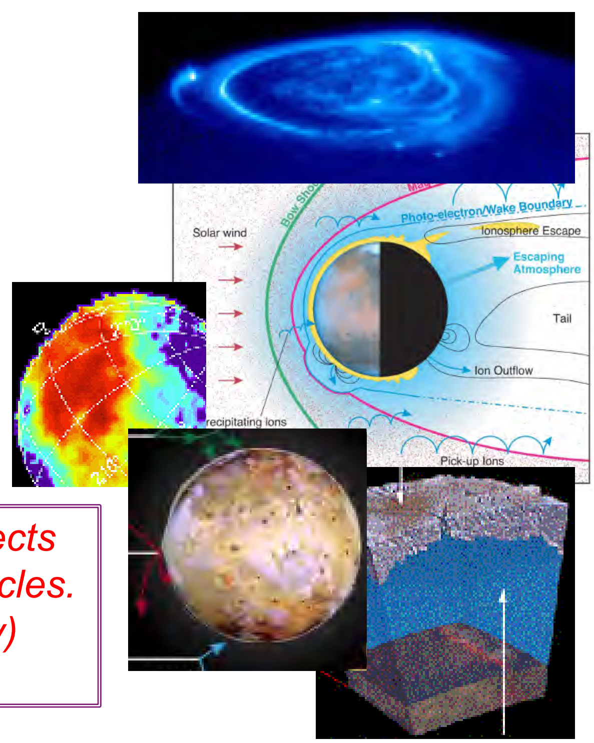
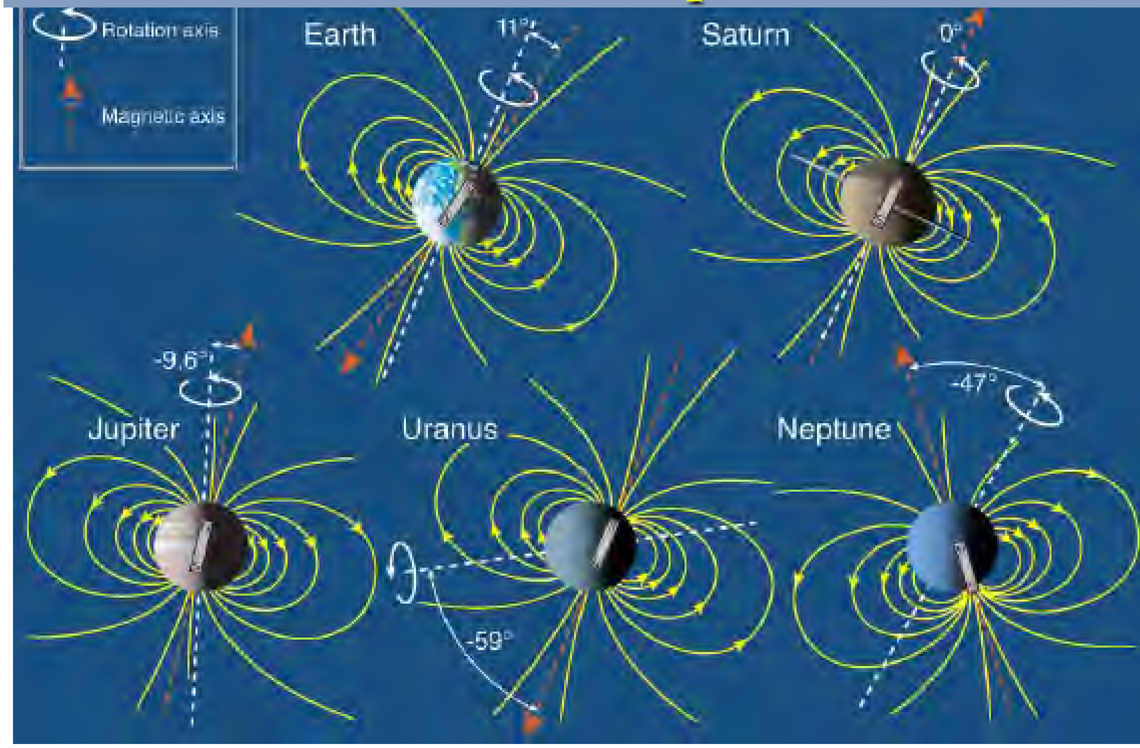
How Magnetic Fields Can Play a Role in ExoClimes.... .... perhaps

- Signature of internal state
- Deflection of energetic particles from planet
- Delivery of energetic particles to the surface
- Delivery of energy to atmosphere – bombardment, joule heating
- Stripping of outer atmosphere

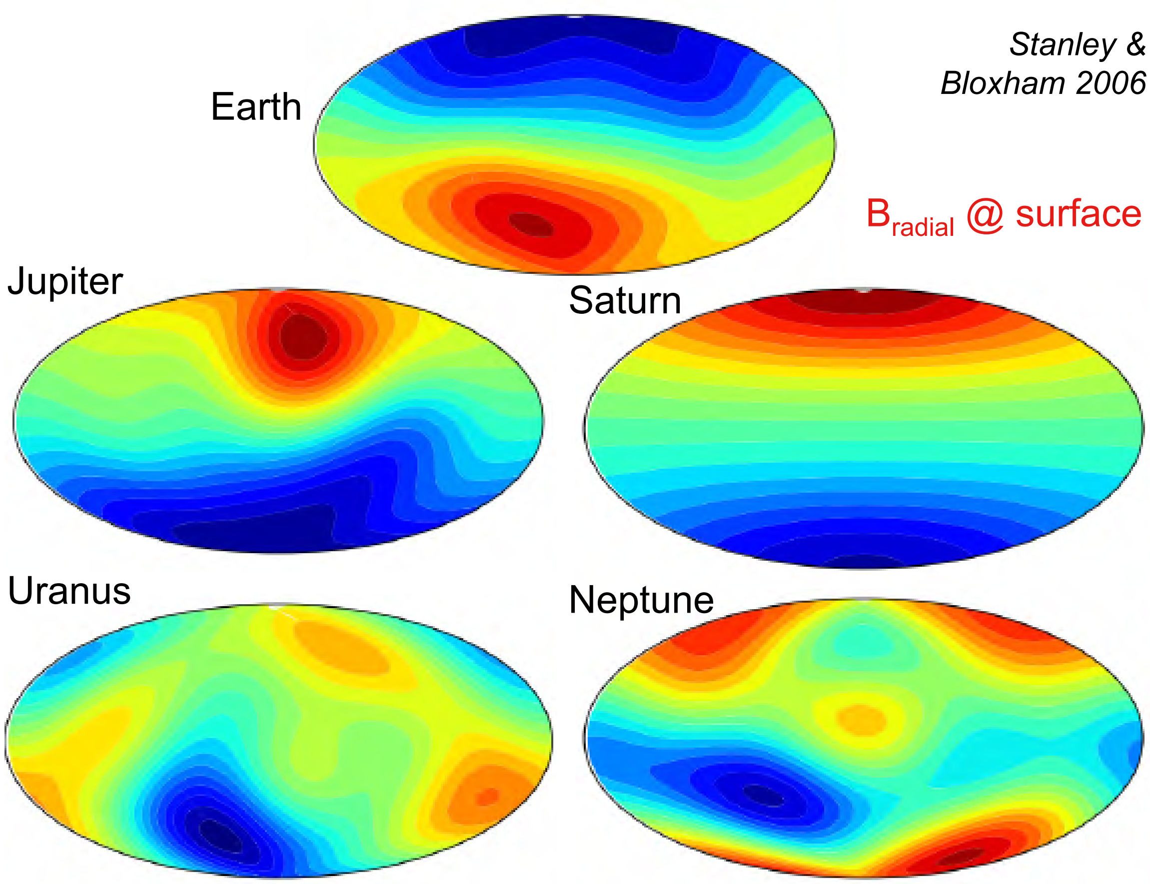


Bottom line: Atmosphere protects biota from nasty energetic particles. The magnetosphere (mostly) protects the atmosphere.

Tilts and Obliquities



Offset Tilted Dipole Approximation



Magnetic Potential
3-D harmonics

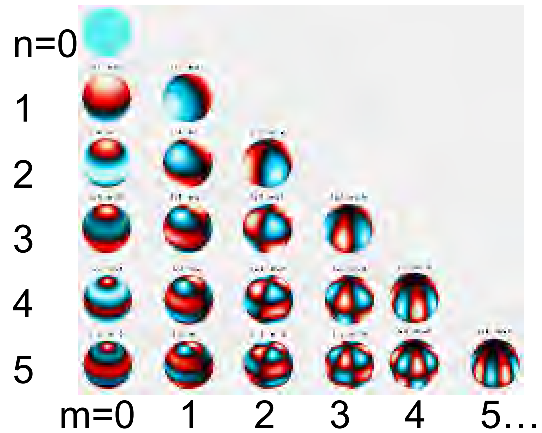
$$\mathbf{B} = -grad\ V$$

$$V = R_p \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(\frac{R_p}{r}\right)^{n+1} P_n^m(\cos\theta)\left(g_n^m \cos m\lambda + h_n^m \sin m\lambda\right), \qquad (7.1)$$

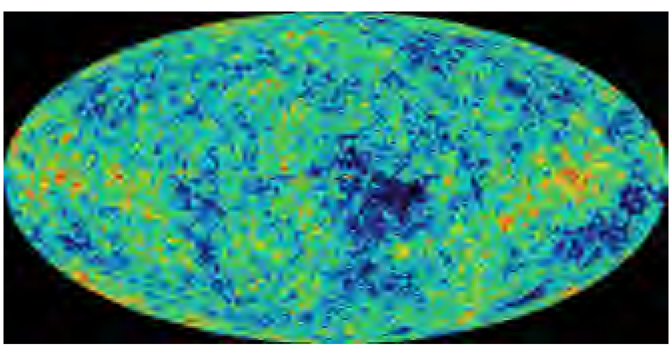
coefficients - constants

functions

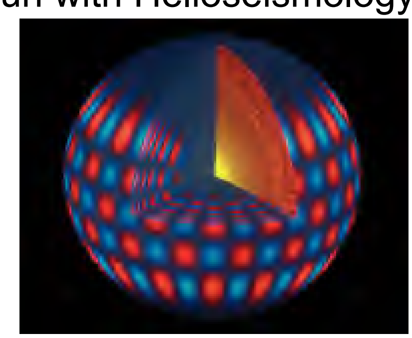
$$P_0^0(\cos\theta) = 1$$
$$P_1^0(\cos\theta) = \cos\theta$$
$$P_1^1(\cos\theta) = -\sin\theta$$
$$P_2^0(\cos\theta) = \tfrac{1}{2}(3\cos^2\theta - 1)$$
$$P_2^1(\cos\theta) = -3\cos\theta\sin\theta$$
$$P_2^2(\cos\theta) = 3\sin^2\theta$$
$$P_3^0(\cos\theta) = \tfrac{1}{2}(5\cos^3\theta - 3\cos\theta)$$



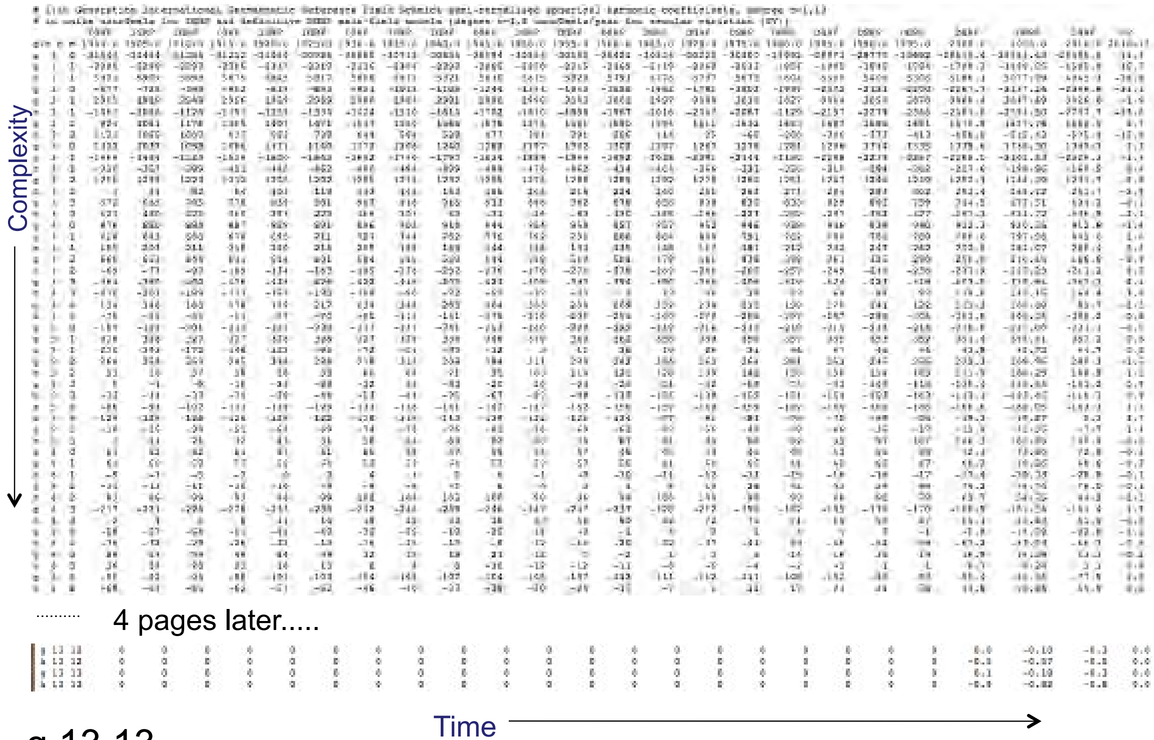
Same technique used to model cosmic microwave background



or interior of Sun with Helioseismology…



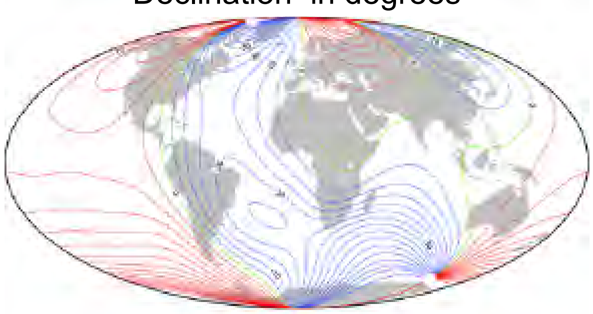
Earth - International Geomagnetic Reference Field



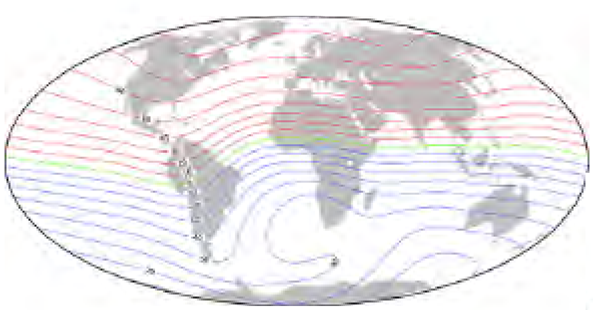
g 13 13
h 13 13

http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html
http://onlinelibrary.wiley.com/doi/10.1111/j.1365-246X.2010.04804.x/full

Declination in degrees

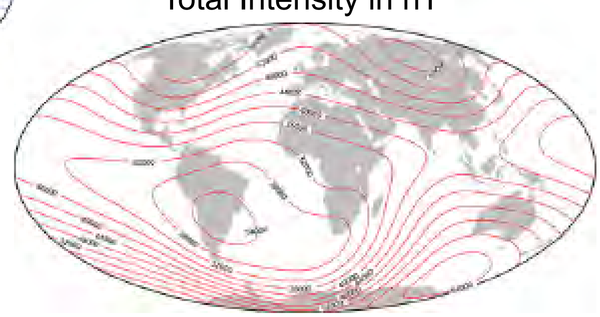


International Geomagnetic Reference Field 2010

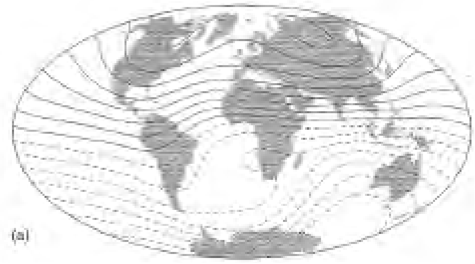


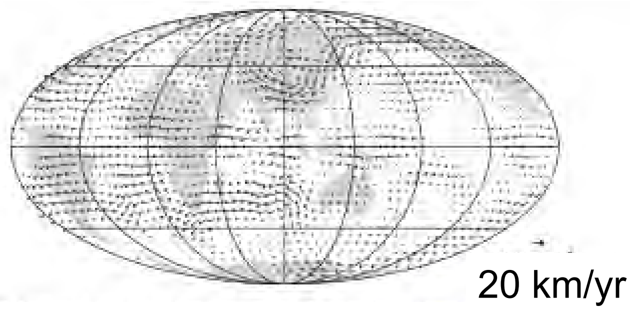
Inclination in degrees

Total Intensity in nT



Br surface





20 km/yr

1. From accurate measurement of surface field:

2. Extrapolate to core-mantle boundary = dynamo

Br core-mantle boundary

lines for outward flux. Contour intervals are arbitrary and different in the two panels.

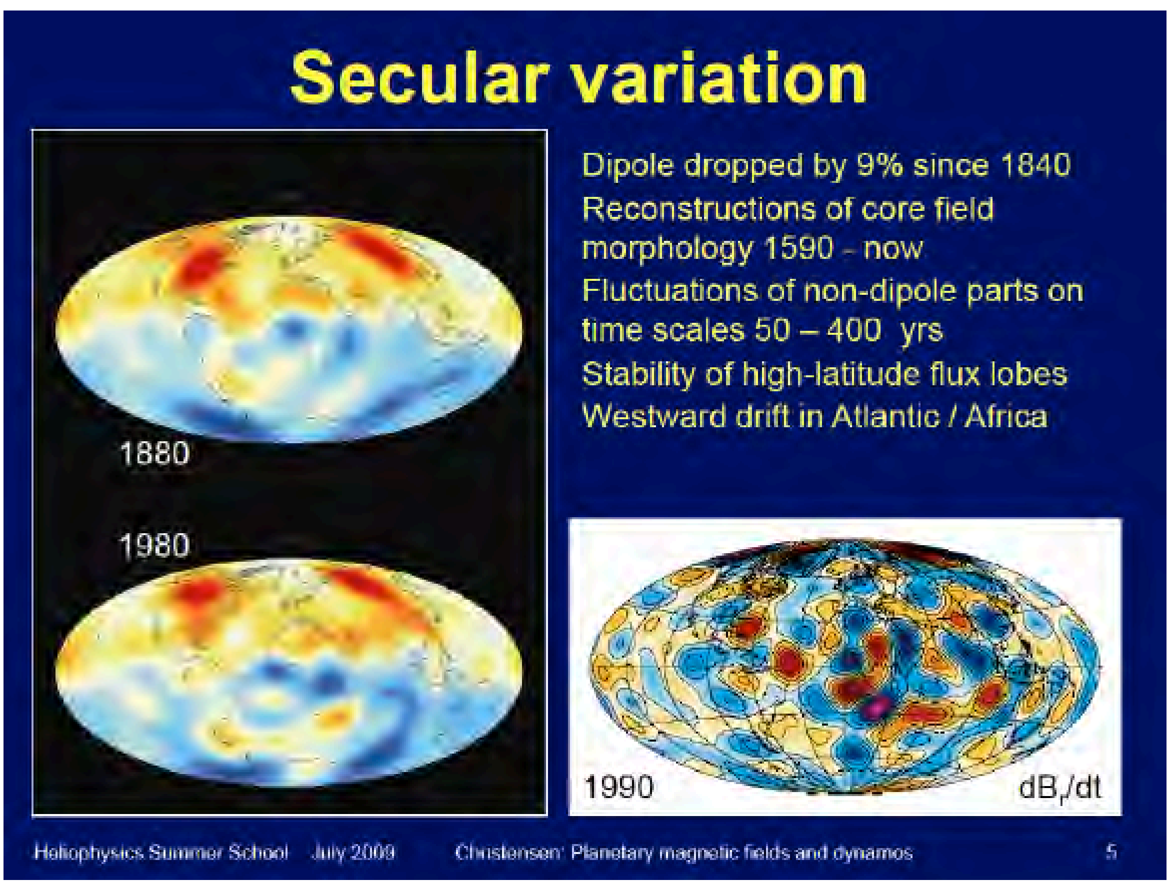
3. Derive core flows

4. Secular variation & reversals.....

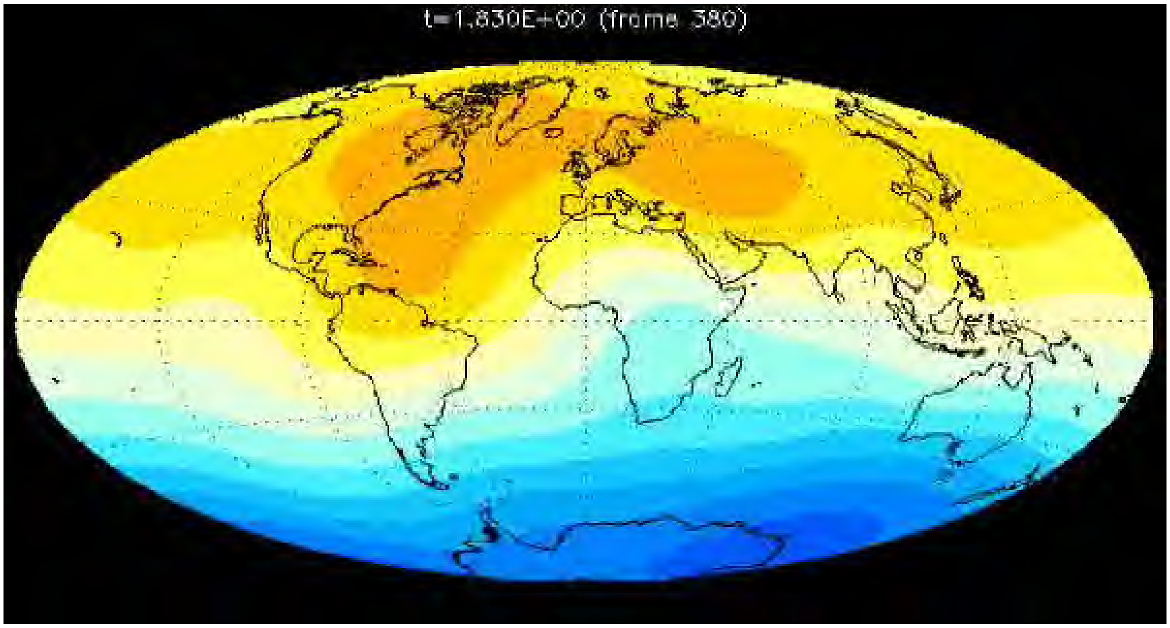
$$\frac{\partial B_r}{\partial t} = -\nabla_h \bullet (\mathbf{u}_h B_r)$$

h=horizontal
r=radial

Hulot et al. 2010



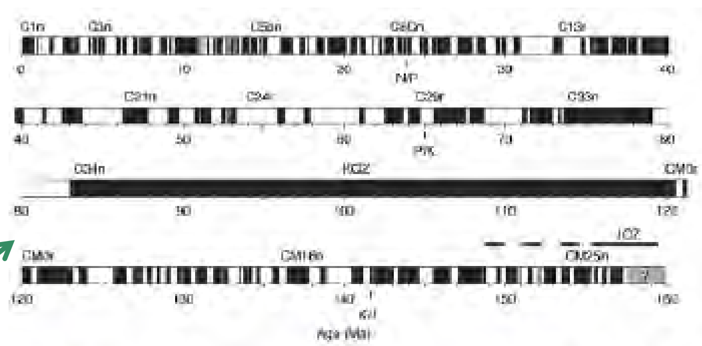
Br through a reversal



Hulot et al. 2010
Pavlov & Gallet 2005

Polarity reversals:

1. variable in duration and
2. rate



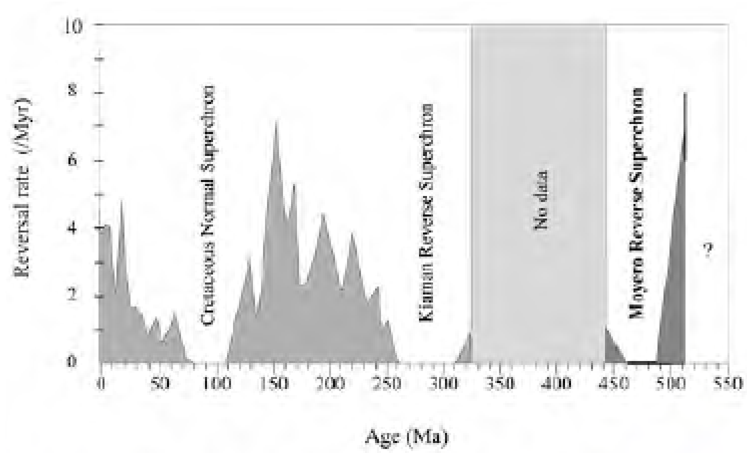
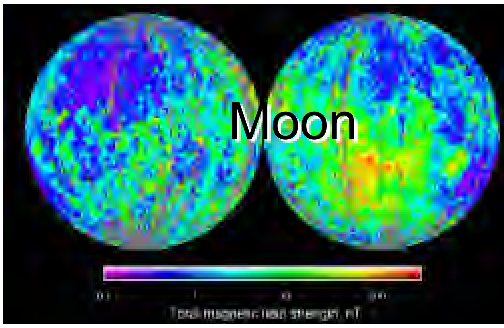
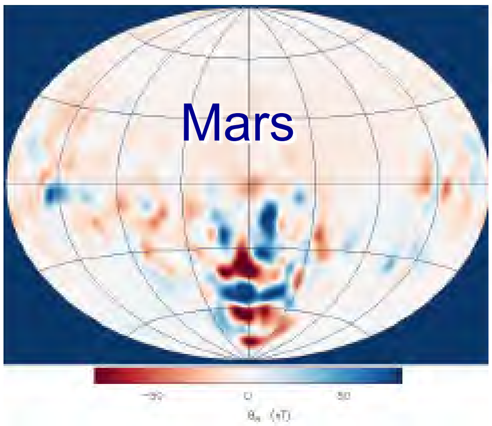
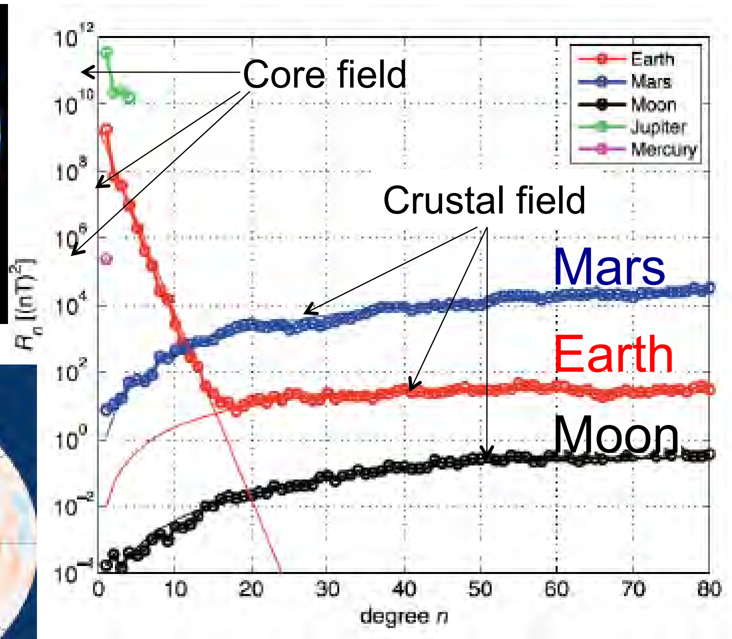


Fig. 29 Estimate of the reversal rate (in My^{-1}) for the time interval 0–500 Ma, where reversal rates are estimated by geological stage, rather than by using a moving window average (as in Fig. 28), to harmonize

Moon & Mars: All Crustal Remanent Magnetization







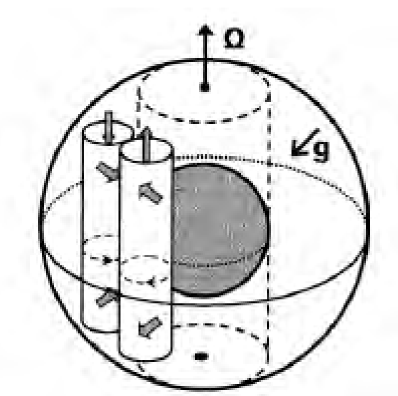
- Did Moon ever have dynamo?
- Mars' dynamo died >3.5 BYA.

Power spectra of the field of internal origin for the Earth (after Olsen et al. 2009a and Maus et al. 2008), Mars (after Cain et al.

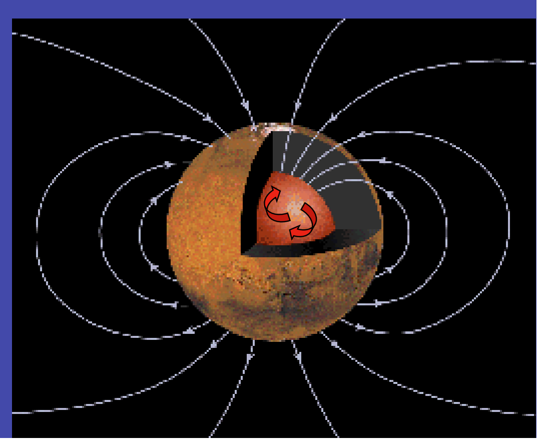
Stanley & Glatzmeier 2010; Christensen 2010

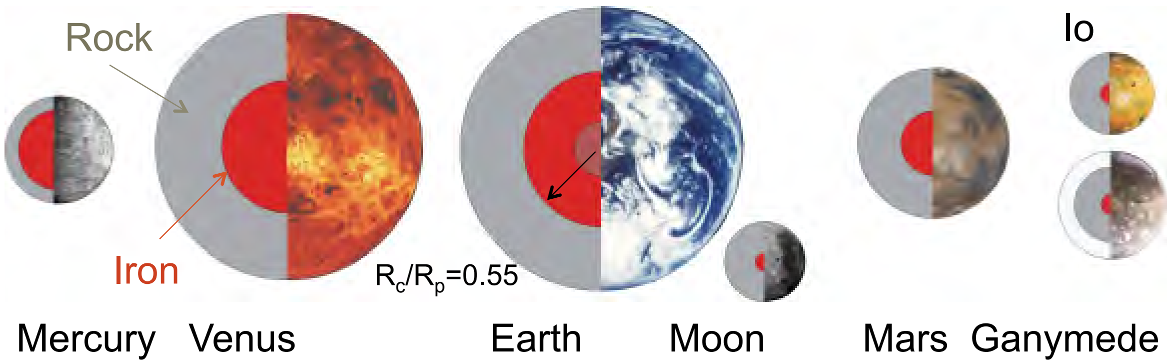
Planetary Dynamos

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



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

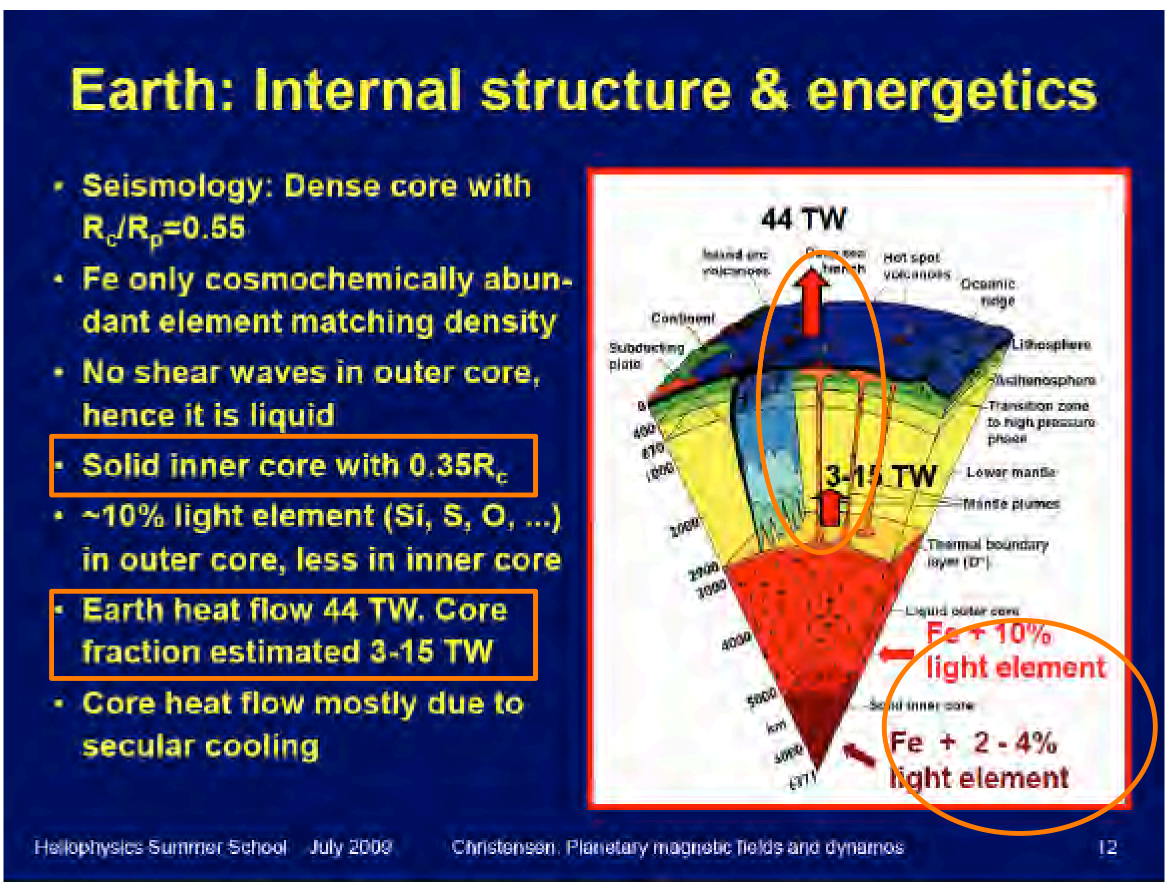


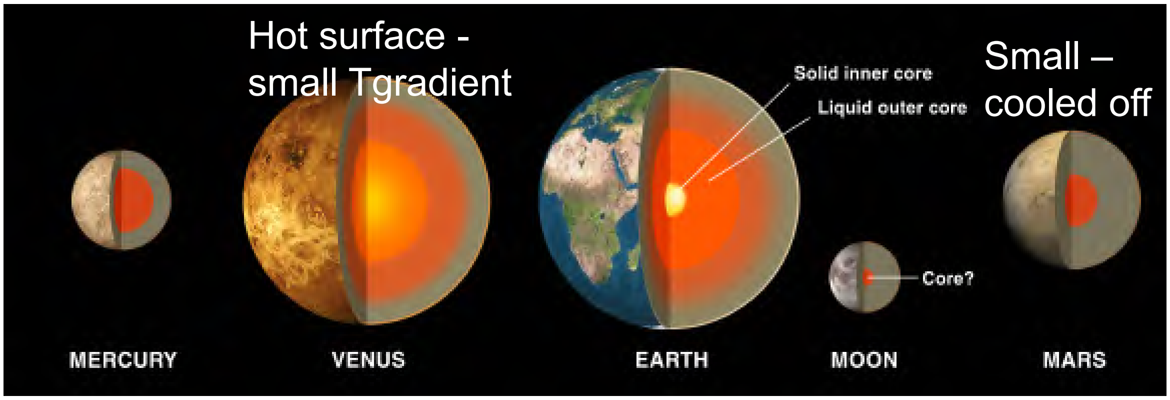


Planet	Dynamo	R_c/R_p	B_o [nT]
Mercury	Yes (?)	0.75	195
Venus	No	0.55	
Earth	Yes	0.55	31,000
Moon	No	0.2?	
Mars	No, but in past	0.5	
Ganymede	Yes	0.3?	720

What drives dynamos in tiny Mercury & Ganymede?

Why don't Venus or Mars have dynamos?



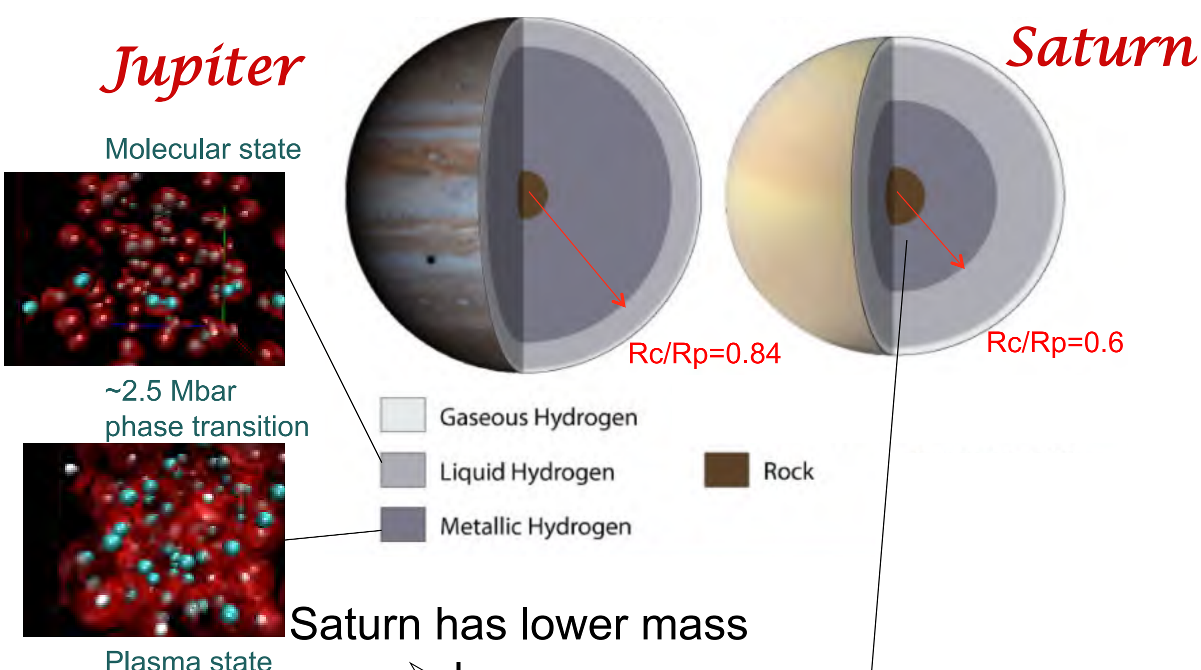


Why Don't Venus or Mars have Dynamos?

Stevensen 2010

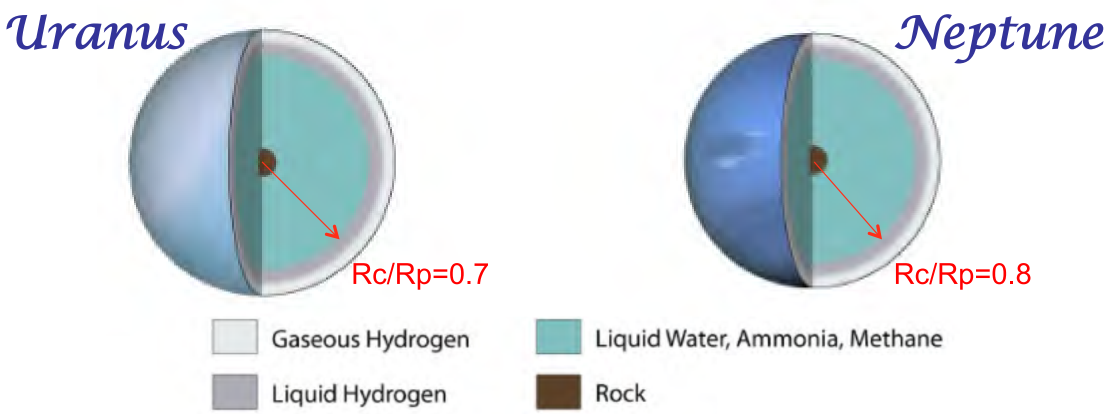
- Enough rotation – even for Venus
- Conducting fluid core – probably
- Lack of convection in core?

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



Saturn has lower mass

- lower pressures
- smaller region of metallic hydrogen
- weaker magnetic field

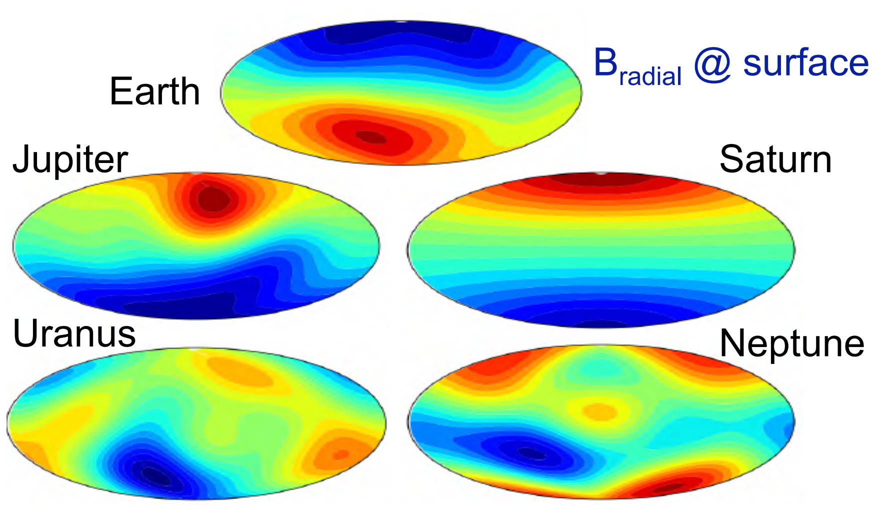


Uranus and Neptune have much less mass

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

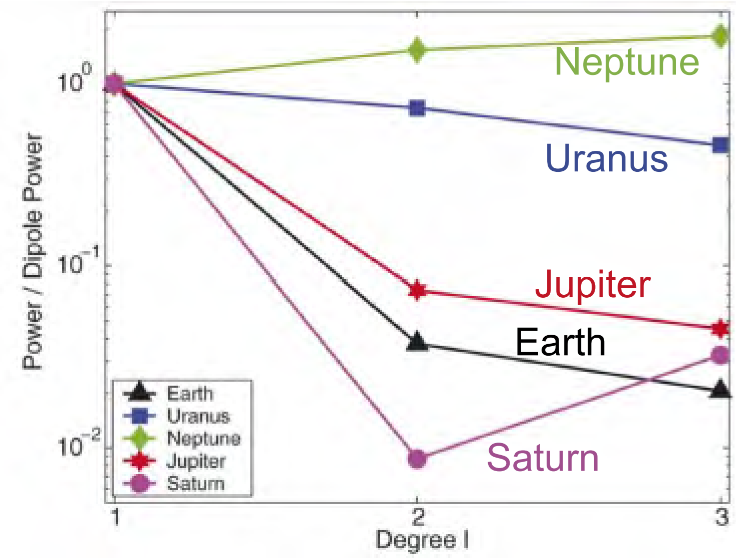
Planet	Rc/Rp	Bo [μT]	Tilt	Quad/ Dipole
Earth	0.55	31	+9.92°	0.04
Jupiter	0.84	428	-9.6°	0.10
Saturn	0.6	21	<-1°	0.02
Uranus	0.7	23	-59°	1.3
Neptune	0.8	14	-47°	2.7

Dipolar (Earth, Saturn)
Irregular (Uranus, Neptune)

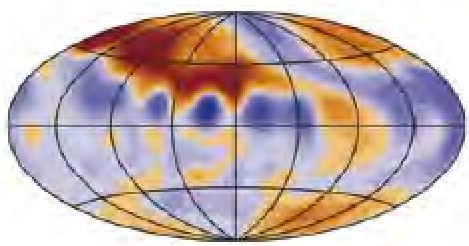


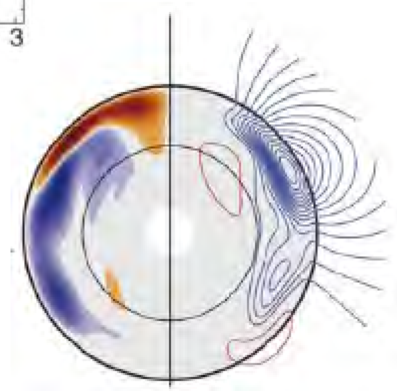
Stanley & Bloxham 2006

Stanley & Bloxham 2006

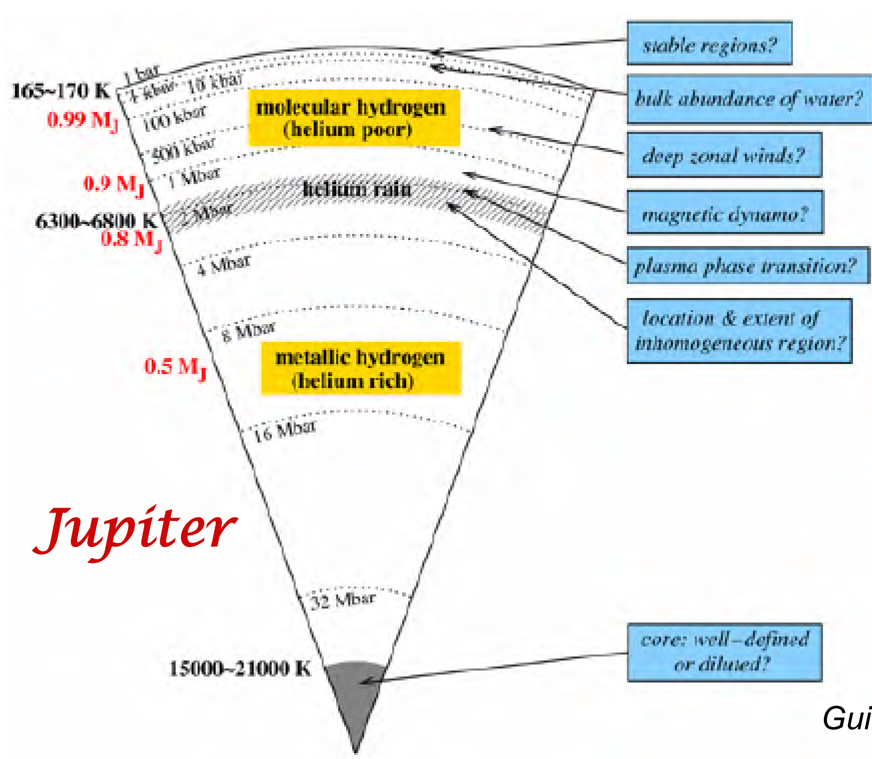


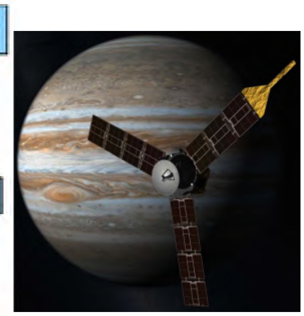
Modeling Uranus' & Neptune's non-dipolar fields with a thin-shell dynamo over a stratified core





Even with the Best Equation of State – Still lots of unknowns





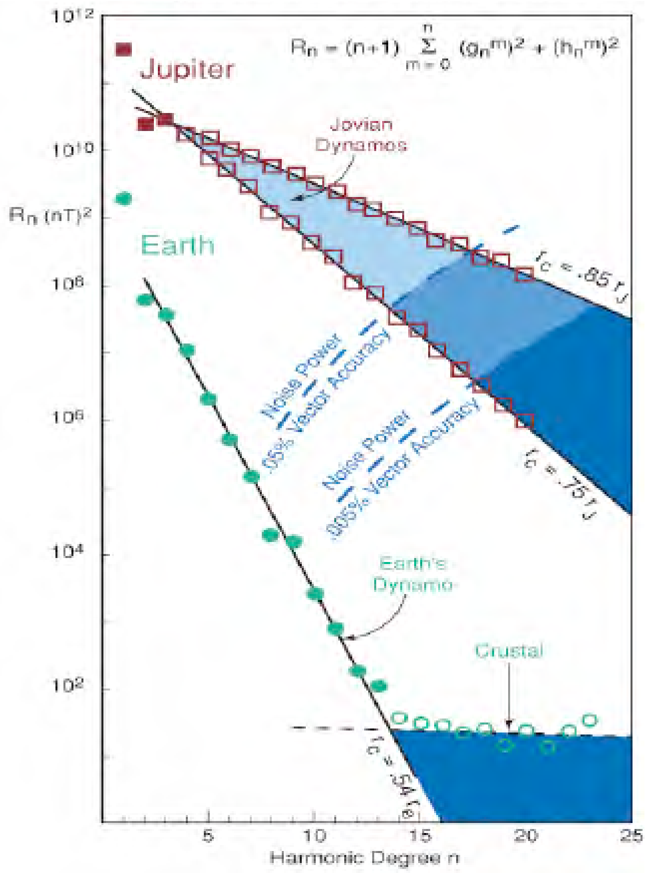
Juno

Launched Aug. 5th
Arrives Jul. 2016

Guillot et al. 2004

Magnetic Spectra of Earth and Jupiter

- Current knowledge of Jupiter is limited to n < 4
- Earth dynamo at n >14 is hidden by crustal field
- Juno will measure out to n ~ 20
- Determine spectral shape, dynamo radius, and secular variations



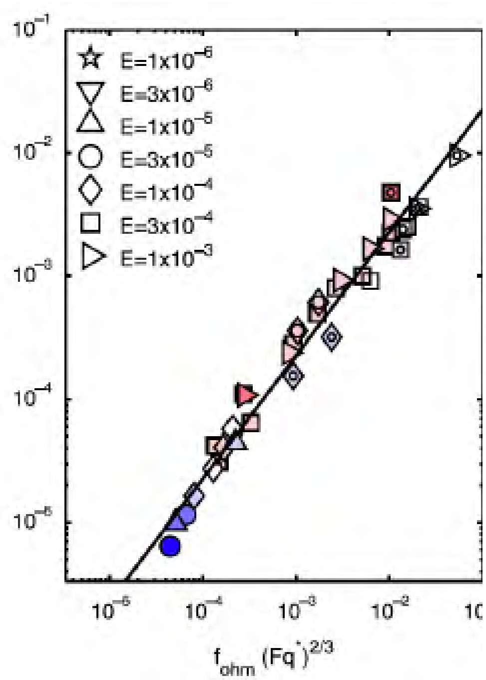
Dynamo Scaling Laws

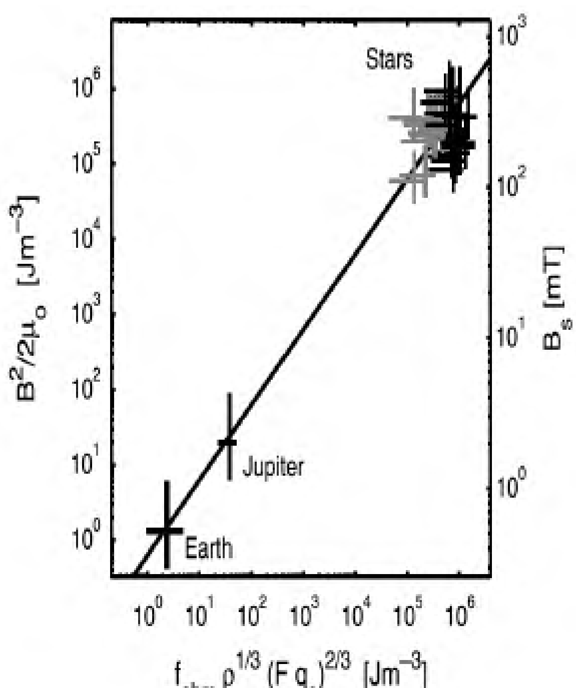
Christensen 2010

Earth Models

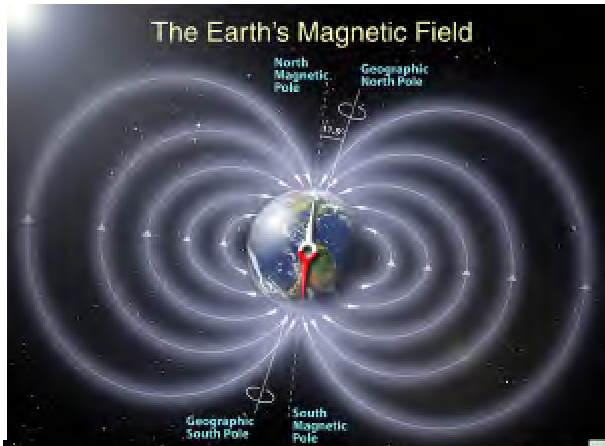
Planets & Stars

Field Energy Density

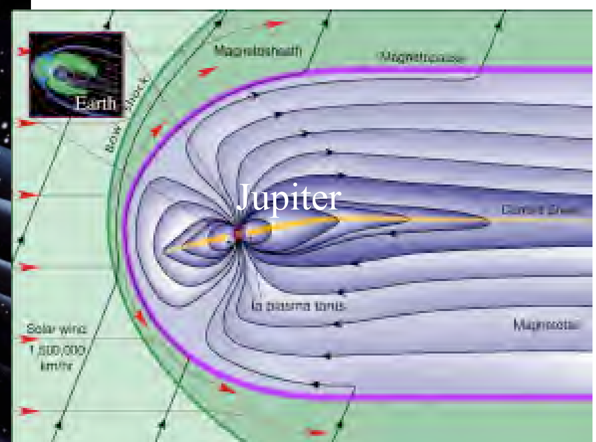


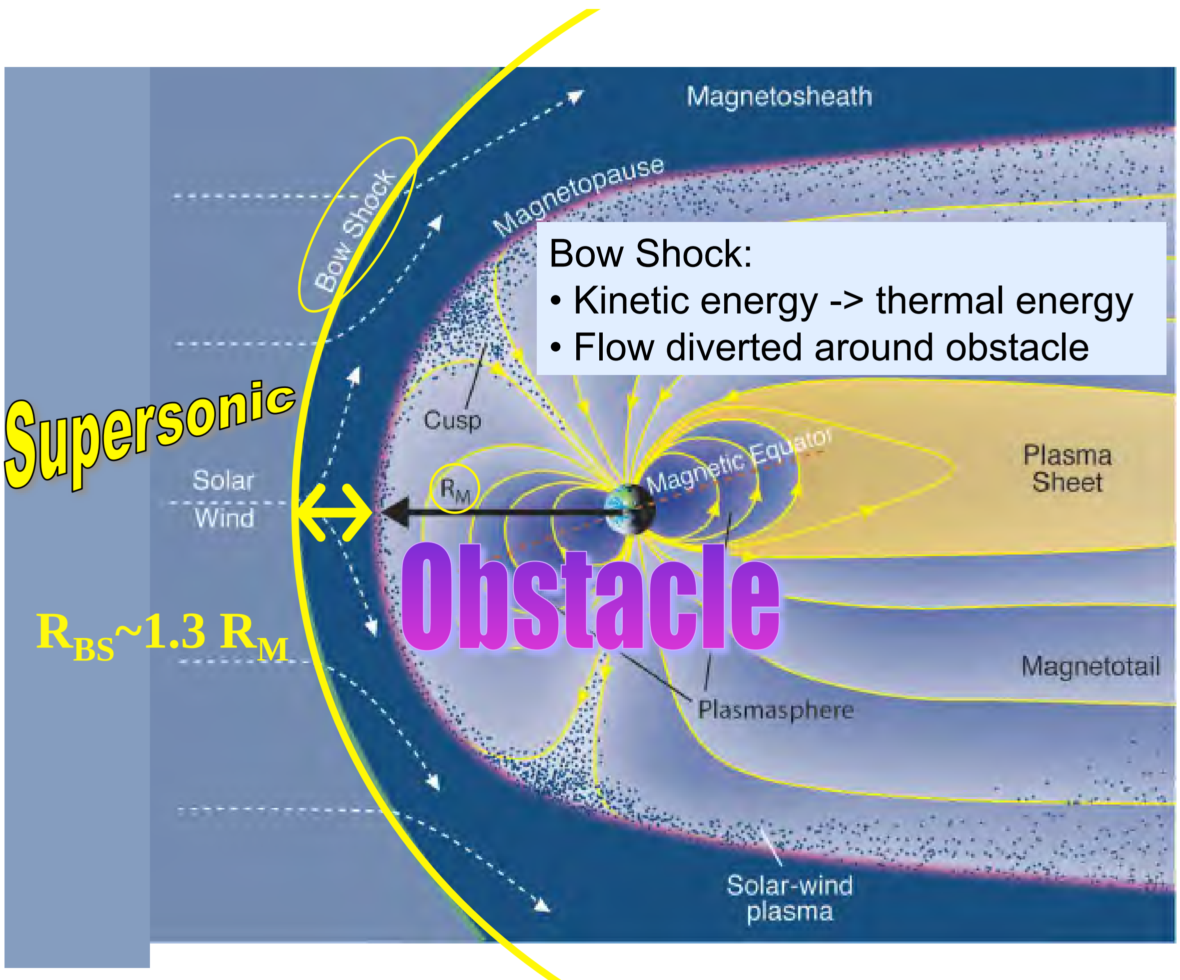


Core Heat Flux



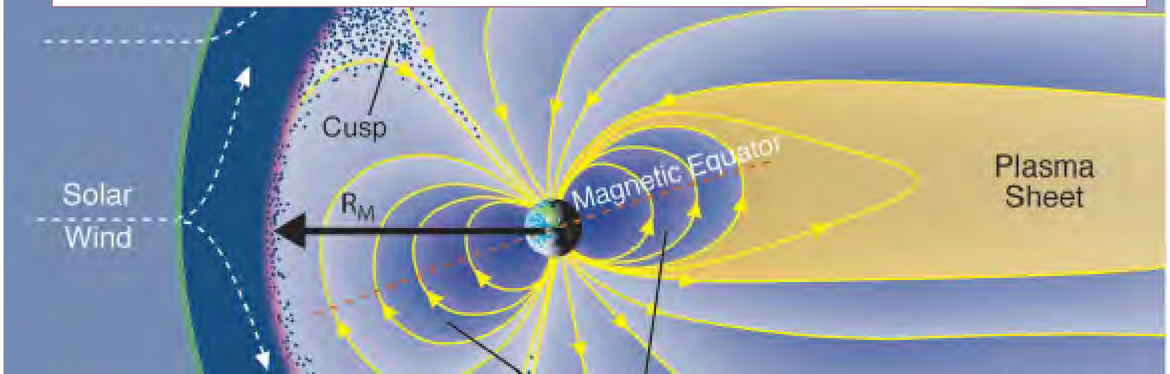
Now we have magnetic fields.... what about magnetospheres?





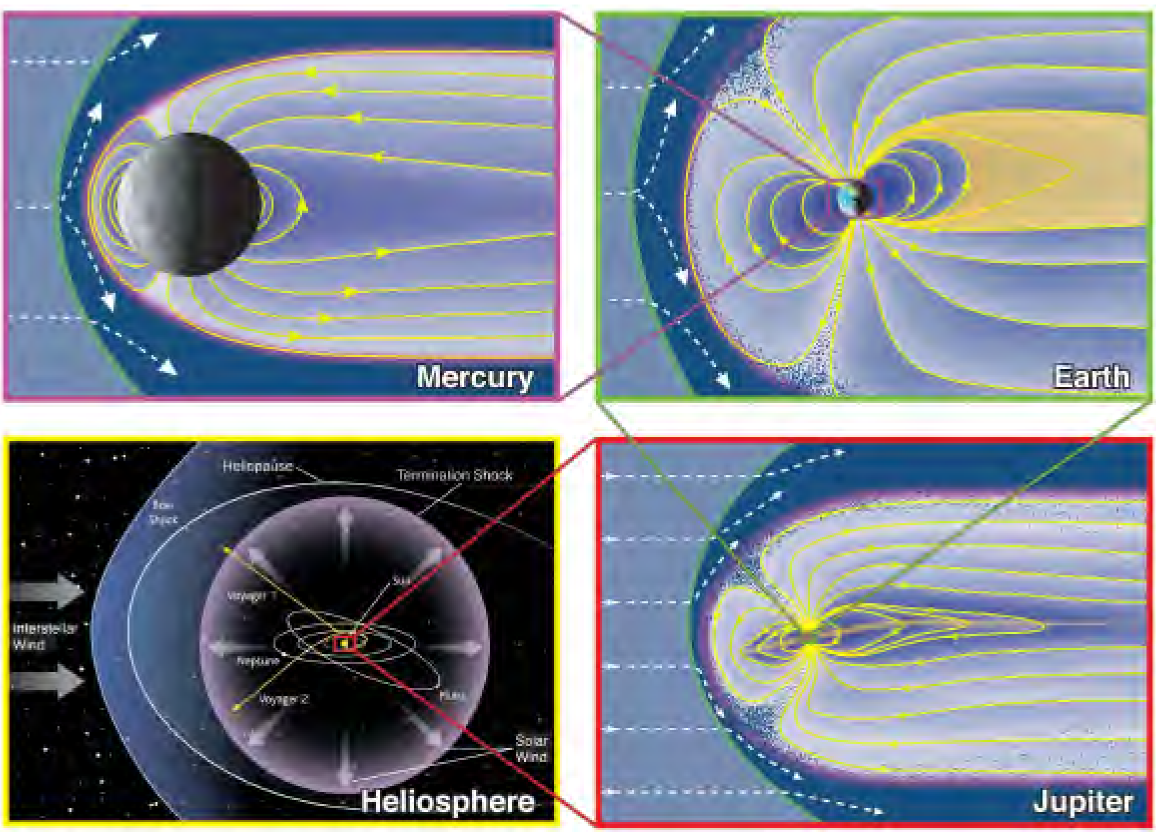
Dipole Magnetic Field in Solar Wind

SW Ram Pressure ⟷ Magnetic Pressure



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

Chapman-Ferraro Distance



Extreme solar wind conditions -> exposed planet

Slavin et al. 2010

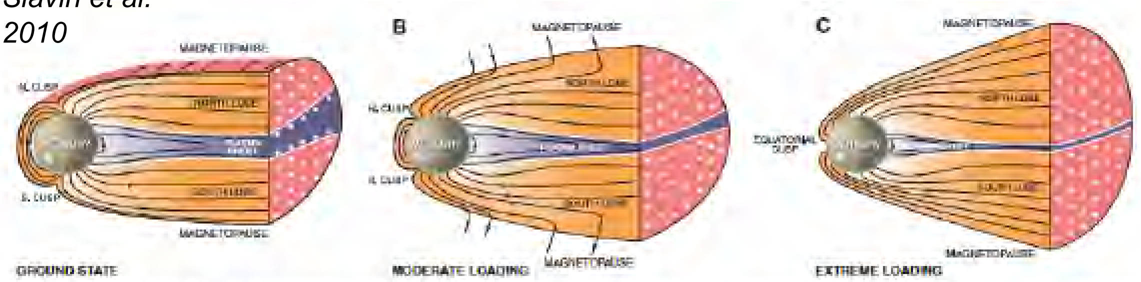
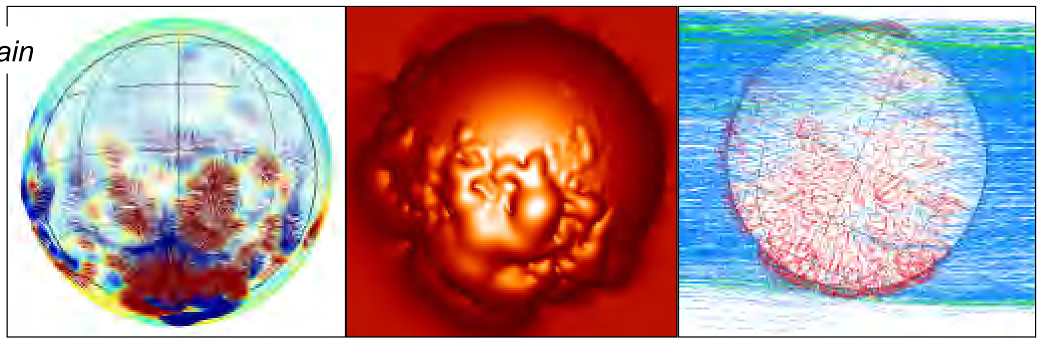
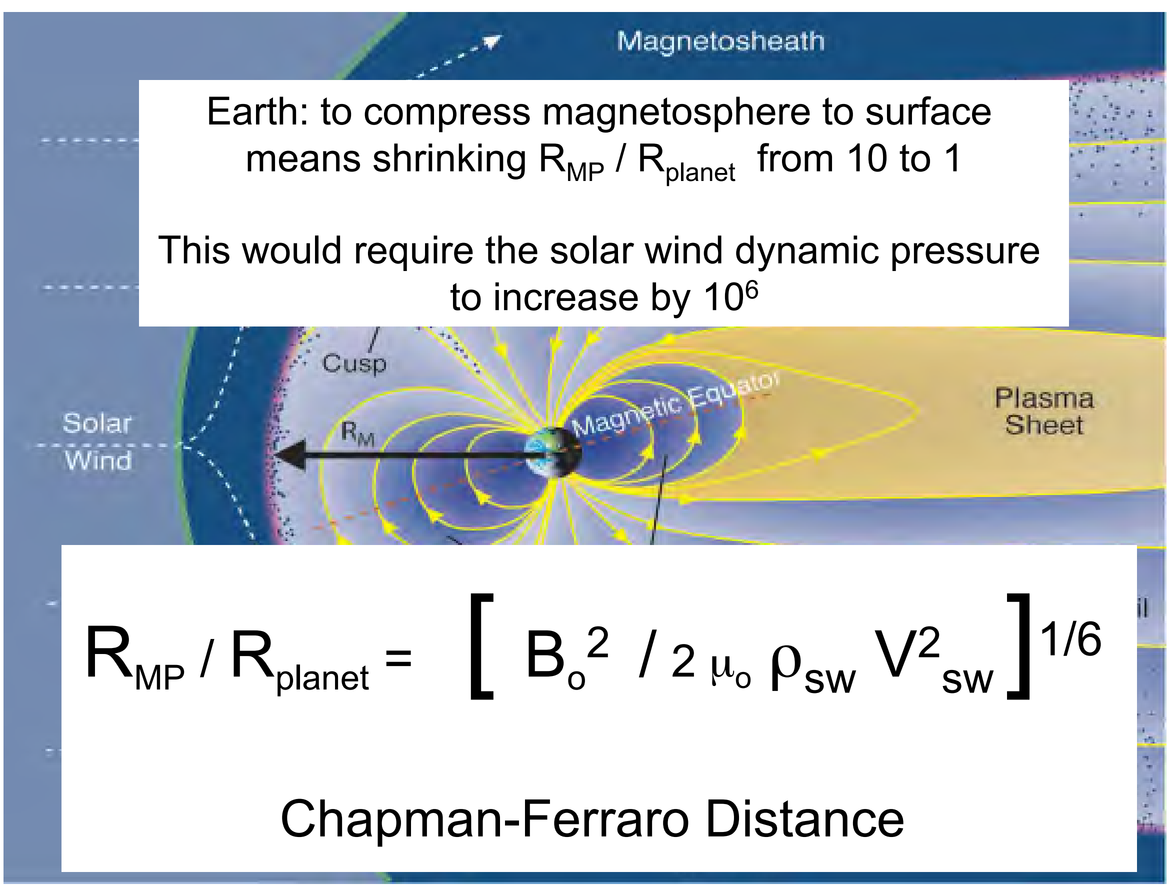


Fig. 4. Schematic view of Mercury's magnetosphere in its ground state (A) and during moderate (B) and extreme (C) tail loading observed by MESSENGER on 29 September 2009.

Weak, irregular field -> bumpy surface + changing topology

David Brain





Earth: to compress magnetosphere to surface means shrinking R_{MP} / R_{planet} from 10 to 1

This would require the solar wind dynamic pressure to increase by 10^6

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

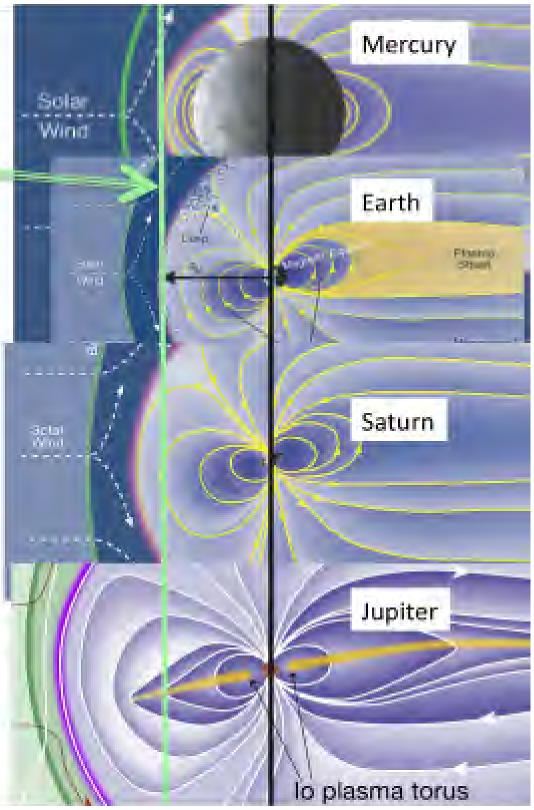
Chapman-Ferraro Distance

Magnetospheres scaled by stand-off distance of dipole field

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

Inflated magnetospheres of Jupiter & Saturn due to HOT PLASMAS

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



Earth ~ Dipole

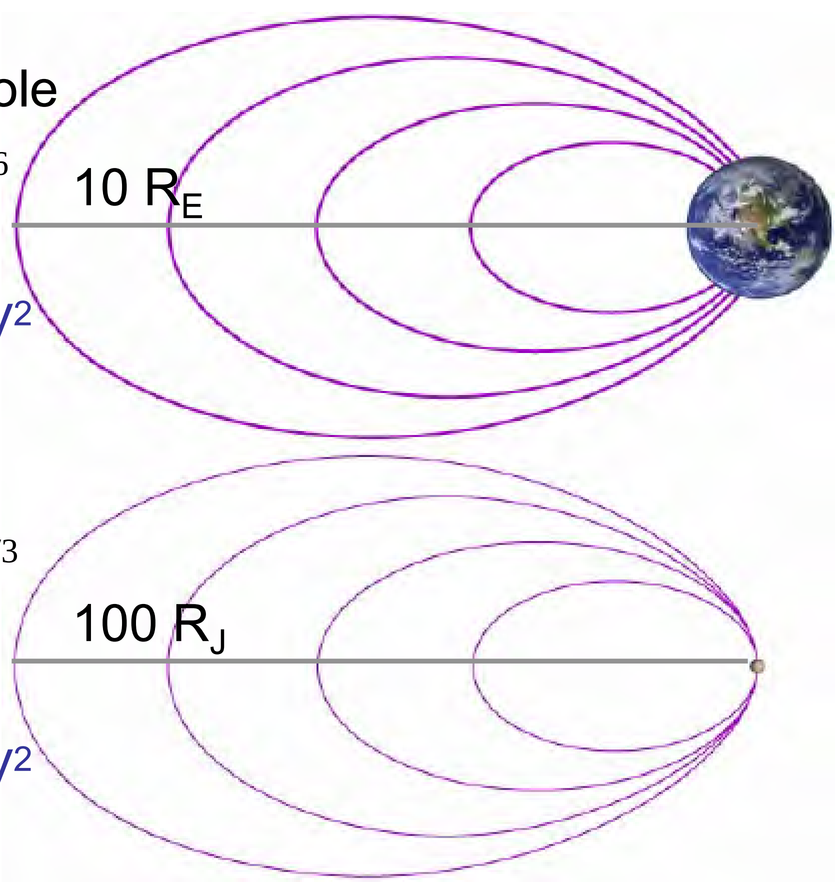
$R_{mp} \sim (\rho V^2)^{-1/6}$

solar wind ρV^2

Jupiter

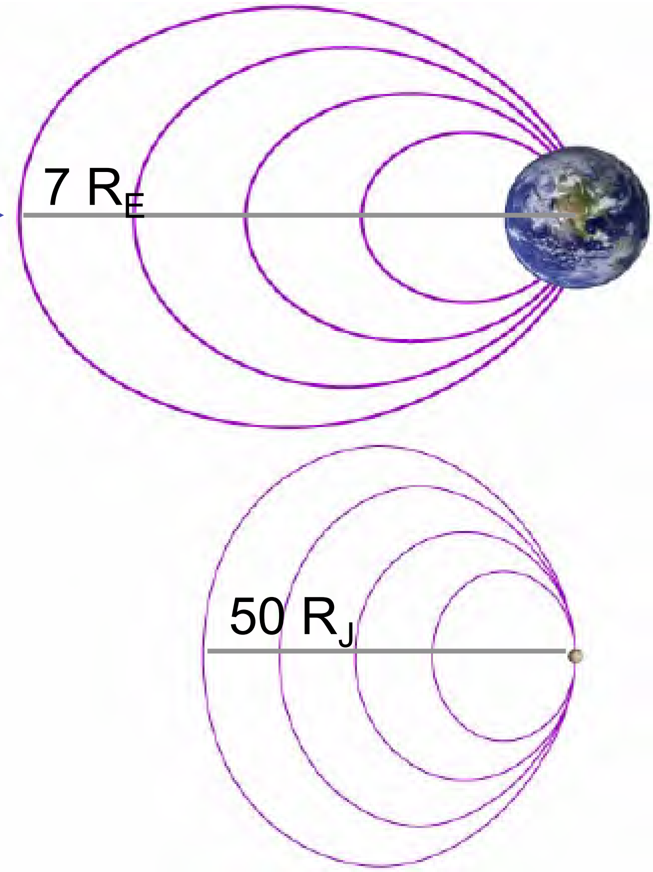
$R_{mp} \sim (\rho V^2)^{-1/3}$

solar wind ρV^2



Earth ~ Dipole

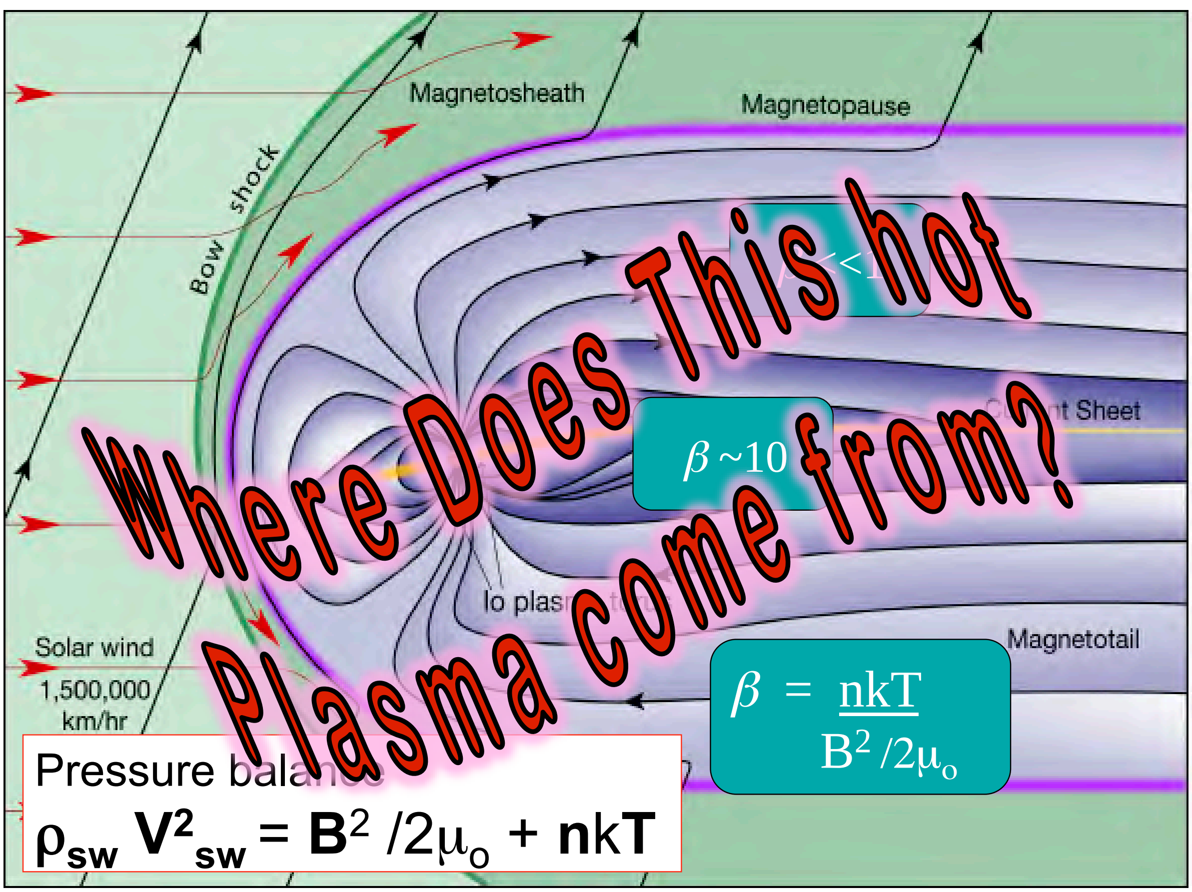
R_{mp} -> 0.7 R_{MP}

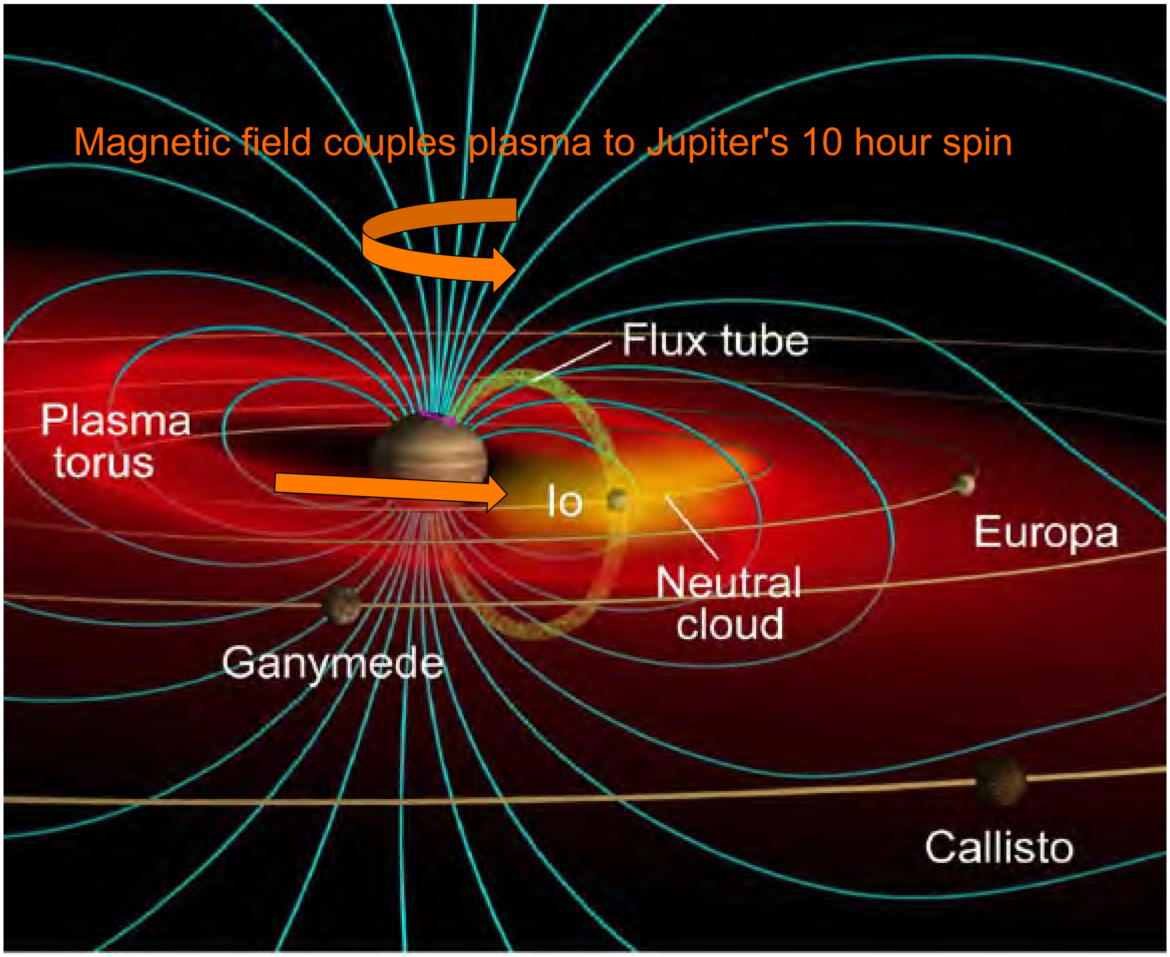


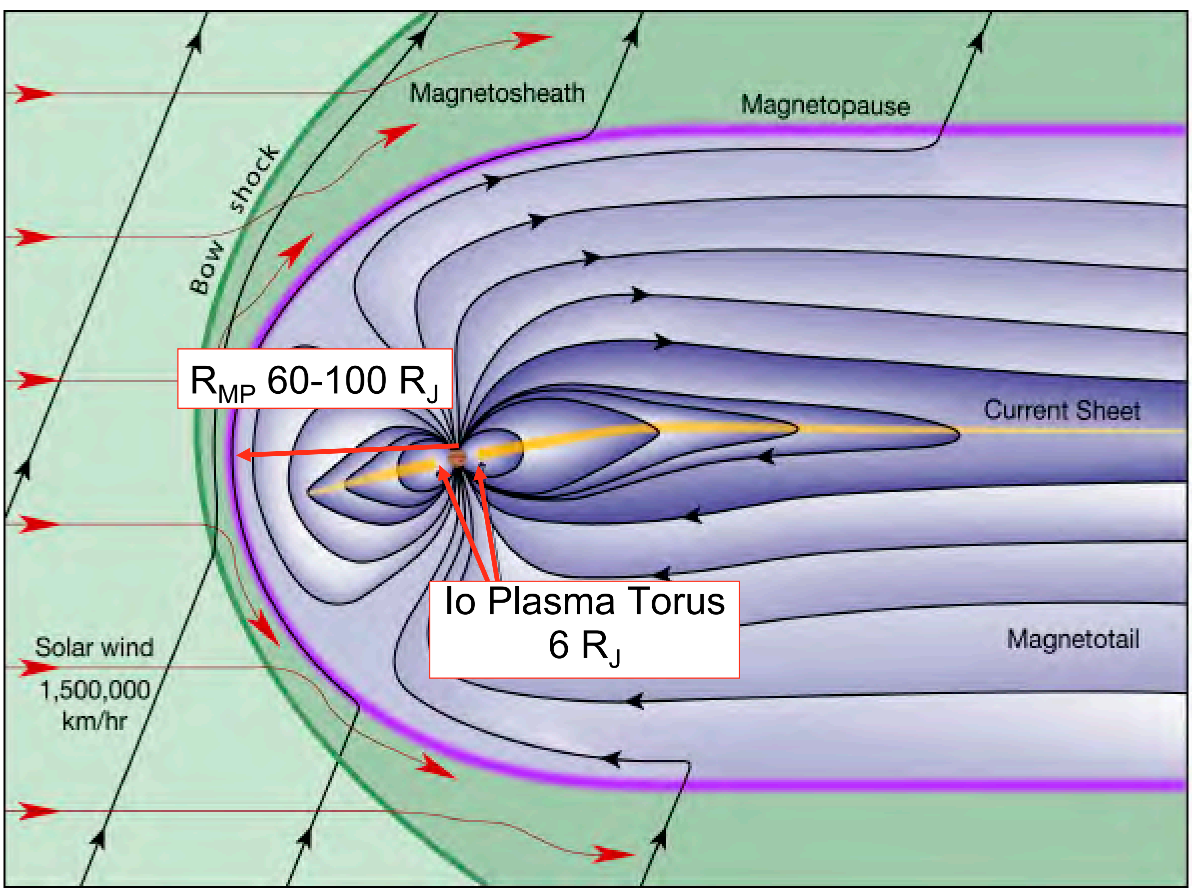
x10 Solar wind pressure

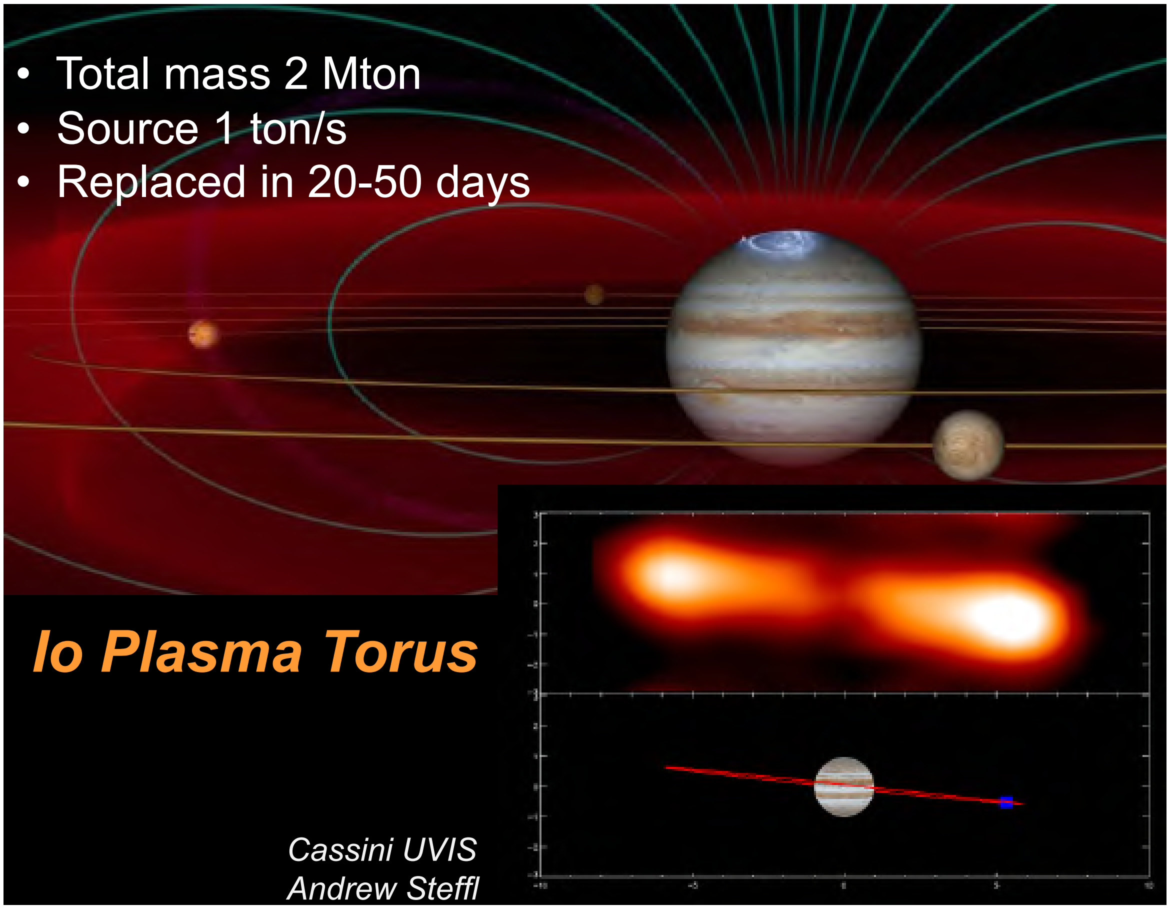
Jupiter

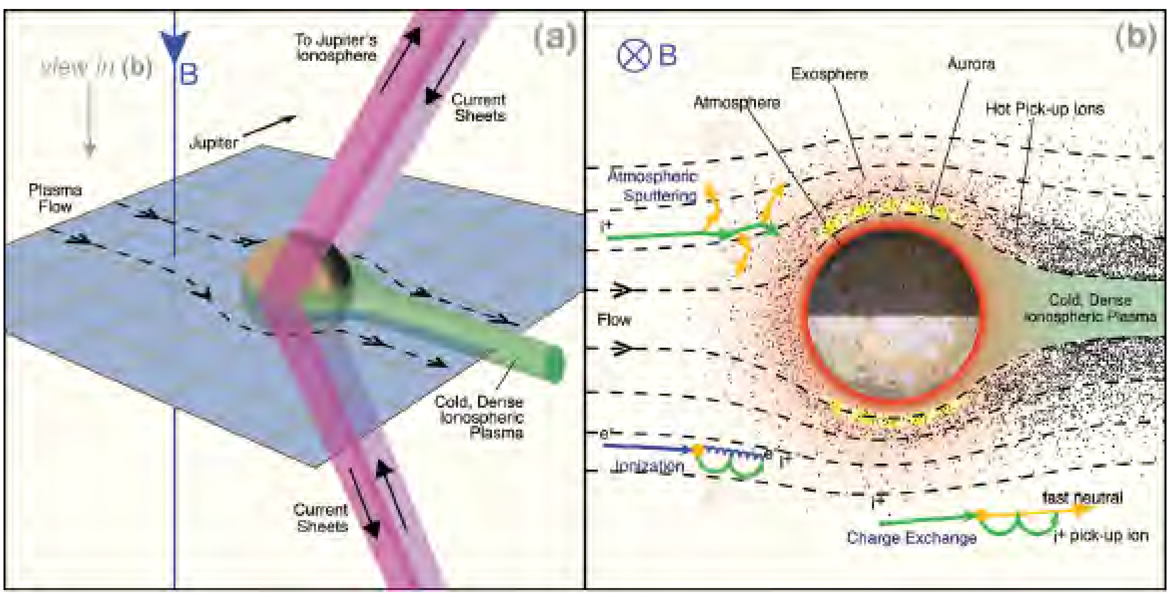
R_{mp}->0.5 R_{MP}




Magnetic field couples plasma to Jupiter's 10 hour spin
Flux tube
Plasma torus
Io
Europa
Neutral cloud
Ganymede
Callisto


Magnetosheath
Magnetopause
Bow shock
R_{MP} 60-100 R_J
Current Sheet
Io Plasma Torus
6 R_J
Solar wind
1,500,000
km/hr
Magnetotail



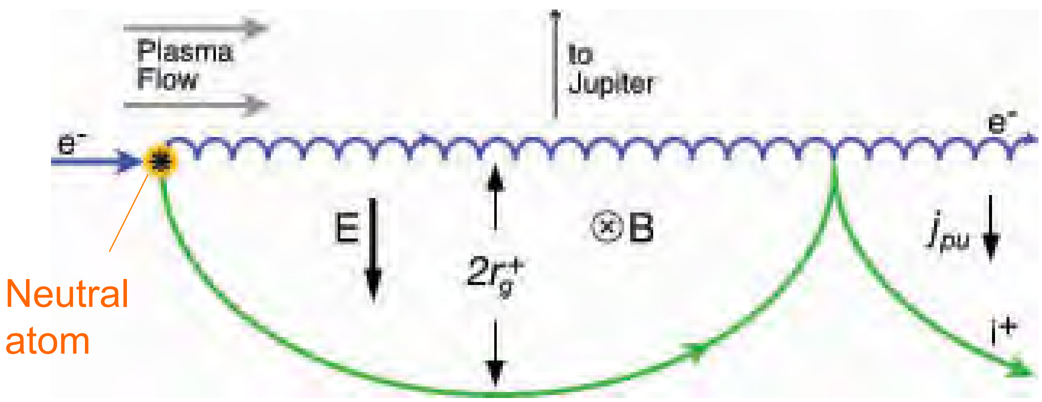


• Strong electrodynamic interaction
• Mega-amp currents between Io and Jupiter

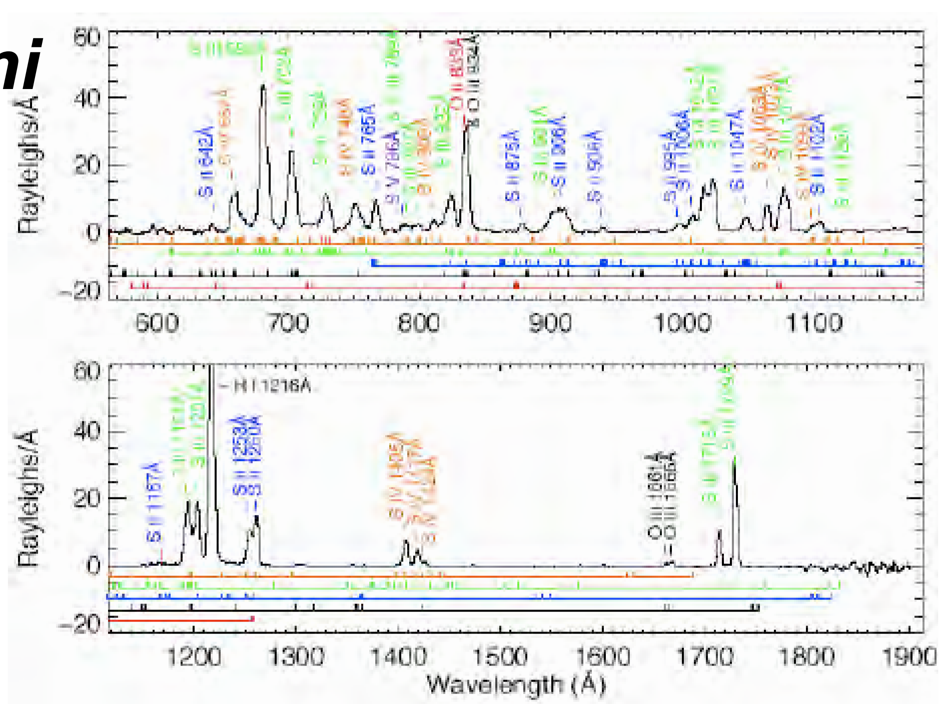
• Plasma interaction with Io's atmosphere
• Heated atmosphere escapes
• ~20% plasma source local

Ion Pick Up

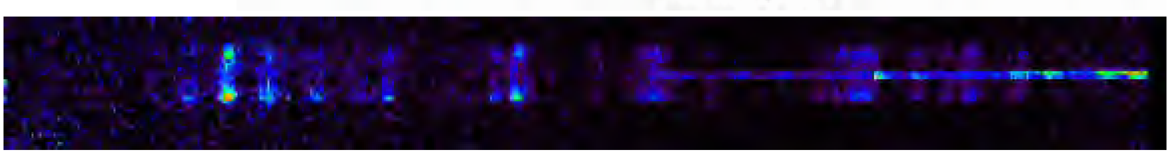
- The magnetic field couples the plasma to the spinning planet
- New ions pick up thermal speed of of plasma flow in neutral rest frame

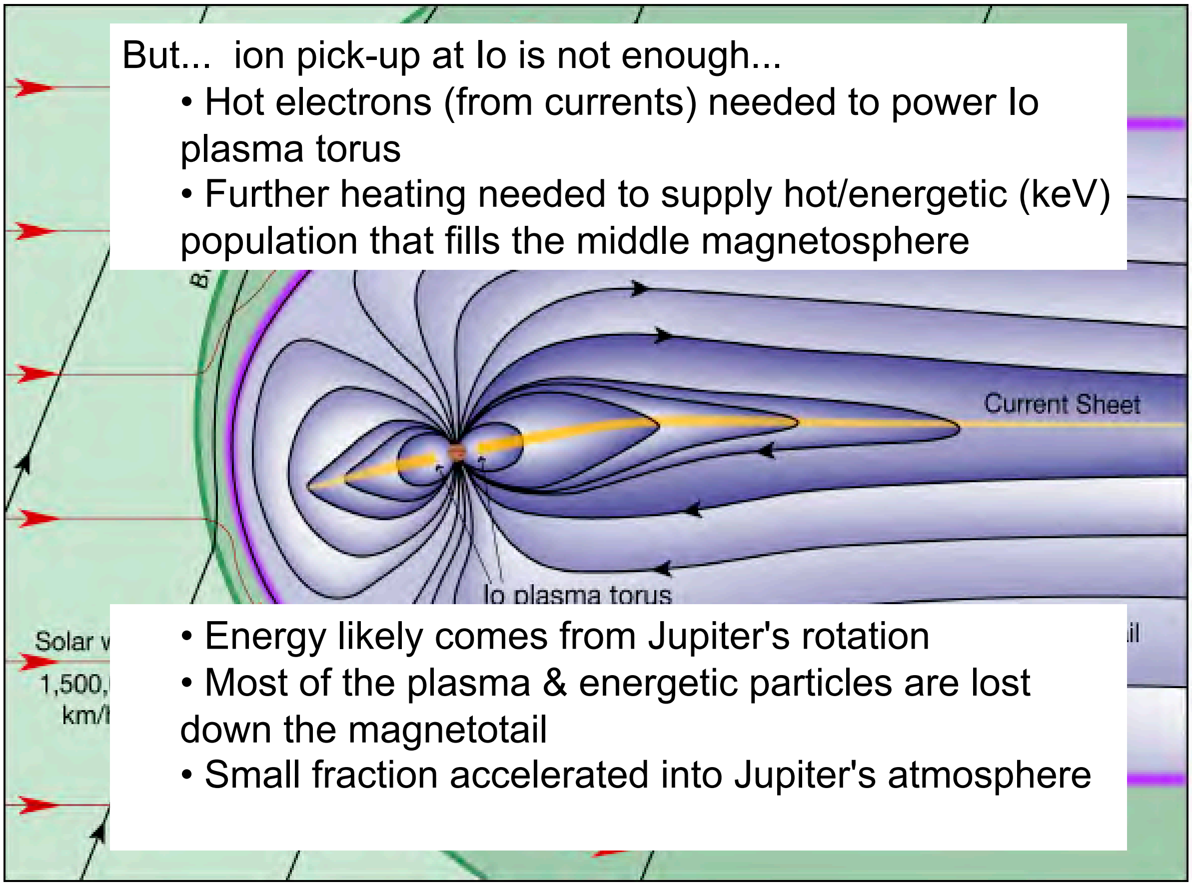


Cassini
UVIS



Steffl et al. 2006,2008





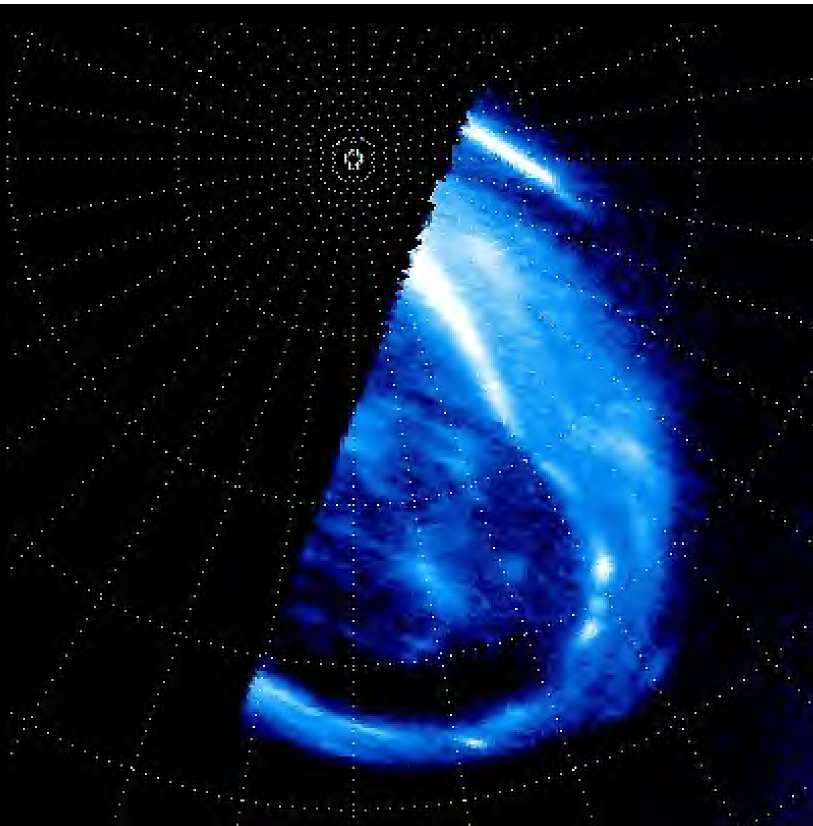
But... ion pick-up at Io is not enough...

- Hot electrons (from currents) needed to power Io plasma torus
- Further heating needed to supply hot/energetic (keV) population that fills the middle magnetosphere

- Energy likely comes from Jupiter's rotation
- Most of the plasma & energetic particles are lost down the magnetotail
- Small fraction accelerated into Jupiter's atmosphere

Jupiter's Aurora - The Movie

Fixed magnetic co-ordinates rotating with Jupiter

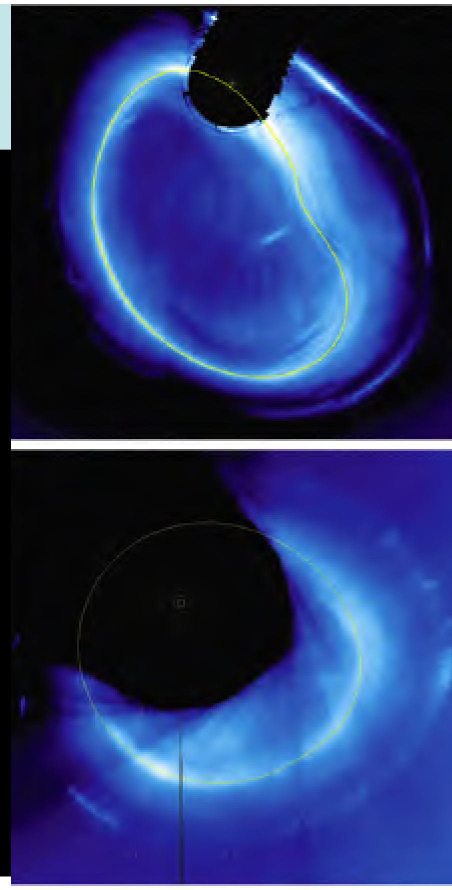


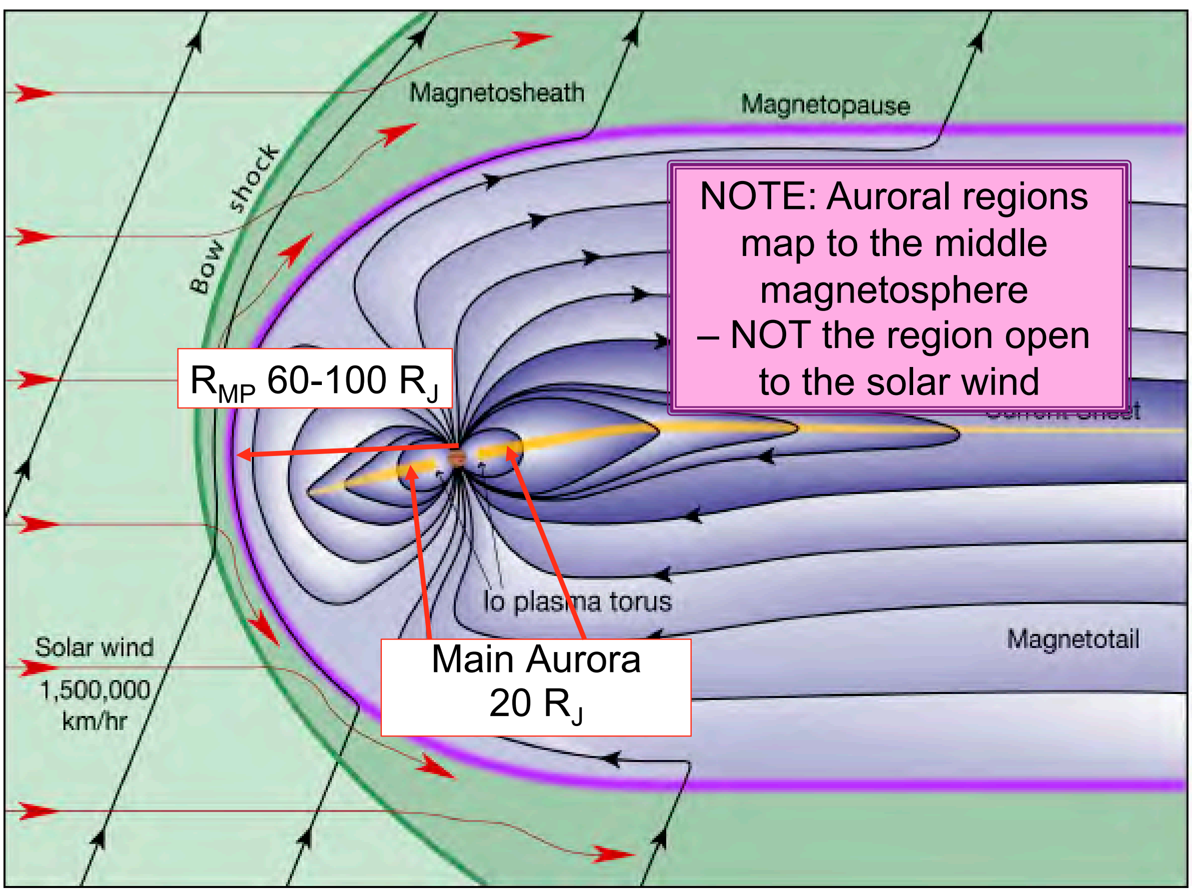
Clarke et al.
Grodent et al.
HST

Main Aurora

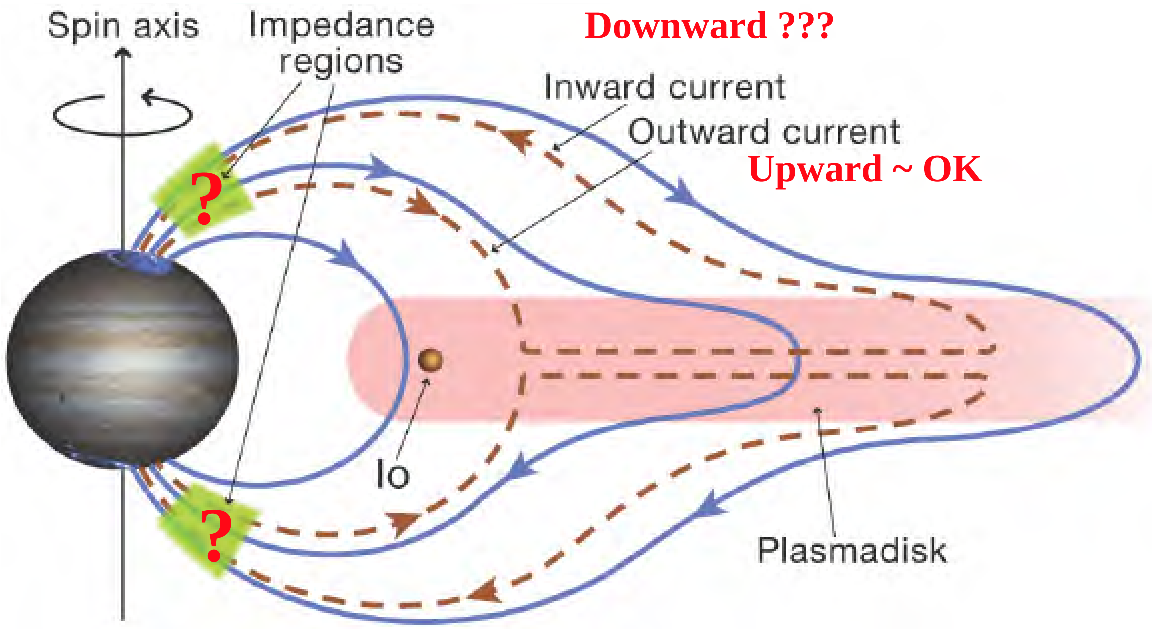
- Shape constant, fixed in magnetic co-ordinates
- Magnetic anomaly in north
- Steady intensity
- ~1° Narrow

Clarke et al., *Grodent et al.* HST

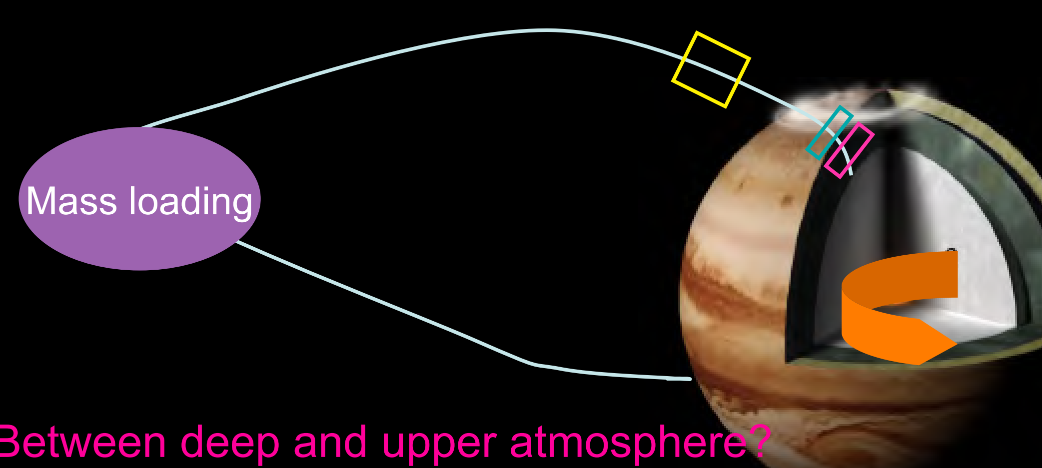




The aurora is the signature of Jupiter's attempt to spin up its magnetosphere



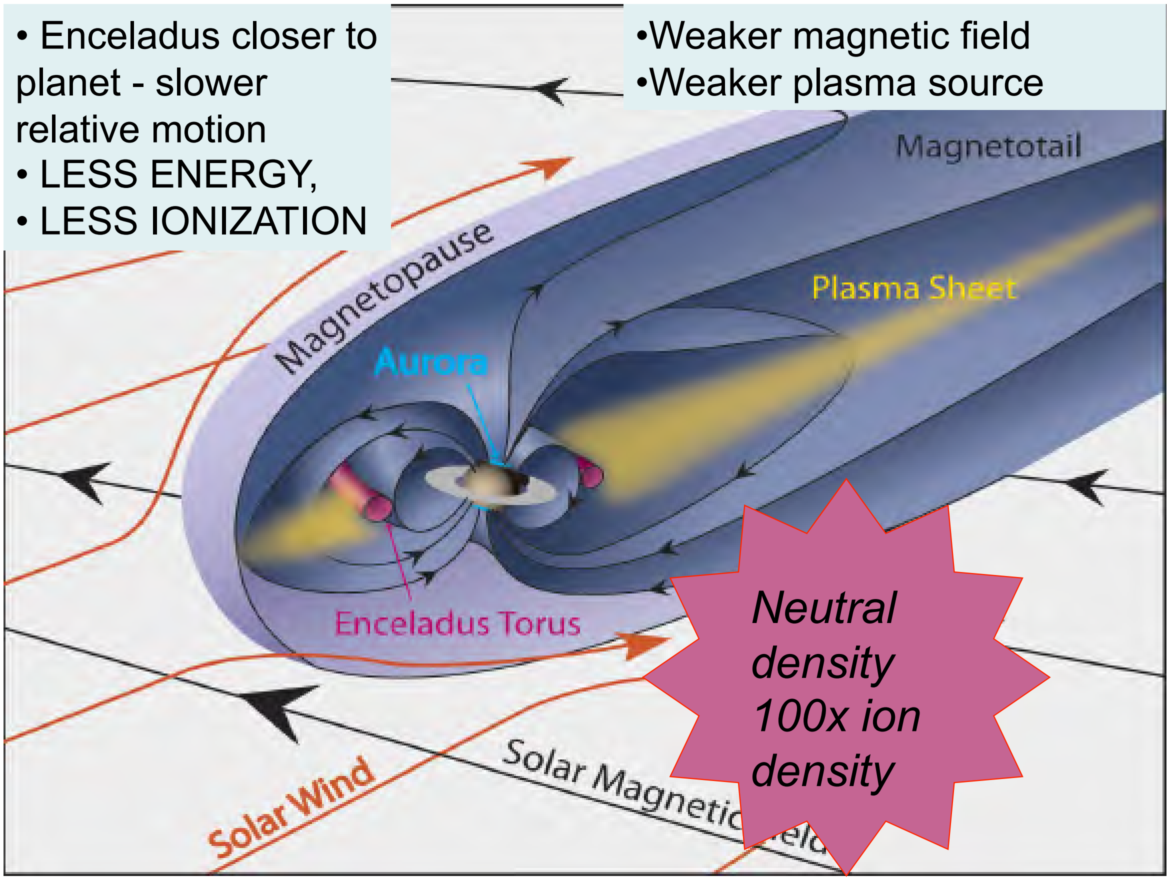
Where is the clutch slipping?



A - Between deep and upper atmosphere?

B - Between upper atmosphere and ionosphere?

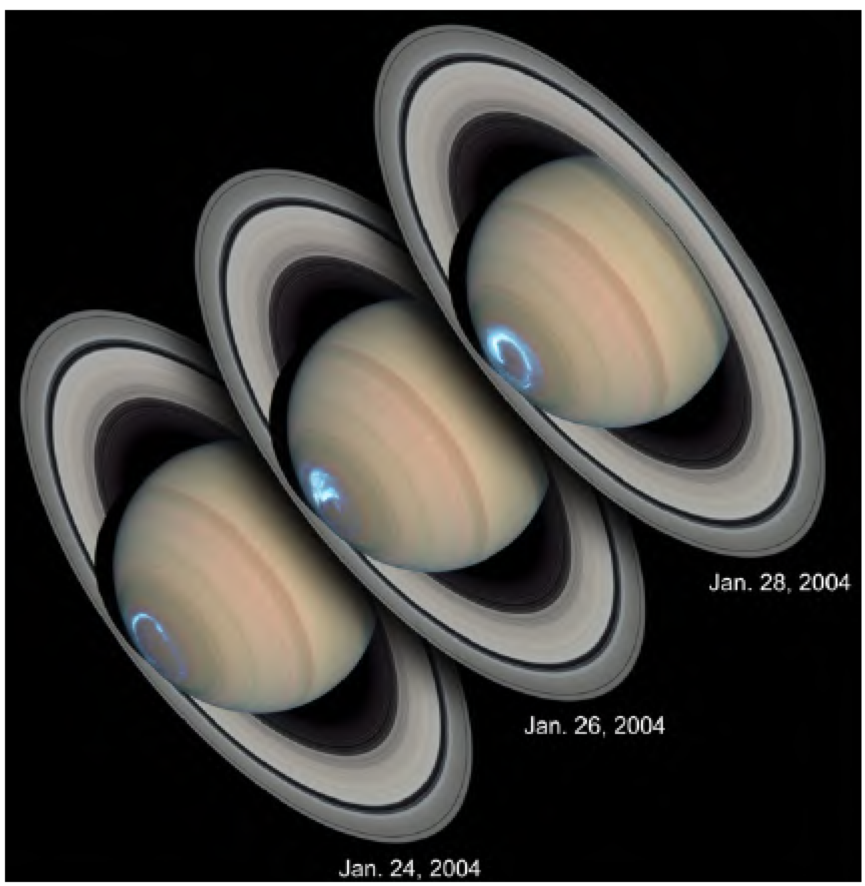
C - Lack of current-carriers in magnetosphere-> $E_{||}$?



Saturn's aurora

• strongly modulated by the solar wind

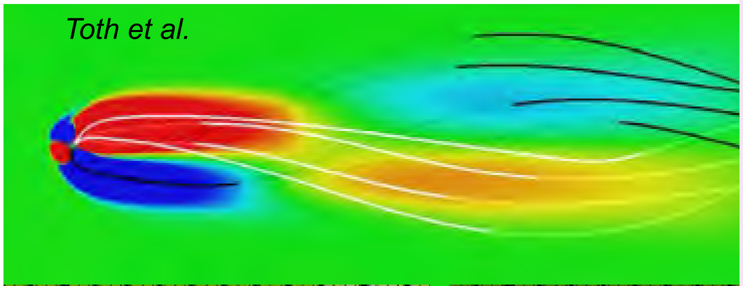
• open-closed boundary?



Clarke et al.

Uranus & Neptune

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

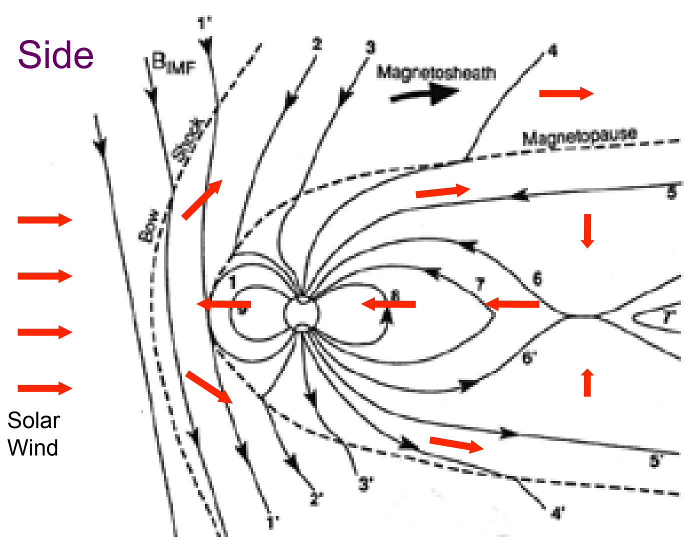


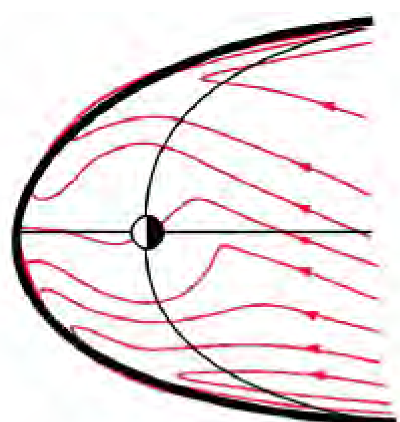
Highly asymmetric, non-dipole fields produce contantly-varying magnetspheric configurations:

little build-up of energetic particles

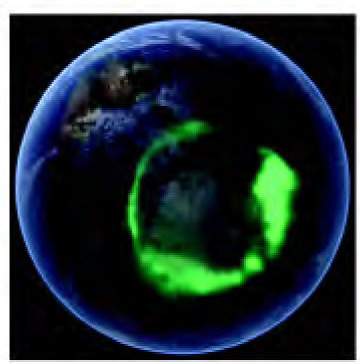
EARTH: Solar Wind Driven Convection

Side





Equatorial plane

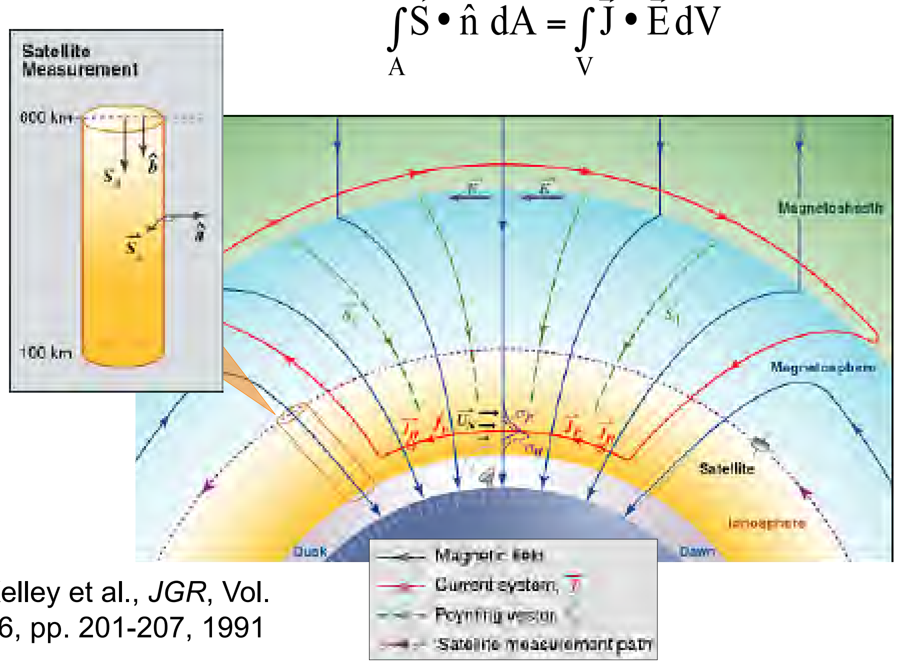


Polar view

Driven by Solar Wind
Dissipated in Ionosphere-Thermosphere

Ionosphere -Thermosphere Poynting Flux

$$\int_A \vec{S} \bullet \hat{n}\, dA = \int_V \vec{J} \bullet \vec{E}\, dV$$

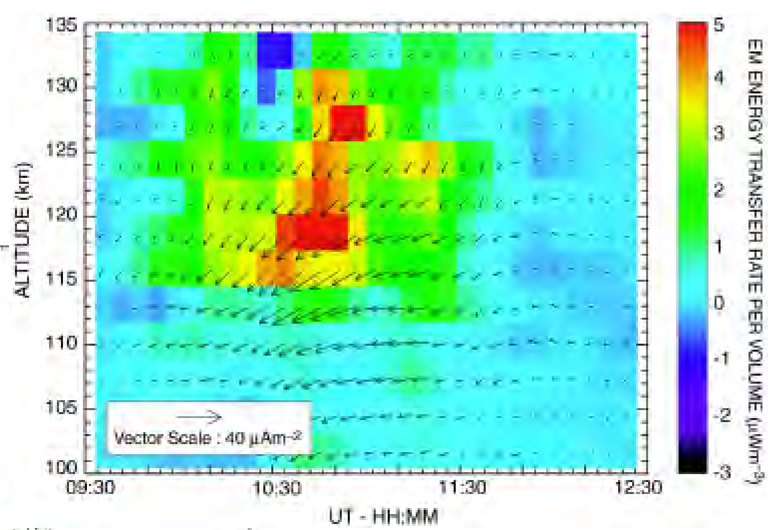


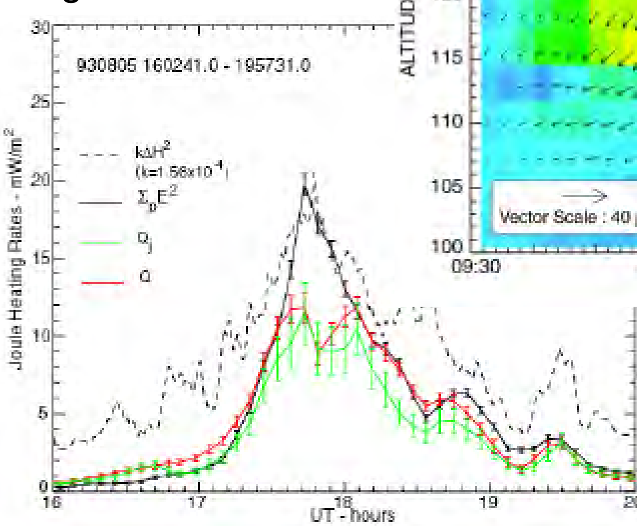
Kelley et al., *JGR*, Vol. 96, pp. 201-207, 1991

Electromagnetic Energy Deposition

Altitude ~ 120 km

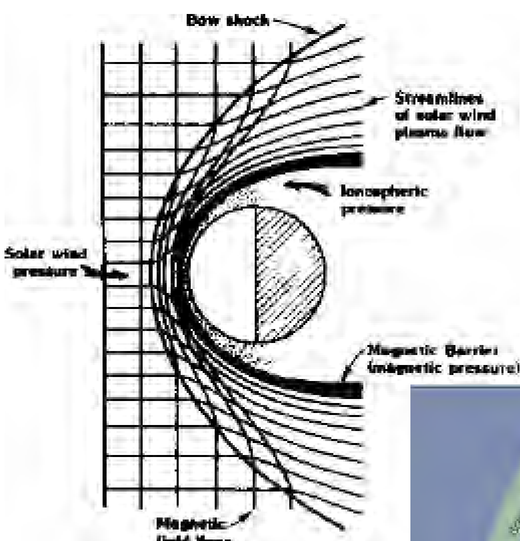
Local to auroral regions





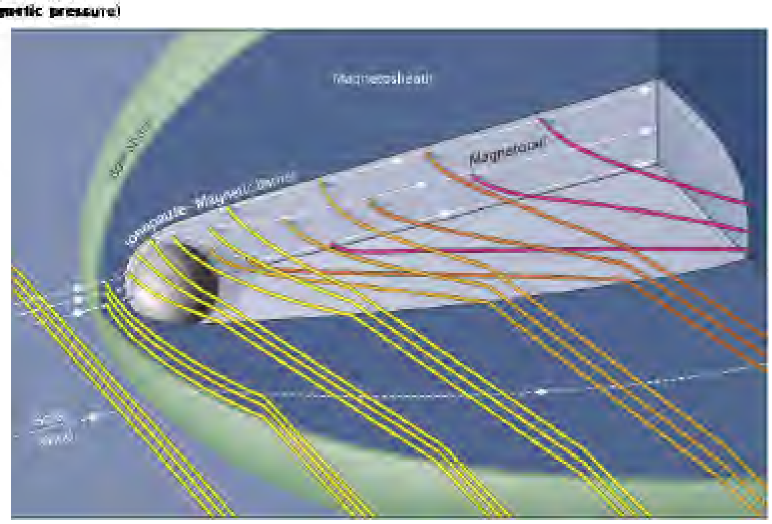
Peak heating rates ~ 20 mW m^{-2}

	Earth	Jupiter	Saturn	Uranus	Neptune
Auroral Emission (Watts)	10^{10}	10^{12}	10^{11}	10^{9}	10^{7}
Energy deposited in atmosphere ~ 10-100 times larger					

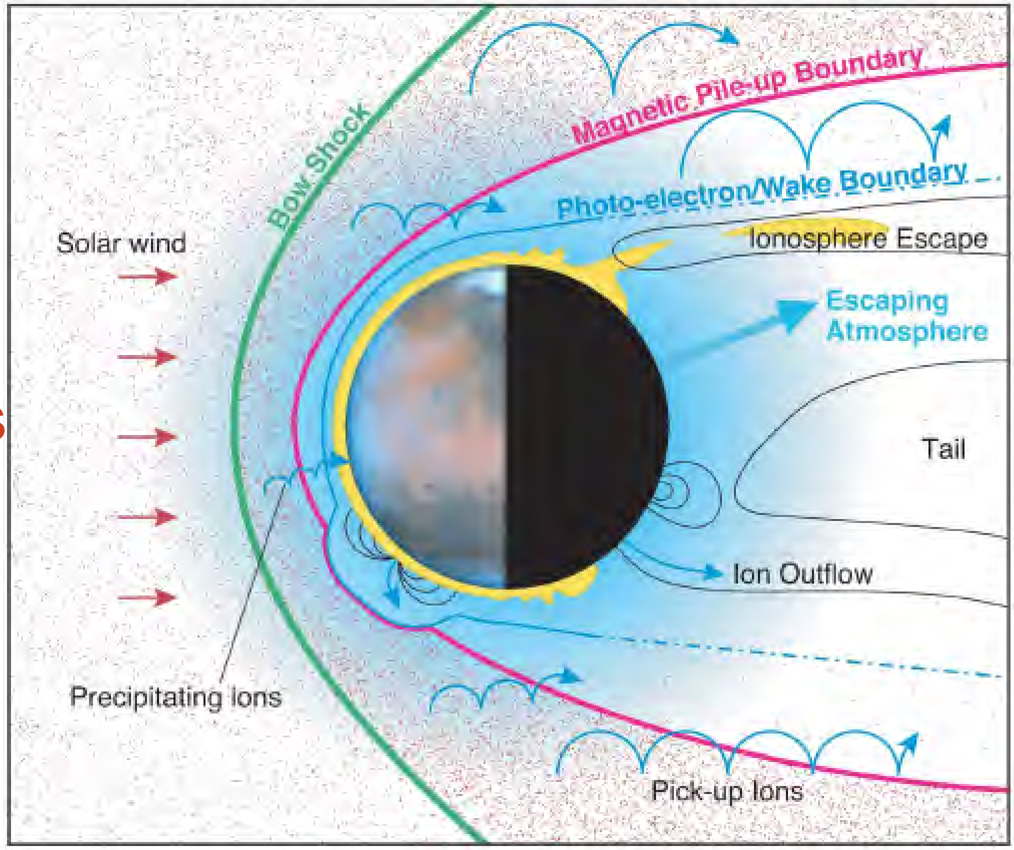


Pressure Balance:
Solar wind ram pressure
-> compressed IMF
-> magnetic pressure
vs. ionospheric thermal pressure

VENUS

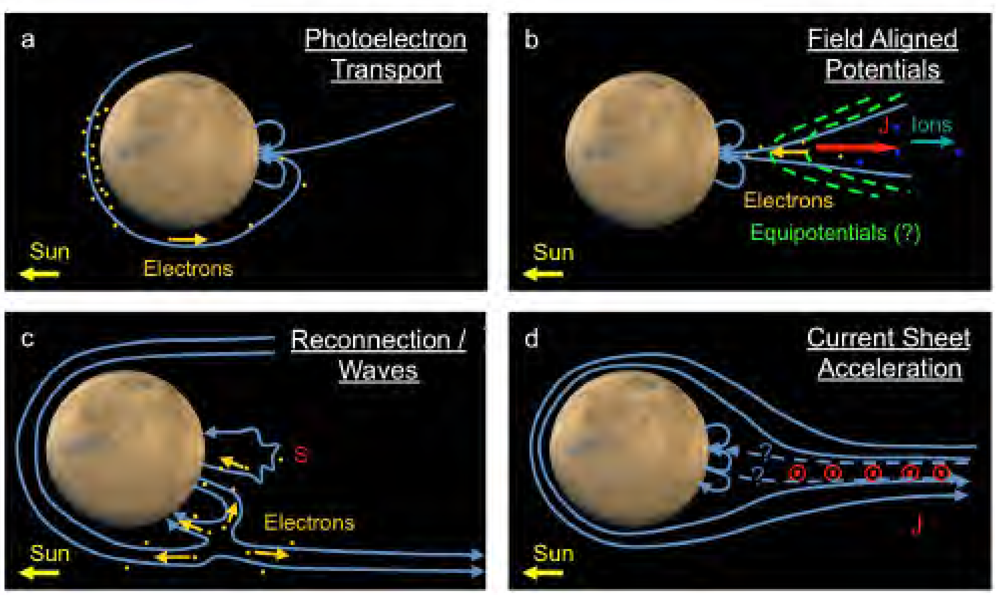


Mars



Brain & Helekas 2012

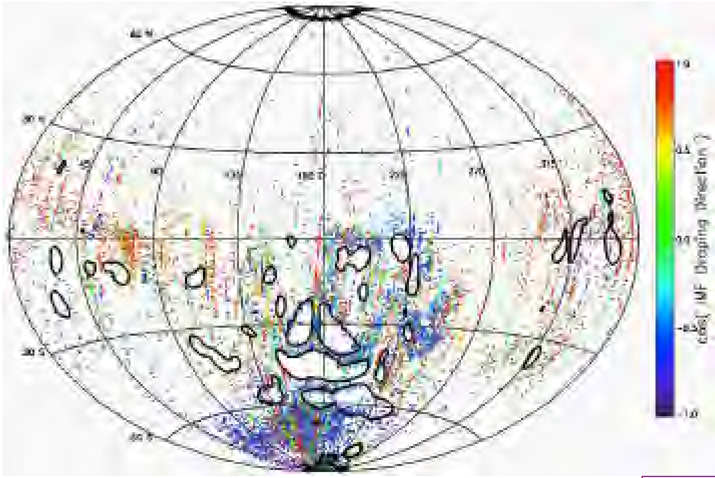
Possible mechanisms for Mars' aurora

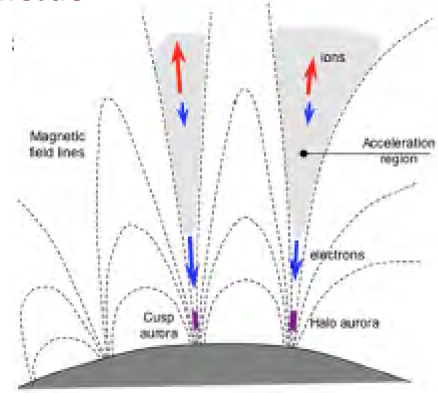


Total auroral precipitated power ~mW m^{-2}

Brain & Helekas 2012

Electron fluxes onto Mars' atmosphere – focussed by magnetic fields



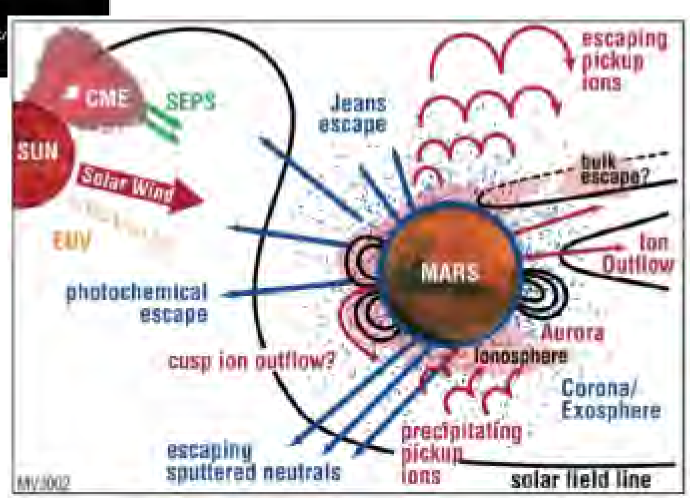


- Total energy flux ~mW m^{-2}
- Outflow estimates 10^{23-25} s^{-1}
- Probably higher for early Mars

Total atmospheric escape ~ 1 ton/hour - ???

MAVEN:
- Launch Nov. 2013
- Orbits Mars Sept. 2014-2016
- PI Bruce Jakosky
  U of Colorado

Goal:
To quantify the processes driving atmospheric escape - both now, and allow extrapolation into past history



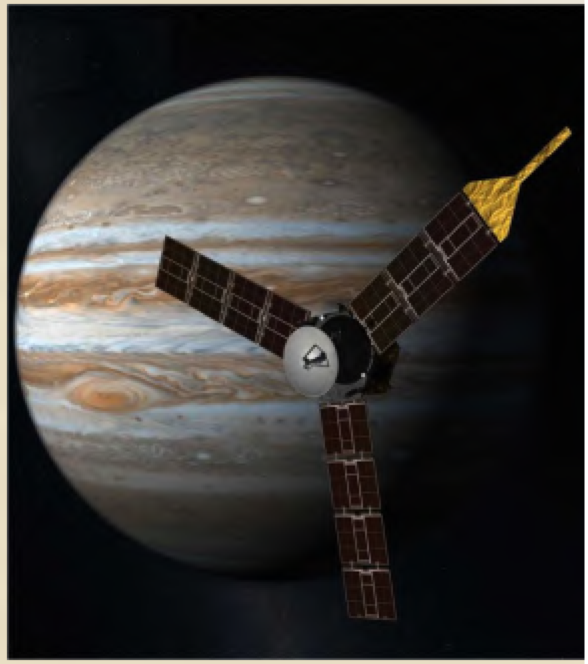
Summary

- Diverse planetary magnetic fields & magnetospheres
- Dynamo primarily requires region of liquid conducting material that is convecting – generally limited by heat flow out of core
- Earth, Mercury, Ganymede magnetospheres driven by reconnection
- Jupiter & Saturn driven by rotation & internal sources of plasma
- Uranus & Neptune are complex – need to be explored!
- Atmospheric escape driven by plasma interactions is very poorly understood – be careful!

Juno

Microwave Radiometer (JPL)
Magnetometer (GSFC/JPL)
Energetic Particle Detector (APL)
Plasma (SwRI)
Waves (Iowa)
UV Spectrometer (SwRI)
IR Spectal Imager (Rome)
Visible Camera (Malin)

Launch 2011
Arrive 2016



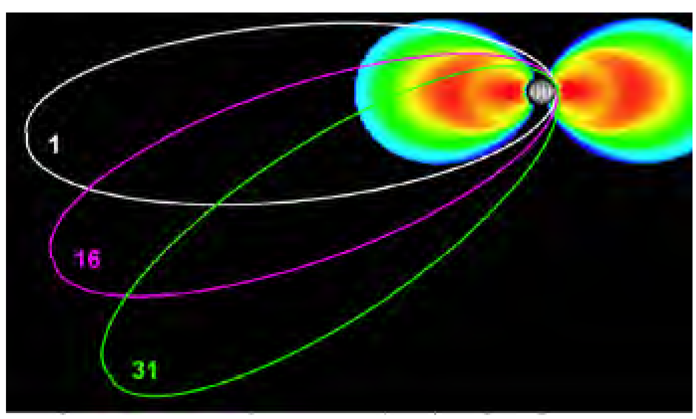
Juno

Juno Mission Design

Launch: August 2011

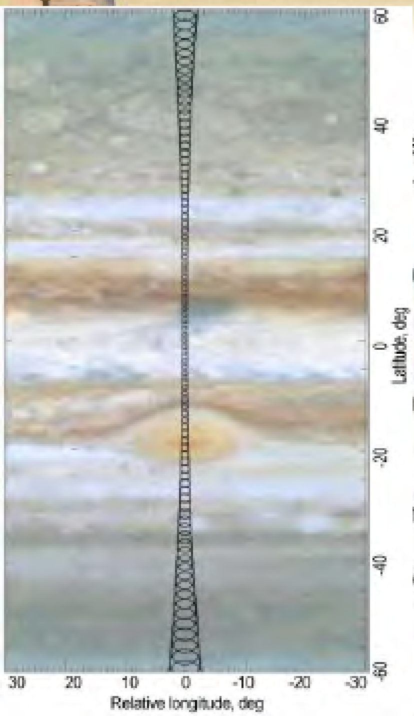
5 year cruise

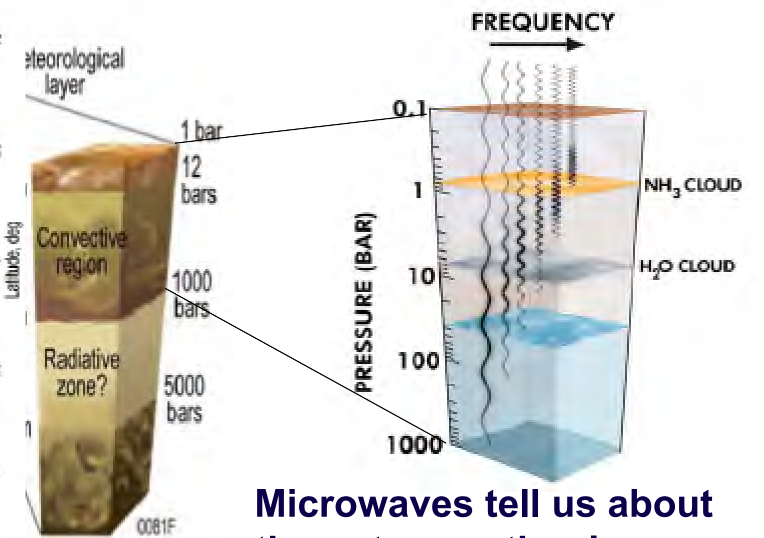
Baseline mission:
- 32 polar orbits
- Perijove ~5000 km
- 11 day period
- Spinner
- Solar-powered



Science Objectives:
- Origin of Jupiter
- Interior Structure
- Atmosphere Composition & Dynamics
- Polar Magnetosphere

Probing Jupiter's Deep Interior





Microwaves tell us about the outer weather layers - the amount of water

Magnetic and Gravity Fields tell us about the deep interior

Juno

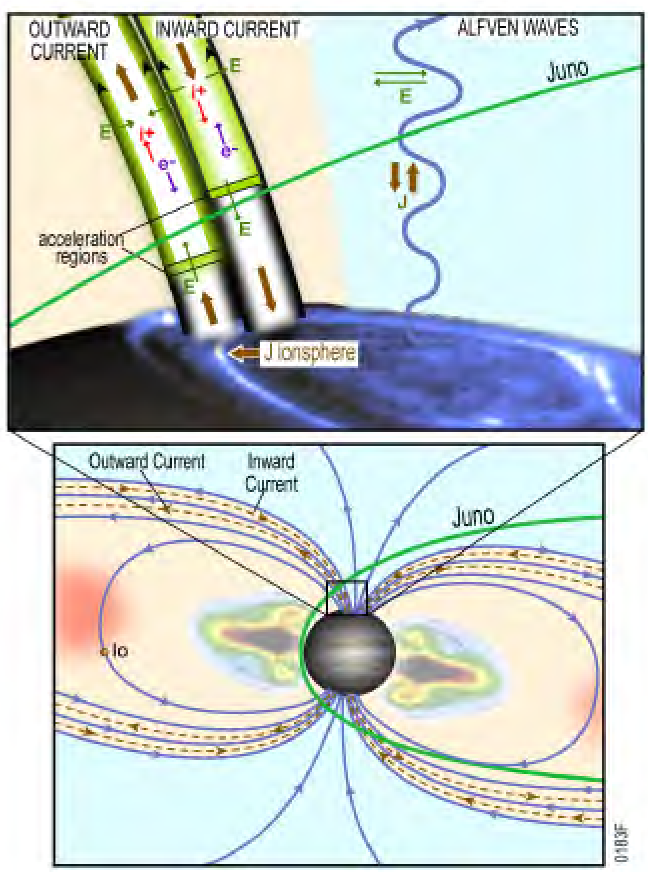
Polar Magnetosphere

Juno passes directly through auroral field lines

Measures particles precipitating into atmosphere creating aurora

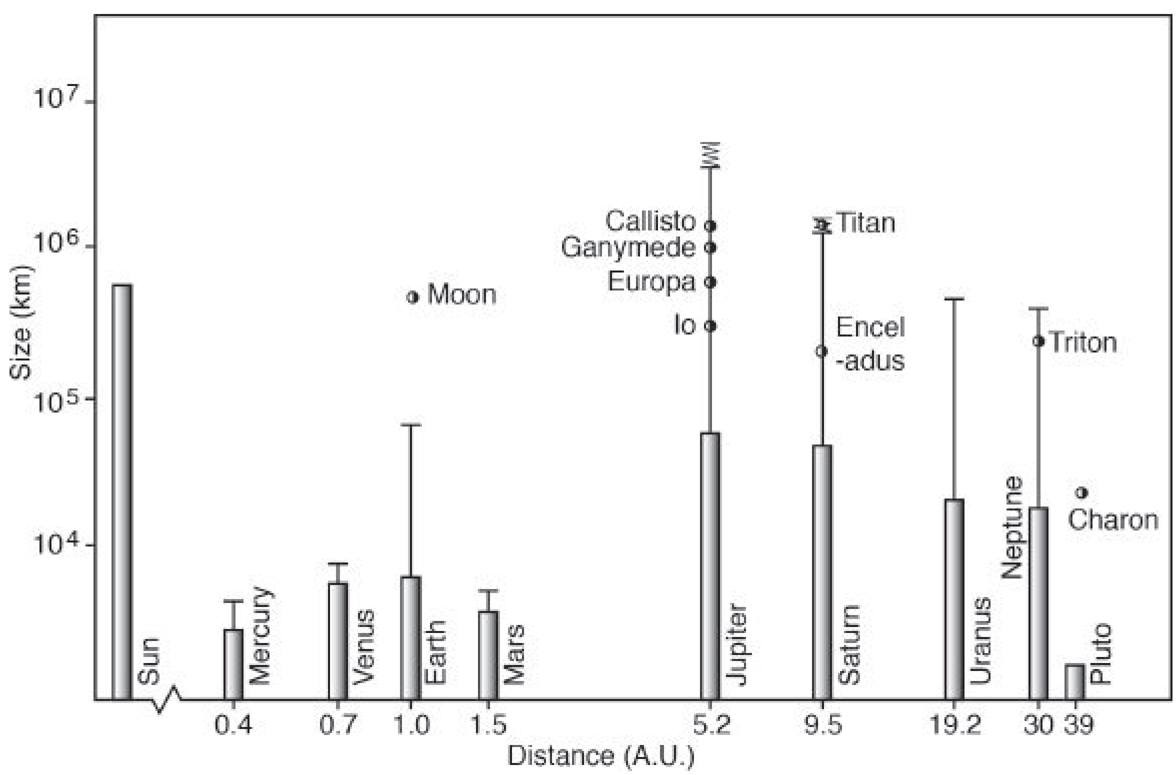
Plasma/radio waves reveal processes responsible for particle acceleration

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



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

	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
B_o Gauss	.003	.31	4.28	.22	.23	.14
R_{CF} Calc.	1.4 R_M	10 R_E	42 R_J	19 R_S	25 R_U	24 R_N
R_M Obs.	1.4-1.6 R_M	8-12 R_E	60-90 R_J	16-22 R_S	18 R_U	23-26 R_N



Plasma Sources

	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
N_{max} cm^{-3}	~1	1-4000	>3000	~100	~3	~2
Comp-osition	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	~~~20~~ 70-700?	~0.02	~0.2

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