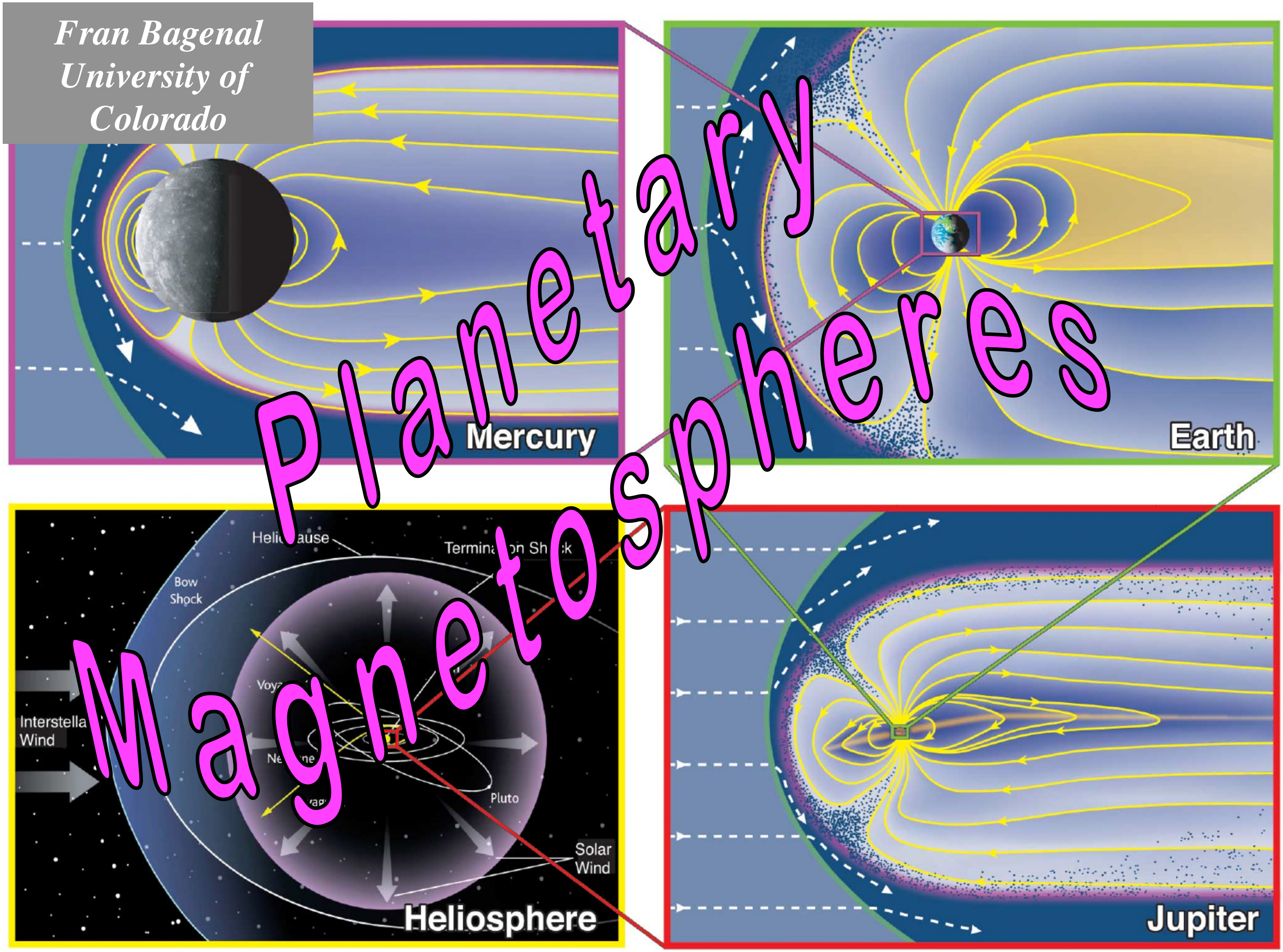
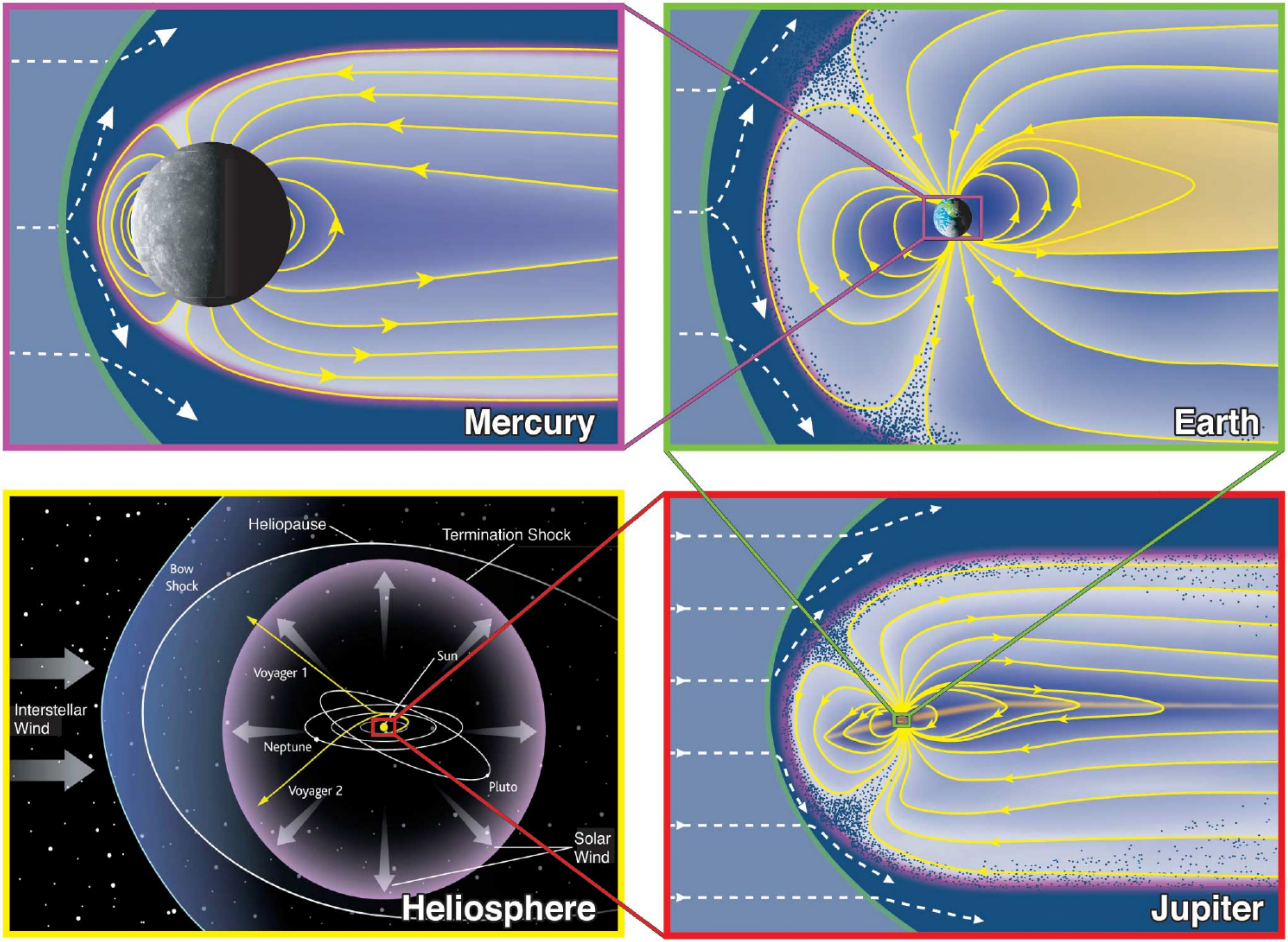
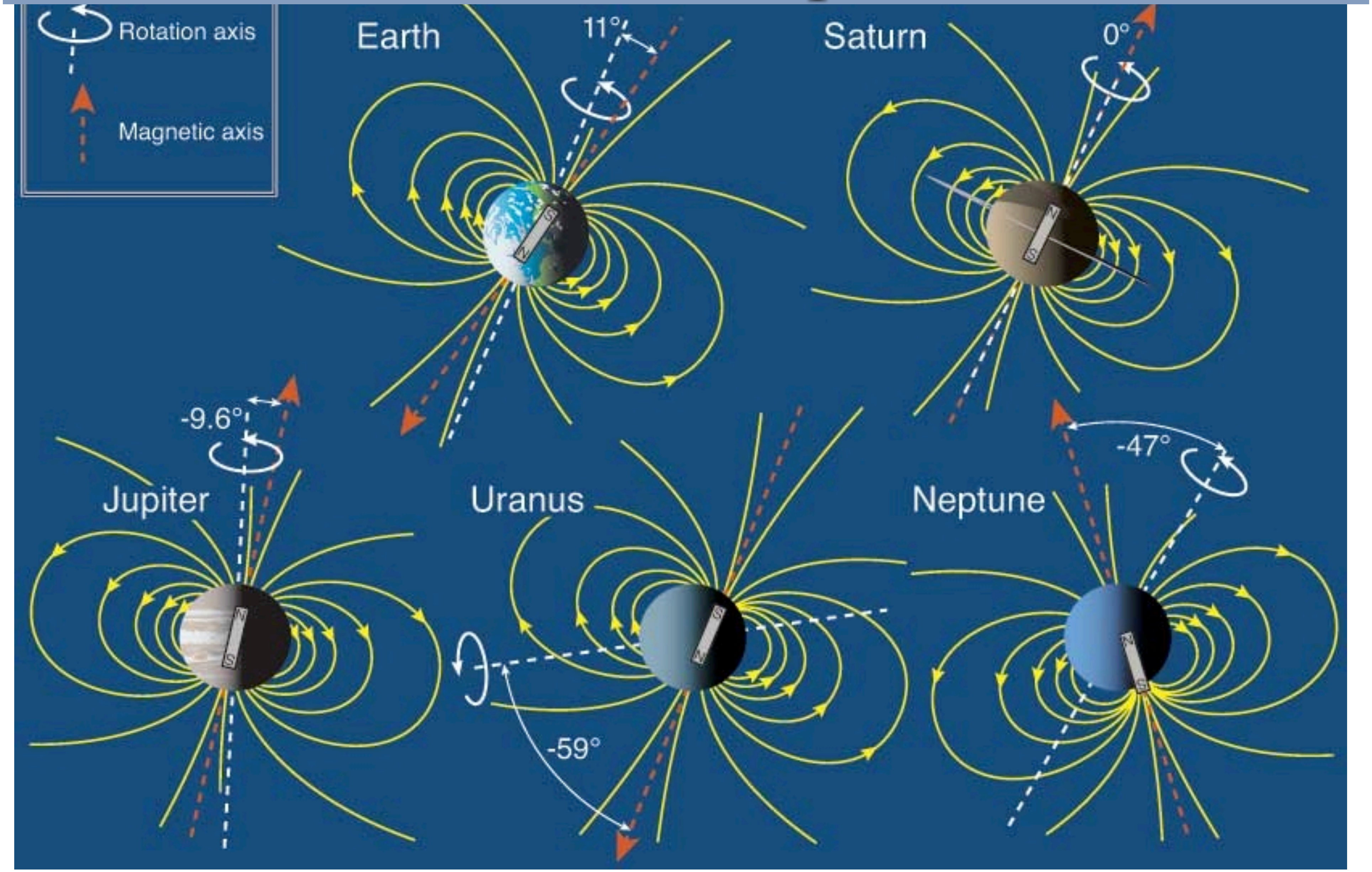
Planetary Magnetospheres

Fran Bagenal
University of Colorado



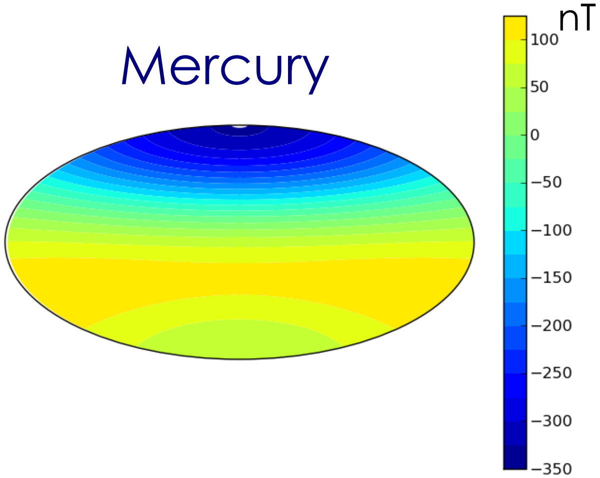

Mercury
Earth
Heliopause
Termination Shock
Bow Shock
Voyager 1
Sun
Interstellar Wind
Neptune
Voyager 2
Pluto
Solar Wind
Heliosphere
Jupiter

Tilts and Obliquities

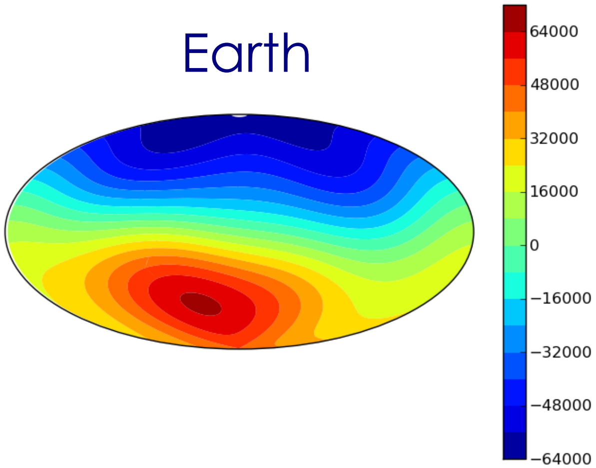


Offset Tilted Dipole (poor) Approximation

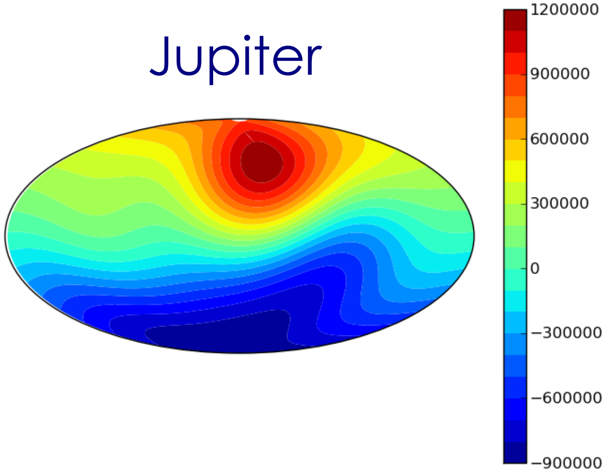
Mercury



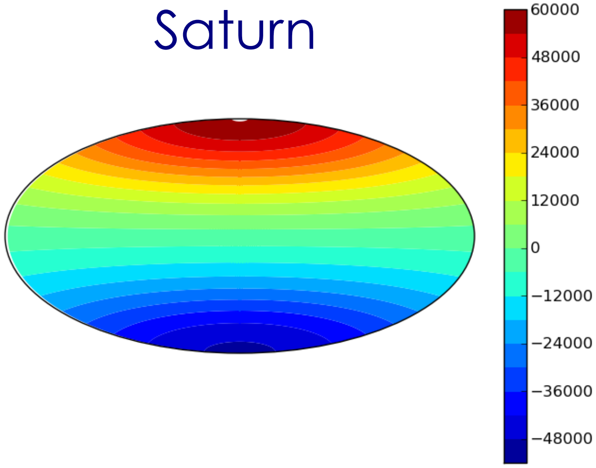
Earth



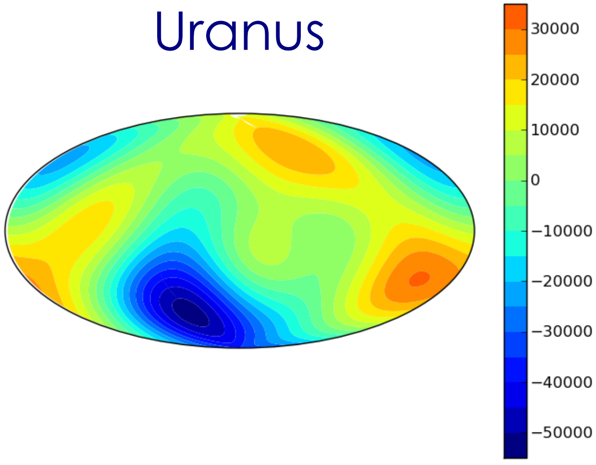
Jupiter



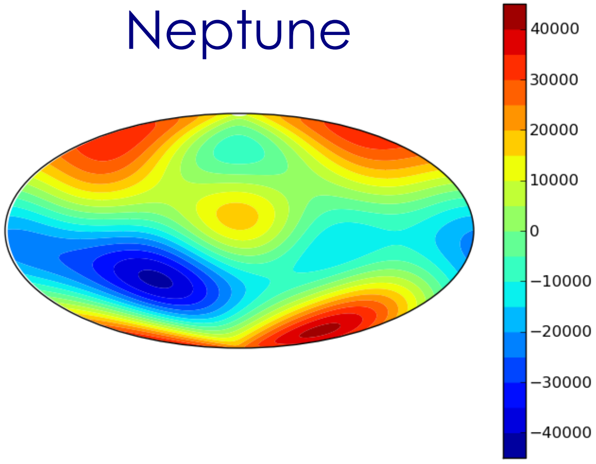
Saturn



Uranus



Neptune



Sabine Stanley’s lecture on dynamos

Magnetic Potential
3-D harmonics

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

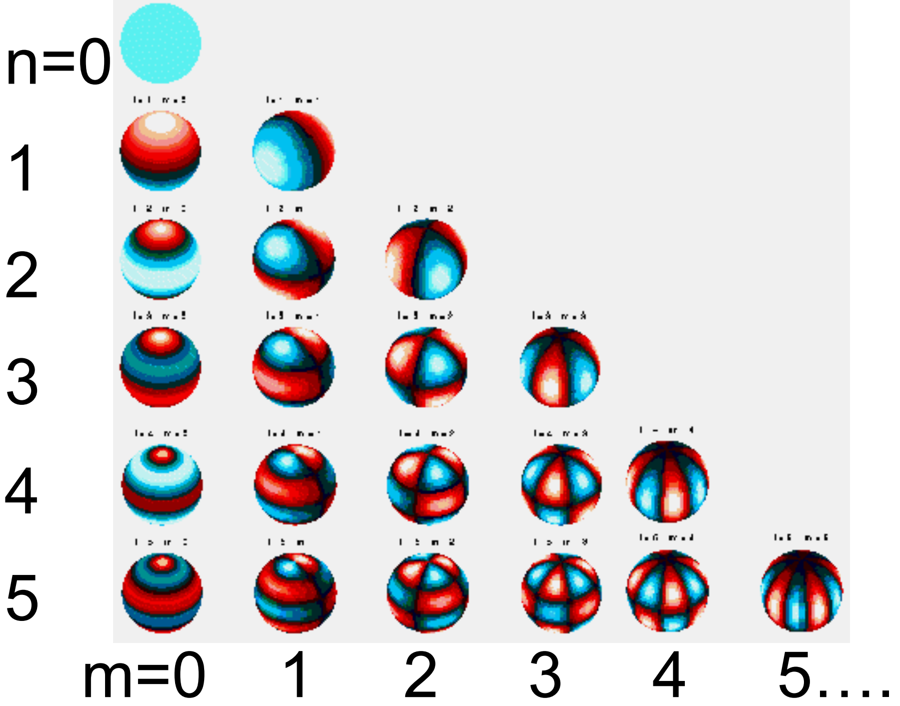
coefficients - constants

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

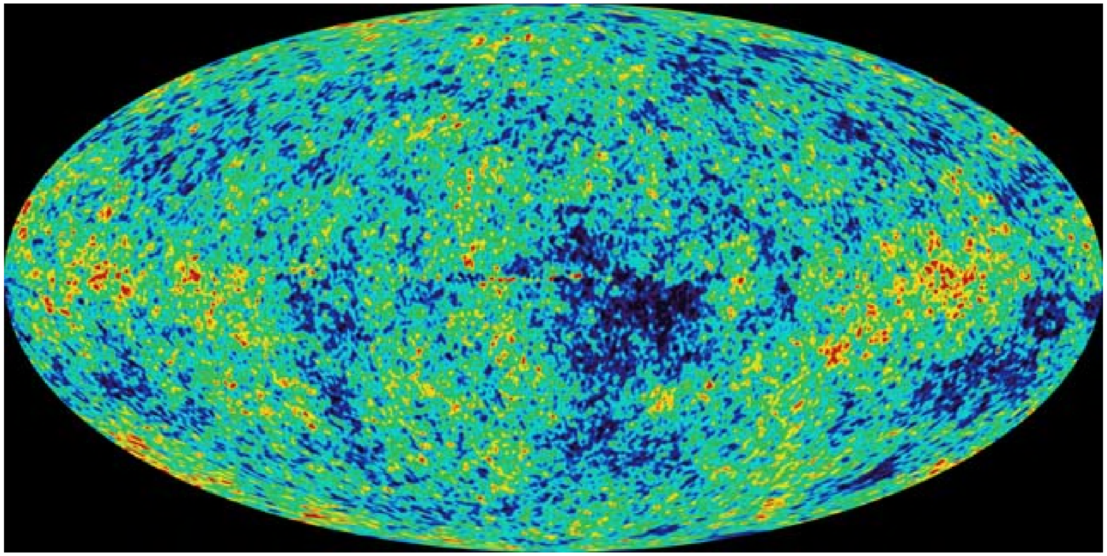
Decreasing with r to increasing power with n

functions

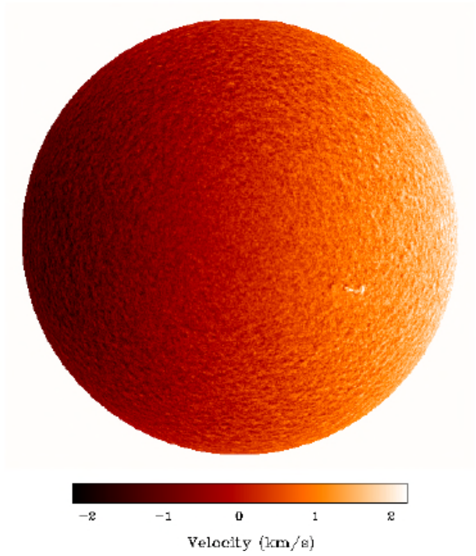
$$P_0^0(\cos\theta) = 1$$
$$P_1^0(\cos\theta) = \cos\theta$$
$$P_1^1(\cos\theta) = -\sin\theta$$
$$P_2^0(\cos\theta) = \tfrac{1}{2}(3\cos^2\theta - 1)$$
$$P_2^1(\cos\theta) = -3\cos\theta\sin\theta$$
$$P_2^2(\cos\theta) = 3\sin^2\theta$$
$$P_3^0(\cos\theta) = \tfrac{1}{2}(5\cos^3\theta - 3\cos\theta)$$

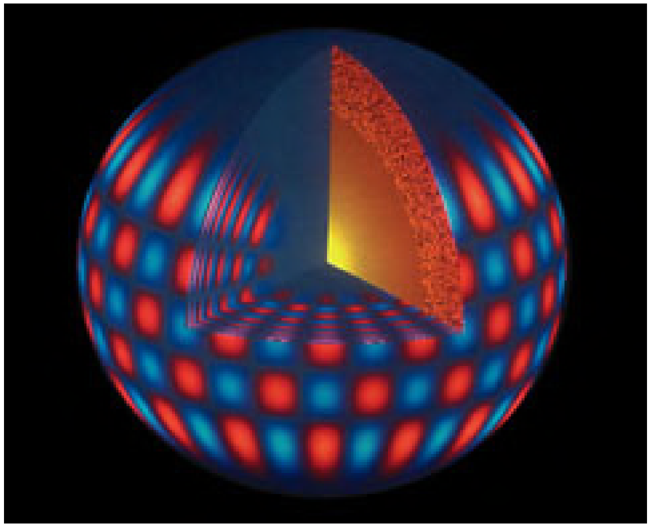


Same technique used to model cosmic microwave background



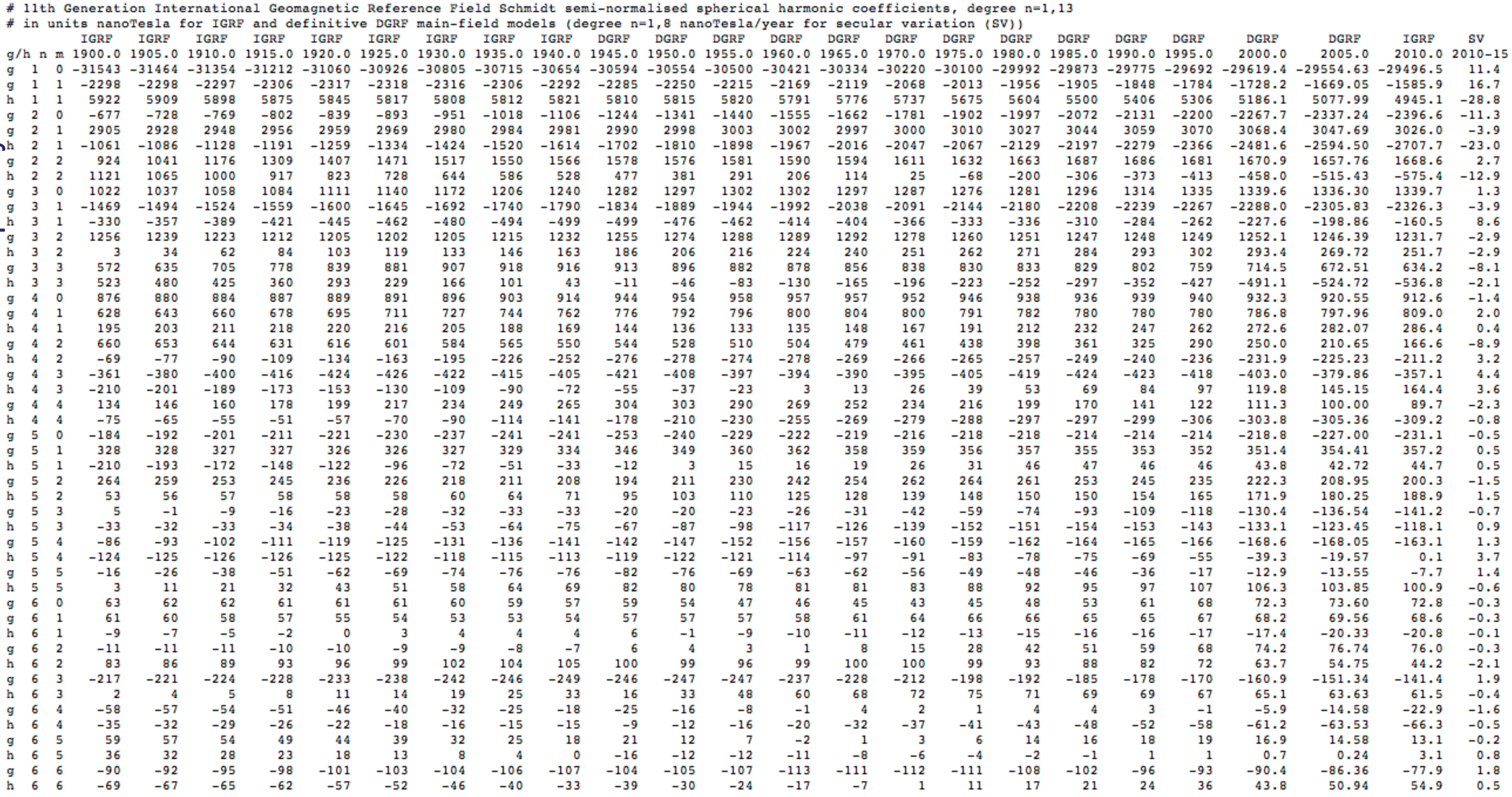
or interior of Sun with Helioseismology…





Earth - International Geomagnetic Reference Field

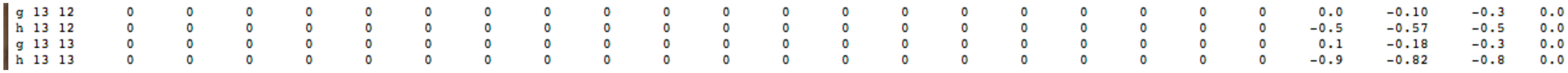
Complexity



```
# 11th Generation International Geomagnetic Reference Field Schmidt semi-normalised spherical harmonic coefficients, degree n=1,13
# in units nanoTesla for IGRF and definitive DGRF main-field models (degree n=1,8 nanoTesla/year for secular variation (SV))
          IGRF   IGRF   IGRF   IGRF   IGRF   IGRF   IGRF   IGRF   IGRF   DGRF   DGRF   DGRF   DGRF   DGRF   DGRF   DGRF   DGRF   DGRF   DGRF   DGRF      DGRF       DGRF      IGRF      SV
g/h n m 1900.0 1905.0 1910.0 1915.0 1920.0 1925.0 1930.0 1935.0 1940.0 1945.0 1950.0 1955.0 1960.0 1965.0 1970.0 1975.0 1980.0 1985.0 1990.0 1995.0    2000.0     2005.0    2010.0 2010-15
g  1  0 -31543 -31464 -31354 -31212 -31060 -30926 -30805 -30715 -30654 -30594 -30554 -30500 -30421 -30334 -30220 -30100 -29992 -29873 -29775 -29692  -29619.4  -29554.63  -29496.5    11.4
g  1  1  -2298  -2298  -2297  -2306  -2317  -2318  -2316  -2306  -2292  -2285  -2250  -2215  -2169  -2119  -2068  -2013  -1956  -1905  -1848  -1784   -1728.2   -1669.05   -1585.9    16.7
h  1  1   5922   5909   5898   5875   5845   5817   5808   5812   5821   5810   5815   5820   5791   5776   5737   5675   5604   5500   5406   5306    5186.1    5077.99    4945.1   -28.8
g  2  0   -677   -728   -769   -802   -839   -893   -951  -1018  -1106  -1244  -1341  -1440  -1555  -1662  -1781  -1902  -1997  -2072  -2131  -2200   -2267.7   -2337.24   -2396.6   -11.3
g  2  1   2905   2928   2948   2956   2959   2969   2980   2984   2981   2990   2998   3003   3002   2997   3000   3010   3027   3044   3059   3070    3068.4    3047.69    3026.0    -3.9
h  2  1  -1061  -1086  -1128  -1191  -1259  -1334  -1424  -1520  -1614  -1702  -1810  -1898  -1967  -2016  -2047  -2067  -2129  -2197  -2279  -2366   -2481.6   -2594.50   -2707.7   -23.0
g  2  2    924   1041   1176   1309   1407   1471   1517   1550   1566   1578   1576   1581   1590   1594   1611   1632   1663   1687   1686   1681    1670.9    1657.76    1668.6     2.7
h  2  2   1121   1065   1000    917    823    728    644    586    528    477    381    291    206    114     25    -68   -200   -306   -373   -413    -458.0    -515.43    -575.4   -12.9
g  3  0   1022   1037   1058   1084   1111   1140   1172   1206   1240   1282   1297   1302   1302   1297   1287   1276   1281   1296   1314   1335    1339.6    1336.30    1339.7     1.3
g  3  1  -1469  -1494  -1524  -1559  -1600  -1645  -1692  -1740  -1790  -1834  -1889  -1944  -1992  -2038  -2091  -2144  -2180  -2208  -2239  -2267   -2288.0   -2305.83   -2326.3    -3.9
h  3  1   -330   -357   -389   -421   -445   -462   -480   -494   -499   -499   -476   -462   -414   -404   -366   -333   -336   -310   -284   -262    -227.6    -198.86    -160.5     8.6
g  3  2   1256   1239   1223   1212   1205   1202   1205   1215   1232   1255   1274   1288   1289   1292   1278   1260   1251   1247   1248   1249    1252.1    1246.39    1231.7    -2.9
h  3  2      3     34     62     84    103    119    133    146    163    186    206    216    224    240    251    262    271    284    293    302     293.4     269.72     251.7    -2.9
g  3  3    572    635    705    778    839    881    907    918    916    913    896    882    878    856    838    830    833    829    802    759     714.5     672.51     634.2    -8.1
h  3  3    523    480    425    360    293    229    166    101     43    -11    -46    -83   -130   -165   -196   -223   -252   -297   -352   -427    -491.1    -524.72    -536.8    -2.1
g  4  0    876    880    884    887    889    891    896    903    914    944    954    958    957    957    952    946    938    936    939    940     932.3     920.55     912.6    -1.4
g  4  1    628    643    660    678    695    711    727    744    762    776    792    796    800    804    800    791    782    780    780    780     786.8     797.96     809.0     2.0
h  4  1    195    203    211    218    220    216    205    188    169    144    136    133    135    148    167    191    212    232    247    262     272.6     282.07     286.4     0.4
g  4  2    660    653    644    631    616    601    584    565    550    544    528    510    504    479    461    438    398    361    325    290     250.0     210.65     166.6    -8.9
h  4  2    -69    -77    -90   -109   -134   -163   -195   -226   -252   -276   -278   -274   -278   -269   -266   -265   -257   -249   -240   -236    -231.9    -225.23    -211.2     3.2
g  4  3   -361   -380   -400   -416   -424   -426   -422   -415   -405   -421   -408   -397   -394   -390   -395   -405   -419   -424   -423   -418    -403.0    -379.86    -357.1     4.4
h  4  3   -210   -201   -189   -173   -153   -130   -109    -90    -72    -55    -37    -23      3     13     26     39     53     69     84     97     119.8     145.15     164.4     3.6
g  4  4    134    146    160    178    199    217    234    249    265    304    303    290    269    252    234    216    199    170    141    122     111.3     100.00      89.7    -2.3
h  4  4    -75    -65    -55    -51    -57    -70    -90   -114   -141   -178   -210   -230   -255   -269   -279   -288   -297   -297   -299   -306    -303.8    -305.36    -309.2    -0.8
g  5  0   -184   -192   -201   -211   -221   -230   -237   -241   -241   -253   -240   -229   -222   -219   -216   -218   -218   -214   -214   -214    -218.8    -227.00    -231.1    -0.5
g  5  1    328    328    327    327    326    326    327    329    334    346    349    360    362    358    359    356    357    355    353    352     351.4     354.41     357.2     0.5
h  5  1   -210   -193   -172   -148   -122    -96    -72    -51    -33    -12      3     15     16     19     26     31     46     47     46     46      43.8      42.72      44.7     0.5
g  5  2    264    259    253    245    236    226    218    211    208    194    211    230    242    254    262    264    261    253    245    235     222.3     208.95     200.3    -1.5
h  5  2     53     56     57     58     58     58     60     64     71     95    103    110    125    128    139    148    150    150    154    165     171.9     180.25     188.9     1.5
g  5  3      5     -1     -9    -16    -23    -28    -32    -33    -33    -20    -20    -23    -26    -31    -42    -59    -74    -93   -109   -118    -130.4    -136.54    -141.2    -0.7
h  5  3    -33    -32    -33    -34    -38    -44    -53    -64    -75    -67    -87    -98   -117   -126   -139   -152   -151   -154   -153   -143    -133.1    -123.45    -118.1     0.9
g  5  4    -86    -93   -102   -111   -119   -125   -131   -136   -141   -142   -147   -152   -156   -157   -160   -159   -162   -164   -165   -166    -168.6    -168.05    -163.1     1.3
h  5  4   -124   -125   -126   -126   -125   -122   -118   -115   -113   -119   -122   -121   -114    -97    -91    -83    -78    -75    -69    -55     -39.3     -19.57       0.1     3.7
g  5  5    -16    -26    -38    -51    -62    -69    -74    -76    -76    -82    -76    -69    -63    -62    -56    -49    -48    -46    -36    -17     -12.9     -13.55      -7.7     1.4
h  5  5      3     11     21     32     43     51     58     64     69     82     80     78     81     81     83     88     92     95     97    107     106.3     103.85     100.9    -0.6
g  6  0     63     62     62     61     61     61     60     59     57     59     54     47     46     45     43     45     48     53     61     68      72.3      73.60      72.8    -0.3
g  6  1     61     60     58     57     55     54     53     53     54     57     57     57     58     61     64     66     66     65     65     67      68.2      69.56      68.6    -0.3
h  6  1     -9     -7     -5     -2      0      3      4      4      4      6     -1     -9    -10    -11    -12    -13    -15    -16    -16    -17     -17.4     -20.33     -20.8    -0.1
g  6  2    -11    -11    -11    -10    -10     -9     -9     -8     -7      6      4      3      1      8     15     28     42     51     59     68      74.2      76.74      76.0    -0.3
h  6  2     83     86     89     93     96     99    102    104    105    100     99     96     99    100    100     99     93     88     82     72      63.7      54.75      44.2    -2.1
g  6  3   -217   -221   -224   -228   -233   -238   -242   -246   -249   -246   -247   -247   -237   -228   -212   -198   -192   -185   -178   -170    -160.9    -151.34    -141.4     1.9
h  6  3      2      4      5      8     11     14     19     25     33     16     33     48     60     68     72     75     71     69     69     67      65.1      63.63      61.5    -0.4
g  6  4    -58    -57    -54    -51    -46    -40    -32    -25    -18    -25    -16     -8     -1      4      2      1      4      4      3     -1      -5.9     -14.58     -22.9    -1.6
h  6  4    -35    -32    -29    -26    -22    -18    -16    -15    -15     -9    -12    -16    -20    -32    -37    -41    -43    -48    -52    -58     -61.2     -63.53     -66.3    -0.5
g  6  5     59     57     54     49     44     39     32     25     18     21     12      7     -2      1      3      6     14     16     18     19      16.9      14.58      13.1    -0.2
h  6  5     36     32     28     23     18     13      8      4      0    -16    -12    -12    -11     -8     -6     -4     -2     -1      1      1       0.7       0.24       3.1     0.8
g  6  6    -90    -92    -95    -98   -101   -103   -104   -106   -107   -104   -105   -107   -113   -111   -112   -111   -108   -102    -96    -93     -90.4     -86.36     -77.9     1.8
h  6  6    -69    -67    -65    -62    -57    -52    -46    -40    -33    -39    -30    -24    -17     -7      1     11     17     21     24     36      43.8      50.94      54.9     0.5
```

……

4 pages later.....



```
g 13 12      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0       0.0      -0.10      -0.3     0.0
h 13 12      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      -0.5      -0.57      -0.5     0.0
g 13 13      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0       0.1      -0.18      -0.3     0.0
h 13 13      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      0      -0.9      -0.82      -0.8     0.0
```

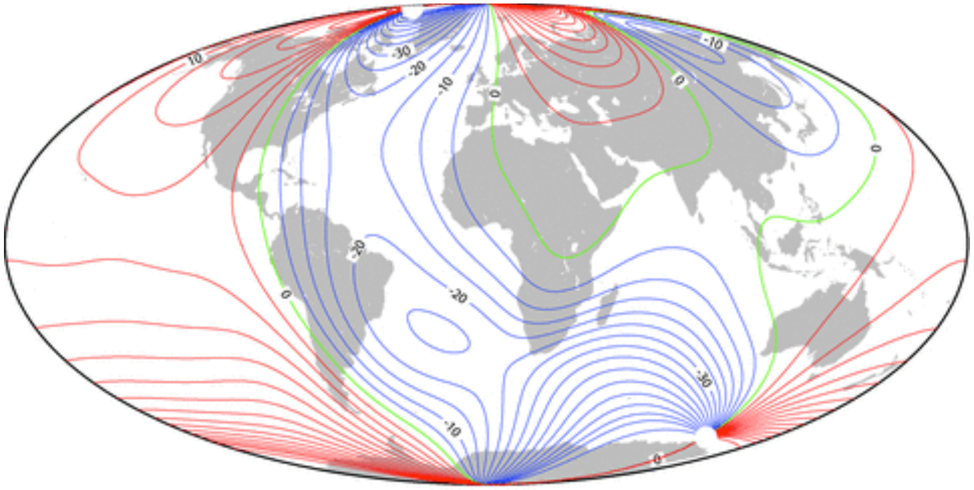
Time

g 13 13
h 13 13

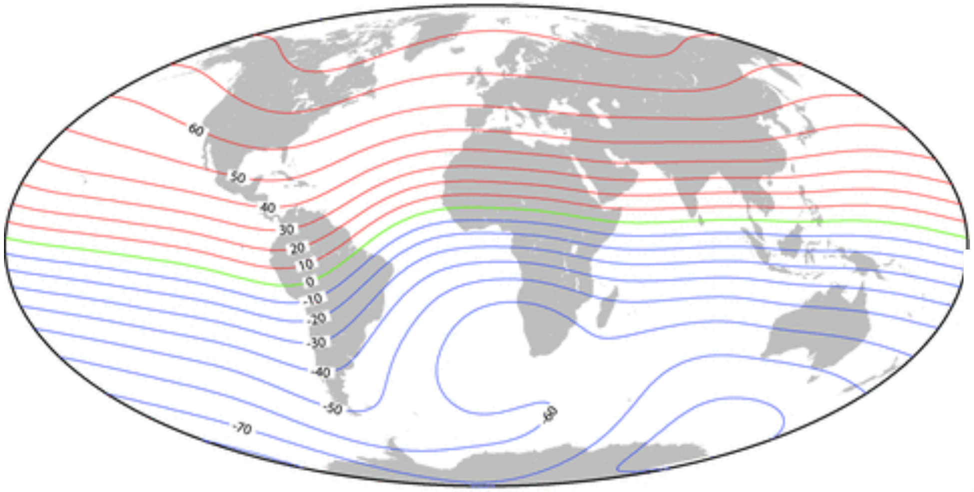
http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html
http://onlinelibrary.wiley.com/doi/10.1111/j.1365-246X.2010.04804.x/full

International Geomagnetic Reference Field – IGRF2010

Declination *D* in degrees in 2010

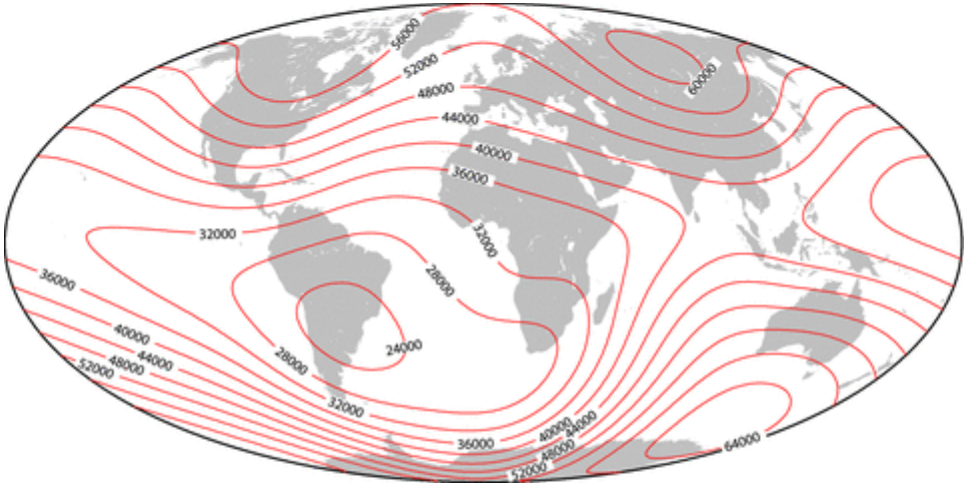


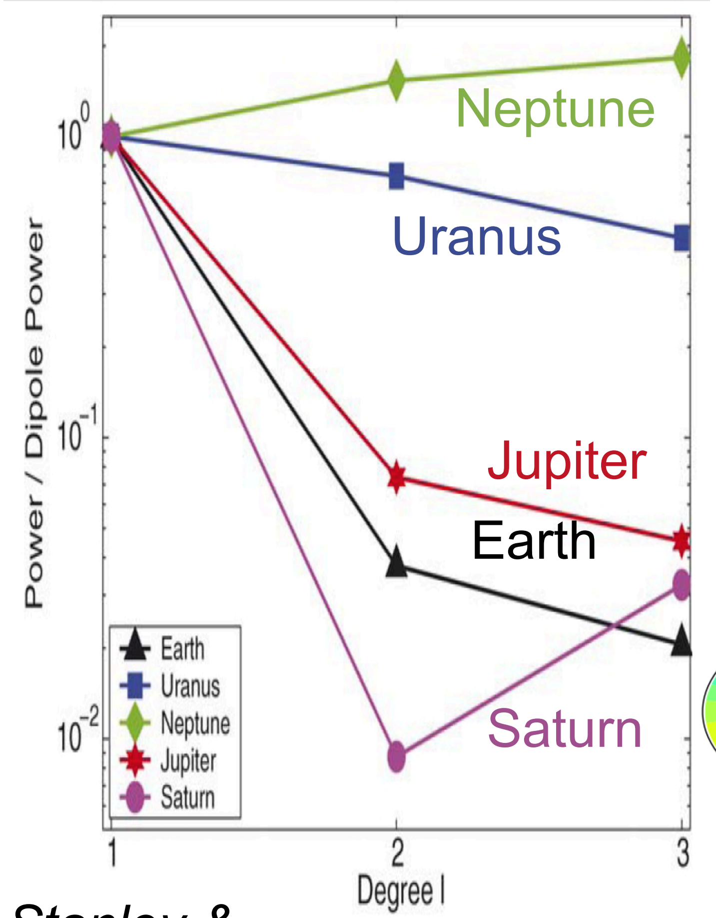
2011 now available!



Inclination *I* in degrees in 2010

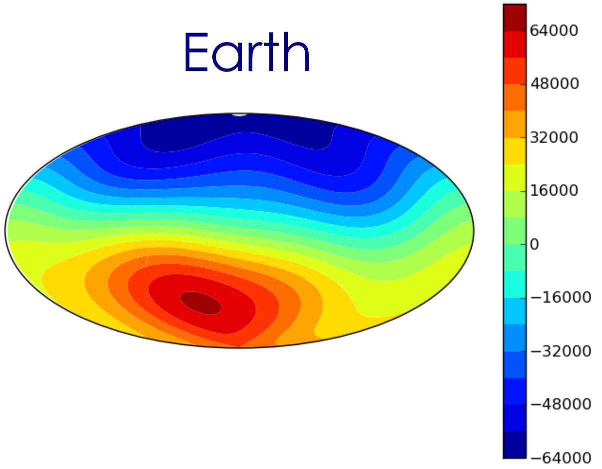
Total Intensity *F* in nT in 2010

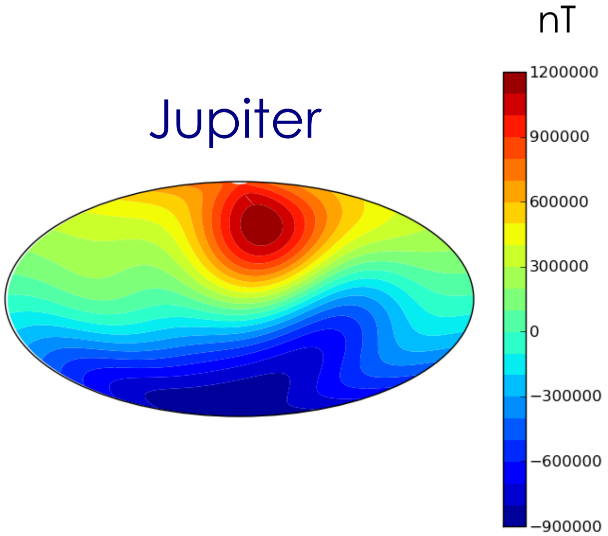


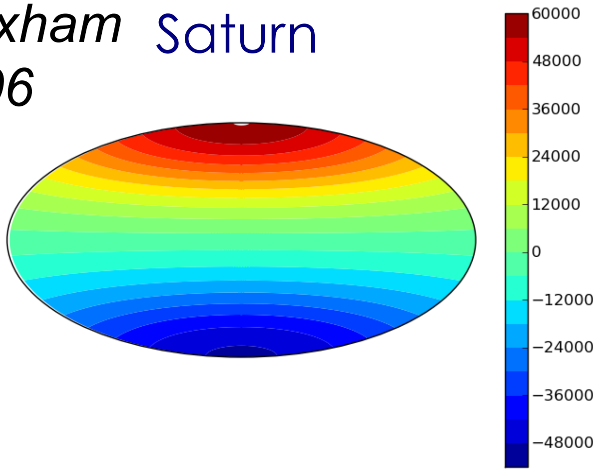


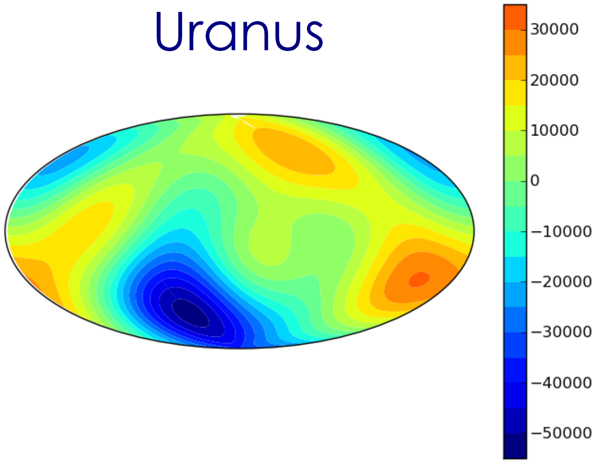
Multipole coefficients / Dipole
Indicates degree of complexity

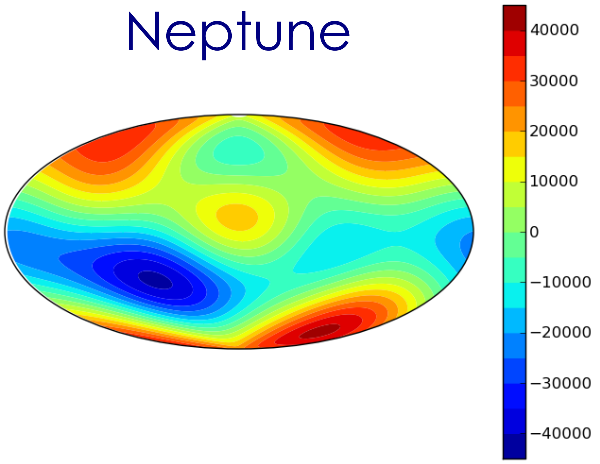
Stanley & Bloxham 2006


Earth

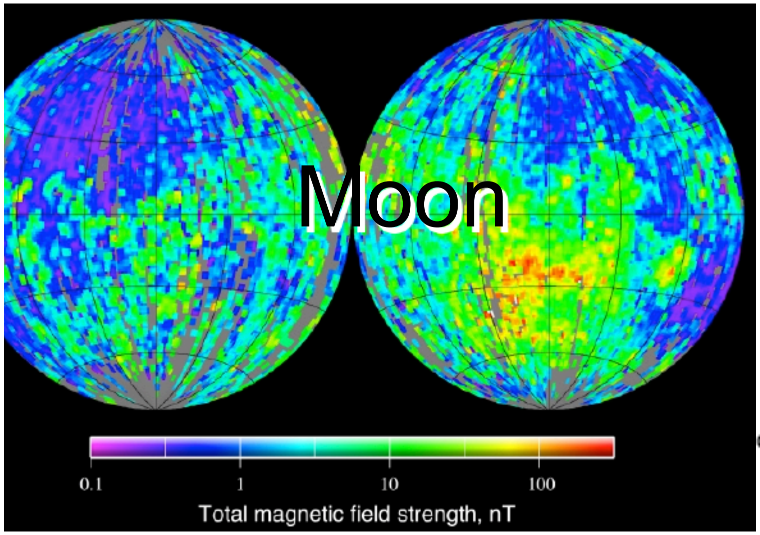

Jupiter

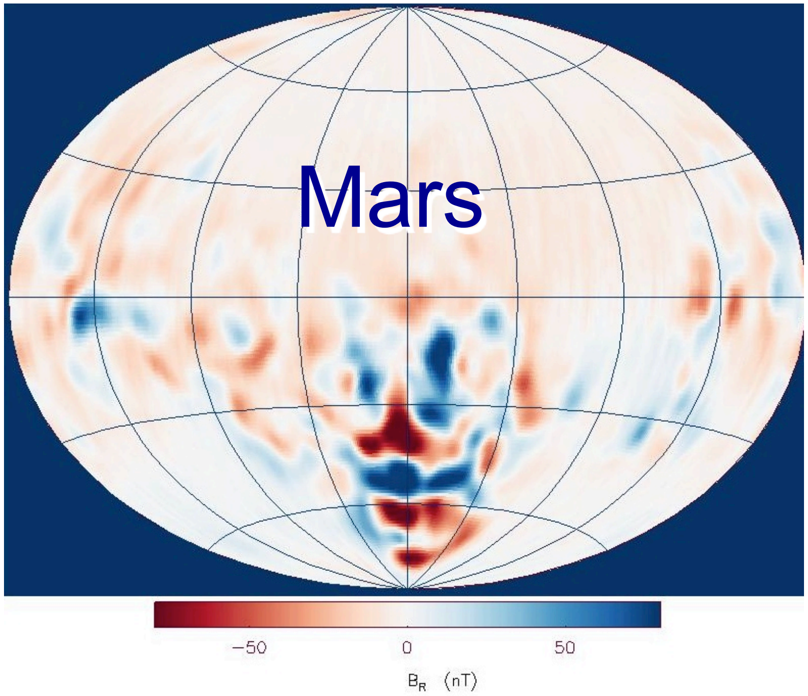

Saturn

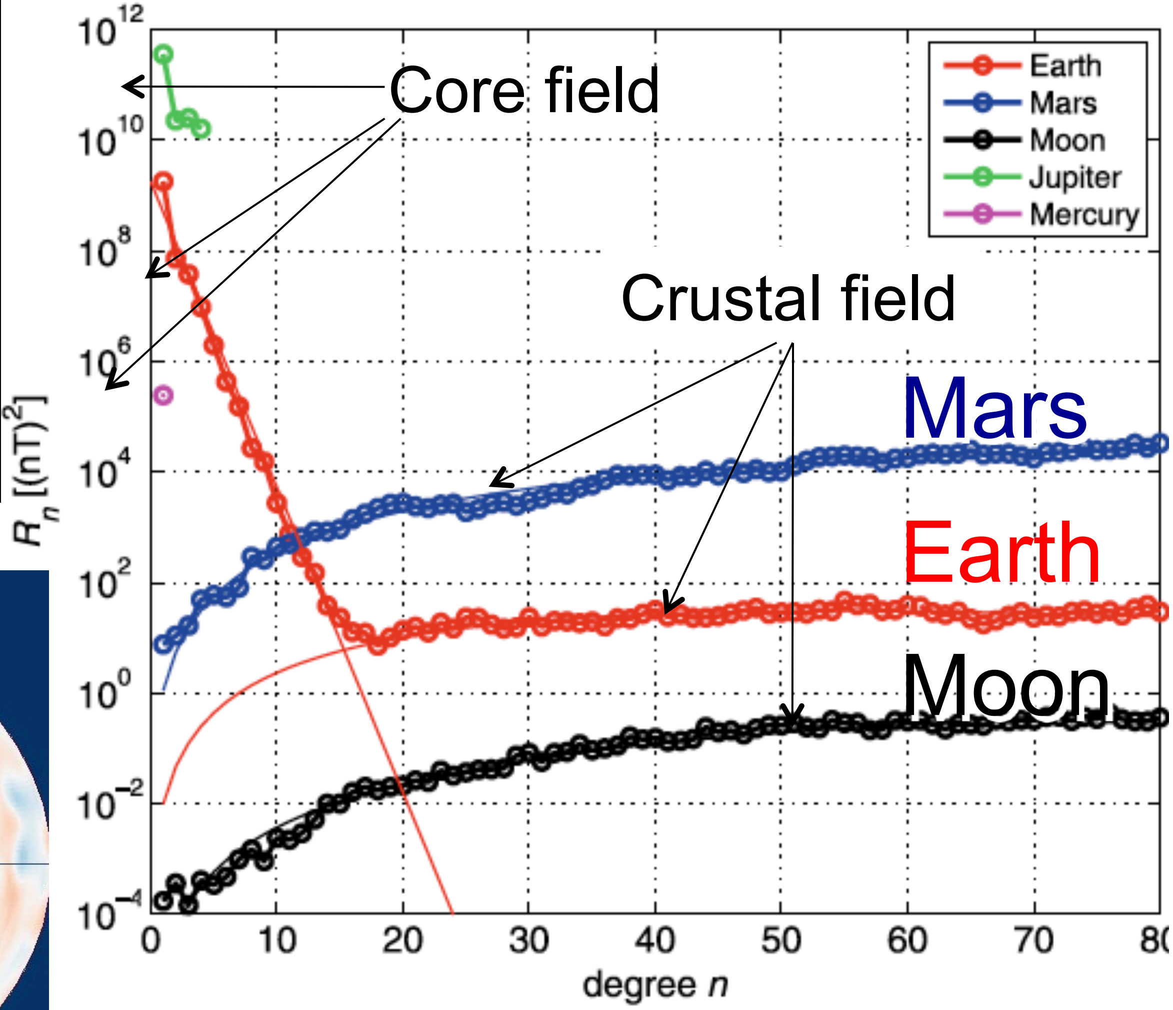

Uranus


Neptune

Moon & Mars: All Crustal Remanent Magnetization



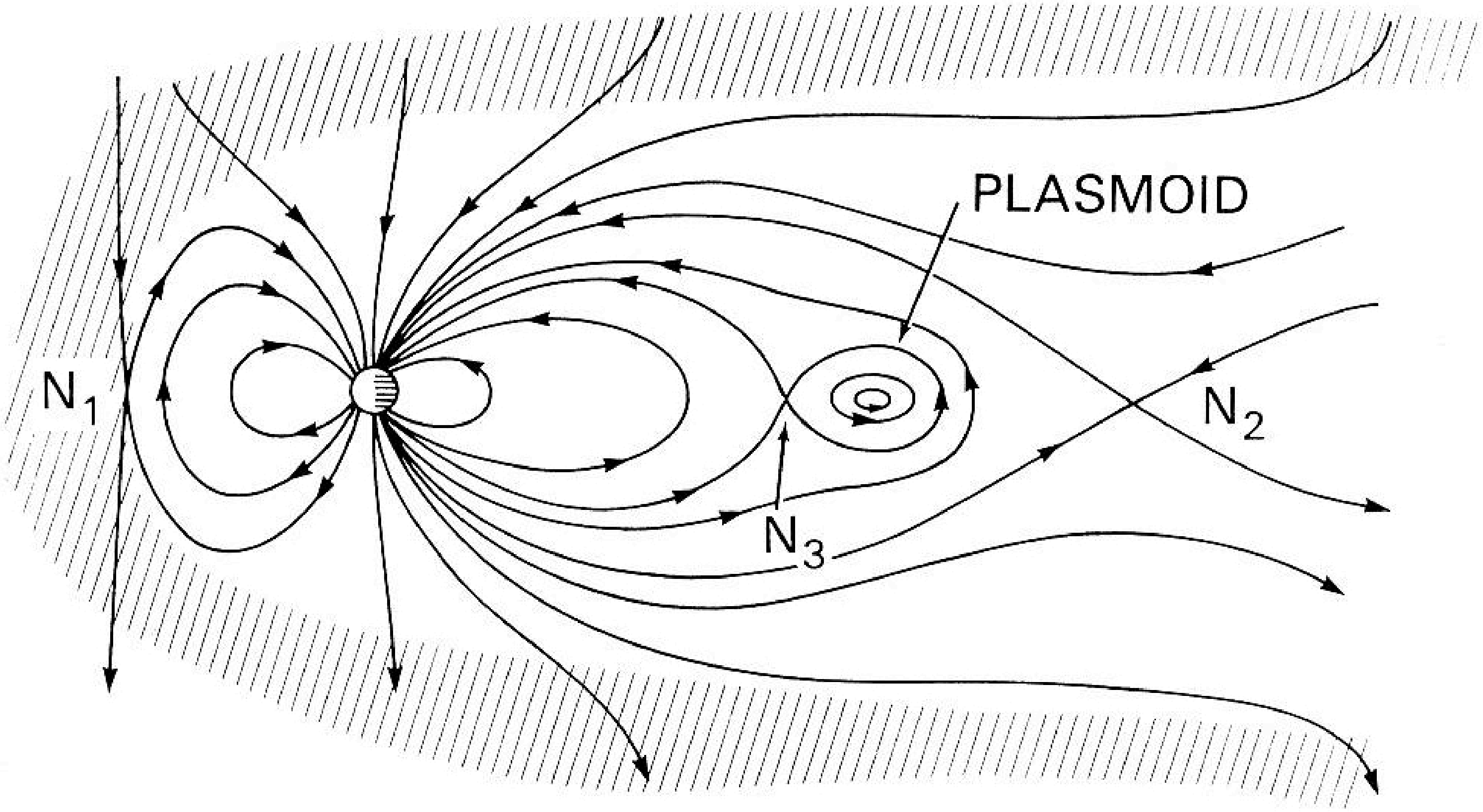




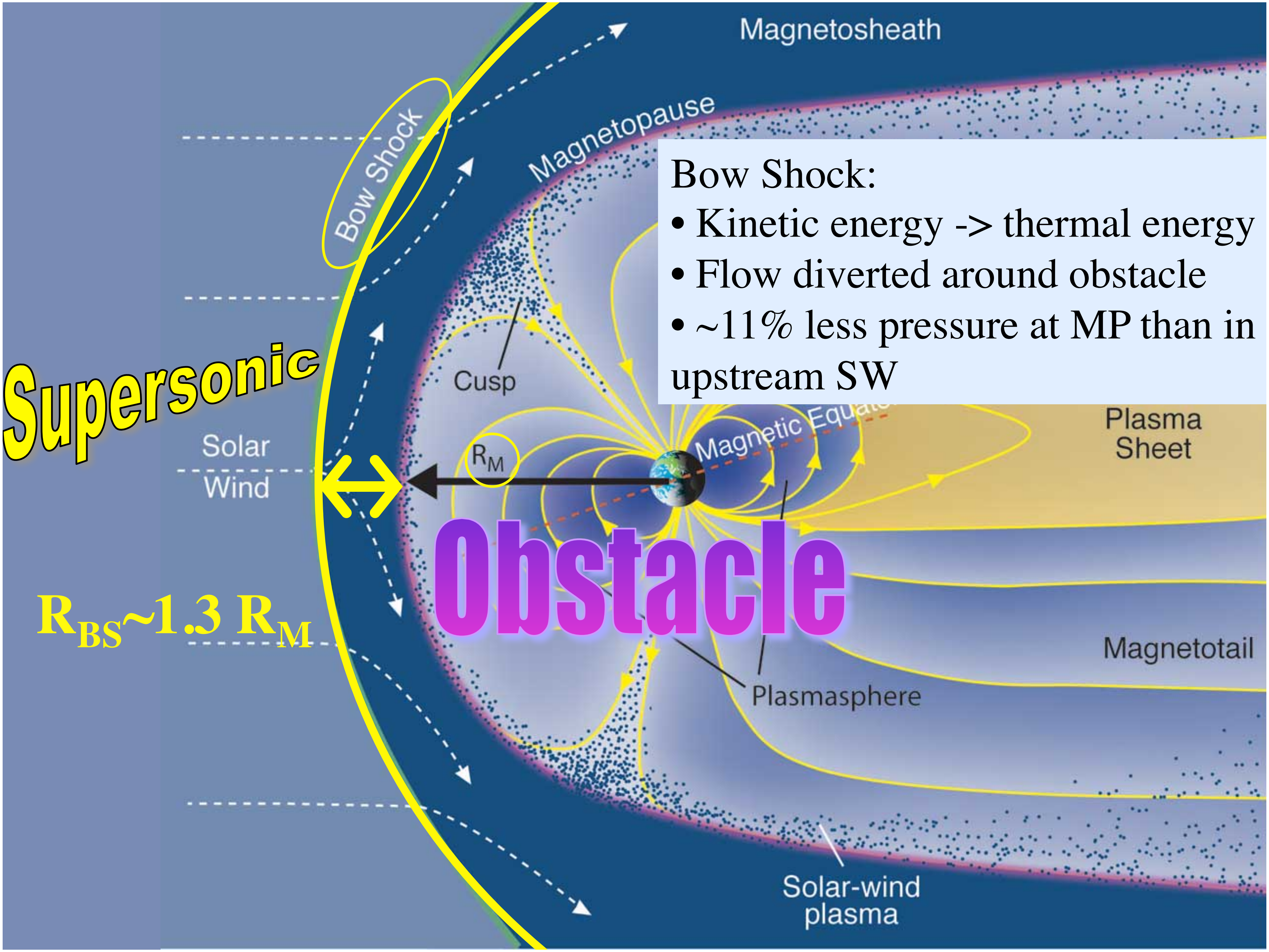
- Did Moon ever have dynamo?
- Mars' dynamo died >3.5 BYA.

Re-Cap: Cavities, Current sheets, Fluxropes

Where would we find each of these in a magnetosphere?



Chat with your neighbors and quickly answer above question as best you can.



Bow Shock:

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

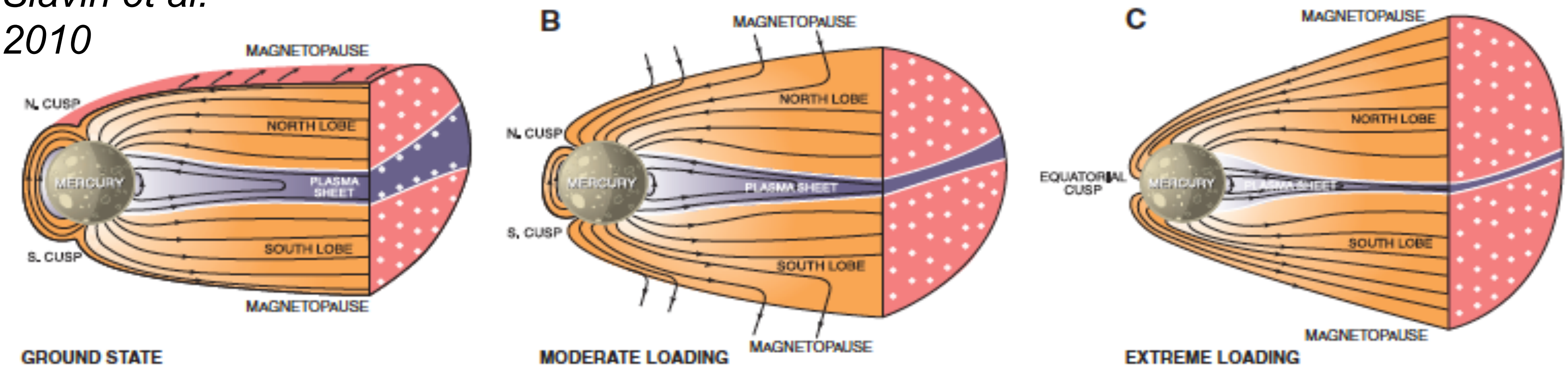
Supersonic

Obstacle

$R_{BS} \sim 1.3\ R_M$

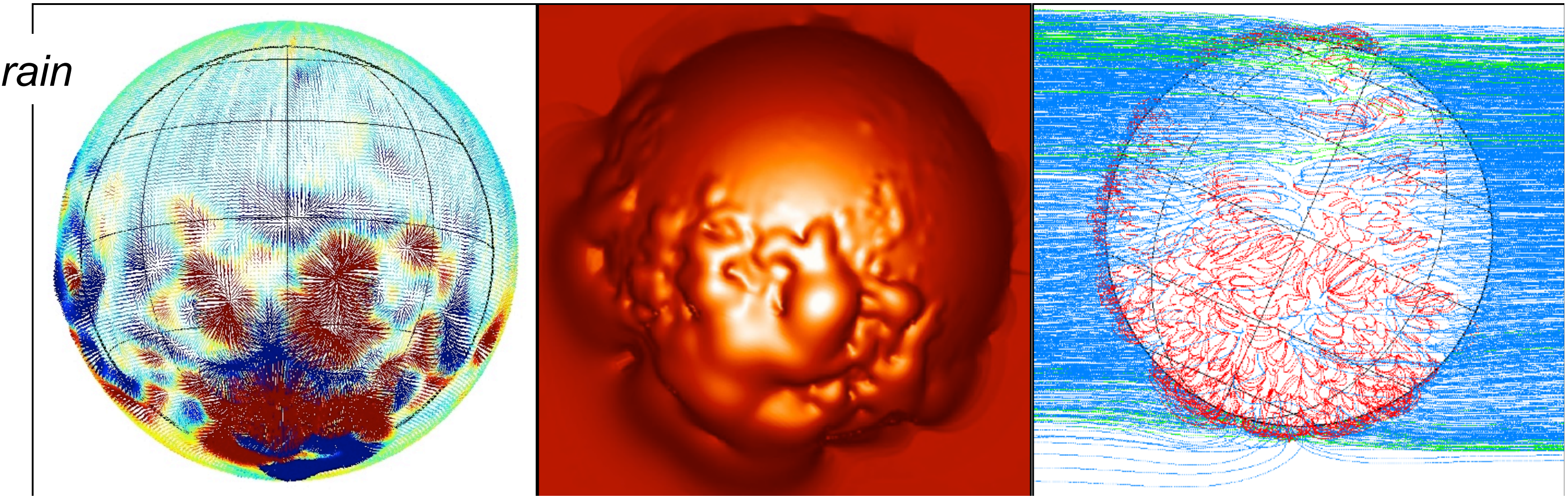
Mercury: Extreme solar wind conditions -> exposed planet

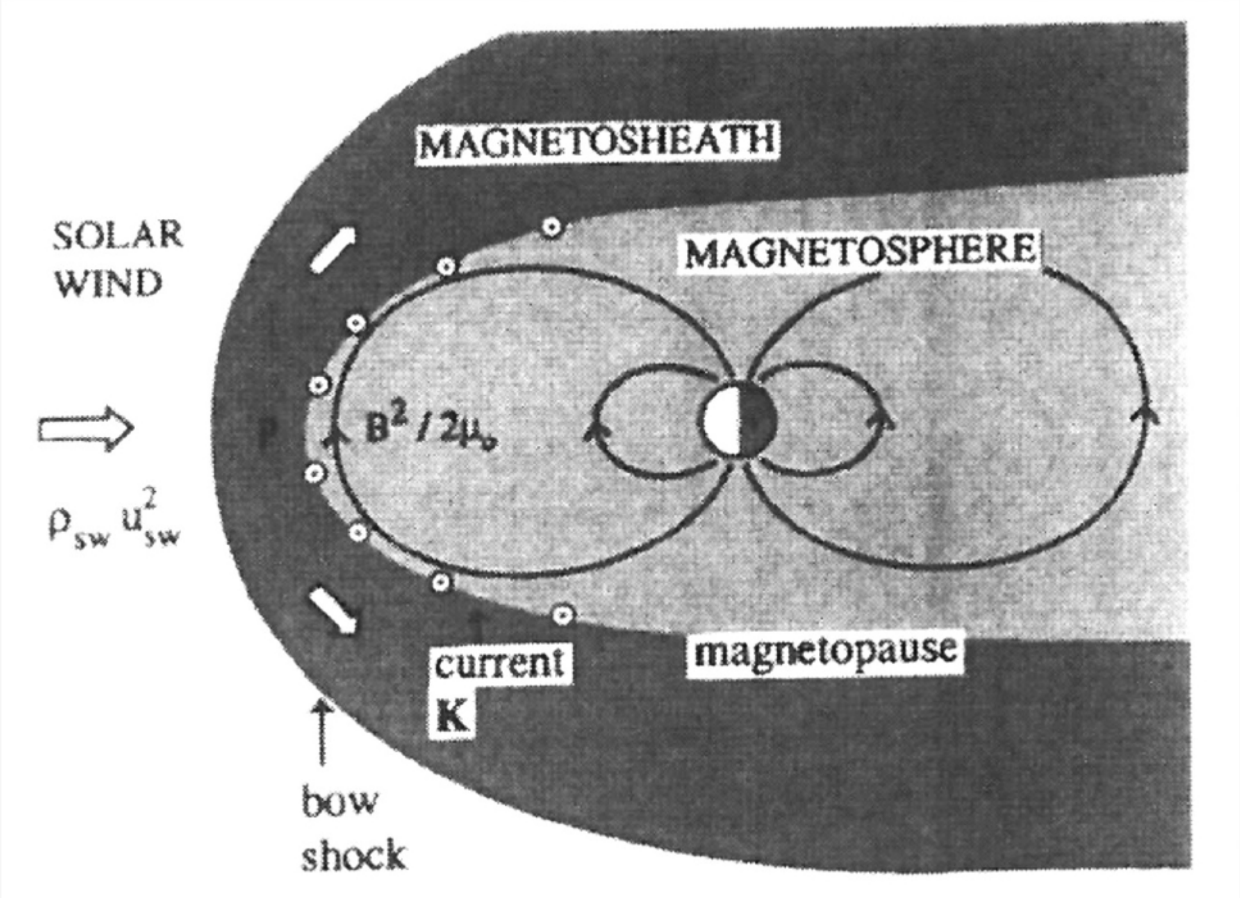
Slavin et al.
2010



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

David Brain





B_{dipole}

$=B_o^2 \ (R_p/r)^3$

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}

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

Yes, I am being a bit sloppy here…

Later this week David Burgess discusses the bow shock.

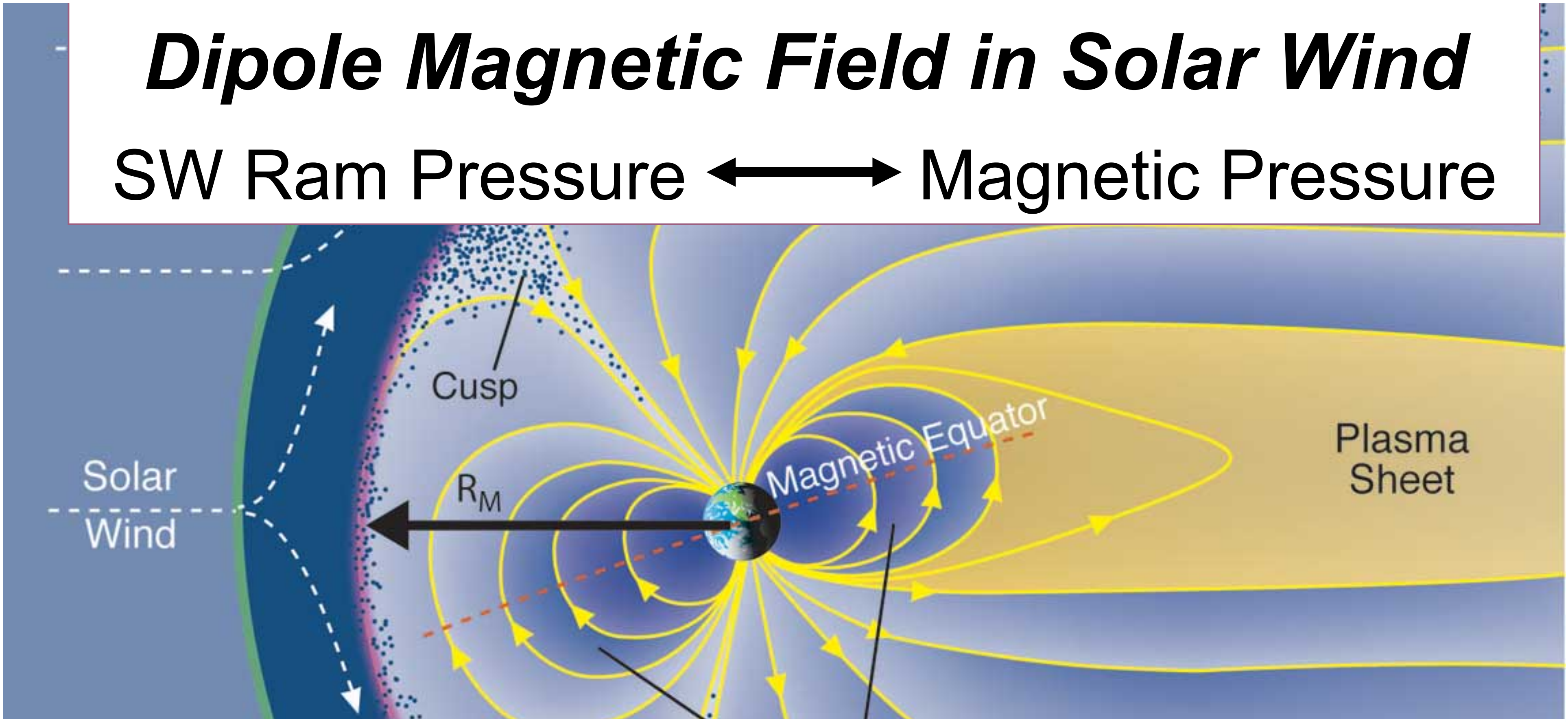
For more comprehensive treatment of magnetosheath, magnetopause (including details of the history) see 2012 HSS lecture by John Dorelli.
http://www.vsp.ucar.edu/Heliophysics/pdf/DorelliTerrestrialMagnetosphere.pdf

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

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

Quick chat with your neighbors….

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

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

	Mercury	Earth	Jupiter	Saturn	Uranus	Neptune
B_o Gauss	.003	.31	4.28	.22	.23	.14
R_{CF} 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

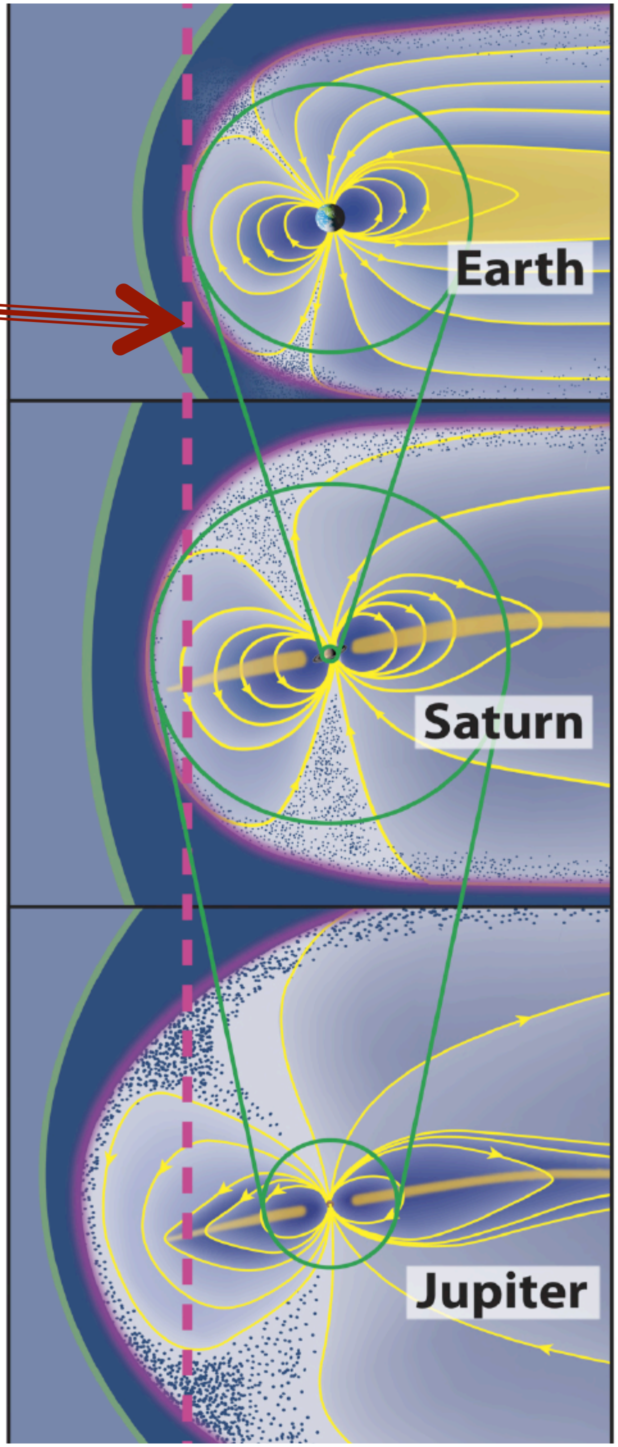
Magnetospheres scaled by stand-off distance of dipole field

	M/M_E	MP_{Dipole}	MP_{mean}	MP_{Range}
Mercury	~8x10^{-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

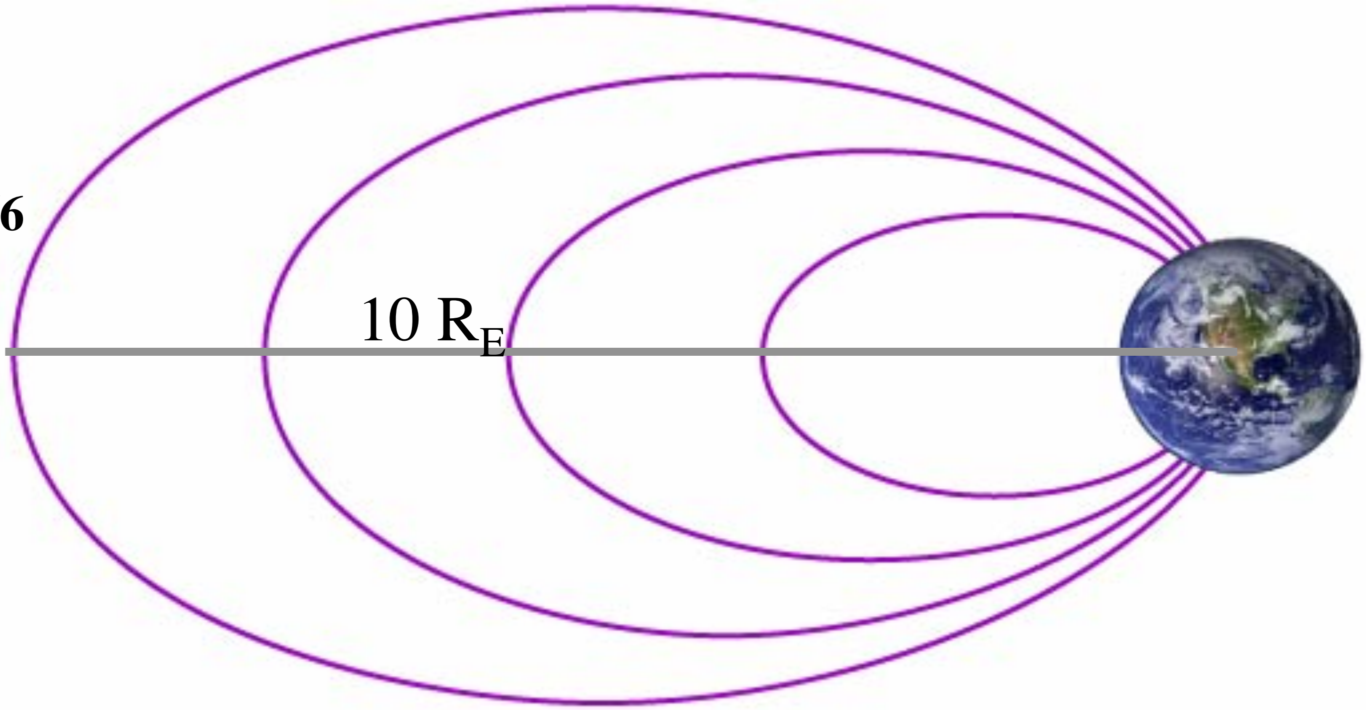
* *Achilleos et al. 2008*   # *Joy et al. 2002*



Earth ~ Dipole

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

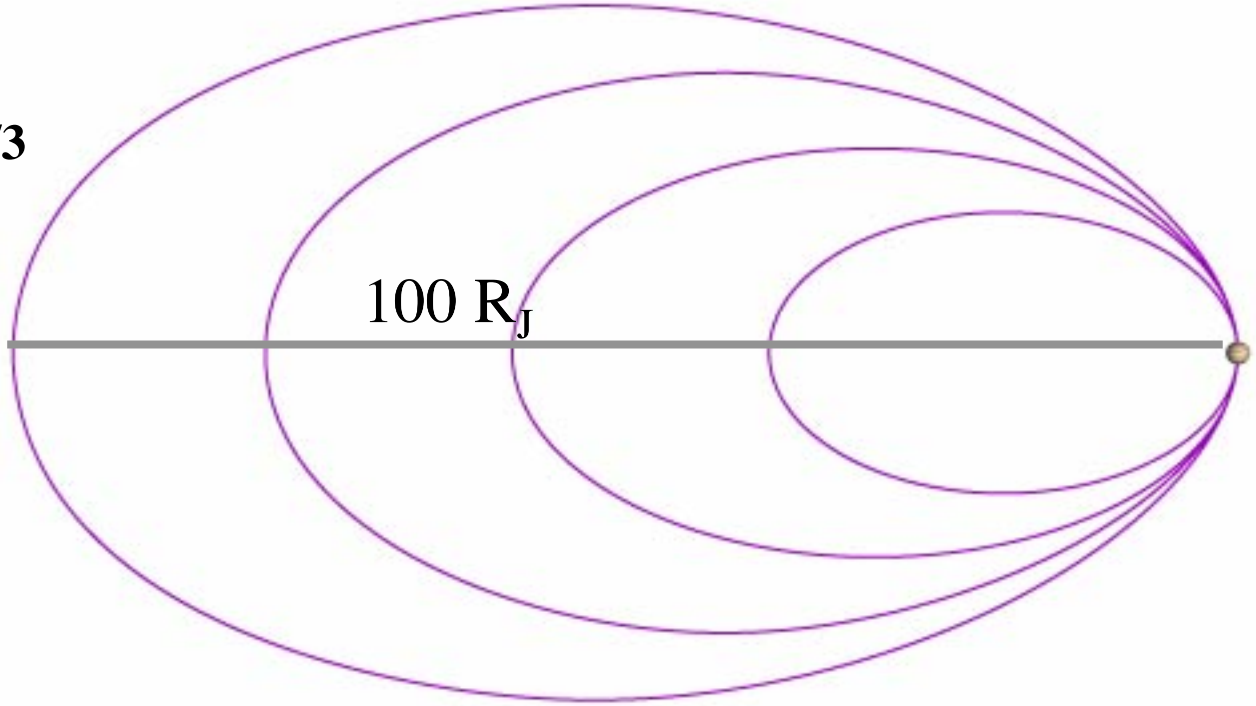
solar wind ρV^2



Jupiter

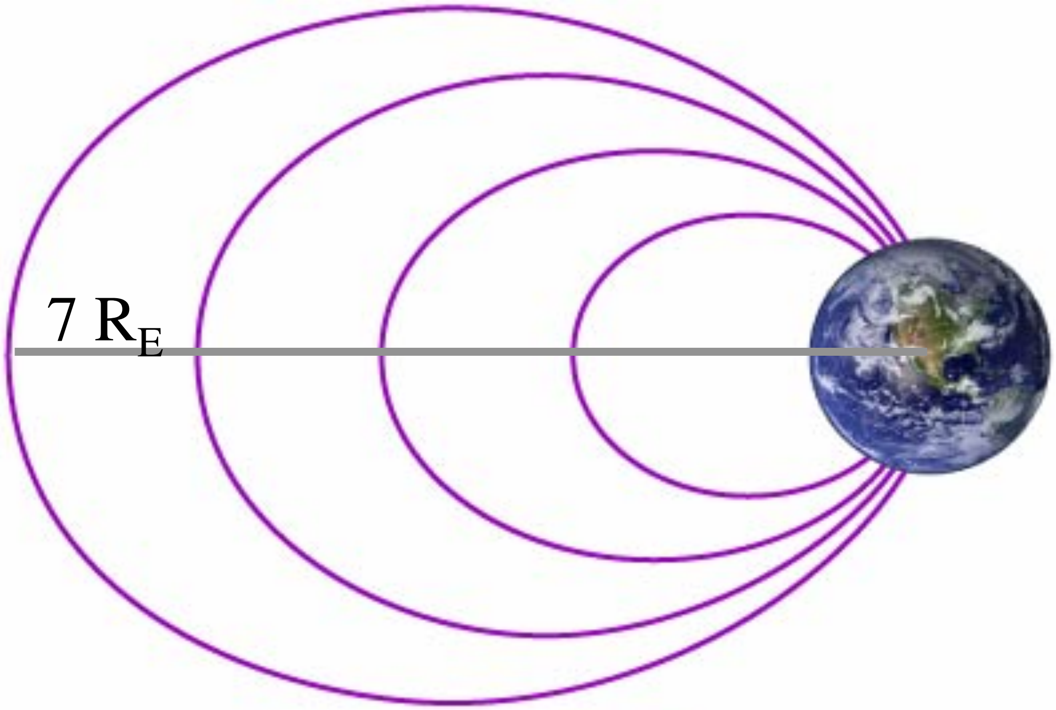
$$R_{mp} \sim (\rho V^2)^{-1/3}$$

solar wind ρV^2



Earth ~ Dipole

R_{mp} -> 0.7 R_{mp}

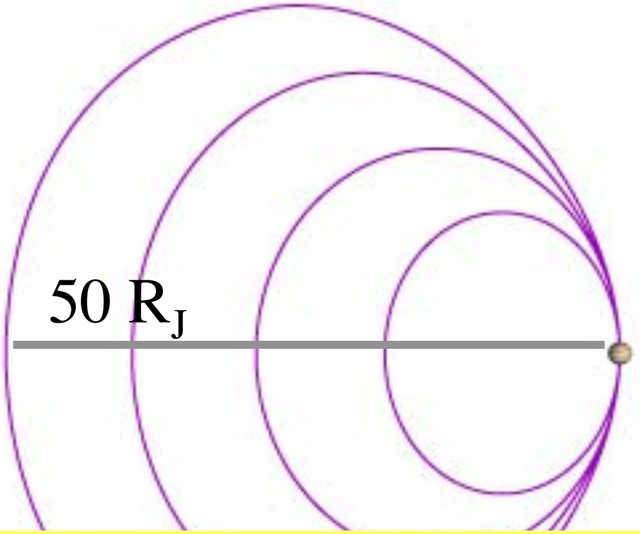


solar wind ρV^2

x10 Solar wind pressure

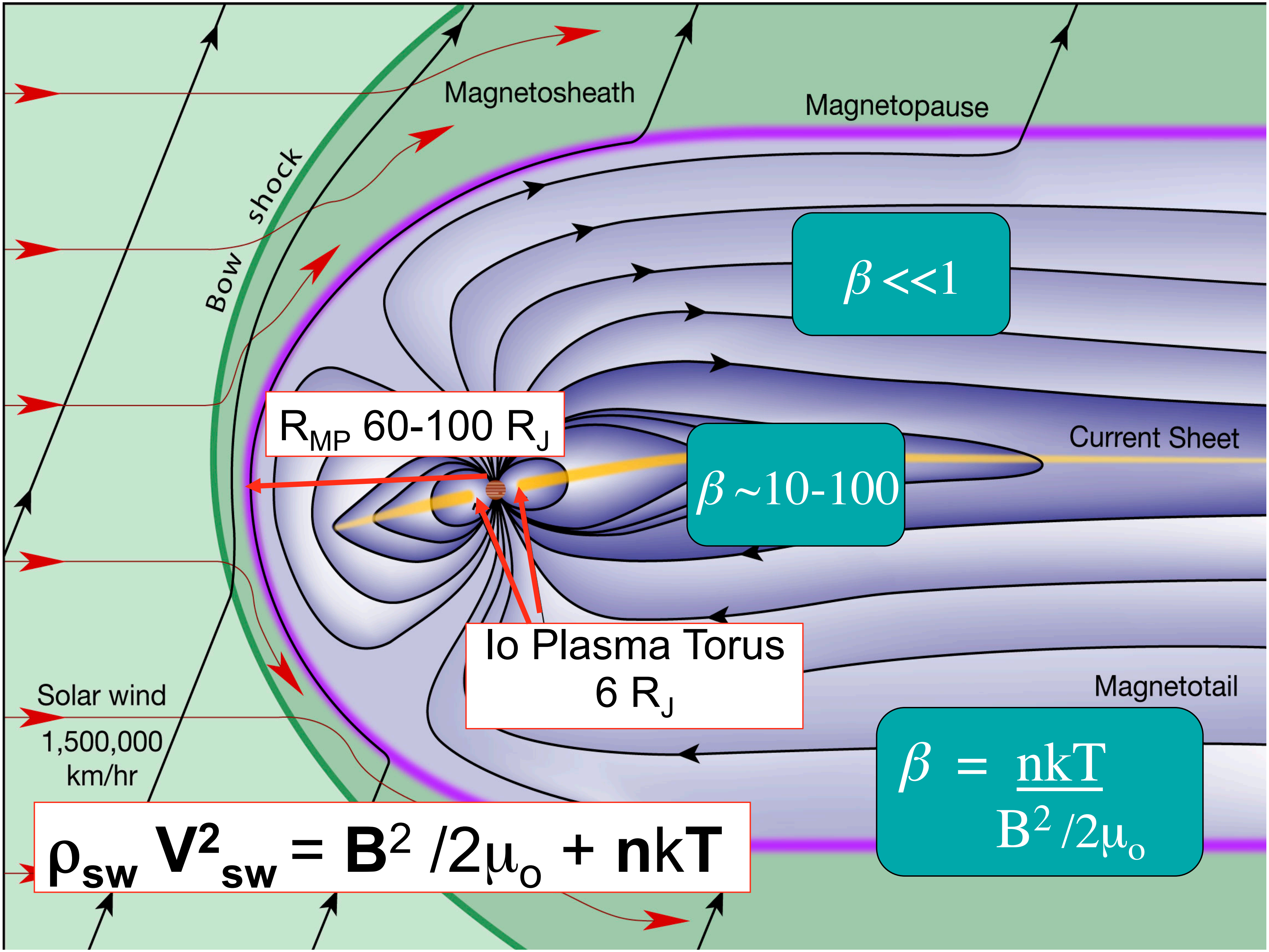
Jupiter

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



R_{MP} 60-100 R_J

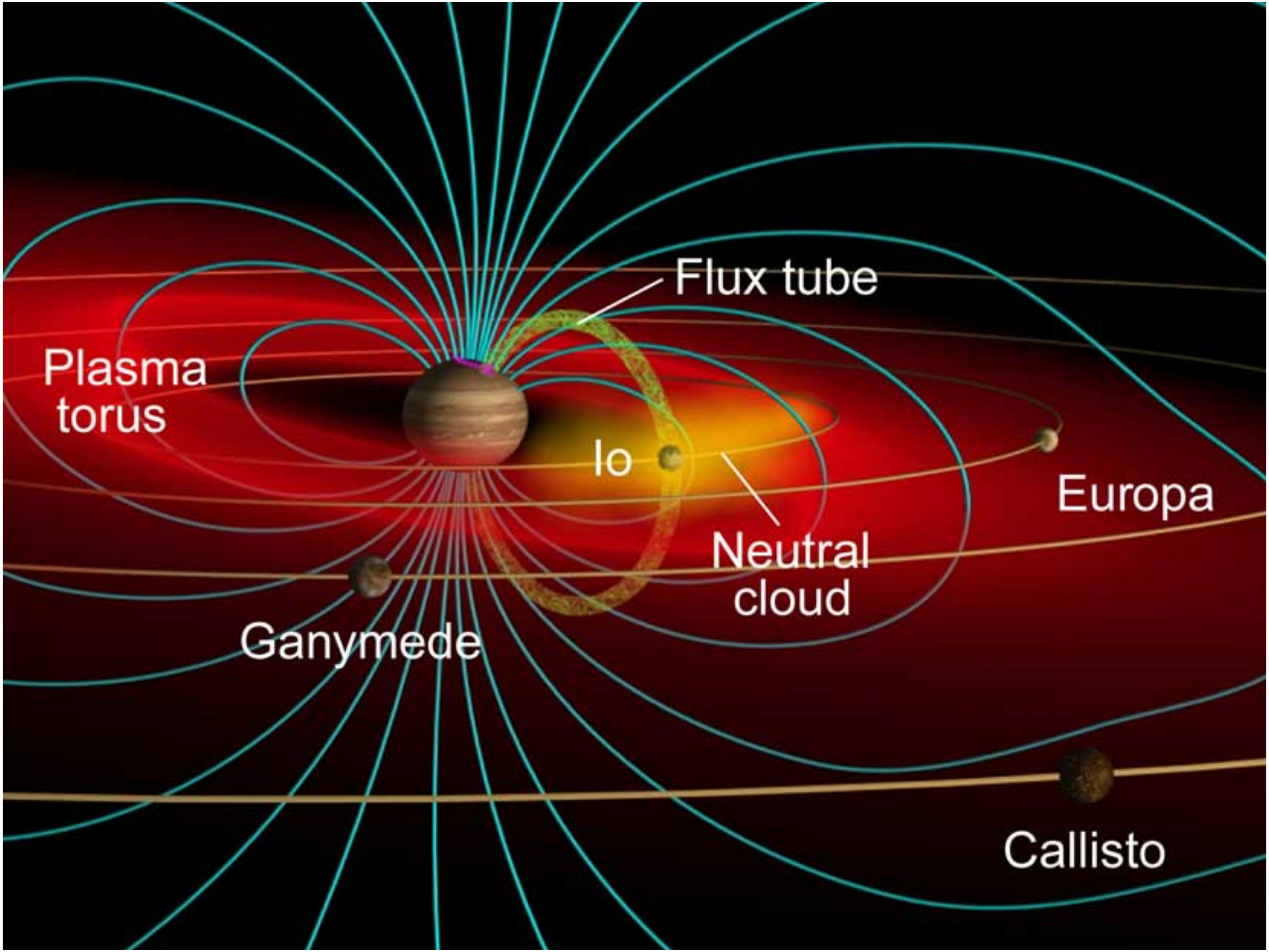
Io Plasma Torus
6 R_J

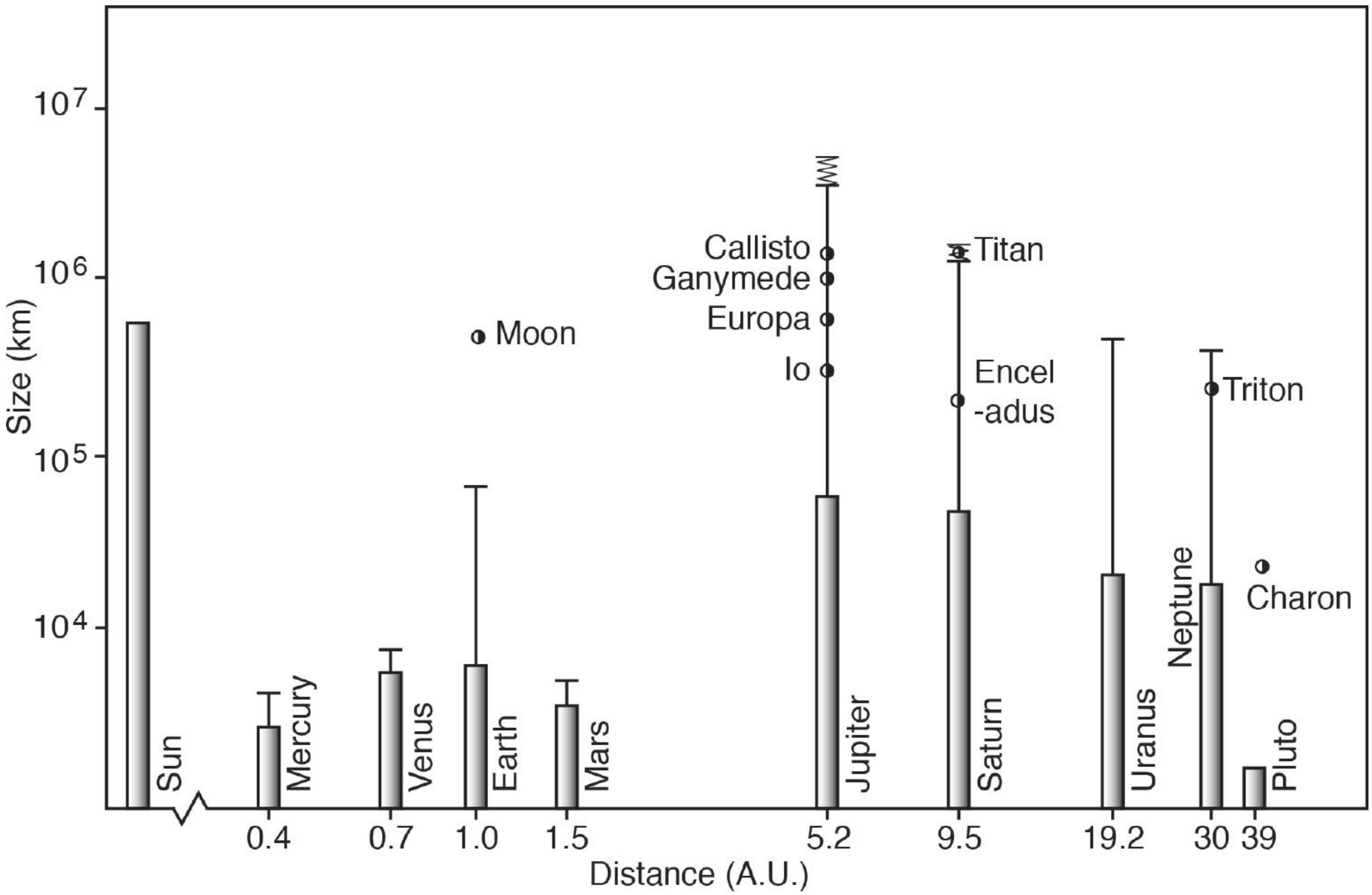
$\beta << 1$

$\beta \sim 10\text{-}100$

$$\beta = \frac{nkT}{B^2/2\mu_o}$$

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


Flux tube
Plasma torus
Io
Europa
Neutral cloud
Ganymede
Callisto

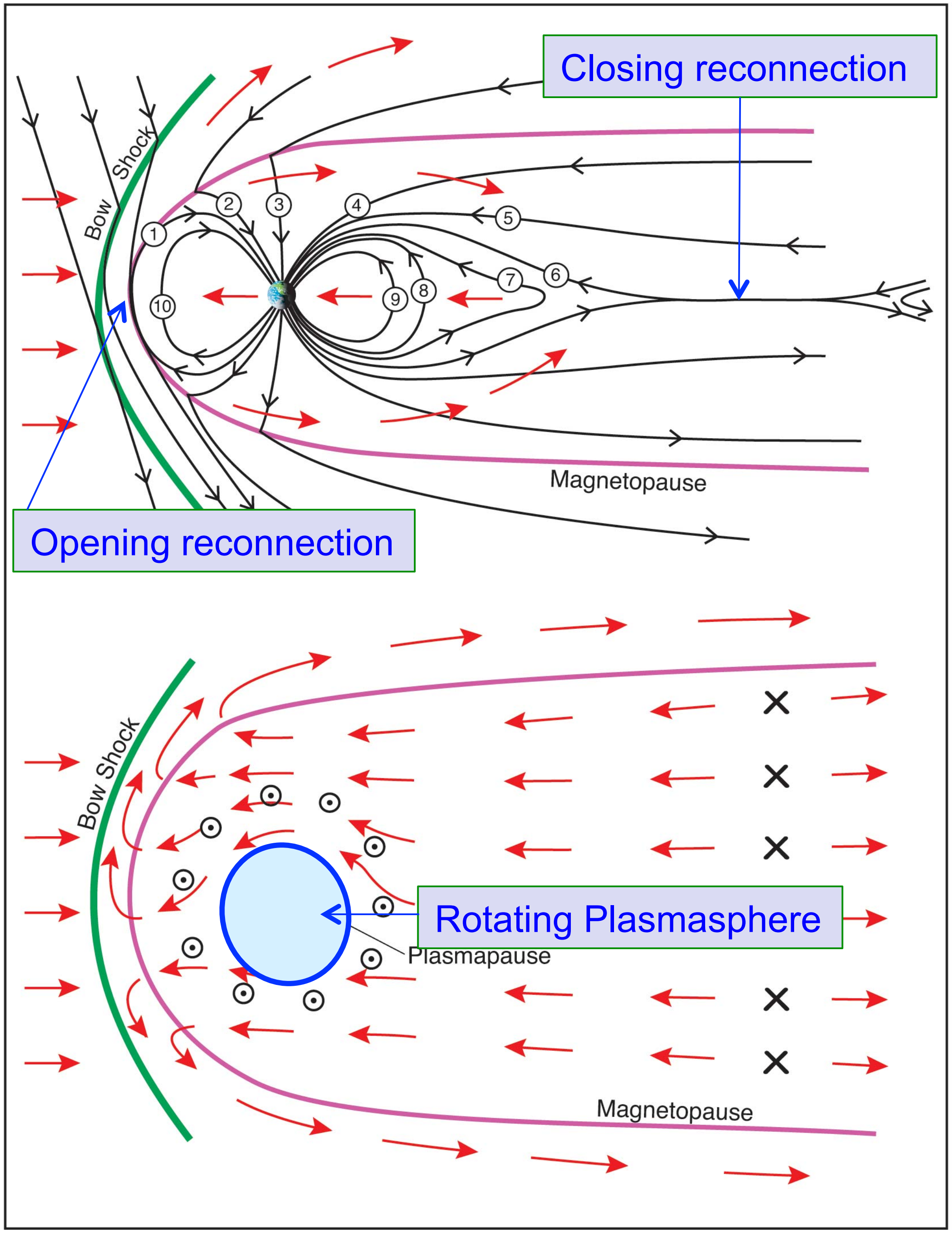

Size (km)
10^7
10^6
10^5
10^4
Sun
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto
Moon
Callisto
Ganymede
Europa
Io
Titan
Encel
-adus
Triton
Charon
0.4
0.7
1.0
1.5
5.2
9.5
19.2
30
39
Distance (A.U.)

Vol. I Ch.10

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

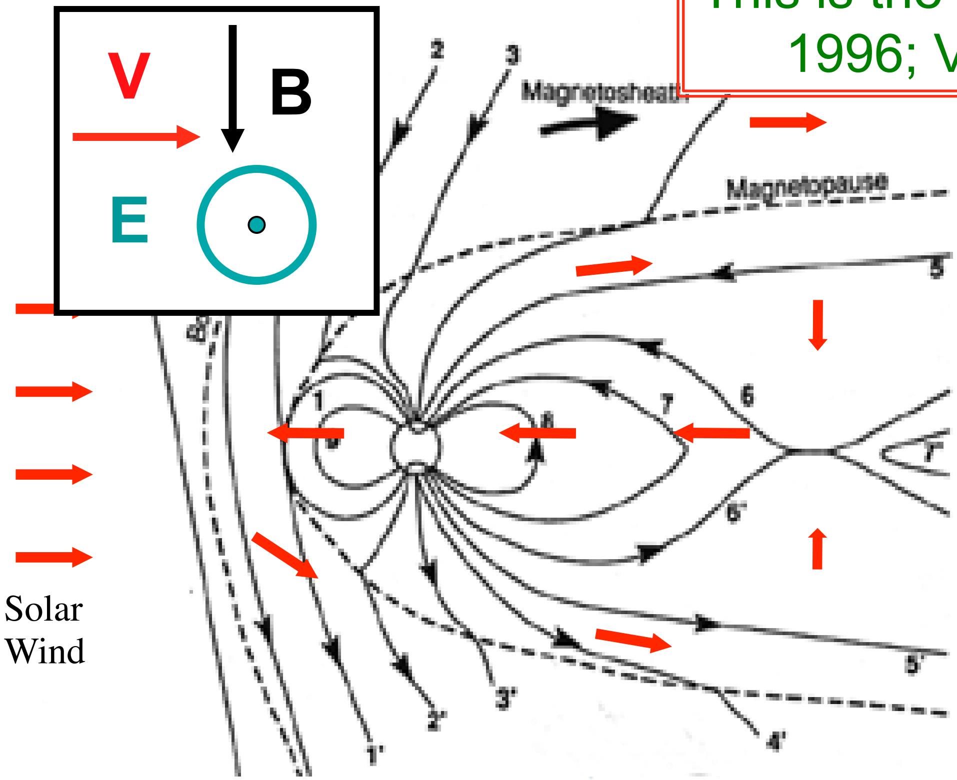


Closing reconnection

Opening reconnection

Rotating Plasmasphere

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



The Dungey Cycle

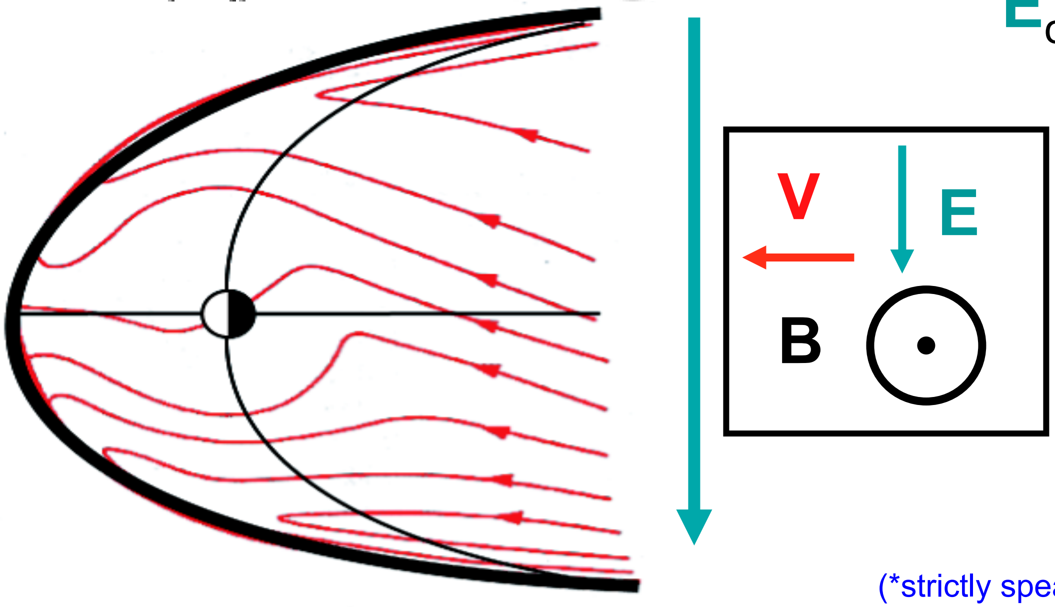
Solar wind driven magnetospheric convection*

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

ζ~ efficiency of reconnection ~10-20%

crude approximation!!

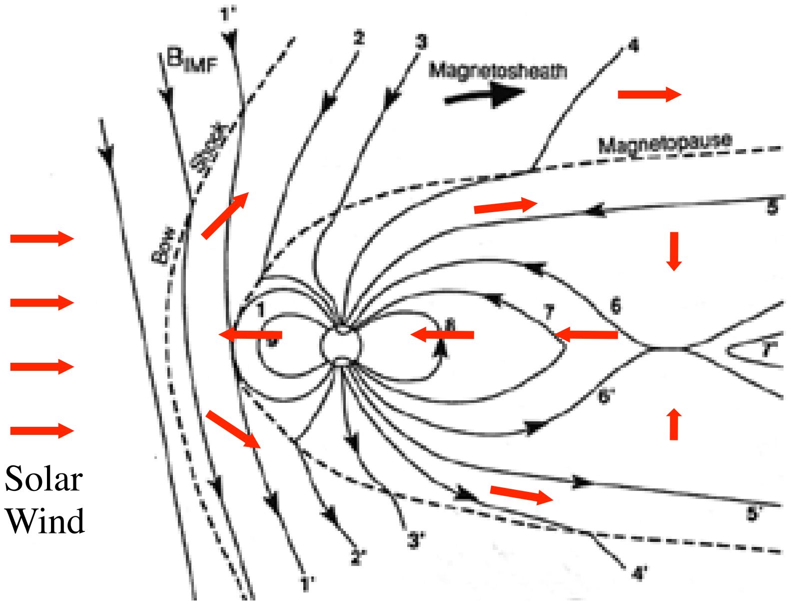
E_{conv}~ constant in m'sphere



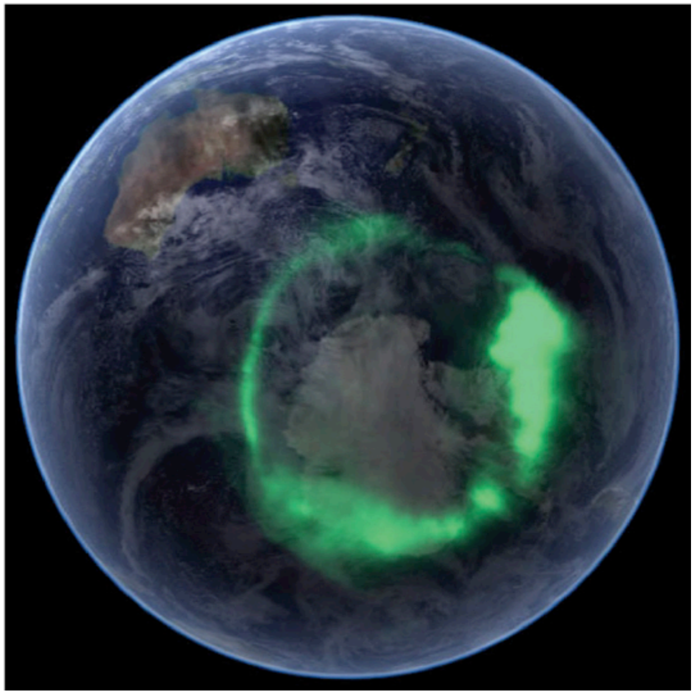
$$V_{convection} \sim \zeta V_{SW}(R/R_{MP})^3$$

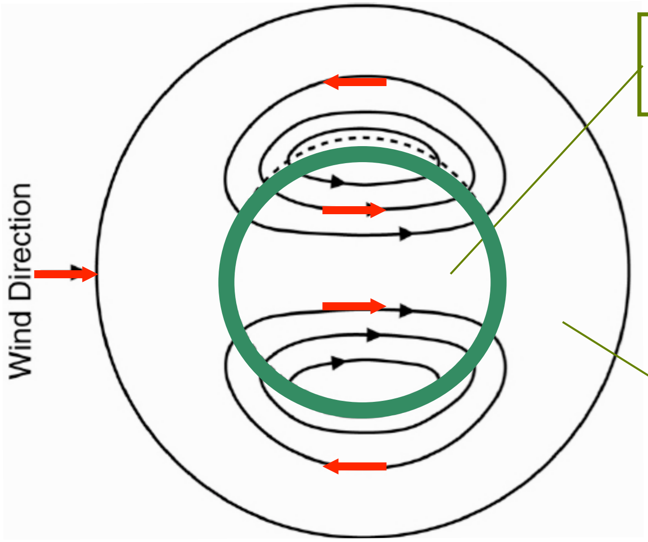
(where 3 power assumes a dipole - in reality, the flow is not uniform and the power somewhat less)

(*strictly speaking not convection but advection or circulation)



Solar
Wind



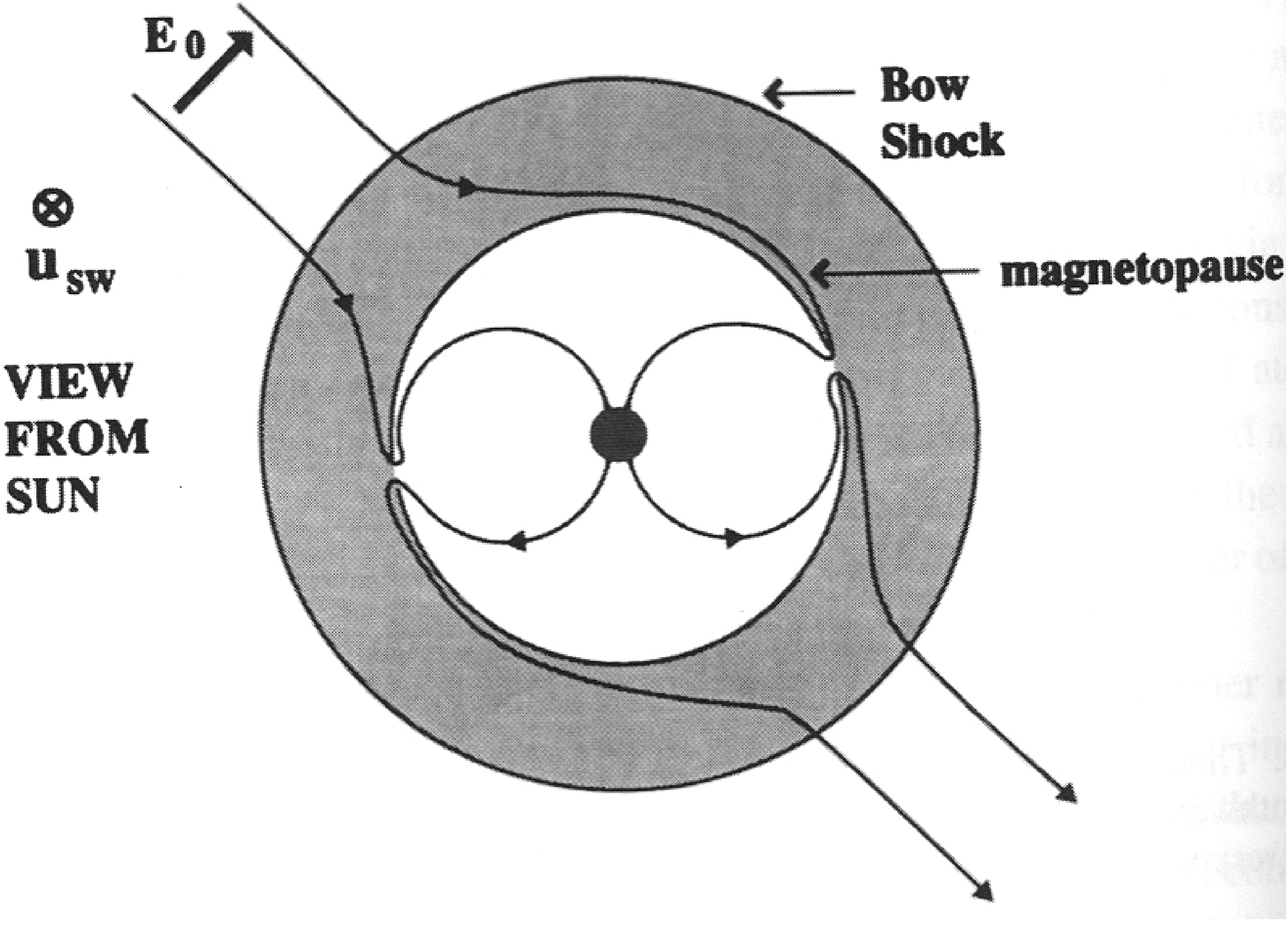


Connected to solar wind

Closed magnetic field

Polar view

Reality = Messy & 3D



Dynamics

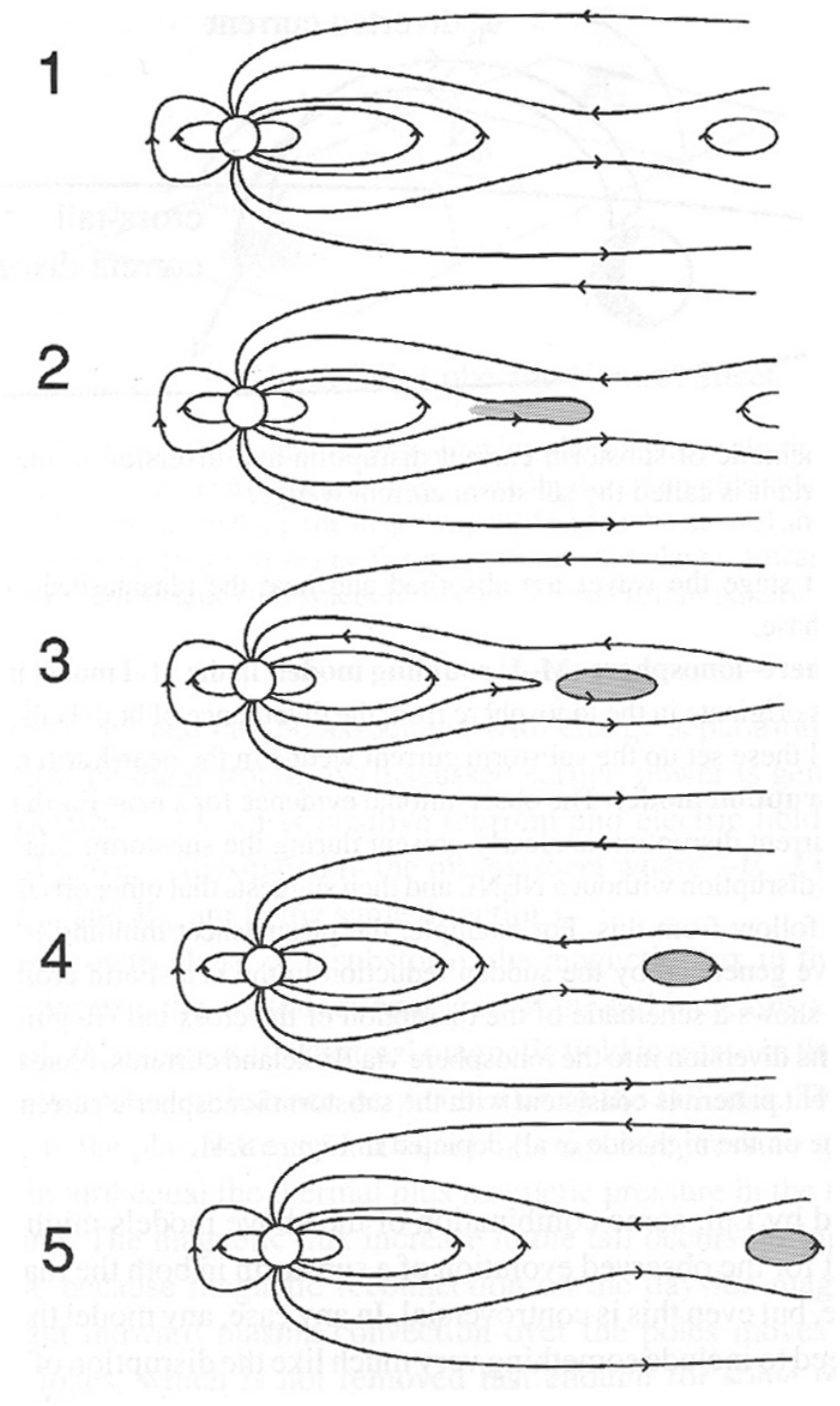
Dayside magnetopause

- Response to B_{SW} direction
- Solar wind ram pressure

Tail Reconnection

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

Space Weather!



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

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

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

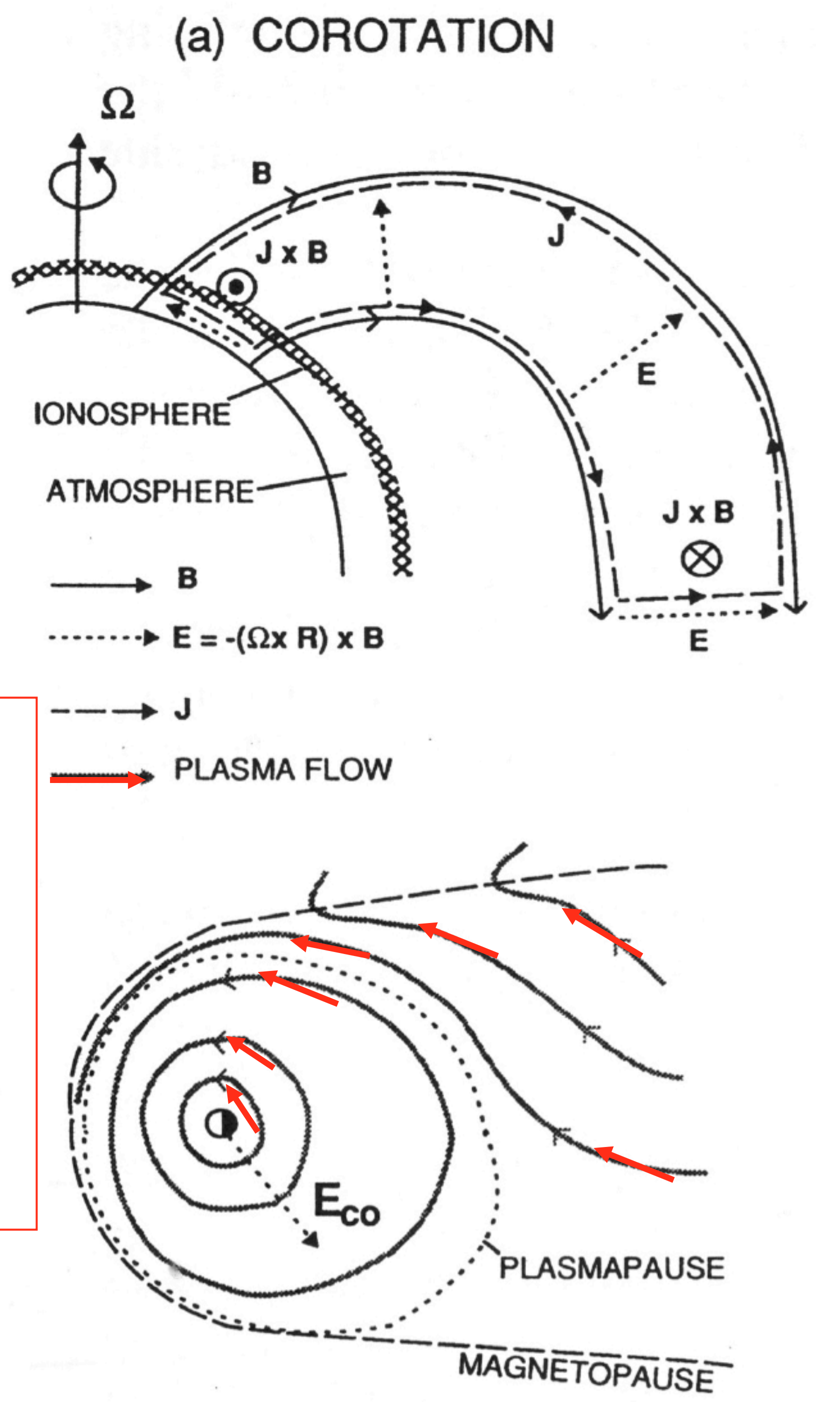
Fraction of planetary magnetosphere that is rotation dominated is…

$$R_{pp}/R_{MP}$$

$$\sim [\, r_p R_{MP}\, \Omega / \zeta V_{SW}]^{1/2}$$

$$\propto \boxed{\Omega^{1/2}\mu^{1/6}} / (\rho_{sw})^{1/12}\, V_{sw}^{2/3}$$

Where r_p=planetary radius
μ= magnetic moment of planet $B_o R_p^3$



(a) COROTATION

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

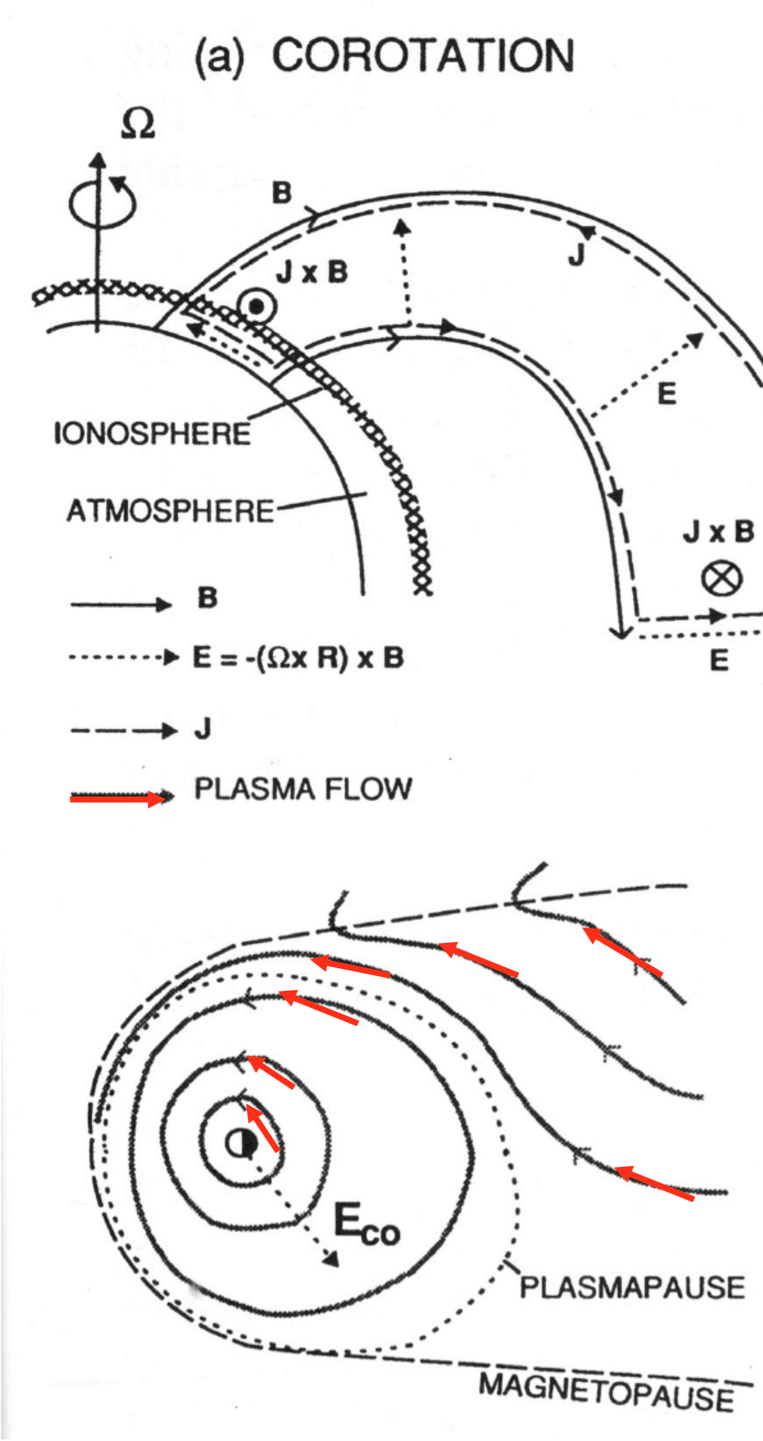
$$\mathbf{V}_{convection}$$

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

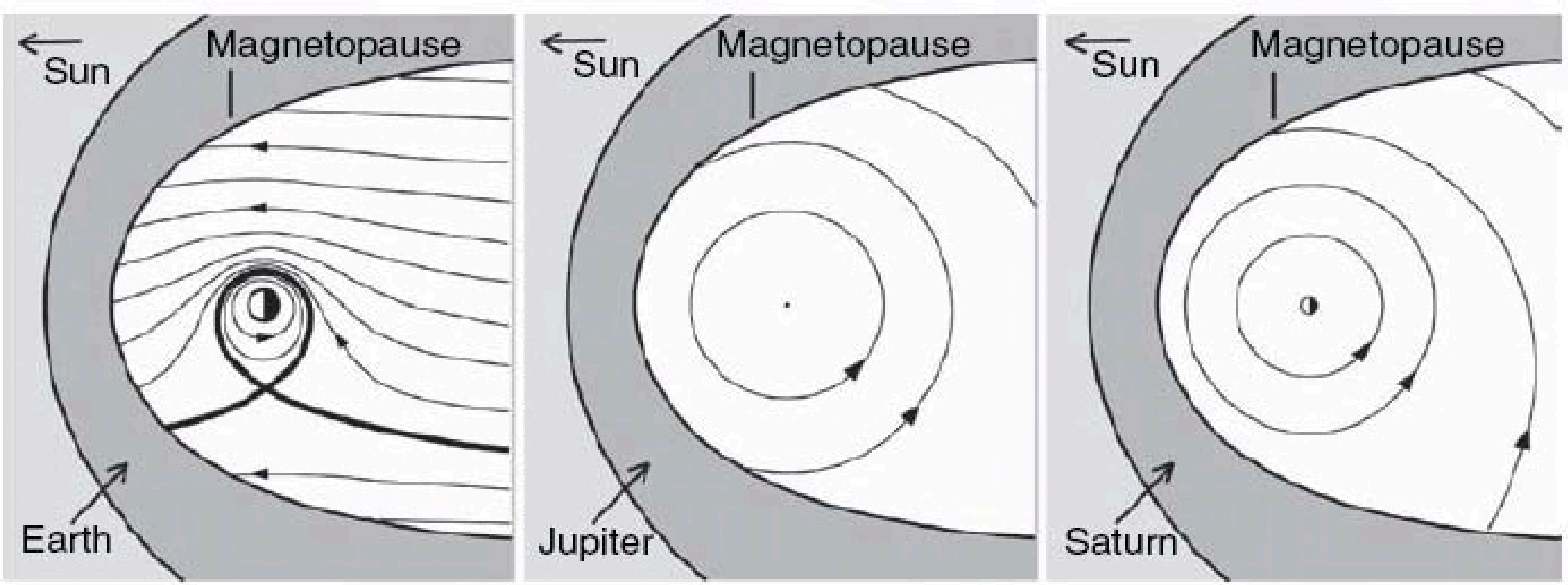
What if... How would location of plasmapause change?

1. Reconnection more/less efficient at harnessing the solar wind momentum

2. Planet’s spin slows down



Solar-wind vs. Rotation-dominated magnetospheres



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

6.7 350 95

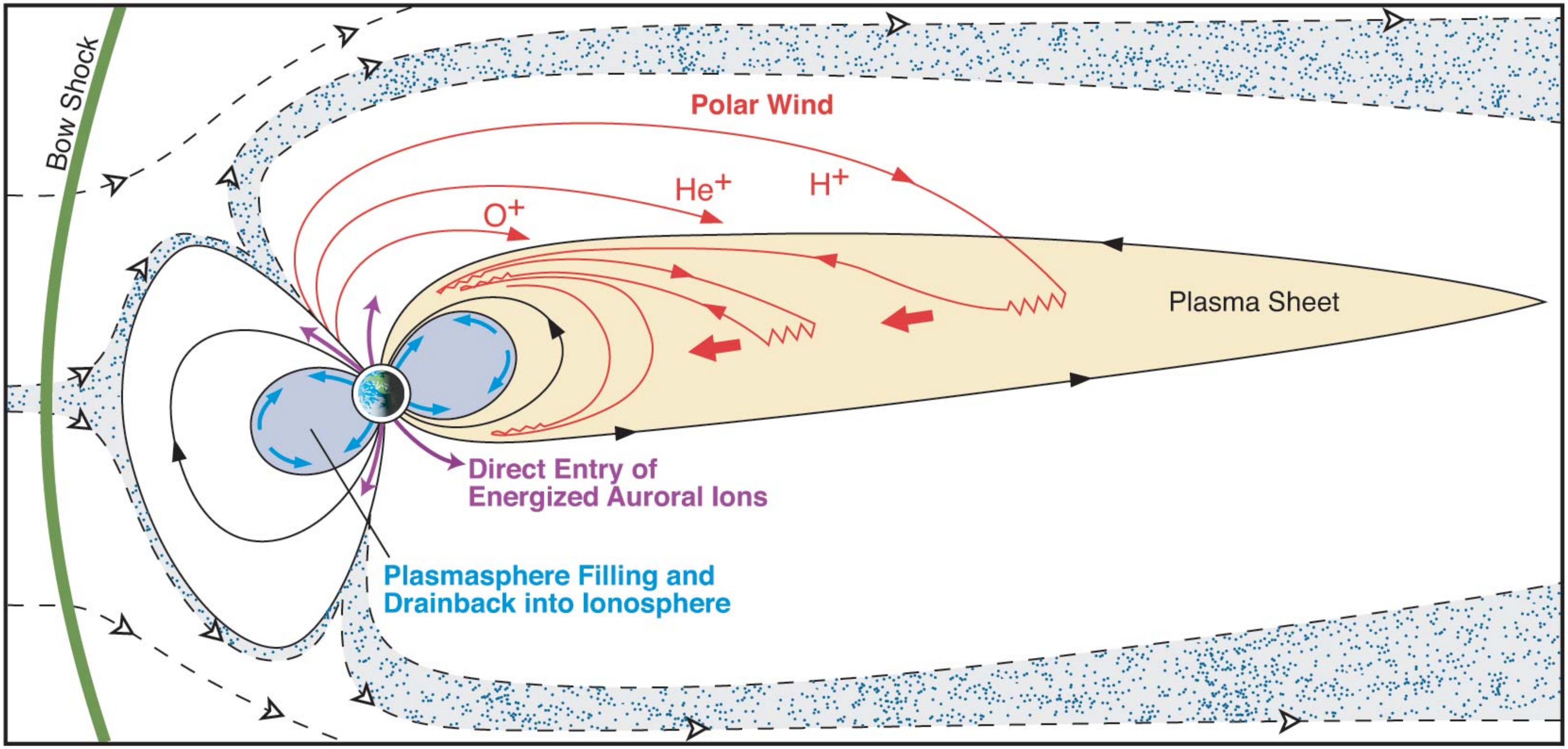
Assumptions:

1. Planet's rotation coupled to magnetosphere
2. Reconnection drives solar wind interaction

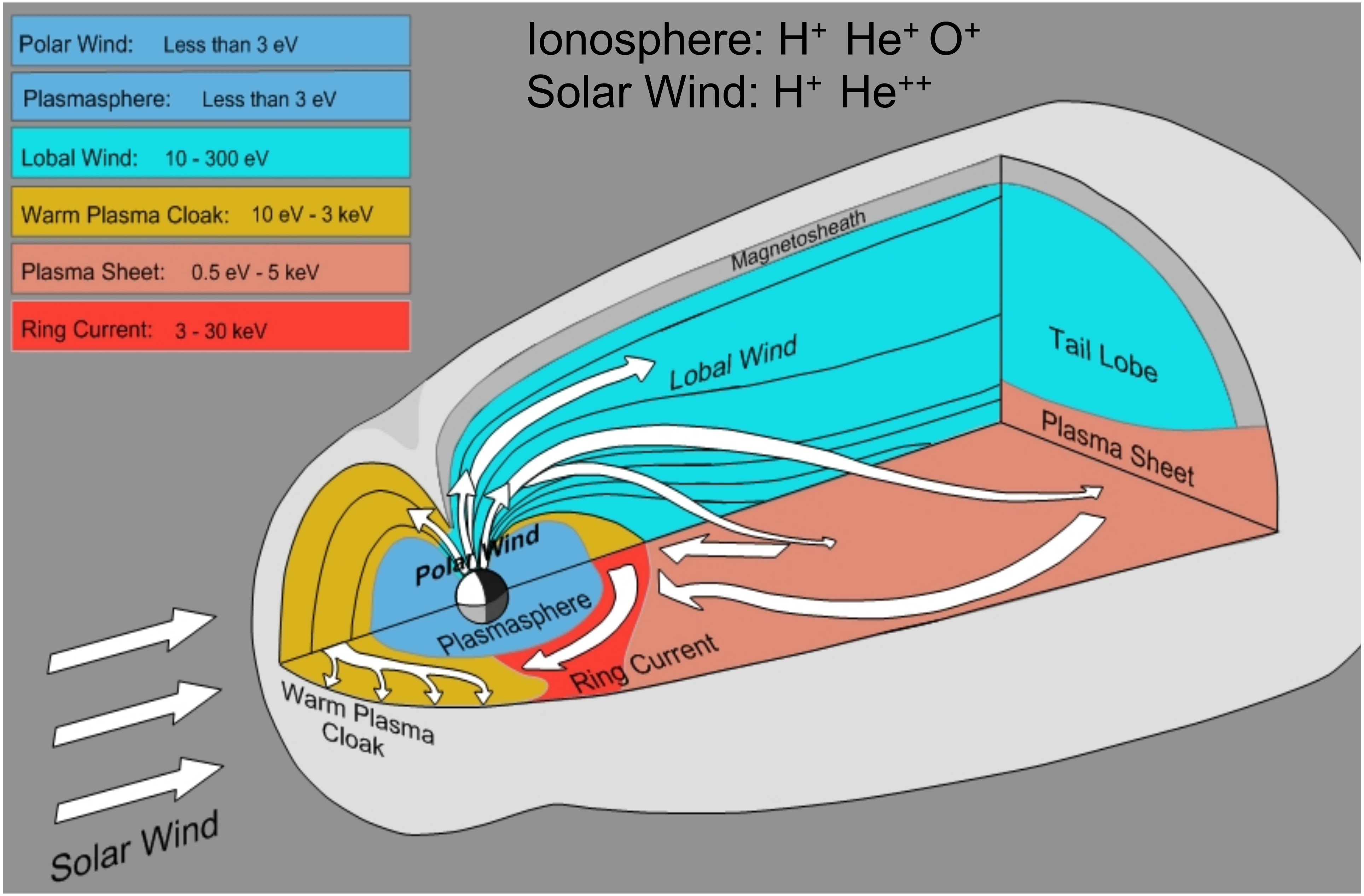
Plasma Sources

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

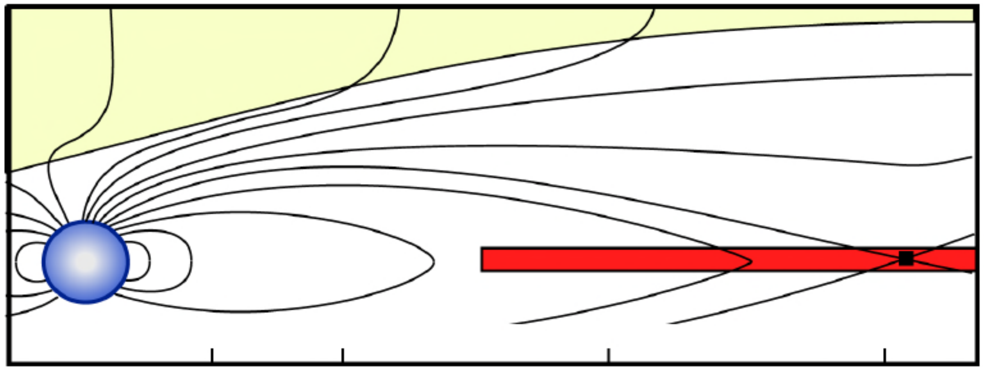
Substorm Energy Storage

solar wind kinetic energy converted to magnetic energy

SW kinetic energy

magnetic energy

growth phase

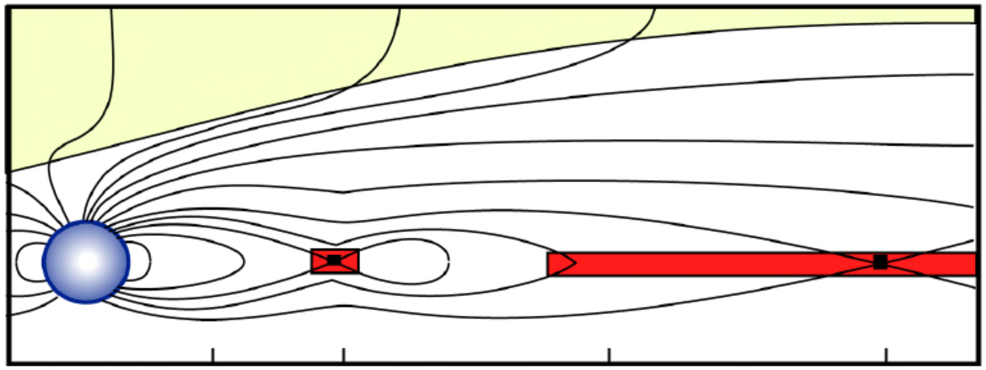


magnetic energy

heat

kinetic

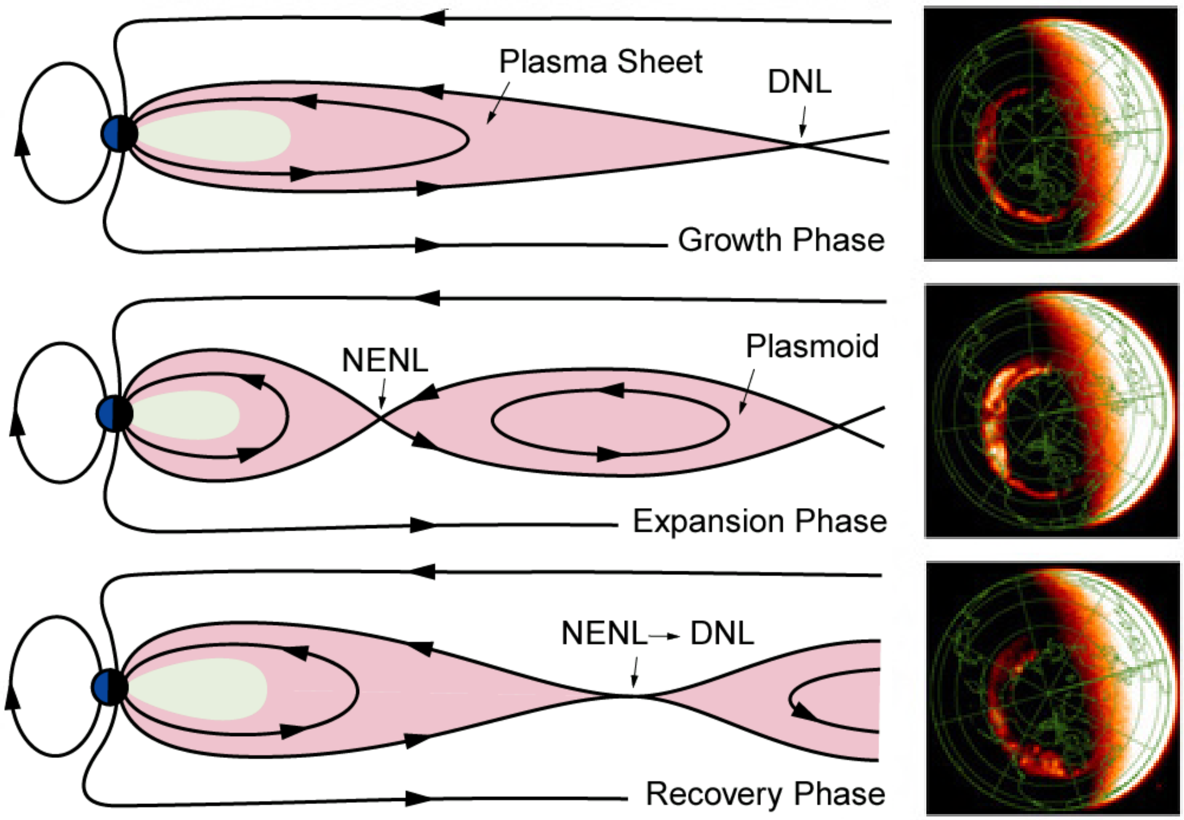
substorm onset



Terry Forbes Friday Lecture

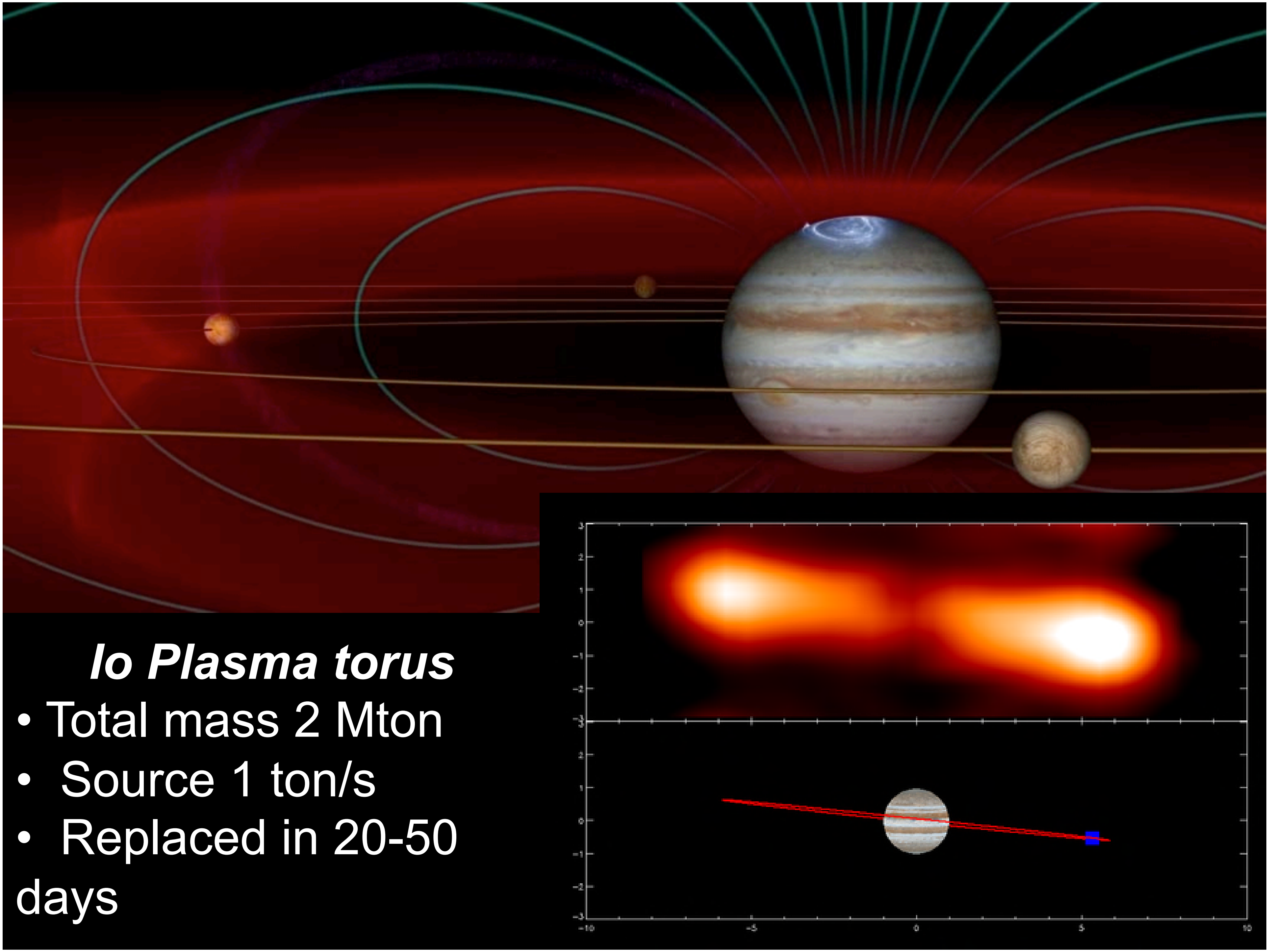
Evolutionary Phases for Substorm Plasmoid

1. Energy storage:
2. Onset:
3. Recovery:



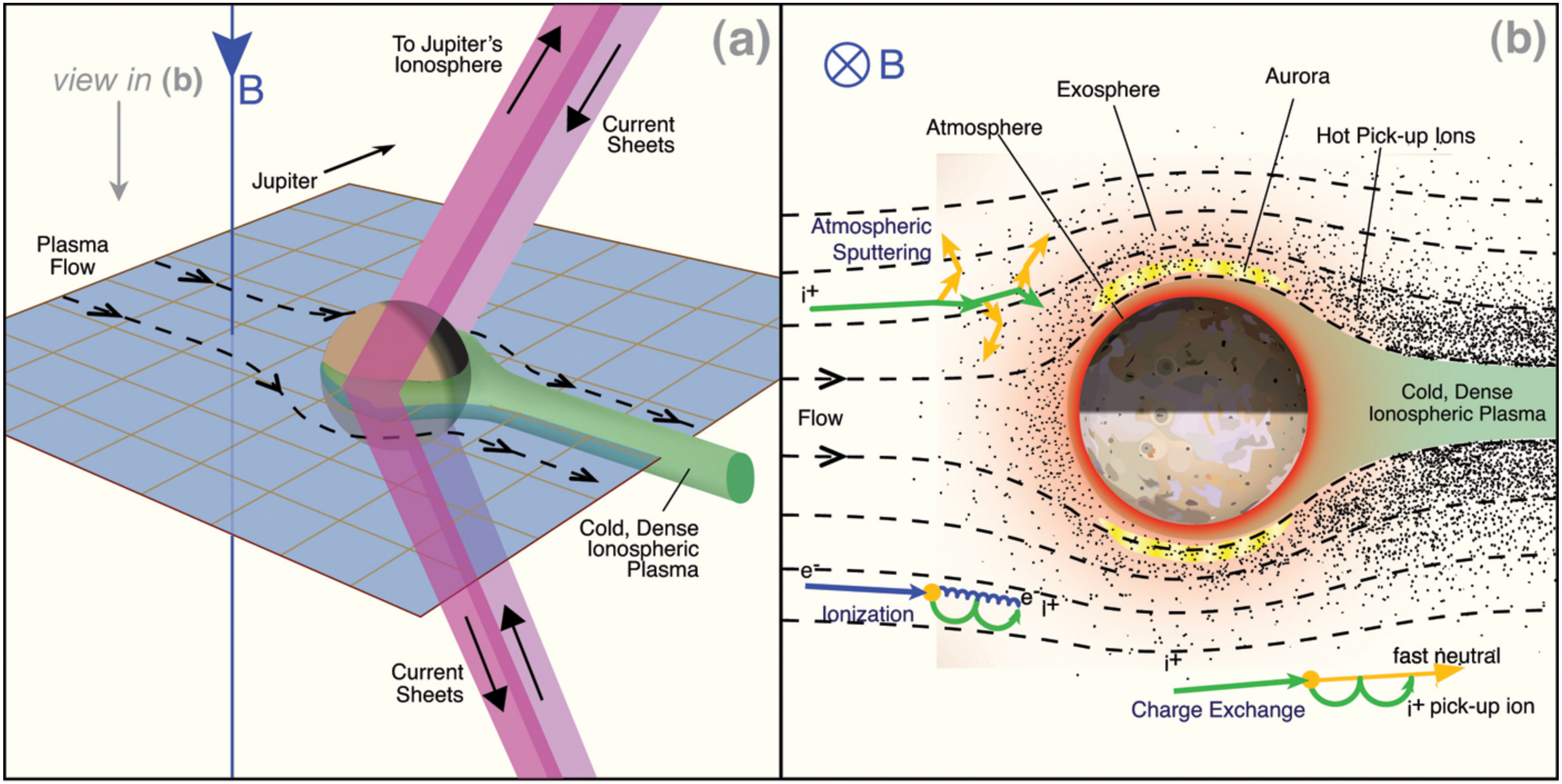
Aurora:
- Open-closed boundary
- Stronger on nightside
- Highly variable

Terry Forbes Friday Lecture



Io Plasma torus

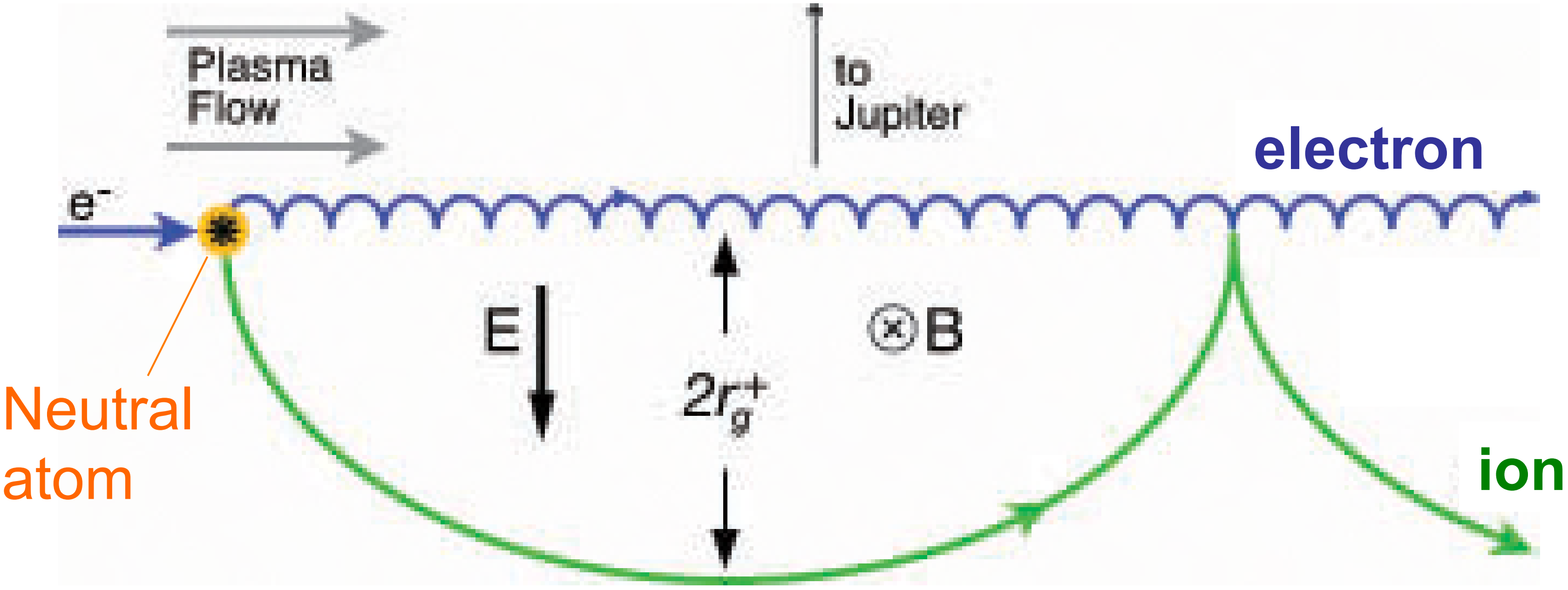
- Total mass 2 Mton
- Source 1 ton/s
- Replaced in 20-50 days



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

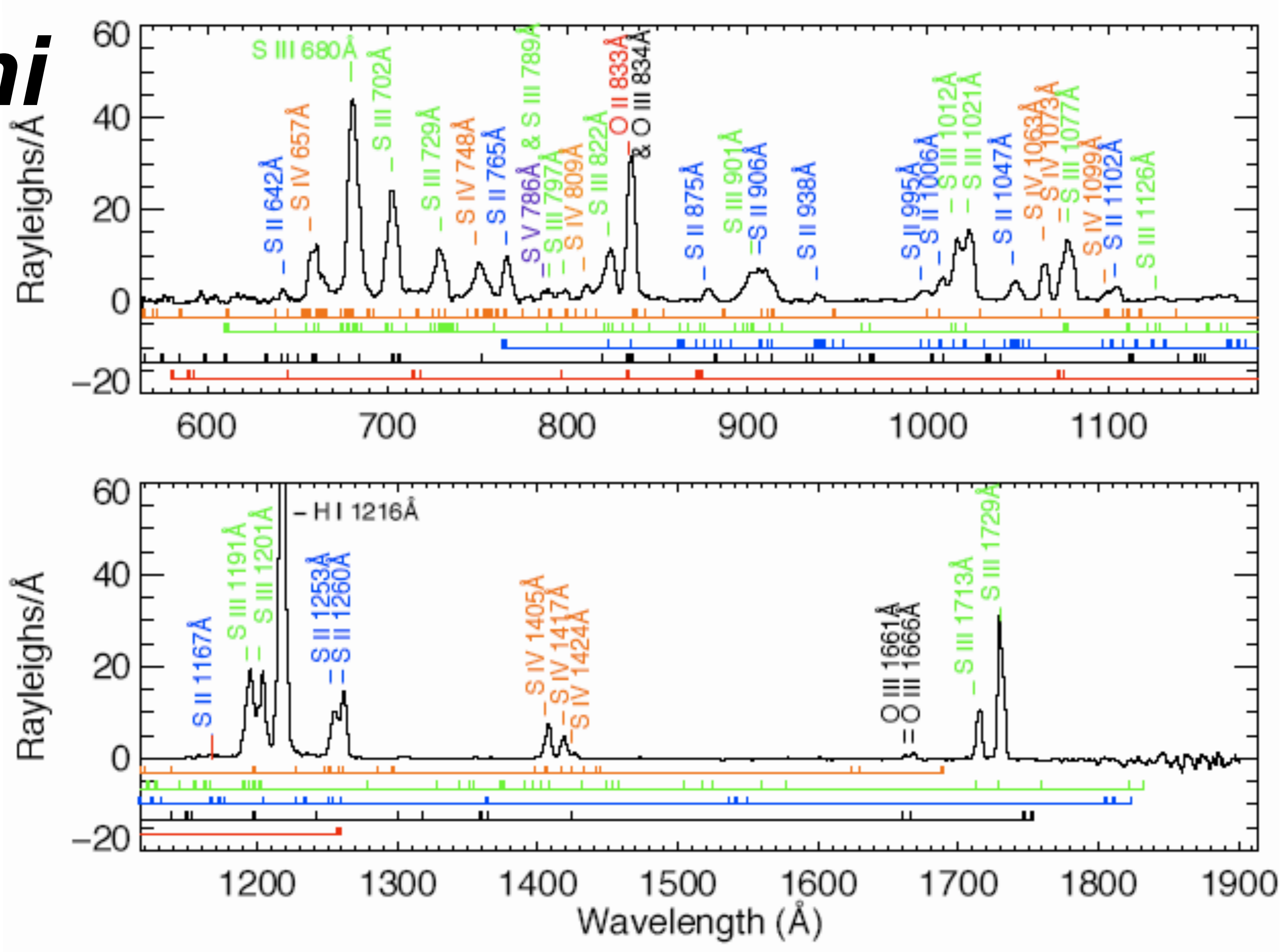
- Plasma interaction with Io's atmosphere
- Heated atmosphere escapes
- ~20% plasma source local

Ion Pick Up

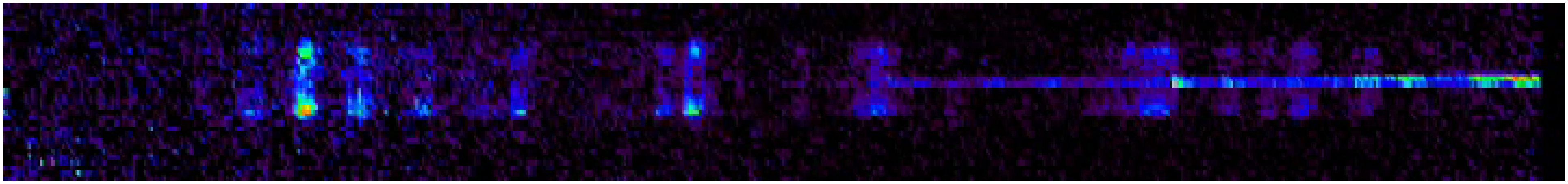


The magnetic field couples the plasma to the spinning planet
Ion gains large gyromotion -> heat

Cassini UVIS

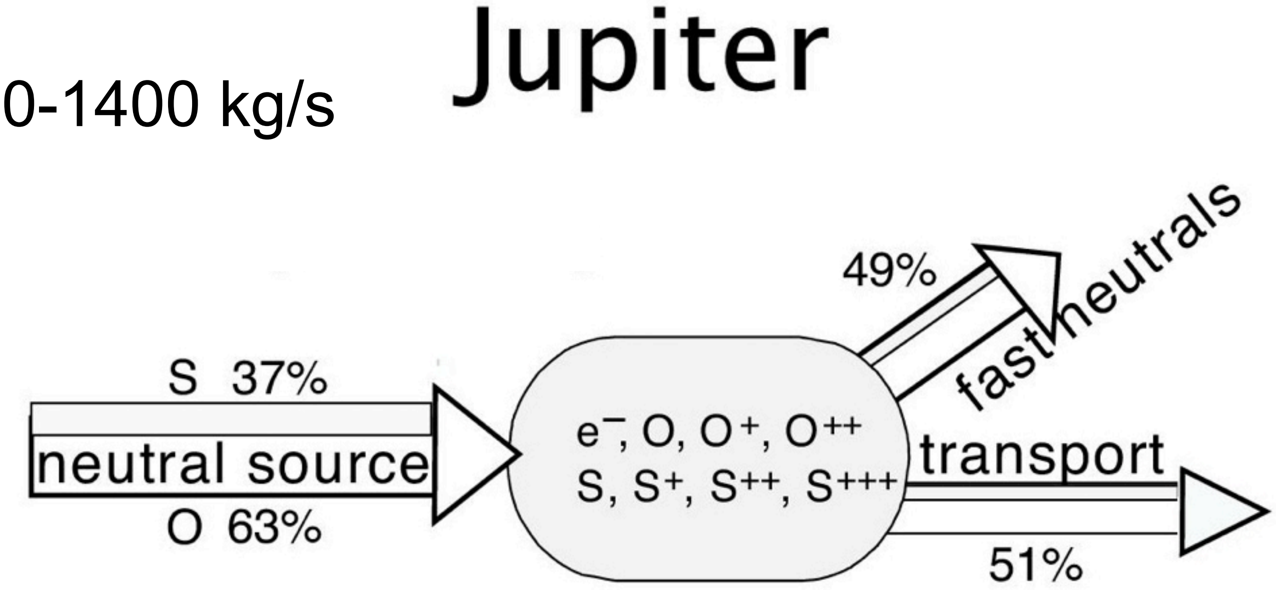


Andrew Steffl



Plasma Torus   Mass Flux

260-1400 kg/s

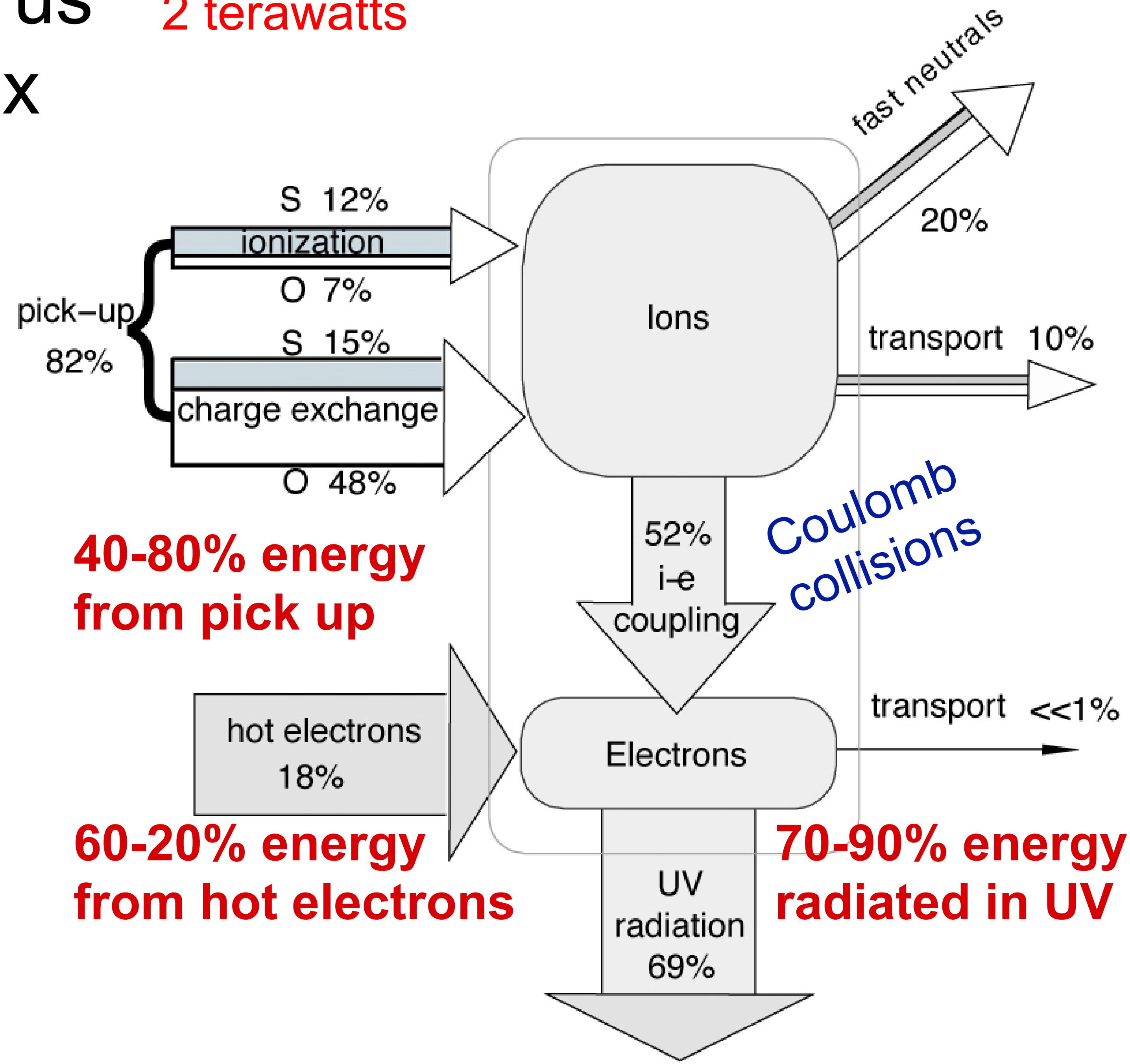


Half lost as fast neutrals
-> extended neutral cloud

Half transported out to plasma disk

Plasma Torus Energy Flux

2 terawatts



Coulomb collisions

40-80% energy from pick up

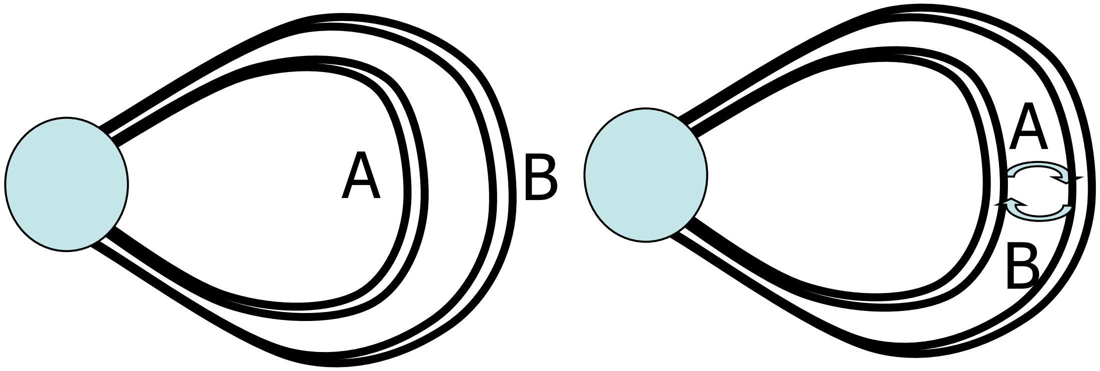
60-20% energy from hot electrons

70-90% energy radiated in UV

Radial Transport

In rotating magnetosphere

If fluxtube A contains more mass than B – they interchange



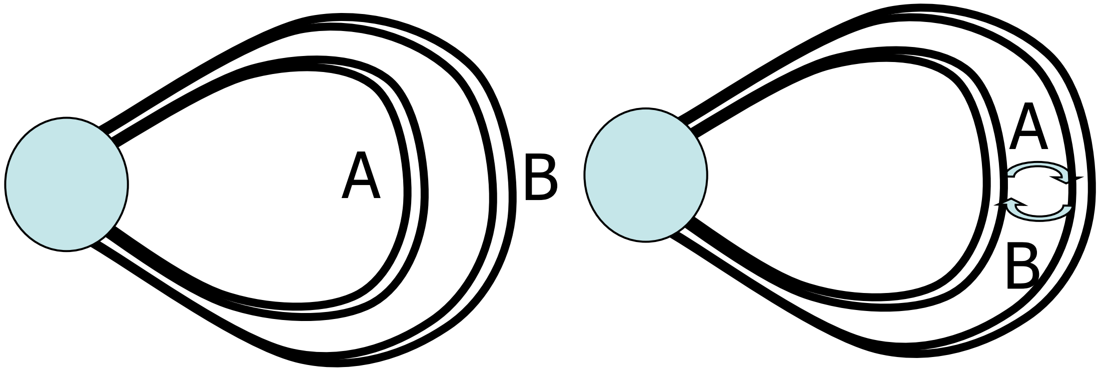
Rayleigh-Taylor instability where centrifugal potential replaces gravity

If $\beta \ll 1$,
interchange of A and B does not change field strength.

Radial Transport

In rotating magnetosphere

If fluxtube A contains more mass than B – they interchange



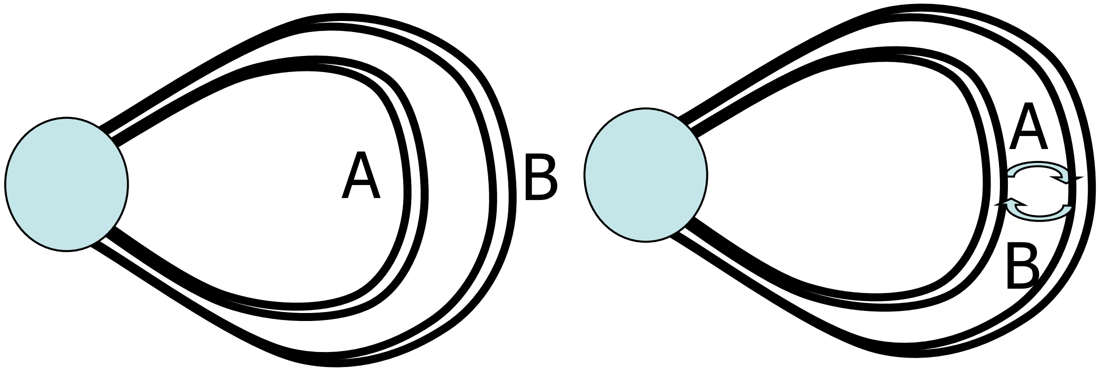
You can think of centrifugally-driven fluxtube interchange as a kind of diffusion.

- How will density vary with distance from the source?
- How will diffusion rate depend on ***gradient*** of density?

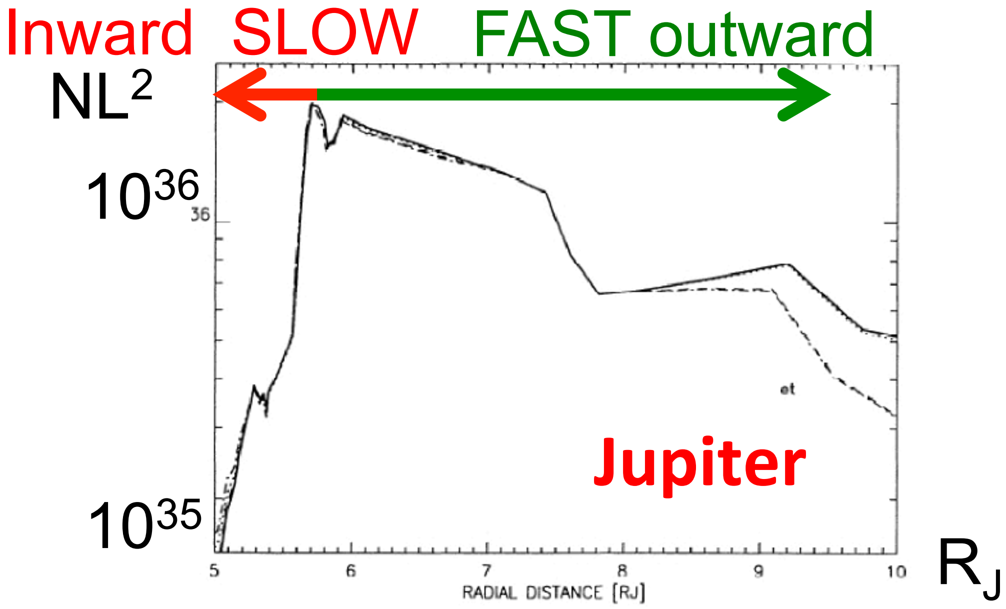
Radial Transport

In rotating magnetosphere

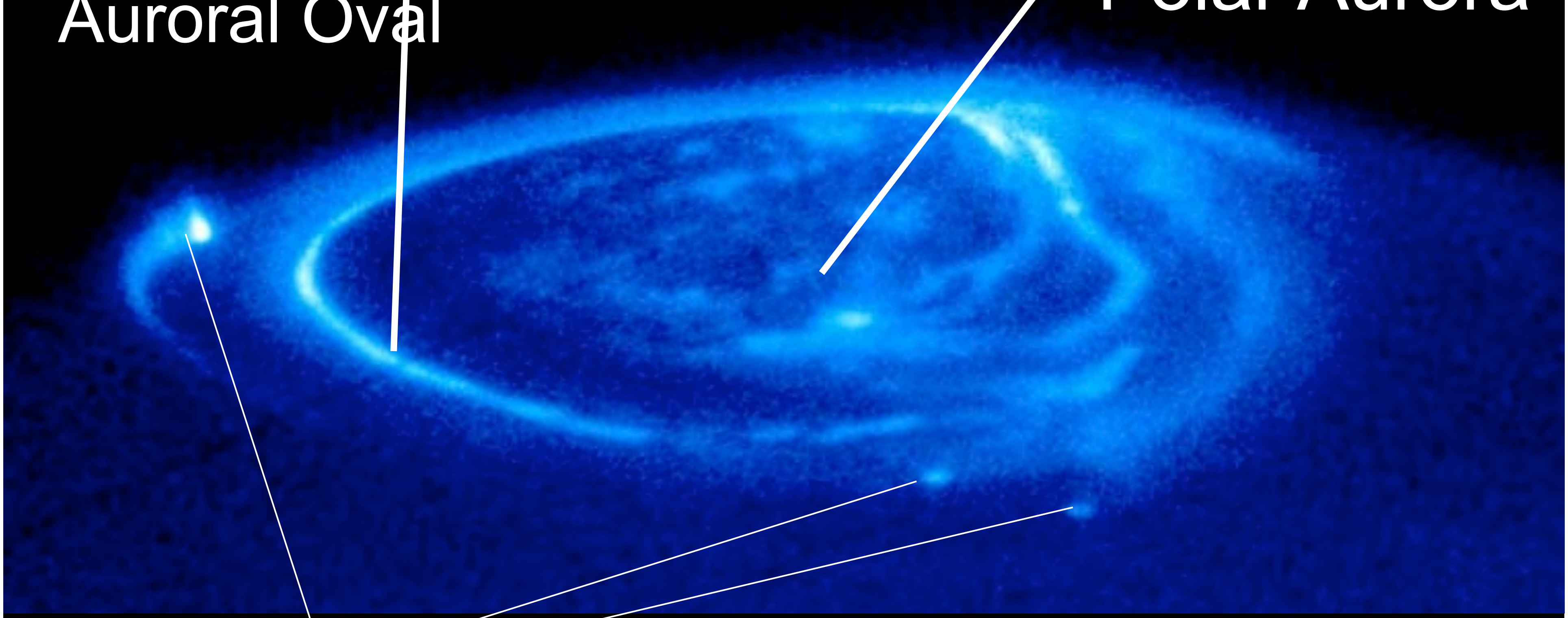
If fluxtube A contains more mass than B – they interchange



If $\beta \ll 1$,
interchange of A and B
does not change field
strength.



Jupiter's 3 Types of Aurora



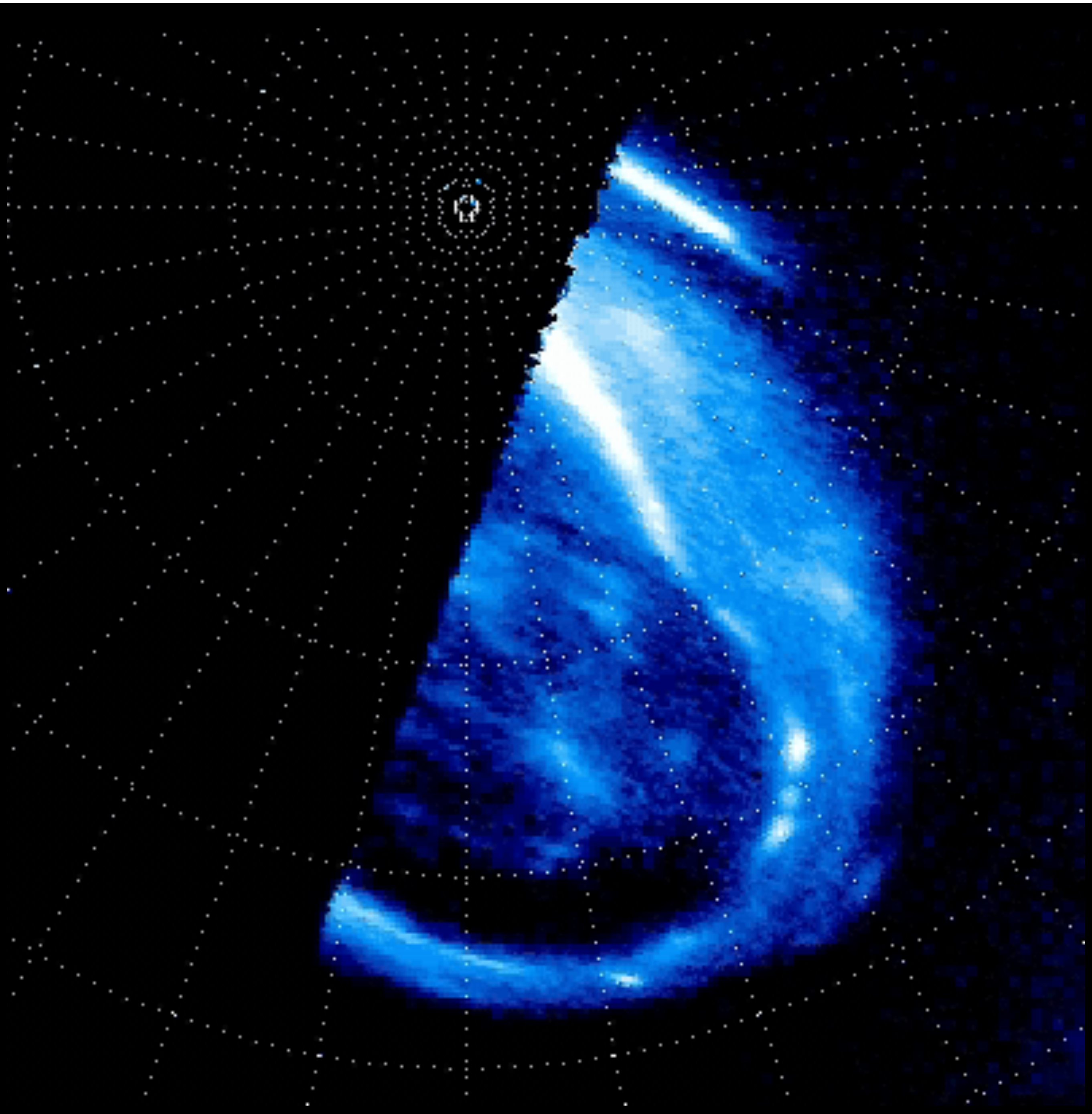
Steady Main Auroral Oval

Variable Polar Aurora

Aurora associated with moons

Jupiter's Aurora - The Movie

Fixed magnetic co-ordinates rotating with Jupiter

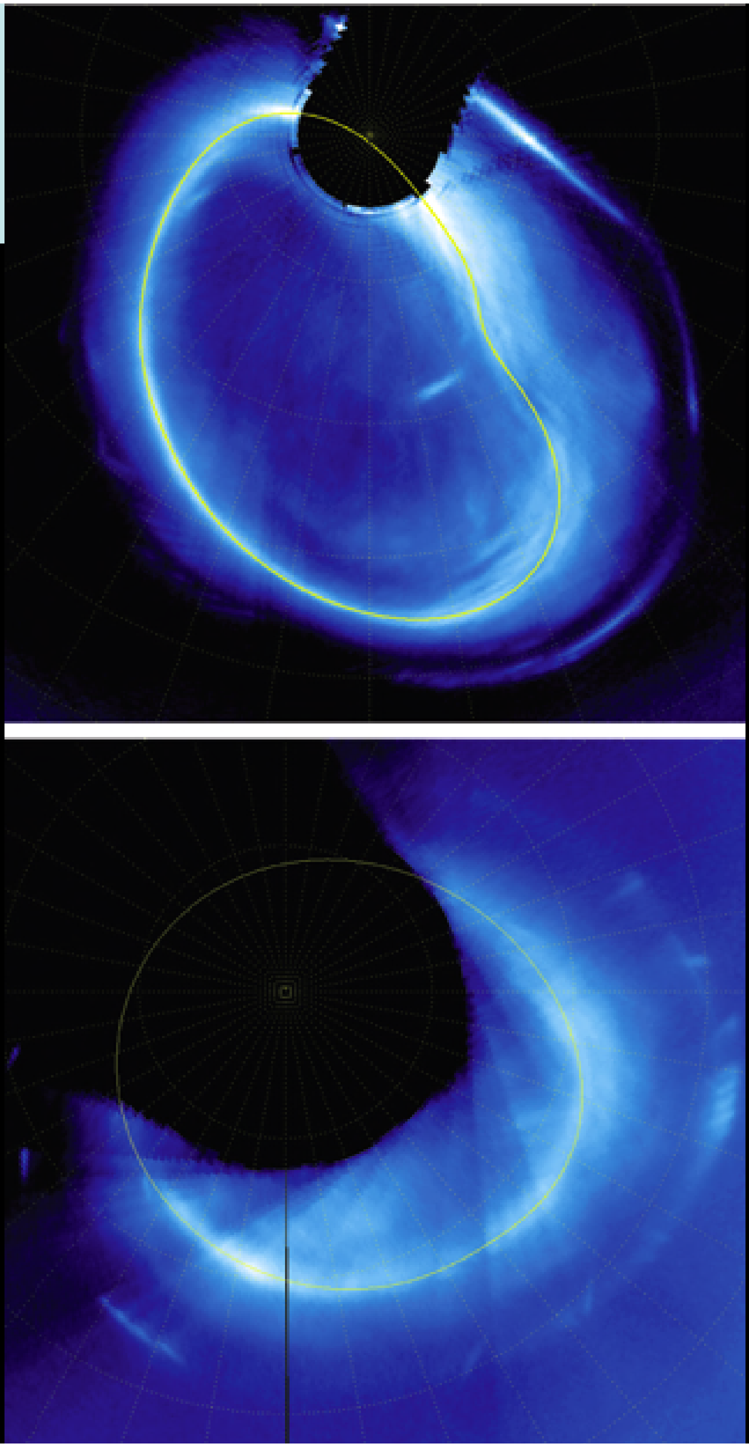


Clarke et al.
Grodent et al.
HST

Main Aurora

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

Clarke et al., Grodent et al. HST

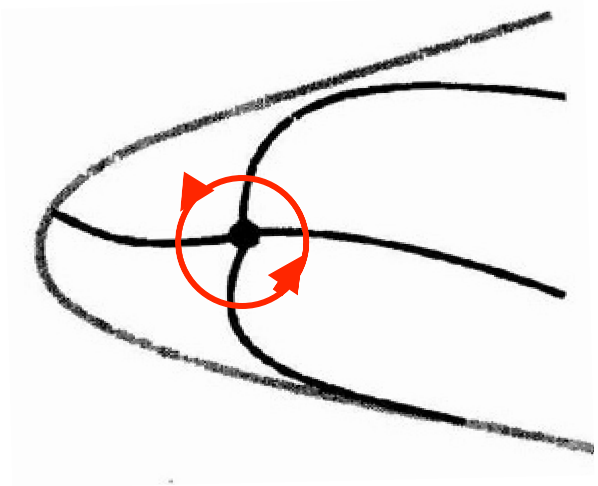


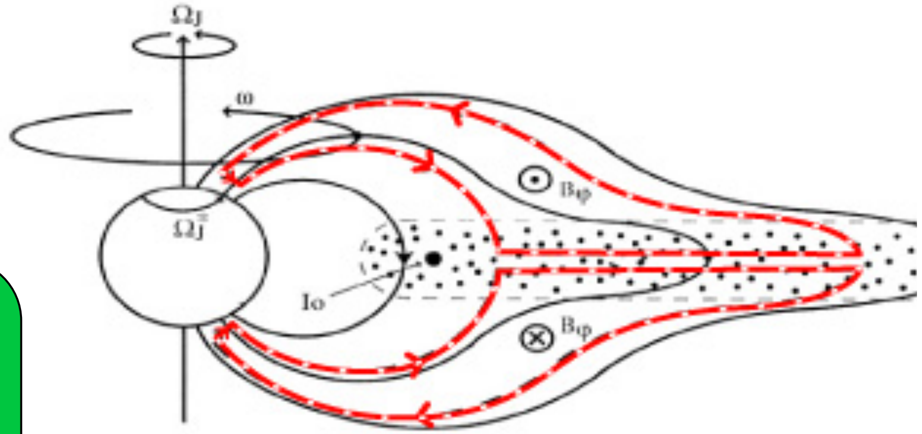
Coupling the Plasma to the Flywheel

- As plasma from Io moves outwards its rotation decreases (conservation of angular momentum)
- Sub-corotating plasma pulls back the magnetic field
- Curl **B** -> radial current J_r
- J_r x **B** force enforces rotation

Field-aligned currents couple magnetosphere to Jupiter’ s rotation

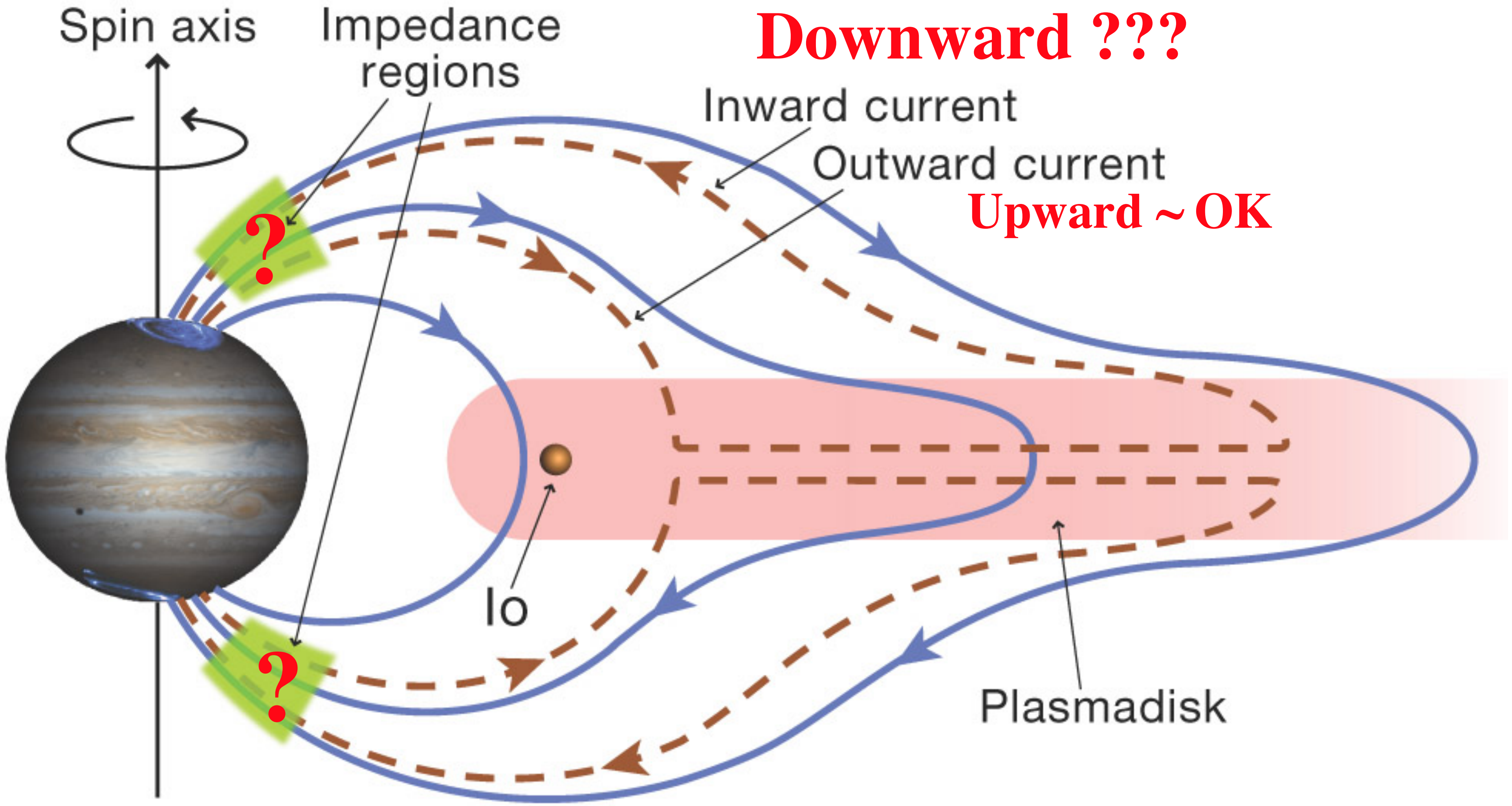
Khurana 2001





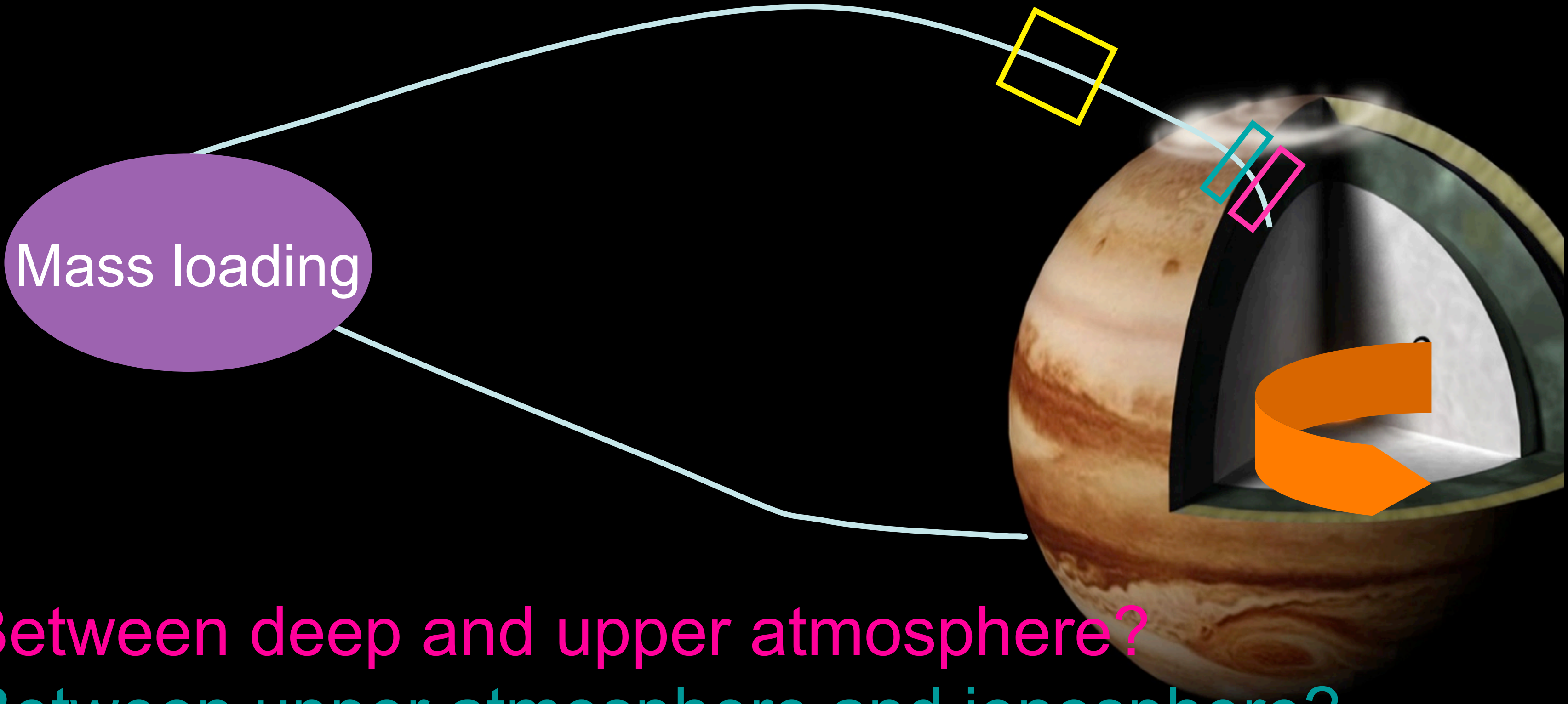
Cowley & Bunce 2001

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



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

Where is the clutch slipping?



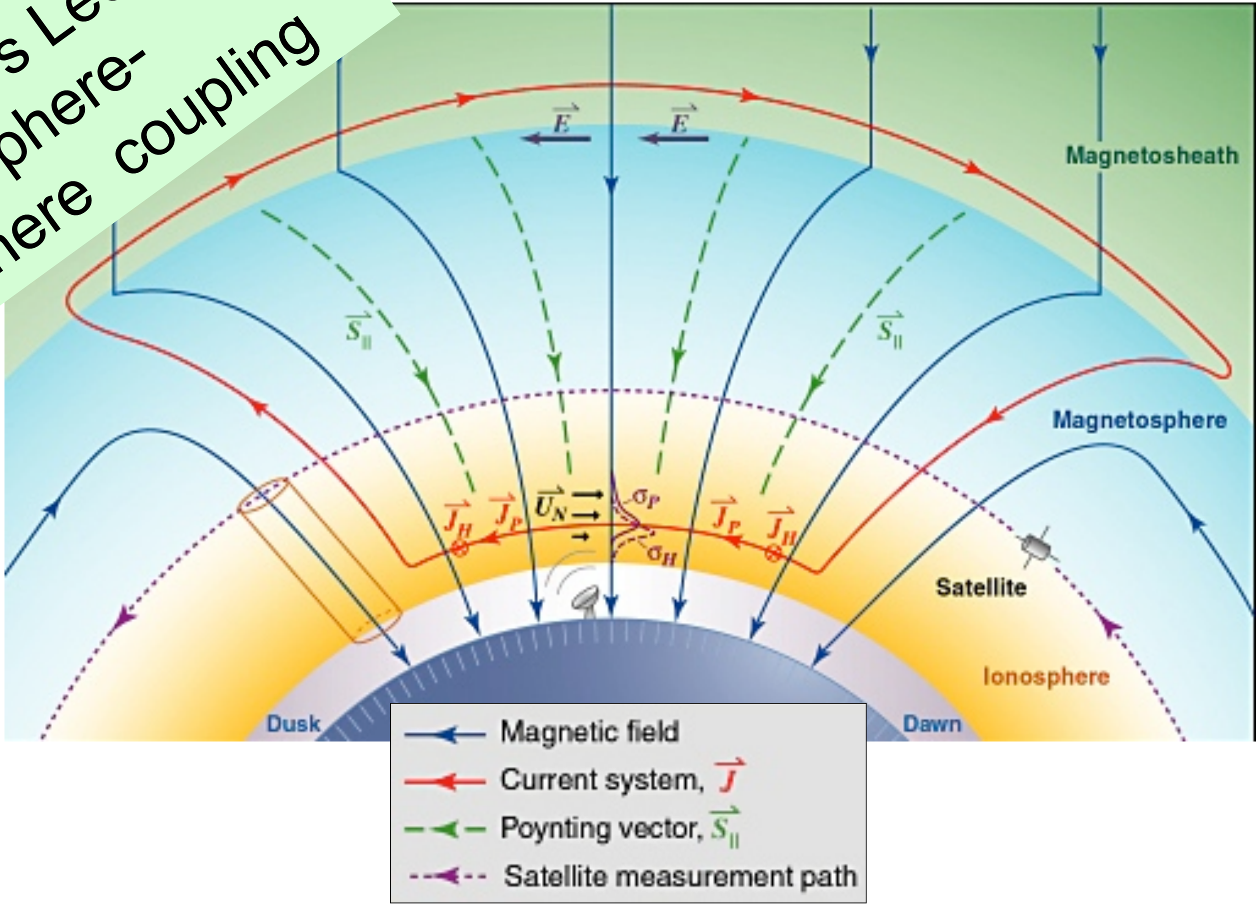
A - Between deep and upper atmosphere?

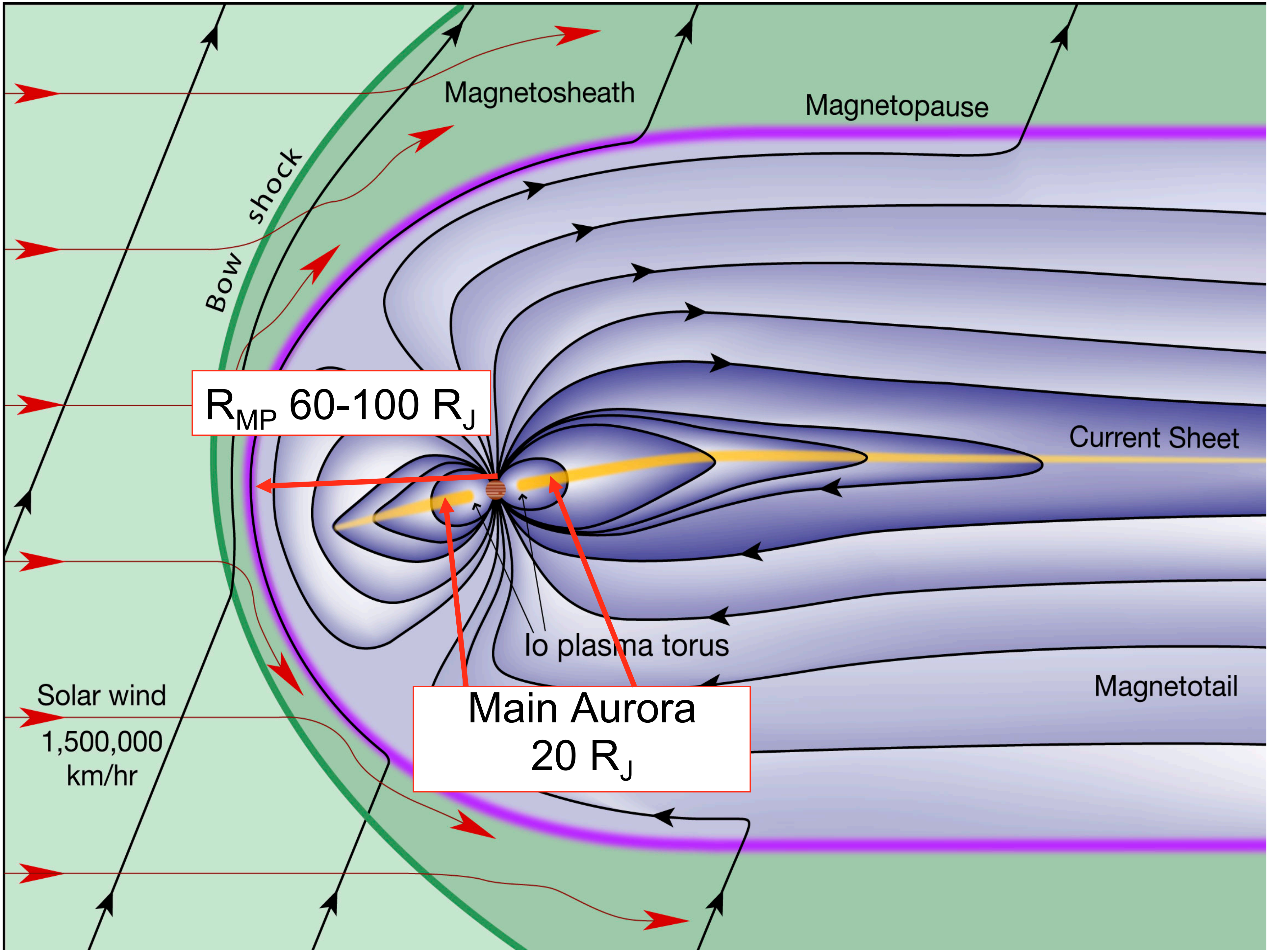
B - Between upper atmosphere and ionosphere?

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

Ionosphere - Sets boundary conditions for magnetospheric dynamics

Marina Galand's Lecture
On ionosphere-
magnetosphere coupling





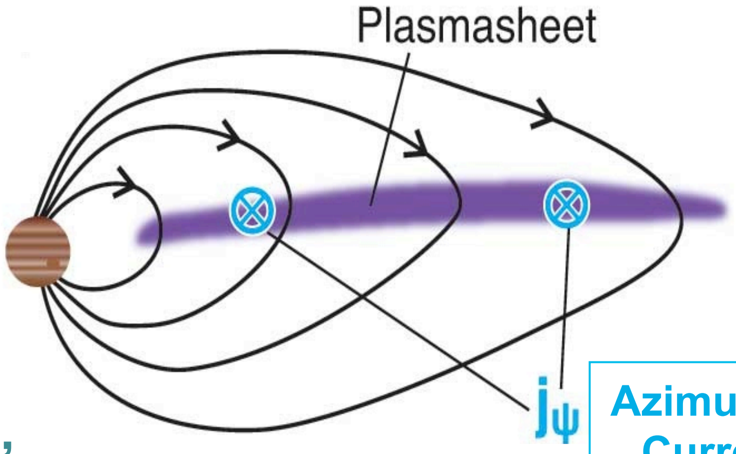
R_{MP} 60-100 R_J

Main Aurora
20 R_J

Configuration

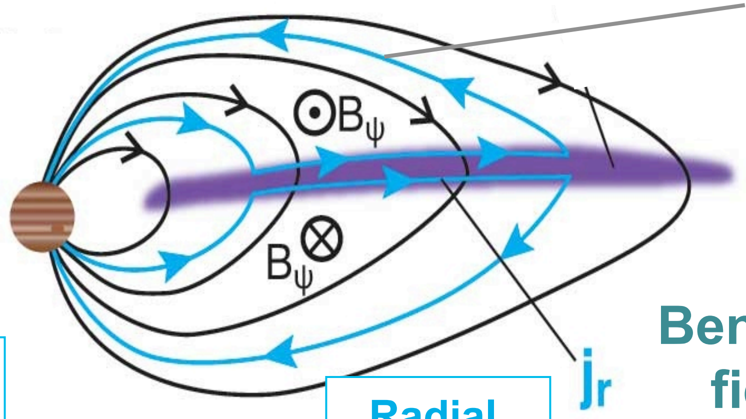
$\nabla \times B_{observed}$
$\rightarrow J$

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



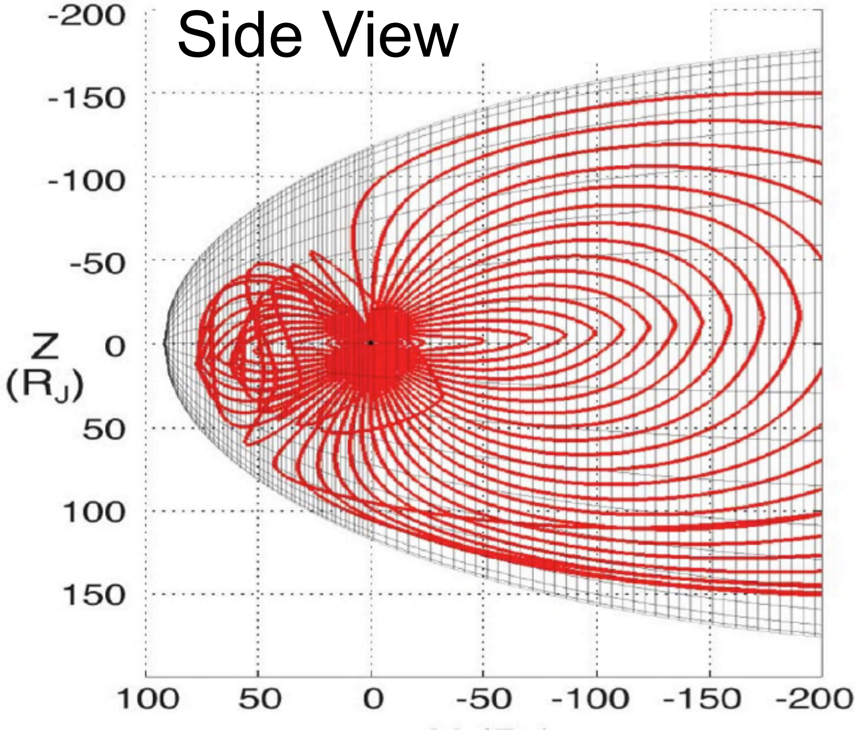
Azimuthal Current

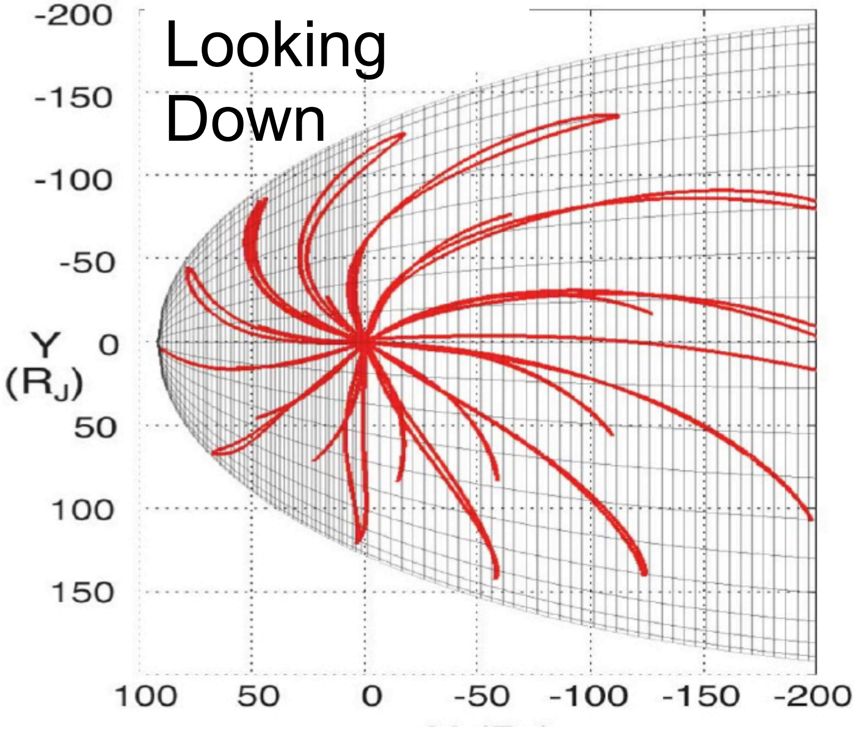
Expands, stretches field



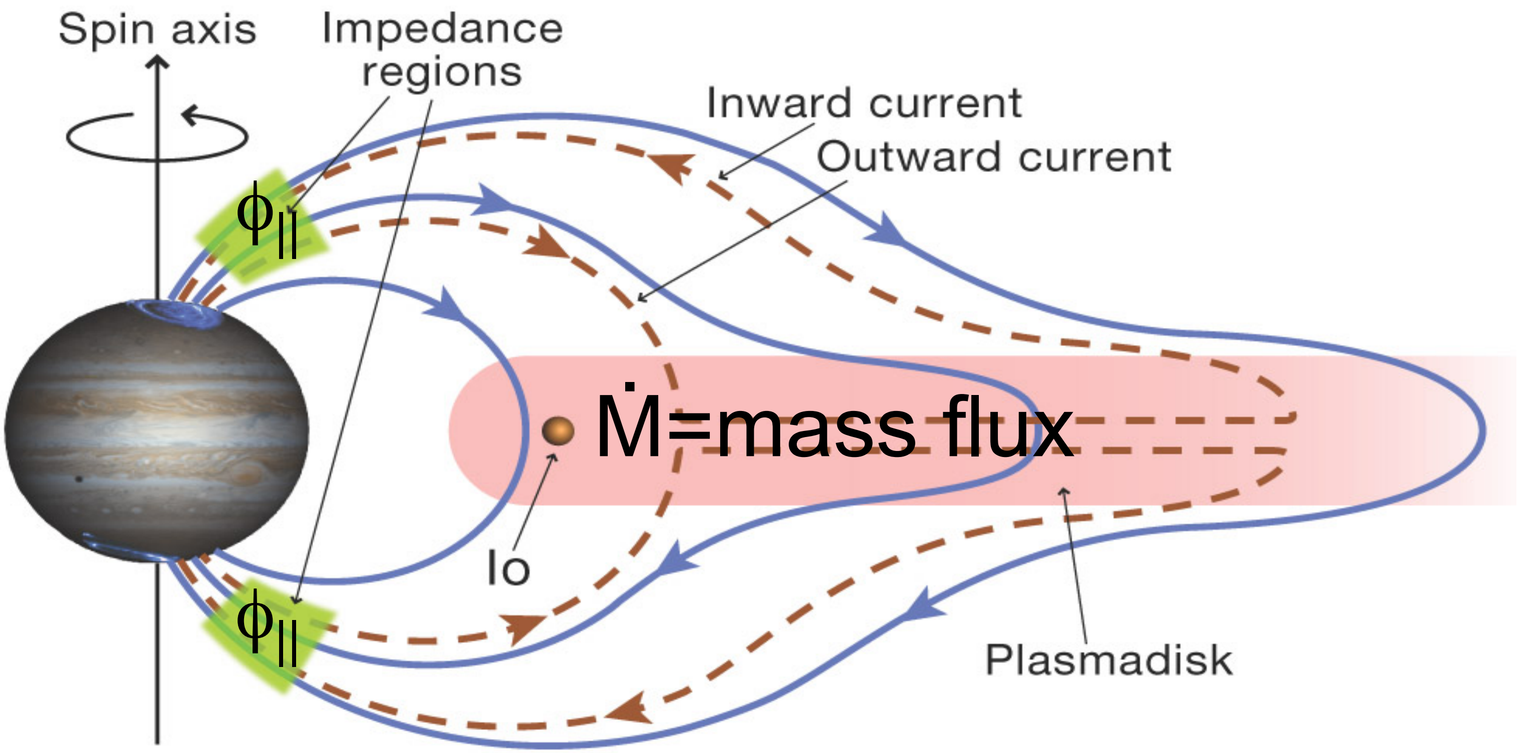
Radial Current

Bends field back


Side View


Looking Down

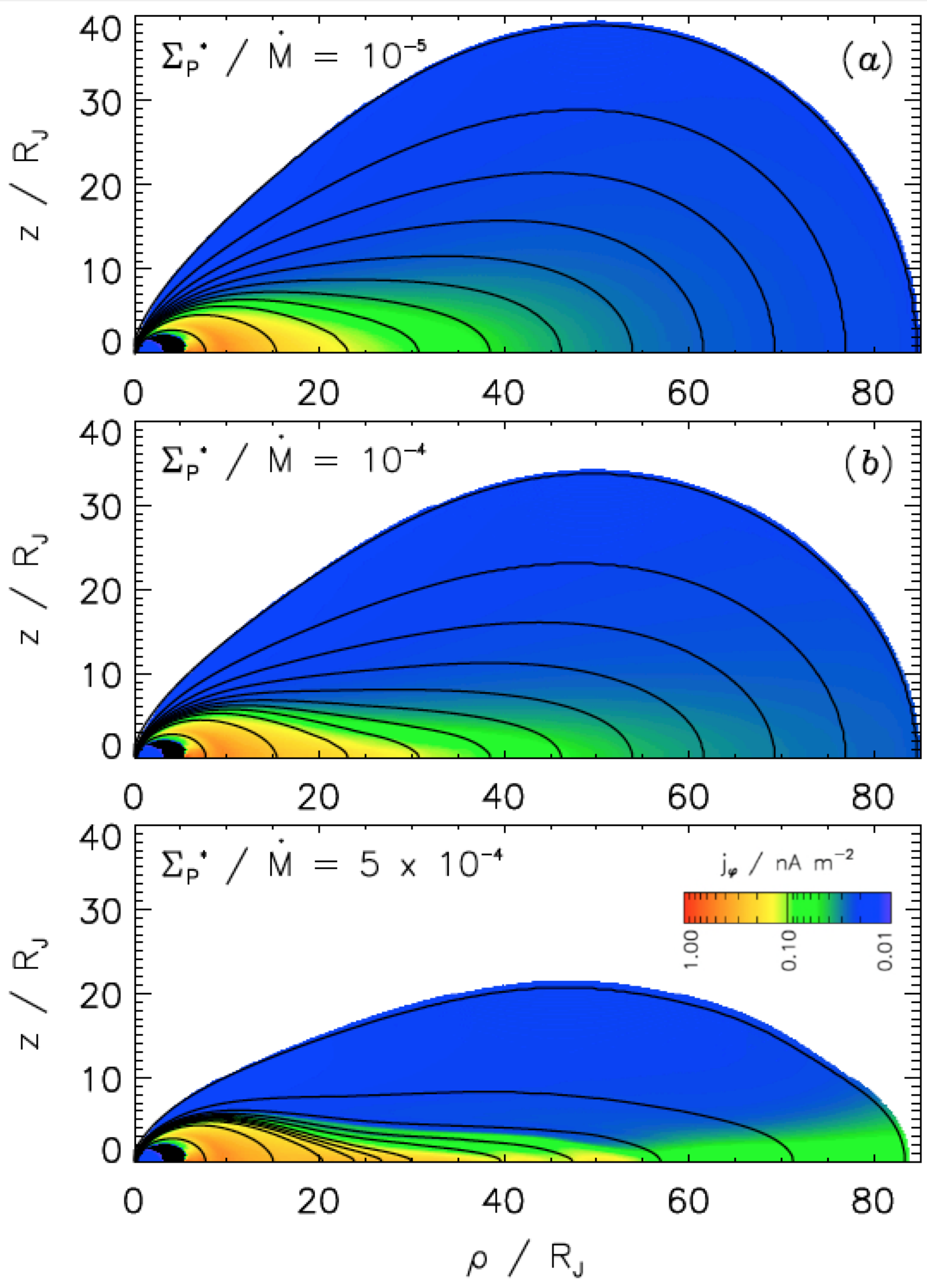
(De-)Coupling - 1



Magnetospheric Factors: $\dot{M}$ $\phi_{||}$
Ionosphere/Thermosphere factors: Σ_p winds, chemistry, heating, radiation, etc;

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

Jupiter



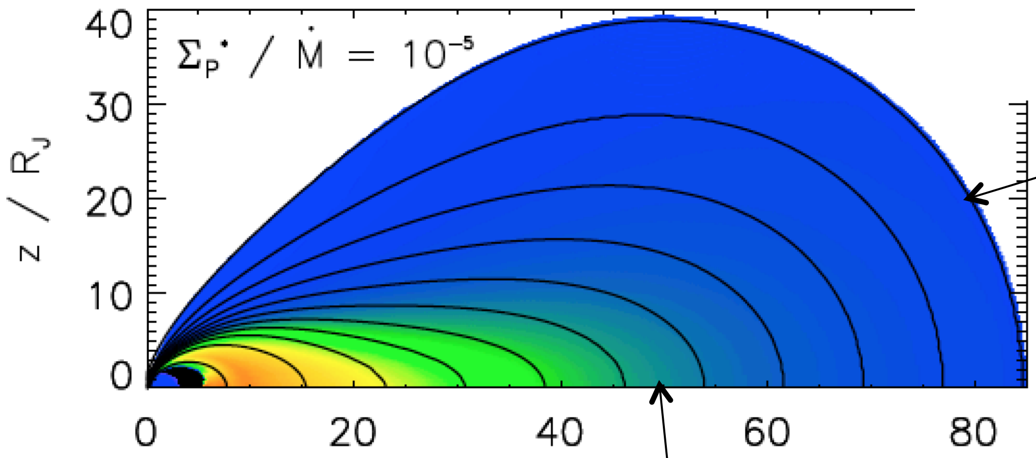
High mass loading

Medium mass loading

Low mass loading

Nichols 20

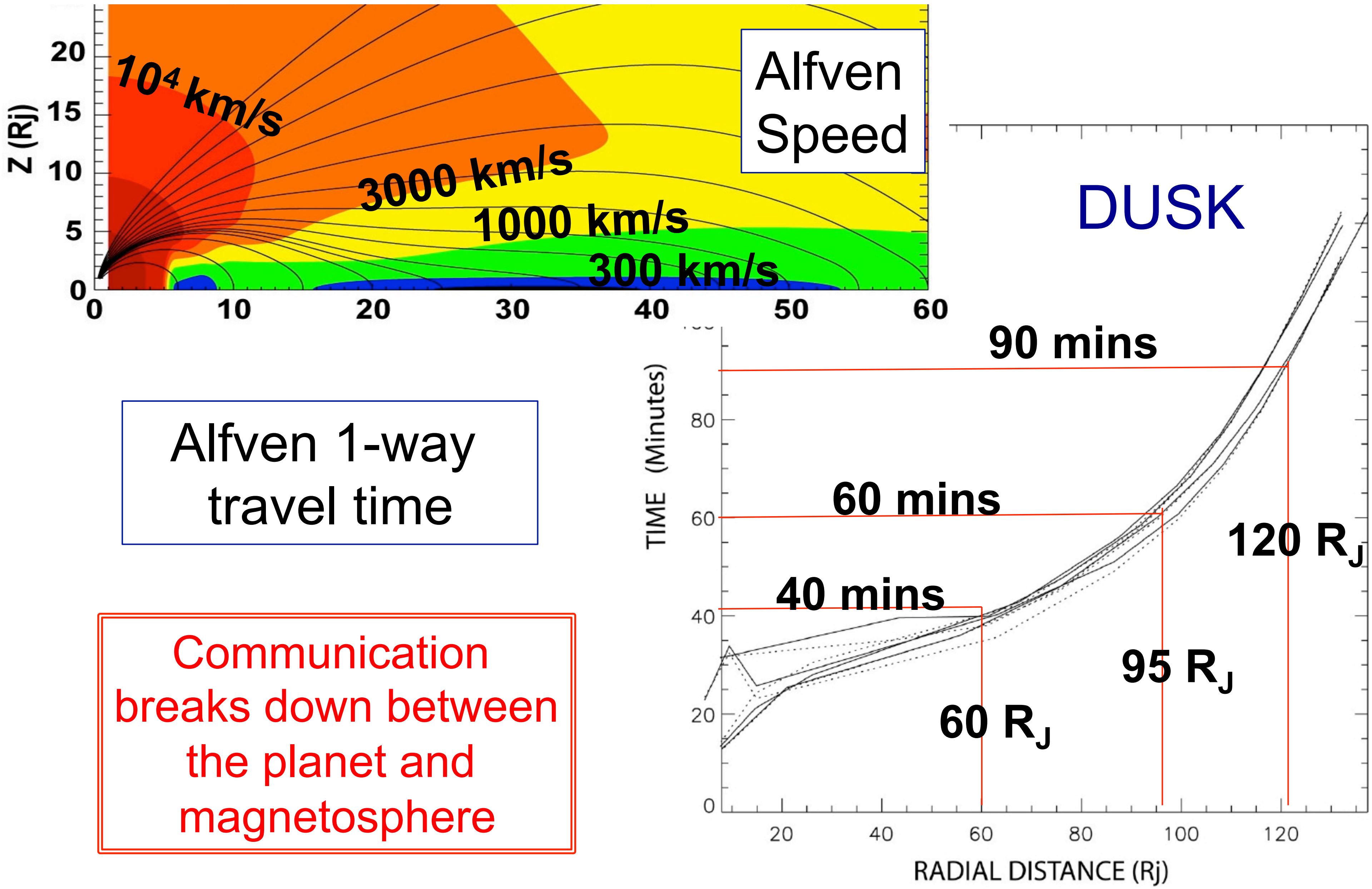
How is information transmitted along magnetic field lines?



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

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

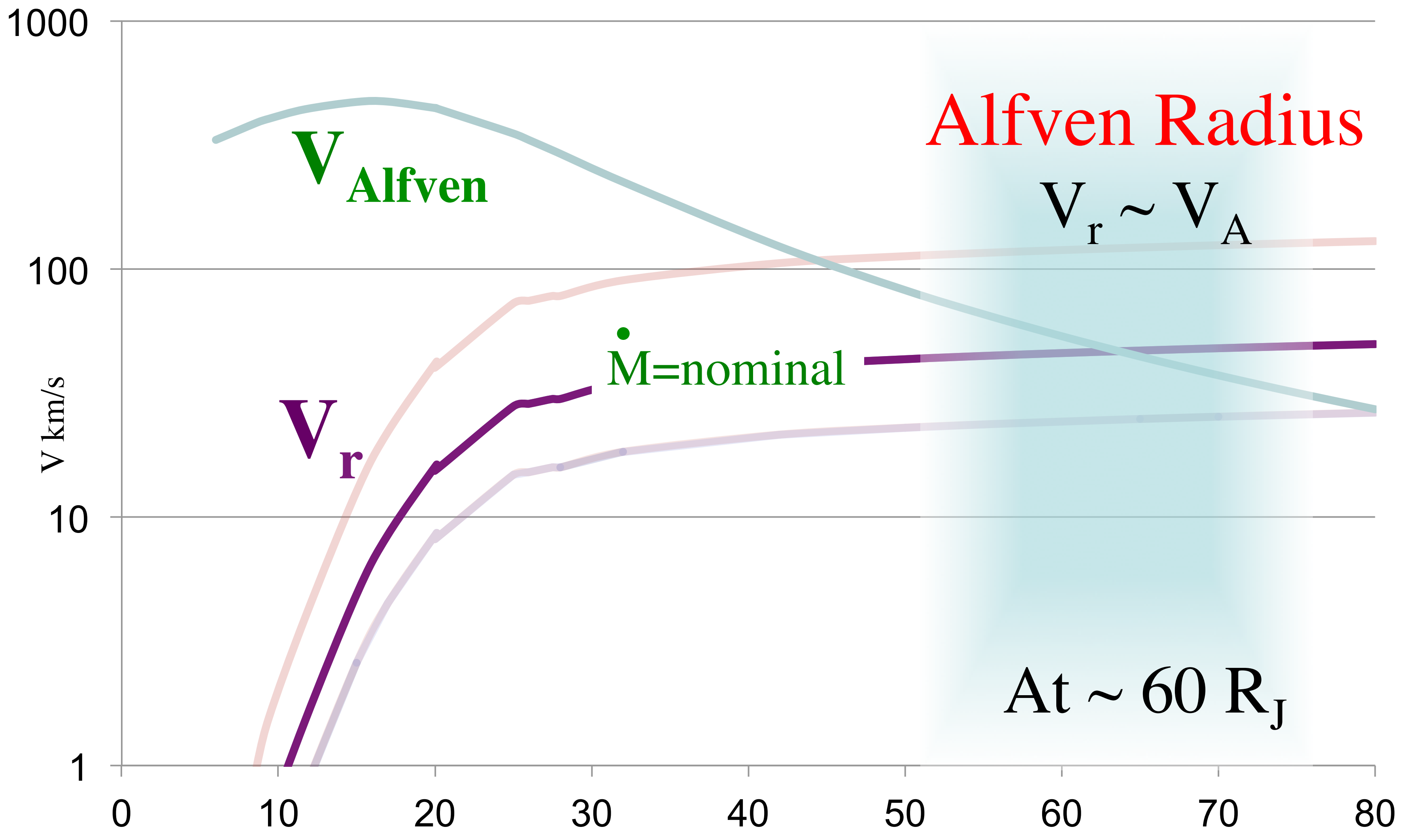
De-Coupling - 2



Alfven 1-way travel time

Communication breaks down between the planet and magnetosphere

De-Coupling - 3

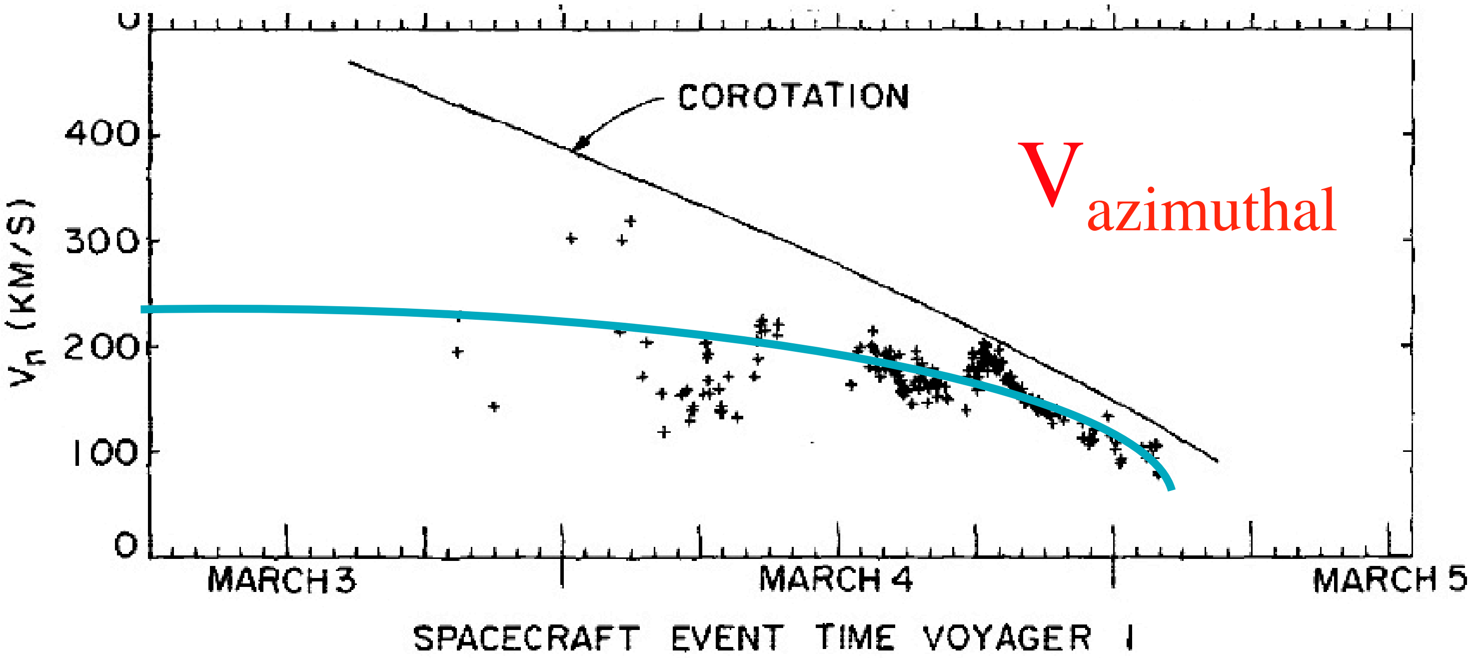


Alfven Radius

$V_r \sim V_A$

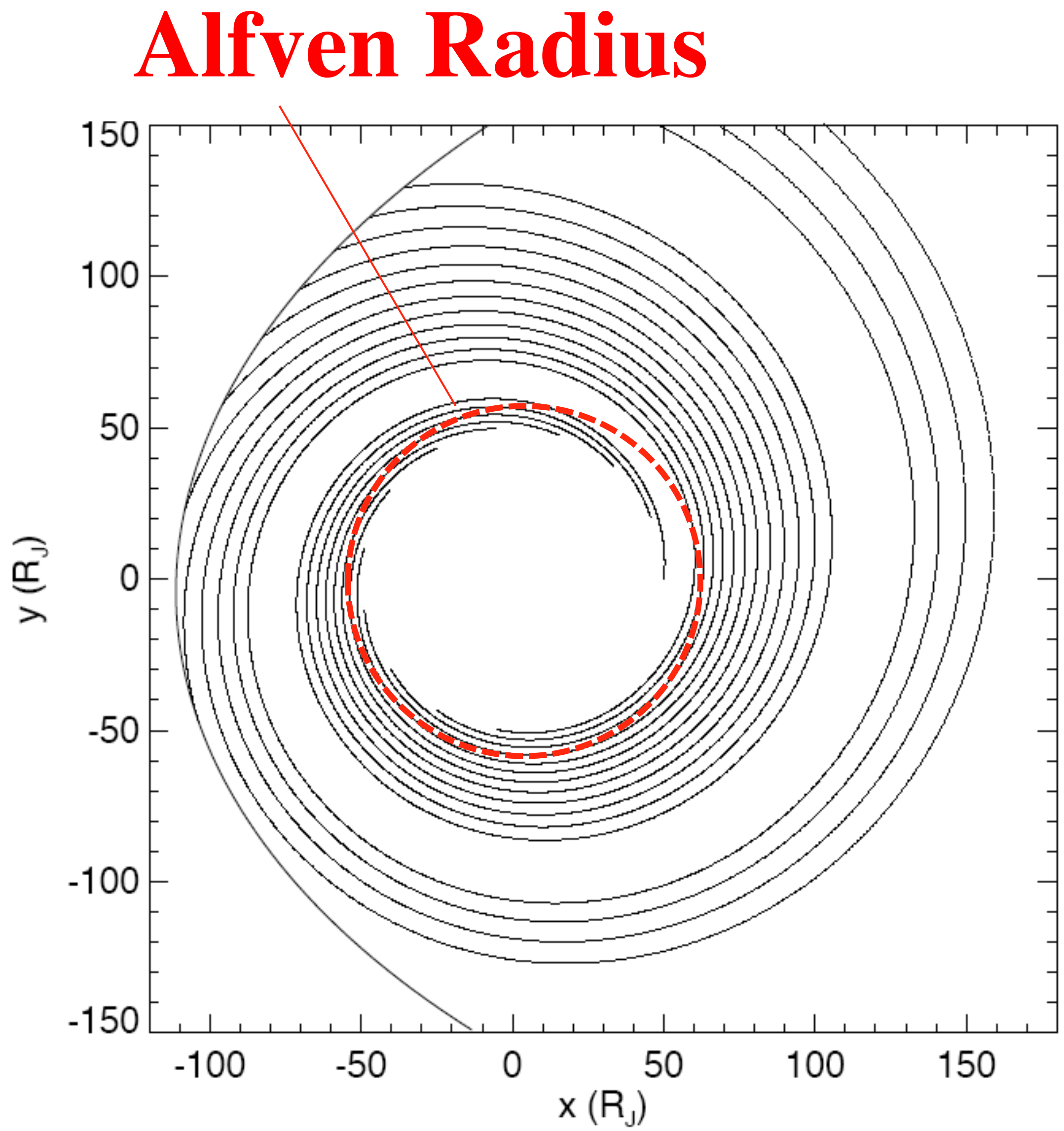
At ~ 60 R_J

Azimuthal Flow Profile



Combining V_r and $V_{azimuthal}$ we get….

Pattern of Net Momentum Flux



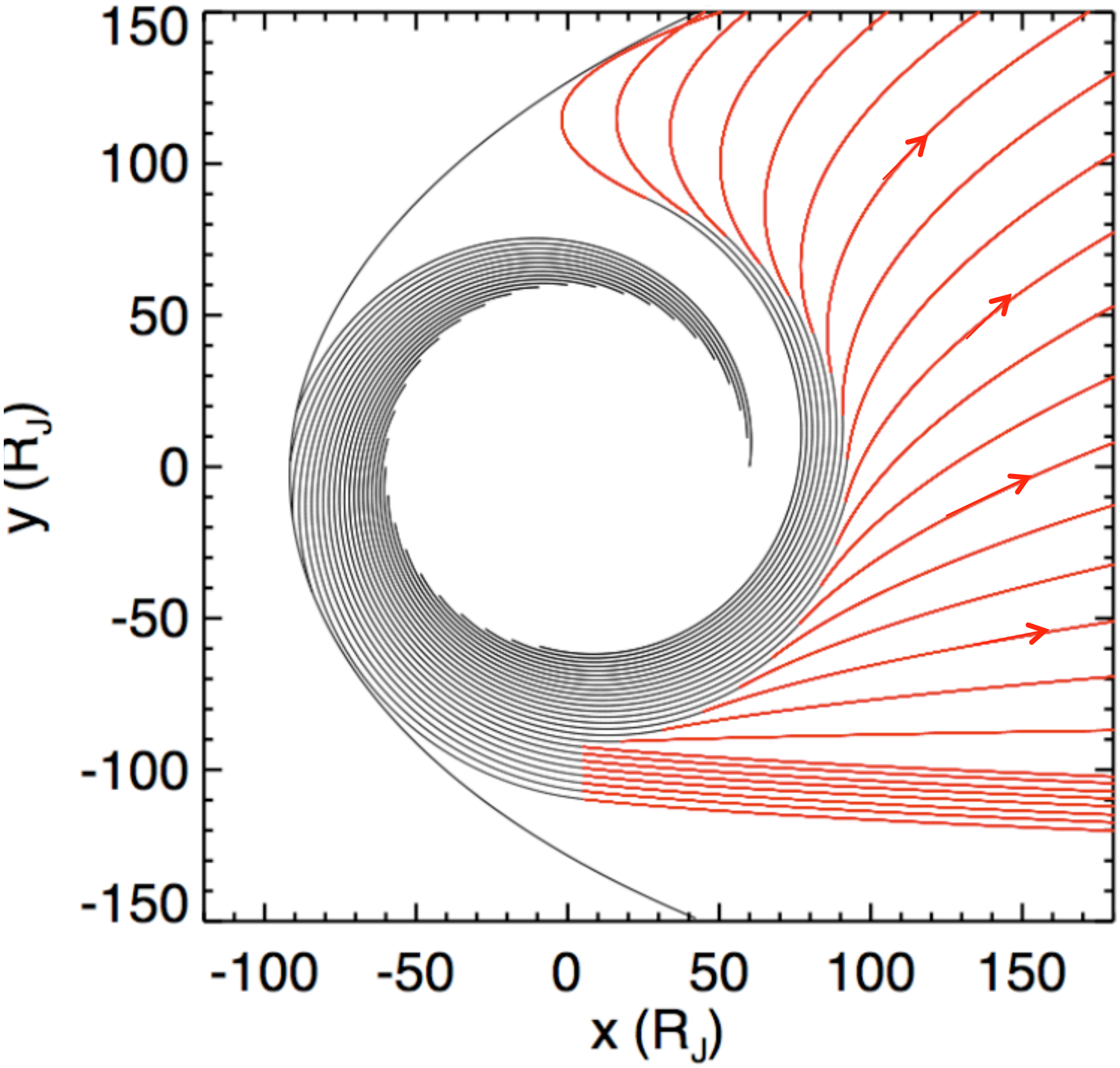
- Beyond ~60 R_J material spirals away from Jupiter in 10s of hours

- Radial transport is still diffusive: Centrifugally-driven fluxtube interchange

Solar Wind Stresses Overcome Rotation

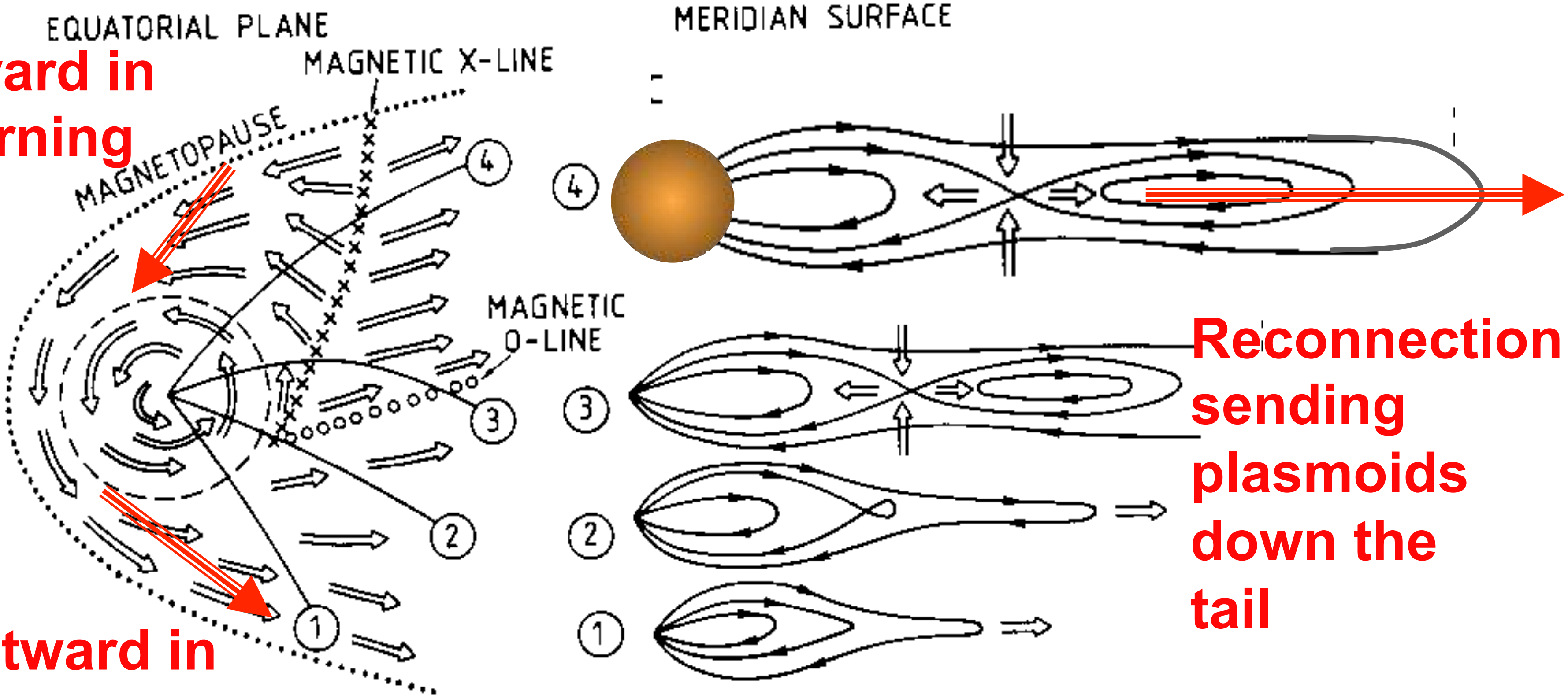
Add Maxwell stresses from solar wind interaction

Stresses from magnetic shear on boundary



Vasyliunas Cycle

Vasyliunas
Cowley et al.
Southwood & Kivelson



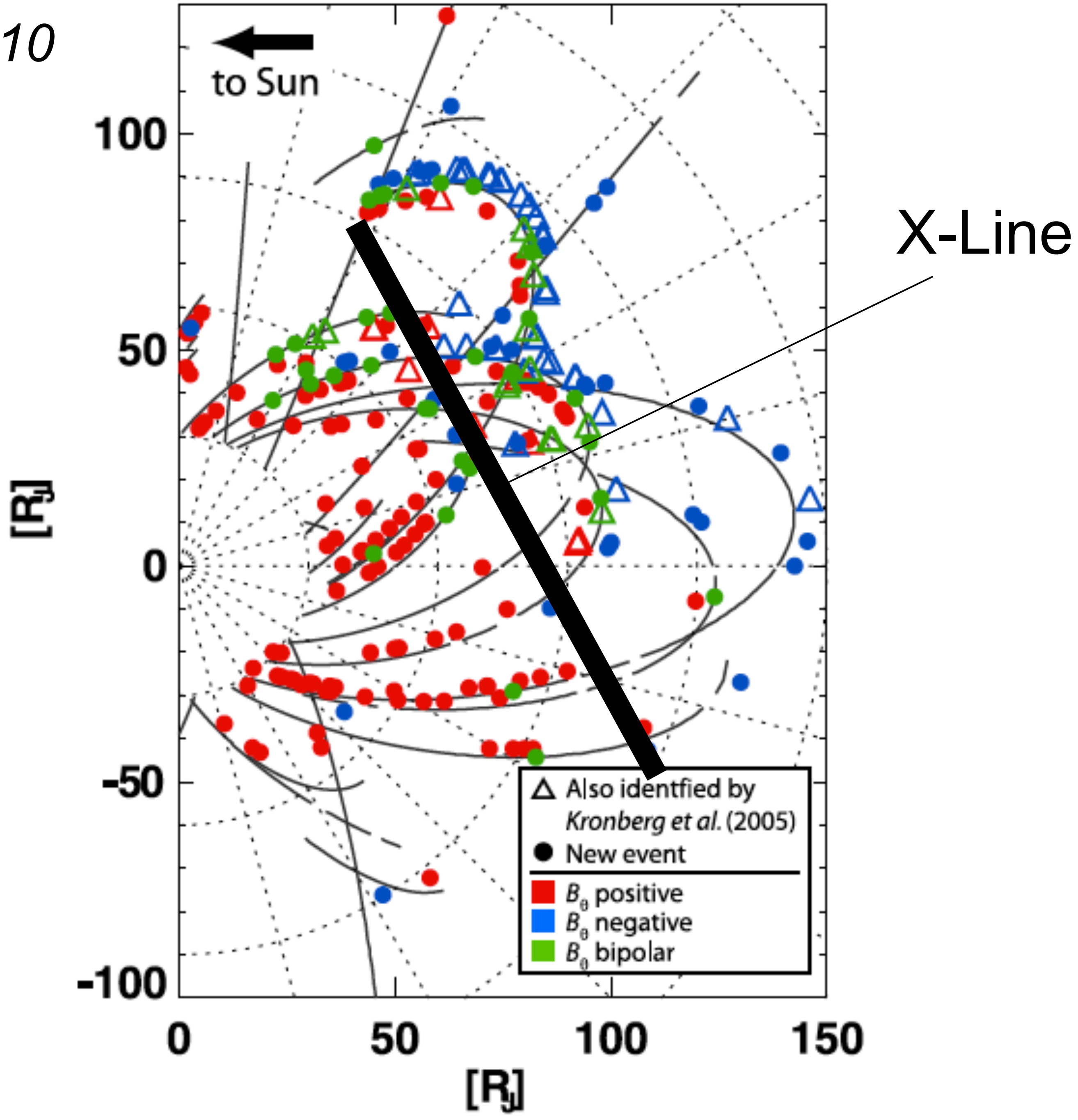
Inward in morning

Outward in afternoon

Reconnection sending plasmoids down the tail

Vogt et al. 2010

Observations of plasmoid events in *Galileo* data

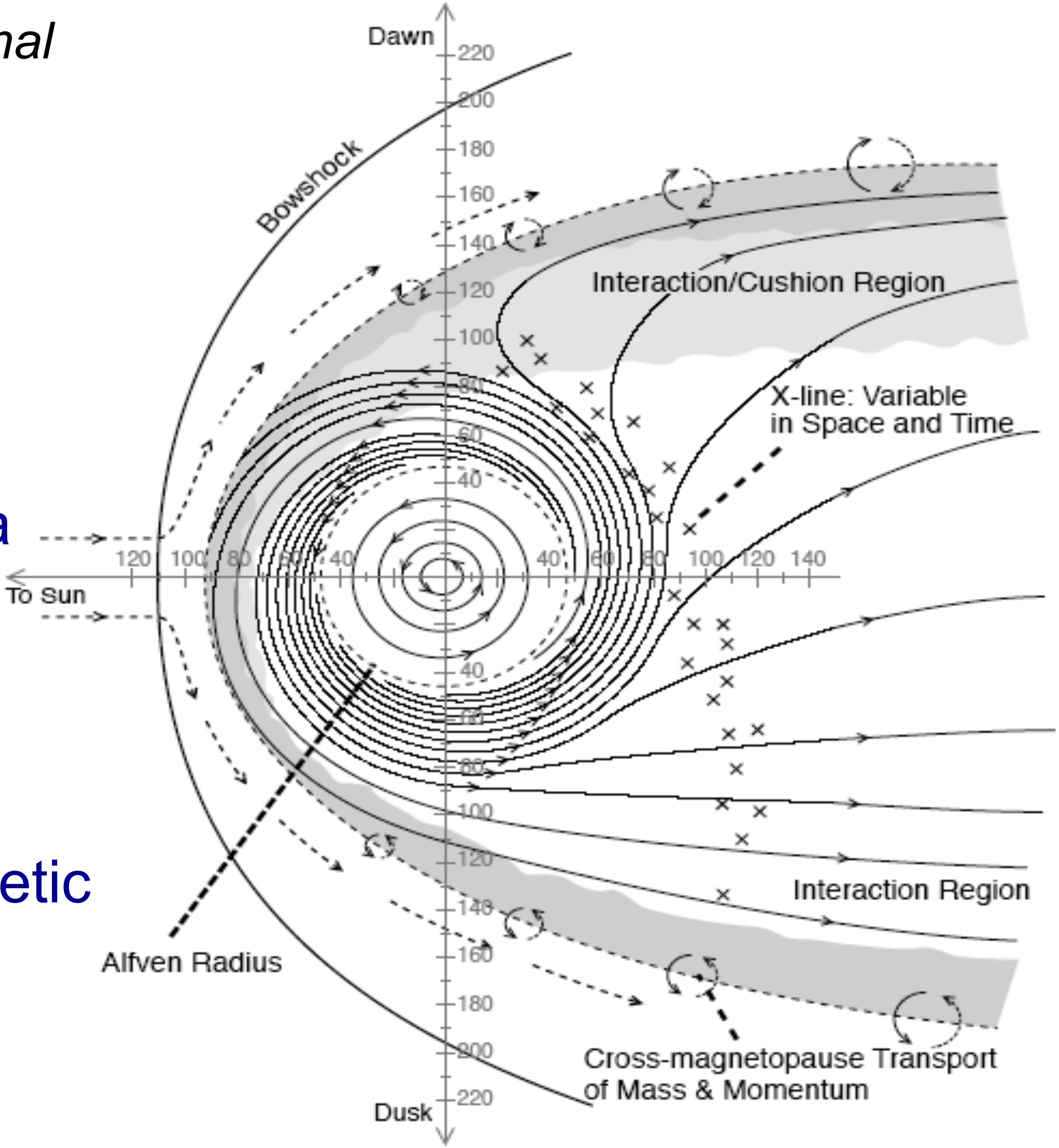


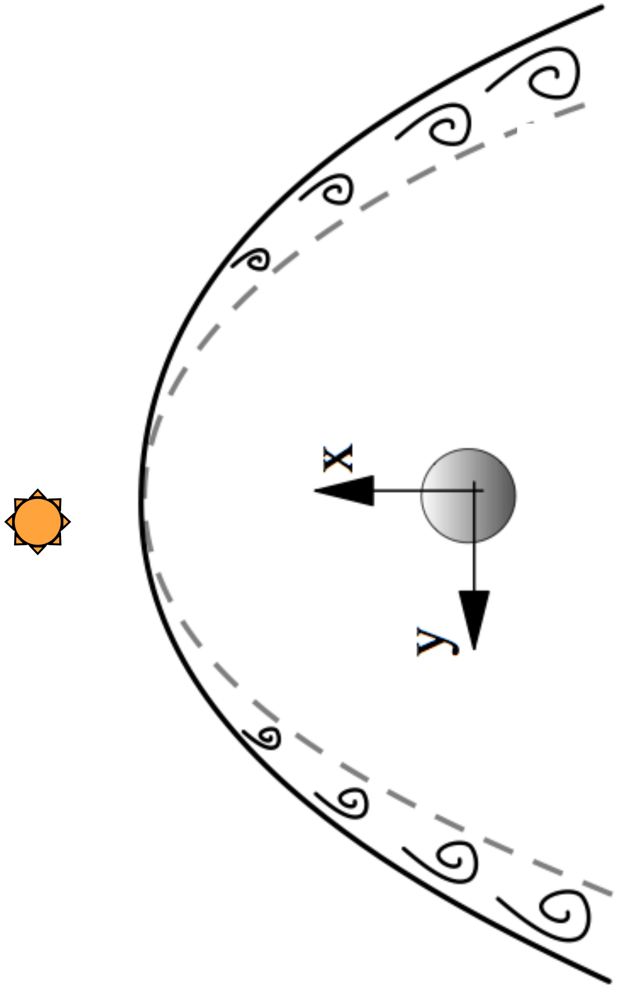
X-Line

Delamere & Bagenal (2011)

Solar wind interaction:

- More of a plasma-plasma interaction
- Less of an interaction between magnetic fields





Reconnection is reduced in the outer solar system:

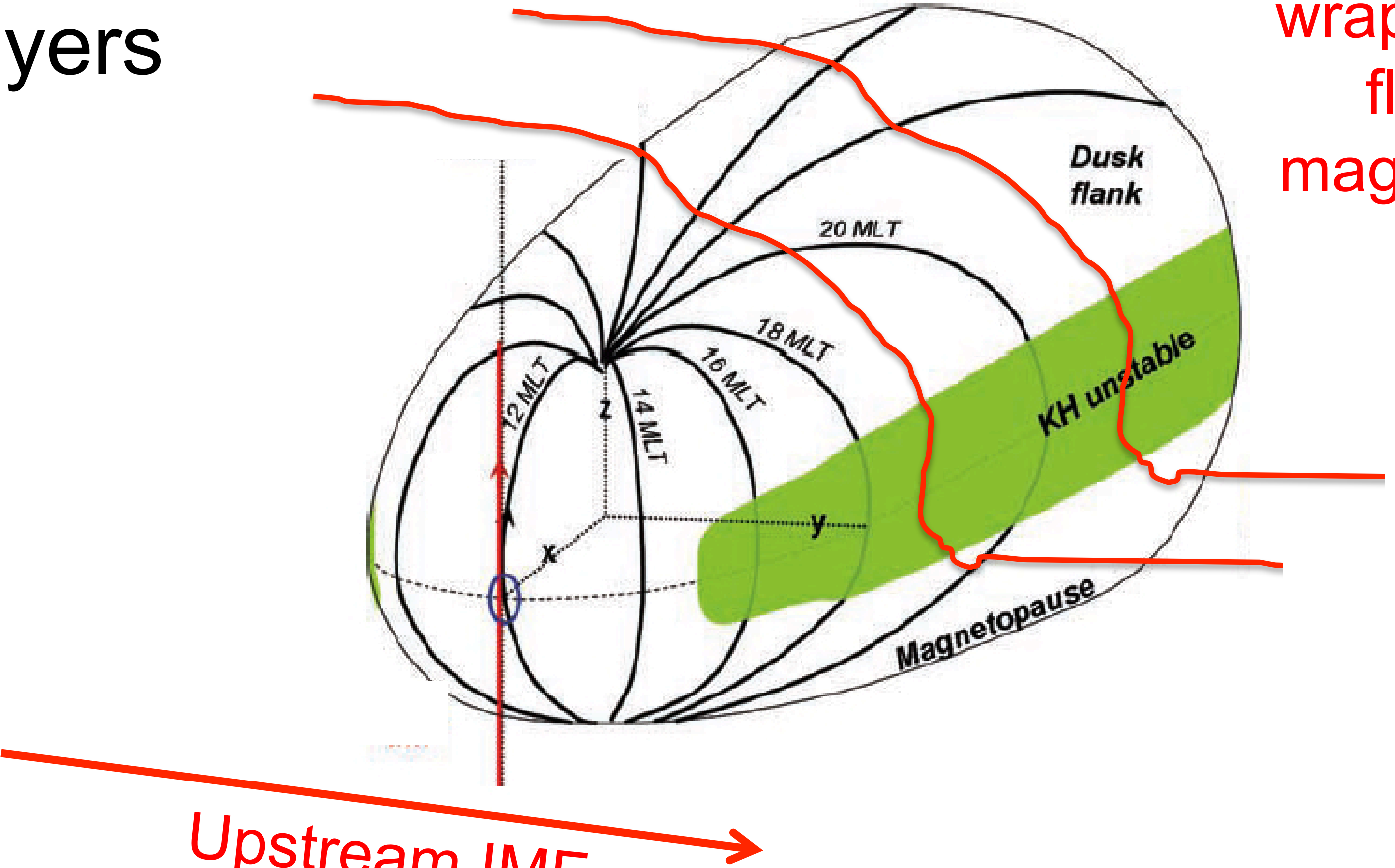
- weaker solar fields
- shear boundaries
- strong change in β

Can small-scale boundary-layer processes act like viscosity?

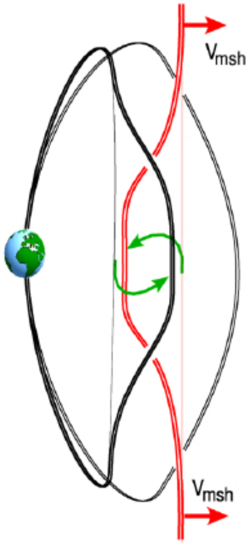
Shear-driven Kelvin-Helmholtz instability

Mass & momentum transport – boundary layers

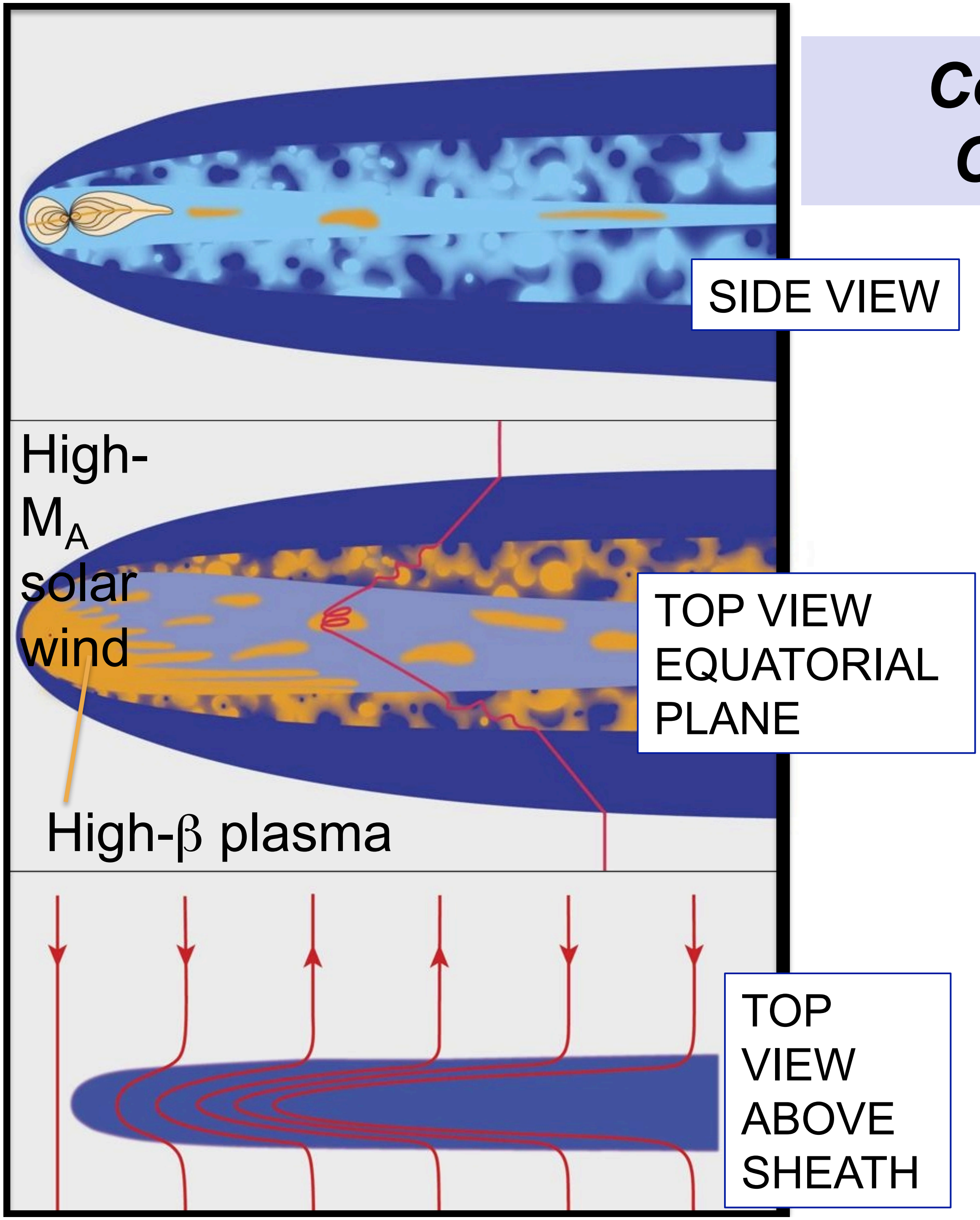
Upstream IMF wrapped around flattened magnetospause



Upstream IMF



Could Jupiter be a Colossal Comet?



- *Plasma-plasma interaction with magnetic field playing less of a role than at Earth*
- Solar wind hung up on the boundary layers
- Venus- or comet-like rather than field-controlled terrestrial tail.

Juno

Arrives at
Jupiter 2016!

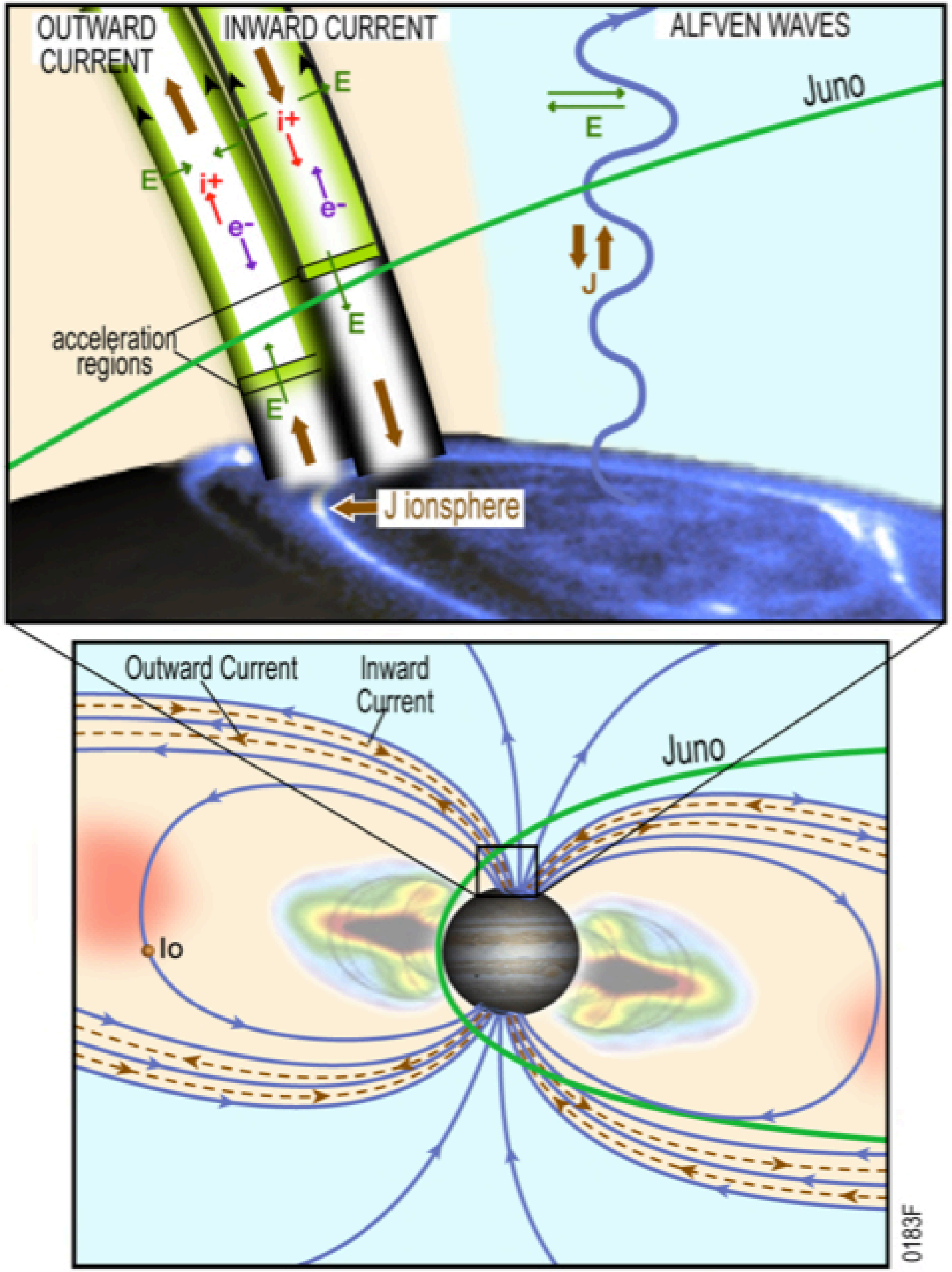
Polar Magnetosphere

Juno passes directly through auroral field lines

Measures particles precipitating into atmosphere creating aurora

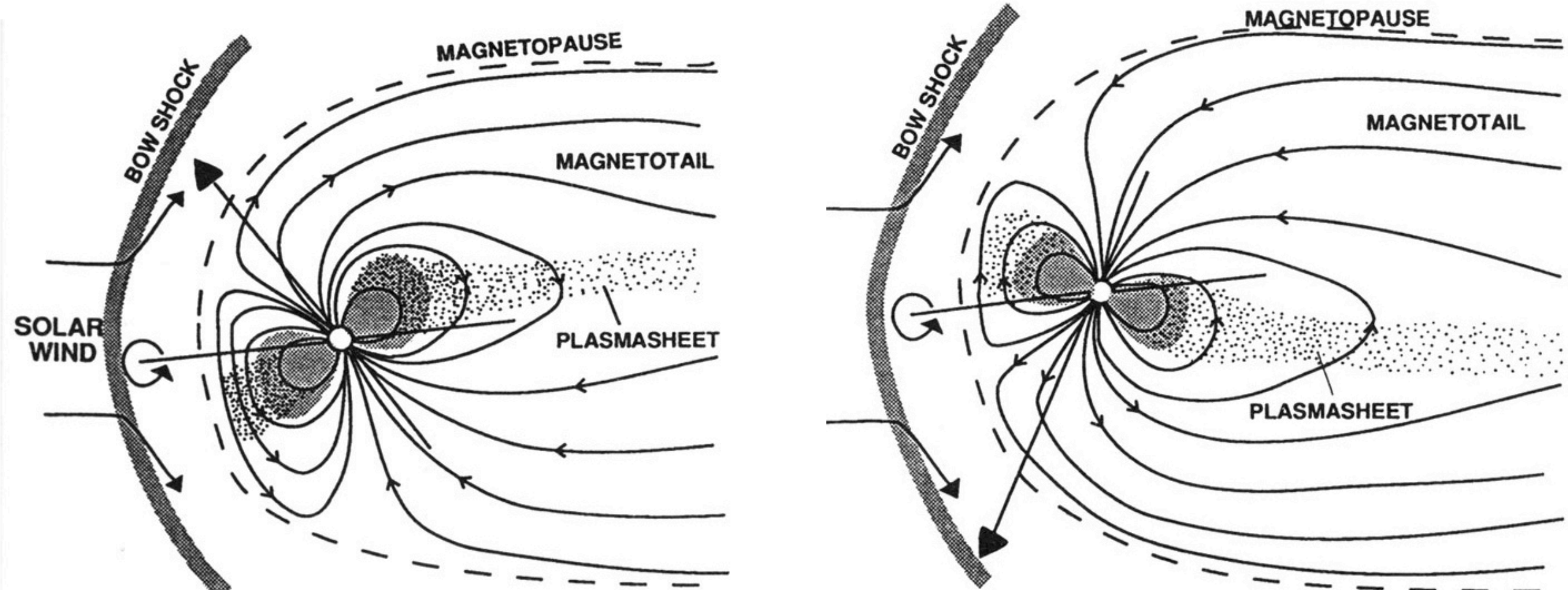
Plasma/radio waves reveal processes responsible for particle acceleration

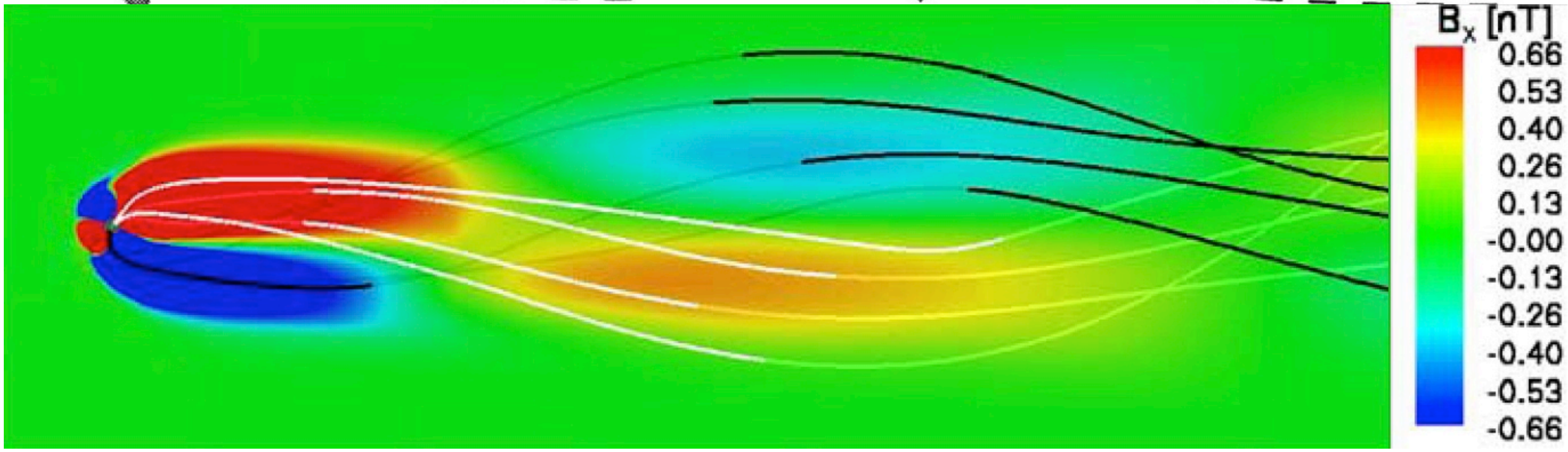
UV & IR images provides context for *in-situ* observations



Uranus

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

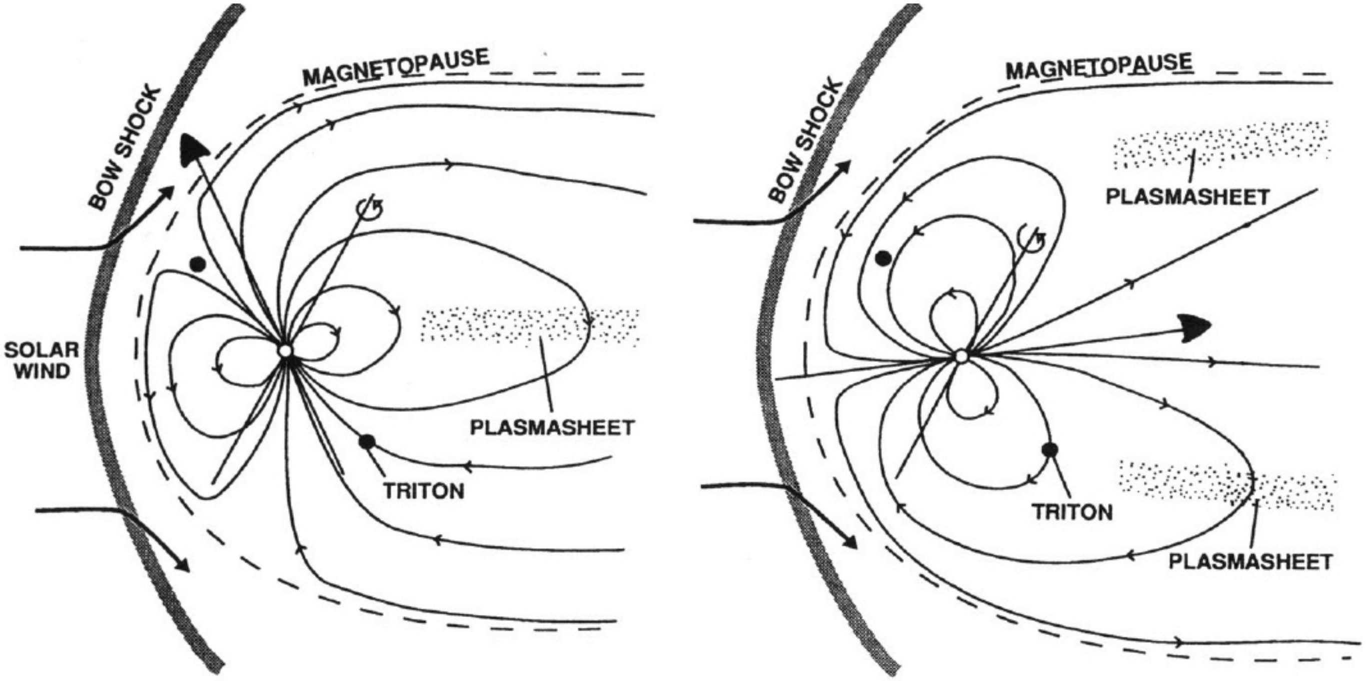


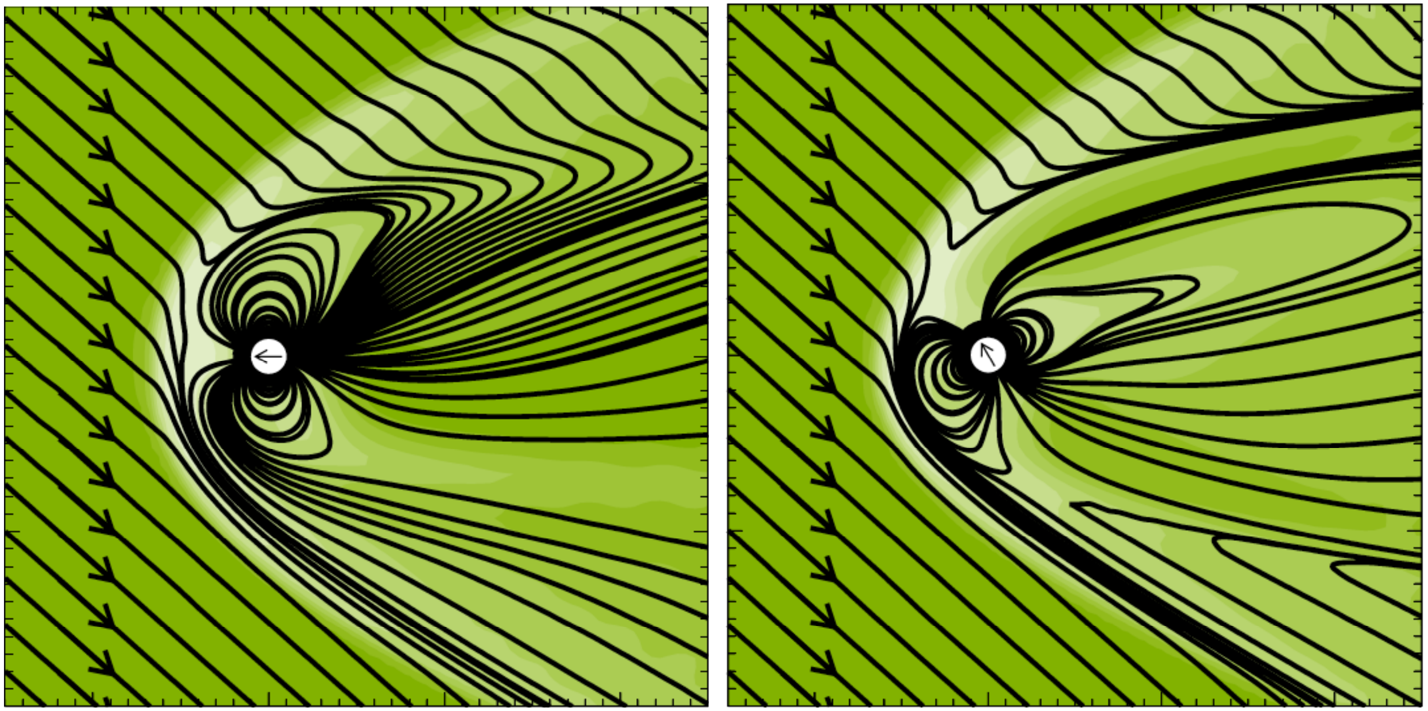


Toth et al.

Neptune

Similarly complex as Uranus



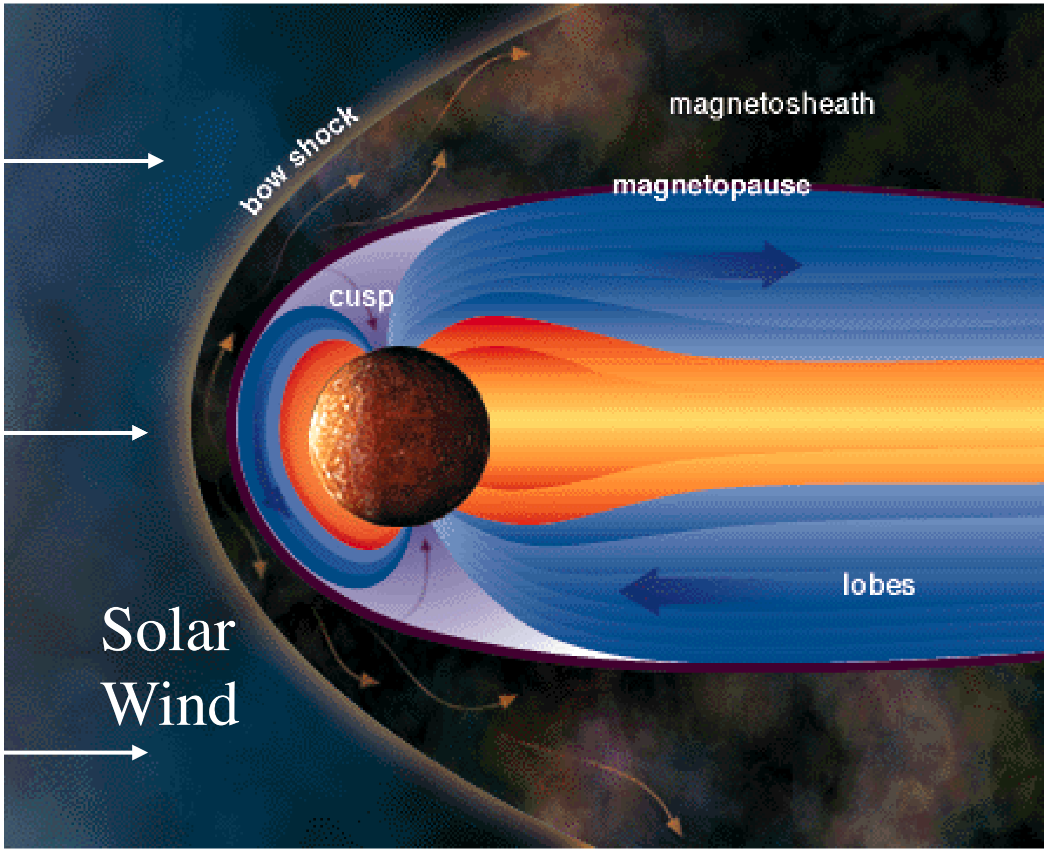


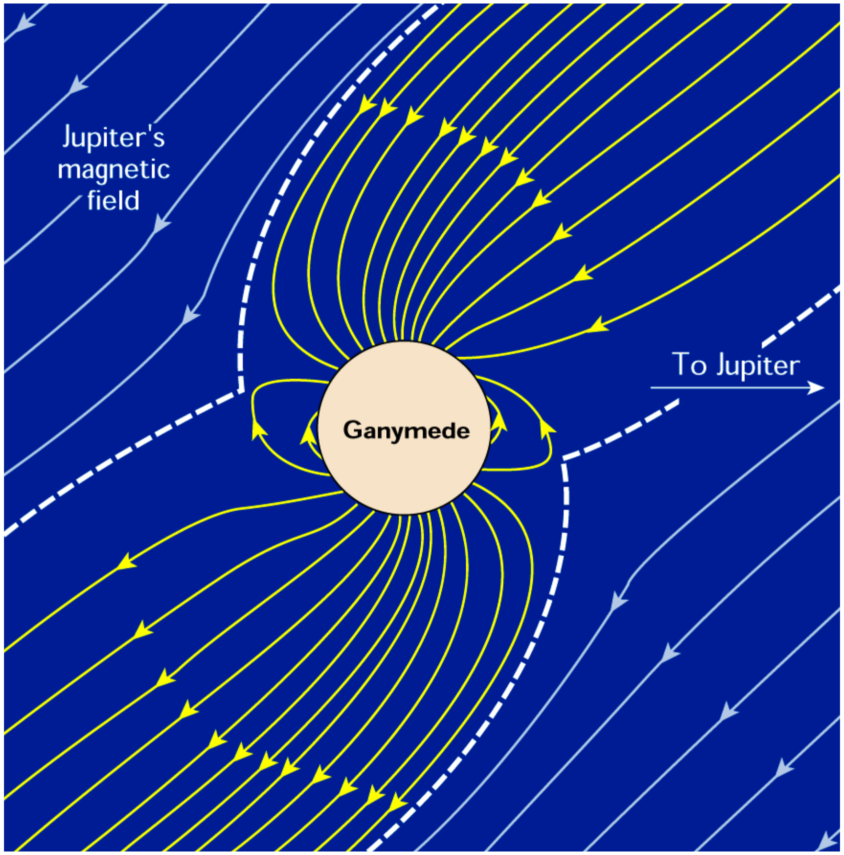
Zieger et al.

Mercury & Ganymede

Mercury - Magnetic field detected by *Mariner 10* in 1974

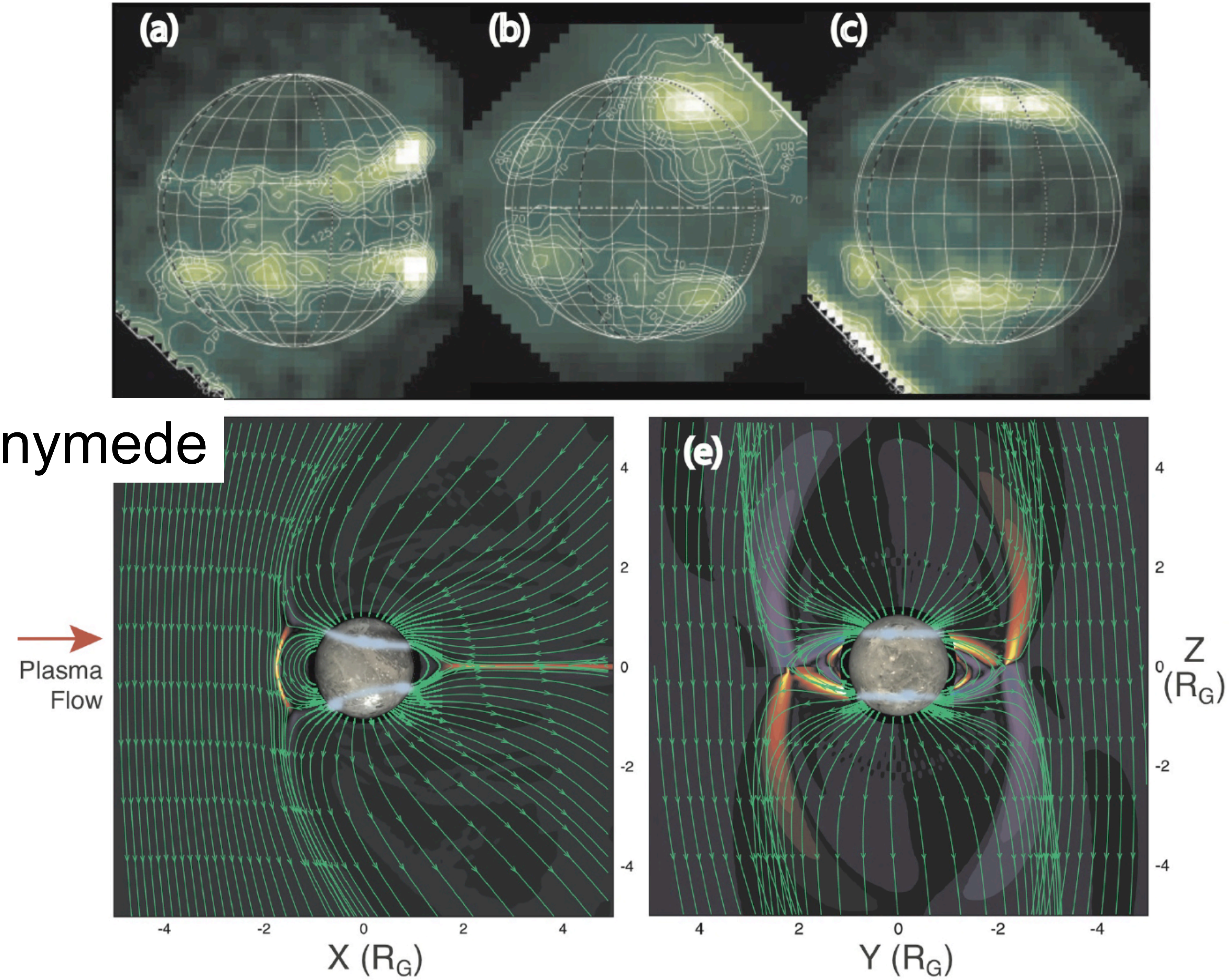
Ganymede - Magnetic field detected by *Galileo* in 1996



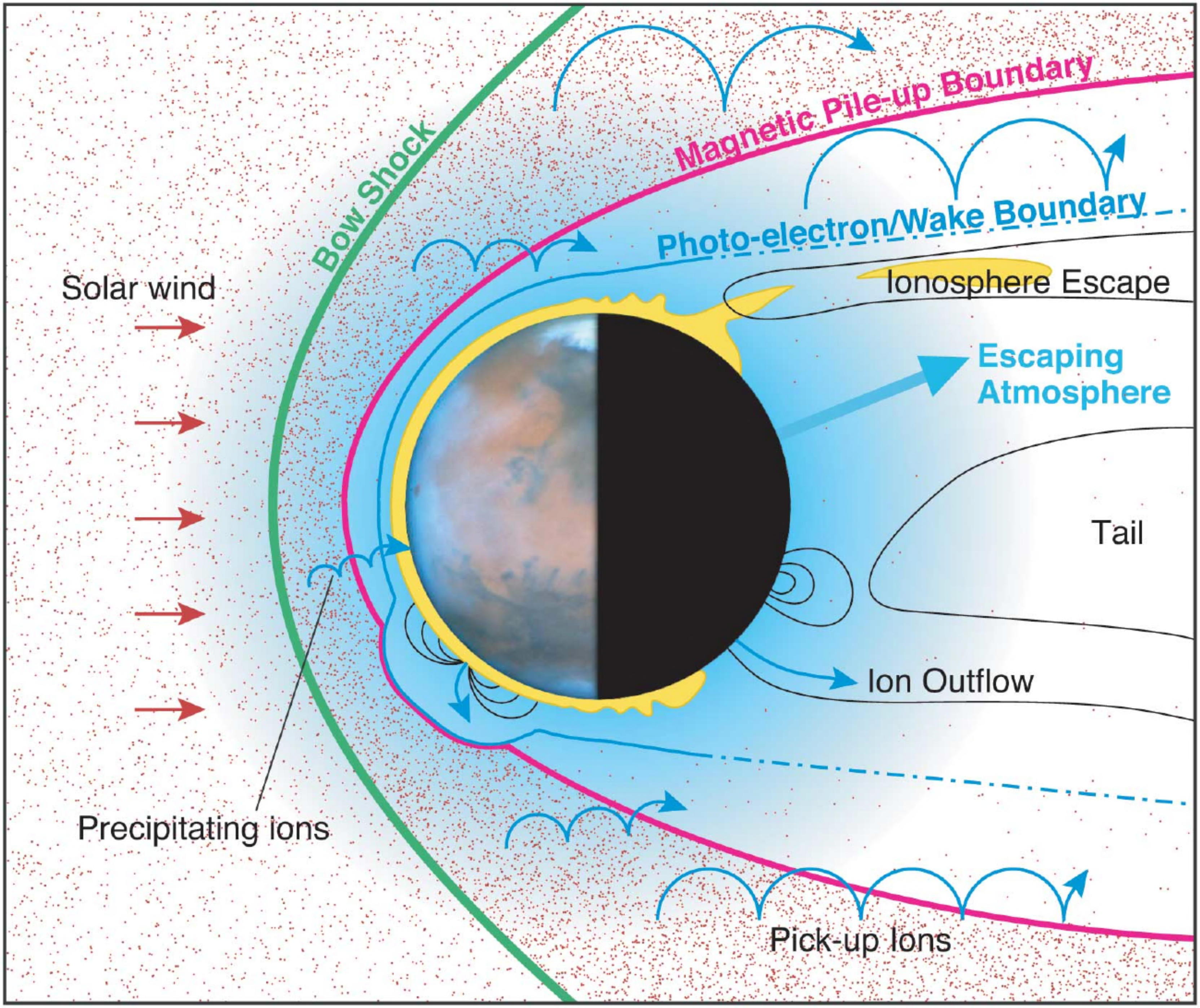


$B_{surface}$ ~ 1/100 Earth |———| **Diameter of Earth**

Ganymede

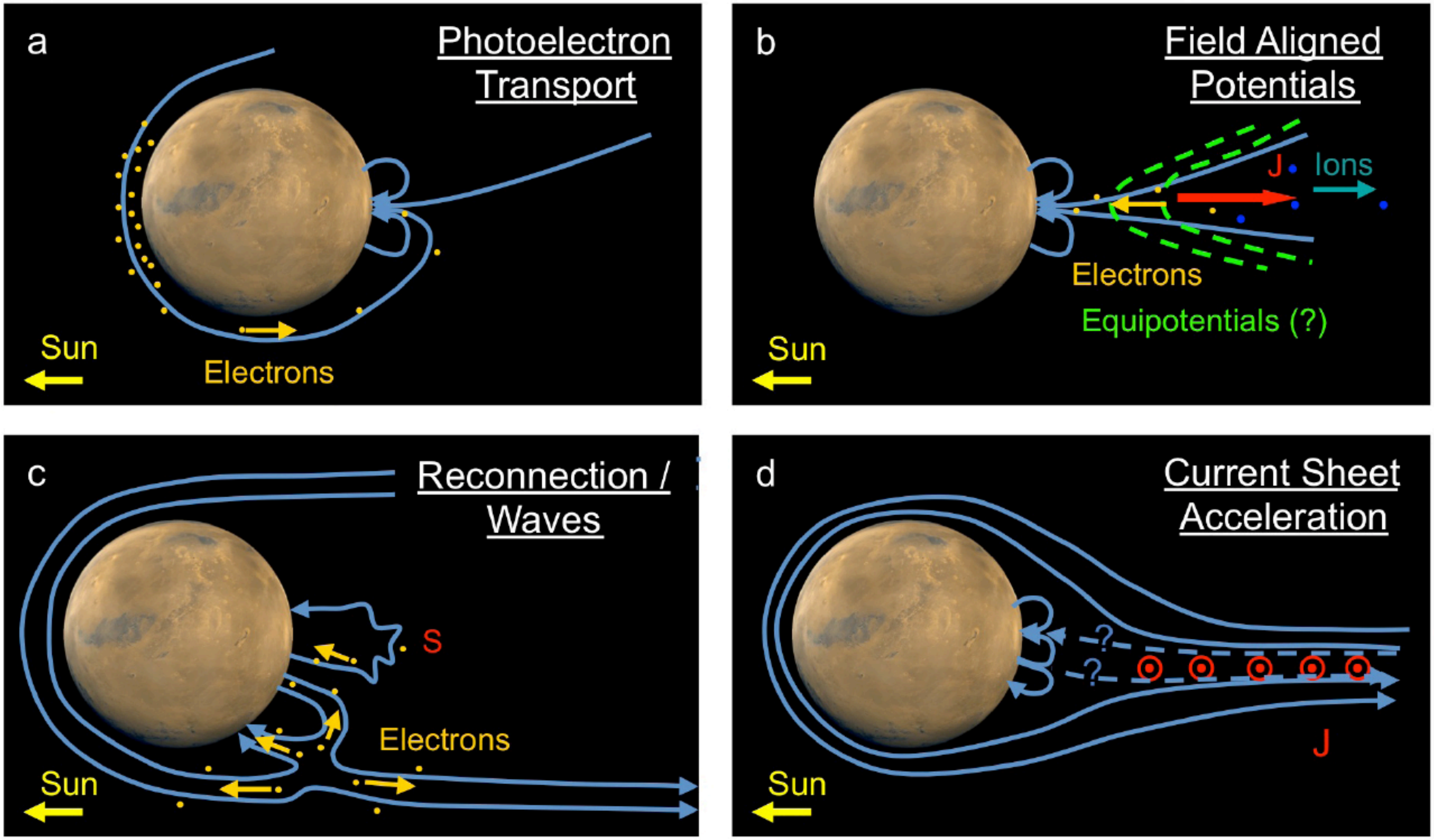


Mars


Bow Shock
Magnetic Pile-up Boundary
Photo-electron/Wake Boundary
Solar wind
Ionosphere Escape
Escaping Atmosphere
Tail
Ion Outflow
Precipitating Ions
Pick-up Ions

Brain & Helekas 2012

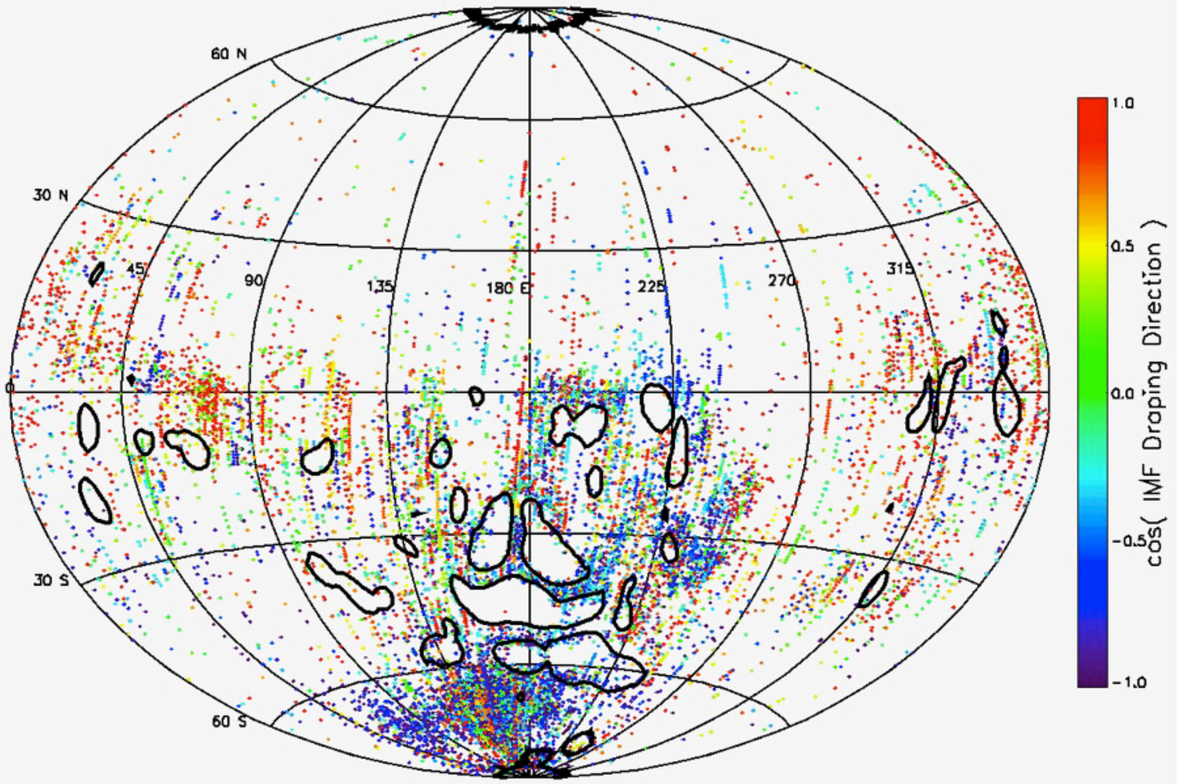
Possible mechanisms for Mars' aurora

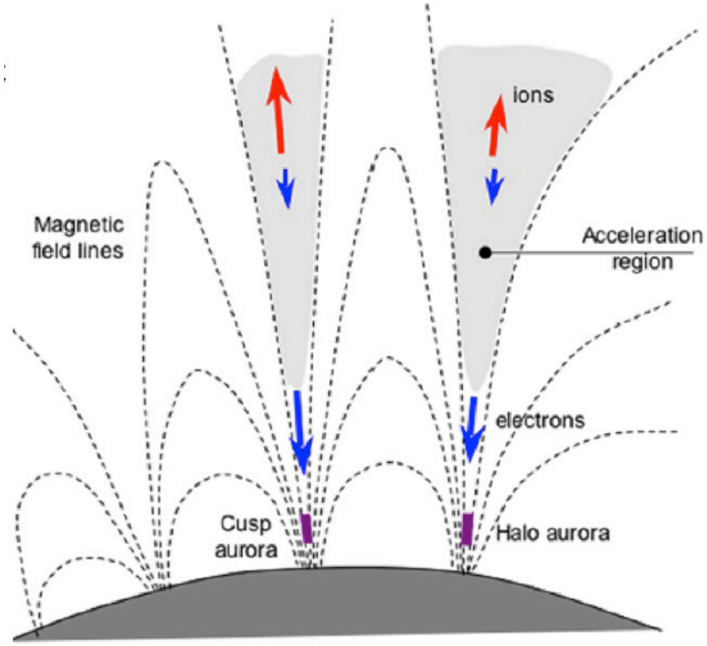


Total auroral precipitated power ~mW m^{-2}

Brain & Helekas 2012

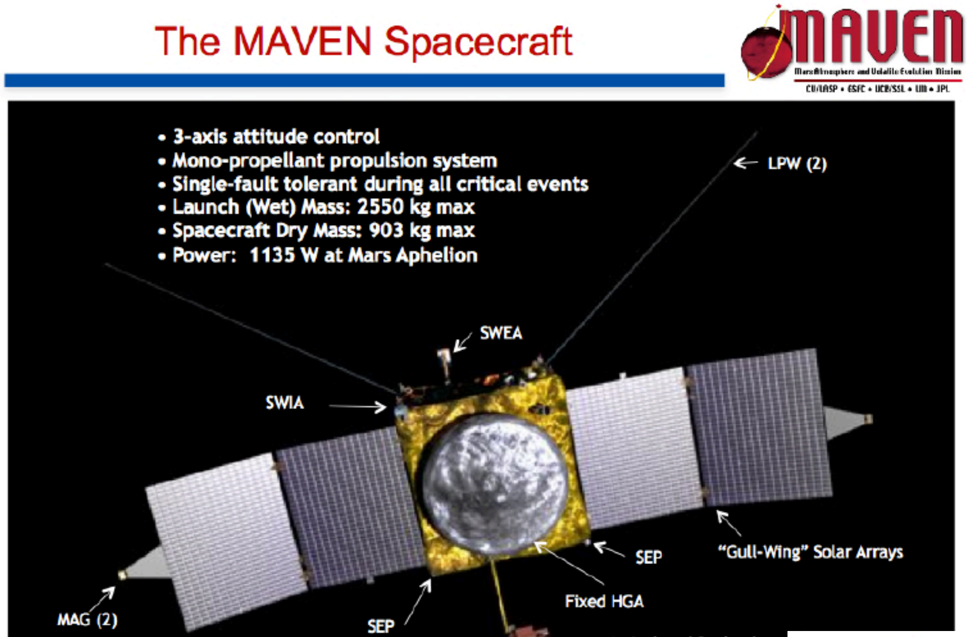
Electron fluxes onto Mars' atmosphere – focussed by magnetic fields





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

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

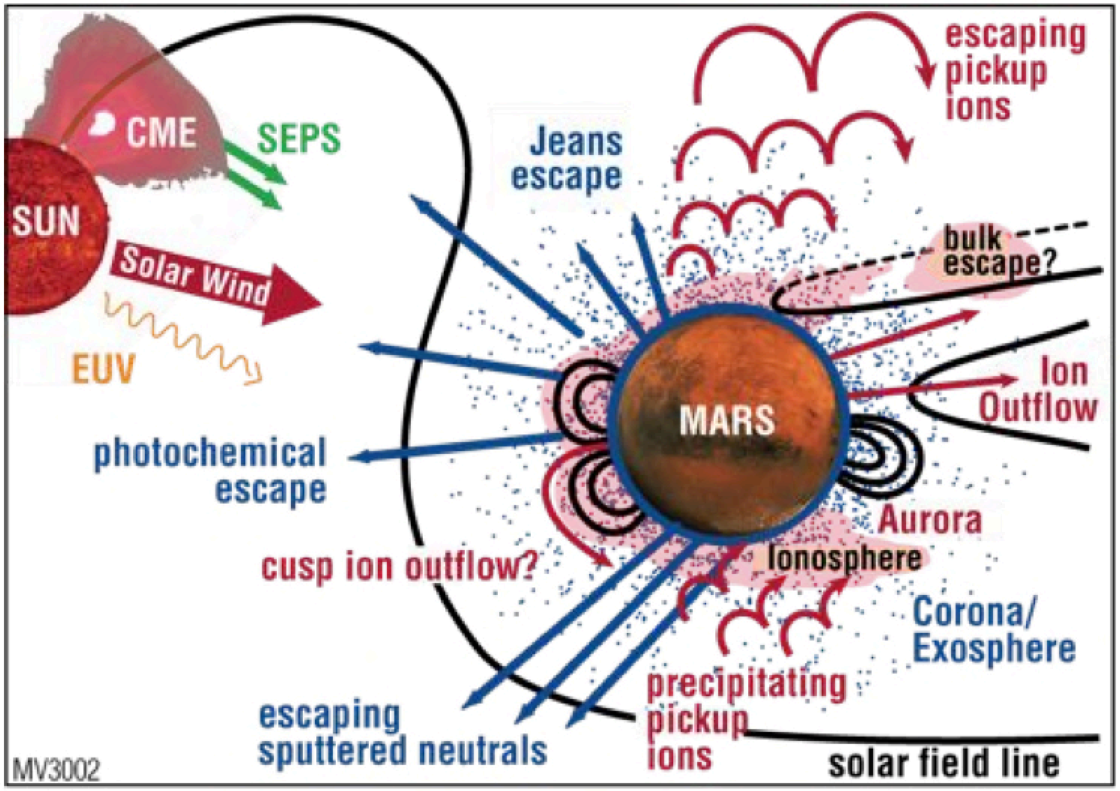


The MAVEN Spacecraft

- 3-axis attitude control
- Mono-propellant propulsion system
- Single-fault tolerant during all critical events
- Launch (Wet) Mass: 2550 kg max
- Spacecraft Dry Mass: 903 kg max
- Power: 1135 W at Mars Aphelion

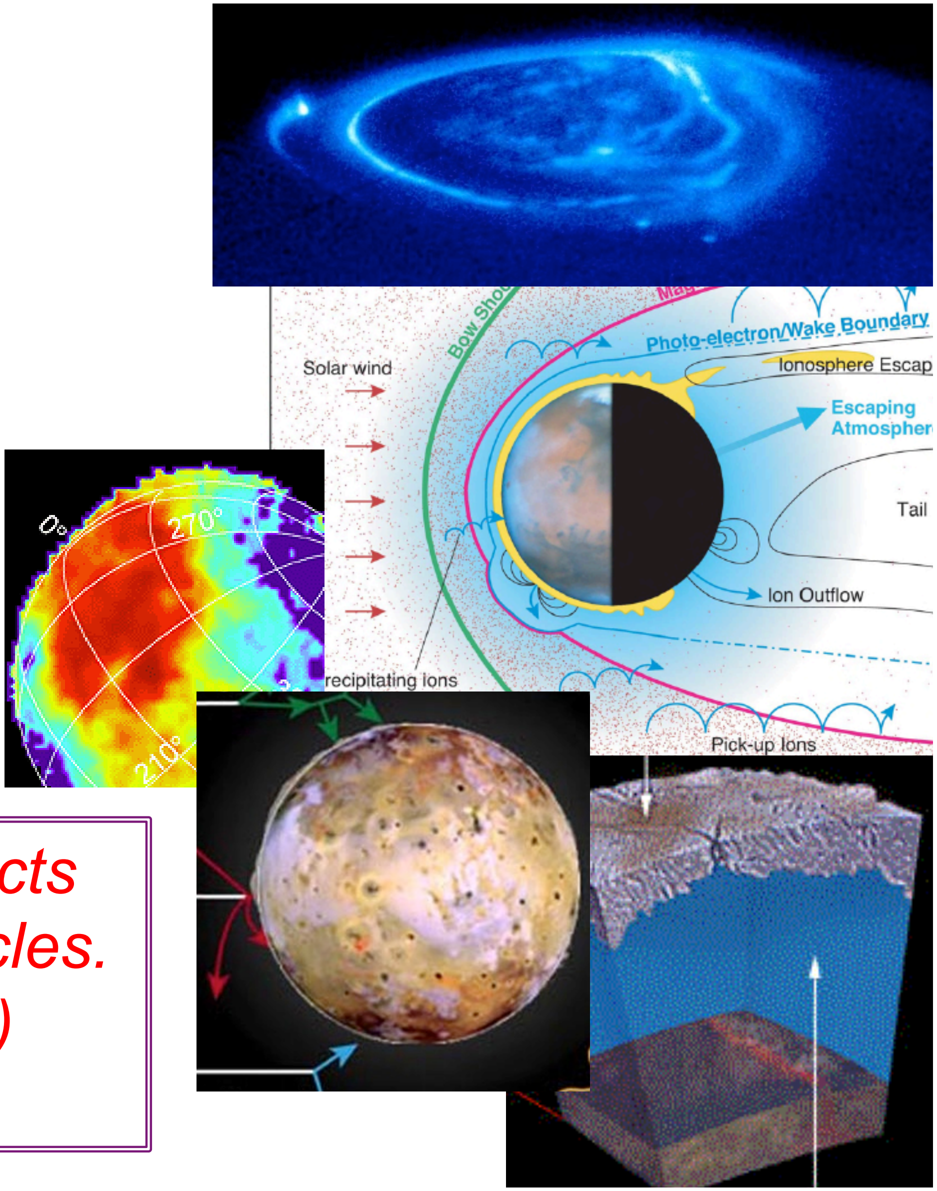
MAVEN:
- Launch Nov. 2013
- Orbits Mars Sept. 2014-2016
- PI Bruce Jakosky
  U of Colorado

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



How Magnetic Fields Could Play a Role in Exoplanet Atmospheres

- 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

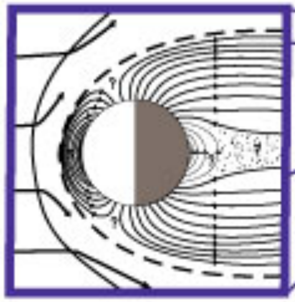


Bottom line: Atmosphere protects biota from nasty energetic particles. The magnetosphere (mostly) protects the atmosphere.

Planetary Magnetospheres

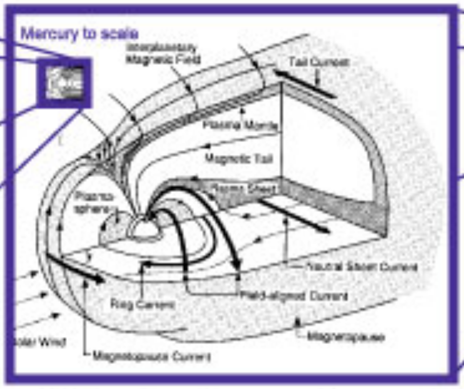
See vol. III ch. 7 & vol. I ch. 13

MERCURY:
- Small
- Minute timescales
- Solar wind dominated



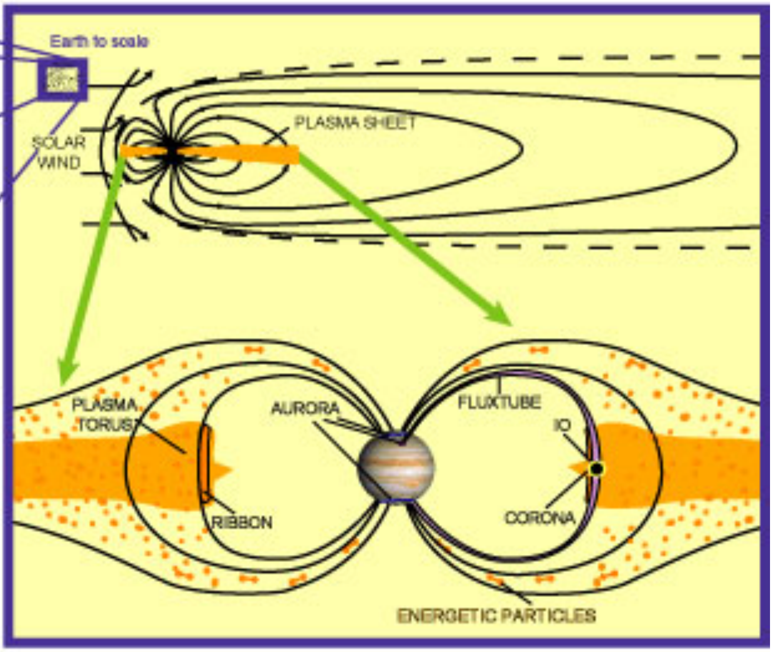
Mariner, MESSENGER

EARTH:
- Intermediate
- Hour timescales
- Solar wind driven



~100 missions since 1957 e.g. Polar, Geotail, FAST, SAMPLEX, Cluster

JUPITER:
- Giant
- Timescales - minutes to months?
- Rotationally driven - solar wind triggered?



Pioneer, Voyager, Ulysses, Galileo, Cassini

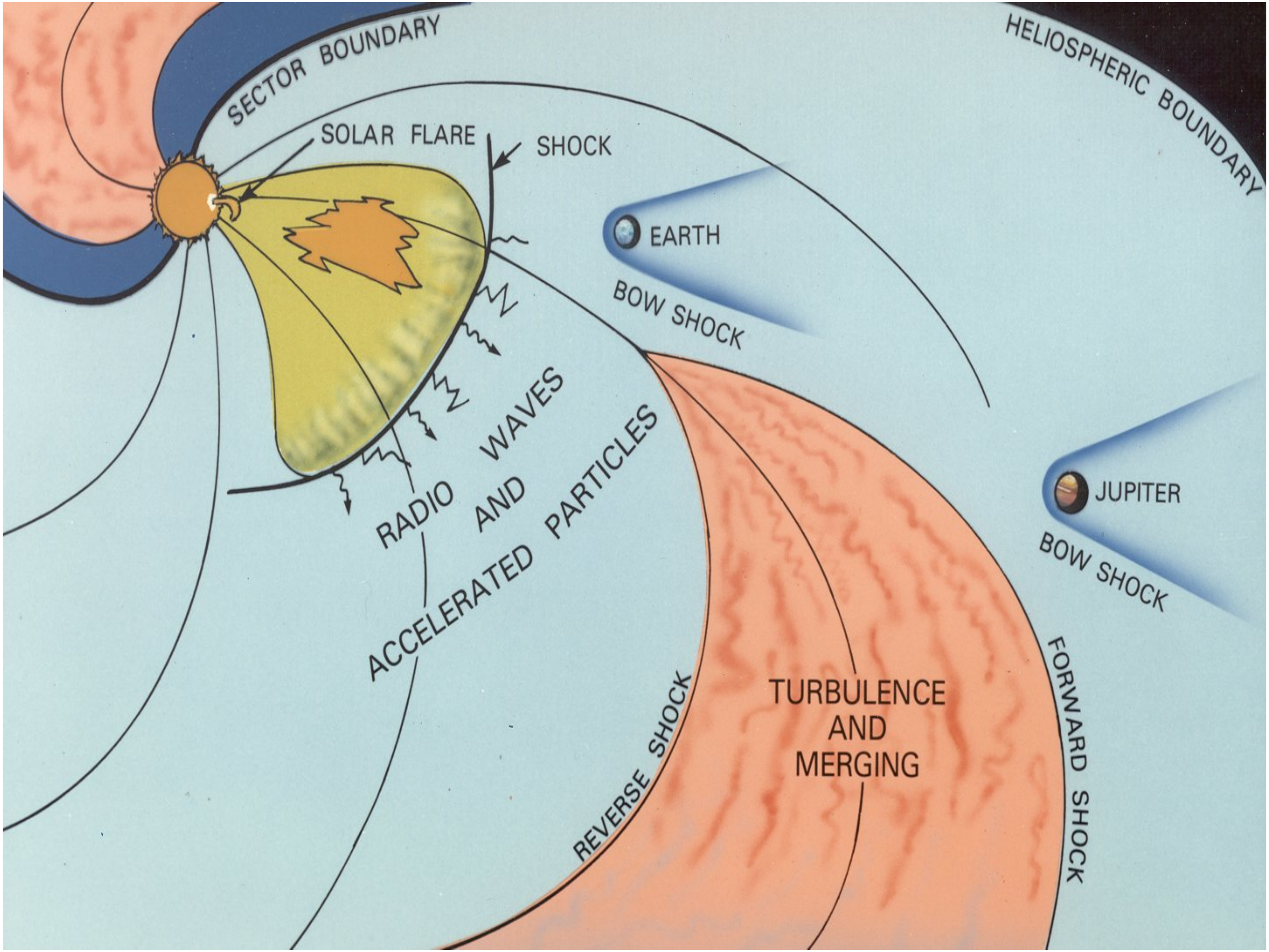
Testing our understanding of Sun-Earth connections through application to other planetary systems

Summary

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

Stay tuned…. *MAVEN mission to Mars*

Juno mission to Jupiter!


SECTOR BOUNDARY
HELIOSPHERIC BOUNDARY
SOLAR FLARE
SHOCK
EARTH
BOW SHOCK
RADIO
AND
WAVES
ACCELERATED
PARTICLES
JUPITER
BOW SHOCK
REVERSE SHOCK
TURBULENCE
AND
MERGING
FORWARD SHOCK