Fran Bagenal
University of Colorado

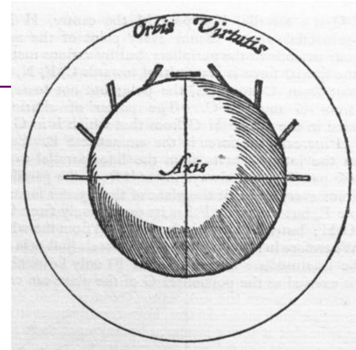
Heliophysics Overview II: Plasma Environments - Magnetosphere-Ionosphere Systems at Earth and Beyond

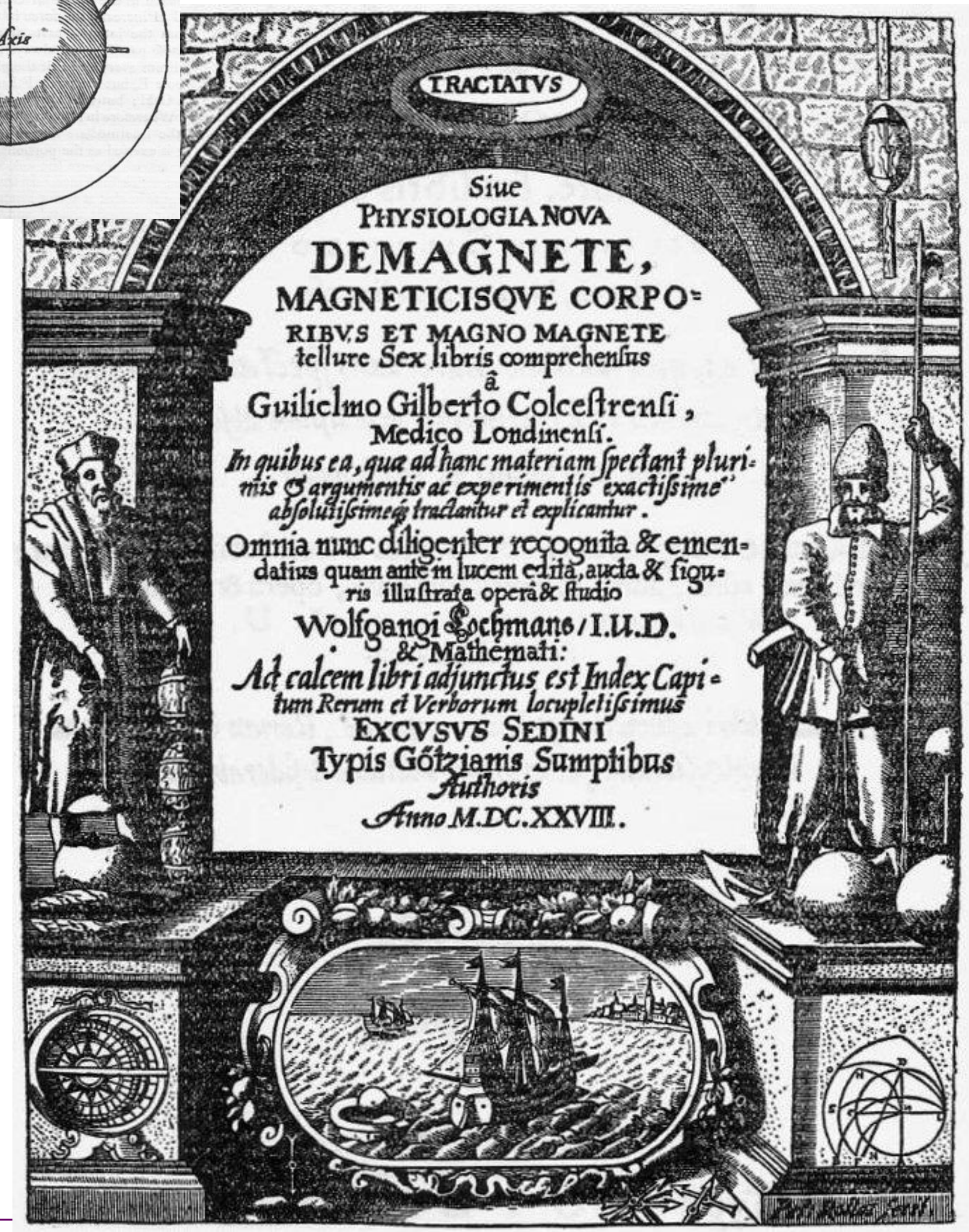
Which topic is your primary interest (probably, at this point in time)?

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 CORPO-
RIBVS ET MAGNO MAGNETE
tellure Sex libris comprehensus
à
Guilielmo Gilberto Colcestrensi,
Medico Londinensi.
*In quibus ea, quæ ad hanc materiam spectant pluri-
mis & argumentis ac experimentis exactissime
absolutissimeq; tractantur et explicantur.*
Omnia nunc diligenter recognita & emen-
datius quam ante in lucem edita, aucta & figu-
ris illustrata operâ & studio
Wolfgangi Lochmans / I.U.D.
& Mathemati:
*Ad calcem libri adjunctus est Index Capi-
tum Rerum et Verborum locupletissimus*
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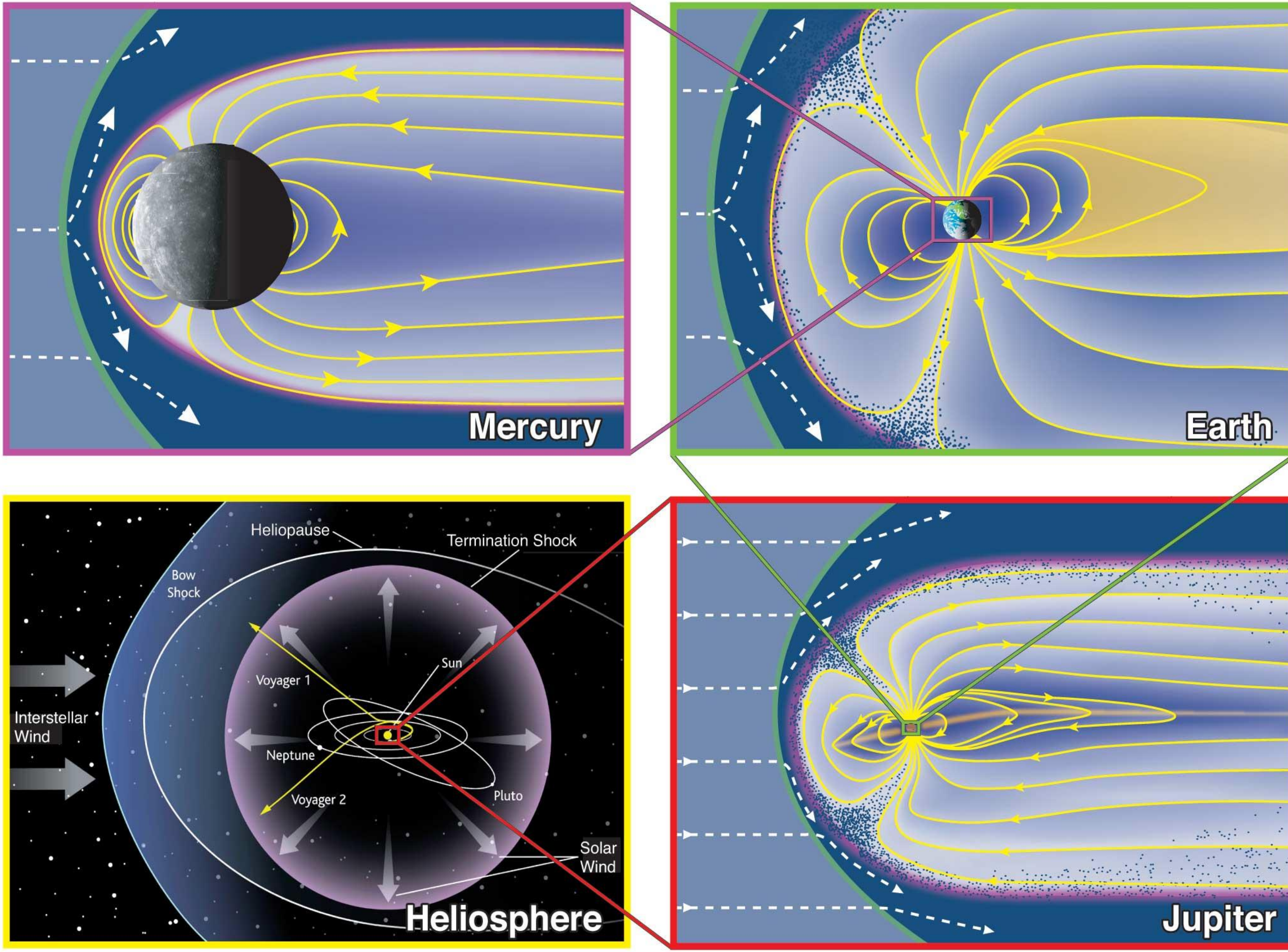
Anno M.DC.XXVIII.


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

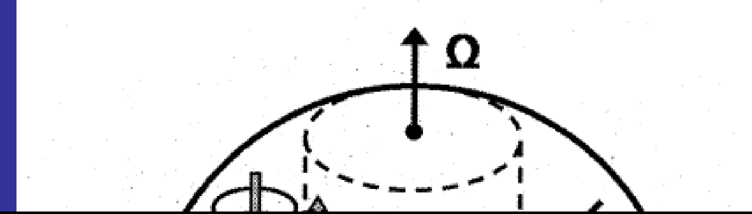
Planetary Magnetic Dynamos

What are the 3 main ingredients for a planetary dynamo?

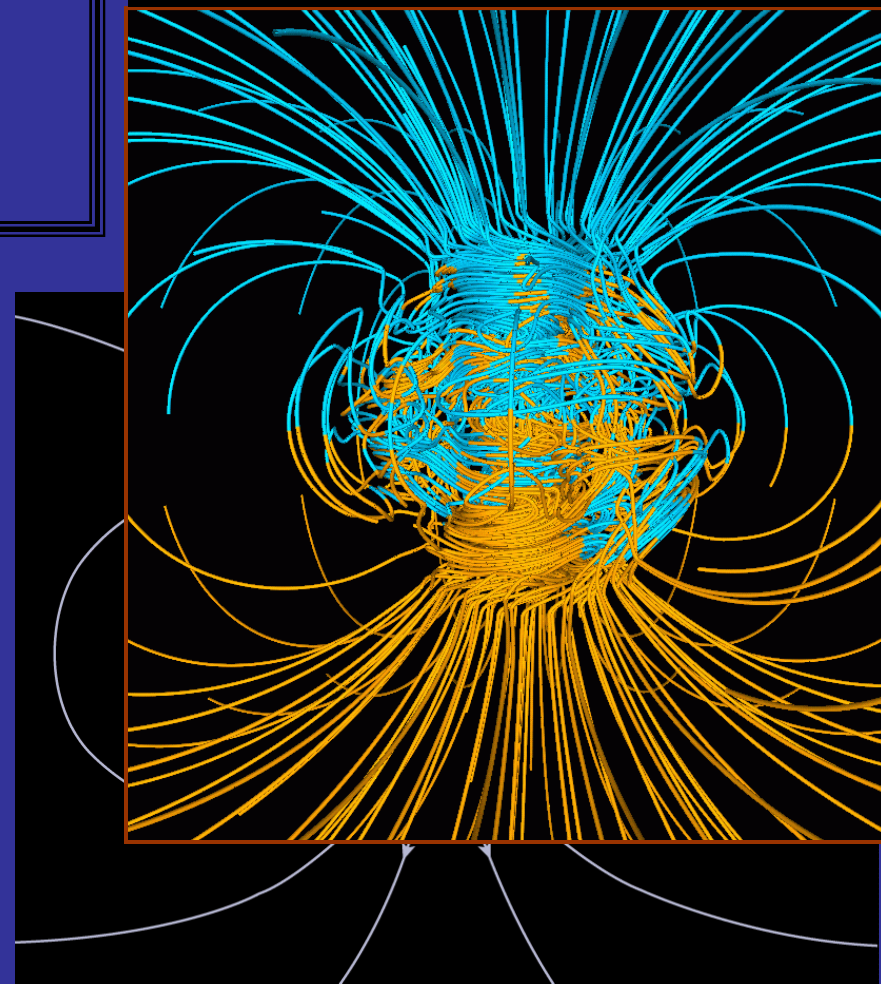
Planetary Dynamos

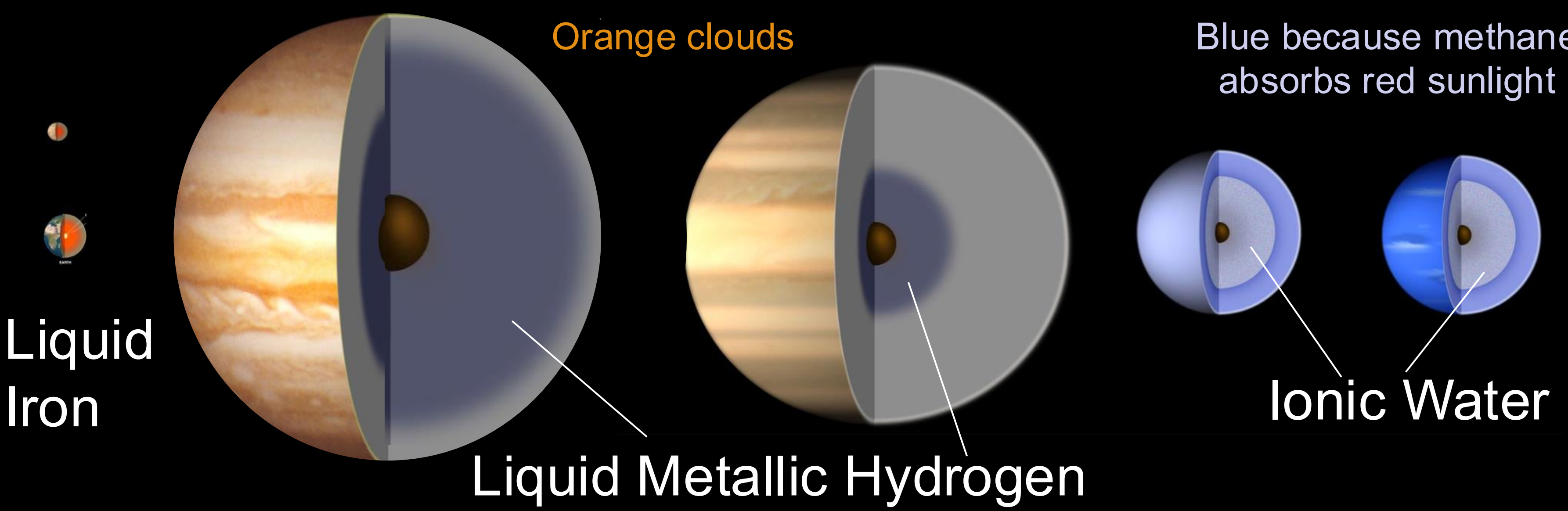
Volume of electrically conducting fluid 1 which is convecting 2 and rotating 3

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



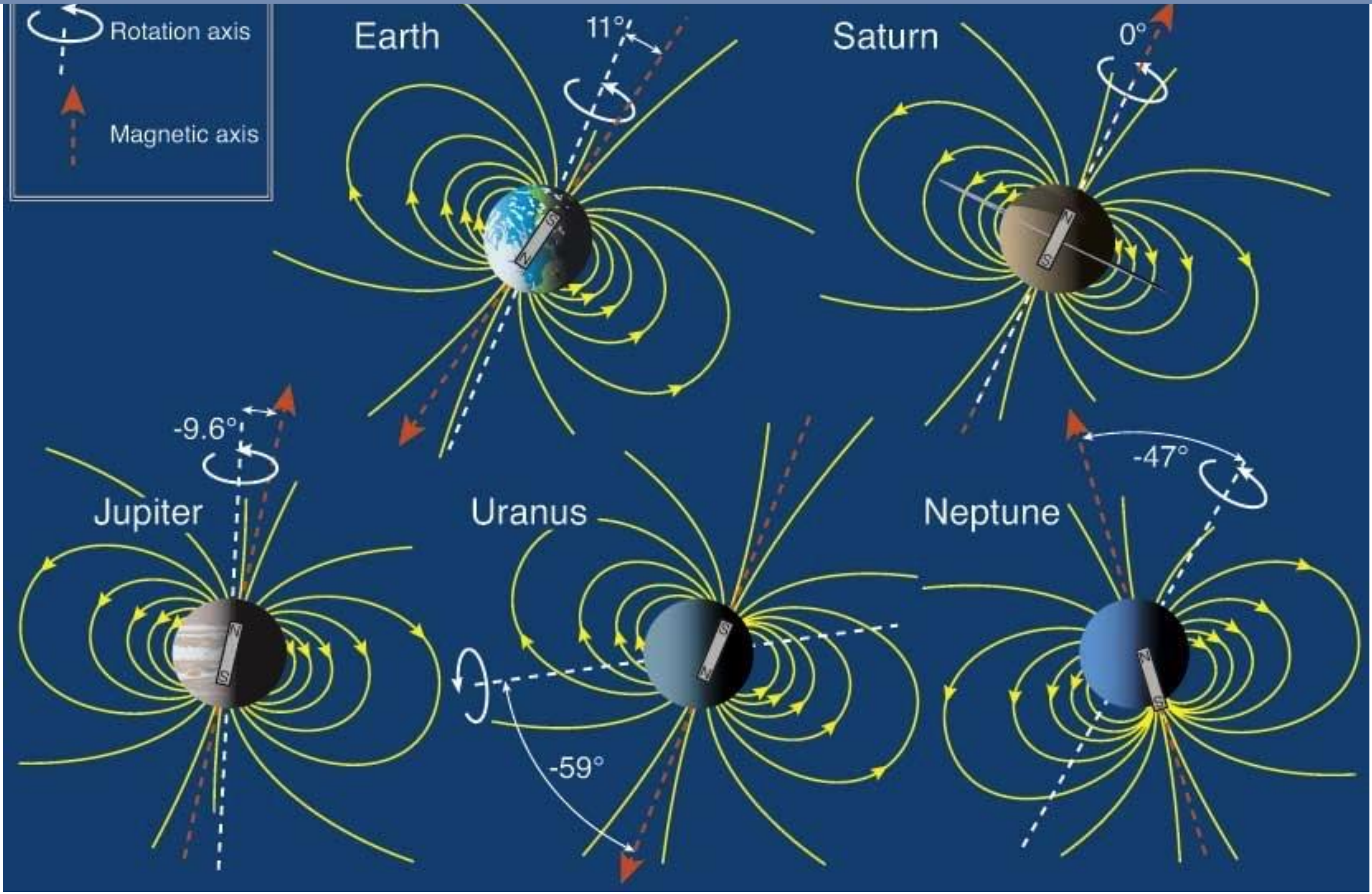
Earth dynamo model - From Glatzmeier and Roberts





	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

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

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

coefficients - constants

functions

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

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

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

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

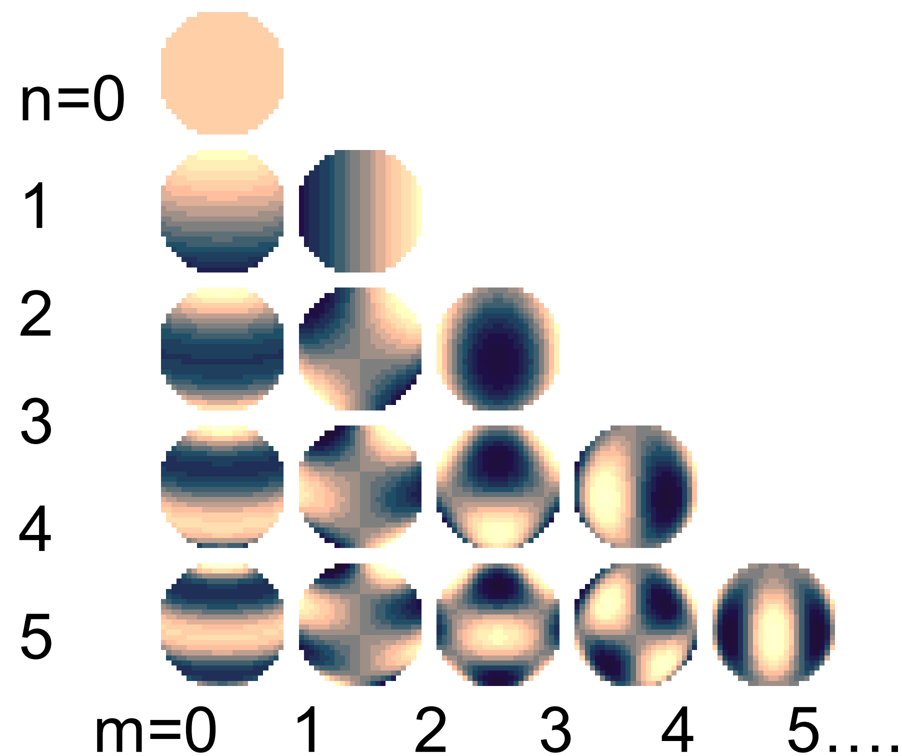
$$P_2^1(\cos\theta) = -3\cos\theta\sin\theta$$

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

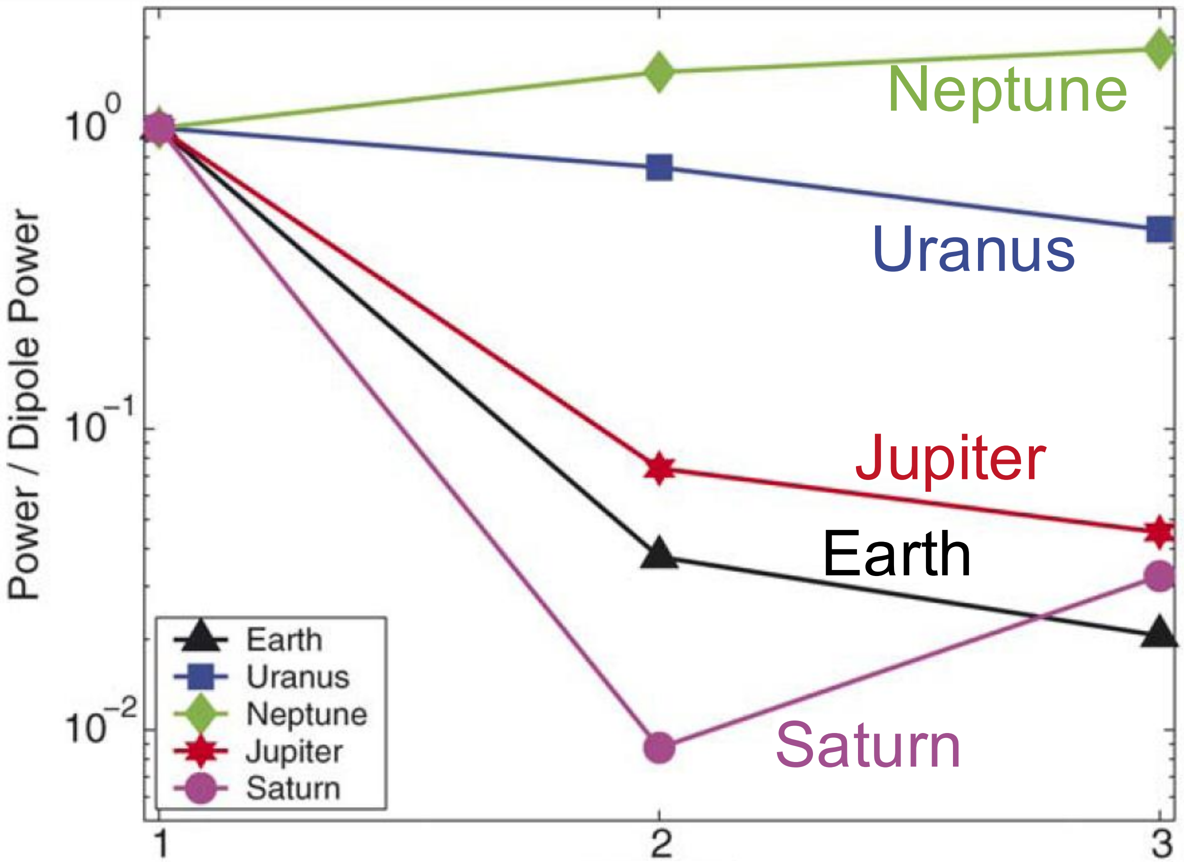
$$P_3^0(\cos\theta) = \tfrac{1}{2}(5\cos^3\theta - 3\cos\theta)$$

Dipole

Quadrupole

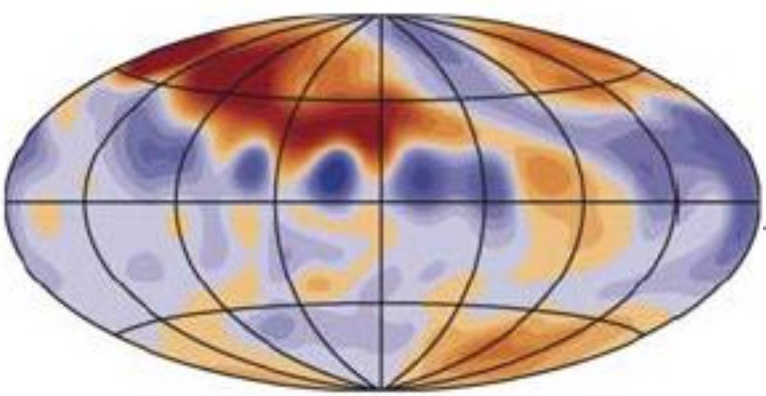


Stanley & Bloxham 2006

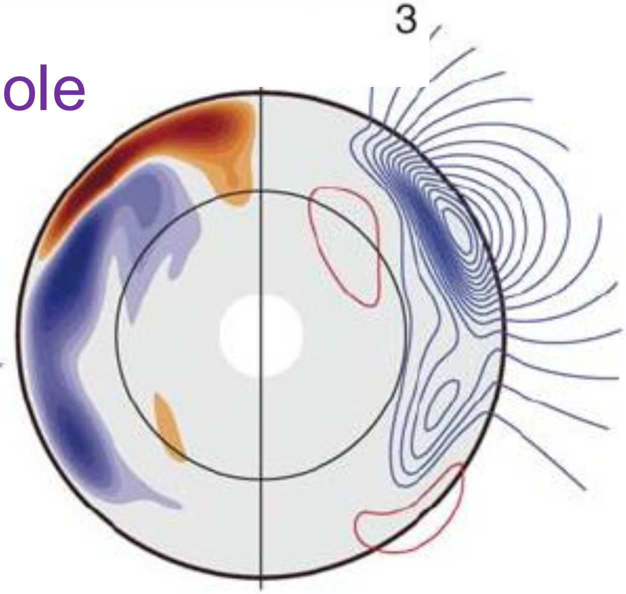


Multipole coefficients / Dipole coefficient Indicates degree of complexity

Dipole



Quadrupole

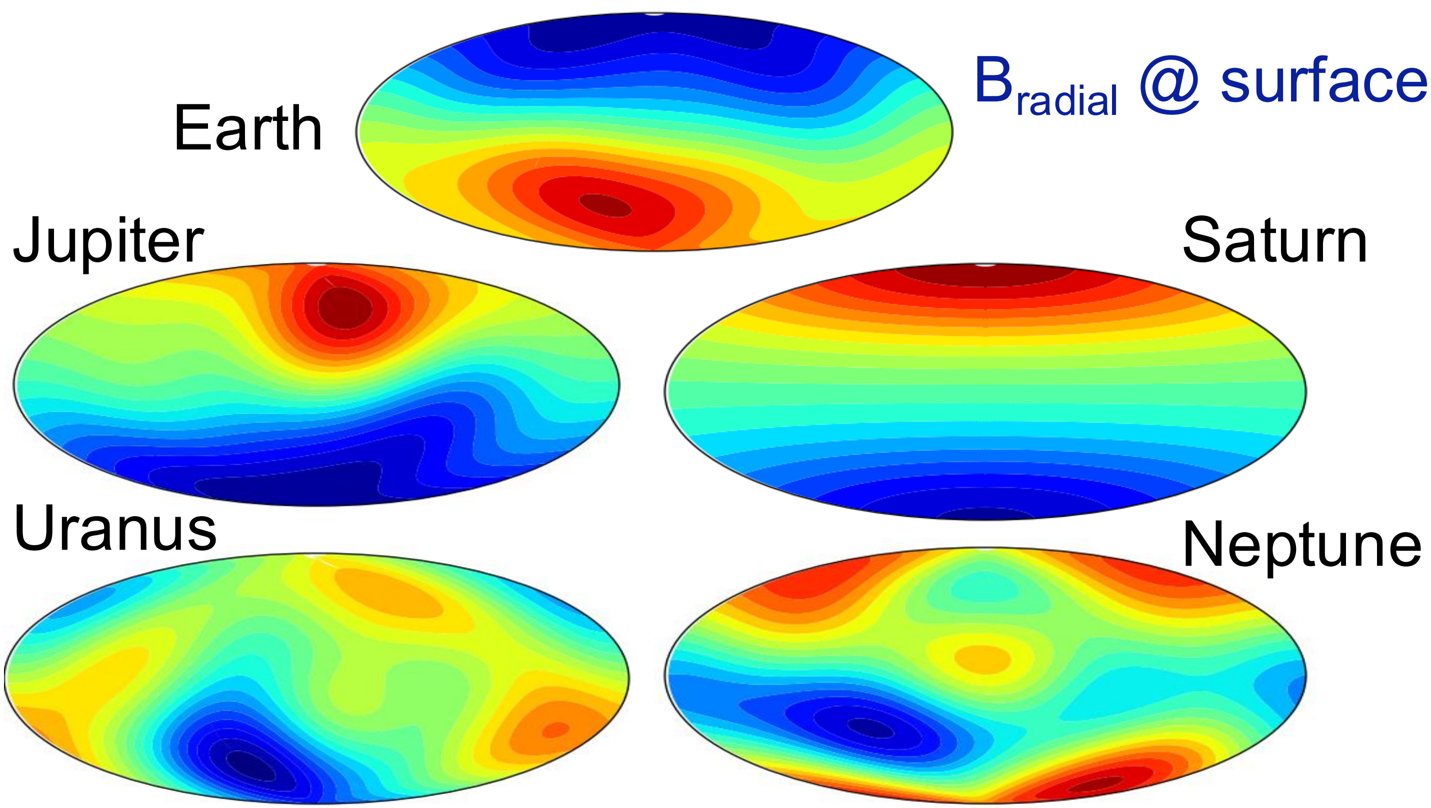


Modeling Uranus' & Neptune's non-dipolar fields with a thin-shell dynamo over a stratified core

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

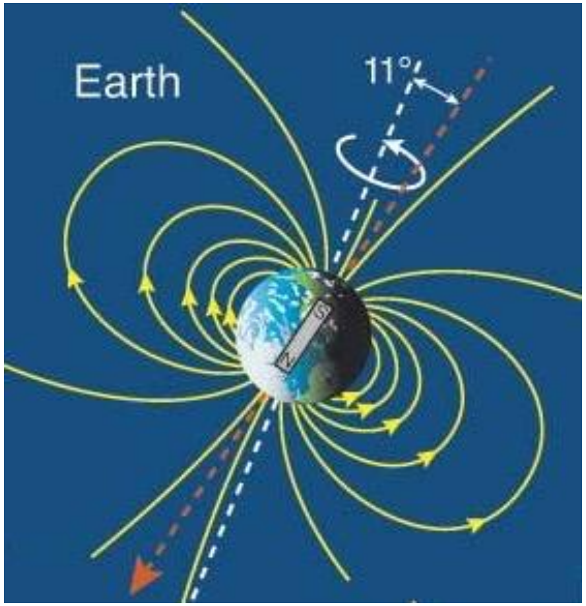
Dipolar

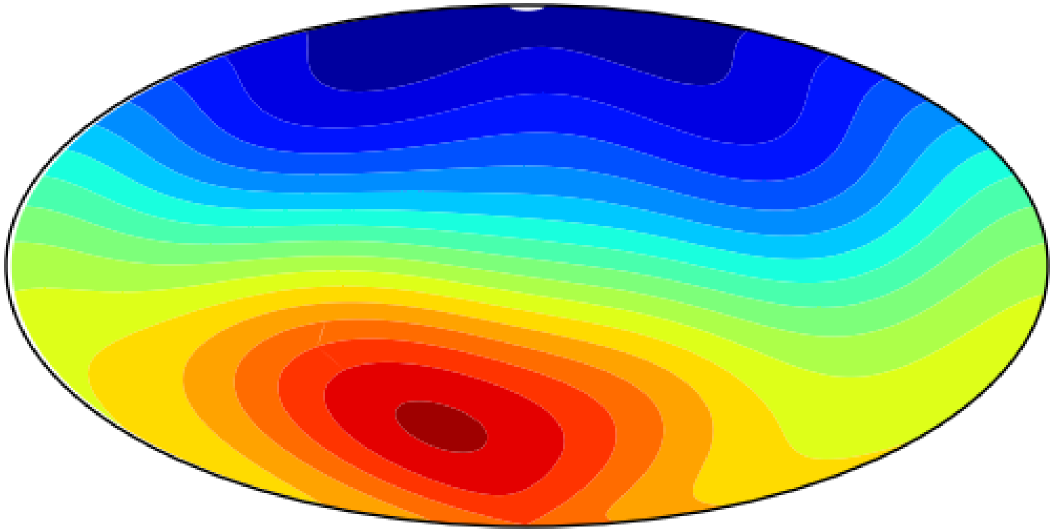
Irregular



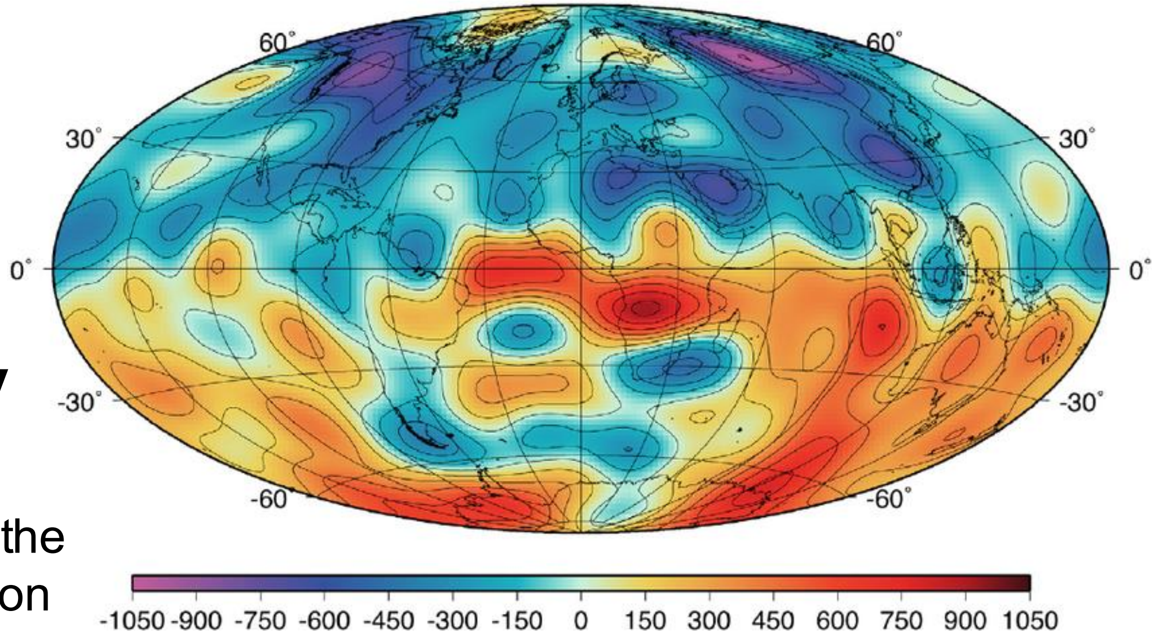
Stanley & Bloxham 2006

Earth's Magnetic Field



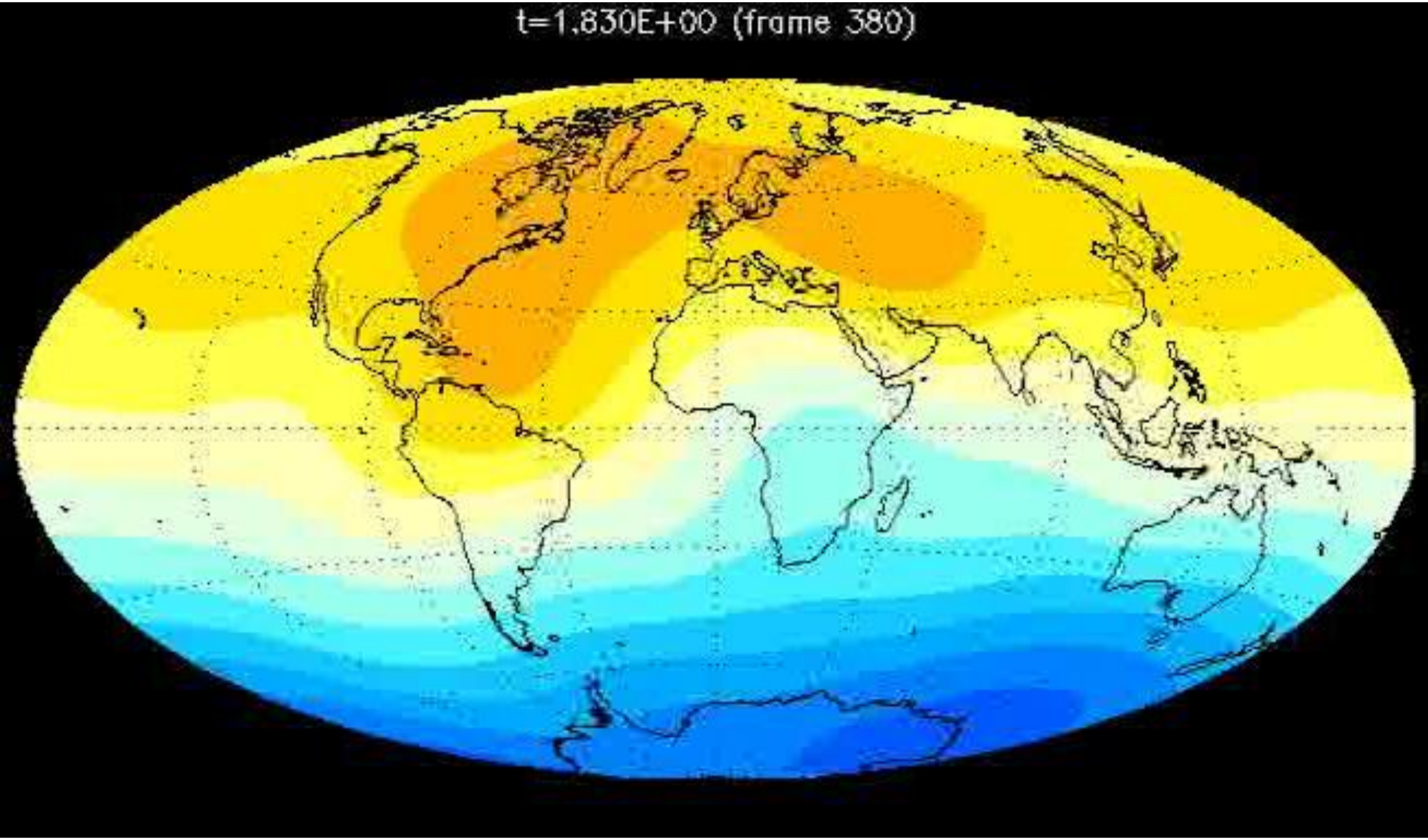


When you look closer there's more complexity



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

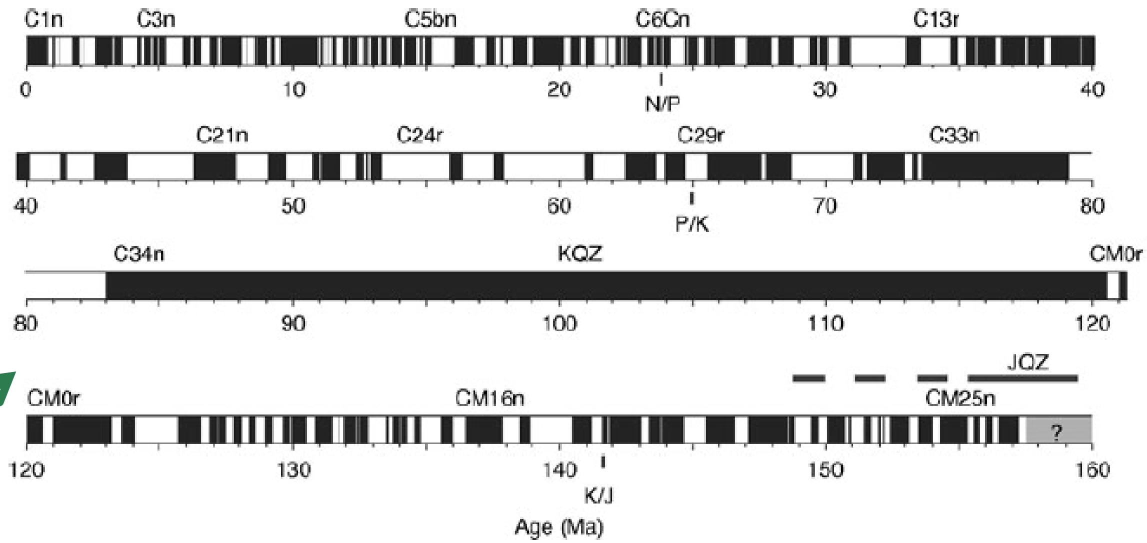
Br through a reversal



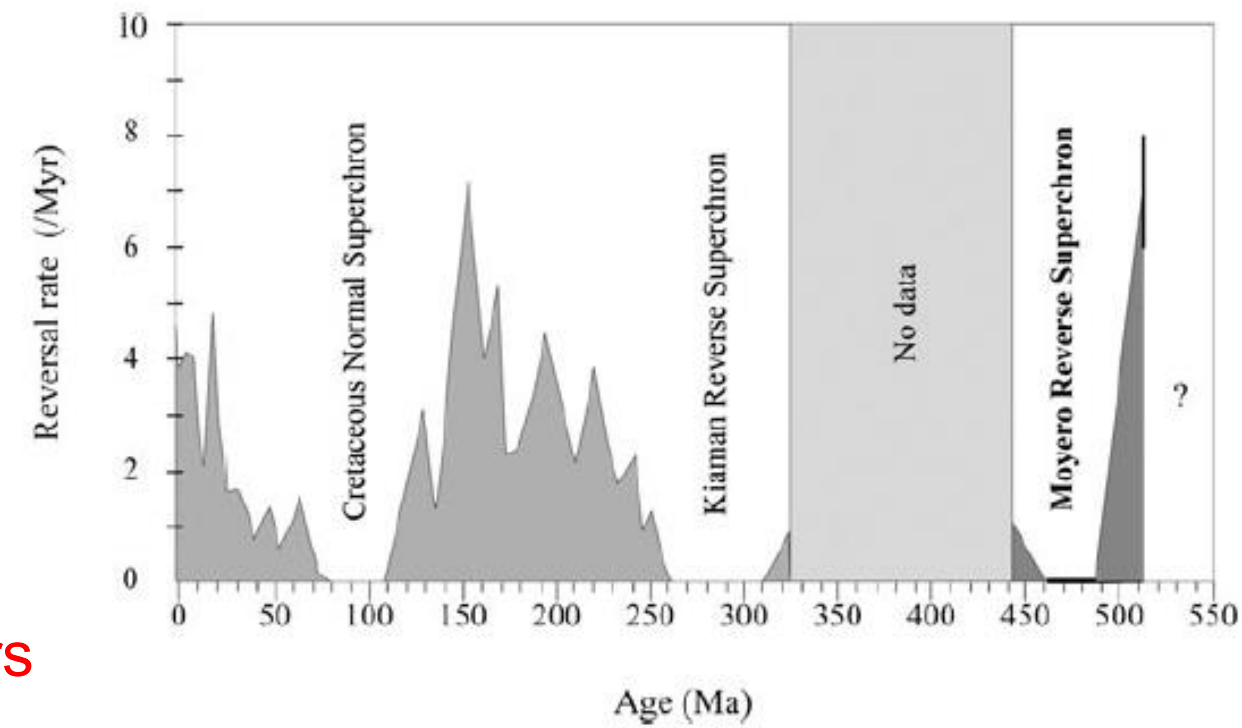
Hulot et al. 2010
Pavlov & Gallet 2005

Polarity reversals:

1. variable in duration and



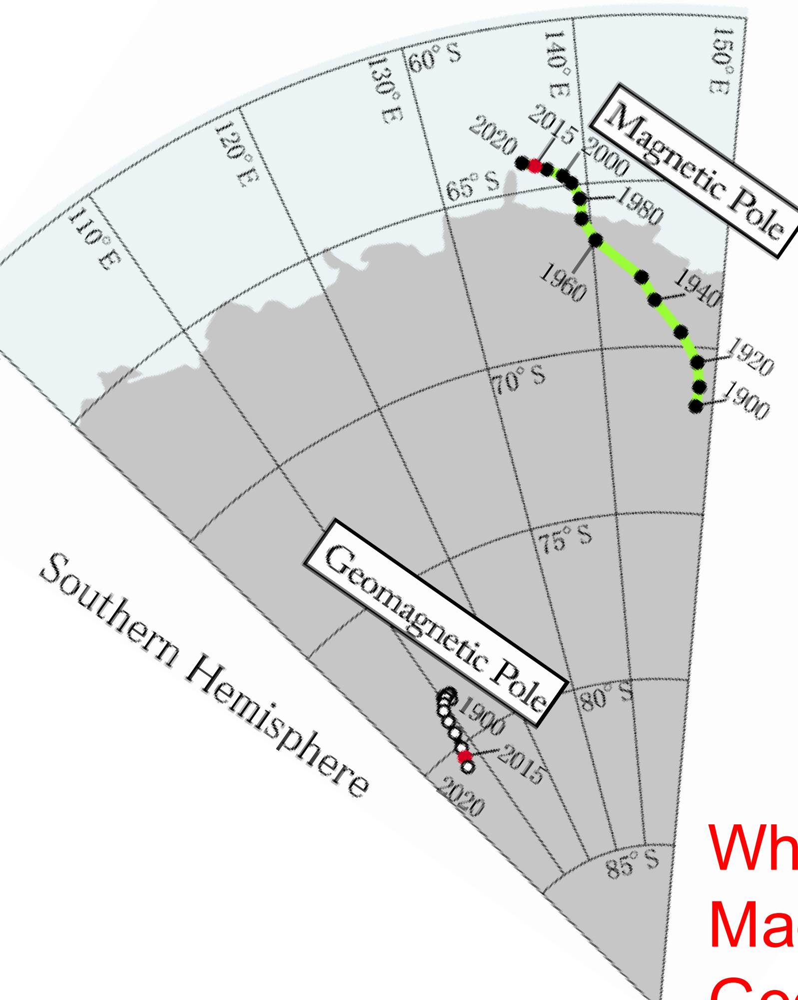
2. rate

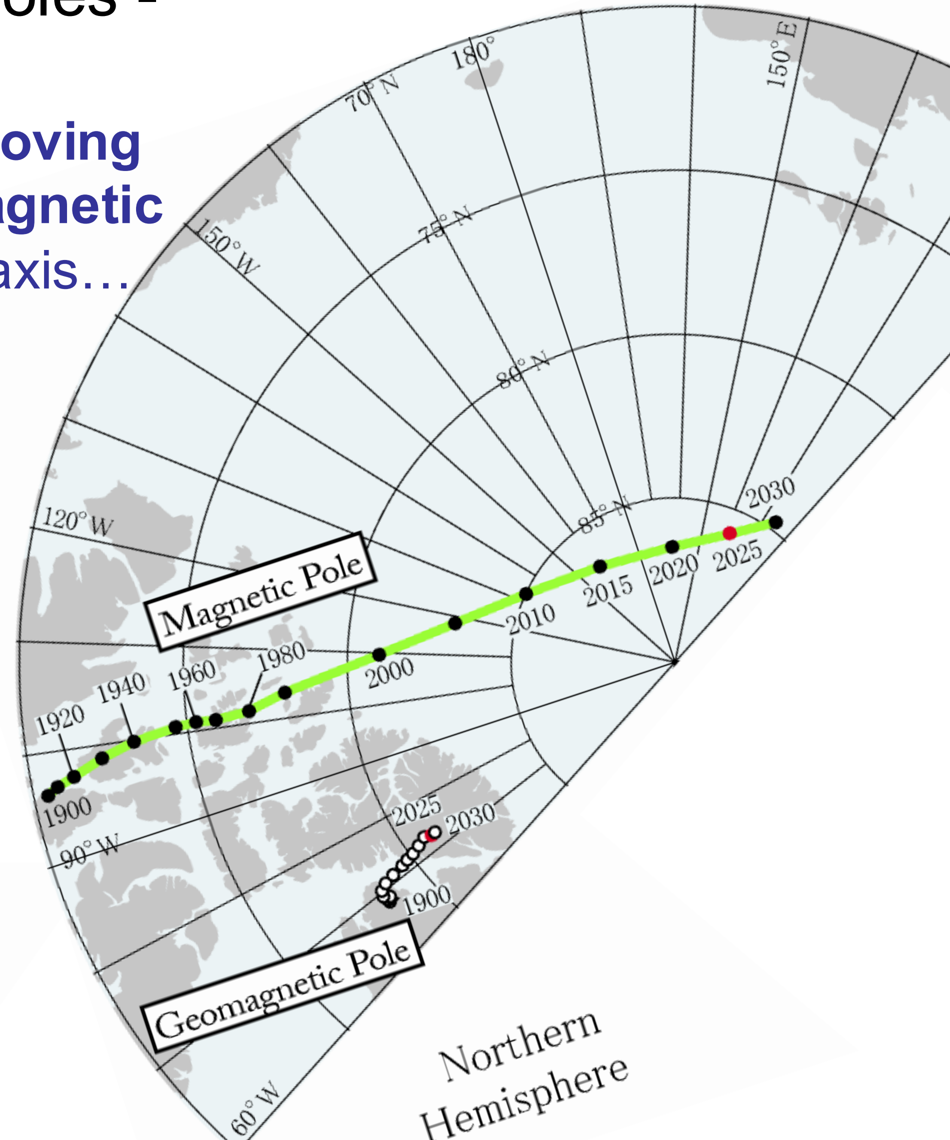


rapid rate
~ 5/million years
~ every 200,000 yrs

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

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





What's the difference?

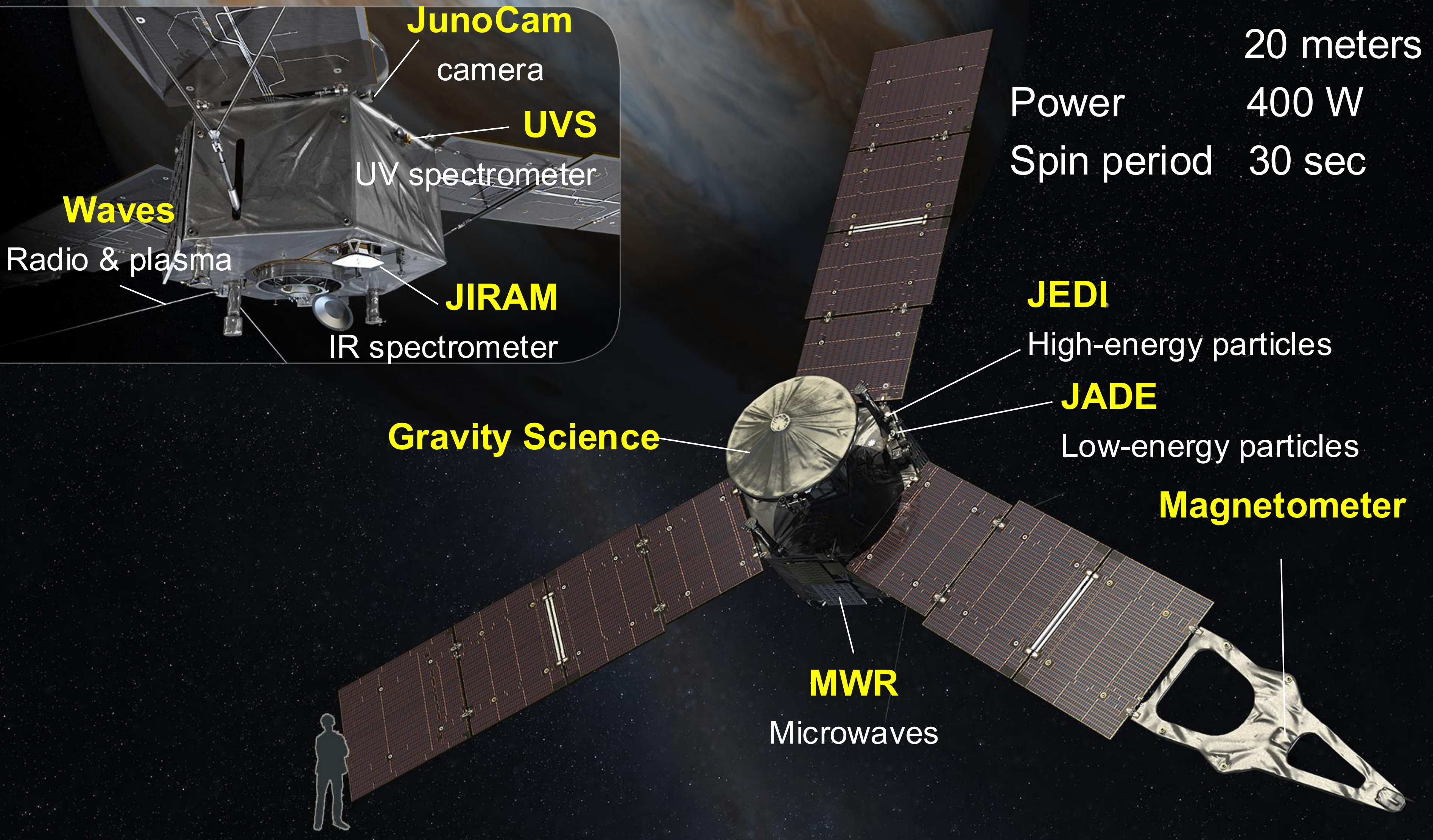
Magnetic Poles = where B = Br

Geomagnetic Poles = best fit dipole

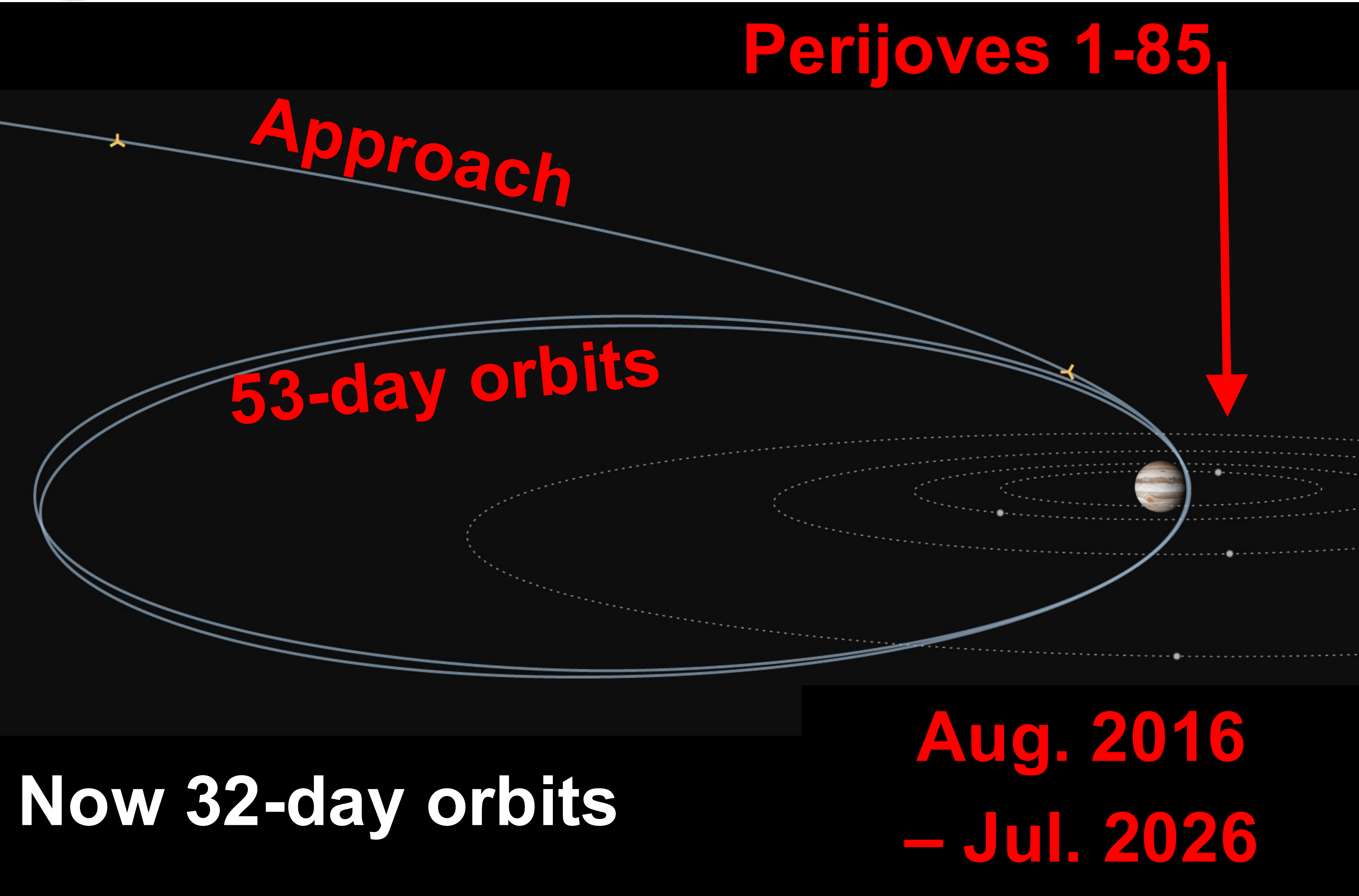
Spacecraft & Payload

Orbit Insertion
4th July 2016

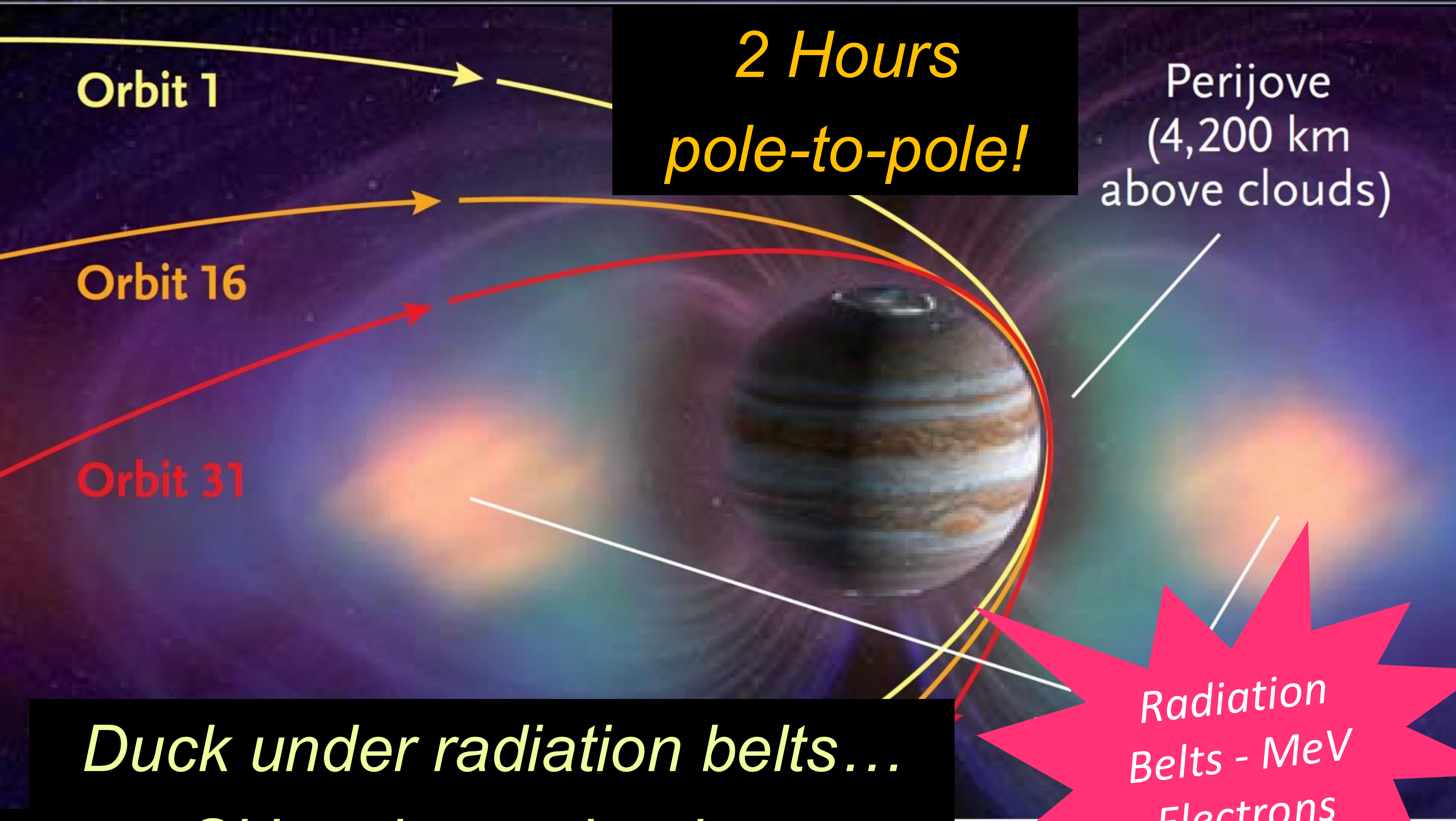
SPACECRAFT
DIAMETER: 66 feet
20 meters
Power 400 W
Spin period 30 sec



Orbiting Jupiter since 2016



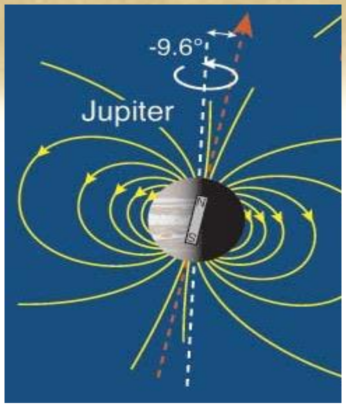
The Orbit: Key to Whole Mission



2 Hours
pole-to-pole!

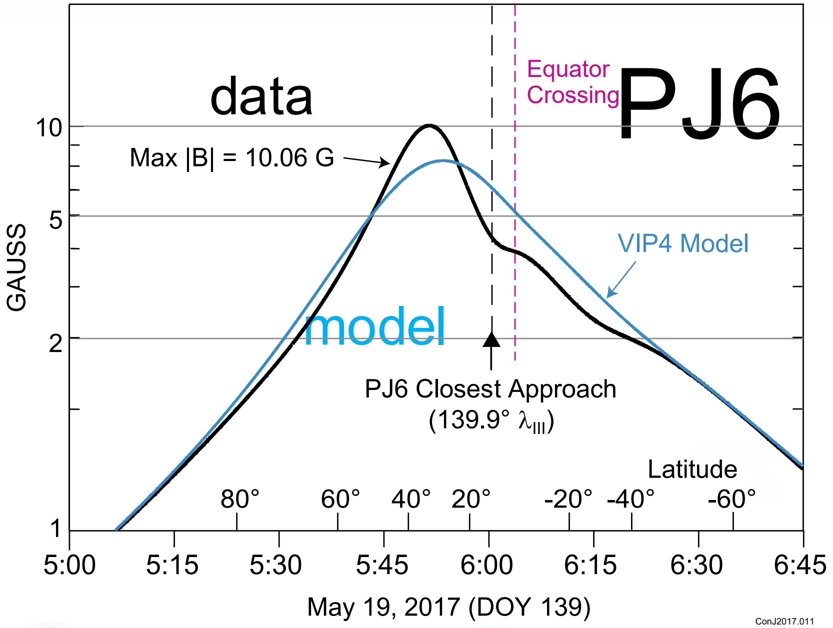
Duck under radiation belts…
Skim above clouds…
Find out what's it like inside.

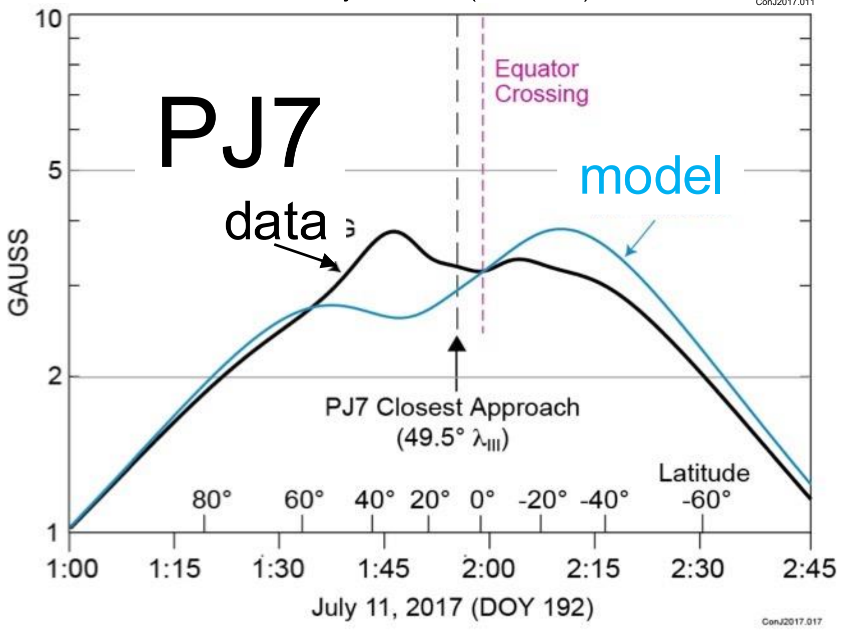
Jupiter's Magnetic Field



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

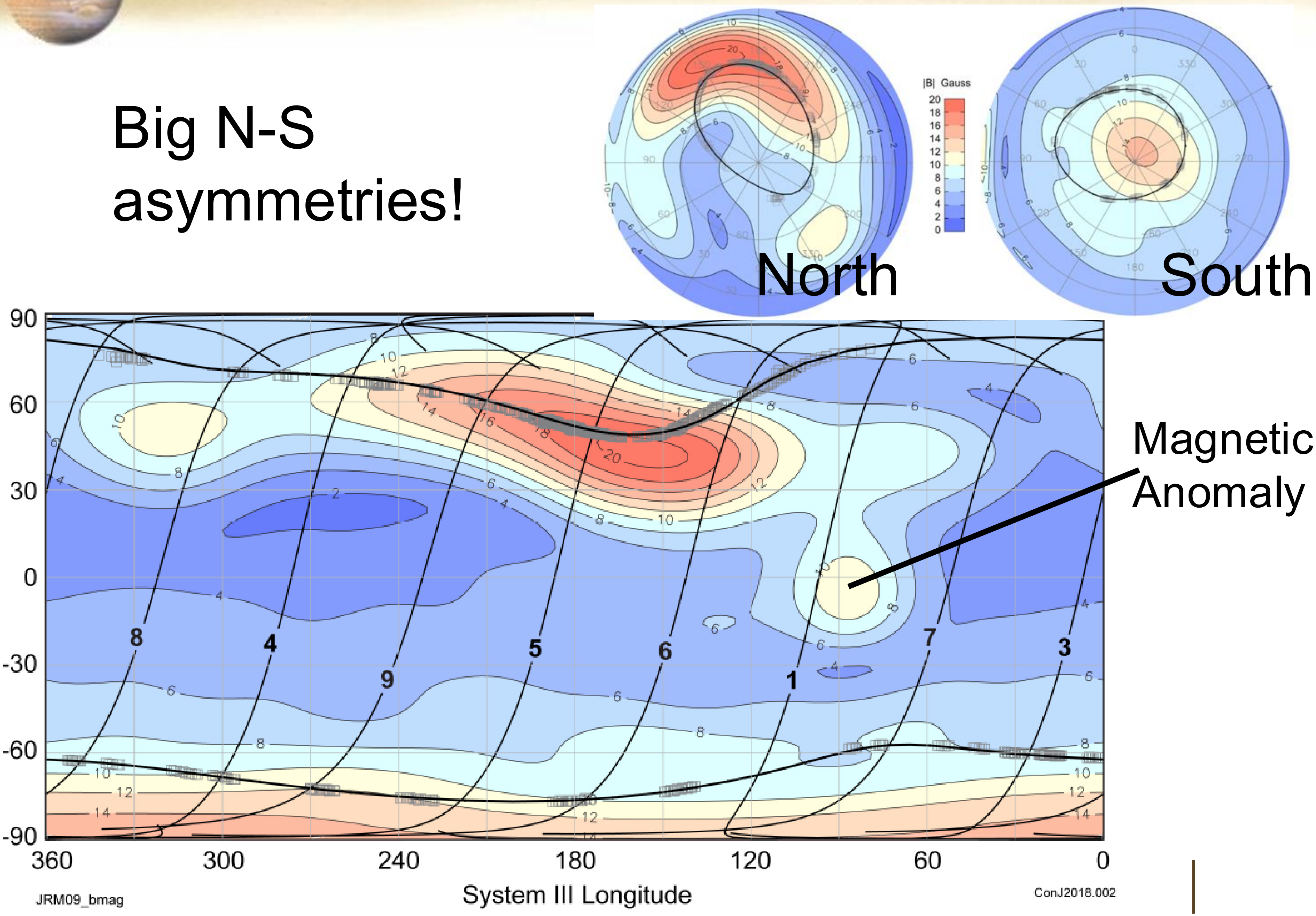
- Hints that the dynamo region is closer to the surface?



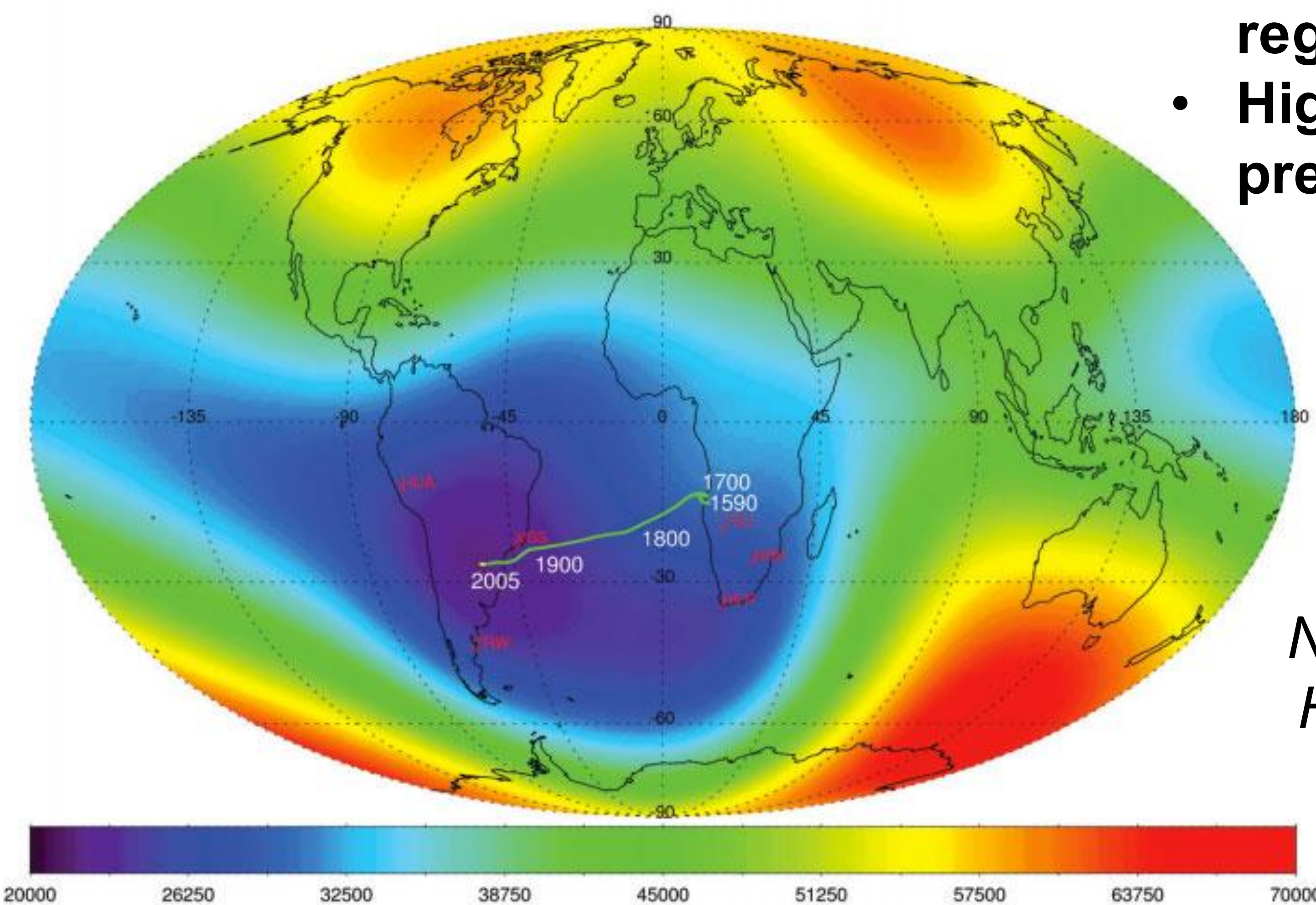


Juno-based magnetic field model

Big N-S asymmetries!



Earth's South American Anomaly



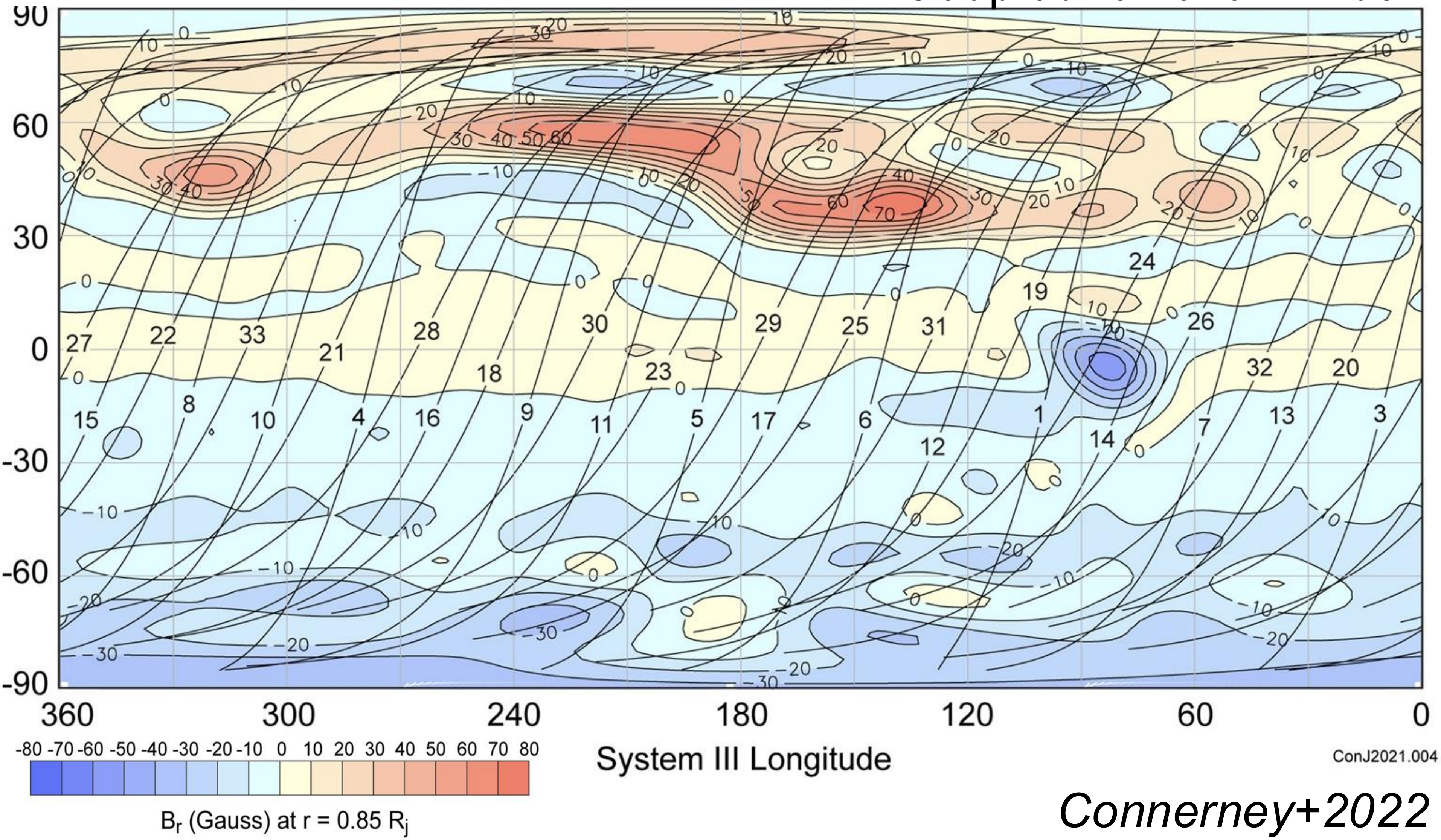
- **Weak field region**
- **High radiation precipitation**

Nasty place for Hubble Space Telescope!

Up close + more orbits -> more detail

- N-S asymmetry
- Secular variation
- Coupled to zonal winds?

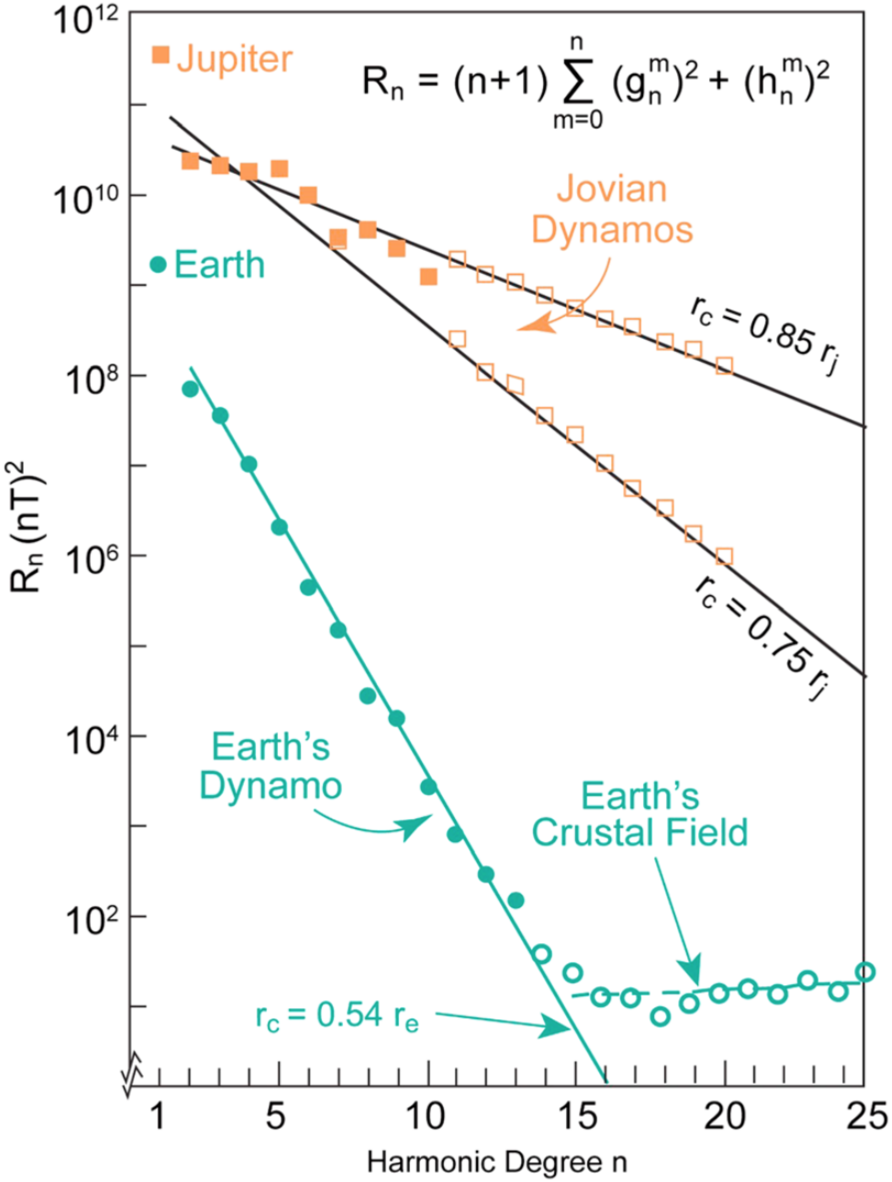
Magnetic Field – JRM033

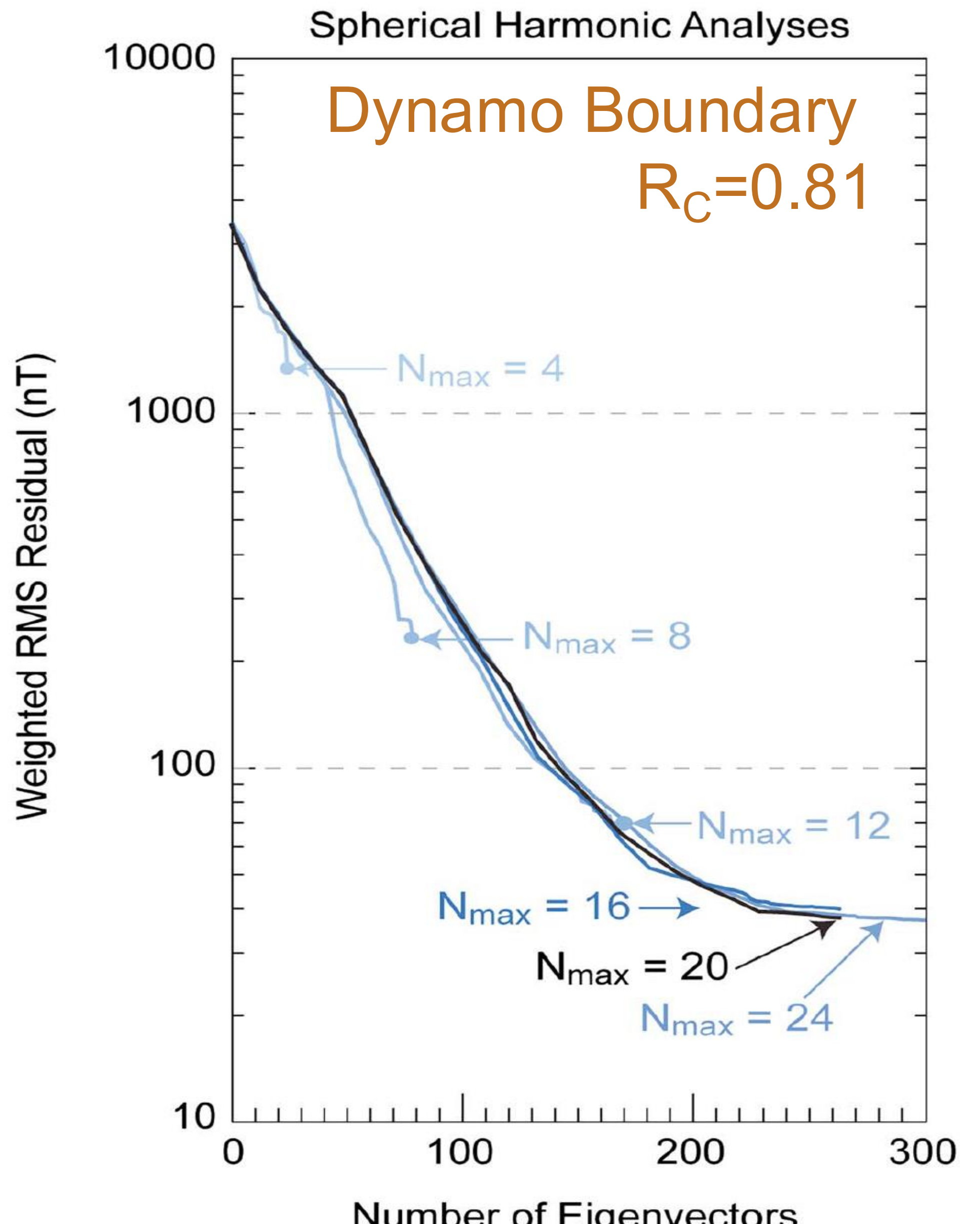


Connerney+2022

Juno

Connerney et al. 2018, 2022

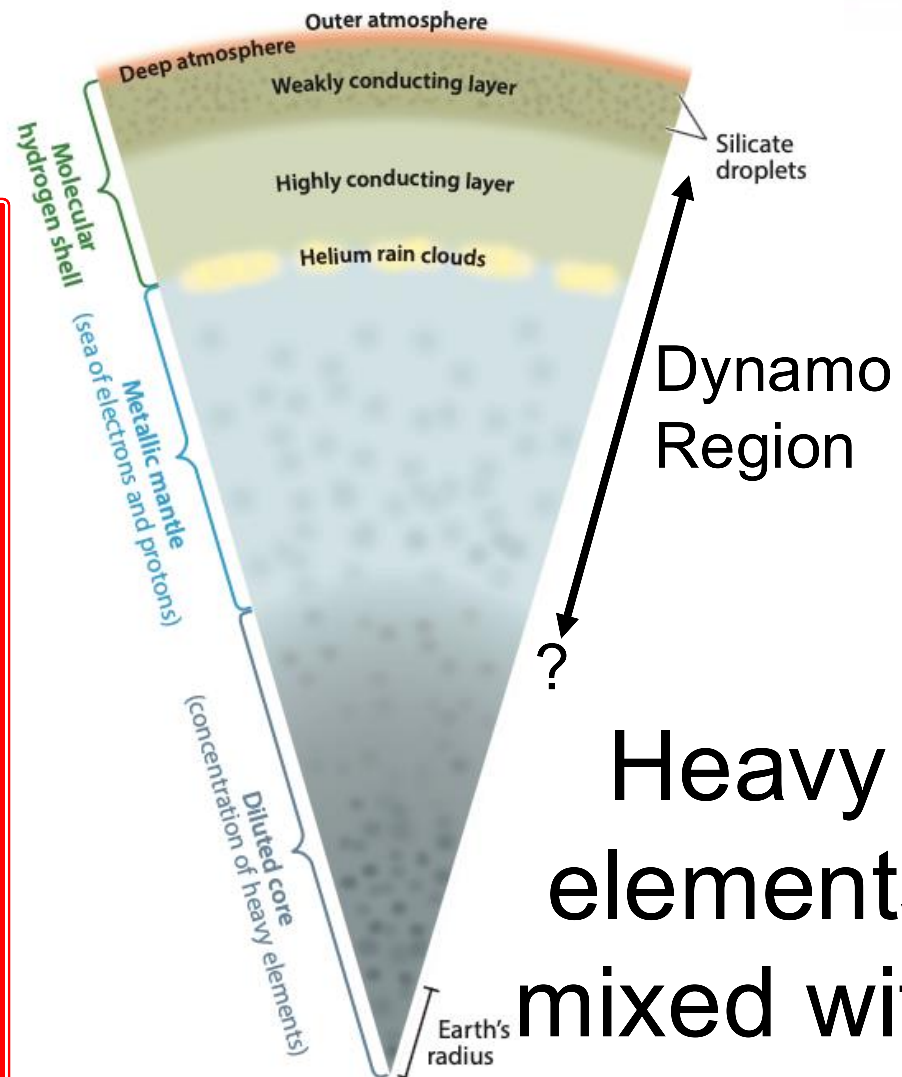




Measured gravity field

Juno

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



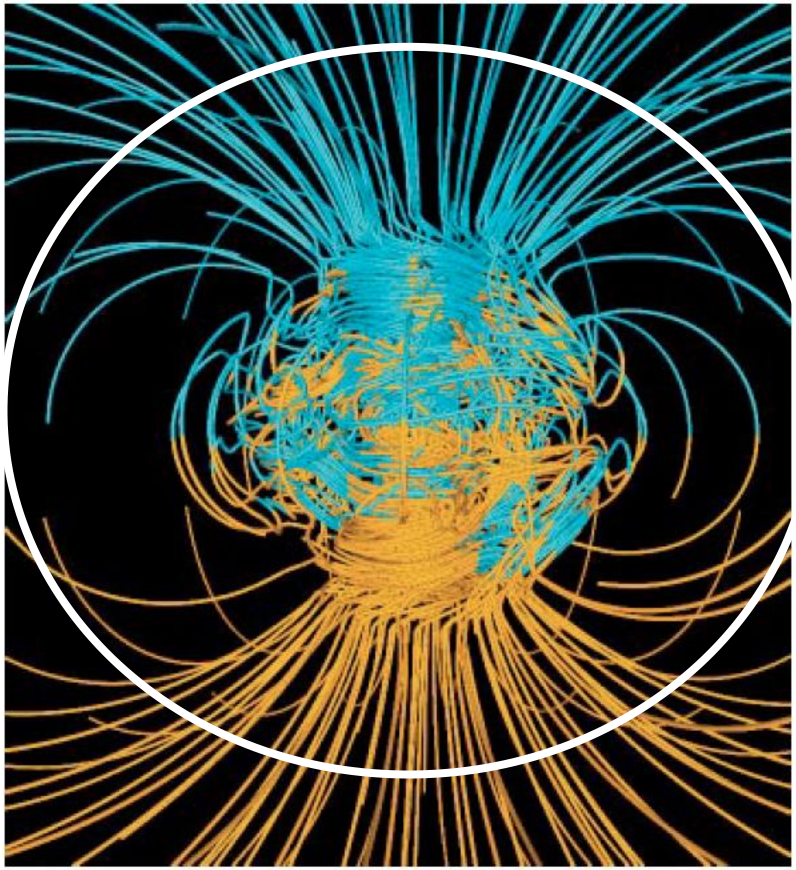
Heavy elements mixed with metallic H to ~40% radius

Iess et al. 2018 *Nature*

Implications for Dynamo

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

Earth: Dynamo deep in core – outer field ~dipole

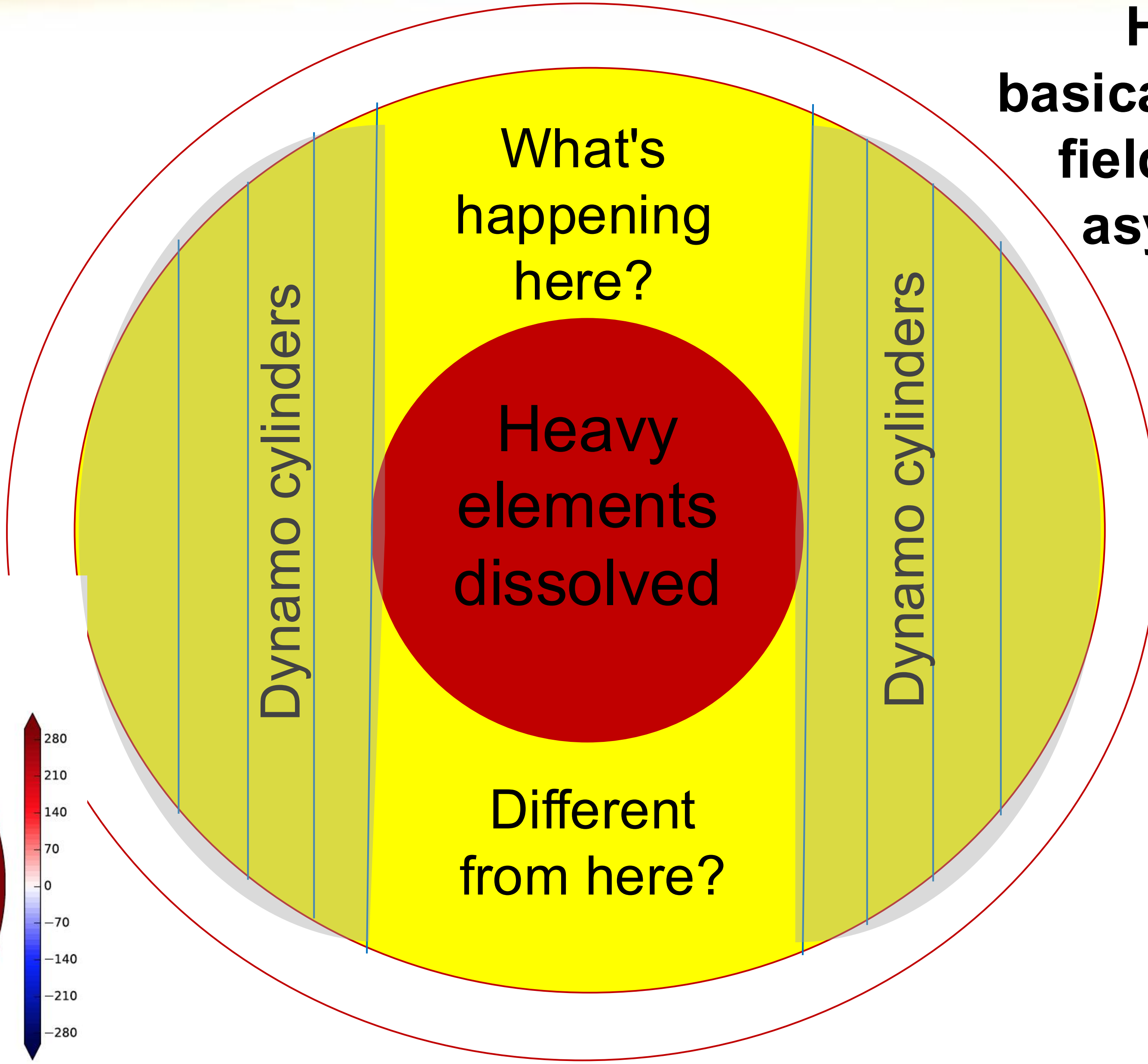


Glatzmeier 2002

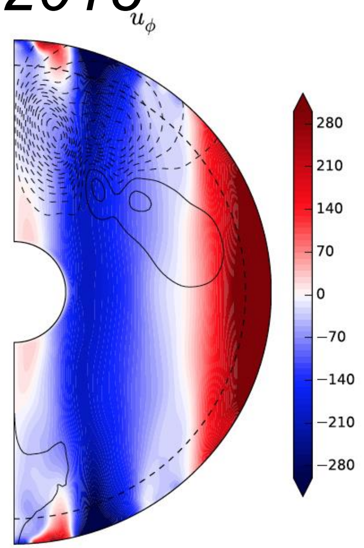
Glatzmeier 2005

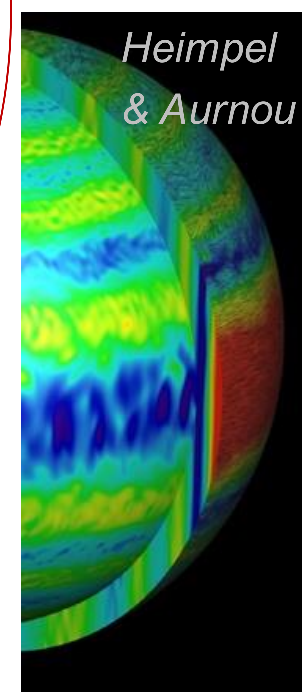
Implications for Dynamo in Rapid Rotator

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

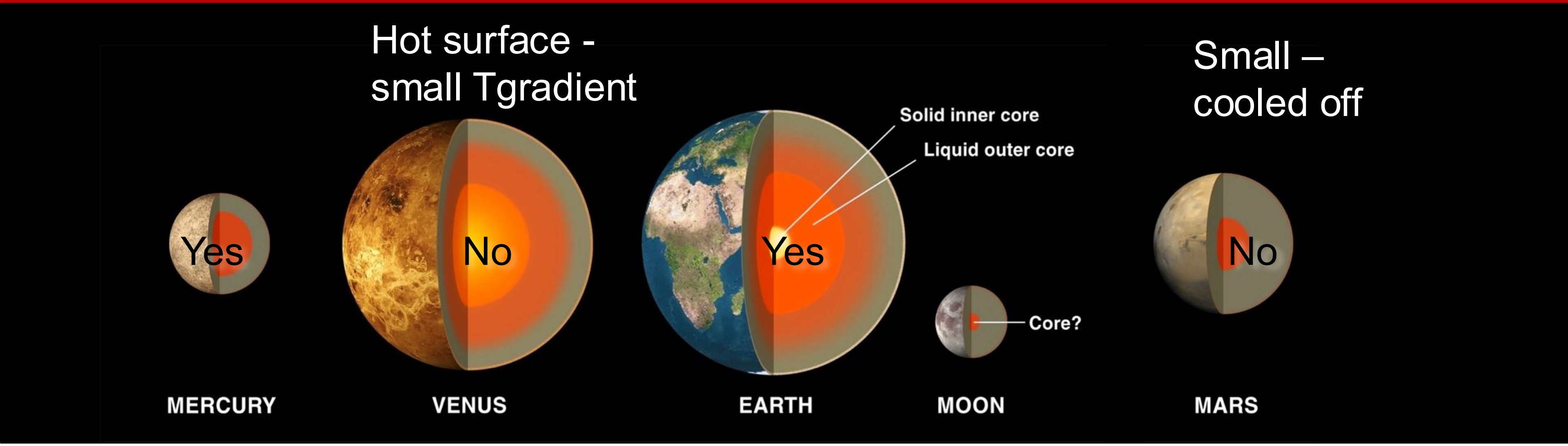


Duarte et al. 2018





WHICH HAVE ACTIVE MAGNETIC DYNAMOS?



Why Don't Venus or Mars have Dynamos?

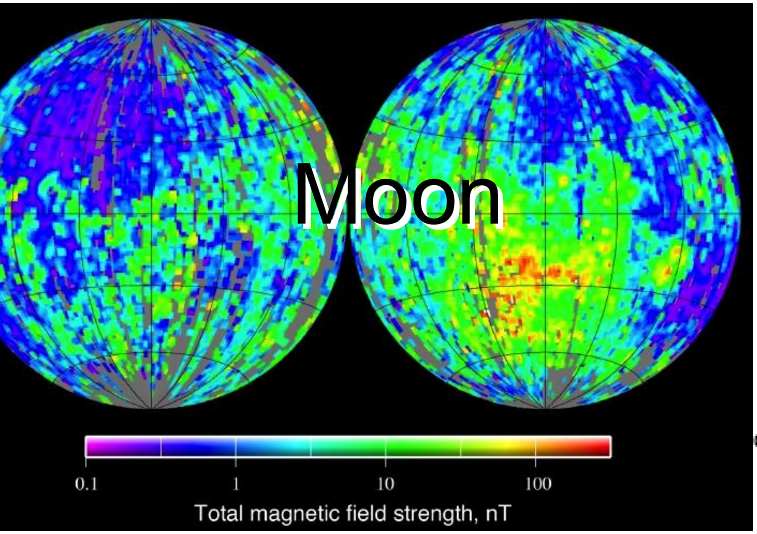
- Enough rotation – even for Venus
- Conducting fluid core – probably
- Lack of convection in core?

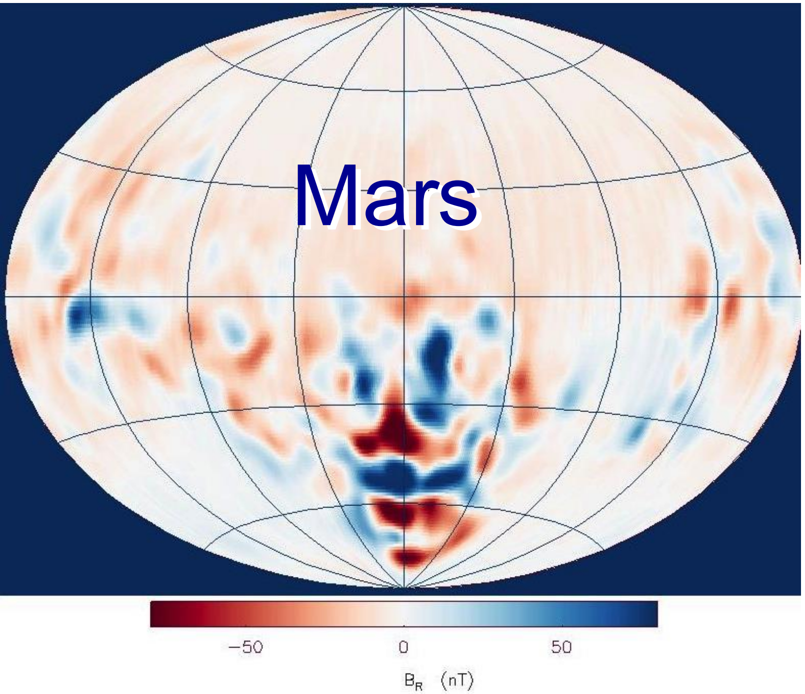
1. If....Mantle convection controls heat flow from core. Then....Lack of plate tectonics suggests less efficient cooling of interior and lower heat flux from core
2. No inner core means no latent heat of solidification and no enhancement of lighter material in the outer core

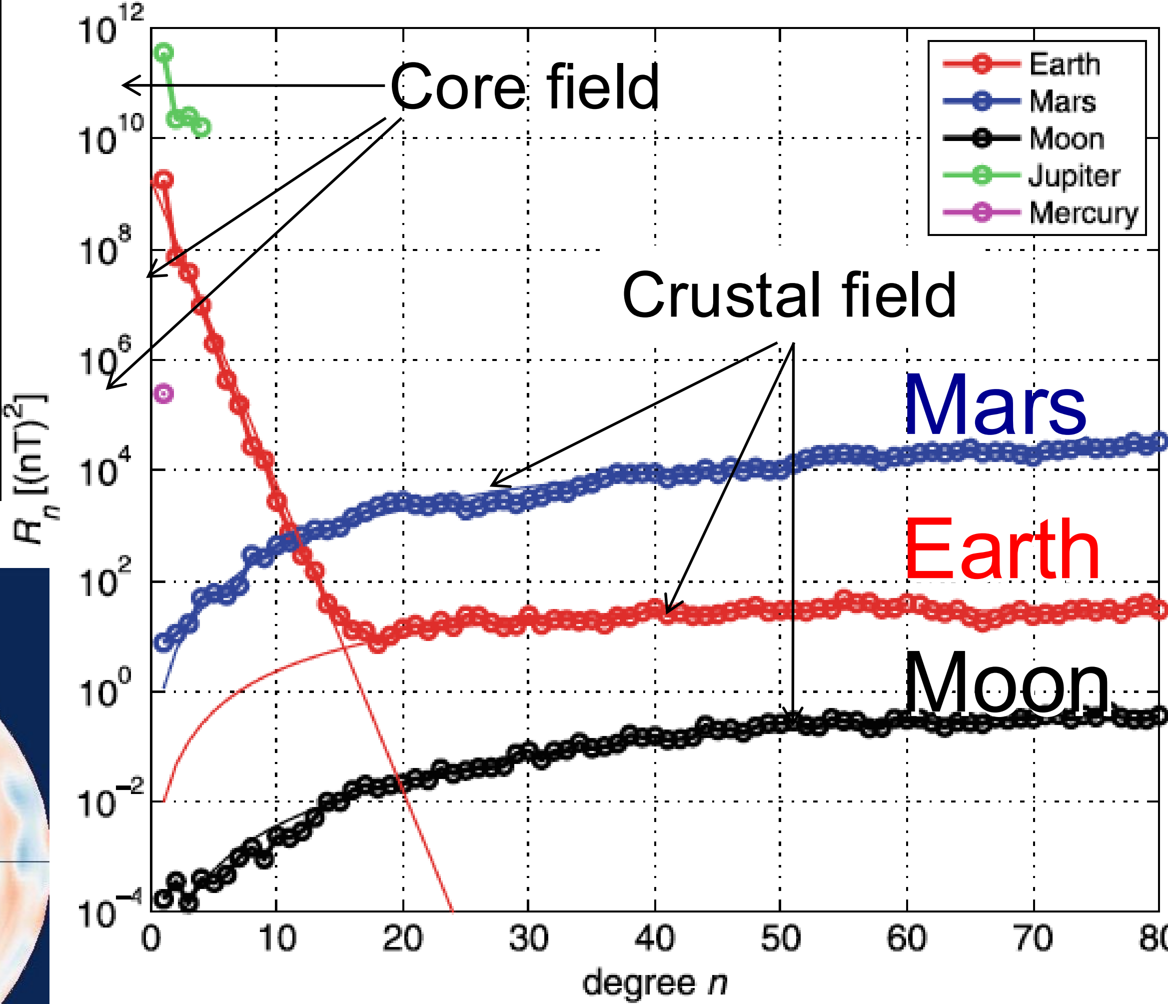
Need geophysics missions that address interior structure

Stevensen 2010

Moon & Mars: All Crustal Remanent Magnetization

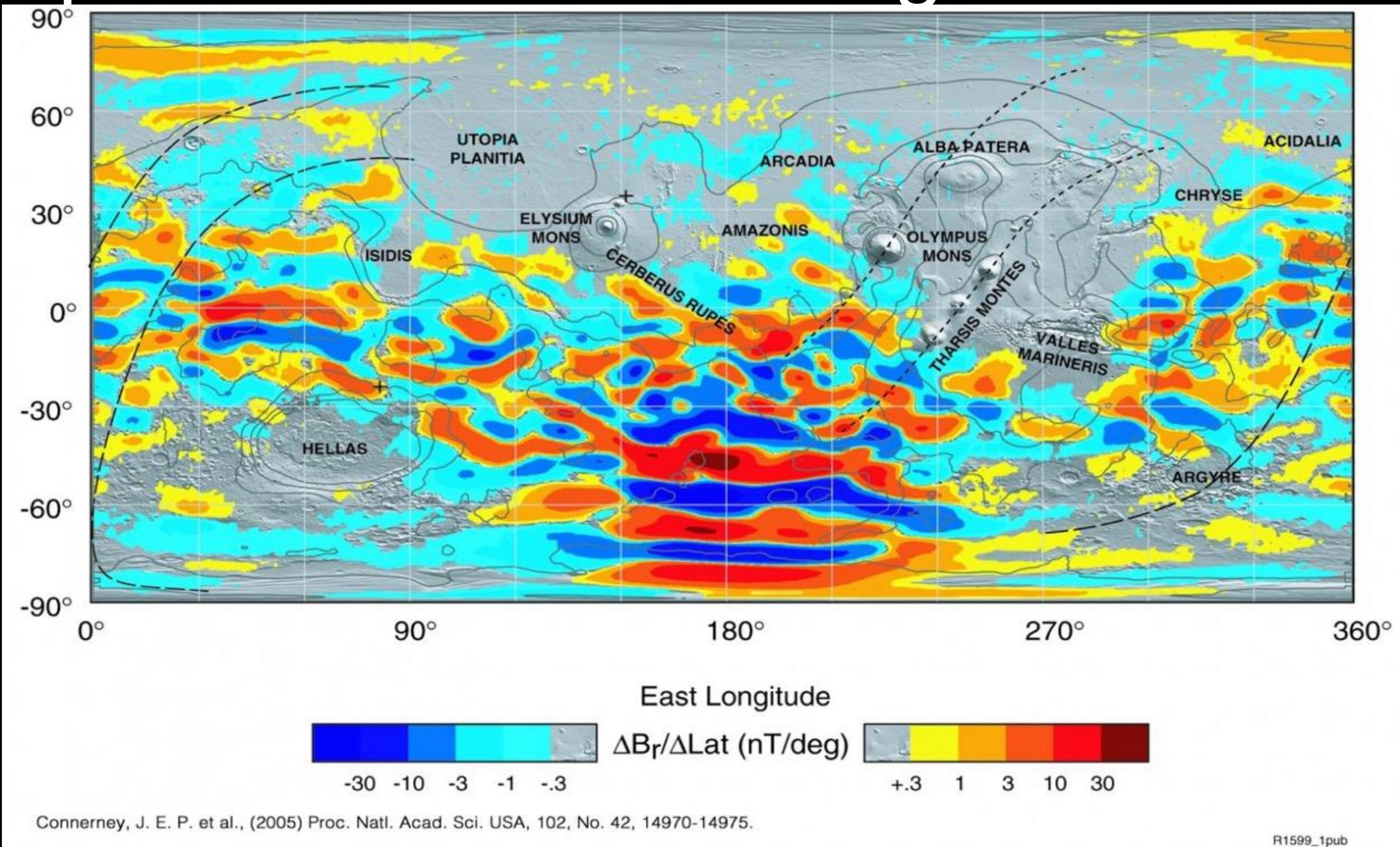






- Did Moon ever have dynamo?
- Mars' dynamo died >3.5 BYA.

Mars has strange arrangement of permanent crustal magnetic fields

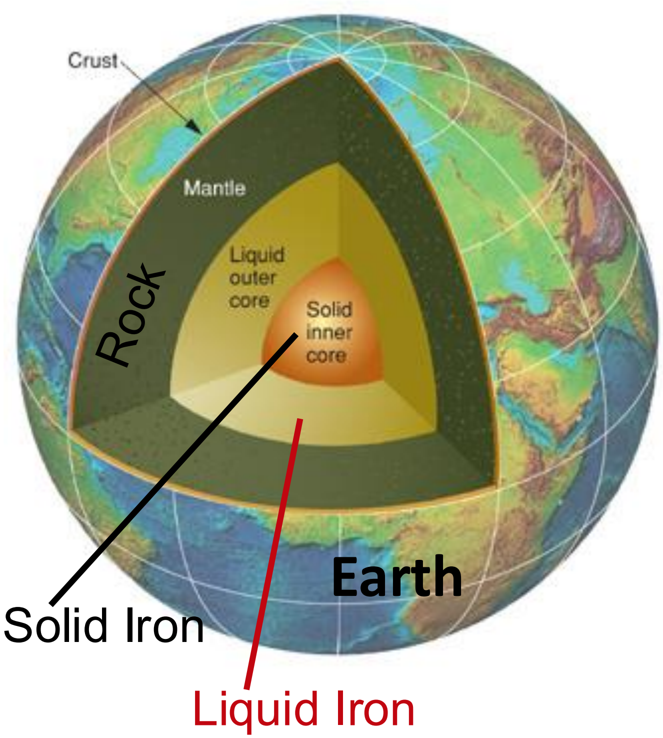


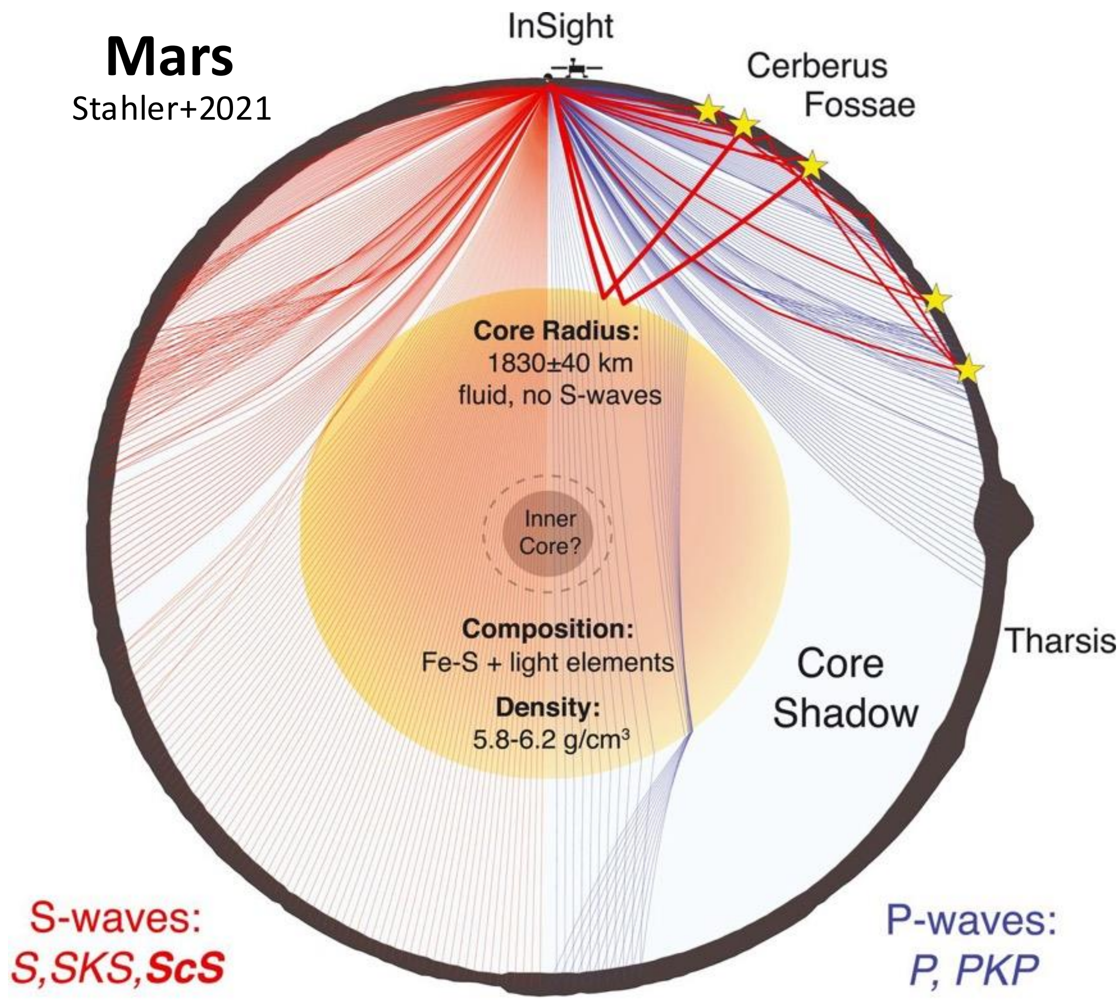
Magnetic dynamo stopped ~3 billion years ago

Why no dipole at Mars and Venus?

At Mars and Venus, the liquid core is wrapped in a stagnant mantle:

- no plate tectonics
- no mantle convection
- no magnetic field
- still not fully understood

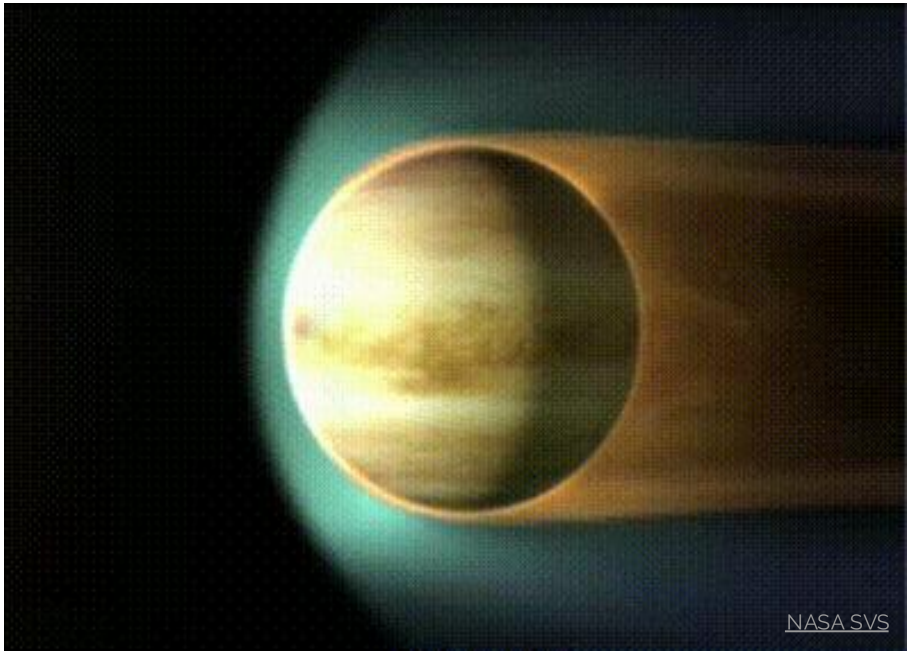




OK – Mars is small and cooled off quickly.
But Venus?? Same size as Earth!

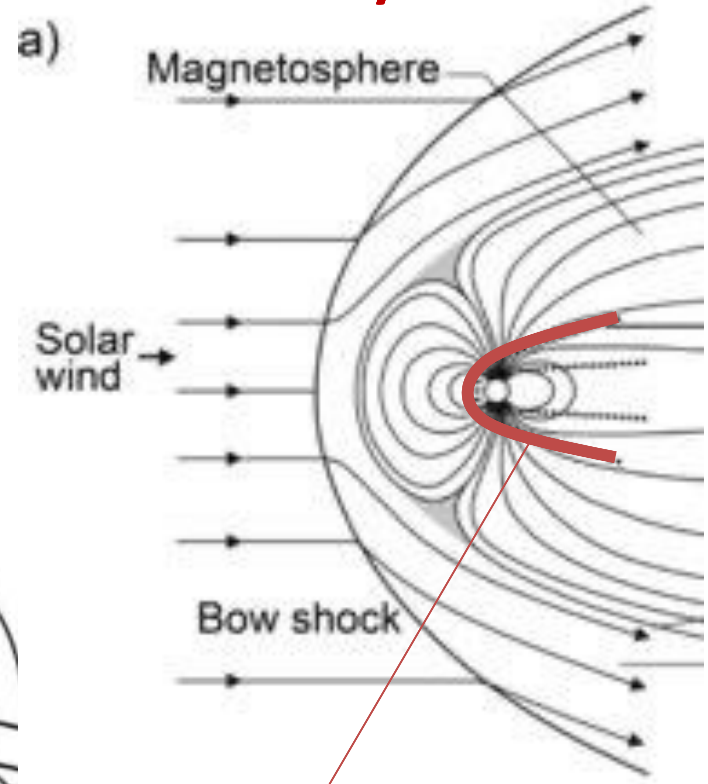
Induced Magnetospheres

Mars & Venus: Induced Magnetospheres

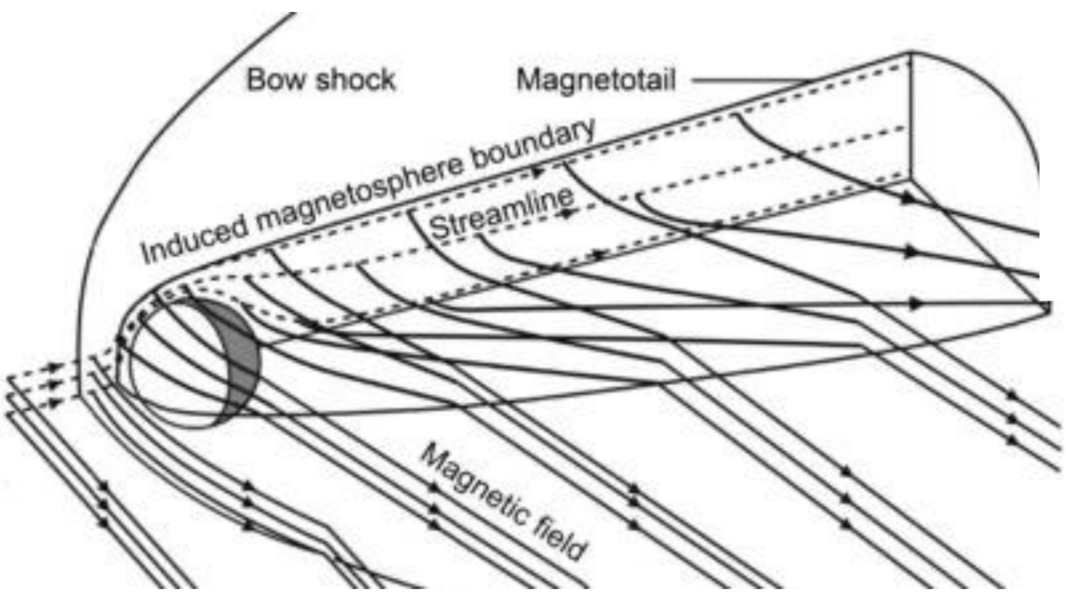


Earth vs. Venus

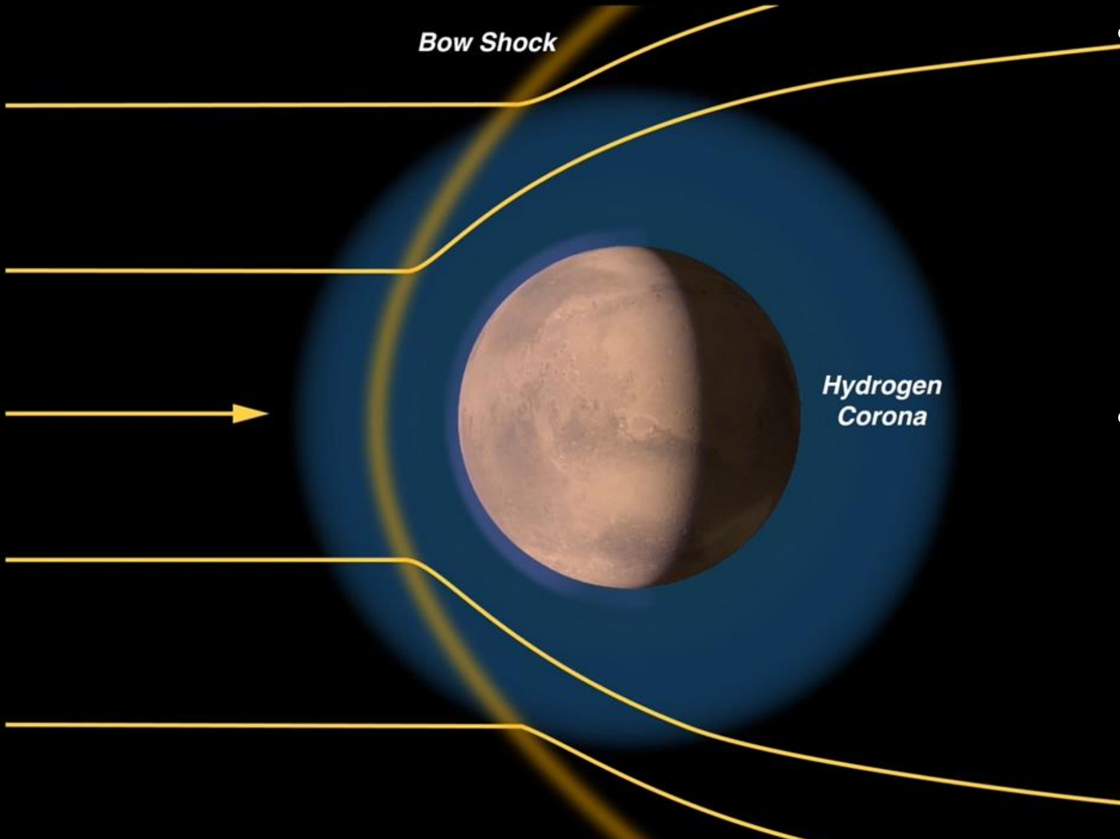
– Why so different??

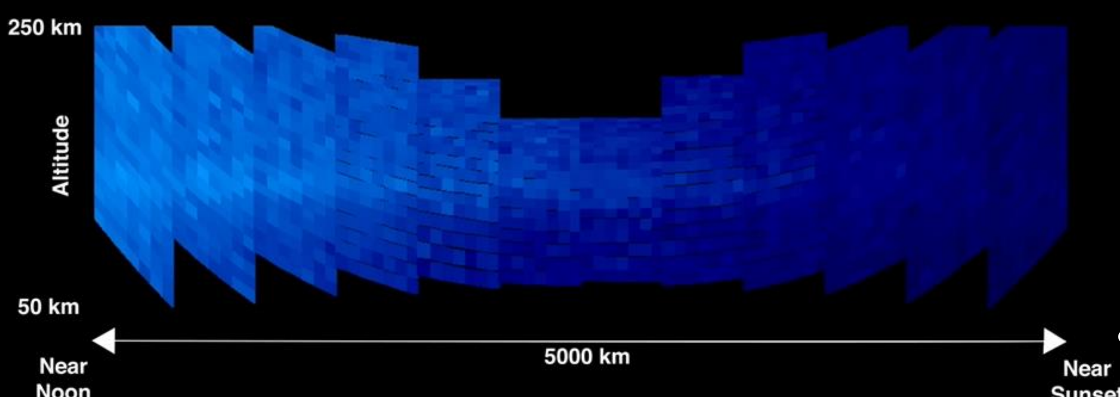


Venus bow shock



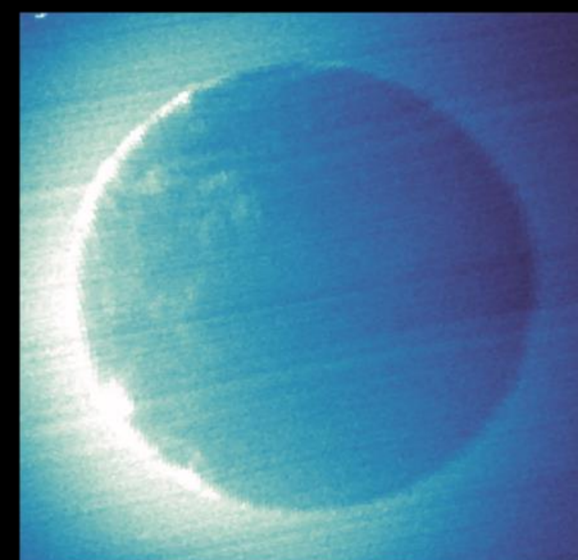
Proton Aurora: Mars' most common aurora





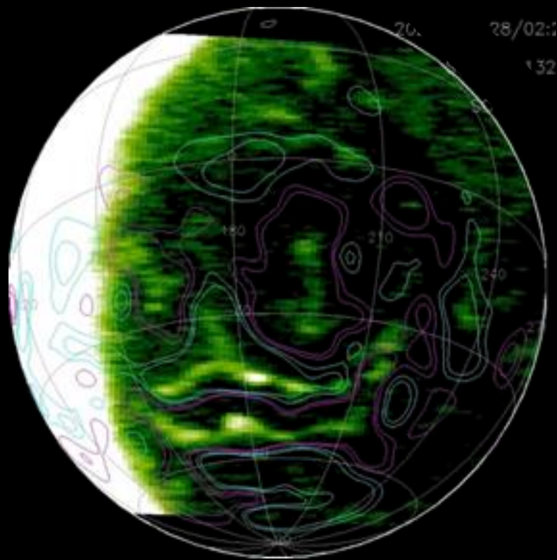
Deighan+ 2018

- Penetrating particles are neutralized by charge exchange, which allows them to pass through the bowshock and emit
- Patchy – varying solar wind structures

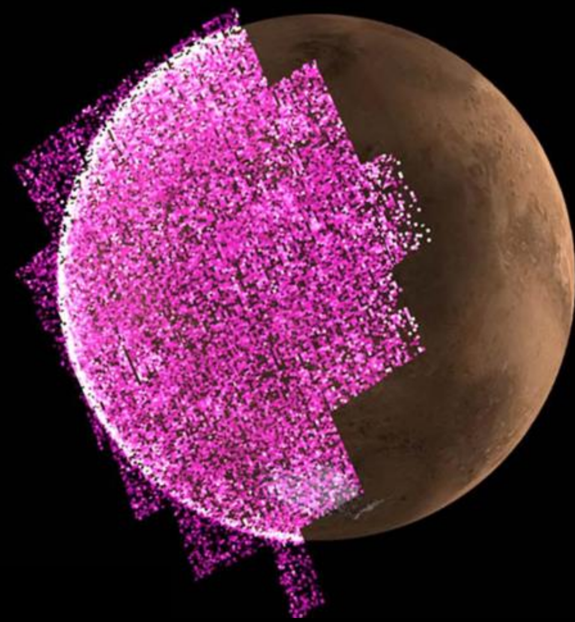


- Likely to occur on Venus, but never been observed

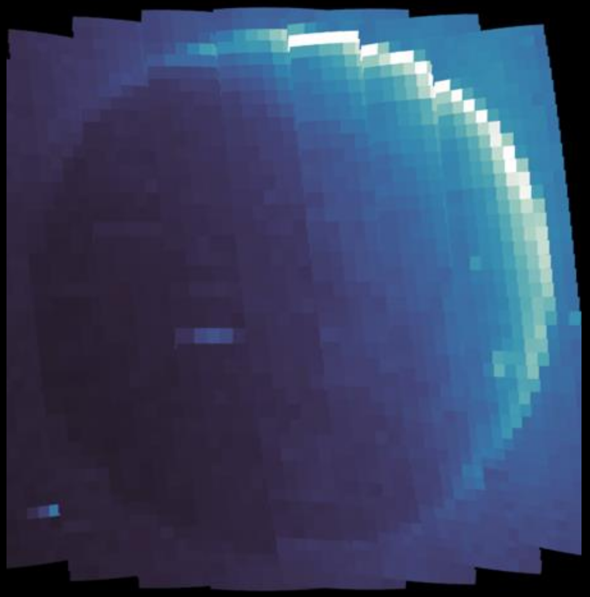
Three Types of Aurora on Mars



Fast electrons power emissions in discrete patterns in and around Mars crustal magnetic fields



Solar Energetic Particles, both protons and electrons, can engulf the entire planet in diffuse aurora



Solar wind protons impact Mars' upper atmosphere, and cause emission across the dayside

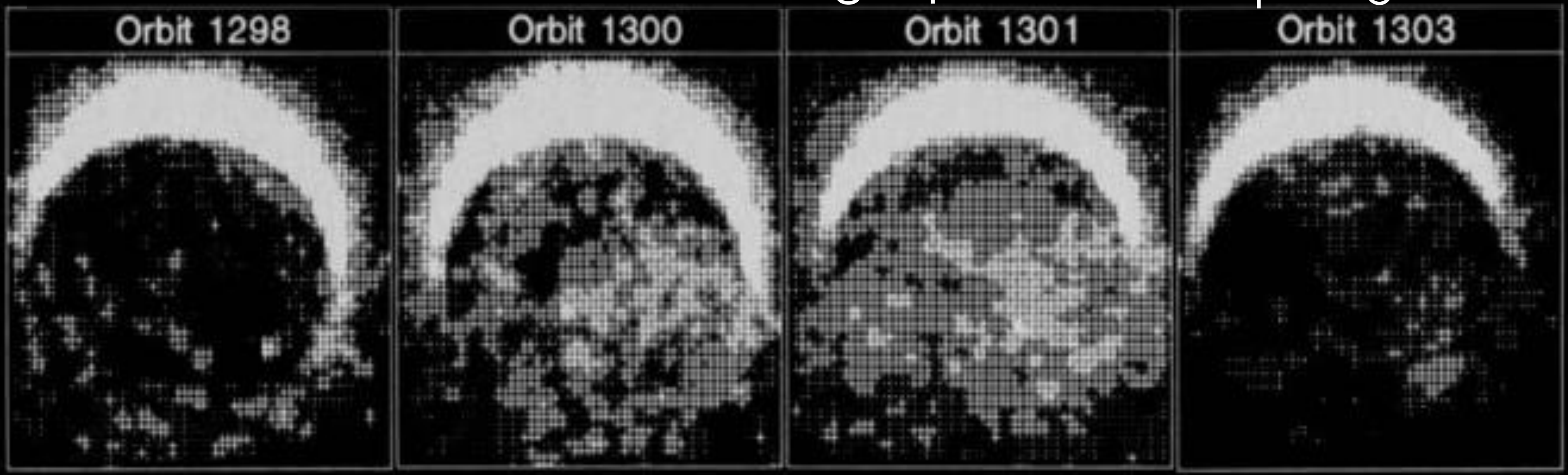
O and H glowing in ultraviolet

Venus: Aurora waiting to be discovered

Sun-Venus interaction **should** produce aurora similar to those seen at Mars outside the crustal fields

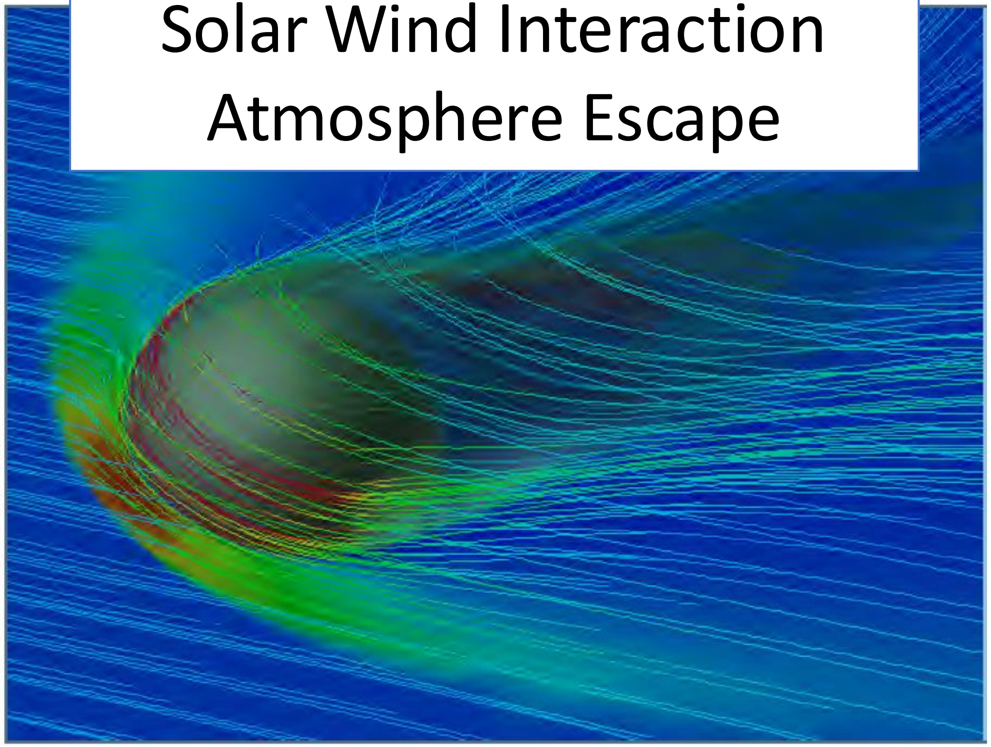
- Pioneer Venus made point observations from a spinning spacecraft, limiting temporal and spatial resolution
- Since 80s - No mission has adequately observed aurora at Venus

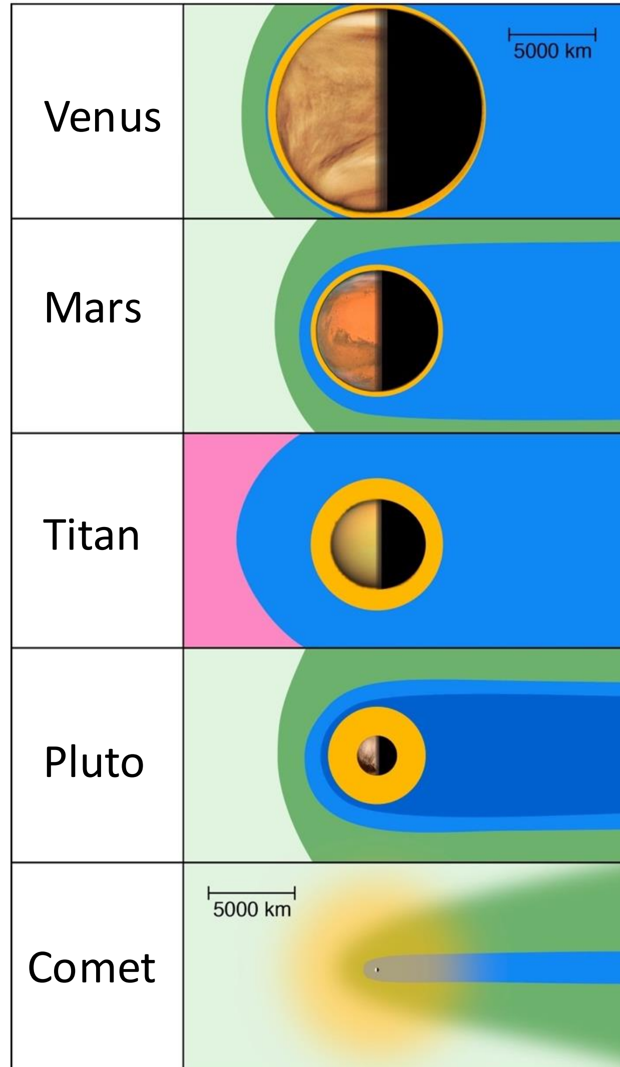
Pioneer Venus UV Aurora 130.4 nm   Phillips+1986



Need a mission to Venus to measure aurora!!

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

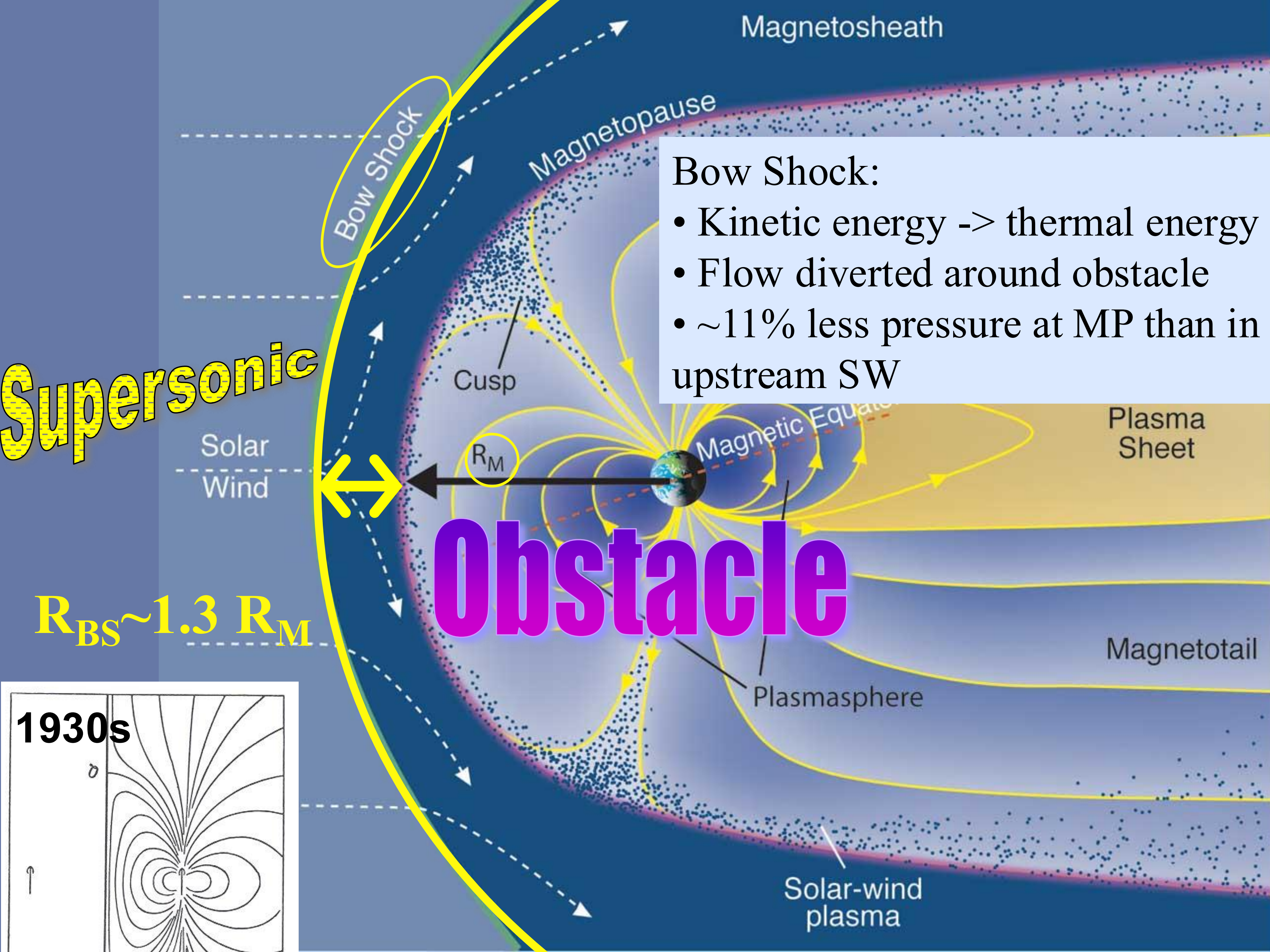
- Ionization of outer atmosphere
- Plasma-atmosphere interaction
- Similar scale!
- Similar loss! few kg/s
- Comets up to ton/s

Brain et al. 2016

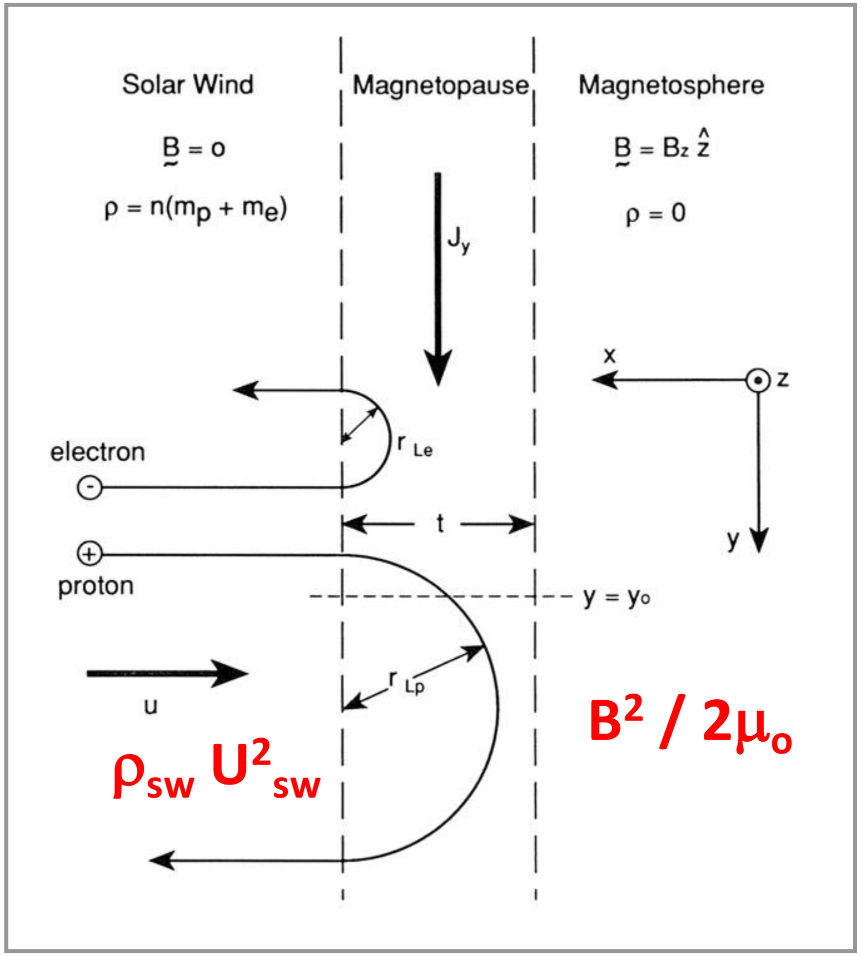
Magnetosphere Sizes

Why do planetary magnetospheres have a bow shock?

What happens to the solar wind at the bow shock?

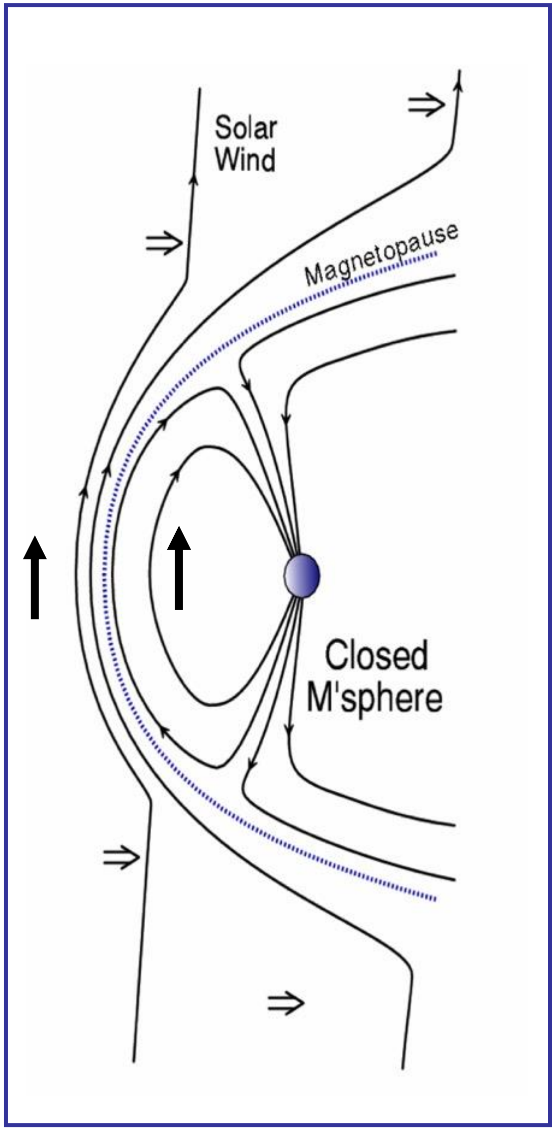

Magnetosheath
Magnetopause
Bow Shock
Bow Shock:
• Kinetic energy -> thermal energy
• Flow diverted around obstacle
• ~11% less pressure at MP than in upstream SW
Supersonic
Cusp
Solar Wind
R_M
Magnetic Equator
Plasma Sheet
Obstacle
R_{BS}~1.3 R_M
Magnetotail
Plasmasphere
1930s
Solar-wind plasma

Chapman-Ferraro Current

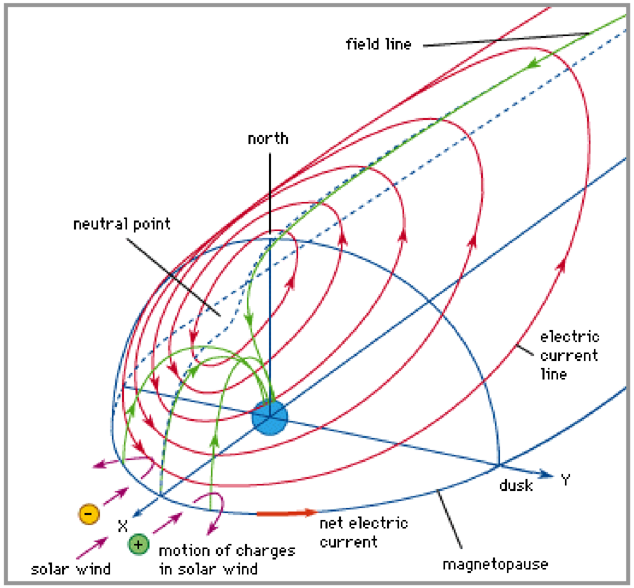


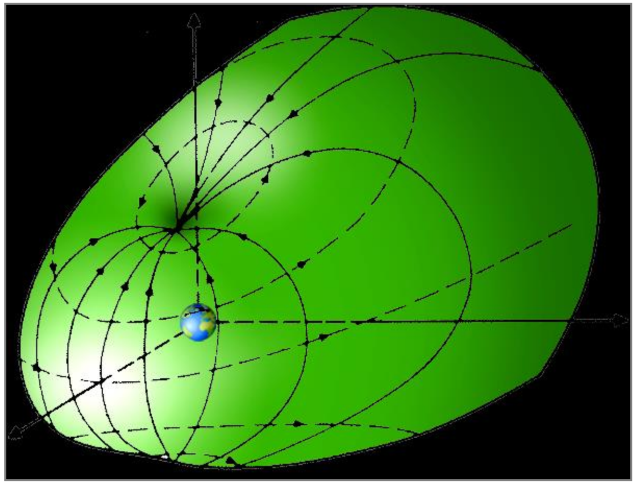
- Internal magnetic field pressure $B^2 / 2\mu_o$
- Balances the solar wind dynamic pressure $\rho_{sw} U^2_{sw}$
- Assumes northward Interplanetary Magnetic Field – IMF
- Chapman-Ferraro current must provide **j** x **B** force integrated across magnetopause

Chapman-Ferraro Current



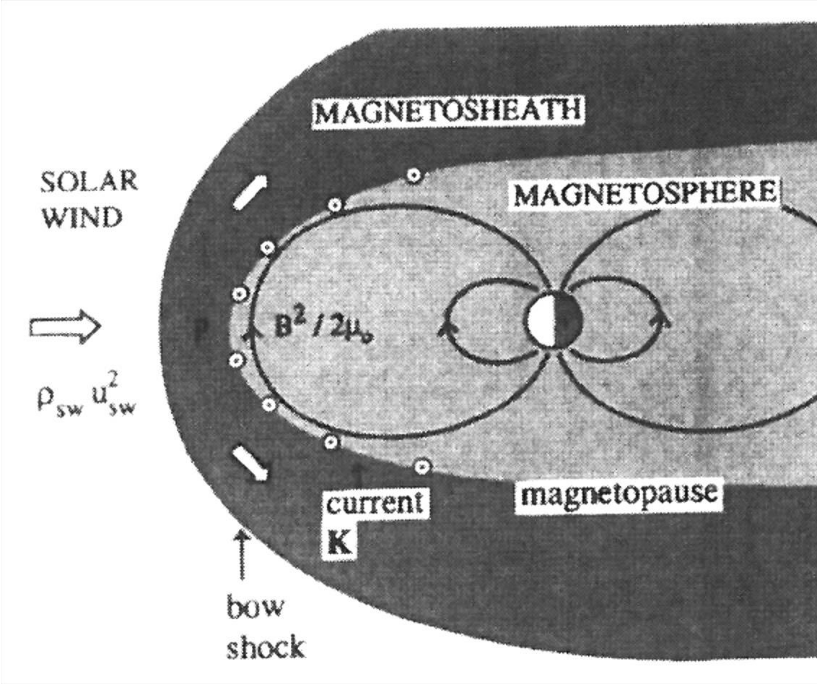
- Creates closed magnetosphere
- Limits size of magnetosphere
- Current pattern over the whole magnetopause.





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

SW ram pressure <=>
internal magnetic field pressure



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

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

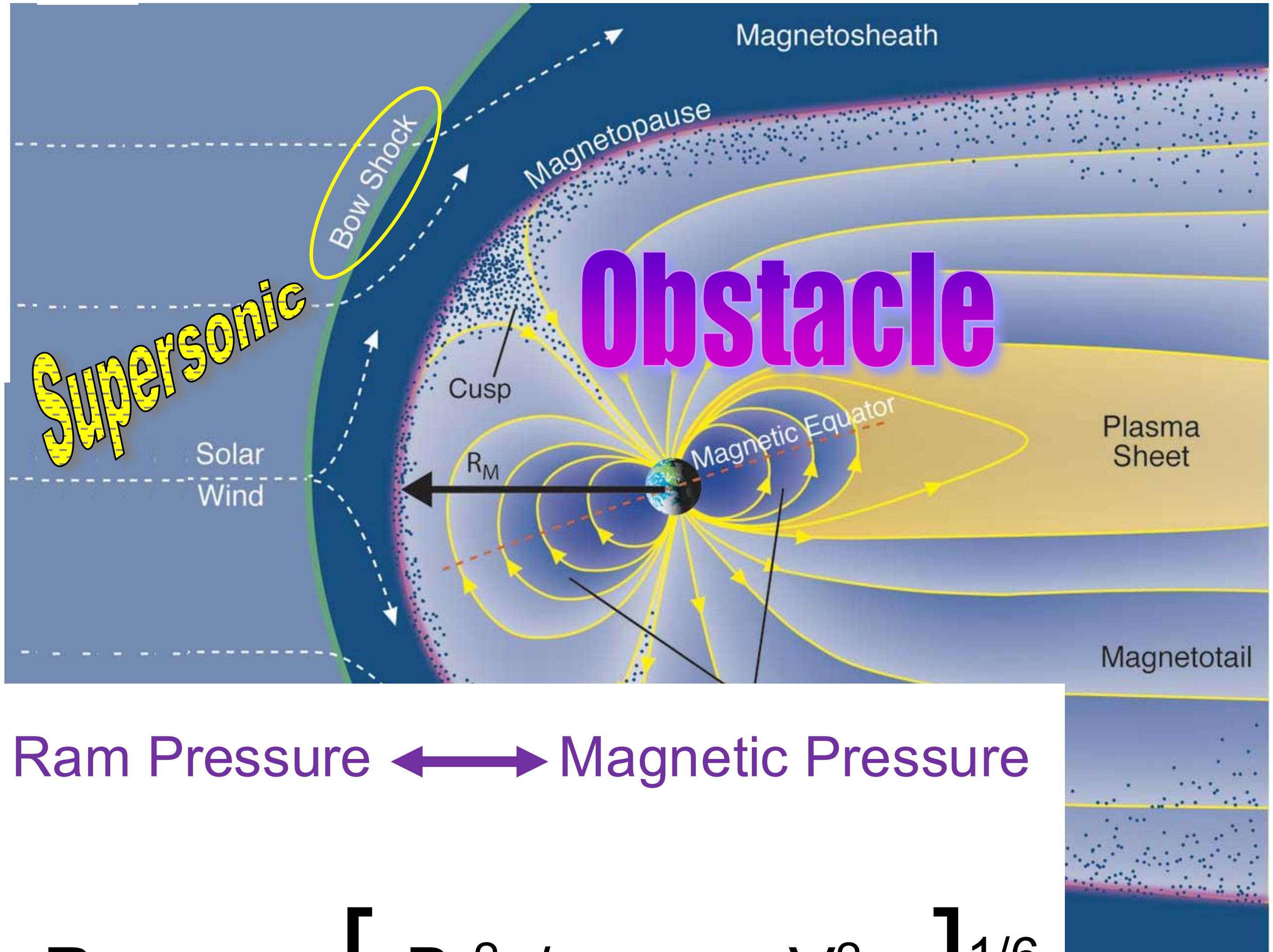
$\rho_{sw} U^2_{sw} = (2B_o)^2 \ (R_p/r)^6 / \ 2\mu_o$

Solve for r=> R_{MP}

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

Chapman-Ferraro Distance

Dipole Magnetic Field in Solar Wind



SW Ram Pressure ⟷ Magnetic Pressure

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

Walker & Russell 1995

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

Quick chat with your neighbors….

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

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

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

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

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

Quick chat with your neighbors….

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

   $\sim 1/D^2$

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

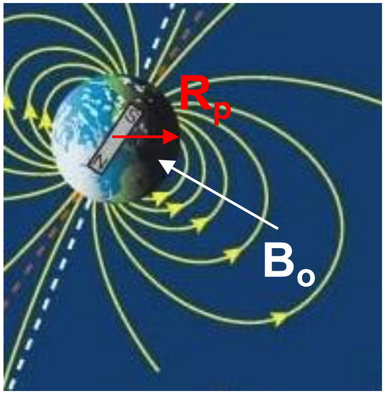
   ~ constant

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

   $\{1/D^2\}^{1/6} \sim D^{1/3}$

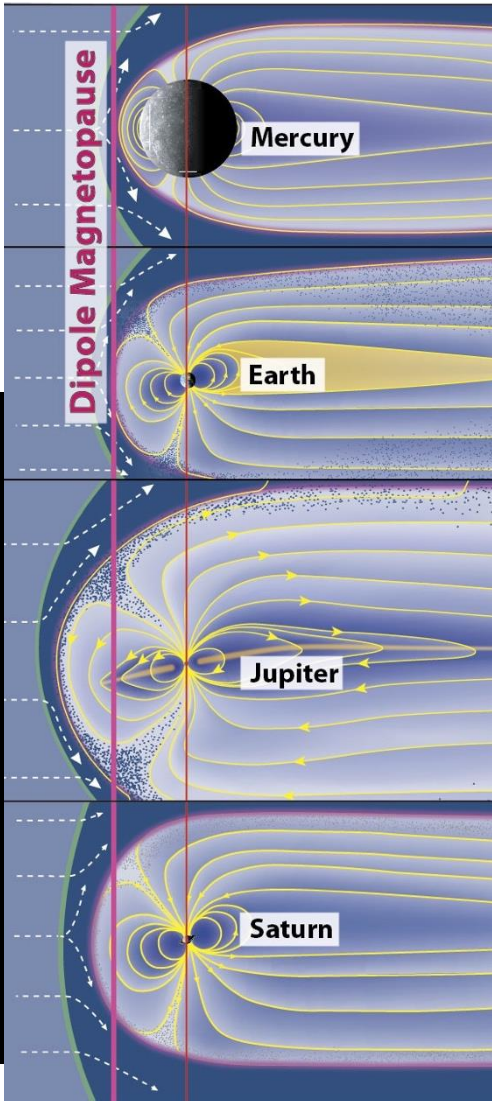
4. Move Earth from 1 AU to 8 AU – How big is the magnetosphere?

   x 2

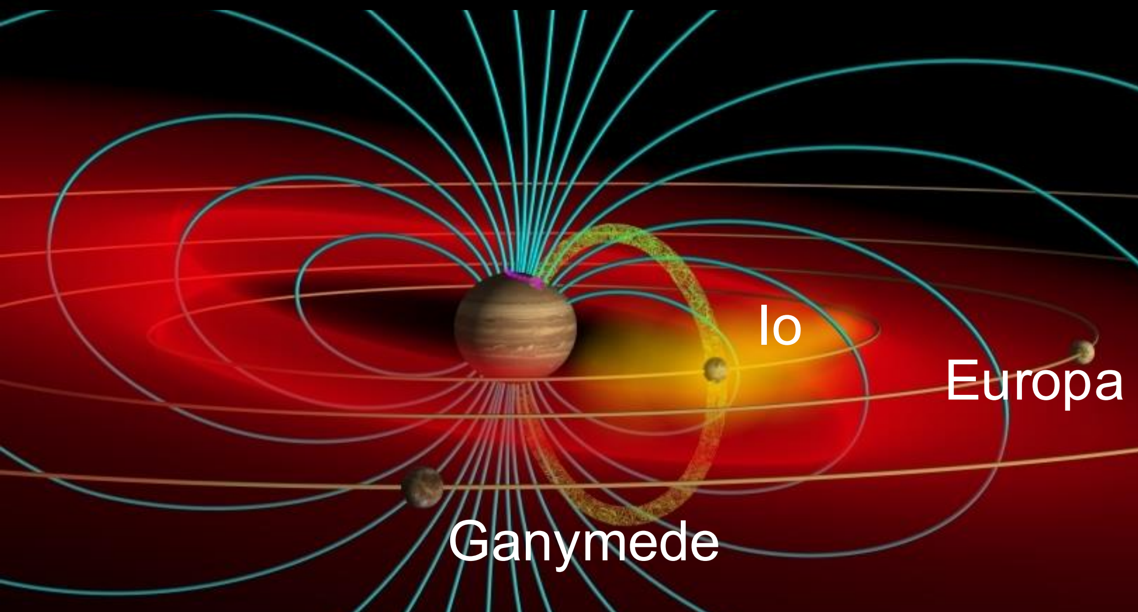


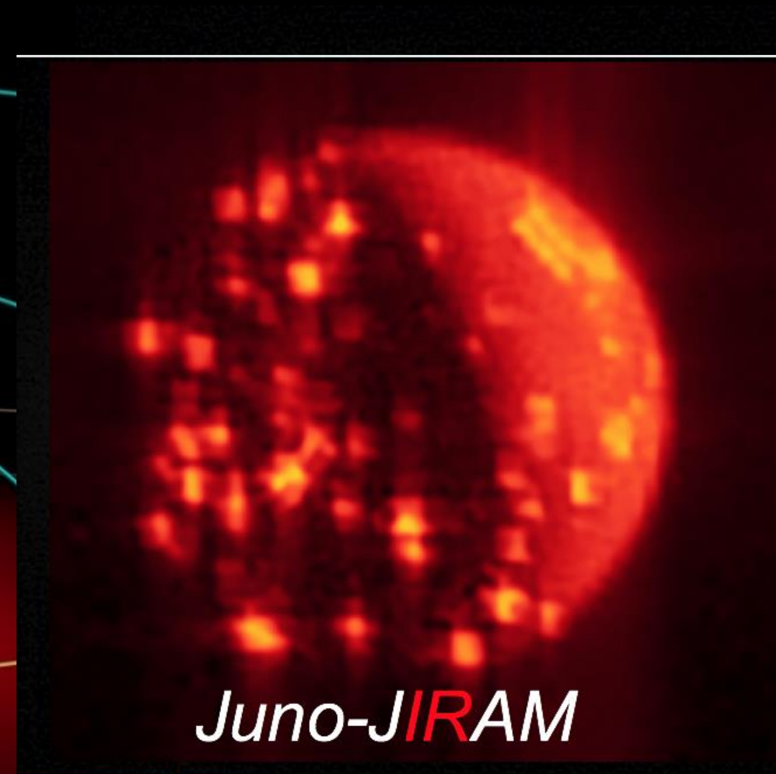
$$R_{CF}/R_p \sim 1.4\,\{\mathbf{B_o}^2/2\,\mu_o\,\rho_{sw}\,V^2_{sw}\}^{1/6}$$

	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

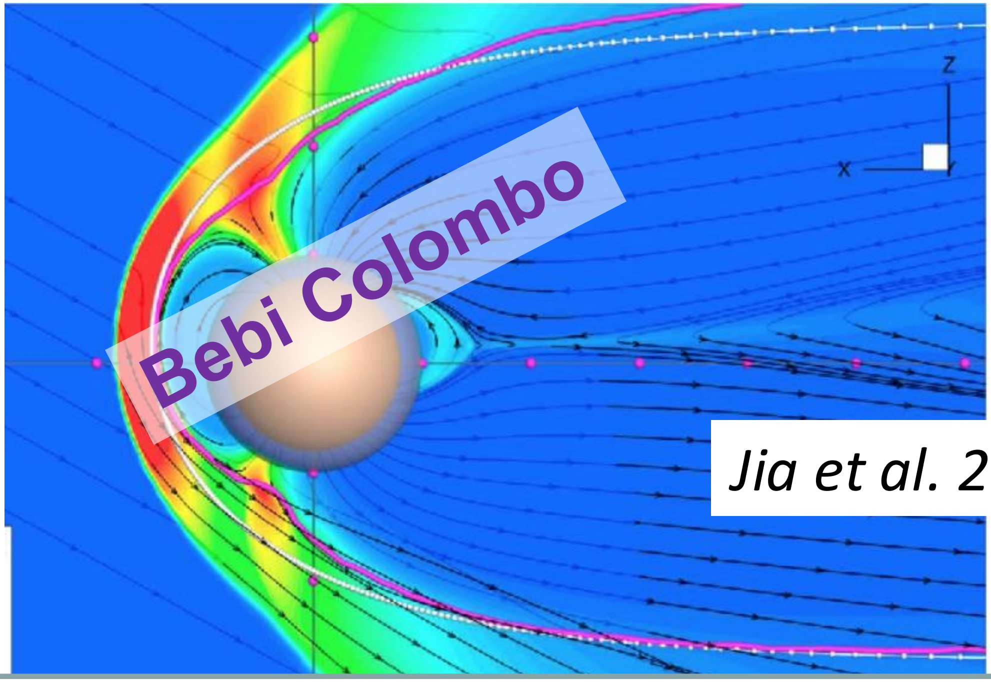
No atmosphere

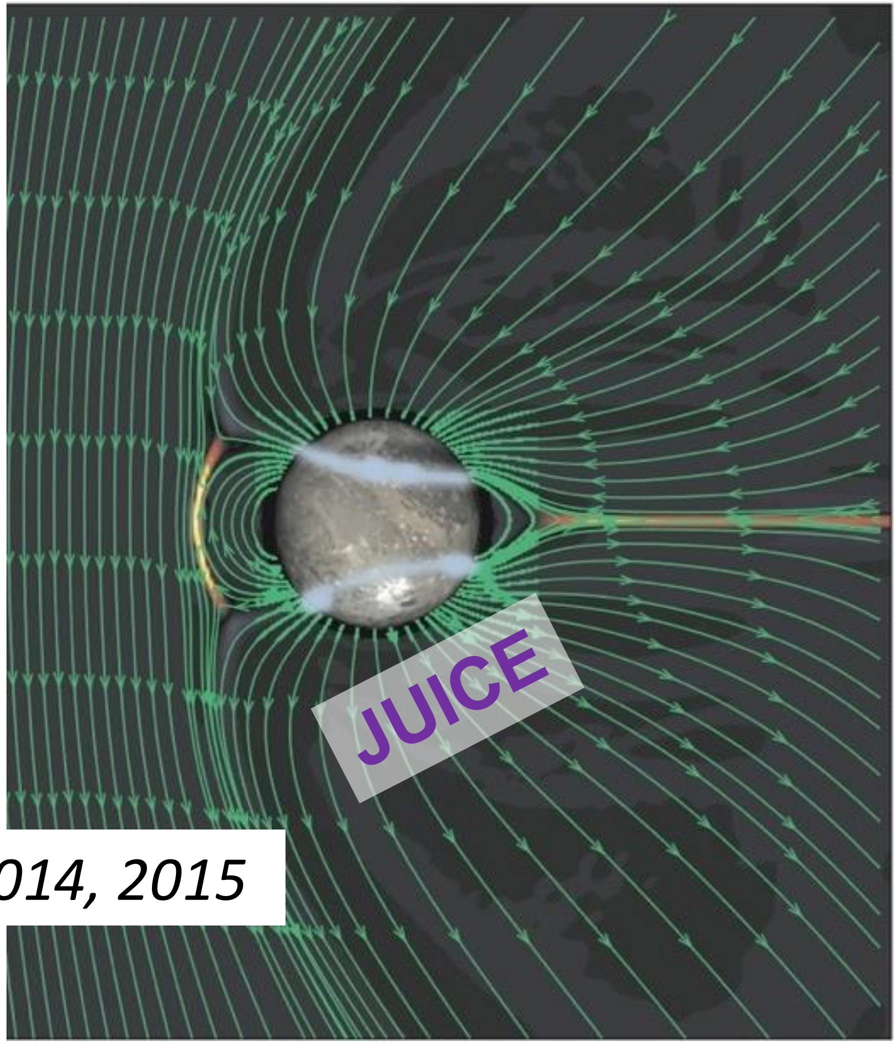
Ganymede

Galileo

In Jupiter m'sphere

Atmospheric aurora





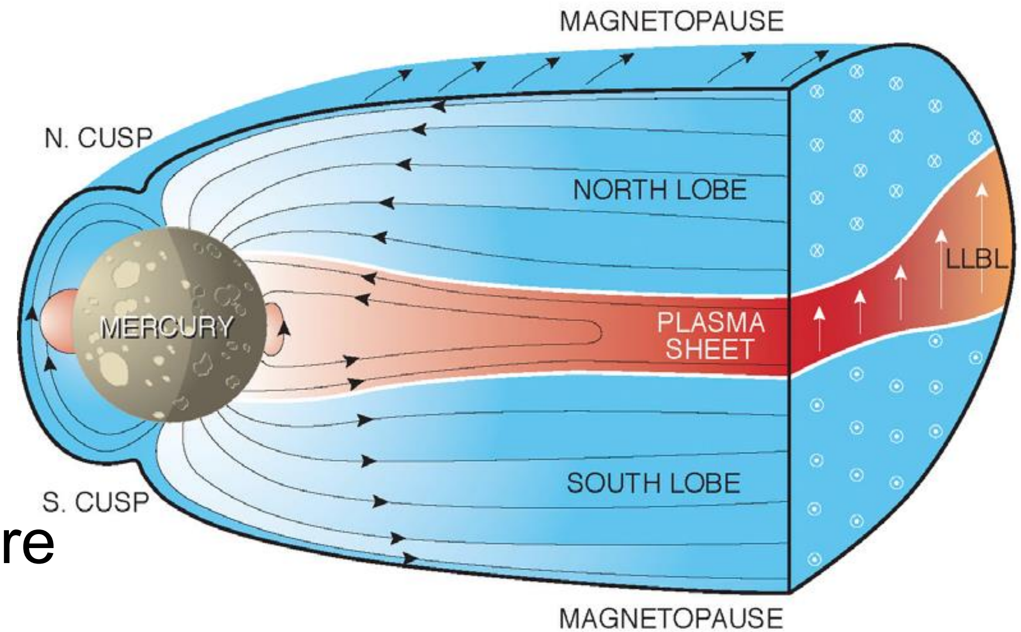
Jia et al. 2014, 2015

$B_{surface}$ ~ 1/100 Earth

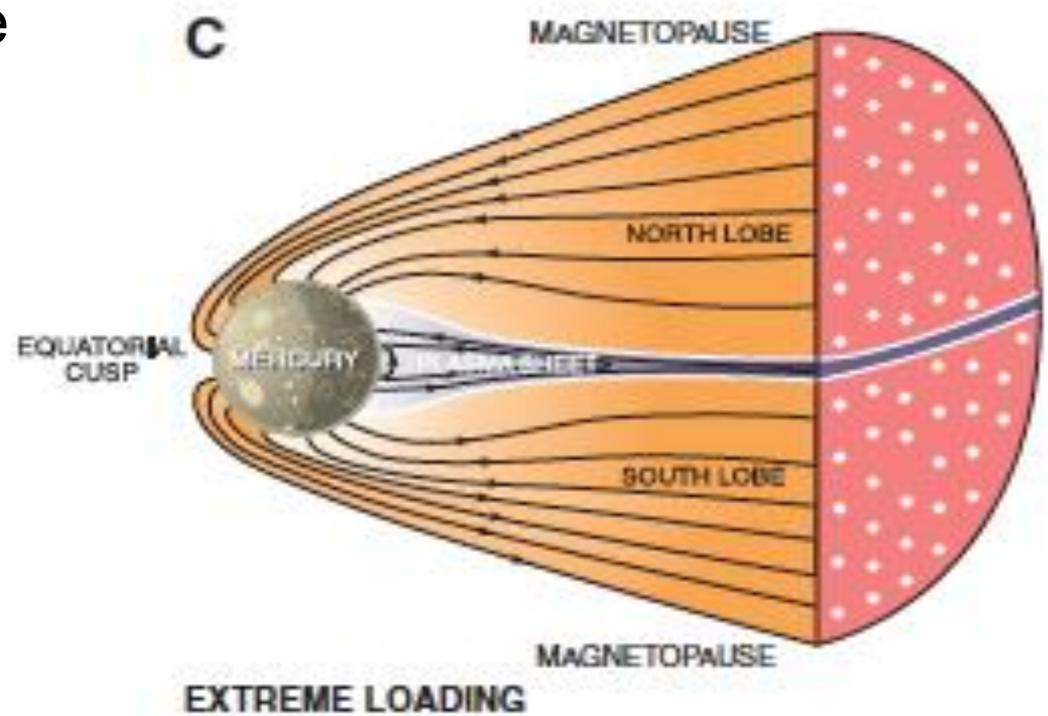
Earth Diameter

Mercury

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



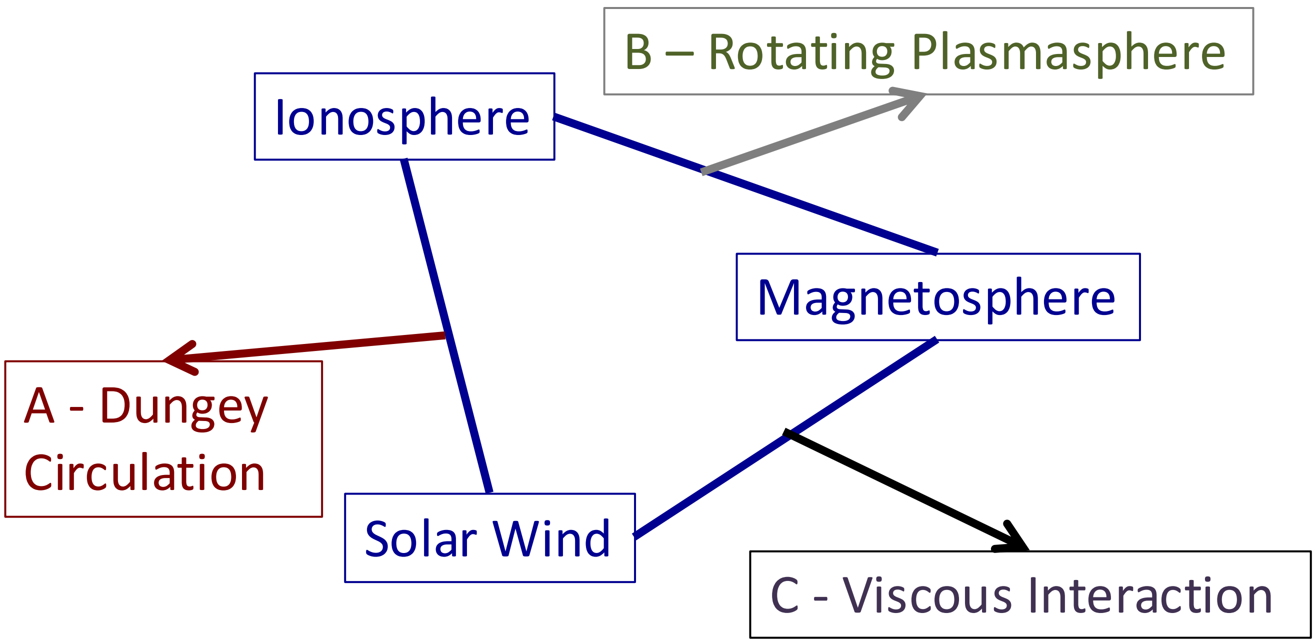
Extreme solar wind conditions -> exposed planet



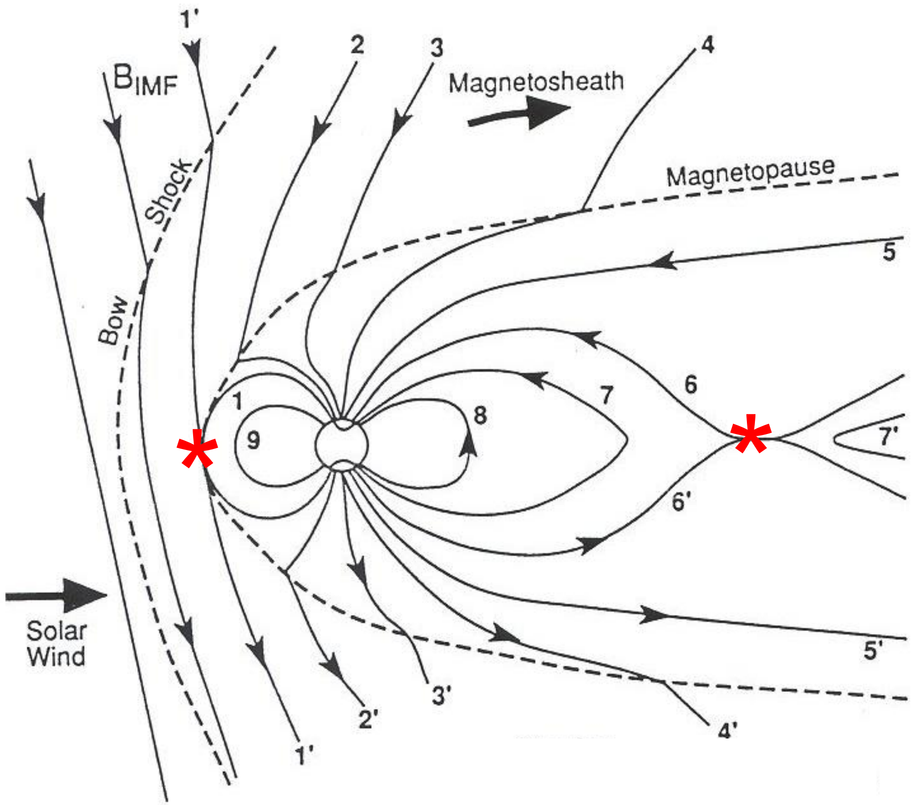
Slavin et al.

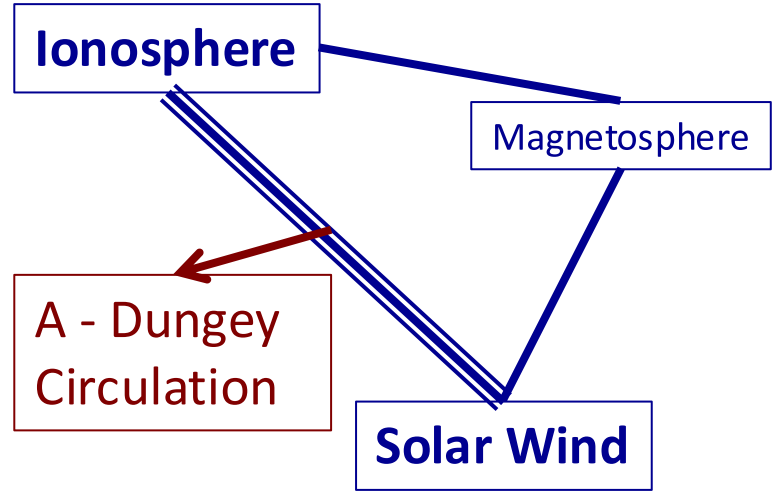
Dynamics

Which Form of Coupling Dominates -> Controls Dynamics



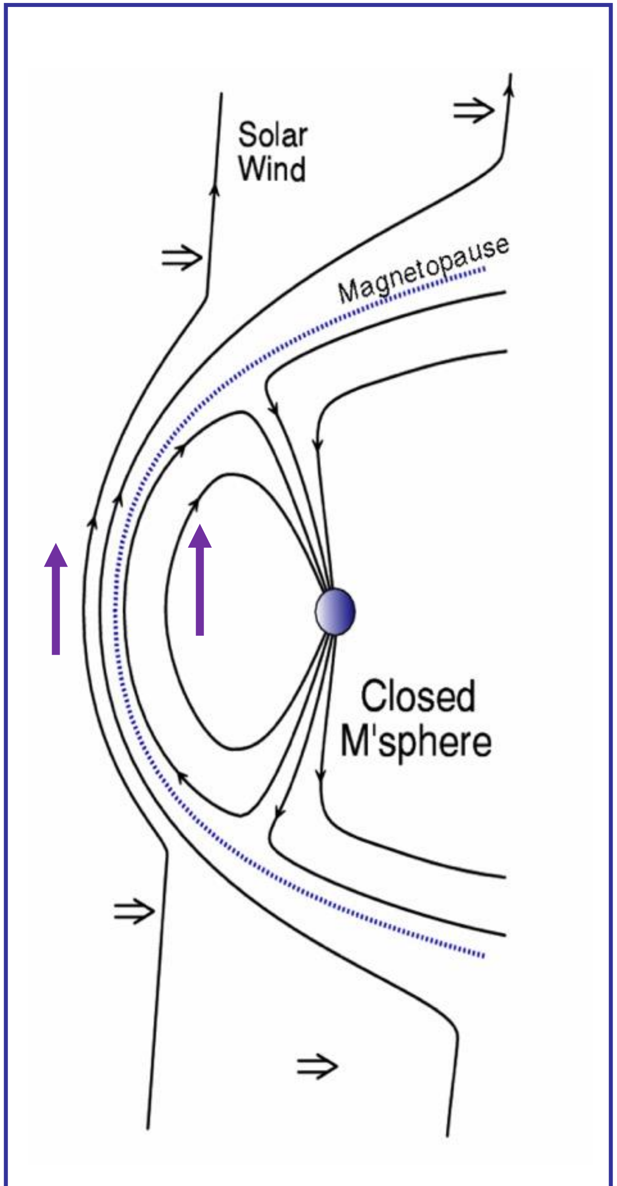
Earth





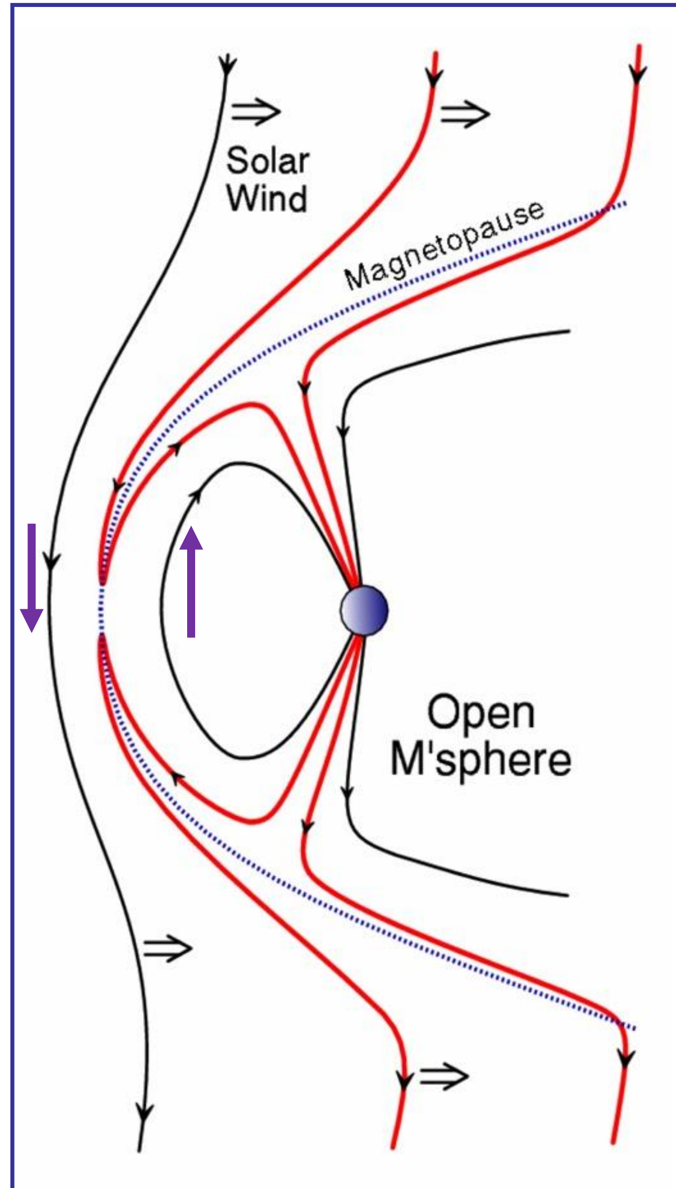
* Reconnection-Driven Global Circulation

Open Magnetosphere



Now flip Interplanetary Magnetic Field direction

Reconnection

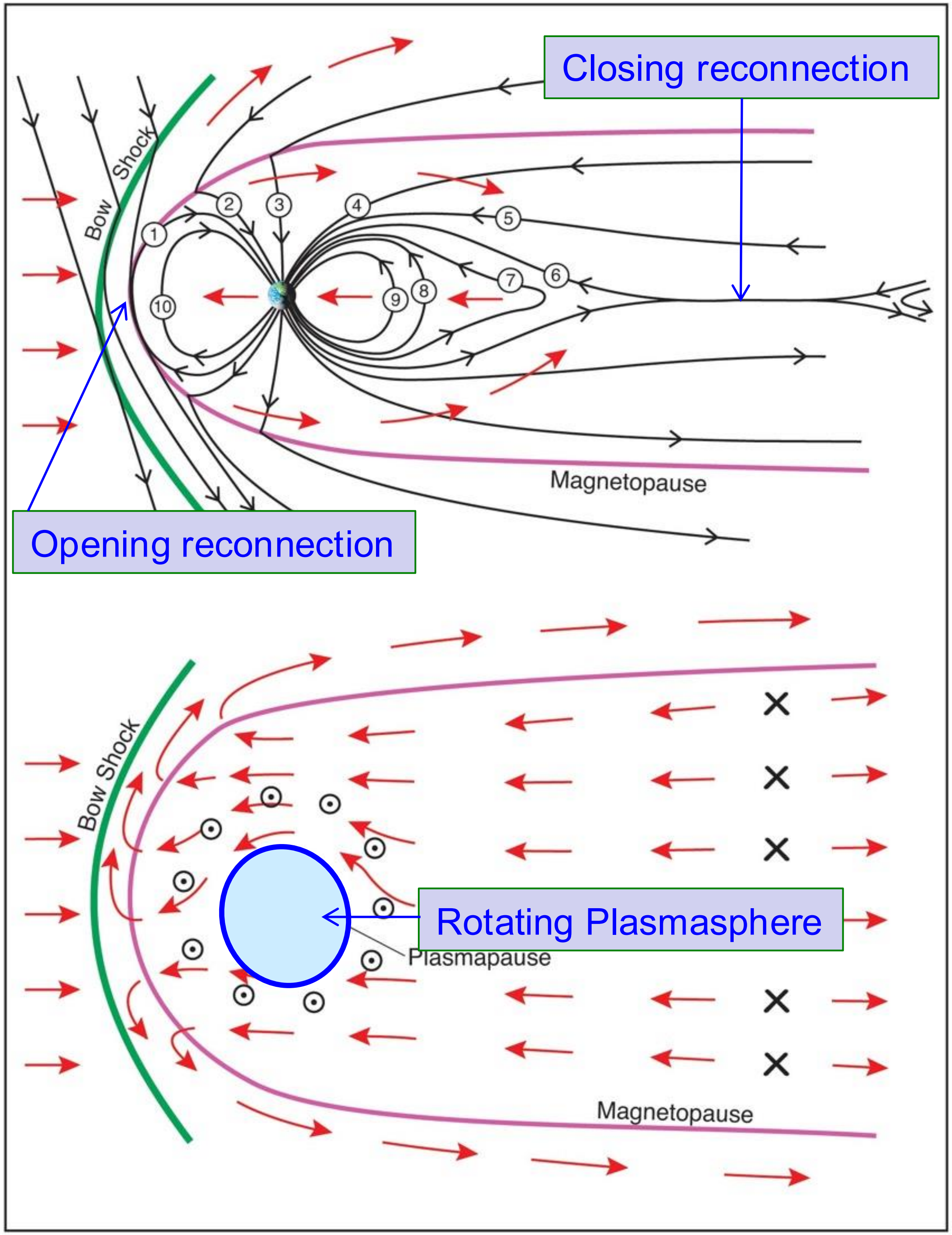


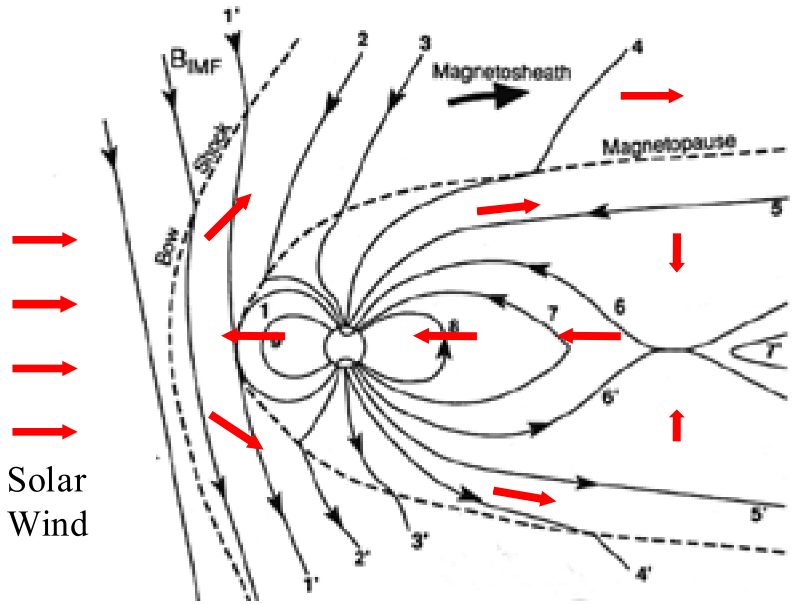
Dungey Cycle

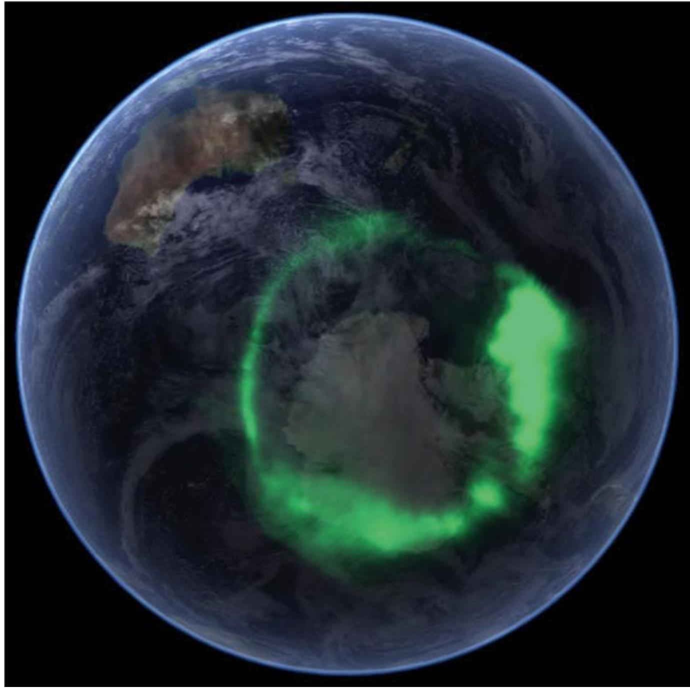
Dynamics at Earth driven by the solar wind coupling the Sun's magnetic field to the Earth's field

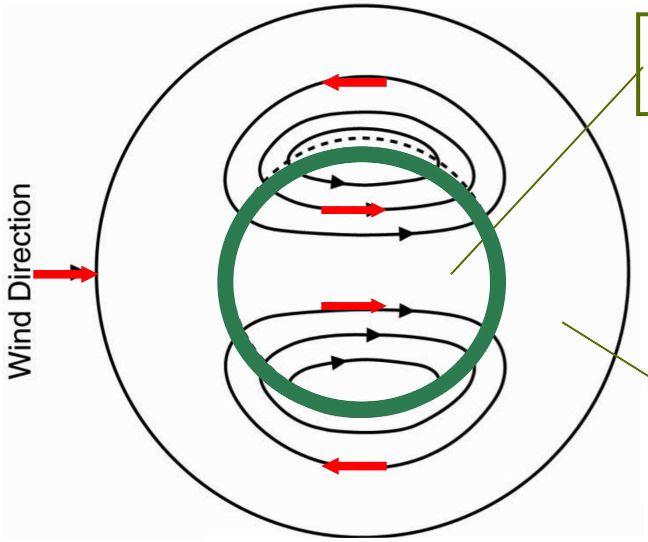
- Variable opening & closing rates
- Must be equal over time to conserve magnetic flux

Plasmapause = boundary between corotation and convection





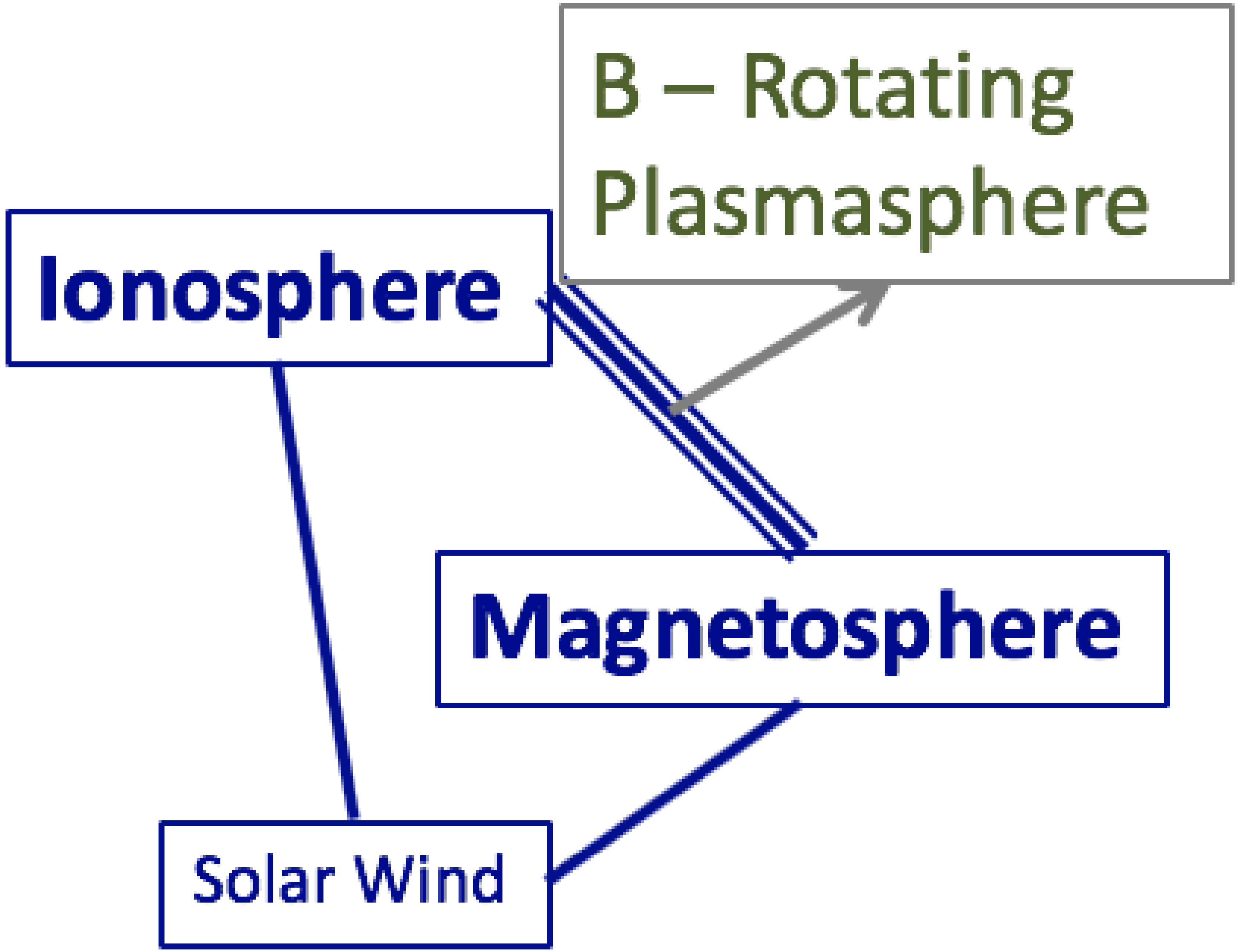




Connected to solar wind

Closed magnetic field

Polar view


B – Rotating Plasmasphere
Ionosphere
Magnetosphere
Solar Wind

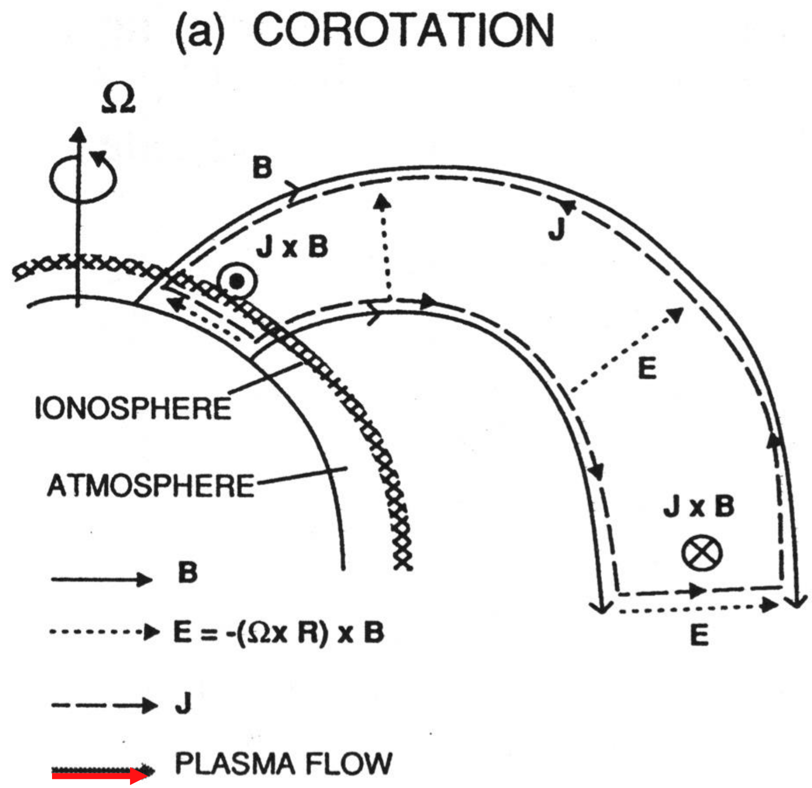
$$\mathbf{V}_{co} \sim \mathbf{\Omega} \times \mathbf{R}$$

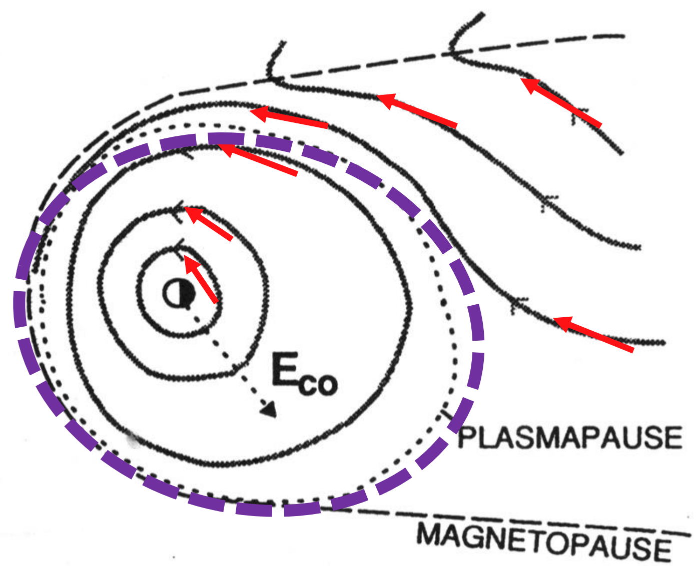
$$\mathbf{V}_{convection}$$

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

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

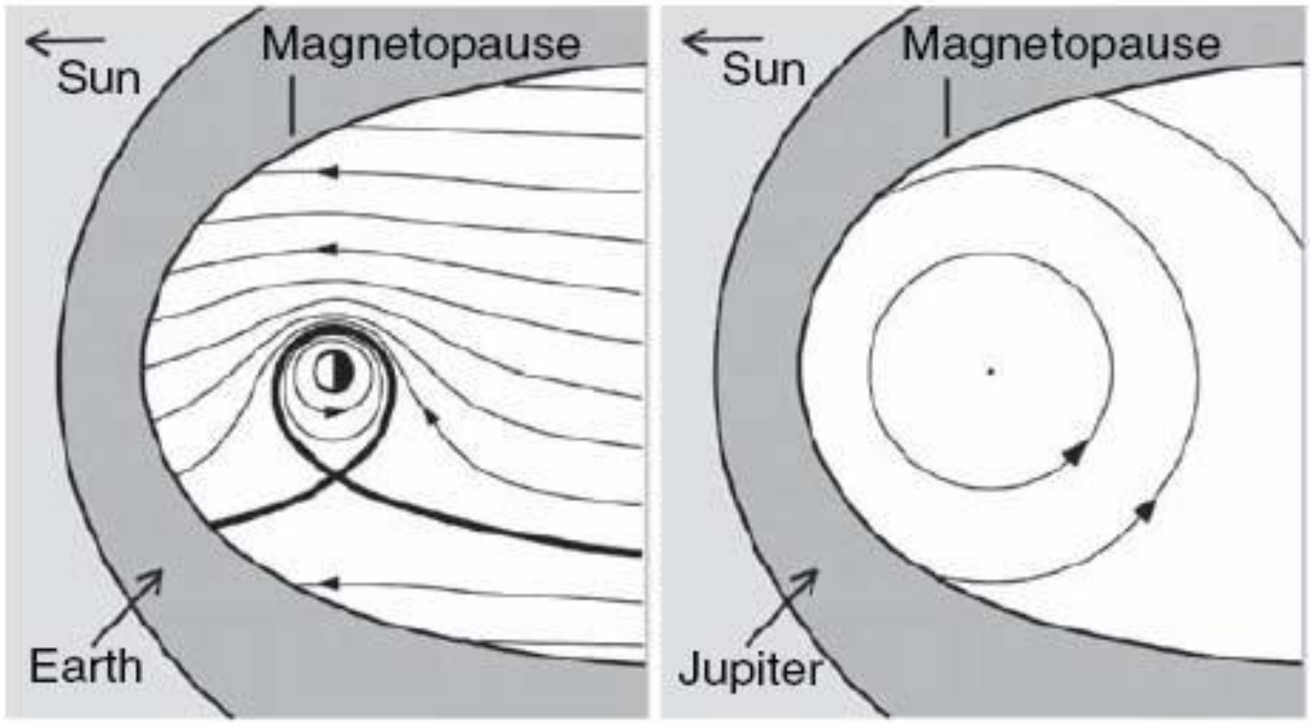
- increases with planetary spin
- increases with field strength
- decreases with solar wind strength





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

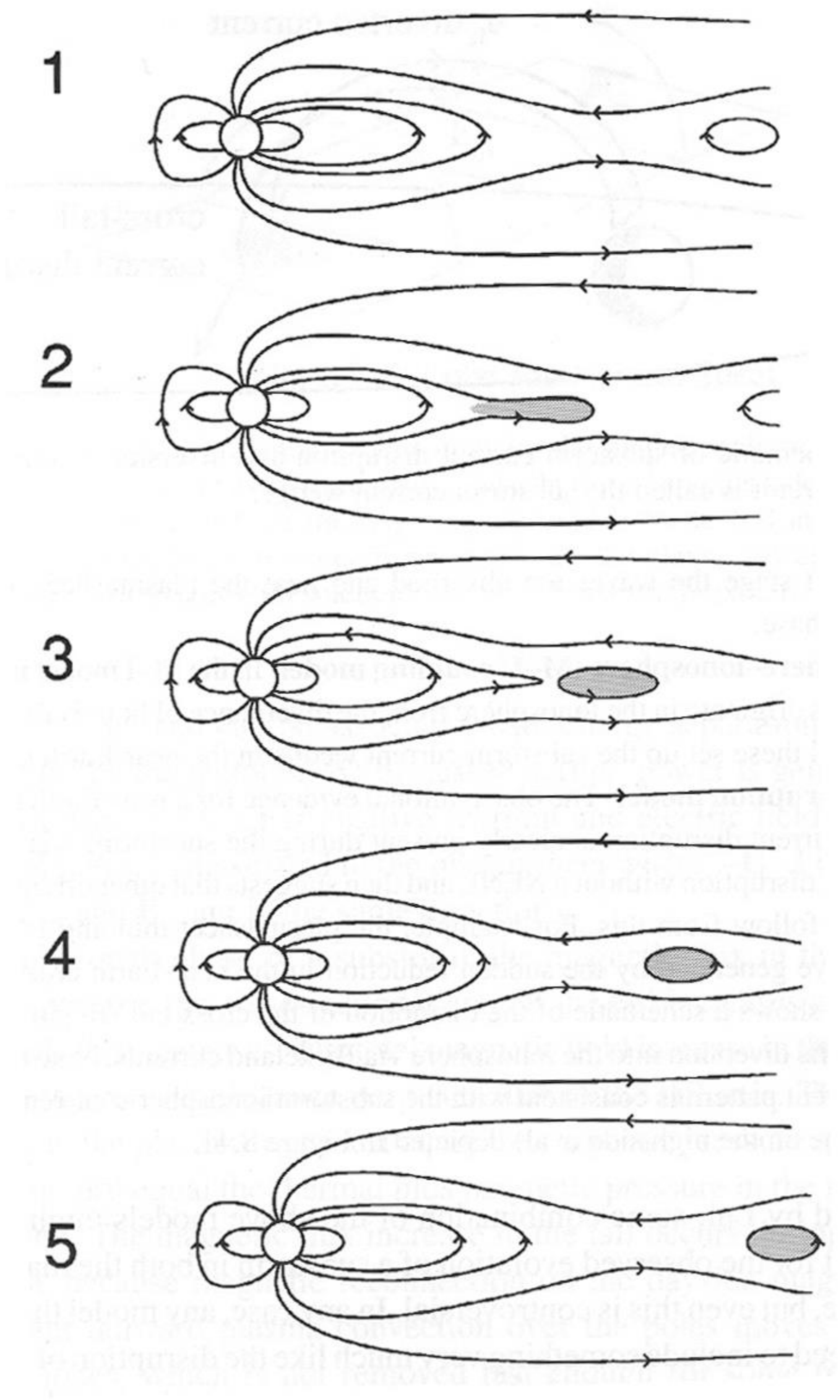
Dayside magnetopause

• Response to B_{SW} direction

• Solar wind ram pressure

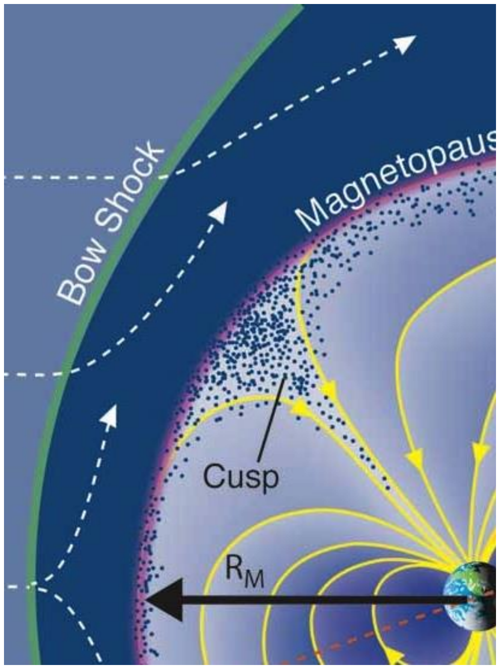
Tail Reconnection

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



Earth vs. *Jupiter*

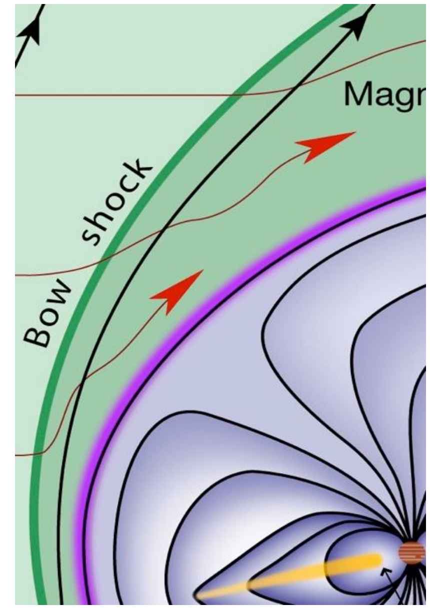
Calculate Transit Time



Time for Solar Wind to Flow Nose-Terminator

$V_{solar\ wind}$

~ 400 km/s



MP~10 R_E

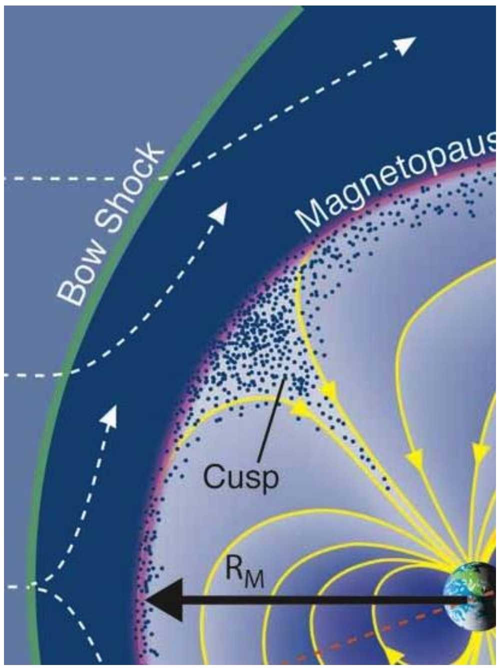
1 R_E~6400 km

MP~100 R_J

1 R_J~72000 km

Earth *vs.* *Jupiter*

$10\ R_E$ <3 minutes



Bob McPherron
Margy Kivelson

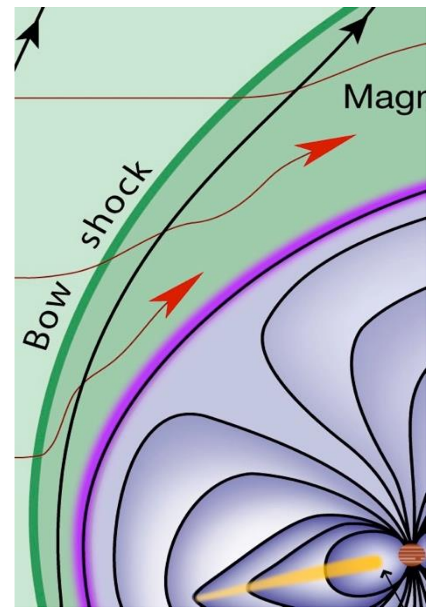
Time for Solar Wind to Flow Nose-Terminator

$V_{solar\ wind}$

~ 400 km/s

$100\ R_J$

~ 5 hours

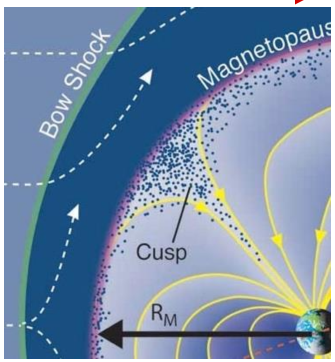


McComas & Bagenal 2007

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

Earth vs. *Jupiter*

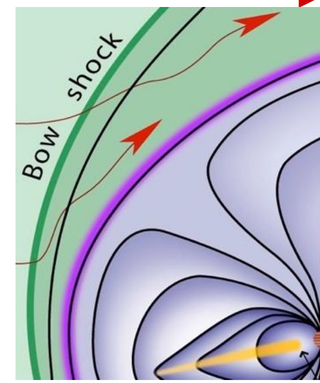
10 R_E <3 minutes



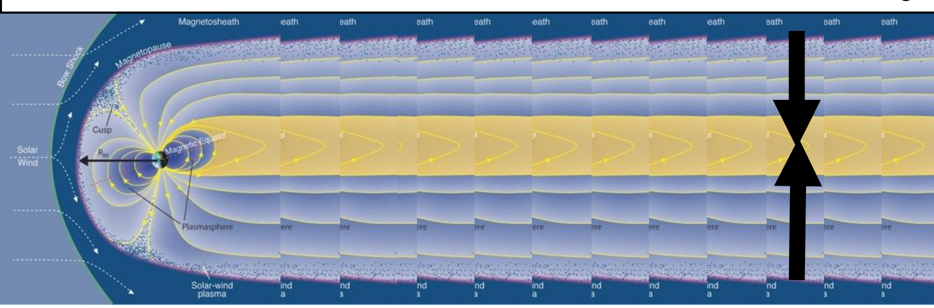
Time for Solar Wind to Flow Nose-Terminator

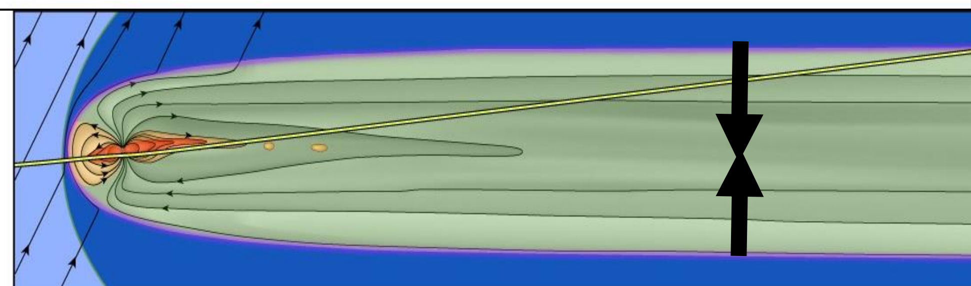
$V_{solar\ wind}$ ~ 400 km/s

100 R_J ~ 5 hours



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





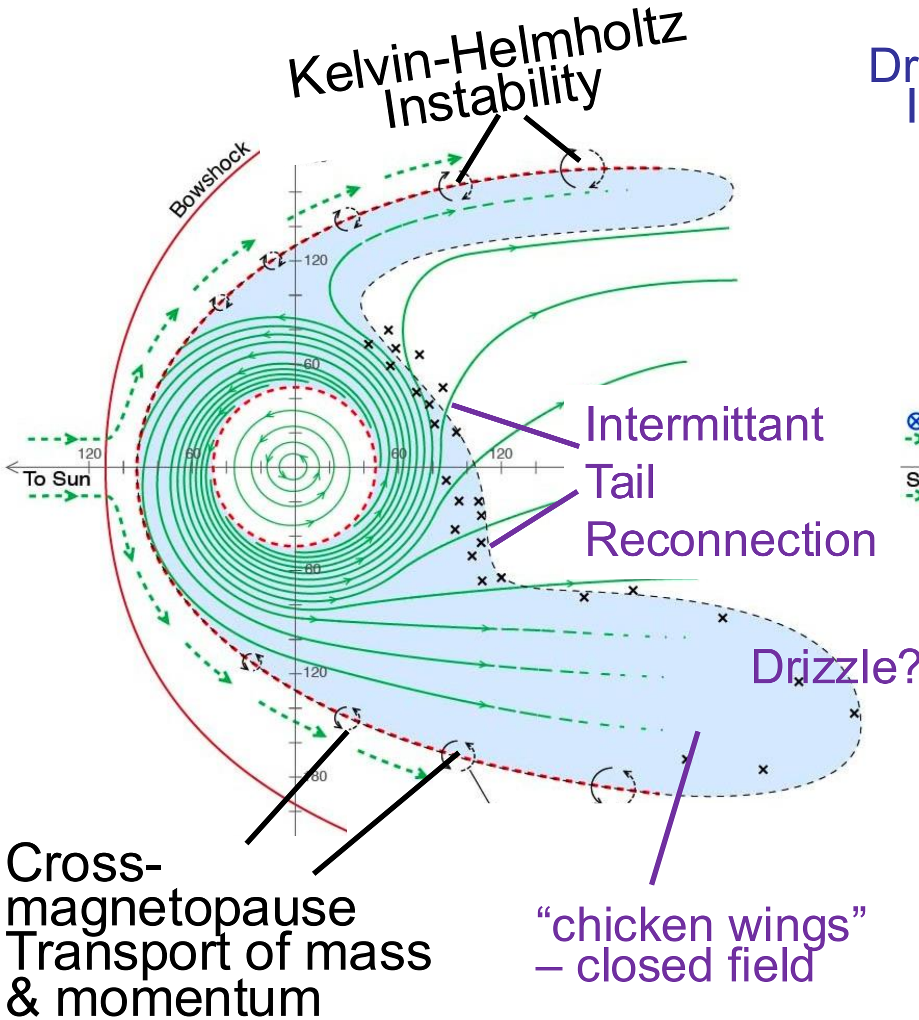
15 R_E ÷ 40 km/s

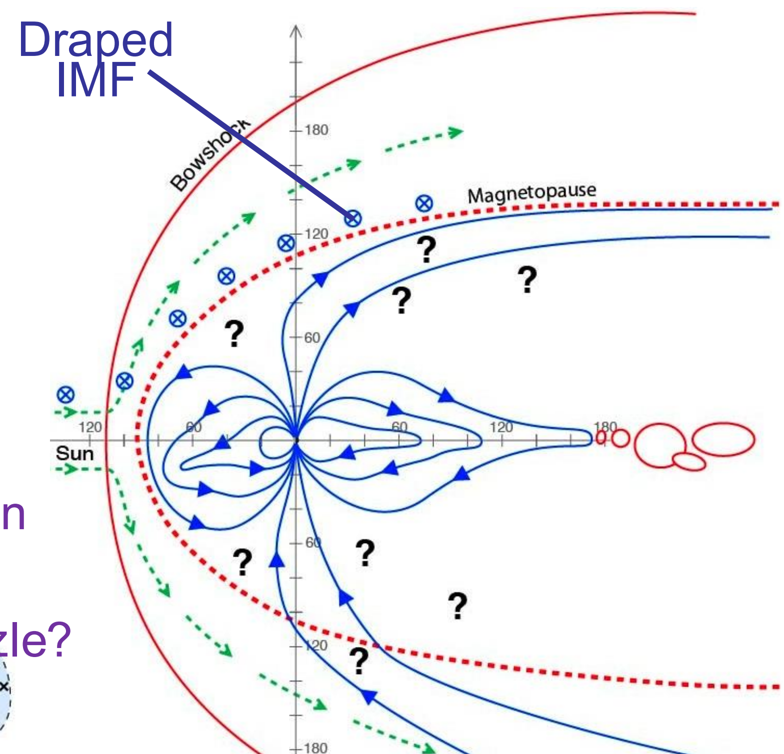
= **40 mins**

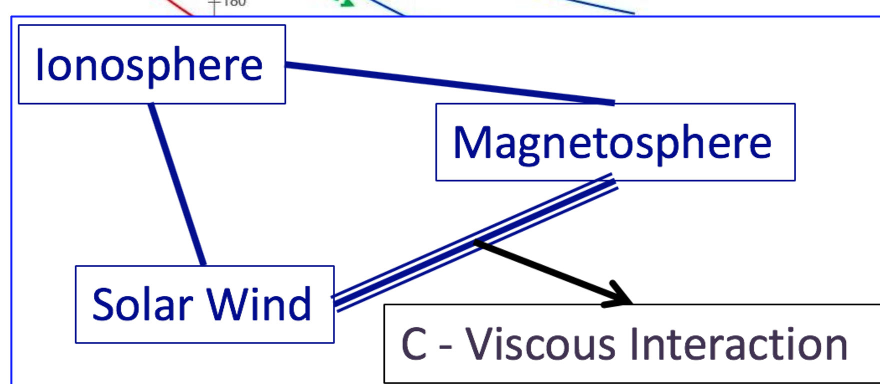
150-200 R_J ÷ 40 km/s

= **75-100 hours**

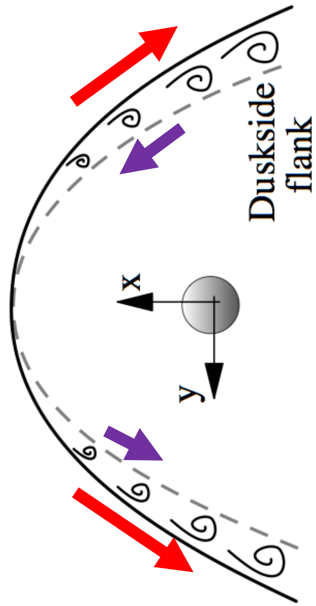
Delamere & Bagenal 2013
Masters 2017

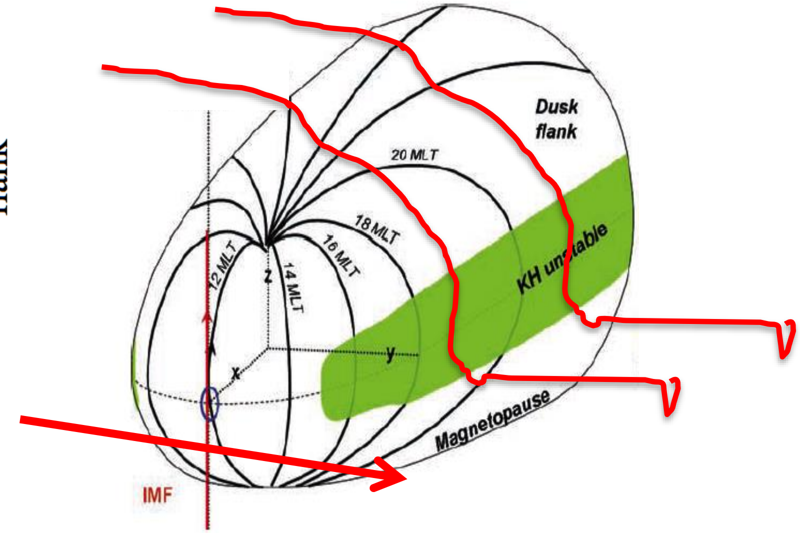


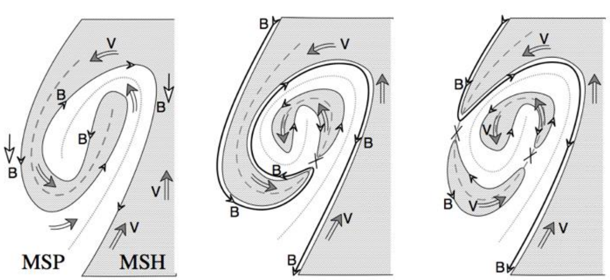


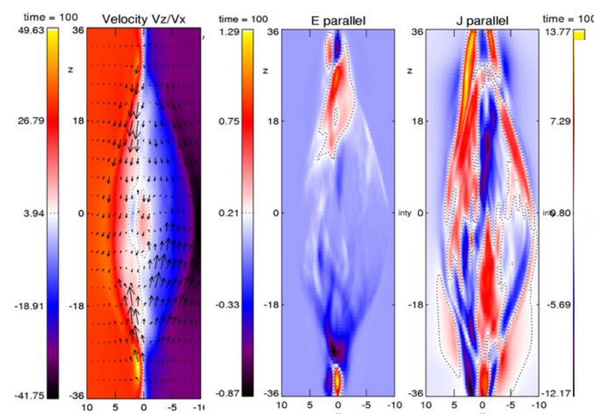


- Not open Dungey cycle
- Viscous interaction
- Shear instabilities
- Small-scale, intermittant reconnection
- Boundary layers

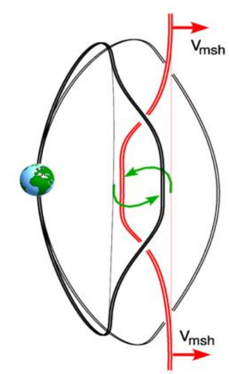








“Candy wrapper”

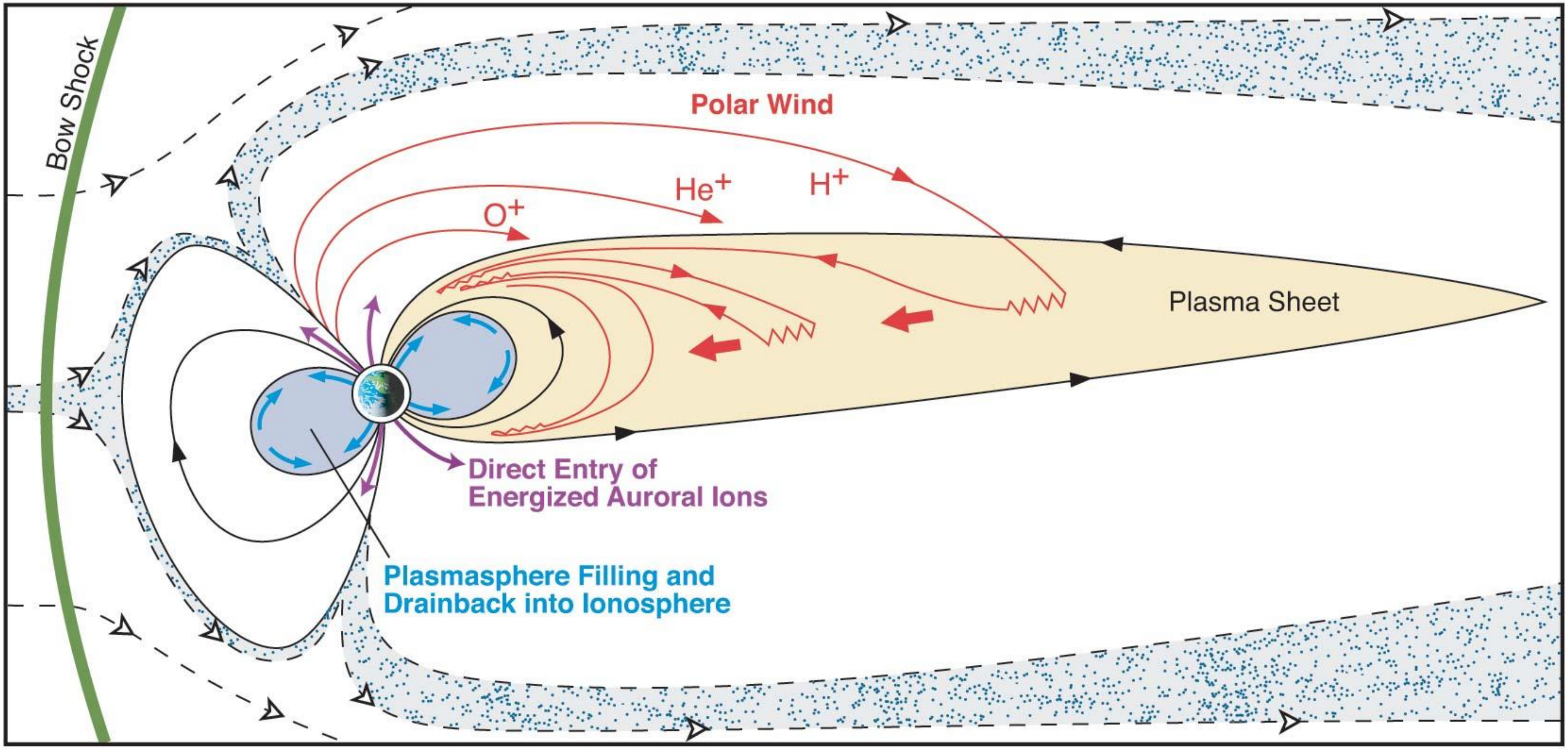


Plasma Sources

Plasma Sources

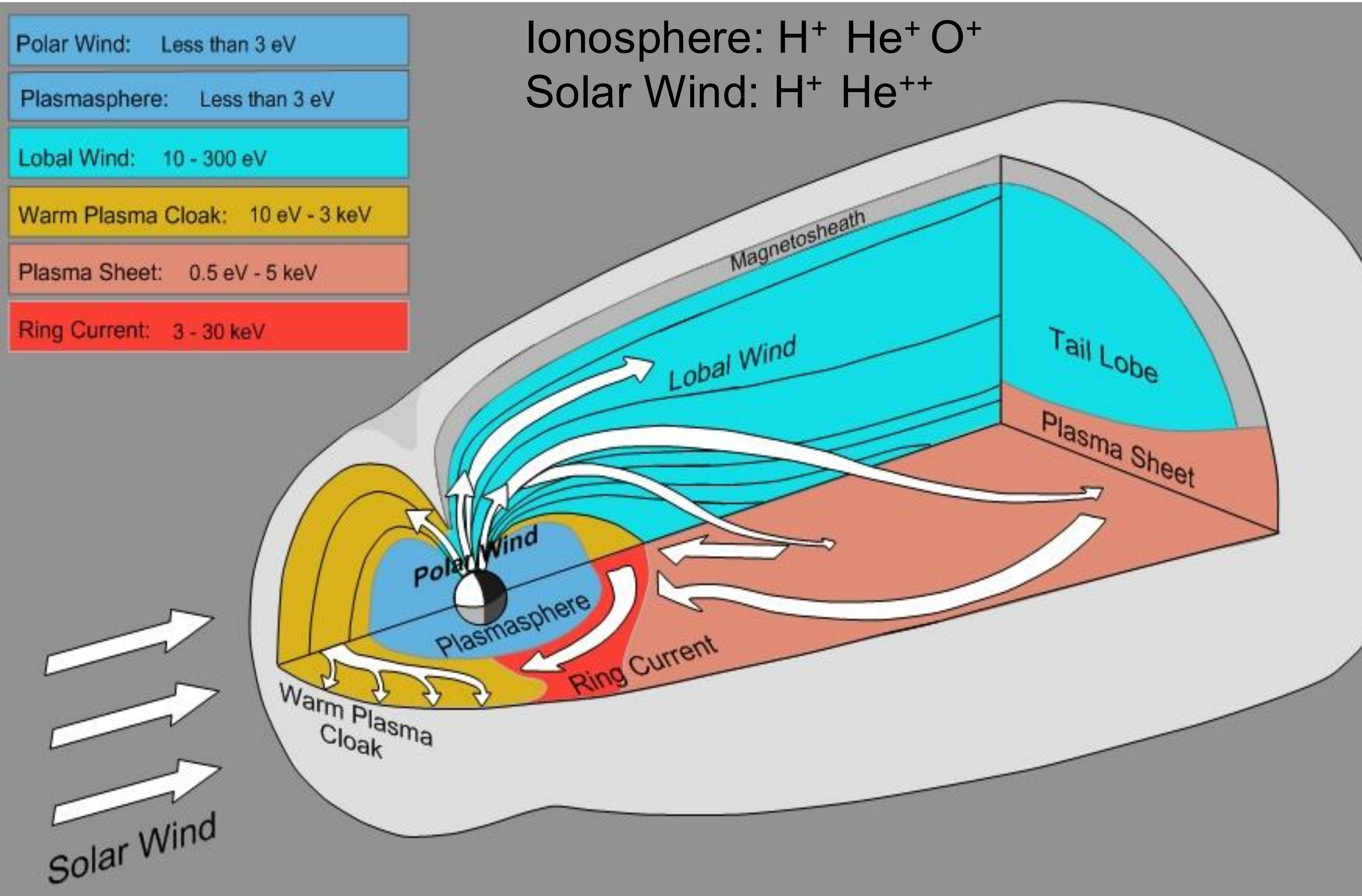
	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
N_{max} cm^{-3}	~1	1-4000	>3000	~100	~3	~2
Composition	H^+ Solar Wind	O^+ H^+ Iono-sphere	O^{n+} S^{n+} Io	O^+ H_2O^+ H^+ Enceladus	H^+ Iono-sphere	H^+ N^+ Triton Iono-sphere
Source kg / s	?	5	700-1200	70-200	~0.02	~0.2

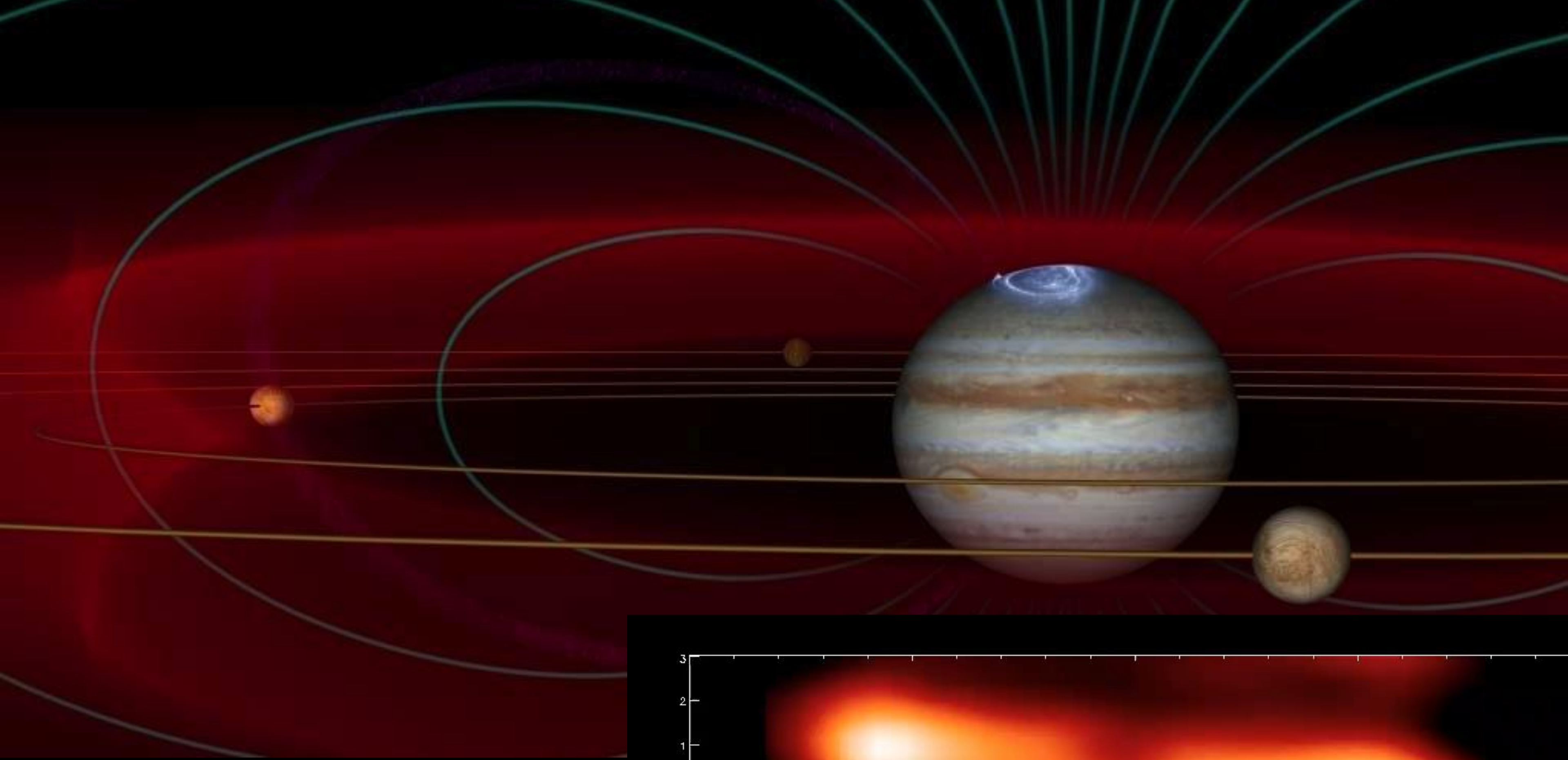
Earth Sources of Plasma (5 kg/s): Solar Wind + ionosphere mixed (over the poles) into magnetotail and convected sunward

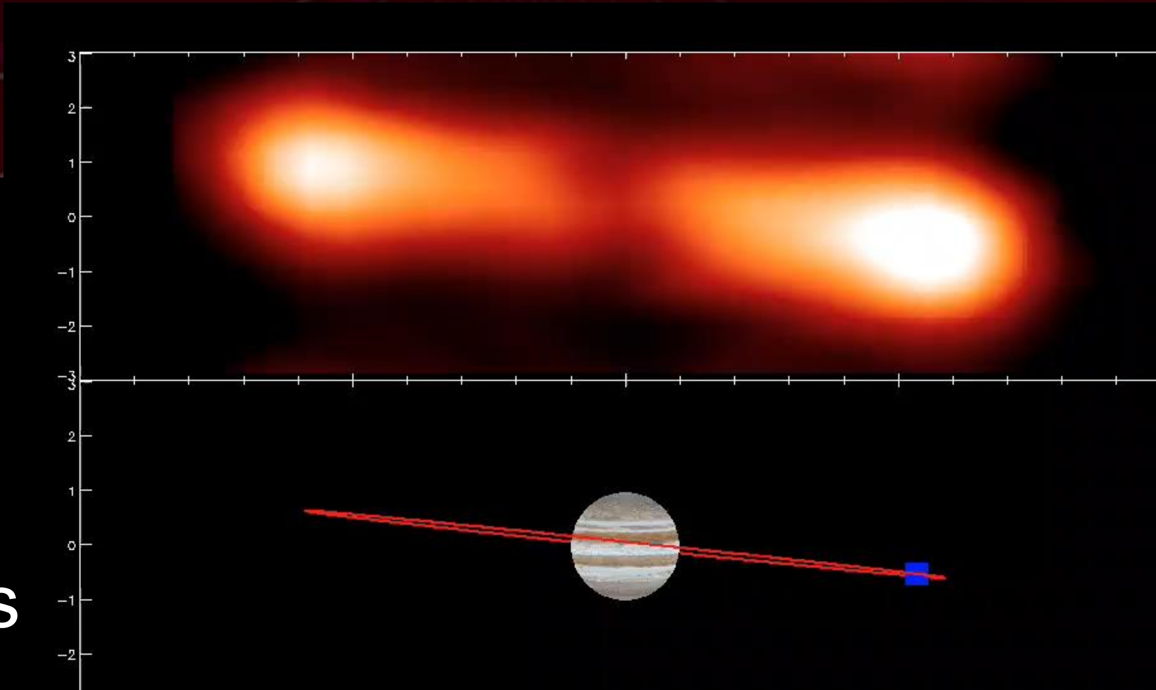


Earth Plasma Flux 5 kg/s

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





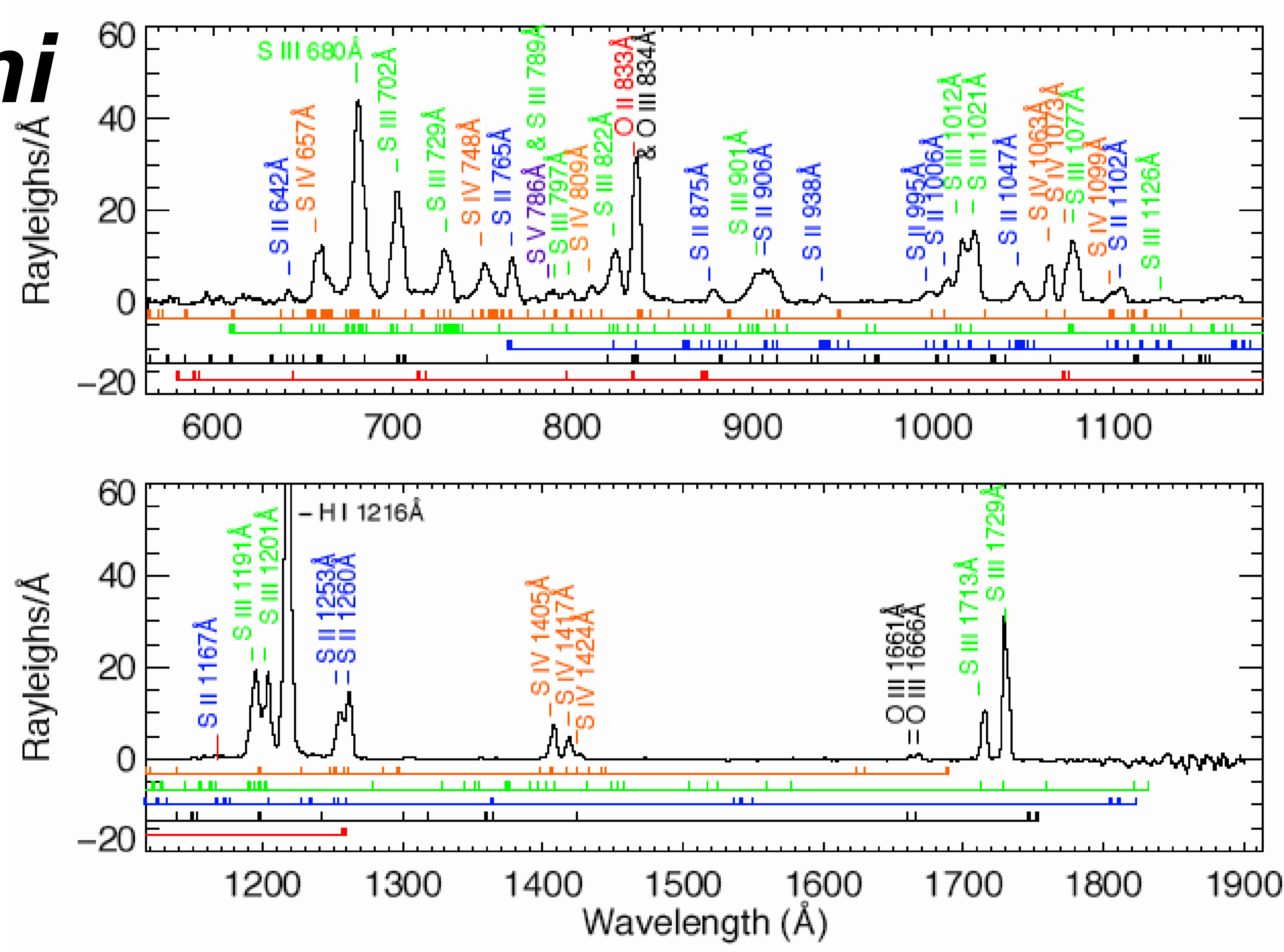


Io Plasma torus

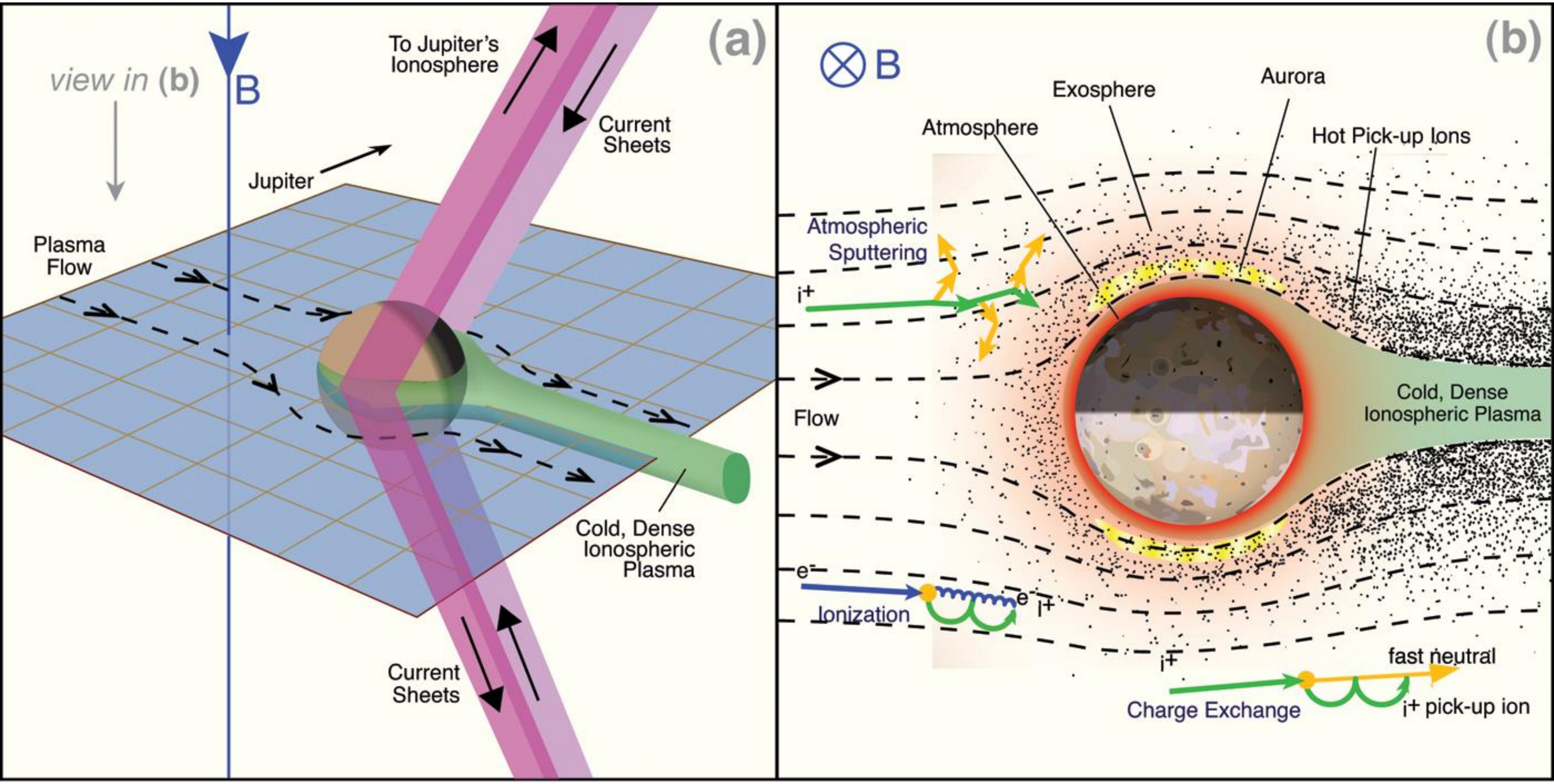
- Total mass 2 Mton
- Source 1 ton/s
- Replaced in 50 days

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



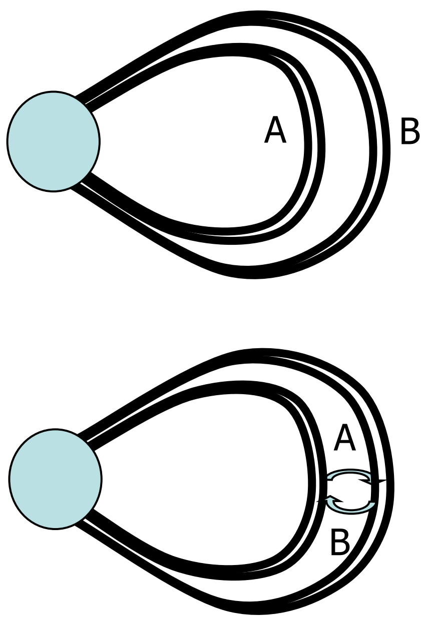
- Strong electrodynamic interaction
- Mega-amp currents between Io and Jupiter

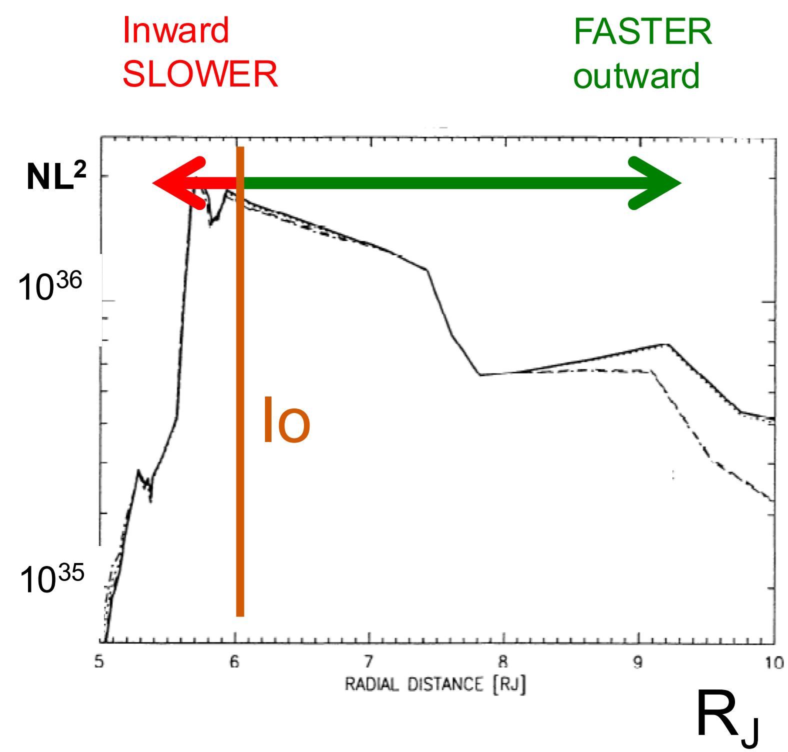
- Plasma interaction with Io's atmosphere
- Heated atmosphere escapes
- ~20% plasma source local

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 $\beta \ll 1$



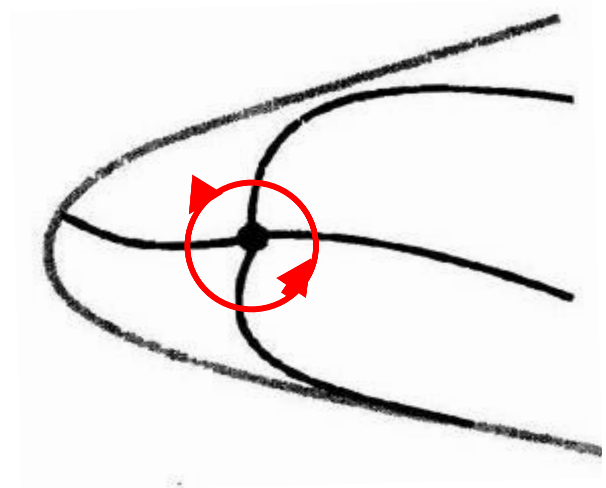


Margy Kivelson

Bagenal 1994

Coupling the Plasma to the Flywheel

Khurana 2001

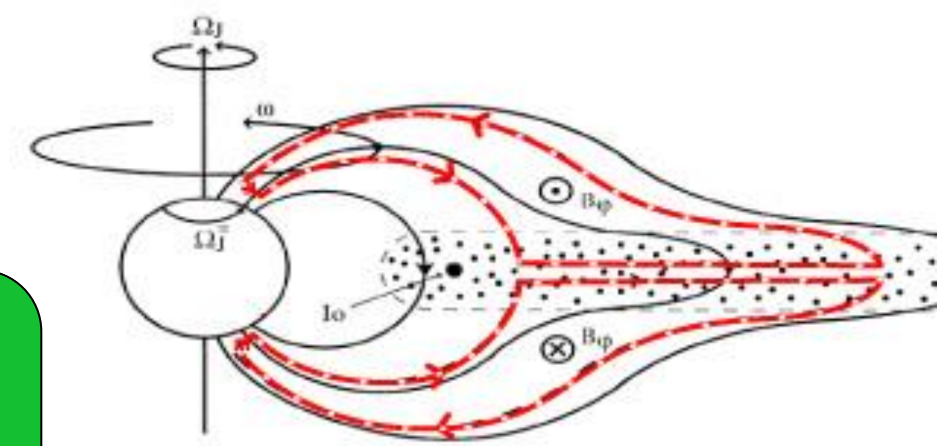


- As plasma from Io moves outwards its rotation decreases (conservation of angular momentum)

- Sub-corotating plasma pulls back the magnetic field

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

- J_r x **B** force enforces rotation

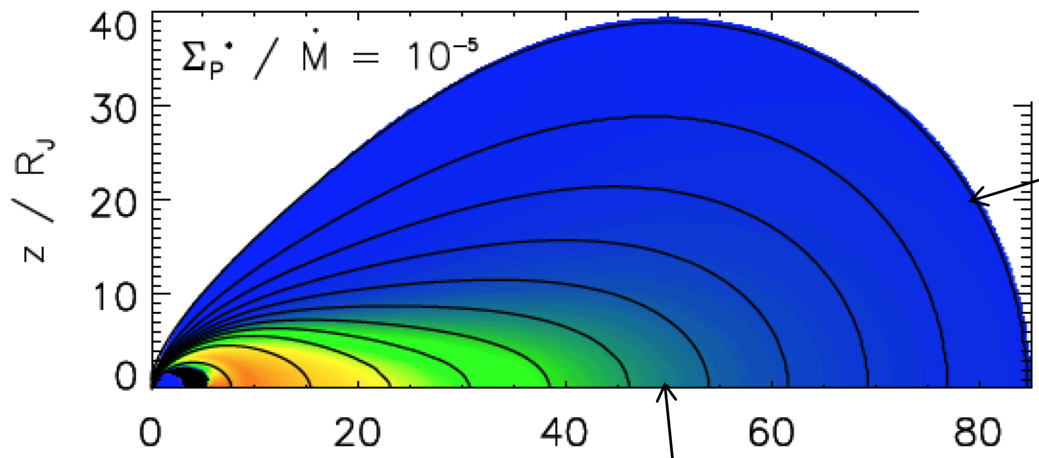


Field-aligned currents couple magnetosphere to Jupiter's rotation

Cowley & Bunce 2001

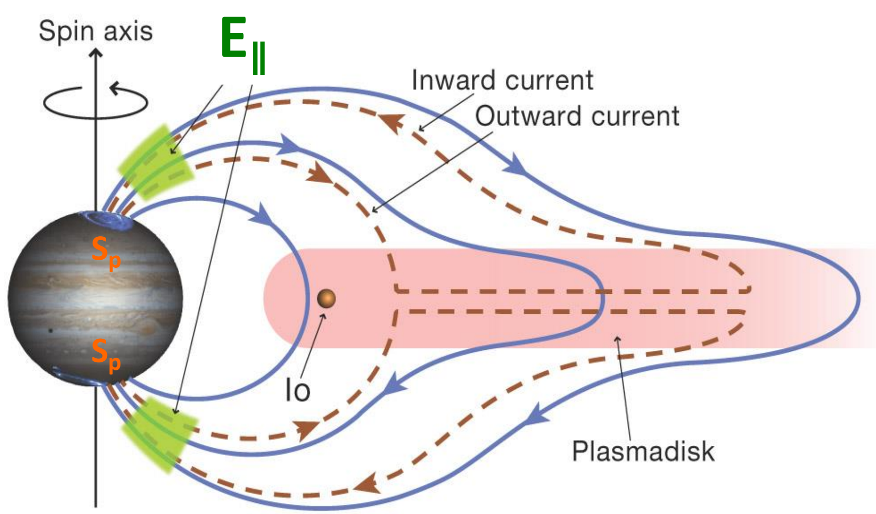
How is information transmitted along magnetic field lines?

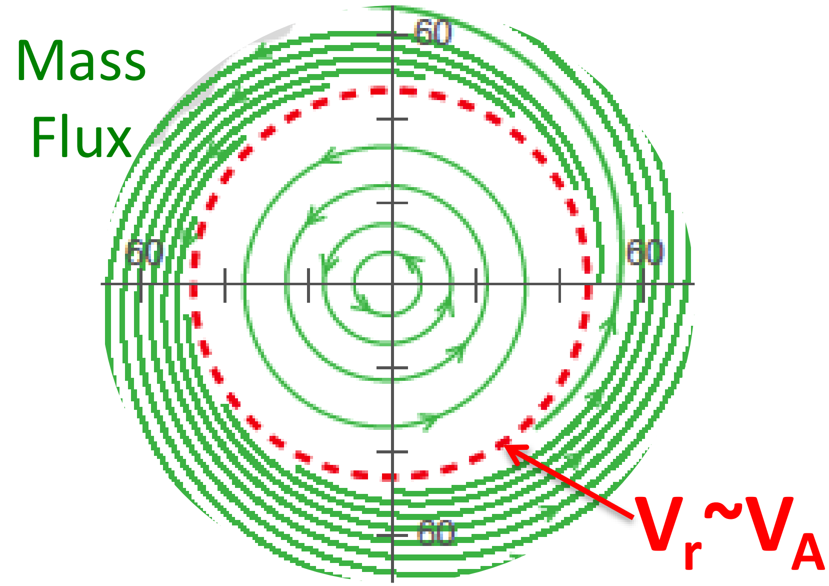
How is a stress from the outside communicated to the planet?



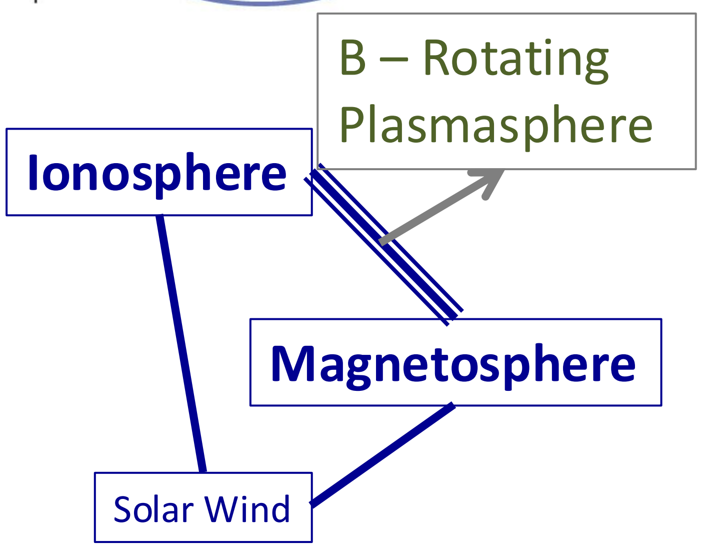
How does a blob of plasma here communicate with the planet?

Alfven waves!





Alfven Radius



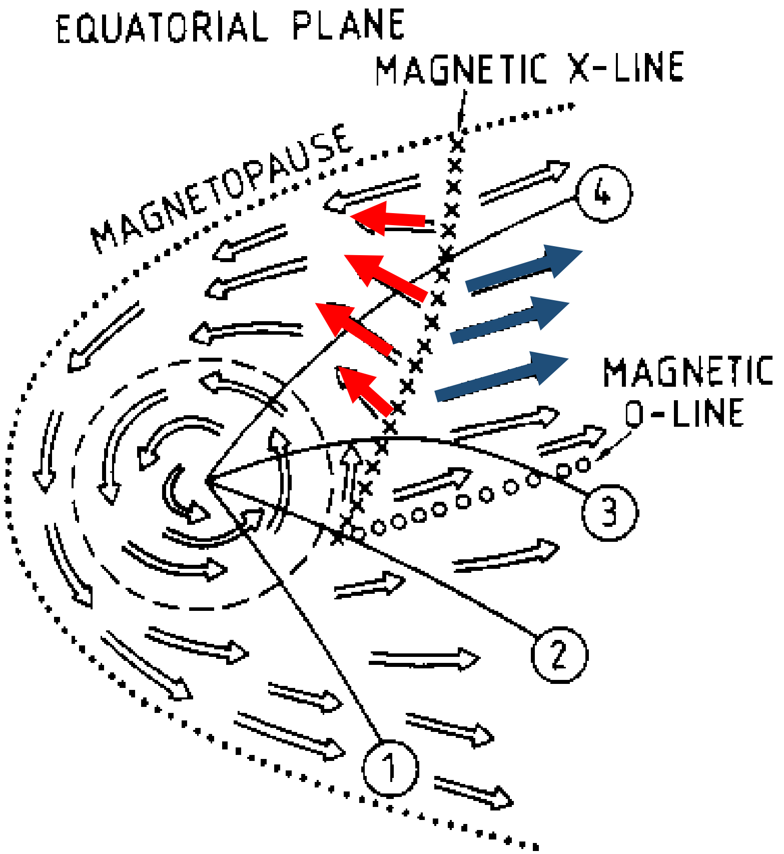
Radial Transport

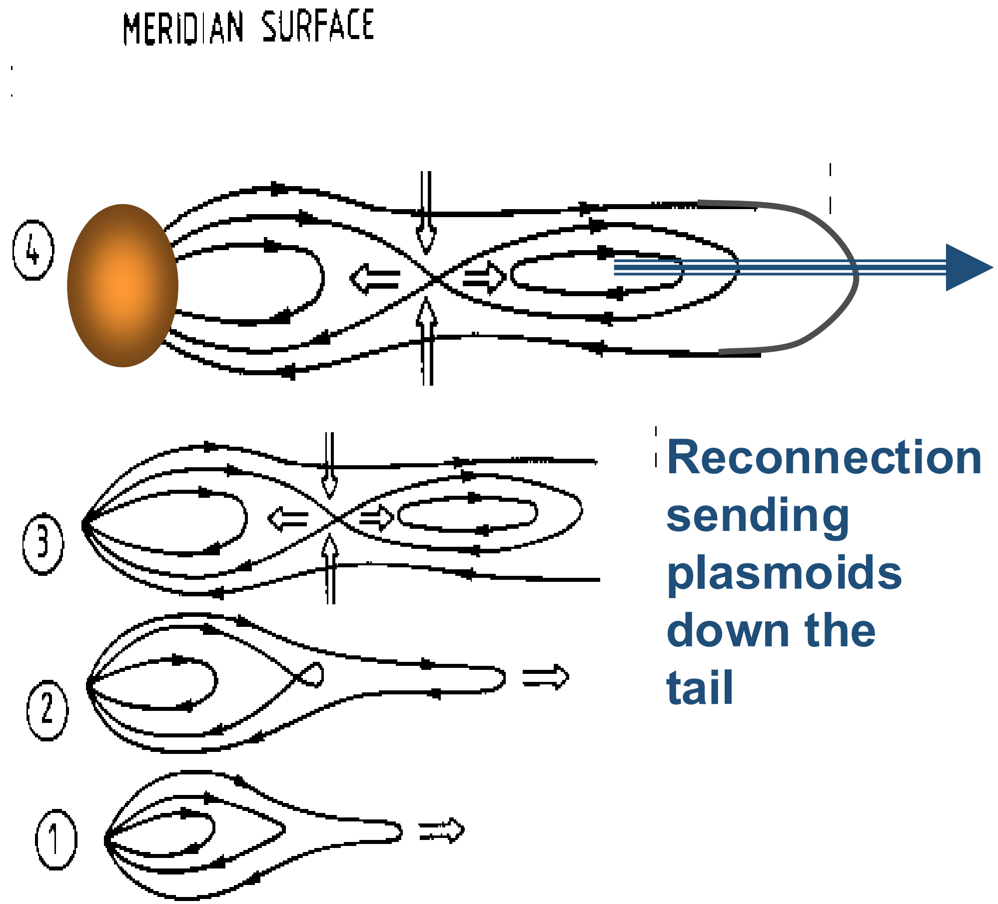
- Fluxtube interchange
- Mass flux out
- Empty magnetic flux in
- **Decoupling**

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

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

Vasyliunas Cycle
driven by centrifugal forces





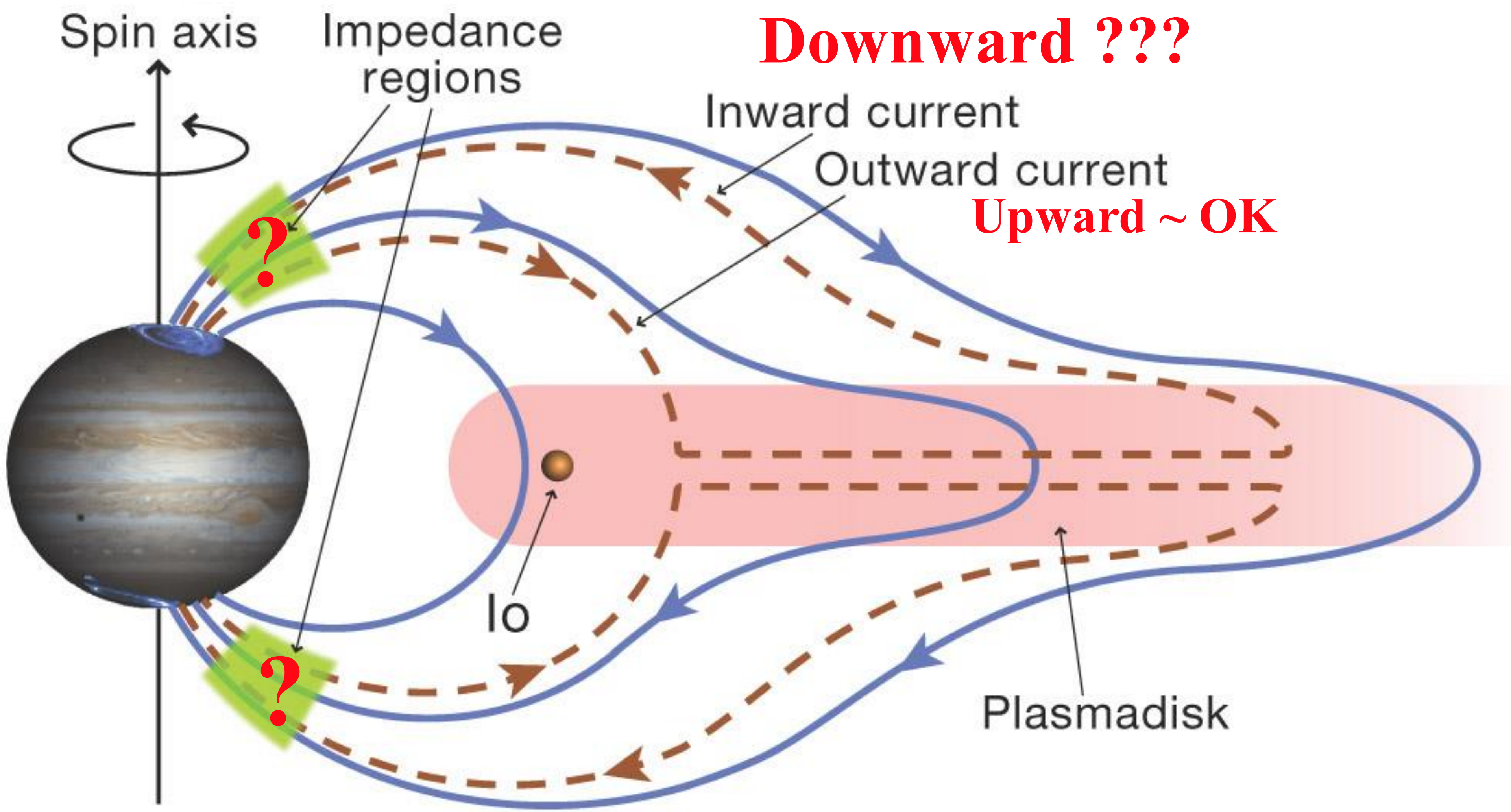
Reconnection sending plasmoids down the tail

Inward Injection **Plasmoid Ejection**

Vasyliunas
Cowley et al.
Southwood & Kivelson

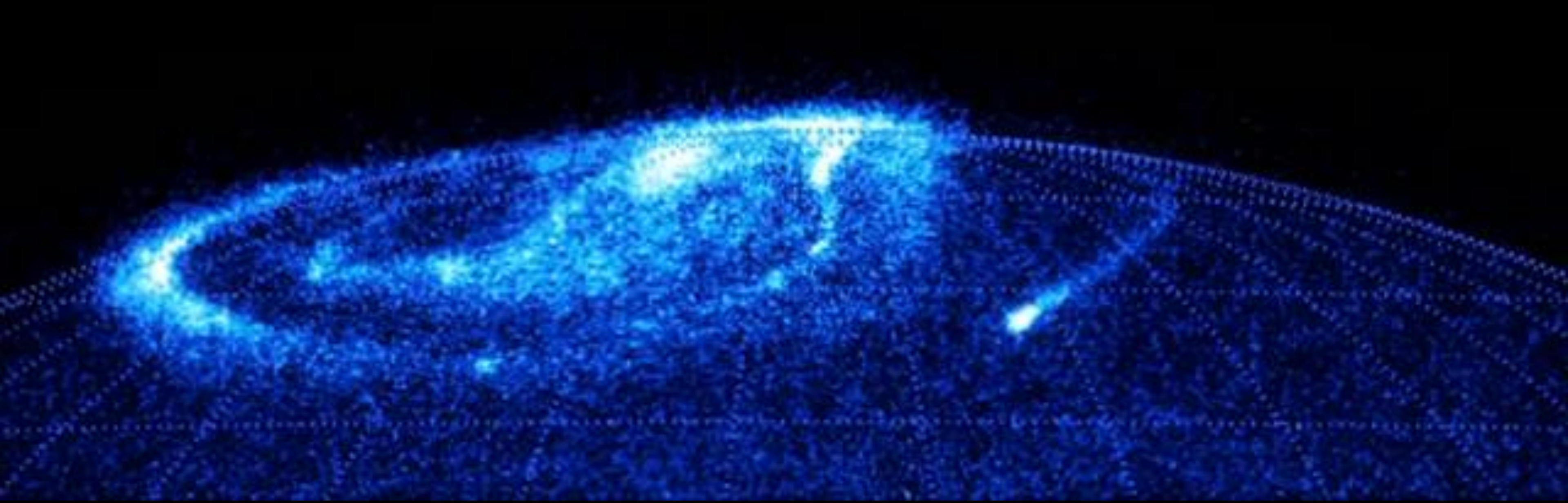
Aurora

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

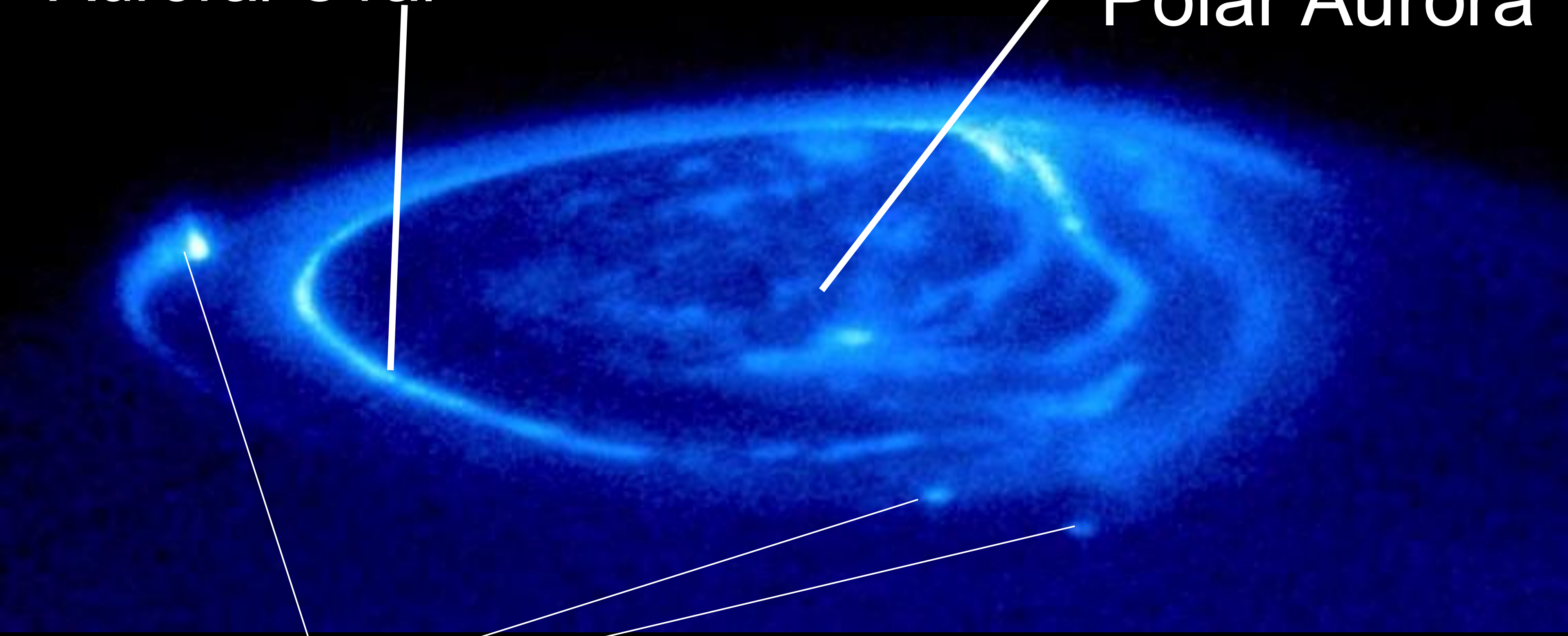


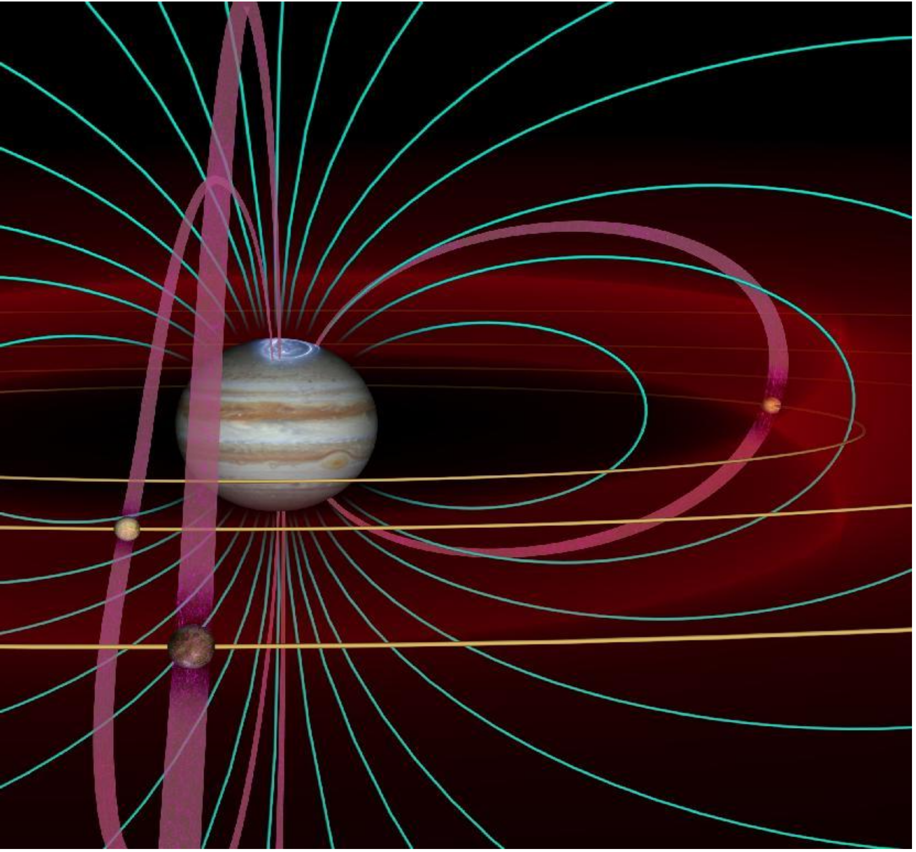
Parallel electric fields: potential layers, $\phi_{||}$, "double layers"

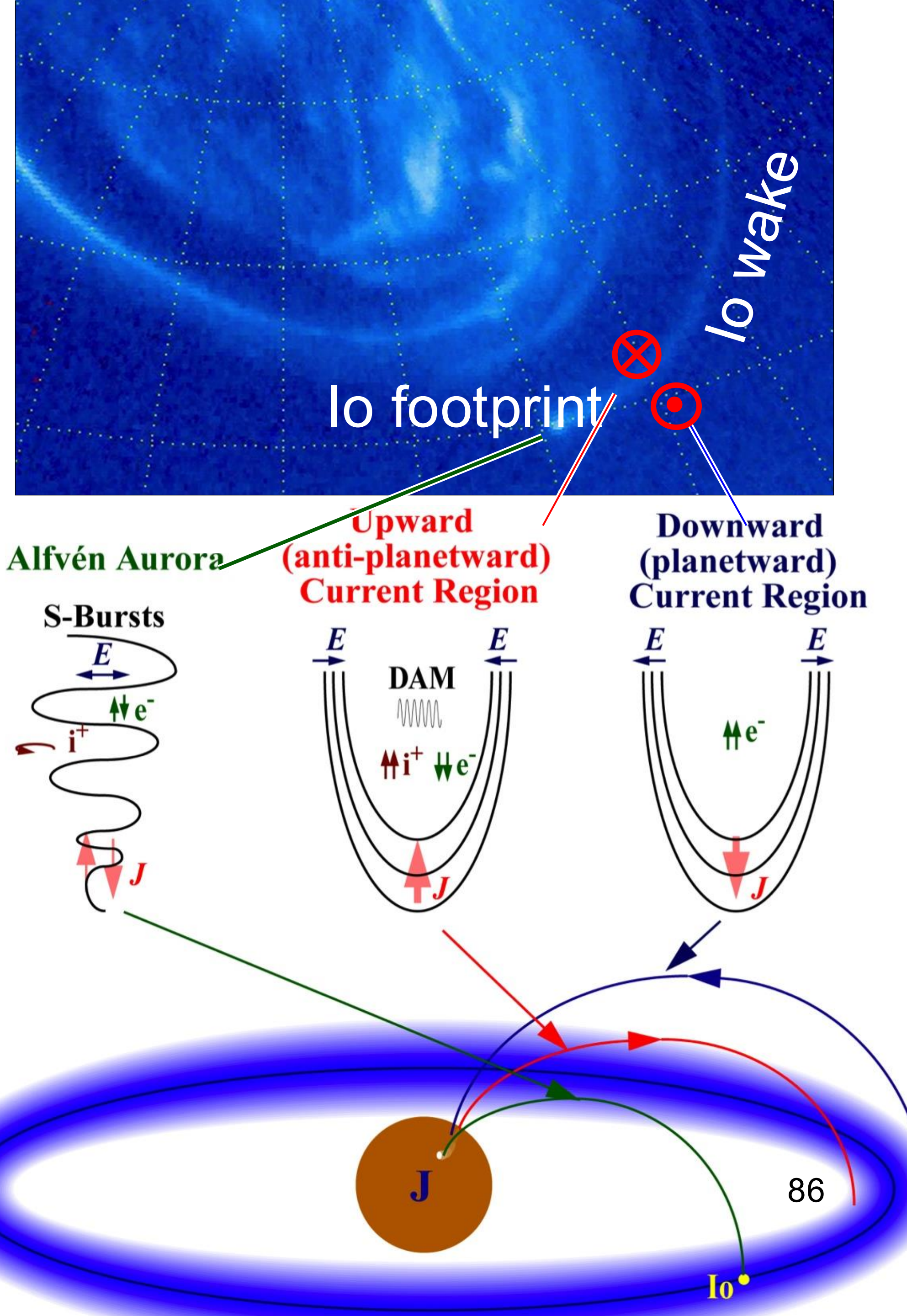
Hubble Space Telescope – *Jon Nichols*



Jupiter's 3 Types of Aurora







Satellite auroral emissions

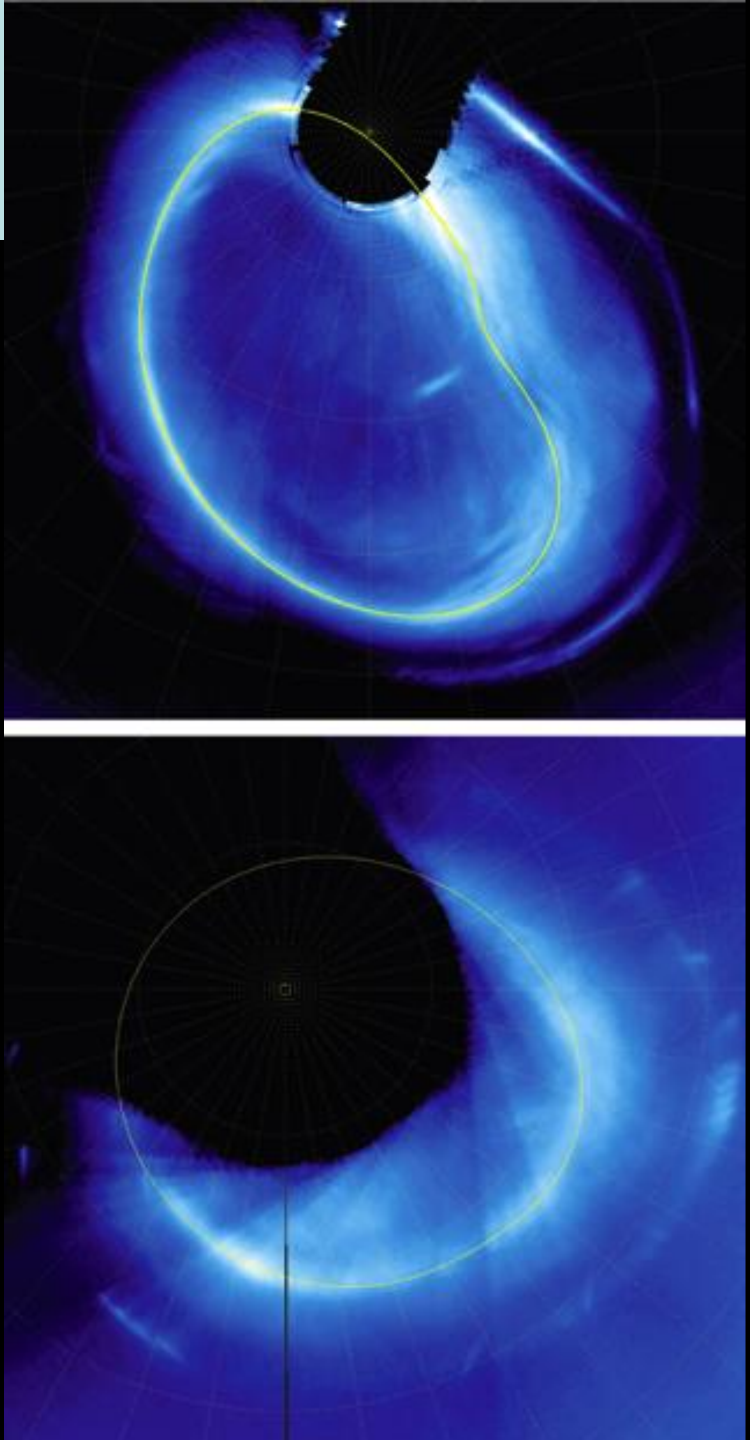
- Plasma-moon electrodynamic interaction
- Mega-amp current systems
- Analogous to Earth auroral processes

Papers by Su, Ergun, Lysak, Hess, Bonfond

Main Aurora

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

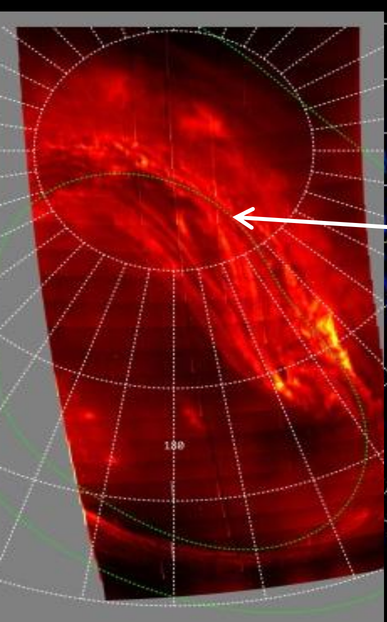
Clarke et al., Grodent et al. HST



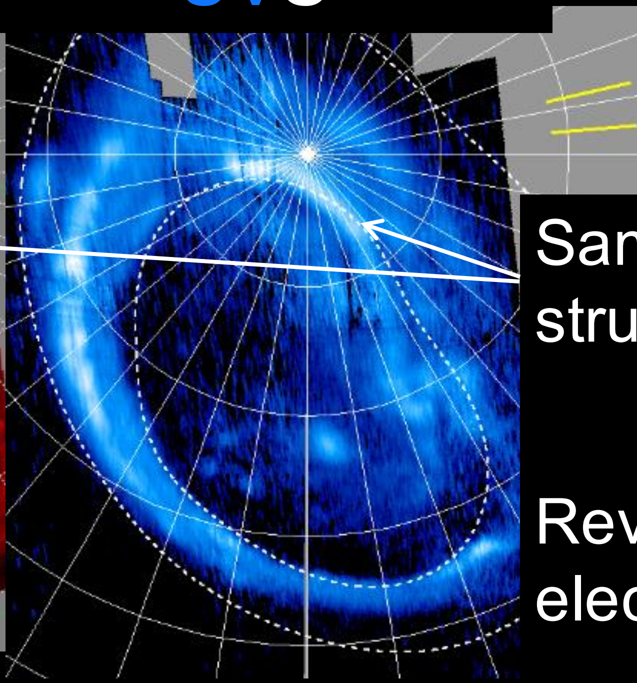
Jupiter's Aurora: Structured & Dynamic

Juno UVS

JIRAM



UVS

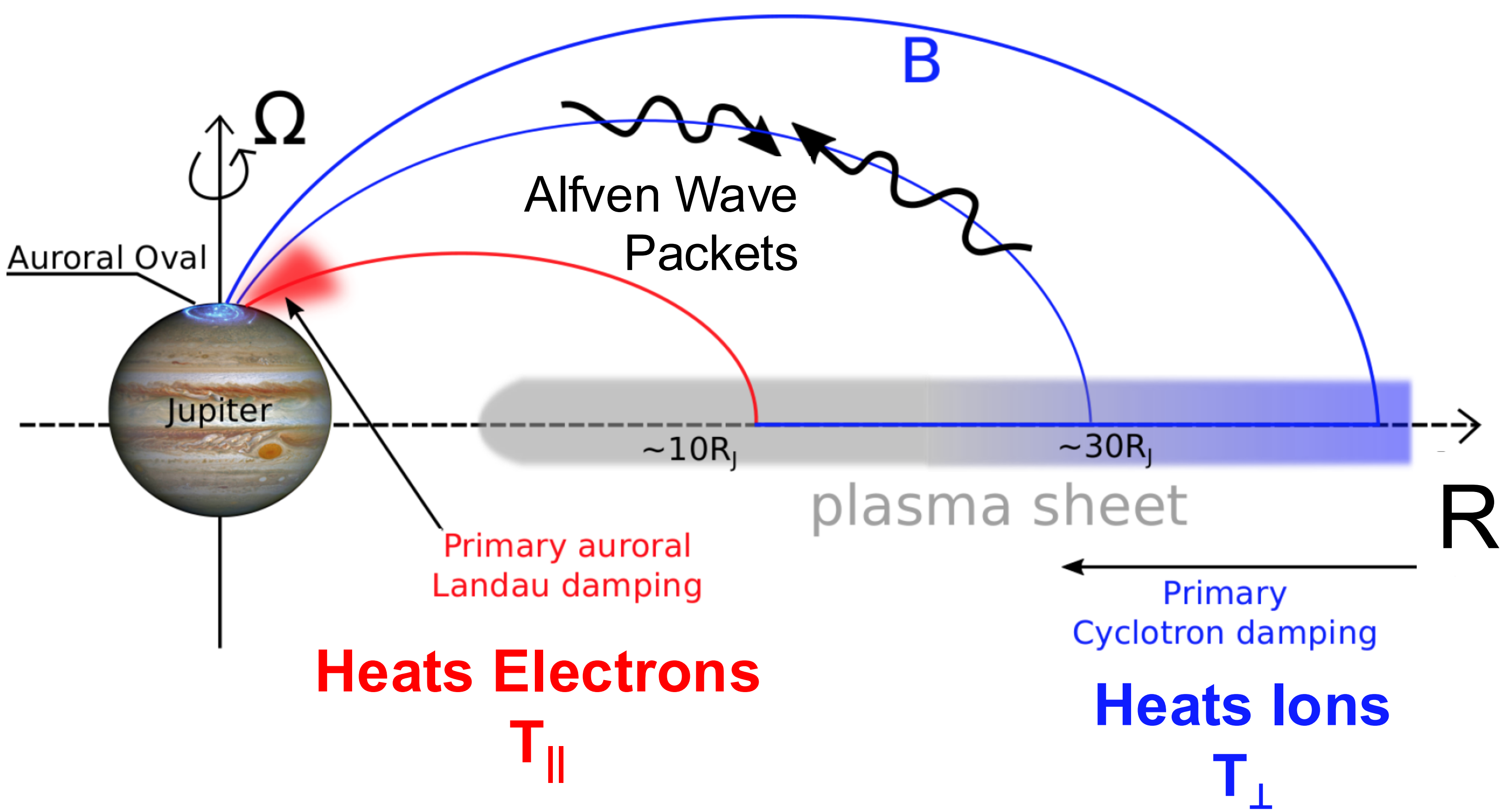


Same region – very different structure in UV vs. IR

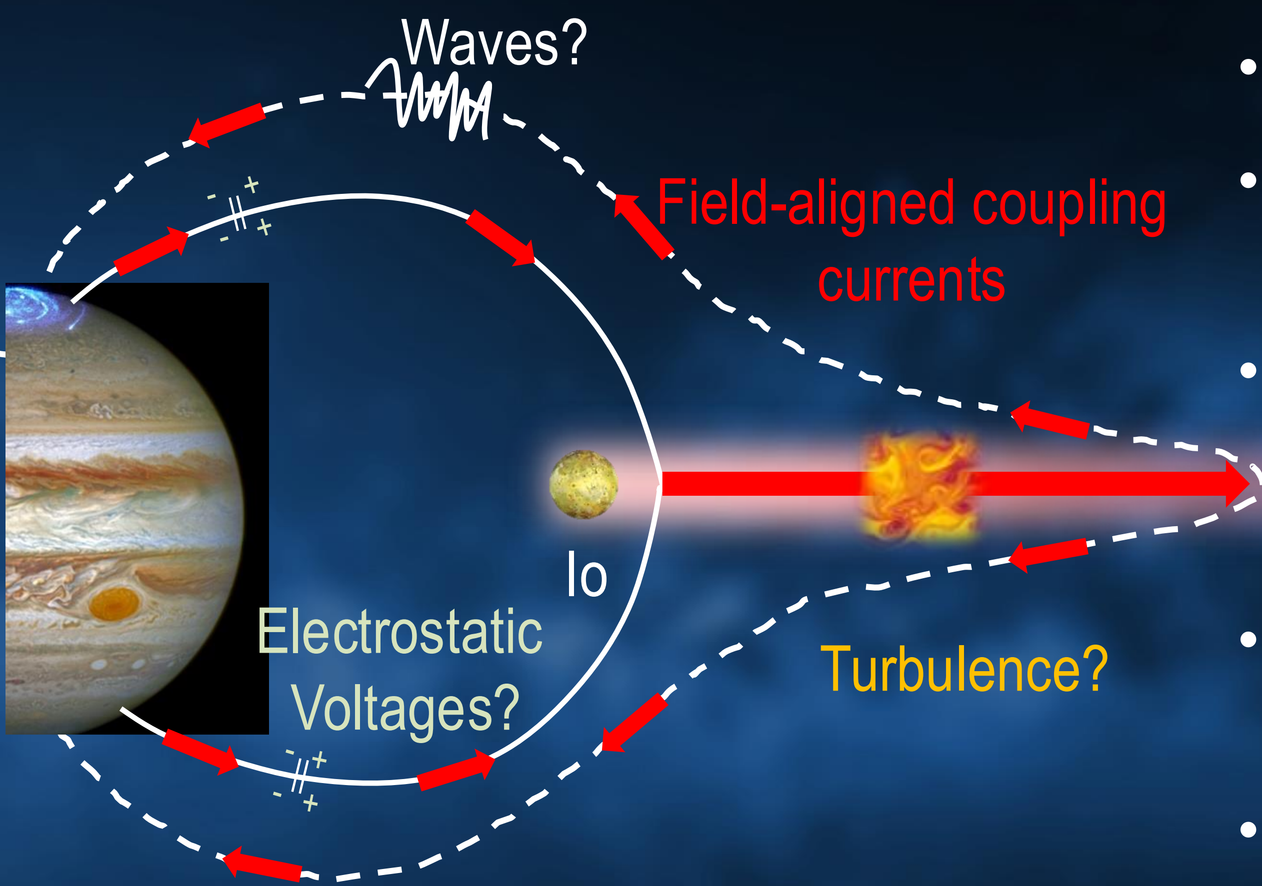
Reveals energy of bombarding electrons & atmospheric chemistry

Gerard et al. 2018

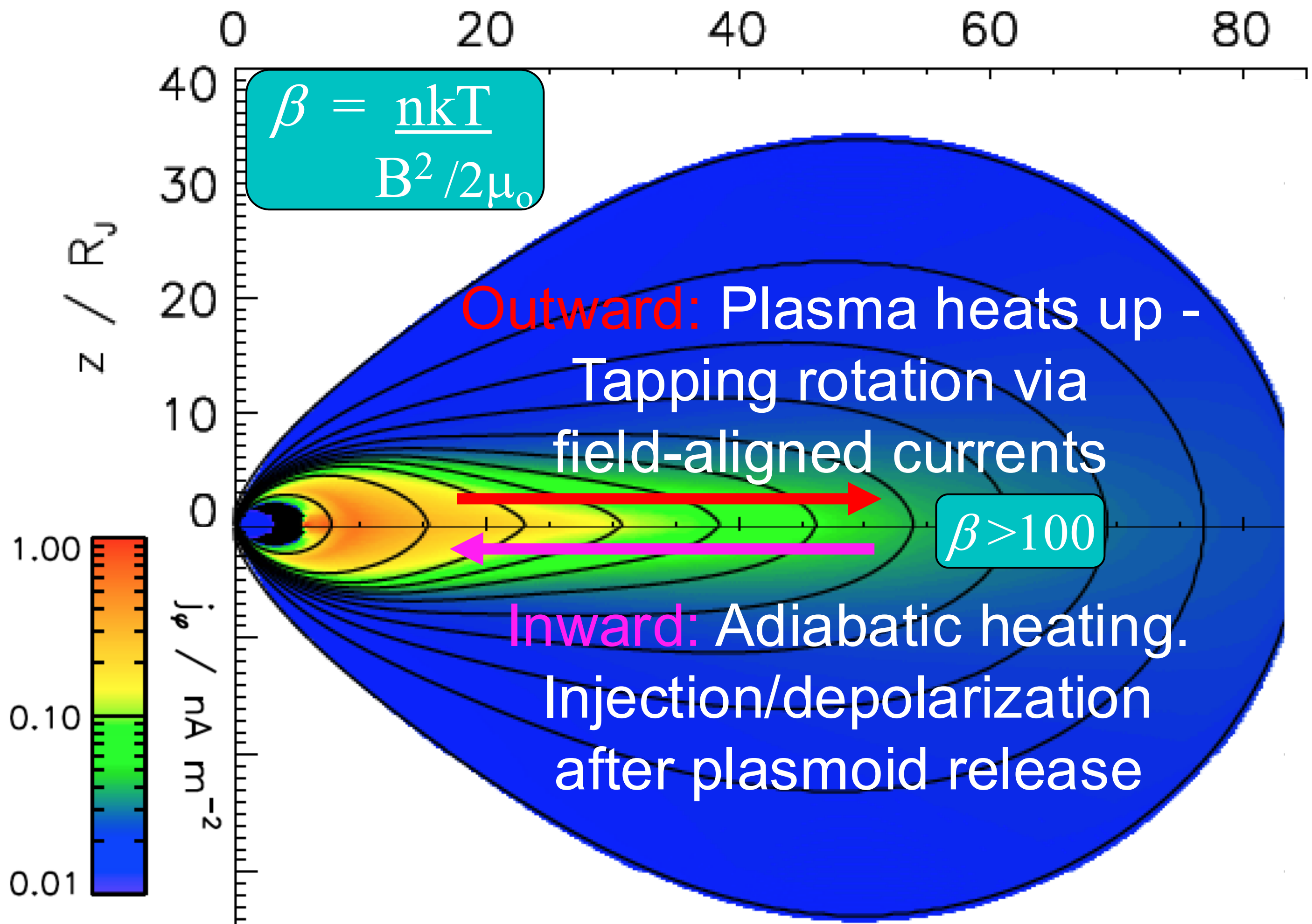
Alfven Wave Heating – Both Ions and Electrons



Saur et al. 2018



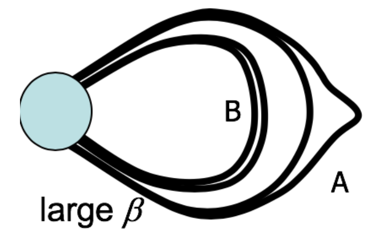
- System quasi-stable?
- Strong coupling currents unstable?
- Fluxtube interchange non-continuous – local force imbalance
- Turbulence cascades to small scales?
- Stochastic accelerations



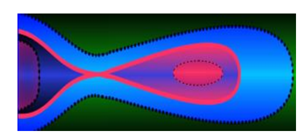
Nichols 2011

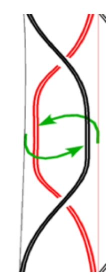
Transport:

Plasma β increases
ballooning replaces
interchange



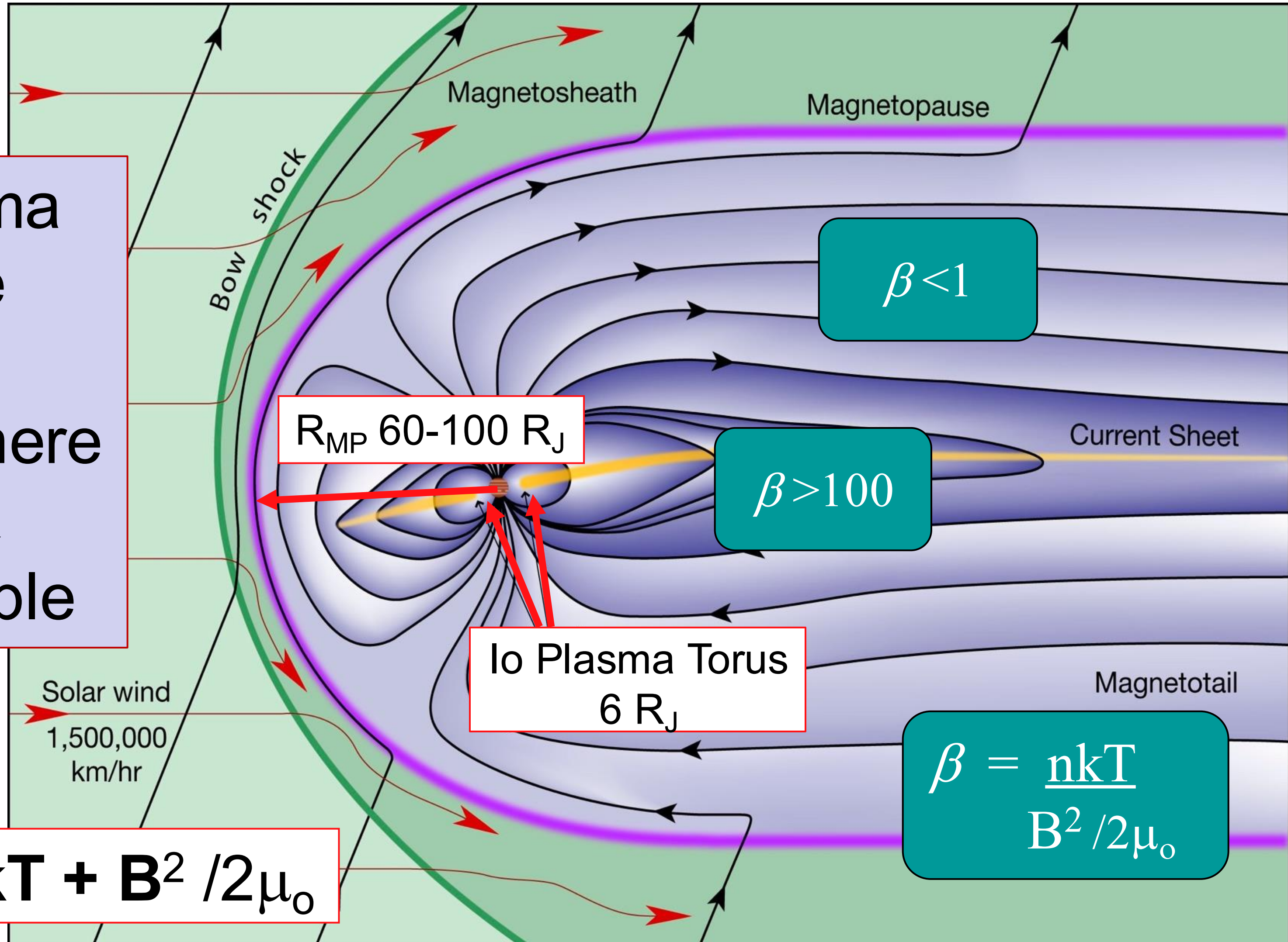
"Drizzle"
Small-scale, local
Kinetic transport?
Reconnection?
Plasmoids?





Fluid -> Kinetic Approach

High Plasma Pressure Makes Magnetosphere Larger & Compressible

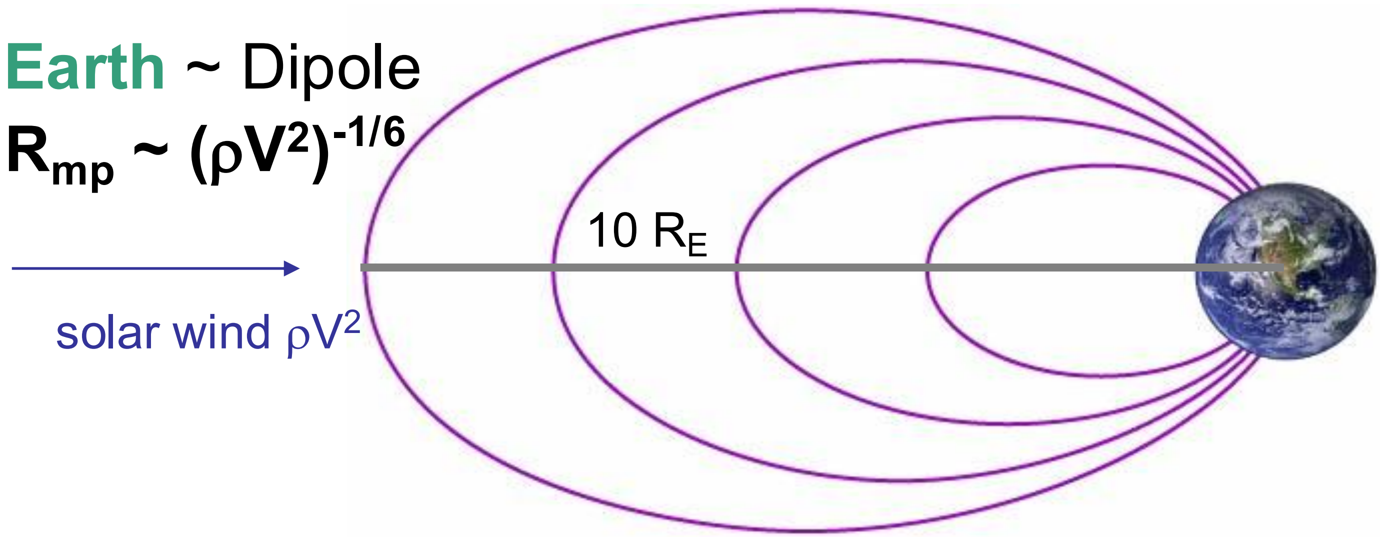


$$\rho_{sw} V^2_{sw} = nkT + B^2/2\mu_o$$

How Compressible with Solar Wind Pressure?

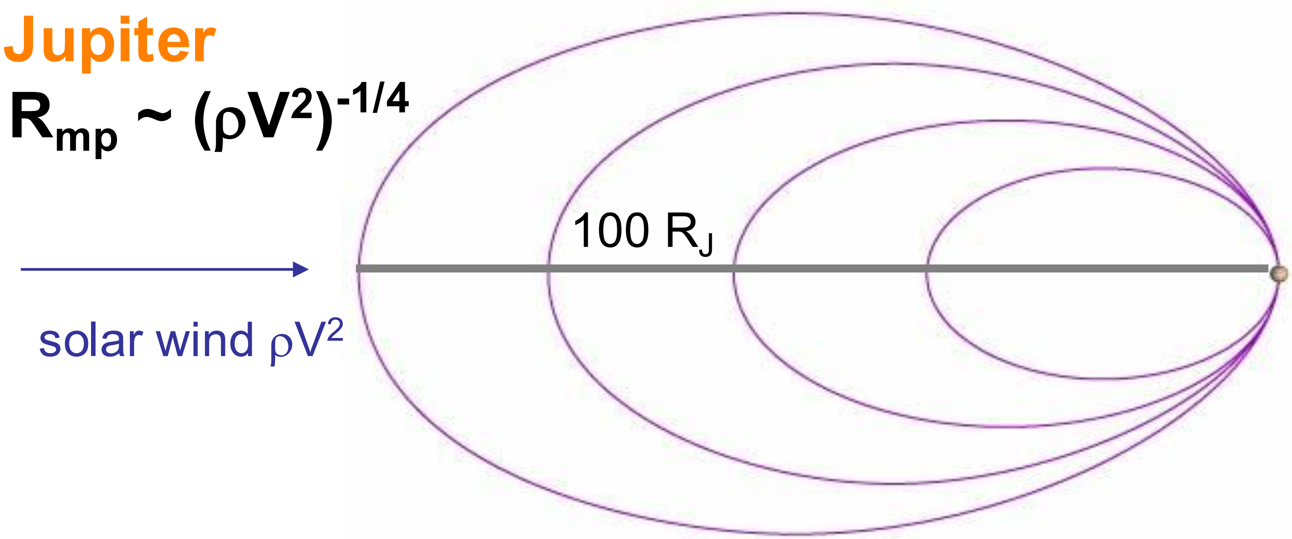
Earth ~ Dipole

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



Jupiter

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



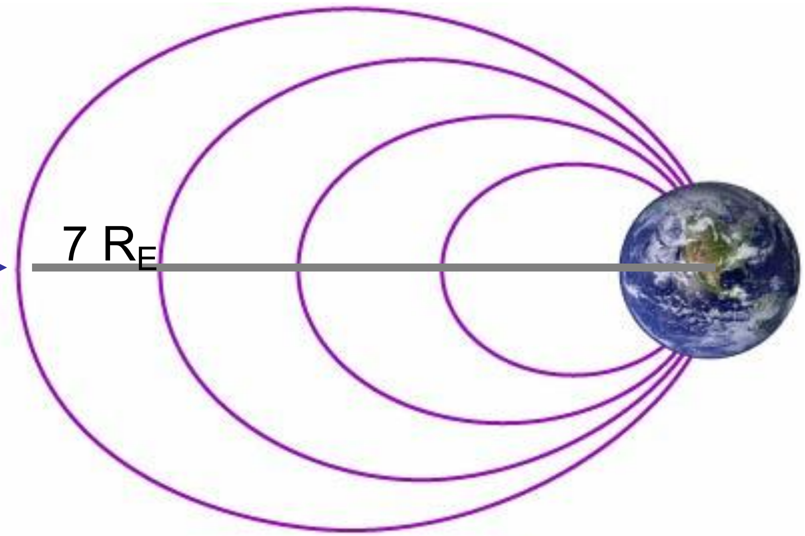
Slavin 1985
Huddleston et al. 1998
Joy et al. 2002

x10 Solar wind pressure

Earth ~ Dipole

R_{mp} -> 0.7 R_{mp}

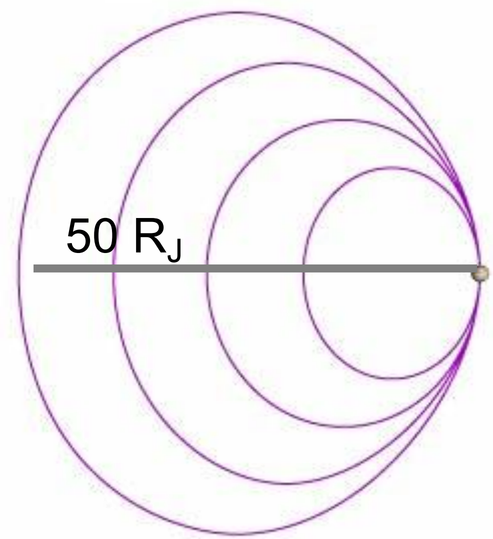
solar wind ρV^2



Jupiter

R_{mp} -> 0.5 R_{mp}

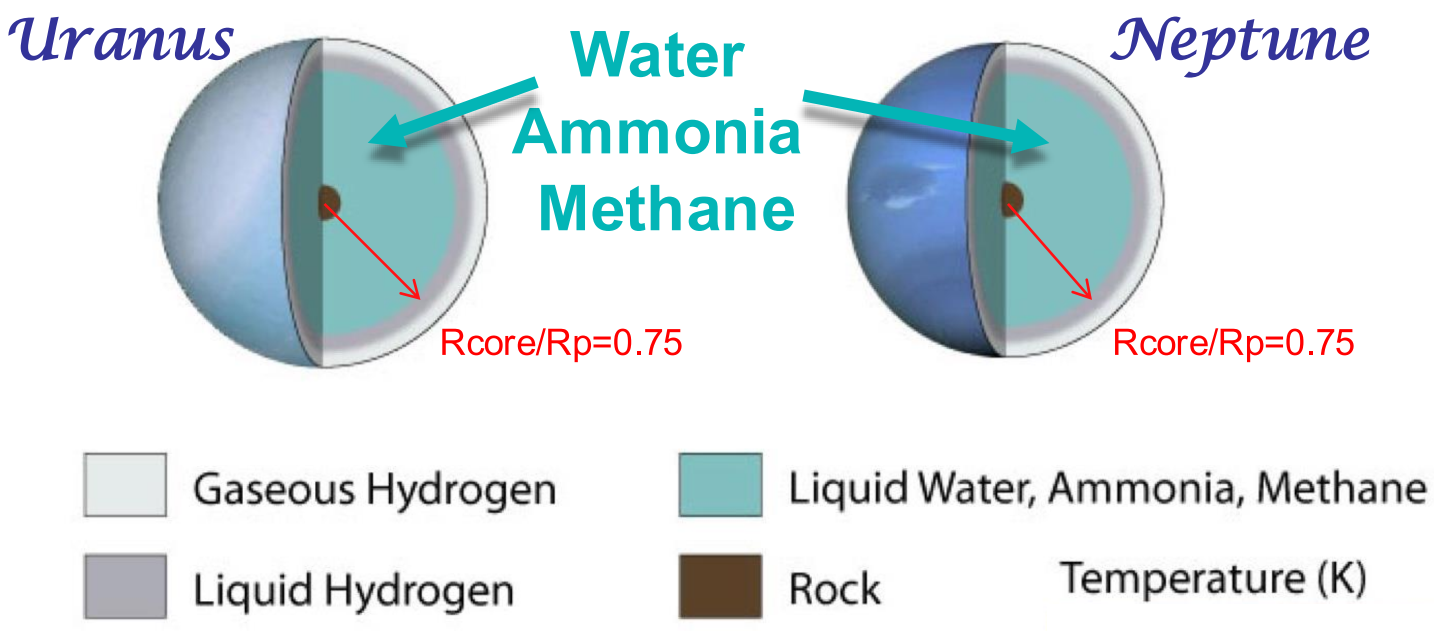
solar wind ρV^2



observed
100-50 R_J
dayside
magnetosphere

Uranus & Neptune

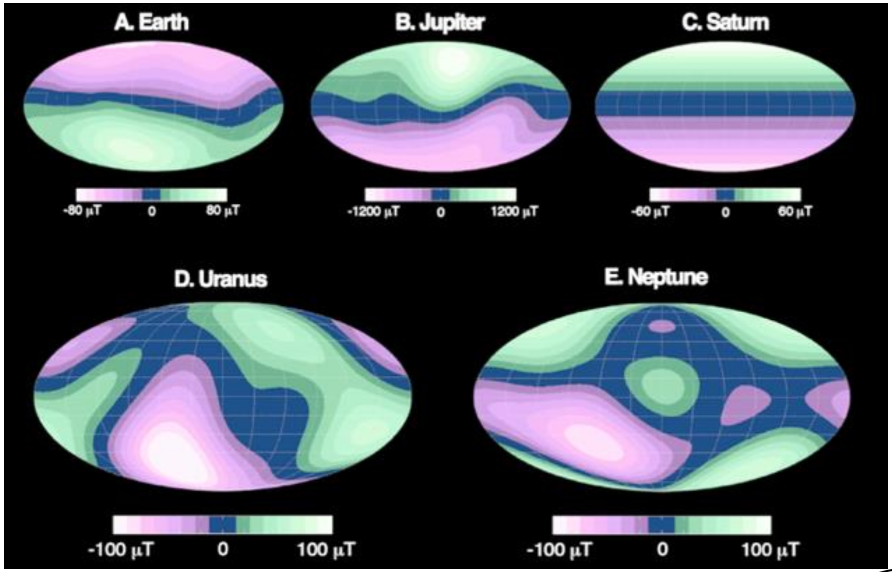
They're Totally Weird!

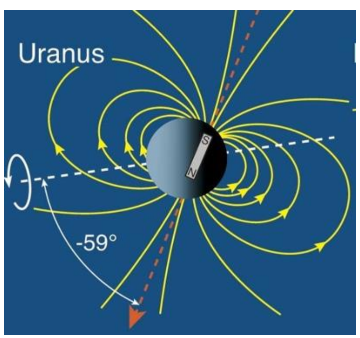


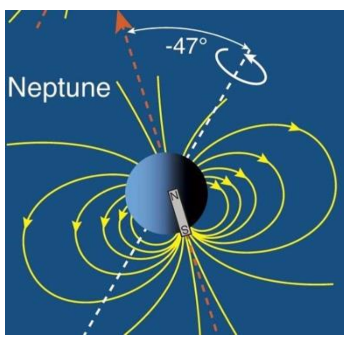
Uranus and Neptune have much less mass

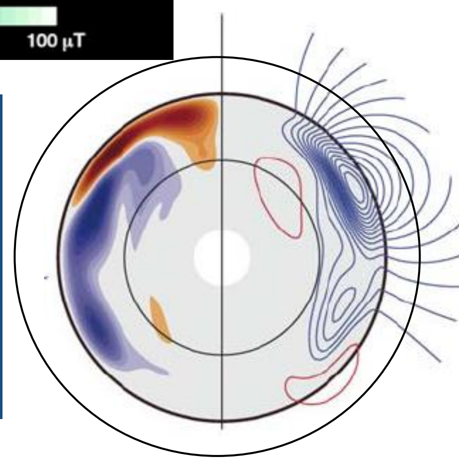
- Lower pressures
- No metallic hydrogen
- Weak & irregular magnetic fields produced in **water layer,** deep below gas envelope

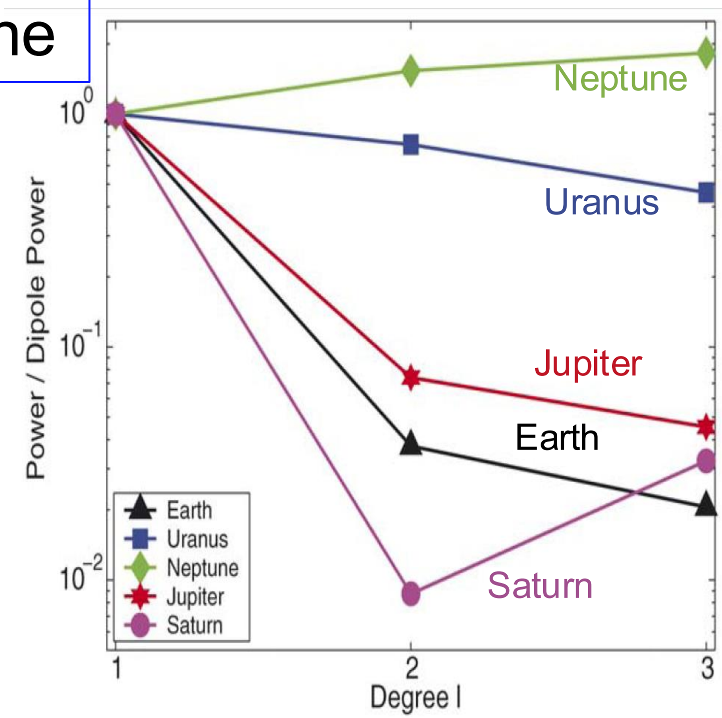
Weird Magnetospheres Uranus & Neptune











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

Stanley & Bloxham 2006

nature astronomy

Article

https://doi.org/10.1038/s41550-025-02507-9

Discovery of H_3^+ and infrared aurorae at Neptune with JWST

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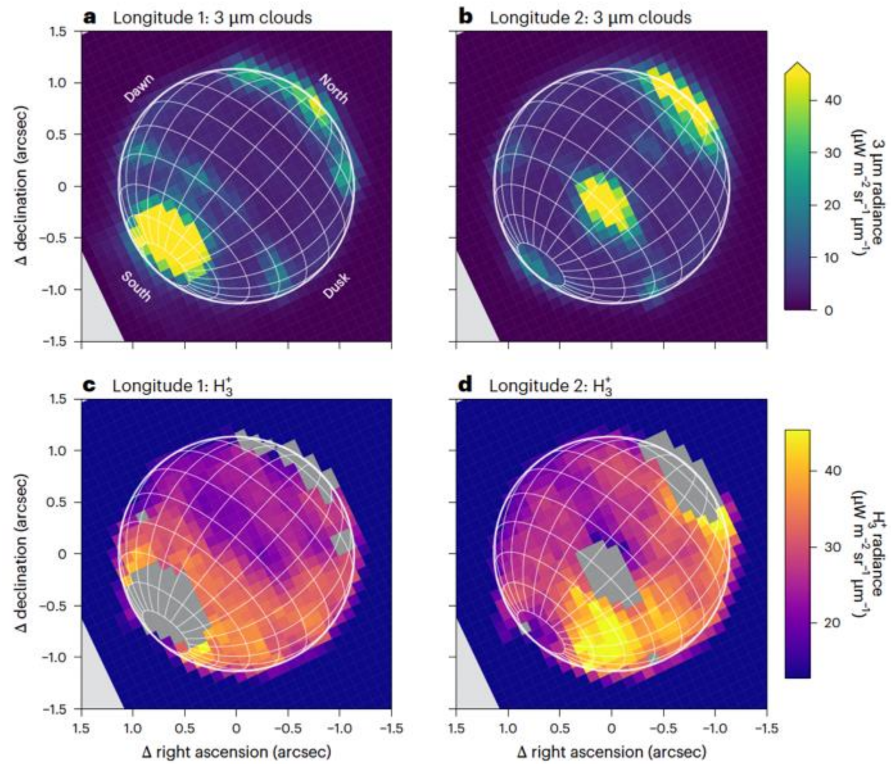
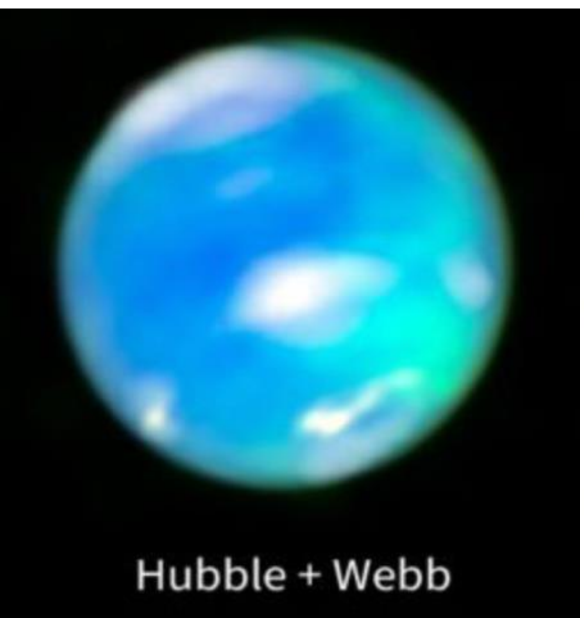
Check for updates

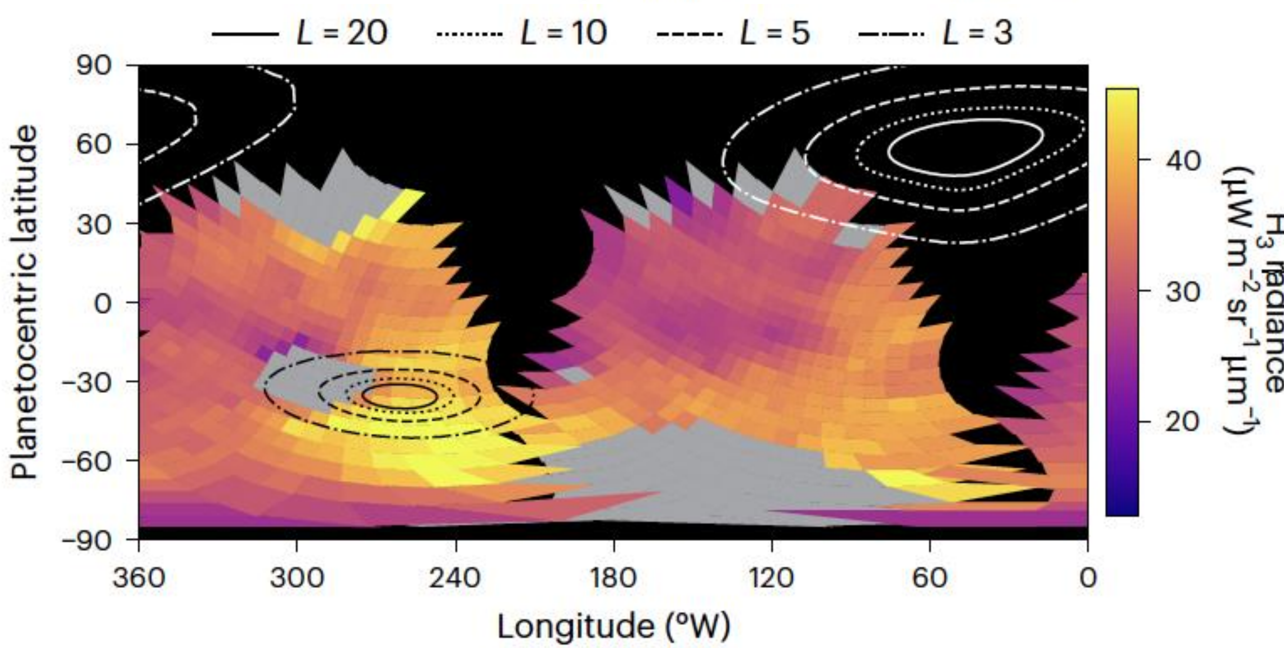
Henrik Melin[1], Luke Moore[2,3], Leigh N. Fletcher[4], Heidi B. Hammel[5], James O'Donoghue[6,7], Tom S. Stallard[1], Stephanie N. Milam[8], Michael Roman[4], Oliver R. T. King[4], Naomi Rowe-Gurney[8], Emma E. Thomas[1], Ruoyan Wang[4], Paola I. Tiranti[1], Jake Harkett[4] & Katie L. Knowles[1]

Hot off the press!!

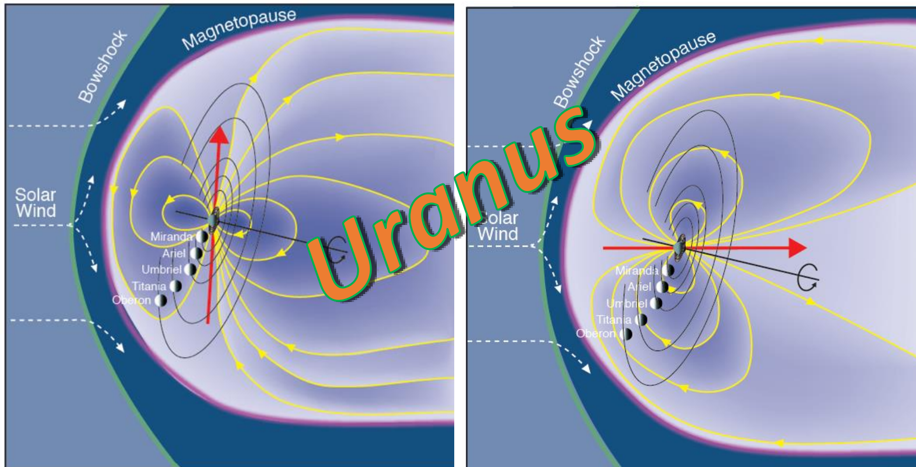
JWST sees IR aurora at Neptune



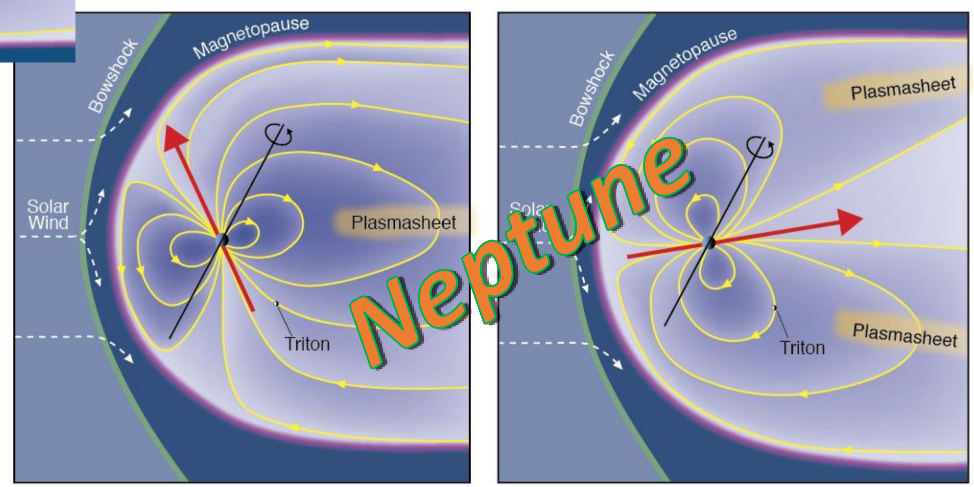


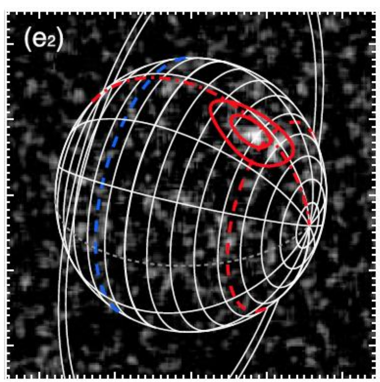


Need to go back to Uranus & Neptune

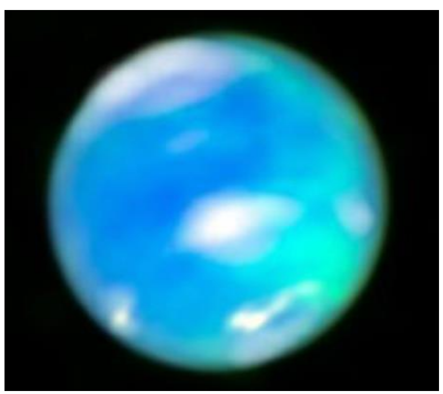


- Voyager got quick glipse!
- Saw irregular, changing field
- How do m'spheres respond to solar wind?

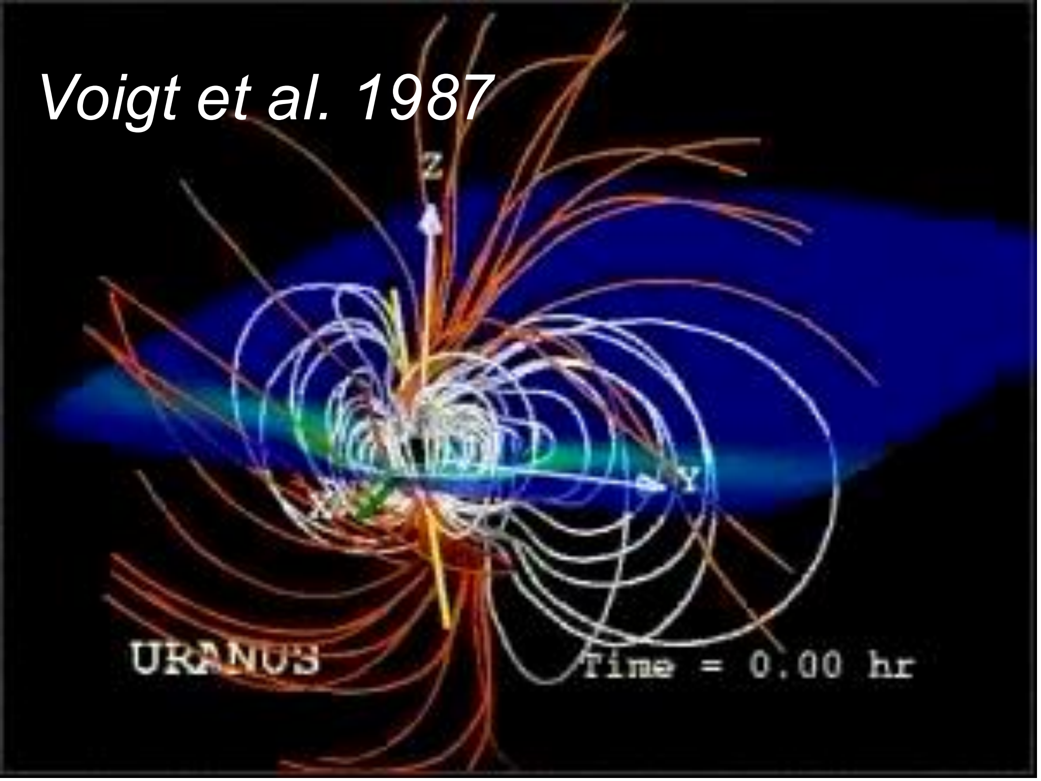




Lamy et al. 2017

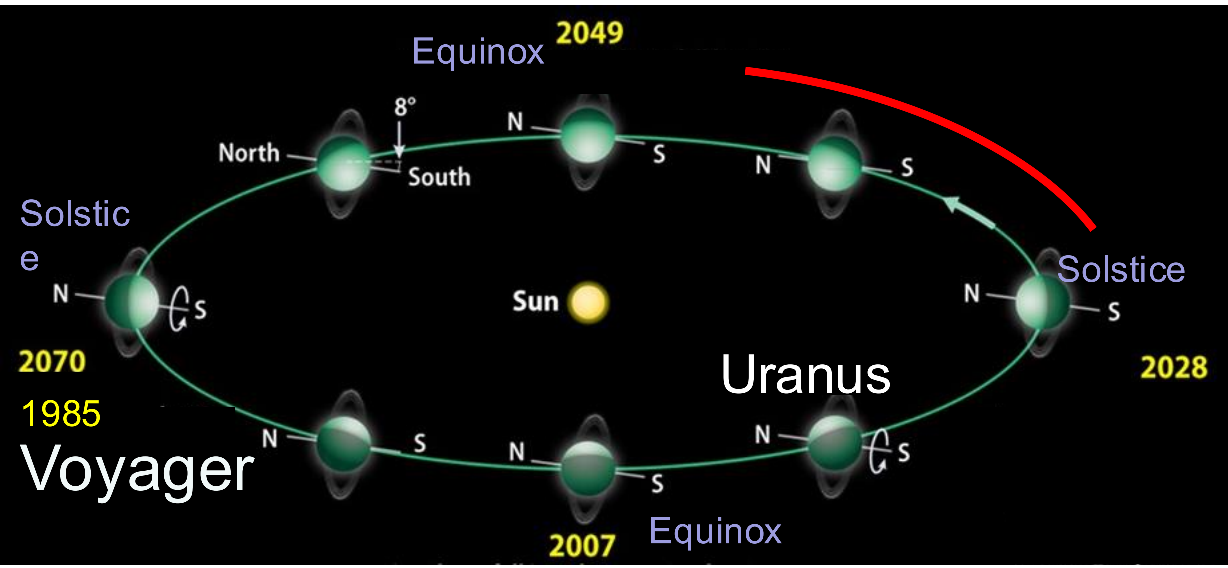

Melin et al. 2025

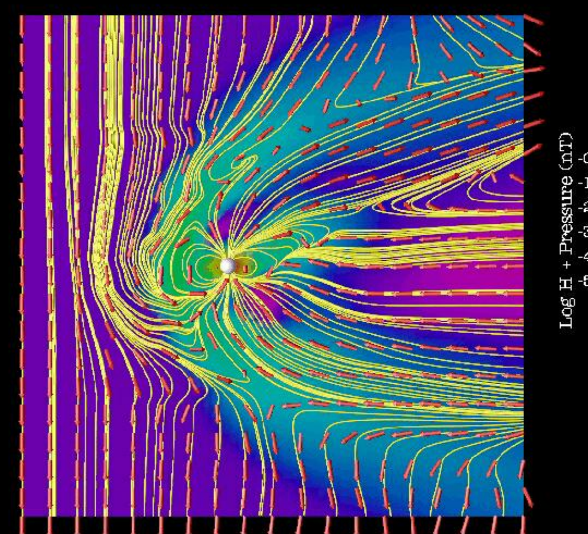
Hints of aurora with H /JWST



Explore weird configurations at different seasons

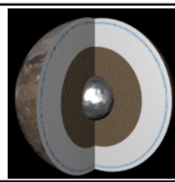
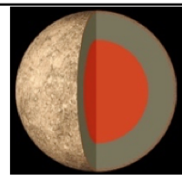
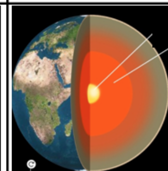
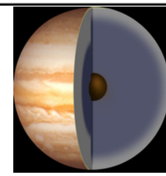
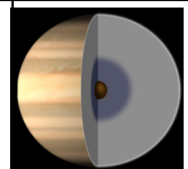
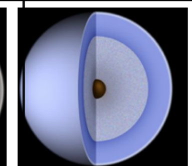
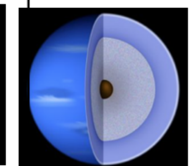
- Full coverage from orbit
- Modern instrumentation
- Onboard data-processing

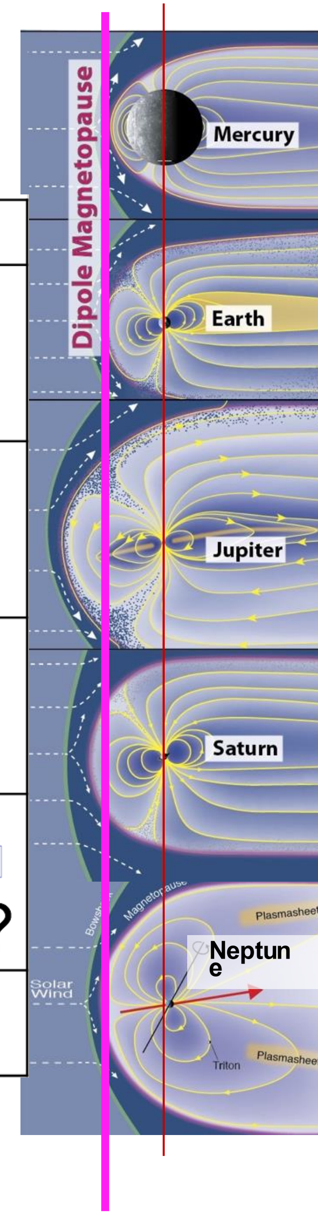




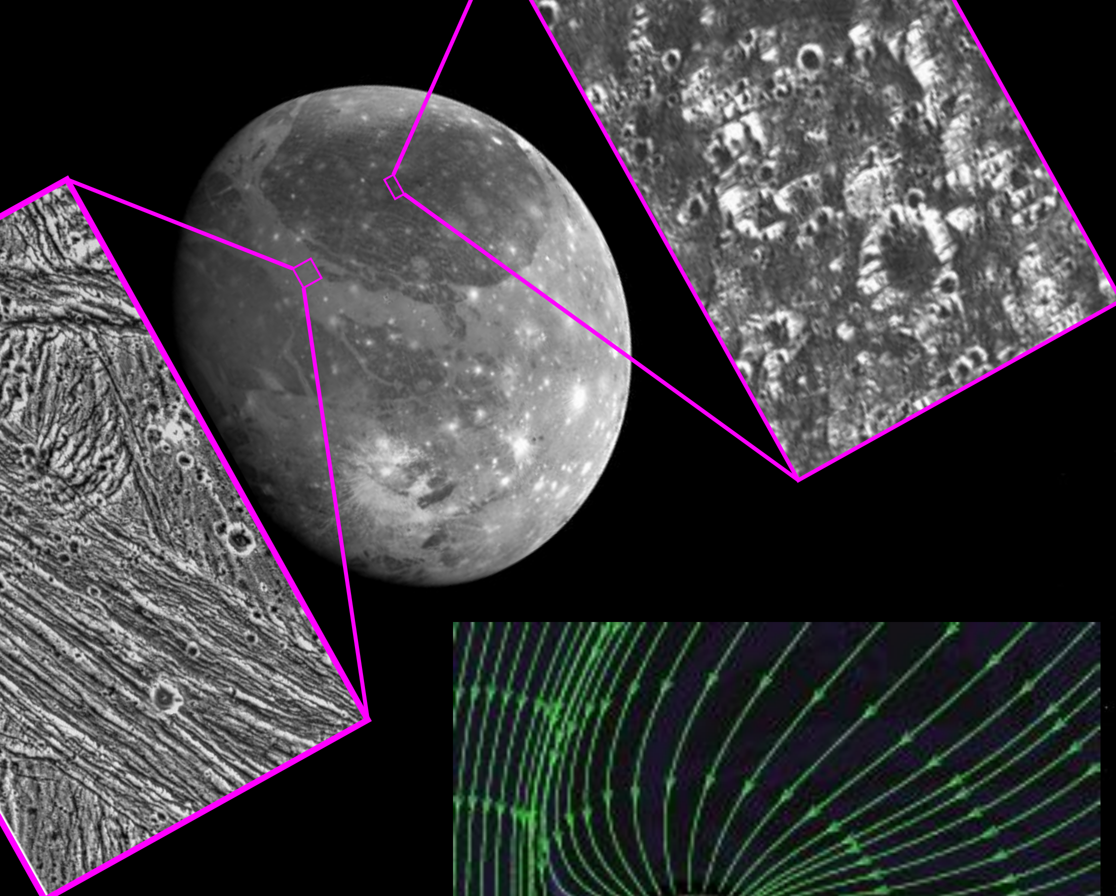
Cao & Paty 2017

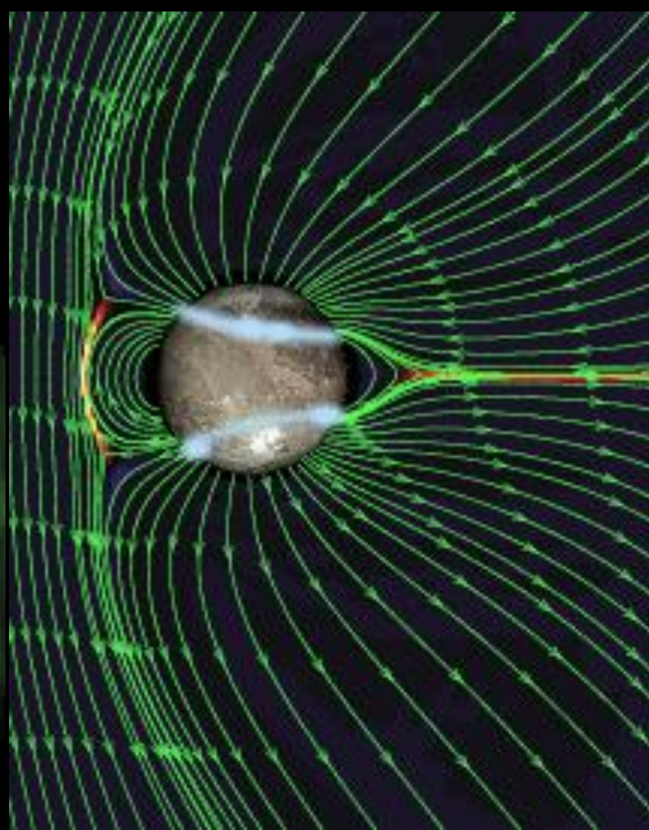
Comparative Planetary Magnetospheres

	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	??	??



ESA's JUICE

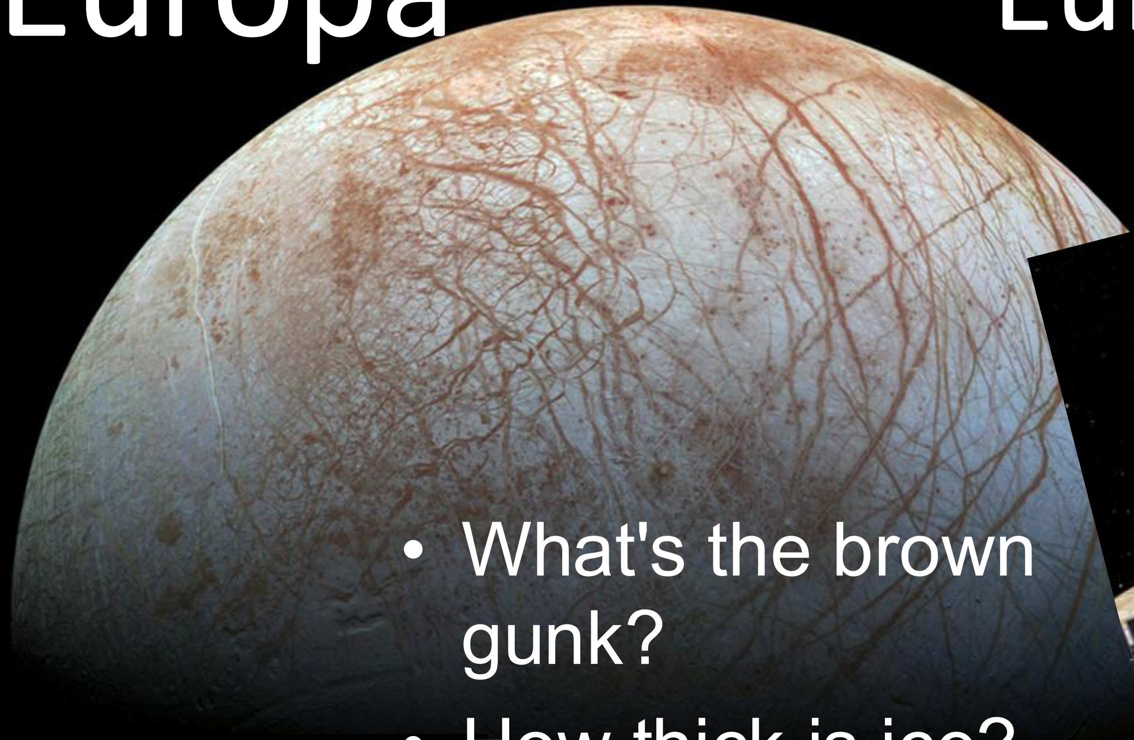




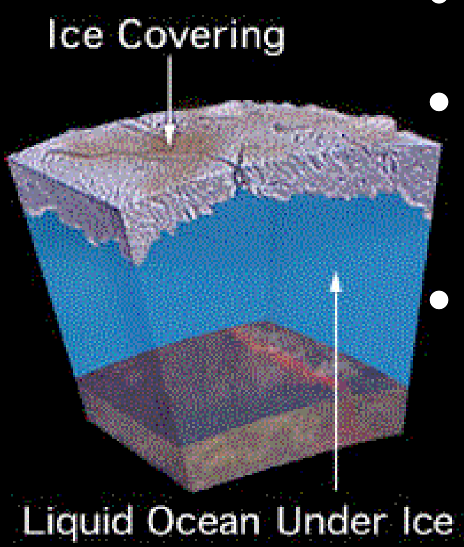
Arrives at Jupiter 2034
Will Orbit Ganymede

Europa

Europa Clipper Mission



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



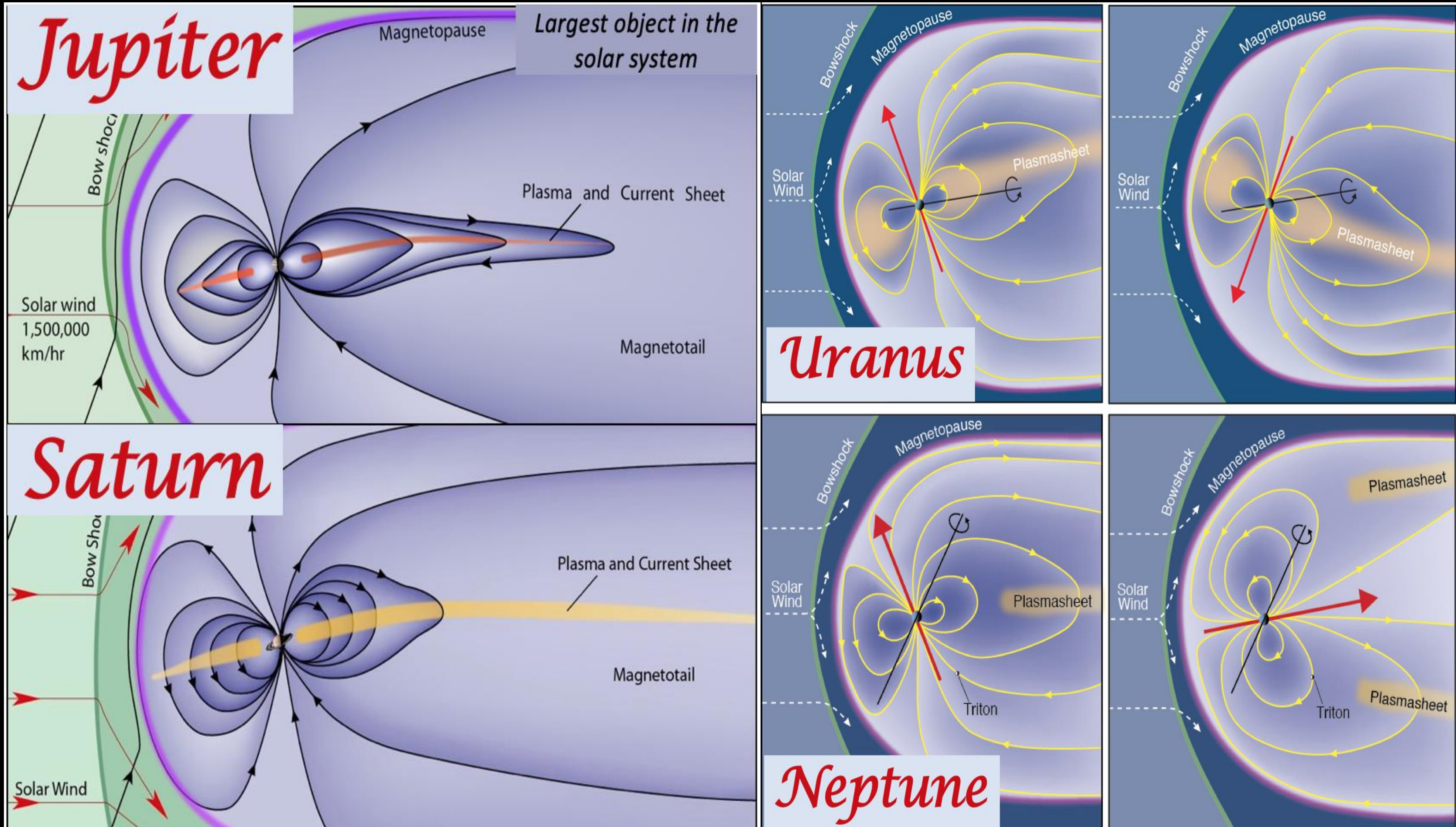
Launched Oct 2024
Orbits Jupiter 2030

Planetary Magnetic Dynamos – Outstanding issues:

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

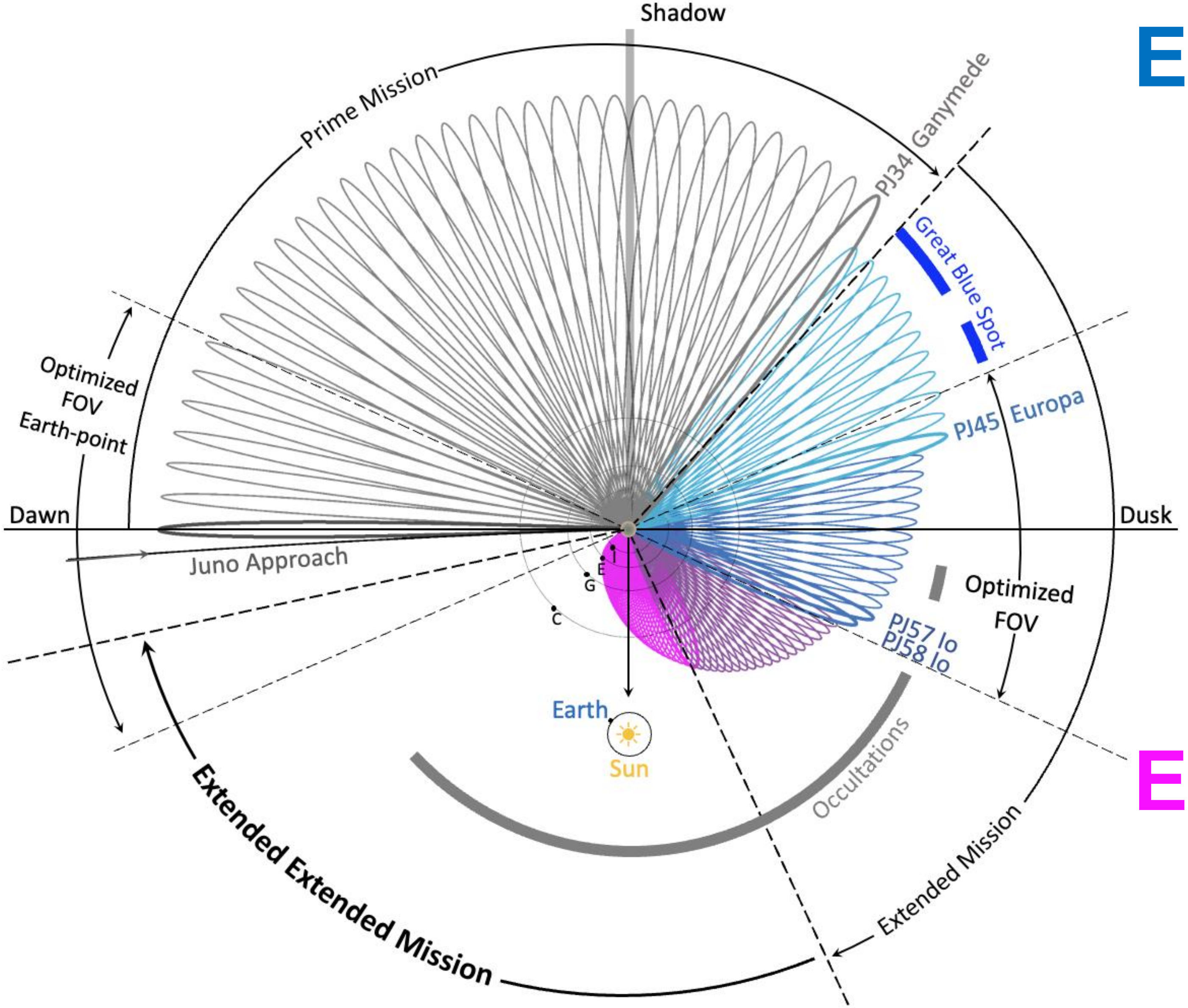
Planetary Magnetospheres Summary

- 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!

Extended Mission – EM2



Looking Down

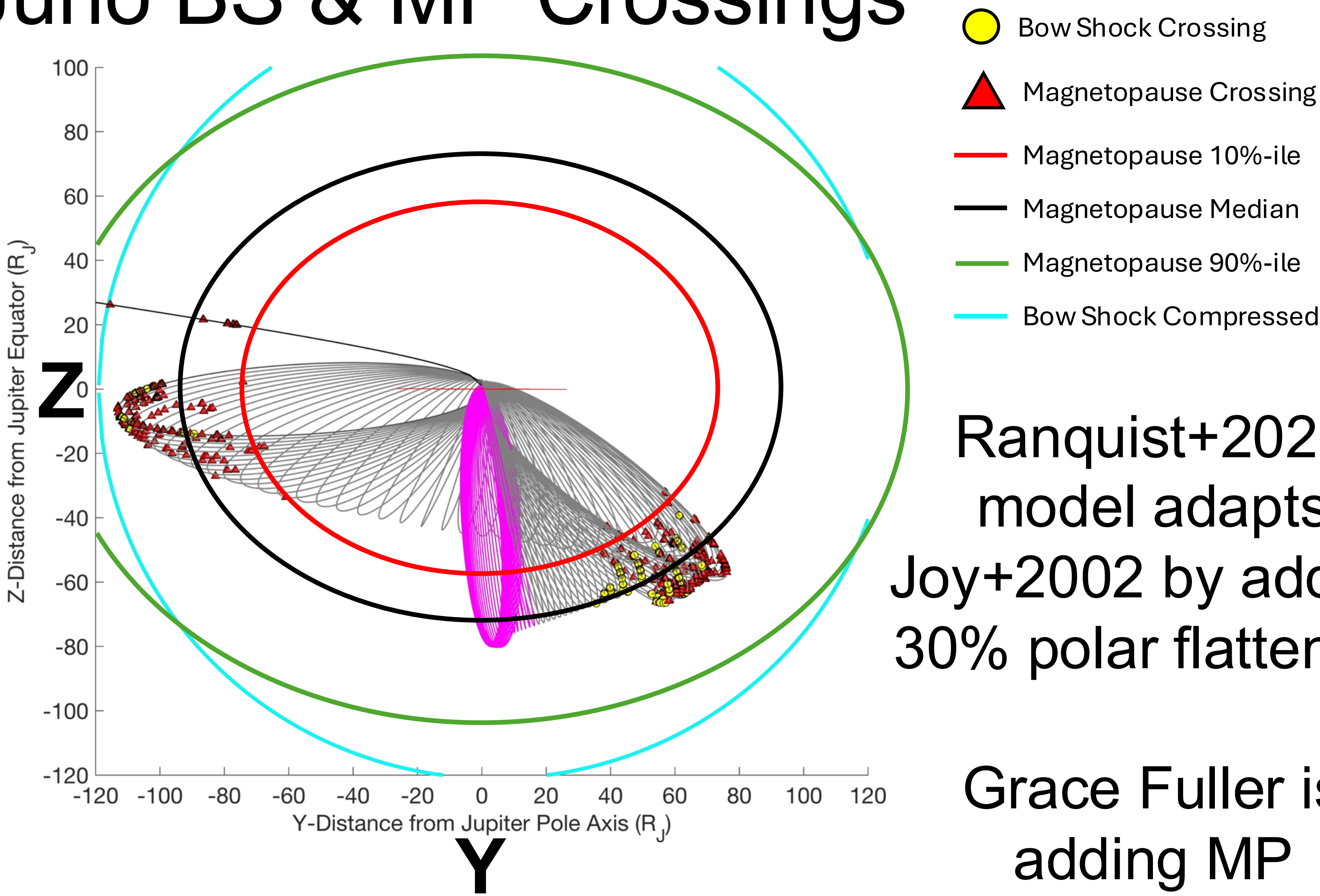
EM1

- PJ35-76
- 2022-25

EM2

- PJ77-110
- 2025-28

Juno BS & MP Crossings

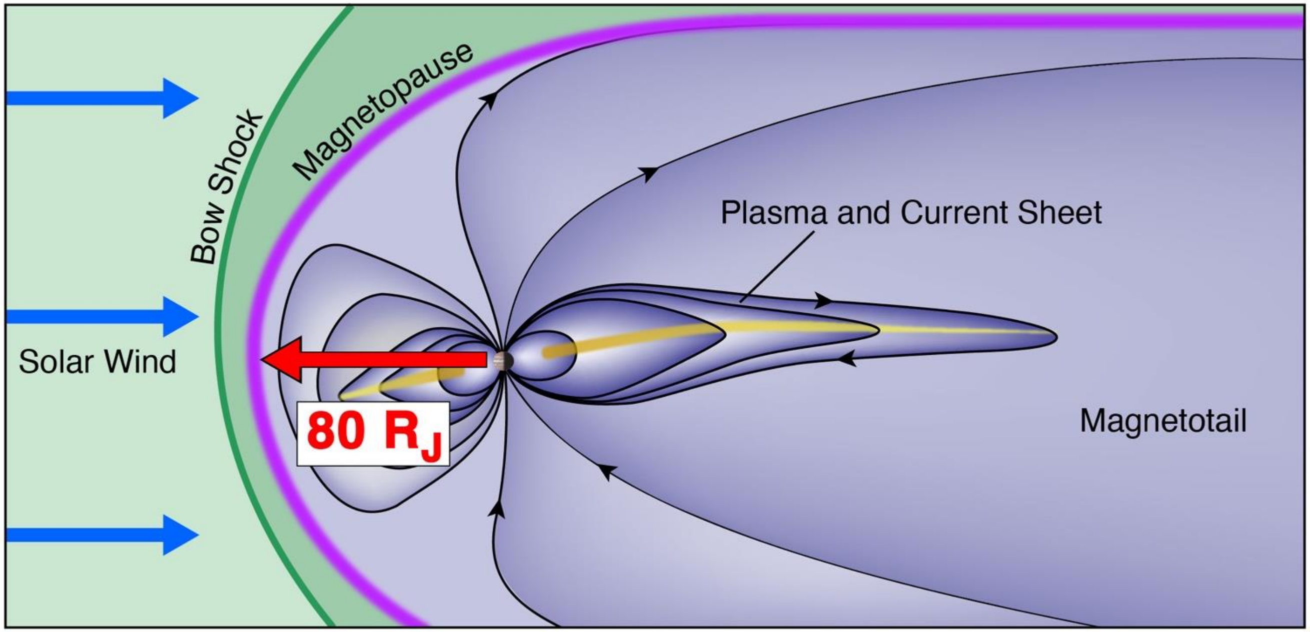


Looking from Sun

Ranquist+2020 model adapts Joy+2002 by adding 30% polar flattening

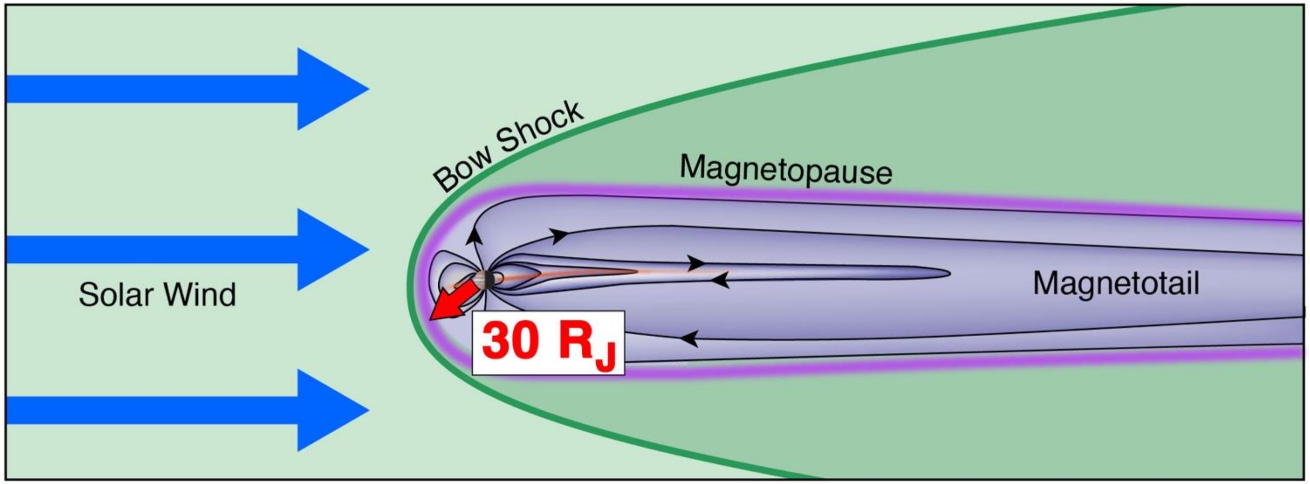
Grace Fuller is adding MP crossings from recent orbits...

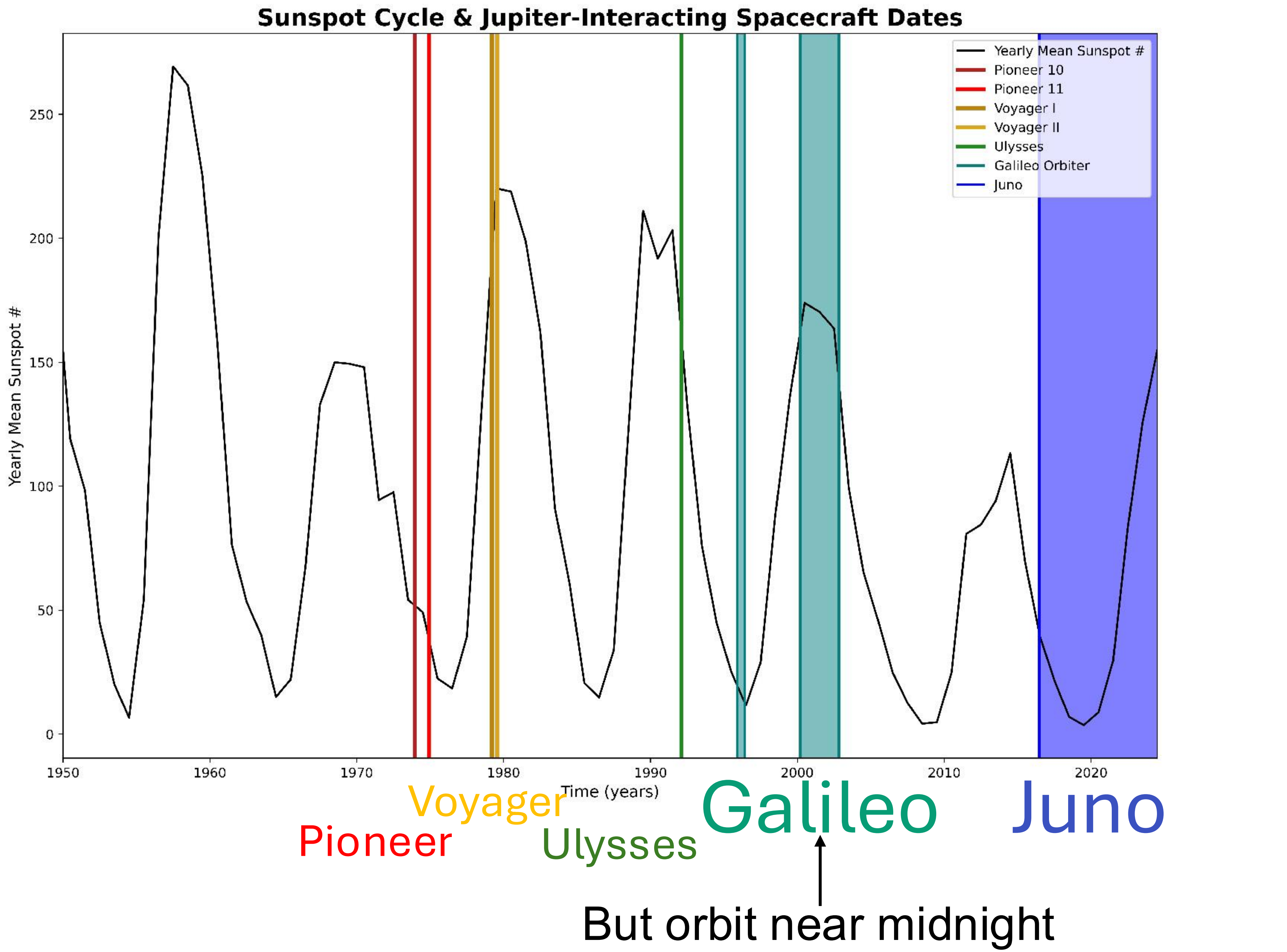
Juno Witnesses Extremely Compressed Magnetosphere



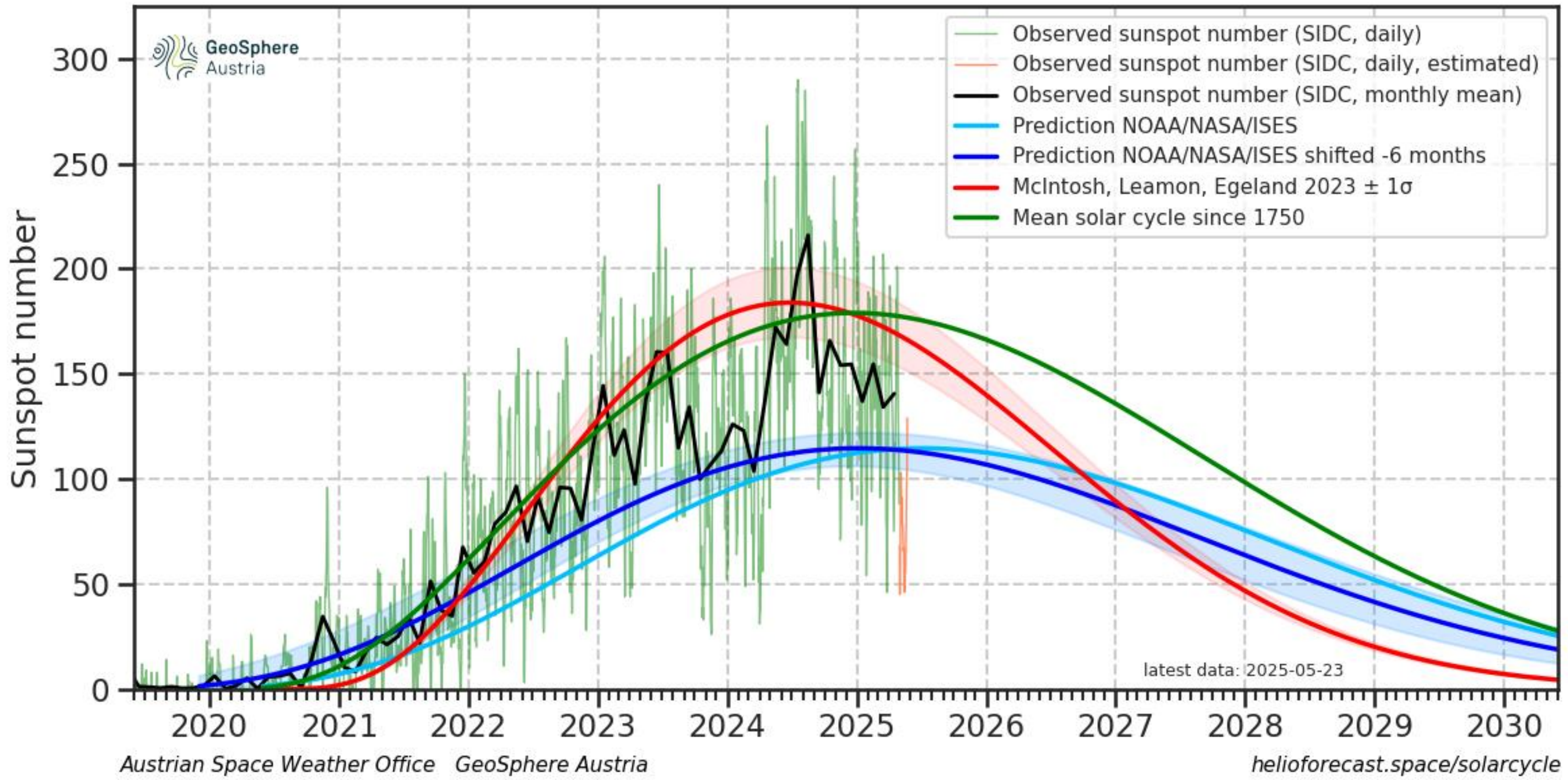
- Oct 2024 Storm
- Solar Max
- Magnetopause at 30 R_J -45° lat.
- Noon MP~20 R_J

That's inside Callisto's orbit!




Sunspot Cycle & Jupiter-Interacting Spacecraft Dates
Yearly Mean Sunspot #
Pioneer 10
Pioneer 11
Voyager I
Voyager II
Ulysses
Galileo Orbiter
Juno
Yearly Mean Sunspot #
0
50
100
150
200
250
1950
1960
1970
1980
1990
2000
2010
2020
Time (years)
Voyager
Pioneer
Ulysses
Galileo
Juno
But orbit near midnight

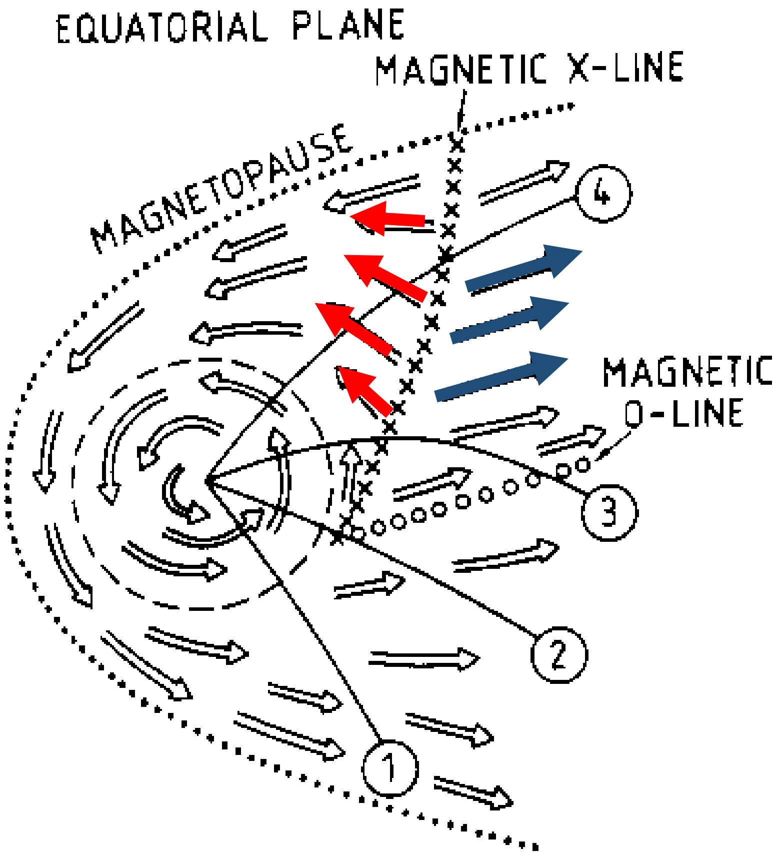
Solar Maximum Highly Variable

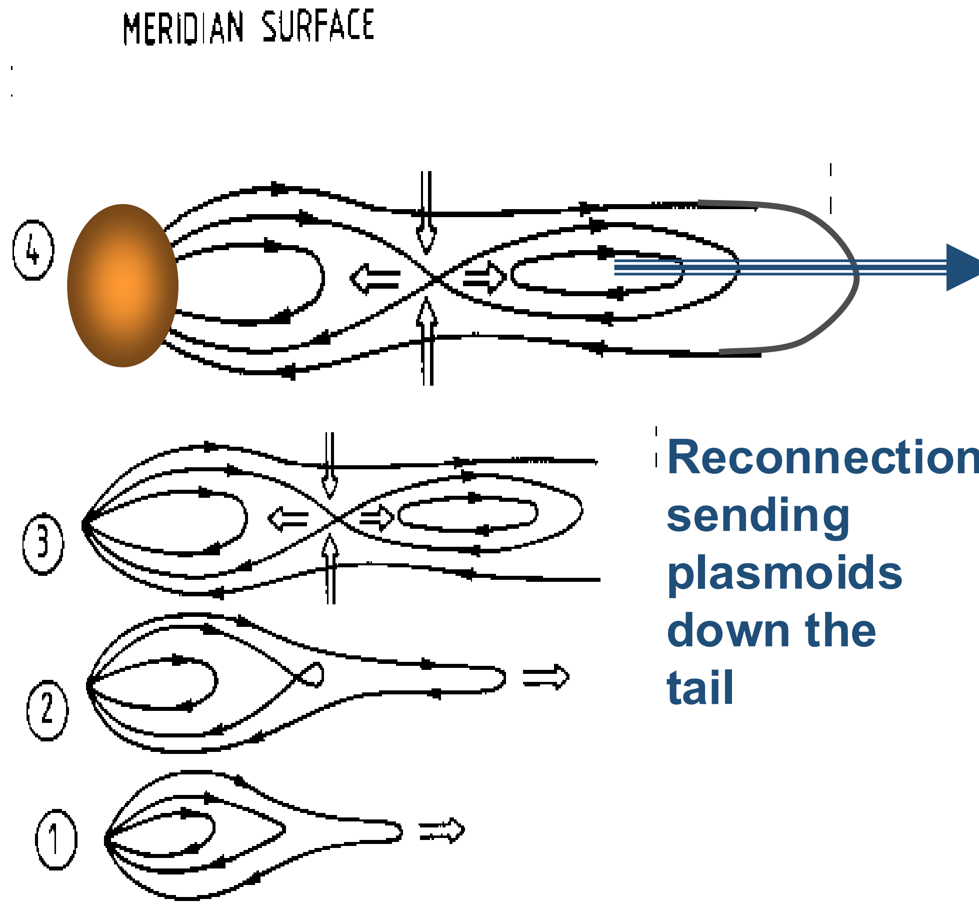


JUICE & Clipper at Jupiter for next Solar Max?

2035? 2036?

Vasyliunas Cycle
driven by centrifugal forces



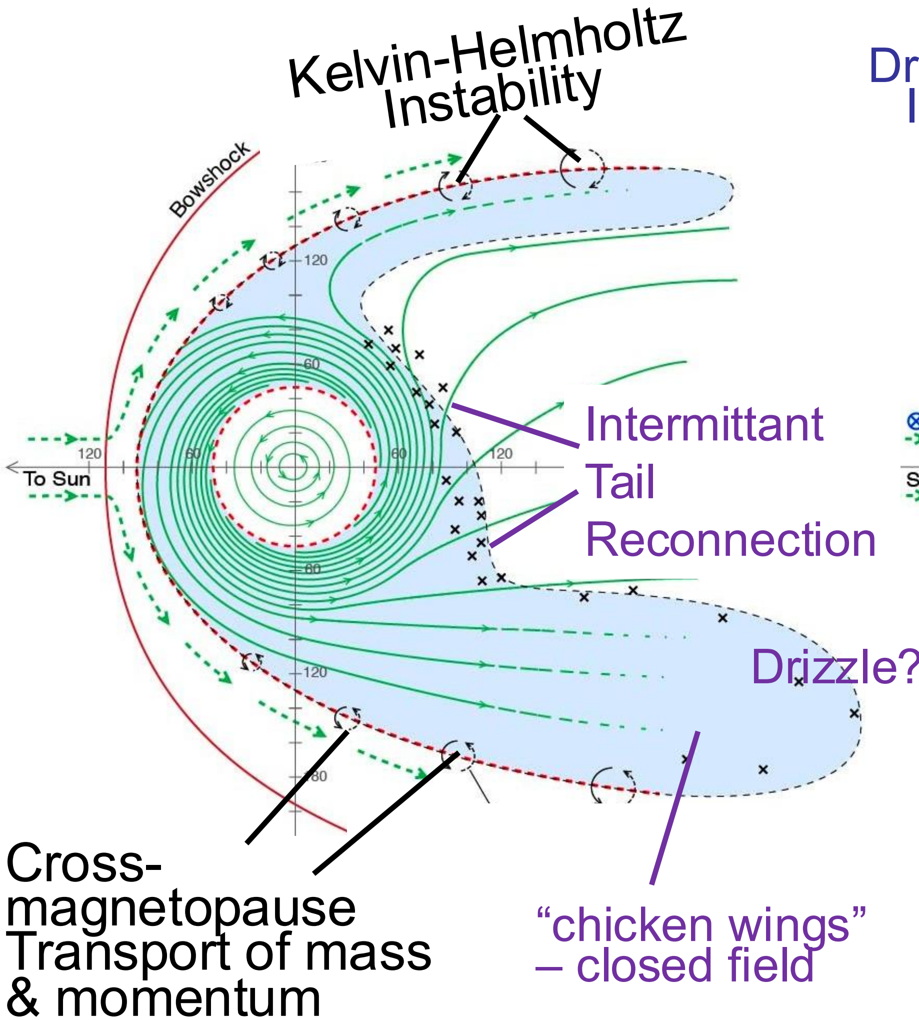


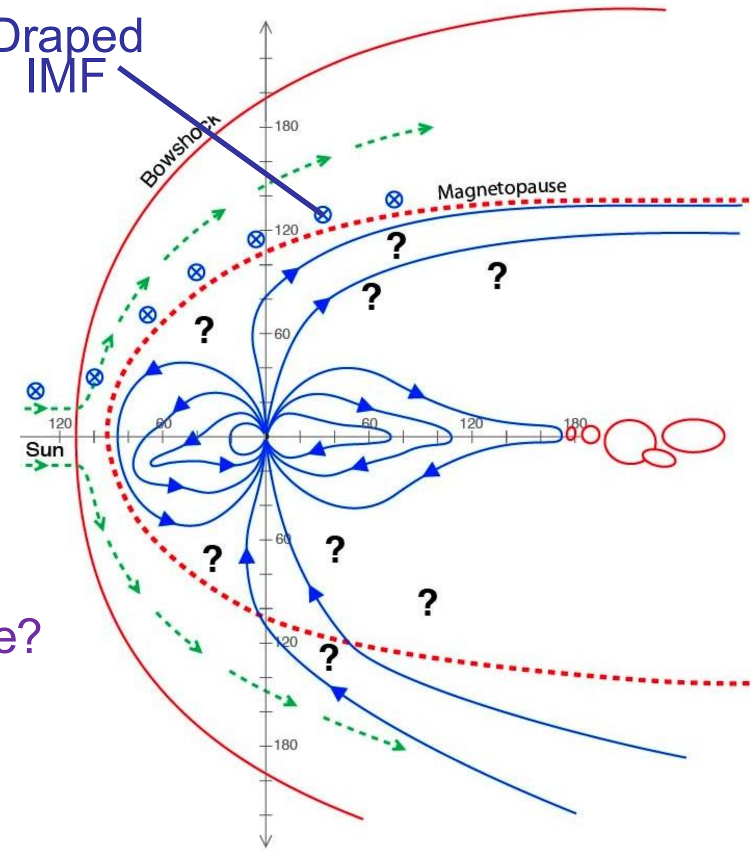
Reconnection sending plasmoids down the tail

Inward Injection **Plasmoid Ejection**

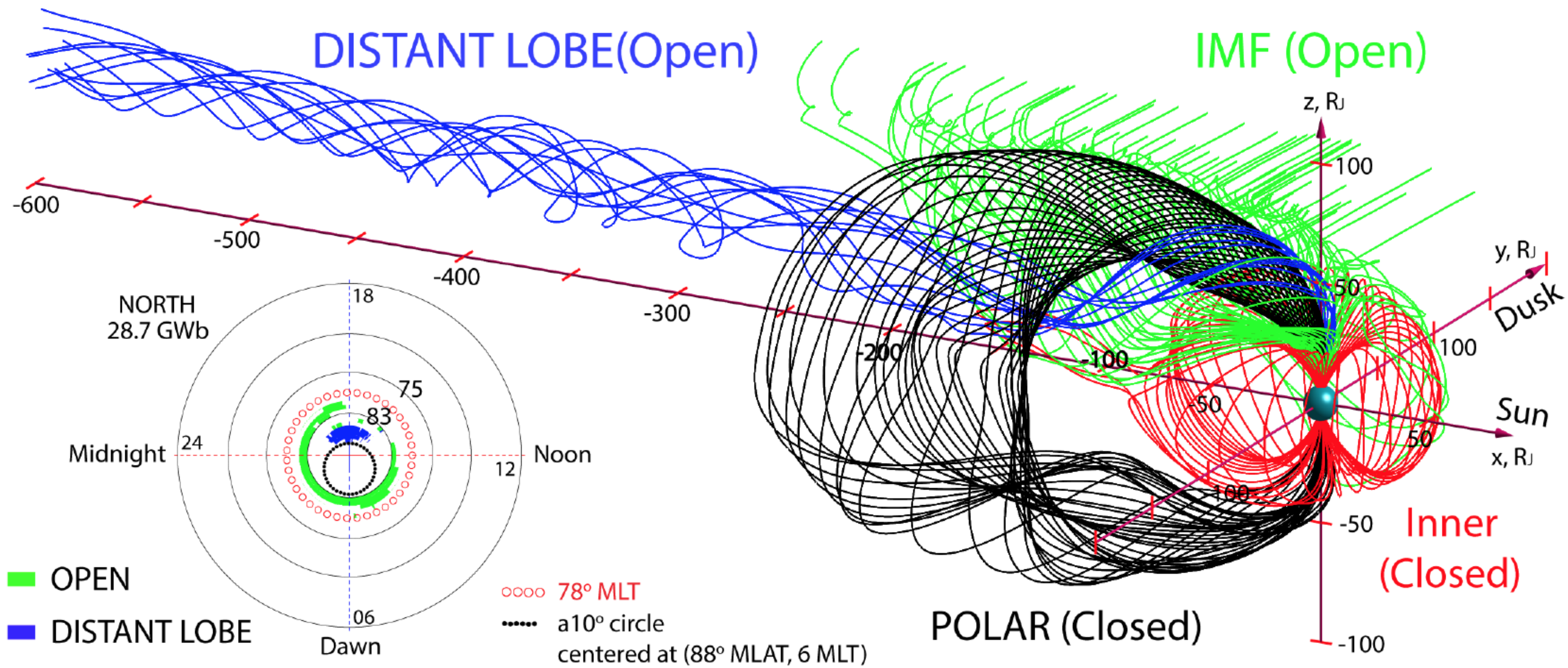
Vasyliunas
Cowley et al.
Southwood & Kivelson

Delamere & Bagenal 2013
Masters 2017





Models Suggest Greater Complexity

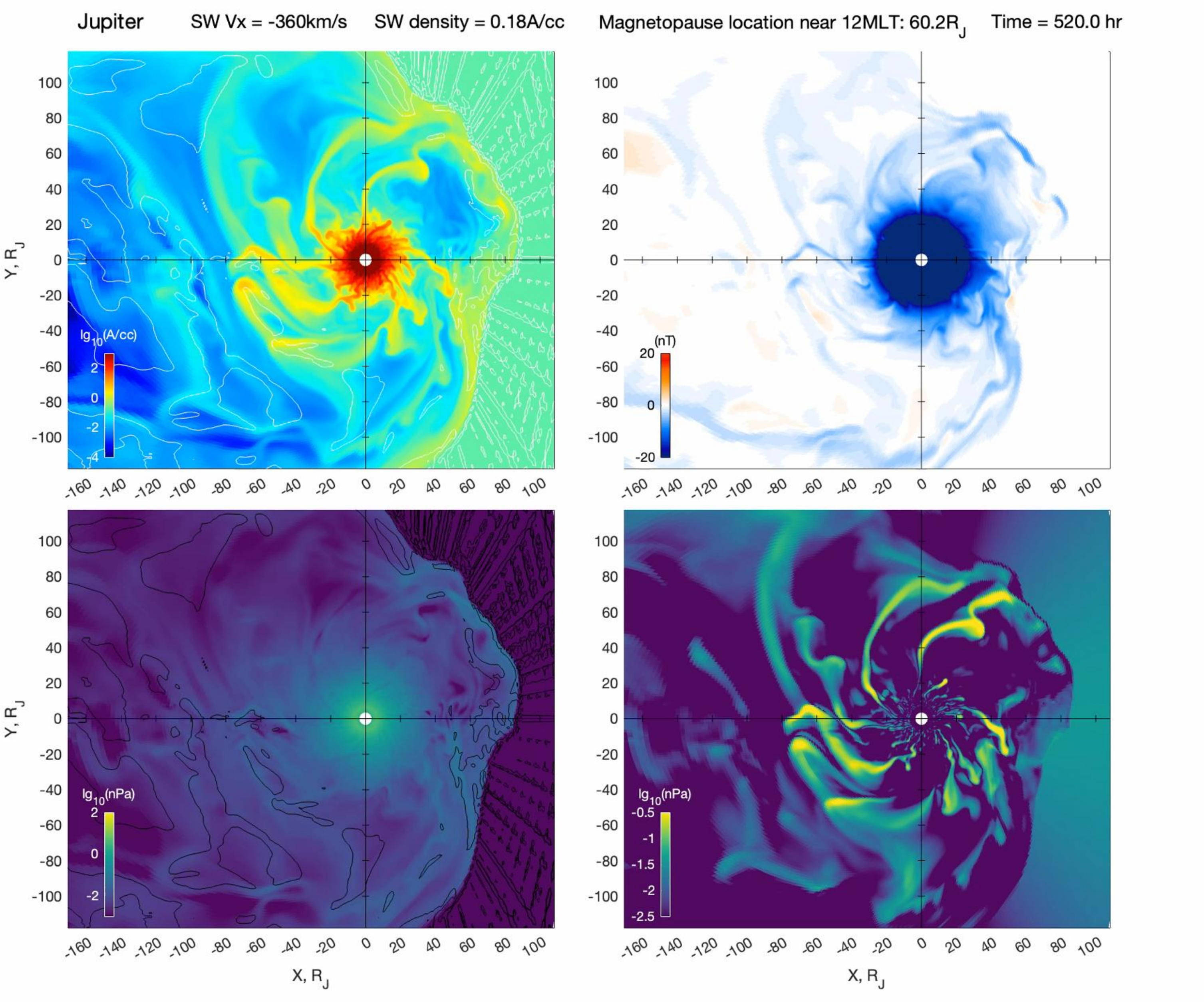


GAMERA Model

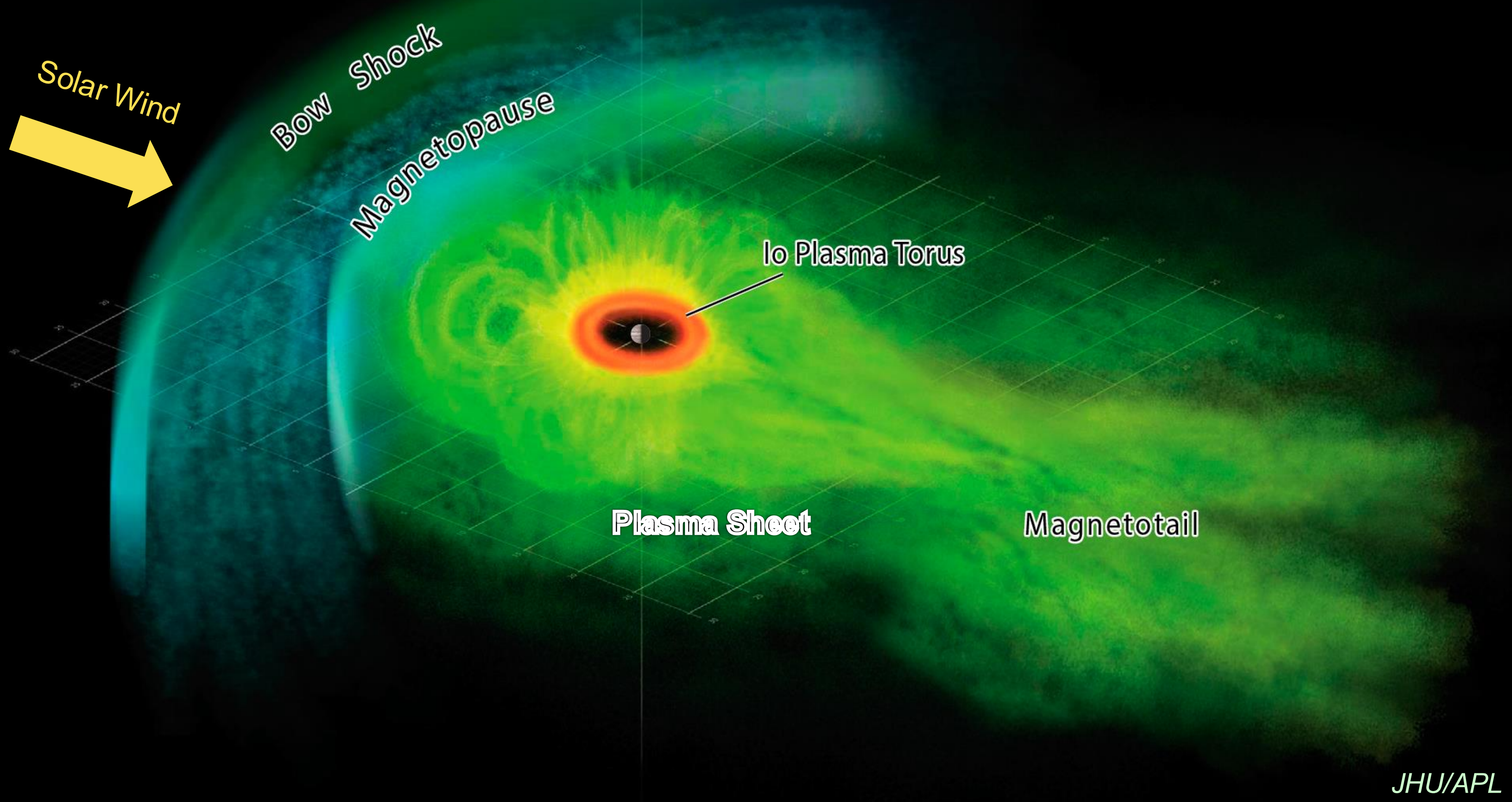
Binzheng Zhang et al. (2021)

GAMERA Model

Feng et al. 2023



Is Jupiter Really Just a Colossal Comet?



Delamere & Bagenal 2013