Planetary Magnetospheres

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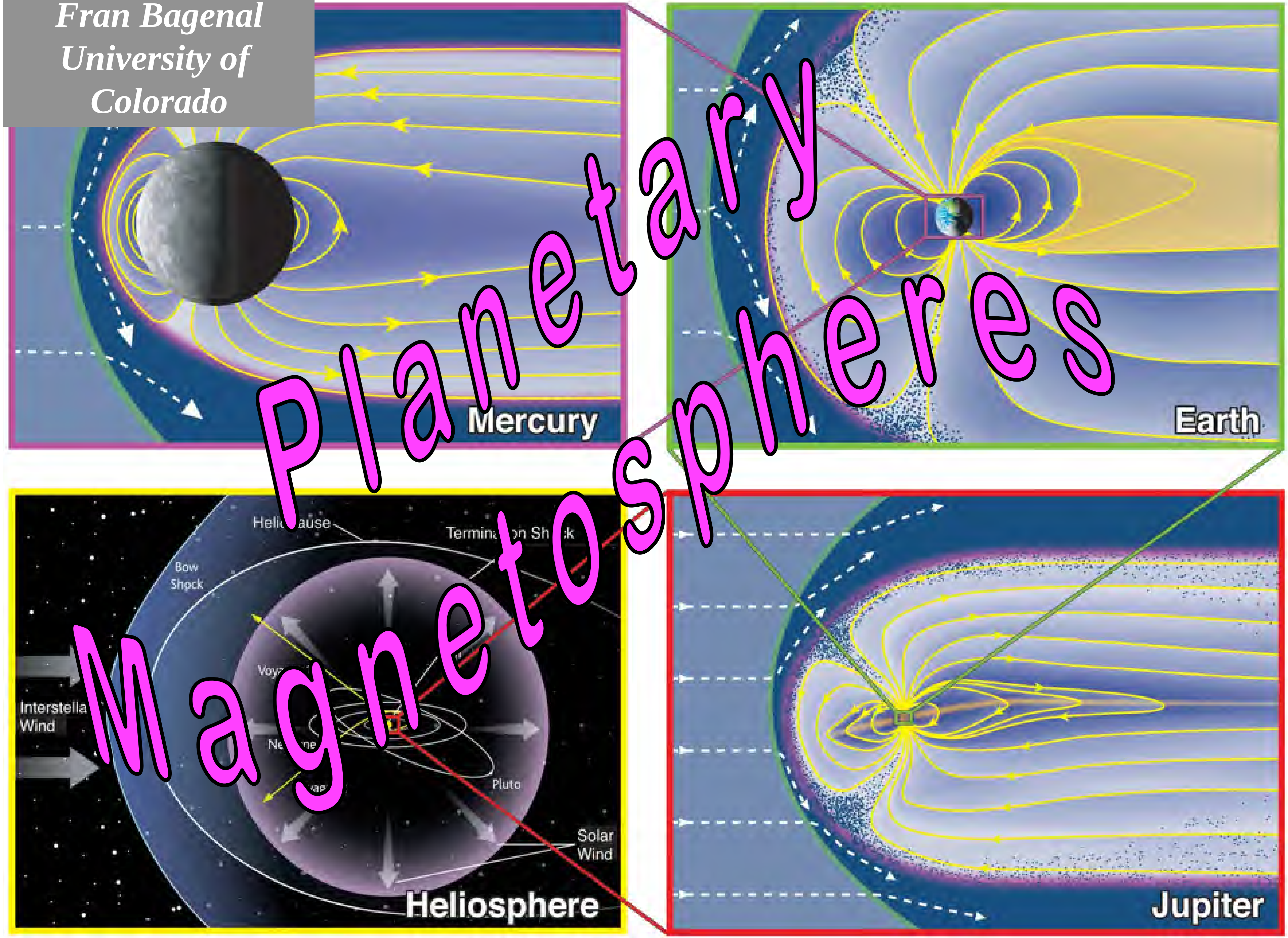
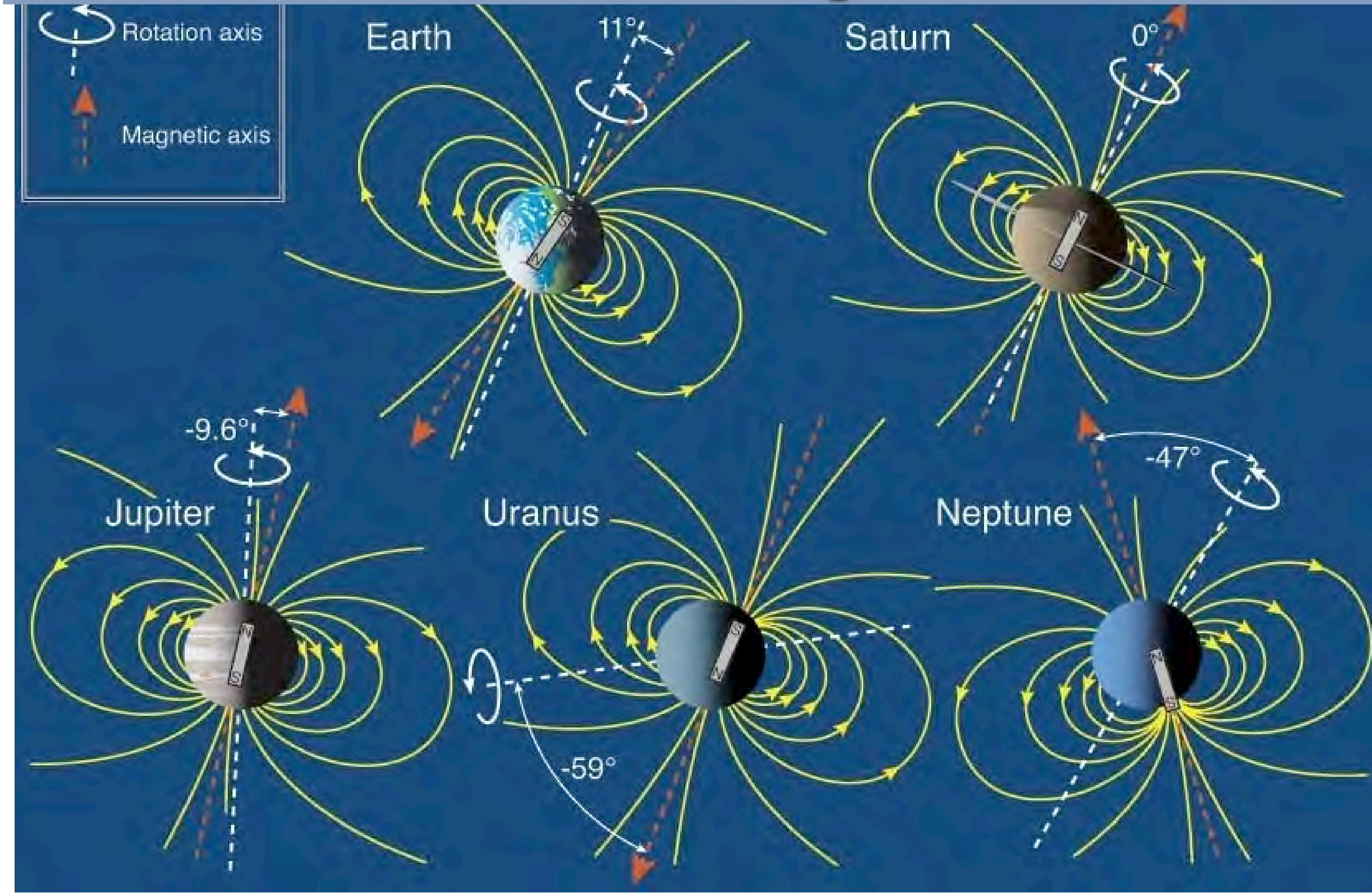


Tilts and Obliquities



Offset Tilted Dipole (poor) Approximation

Radiation Belts

The discovery of Earth's radiation belts Van Allen (1958)

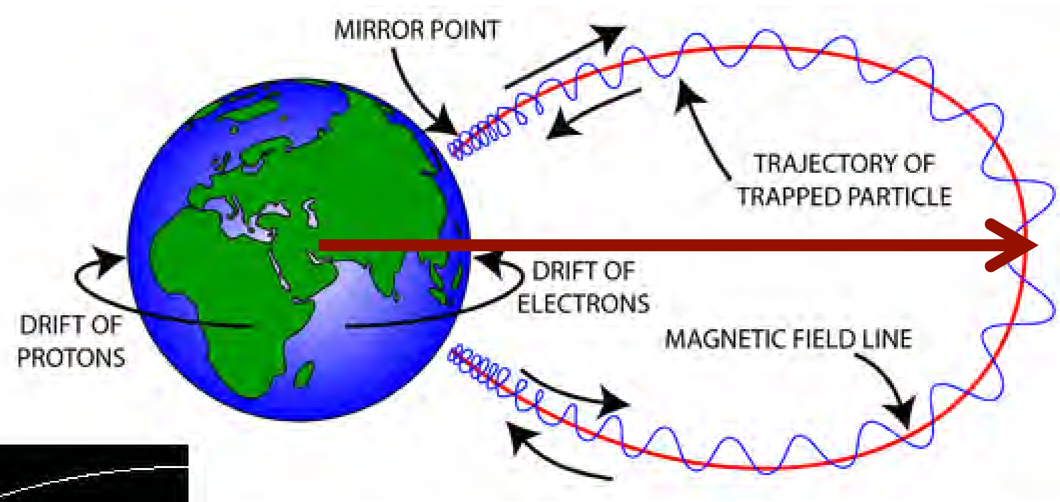
Pickering, Van Allen and Von Braun with Explorer 1

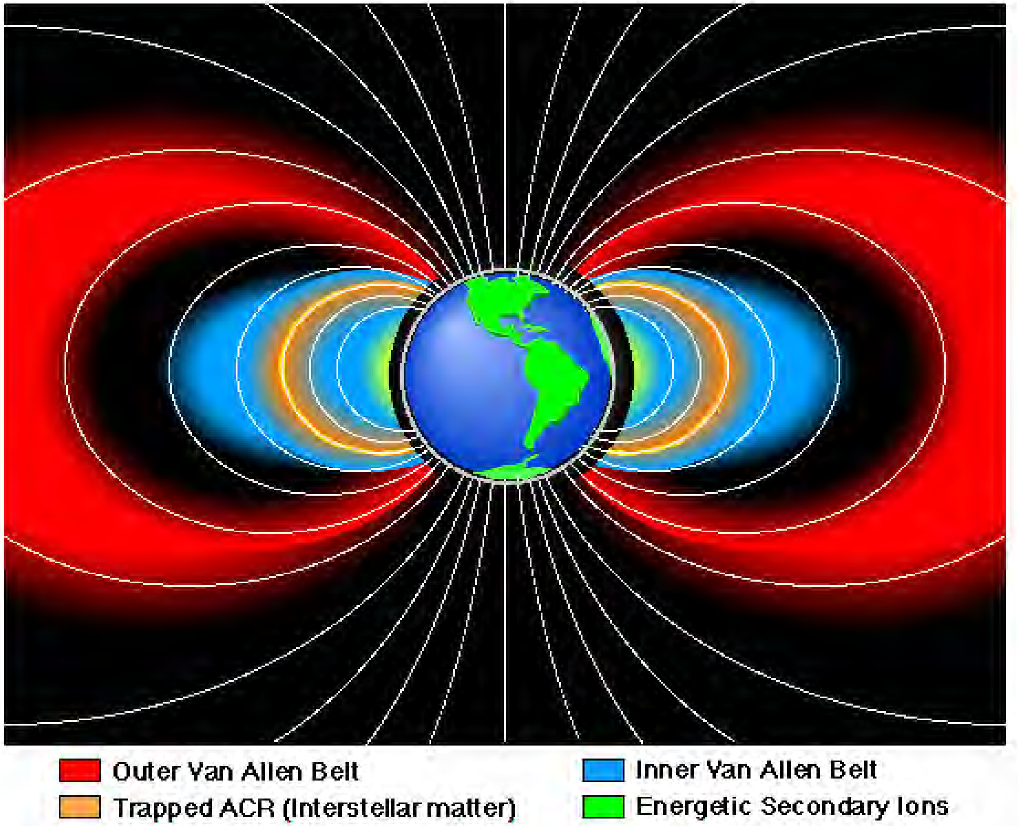
If you get the chance, go see the museum at Cape Canaveral

Adiabatic Invariants

Associated with each motion is a corresponding *adiabatic invariant:*

- Gyro: *M* *t~milliseconds*
- Bounce: *K* *t~0.1-1 sec*
- Drift: *L* *t~1-10 mins*

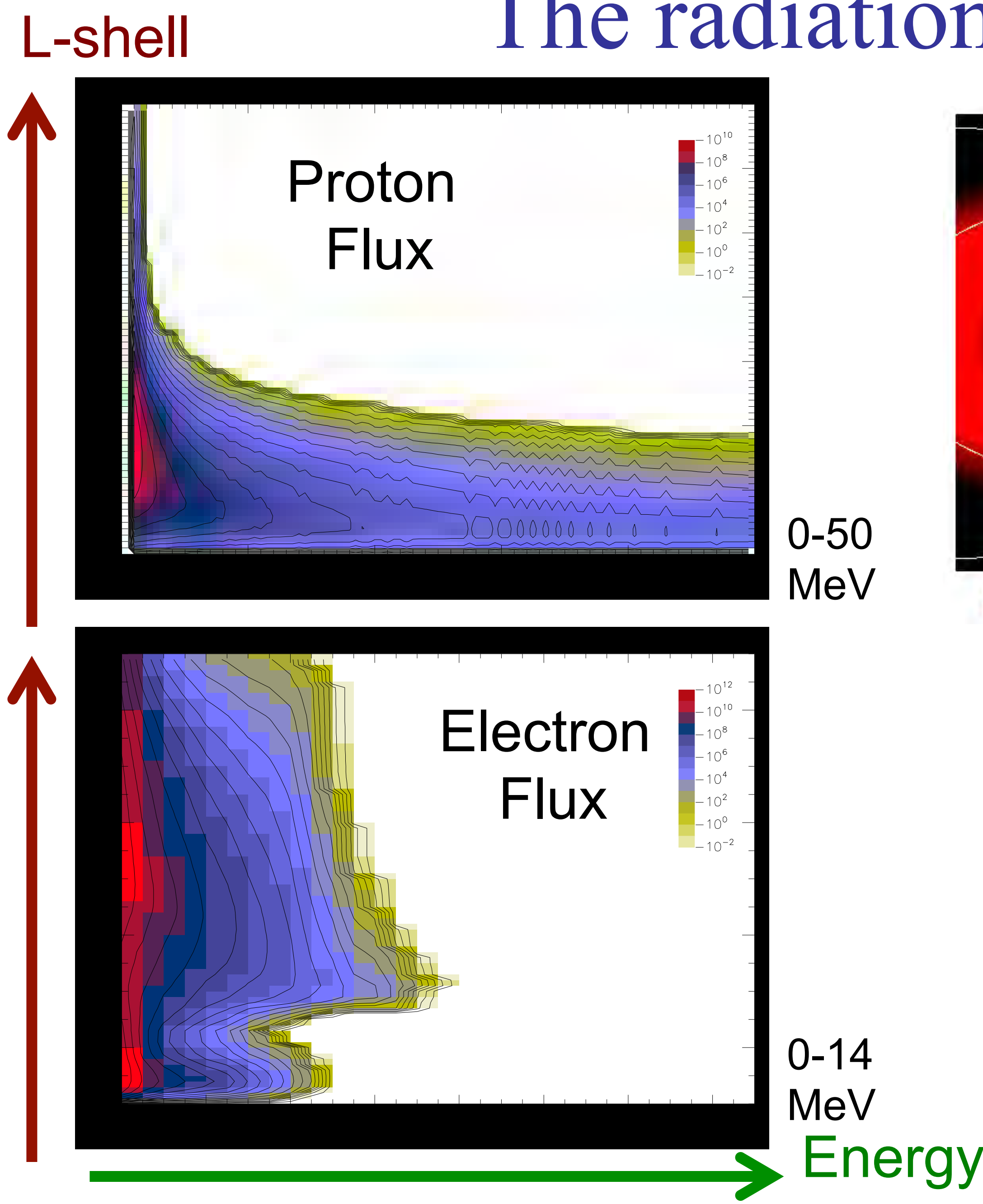


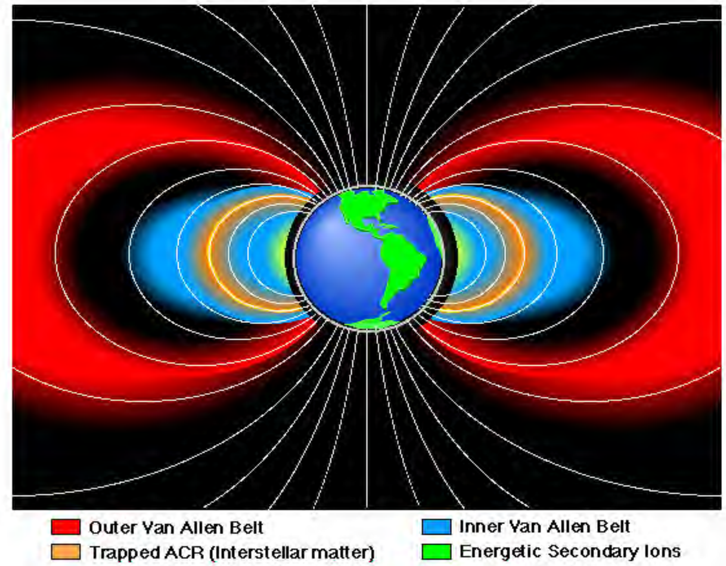


L: radial distance equator crossing in dipole field

If field guiding particles change slowly compared to characteristic motion - corresponding invariant is conserved.

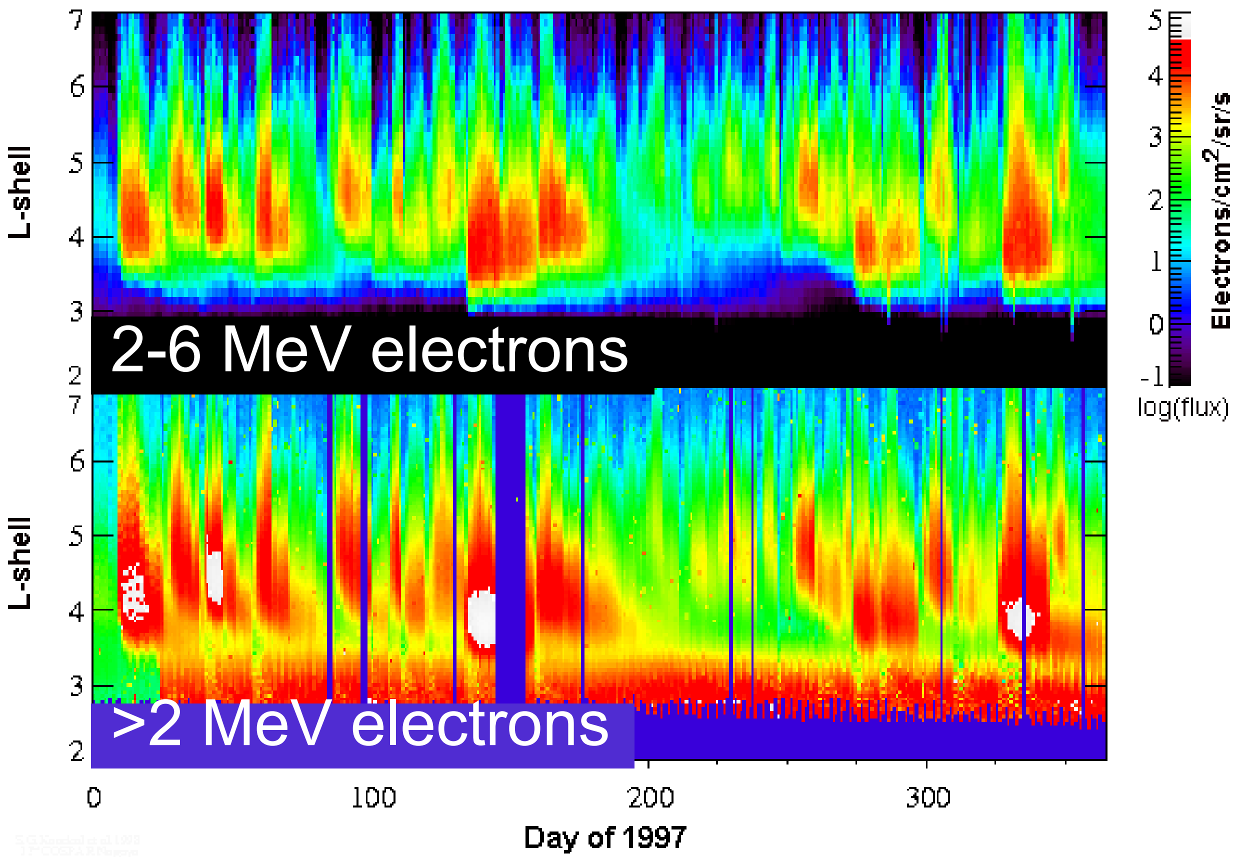
The radiation belts





- Trapped particles drifting in orbits encircling Earth.
- Two spatial populations: inner zone and outer zone.
- Energies from ~200 keV to > few MeV

The radiation belts exhibit substantial variation in time



Storm commencement:
minutes

Storm main phase:
hours

Storm recovery:
days

Solar rotation:
13-27 days

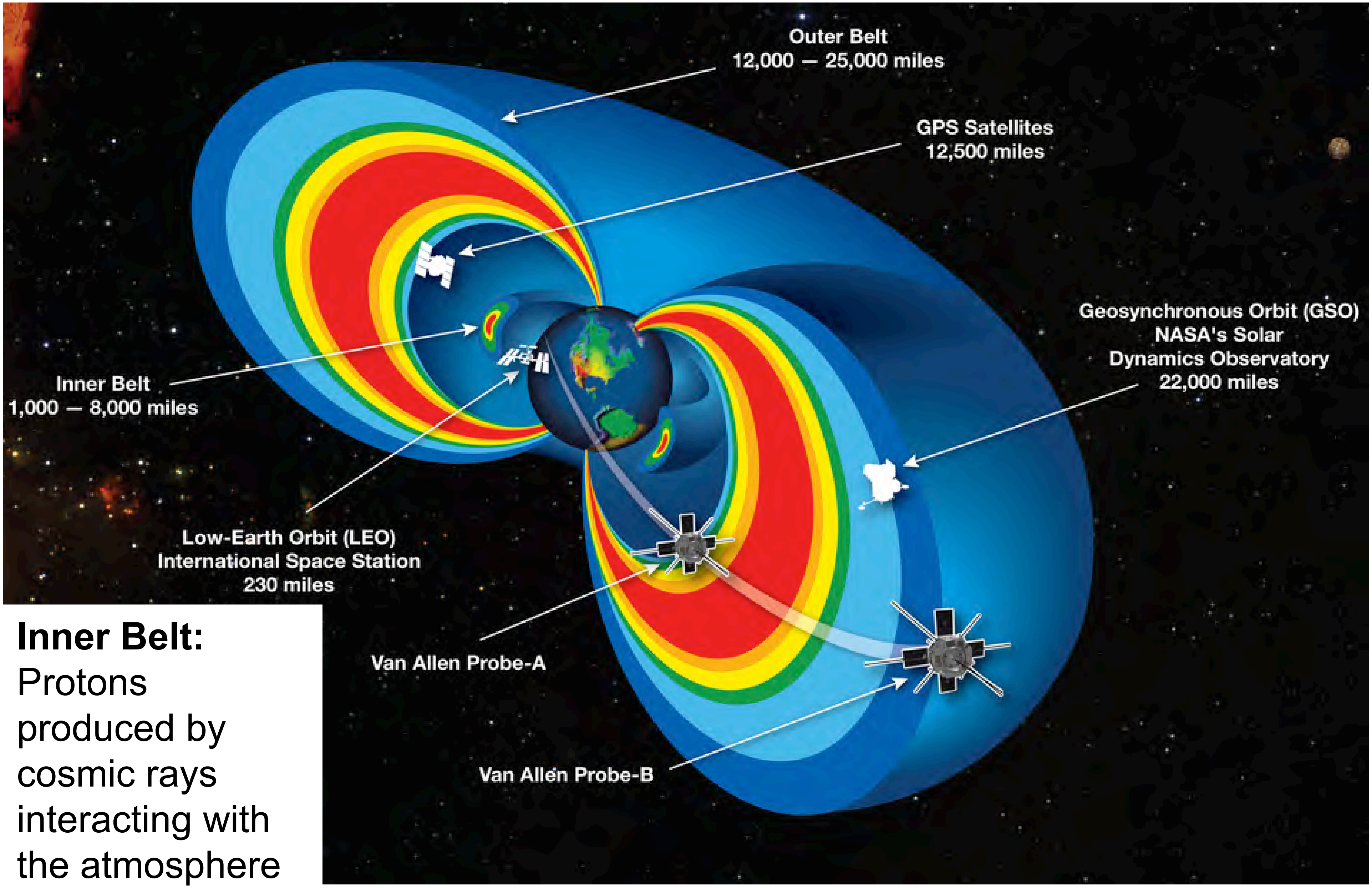
Season:
months

Solar cycle: years

You have an instrument on a satellite in space that measures the flux of, say, electrons in the energy range, say 4-6 MeV.

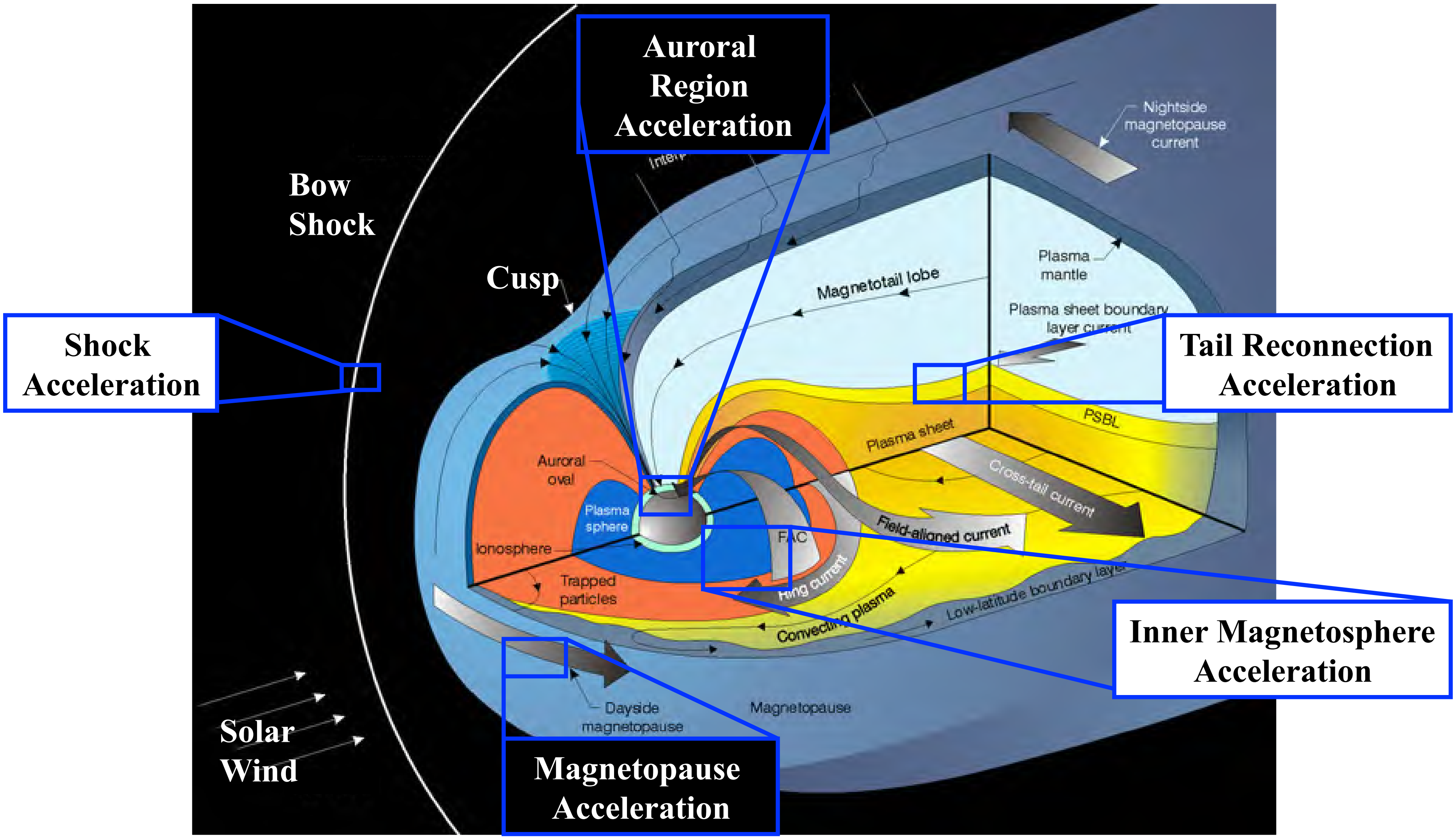
What physical processes might cause the measured flux to increase / decrease with time?

Outer Belt: Inward transport of particles, heated via conservation of 1st adiabatic invarient and waves. Lost via wave scattering into atmosphere



Inner Belt: Protons produced by cosmic rays interacting with the atmosphere

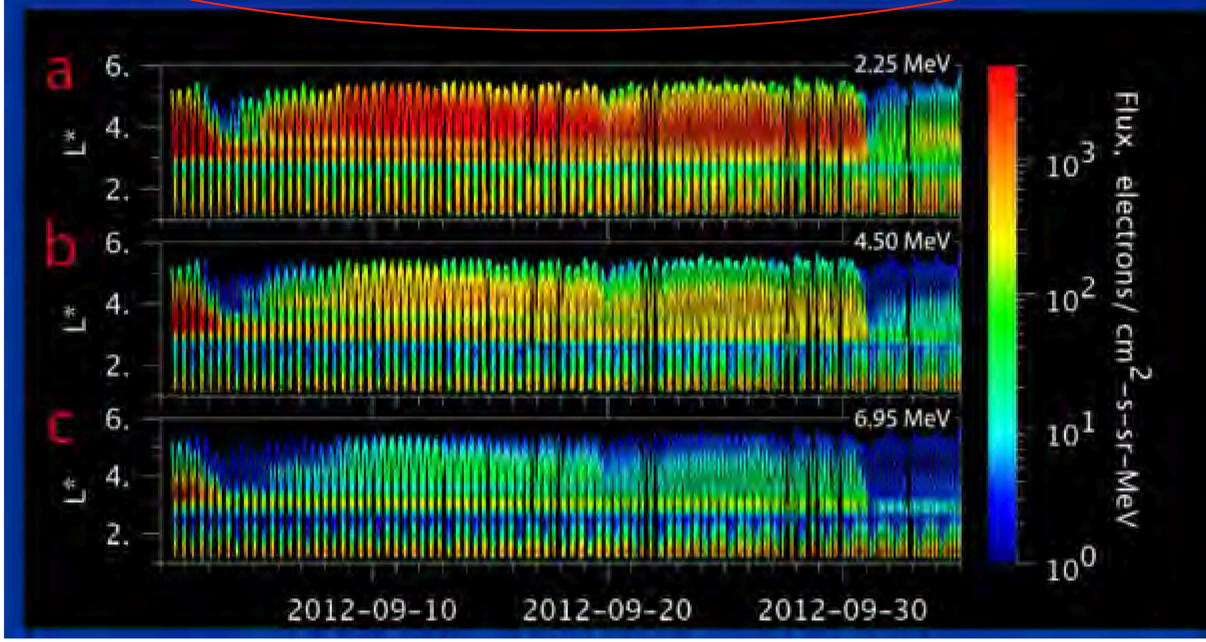
Key Regions of Magnetospheric Particle Acceleration

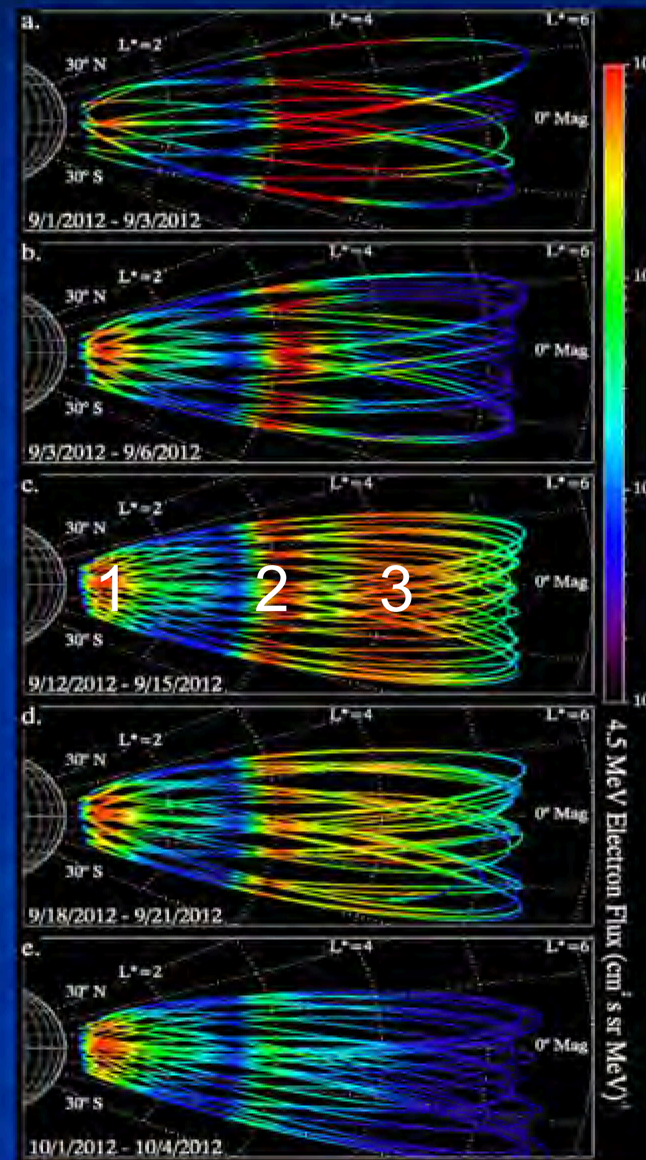


RBSP, sources, and losses: the third radiation belt

Shortly after "First Light" for the Van Allen Probe's Relativistic Electron-Proton Telescope (REPT), an unusual radiation belt configuration was observed to form, consisting of three belts and two slot regions.

What combination of energization, transport, and loss could have led to this configuration?

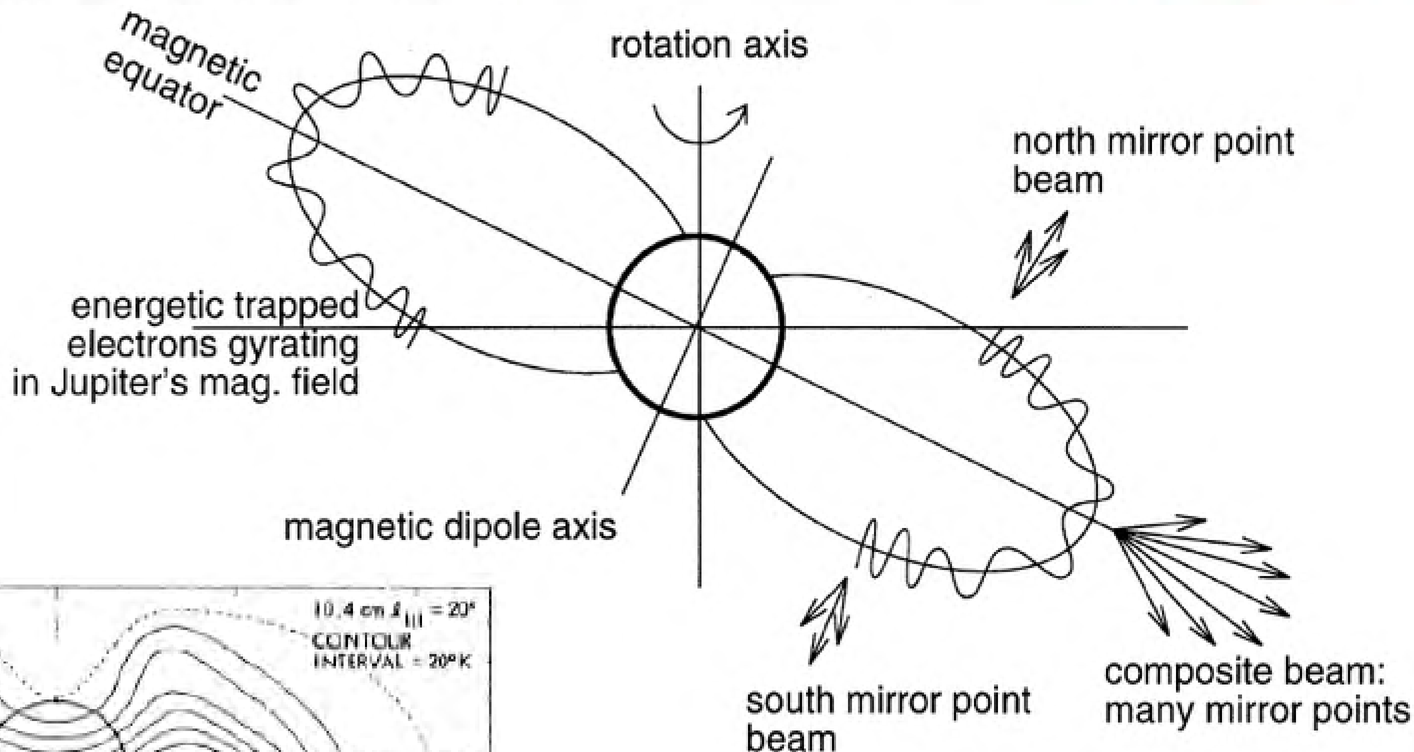




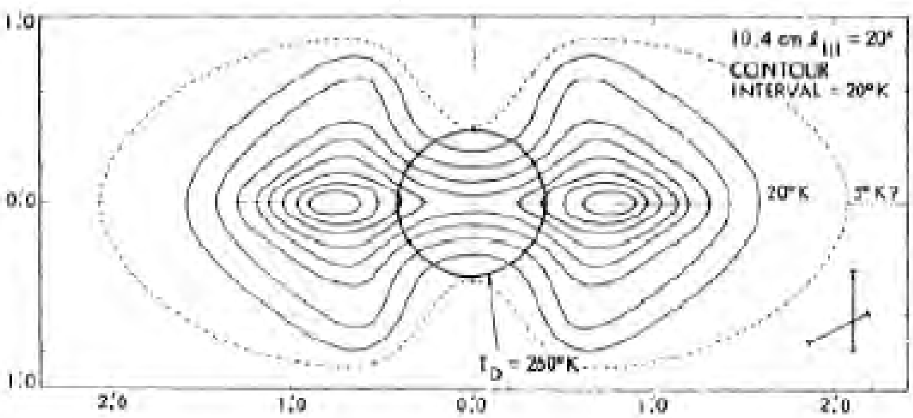
- Nonthermal radiation detected at 20-70 cm [1959, several observers]
    - Linearly polarized approximately parallel to rotational equator, rocking as Jupiter rotates
    - Minima when polarization parallel to planetary equator
    - Emission extended out to 3 R_J

Decimetric Radiation

Jupiter's Radiation Belts



10.4 cm



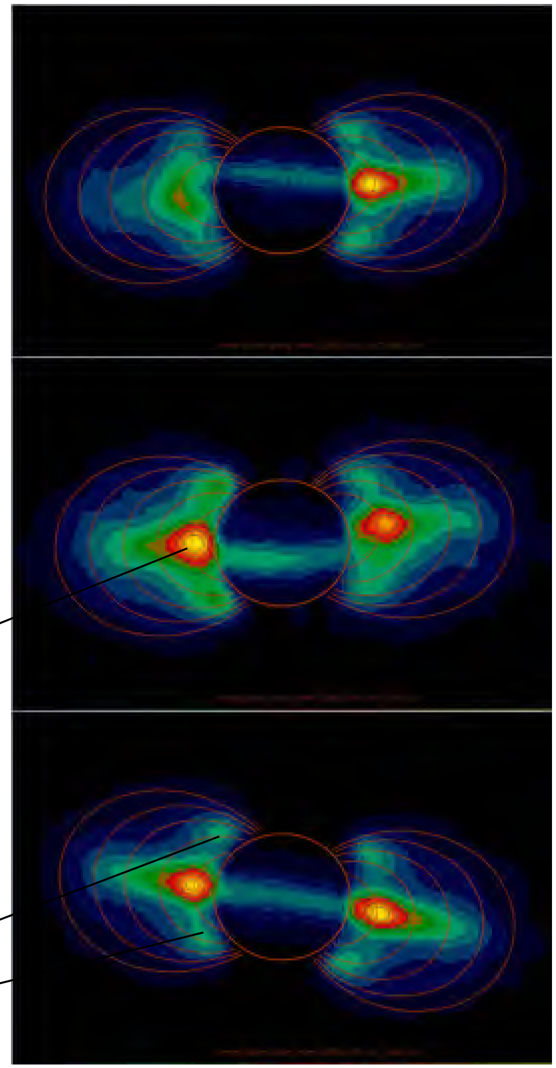
Synchrotron Emission 10s MeV electrons

Jupiter's Synchrotron Radiation Belts

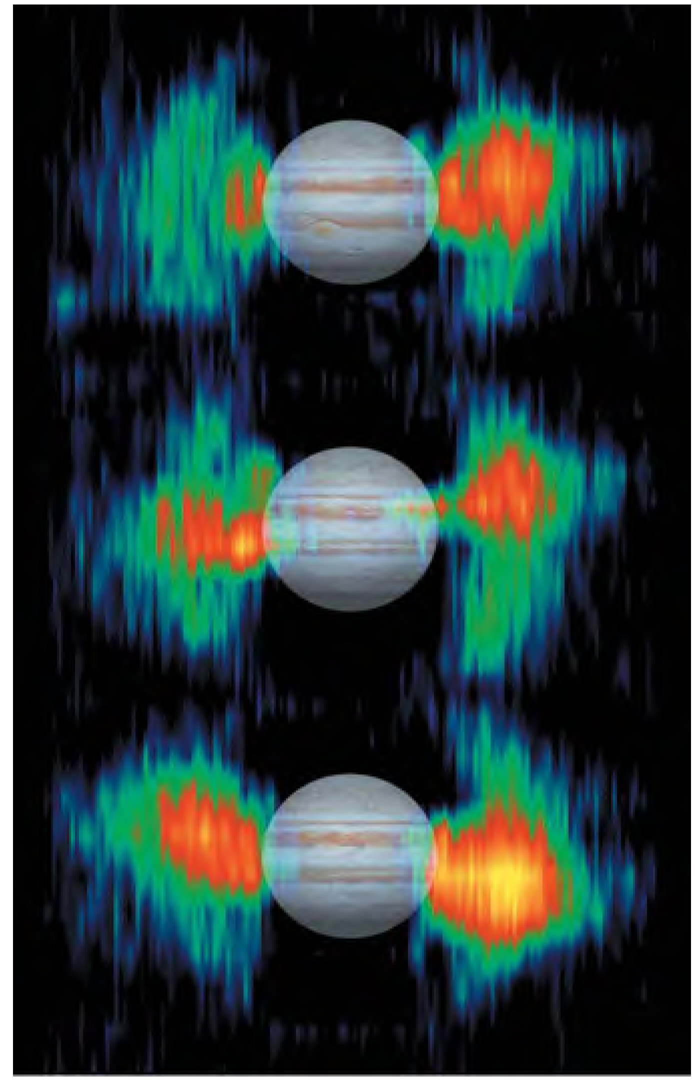
Synchrotron emission is emitted perpendicular to the local magnetic field and by particles when they are moving perpendicular to the field

What pitch angle distribution of the electron population producing these emissions?

…and these emissions?



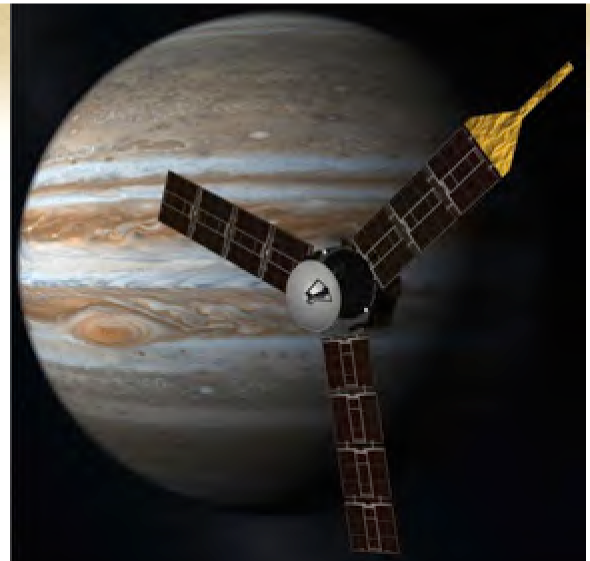
VLA Radio Telescope



Cassini Radio

Moon Amalthea + dust absorbs / scatters particles with pitch angles near 90 deg.

Juno Mission Design

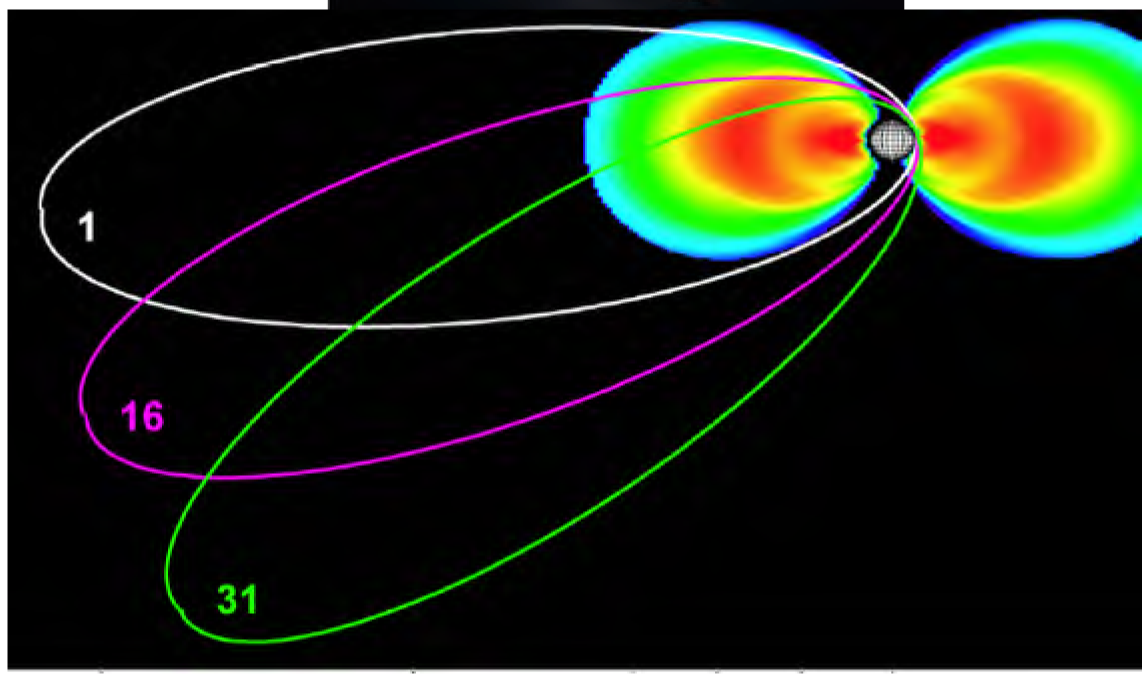


Launch: August 2011

Jupiter Orbit: July 2016

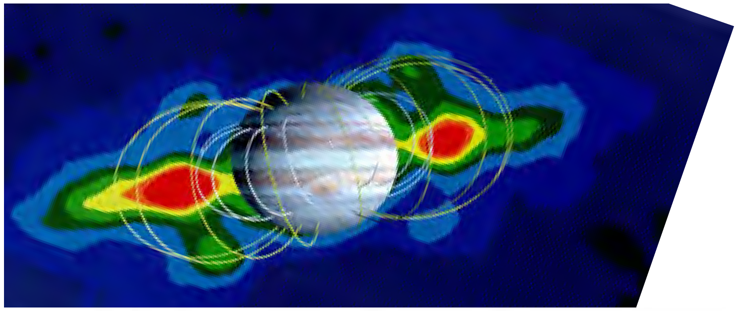
Baseline mission:

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

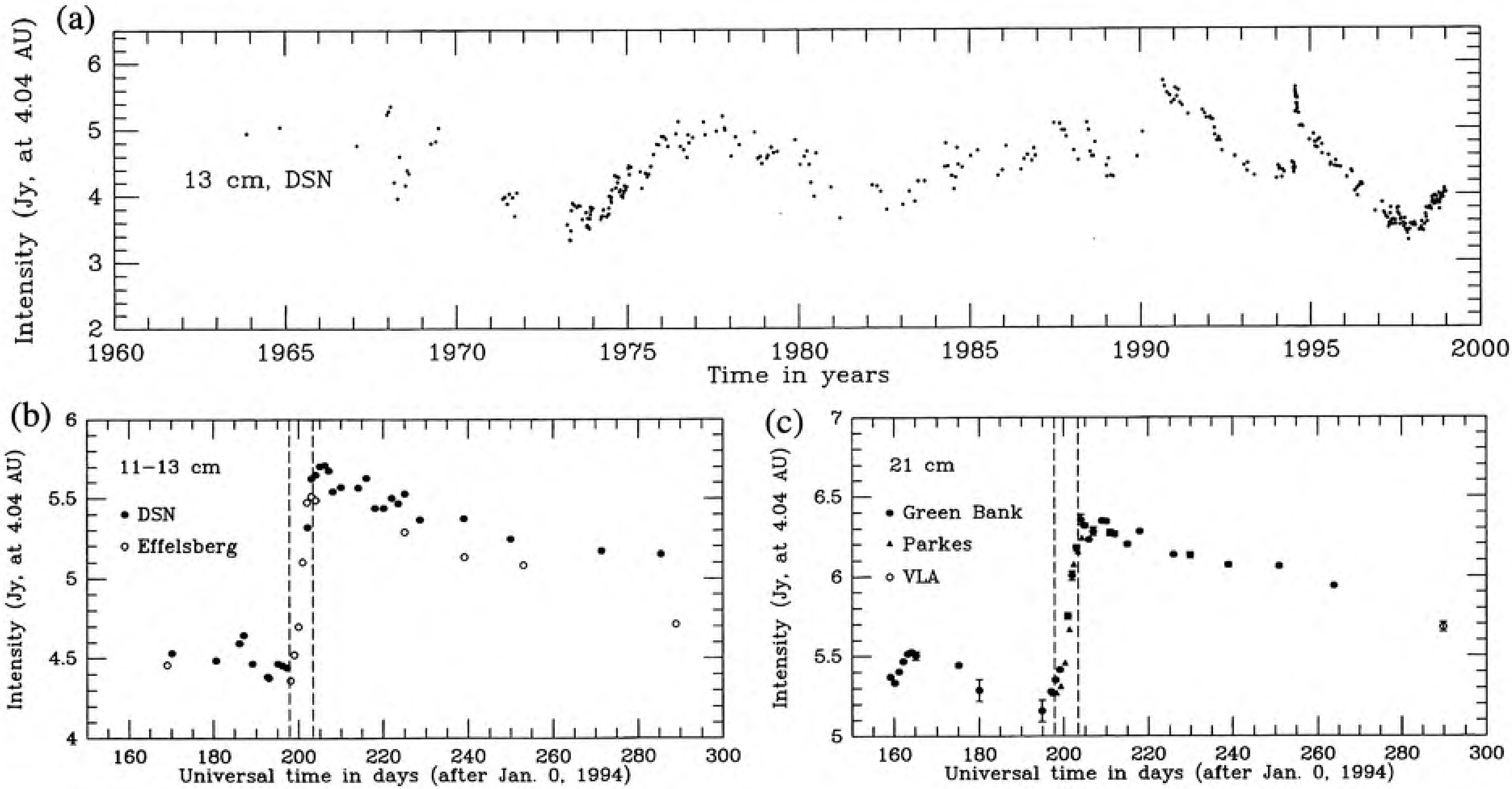


Science Objectives:

Origin of Jupiter
Interior Structure
Atmosphere Composition & Dynamics
Polar Magnetosphere



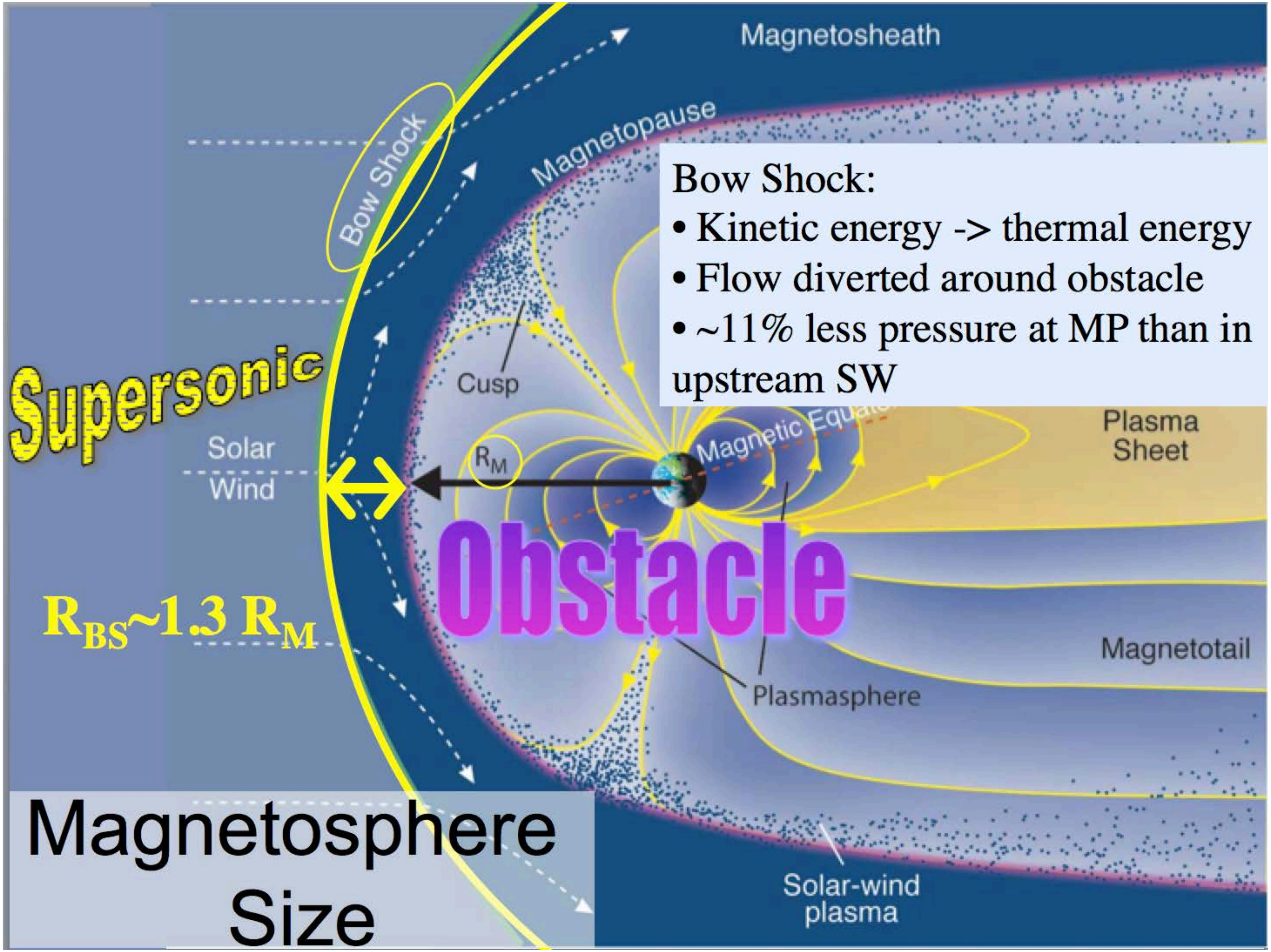
Very steady synchrotron emission from radiation belts - except when something big happens…..



Shoemaker-Levy-9 impacts July 1994

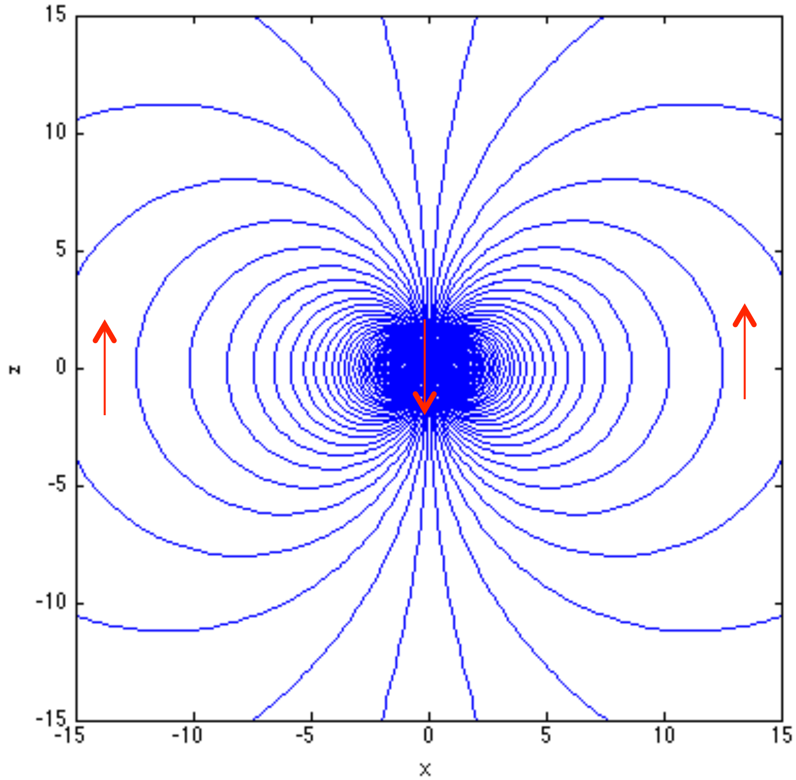
Magnetosphere Size

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



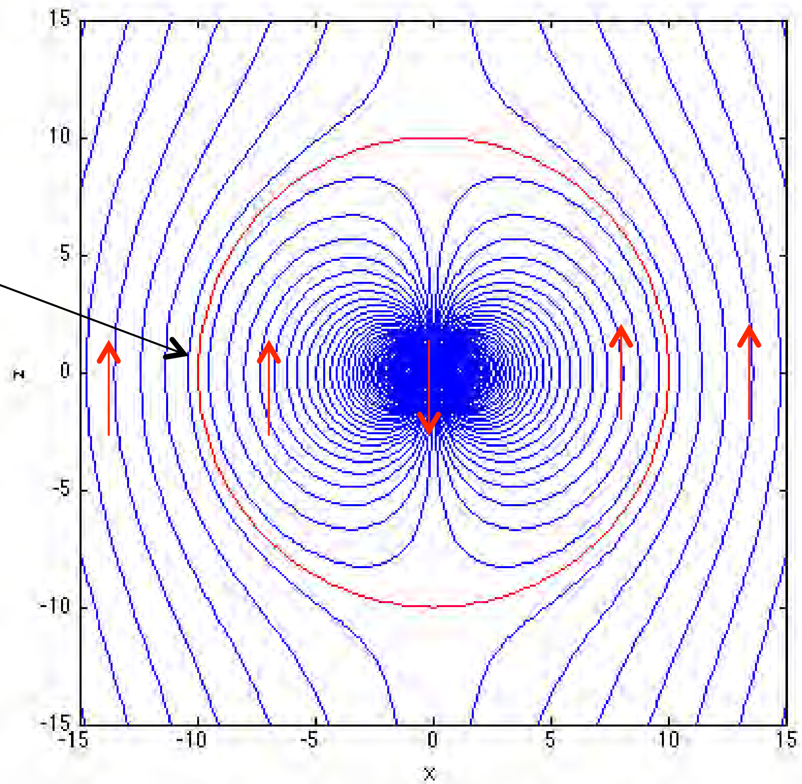
http://www.vsp.ucar.edu/Heliophysics/pdf/2011_Toffoletto-lecture.pdf

Dipole field



Dipole field with an added external Northward field

B = 3x dipole



Effect of currects on the boundary of the m'sphere

Dipole field with an added external Southward field

B = 2x dipole

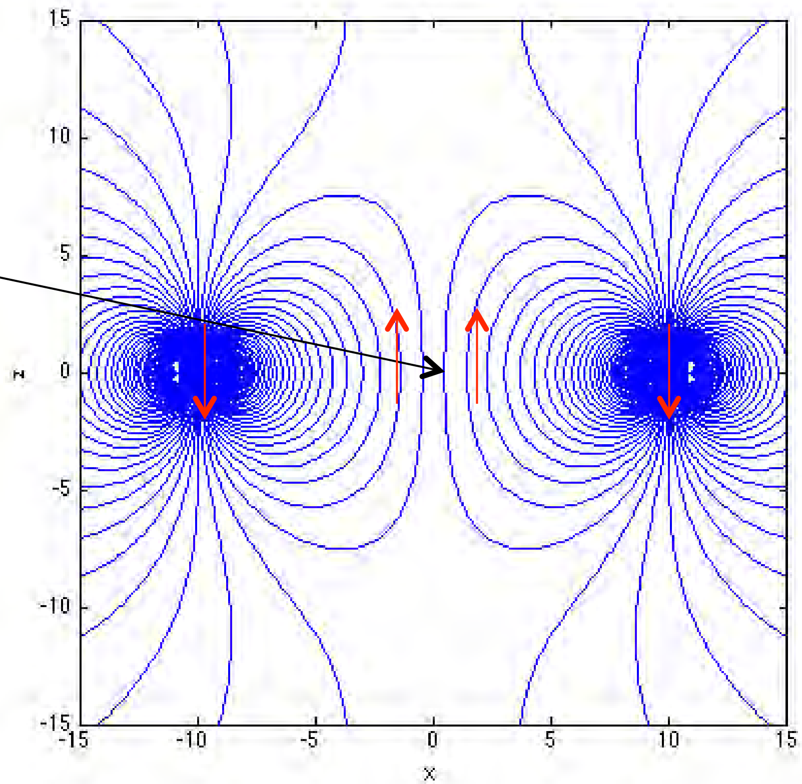
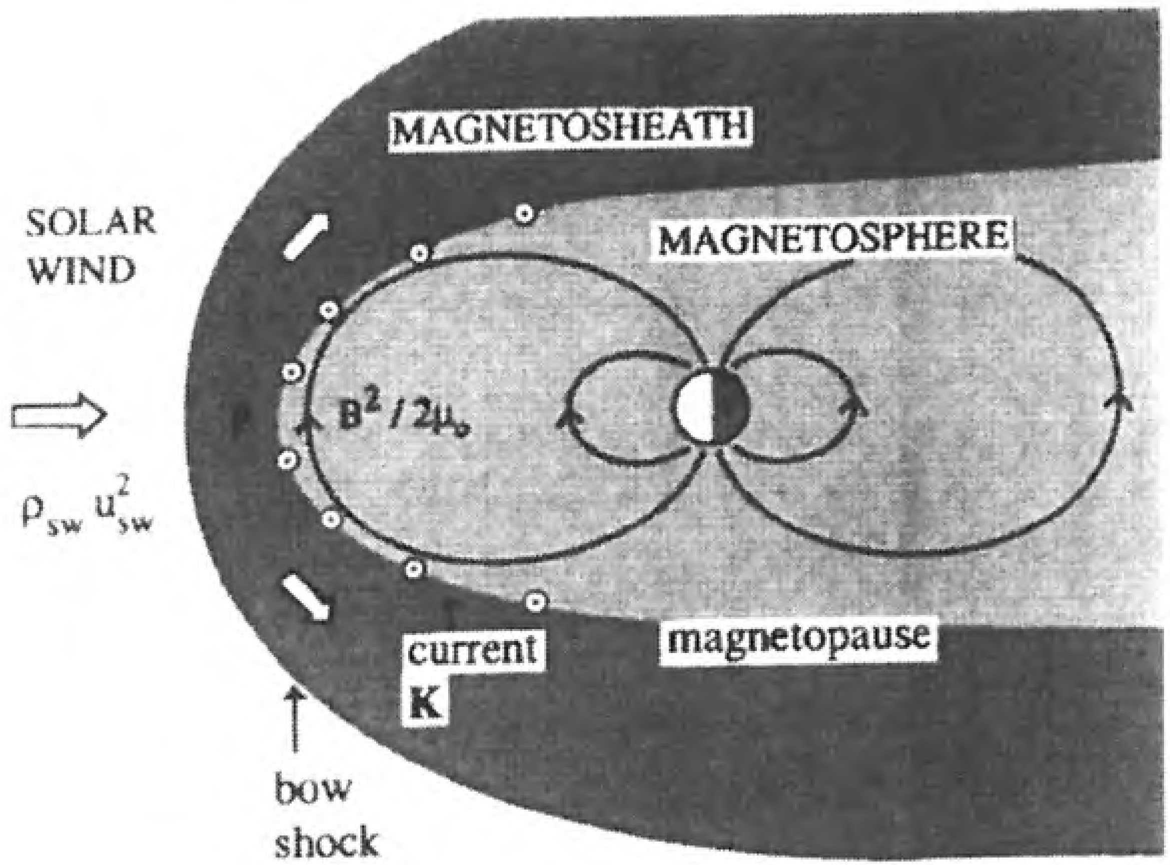


Image dipole

Effect of currects on the boundary of the m'sphere



B_{dipole}

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

From Cravens' CUP text

SW ram pressure <=> internal magnetic field pressure

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

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

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

Solve for r=> R_{MP}

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

Yes, I am being a bit sloppy here…

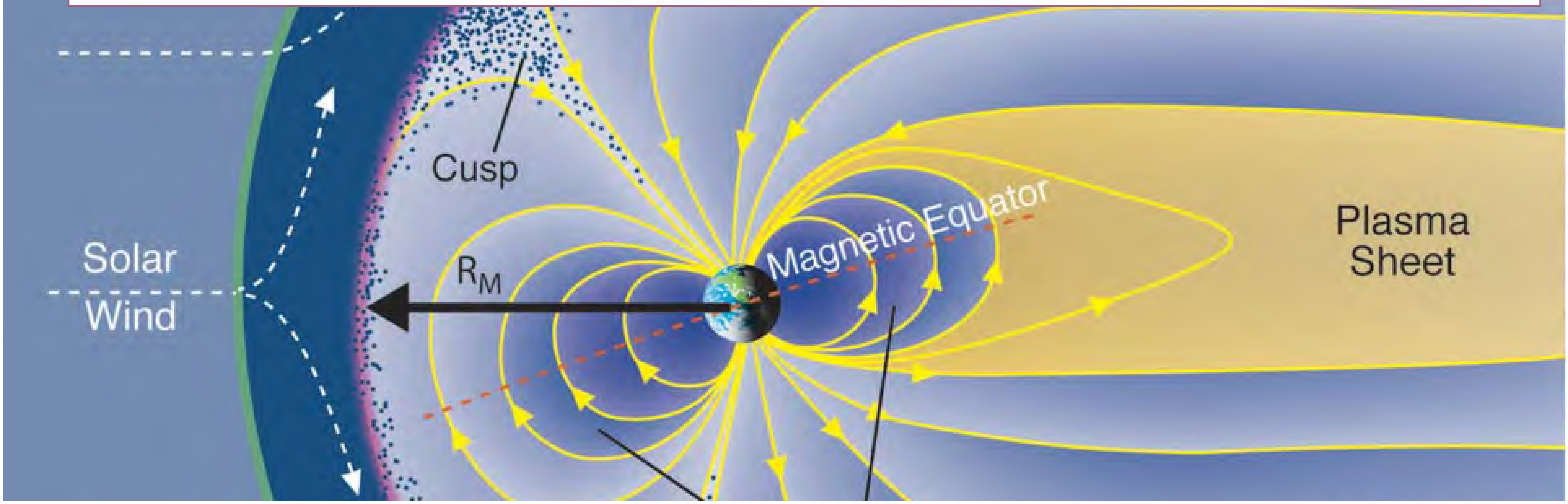
For more comprehensive treatment of magnetosheath, magnetopause (including details of the history) see 2012 HSS lecture by John Dorelli.
http://www.vsp.ucar.edu/Heliophysics/pdf/DorelliTerrestrialMagnetosphere.pdf

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

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

Dipole Magnetic Field in Solar Wind

SW Ram Pressure ⟷ Magnetic Pressure



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

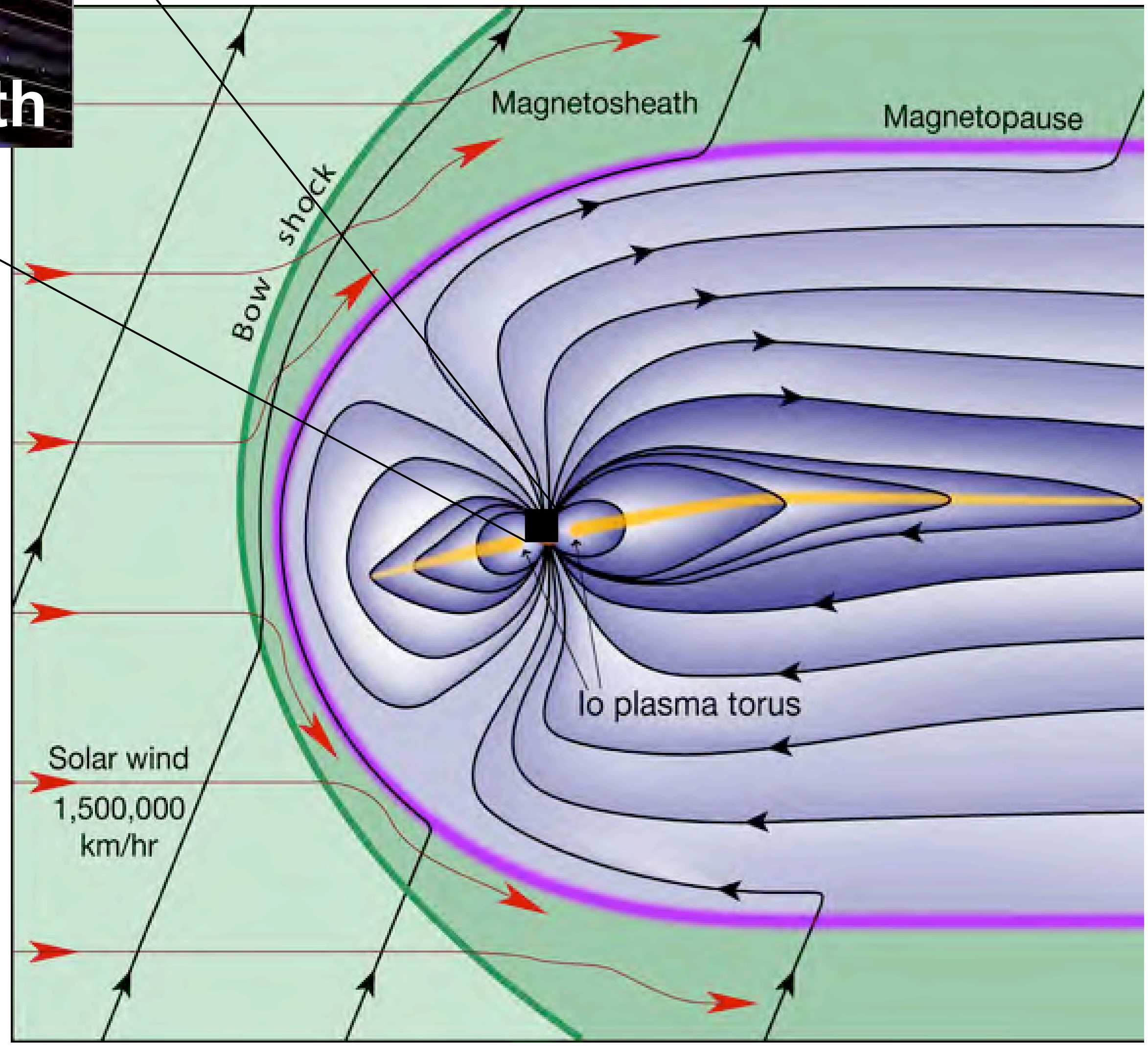
Chapman-Ferraro Distance

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

Quick chat with your neighbors….

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

Jupiter's Magnetosphere



- Strong Magnetic Field
- Large
  100 x Earth's magnetosphere
- Rotation-dominated
  10 hour period
- Io plasma source
  ~1 ton/sec S,O ions

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

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

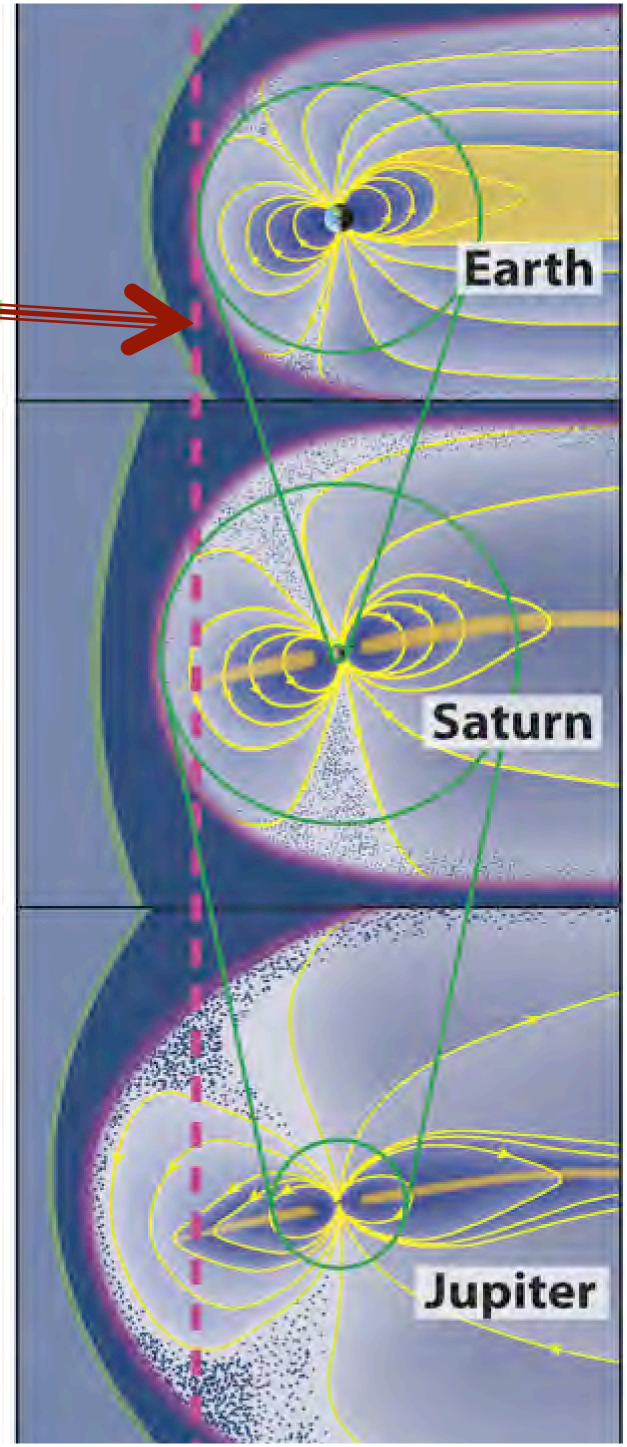
Magnetospheres scaled by stand-off distance of dipole field

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

Inflated magnetospheres of Jupiter & Saturn due to HOT PLASMAS

Note bimodal average locations

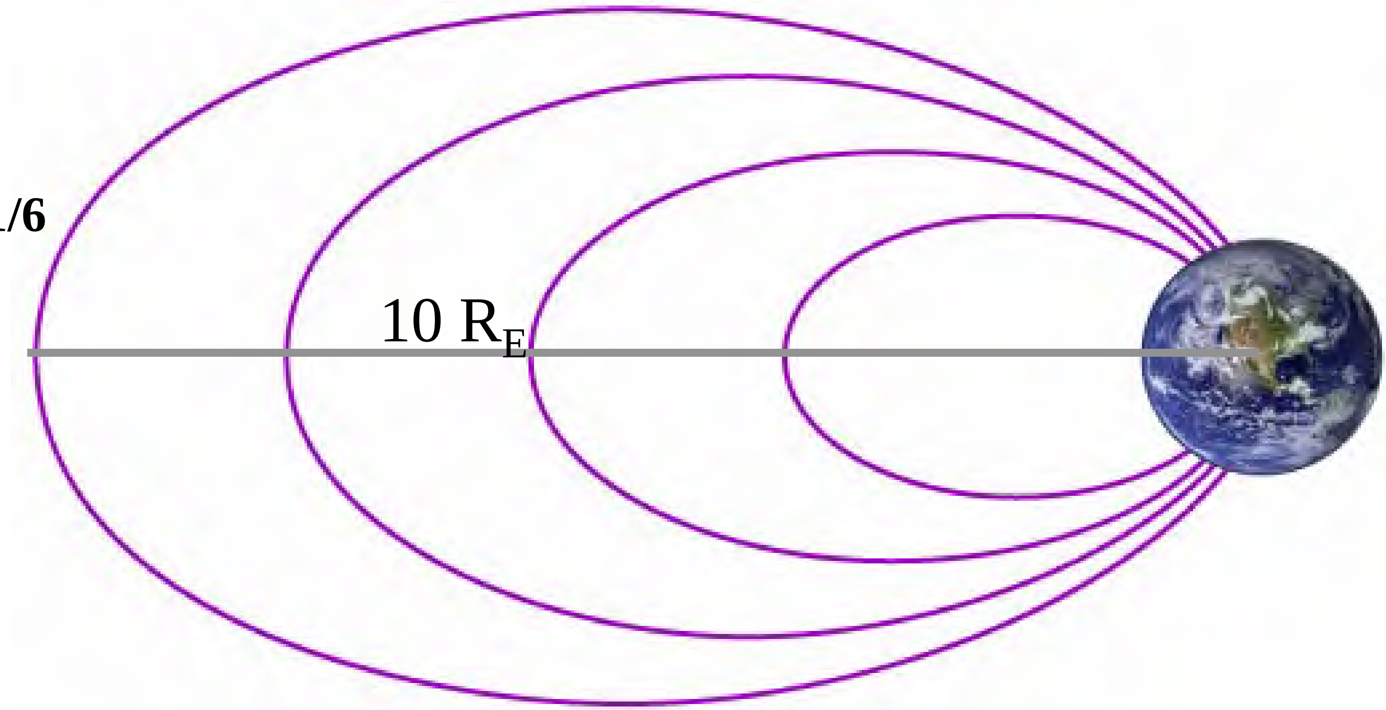
* *Achilleos et al. 2008* # *Joy et al. 2002*



Earth ~ Dipole

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

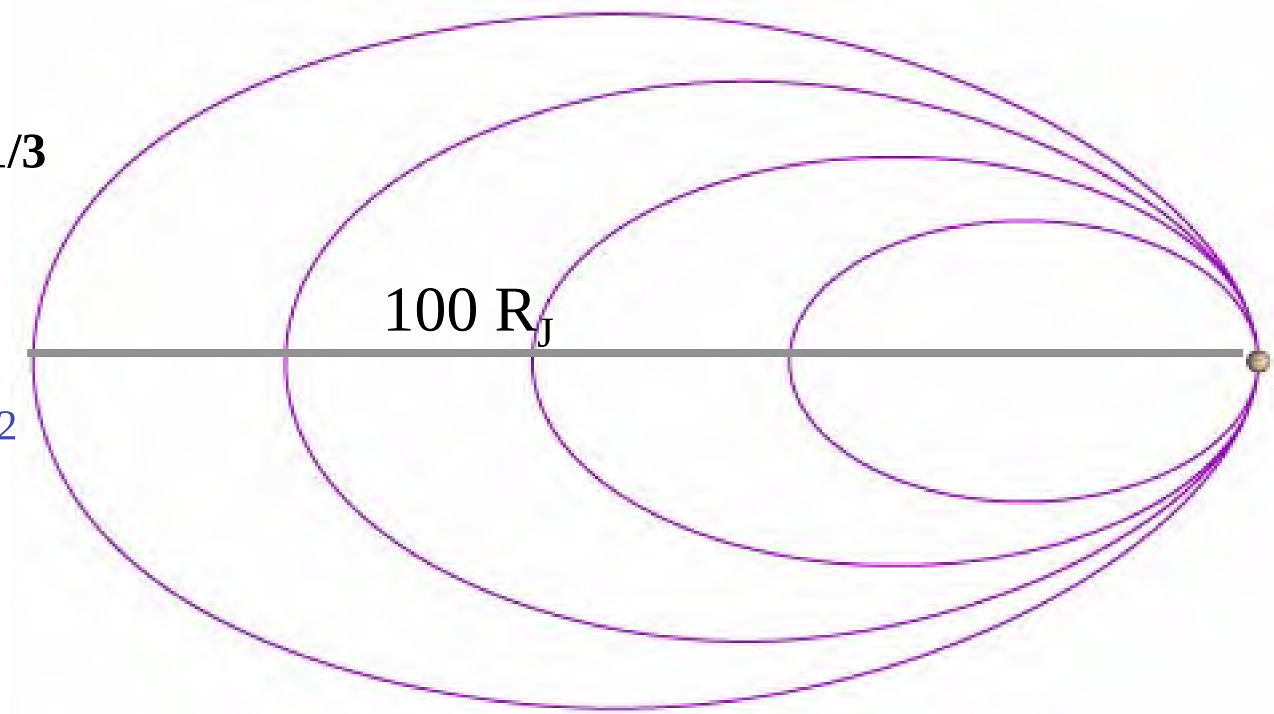
solar wind ρV^2



Jupiter

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

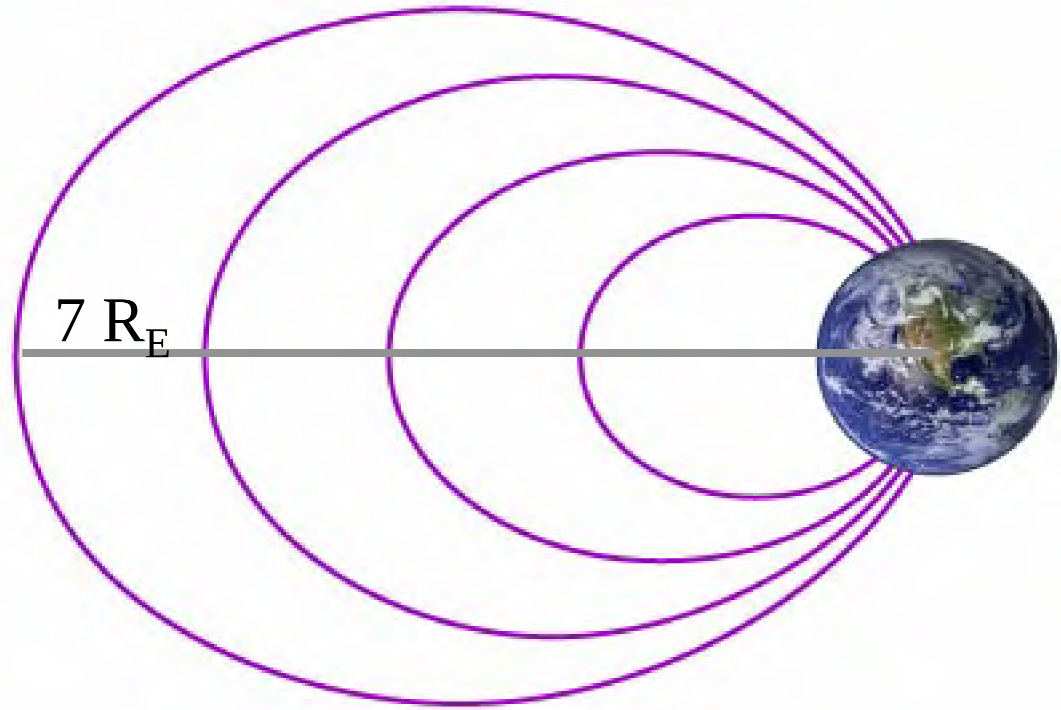
solar wind ρV^2



Earth ~ Dipole

R_{mp} -> 0.7 R_{mp}

solar wind ρV^2

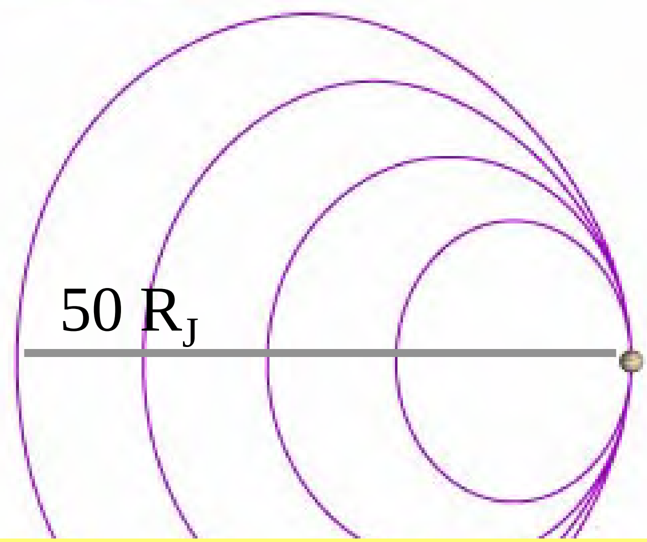


x10 Solar wind pressure

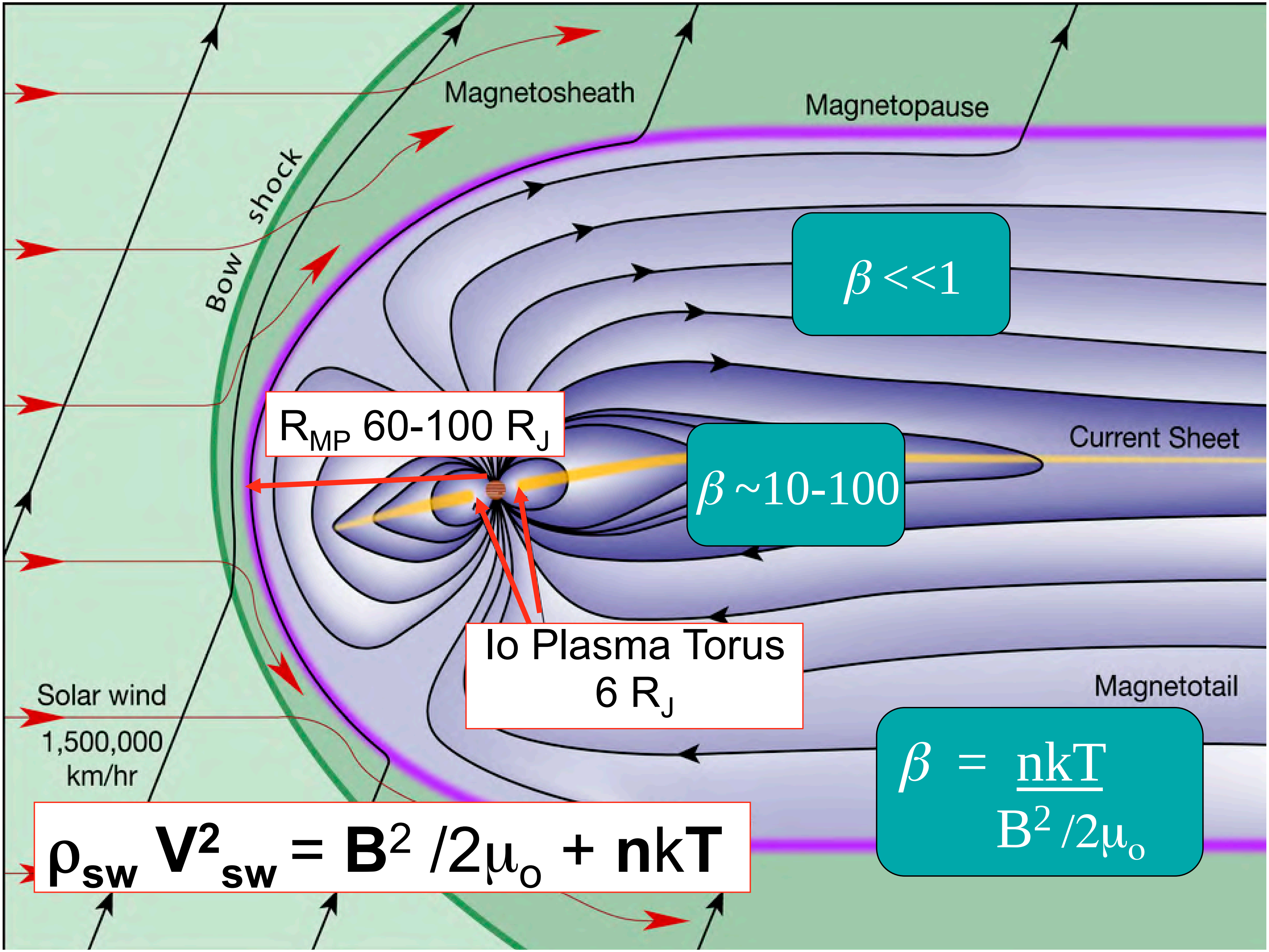
Jupiter

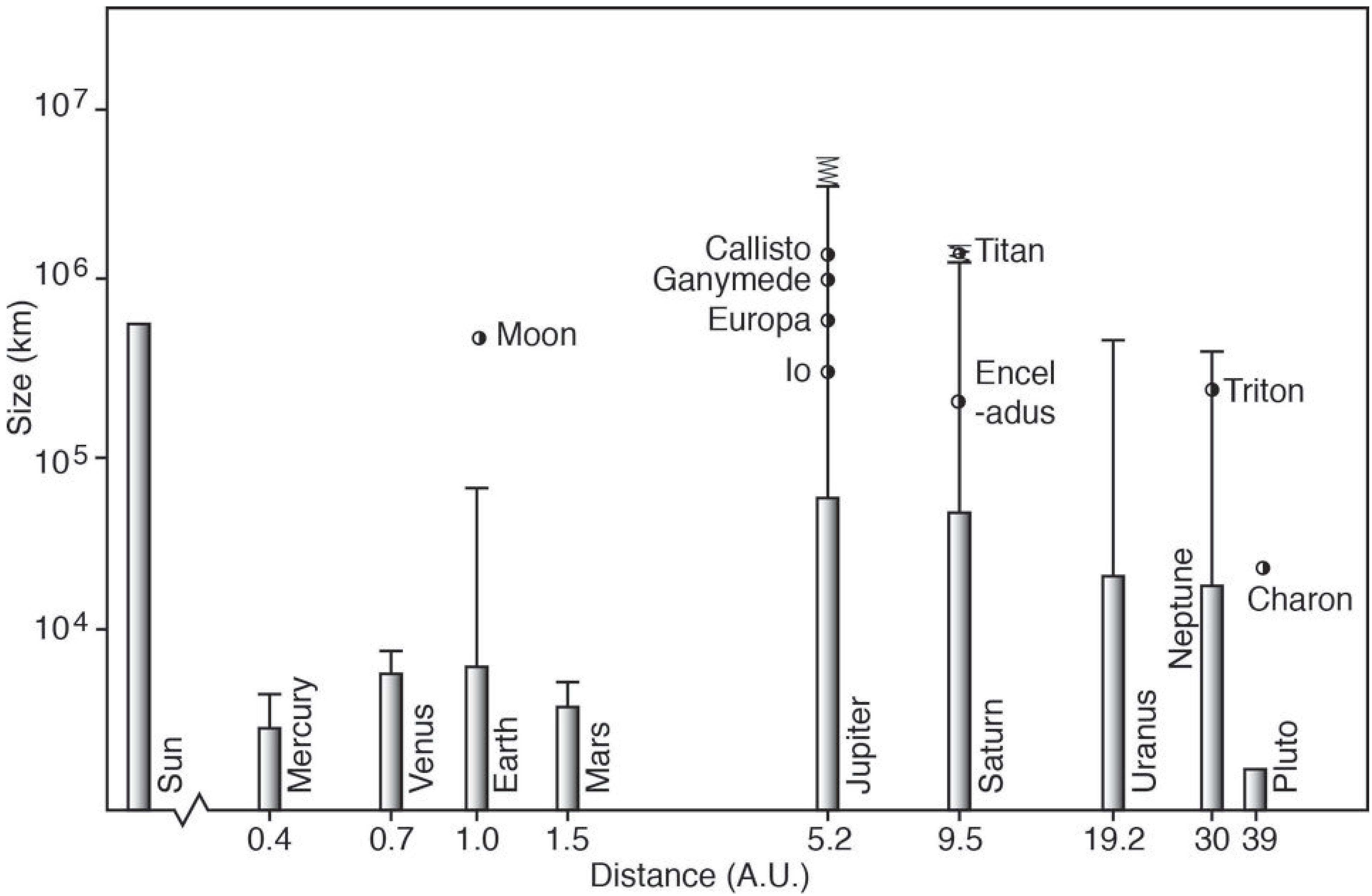
R_{mp} -> 0.5 R_{mp}

solar wind ρV^2

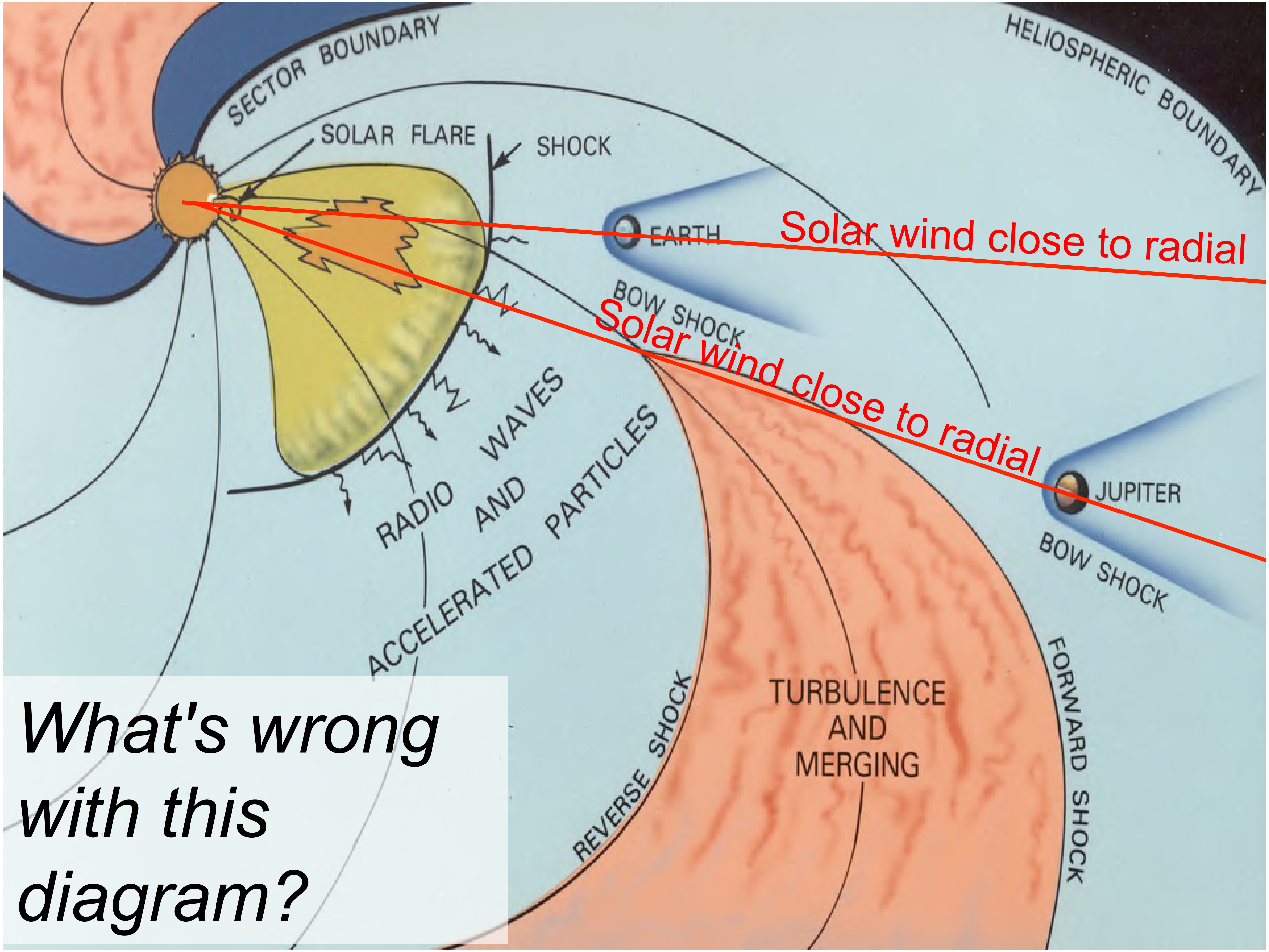


Factor ~10 variations in solar wind pressure at 5 AU
-> observed 100-50 Rj size of dayside magnetosphere


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

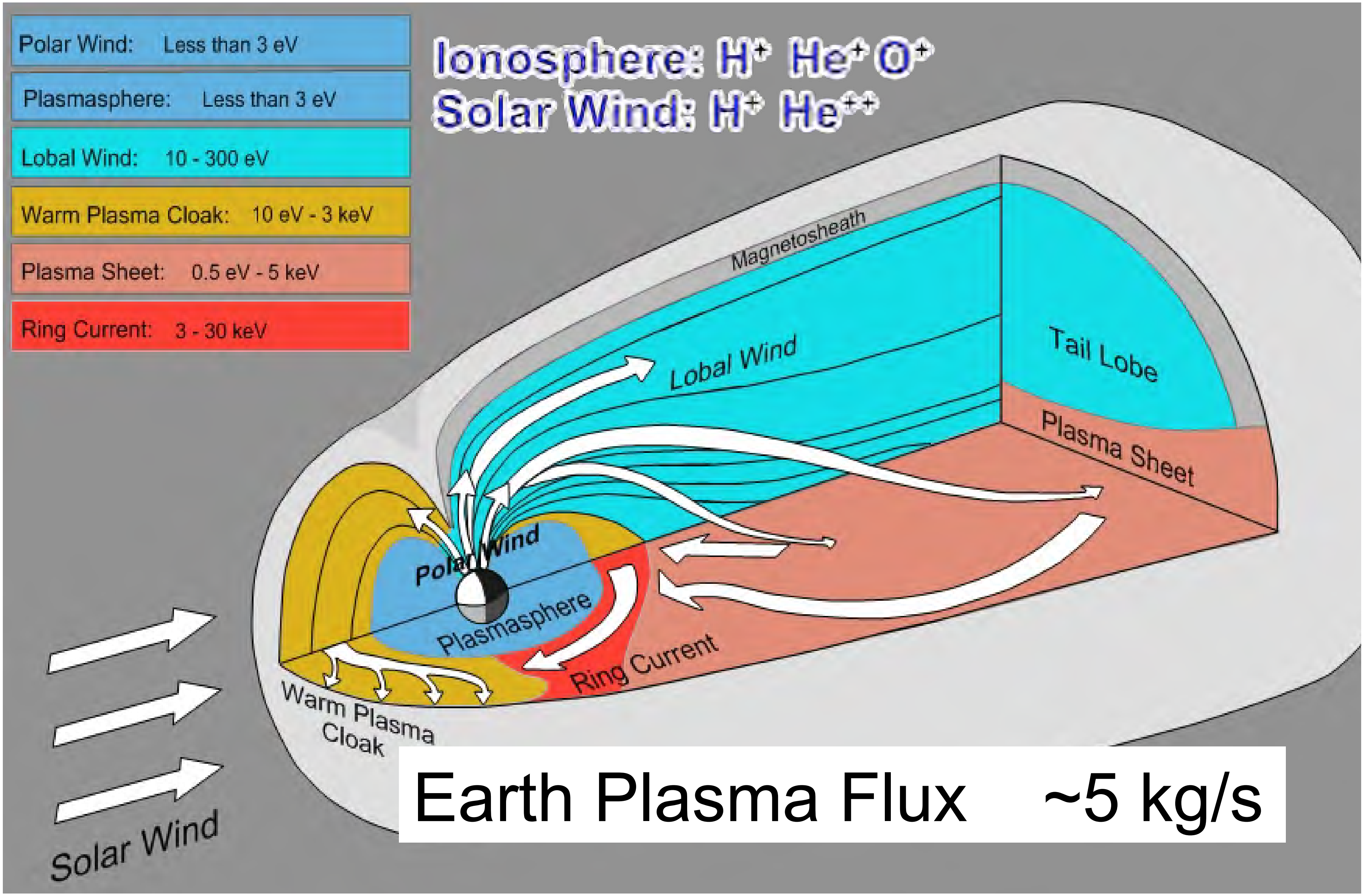


10^7
10^6
10^5
10^4
Size (km)
Callisto
Ganymede
Europa
Io
Moon
Titan
Encel
-adus
Triton
Charon
Sun
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto
0.4
0.7
1.0
1.5
5.2
9.5
19.2
30
39
Distance (A.U.)

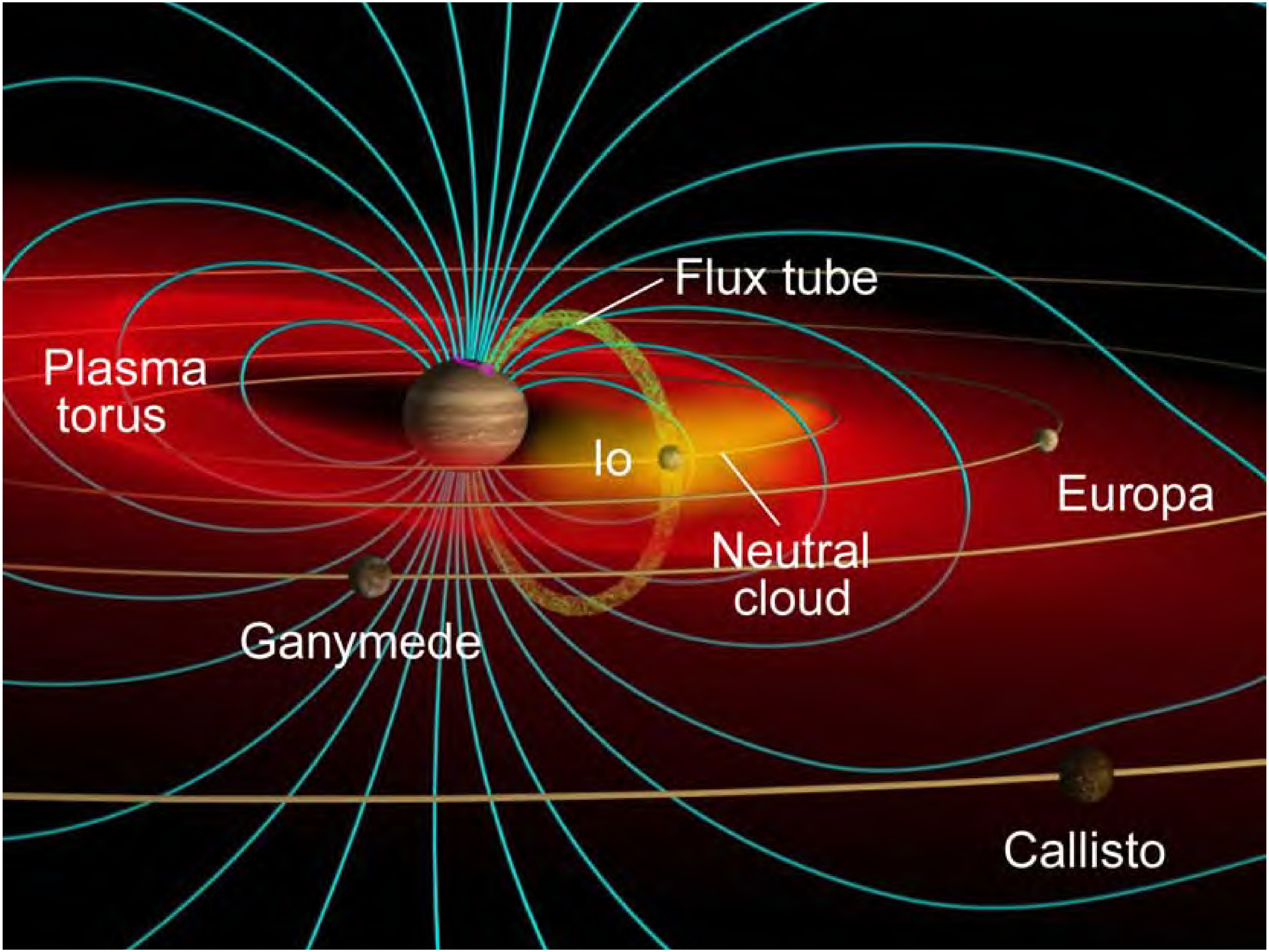


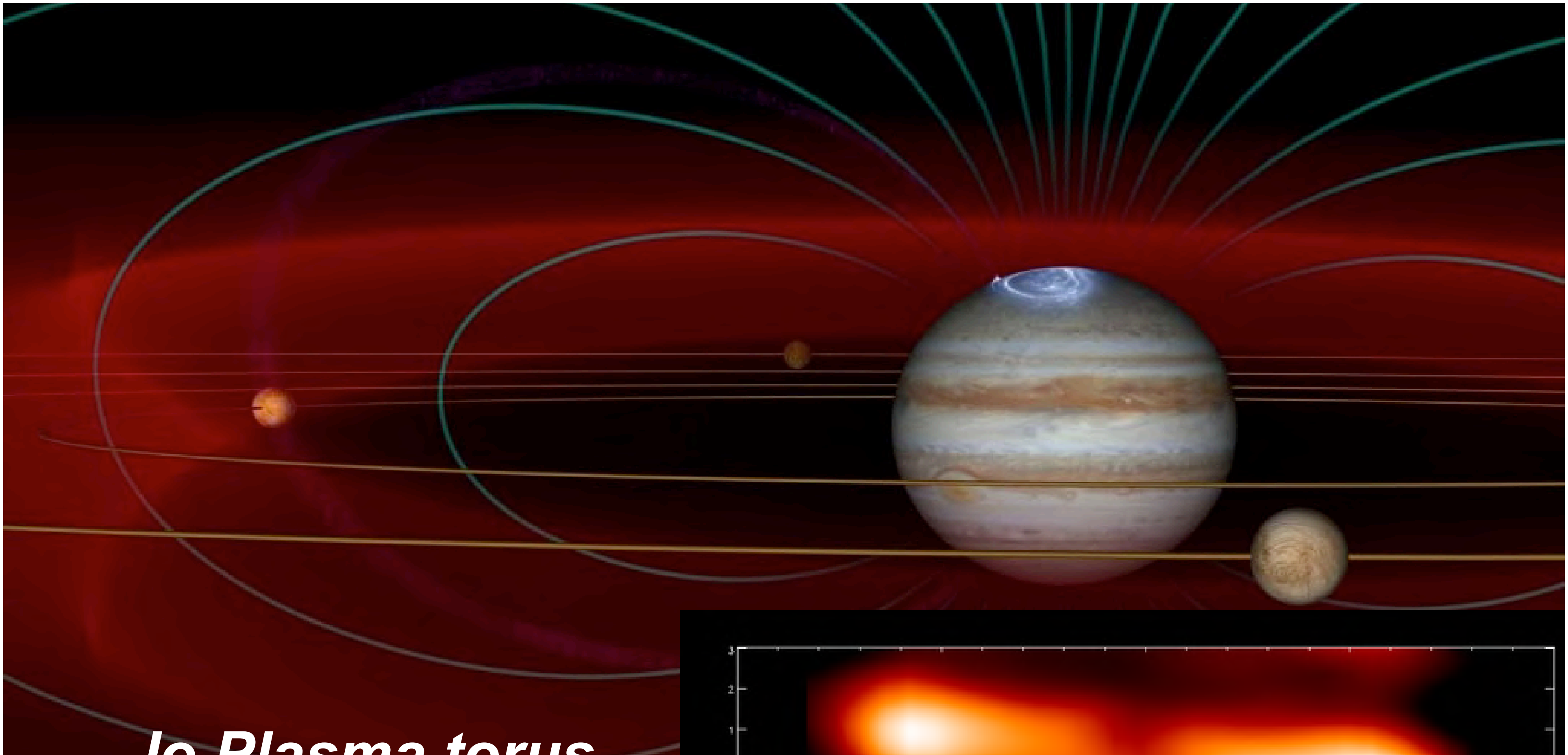
What's wrong with this diagram?

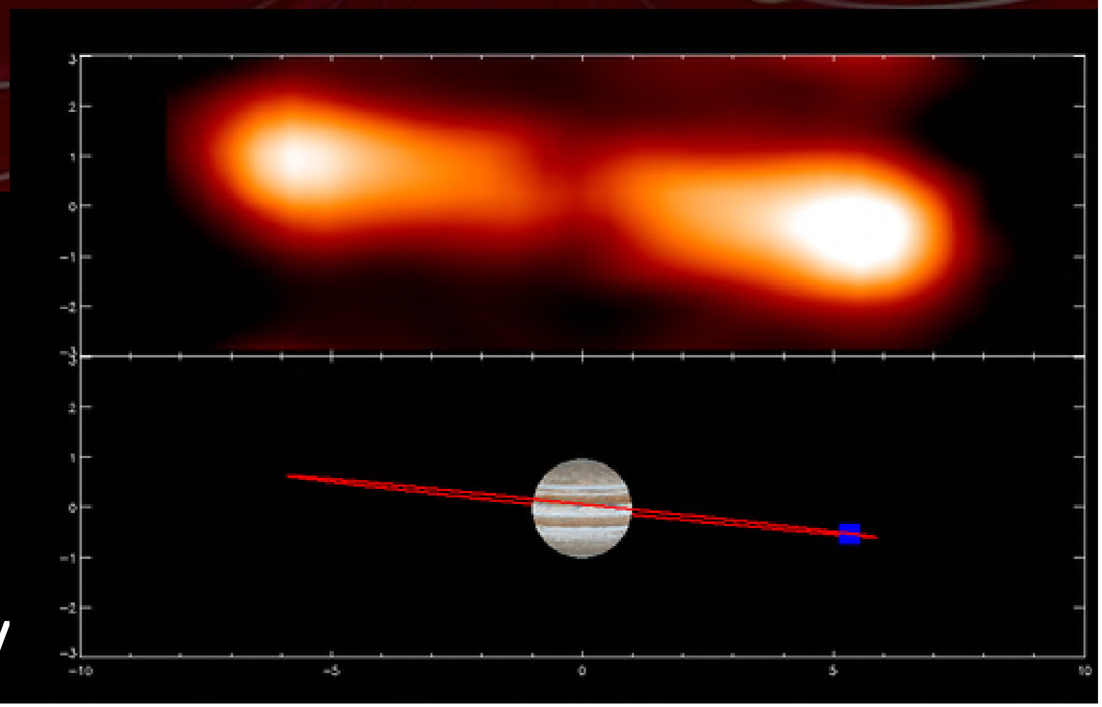
Plasma Sources



Earth Plasma Flux ~5 kg/s


Flux tube
Plasma
torus
Io
Europa
Neutral
cloud
Ganymede
Callisto

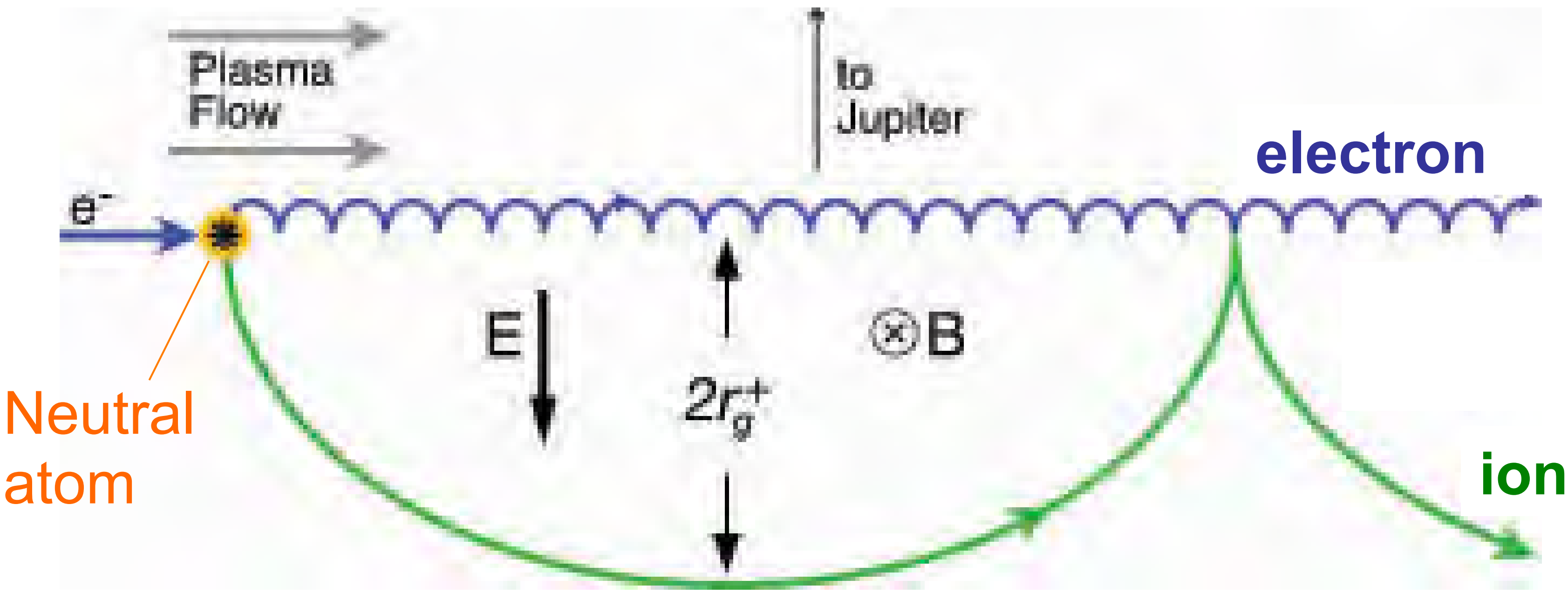




Io Plasma torus

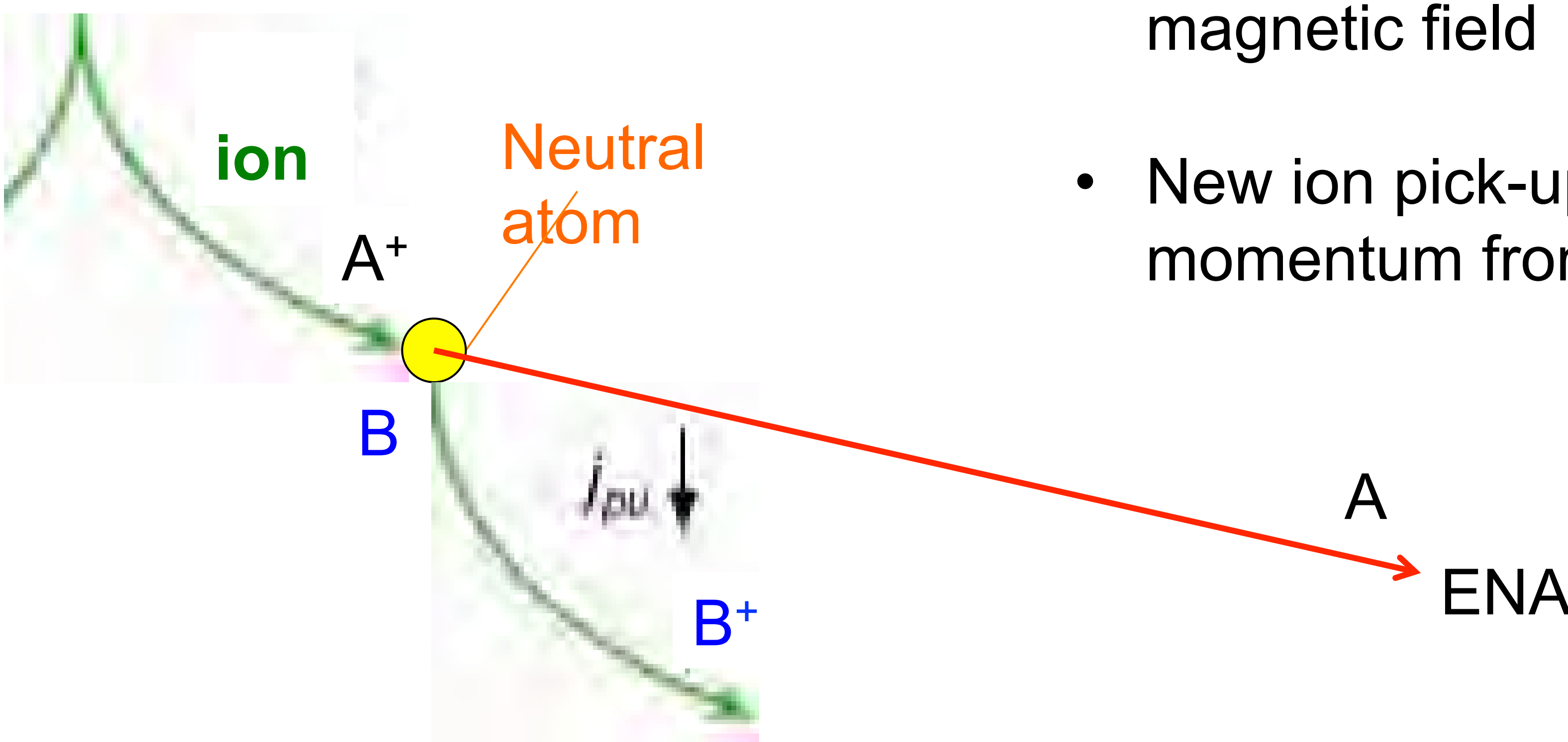
- 2 terraWatt EUV emission
- Total mass 2 Mton
- Source 1 ton/s
- Replaced in 20-50 day

Ion Pick Up



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

Charge-Exchange
-> Fast Neutral = Energetic Neutral Atoms



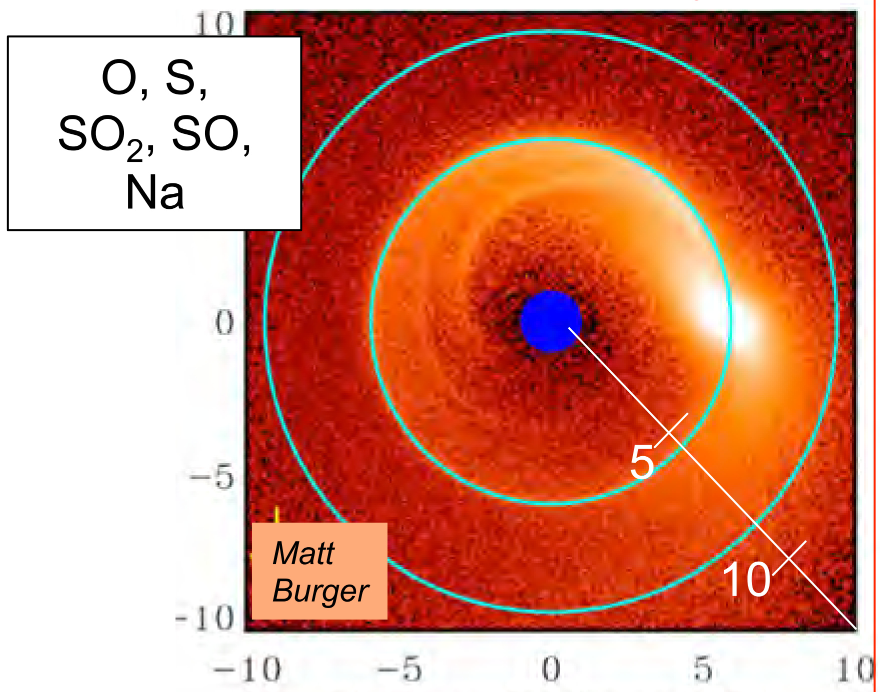
- Neutralized particle no longer confined by magnetic field
- New ion pick-up, extracts momentum from plasma

Thomas et al. 2004
Schneider & Bagenal 2007

Neutral Clouds

Melin et al. 2009
Hartogh et al. 2011
Smith et al. 2010
Cassidy & Johnson 2010
Fleshman et al. 2012

Jupiter – Io @ 5.9 R_J



Confined 5.5 – 6.5 R_J

Neutral mass ~ 70 kton

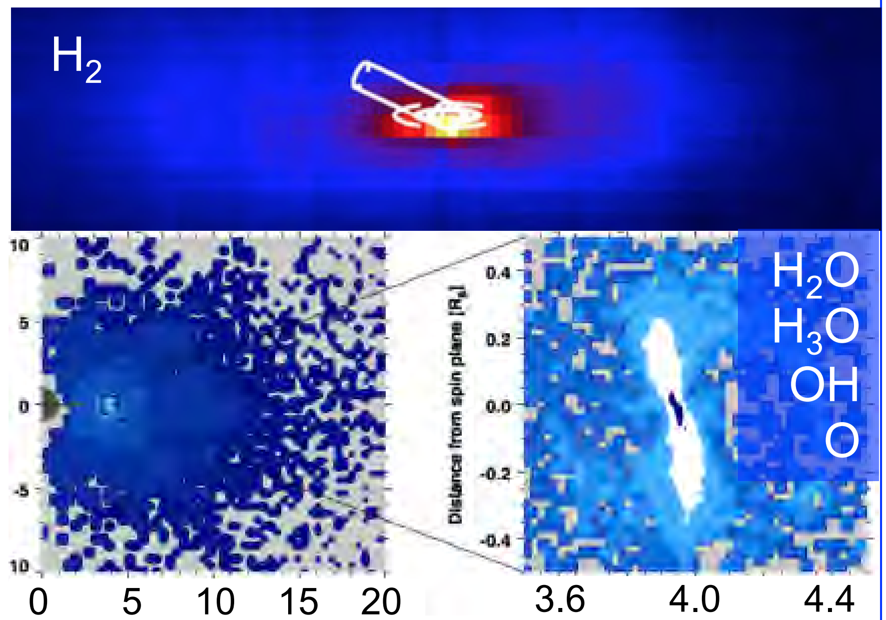
Neutral density ~ 50 – 100 cm^{-3}

Neutral source ~ 600 – 2600 kg/s

Ion source ~ 260 – 1400 kg/s

Neutrals : Ions ~ 1:50

Saturn – Enceladus @ 4 R_S



"Puffed up" from 4 R_S to 0 – 15 R_S

- Neutral-neutral collisions
- Charge exchange

Neutral mass ~ 1Mton

Neutral density ~ 4000 cm^{-3}

Neutral source ~ 70 – 750 kg/s

Ion source ~ 20-80 kg/s

Neutrals : Ions ~ 100:1

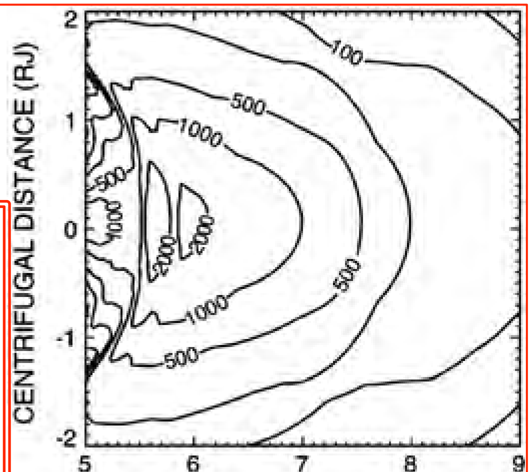
Thomas et al. 2004
Schneider & Bagenal 2007
Steffl et al. 2004,6,8,

Plasma Torus

Fleshman et al. 2013
Persoon et al. 2013

Jupiter

T_{pu} ~ 400 eV
T_e ~ 5 eV
UV emission ~ 2 TW

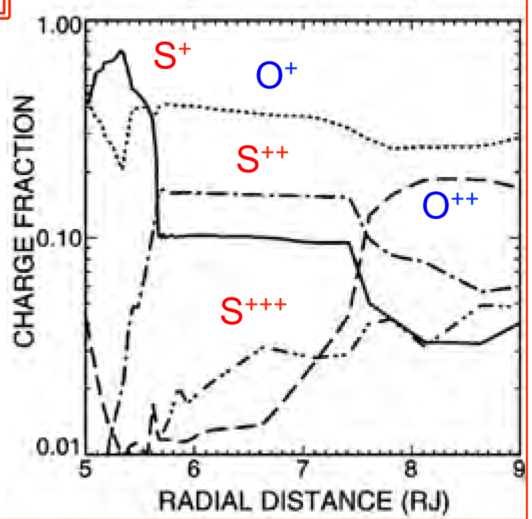


N_{max}~2000 cm^{-3}

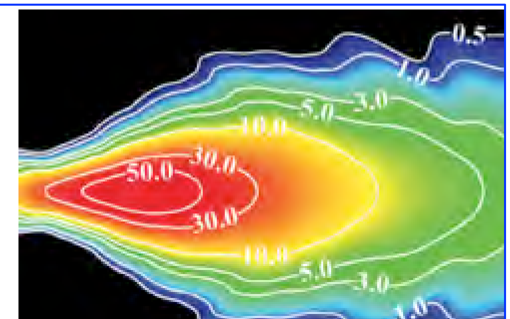
Total ~ 1.5 Mton

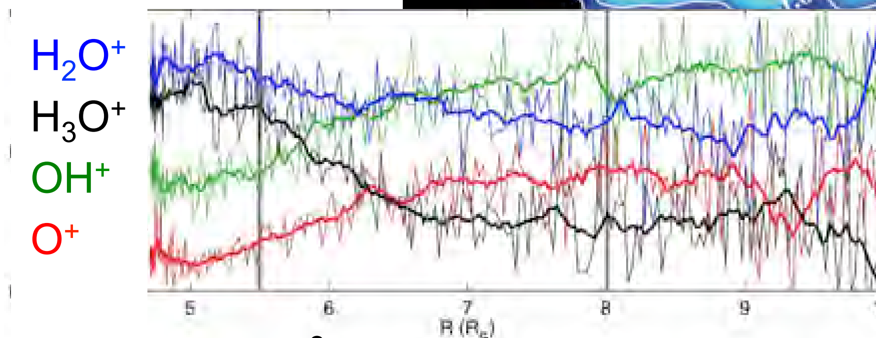
Plasma transport

~250-1750 kg/s



Saturn





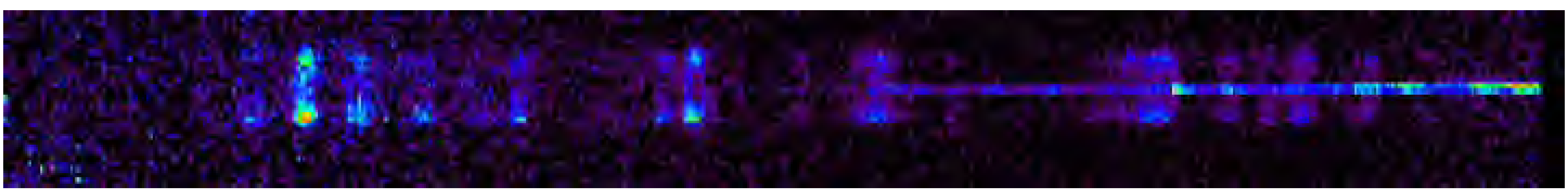
N_{max}~100 cm^{-3}

Total ~ 85 kton

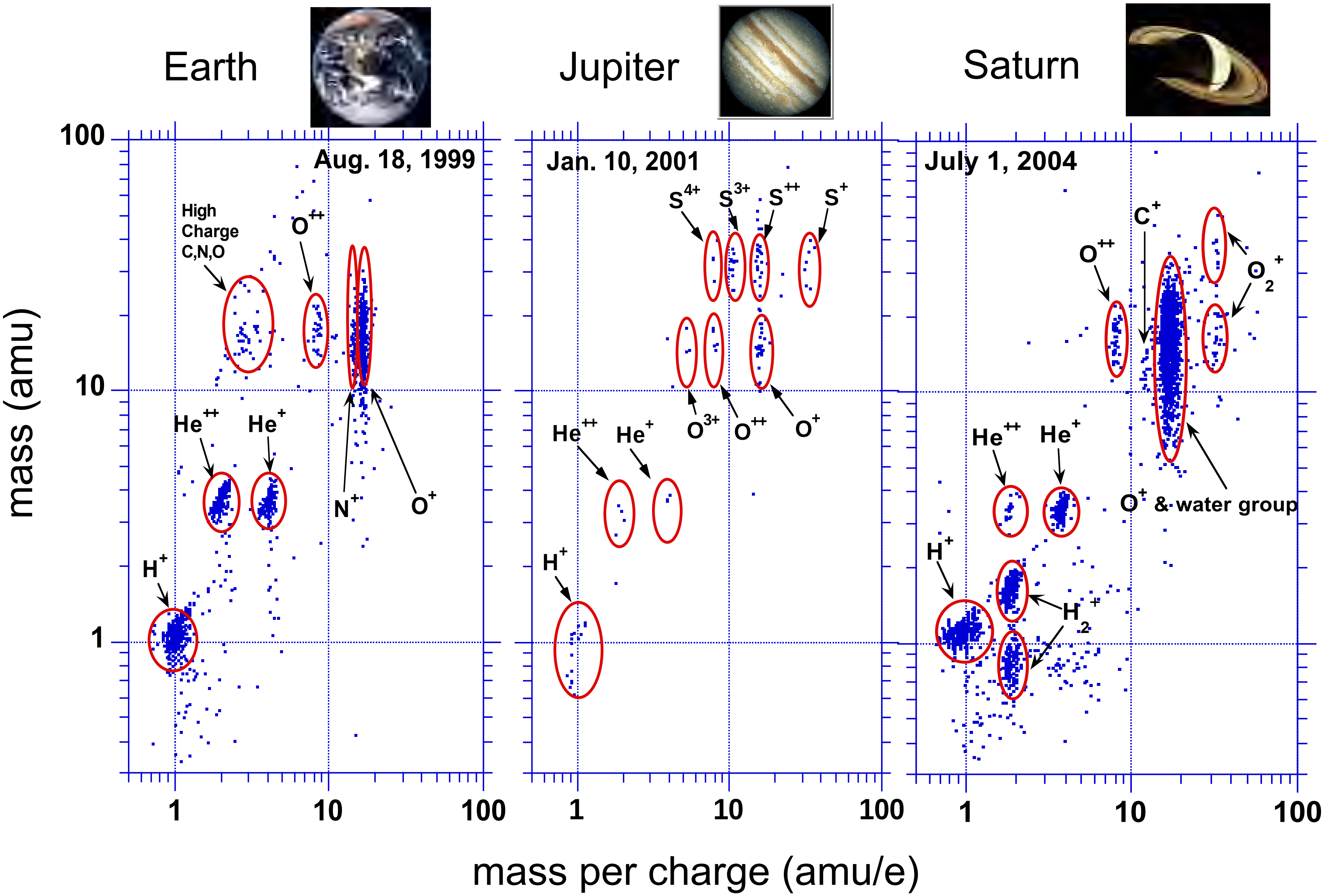
Plasma transport

~12 – 250 kg/s

T_{pu} ~ 100 eV
T_e ~ <2 eV
No UV emission



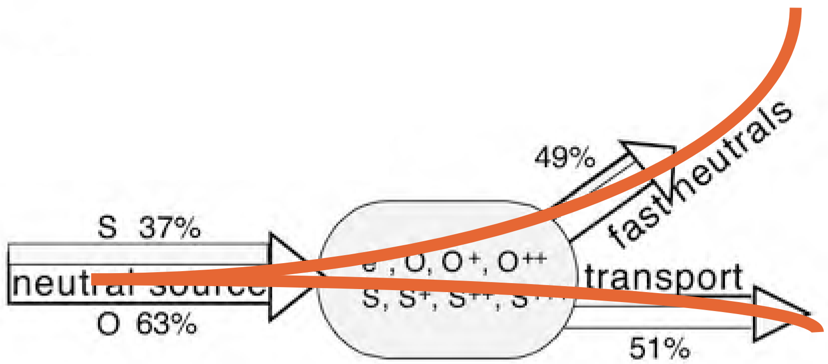
Charge Energy Mass Spectrometer (CHEMS) on Cassini records "fingerprints" of ion composition at Earth, Jupiter, and Saturn (Hamilton et al, 2005)



Delamere & Bagenal 2003

Plasma Torus
Mass Flux

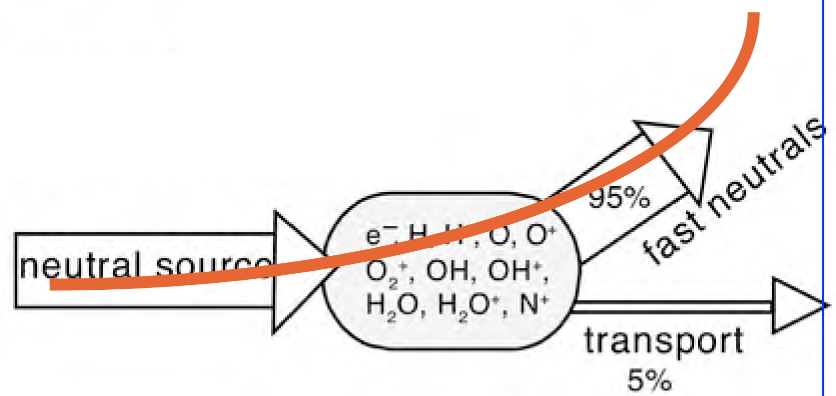
Jupiter



Half lost as fast neutrals
-> extended neutral cloud

Half transported out to plasma disk

Saturn



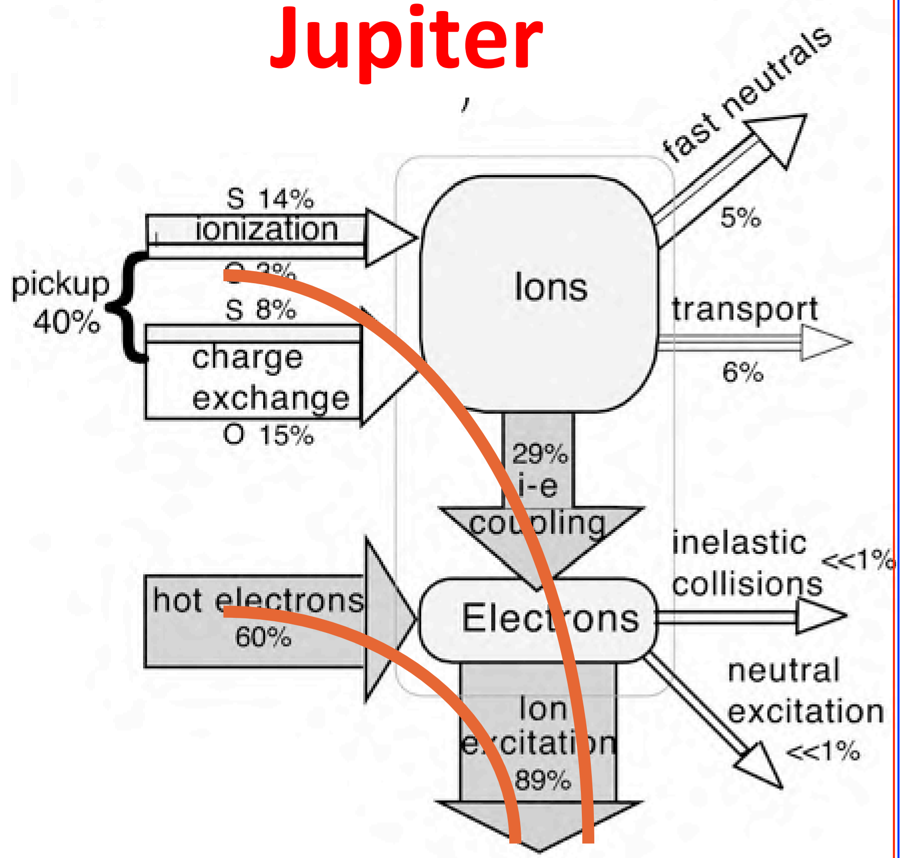
MOST lost as fast neutrals
-> extended neutral cloud

Few% transported out to plasma disk

Delamere & Bagenal 2003

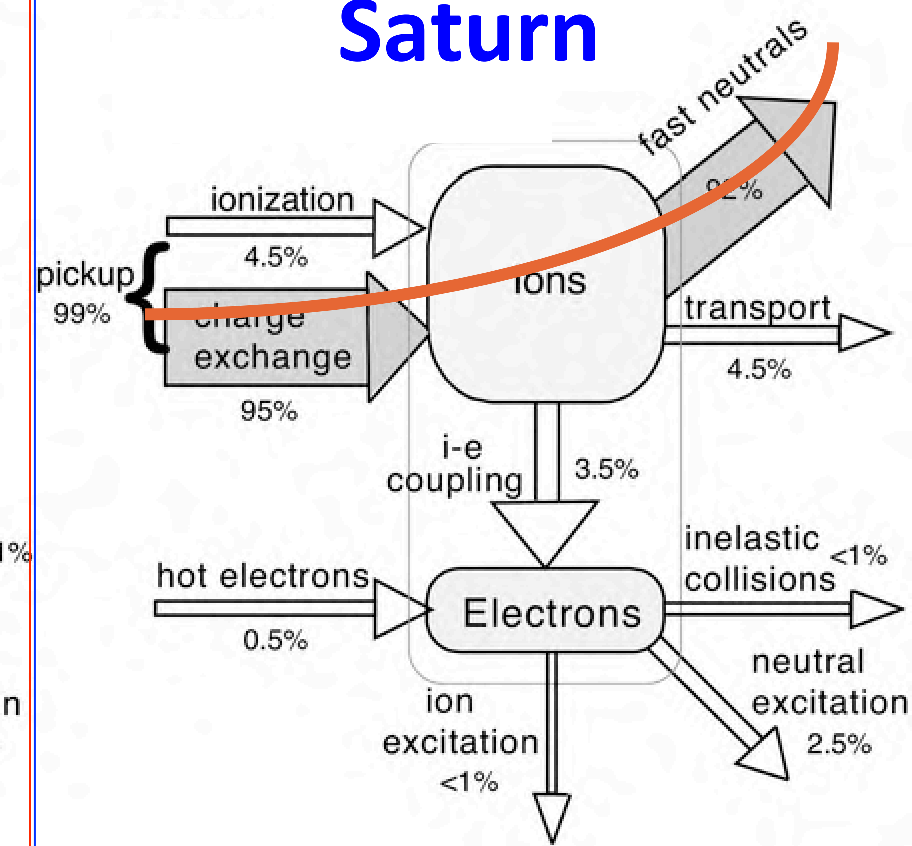
Plasma Torus Energy Flux

Jupiter



Heating: Half pick-up, Half hot electrons
Cooling: UV emissions

Saturn



Heating: Charge exchange pick-up
Cooling: Charge exchange escape

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	70-700	~0.02	~0.2