Planetary magnetic fields and magnetospheres

Philippe Zarka

LESIA, Observatoire de Paris - CNRS, France
philippe.zarka@obspm.fr

- Planetary Magnetic Fields
- Magnetospheric structure
- Magnetospheric dynamics
- Electromagnetic emissions
- Exoplanets

- Planetary Magnetic Fields
- Magnetospheric structure
- Magnetospheric dynamics
- Electromagnetic emissions
- Exoplanets

- $\nabla \times B = 0$ out of the sources (above the planetary surface)

  $\Rightarrow B = -\nabla\psi$ (ψ = scalar potential)

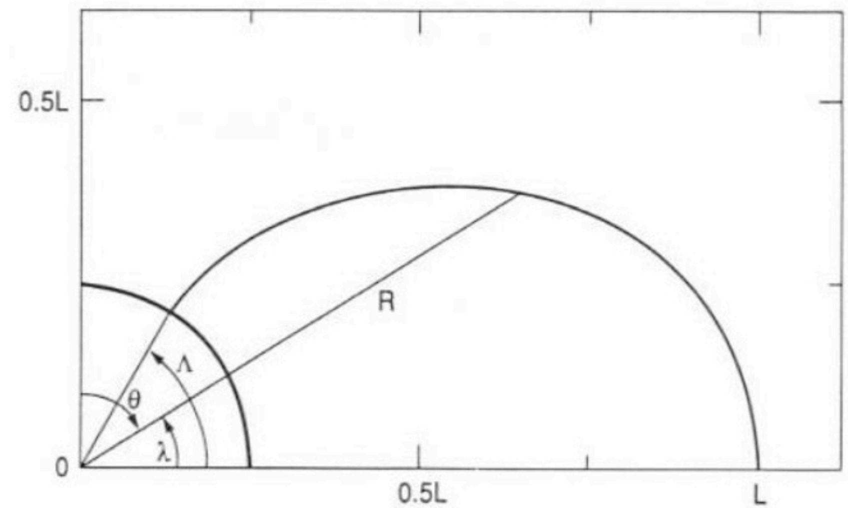
- Dipolar approximation :

  $\psi = M.r/r^3 = M \cos\theta / r^2$

  $\Rightarrow$ B : $B_r = -\partial\psi/\partial r = 2 M \cos\theta / r^3$

  $B_\theta = -1/r\ \partial\psi/\partial\theta = M \sin\theta / r^3$

  $B_\phi = 0$



$|B| = M/r^3 (1+3\cos^2\theta)^{1/2} = B_e/L^3 (1+3\cos^2\theta)^{1/2}$

with $B_e = M/R_P^3$ = field intensity at the equatorial surface and $r = L R_P$

Equation of a dipolar field line : $r = L \sin^2\theta$

- Multipolar development in spherical harmonics :

$$\psi = R_P \Sigma_{n=1\rightarrow\infty} \ (R_P/r)^{n+1} S_i^n \ + (r/R_P)^n S_e^n$$

S_i^n = internal sources (currents)

S_e^n = external sources (magnetopause currents, equatorial current disc ...)

with

$$S_i^n = \Sigma_{m=0\rightarrow n} P_n^m(\cos\theta) [g_n^m \cos m\varphi + h_n^m \sin m\varphi]$$

$$S_e^n = \Sigma_{m=0\rightarrow n} P_n^m(\cos\theta) [G_n^m \cos m\varphi + H_n^m \sin m\varphi]$$

$P_n^m(\cos\theta)$ = orthogonal Legendre polynomials

g_n^m, h_n^m, G_n^m, H_n^m = Schmidt coefficients (internal and external)

This representation is valid out of the sources (currents). Specific currents (e.g. equatorial disc at Jupiter & Saturn) are described by an additional explicit model, not an external potential.

Degree n=1 corresponds to the dipole, n=2 to quadrupole, n=3 to octupole, …

- Origin of planetary magnetic fields :

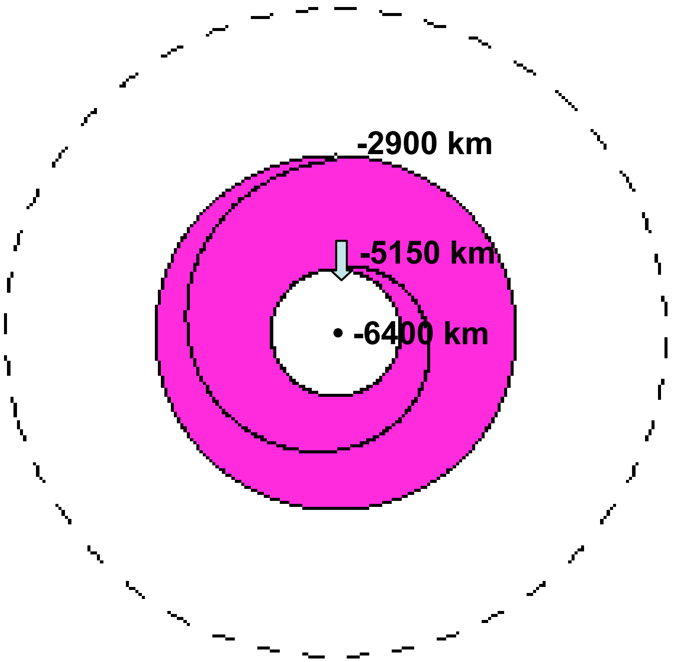
  - Dynamo :

    Rotation +

    Convection (thermal, compositional) +

    Conducting fluid (Earth : liquid Fe-Ni in external core, Jupiter : metallic H)

    ⇒ sustained B field



  - Remanent / ancient dynamo (Mars, Moon...)

  - Induced (Jovian / Saturnian satellites)

Planet or satellite	Observed surface field (in T, approximate)	Comments and interpretation
Mercury	2×10^{-7}	Not well characterized or understood
Venus	$<10^{-8}$ (global); no useful constraint on local fields.	No dynamo. Small remanence
Earth	5×10^{-5}	Core dynamo
Moon	Patchy (10^{-9}–10^{-7}). Impact-generated? No global field	Ancient dynamo?
Mars	Patchy but locally strong (10^{-9}–10^{-4}) field	Ancient dynamo, remanent magnetic lineations
Jupiter	4.2×10^{-4}	Dynamo (extends to near surface)
Io	$<10^{-6}$?	Complex (deeply imbedded in Jovian field)
Europa	10^{-7}	Induction response (salty water ocean)
Ganymede	2×10^{-6}	Dynamo likely
Callisto	4×10^{-9}	Induction response (salty water ocean)
Saturn	2×10^{-5}	Dynamo (deep down)
Titan	$<10^{-7}$	Need more data
Uranus	2×10^{-5}	Dynamo(uncertain depth)
Neptune	2×10^{-5}	Dynamo (uncertain depth)

$1\ G = 10^{-4}\ T = 10^{5}\ nT$

[Stevenson, 2003]

- In-situ measurements of Terrestrial magnetic field, up to order n=14.

- Ground-based radio discovery and first measurements of Jovian magnetic field :

~20 MHz

~1 GHz

VARIABLE RADIO SOURCE ASSOCIATED WITH JUPITER 215

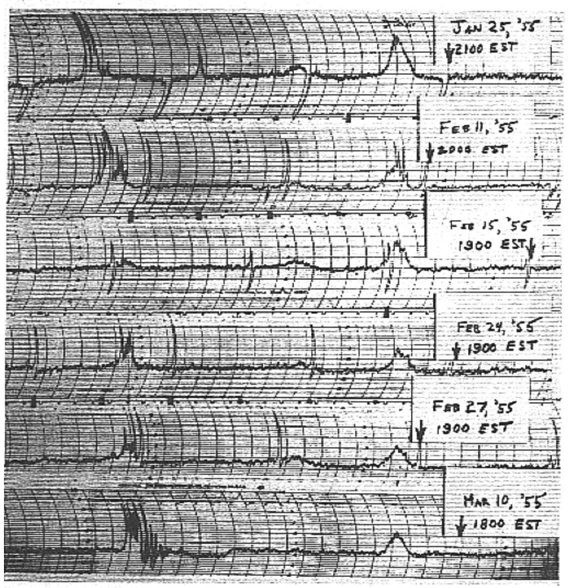
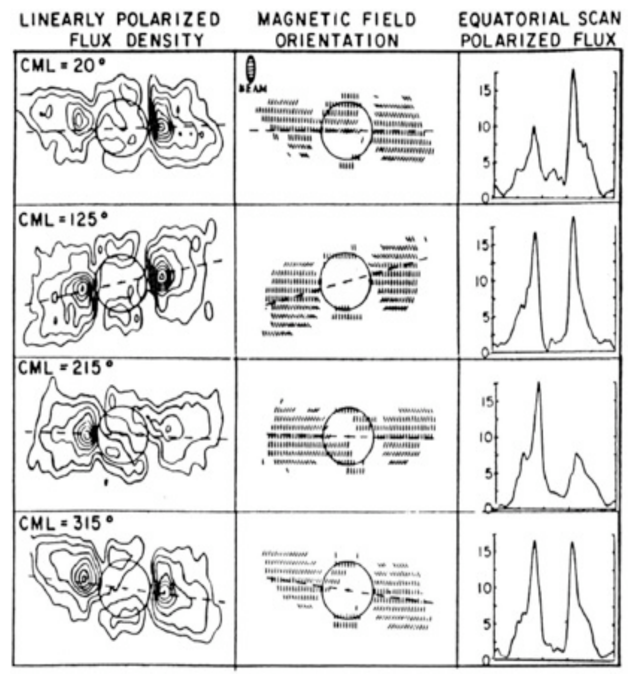


FIG. 2—Phase-switching records showing the appearance of the variable source

[Burke & Franklin, 1955]



[Radhakrishnan & Roberts, 1958]

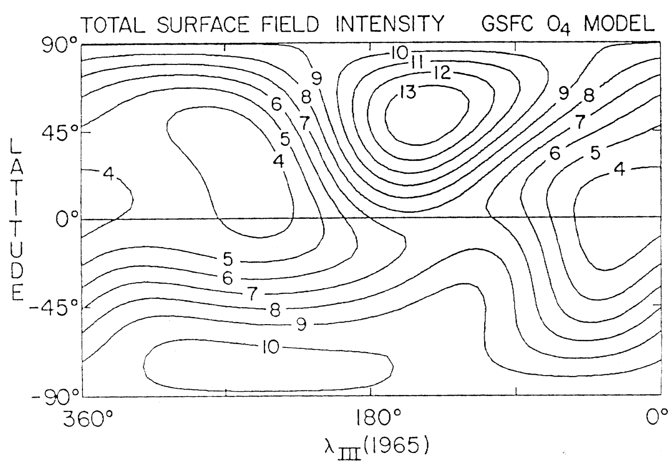
⇒ existence, maximum amplitude, inclination of Jovian B field

system III of magnetic longitudes : P = 9 h 55 min 29.37 sec

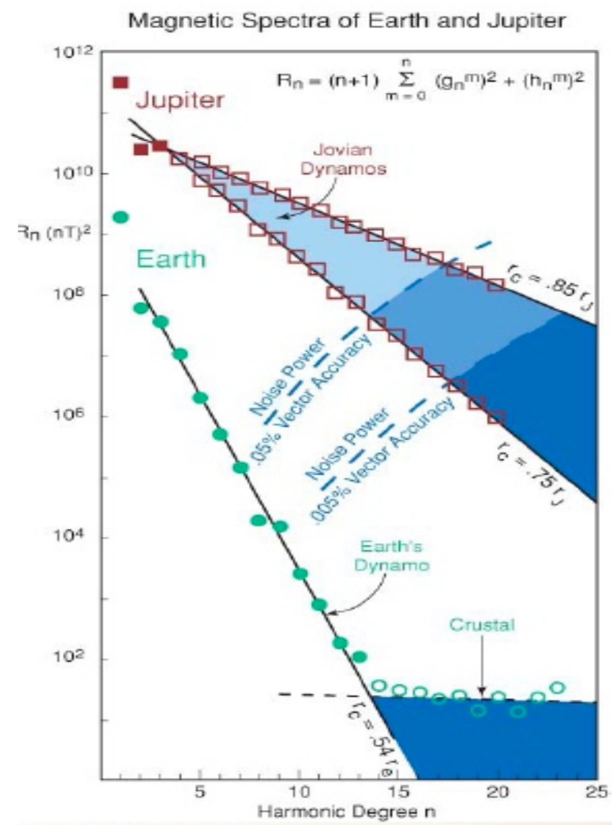
- Spacecraft measurements of planetary magnetic fields :

  - Jupiter : Pioneer 10 & 11 (1973-74), Voyager 1 & 2 (1979), (Ulysses 1992, Galileo 1995-2003)

	O_4	O_6	VIP 4
g_1^0	4,218	4,242	4,205
g_1^1	-0,664	-0,659	-0,659
h_1^1	0,264	0,241	0,250
g_2^0	-0,203	-0,022	-0,051
g_2^1	-0,735	-0,711	-0,619
g_2^2	0,513	0,487	0,497
h_2^1	-0,469	-0,403	-0,361
h_2^2	0,088	0,072	0,053
g_3^0	-0,233	0,075	-0,016
g_3^1	-0,076	-0,155	-0,520
g_3^2	0,168	0,198	0,244
g_3^3	-0,231	-0,180	-0,176
h_3^1	-0,580	-0,388	-0,088
h_3^2	0,487	0,342	0,408
h_3^3	-0,294	-0,224	-0,316
g_4^0			-0,168
g_4^1			0,222
g_4^2			-0,061
g_4^3			-0,202
g_4^4			0,066
h_4^1			0,076
h_4^2			0,404
h_4^3			-0,166
h_4^4			0,039



[Ness, 1988]

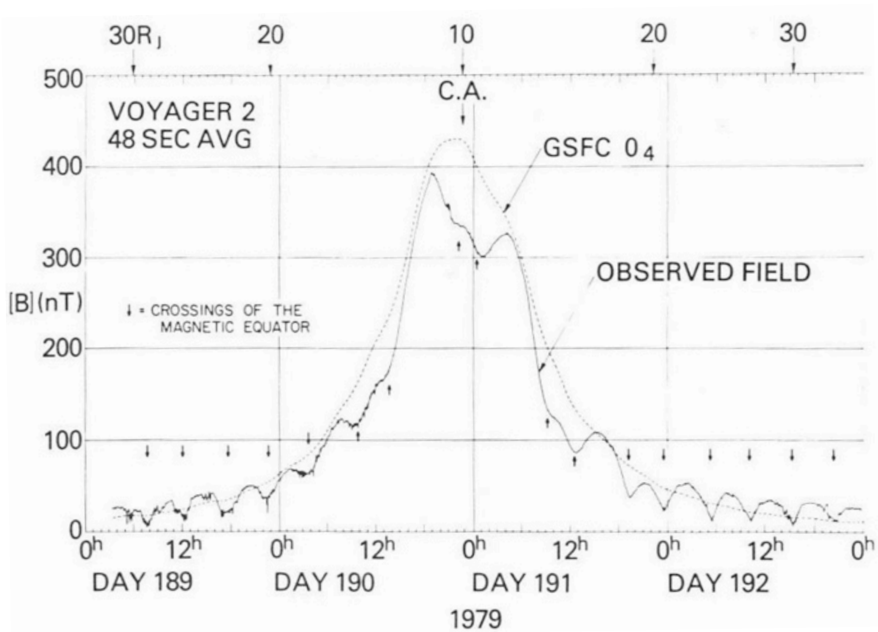


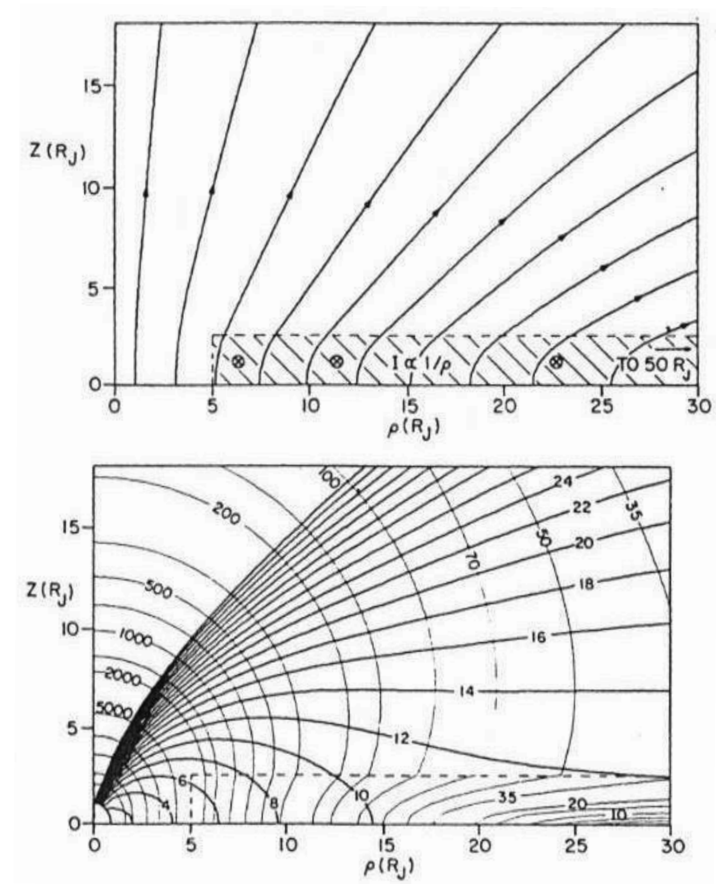
[Connerney, 1992]

⇒ intense, N anomaly, no secular variation 1973-2001

- Spacecraft measurements of planetary magnetic fields :

  - Jupiter : Pioneer 10 & 11 (1973-74), Voyager 1 & 2 (1979), (Ulysses 1992, Galileo 1995-2003)





⇒ current disc, 300 MA, in centrifugal equator

explicit model 5-50 x 5 R_J

[Acuña et al., 1983]

- Spacecraft measurements of planetary magnetic fields :

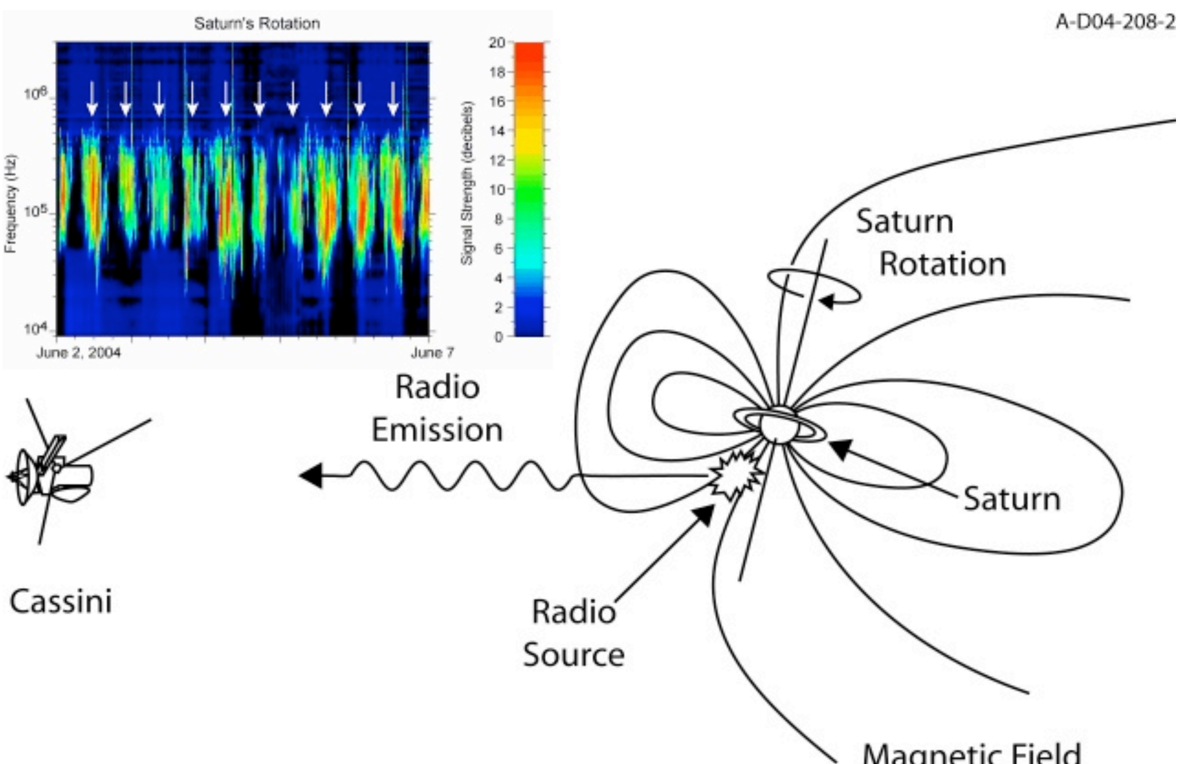
  - Saturn : Pioneer 11 (1979), Voyager 1 & 2 (1980-81), (Cassini 2004-2017)

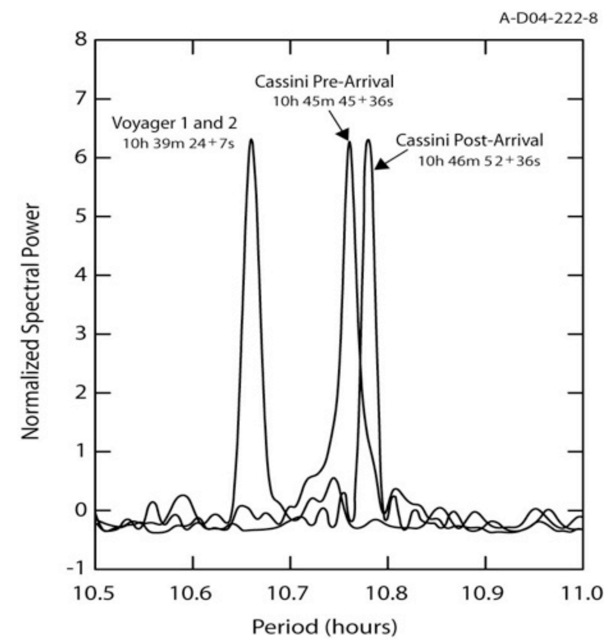
    ⇒ axisymmetric field, contradicts Cowling's antidynamo theorem

    ⇒ filtering or shadowing multipolar terms ?

    ⇒ origin of magnetospheric periodicities ?

    (complex & variable → unknown rotation period)



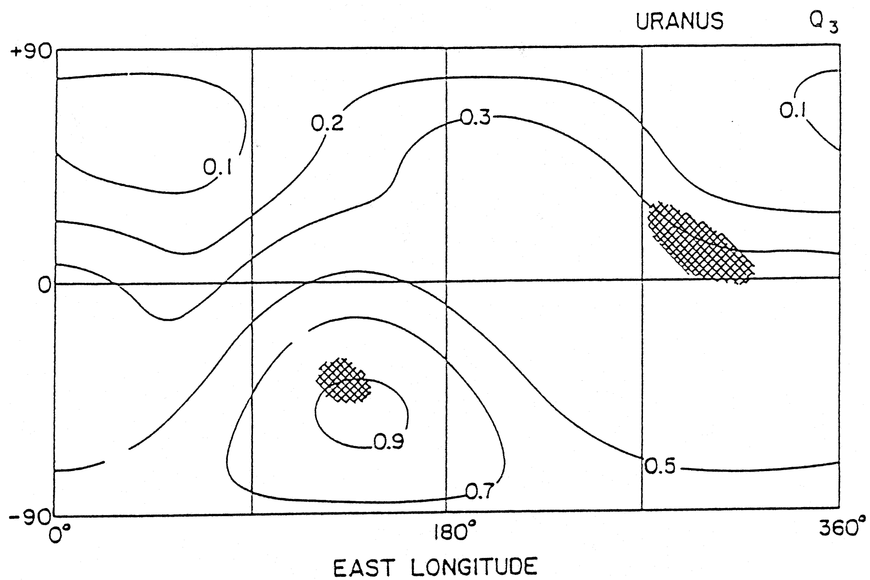


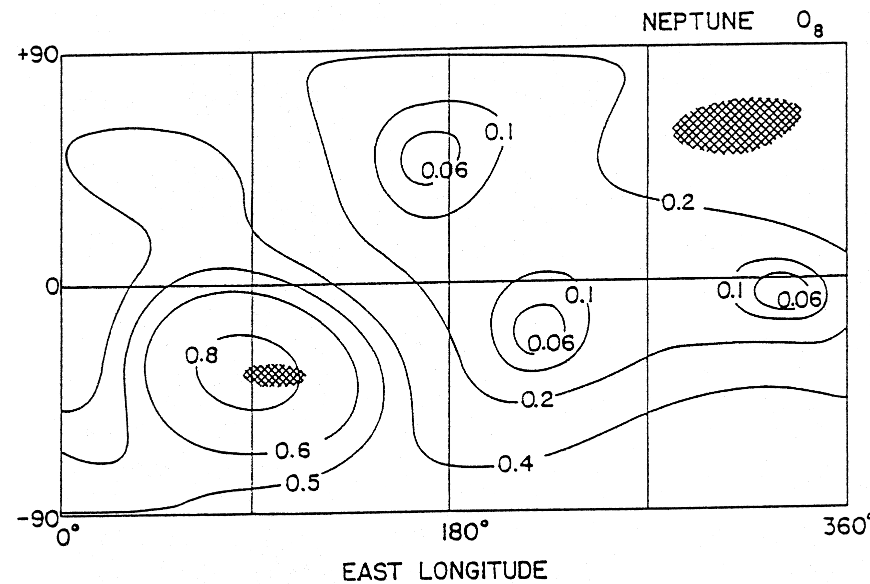
[Gurnett et al., 2005]

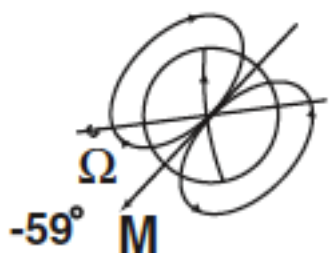
- Spacecraft measurements of planetary magnetic fields :

- Uranus, Neptune : Voyager 2 (1986 & 1989)

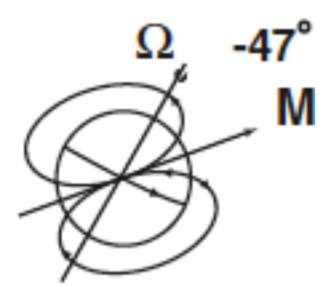
⇒ strongly offset & tilted B fields





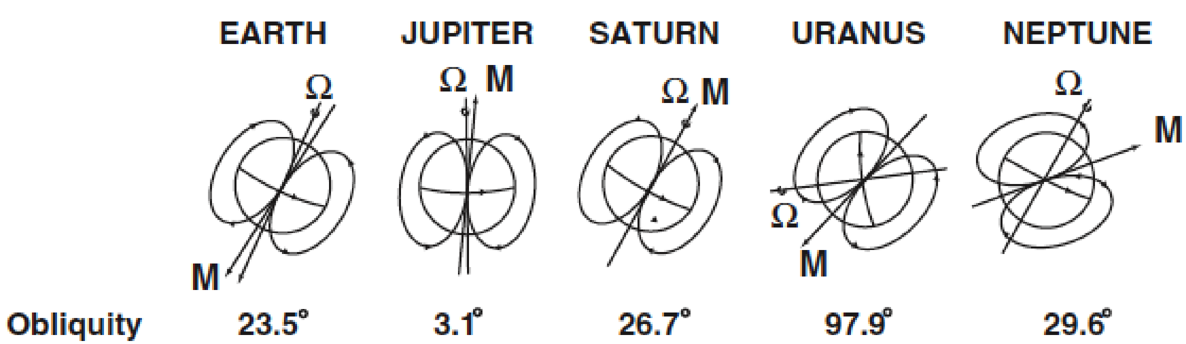


[adapted from Ness, 1992]



- Magnetic field of Giant planets compared to Earth :

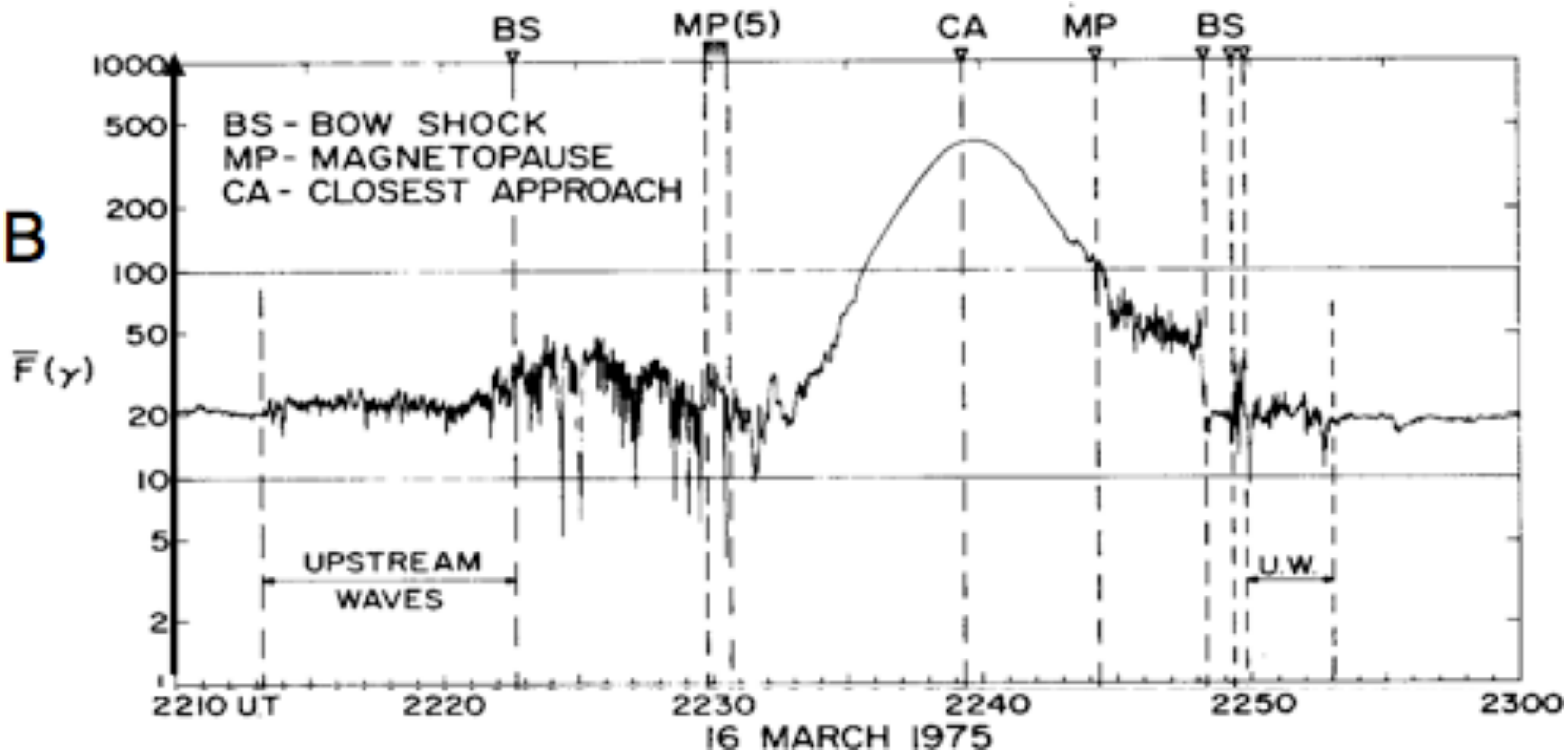
Planète	Terre	Jupiter	Jupiter	Saturne	Uranus	Neptune
R_P (km)	6378	71372	71372	60330	25600	24765
Modèle	IGRF 2000	O6	VIT4	Z3	Q3	O8
g_1^0	−0.29615	+4.24202	+4.28077	+0.21535	+0.11893	+0.09732
g_1^1	−0.01728	−0.65929	−0.75306	0	+0.11579	+0.03220
h_1^1	+0.05186	+0.24116	+0.24616	0	−0.15685	−0.09889
g_2^0	−0.02267	−0.02181	−0.04283	+0.01642	−0.06030	+0.07448
g_2^1	+0.03072	−0.71106	−0.59426	0	−0.12587	+0.00664
h_2^1	−0.02478	−0.40304	−0.50154	0	+0.06116	+0.11230
g_2^2	+0.01672	+0.48714	+0.44386	0	+0.00196	+0.04499
h_2^2	−0.00458	+0.07179	+0.38452	0	+0.04759	−0.00070
g_3^0	+0.01341	+0.07565	+0.08906	+0.02743	0	−0.06592
g_3^1	−0.02290	−0.15493	−0.21447	0	0	+0.04098
h_3^1	−0.00227	−0.38824	−0.17187	0	0	−0.03669
g_3^2	+0.01253	+0.19775	+0.21130	0	0	−0.03581
h_3^2	+0.00296	+0.34243	+0.40667	0	0	+0.01791
g_3^3	+0.00715	−0.17958	−0.01190	0	0	+0.00484
h_3^3	−0.00492	−0.22439	−0.35263	0	0	−0.00770
M^t dipolaire ($G.R_P^3$)	0.305	4.26		0.215	0.228	0.142
Inclinaison (B / Ω)	+11°	-9.6°		-0°	-58.6°	-46.9°
Offset centre dipôle / centre planète (R_P)	0.08	0.07		0.04	0.31	0.55



- Spacecraft measurements of planetary magnetic fields :

- Mercury: Mariner 10 (1974-75), (Messenger 2011-13)

⇒ weak B ~400 nT, tilt ~10°



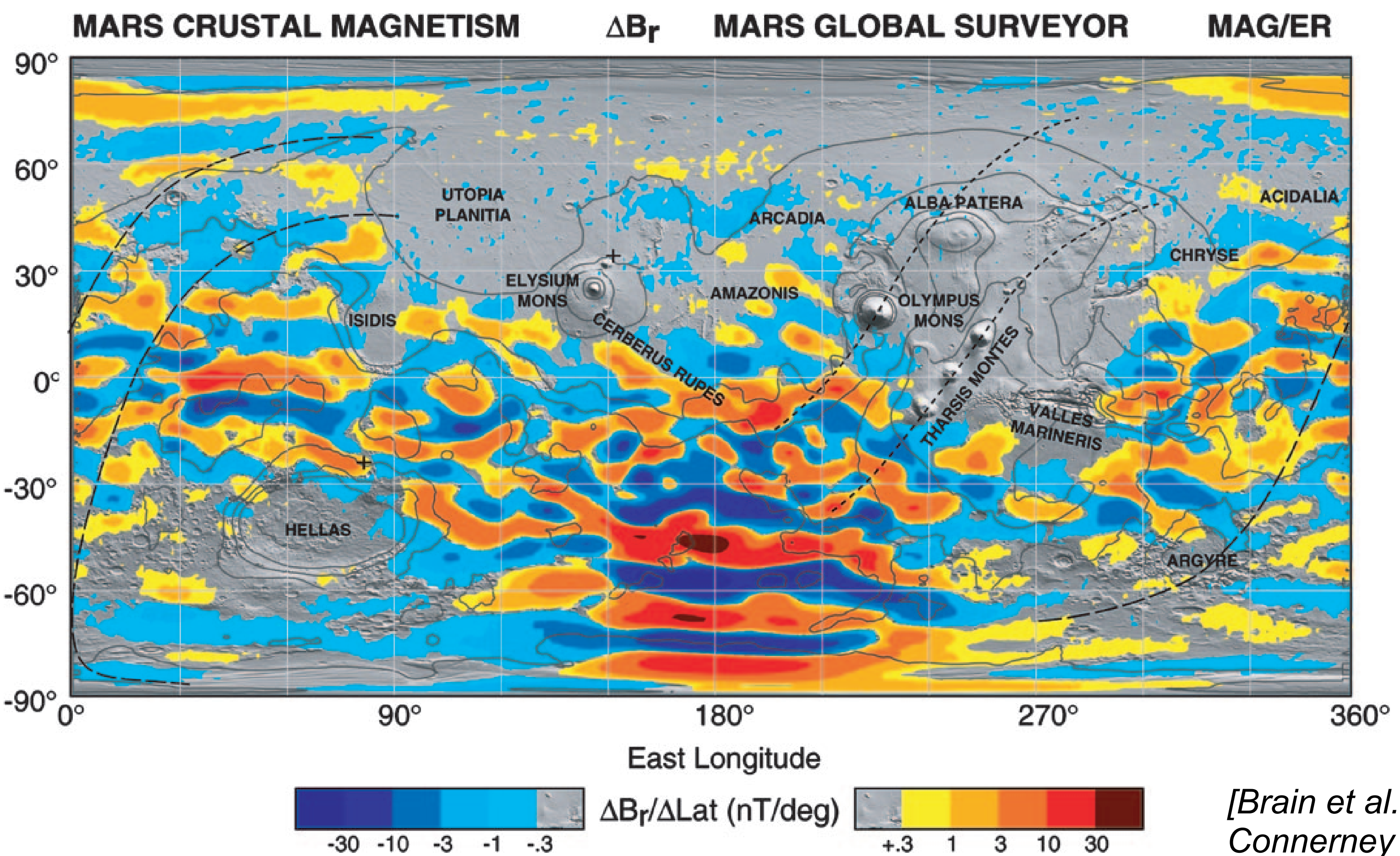
[Ness et al., 1976, Connerney et al., 1988]

- Spacecraft measurements of planetary magnetic fields :

- Mars: Mars Global Surveyor (1996-2006)

⇒ no global magnetosphere, up to 10^{4-5} nT locally at surface tectonics-related ?

"mini-MS" form small bumps above the ionosphere, up to >1000 km altitude

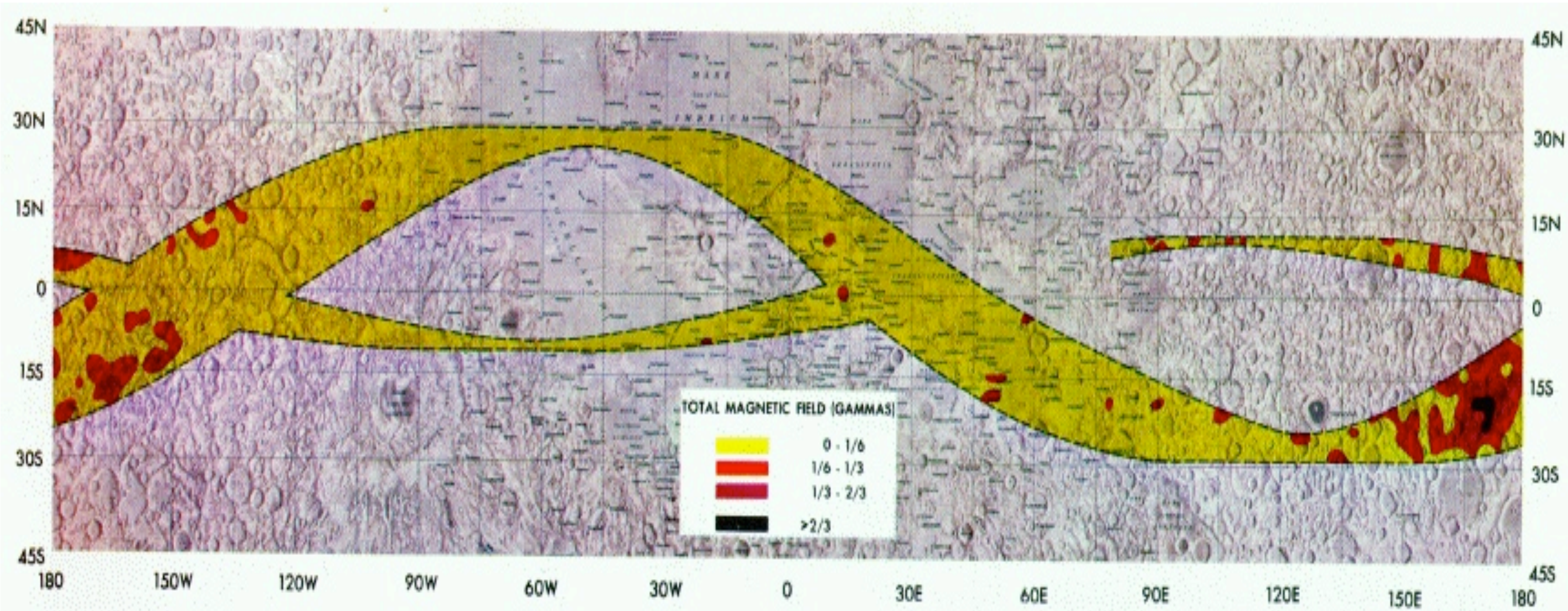


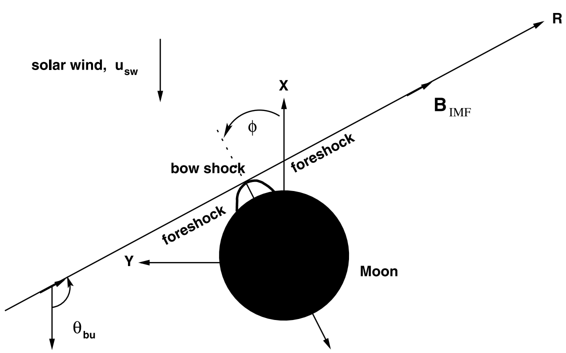
[Brain et al., 2003 ; Connerney et al., 2005]

- Spacecraft measurements of planetary magnetic fields :

- Moon: Lunar Prospector (1998-99)

⇒ no global MS, B up to 100 nT at surface, opposed to impact craters





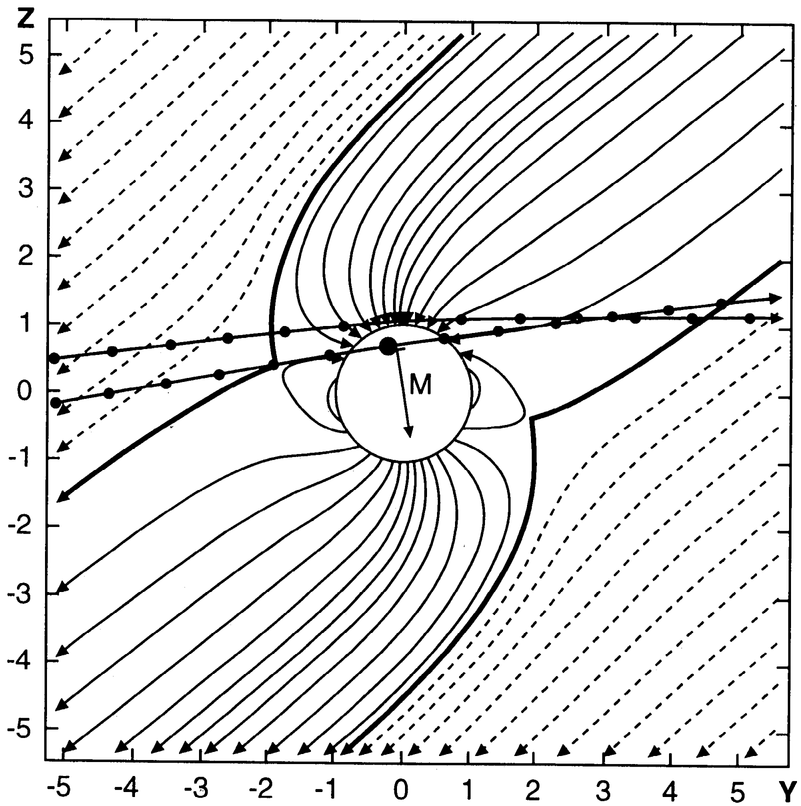
mini-MS (+ associated radio emissions detected by WIND)

[Kuncic & Cairns, 2004]

- Spacecraft measurements of planetary magnetic fields :

- Ganymede: Galileo (1996-2003)

⇒ internal B field and magnetosphere (embedded in Jupiter’s, ~100 nT)



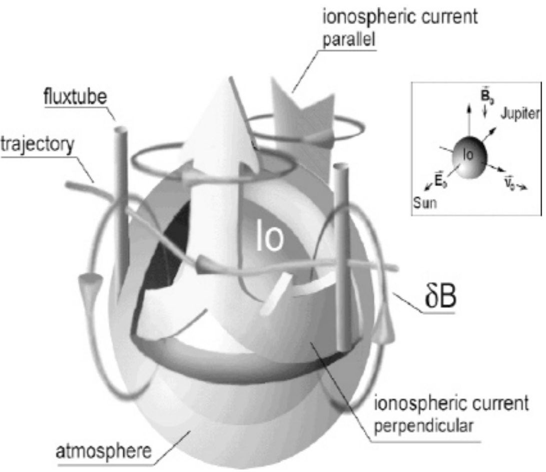
1996 June 27 06:00:00 - 07:05:00 ●—● 5 Minutes
1996 Sept 06 18:30:00 - 19:32:00

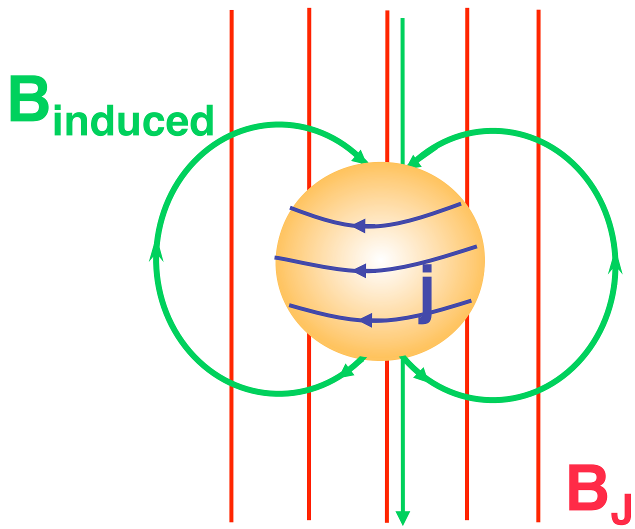
View from downstream looking into flow direction

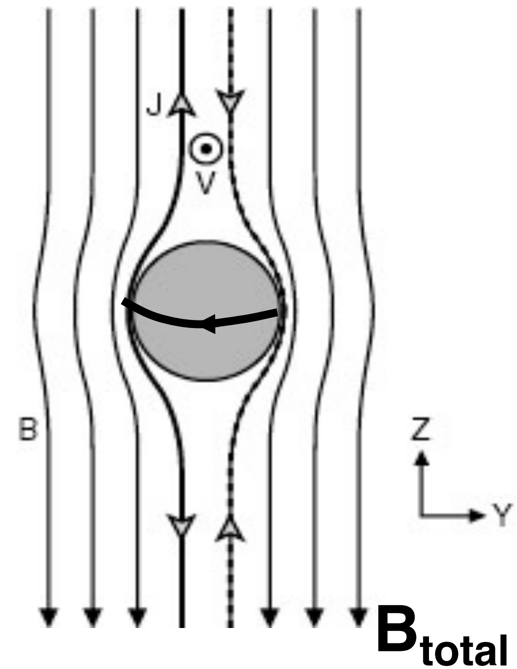
[Gurnett et al., 1996, Kivelson et al., 1997]

- Spacecraft measurements of planetary magnetic fields :

- other Galilean satellites, Enceladus: induced field







to Jupiter →

[Saur et al., 2002,
Khurana, 2009]

Planet or satellite	Observed surface field (in T, approximate)	Comments and interpretation
Mercury	2×10^{-7}	Not well characterized or understood
Venus	$<10^{-8}$ (global); no useful constraint on local fields.	No dynamo. Small remanence
Earth	5×10^{-5}	Core dynamo
Moon	Patchy (10^{-9}–10^{-7}). Impact-generated? No global field	Ancient dynamo?
Mars	Patchy but locally strong (10^{-9}–10^{-4}) field	Ancient dynamo, remanent magnetic lineations
Jupiter	4.2×10^{-4}	Dynamo (extends to near surface)
Io	$<10^{-6}$?	Complex (deeply imbedded in Jovian field)
Europa	10^{-7}	Induction response (salty water ocean)
Ganymede	2×10^{-6}	Dynamo likely
Callisto	4×10^{-9}	Induction response (salty water ocean)
Saturn	2×10^{-5}	Dynamo (deep down)
Titan	$<10^{-7}$	Need more data
Uranus	2×10^{-5}	Dynamo(uncertain depth)
Neptune	2×10^{-5}	Dynamo (uncertain depth)

$$1 \text{ G} = 10^{-4} \text{ T} = 10^{5} \text{ nT}$$

[Stevenson, 2003]

- Planetary Magnetic Fields
- Magnetospheric structure
- Magnetospheric dynamics
- Electromagnetic emissions
- Exoplanets

- **Context**

High plasma conductivity

$\Rightarrow$ B frozen-in

$\Rightarrow$ $E = -V \times B$ almost everywhere (0 in plasma frame)

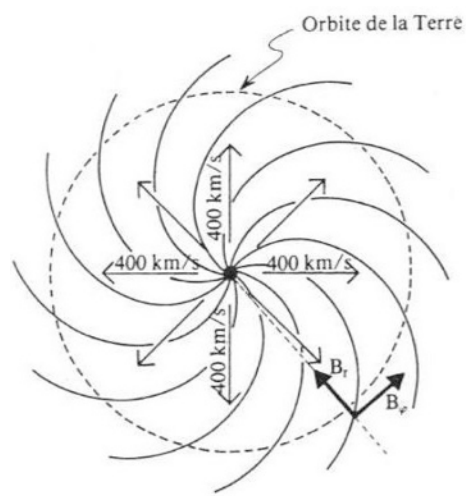
$\Rightarrow$ quasi-neutrality

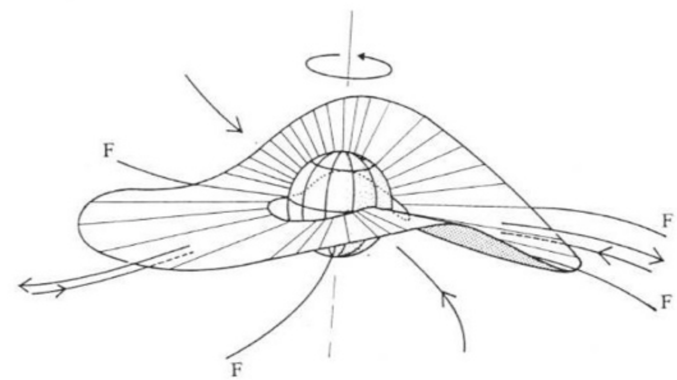
& $E.B=0$ ($\Delta\phi$ conserved along B lines,

= electric equipotentials)

• **Solar Wind**

- dominated by bulk energy density : $NmV^2/2$
- carries away solar B rooted in the Sun ⇒ ballerina skirt





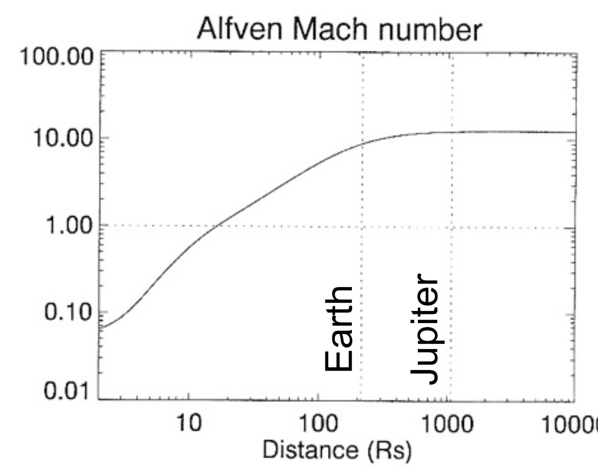
- SW parameters at planetary orbits (r in AU) :

$V \sim 400/r^{2/7}$ km/s $\qquad T \sim 2\times10^5/r^{2/7}$ K

$N = 5/r^2\ cm^{-3}$

$B_r = 3/r^2$ nT $\qquad B_\varphi = B_r\Omega r/V = 3/r$ nT

$V_S \sim 60/r^{1/7}$ km/s $\qquad V_A \sim 40\times(1/2+r^{-2}/2)^{1/2}$ km/s



• **Solar Wind - Obstacle interaction**

- depends on presence of obstacle's :

intrinsic large-scale B

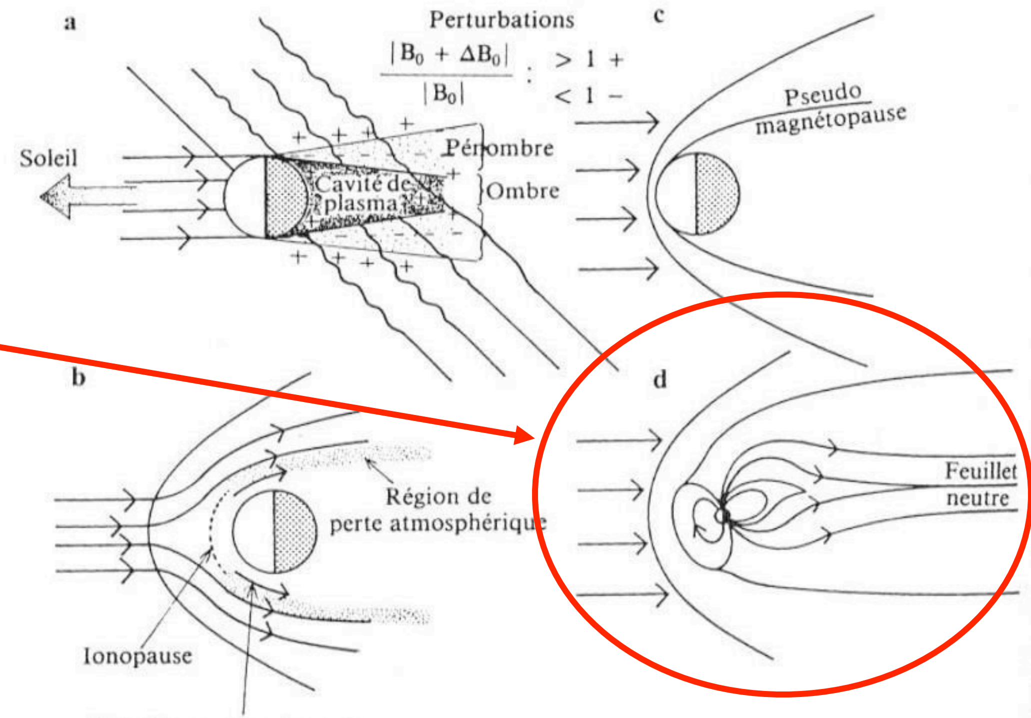
ionosphere

conductivity

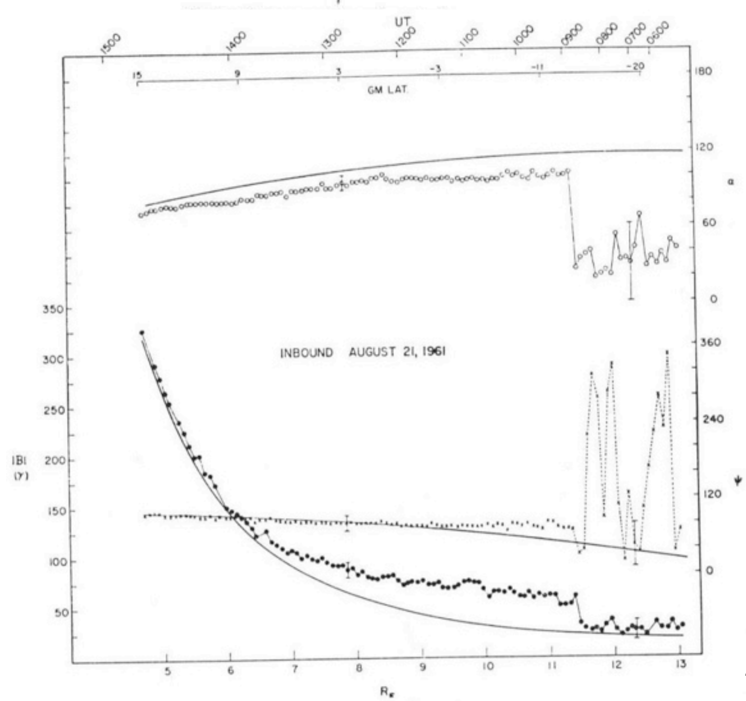
-1st case ⇒ abrupt boundary

in planetary B

= magnetopause

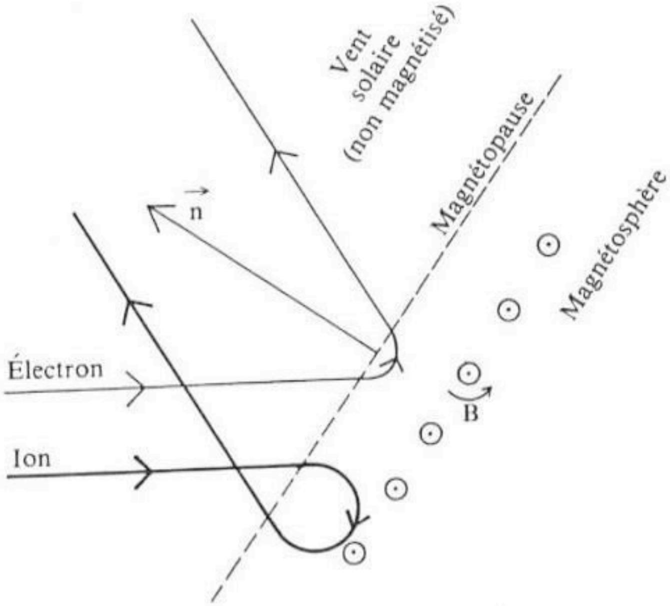


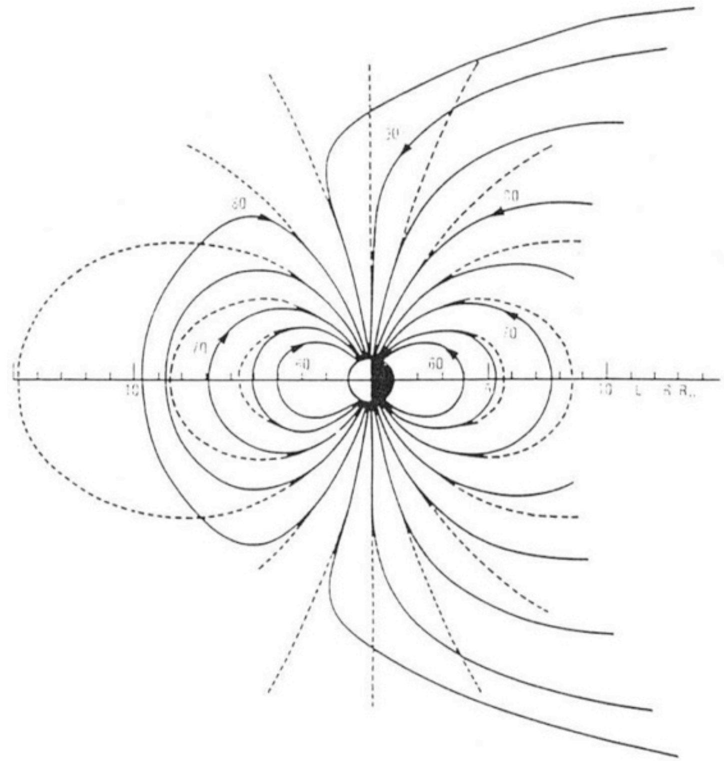
[Lepping, 1986]



[Cahill & Patel, 1967]

• **Magnetopause**





- Pressure equilibrium : $P_{SW} = KNmV^2\cos^2\chi$ = $P_{MS} = B_T^2/2\mu_o$

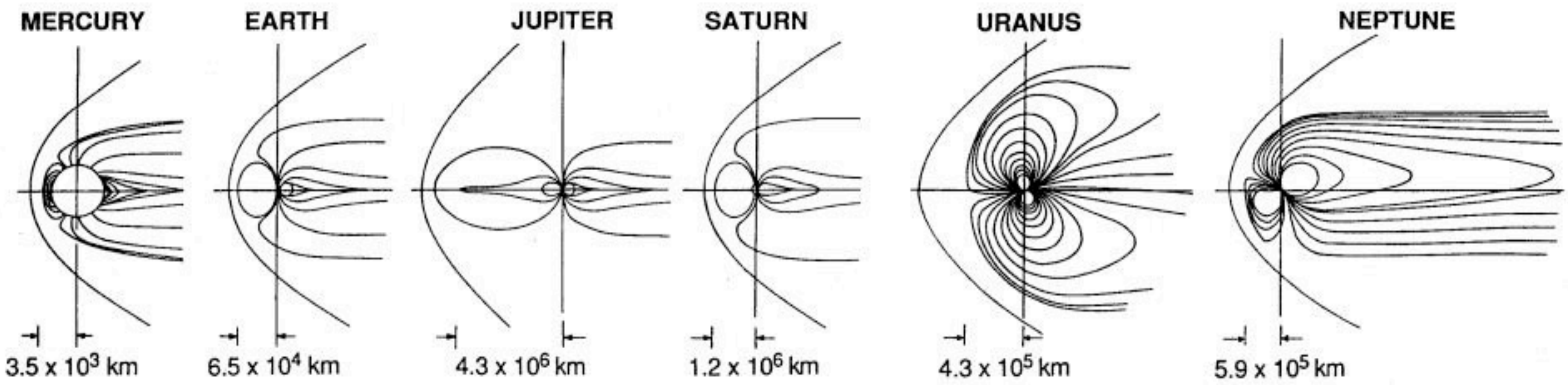
  with $B_T = B_P+B_C = 2\ B_P$ at MP nose   K = 1-2

  $\Rightarrow$ MP shape

- MP sub-solar point (dipolar field : $B_P = B_{eq}\ (1+3\cos^2\theta)^{1/2}/R^3$) :

  $R_{MP} = (2\ B_{eq}^2/\mu_o KNmV^2)^{1/6}$

• **Magnetopause**



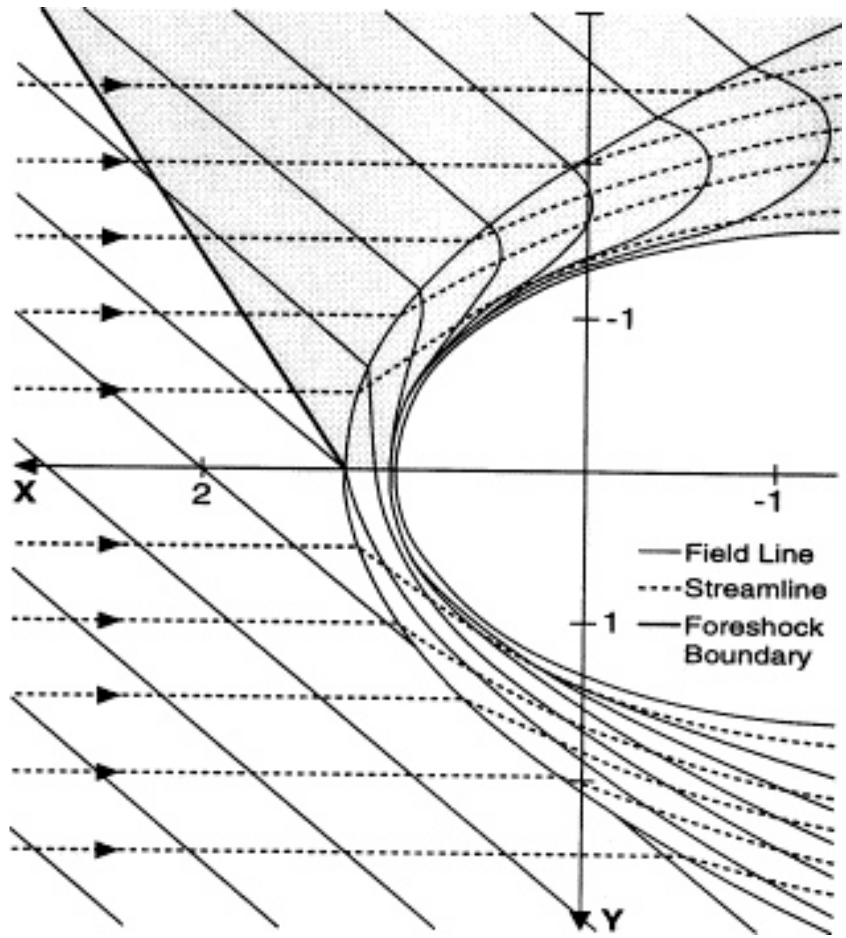
	Mercure	Terre	Jupiter	Saturne	Uranus	Neptune
R_P (km)	2 439	6 378	71 492	60 268	25 559	24 764
D orbitale (UA)	0.39	1	5.2	9.5	19.2	30.1
M_{dip} (G.km^3)	5.5×10^7	7.9×10^{10}	1.6×10^{15}	4.7×10^{13}	3.8×10^{12}	2.2×10^{12}
Champ à l'équateur B_e (G)	0.003	0.31	4.3	0.21	0.23	0.14
Inclinaison [B,Ω] (°) et sens	+14	+11.7	-9.6	-0.	-58.6	-46.9
R_{MP} (R_P) calculée [mesurée]	1.4 [~1.5]	9 [~10]	40 [~90]	17 [~20]	22 [~18]	21 [~23]

[Encrenaz et al., 2003]

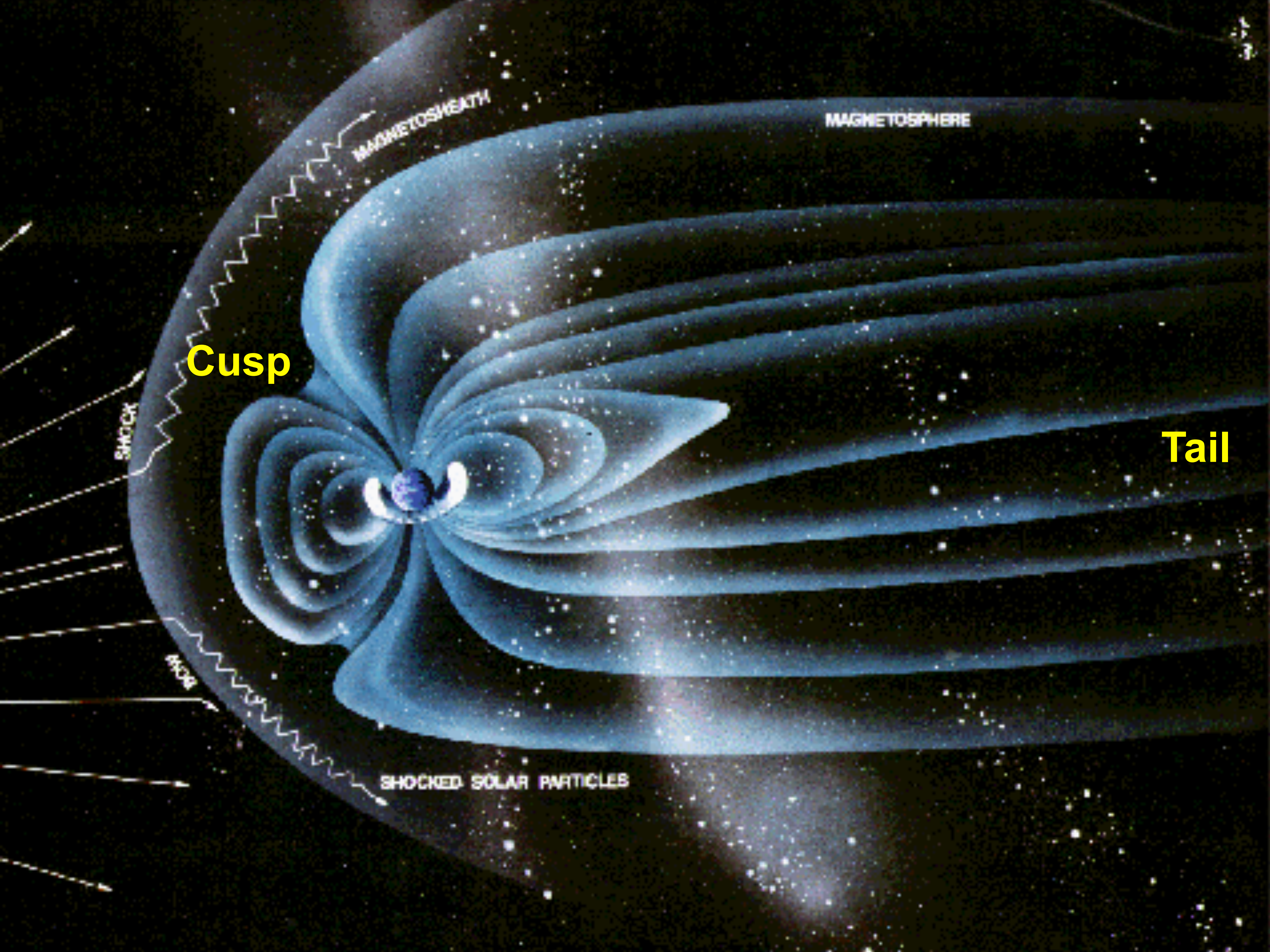
- **Bow Shock**

- supersonic / super-Alfvénic flow ⇒ bow shock ahead of MP
- in magnetosheath : slowed flow (V:4 for $M_A >> 1$)

⇒ B draping / pile-up ($|\mathbf{V}|.|\mathbf{B}| = c^t$)

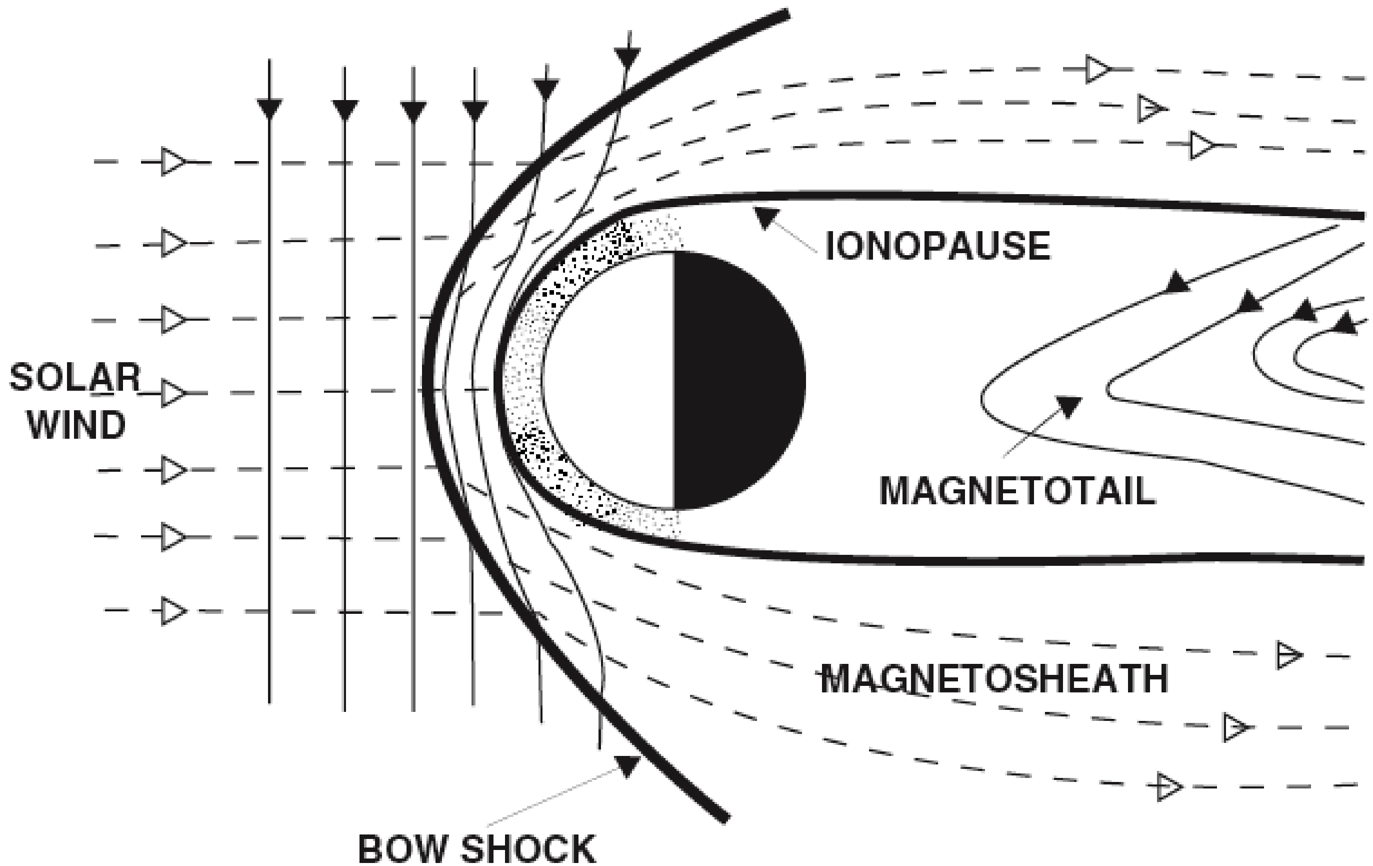


[Spreiter et al., 1966]



MAGNETOSHEATH
MAGNETOSPHERE
Cusp
Tail
SHOCK
BOW
SHOCKED SOLAR PARTICLES

- if no intrinsic B field $\Rightarrow$ induced MS, bow shock, B draping, tail, but no cusp



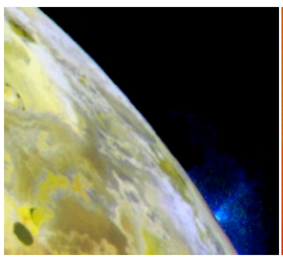
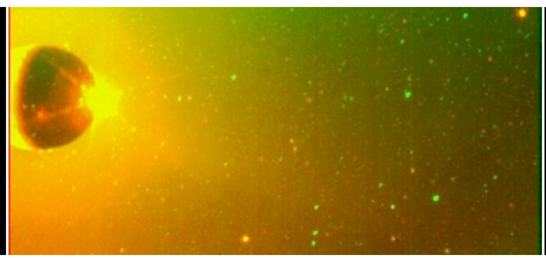
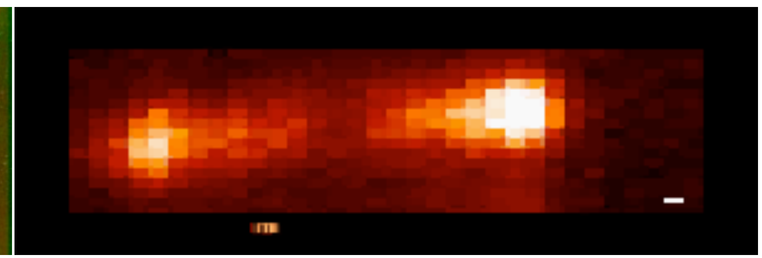
[Bagenal, 2002]

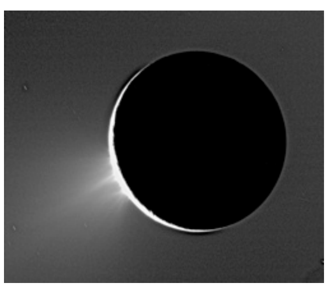
- Planetary Magnetic Fields
- Magnetospheric structure
- Magnetospheric dynamics
- Electromagnetic emissions
- Exoplanets

- **Plasma Sources**

- Solar Wind : cusp + diffusion/reconnection across Magnetopause
  (H & He, T~100 eV, ~1% of SW flow)
- Ionosphere : vertical diffusive equilibrium of cold plasma (T~0.1-1. eV)

- Satellites : Io : volcanism ⇒ plasma torus *[Bagenal, 1994]*



Titan : atmospheric escape *[Sittler et al;, 2005]*

Enceladus : exosphere, plumes *[Dougherty et al., 2005]*

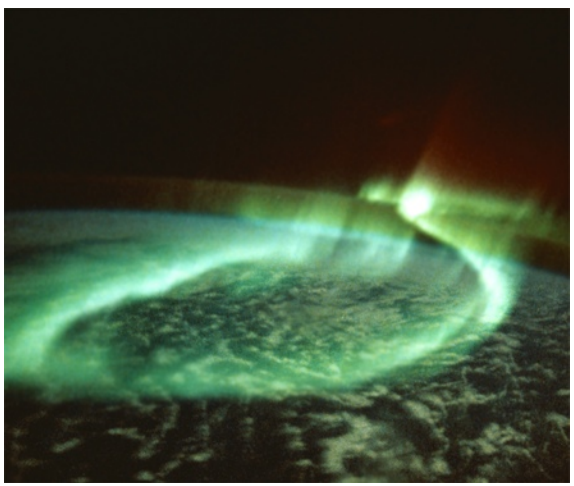
Icy satellites or Mercury's surface : sputtering

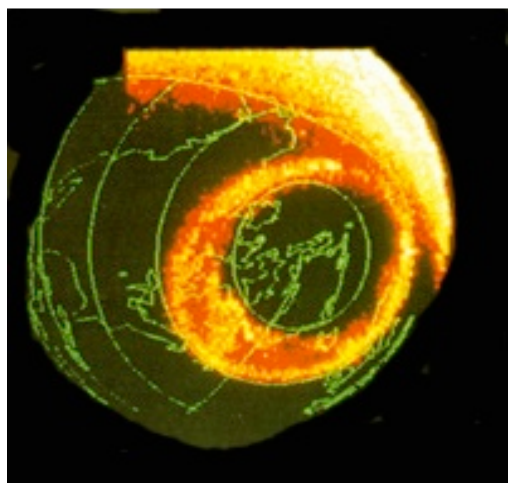
- Rings : sputtering / photo-dissociation + ionisation *[Young et al., 2005]*

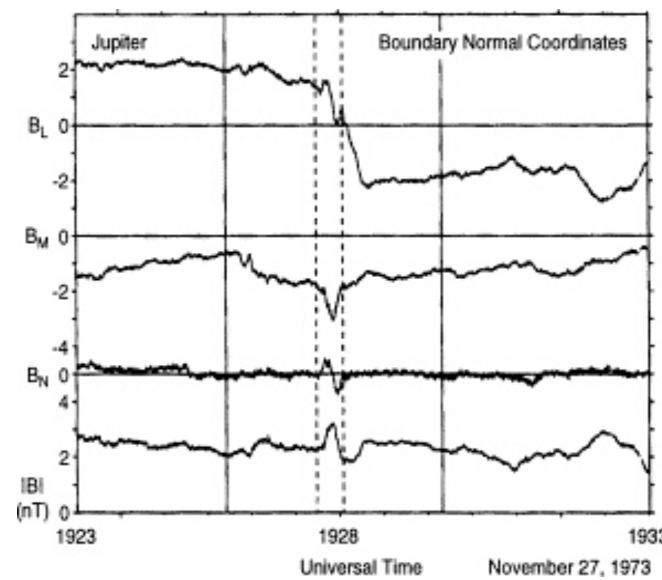
⇒ Total MS mass ~10^{10} kg @ Jupiter, ~10^{7} kg @ Earth

- **Plasma Circulation**

  - 2 convection cells + large scale E (dawn → dusk) inside Earth's MS
  - energetic plasma inside MS
  - quasi permanent circumpolar aurora (∅ = 10°-20°)
  - SW control (B_z) of MS activity : $B_N \neq 0$ when B_z // B_P

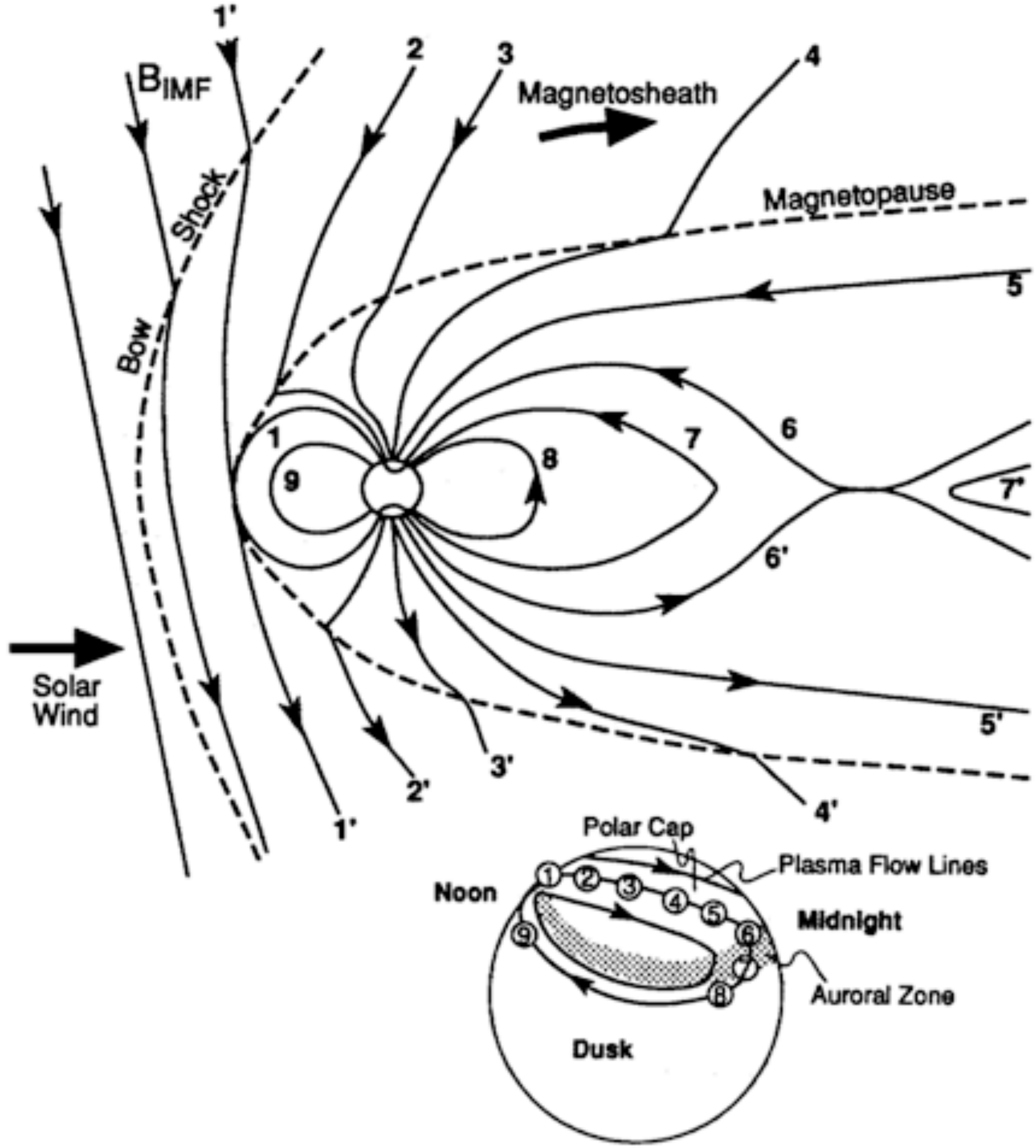






⇒ Open magnetosphere concept + Dungey cycle *[Dungey, 1961]*

cycle of plasma and B field circulation in the Earth's magnetosphere



[Hughes, 1995]

- **Plasma Circulation**

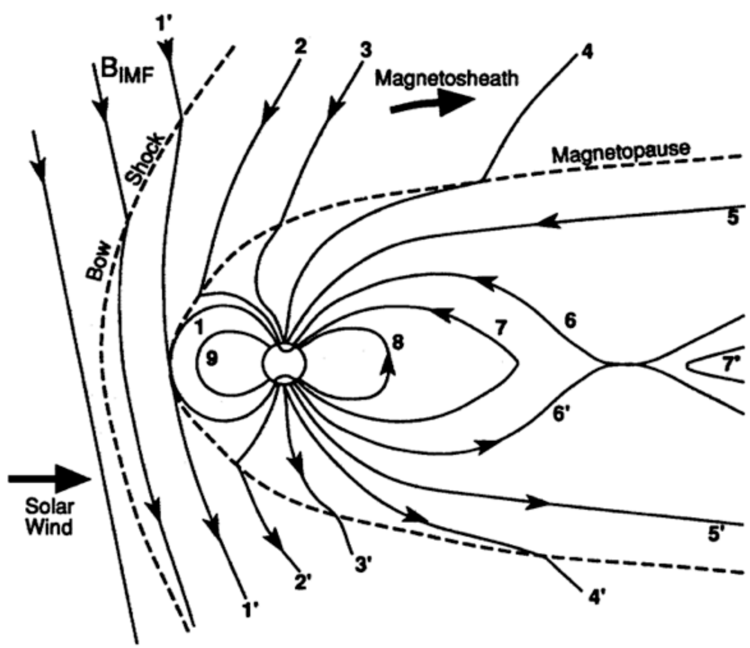
- Neutral (X) line at equator : penetration of plasma in MS ⇒ MP no more equipotential

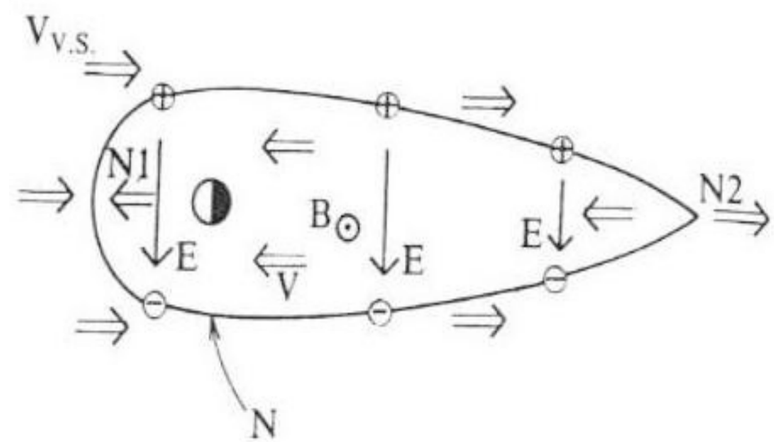
- Auroral oval = limit open/closed field lines

  = projection of equatorial neutral line on ionosphere

- Tail stores / releases energy and magnetic flux

- Poynting flux on obstacle : $P_m = B_\perp^2/\mu_o \, V \;\; \pi R_{obs}^2$





• **Plasma Circulation**

- <u>Solar Convection</u> in MS [antisolar above the poles]

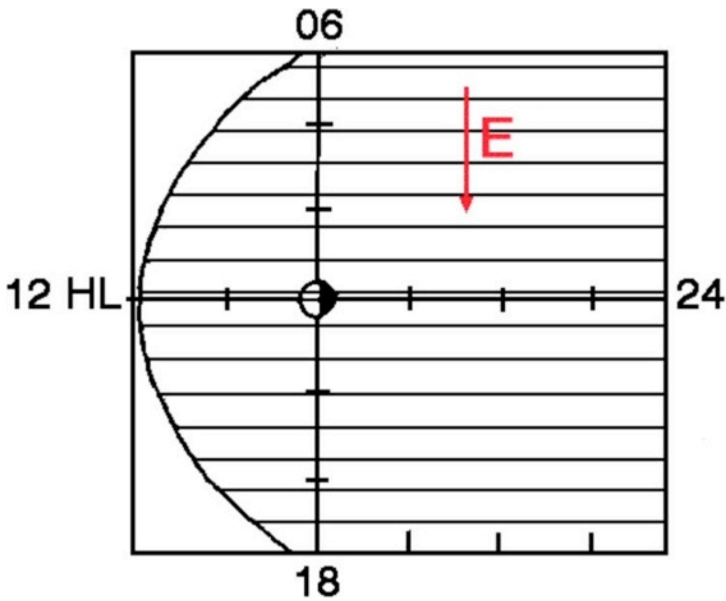
$E = -V \times B \sim \varepsilon V_{SW} \times B_{SW}$ (dawn → dusk)

$\varepsilon = 0.1\text{-}0.2$

$\Delta\phi \sim \varepsilon V_{SW} B_{SW} \times 3 R_{MP}$

~ 50 kV @ Earth

~ 1 MV @ Jupiter



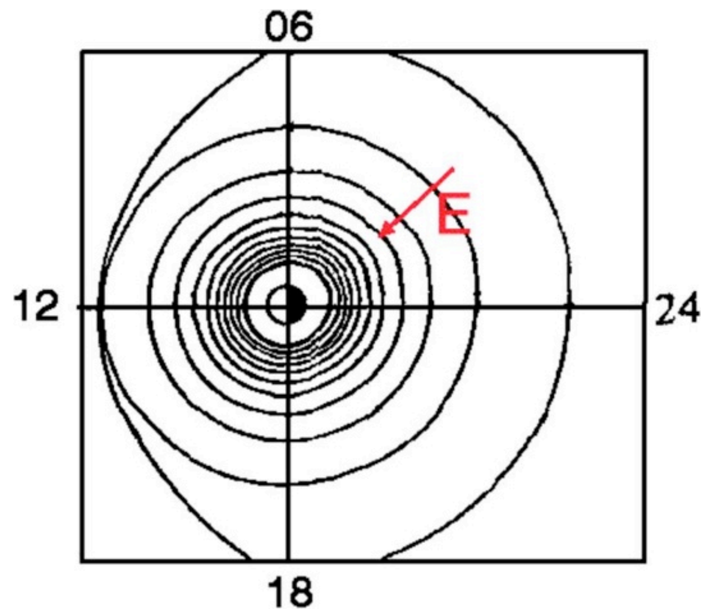
- <u>Corotation</u>

$E = \Omega R \times B$ (radial)

$\Delta\phi \sim \Omega B_{eq} R_P^2$

~ 90 kV @ Earth

~ 400 MV @ Jupiter

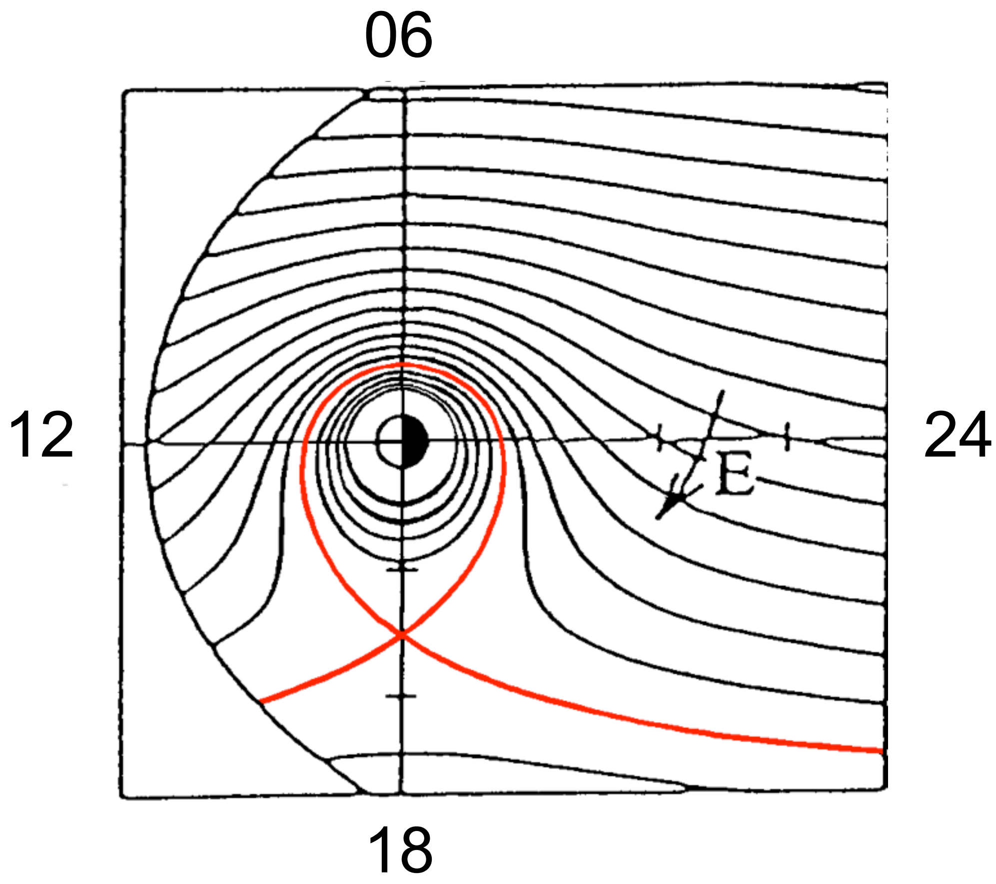


• Plasma Circulation

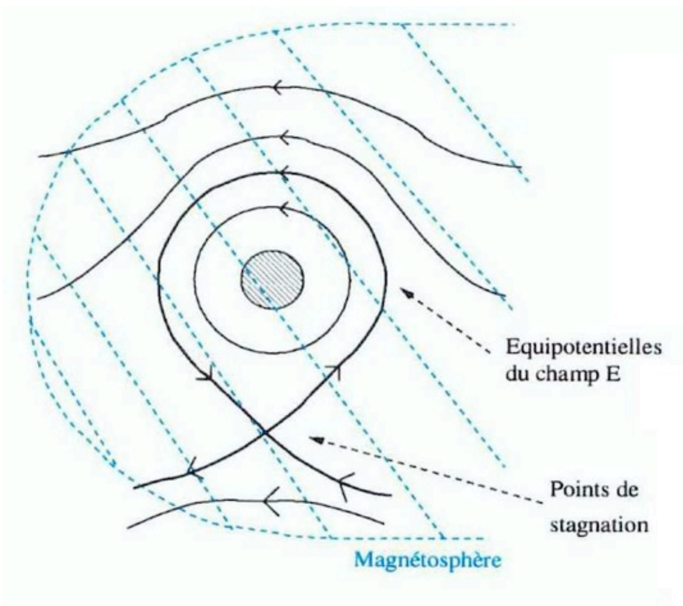
- <u>Global circulation = Convection + Corotation</u>

Equipotentials = flow lines

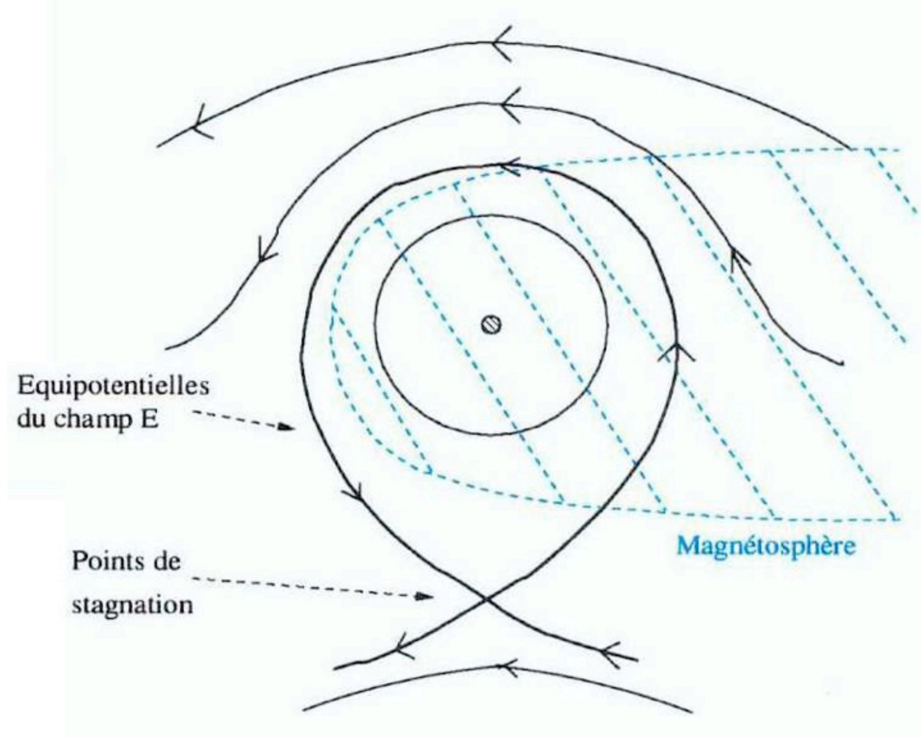
Stagnation point at LT = 18 h



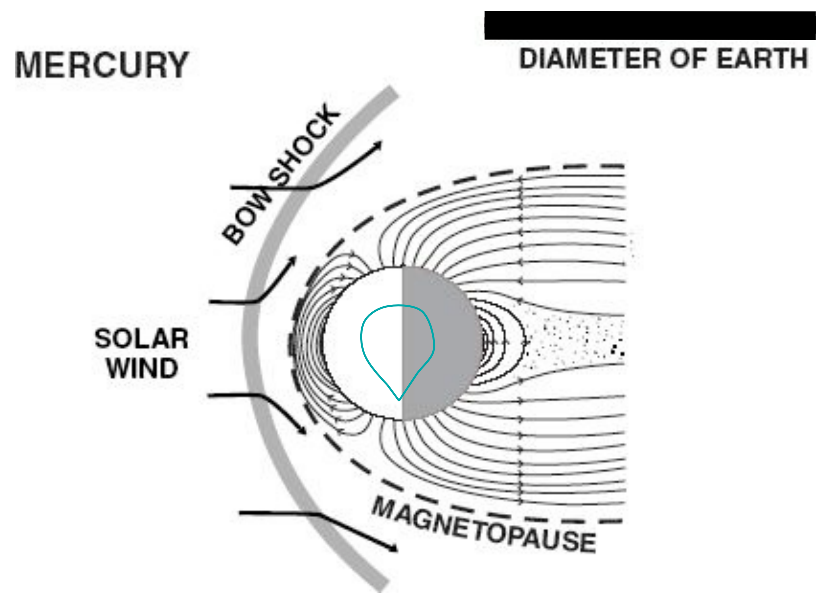
• **Plasma Circulation**



Earth

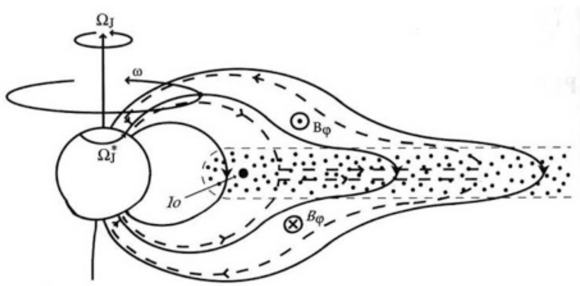


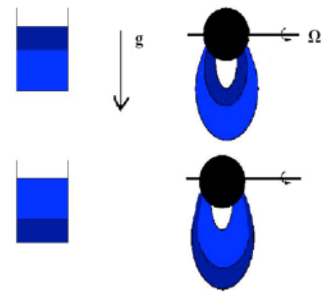
Jupiter



• **Plasma Circulation**

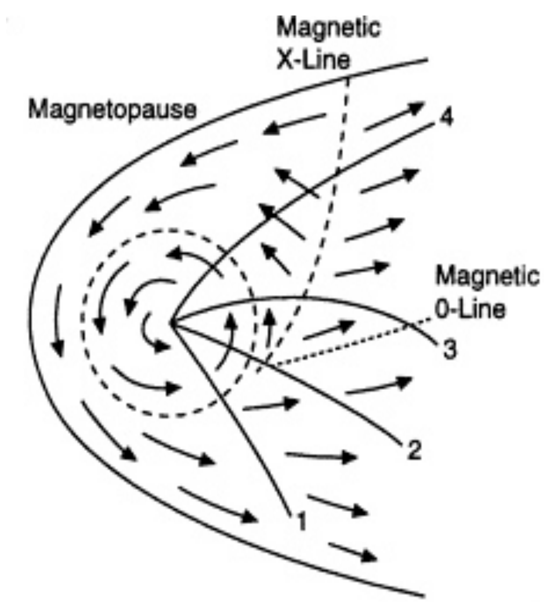
- Jupiter : outward radial transport (centrifugal interchange instability)

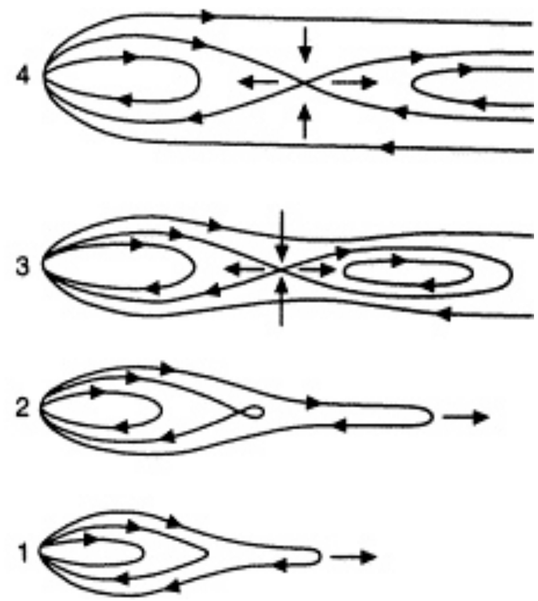




[André, 2006]

⇒ Vasyliunas cycle ~ rotation driven Dungey cycle



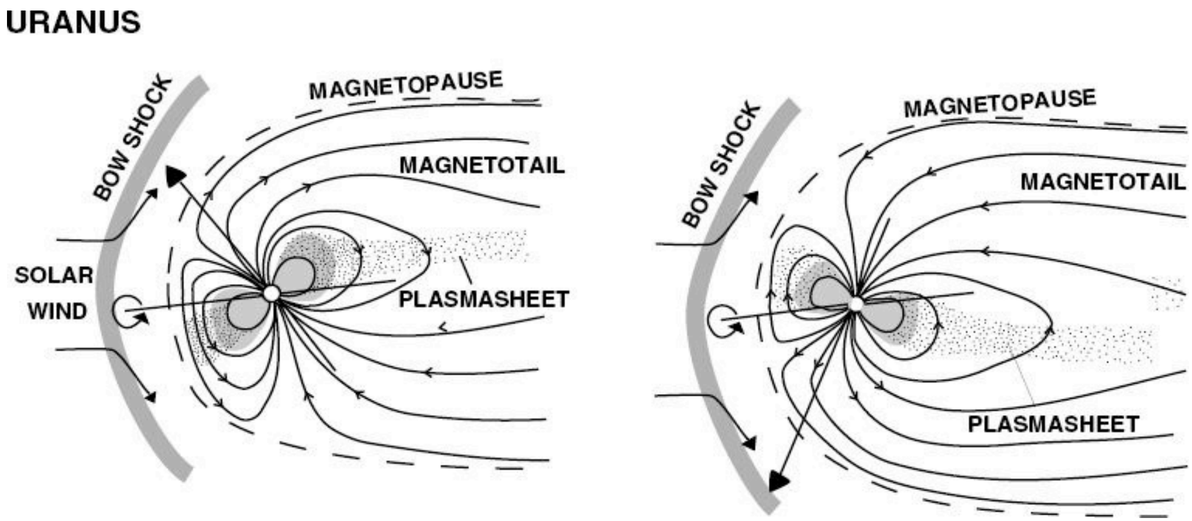


[Vasyliunas, 1983]

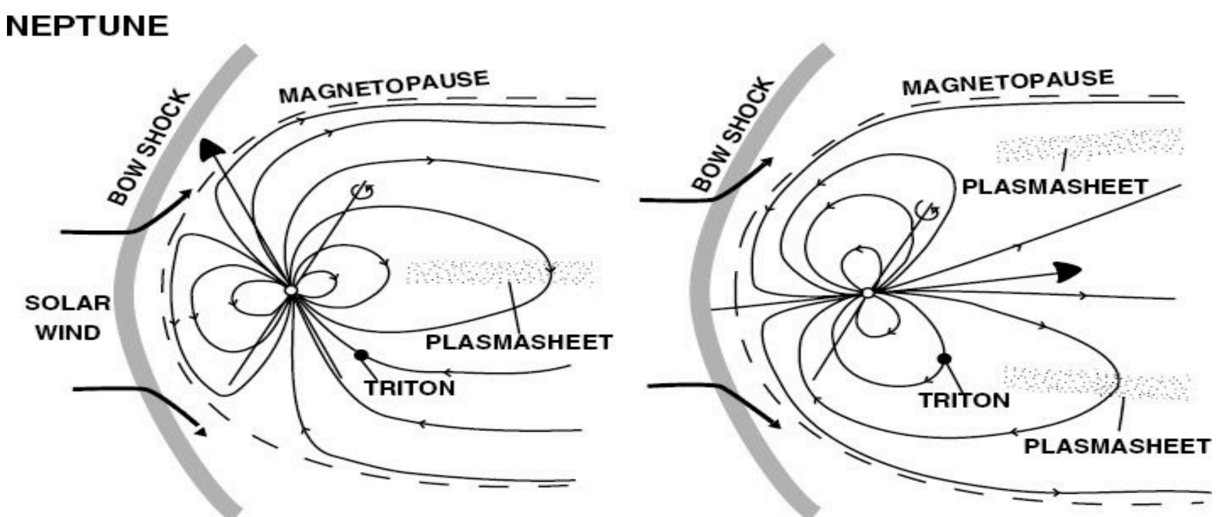
- Saturn : intermediate Earth - Jupiter ?

- **Plasma Circulation**

- Uranus : convection ⊥ corotation ⇒ helicoidal plasma trajectories ?



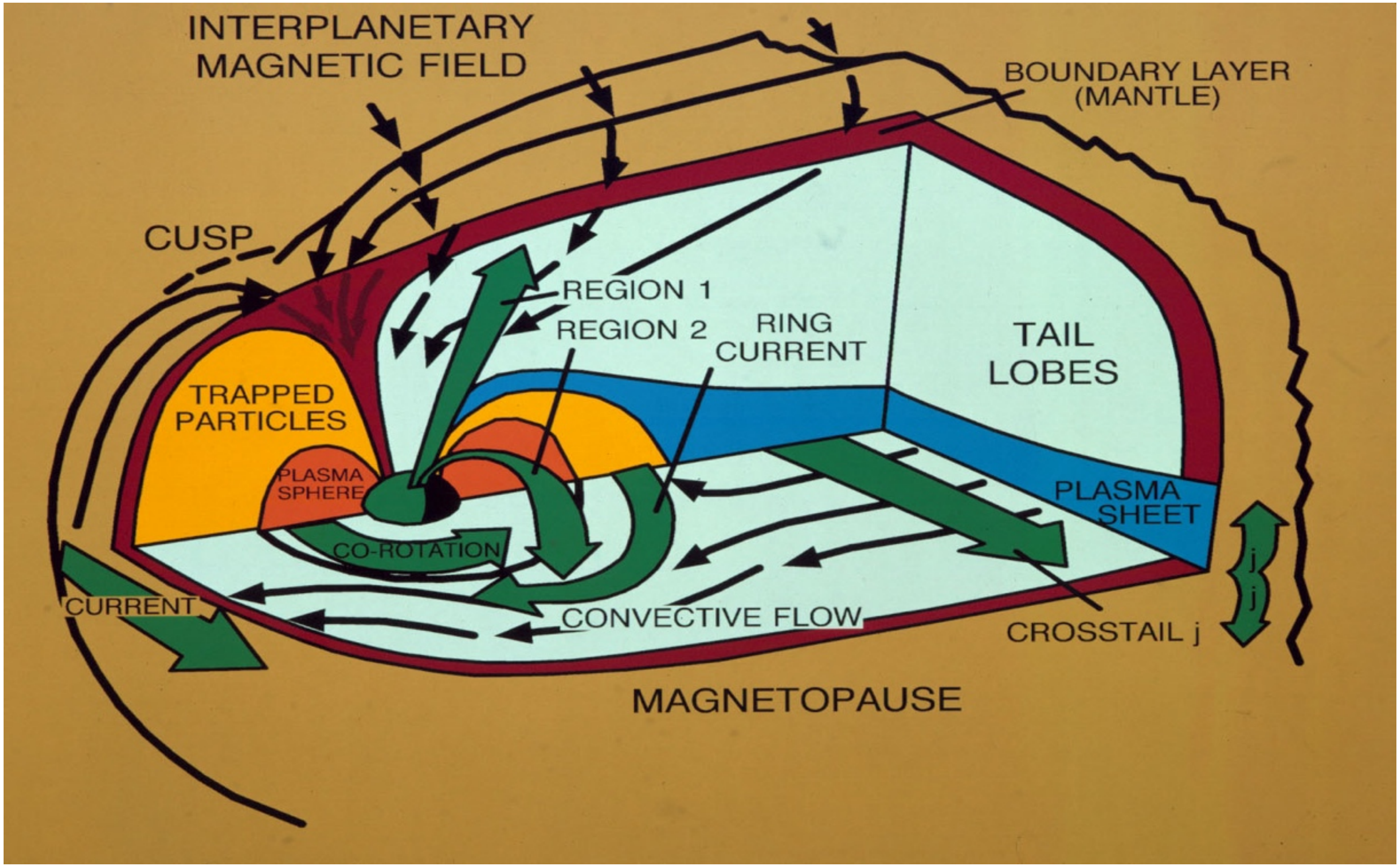
- Neptune : Magnetosphere alternately Earth-like & pole-on
  ⇒ no plasmasphere, mid-latitude aurorae



• **Currents, Magnetosphere - Ionosphere coupling**

$\partial N_i/\partial t + \nabla. N_iV_i = Q_i - L_i \quad \Rightarrow \quad \nabla.J = 0$

$\Rightarrow$ closed current circuits, M-I coupling (region 2)



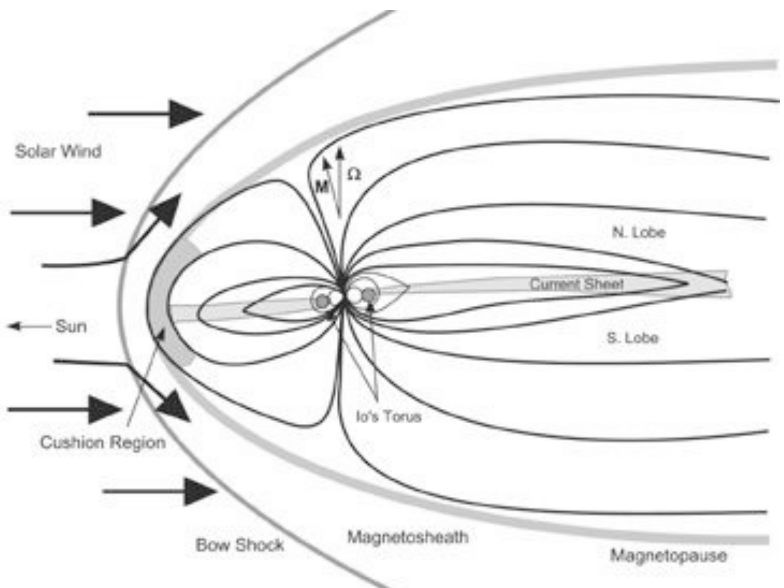
• Currents, Magnetosphere - Ionosphere coupling

- Plasma sources vs Synchronous orbit (where $F_{centrifugal} = F_{gravitation}$)

Planet	R_p [km]	Ω [rads/s]	G_{surf} [ms^{-2}]	R_{synch}/R_{planet}	Plasma sources
Mercury	2440	1.24×10^{-6}	3.3	96	None
Earth	6371	7.29×10^{-5}	9.8	6.6	Ionosphere
Jupiter	70000	1.77×10^{-4}	25.6	2.3	Io
Saturn	60000	1.71×10^{-4}	10.8	1.8	Rings, moons
Uranus	25500	1.01×10^{-4}	8.6	3.2	Moons
Neptune	24830	1.01×10^{-4}	10.1	3.4	Moons

[Russell, 2004]

- At Jupiter : extended current disk



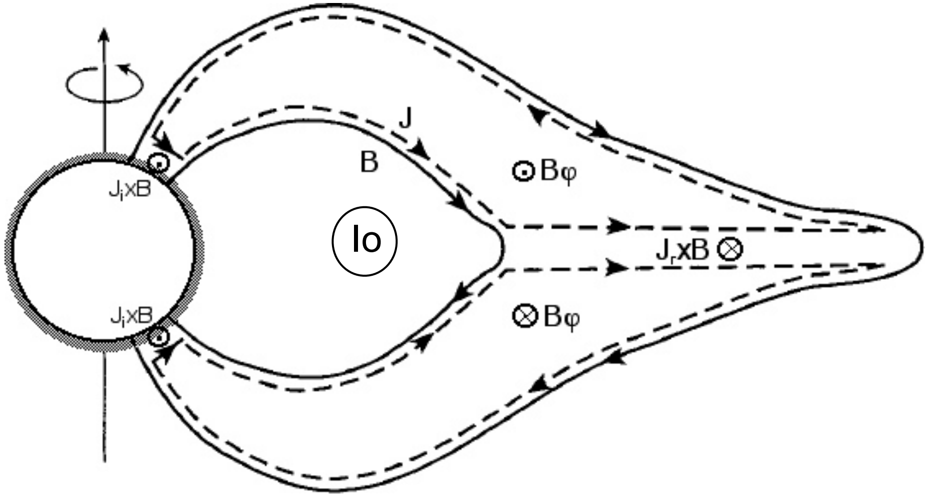
- **Currents, Magnetosphere - Ionosphere coupling**

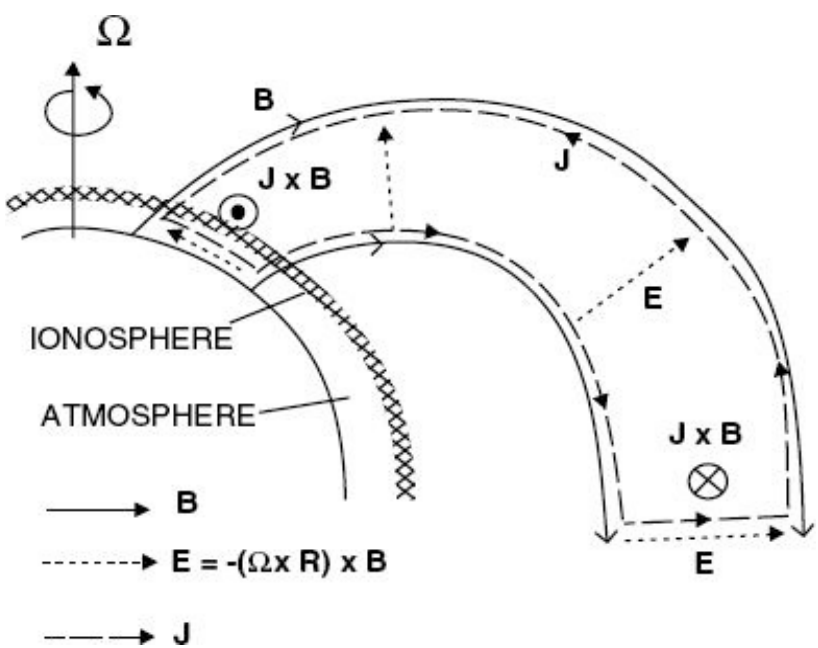
- radial diffusion from Io $\Rightarrow$ J_r

- plasma pick-up + mass-loading, acceleration to corotation by $J_r \times B_{MS}$ at expense of ionospheric plasma momentum via $J_i \times B_i$

$$\nabla.J = 0 \Rightarrow J_i = J_r B_i/B_{MS} \sim 2R^3 J_r \leq \sigma_i E_i \sim \sigma_i \Omega R B_e/R^3 R^{3/2} = \sigma_i \Omega B_e/R^{1/2}$$

$$\Rightarrow \text{possible as long as } J_r \leq \sigma_i \Omega B_e/2R^{7/2}$$



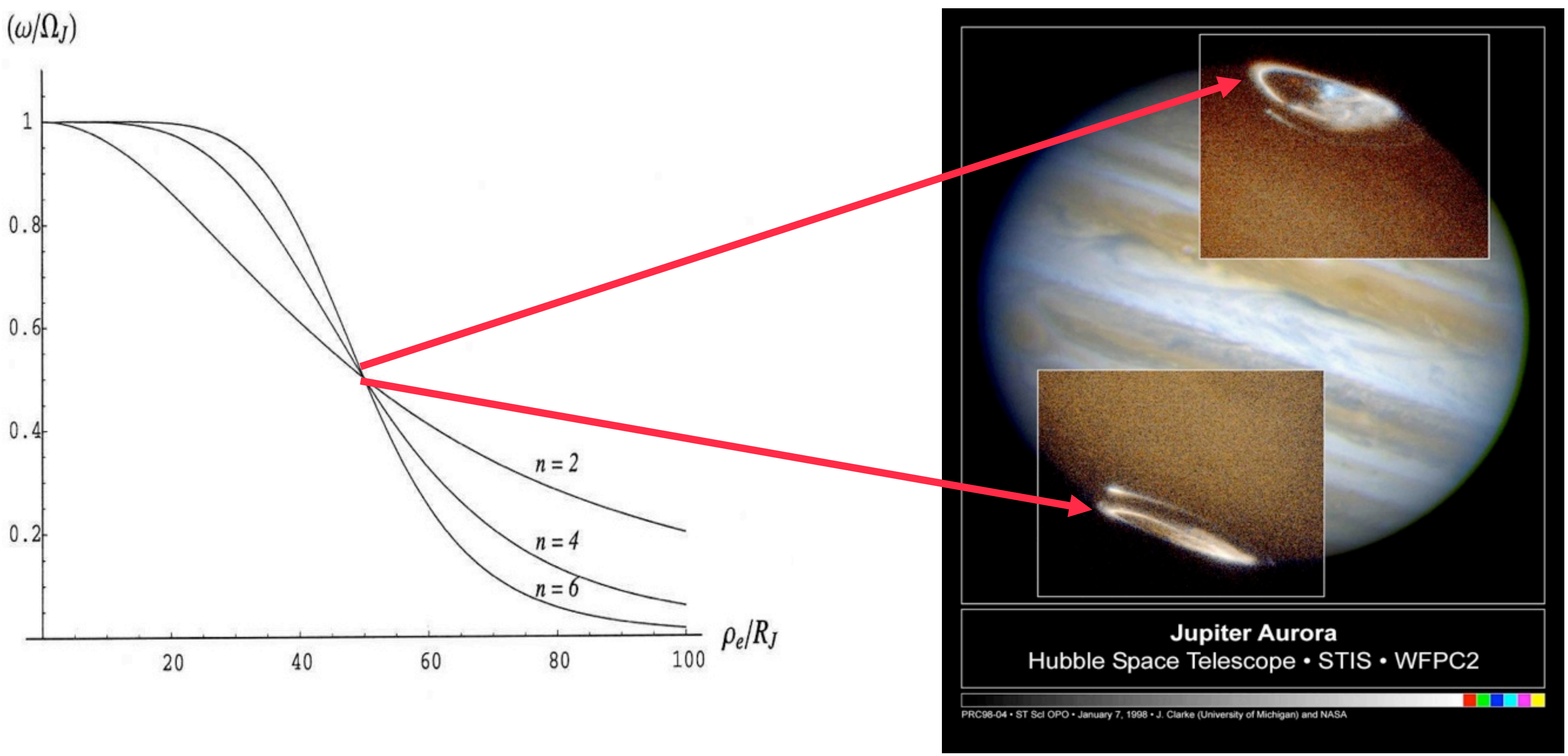


[Bagenal, 1989]

• **Currents, Magnetosphere - Ionosphere coupling**

- Corotation breakdown at 20-50 R_J

$\Rightarrow J_{//}$ max $\Rightarrow$ main auroral oval at Jupiter



[Cowley & Bunce, 2001]

- **Magnetosphere-Satellites coupling**

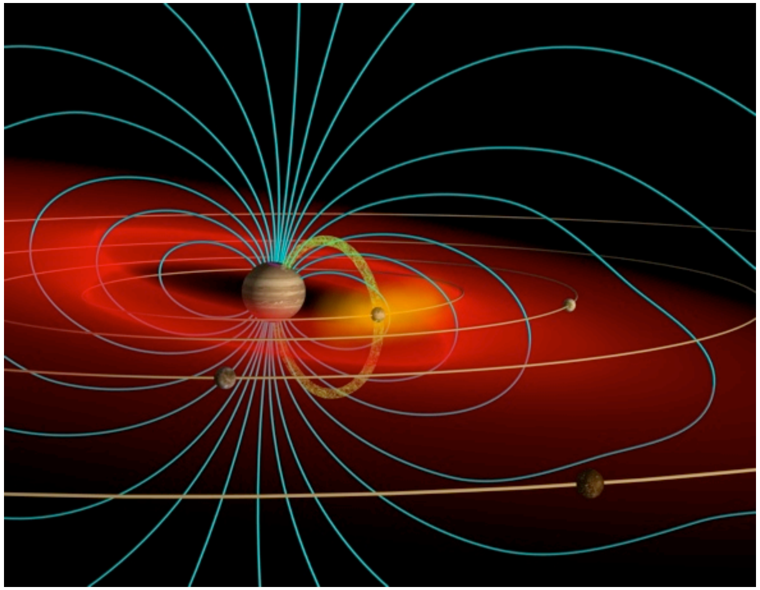
- Unmagnetized satellite / MS interaction *[Saur et al., 2004]*

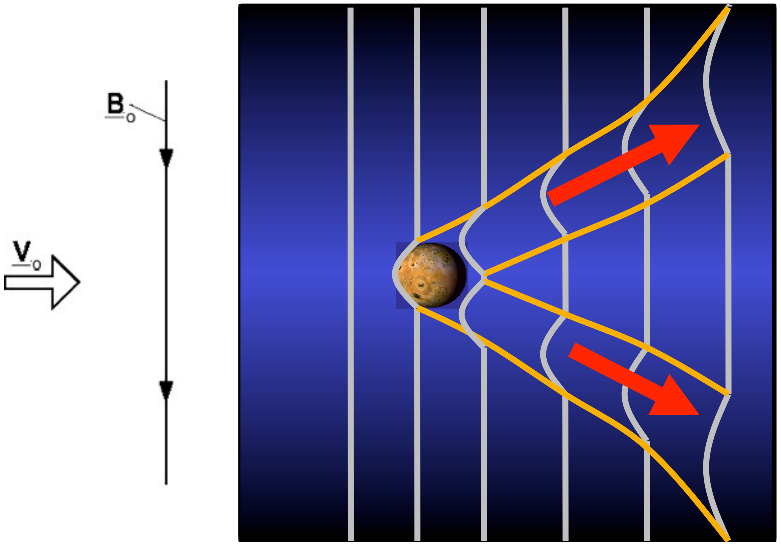
$E = -V \times B_J$ with $V = V_{corot} - V_K$ (=57 km/s @ Io)

$\Delta\phi \sim 2 R_{sat} E$ (=4×10^5 V @ Io) $\Rightarrow$ induced current (a few 10^6 A)

$M_A < 1$ (no bow shock) $\Rightarrow$ Alfvén wings / unipolar inductor ?

[Goldreich & Lynden-Bell, 1969; Neubauer, 1980]



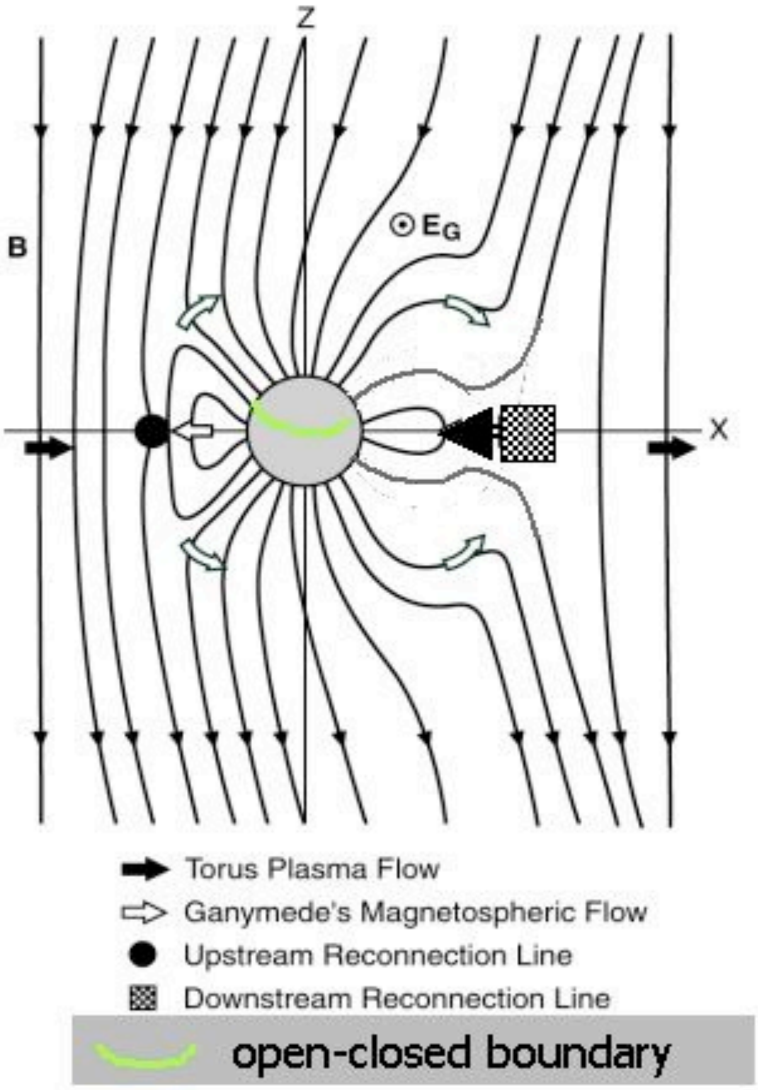


Flow dominated by magnetic energy, dissipated powed : $P_d = \varepsilon B_J^2/\mu_o V \pi R_{obs}^2$

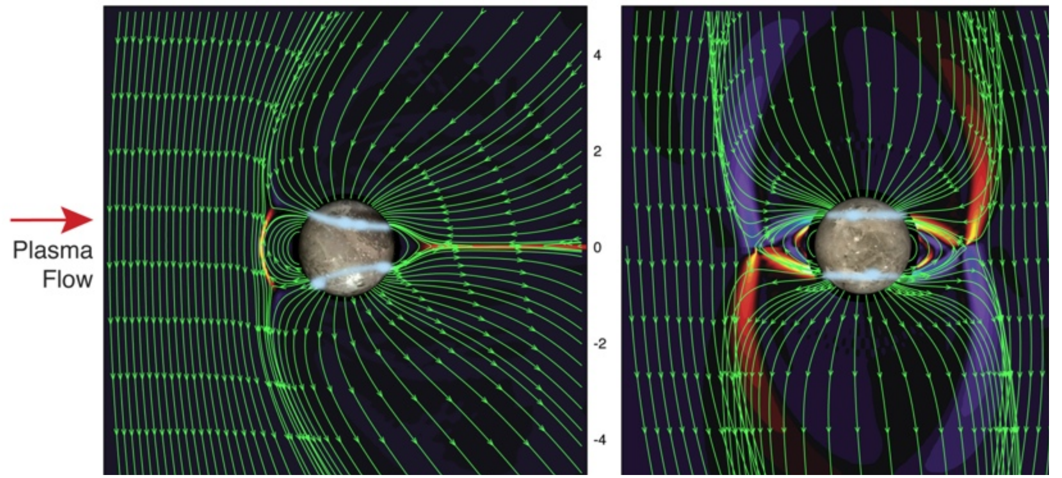
($\varepsilon \sim M_A = 0.1 - 0.2$)

• **Magnetosphere-Satellites coupling**

- <u>Magnetized satellite / MS interaction</u> : B reconnection



[Kivelson et al., 2004]



Dissipated powed :

$$P_d = \varepsilon\, k\, B_J^2/\mu_o\, V \;\; \pi R_{obs}^2$$

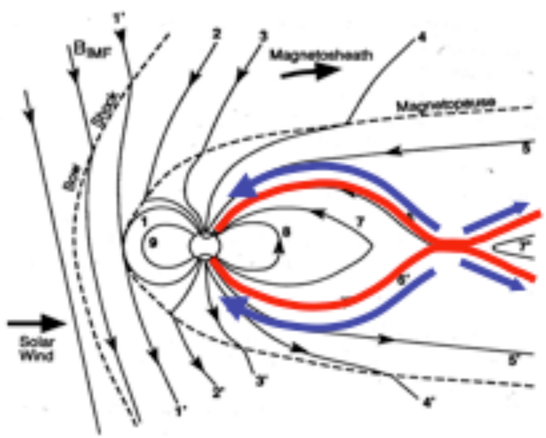
$$(k = \cos^4(\theta/2) = 1 \; ; \; \varepsilon = 0.1 - 0.2)$$

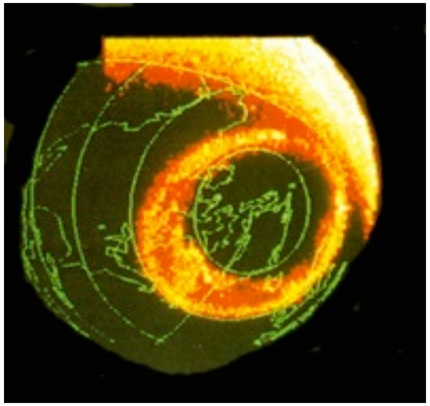
- Planetary Magnetic Fields
- Magnetospheric structure
- Magnetospheric dynamics
- Electromagnetic emissions
- Exoplanets

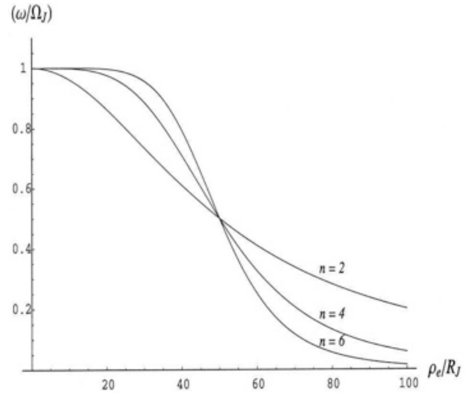
- **Aurorae**

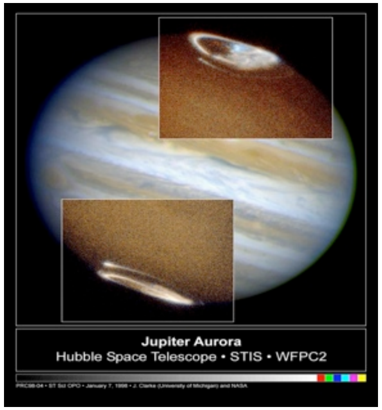
  - reconnection at limit open / closed B lines at Earth
  - corotation breakdown at Jupiter
  - ? at Saturn

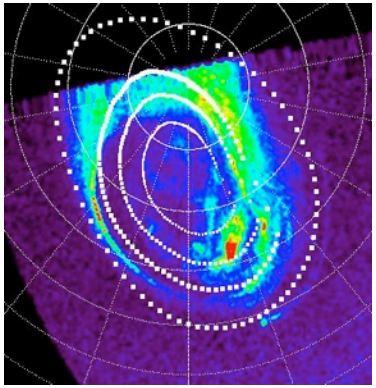
  ⇒ e- acceleration 1-10 keV ⇒ visible (O, N, N_2) & UV (H, H_2) aurorae





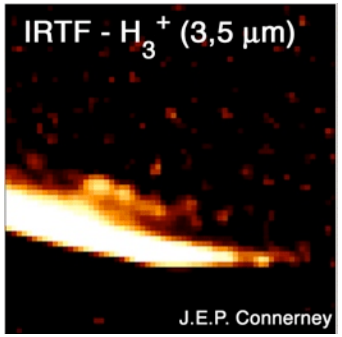


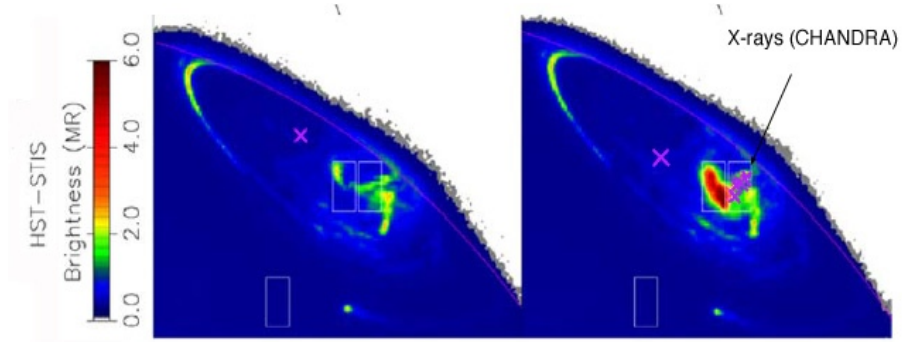


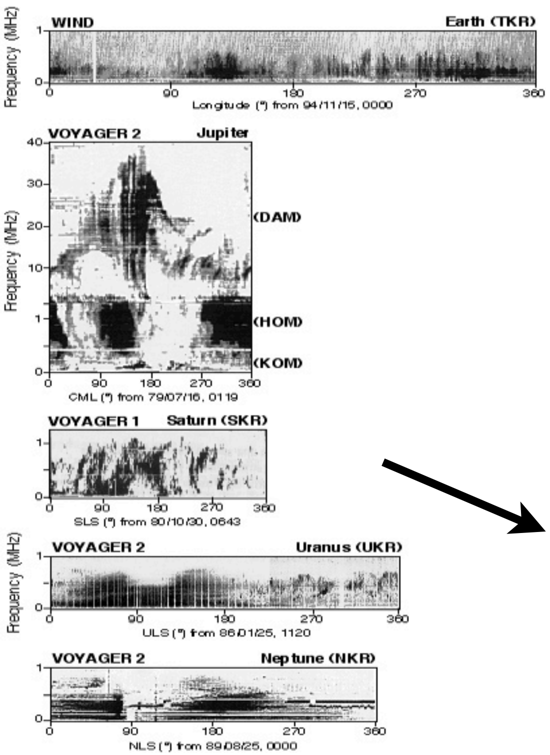


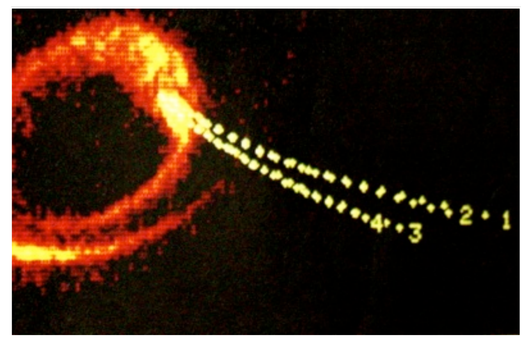
- **Aurorae**

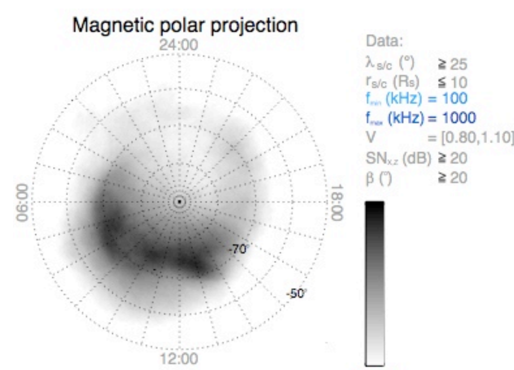
  - IR, X and radio counterparts

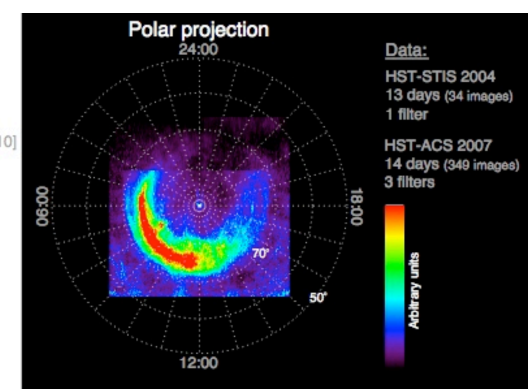












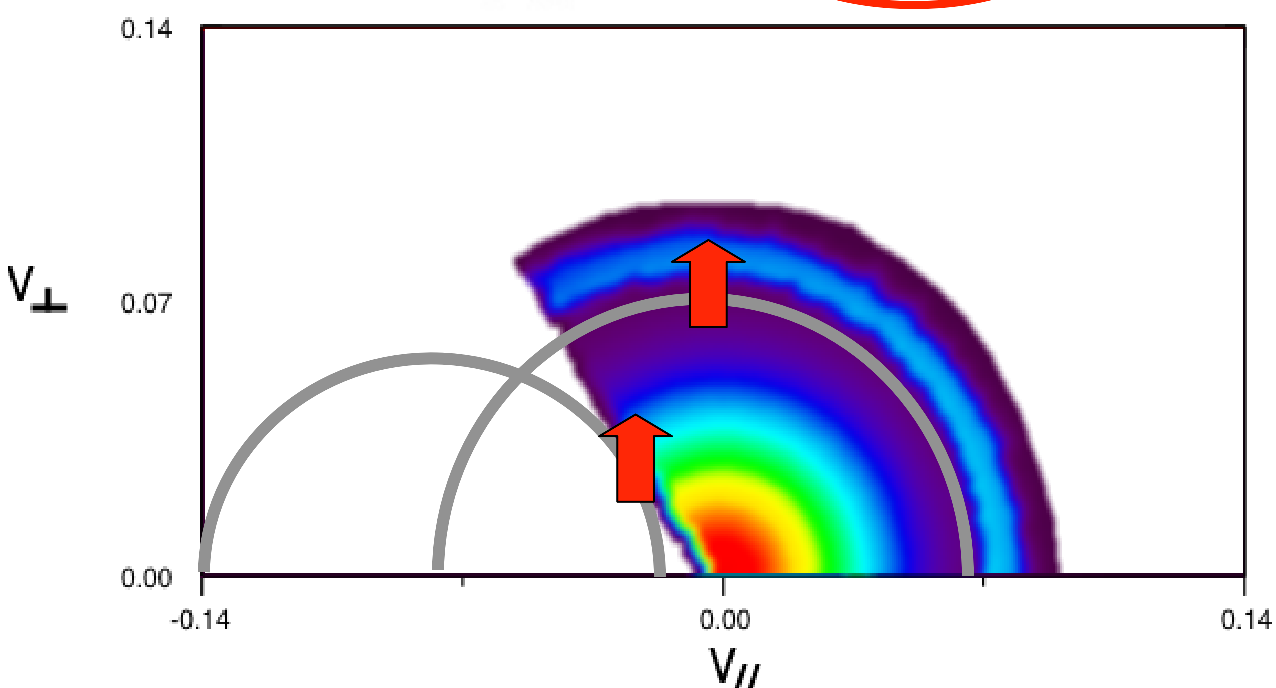
- **Radio emission process** : the Cyclotron Maser Instability

  - Emissions intense ($T_B \geq 10^{15\text{-}20}$ K), broadband ($f \sim f_{ce}$), 100% elliptical consistent with X mode, very anisotropic (widely open hollow cone)

  - Sources where B, $f_{pe} << f_{ce}$, unstable keV e^- distributions (high latitude)

Resonance condition : $\omega = \omega_c / \Gamma - k_{\|} v_{\|}$

Growth rate : $\gamma = \frac{\omega_p^2}{8\omega_c} \int_0 v_{\perp}^2(\theta) \nabla_{v_{\perp}} f(\mathbf{v}_0, \mathbf{R}(\theta)) d\theta$

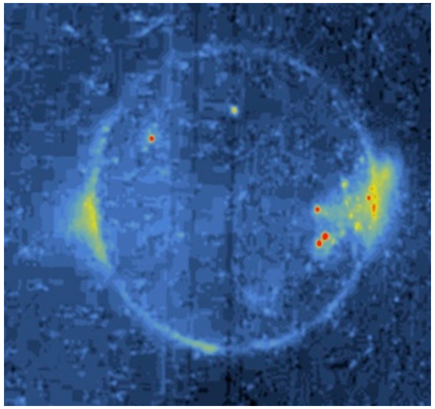


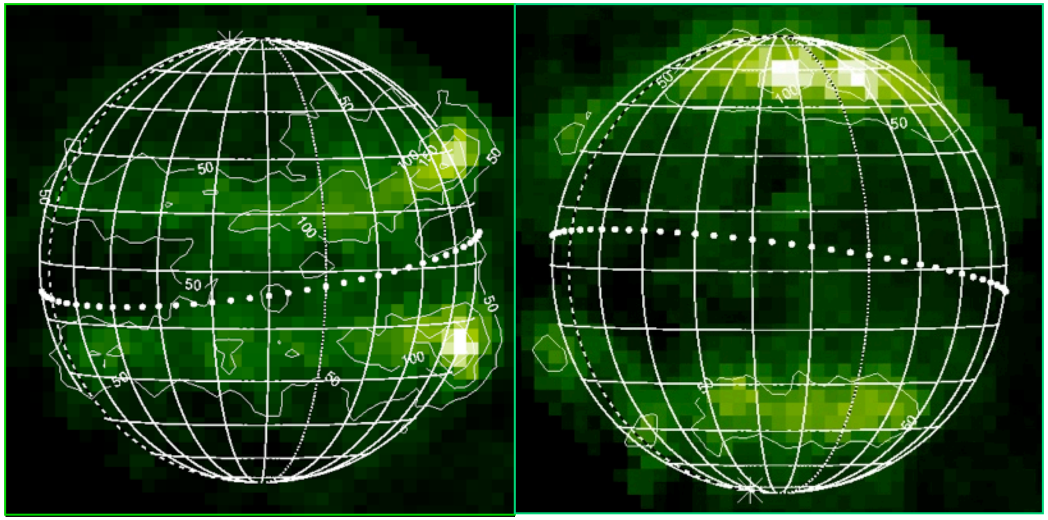
[Wu, 1985]

- **Satellite-induced emissions)**

  - strong currents + low plasma density *[Knight, 1972]*

  ⇒ e- acceleration 1-10 keV ⇒ auroral-like emissions





Downstream / Upstream

[Feldman et al., 2000 ; McGrath et al., 2002]

- Planetary Magnetic Fields
- Magnetospheric structure
- Magnetospheric dynamics
- Electromagnetic emissions
- Exoplanets

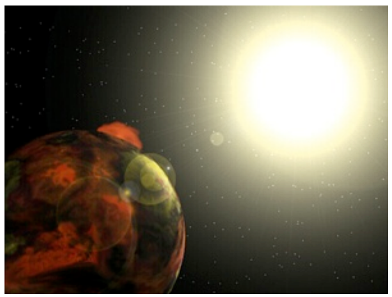
~862 exoplanets (in >678 systems)

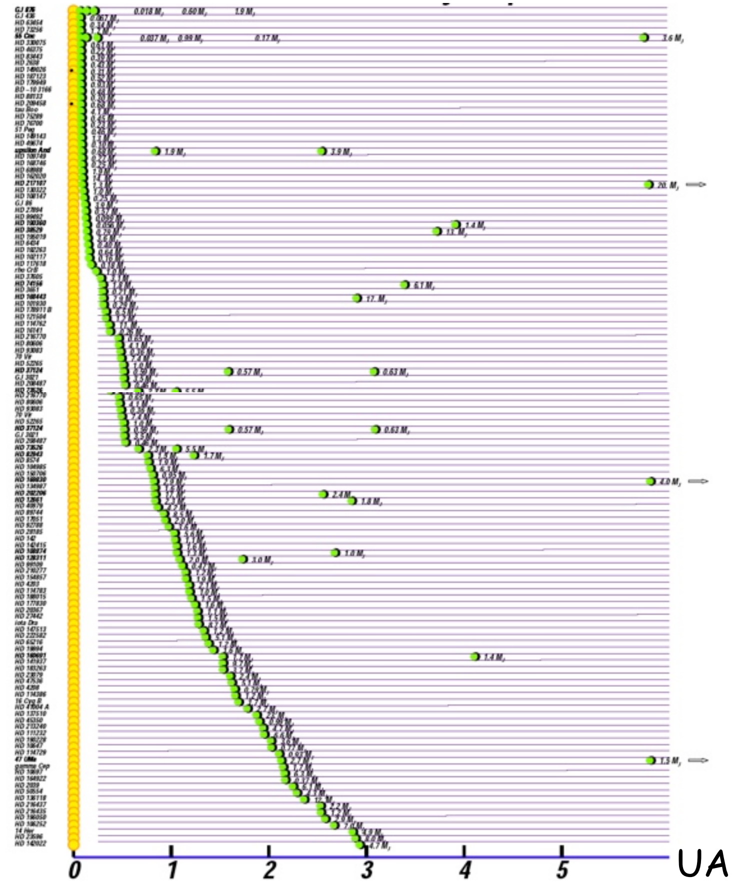
~157 (18%) with a ≤ 0.05 AU = 10 Rs

« hot Jupiters »

~272 (32%) with a ≤ 0.1 AU

exoplanet.eu





B field at Solar surface :

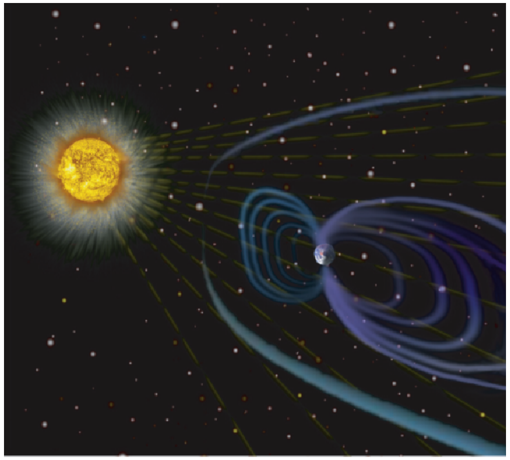
→ large scale ~1 G

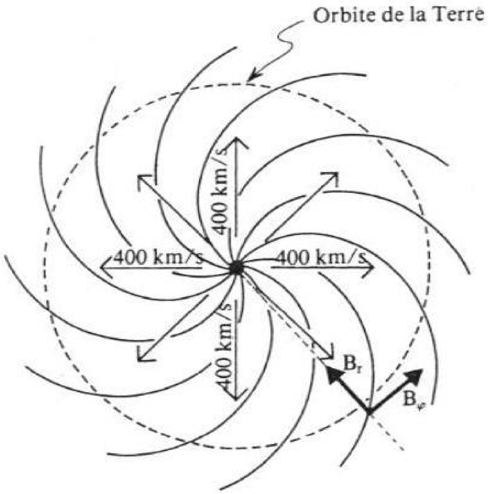
→ magnetic loops ~10^3 G over a few % of the surface

Magnetic stars : > 10^3 G

(cf. ESPADONS / NARVAL measurements)

• **Types of interaction** : Magnetospheric interaction



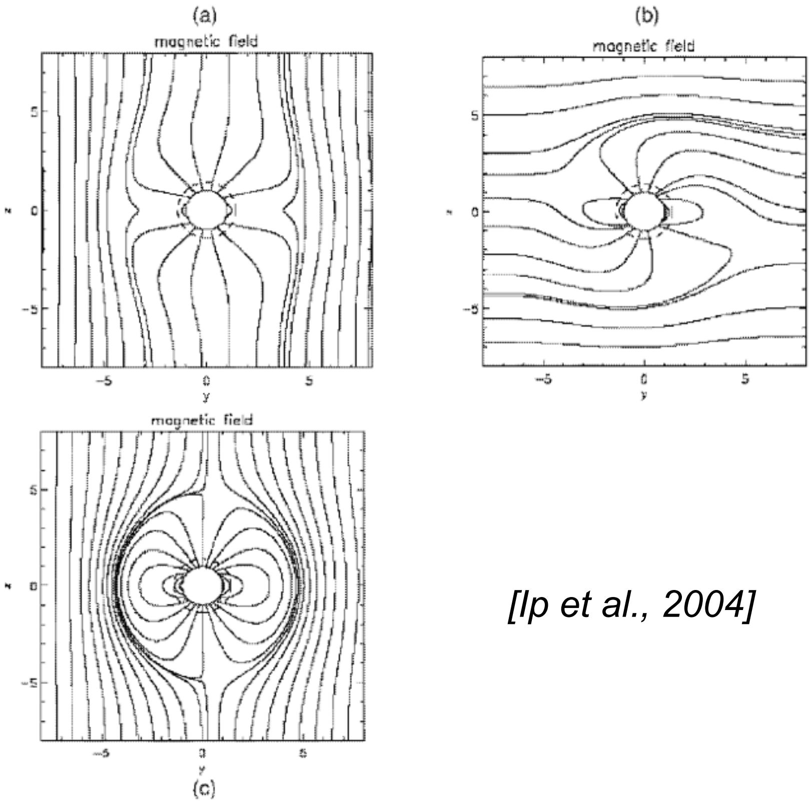


Poynting flux of B_{IMF} on obstacle :

$$P_m = B_\perp^2/\mu_o \; V \;\; \pi R_{obs}^2$$

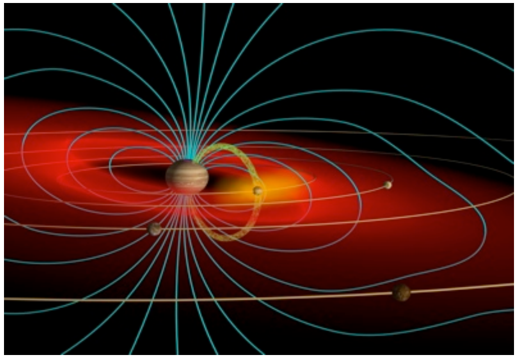
Dissipated power :

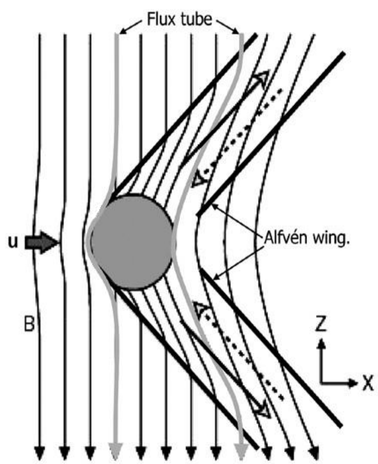
$$P_d = \varepsilon \, P_m \qquad (\varepsilon = 0.1 - 0.2)$$



[Ip et al., 2004]

• **Types of interaction** : Unipolar inductor



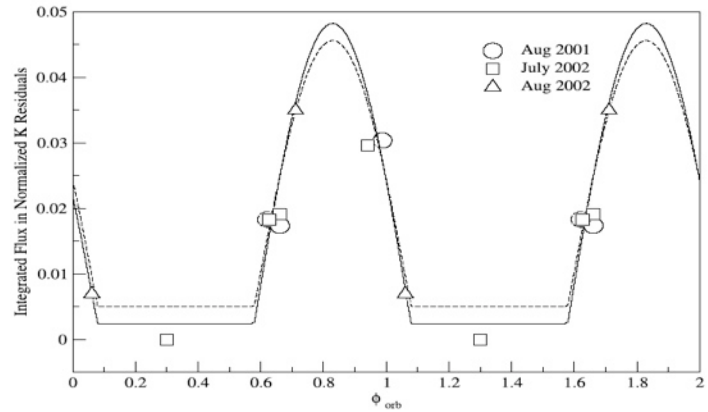


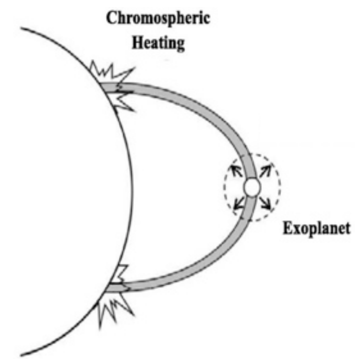
Dissipated power :

$P_d = \varepsilon \, V B_\perp^2/\mu_o \, \pi R_{obs}^2 = \varepsilon \, P_m$

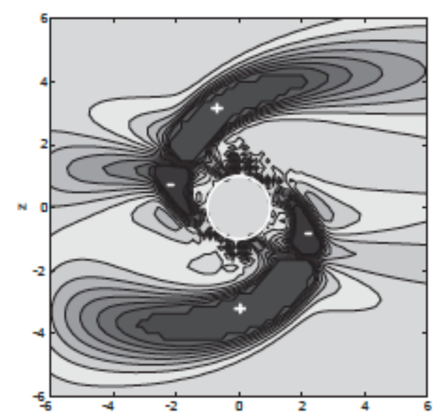
($\varepsilon \sim M_A = 0.1 - 0.2$)

Chromospheric hot spot on HD179949 & υ And ?



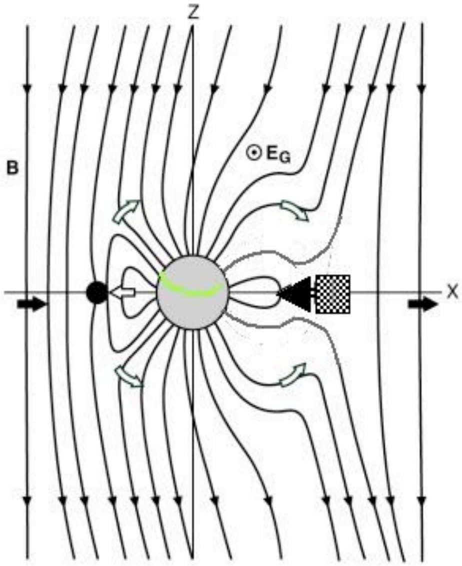


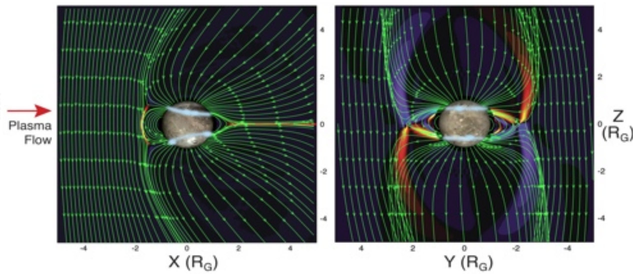
[Shkolnik et al., 2005, 2008]

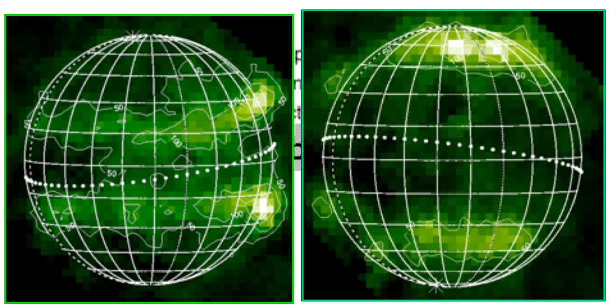


[Preusse et al., 2006]

• **Types of interaction** : Dipolar interaction







Downstream

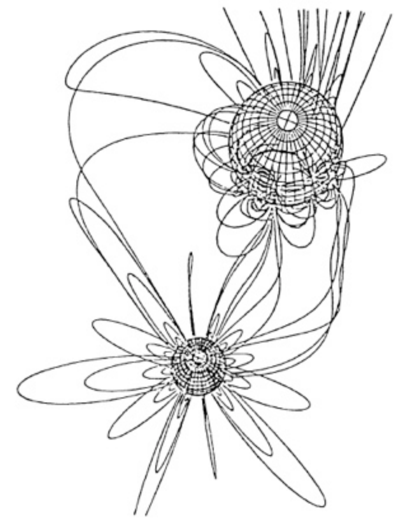
Upstream

Dissipated power :

$$P_d = \varepsilon\, k\, V B_\perp^2/\mu_o\, \pi R_{obs}^2 = \varepsilon\, k\, P_m$$

$(k = \cos^4(\theta/2) = 1\ ;\ \varepsilon = 0.1 - 0.2)$

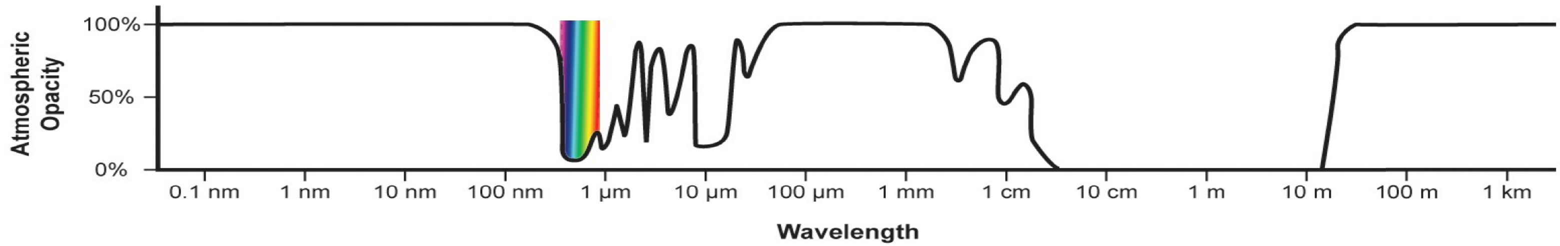
Interacting magnetic binaries or star-planet systems

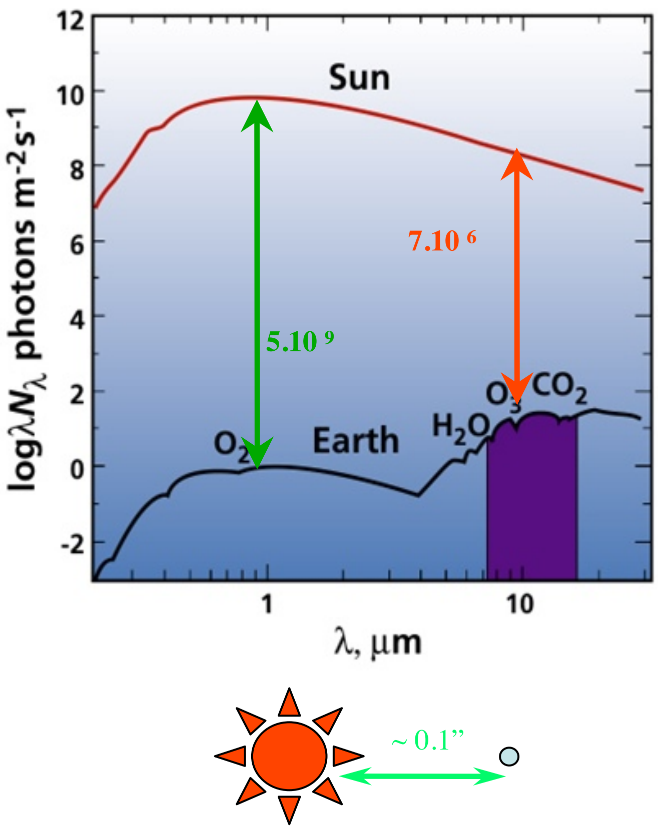


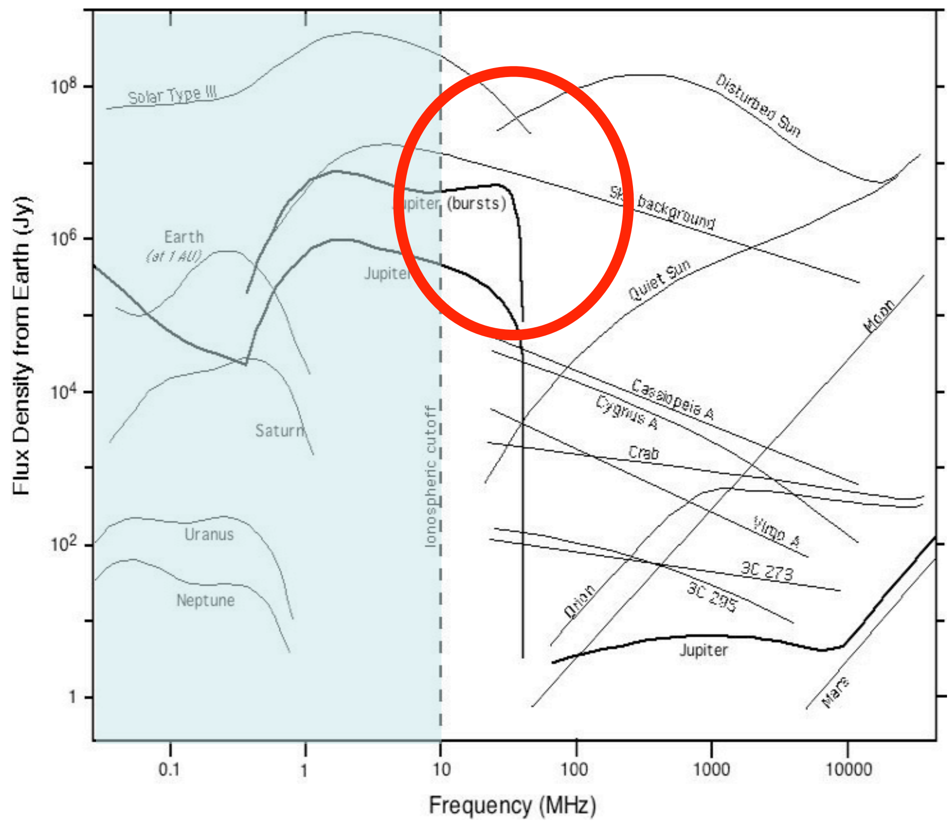
• **Electromagnetic emissions**

UV ?

Radio ?

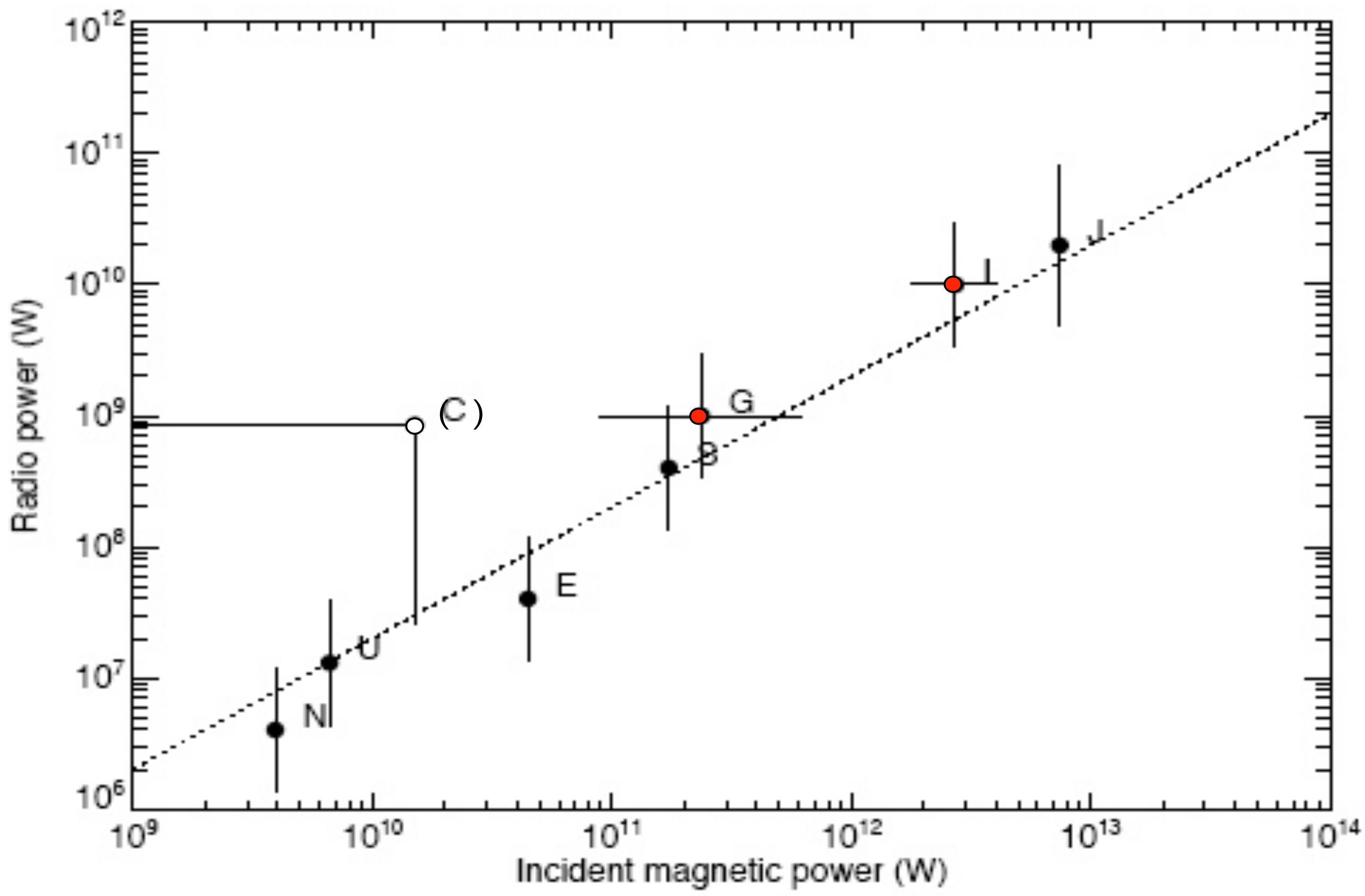






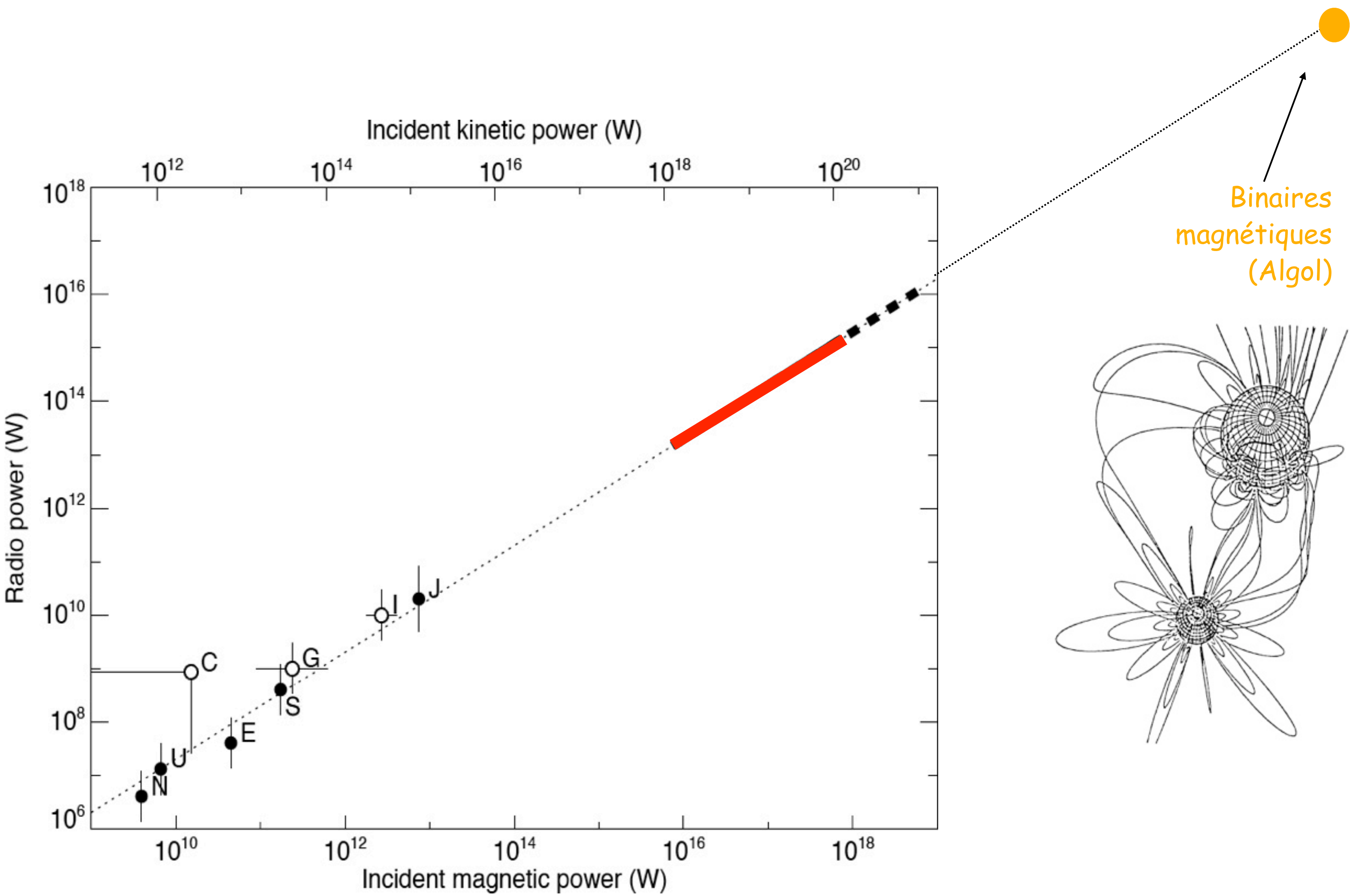
• **Electromagnetic emissions** : Radio-Magnetic Bode's law

∀ radio emission $P_{Radio} \sim \eta \times P_m$ with $\eta \sim 2\text{-}10 \times 10^{-3}$



[Zarka et al., 2001, 2007]

• **Electromagnetic emissions** : Radio-Magnetic Bode's law



Hot Jupiters ⇒ $P_{Radio} = P_{Radio\text{-}J} \times 10^{3\text{-}5}$ (except if saturation or magnetic field decay)

[Zarka et al., 2001, 2007]

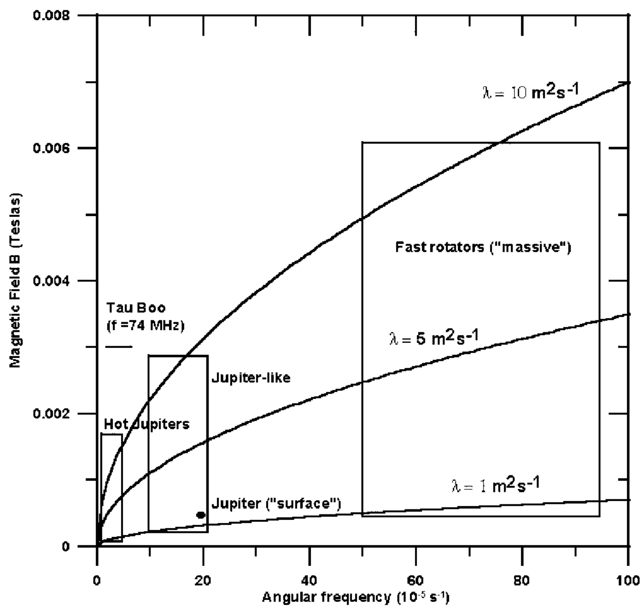
• **Magnetic field decay for hot Jupiters ?**

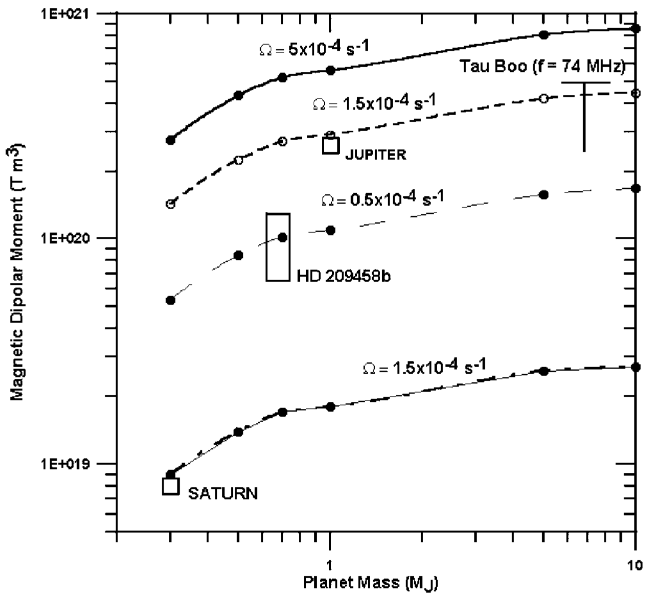
- Spin-orbit synchronisation (tidal forces) ⇒ ω↓

but $M \propto \omega^{\alpha}$ with ½ ≤ α ≤ 1 ⇒ M↓ (B decay) ?

- Internal structure + convection models

⇒ self-sustained dynamo ⇒ M could remain ≥ a few $G.R_J^3$





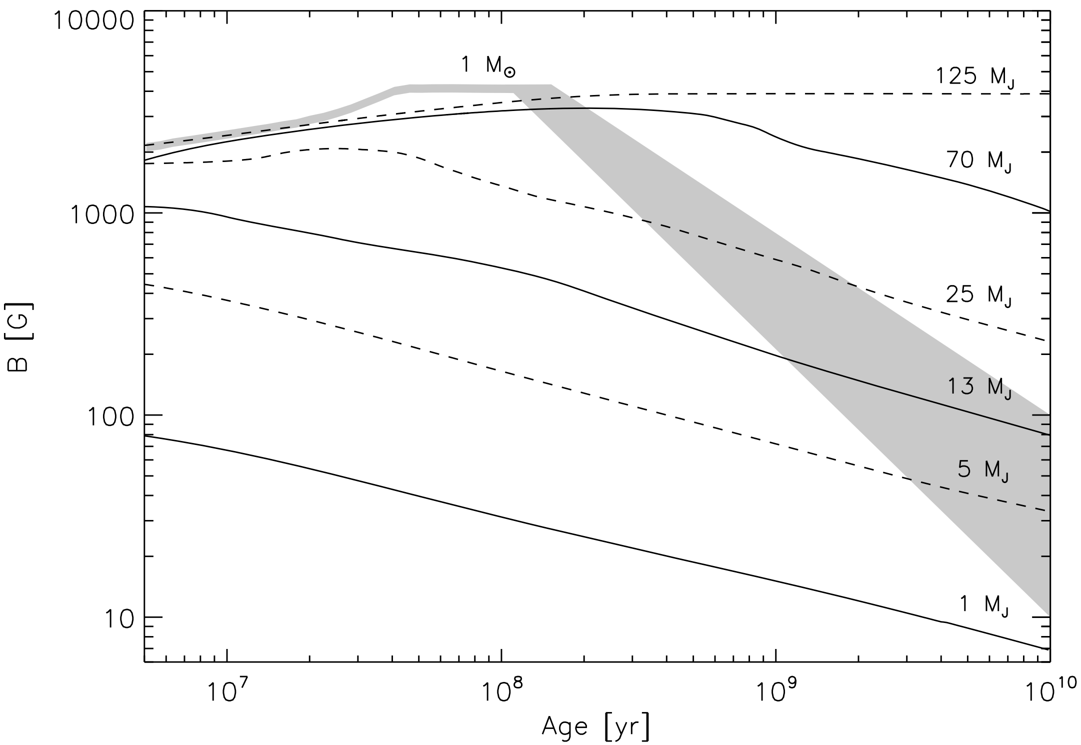
Upper Limit of Magnetic Fields in Hot Jupiters

Planet	M (M_J)	P_{orb} (days)	R (R_J)	M_D (G m^3)	B_s (G)
HD 179949b[a]	0.84	3.093	1.3	1.1×10^{24}	1.4
HD 209458b	0.69	3.52	1.43	0.8×10^{24}	0.8
τ Boo b[a]	3.87	3.31	1.3	1.6×10^{24}	2
OGLE-TR-56b	0.9	1.2	1.3	2.2×10^{24}	2.8

[Sanchez-Lavega, 2004]

• Magnetic field decay for hot Jupiters ?

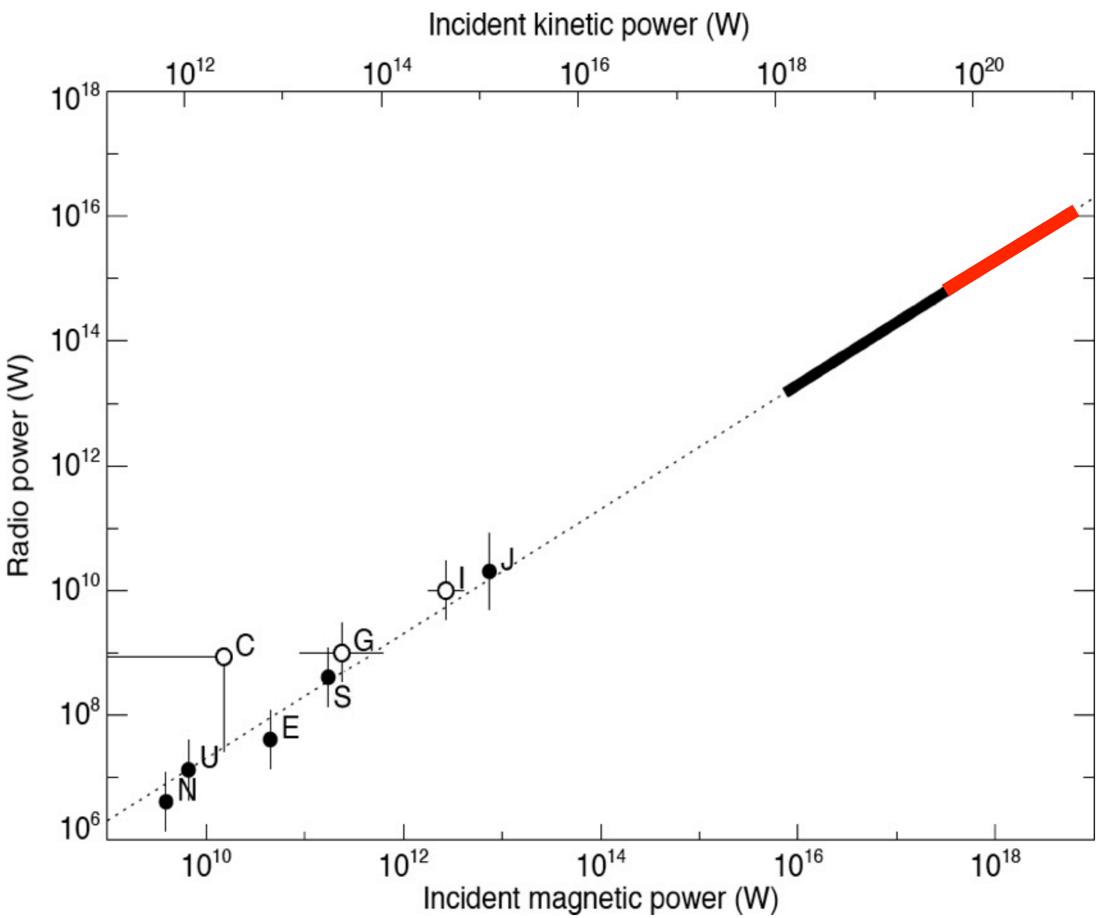
- Scaling for fast rotators

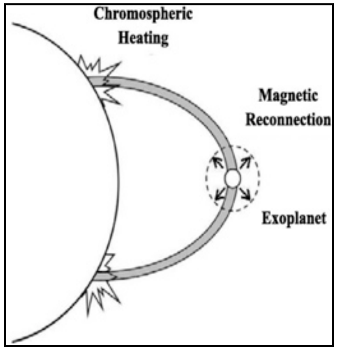


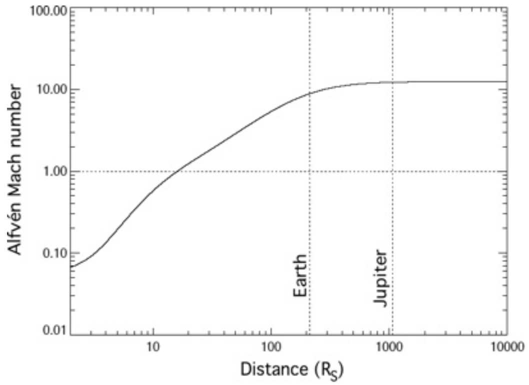
Planet name	Planet mass [$M_{\rm Jup} \sin i$]	a [AU]	d^1 [pc]	$\dot{M}$ [$\dot{M}_\odot$]	Age [Gyr]	$B_{\rm dip}^{\rm pol}$ [G]
Jupiter	1.00	5.20		1.0	4.5	9
eps Eridani b	1.55	3.39	3.2	25.9	1.7	19
Gliese 876 b	1.93	0.21	4.7	0.1	2.4	23
Gliese 876 c	0.56	0.13	4.7	0.1	2.4	6
GJ 832 b	0.64	3.40	4.9	0.2	2.0	7
HD 62509 b	2.90	1.69	10.3	0.3	5.6	24
Gl 86 b	4.01	0.11	11.0	9.4	2.9	40
HD 147513 b	1.00	1.26	12.9	150.4	0.8	15
ups And b	0.69	0.06	13.5	20.2	1.4	10
ups And c	1.98	0.83	13.5	20.2	1.4	30
ups And d	3.95	2.51	13.5	20.2	1.4	58
gamma Cephei b	1.60	2.04	13.8	1.1	3.6	16
51 Peg b	0.47	0.05	14.7	0.2	6.2	3
tau Boo b	3.90	0.05	15.0	198.5	0.8	58
HR 810 b	1.94	0.91	15.5	103.9	0.8	30
HD 128311 b	2.18	1.10	16.6	39.9	0.9	33
HD 128311 c	3.21	1.76	16.6	39.9	0.9	48
HD 10647 b	0.91	2.10	17.3	22.9	1.4	14
GJ 3021 b	3.32	0.49	17.6	170.2	0.8	49
HD 27442 b	1.28	1.18	18.1	1.9	2.7	14
HD 87883 b	1.78	3.60	18.1	2.6	3.3	19
HD 189733 b	1.13	0.03	19.3	17.3	1.7	14
HD 192263 b	0.72	0.15	19.9	7.1	2.5	8

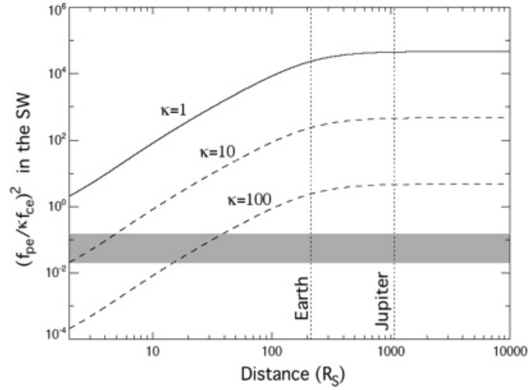
[Reiners & Christensen, 2010]

• **Electromagnetic emissions**









[Zarka et al., 2001, 2007]

Emission radio possible only if $f_{pe}/f_{ce} << 1$

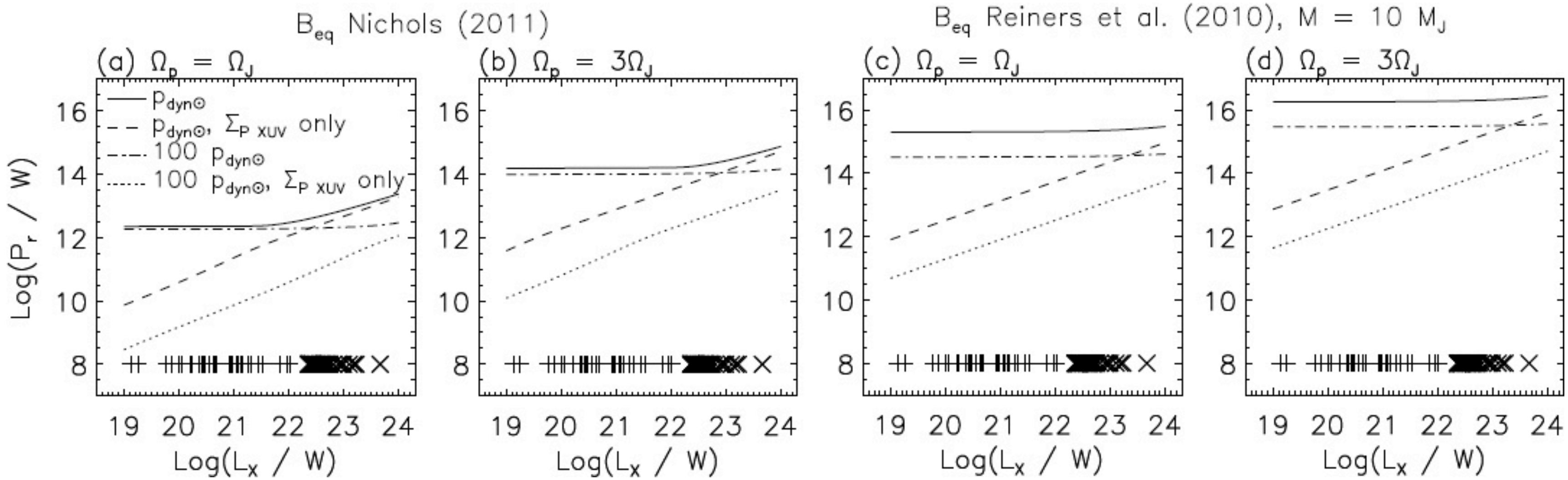
⇒ intense B* required (10-100 x B_{Sun})

⇒ emission ≥ 30-250 MHz at 1-2 R_S

$P_{Radio} = P_J \times 10^5 \times (R_{exo\text{-}ionosphere}/R_{magnetosphere})^2 \times (B_*/B_{Sun})^2 = P_{Radio\text{-}J} \times 10^6$

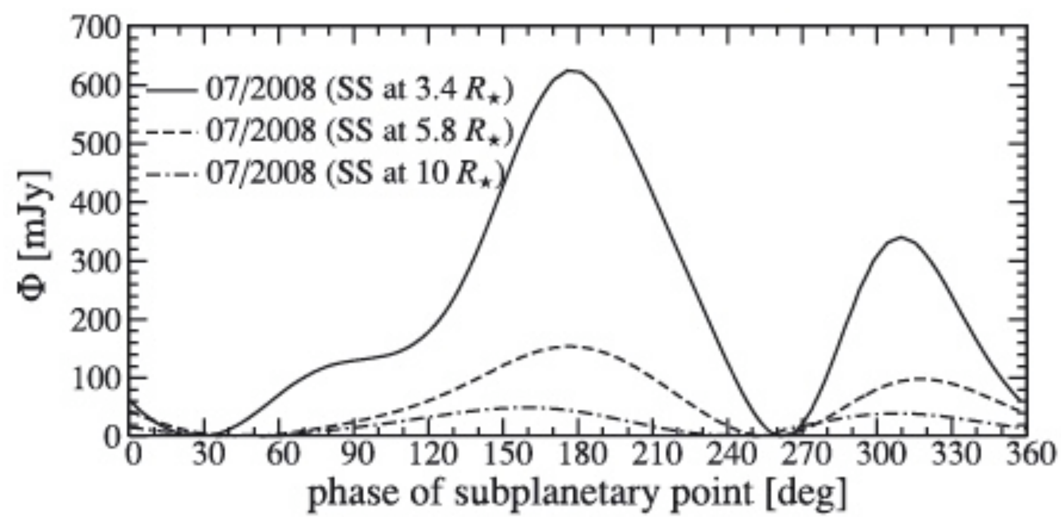
• **Electromagnetic emissions** : other predictions

- M-I coupling for fast rotators *[Nichols, 2011, 2012]*



- Variable SPI for HD 189733 ?

[Farès et al., 2010]



- **Prospects for radio detection**

  - measurement of B ⇒ constraints on internal structure
  - measurement of Prot ⇒ test spin-orbit synchronization
  - possible access to inclination *[Hess & Zarka, 2011]*
  - comparative magnetospheric physics, planet-star plasma interactions
  - implications for exobiology (magnetosphere limits atmospheric erosion by SW and CME, cosmic ray bombardment) *[Griessmeier et al., 2004 ; Khodachenko et al., 2006]*

⇒ LOFAR, UTR-2, GMRT, VLA observations ongoing ...