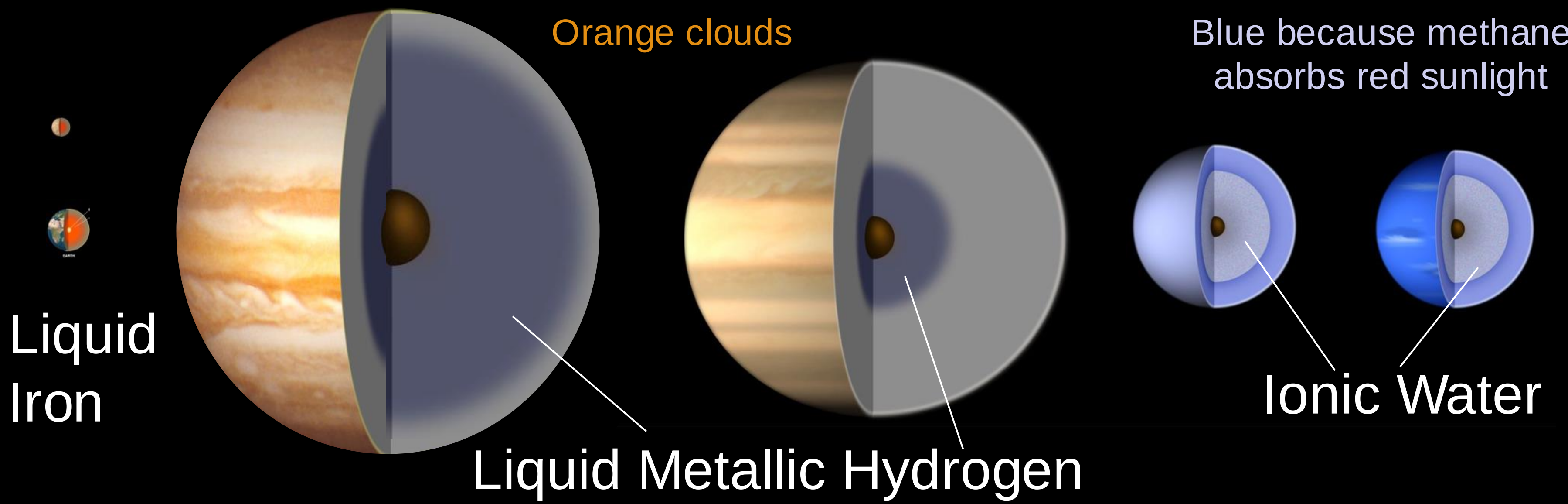


Volume of electrically conducting fluid (1) which is convecting (2) and rotating (3)

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

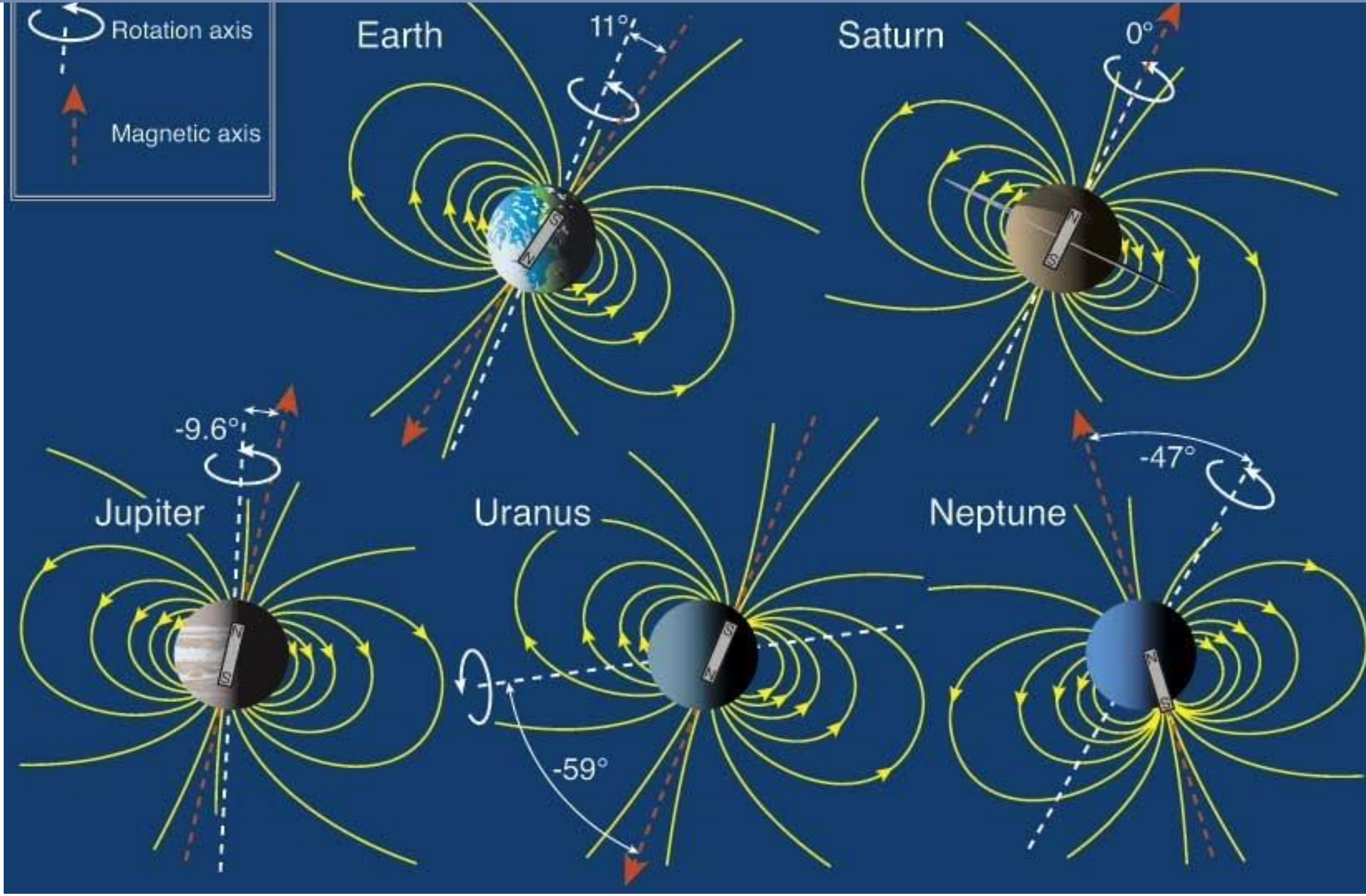
Earth dynamo model - From Glatzmeier and Roberts





	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

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

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

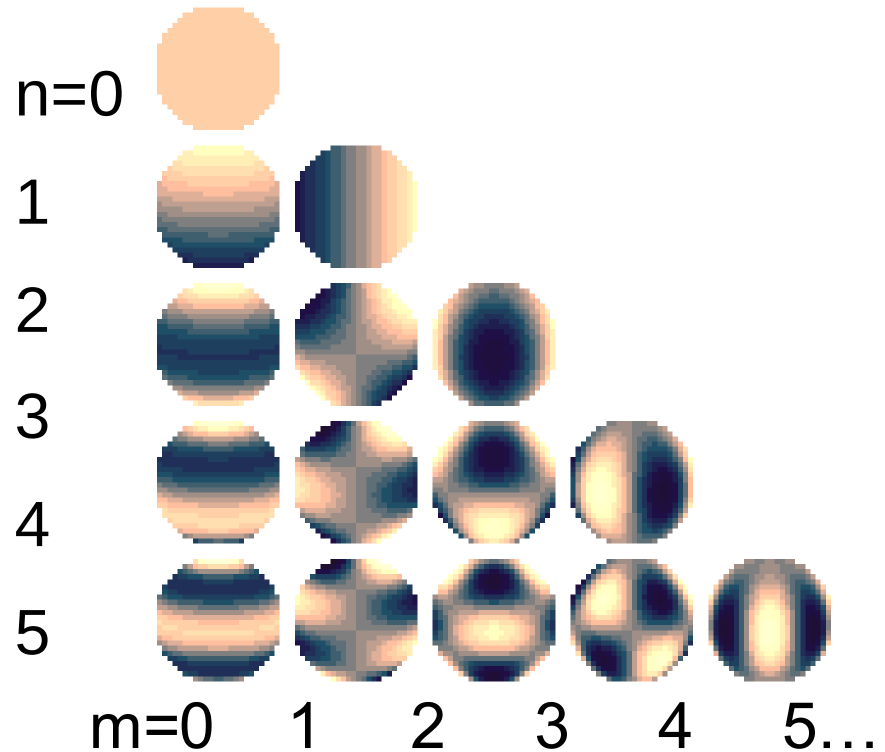
coefficients - constants

functions

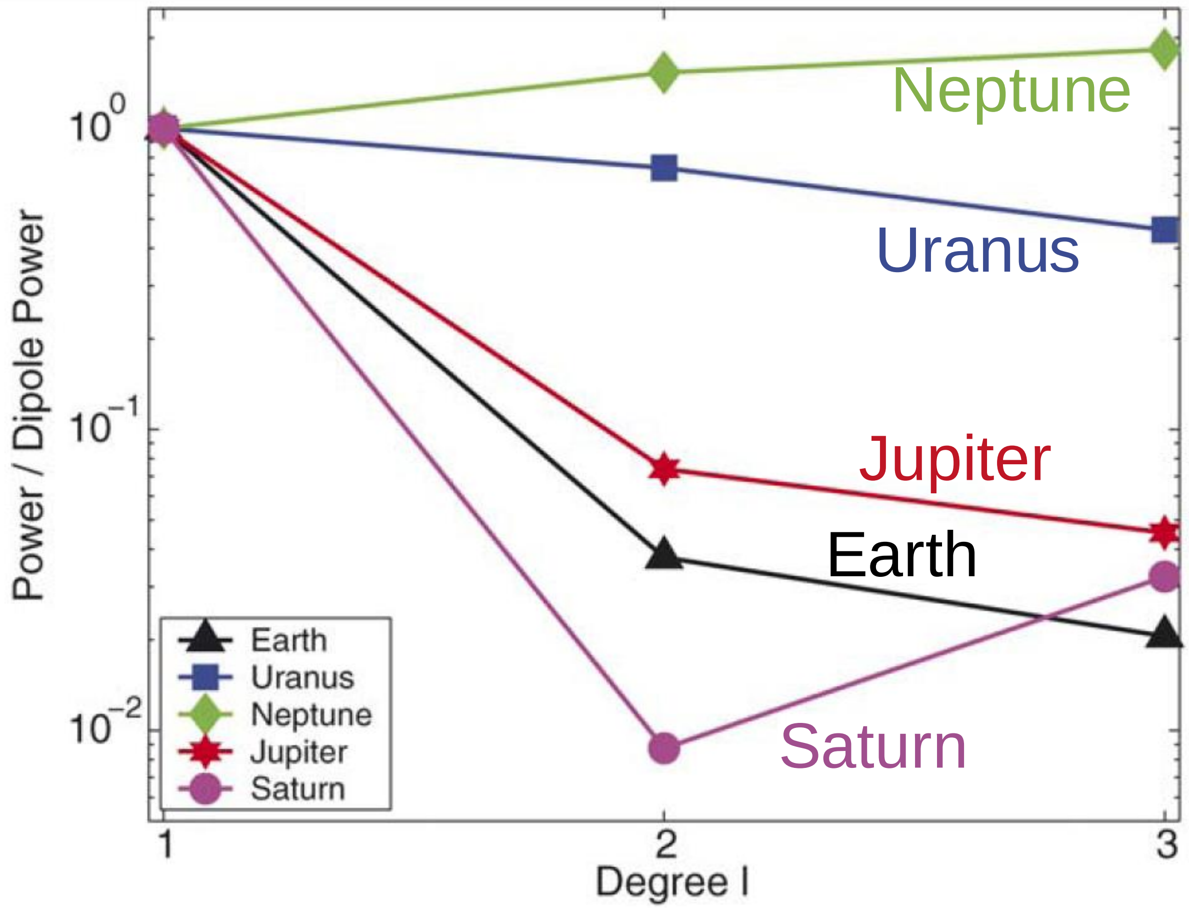
$$P_0^0(\cos\theta) = 1$$
$$P_1^0(\cos\theta) = \cos\theta$$
$$P_1^1(\cos\theta) = -\sin\theta$$
$$P_2^0(\cos\theta) = \tfrac{1}{2}(3\cos^2\theta - 1)$$
$$P_2^1(\cos\theta) = -3\cos\theta\sin\theta$$
$$P_2^2(\cos\theta) = 3\sin^2\theta$$
$$P_3^0(\cos\theta) = \tfrac{1}{2}(5\cos^3\theta - 3\cos\theta)$$

Dipole

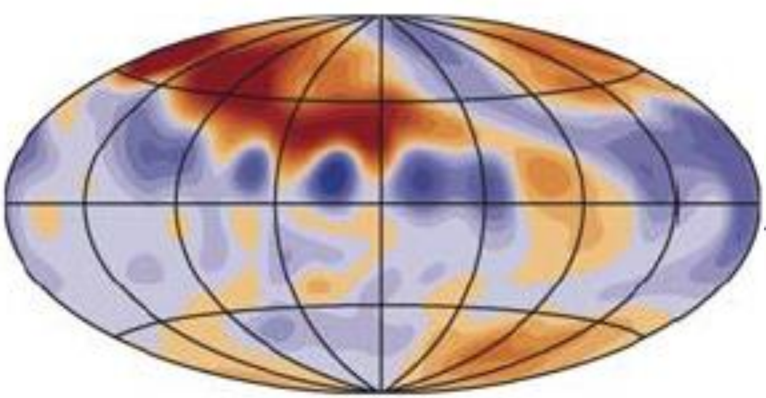
Quadrupole

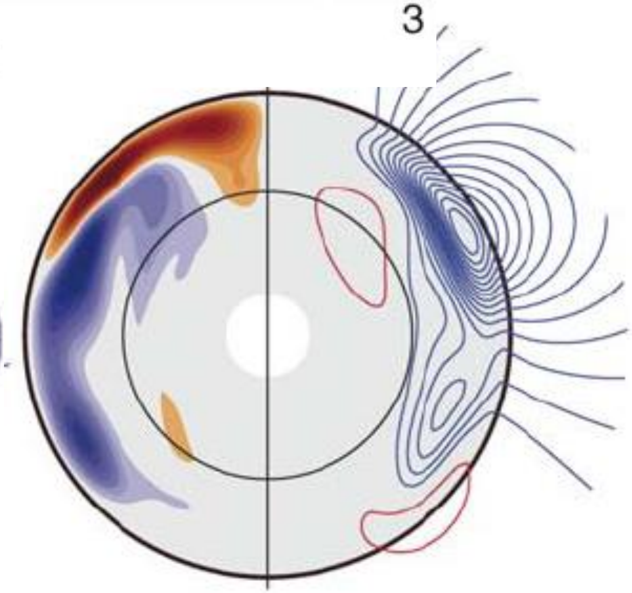


Stanley & Bloxham 2006



Multipole coefficients / Dipole coefficient Indicates degree of complexity



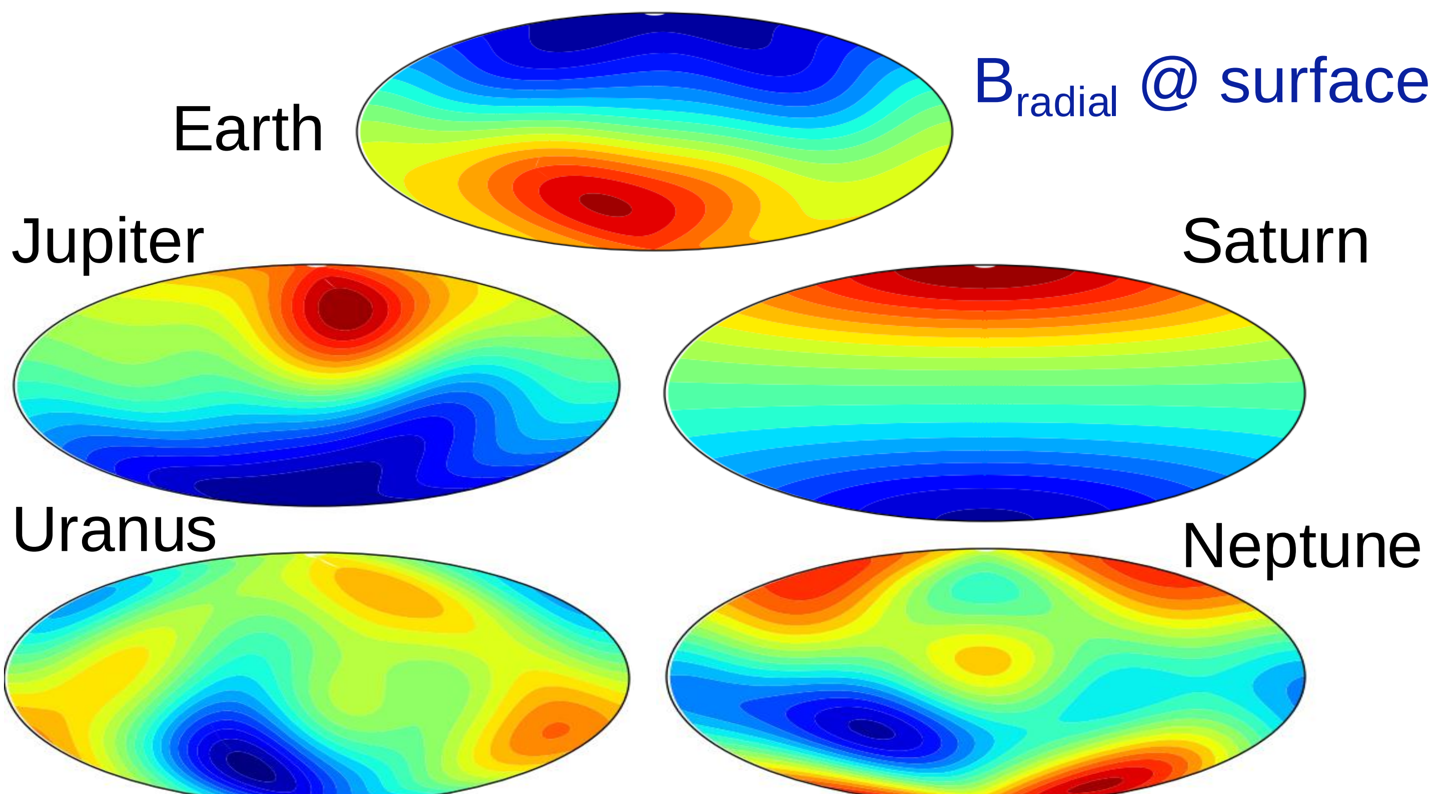


Modeling Uranus' & Neptune's non-dipolar fields with a thin-shell dynamo over a stratified core

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

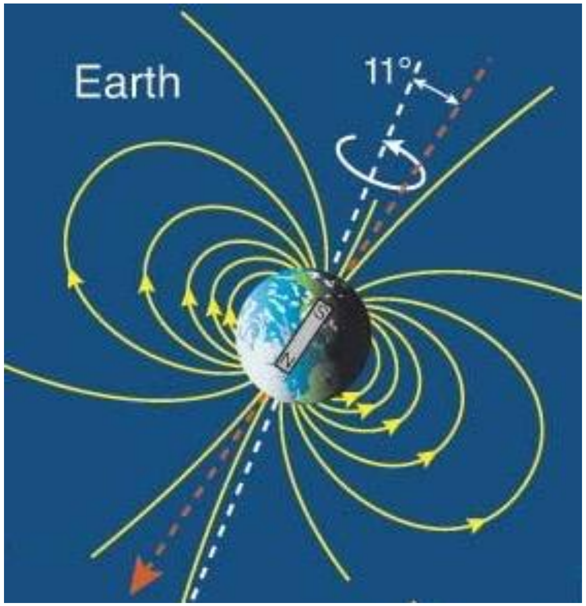
Dipolar (Earth, Jupiter, Saturn)

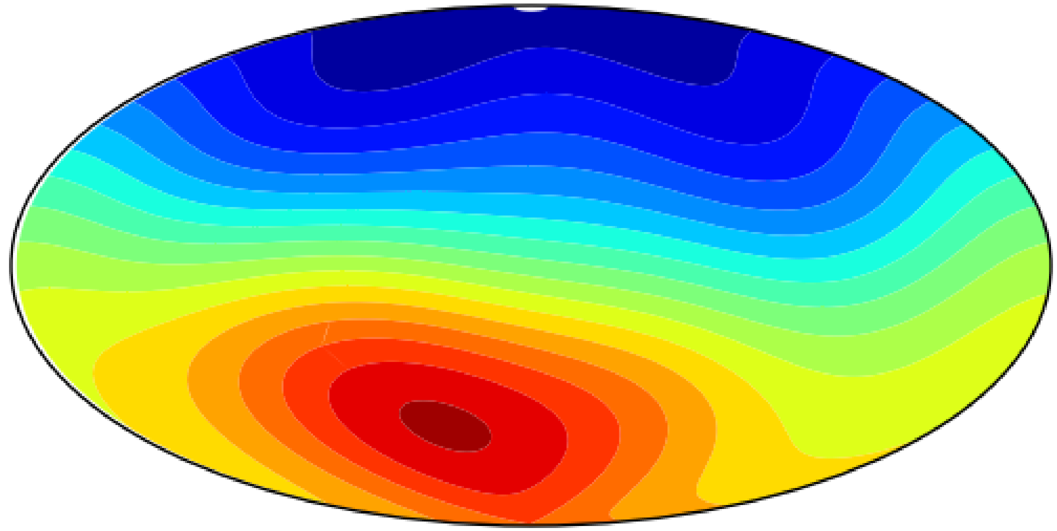
Irregular (Uranus, Neptune)



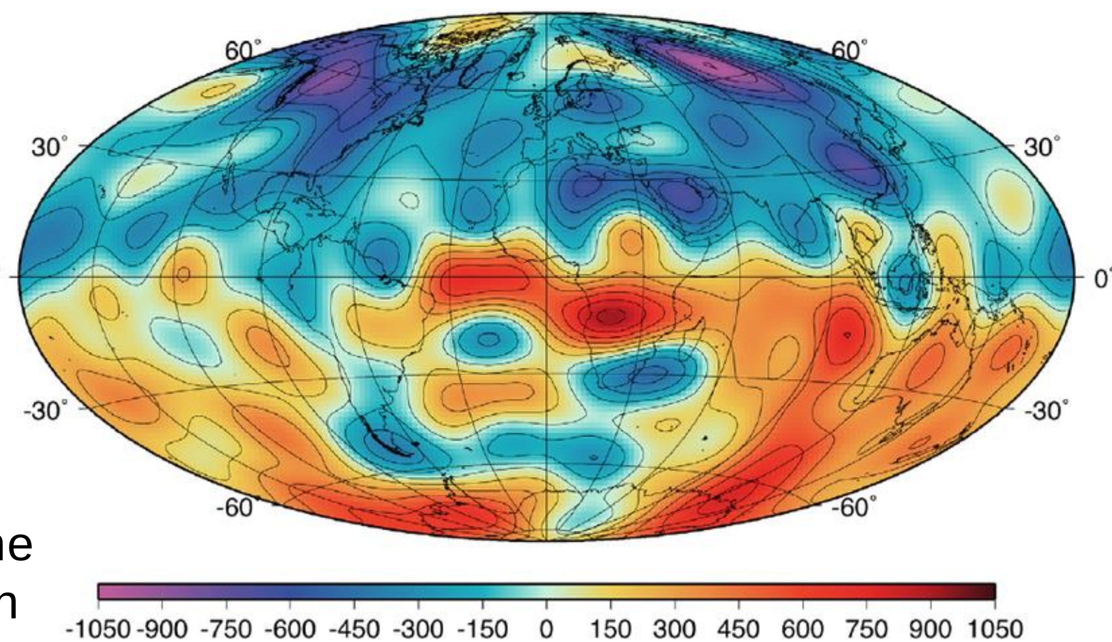
Stanley & Bloxham 2006

Earth's Magnetic Field



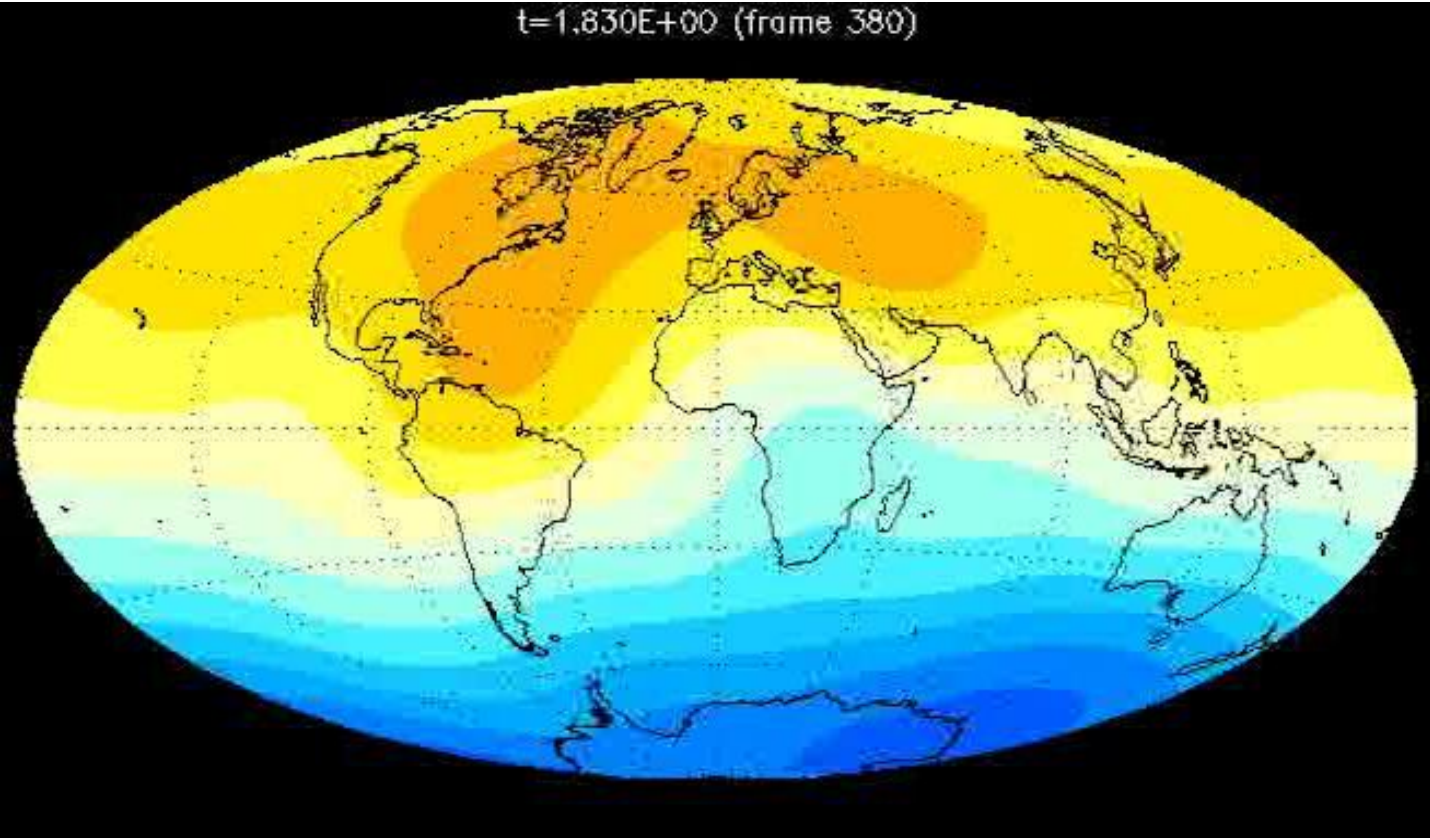


When you look closer there's more complexity



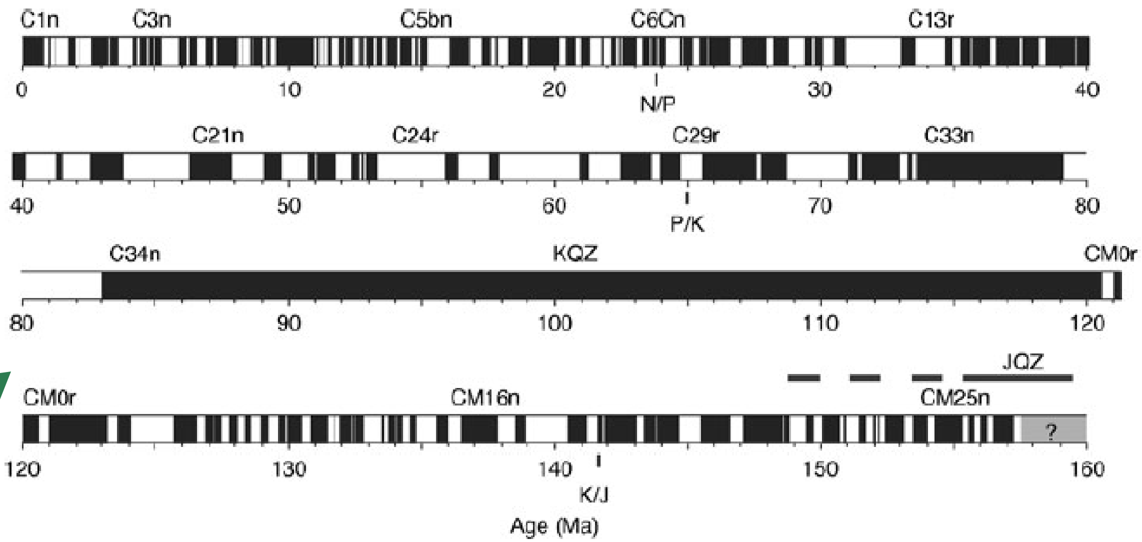
Earth's field extrapolated down to the top of the outer core dynamo region

Br through a reversal



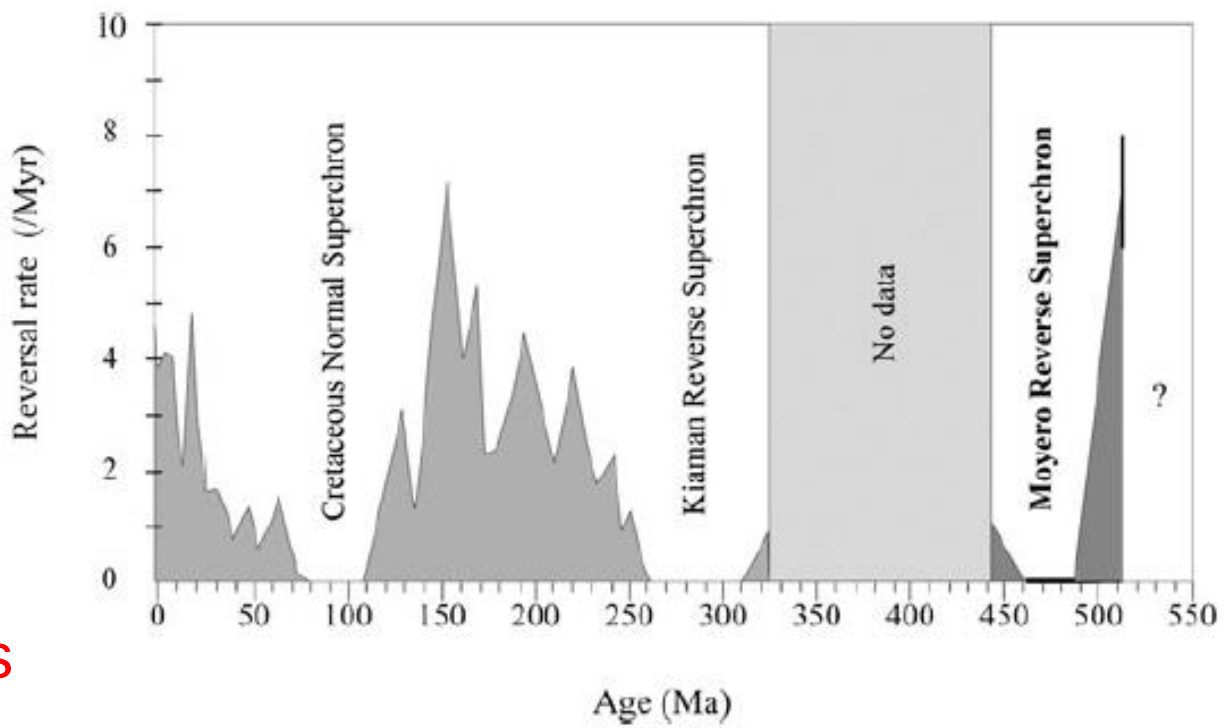
Hulot et al. 2010
Pavlov & Gallet 2005

Polarity reversals:



1. variable in duration and

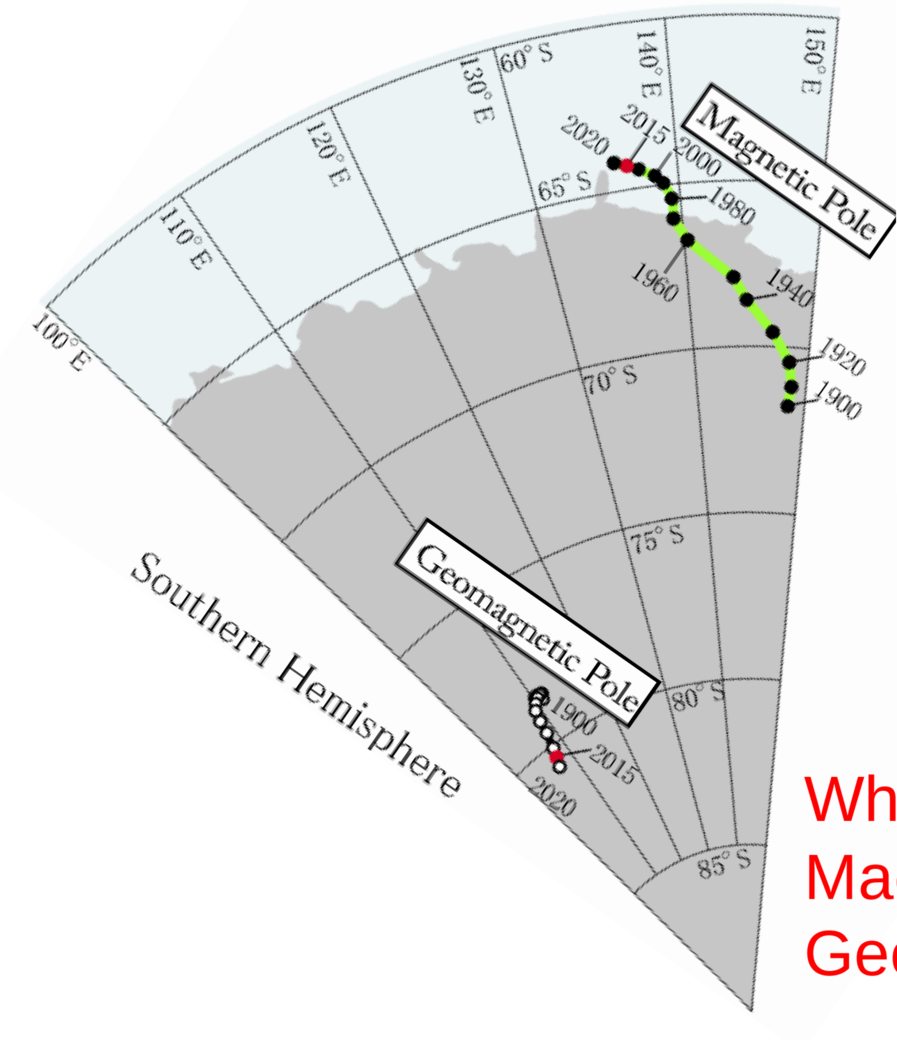
2. rate

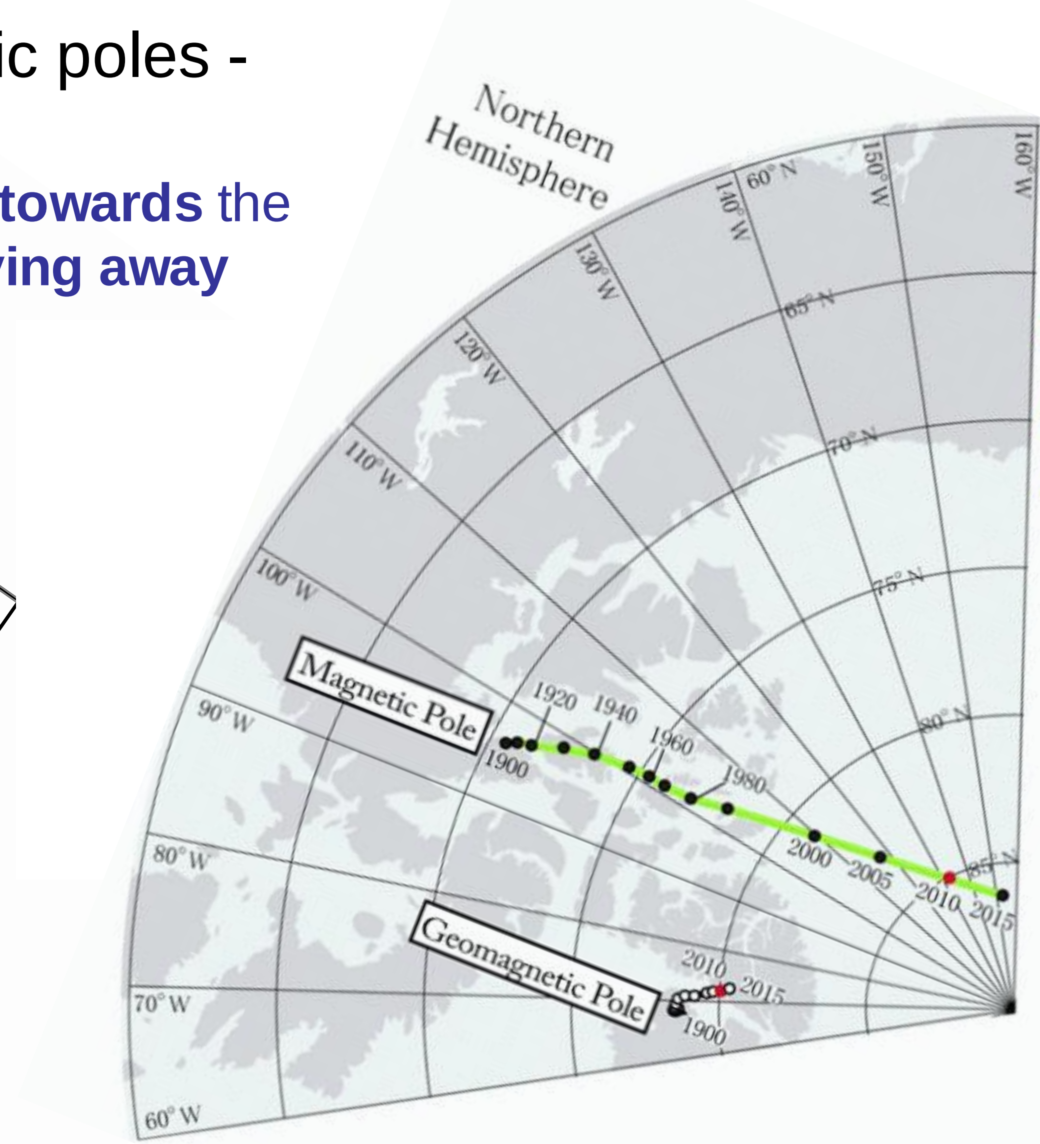


rapid rate
~ 5/million years
~ every 200,000 yrs

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?

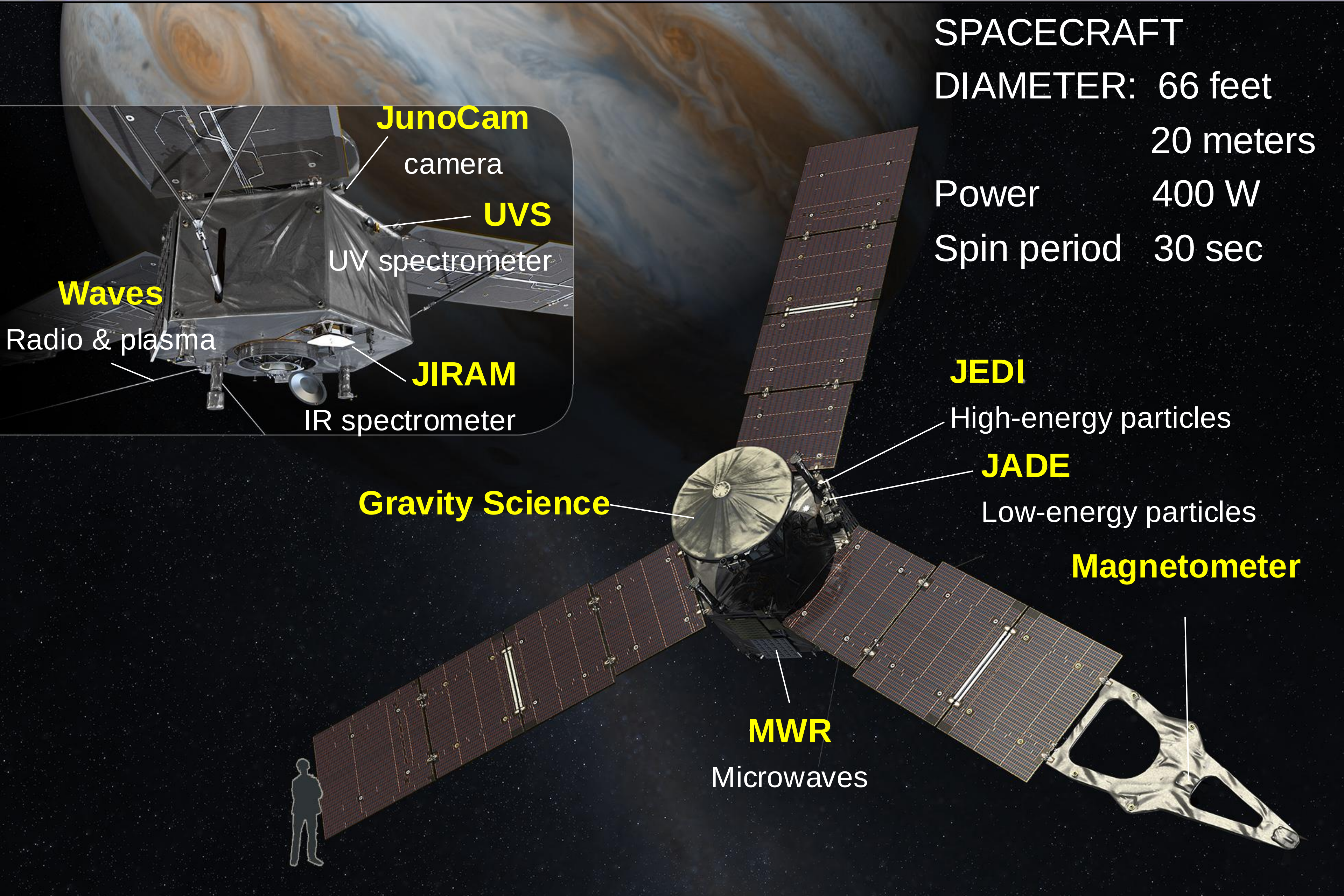
Magnetic Poles = where B = Br

Geomagnetic Poles = best fit dipole

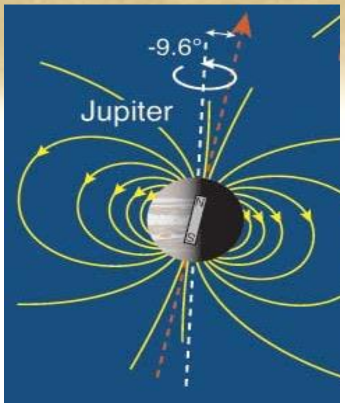
Spacecraft & Payload

Orbit Insertion
4th July 2016

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

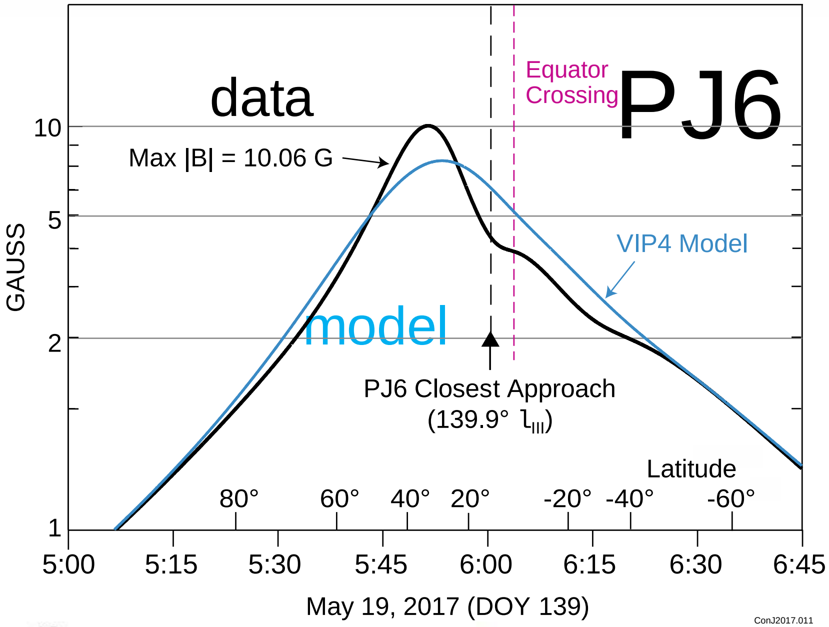


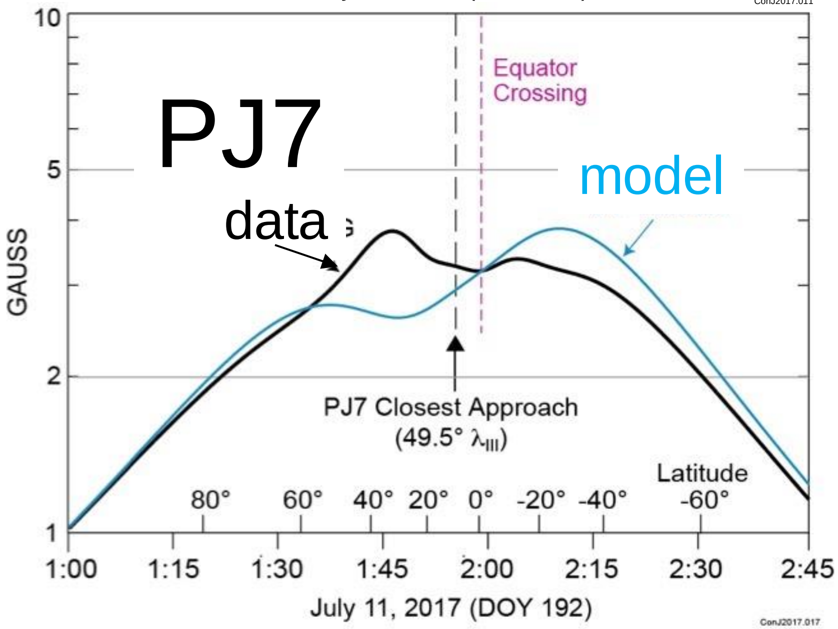
Jupiter's Magnetic Field



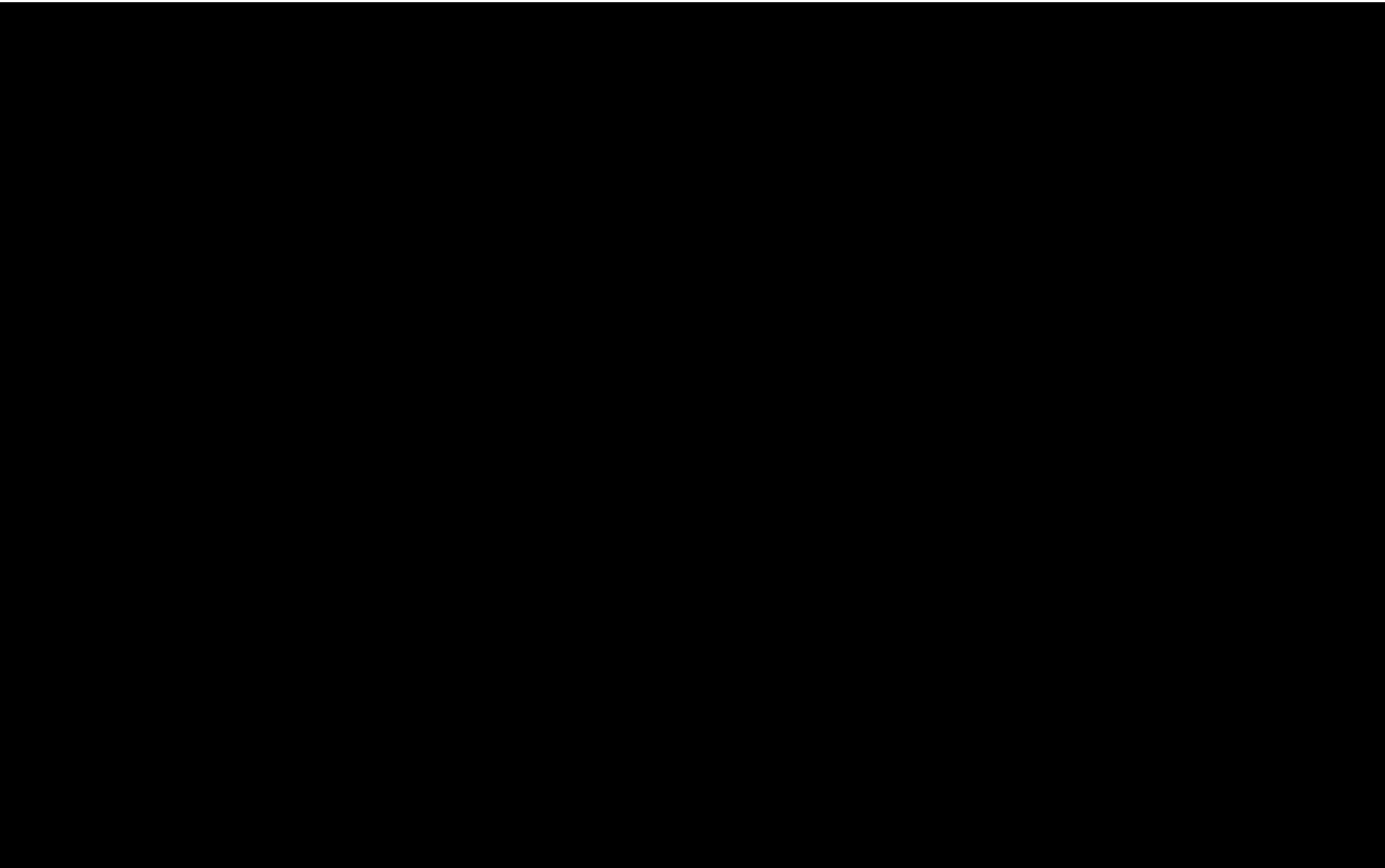
- Juno's first few passes are showing deviations from previous simple models

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



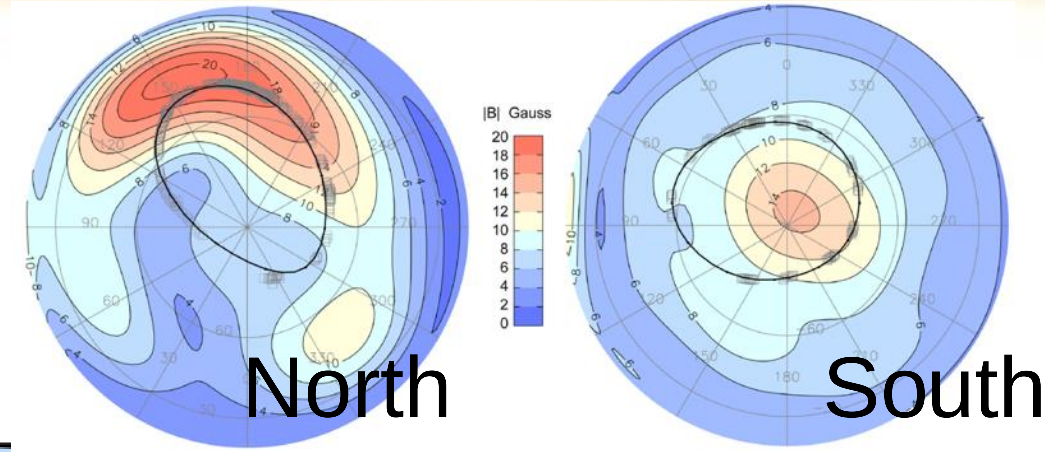


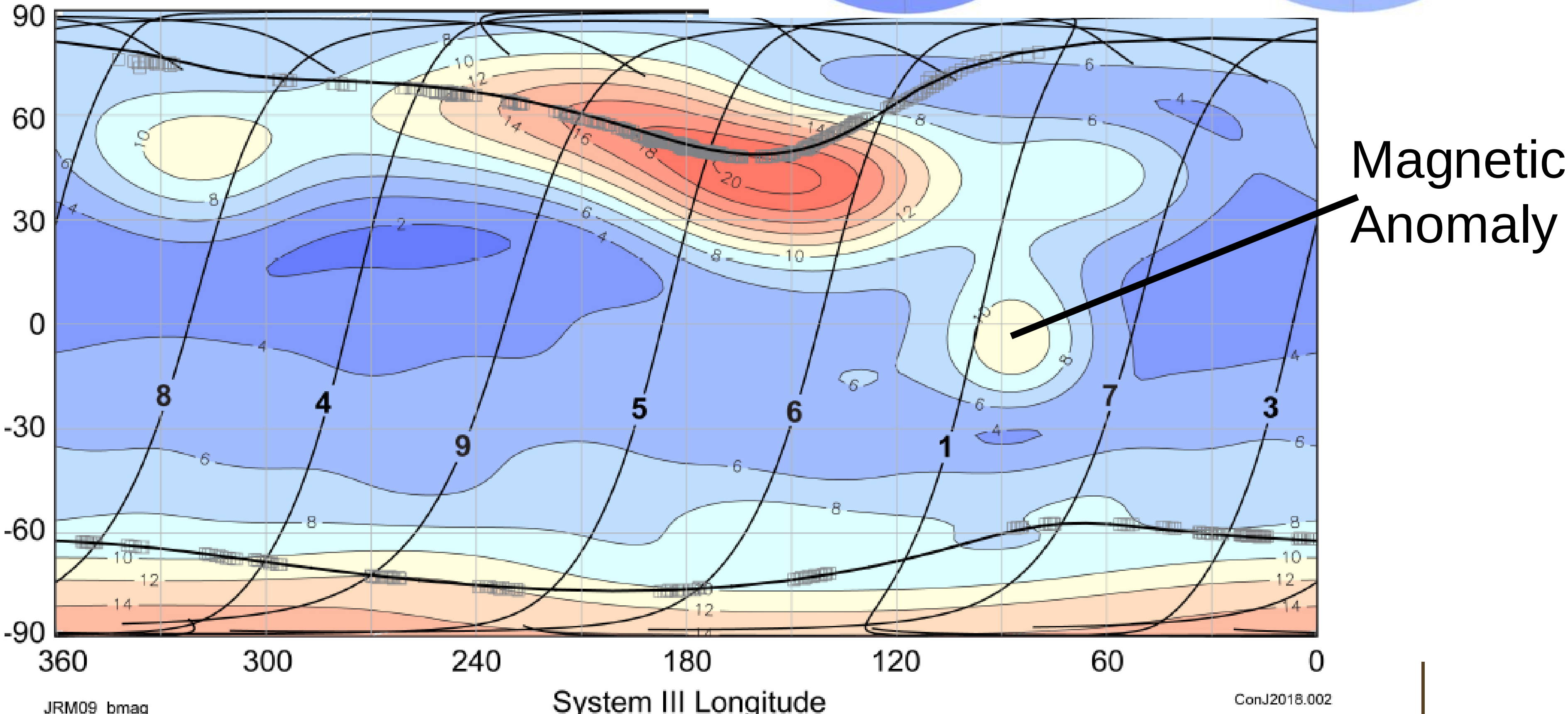
Juno - based magnetic field model



Juno-based magnetic field model

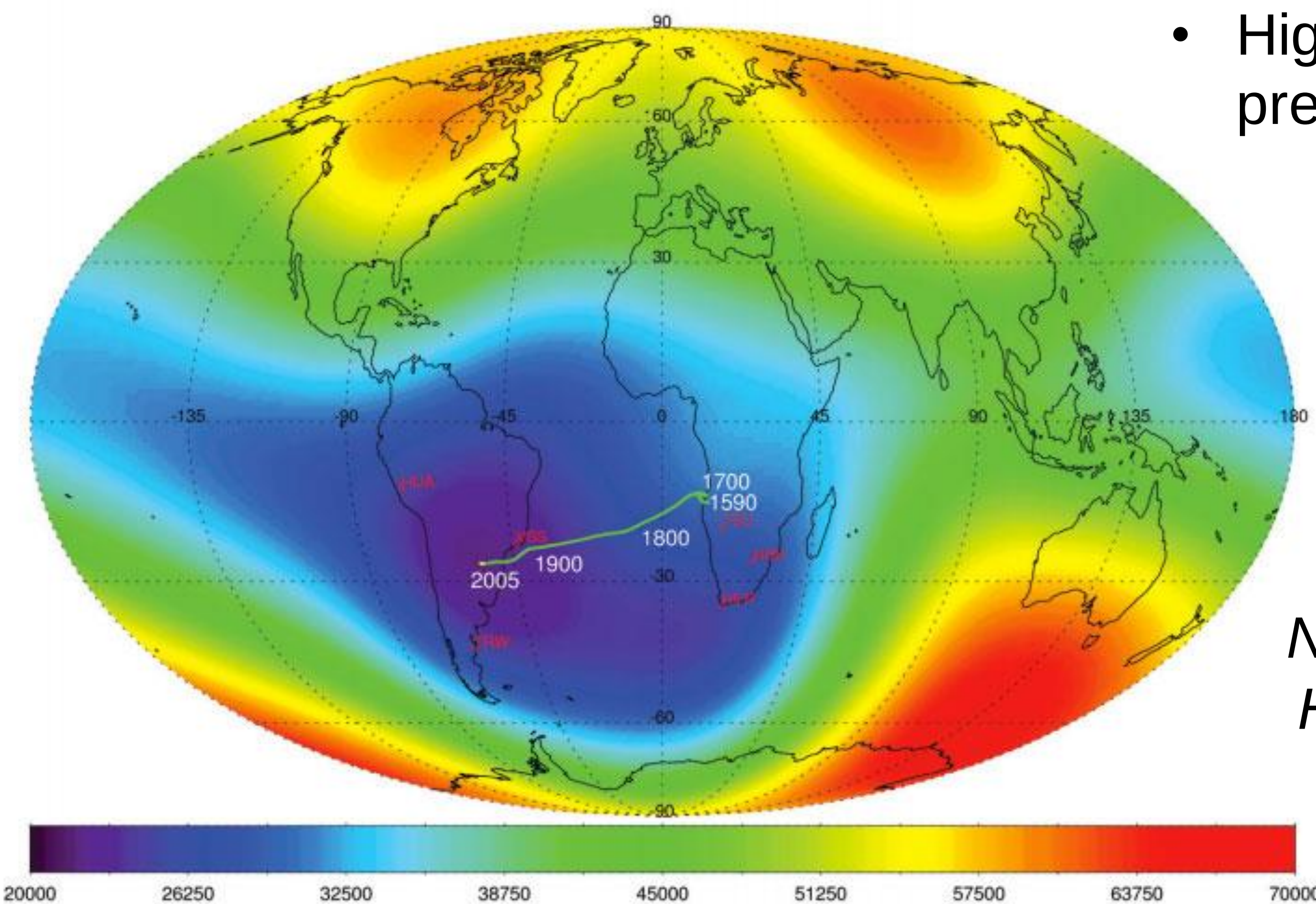
Big N-S asymmetries!





Earth's South American Anomaly

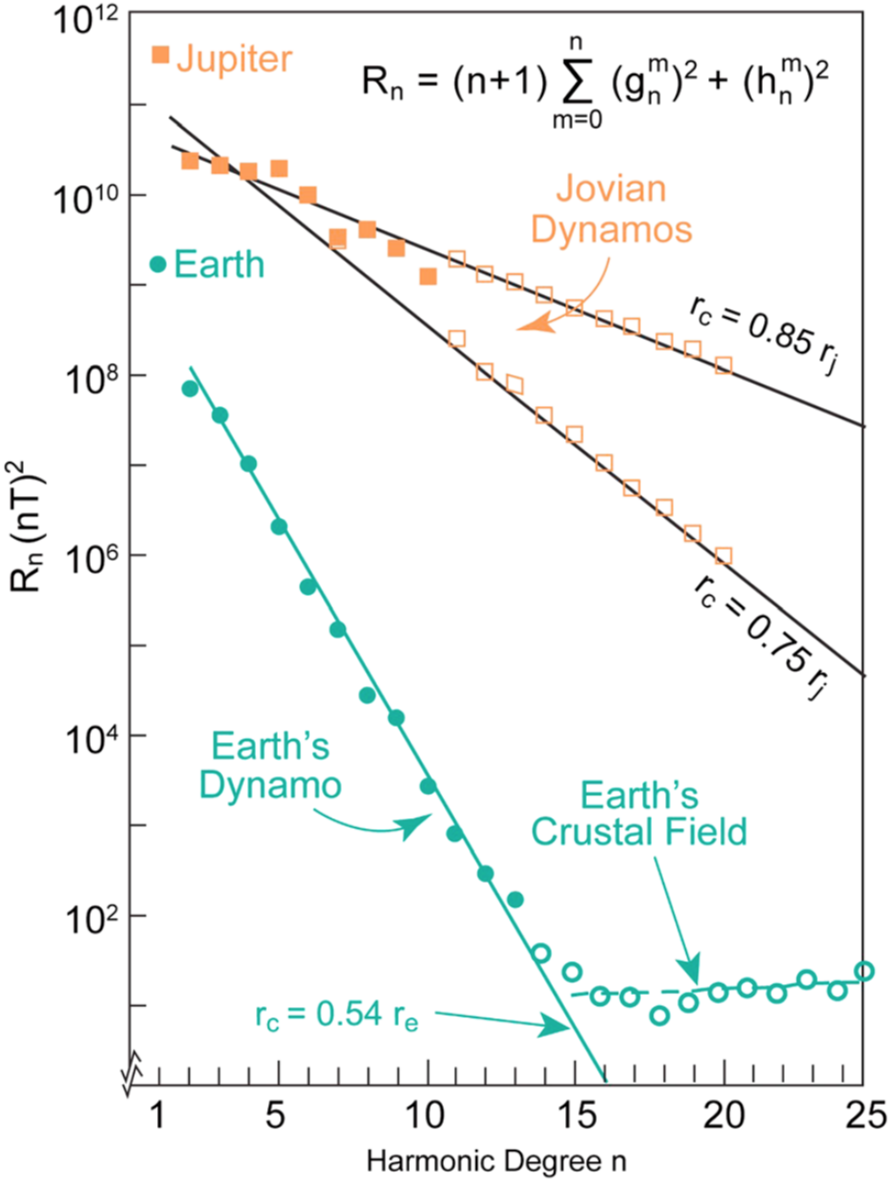
- Weak field region
- High radiation precipitation

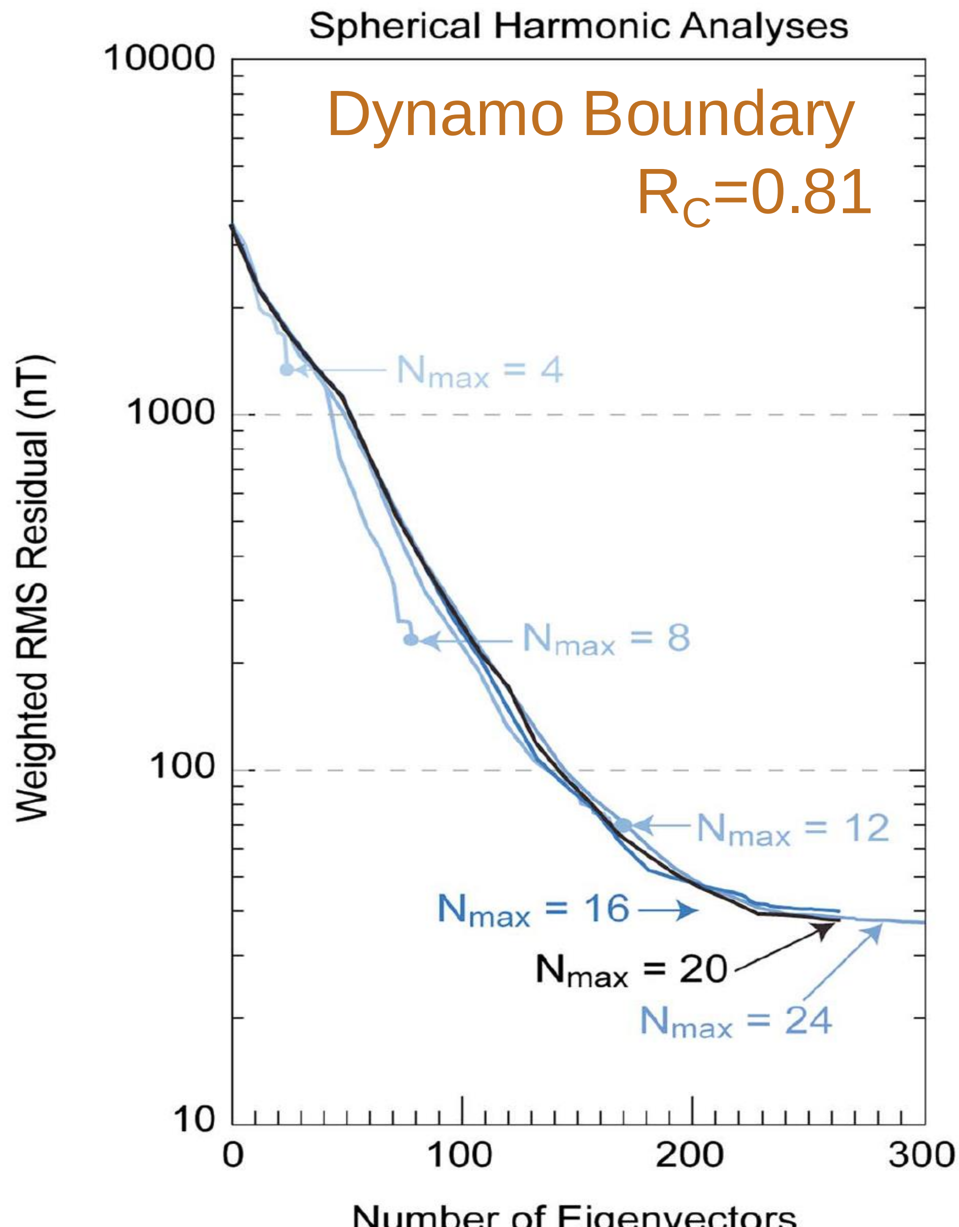


Nasty place for Hubble Space Telescope!

Juno

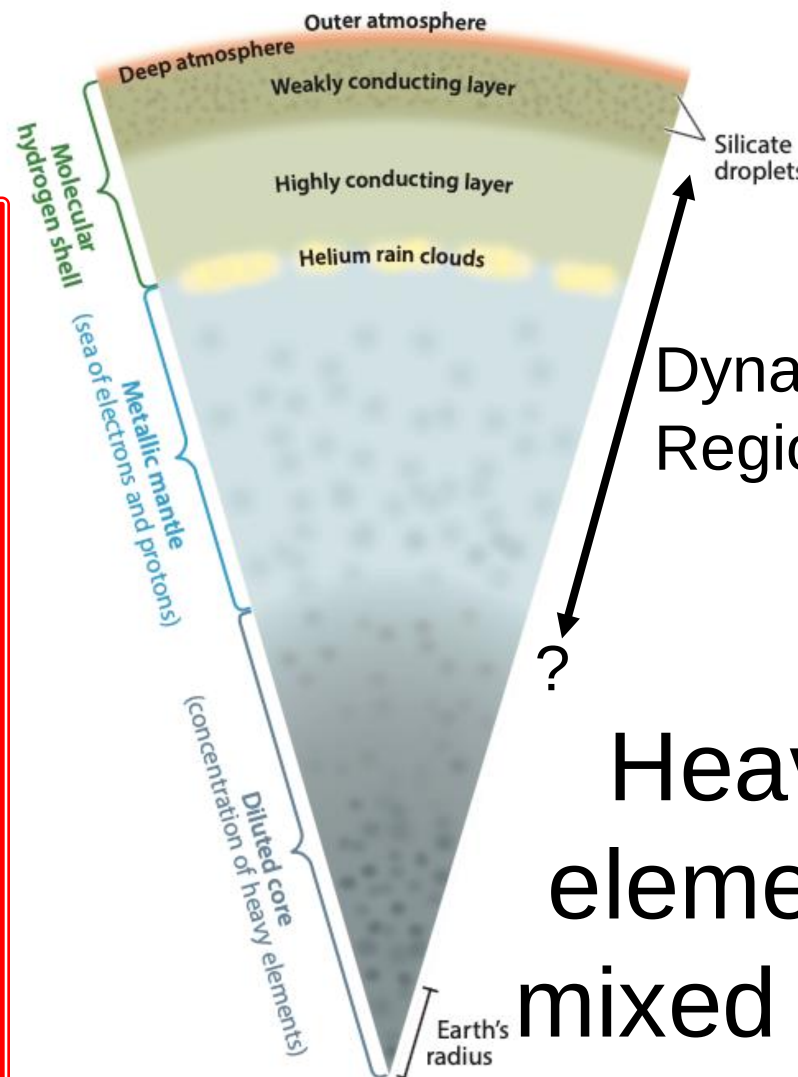
Connerney et al. 2018, 2022





Measured gravity field

- *No distinct core*
- *Heavy elements partially mixed*
- *Helium raining out of outer layer*
- *All boundaries fuzzy?!*



Dynamo Region

?

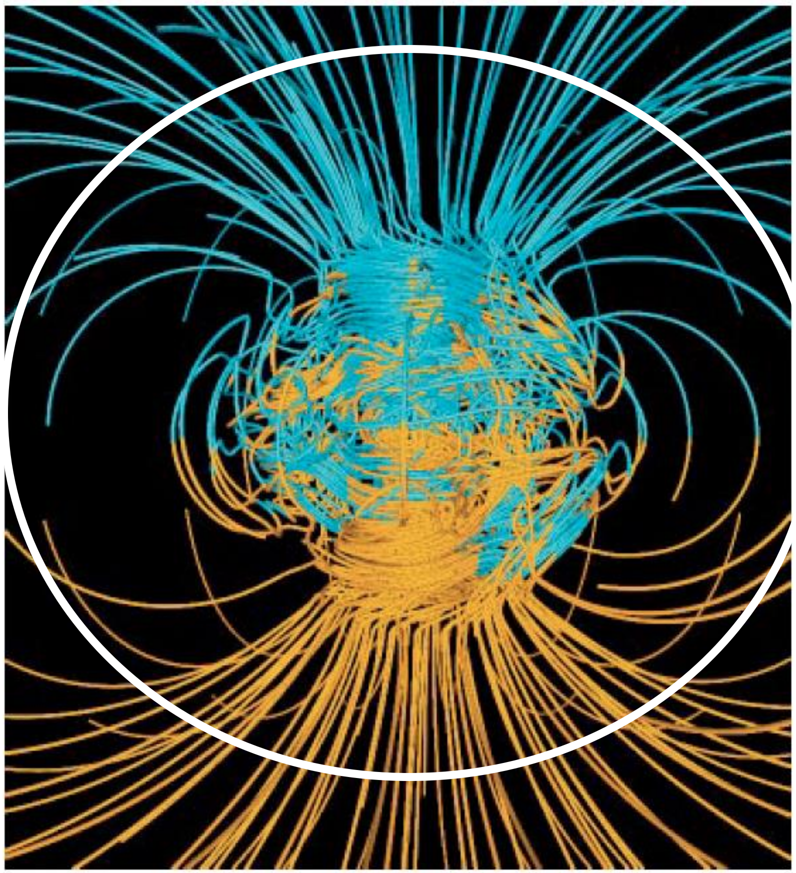
Heavy elements mixed with metallic H to ~40% radius

Iess et al. 2018 *Nature*

Implications for Dynamo

Earth: Dynamo deep in core – outer field ~dipole

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

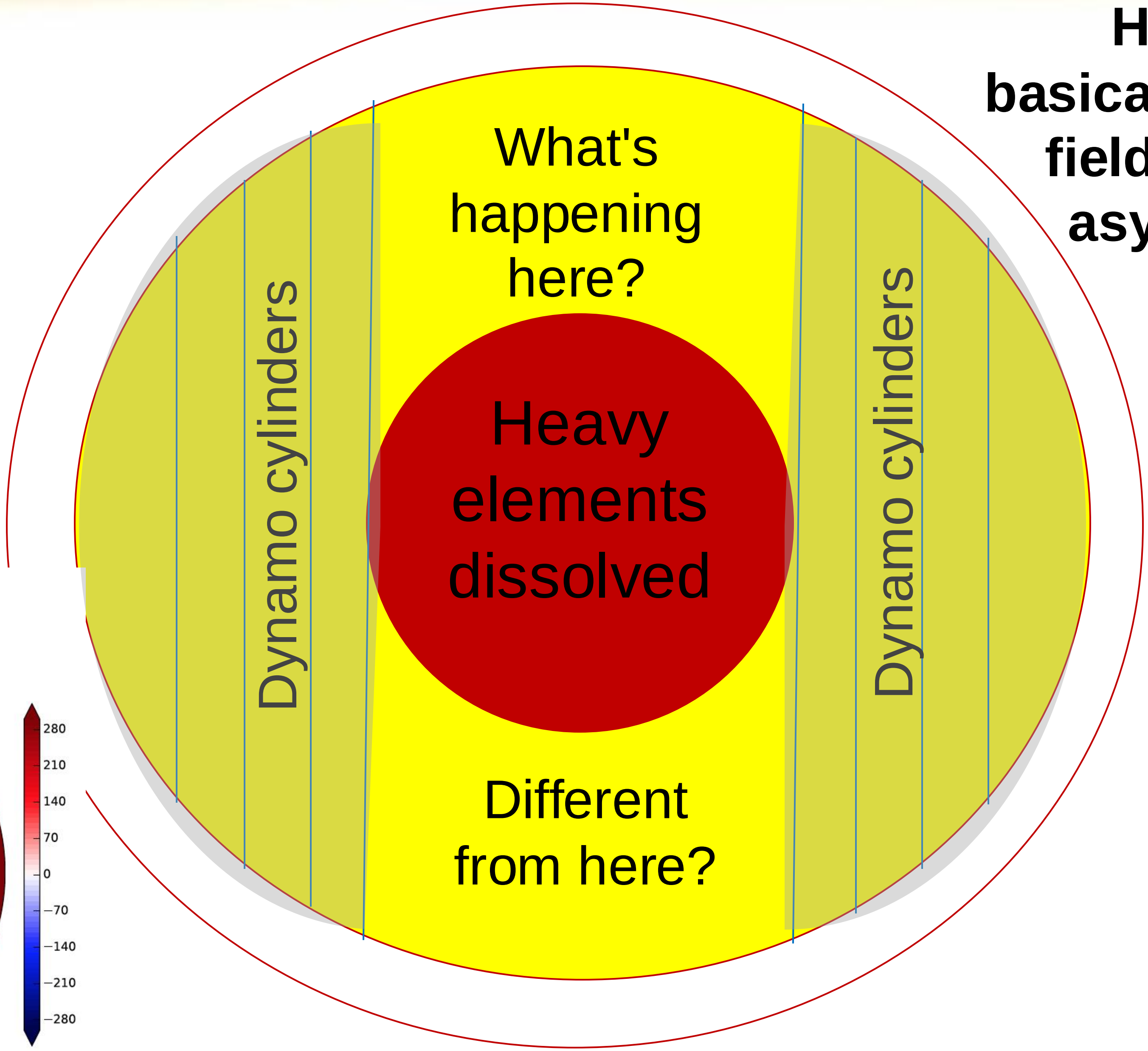


Glatzmeier 2002

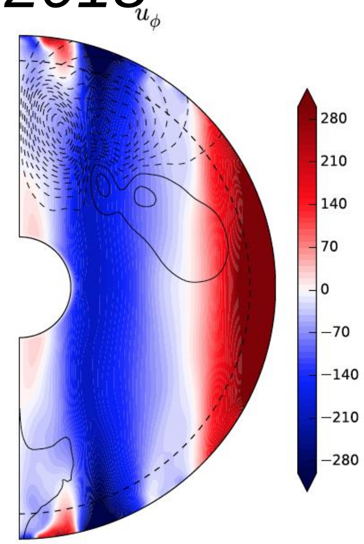
Glatzmeier 2005

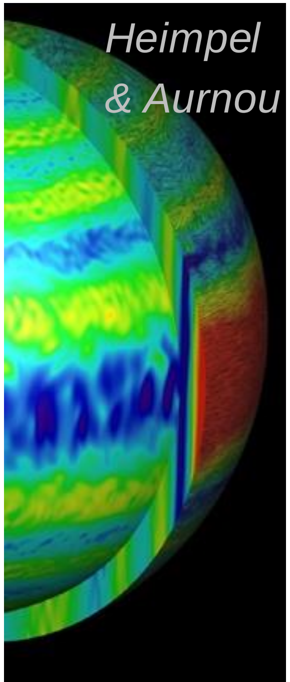
Implications for Dynamo in Rapid Rotator

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

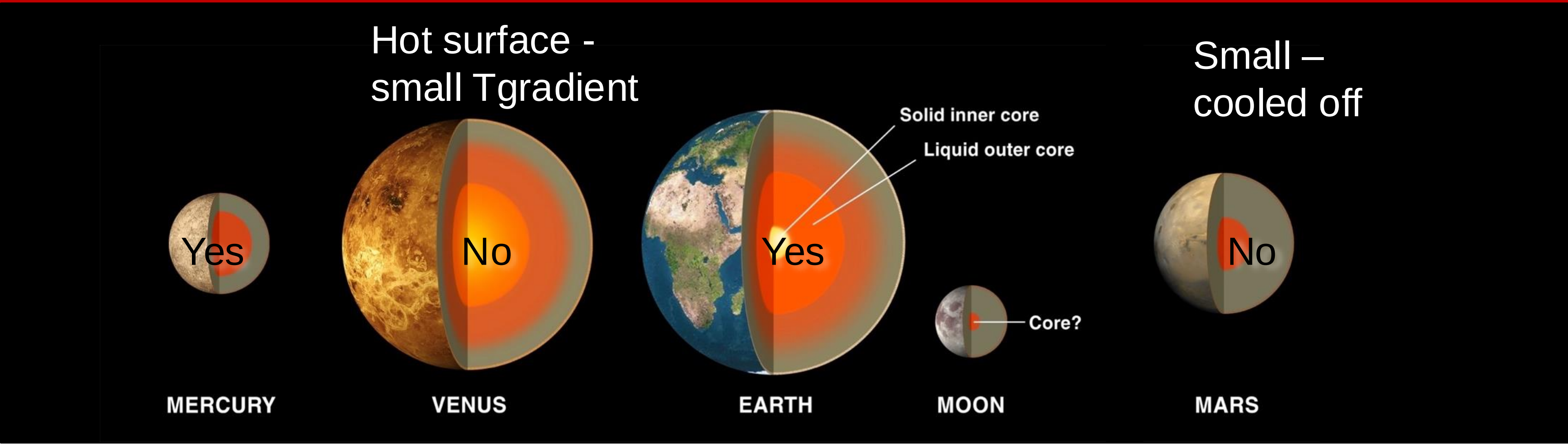


Duarte et al. 2018





WHICH HAVE ACTIVE MAGNETIC DYNAMOS?



Why Don't Venus or Mars have Dynamos?

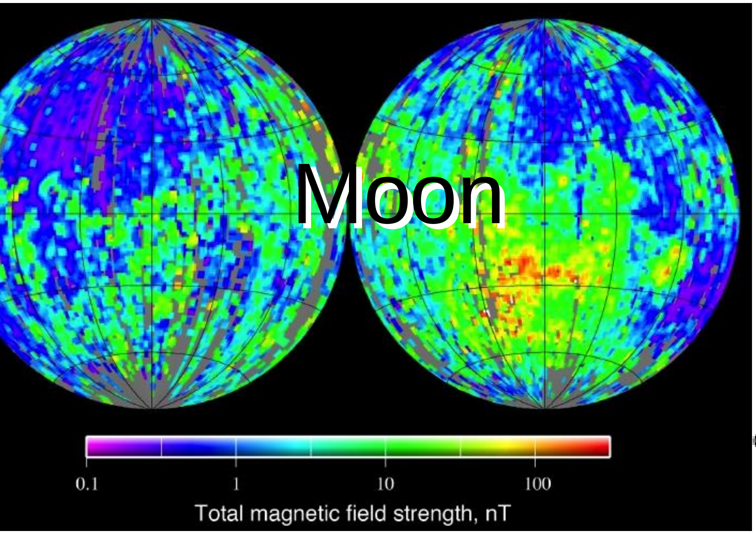
- Enough rotation – even for Venus
- Conducting fluid core – probably
- Lack of convection in core?

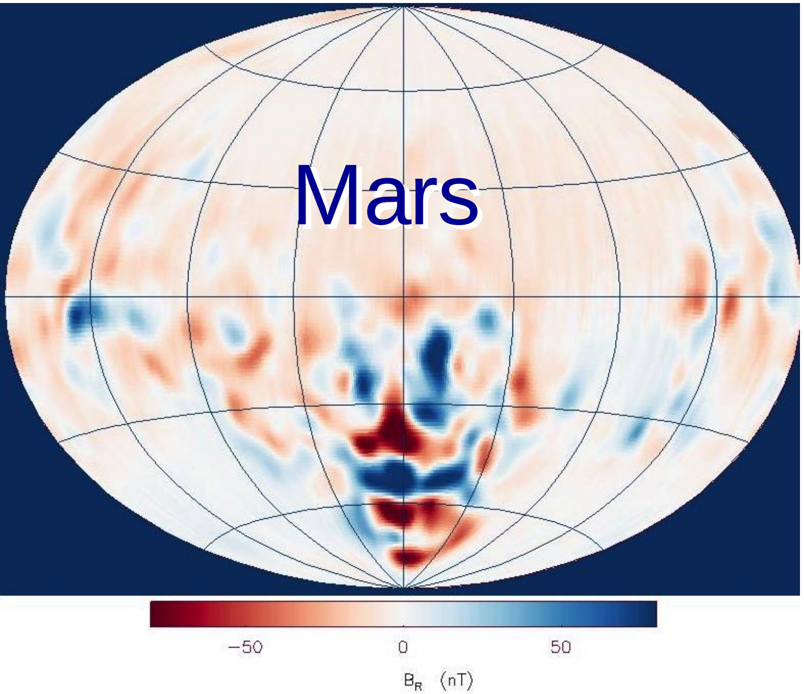
1. If....Mantle convection controls heat flow from core. Then....Lack of plate tectonics suggests less efficient cooling of interior and lower heat flux from core
2. No inner core means no latent heat of solidification and no enhancement of lighter material in the outer core

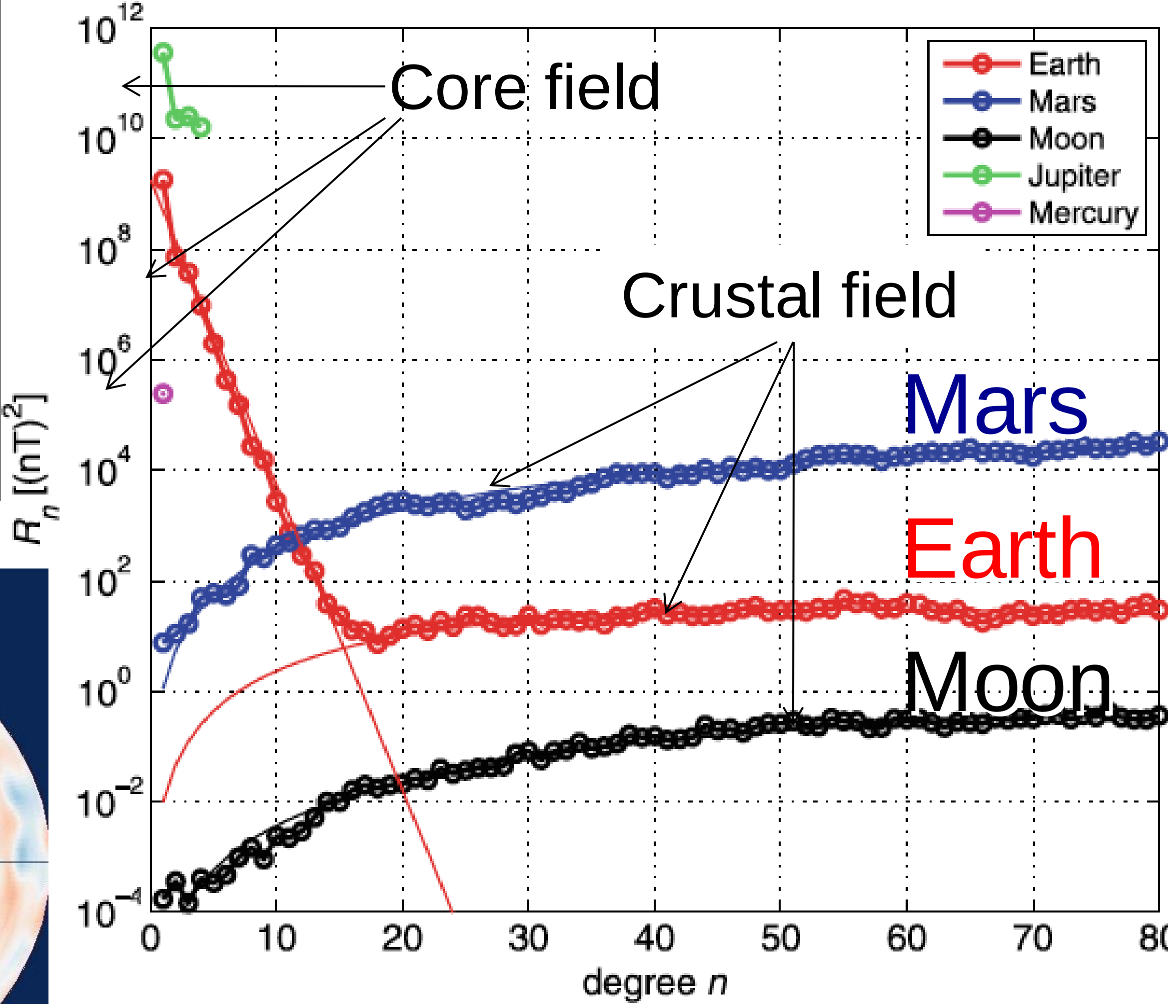
Need geophysics missions that address interior structure

Stevensen 2010

Moon & Mars: All Crustal Remanent Magnetization

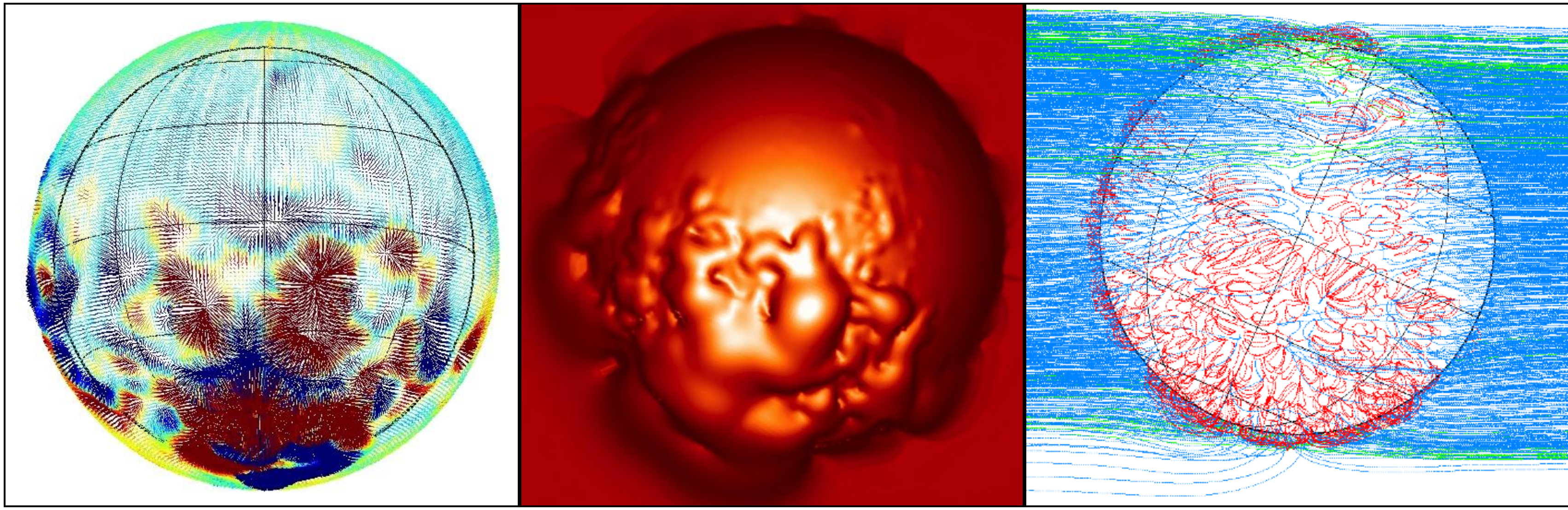






- Did Moon ever have dynamo?
- Mars' dynamo died >3.5 BYA.

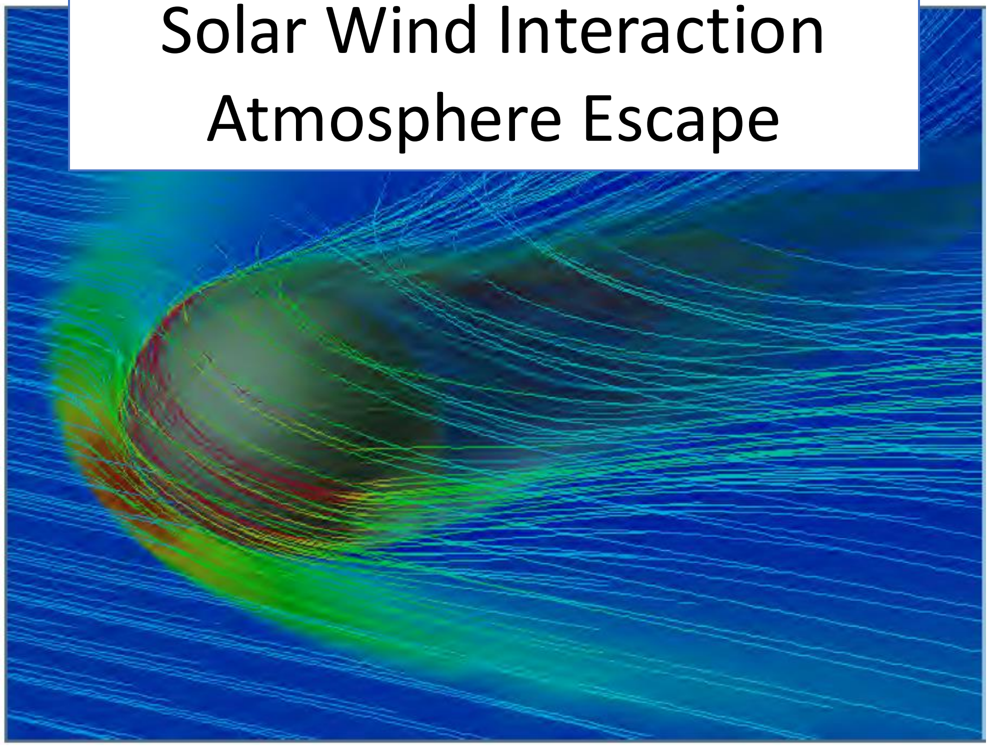
Mars:
Weak, irregular field
-> bumpy surface + changing topology



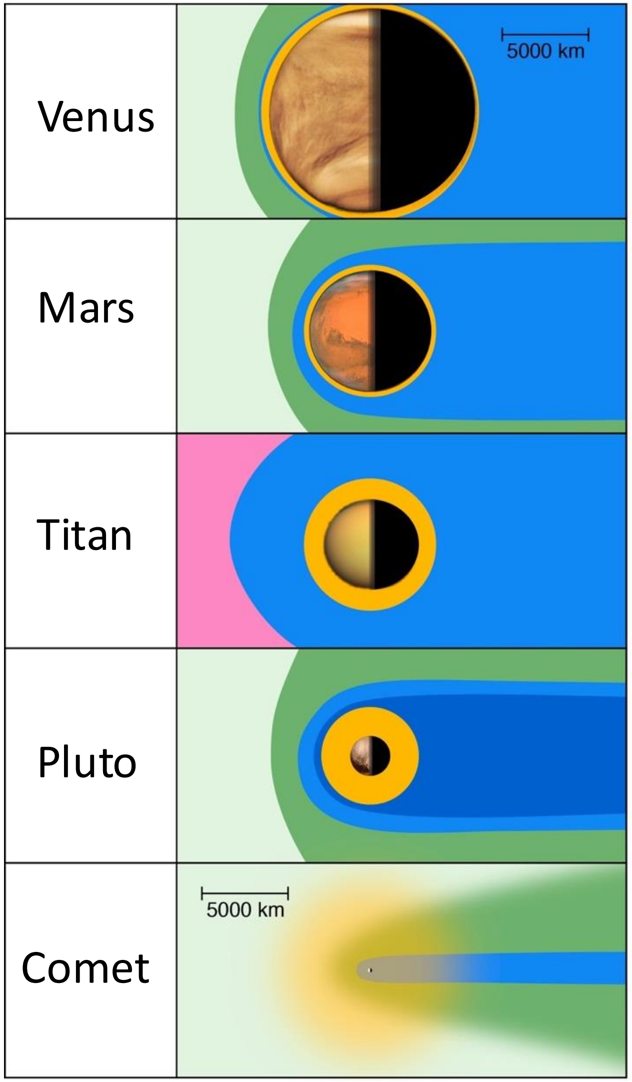
MGS mission
MAVEN mission

David Brain

Solar Wind Interaction
Atmosphere Escape



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

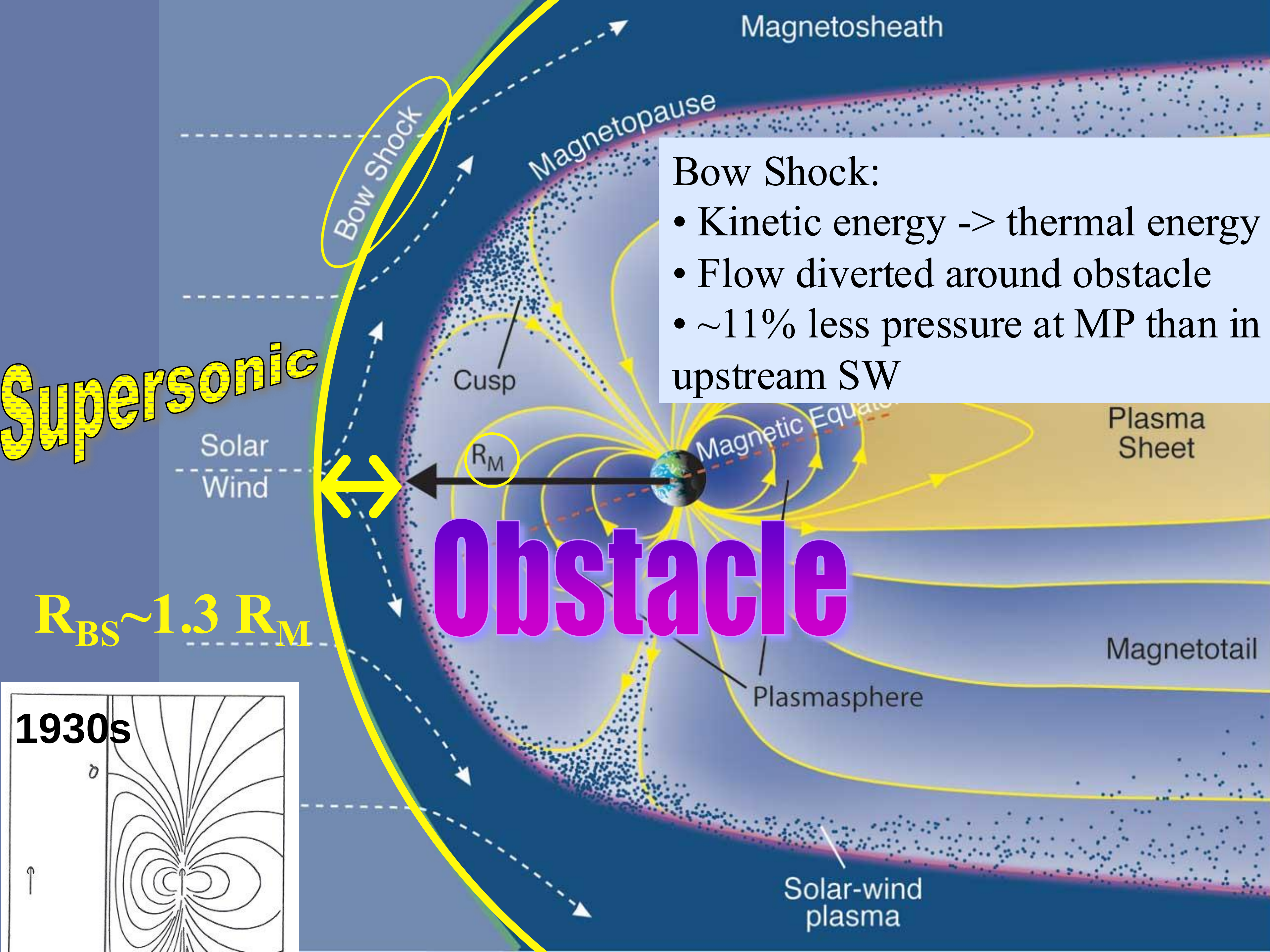


Brain et al. 2016

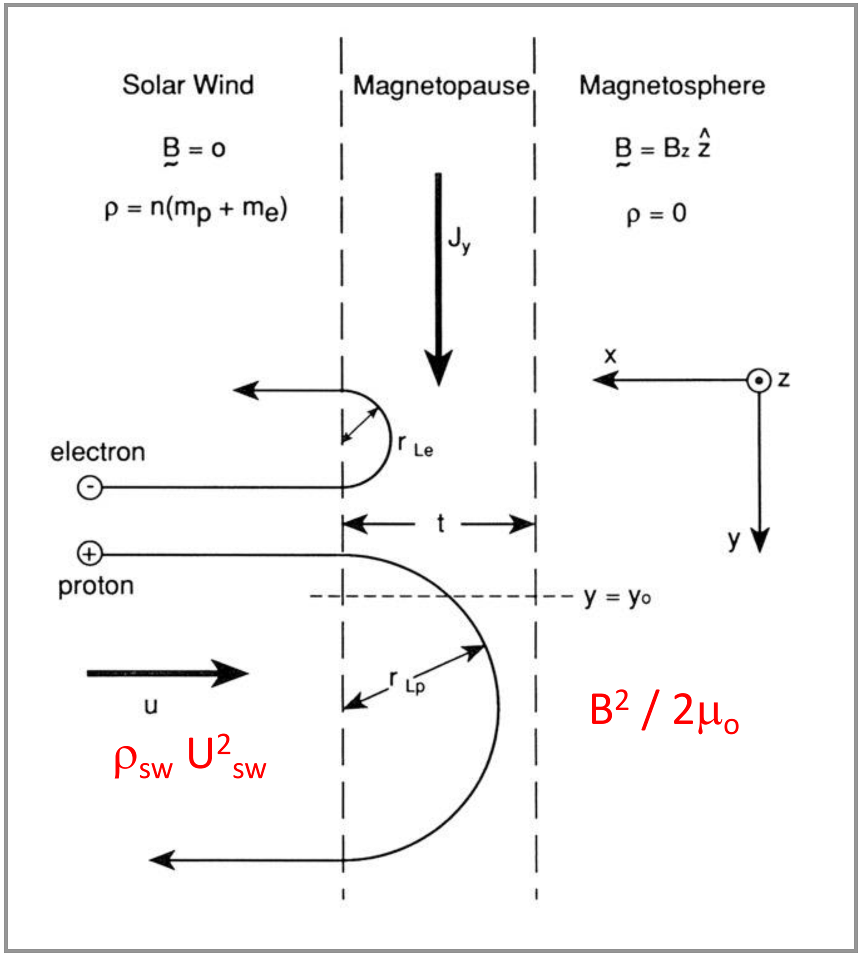
Magnetosphere Sizes

Why to planetary magnetospheres have a bow shock?

What happens to the solar wind at the bow shock?

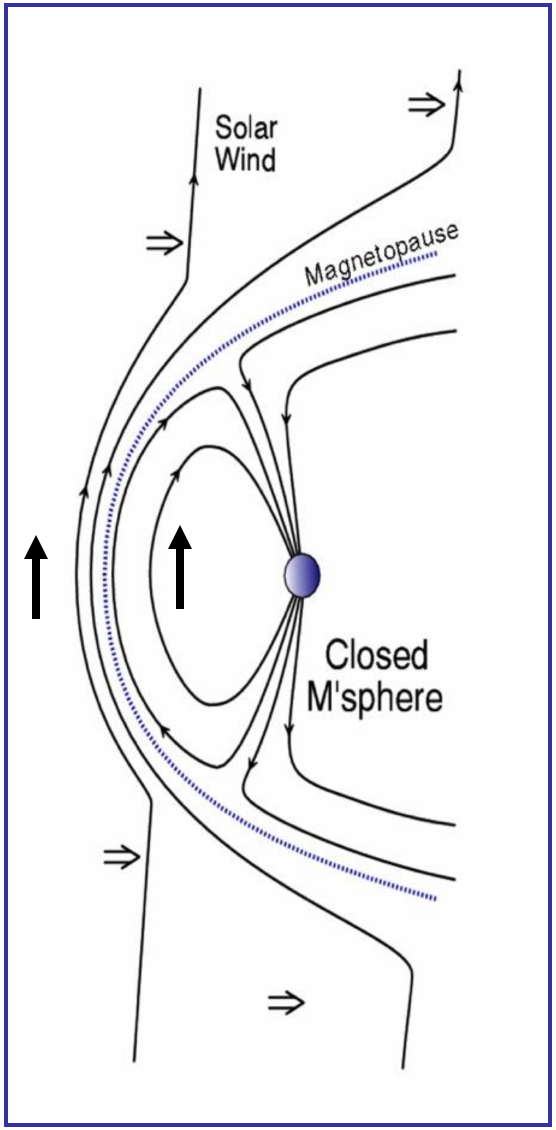

Magnetosheath
Magnetopause
Bow Shock
Bow Shock:
• Kinetic energy -> thermal energy
• Flow diverted around obstacle
• ~11% less pressure at MP than in upstream SW
Supersonic
Solar Wind
Cusp
R_M
Magnetic Equator
Plasma Sheet
Obstacle
R_{BS}~1.3 R_M
Magnetotail
Plasmasphere
Solar-wind plasma
1930s

Chapman-Ferraro Current

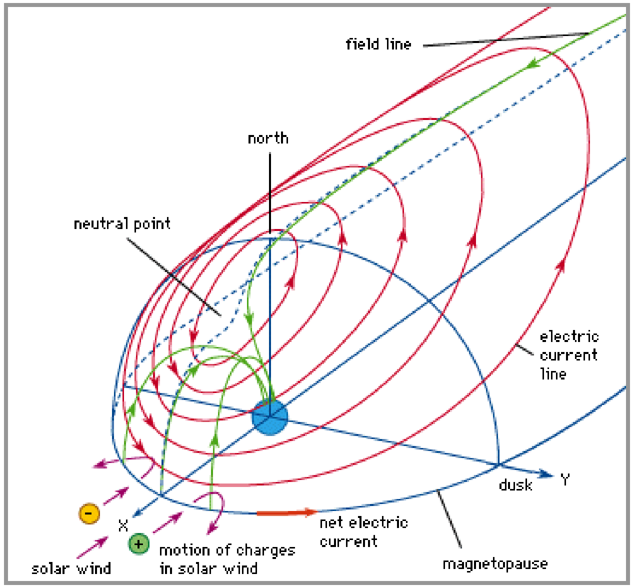


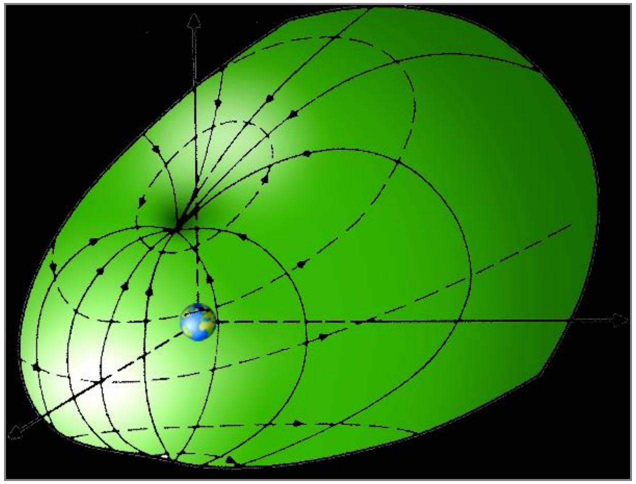
- Internal magnetic field pressure $B^2 / 2\mu_o$
- Balances the solar wind dynamic pressure $\rho_{sw} U^2_{sw}$
- Assumes northward Interplanetary Magnetic Field – IMF
- Chapman-Ferraro current must provide **j** x **B** force integrated across magnetopause

Chapman-Ferraro Current



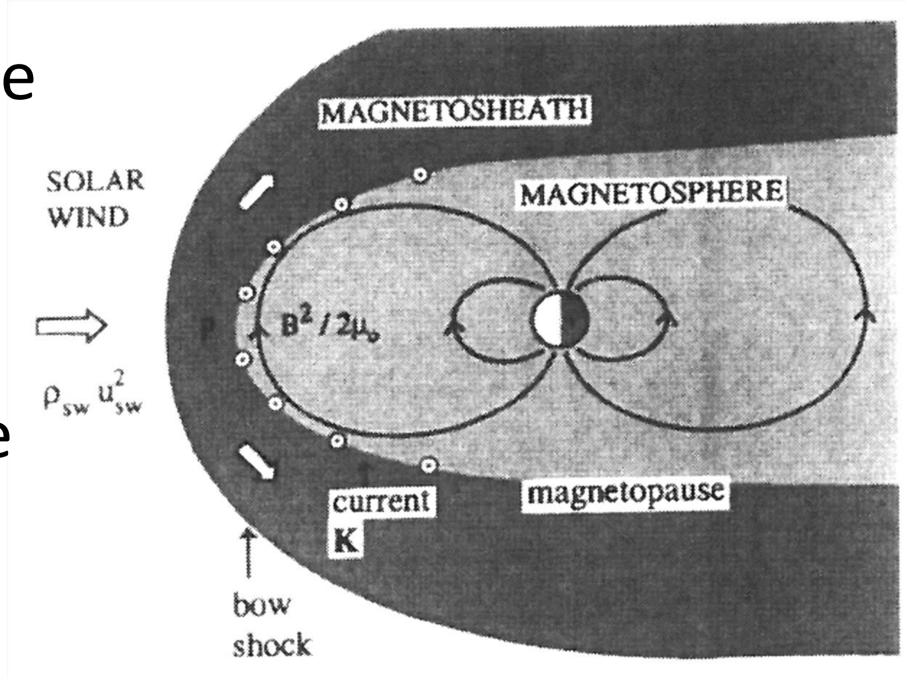
- Creates closed magnetosphere
- Limits size of magnetosphere
- Current pattern over the whole magnetopause.





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

SW ram pressure <=>
internal magnetic field pressure



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

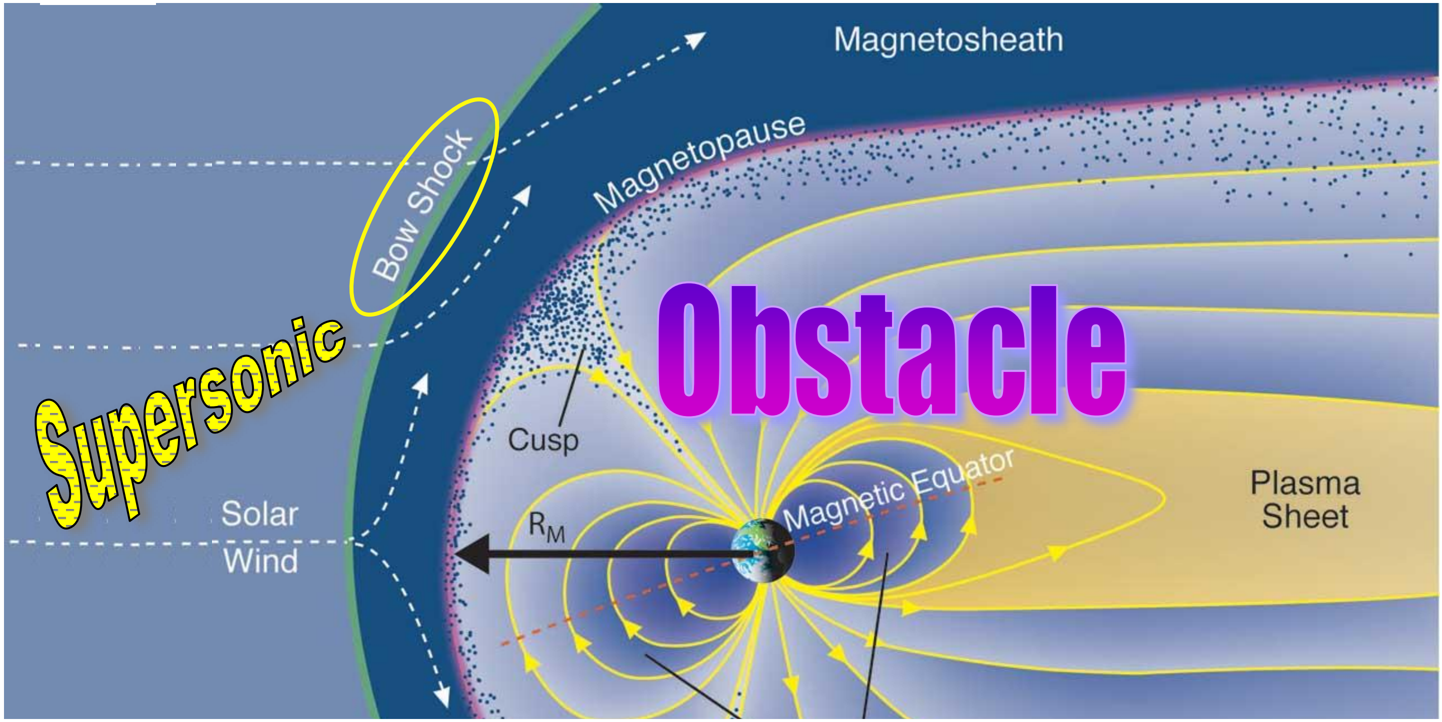
BUT what about currents at the magnetopause? -> $2B_{dipole}$

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

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

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

Quick chat with your neighbors….

1. How does ρ_{sw} vary with distance D from Sun?
2. How does U_{SW} vary with distance D from Sun?
3. How does $\{1/\rho_{sw} U^2_{sw}\}^{1/6}$ vary with distance?
4. Move Earth from 1 AU to 8 AU – How big is the magnetosphere?

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

Quick chat with your neighbors….

1. How does $\boldsymbol{\rho}_{\mathbf{sw}}$ vary with distance D from Sun?

   $\sim 1/D^2$

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

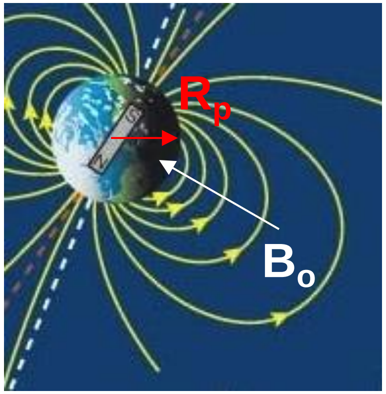
   ~ constant

3. How does $\{1/\boldsymbol{\rho}_{\mathbf{sw}}\ U^2_{\mathbf{sw}}\}^{1/6}$ vary with distance?

   $\sim D^{1/3}$

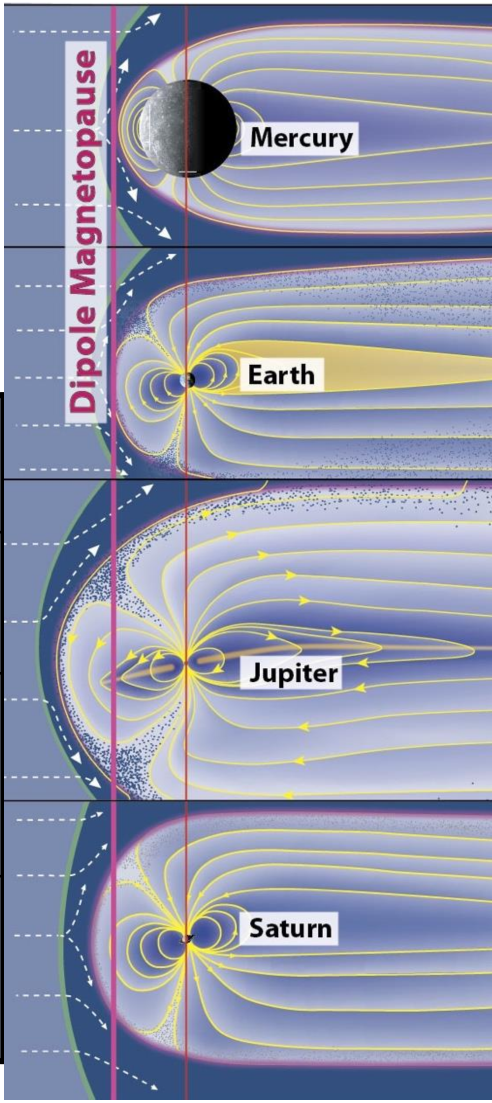
4. Move Earth from 1 AU to 8 AU – How big is the magnetosphere?

   x 2

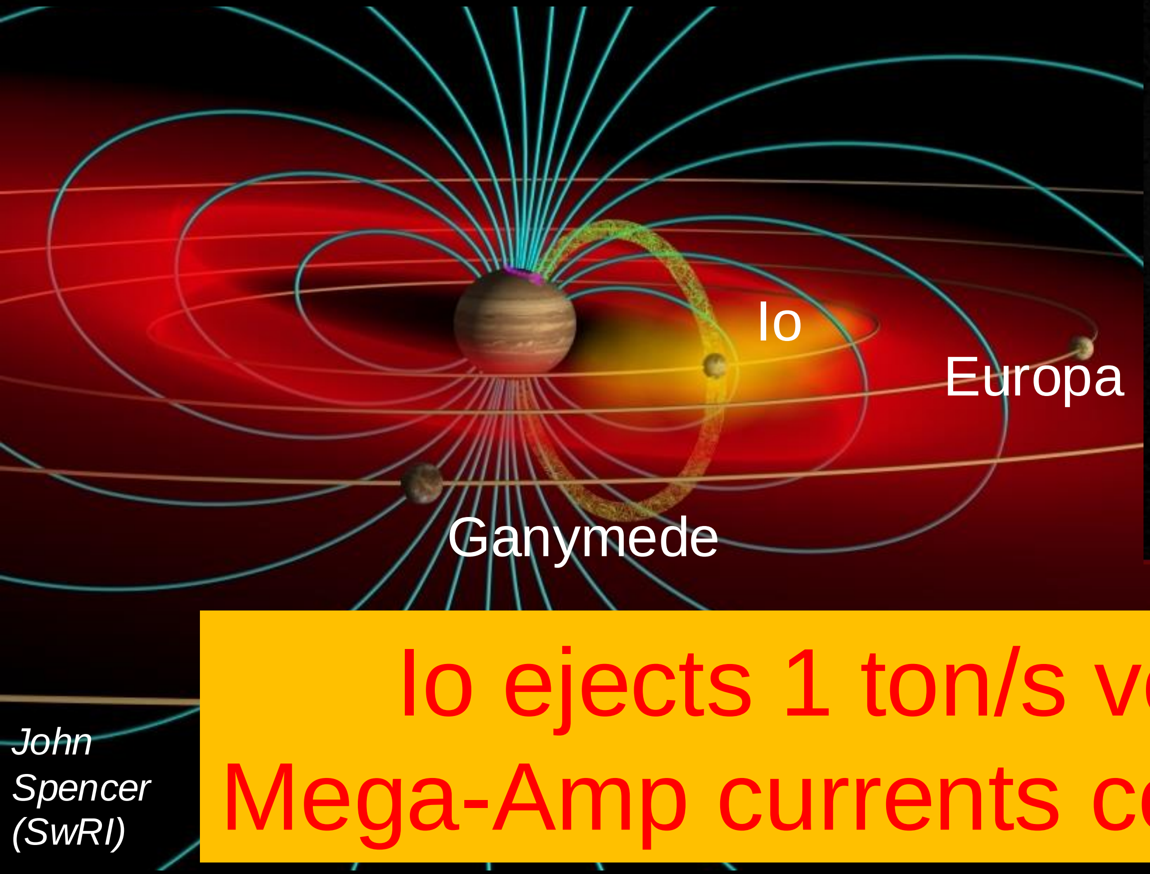


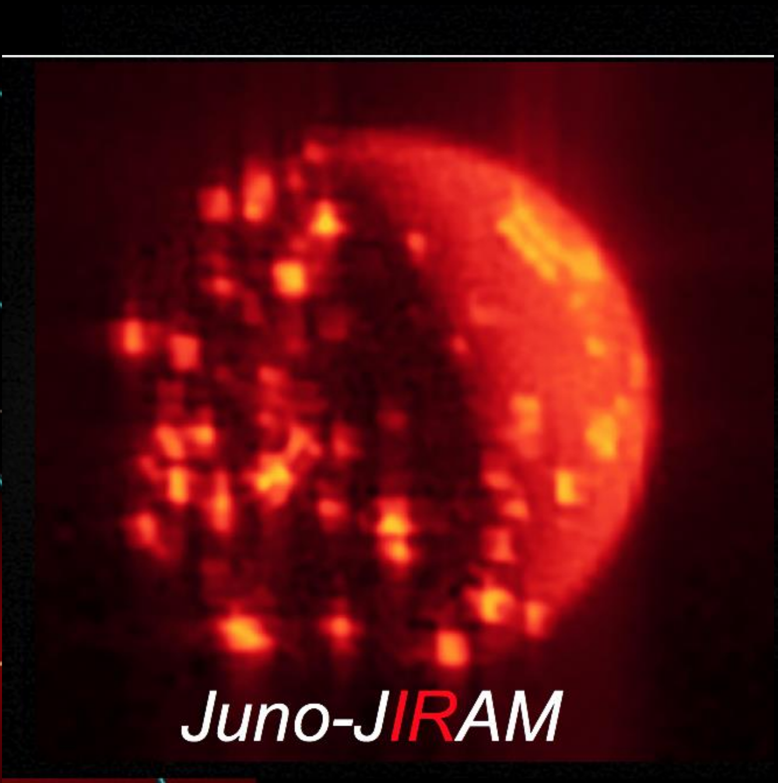
$$R_{CF}/R_p \sim 1.4\ \{\mathbf{B_o}^2 / 2\ \mu_o\ \boldsymbol{\rho}_{sw}\ V^2_{sw}\}^{1/6}$$

	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

Small Magnetospheres

Mercury

Mariner 10

MESSENGER

In solar wind

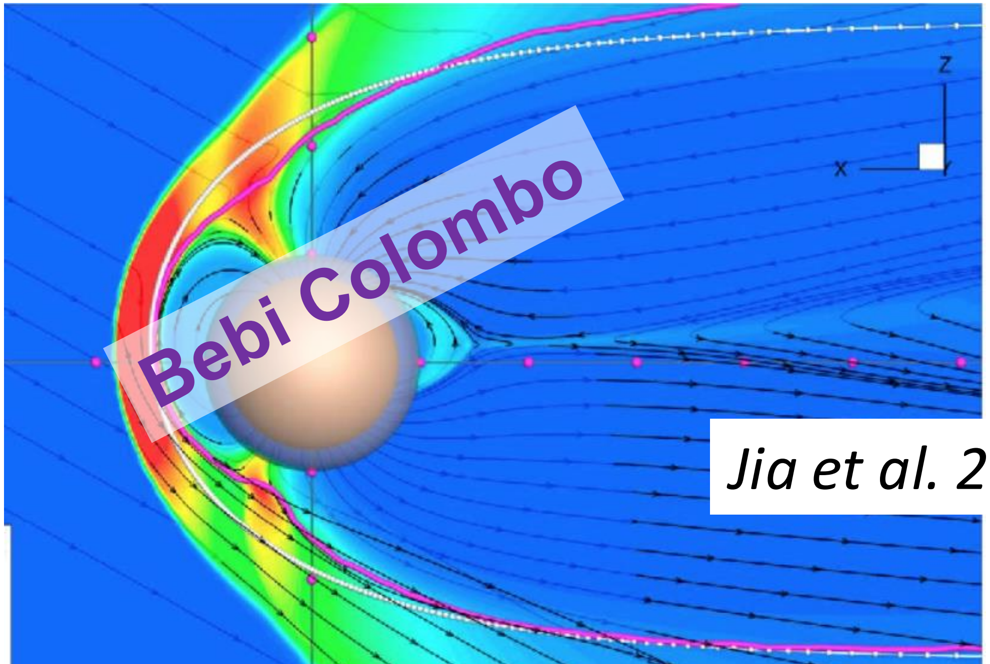
No atmosphere

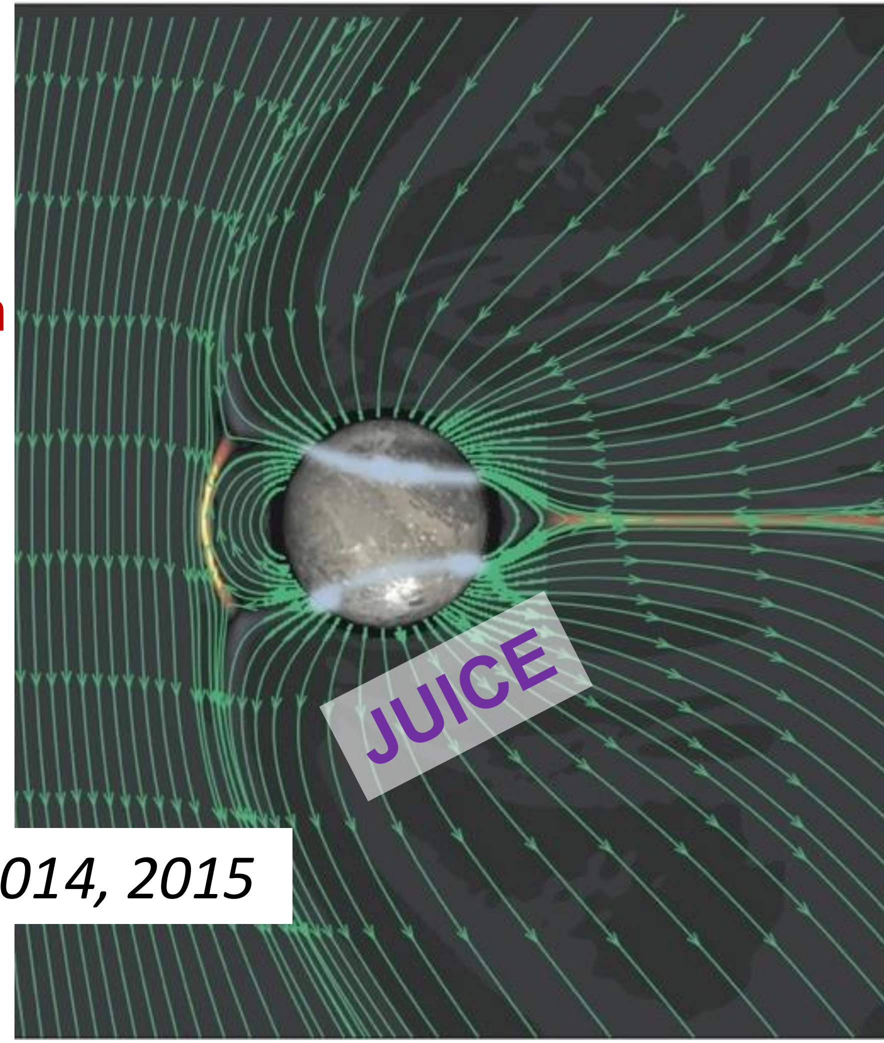
Ganymede

Galileo

In Jupiter m'sphere

Atmospheric aurora



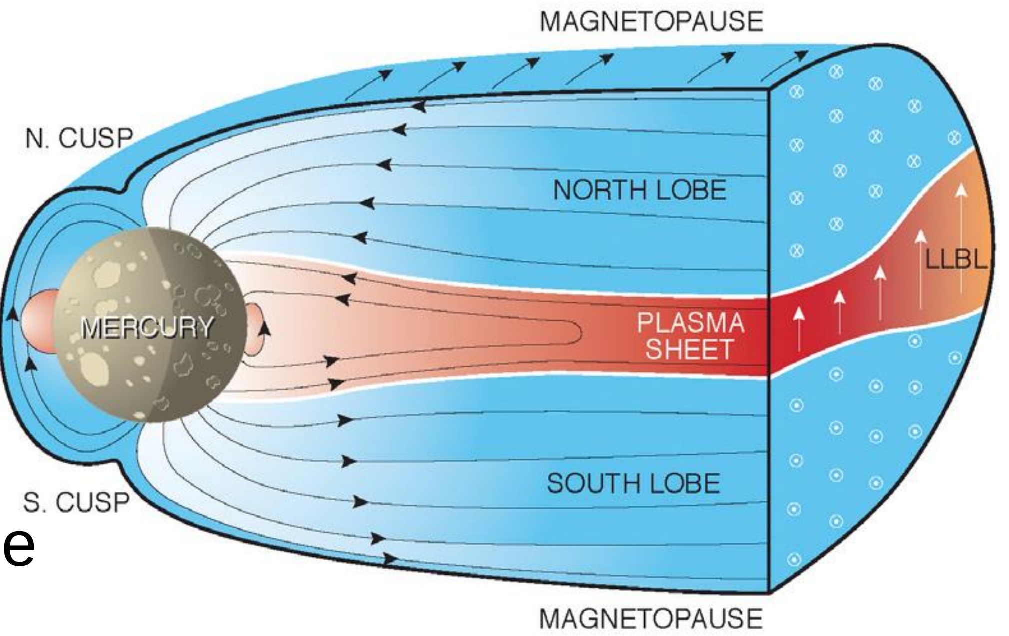


Jia et al. 2014, 2015

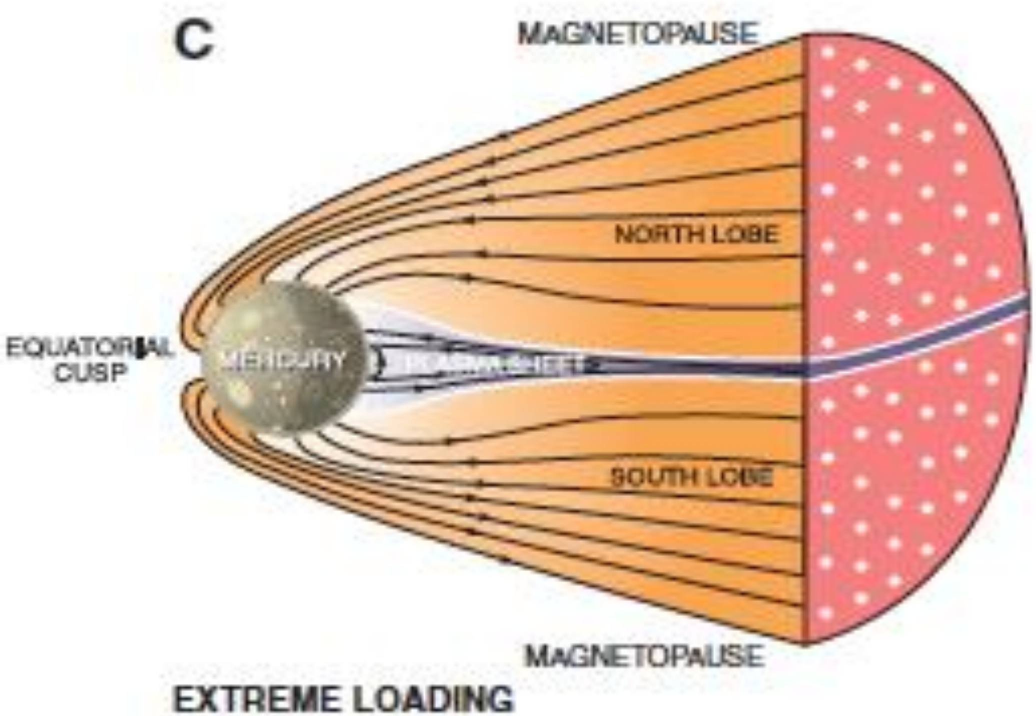
$B_{surface}$ ~ 1/100 Earth

Earth Diameter

Mercury



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

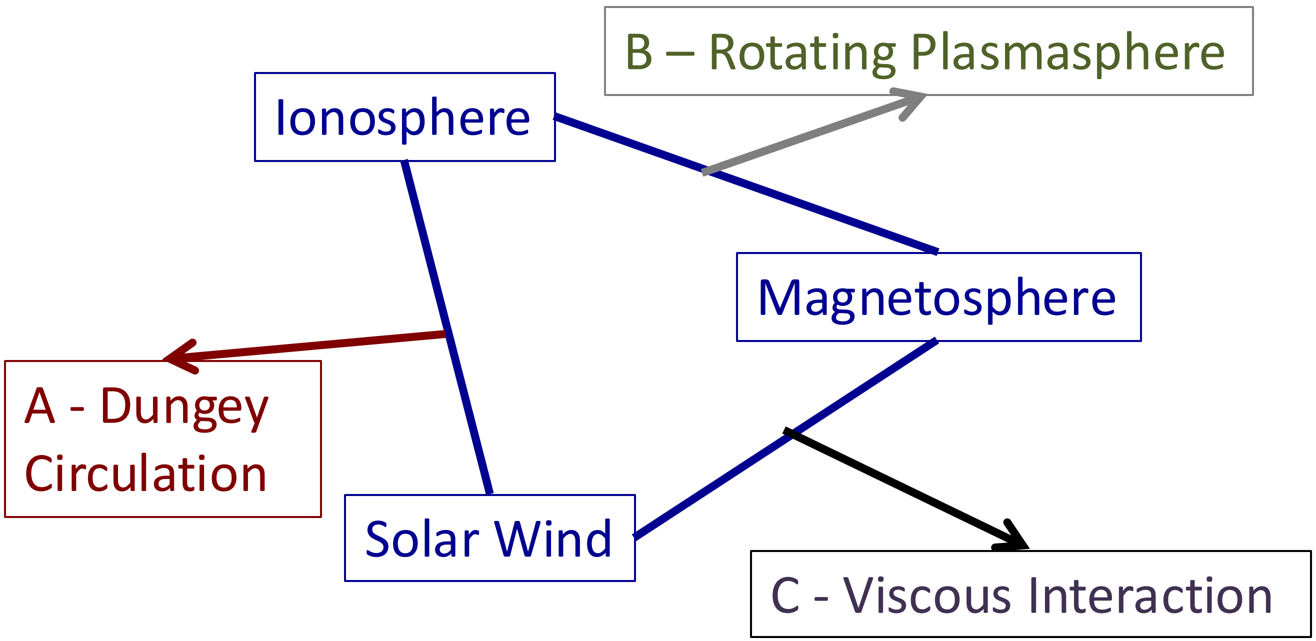


Extreme solar wind conditions -> exposed planet

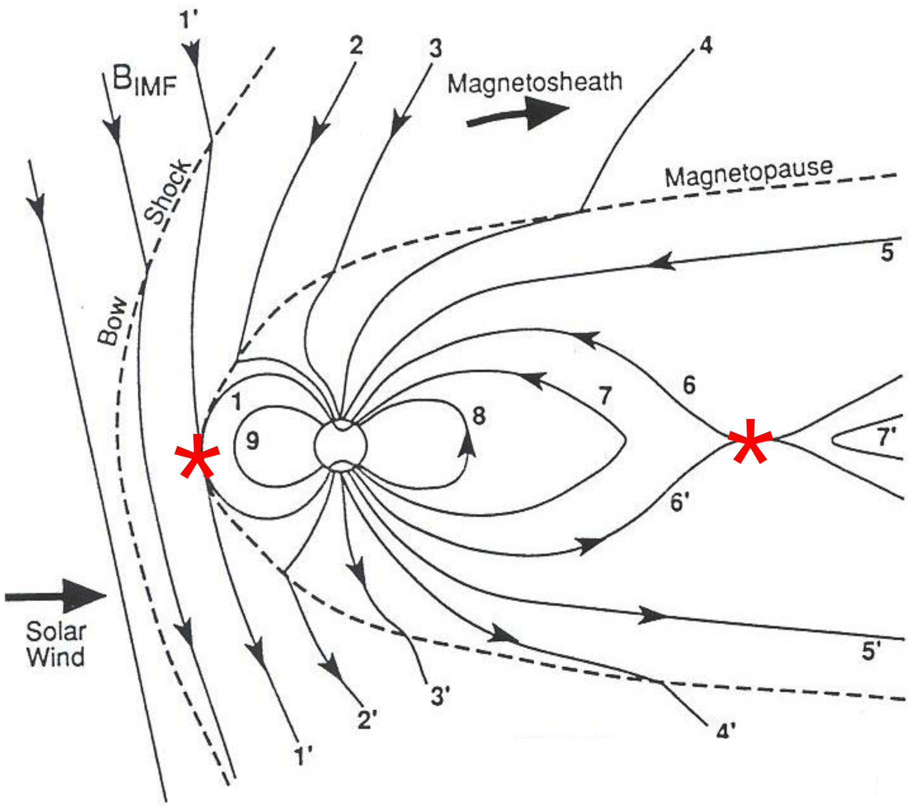
Slavin et al.

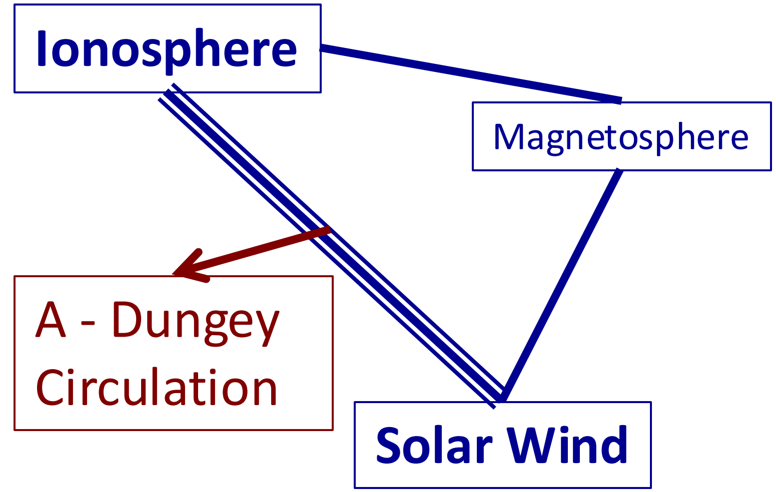
Dynamics

Which Form of Coupling Dominates -> Controls Dynamics



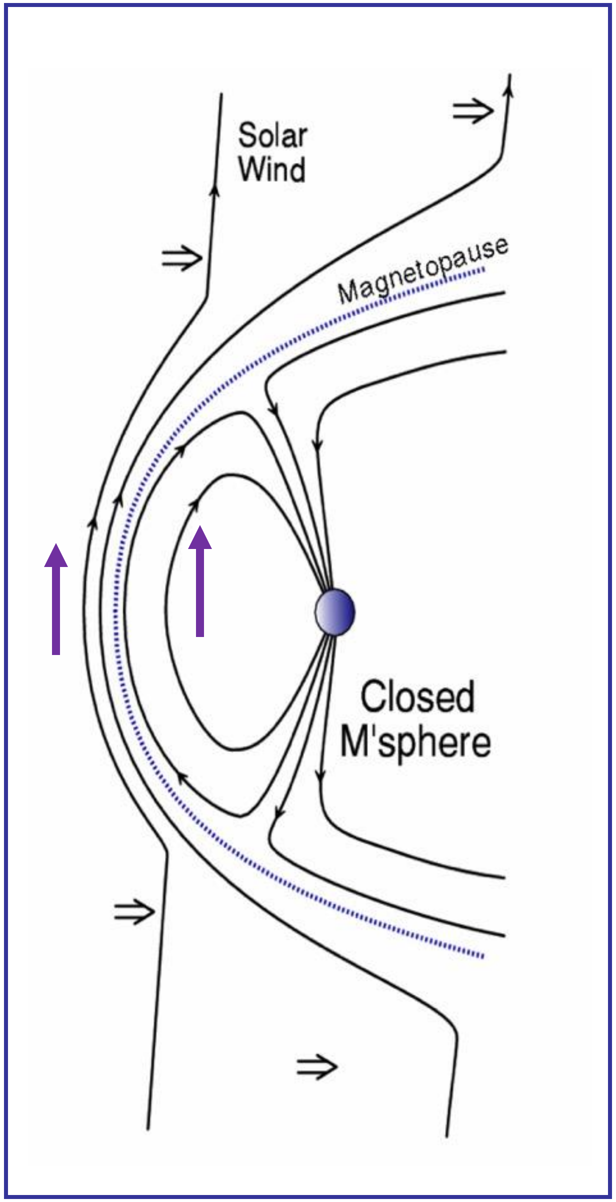
Earth





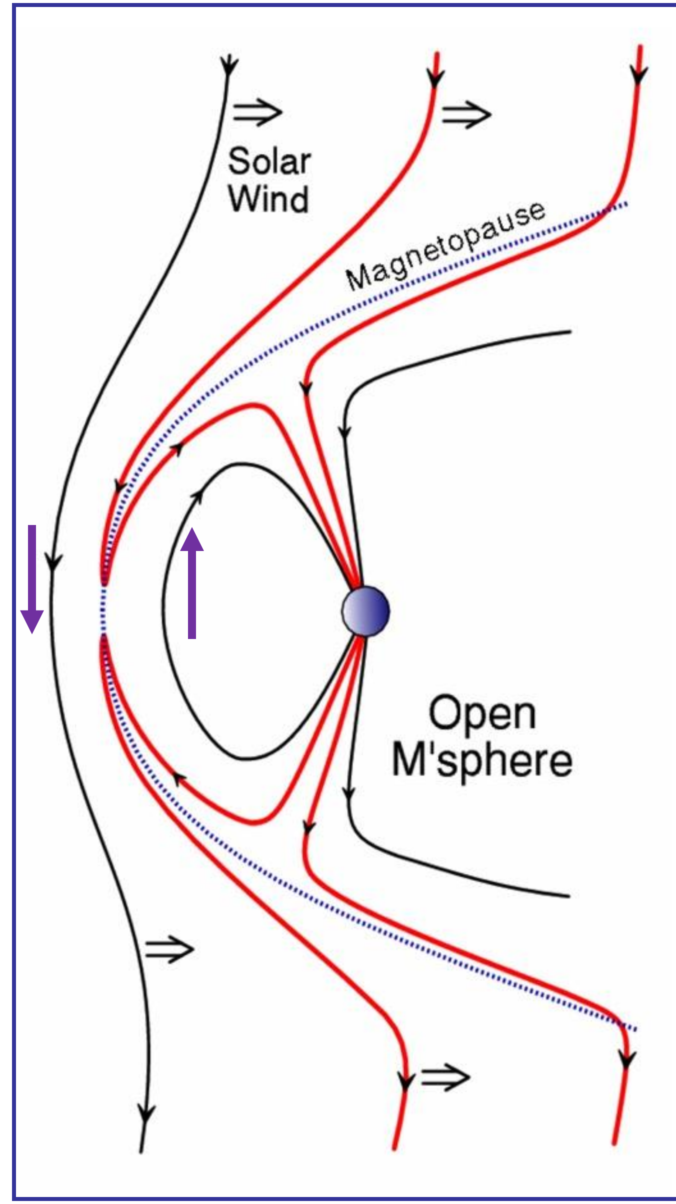
*Reconnection-Driven Global Circulation

Open Magnetosphere



Now flip Interplanetary Magnetic Field direction

Reconnection

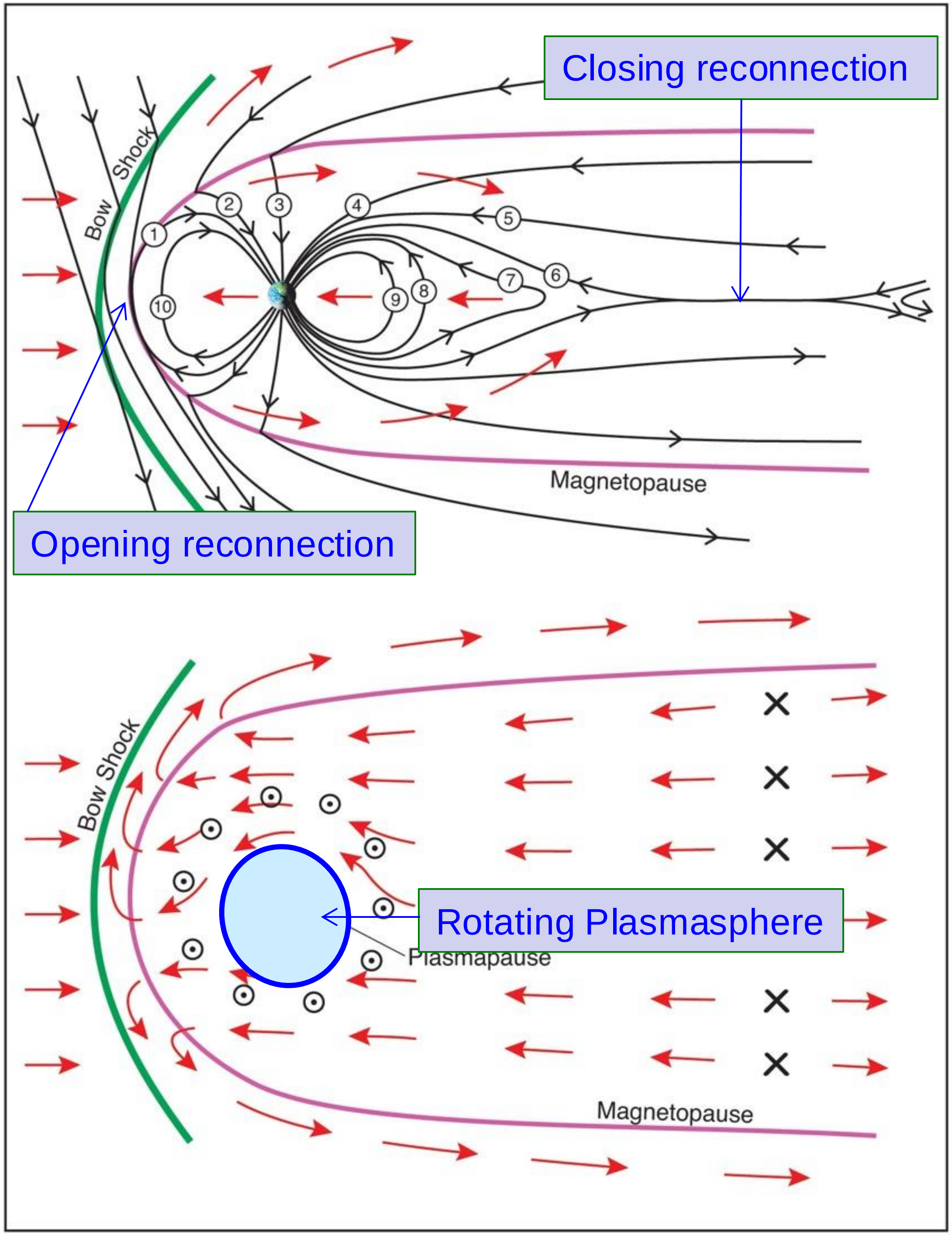


Dungey Cycle

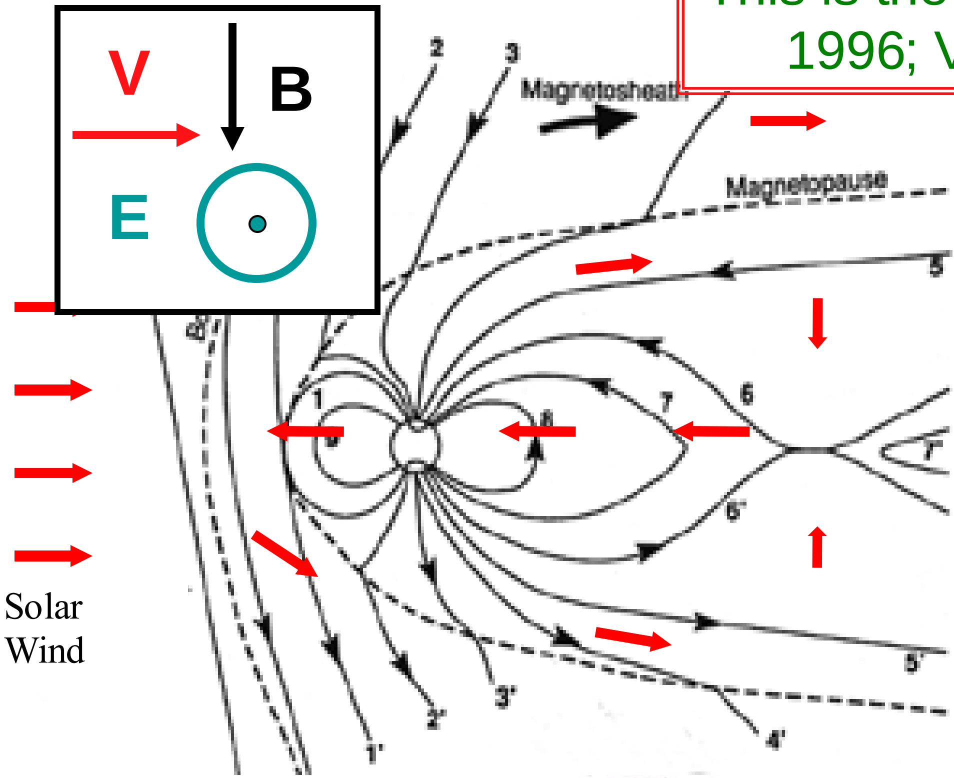
Dynamics at Earth driven by the solar wind coupling the Sun's magnetic field to the Earth's field

- 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

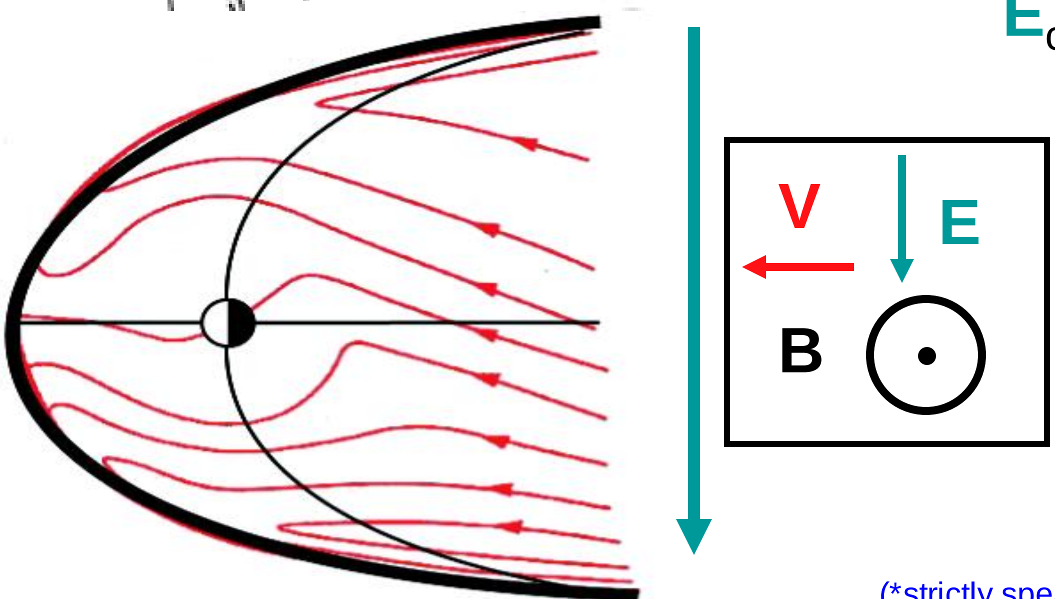
Solar wind driven magnetospheric convection*

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

ζ~ efficiency of reconnection ~10-20%

crude approximation!!

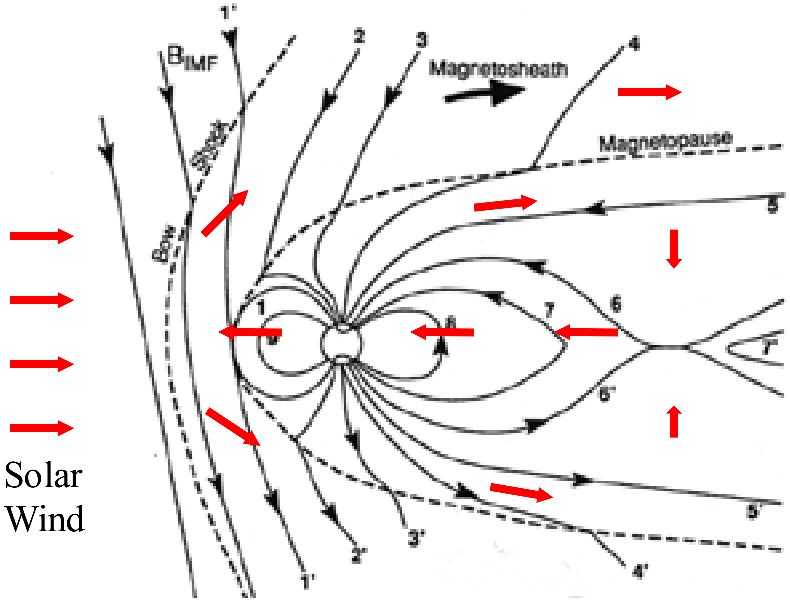
E_{conv}~ constant in m'sphere

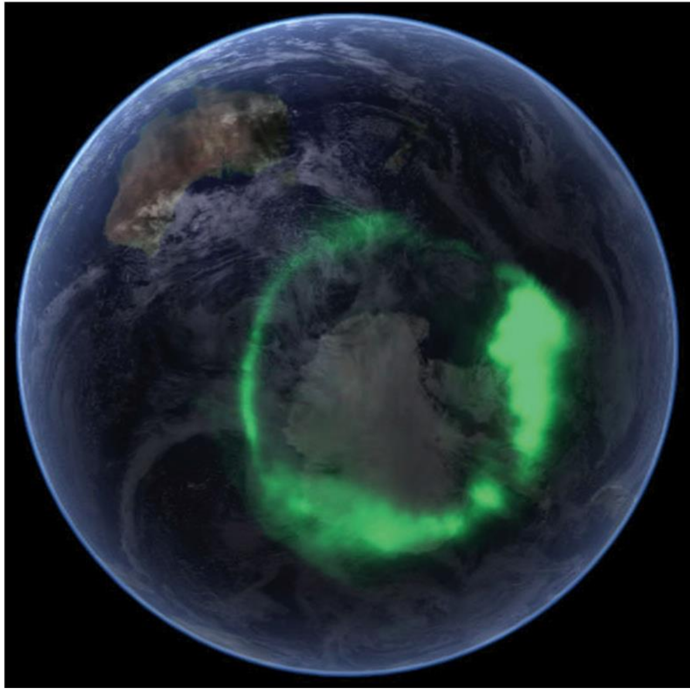


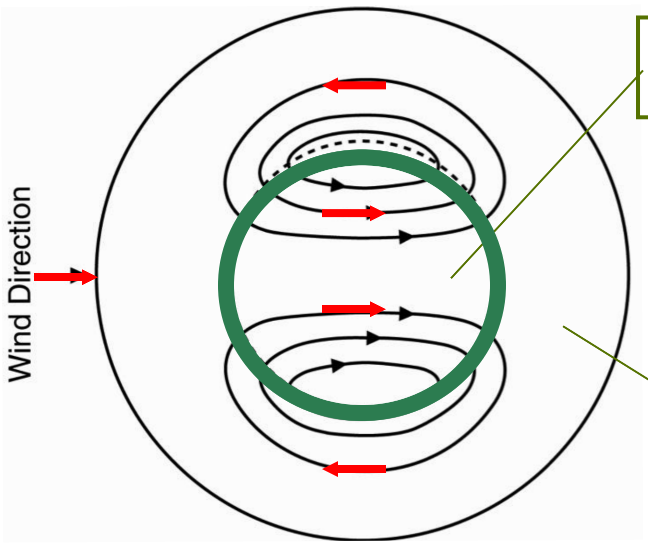
$V_{convection} \sim \zeta V_{SW}(R/R_{MP})^3$

(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)



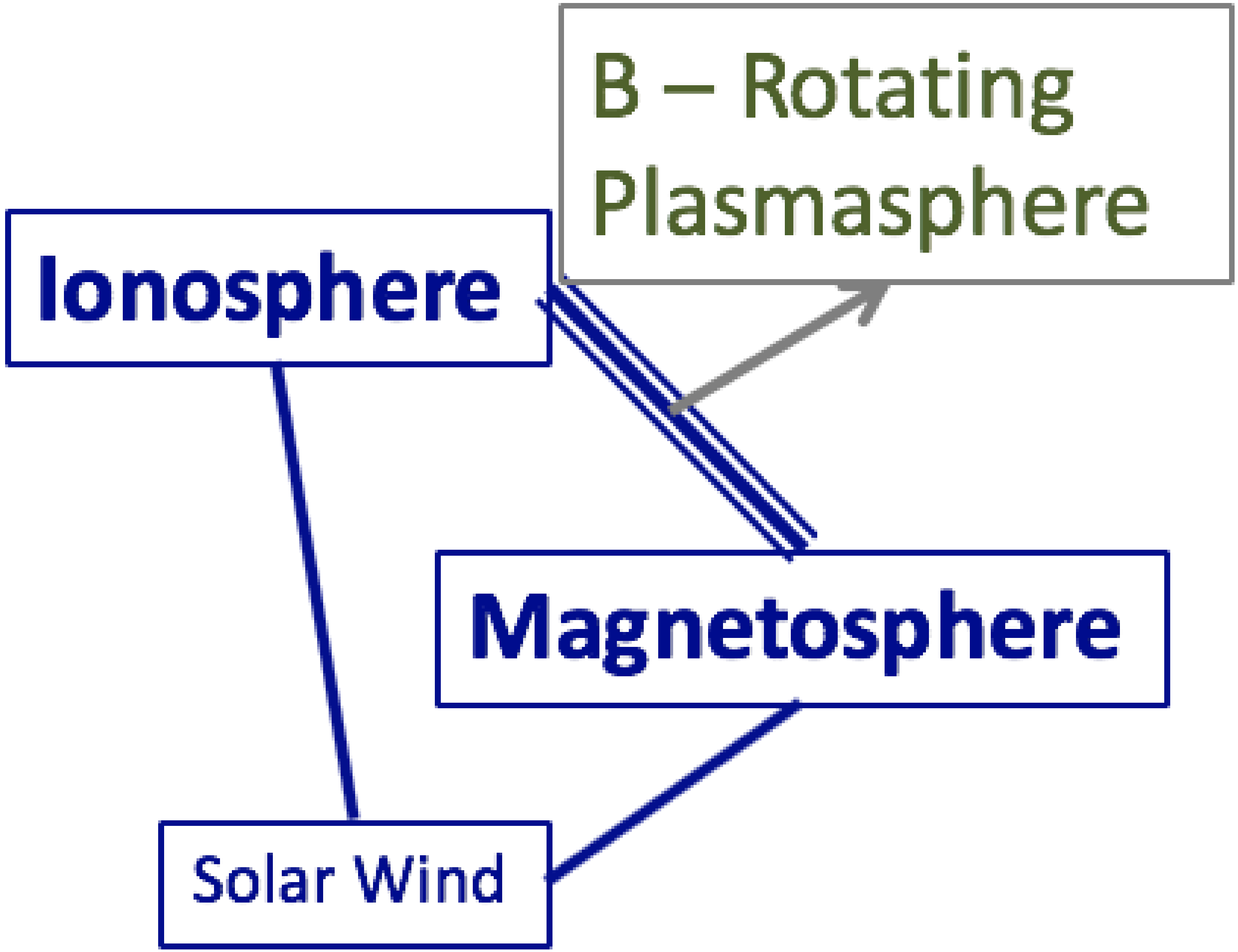




Connected to solar wind

Closed magnetic field

Polar view

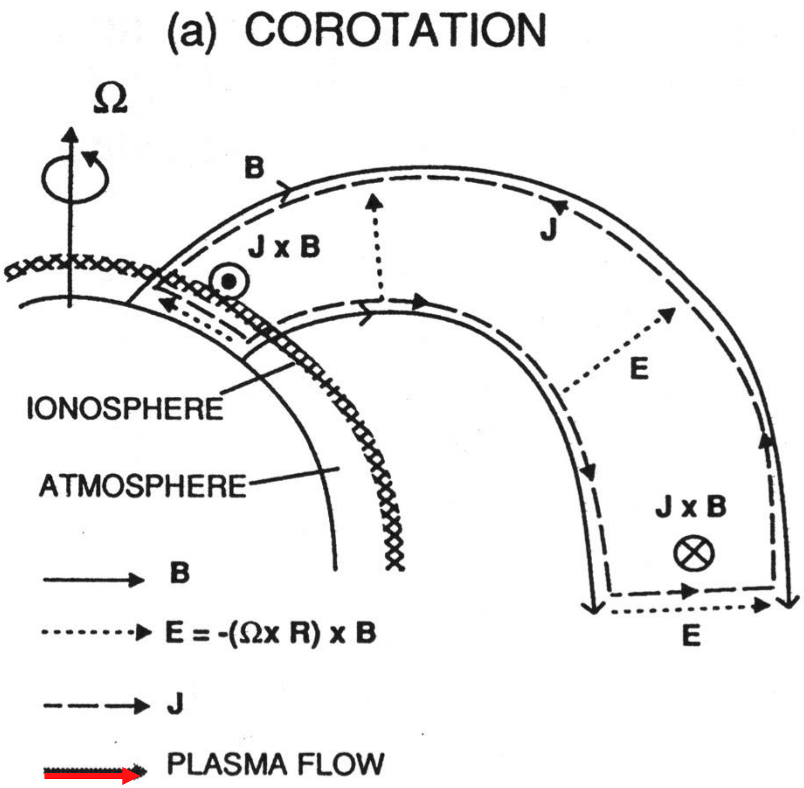

B – Rotating Plasmasphere
Ionosphere
Magnetosphere
Solar Wind

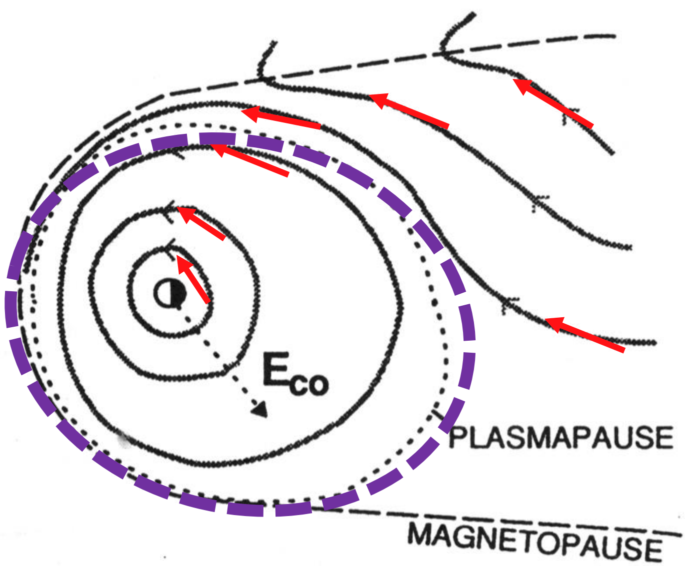
$$\mathbf{V}_{co} \sim \boldsymbol{\Omega} \times \mathbf{R}$$

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

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

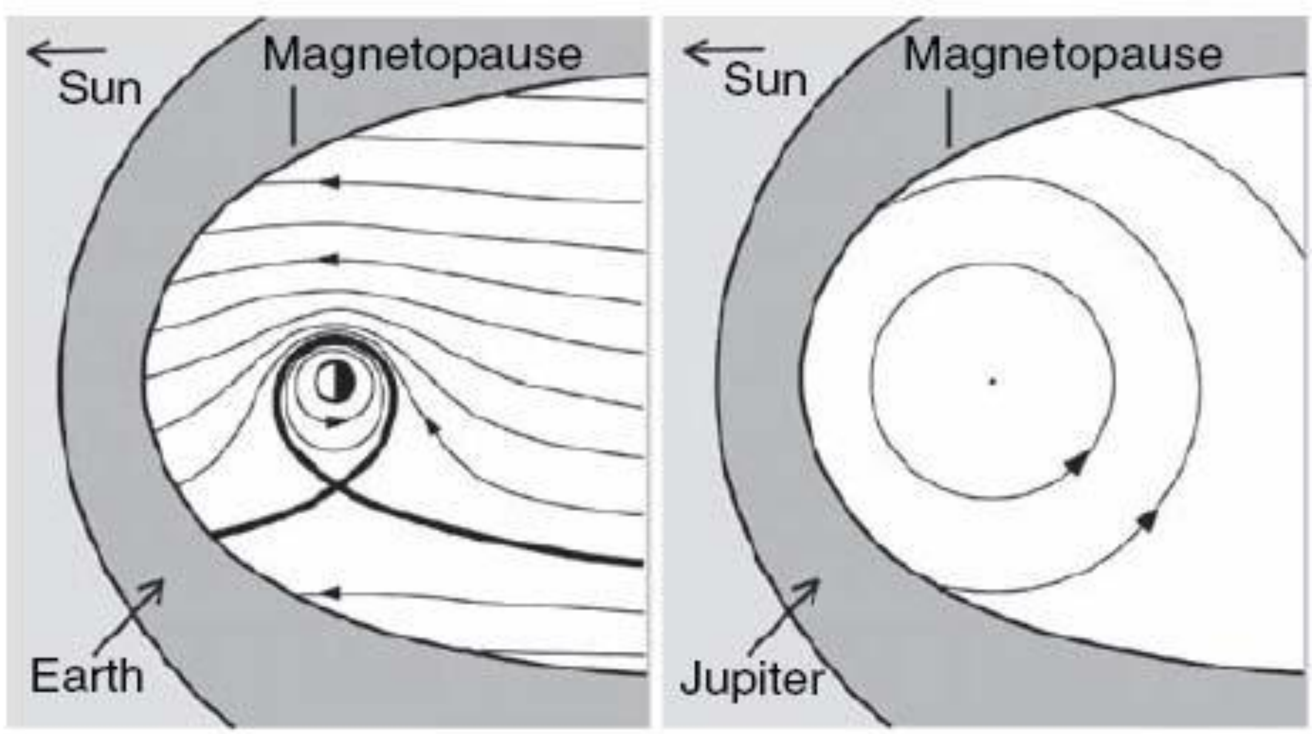
- increases with planetary spin
- increases with field strength
- decreases with solar wind strength





Kivelson 2007

Solar-wind vs. Rotation-dominated magnetospheres



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

6.7 350

Assumptions:

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

Dynamics

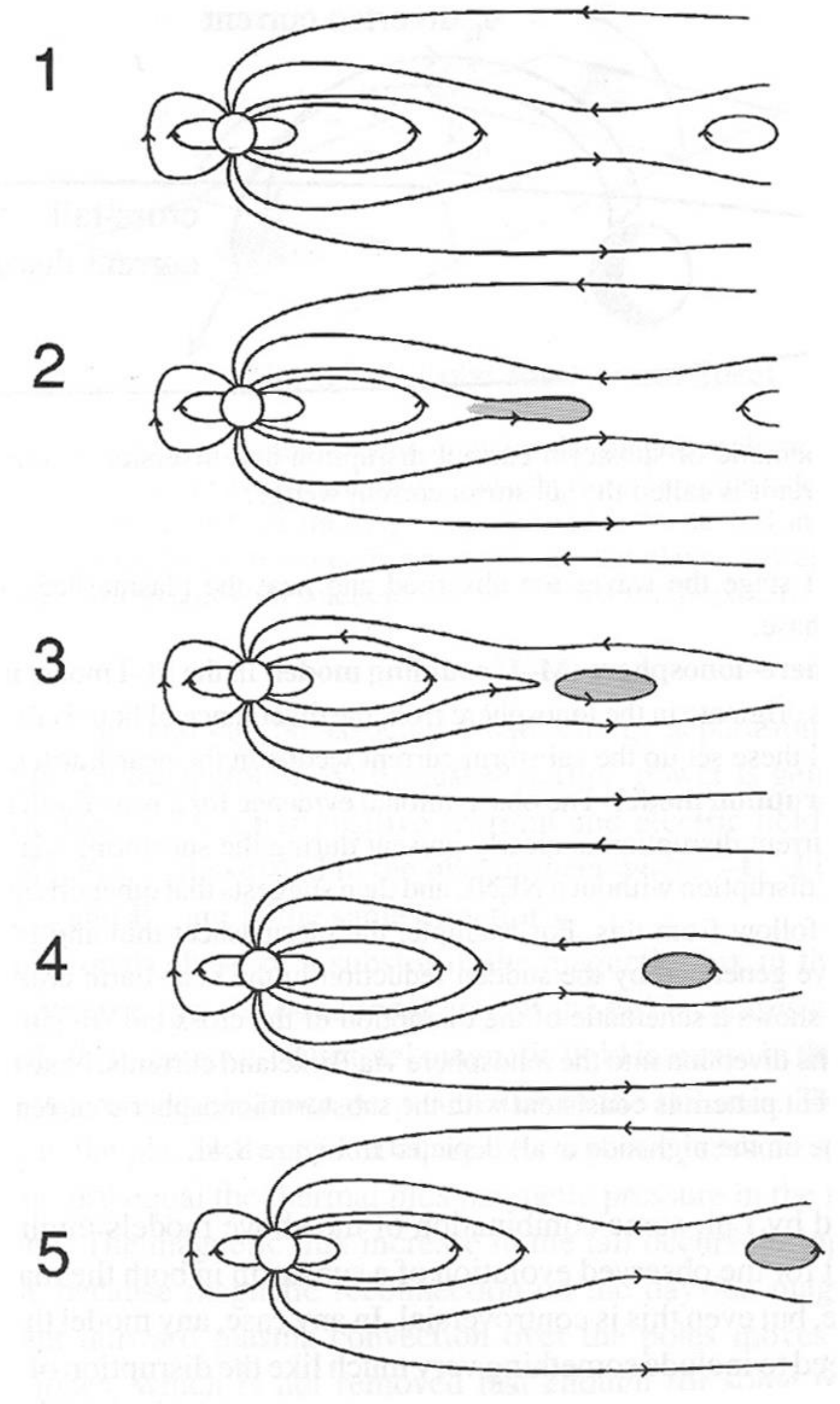
Dayside magnetopause

• Response to B_{SW} direction

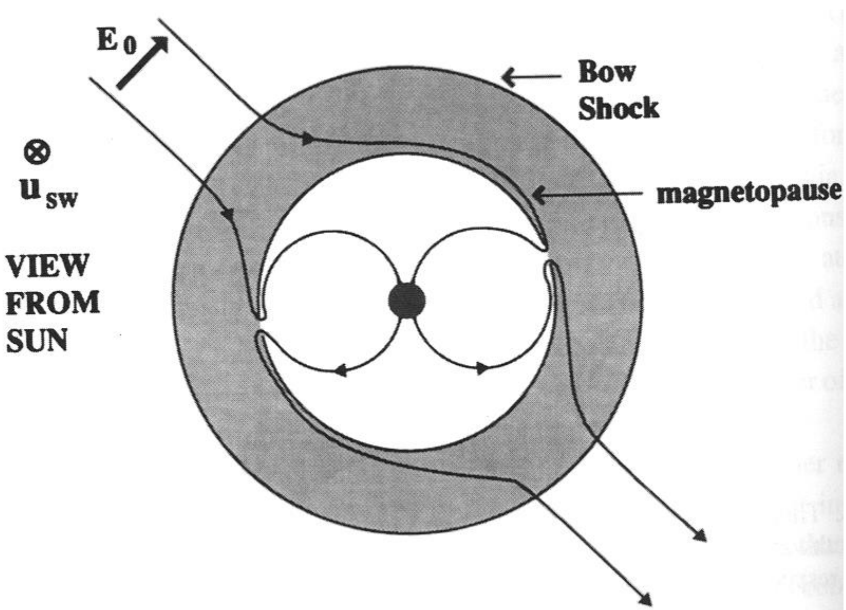
• Solar wind ram pressure

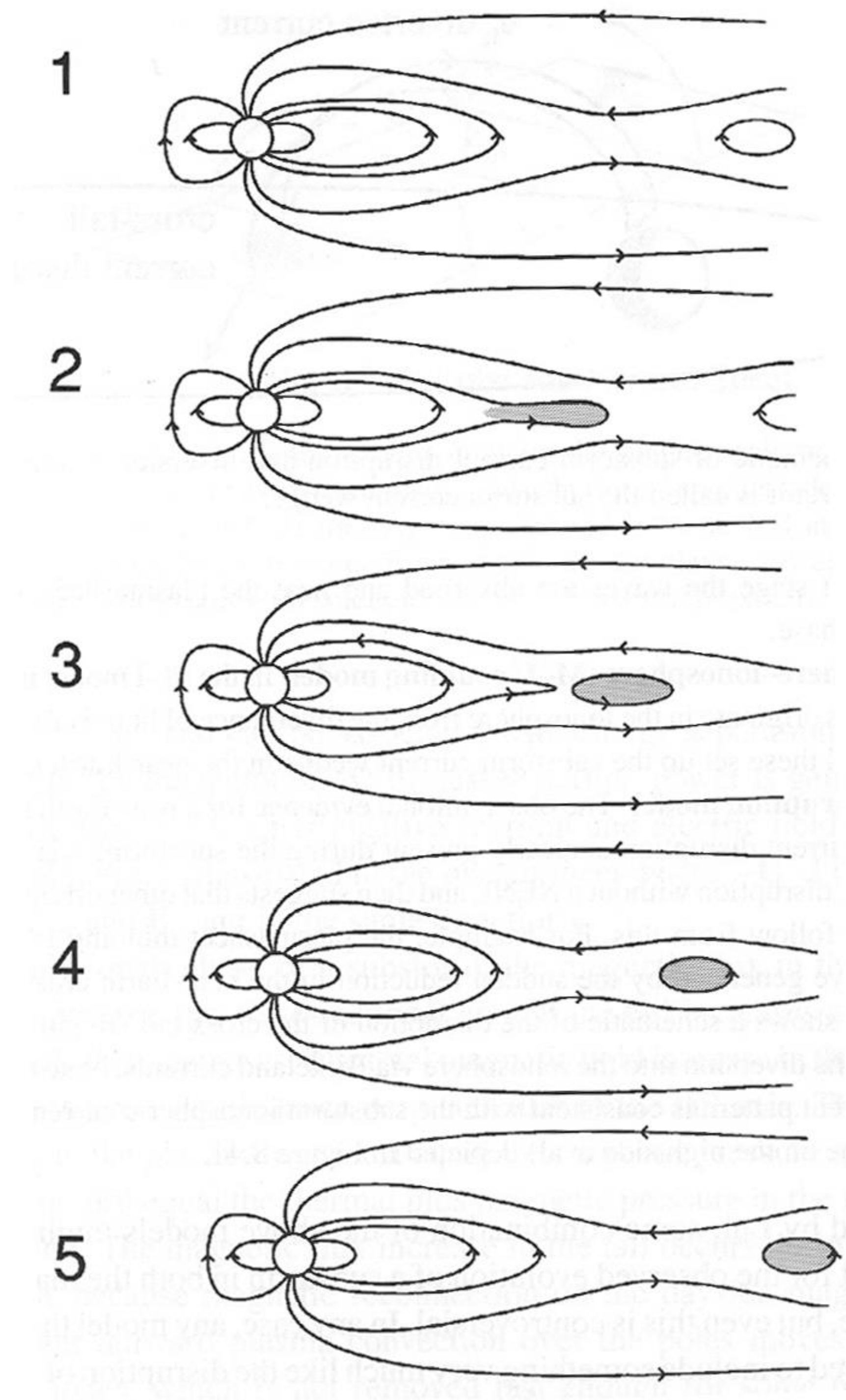
Tail Reconnection

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



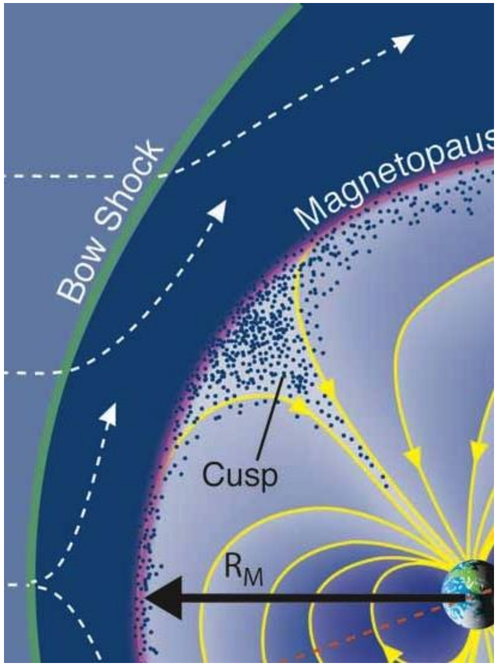
Reality = Messy & 3D





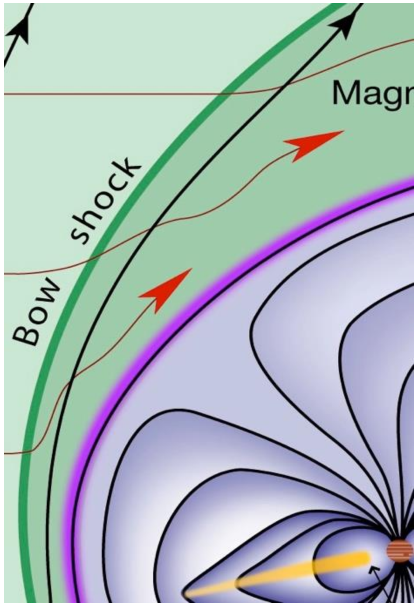
Earth vs. *Jupiter*

Calculate Transit Time



Time for Solar Wind to Flow Nose-Terminator

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

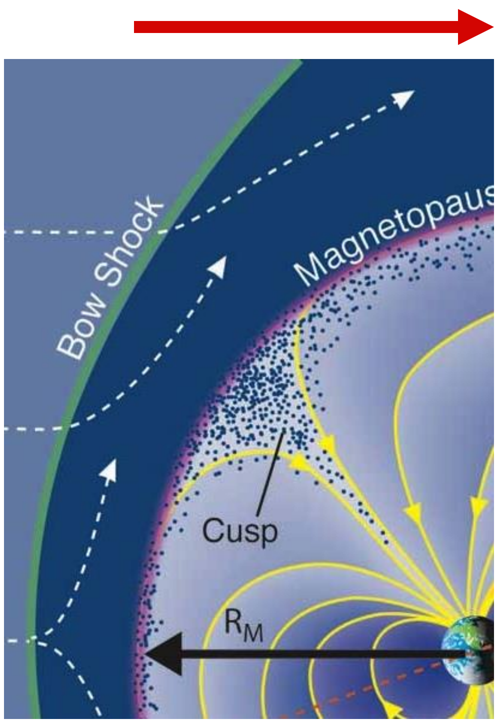


MP~10 R_E
1 R_E~6400 km

MP~100 R_J
1 R_J~72000 km

Earth *vs.* *Jupiter*

$10\ R_E$ <3 minutes



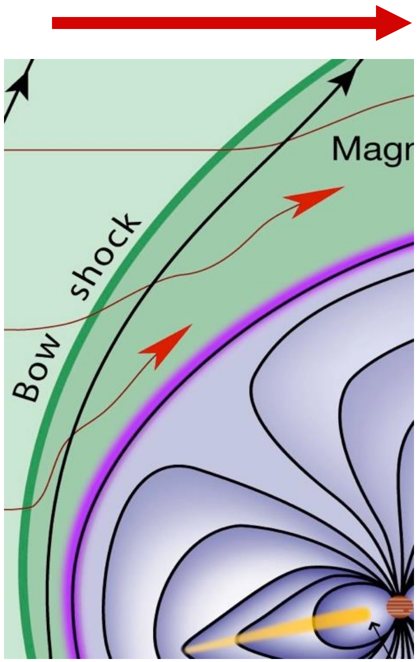
Bob McPherron
Margy Kivelson

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 $\sim 10^{-3}$

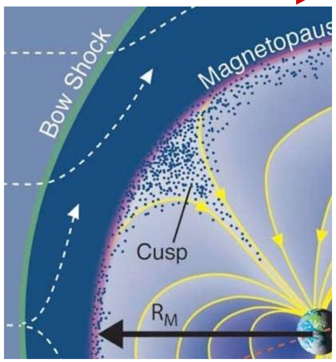
$100\ R_J$
~ 5 hours



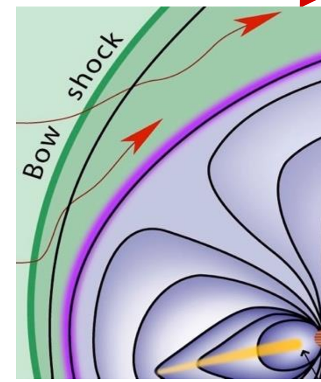
McComas & Bagenal 2007

Earth vs. Jupiter

10 R_E <3 minutes



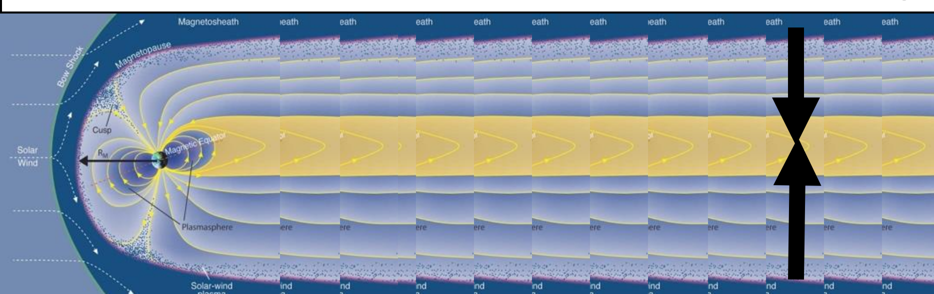
100 R_J ~ 5 hours

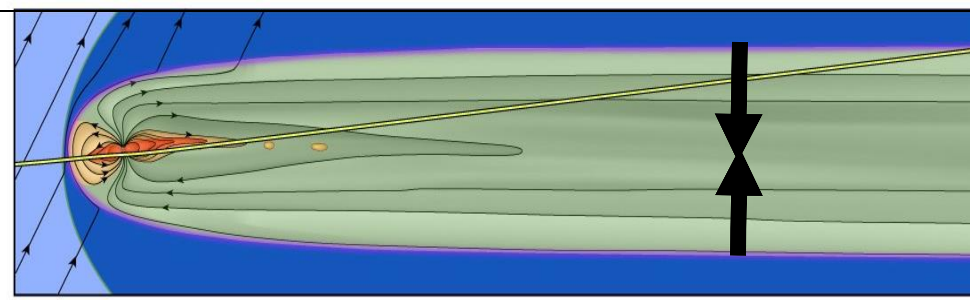


Time for Solar Wind to Flow Nose-Terminator

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

10% reconnection efficiency -> equatorward drift ~40 km/s





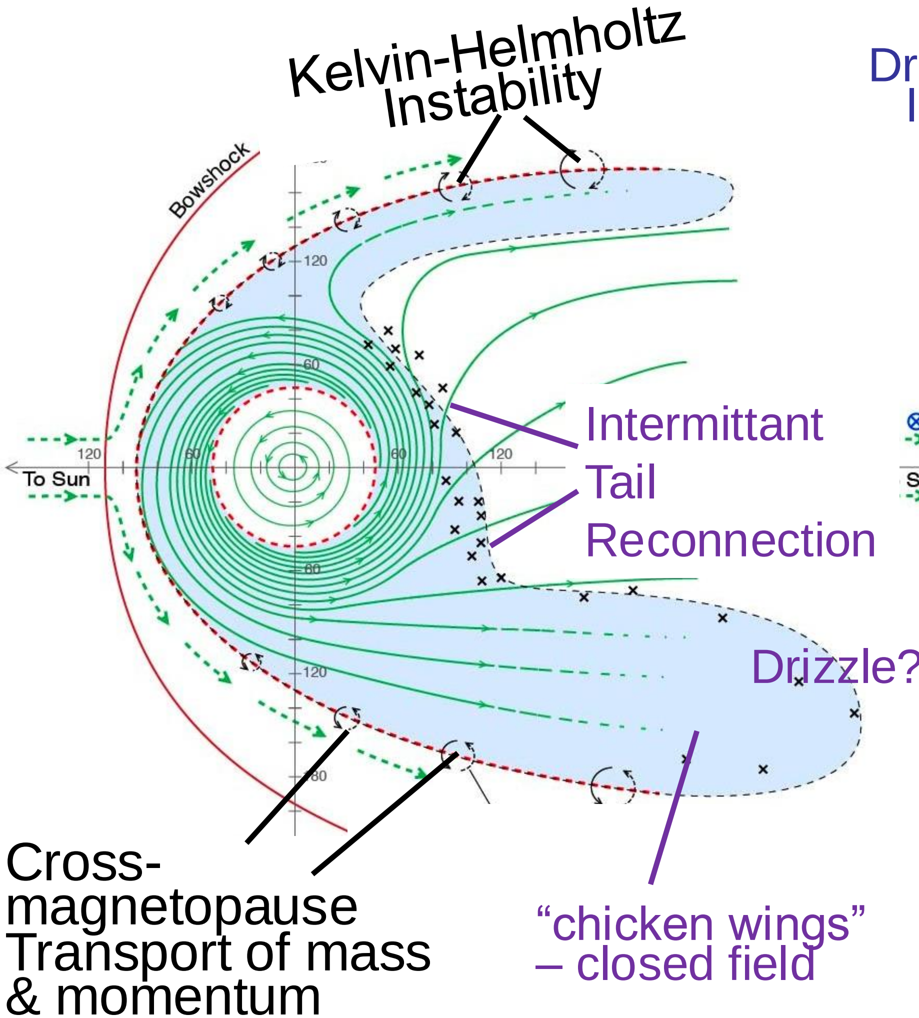
15 R_E ÷ 40 km/s

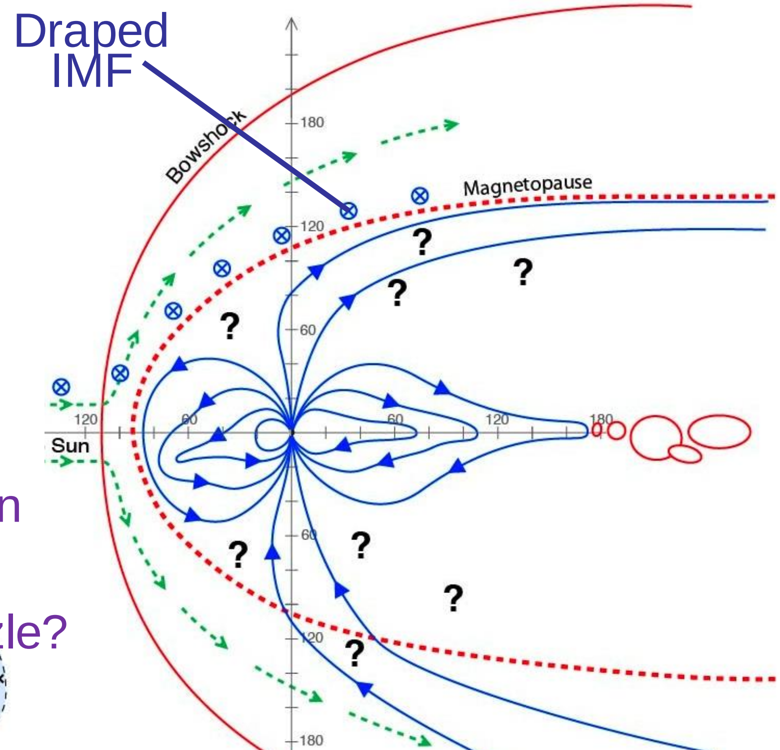
= **40 mins**

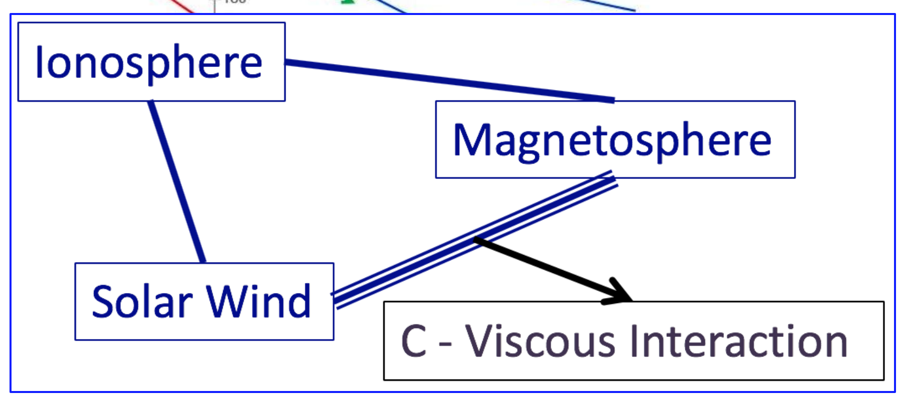
150-200 R_J ÷ 40 km/s

= **75-100 hours**

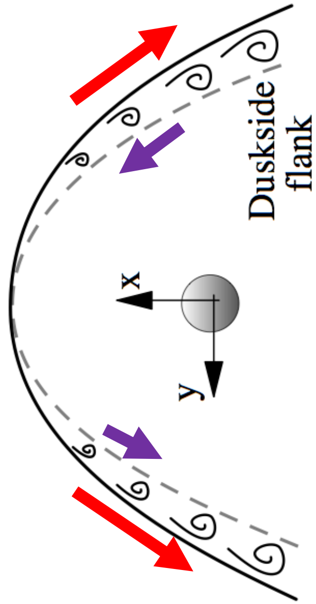
Delamere & Bagenal 2013
Masters 2017

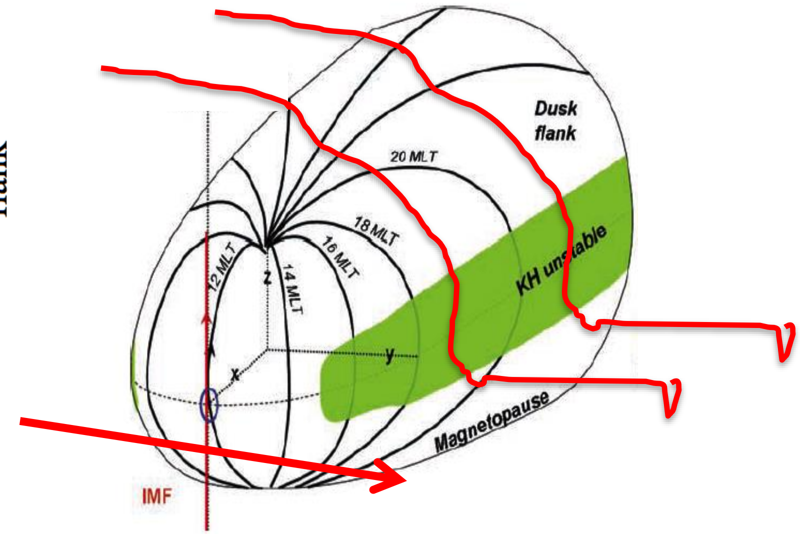


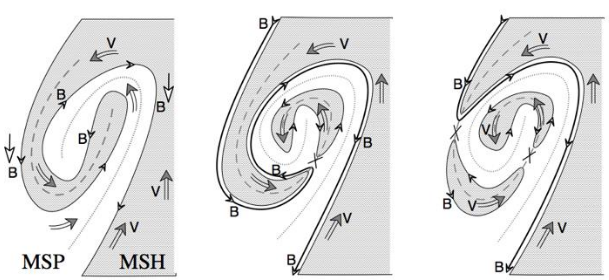




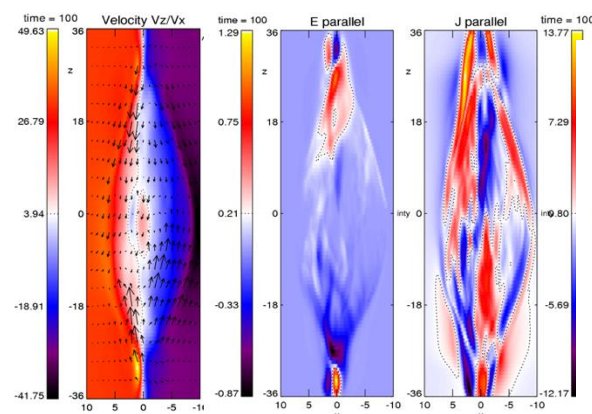
- Not open Dungey cycle
- Viscous interaction
- Shear instabilities
- Small-scale, intermittant reconnection
- Boundary layers

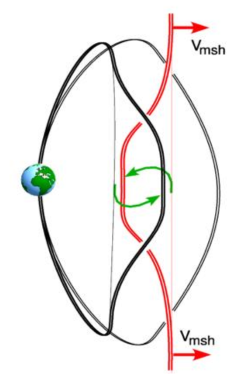






"Candy wrapper"



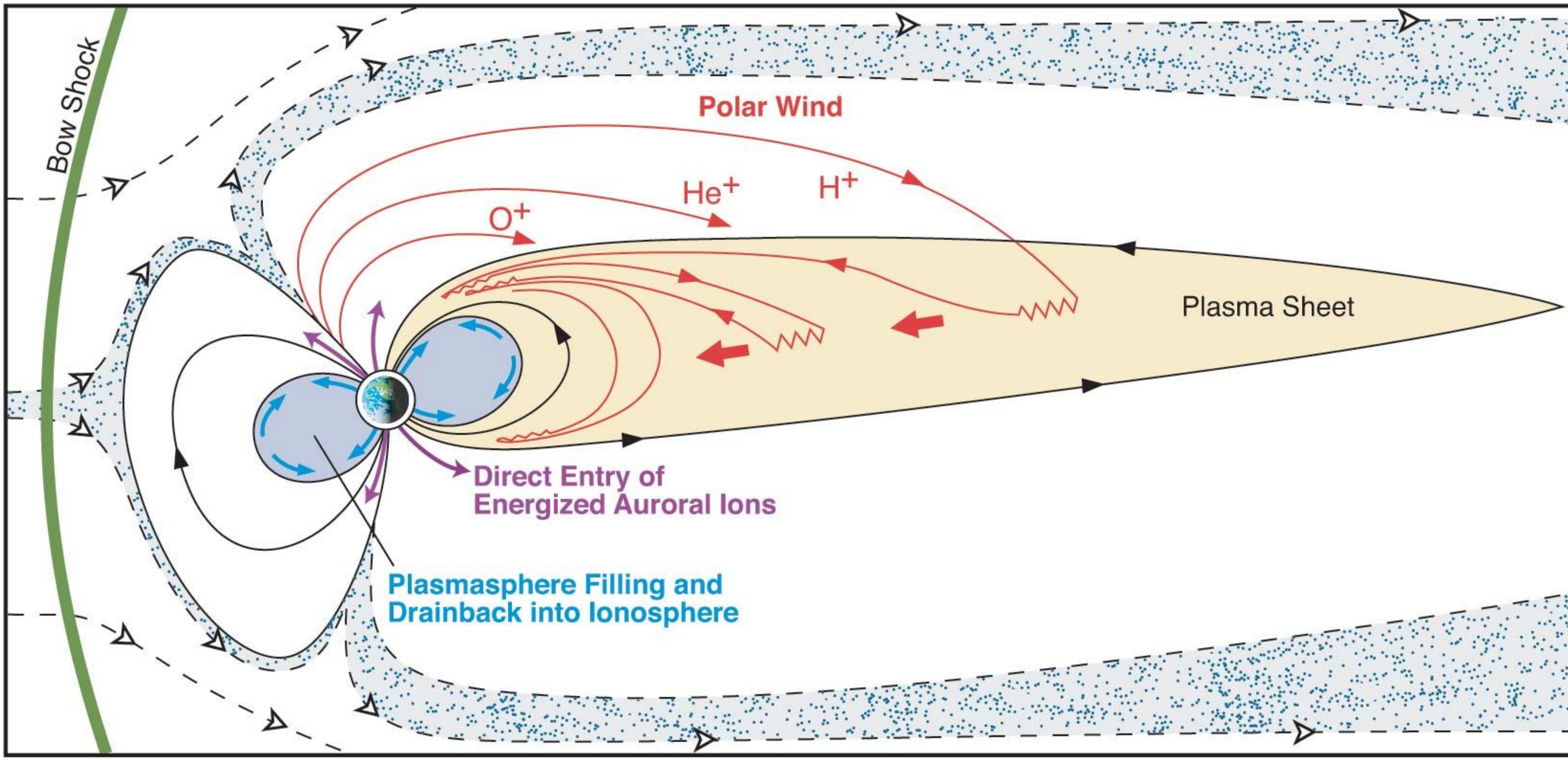


Plasma Sources

Plasma Sources

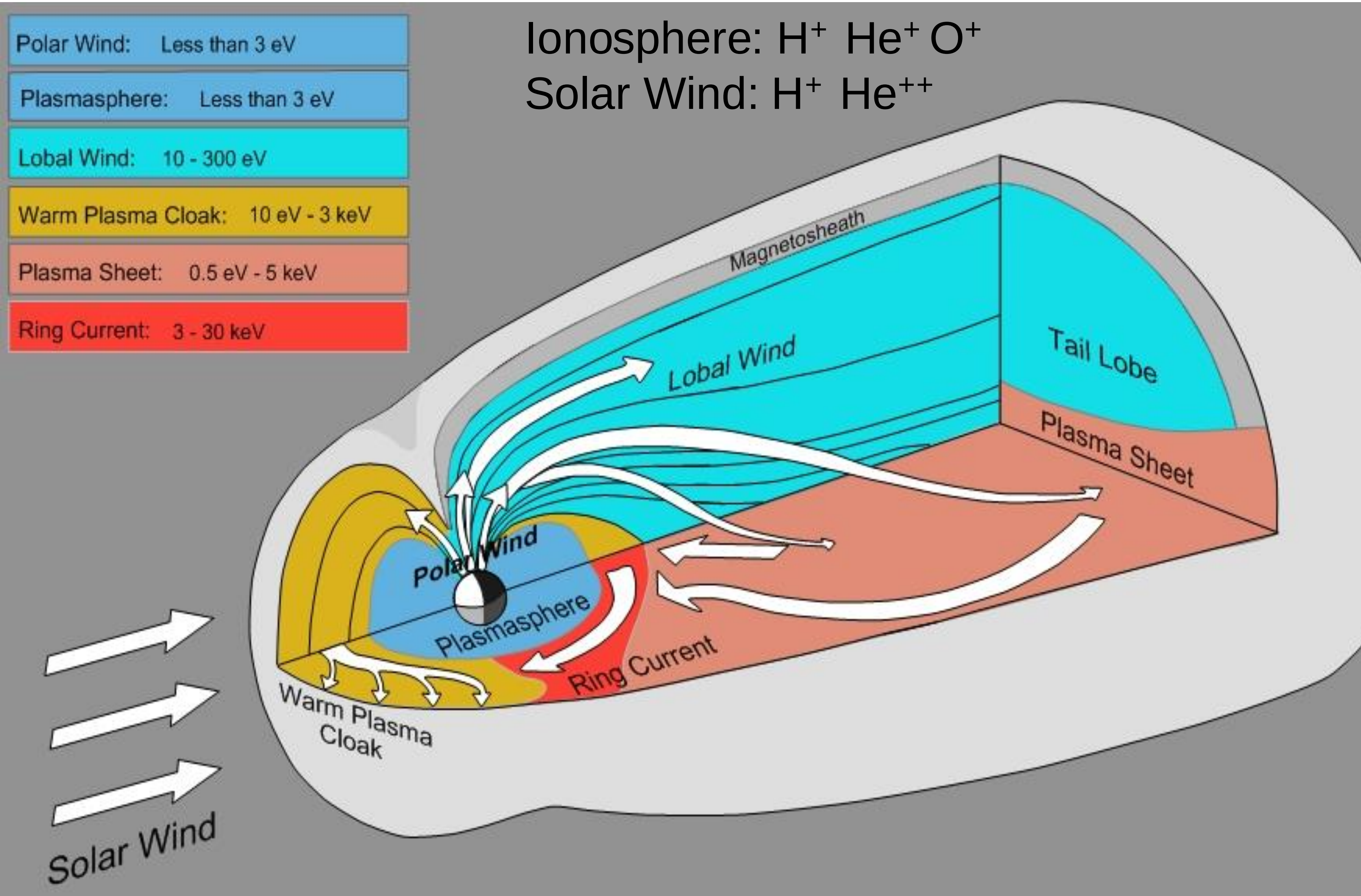
	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
N_{max} cm^{-3}	~1	1-4000	>3000	~100	~3	~2
Composition	H^+ Solar Wind	O^+ H^+ Iono-sphere	O^{n+} S^{n+} Io	O^+ H_2O^+ H^+ Enceladus	H^+ Iono-sphere	H^+ N^+ Triton Iono-sphere
Source kg / s	?	5	700-1200	70-200	~0.02	~0.2

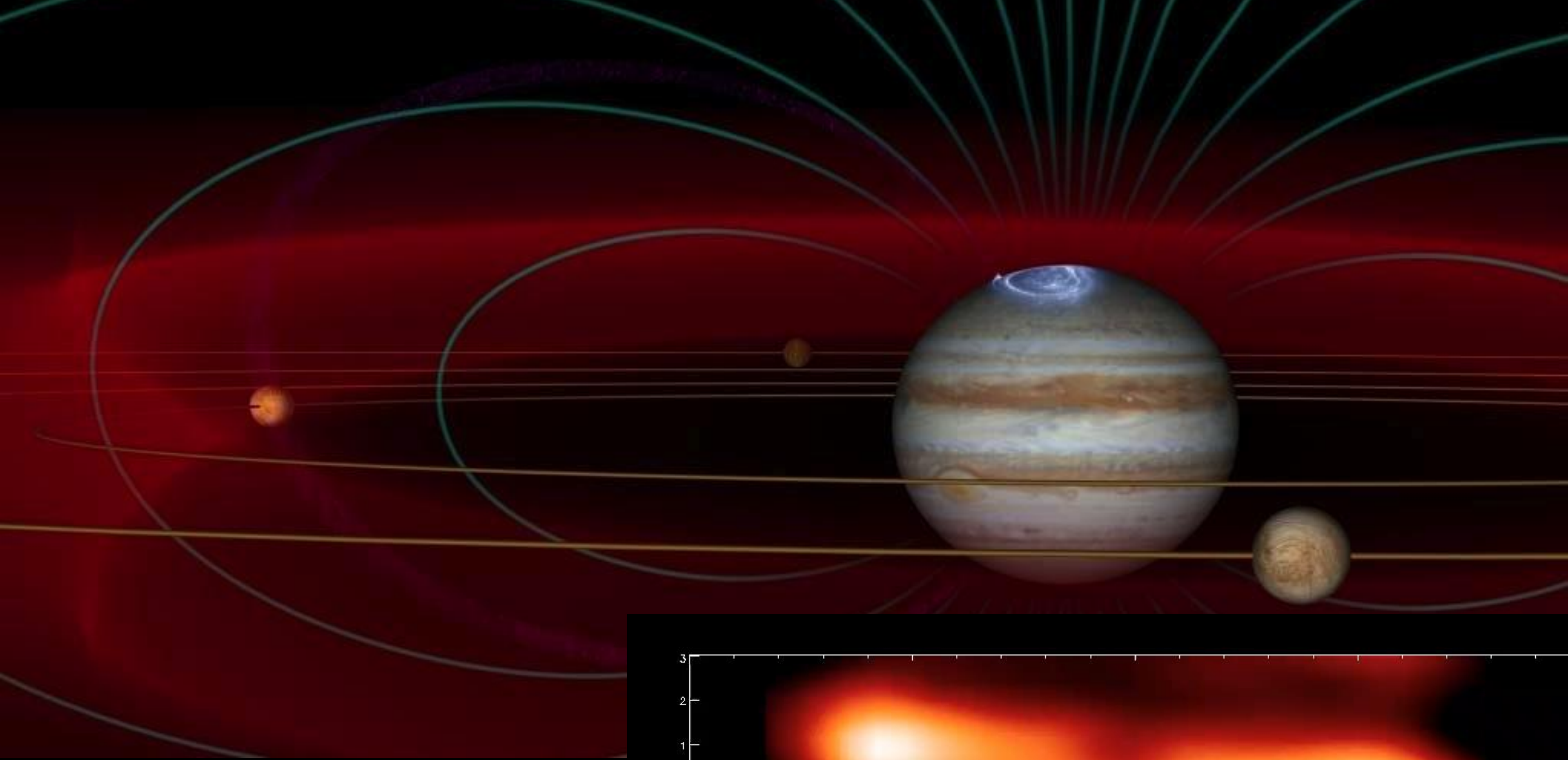
Earth Sources of Plasma (5 kg/s):
Solar Wind + ionosphere mixed (over the poles) into magnetotail and convected sunward

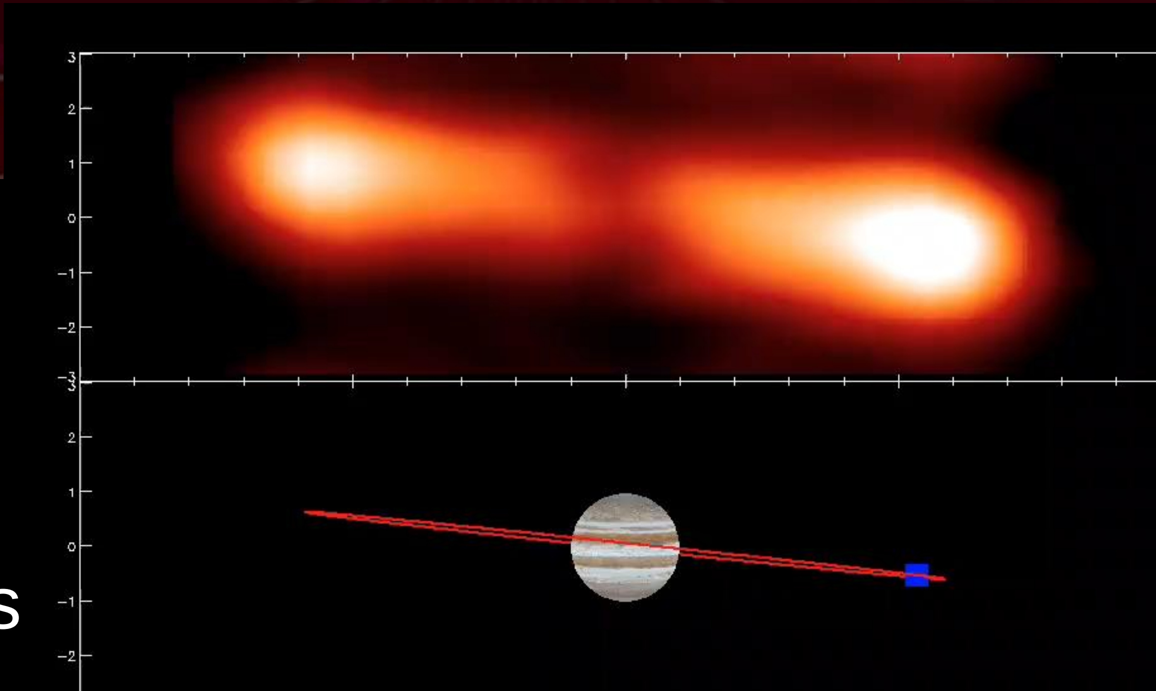


Earth Plasma Flux   5 kg/s

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





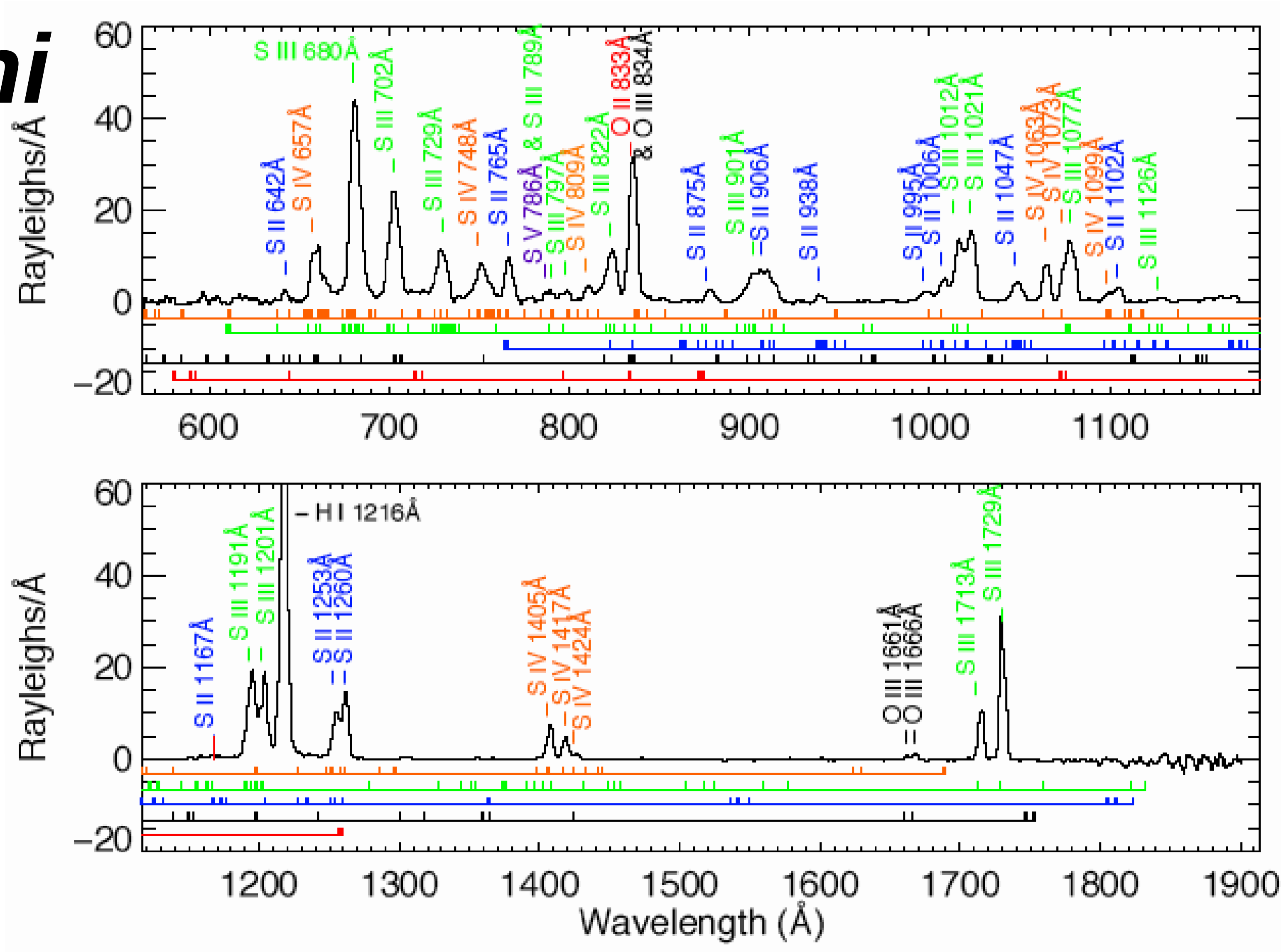


Io Plasma torus

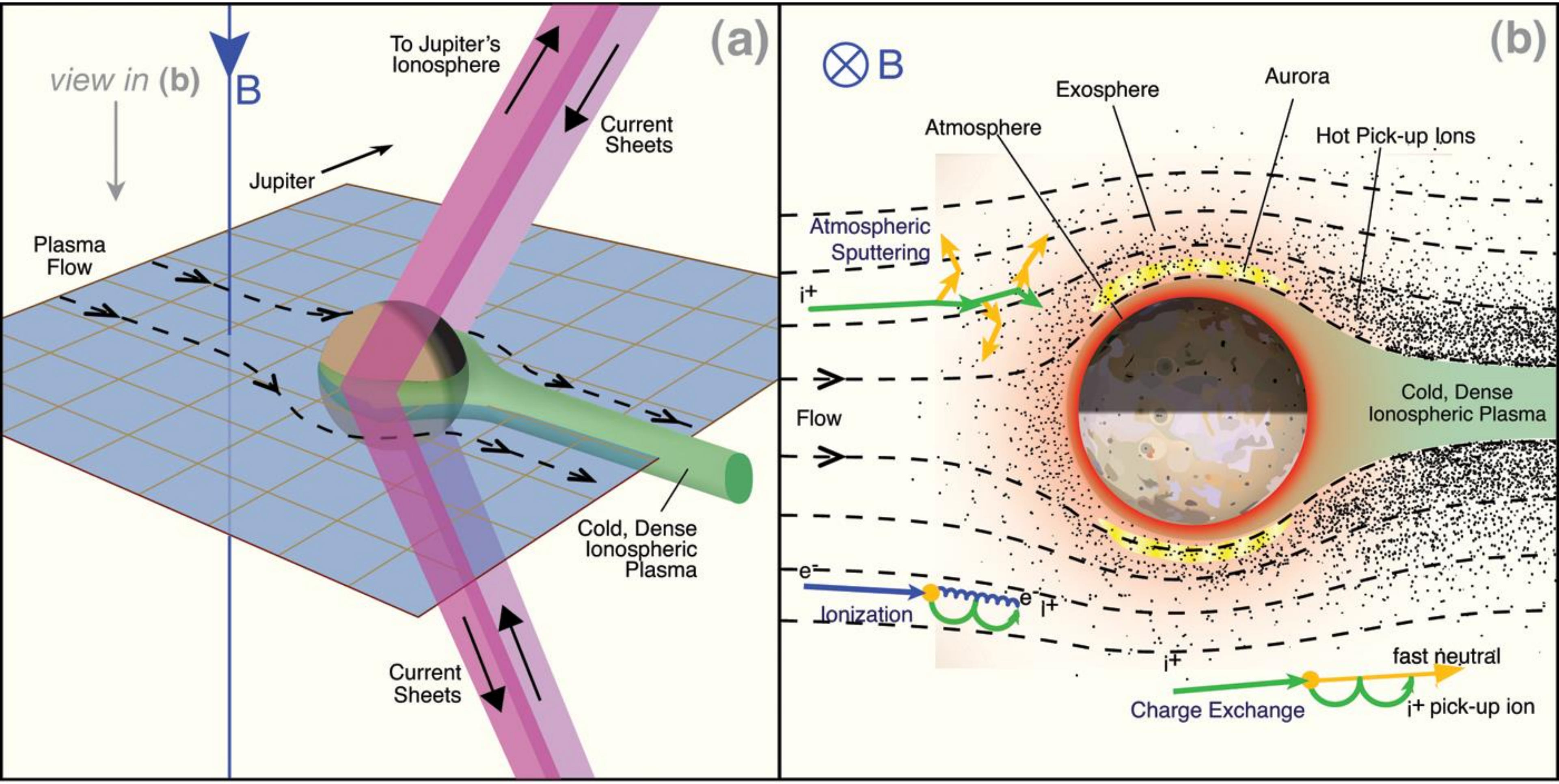
- Total mass 2 Mton
- Source 1 ton/s
- Replaced in 50 days

Cassini
UVIS

Spectral diagnosis of plasma conditions
Ni, Ne, Te



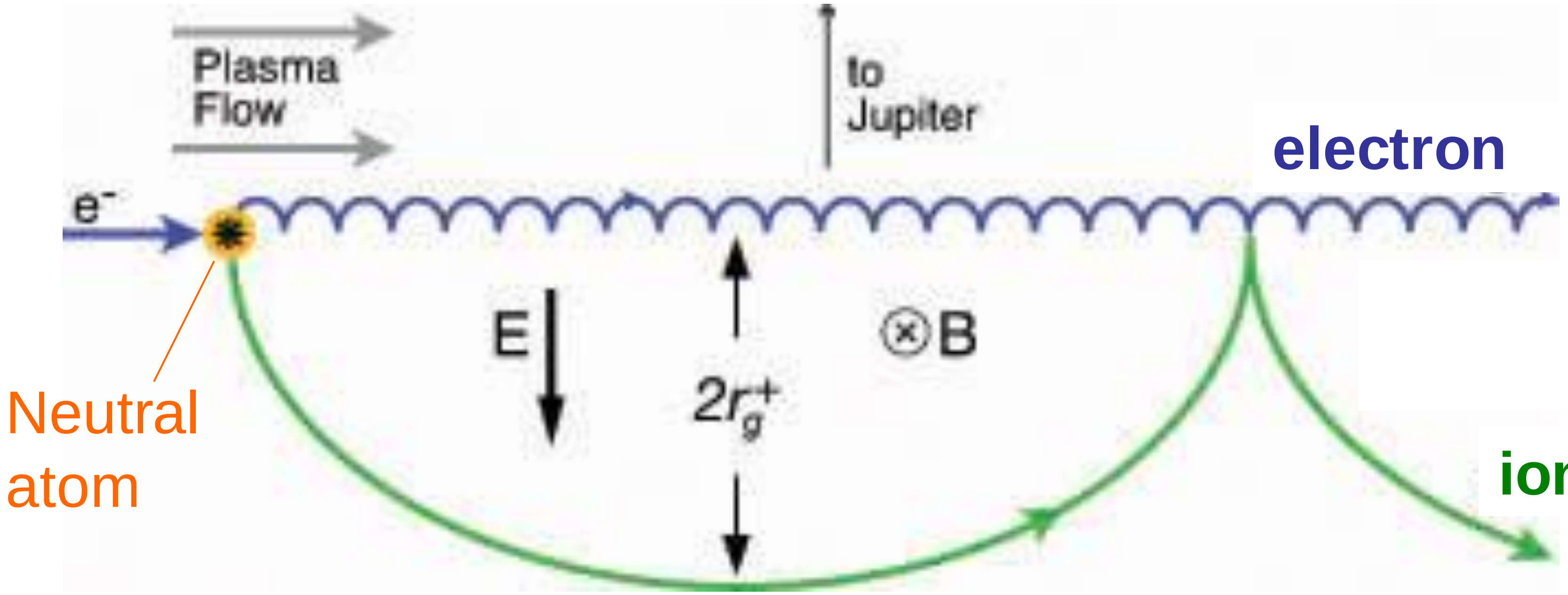
- Electron impact excitation
- ~2 TerraWatts UV emission
- Ion composition, electron temperature
- Torus structure & Variability
- Physical chemistry model



- 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

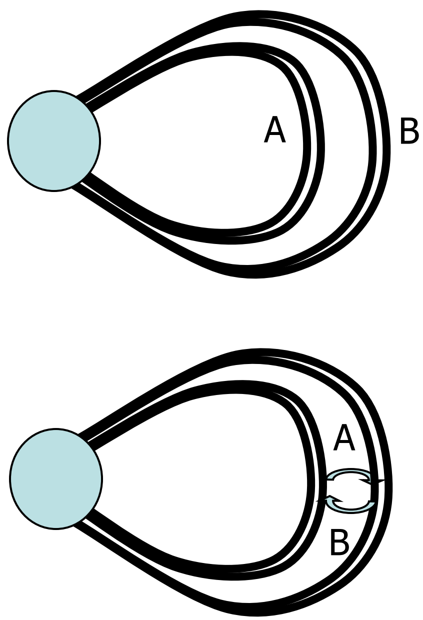


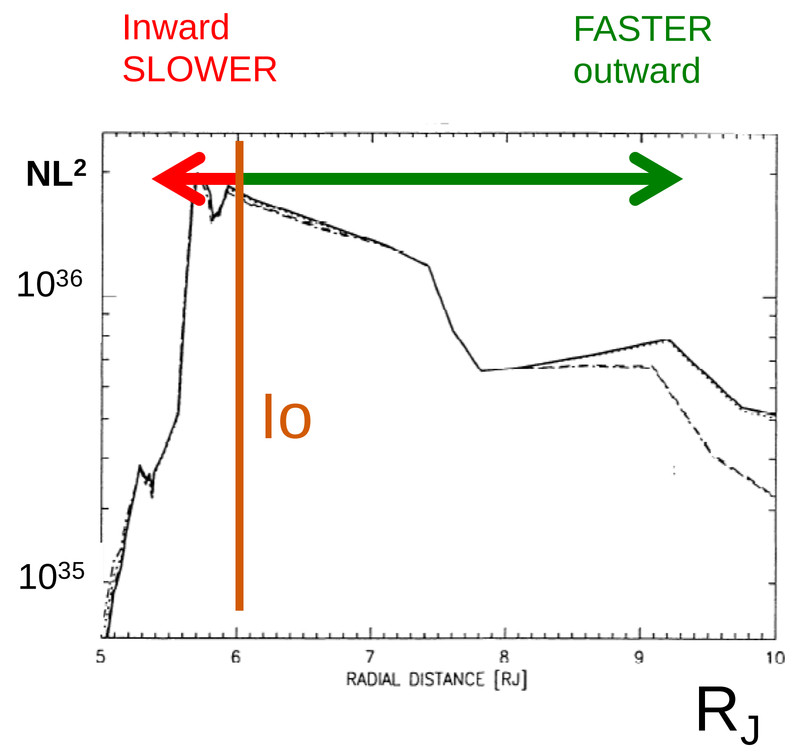
- The magnetic field couples the plasma to the spinning planet
- Ion gains large gyromotion -> heat

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

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

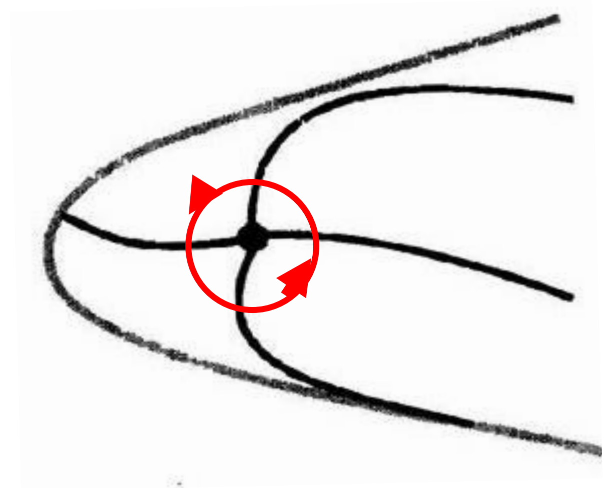
- Sub-corotating plasma pulls back the magnetic field

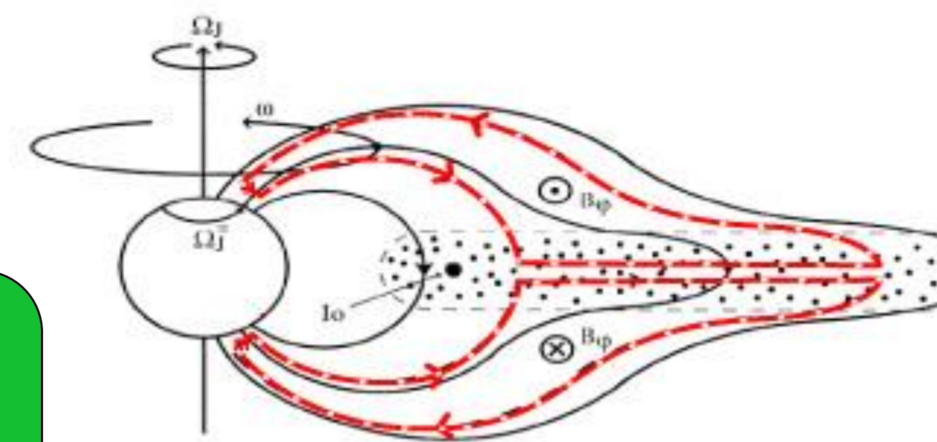
- Curl **B** -> radial current J_r

- J_r x **B** force enforces rotation

Field-aligned currents couple magnetosphere to Jupiter's rotation

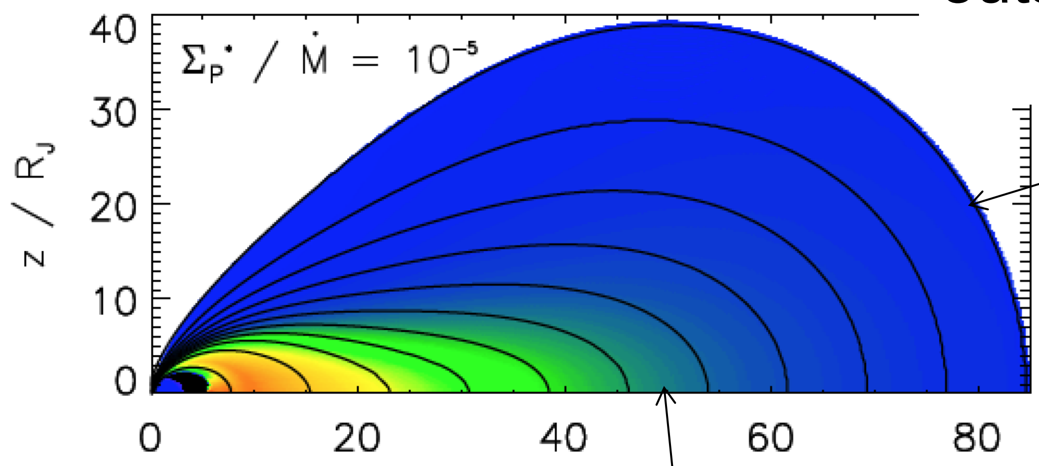
Khurana 2001





Cowley & Bunce 2001

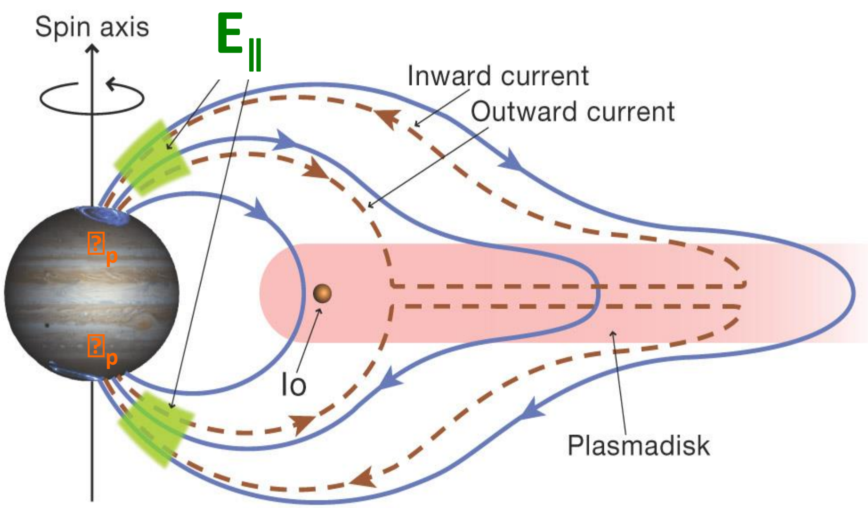
How is information transmitted along magnetic field lines?

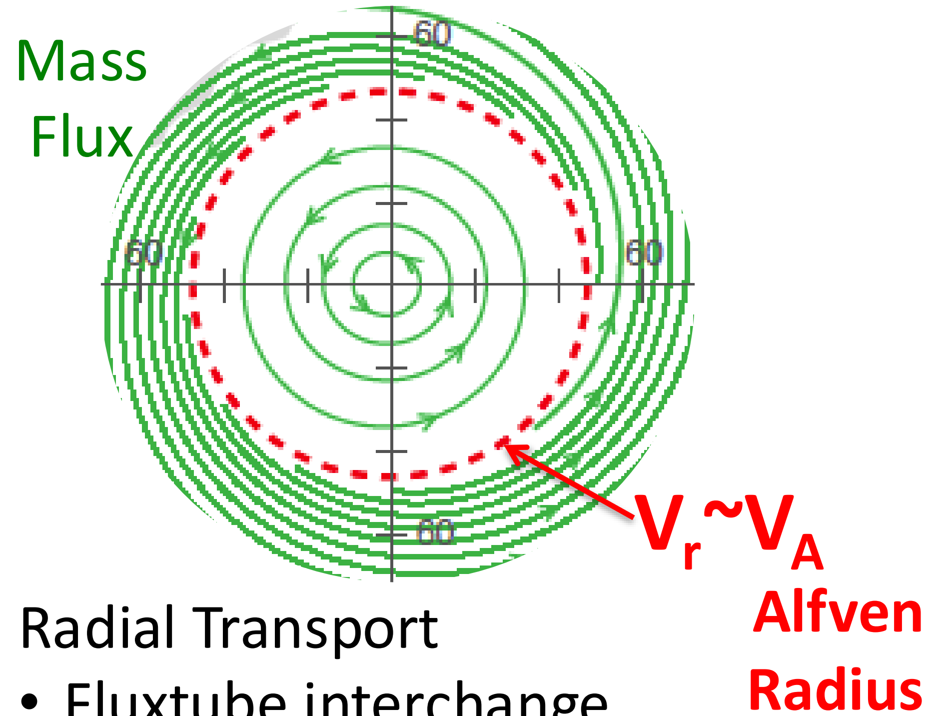


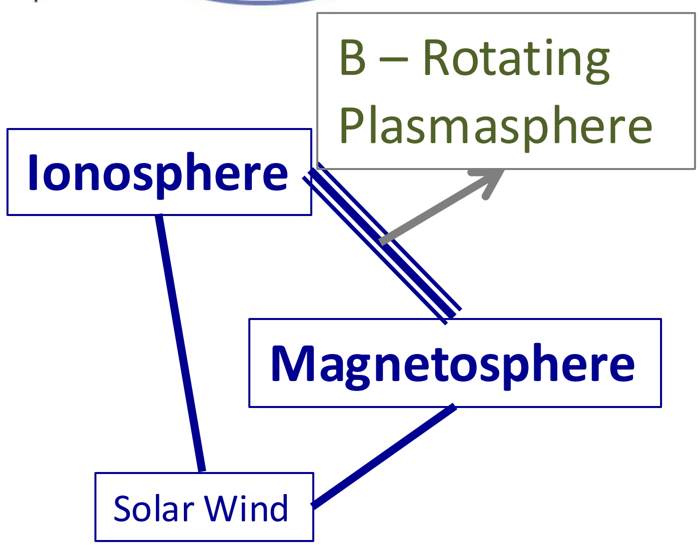
How is a stress from the outside communicated to the planet?

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

Alfven waves!







Radial Transport

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

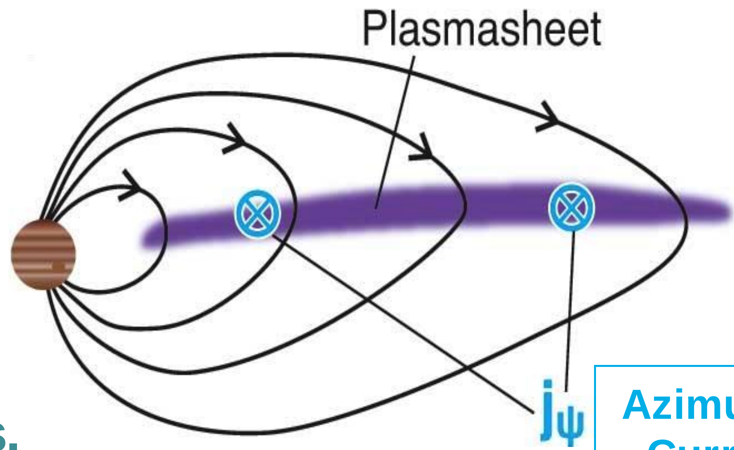
□□□□□□□□□□$_p$, $E_\parallel$ and/or $V_r \sim V_A$

Communication breaks down ~25R$_J$.
Magnetosphere & atmosphere stop talking > 60 R$_J$

Configuration

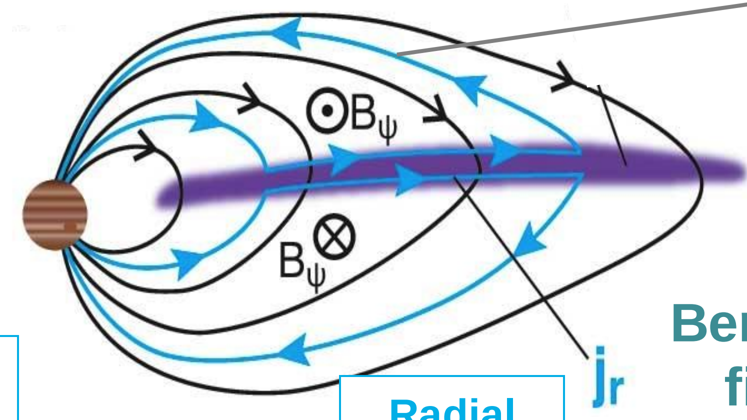
$\nabla \times B_{observed}$
$\rightarrow J$

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



Azimuthal Current

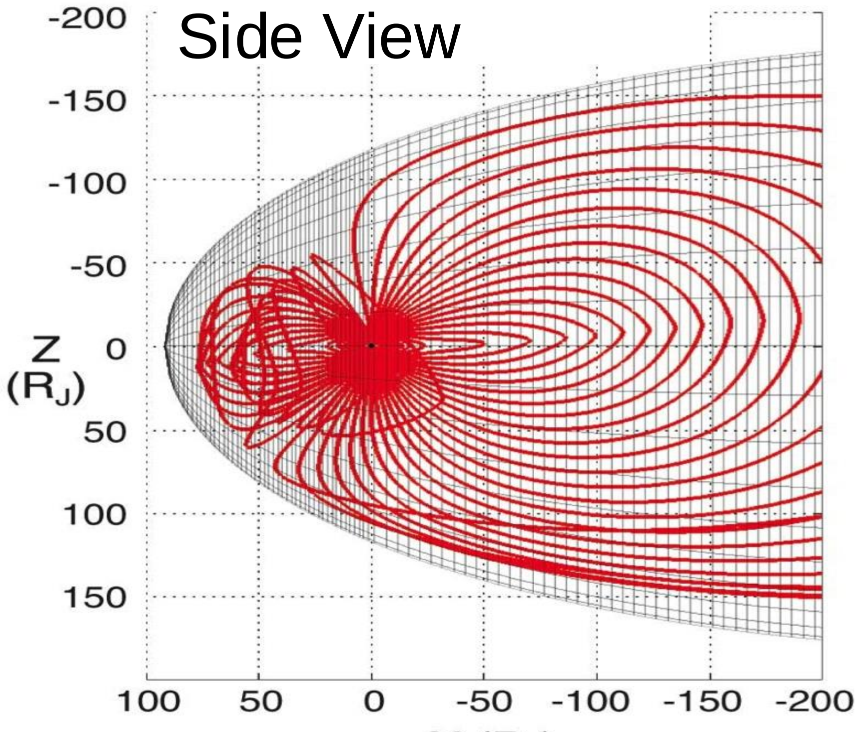
Expands, stretches field



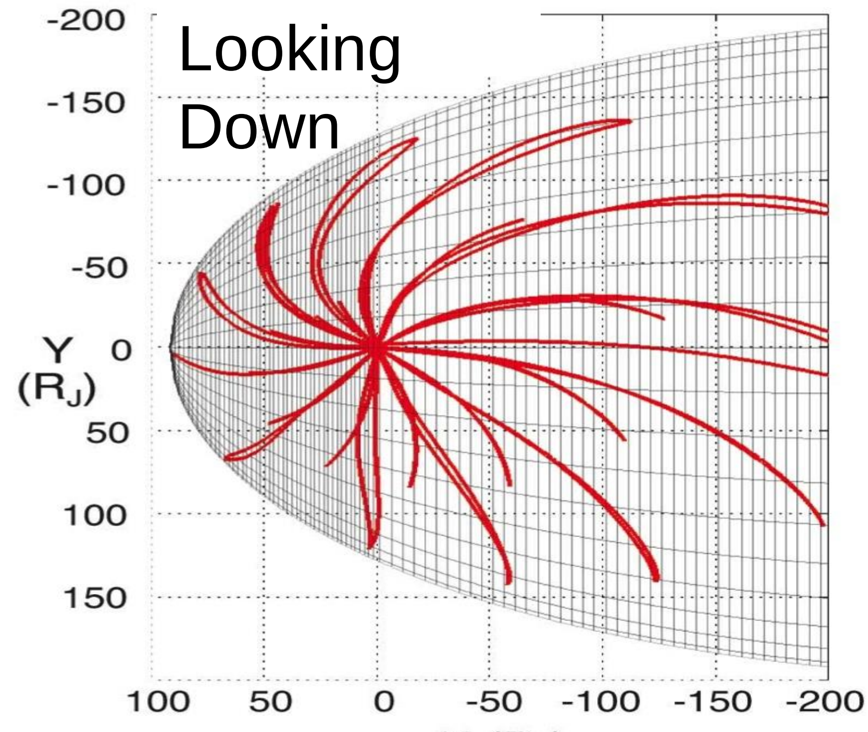
Radial Current

Bends field back

Side View

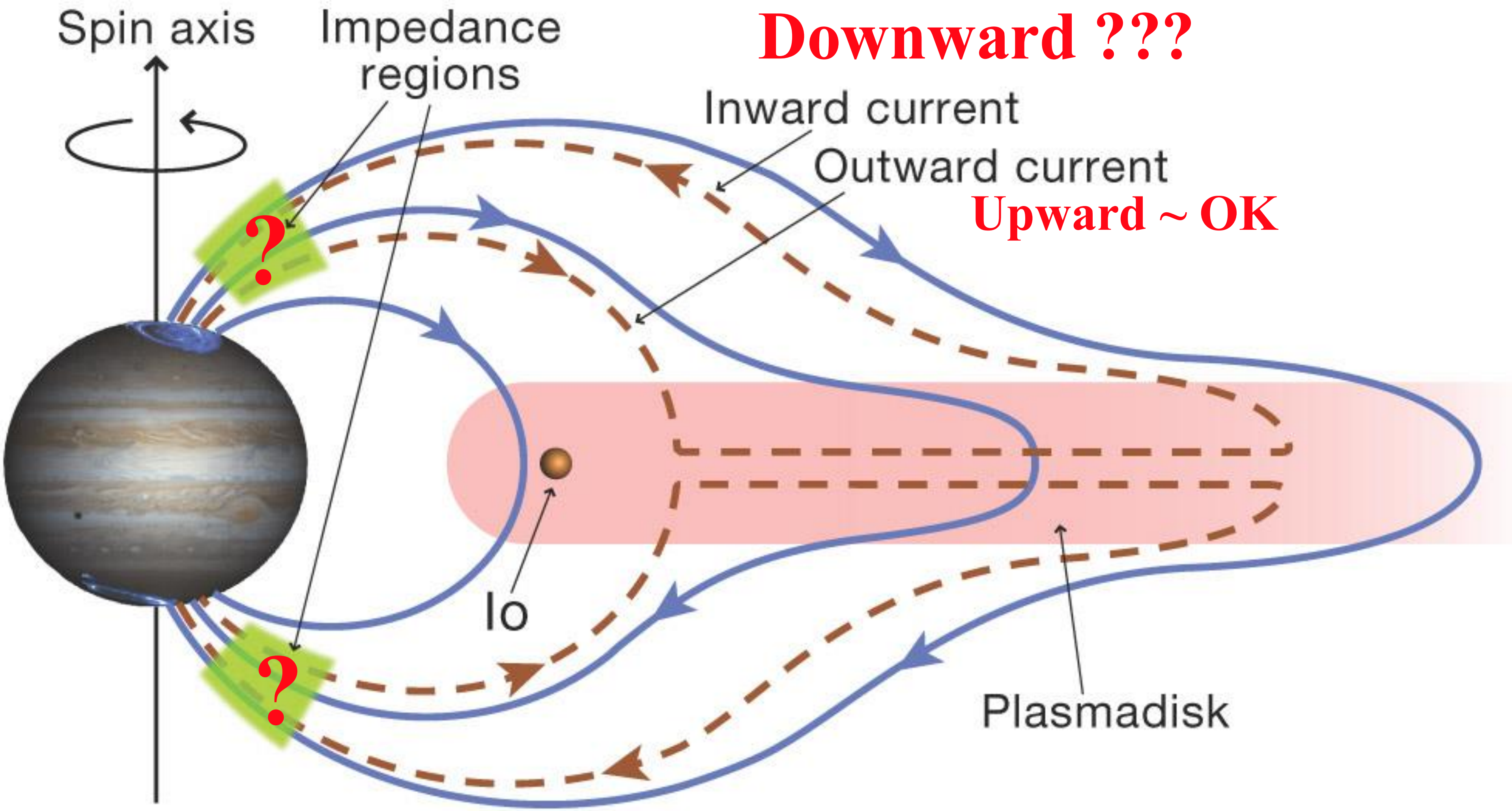


Looking Down



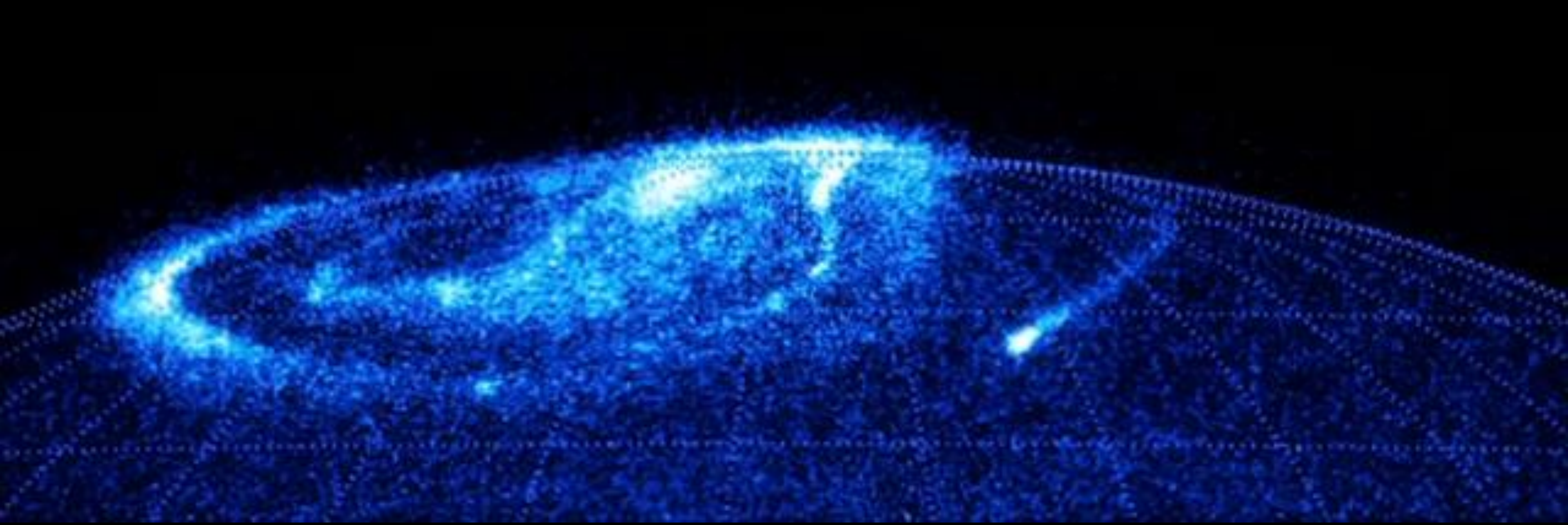
Aurora

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

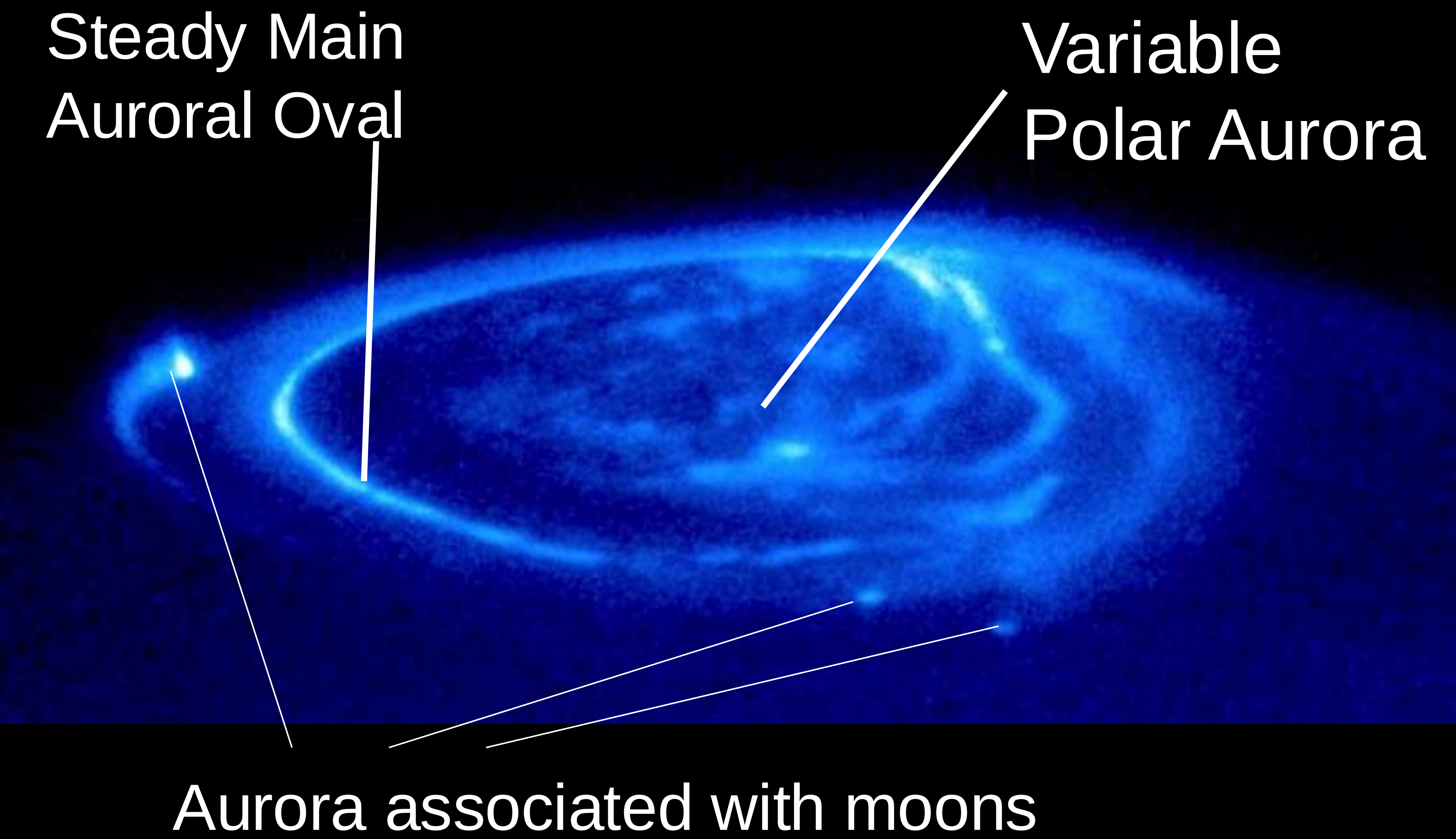


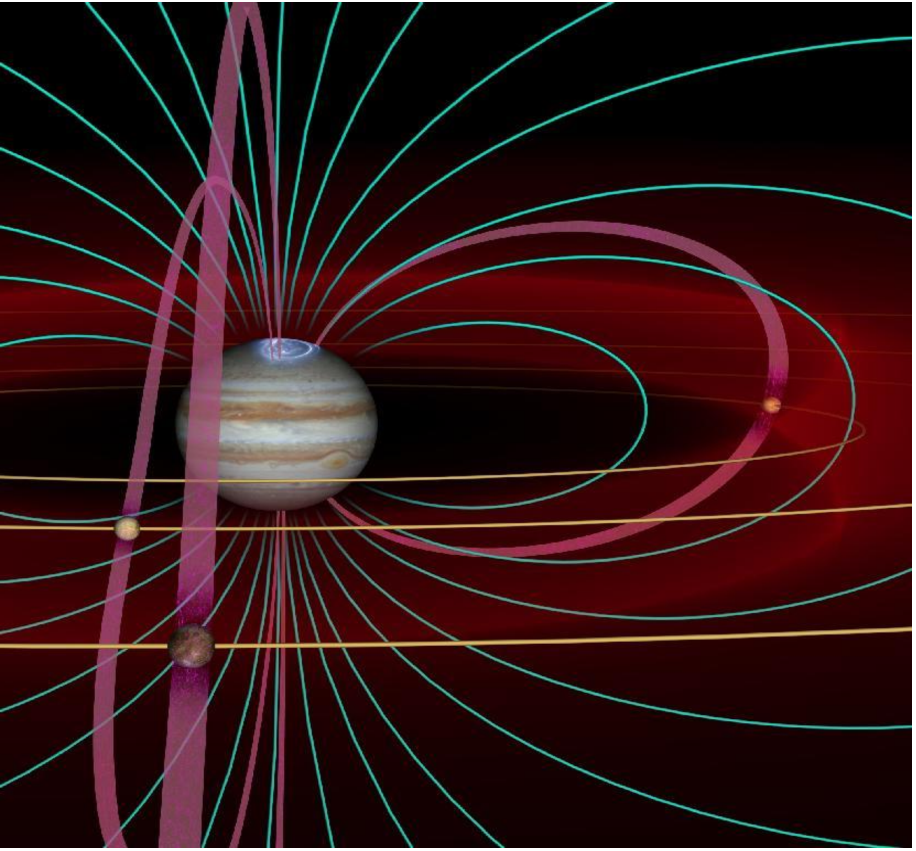
Parallel electric fields: potential layers, $\phi_{||}$, "double layers"

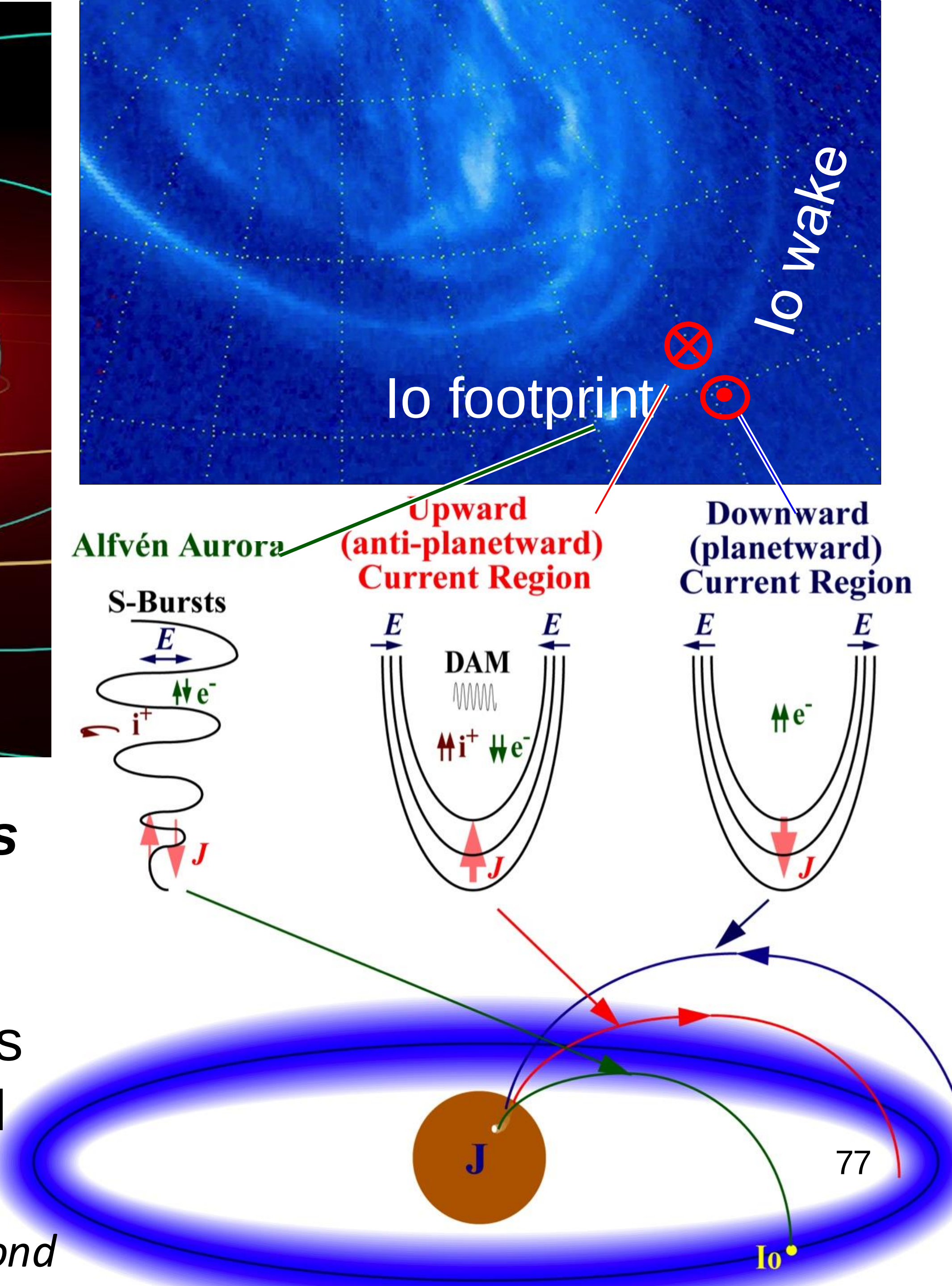
Hubble Space Telescope – *Jon Nichols*



Jupiter's 3 Types of Aurora







Satellite auroral emissions

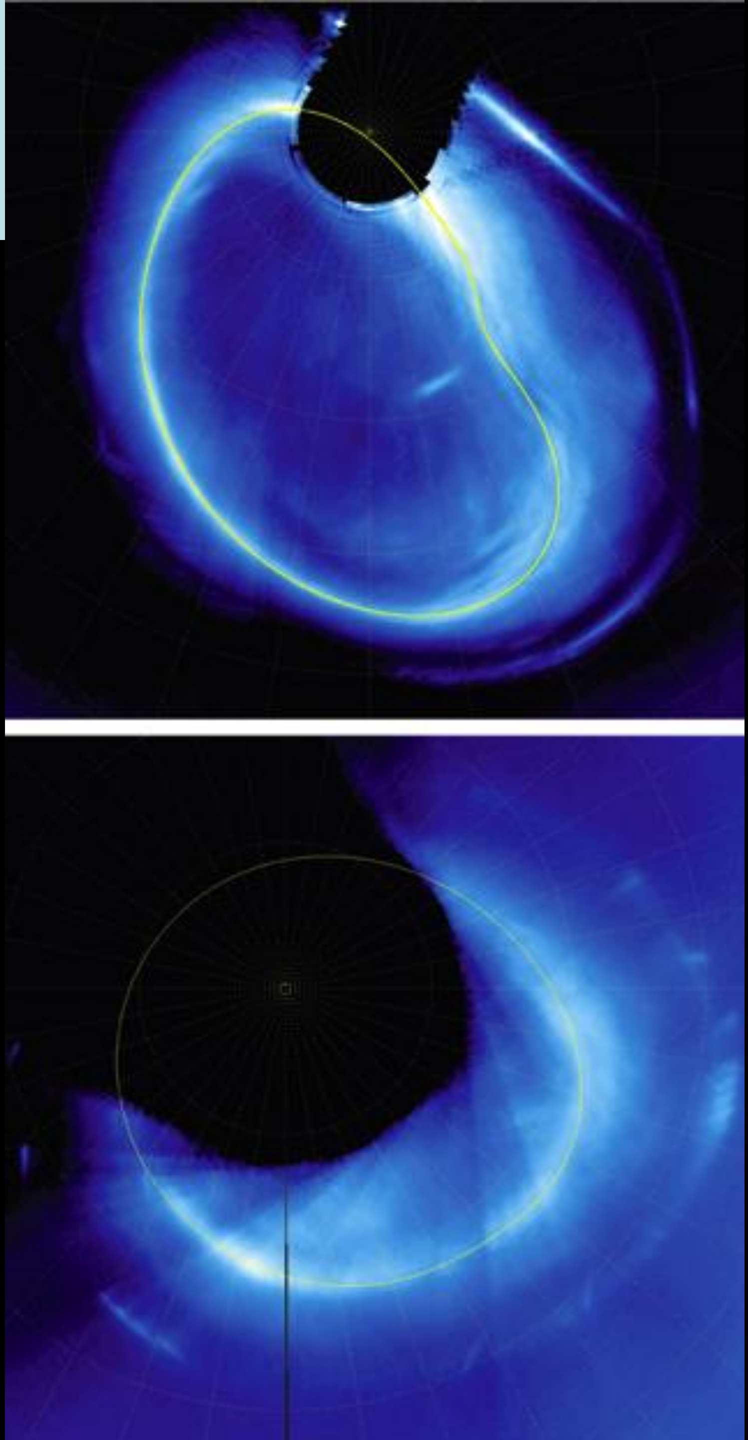
- Plasma-moon electrodynamic interaction
- Mega-amp current systems
- Analogous to Earth auroral processes

Papers by Su, Ergun, Lysak, Hess, Bonfond

Main Aurora

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

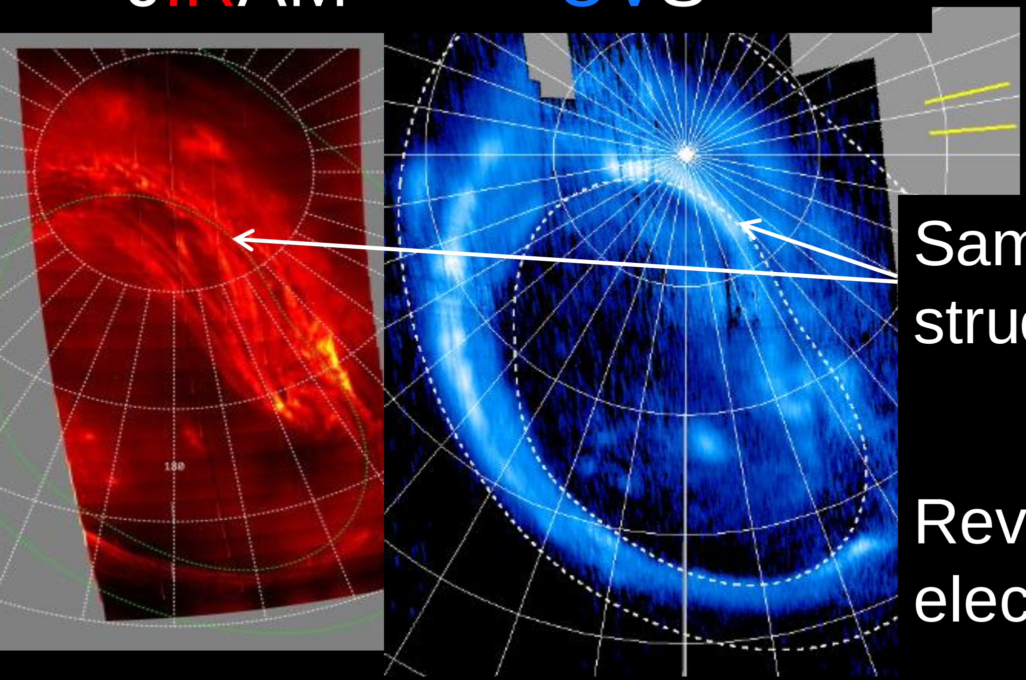
Clarke et al., Grodent et al. HST



Jupiter's Aurora: Structured & Dynamic

Juno UVS

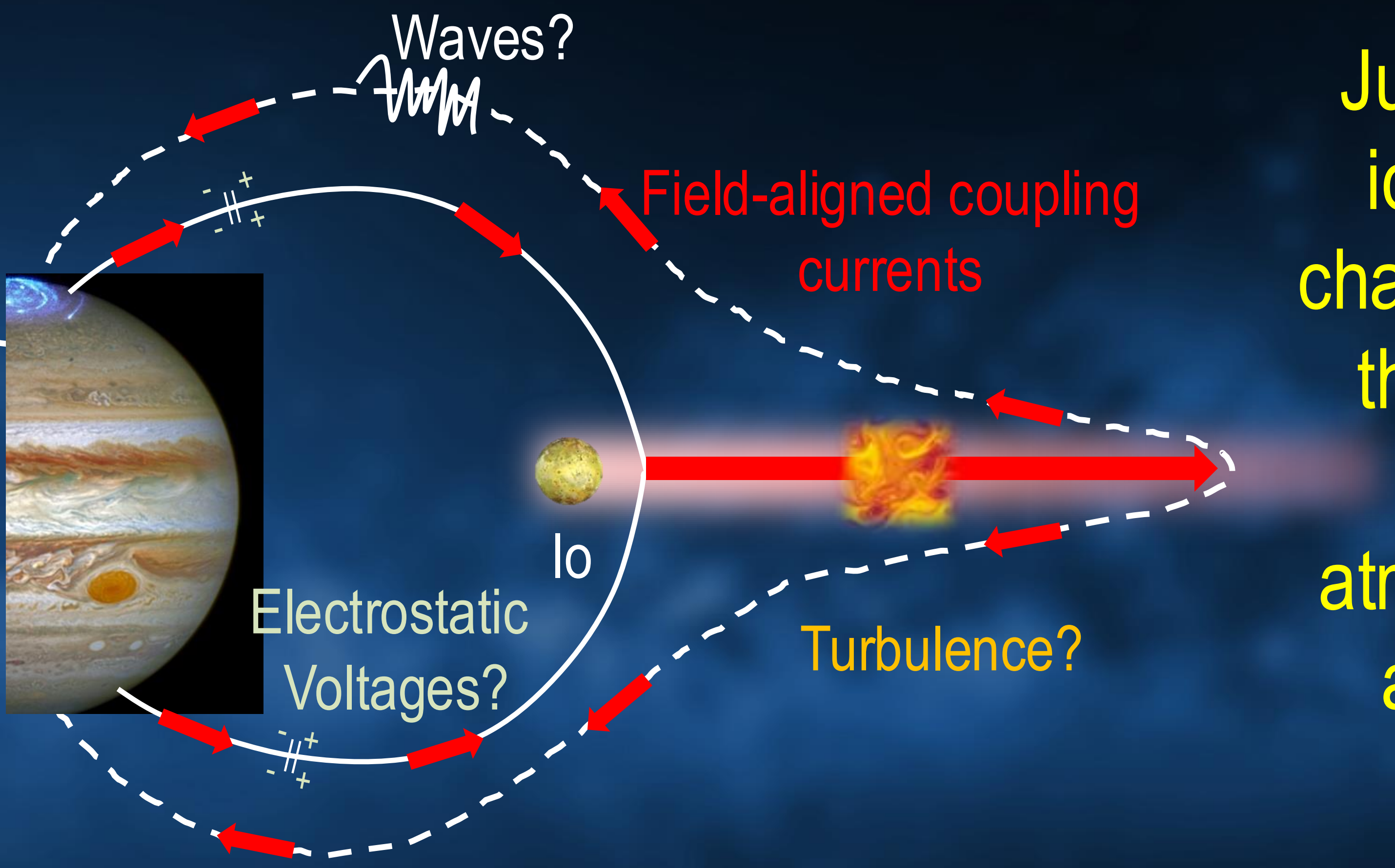
JIRAM UVS



Same region – very different structure in UV vs. IR

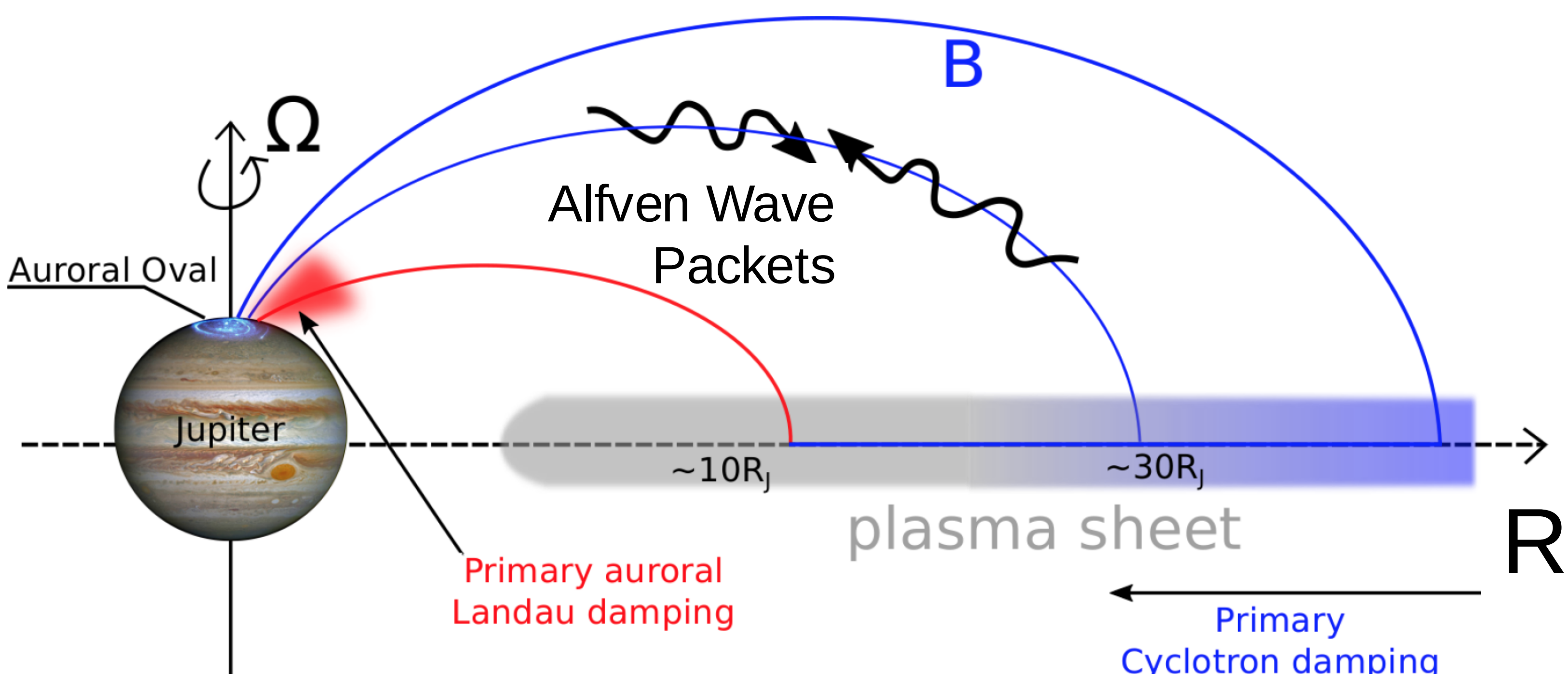
Reveals energy of bombarding electrons & atmospheric chemistry

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

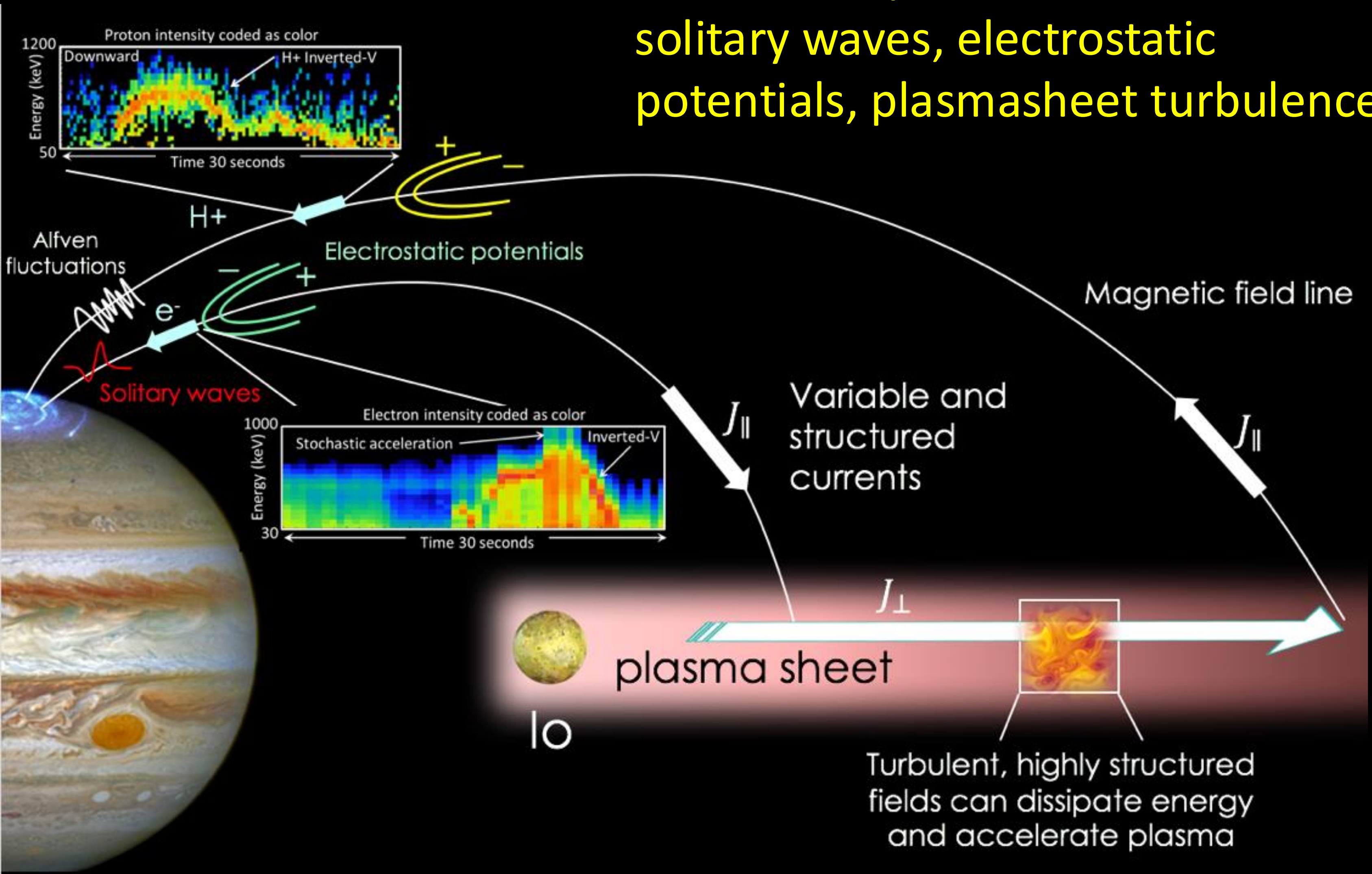


Heats Electrons
$T_{\parallel}$

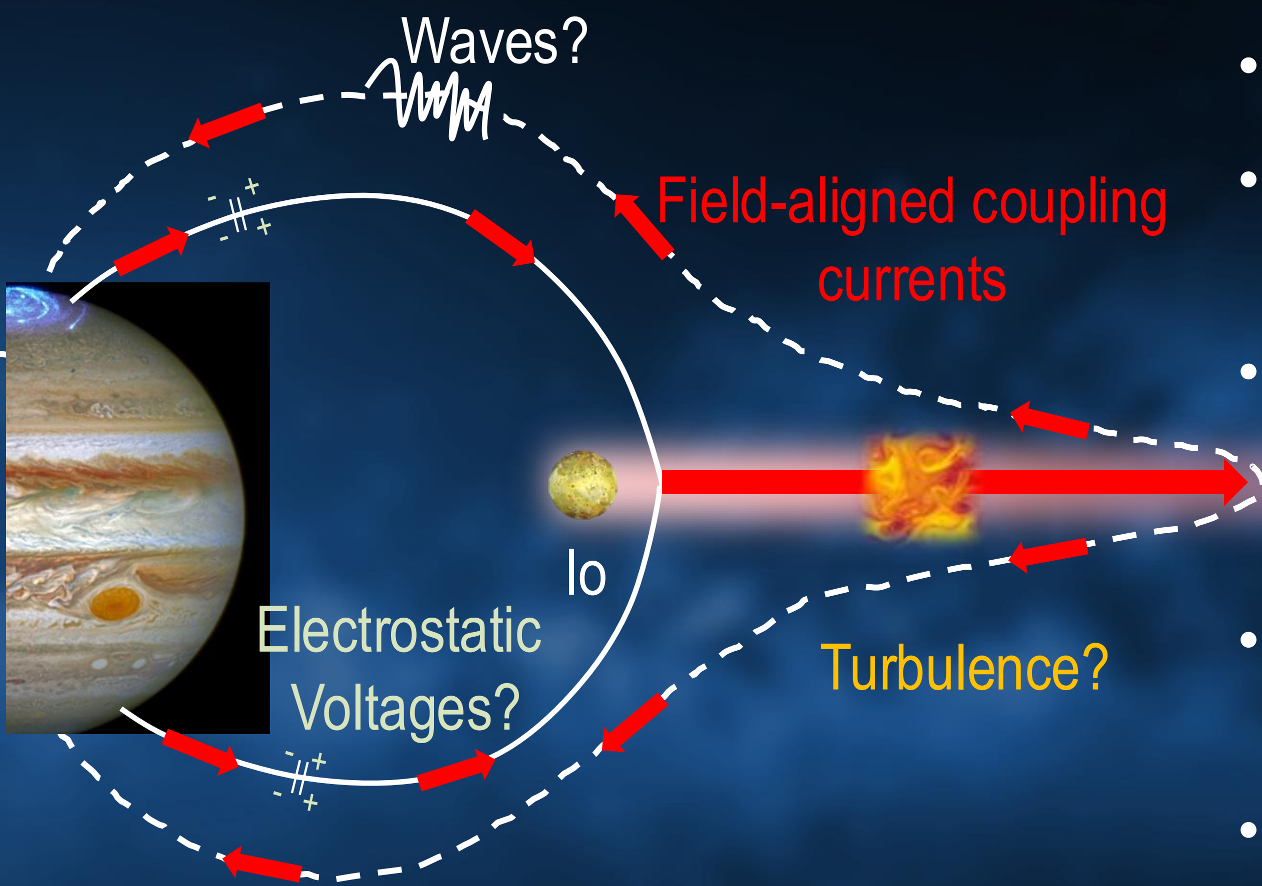
Heats Ions
$T_{\perp}$

Saur et al. 2018

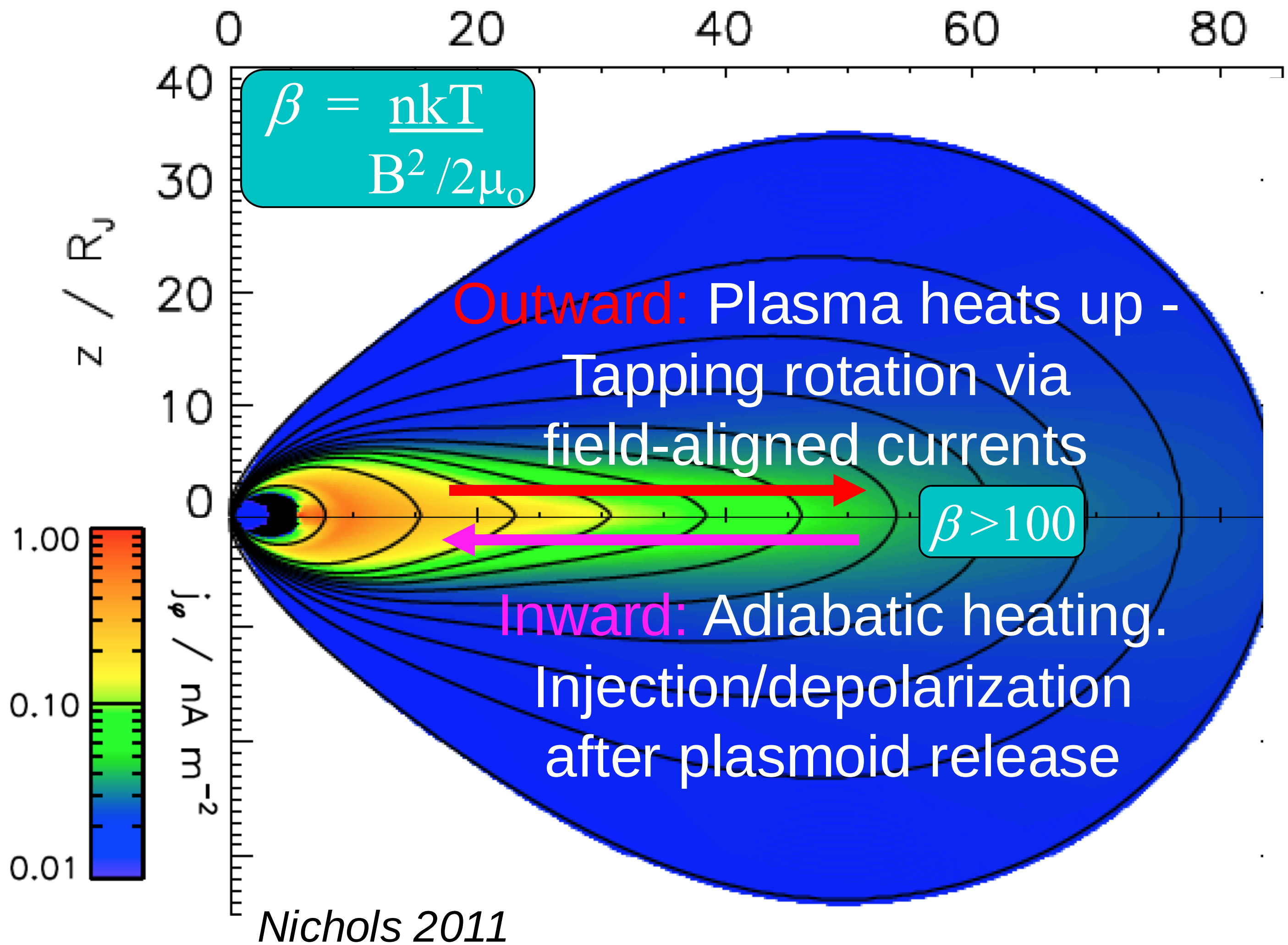
- Electrons reach >1 MeV
- Acceleration processes unclear: solitary waves, electrostatic potentials, plasmasheet turbulence



Mauk et al. 2018

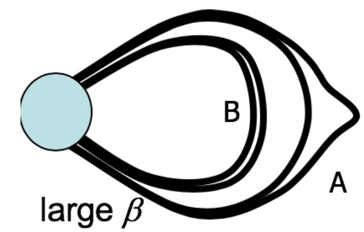


- System quasi-stable?
- Strong coupling currents unstable?
- Fluxtube interchange non-continuous – local force imbalance
- Turbulence cascades to small scales?
- Stochastic accelerations

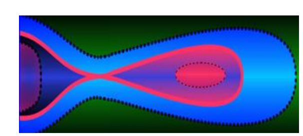


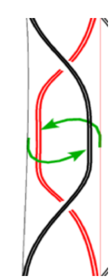
Transport:

Plasma β increases
ballooning replaces
interchange

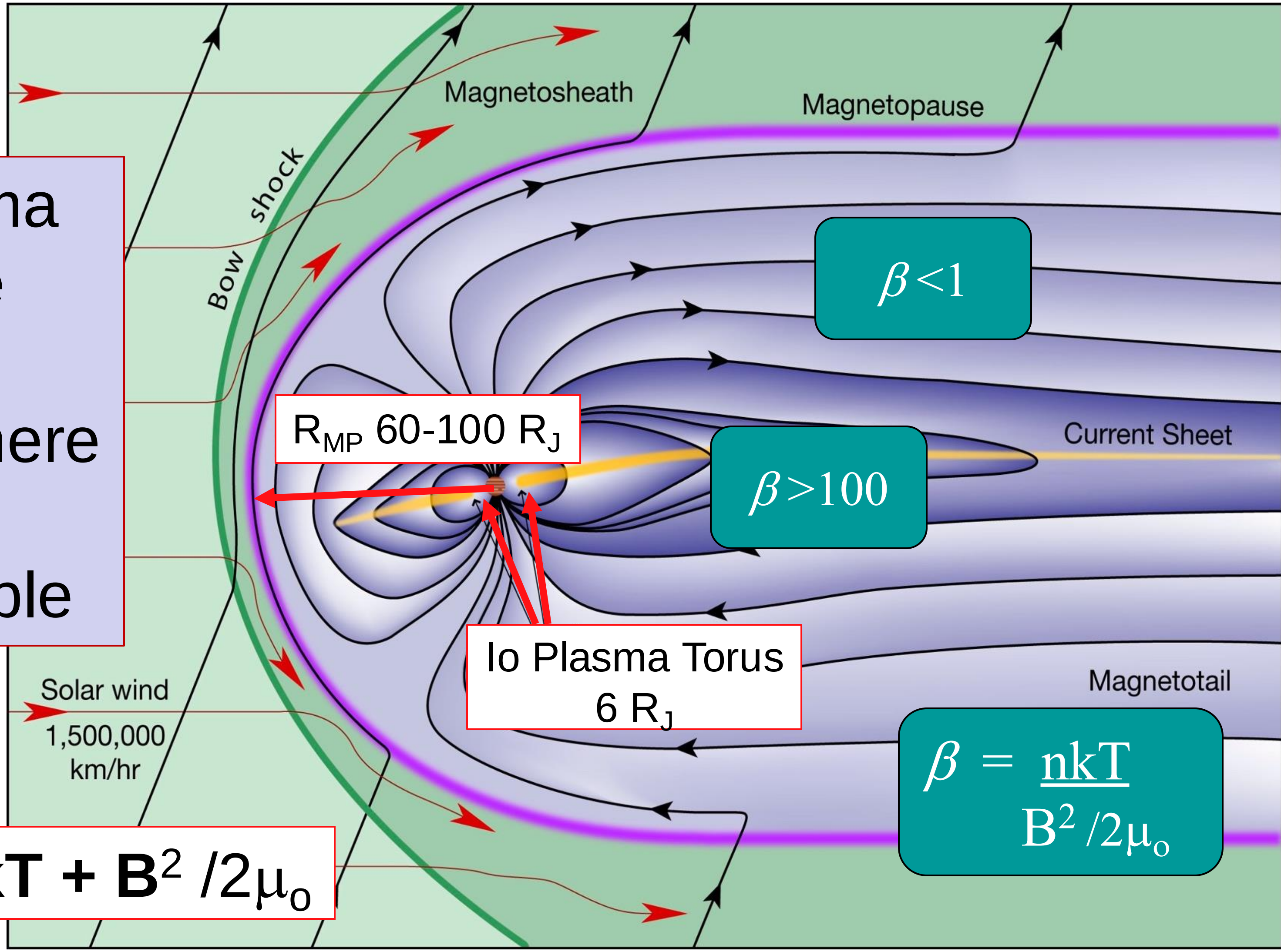


"Drizzle"
Small-scale, local
Kinetic transport?
Reconnection?
Plasmoids?





High Plasma Pressure Makes Magnetosphere Larger & Compressible



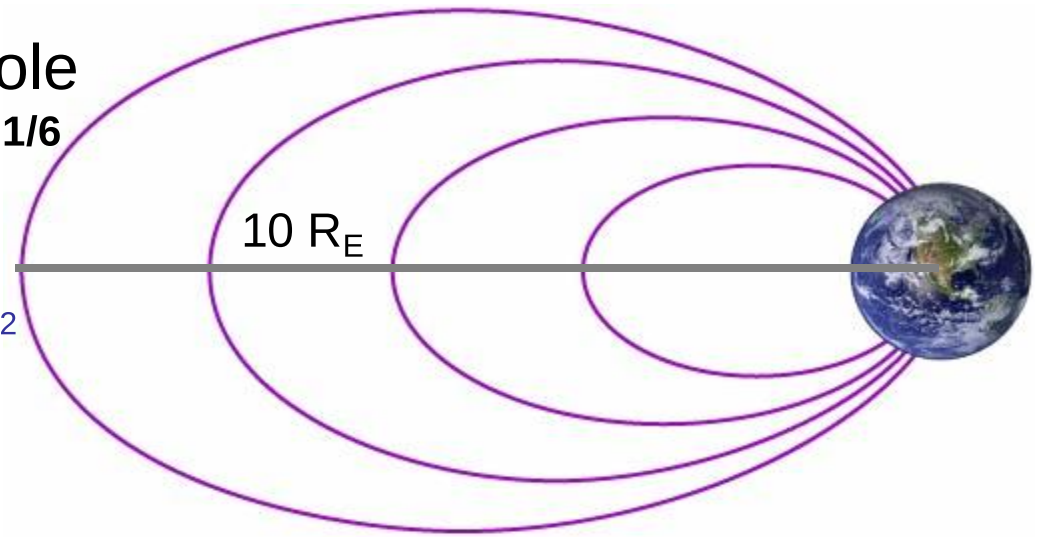
$$\rho_{sw} V^2_{sw} = nkT + B^2/2\mu_o$$

How Compressible with Solar Wind Pressure?

Earth ~ Dipole

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

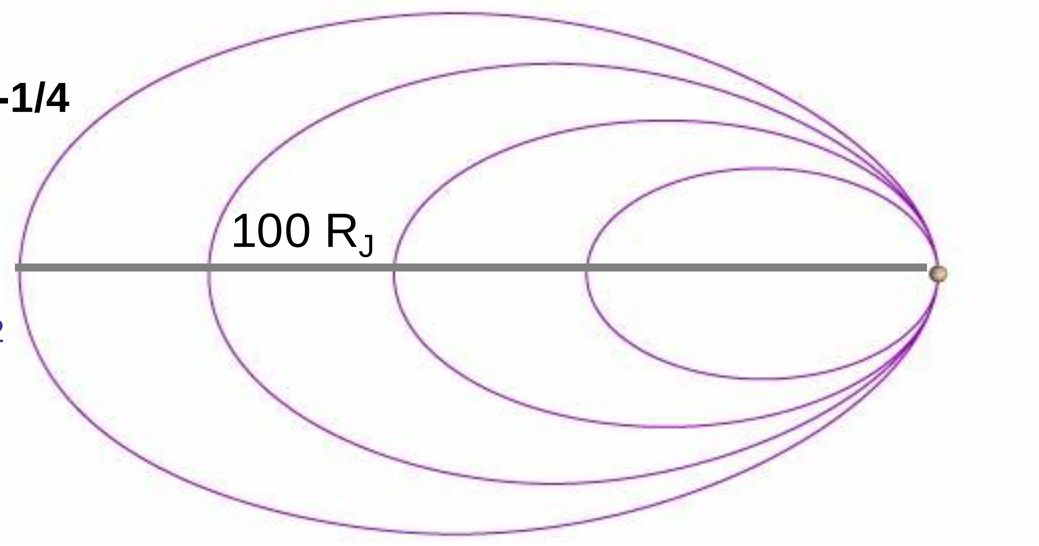
solar wind ρV^2



Jupiter

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

solar wind ρV^2



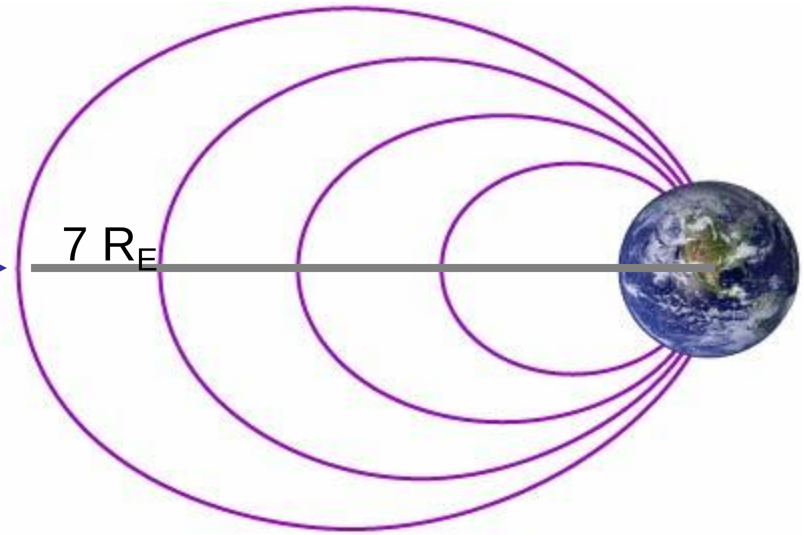
Slavin 1985
Huddleston et al. 1998
Joy et al. 2002

x10 Solar wind pressure

Earth ~ Dipole

R_{mp} -> 0.7 R_{mp}

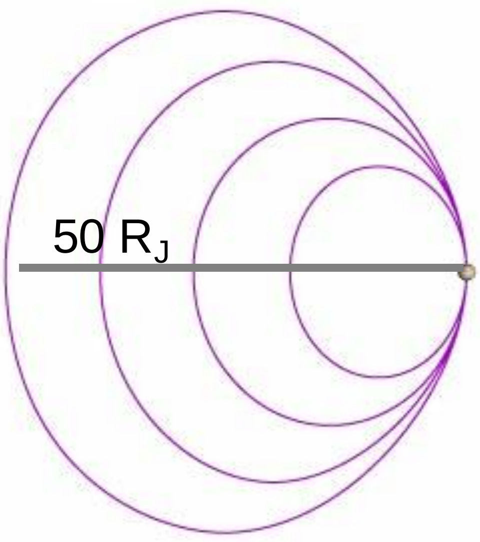
solar wind ρV^2



Jupiter

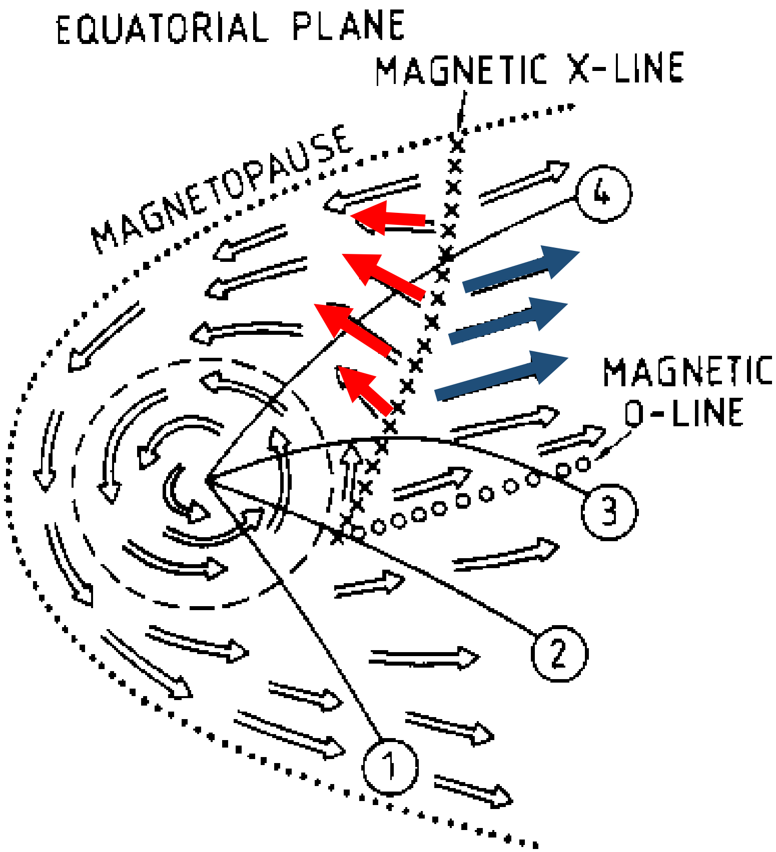
R_{mp} -> 0.5 R_{mp}

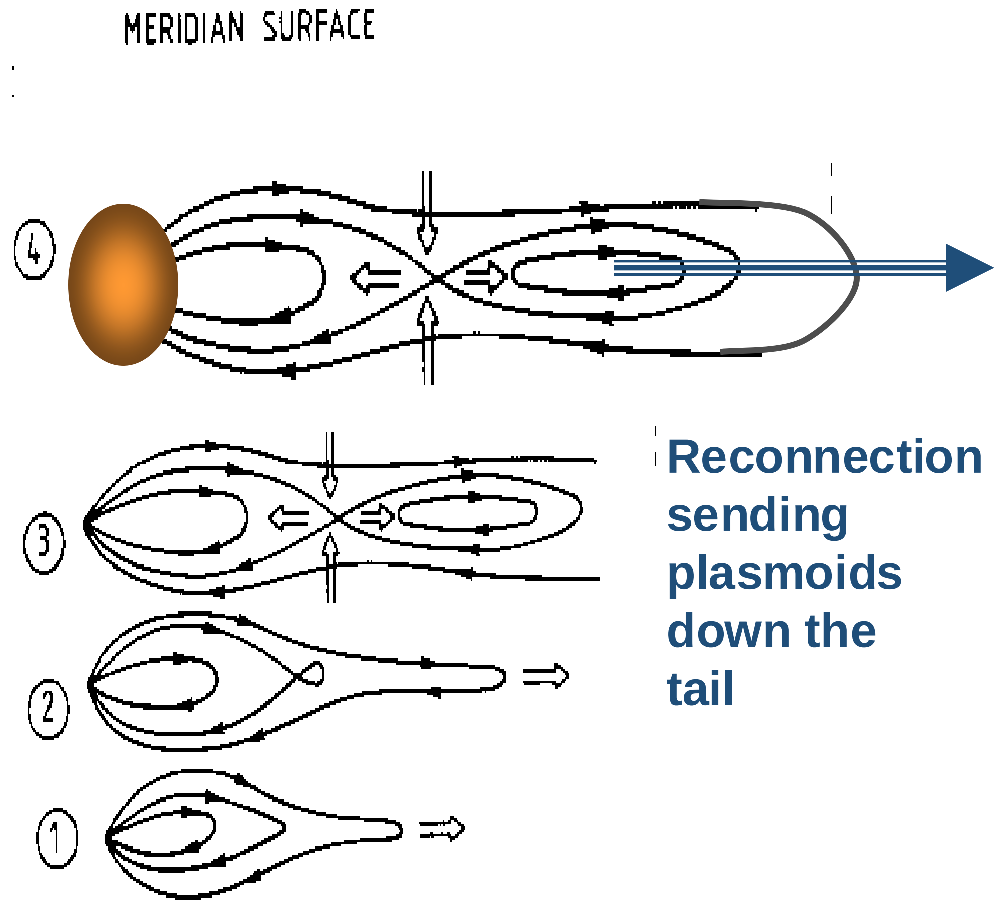
solar wind ρV^2



observed
100-50 R_J
dayside
magnetosphere

Vasyliunas Cycle
driven by centrifugal forces



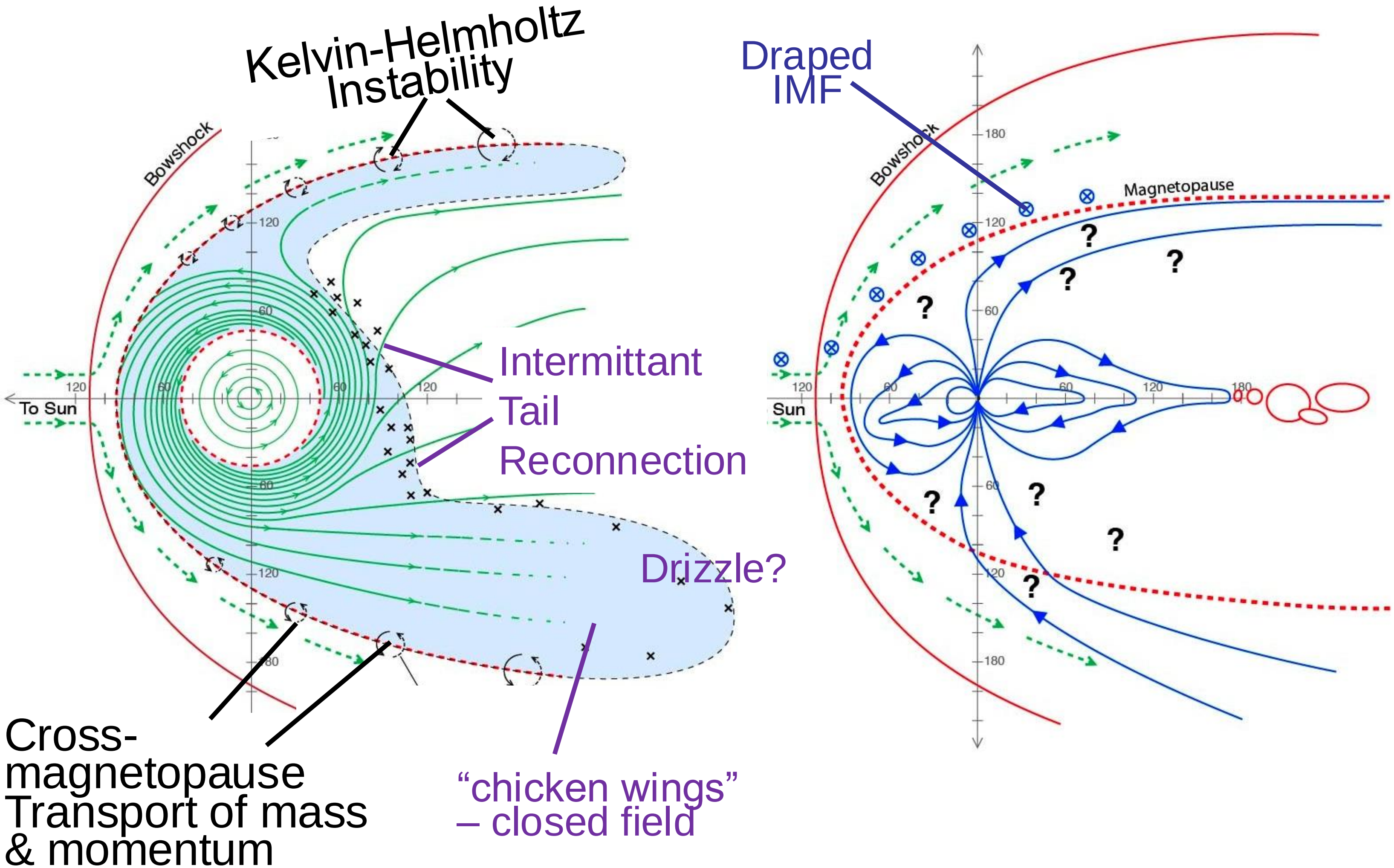


Reconnection sending plasmoids down the tail

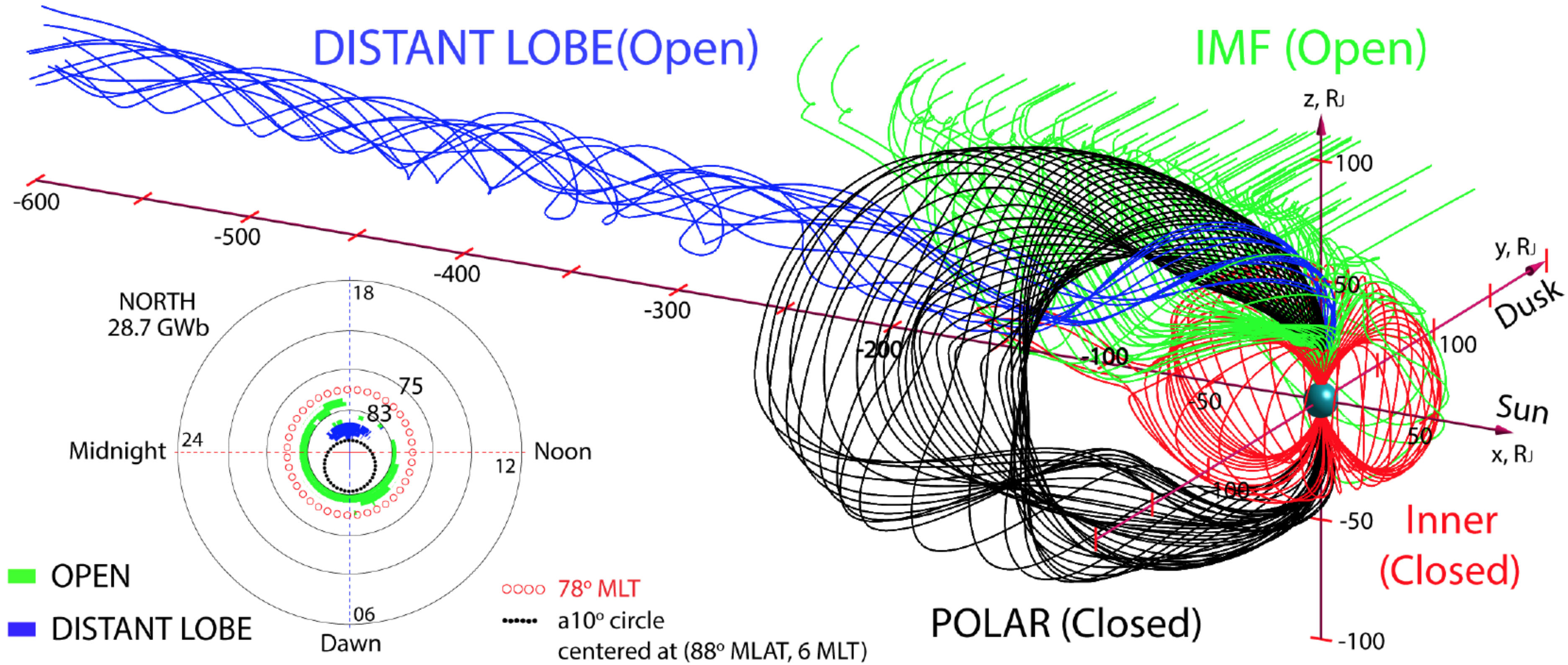
Inward Injection **Plasmoid Ejection**

Vasyliunas
Cowley et al.
Southwood & Kivelson

Delamere & Bagenal 2013
Masters 2017



Models Suggest Greater Complexity

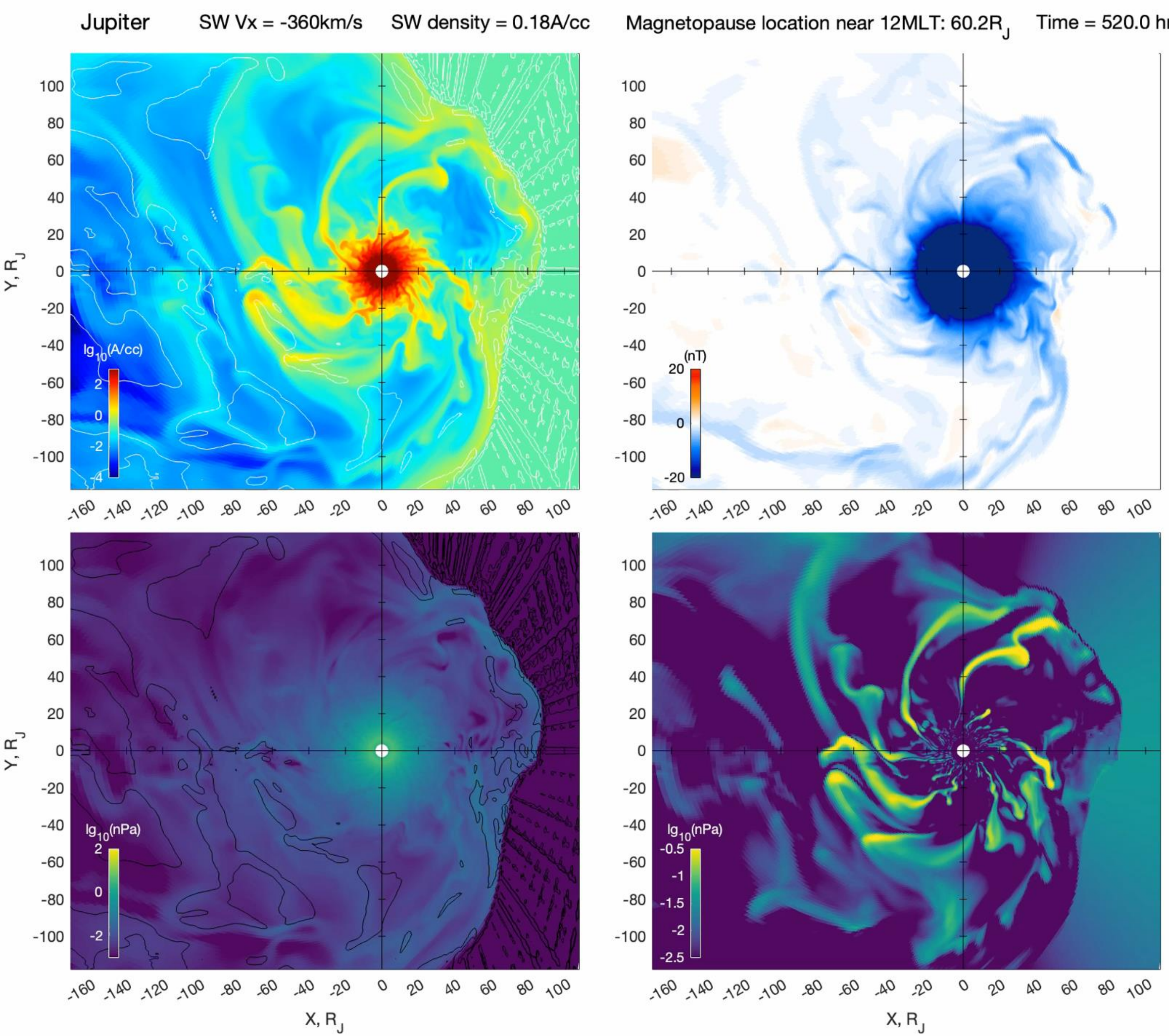


GAMERA Model

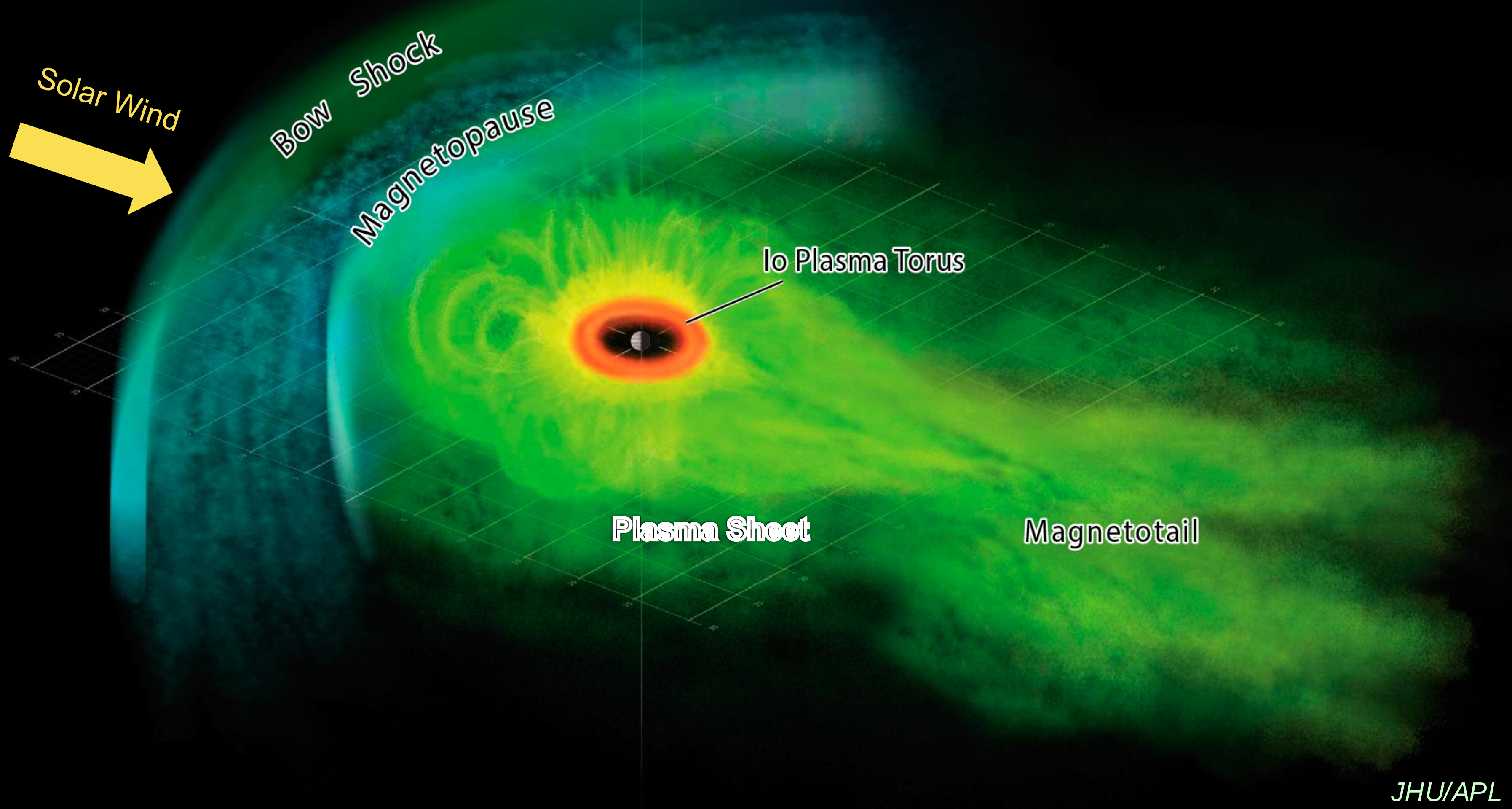
Binzheng Zhang et al. (2021)

GAMERA Model

Feng et al. 2023



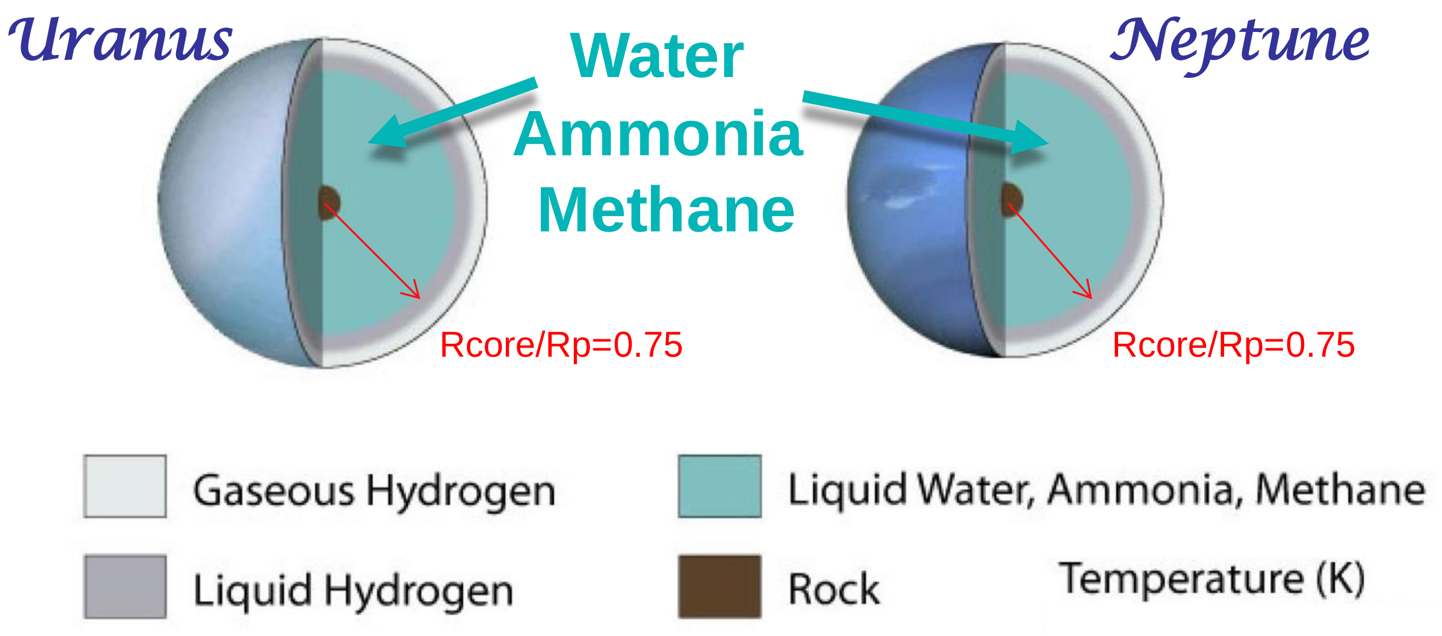
Is Jupiter Really Just a Colossal Comet?



Delamere & Bagenal 2013

Uranus & Neptune

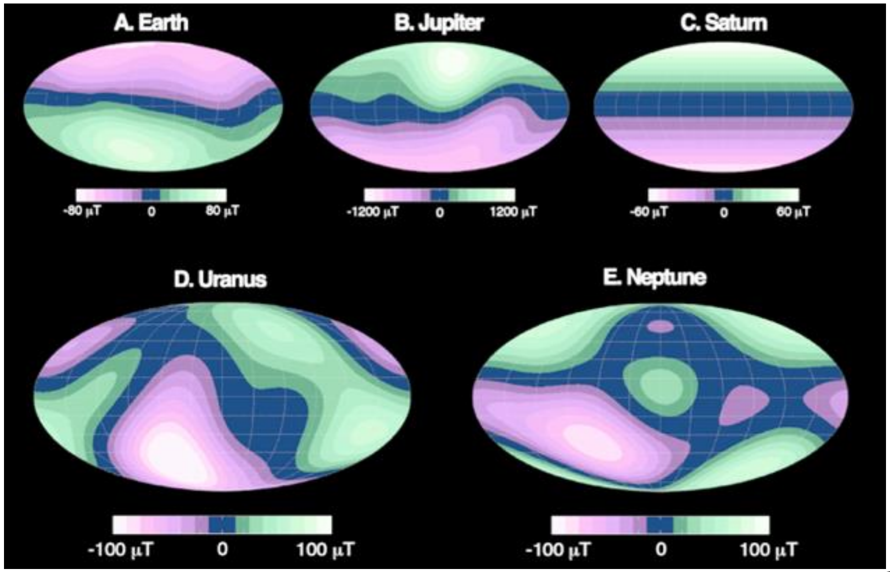
They're Totally Weird!

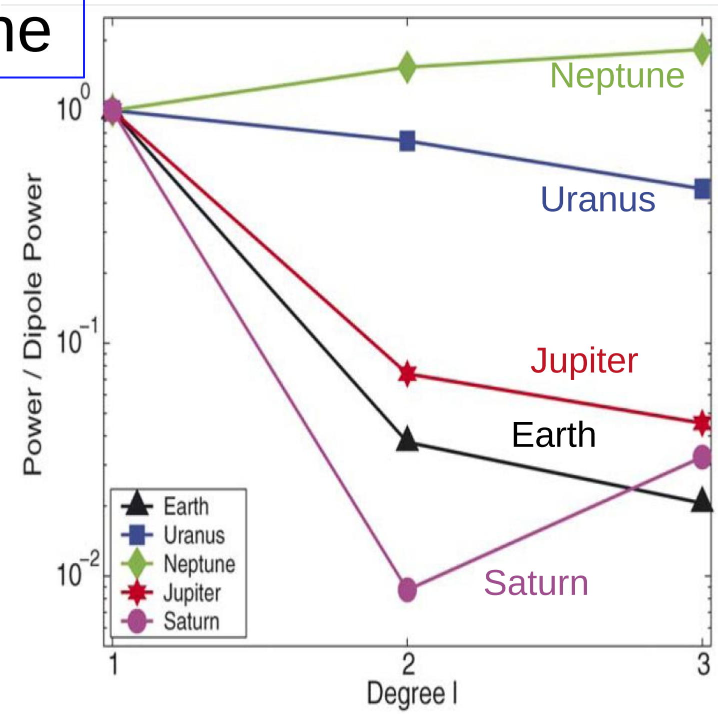


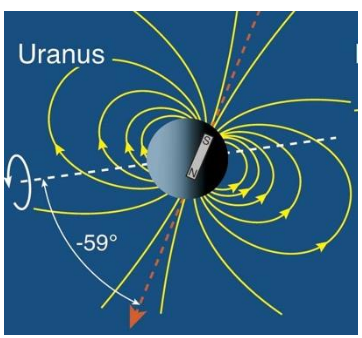
Uranus and Neptune have much less mass

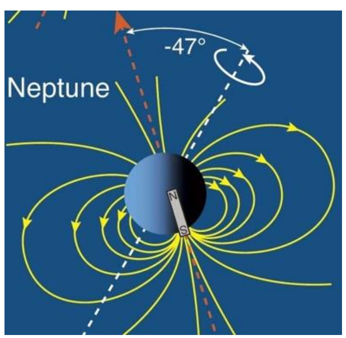
- Lower pressures
- No metallic hydrogen
- Weak & irregular magnetic fields produced in **water layer,** deep below gas envelope

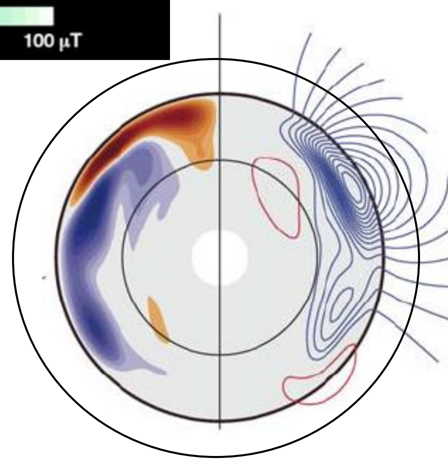
Weird Magnetospheres Uranus & Neptune







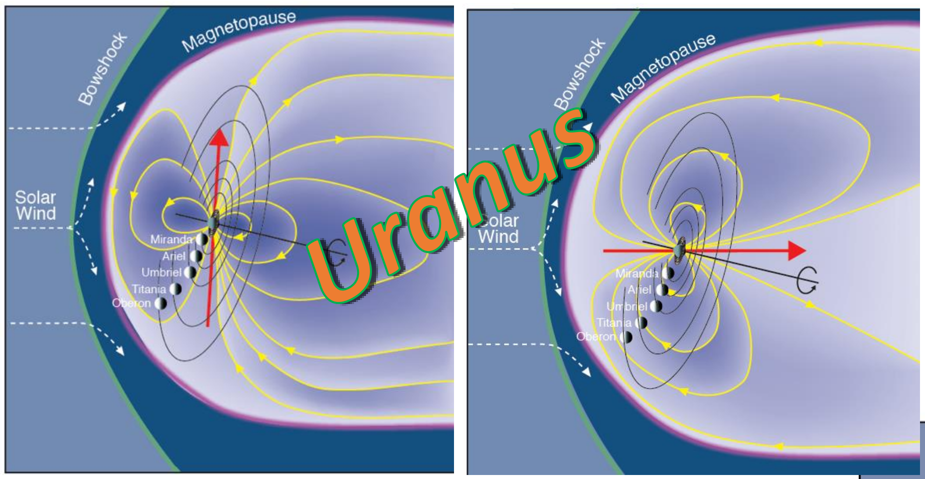




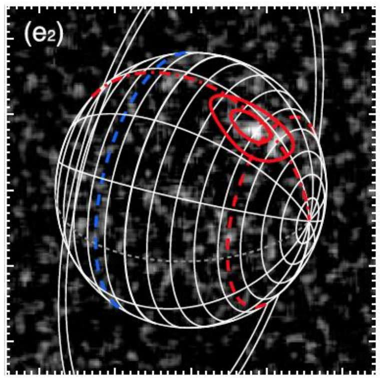
Modeling Uranus & Neptune non-dipolar fields with thin-shell dynamo over a stratified core

Stanley & Bloxham 2006

Need to go back to Uranus & Neptune

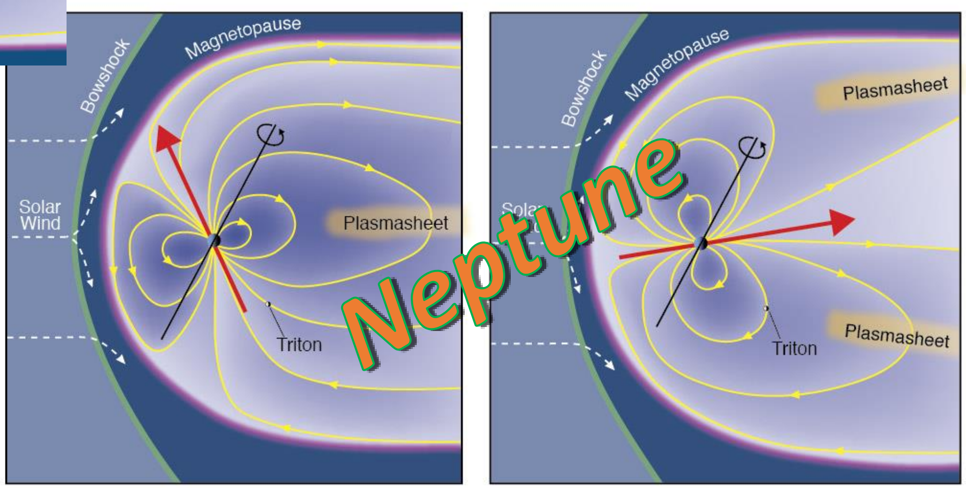


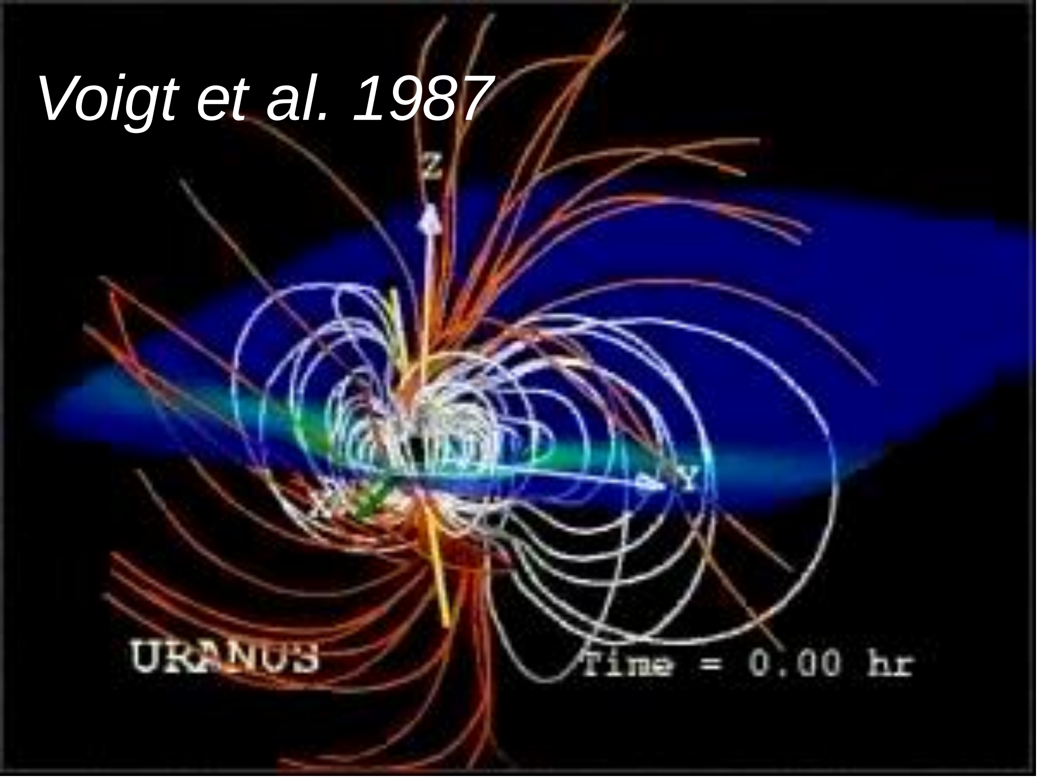
- Voyager got quick glipse!
- Saw irregular, changing field
- How do m'spheres respond to solar wind?



Lamy et al. 2017

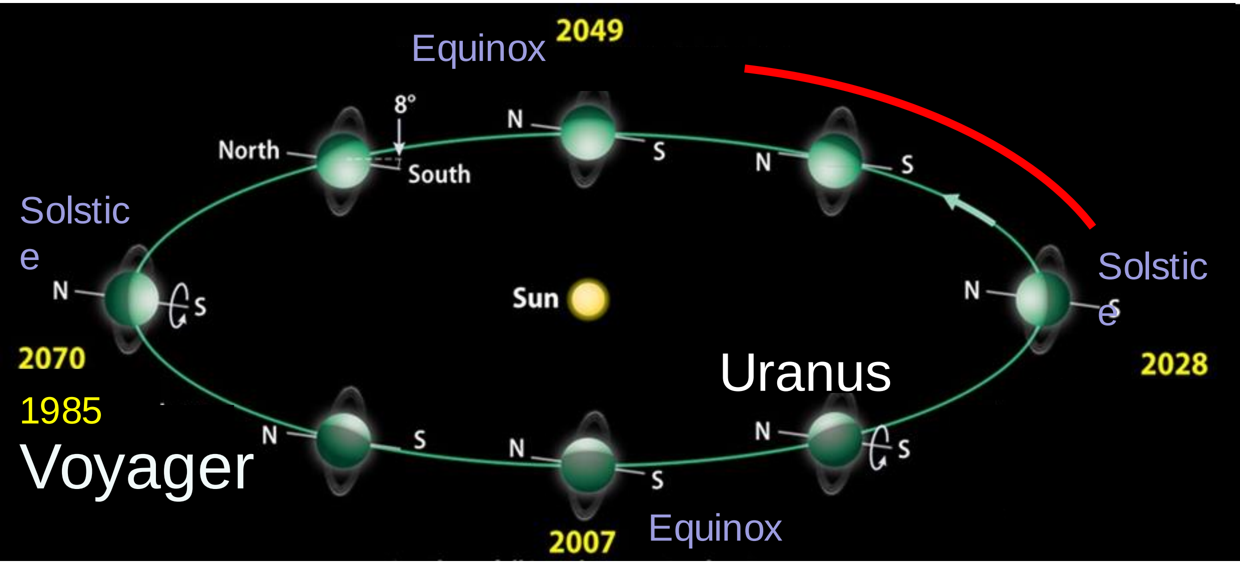
Hints of aurora with HST

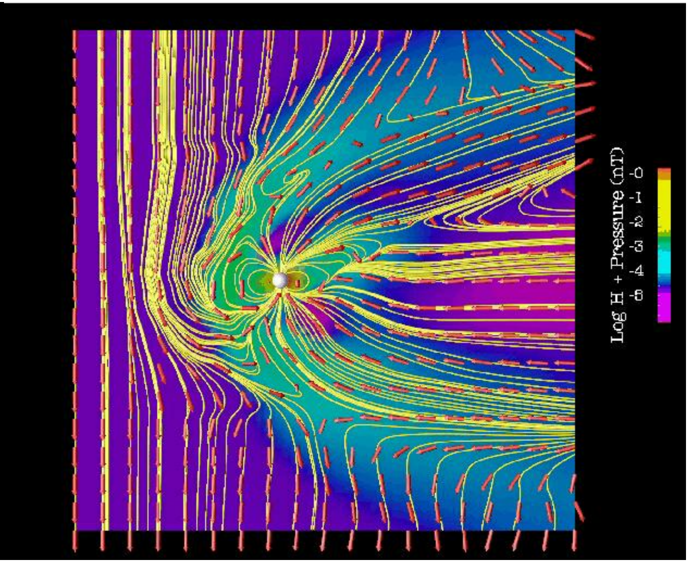




Explore weird configurations at different seasons

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

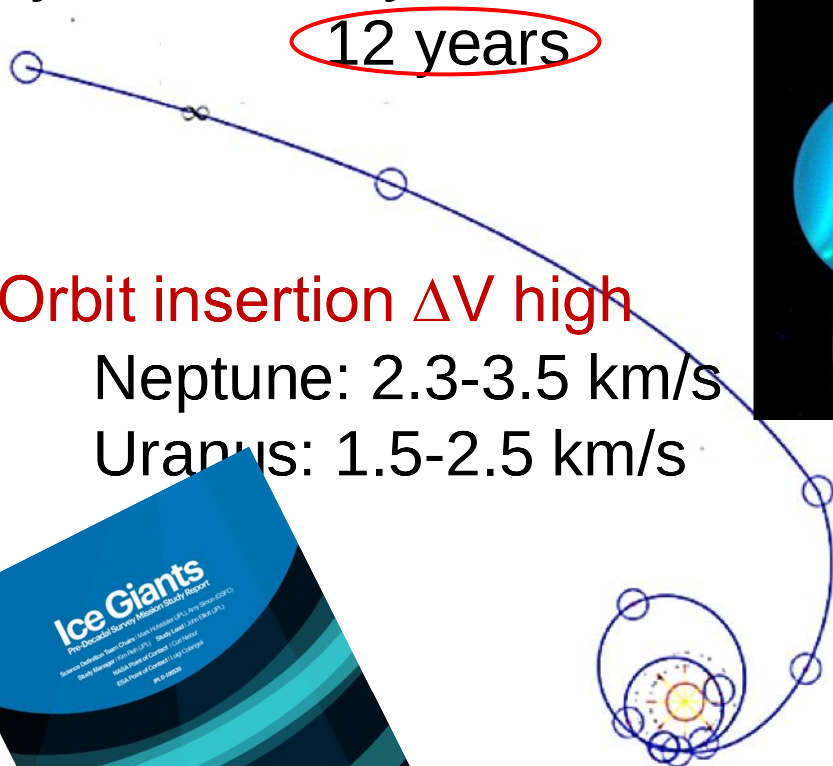




Cao & Paty 2017

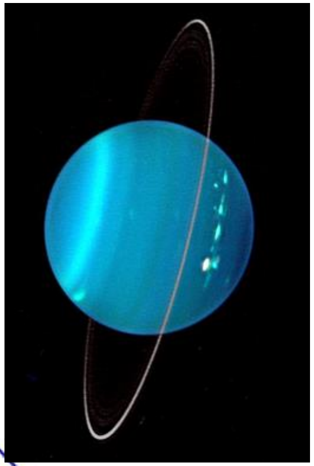
Long Cruise

Sample Trajectory to Uranus:
Earth-Venus-Earth-Earth-Jupiter
Gravity Assist
May 2031 – May 2043
12 years

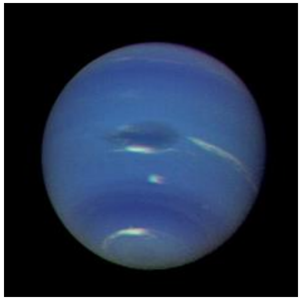


Orbit insertion ΔV high
Neptune: 2.3-3.5 km/s
Uranus: 1.5-2.5 km/s

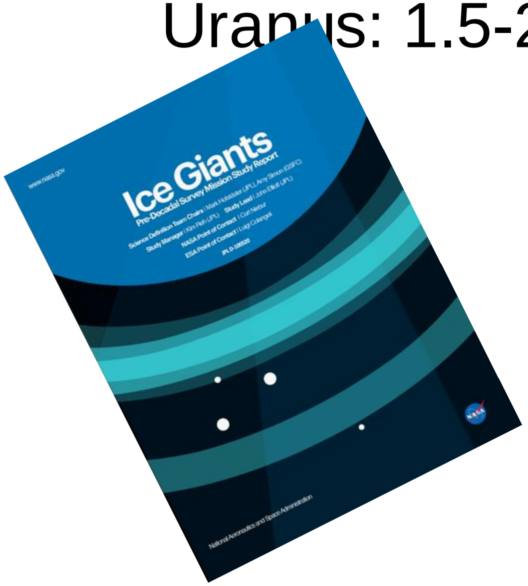
Uranus



Neptune



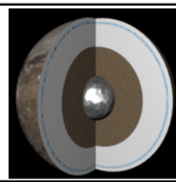
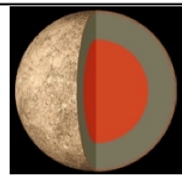
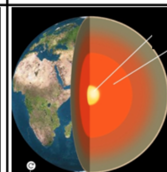
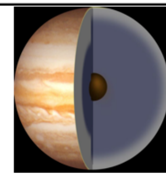
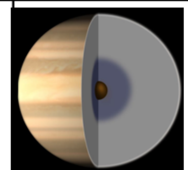
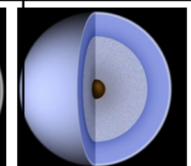
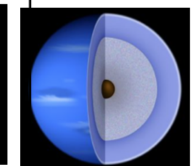
SLS

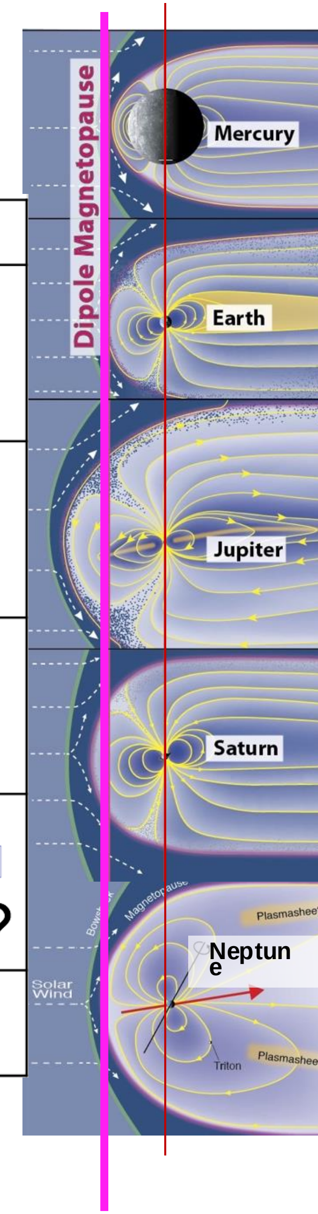


We'll have the Pu-238

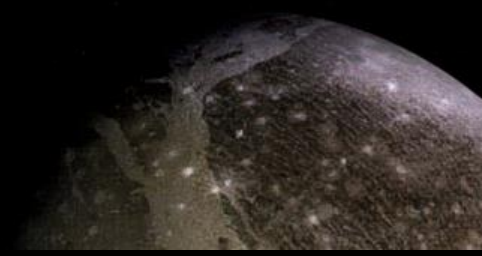
Plus aerocapture capability, enables very lowers flight times
Uranus < 5 yr
Neptune < 7 yr
Delivers more mass....

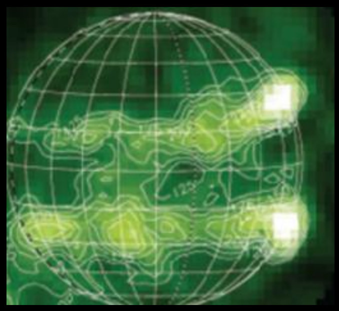
Comparative Planetary Magnetospheres

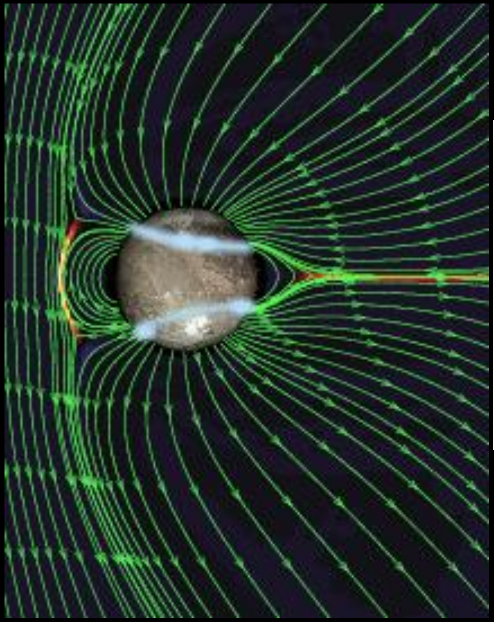
	Ganymede	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
							
Moment $/M_E$	$5x10^{-4}$	$5x10^{-4}$	1	20,000	600	50	25
$R_{M'pause}$ $/R_P$	1.8	1.5	8-12	63-92	22-27	18	23-26
Coupling Process	Ionosphere, M'sphere, Jup. M'Sphere	Ionosphere, Magnetosphere, Solar Wind	Ionosphere, Magnetosphere, Solar Wind	Ionosphere, Magnetosphere, Solar Wind	Ionosphere, Magnetosphere, Solar Wind	Ionosphere, Magnetosphere, Solar Wind ??	Ionosphere, Magnetosphere, Solar Wind ??
Timescale	mins	mins	hrs	wks	days	??	??



ESA's JUICE Mission



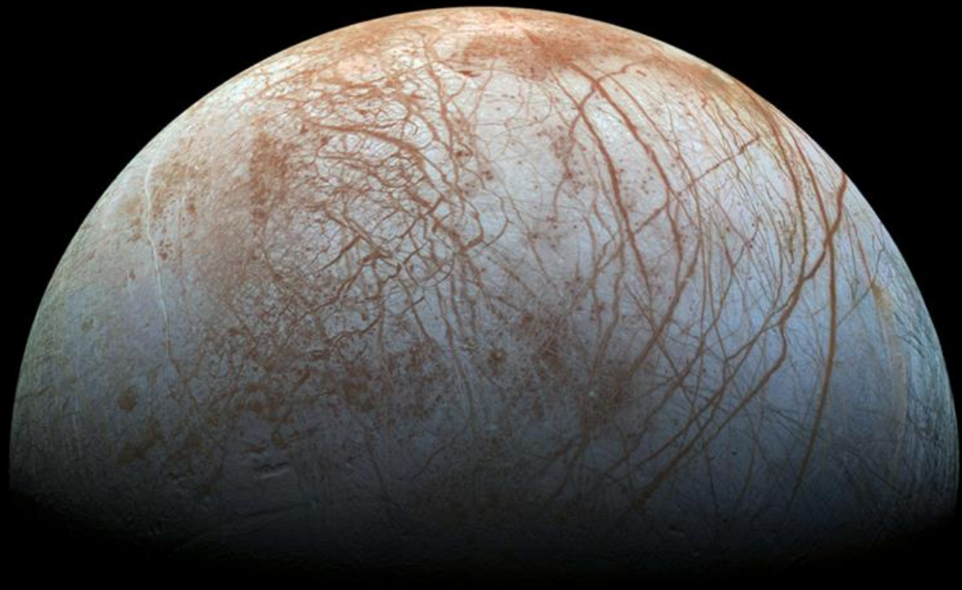




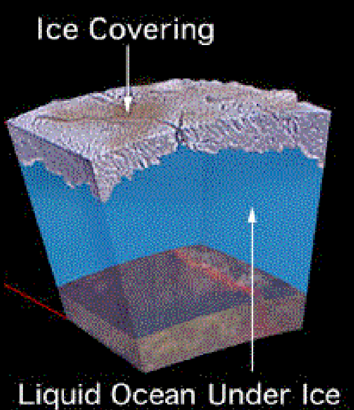
Particle & field measurements key for science goals

Launched April 2023
Orbits Ganymede
in 2030s

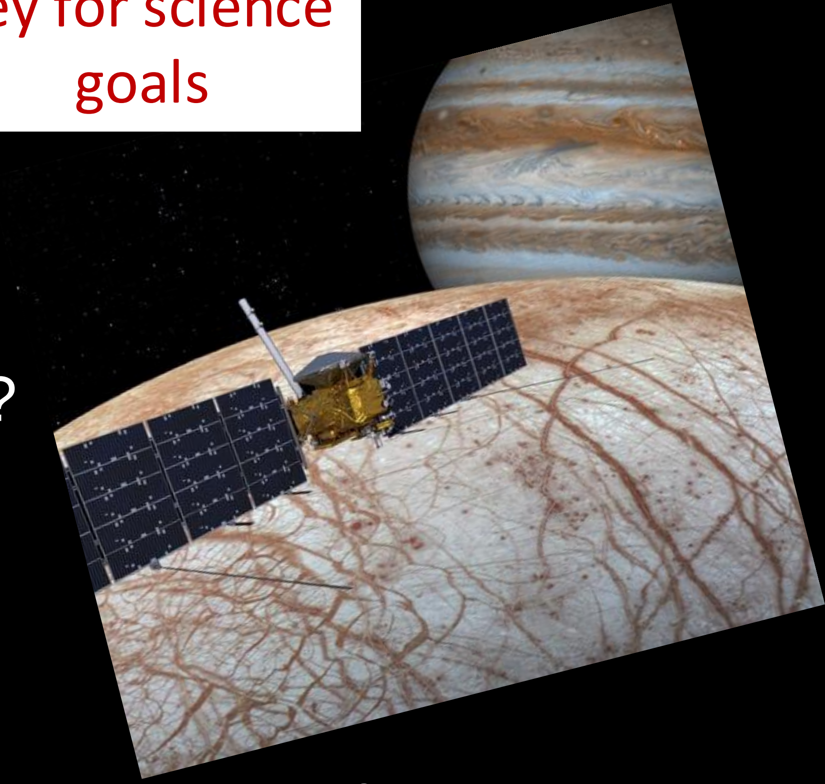
NASA's ***Europa Clipper*** Mission



Particle & field measurements key for science goals



- What's the brown gunk?
- How thick is ice?
- Does water reach surface?
- What's in the water??



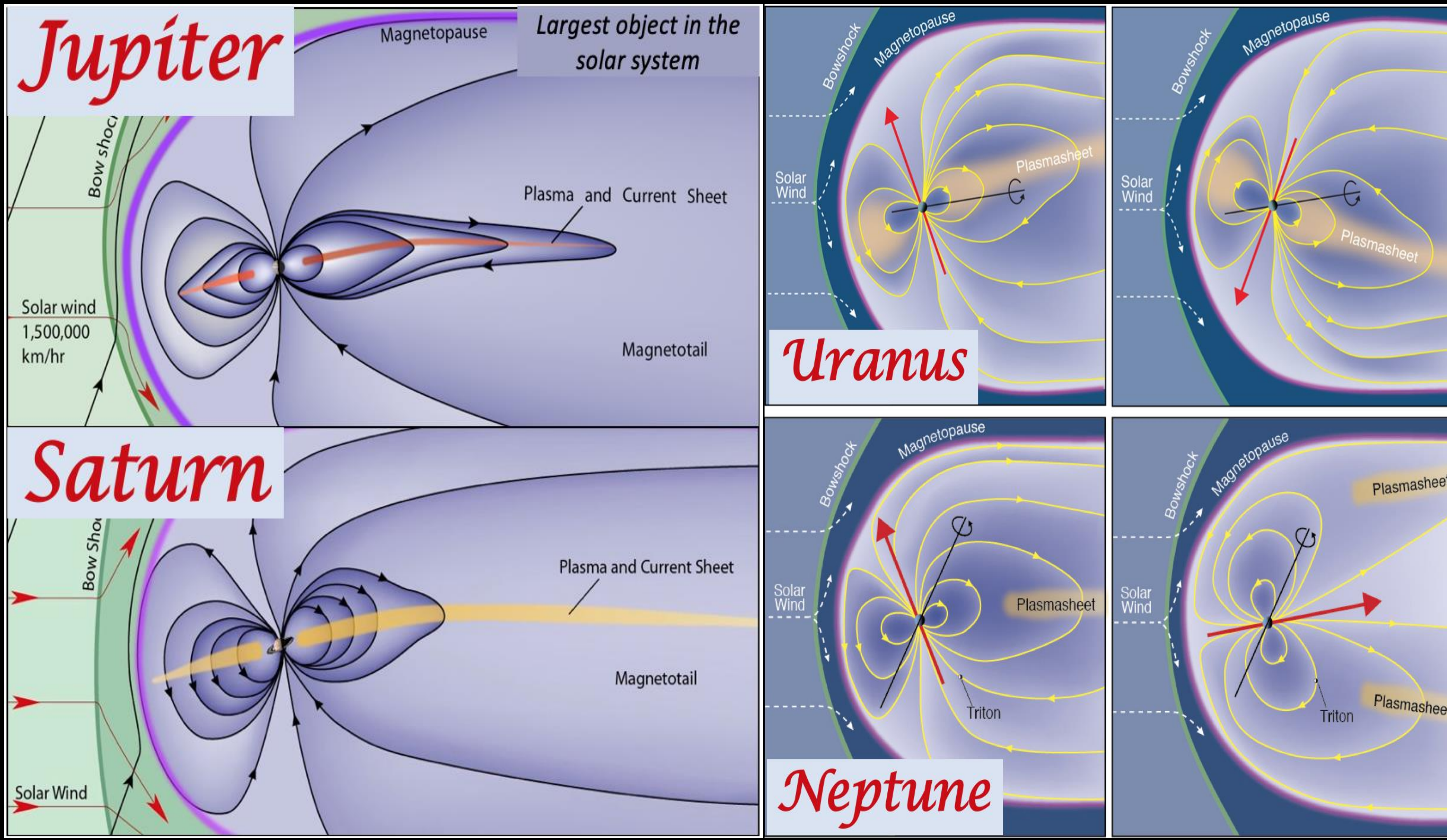
Launch Oct 2024

Planetary Magnetic Dynamos
– Outstanding issues:

- What controls amount of non-dipole field?
- Dynamos of Earth, Jupiter, Sun: similarities / differences?
- What controls variation in time?
- Why do some dynamos die out?

Planetary Magnetospheres 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!*



Let’s Keep Exploring!