Observations of Earth & planetary magnetospheres

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• **Magnetospheres** : "object-worlds"

• **Context of ~all studies :**

High plasma conductivity

Maxwell equations + Ohm law $\Rightarrow$ $\partial \boldsymbol{B}/\partial t = \eta \nabla^2 \boldsymbol{B} - \boldsymbol{B}(\nabla.\boldsymbol{V}) \approx - \boldsymbol{B}(\nabla.\boldsymbol{V})$

$\Rightarrow$ B frozen-in

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

$\Rightarrow$ quasi-neutrality

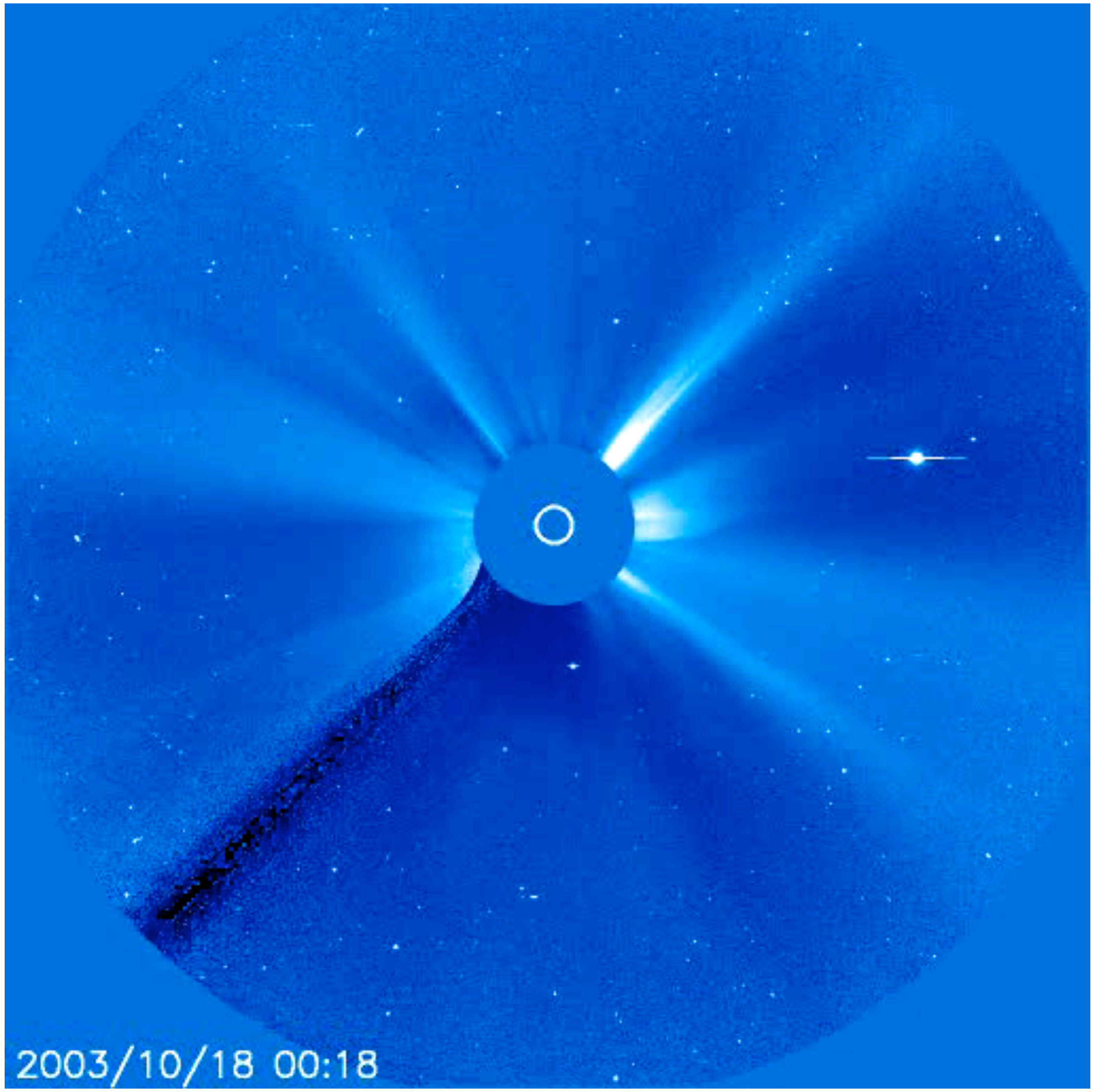
& $\boldsymbol{E}.\boldsymbol{B}=0$ (Δφ conserved along B lines, = electric equipotentials)

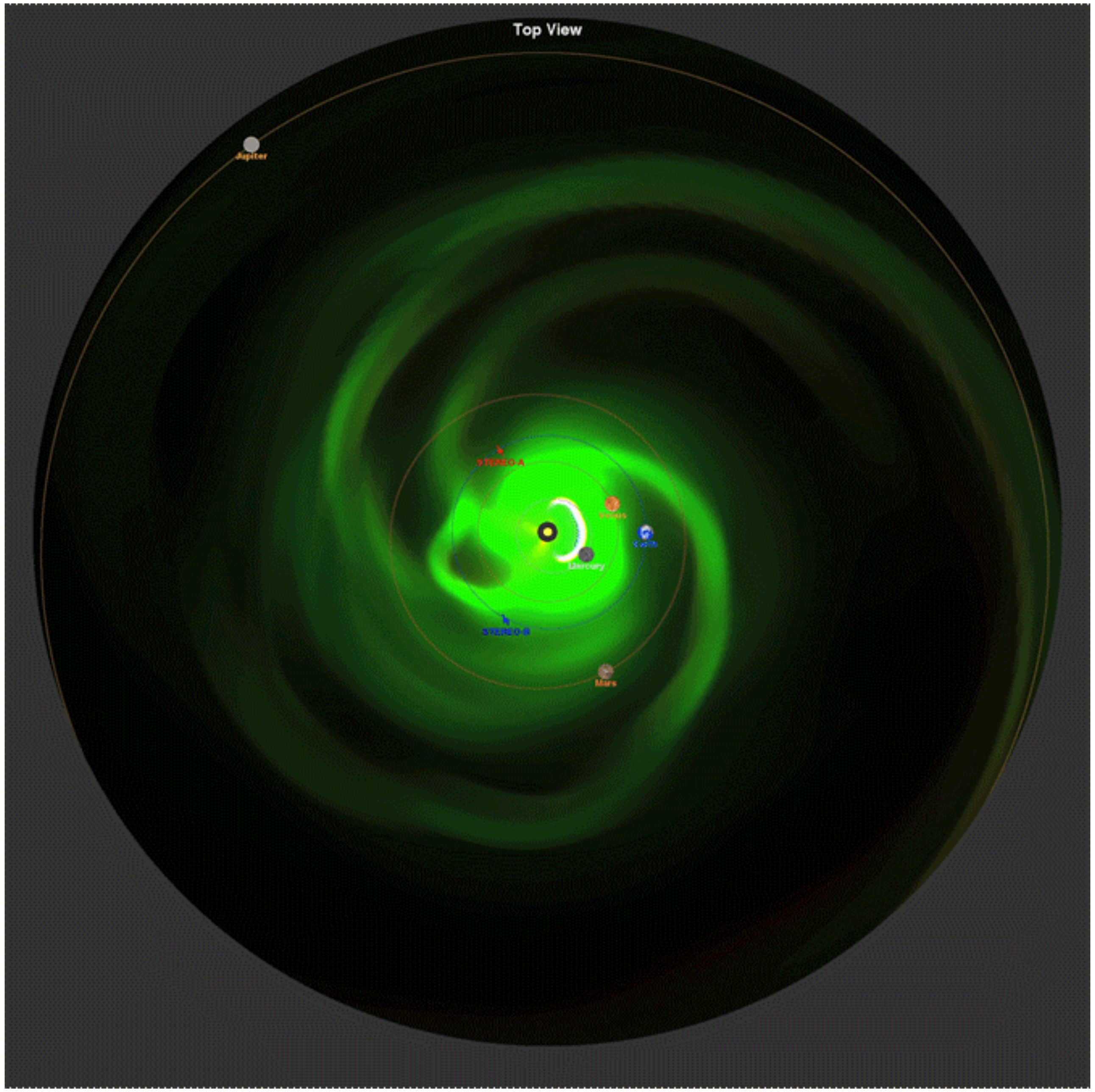
• Kivelson, M. G. & C. T. Russell, eds., *Introduction to Space Physics,* Cambridge University Press, **1995**.

• Encrenaz, T., J. -P. Bibring, M. Blanc, A. Barucci, F. Roques & P. Zarka, *Le système solaire (3ème édition),* Savoirs Actuels, EDP-Sciences / CNRS-Éditions, Paris, **2003.**

- Solar Wind
- Planetary magnetic fields
- Origin & size of the magnetospheres
- Magnetospheric dynamics
- Currents, M-I & M-S coupling
- Aurora and radio emissions
- Radiation belts
- Radio Observations & simulations
- Application to Exoplanets
- Perspectives

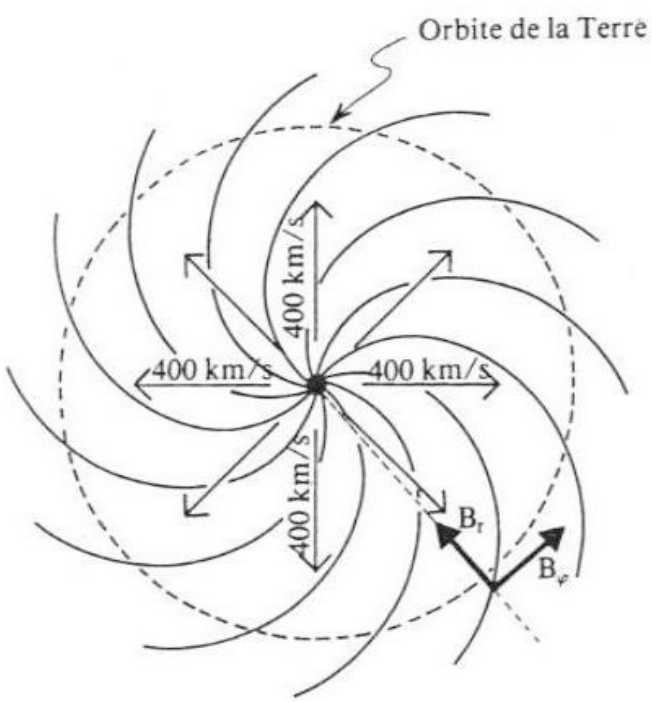
Solar wind

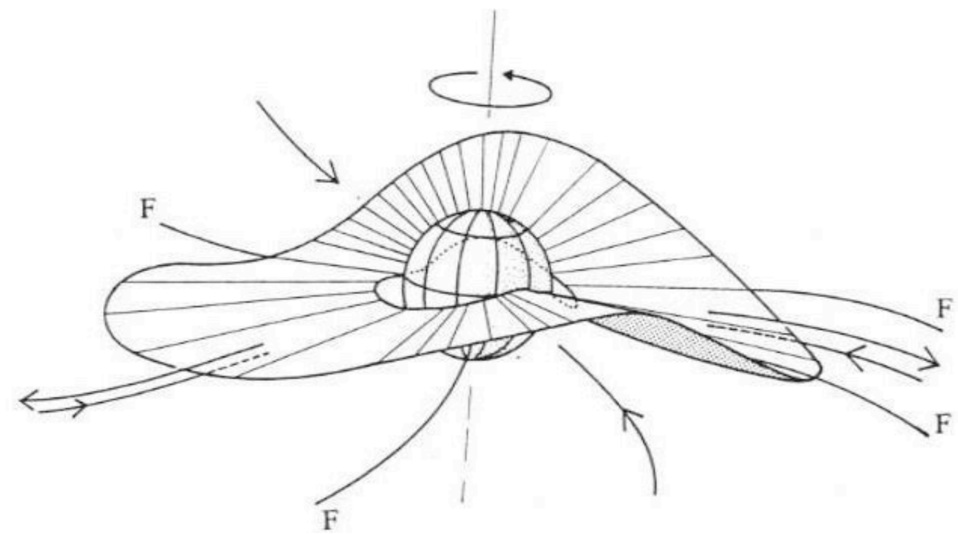




• **Solar Wind**

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





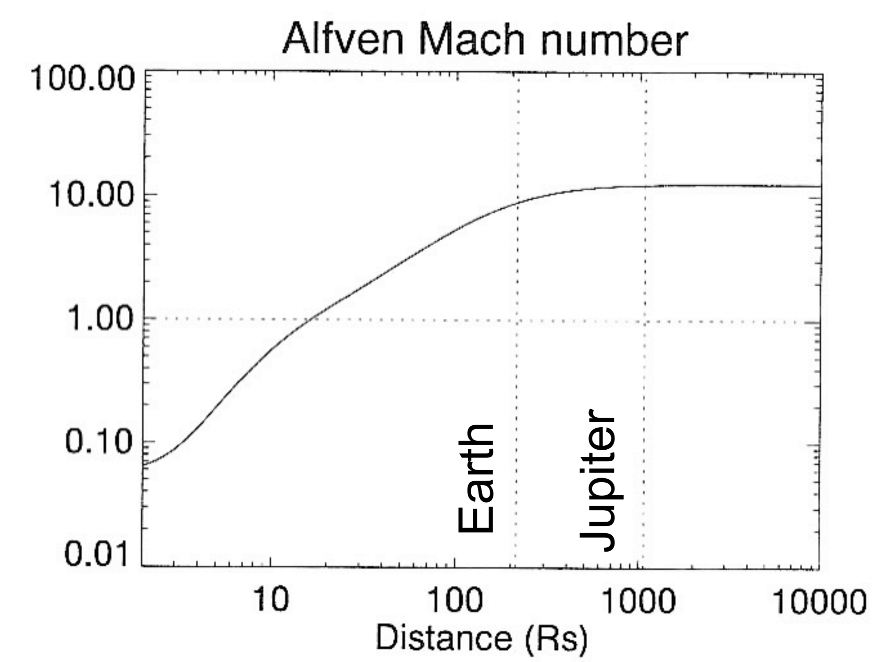
- SW parameters at planetary orbits (r in AU) :

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

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

$B_r = 3/r^2$ nT $\quad$ $B_\phi = B_r\Omega r/V = 3/r$ nT

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



• **Solar Wind - Obstacle interaction**

- depends on nature of obstacle :

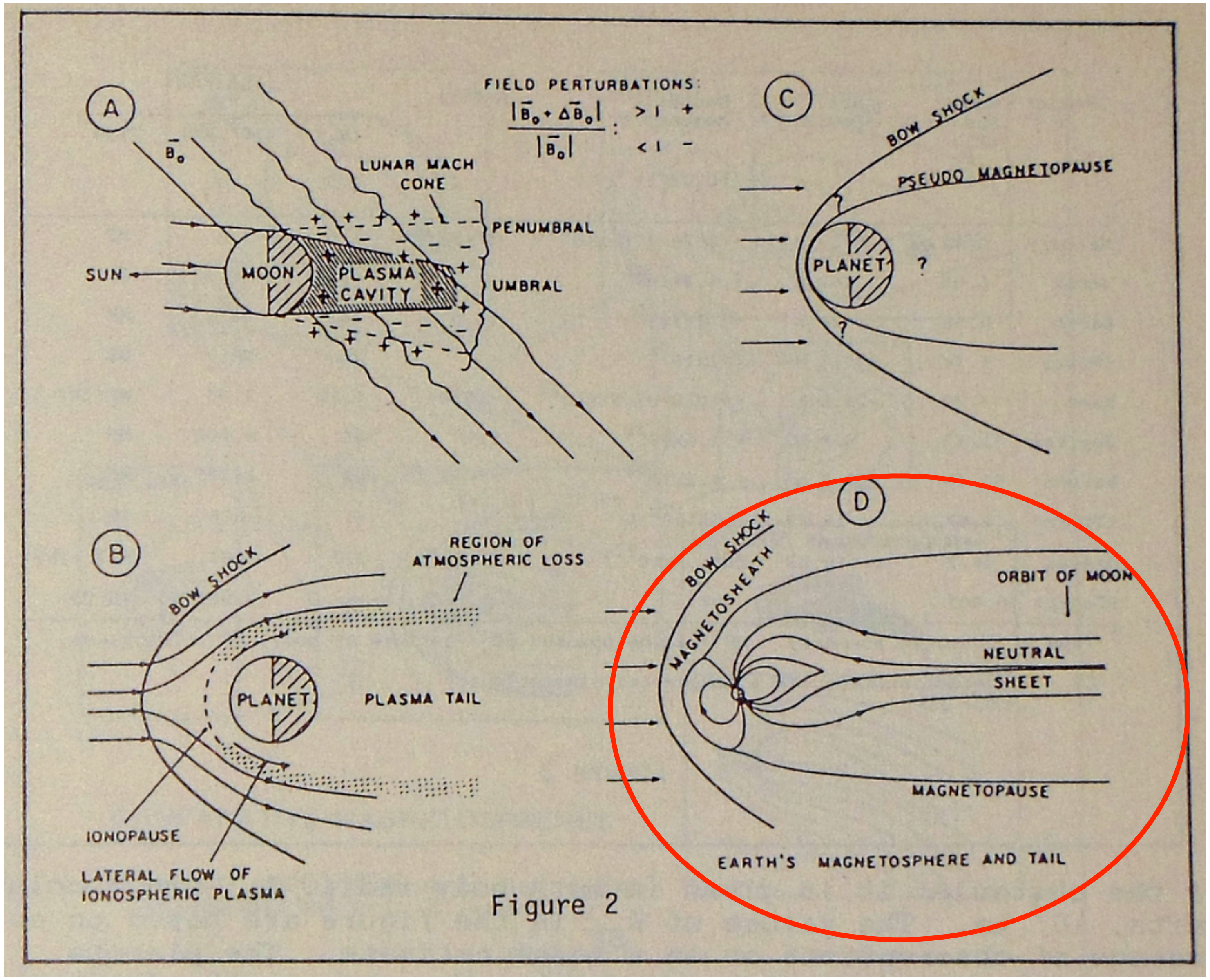


Figure 2

[Lepping, 1986]

A: SW - absorber (Moon) ⇒ wake

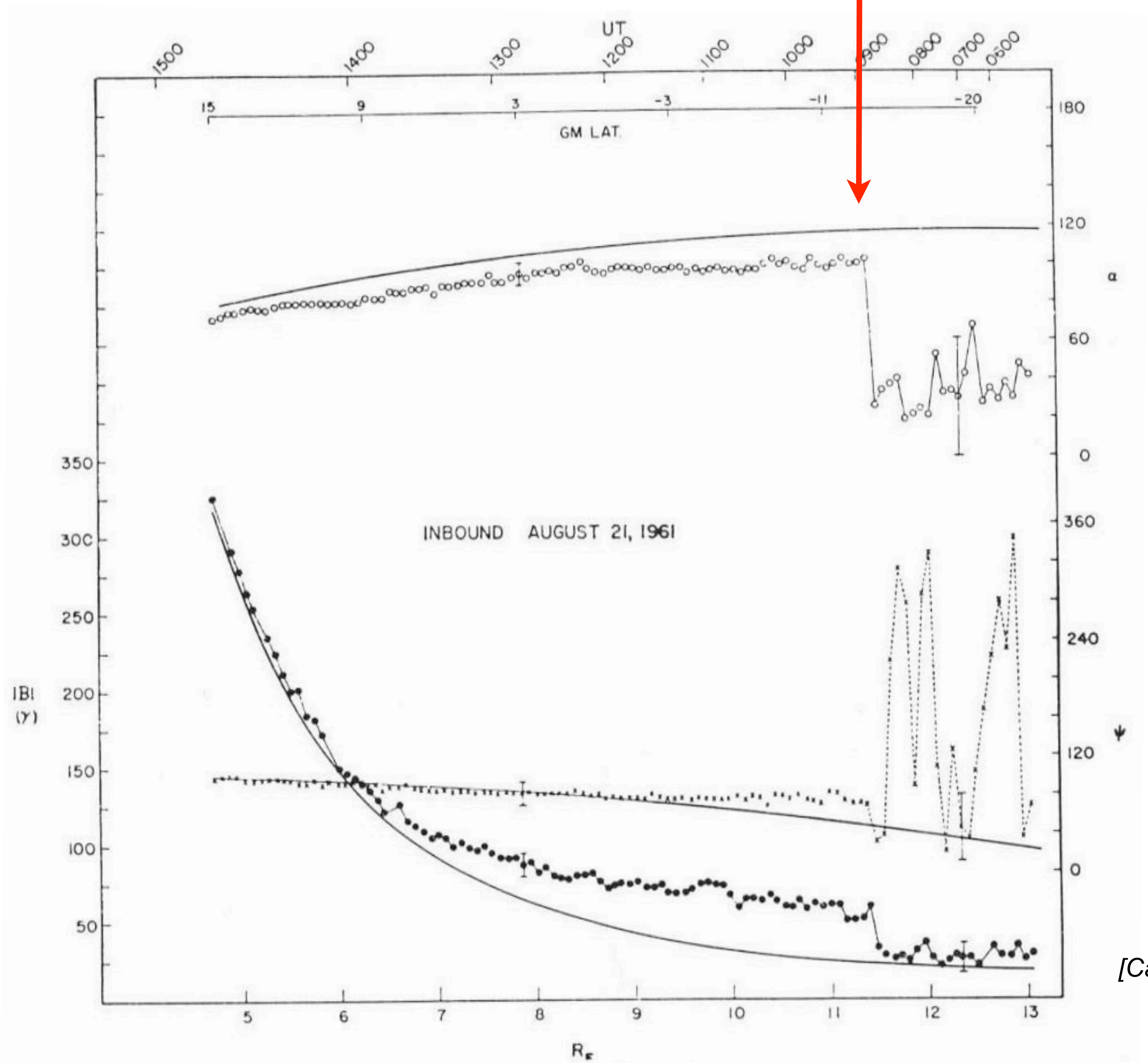
B: SW - atmosphere/ionosphere, no B (Venus, Comets, Titan/SW) ⇒ induced MS

C: SW - conducting body, no atmosphere: $V_{VS} \times B_{VS}$ ⇒ E ⇒ B (no example in the SW)

D: SW - intrinsic large-scale B, strong enough for P_B balances P_{DYN} ⇒ MS

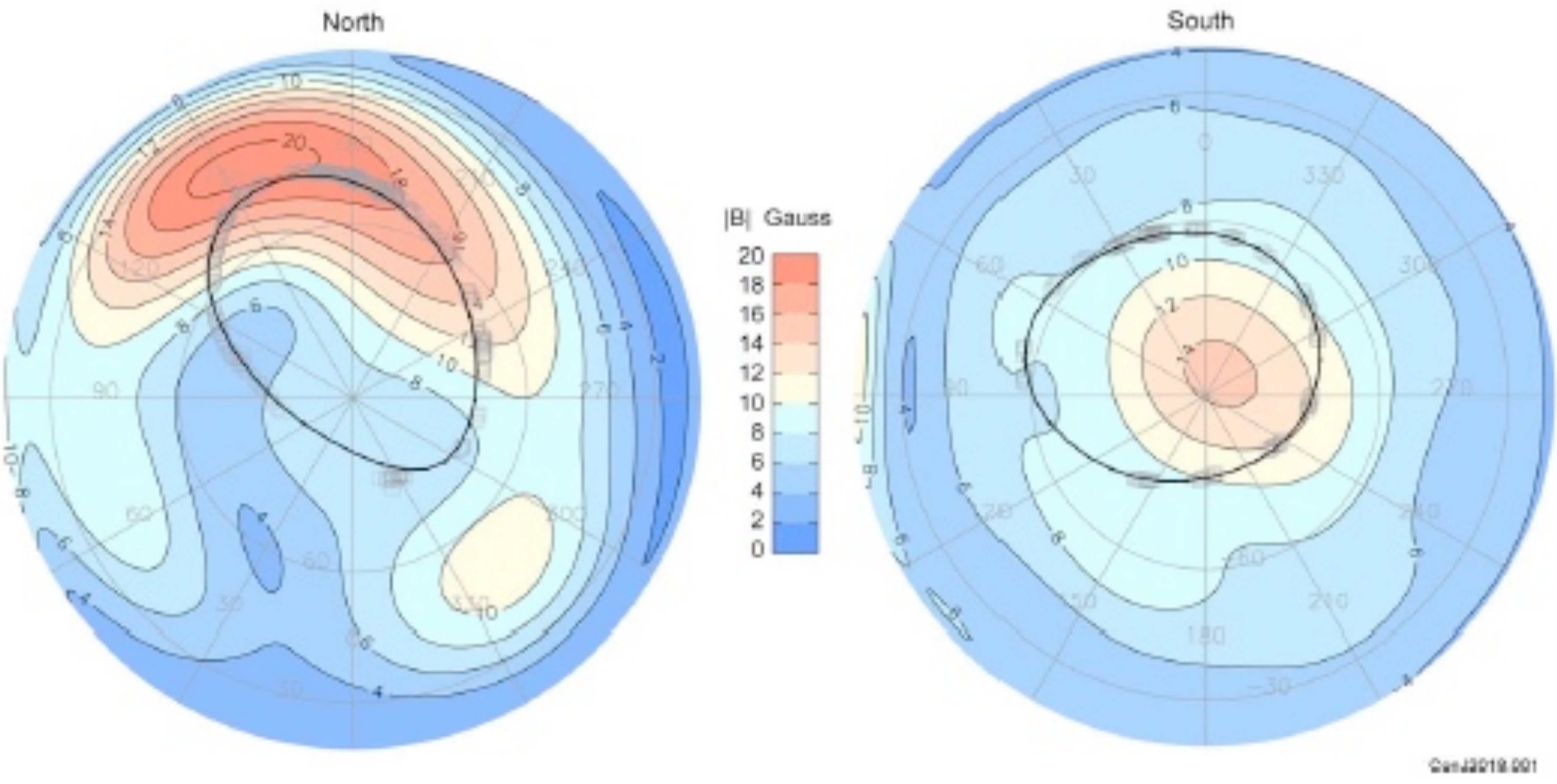
(B,C,D) : bow shock ; A : no shock

D: ⇒ abrupt boundary in planetary B = magnetopause



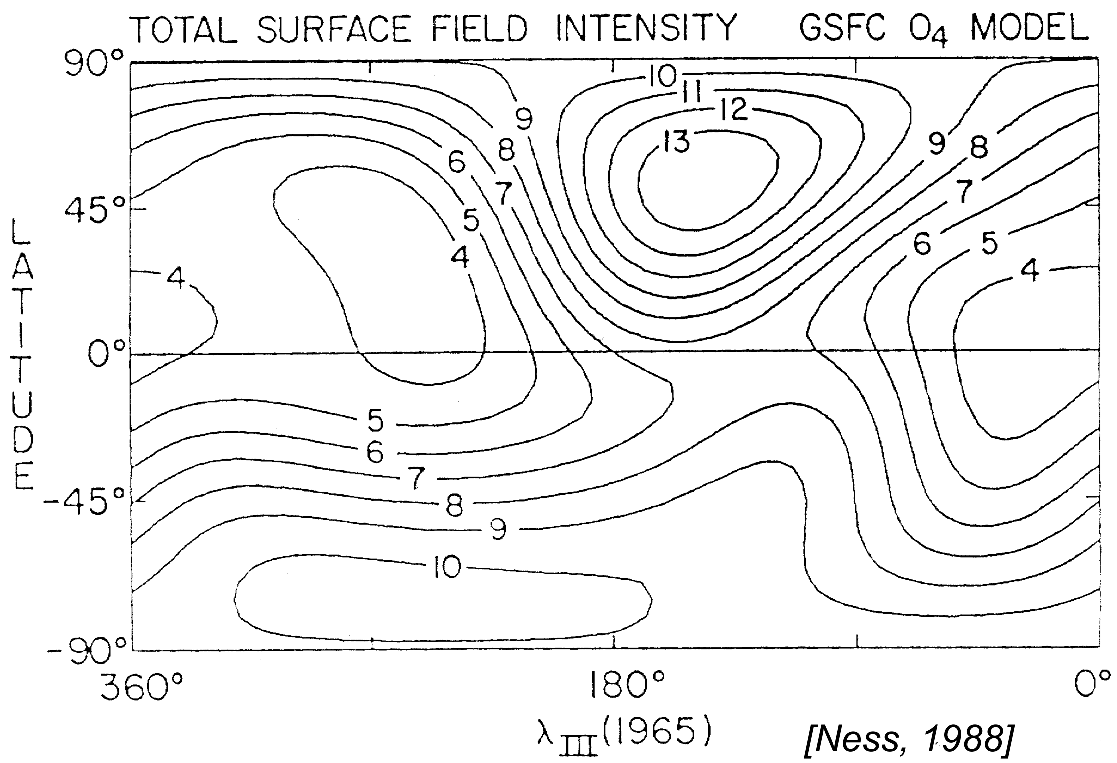
[Cahill & Patel, 1967]

Planetary magnetic fields



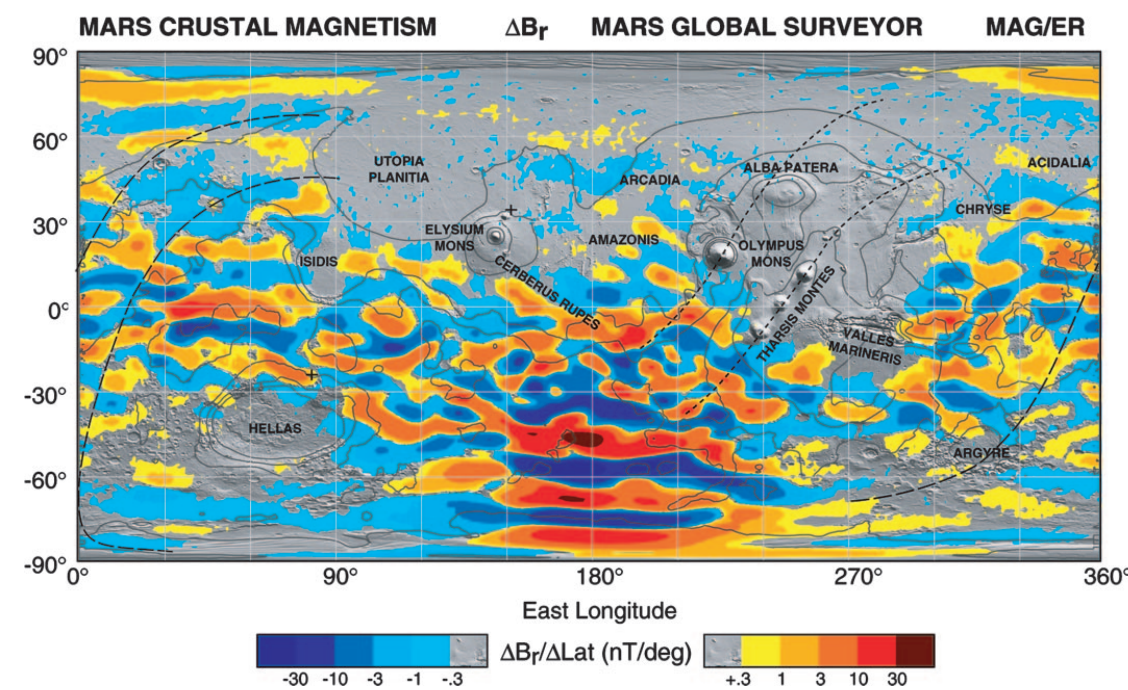
• **Origin**

- Dynamo : Rotation + Convection *(thermal, compositional)* + Conducting fluid *(Earth : liquid Fe-Ni in external core, Jupiter : metallic H)* ⇒ sustained B field



[Ness, 1988]

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



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

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

- 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)

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

[Stevenson, 2003]

- **Description / Representation**

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

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

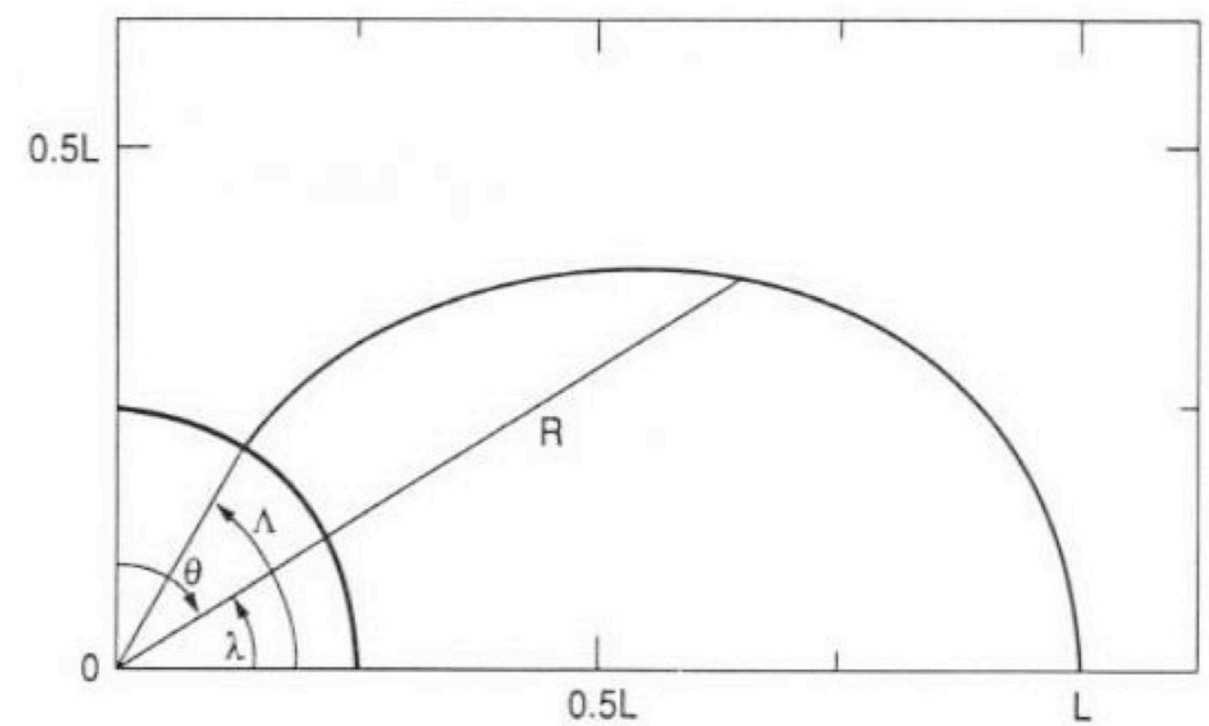
Dipolar approximation :

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

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

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

$$B_\phi = 0$$



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

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)

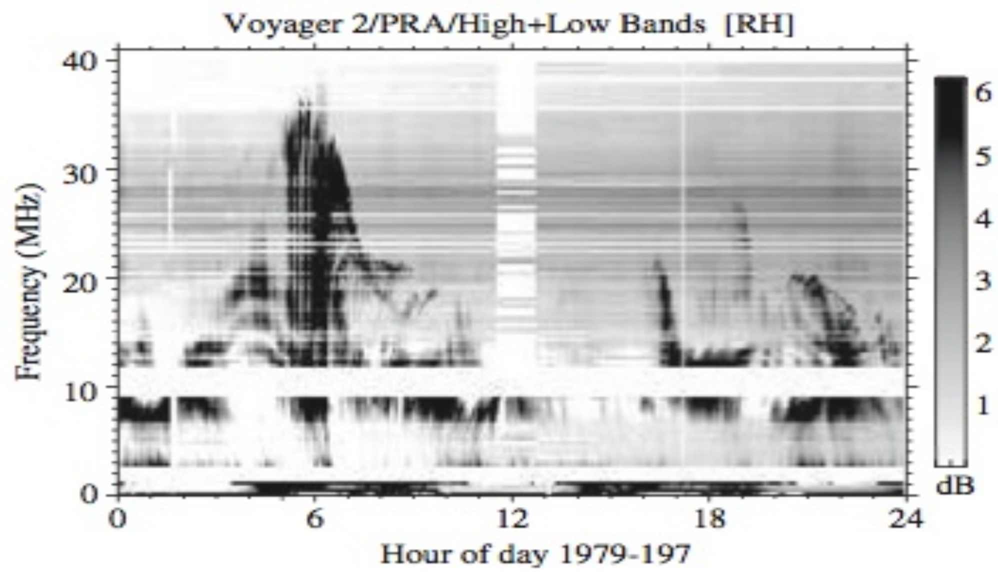
This representation is valid out of the sources (currents). Specific currents (e.g. equatorial disc at Jupiter & Saturn) are described by an additional explicit model, not an external potential.

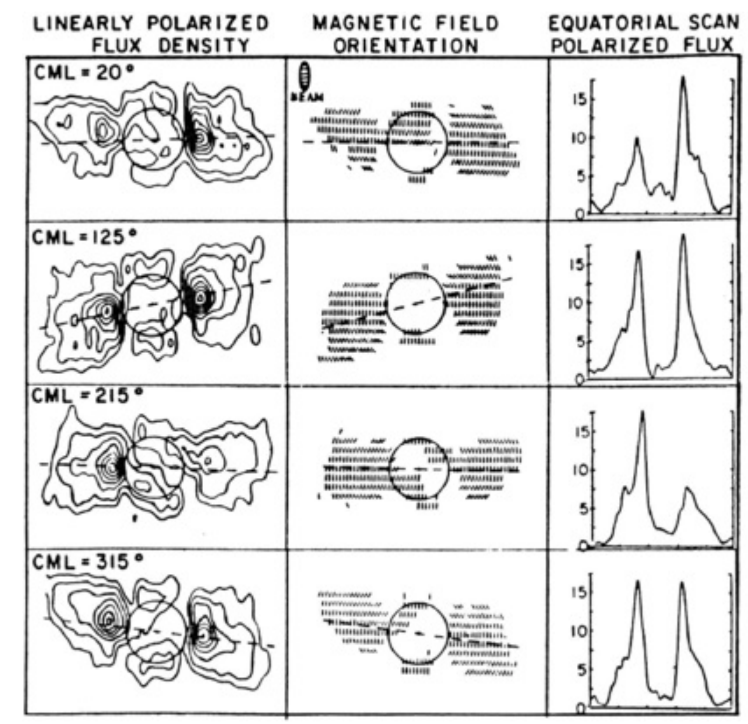
Degree n=1 corresponds to the dipole, n=2 to quadrupole, n=3 to octupole, …

• Measurements

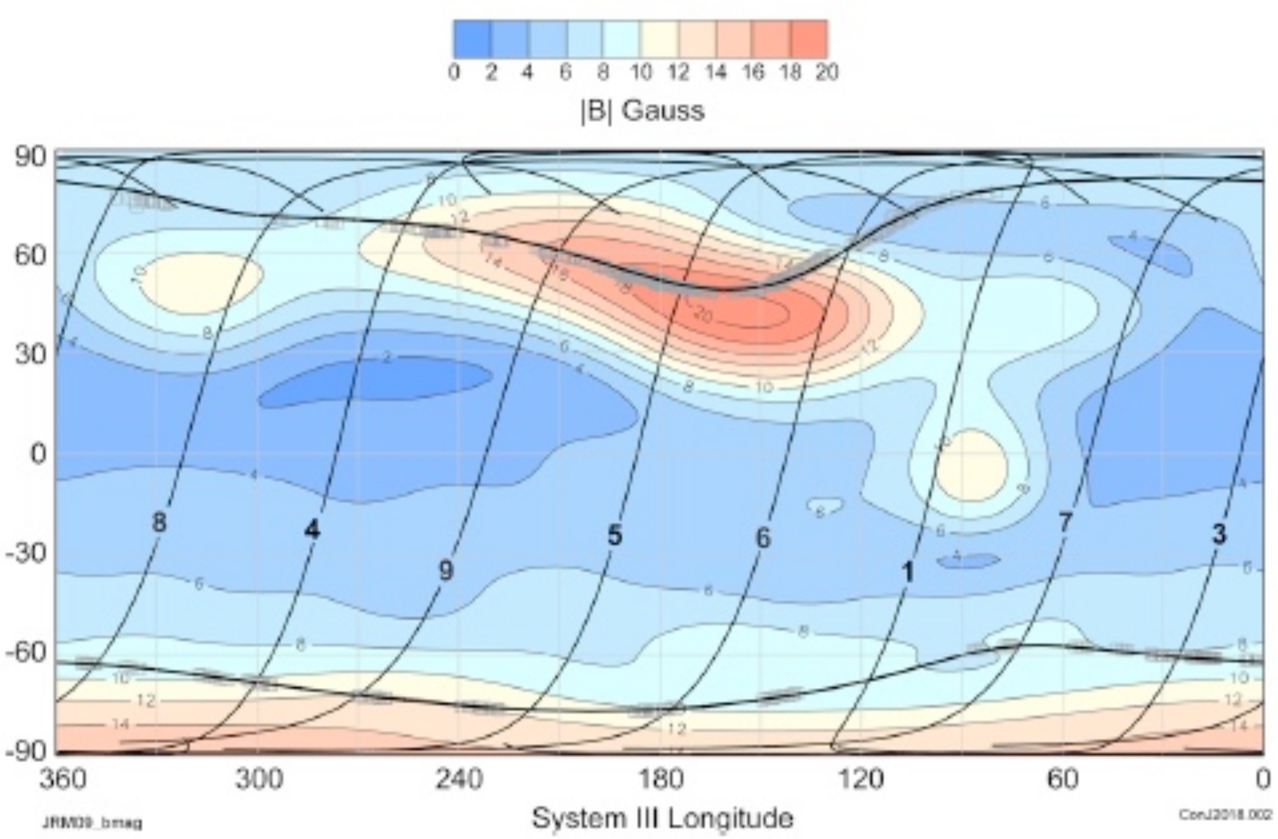
- remote : radio ⇒ existence, intensity, inclination of Jupiter's B field

+ rotation (magnetic longitude system III,1965.0 : P = 9 h 55 min 29.711 sec)





- in-situ : magnetometers along orbital or fly-by trajectories



Jupiter : Pioneer 10 & 11 (1973-74), Voyager 1 & 2 (1979), (Ulysses 1992, Galileo 1995-2003), Juno (≥2016)

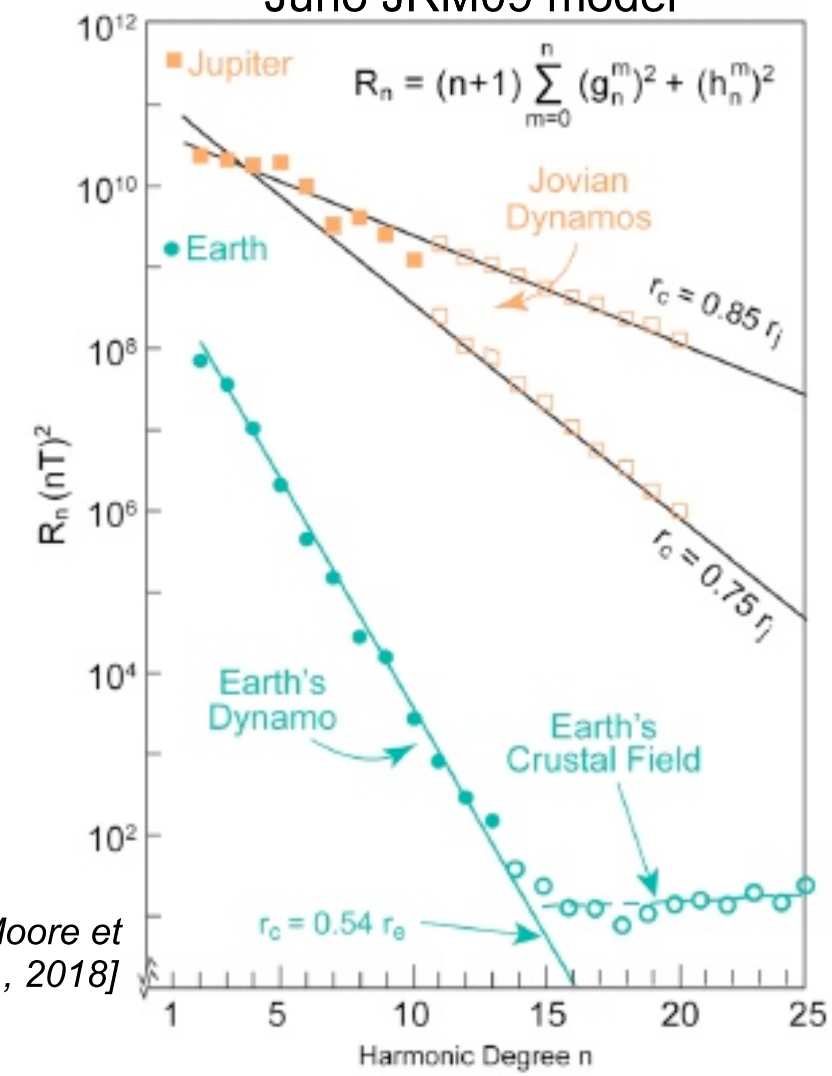
⇒ intense, N anomaly, secular variation 1973-2019 detected recently

[Moore et al., 2018]

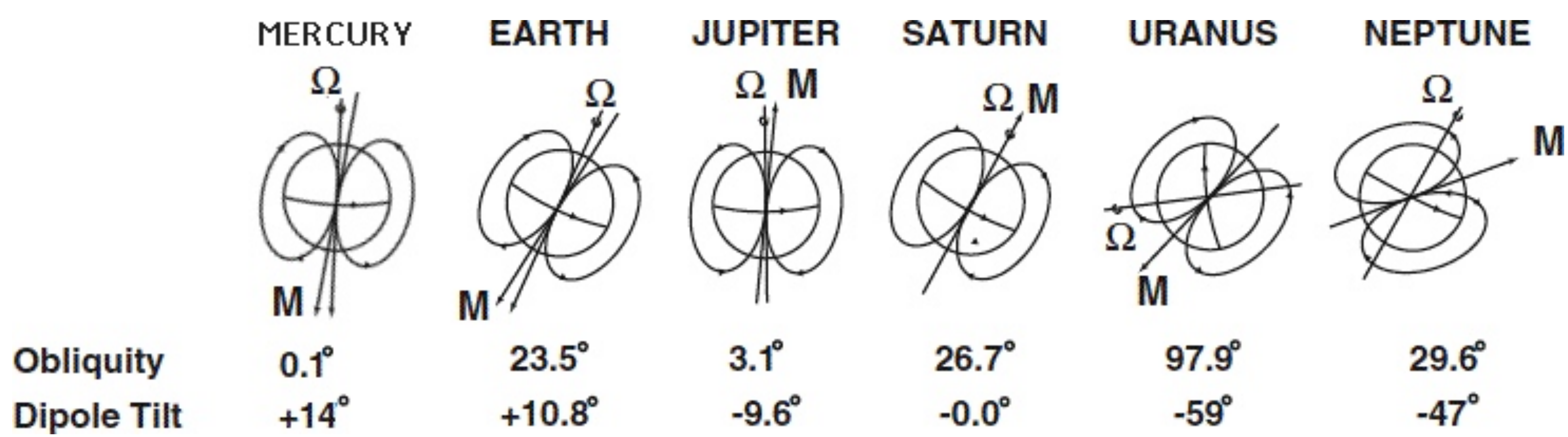
- Description up to order 3-5 (S,U,N), 9 (J), 14 (E) = truncations of higher order developments

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

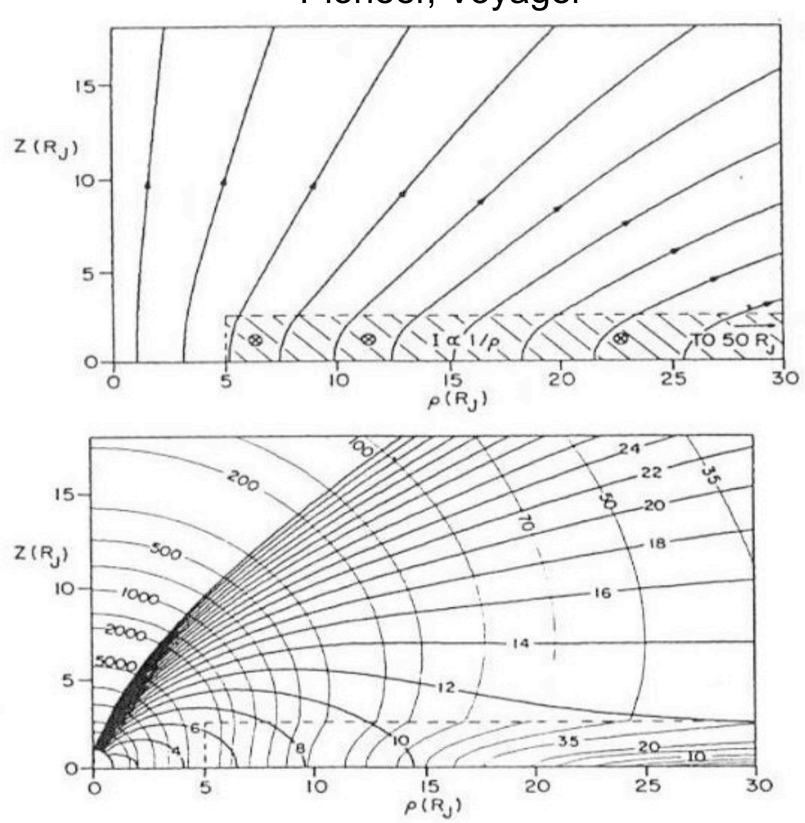
Juno JRM09 model

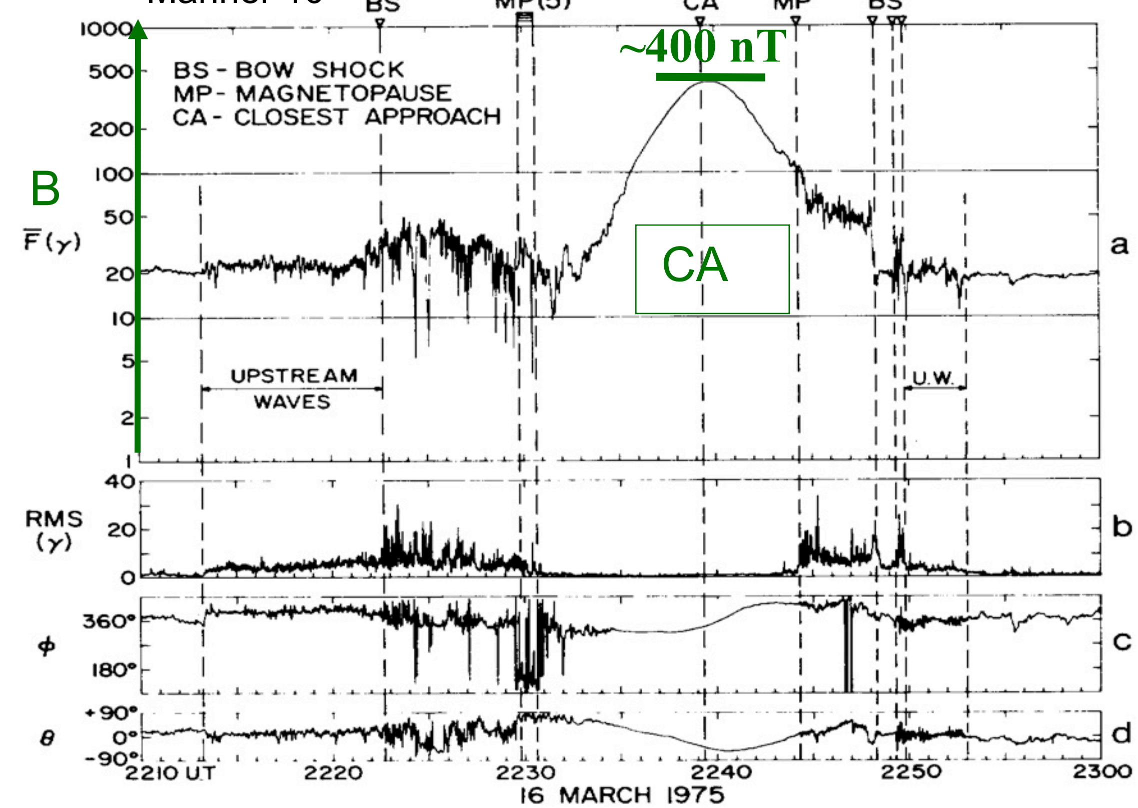


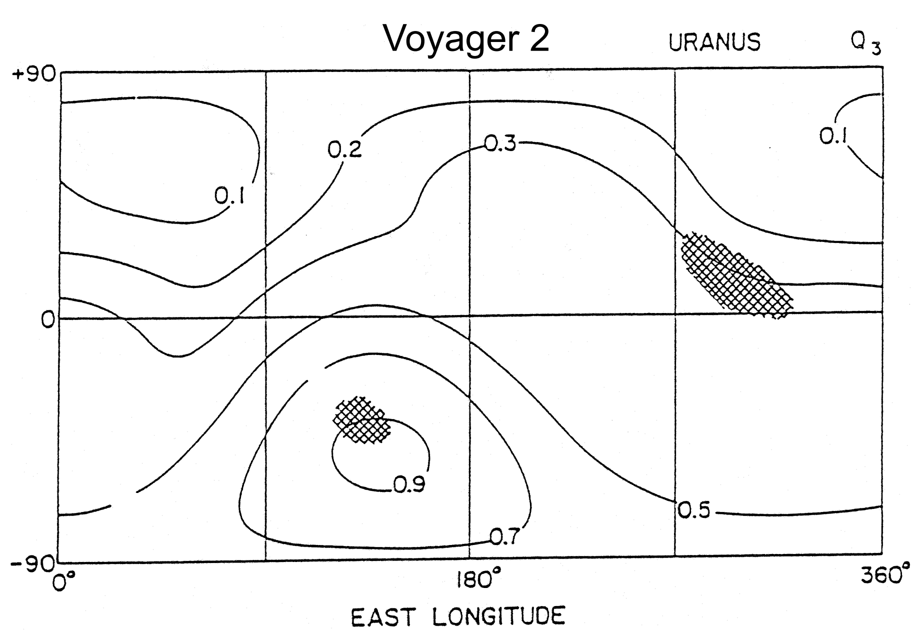
[Moore et al., 2018]

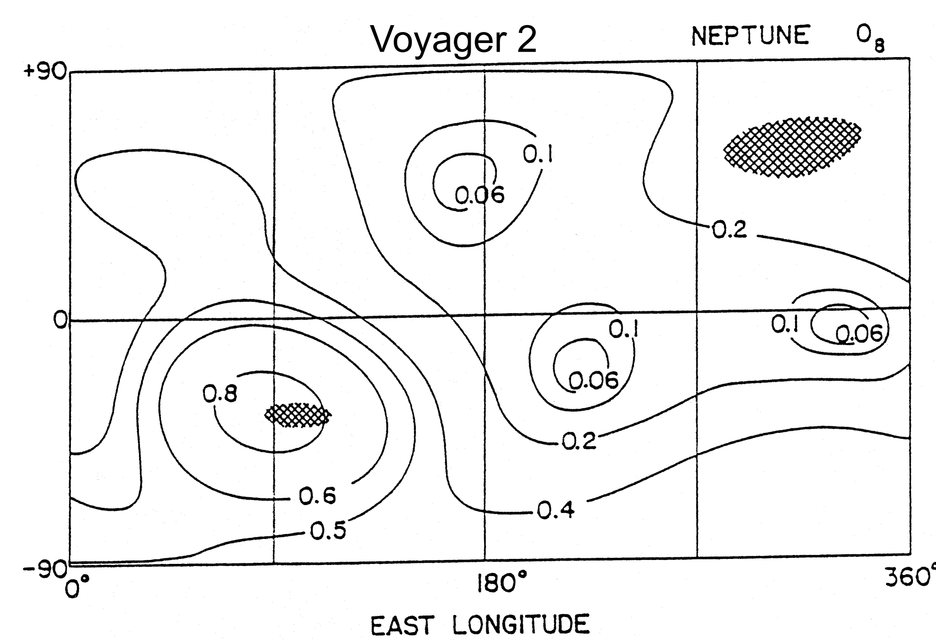


- Jupiter (& Saturne) : current disk in centrifugal equator (300 MA, 5-50 x 5 R_J)
- Saturn : B aligned with rotation axis
- Mercury : N/S asymetry, magnetic equator shifted by 0,2 R_M Northward
- Uranus, Neptune : strongly offset & tilted B fields



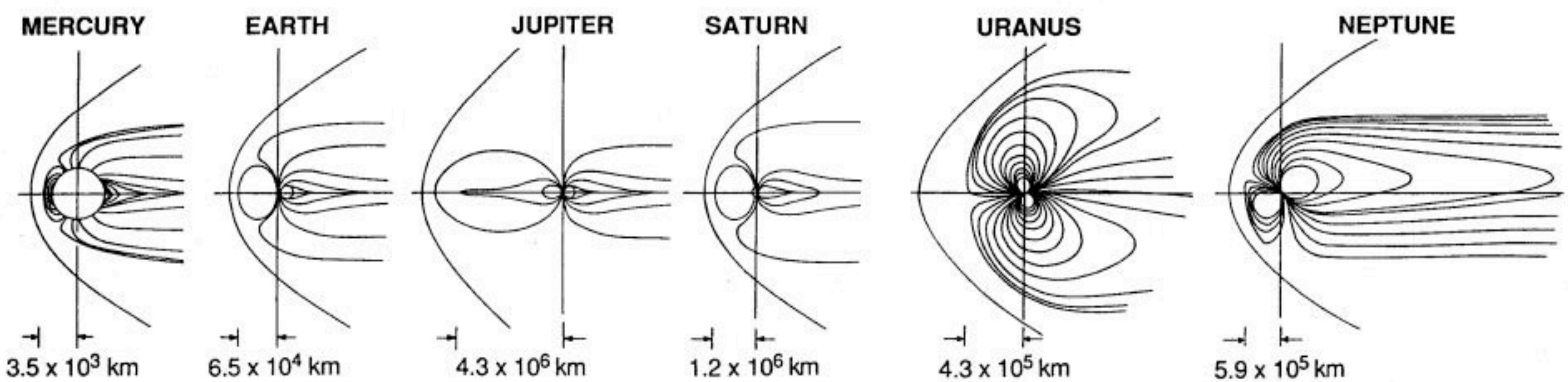




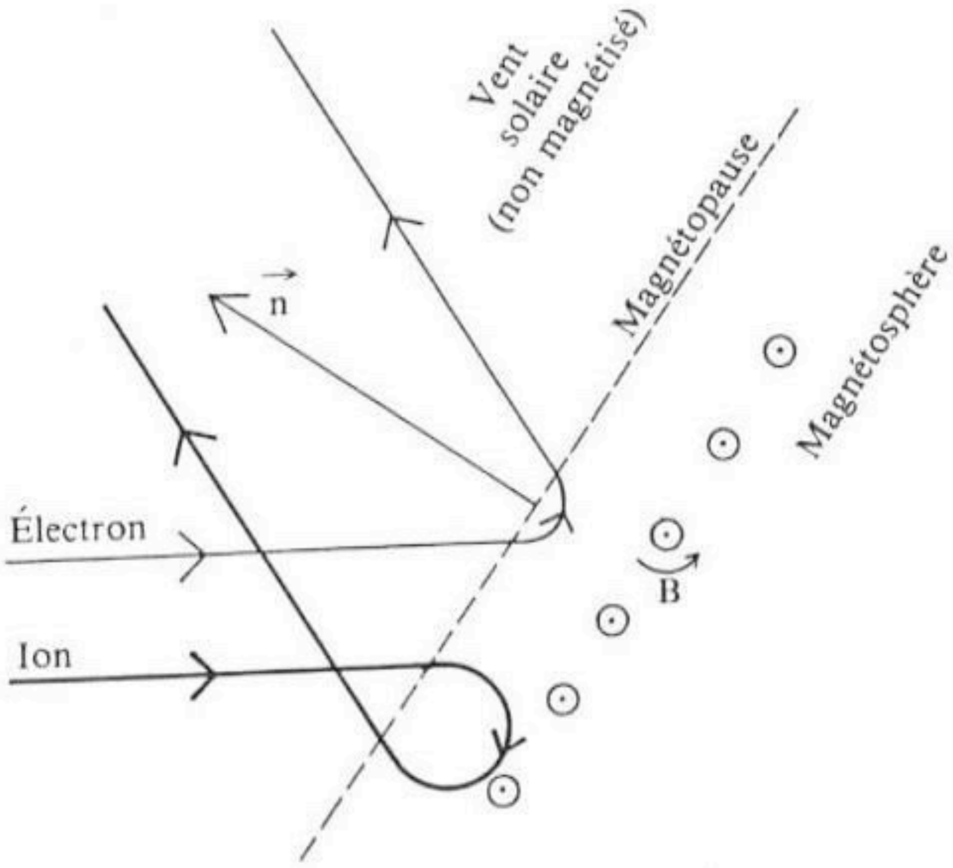


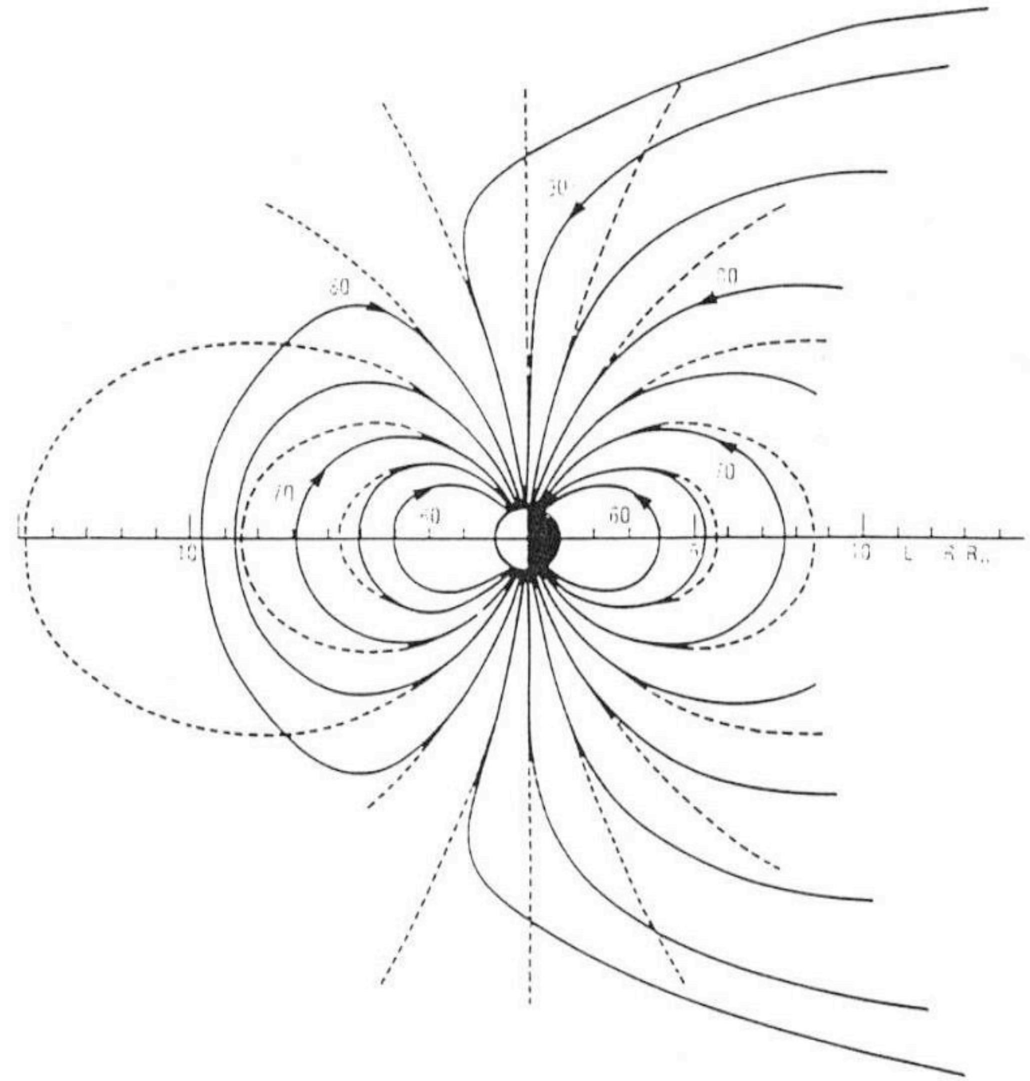
[adapted from Ness, 1992]

Origin & size of the magnetospheres



• Magnetopause





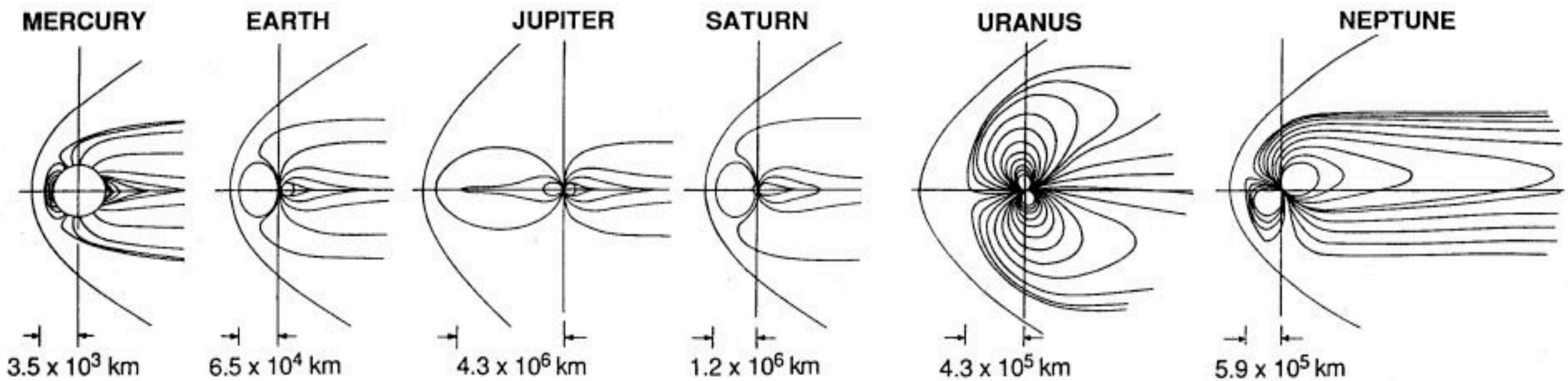
- Pressure equilibrium SW / planetary B :

$$P_{SW} = KNm(V\cos\chi)^2 \quad = \quad P_{MS} = B_T^2/2\mu_o \qquad (K = 1\text{-}2)$$

with $B_T = B_P + B_C = 2\ B_P$ at MP nose $\Rightarrow$ MP shape and size

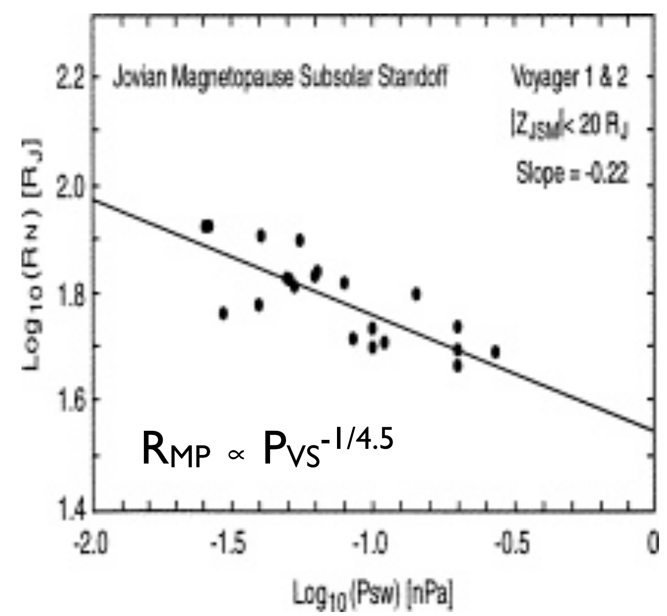
- MP sub-solar point :

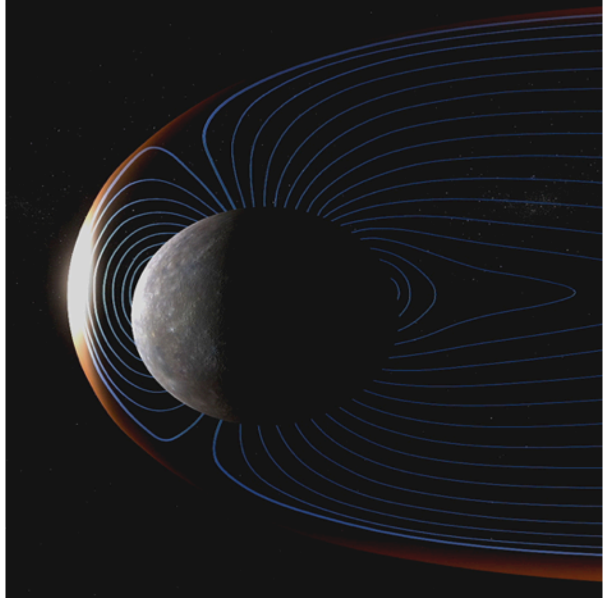
$$R_{MP} = (2\ B_{eq}^2/\mu_o KNmV^2)^{1/6} \qquad (\text{dipolar field : } B_P = B_{eq}\ (1+3\cos^2\theta)^{1/2}/R^3\ )$$

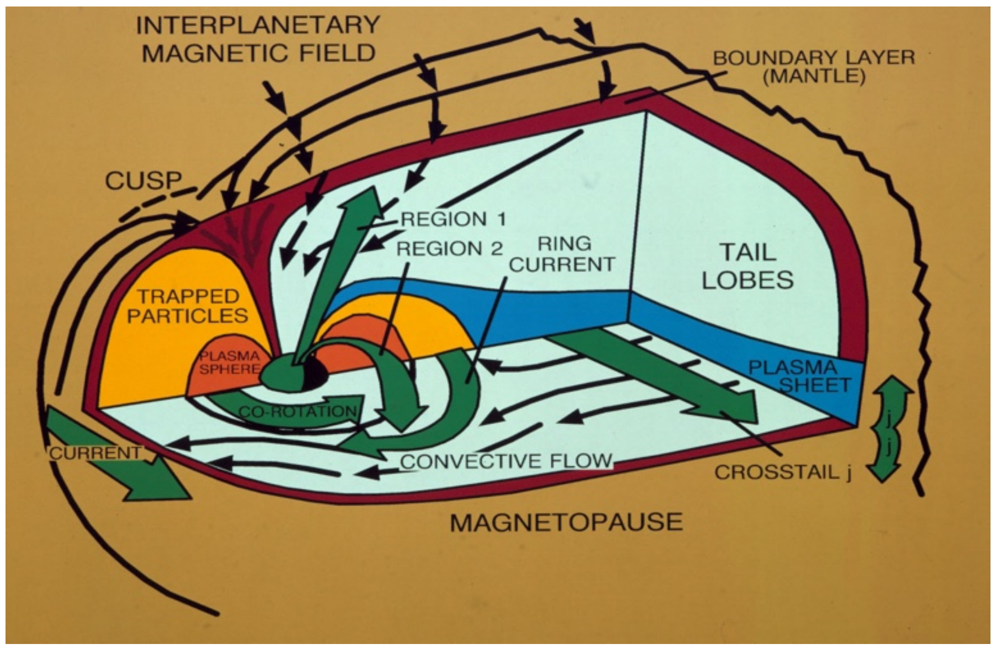


	Mercure	Terre	Jupiter	Saturne	Uranus	Neptune
R_P (km)	2 439	6 378	71 492	60 268	25 559	24 764
D orbitale (UA)	0.39	1	5.2	9.5	19.2	30.1
M_{dip} (G.km^3)	5.5×10^7	7.9×10^{10}	1.6×10^{15}	4.7×10^{13}	3.8×10^{12}	2.2×10^{12}
Champ à l'équateur B_e (G)	0.003	0.31	4.3	0.21	0.23	0.14
Inclinaison [B,Ω] (°) et 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]

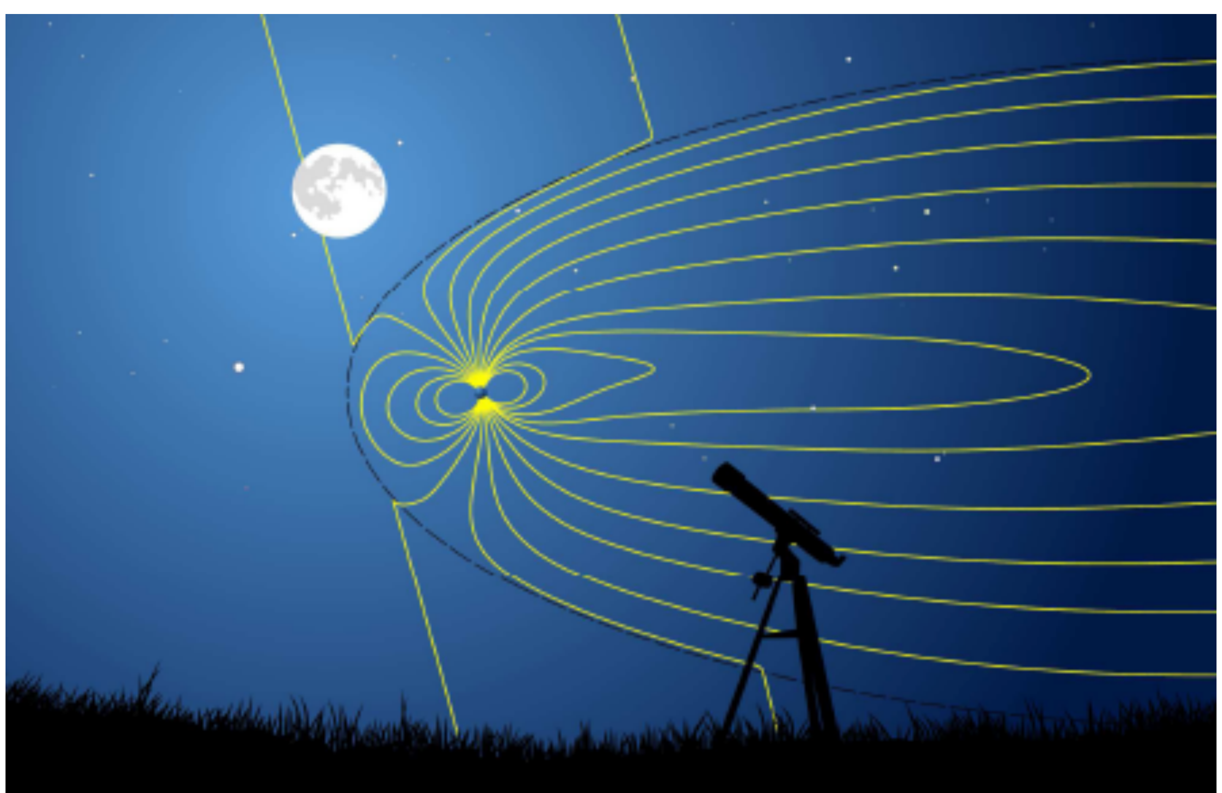
[Encrenaz et al., 2003]

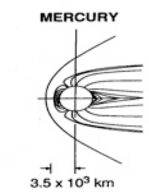




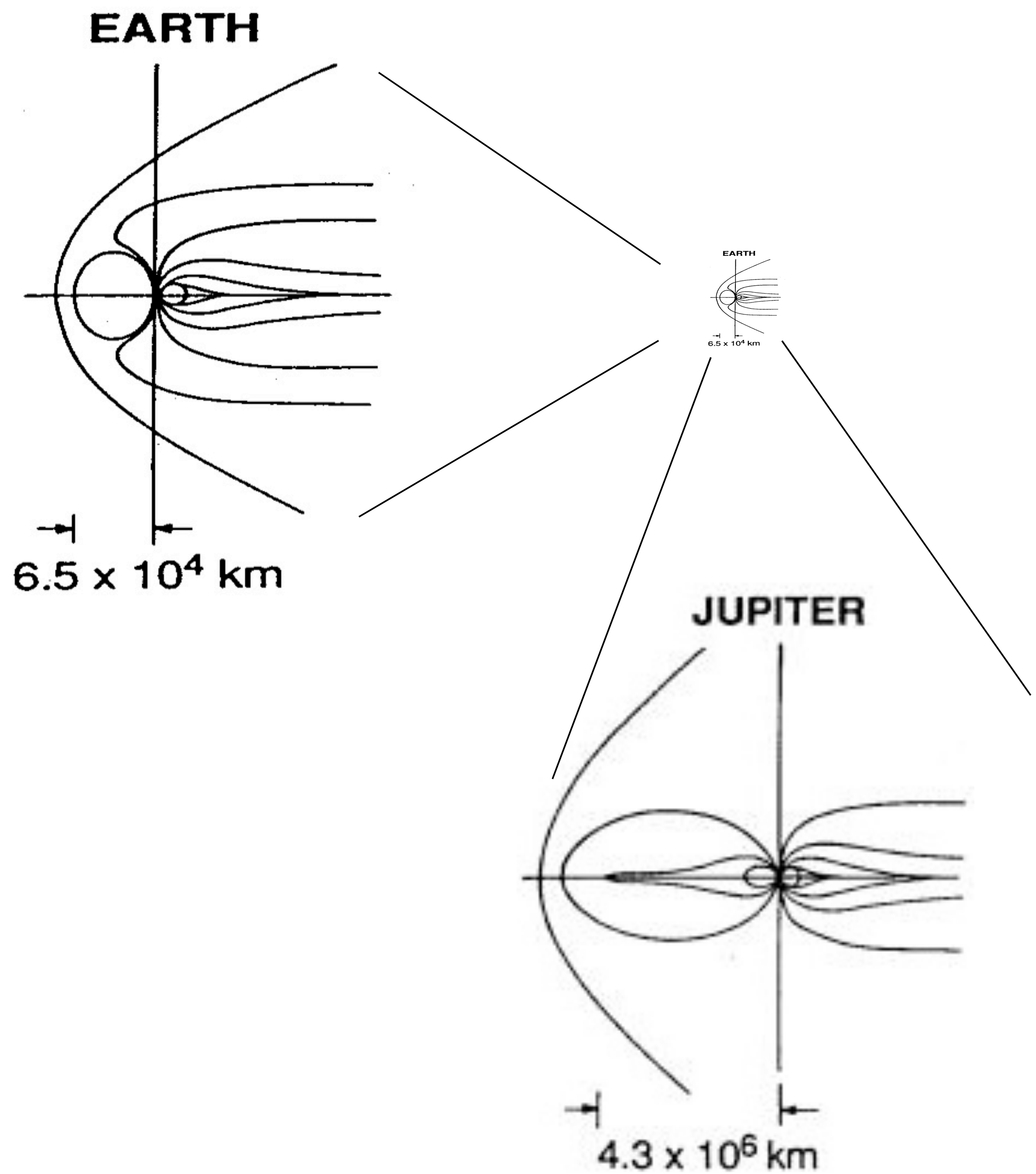


INTERPLANETARY MAGNETIC FIELD
BOUNDARY LAYER (MANTLE)
CUSP
REGION 1
REGION 2
RING CURRENT
TAIL LOBES
TRAPPED PARTICLES
PLASMA SPHERE
PLASMA SHEET
CO-ROTATION
CURRENT
CONVECTIVE FLOW
CROSSTAIL j
MAGNETOPAUSE

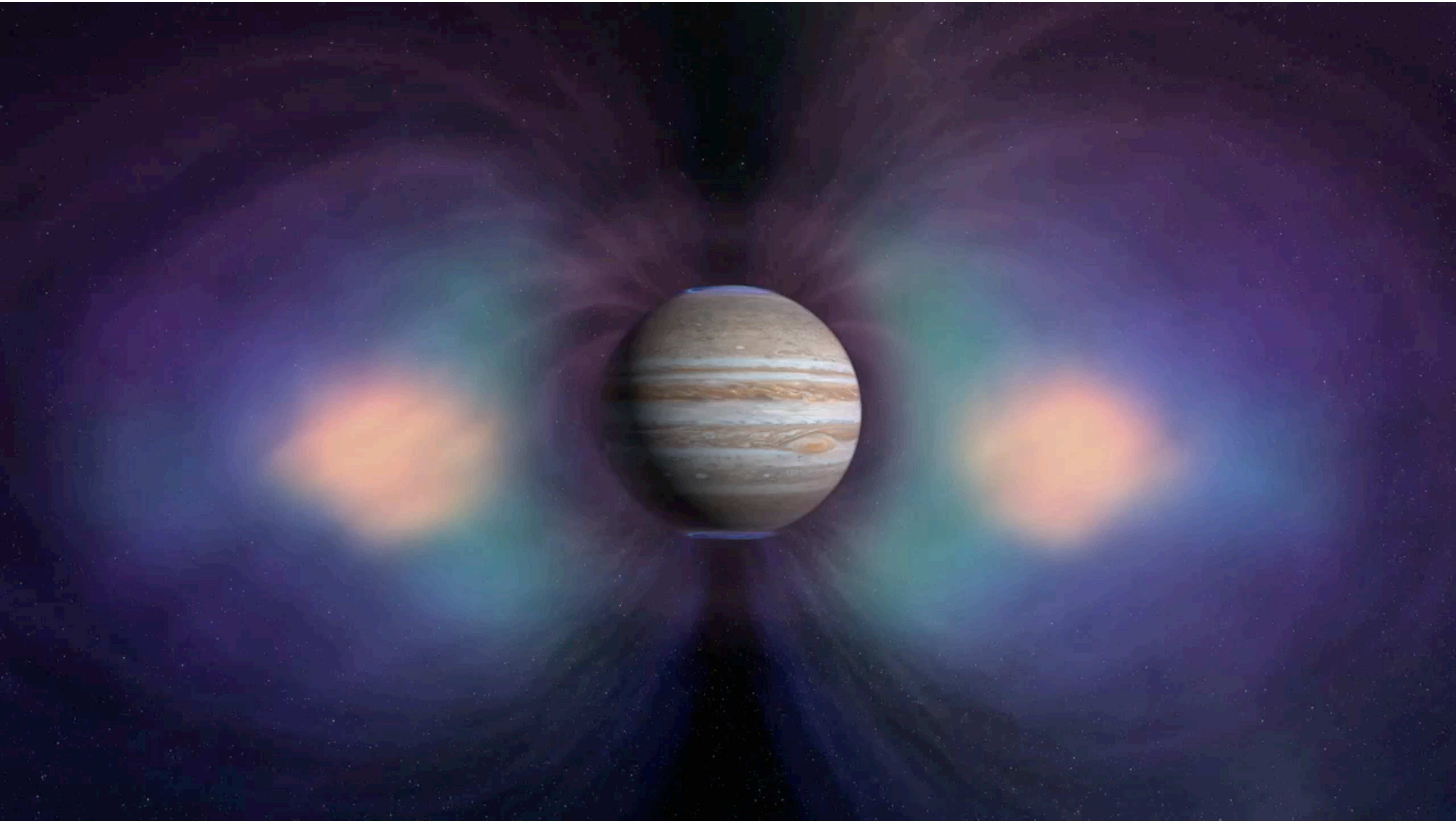




MERCURY
3.5 x 10^3 km



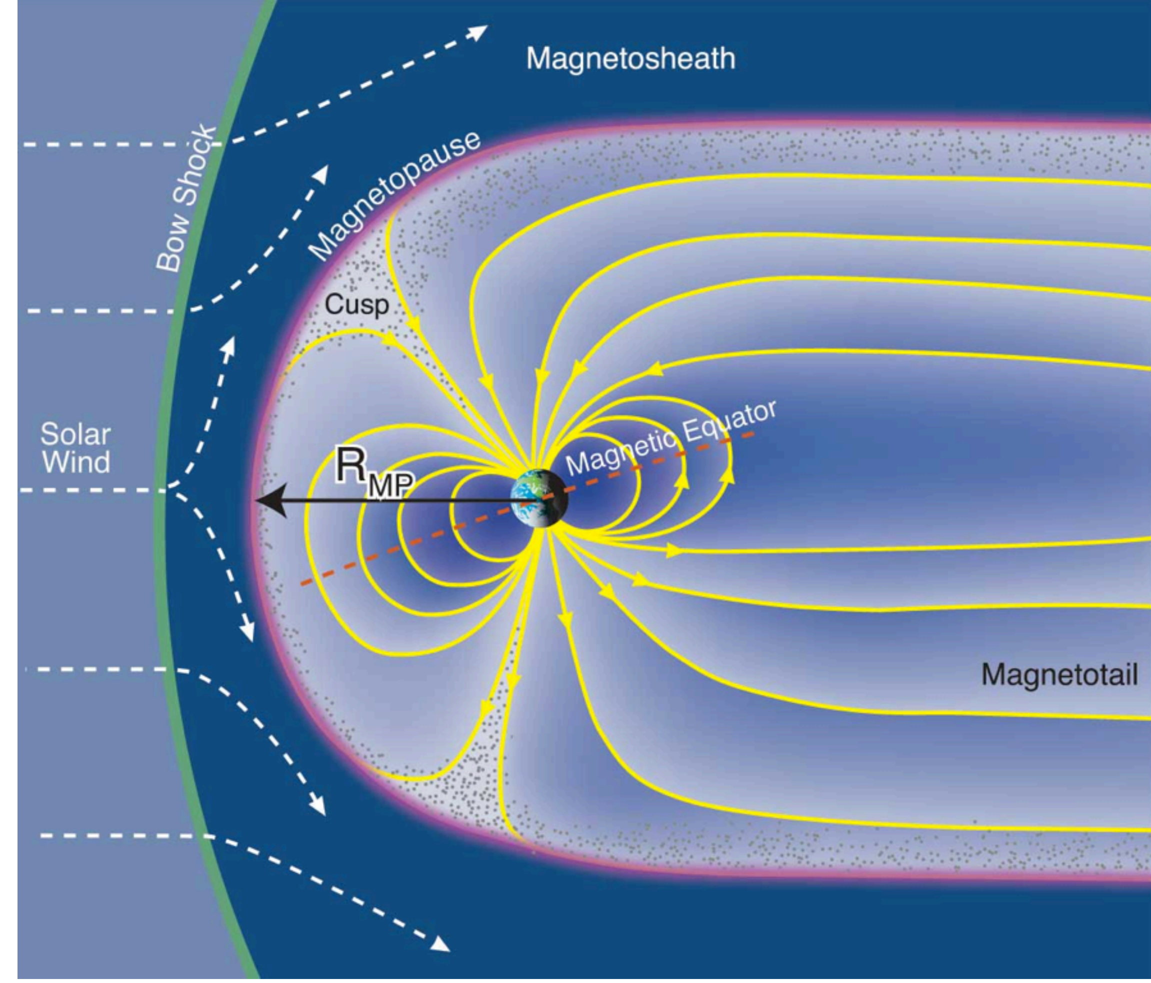
EARTH
6.5 x 10^4 km
JUPITER
4.3 x 10^6 km

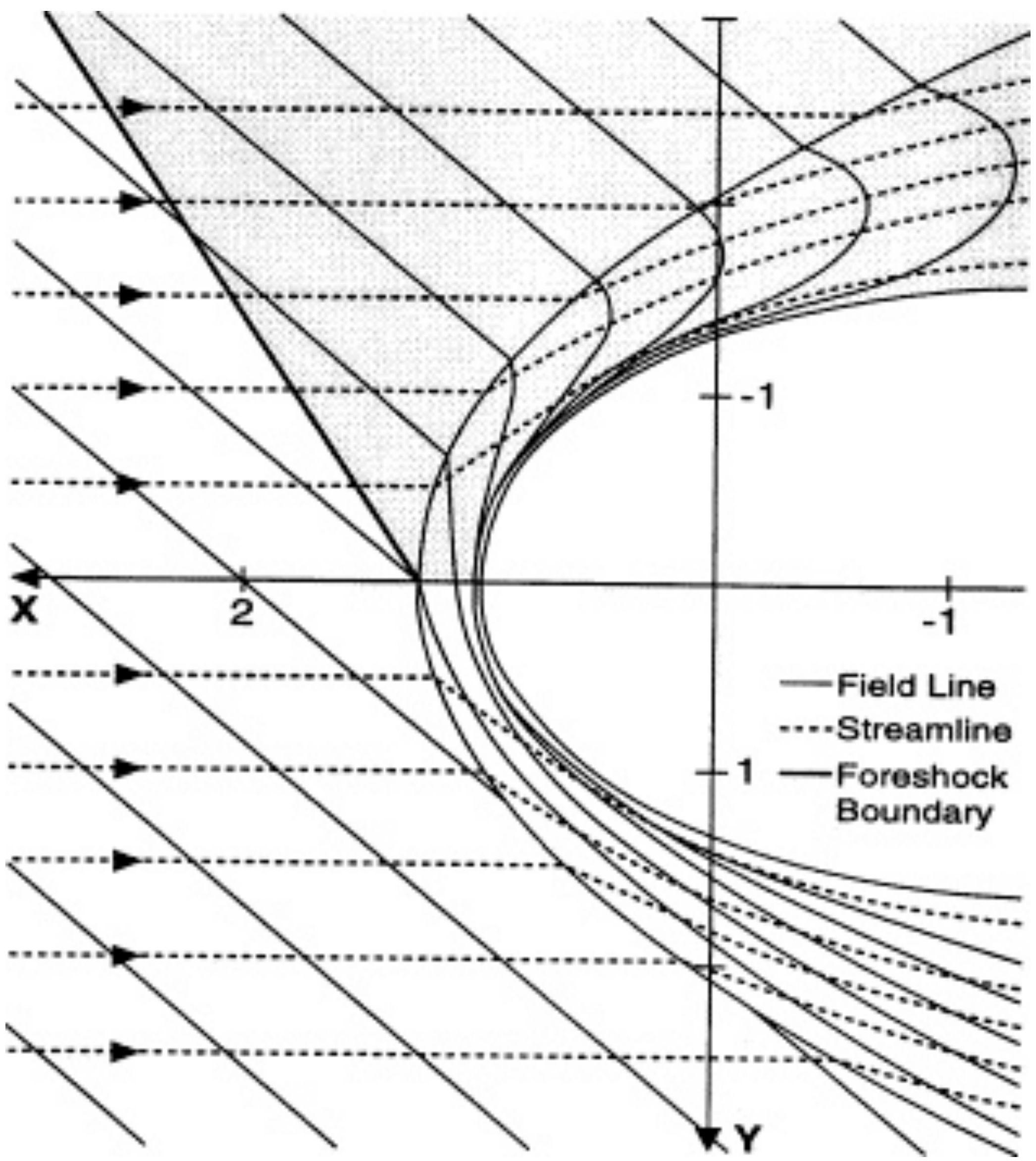


- **Bow Shock**

- supersonic / super-Alfvénic flow

$\Rightarrow$ bow shock ahead of MP





[Spreiter et al., 1966]

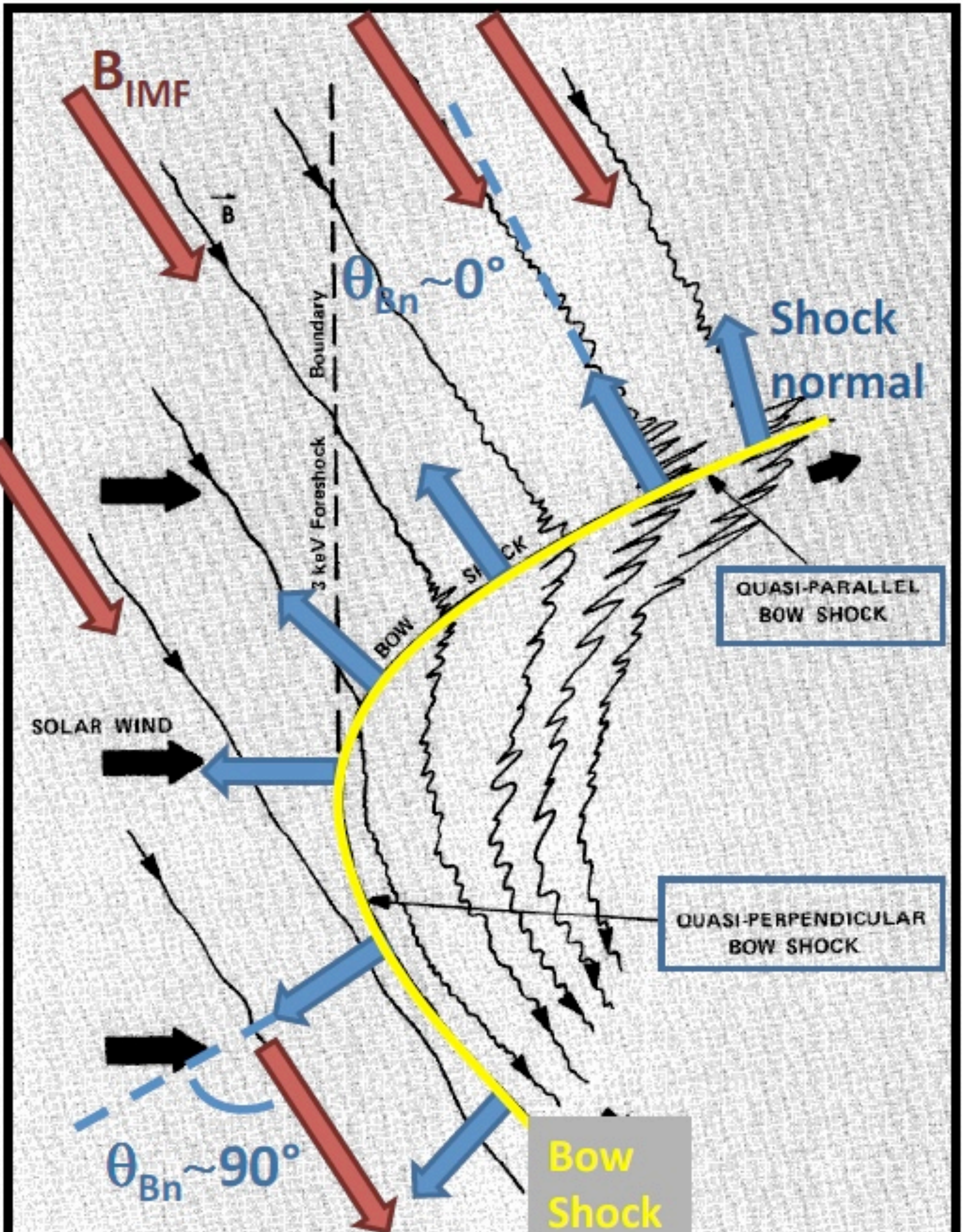
- in magnetosheath : slowed flow (V:4 for M_A >> 1)

$\mathbf{E} = -\,\mathbf{V}\times\mathbf{B}$ & $\nabla\times\mathbf{E} = -\partial\mathbf{B}\partial t$

$\Rightarrow \partial\mathbf{B}/\partial t + \nabla\times(\mathbf{V}\times\mathbf{B}) = 0 \approx \nabla\times(\mathbf{V}\times\mathbf{B}) \approx \partial(\mathbf{V}\times\mathbf{B})/\partial x$

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

Properties of Bow Shocks



plasma properties **upstream** and **downstrean** regions can be described in terms of :

- Bulk flow **V**
- Magnetic field **B**
- Plasma density **ρ**
- Pressure **P**

BS position is sensitive to several factors (M_A, P_{dyn}, …)

BS can be classified with the θ_{Bn} angle:

- $\theta_{Bn} \sim 0°$ quasi-parallel
- $0° < \theta_{Bn} < 90°$ oblique
- **$\theta_{Bn} \sim 90°$ quasi-perp**

Rankine-Hugoniot (RH) relations

1- Mass conservation : $[\rho U_n] = 0$ $\Rightarrow$ RH-1

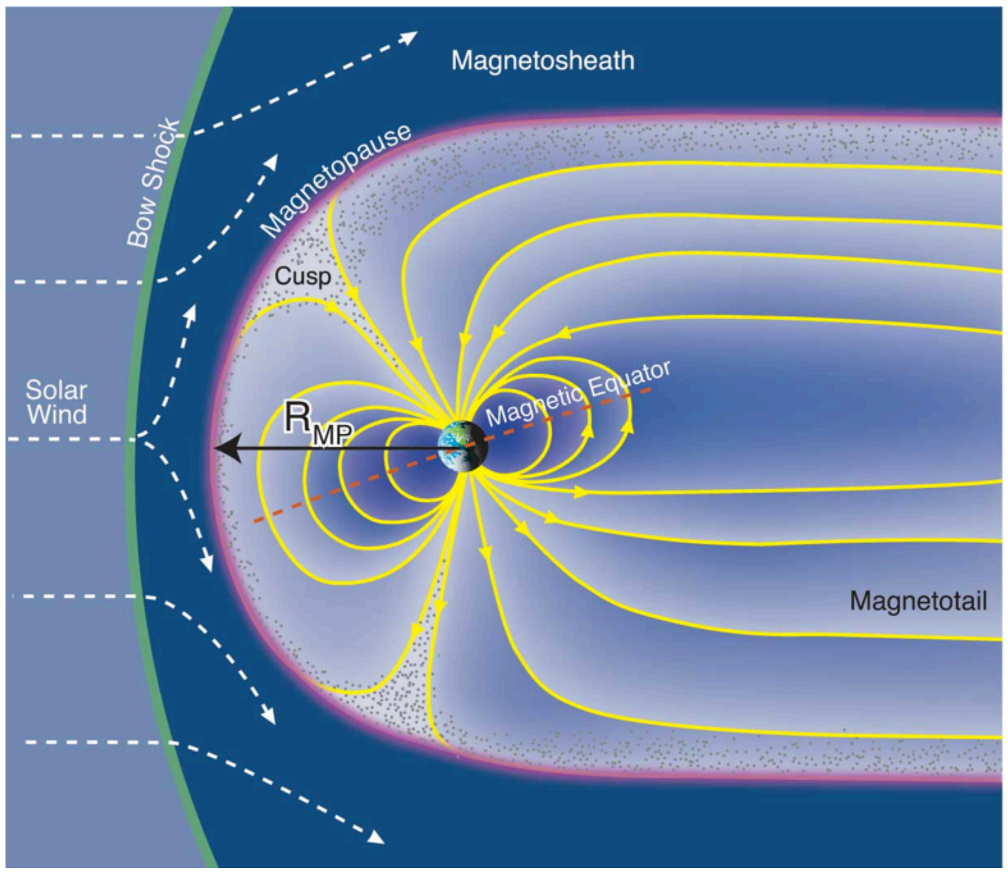
2a- normal momentum cons.: $\left[\rho U_n^2 + p + \frac{B^2}{\mu_o}\right]$ $\Rightarrow$ RH-2a

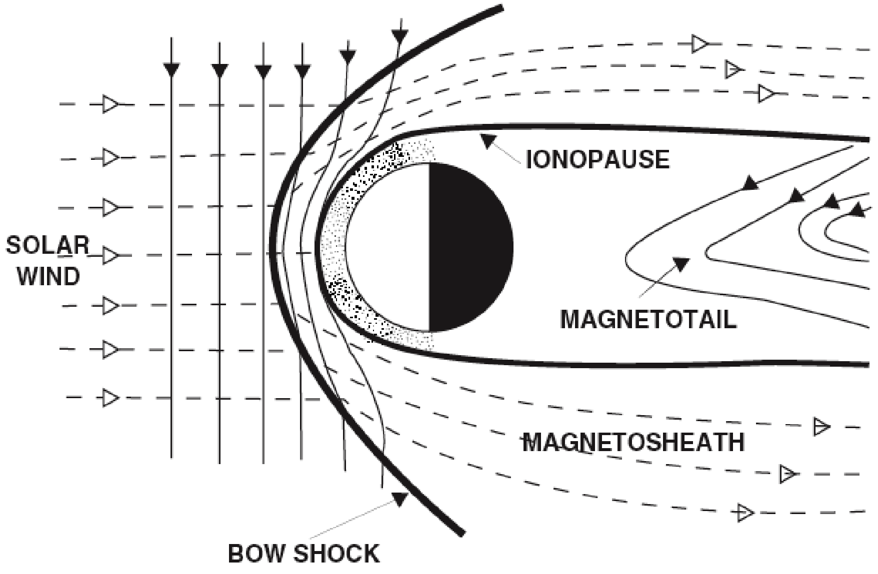
2b- transverse momentum cons.: $\left[\rho U_n \vec{U_t} + p + \frac{B_n \vec{B_t}}{\mu_o}\right] = 0 \Rightarrow$ RH-2b

3- Energy conservation : $\left[\rho U_n \left(\frac{1}{2} U^2 + \frac{\gamma}{\gamma - 1} \frac{P}{\rho}\right) + U_n \frac{B^2}{\mu_o} - \vec{U}.\vec{B} \frac{B_n}{\mu_o}\right] = 0 \Rightarrow$ RH-3

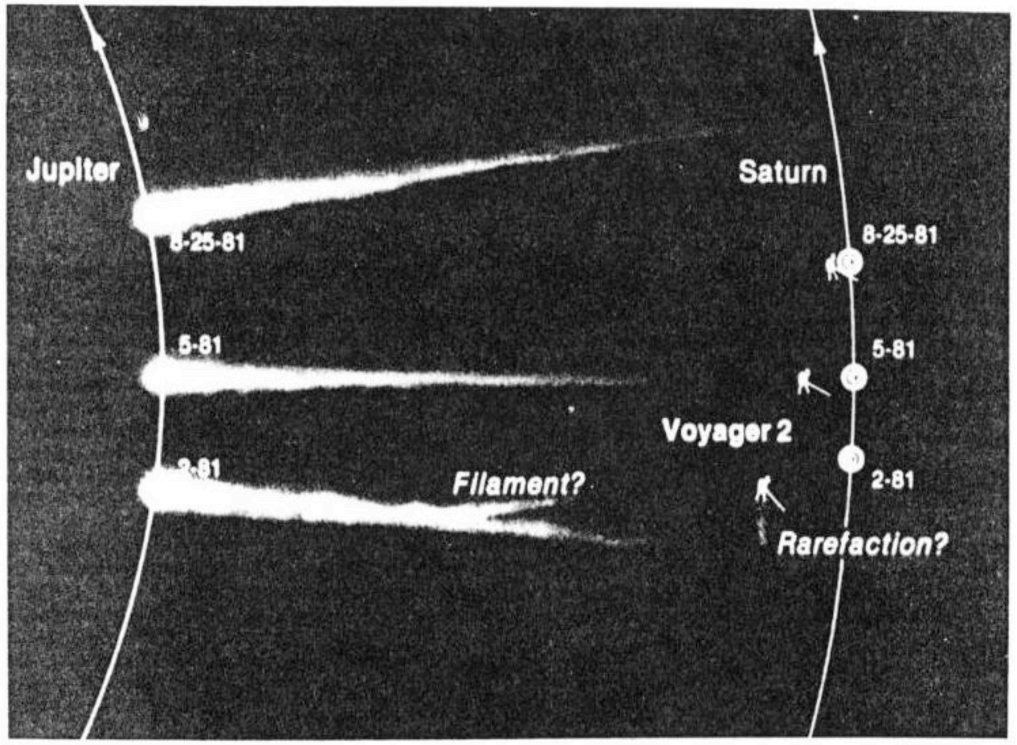
4- Magnetic flux cons.: $\vec{\nabla}.\vec{B} = 0 \leftrightarrow [B_n] = 0$ $\Rightarrow$ RH-4

- Cusp above magnetic poles : direct entry of SW plasma (<u>but not main source of aurora !</u>)
- At Mercury : asymetric B ⇒ S cusp widely open ⇒ plasma bombardment of surface
- if no intrinsic B field ⇒ induced MS, bow shock, B draping, tail, but no cusp
- Jupiter's magnetic tail ⇒ extends to Saturn's orbit



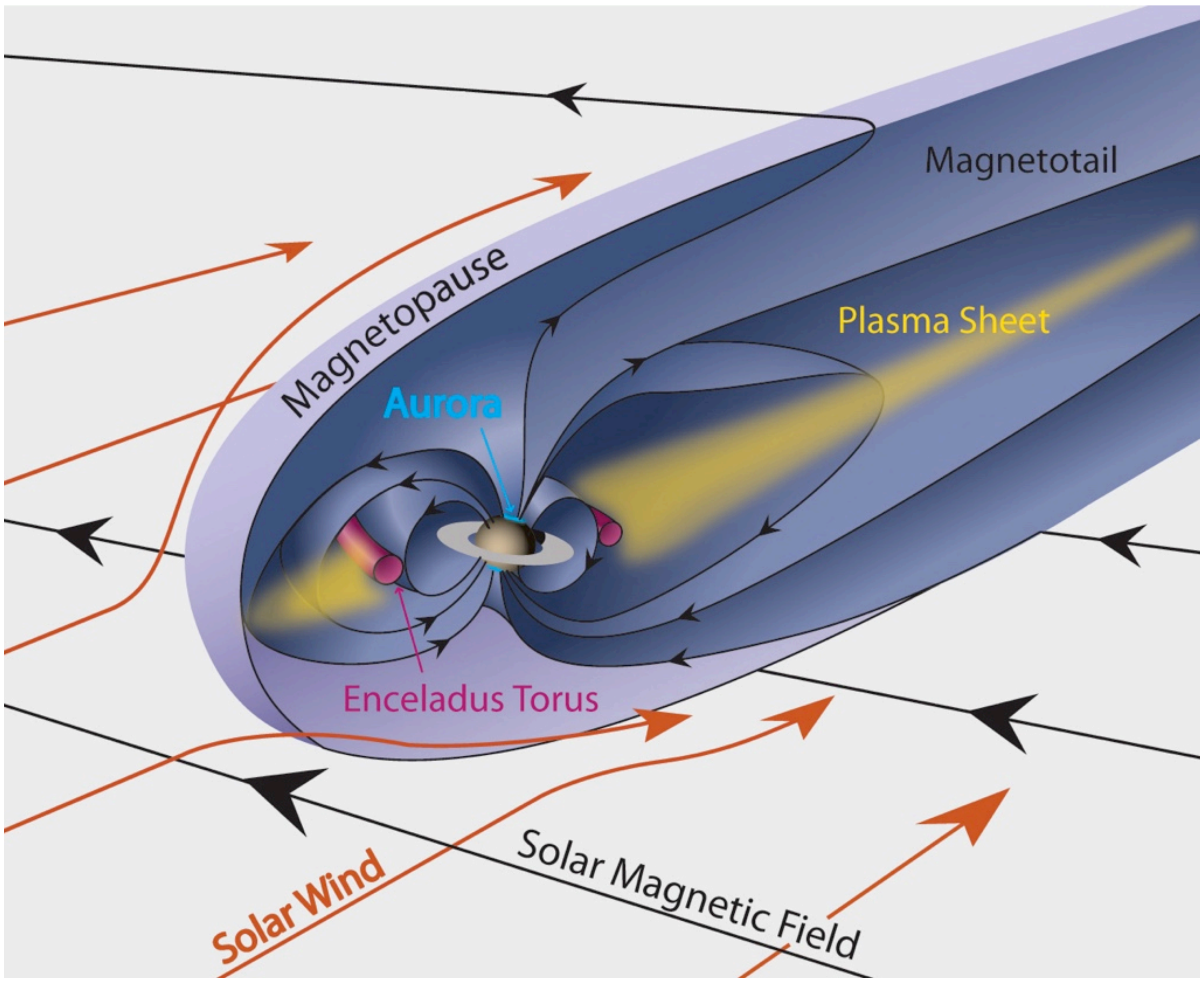


[Bagenal, 2002]



[Desch, 1983]

Magnetosphere dynamics



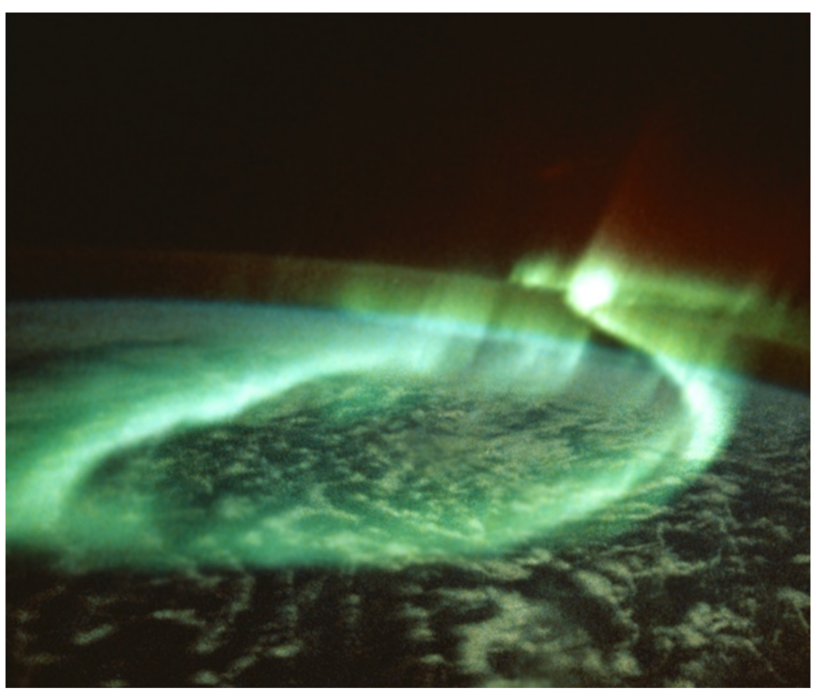
• **Plasma circulation**

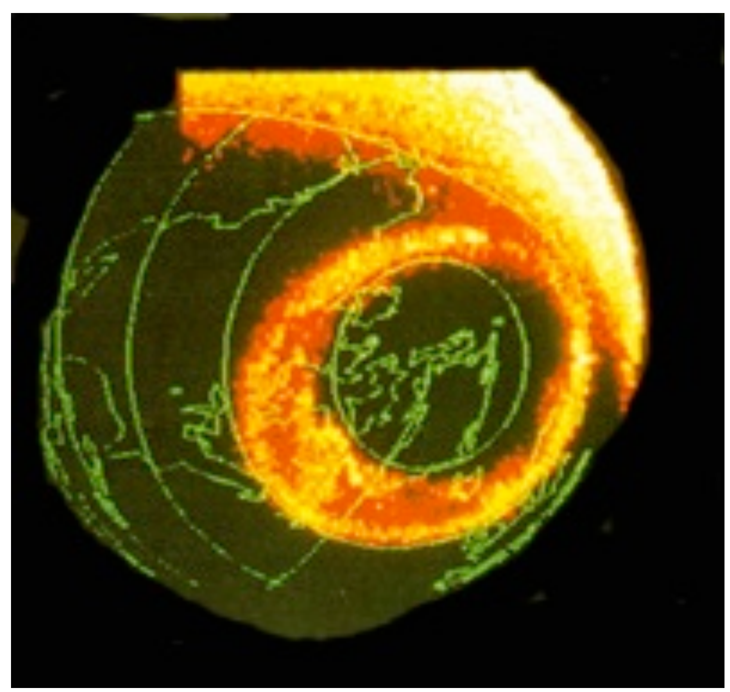
- 2 convection cells + large scale E (dawn → dusk) inside Earth's MS

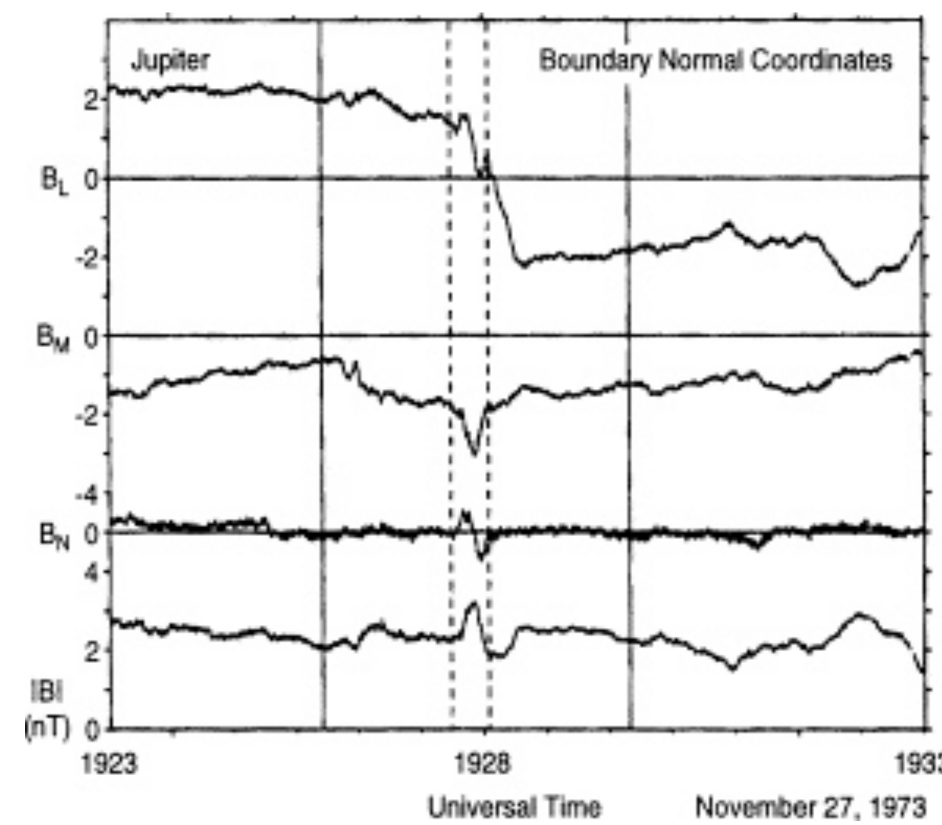
- energetic plasma inside MS

- quasi-permanent circumpolar aurora (∅ = 10°-20°)

- SW control (B_z) of MS activity : $B_N \neq 0$ when B_z // B_P

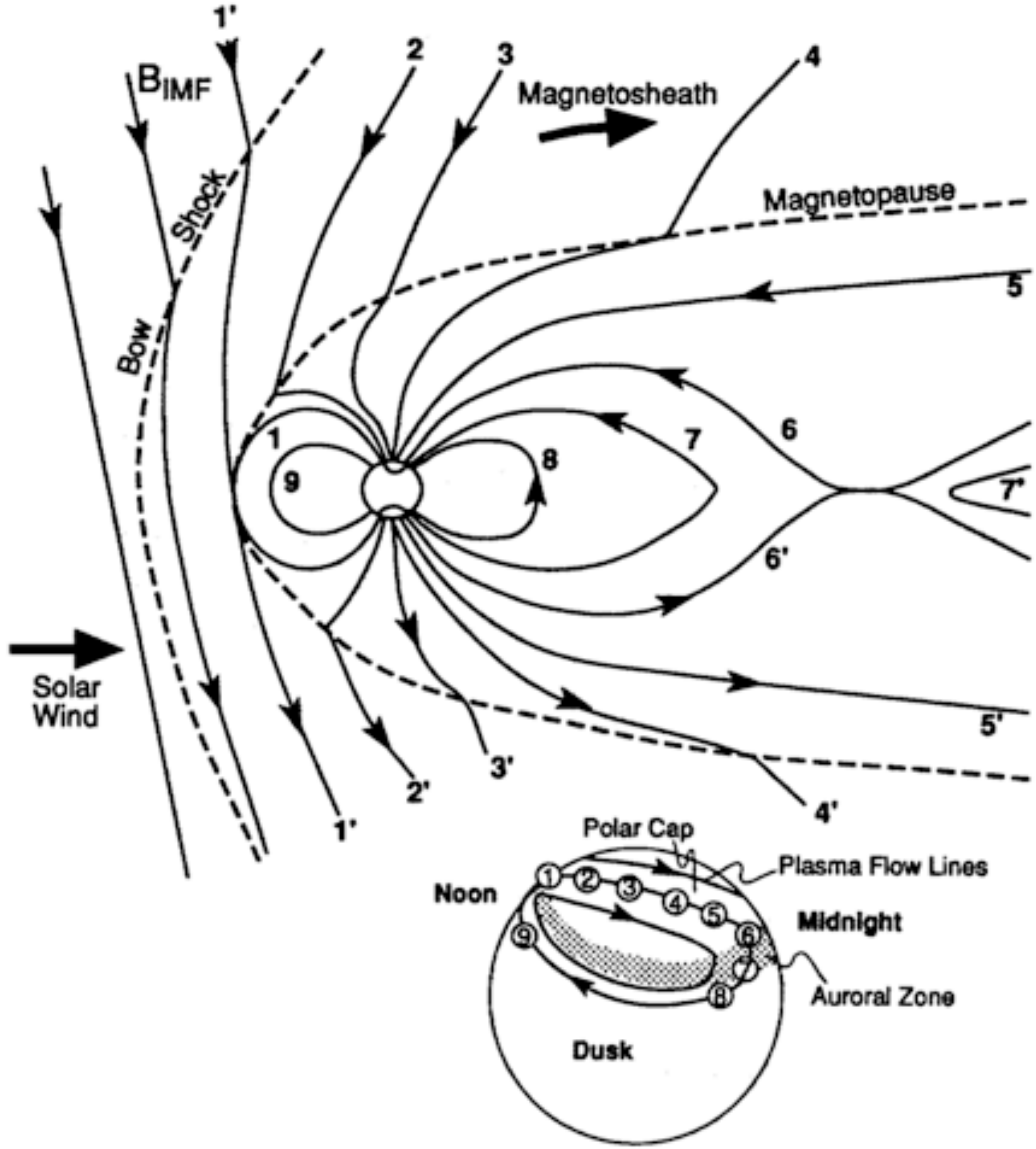






⇒ Open magnetosphere concept + Dungey cycle *[Dungey, 1961]*

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

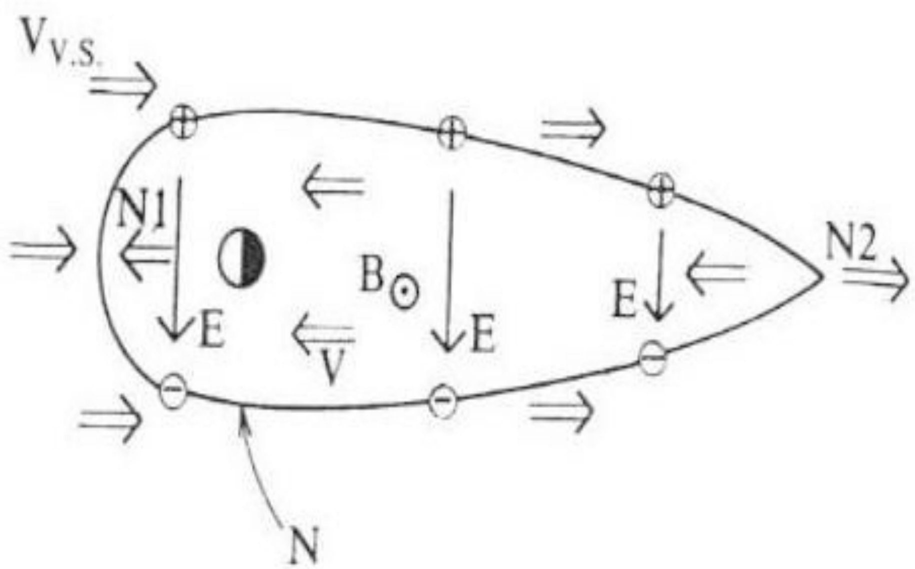


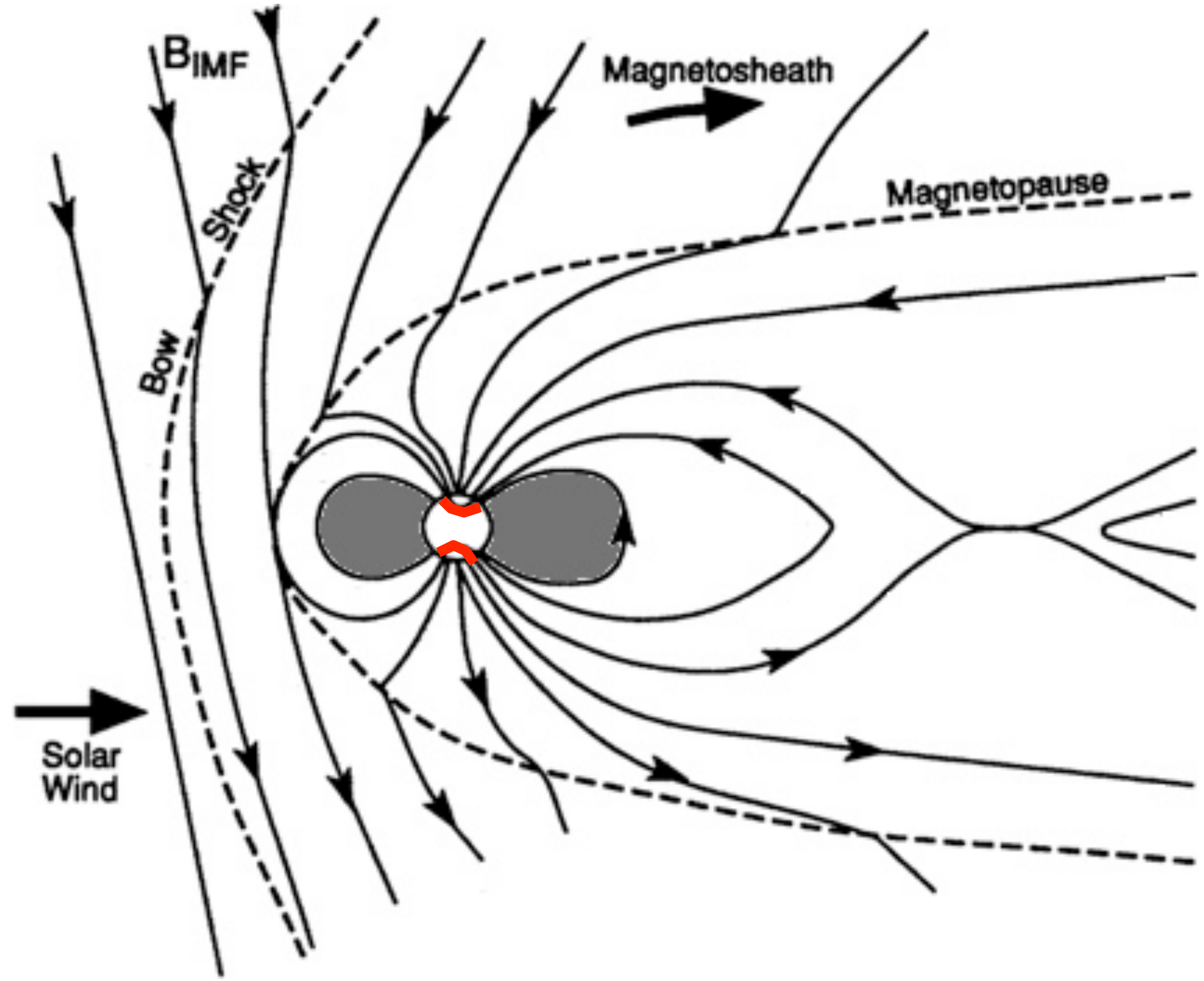
[Hughes, 1995]

- **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 neutral line on ionosphere





- Corotation ⇒ plasmasphère

- Tail stores / releases energy and magnetic flux

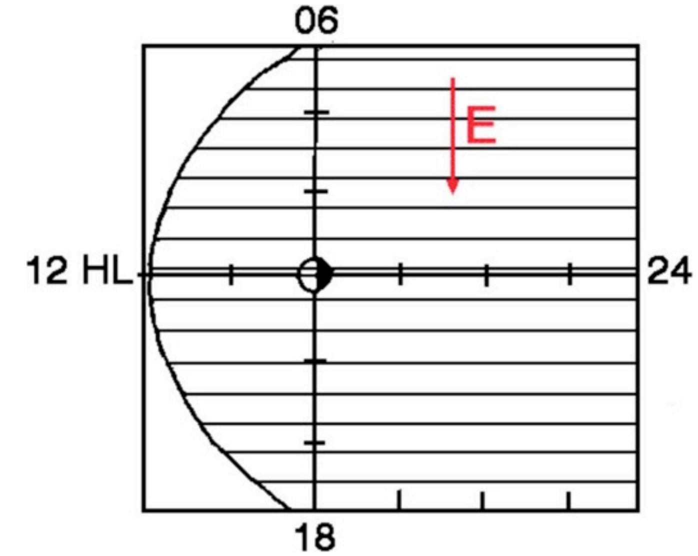
- Poynting flux on obstacle : $P_m = B_{\perp}^2/\mu_o \, V \;\; \pi R_{obs}^2$

- Convection = Dungey Cycle : (θ relative to 12-24h line)

$$\mathbf{E}_{conv} = -\varepsilon\, \mathbf{V}_{SW} \times \mathbf{B}_{SW}$$

$$= - E_o \sin\theta\, \mathbf{e}_r - E_o \cos\theta\, \mathbf{e}_\theta = 1/r \;\; \partial\varphi/\partial\theta\, \mathbf{e}_\theta$$

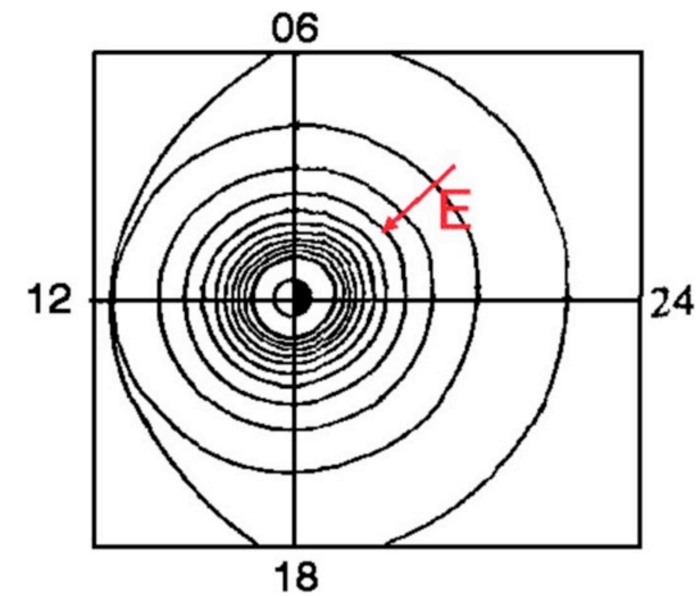
$$\varphi_{conv} \sim \varepsilon\, V_{SW}\, B_{SW}\, R\, R_P \sin\theta$$



- Corotation :

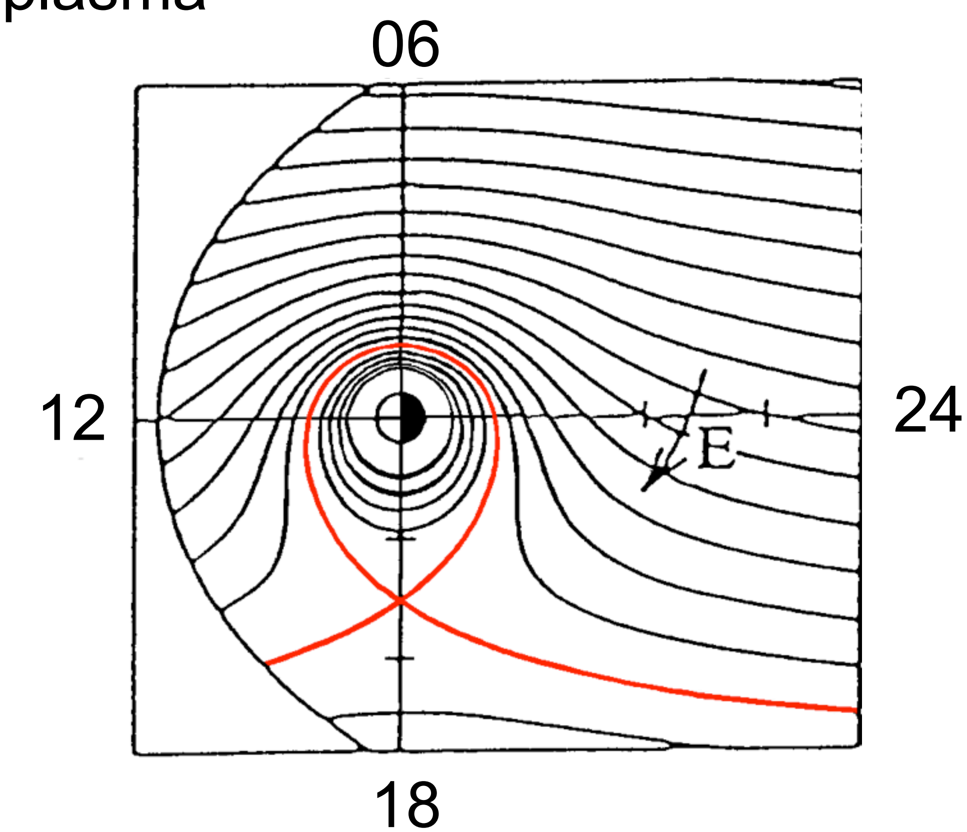
$$\mathbf{E}_{corot} = \mathbf{- (\Omega \times r) \times B} = -\Omega\, r\, B\, \mathbf{e}_r = \partial\varphi/\partial r\, \mathbf{e}_r$$

$$\varphi_{corot} \sim \Omega\, B_e\, R_P^2/R$$

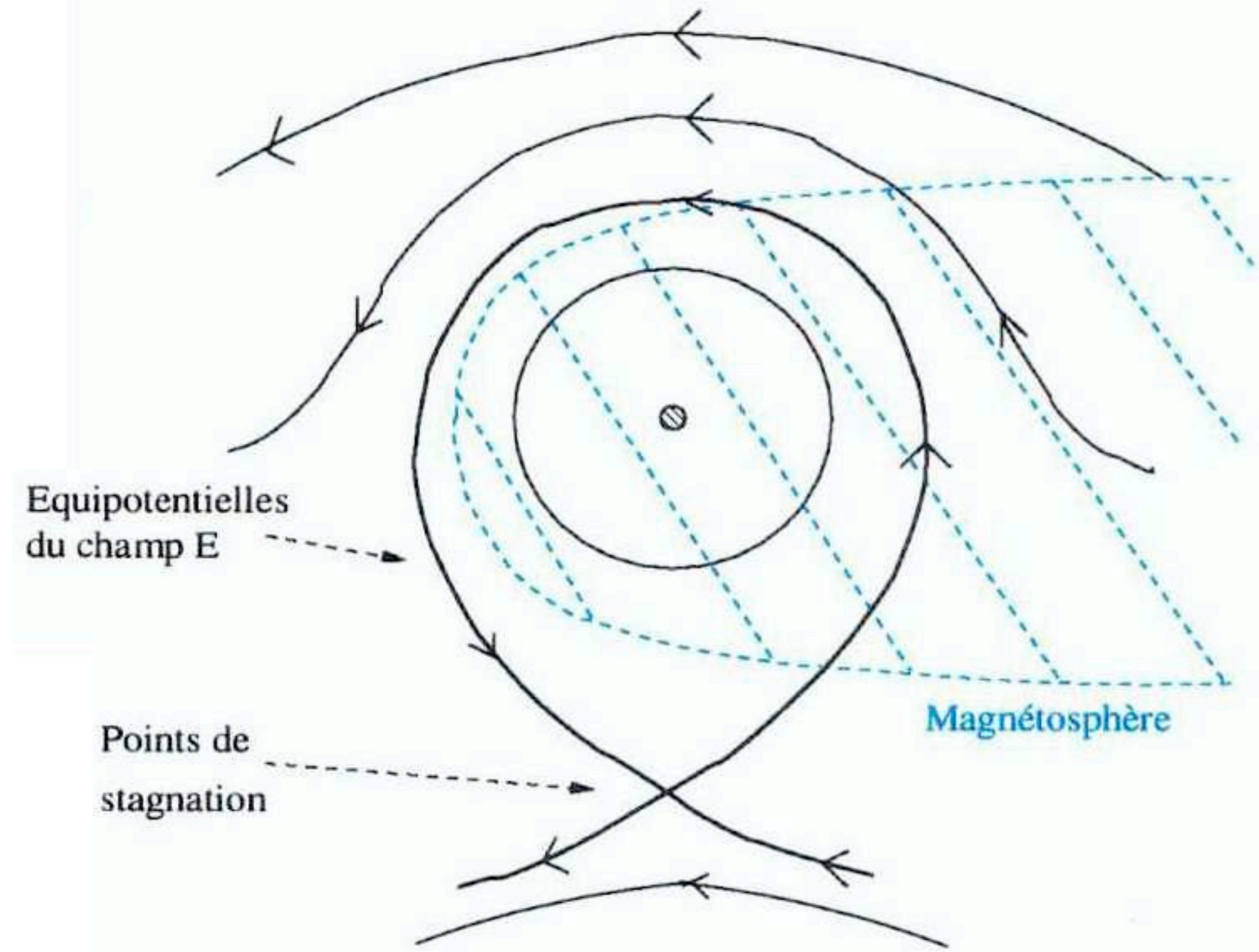


⇒ équipotentials = flow lines of thermal plasma

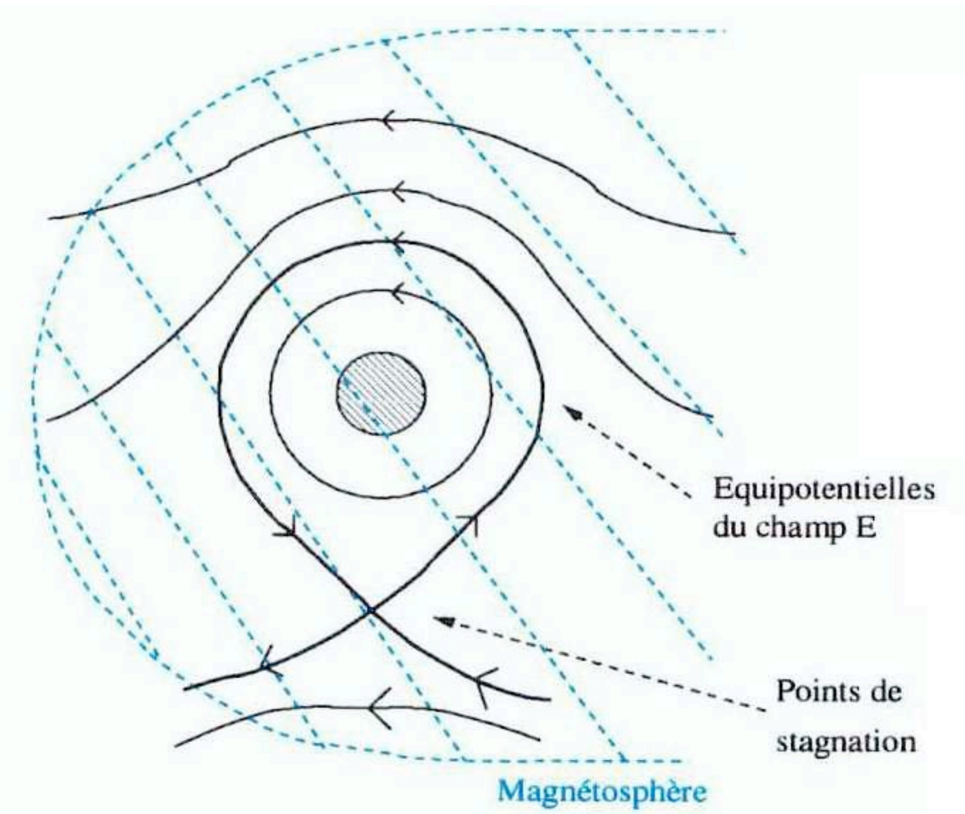
⇒ superposition = global circulation



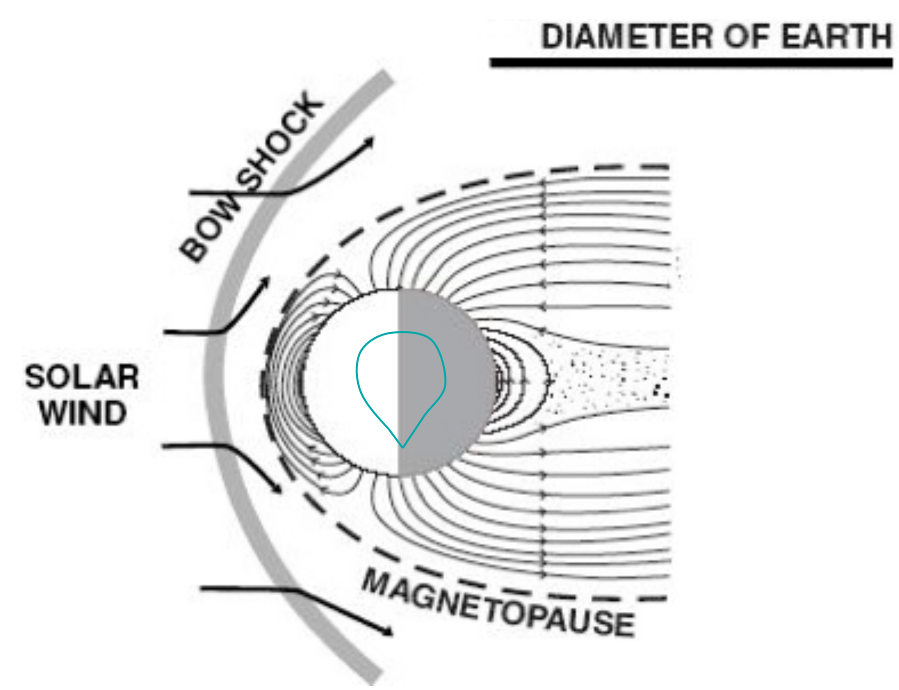
	Mercure	Terre	Jupiter	Saturne	Uranus	Neptune
R_P (km)	2 439	6 378	71 492	60 268	25 559	24 764
M_{dip} ($G.km^3$)	5.5×10^7	7.9×10^{10}	1.6×10^{15}	4.7×10^{13}	3.8×10^{12}	2.2×10^{12}
Champ à l'équateur B_e (G)	0.003	0.31	4.3	0.21	0.23	0.14
R_{MP} (R_P) calculée [mesurée]	1.4 [~1.5]	9 [~10]	40 [~90]	17 [~20]	22 [~18]	21 [~23]
B VS (nT)	10 (20)	4	0.8	0.4	0.2	0.13
Prot (h,m)	1407 h 30 m	24 h	9 h 55.5 m	10 h 39.4 m	17 h 14.4 m	16 h 6.6 m
E_{conv} (mV) [ε=0.15]	0.6	0.24	0.05	0.025	0.013	0.008
$\Delta\phi_{conv}$ (kV) [ε=0.15]	7	46	900	90	17	14
$\Delta\phi_{corot}$ (kV)	0.002	90	400 000	12 000	1 500	1000
R_S/R_{MP}	0.02	0.8	4	4	4	3



Jupiter



Earth



Mercury

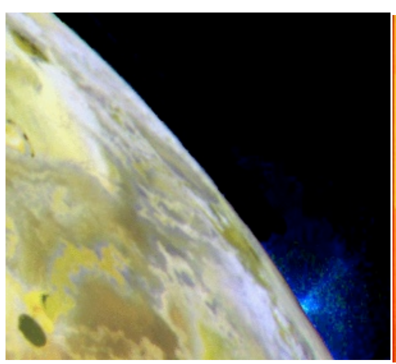
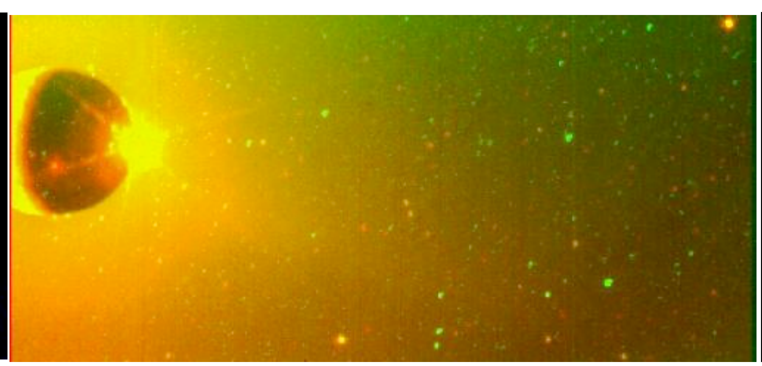
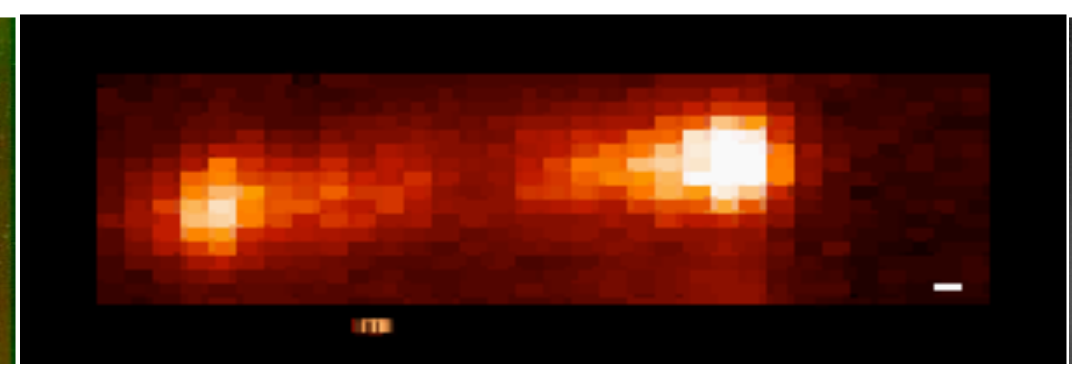
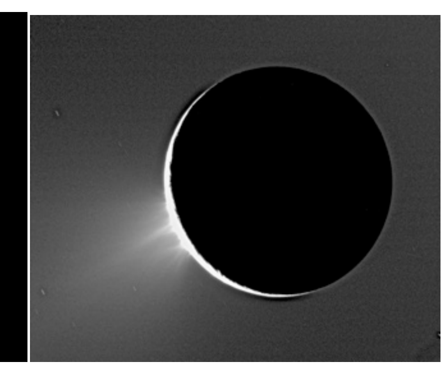
• **Plasma sources**

- Solar Wind : cusp + diffusion/reconnection across Magnetopause (H & He, T~100 eV)
- 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]*

- Rings, Icy satellites & Mercury's surfaces : sputtering / photo-dissociation + ionisation *[Young et al., 2005]*

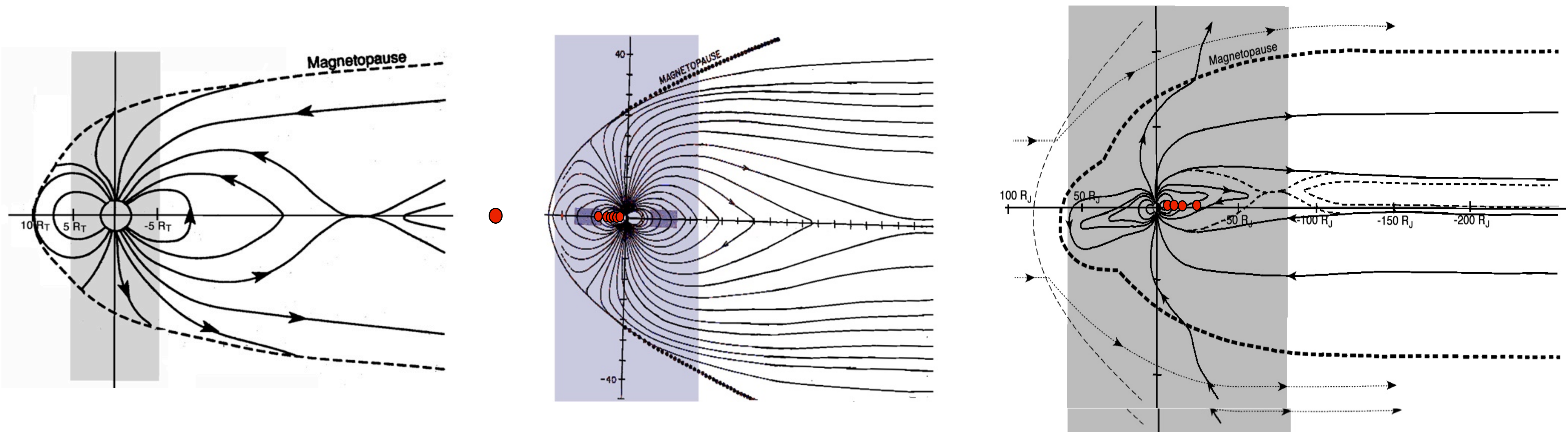
• Jupiter sources >> Saturn, Uranus, Neptune

• $N_{neutrals}/N_{plasma}$ = 100 @ Saturn, 0.003 @ Jupiter

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

- satellites = plasma sources in the corotation region, beyond the synchronous orbit (J, S...)

$$F_{centrifuge} = F_{gravitation}$$



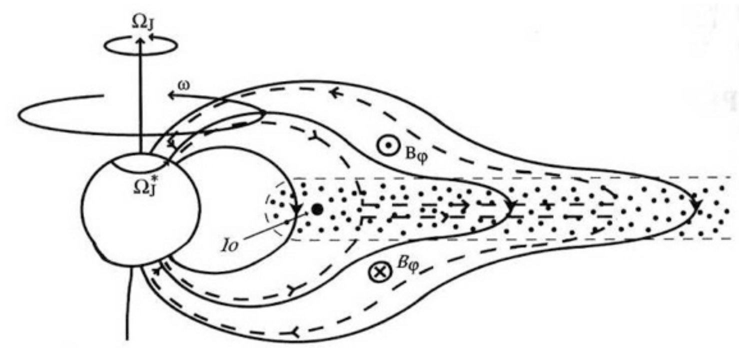
Planet	R_p [km]	Ω [rads/s]	G_{surf} [ms^{-2}]	R_{synch}/R_{planet}	Plasma sources
Mercury	2440	$1{,}24 \times 10^{-6}$	3.3	96	None
Earth	6371	$7{,}29 \times 10^{-5}$	9.8	6.6	Ionosphere
Jupiter	70000	$1{,}77 \times 10^{-4}$	25.6	2.3	Io
Saturn	60000	$1{,}71 \times 10^{-4}$	10.8	1.8	Rings, moons
Uranus	25500	$1{,}01 \times 10^{-4}$	8.6	3.2	Moons
Neptune	24830	$1{,}01 \times 10^{-4}$	10.1	3.4	Moons

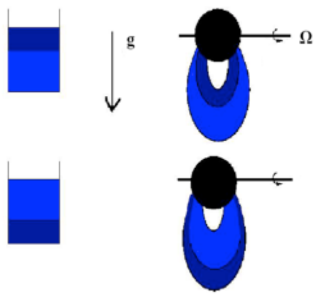
- **Plasma transport**

  - pickup / mass-loading ⇒ corotation + centrifugal force (interchange instability)

    ⇒ radial transport ⇒ from corotation to sub-corotation

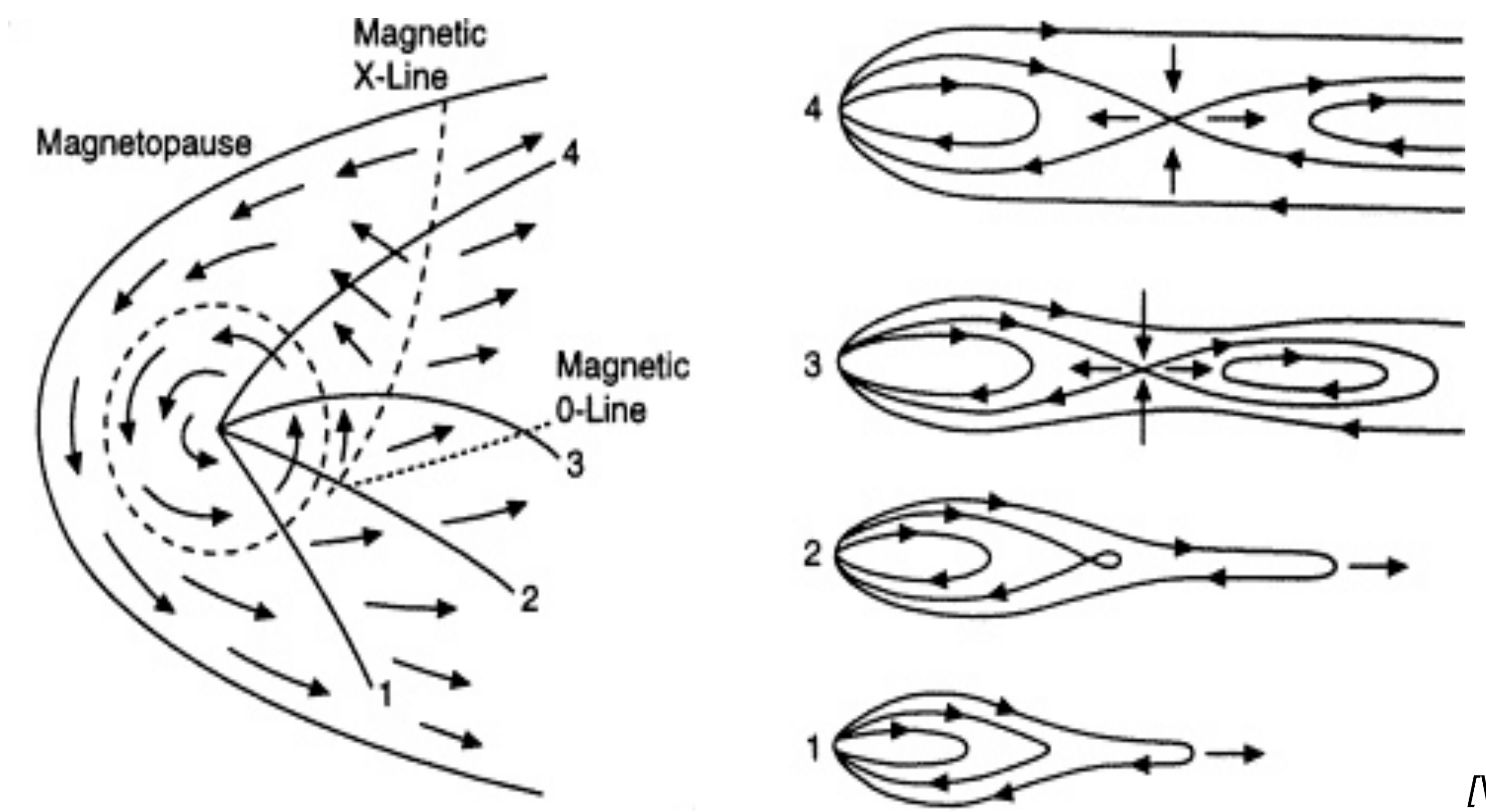
    ⇒ internally driven "rotational" dynamics





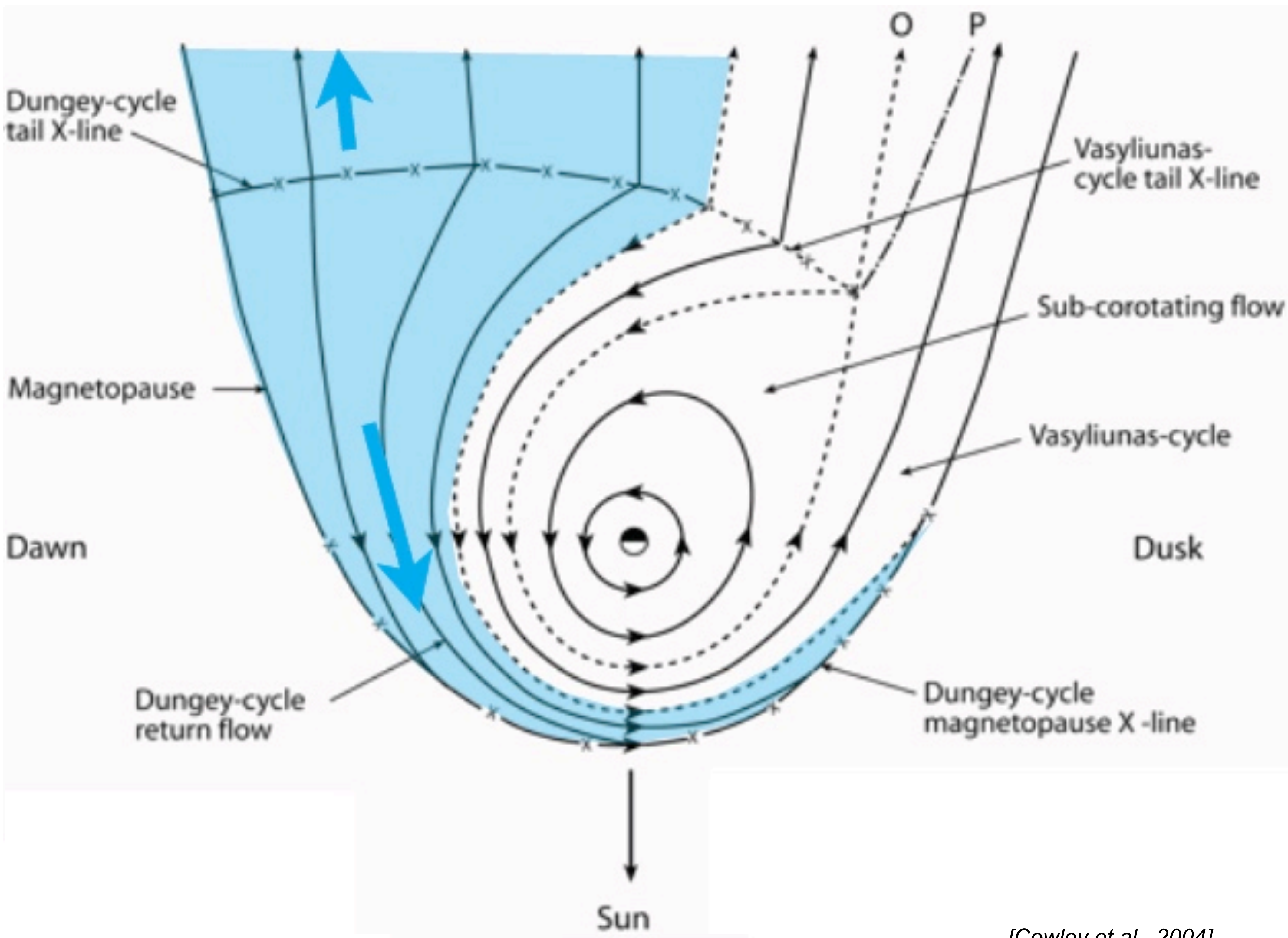
[André, 2006]

⇒ Vasyliunas cycle (depends on B, R, Ω)



[Vasyliunas, 1983]

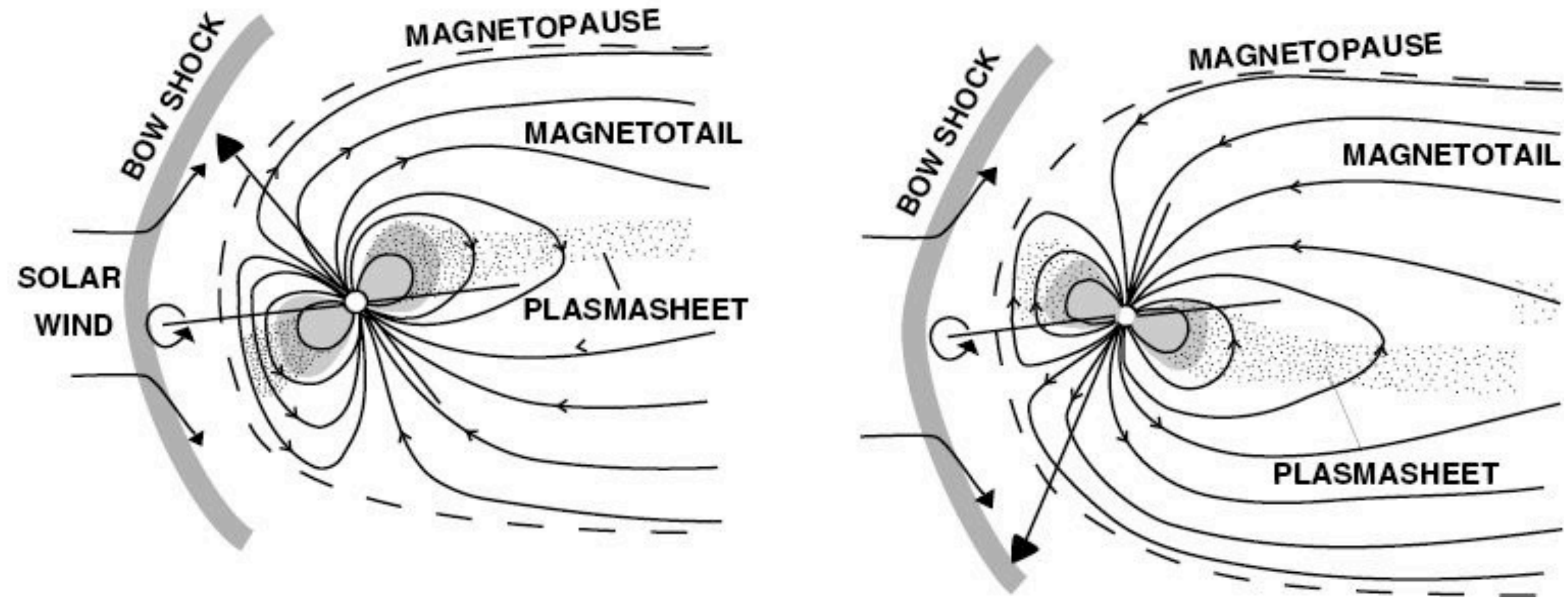
- Saturn : intermediate Earth - Jupiter ? Dungey + Vasyliunas cycles superimposed ?



[Cowley et al., 2004]

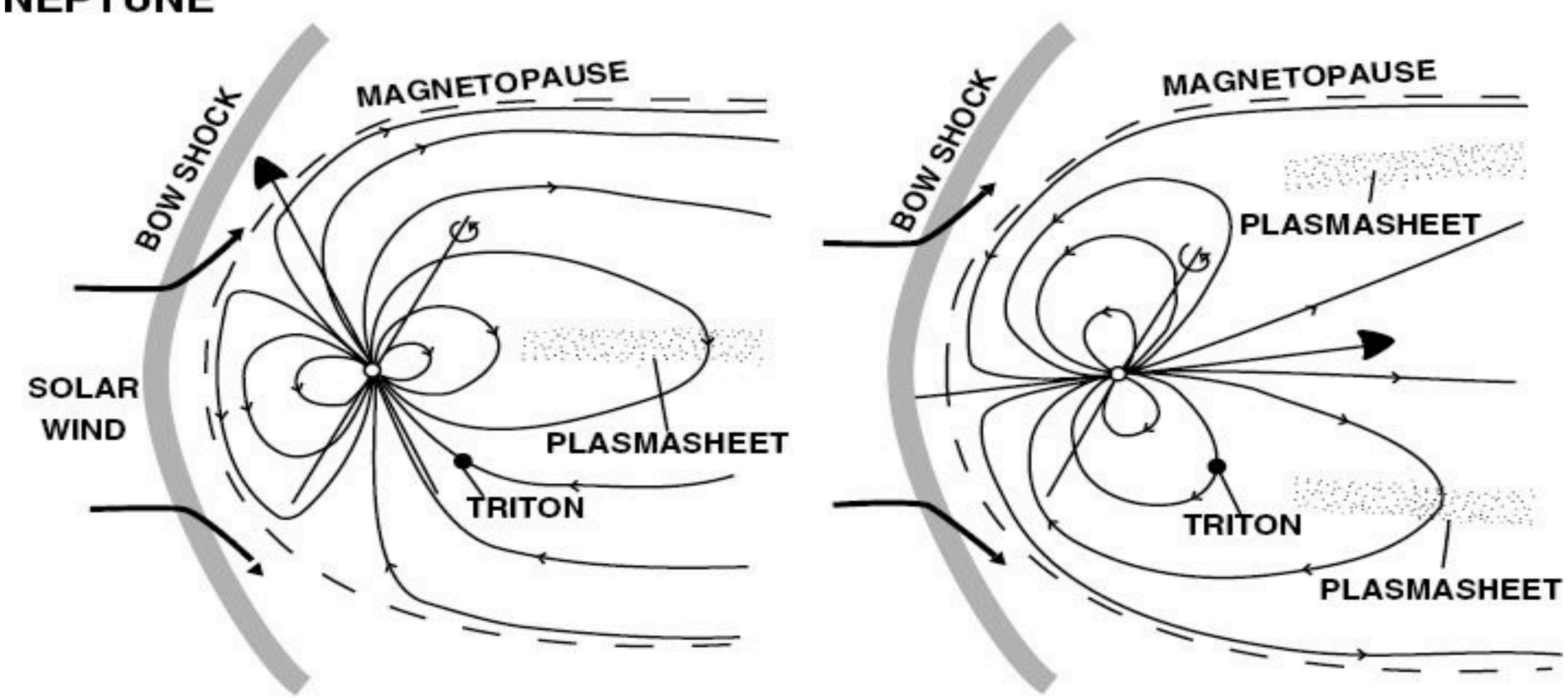
- Uranus : convection ⊥ corotation ⇒ helicoidal plasma trajectories ?

URANUS



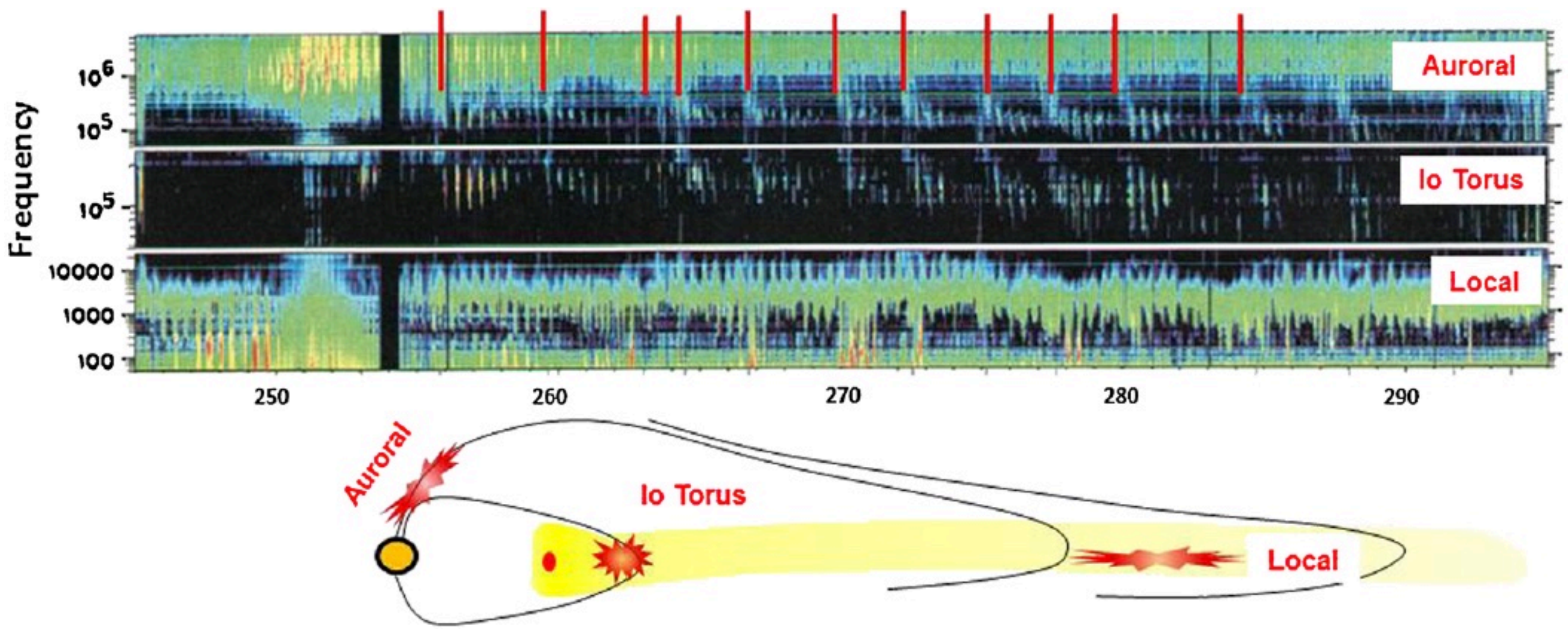
- Neptune : Magnetosphere alternately Earth-like & pole-on
  ⇒ no plasmasphere, mid-latitude aurorae

NEPTUNE



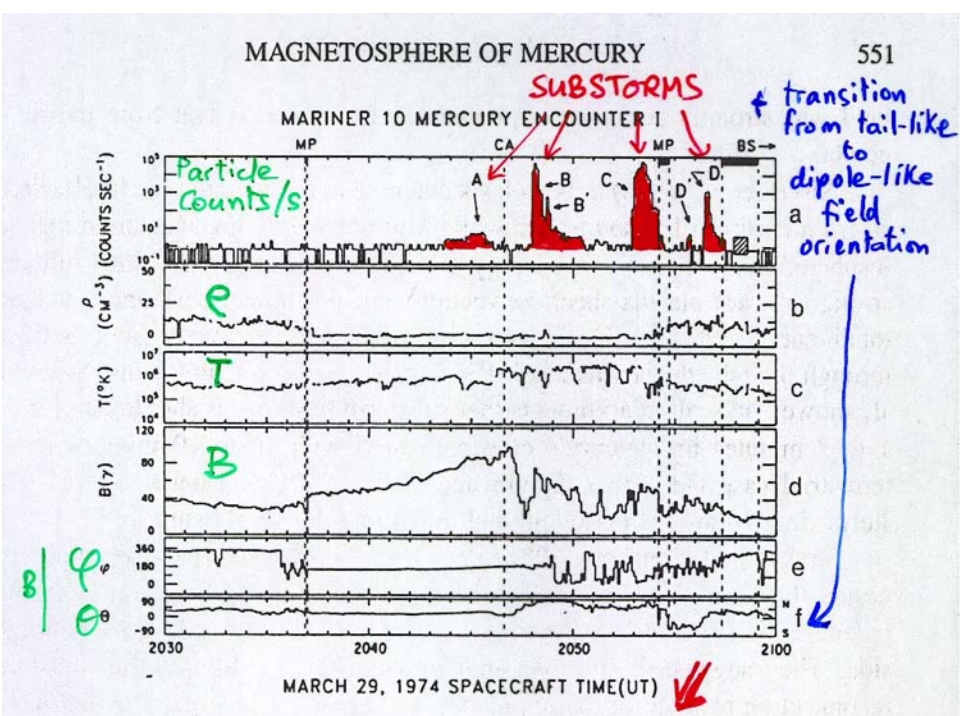
• **Sporadic dynamics**

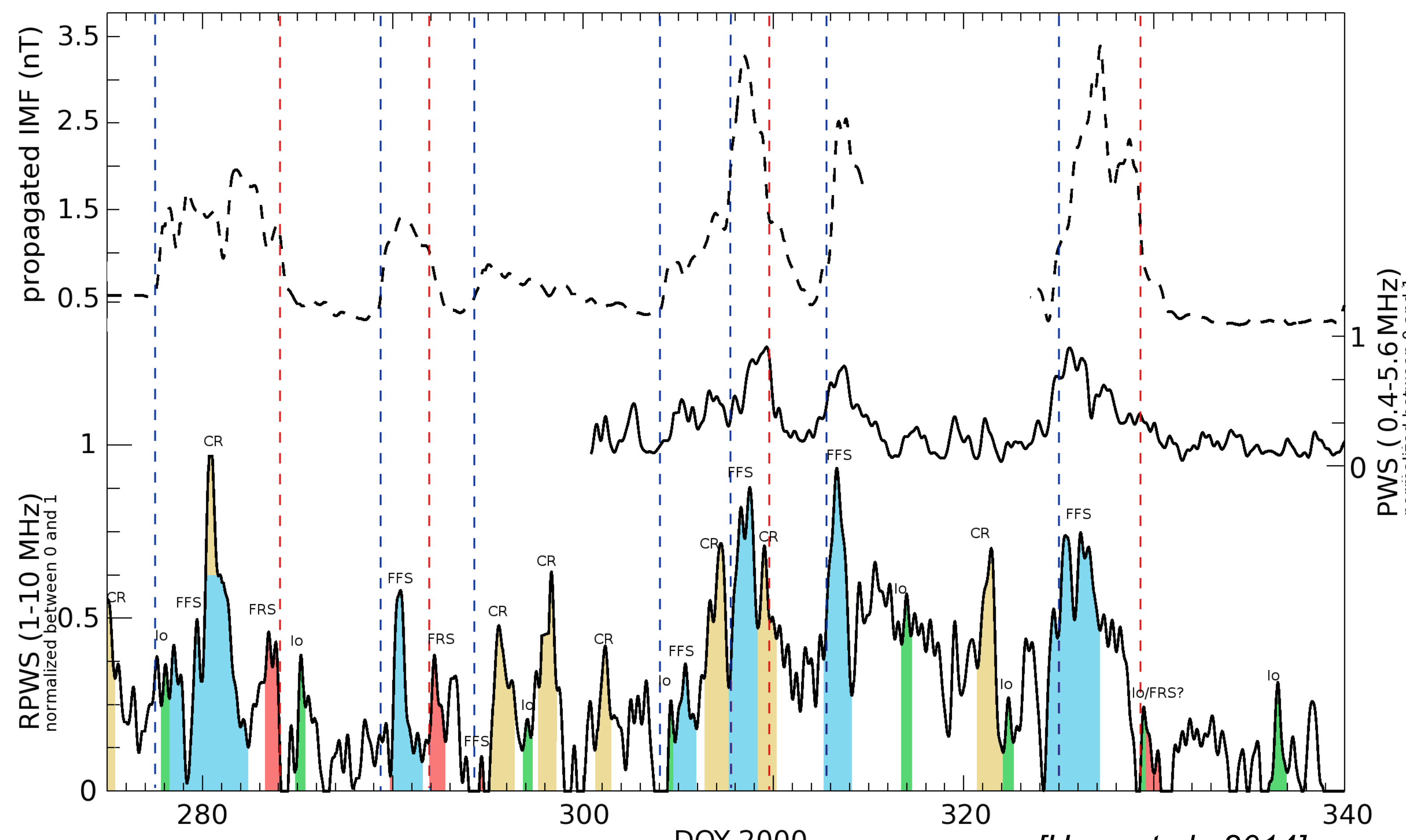
- Internally controlled : Vasyliunas cycle ⇒ centrifugal ejections



[Louarn et al., 2014 ; 2015]

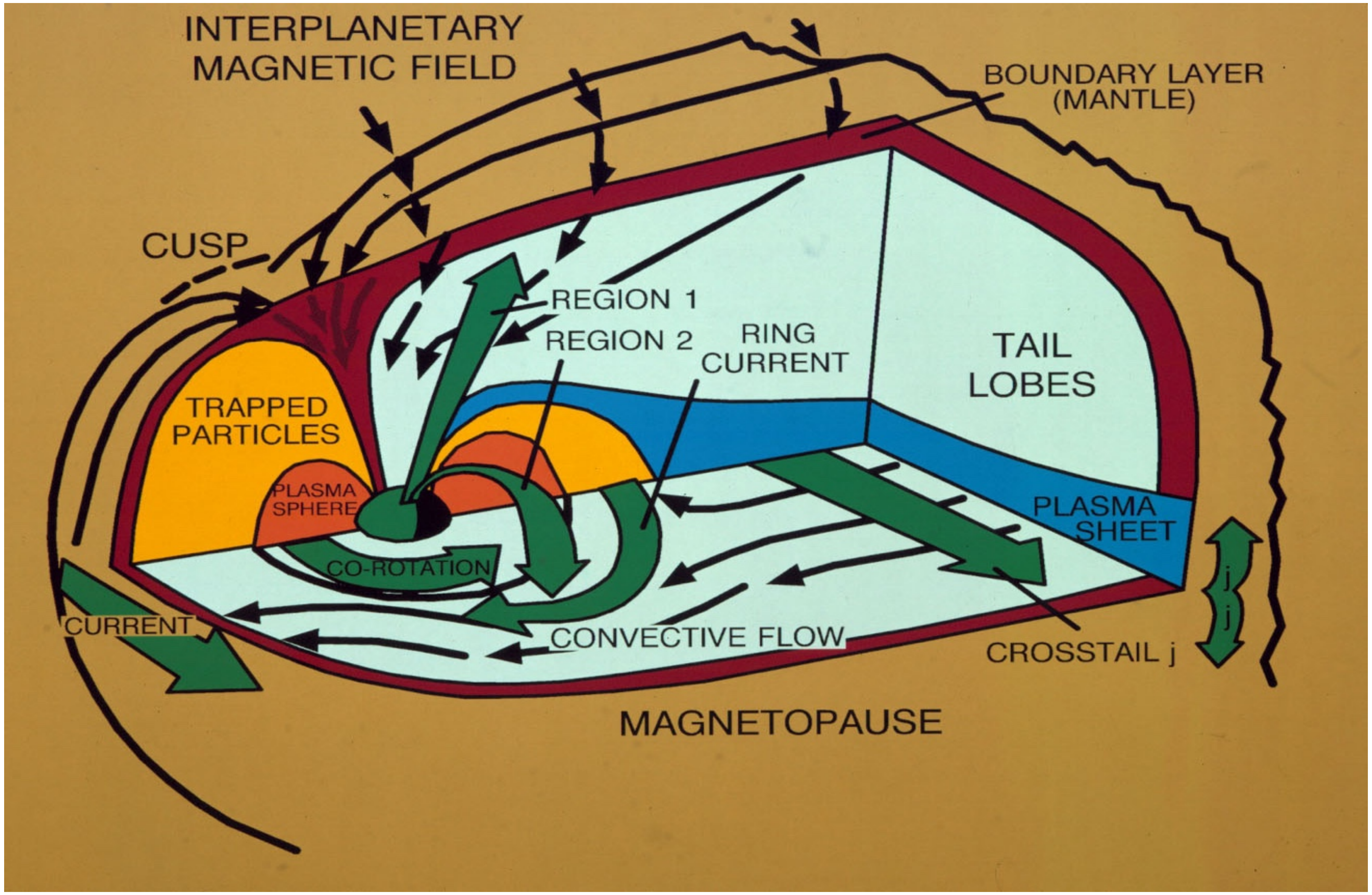
- Externally controlled : Dungey cycle ⇒ substorms, + MS compressions





[Hess et al., 2014]

Currents, M-I & M-S coupling



$$e \times \sum_{\text{all species}} \left(\partial N_i/\partial t + \nabla . N_i V_i = Q_i - L_i \right) \Rightarrow \nabla . J = 0 \Rightarrow \text{closed current circuits}$$

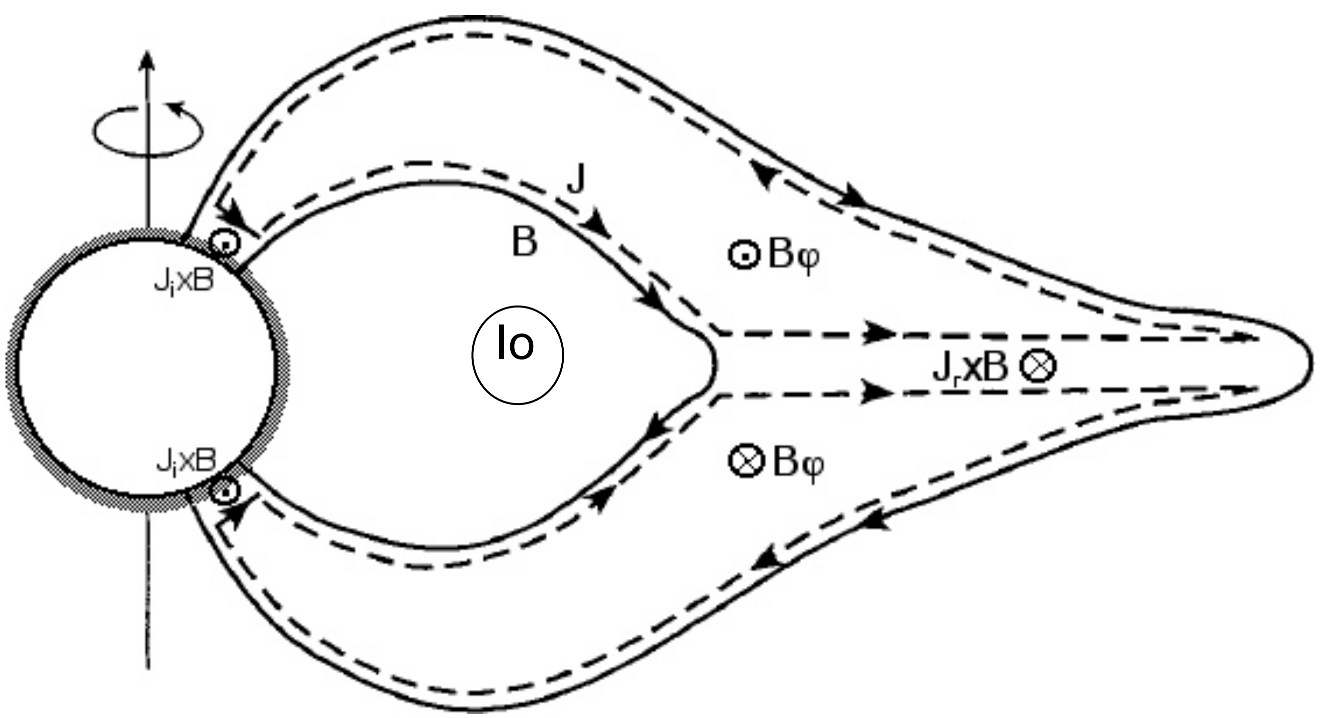
- **Magnetosphere - Ionosphere coupling**

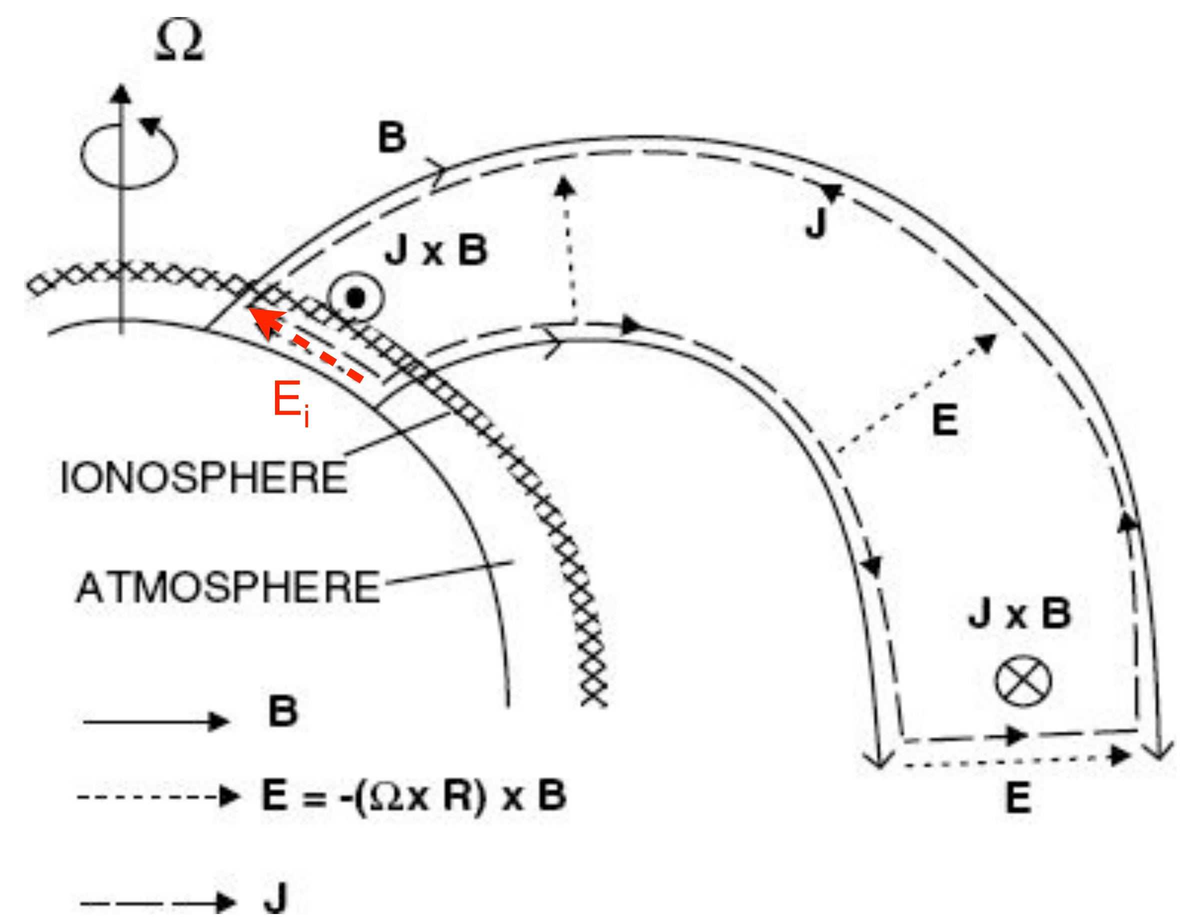
  - radial diffusion from Io $\Rightarrow$ J_r

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

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

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

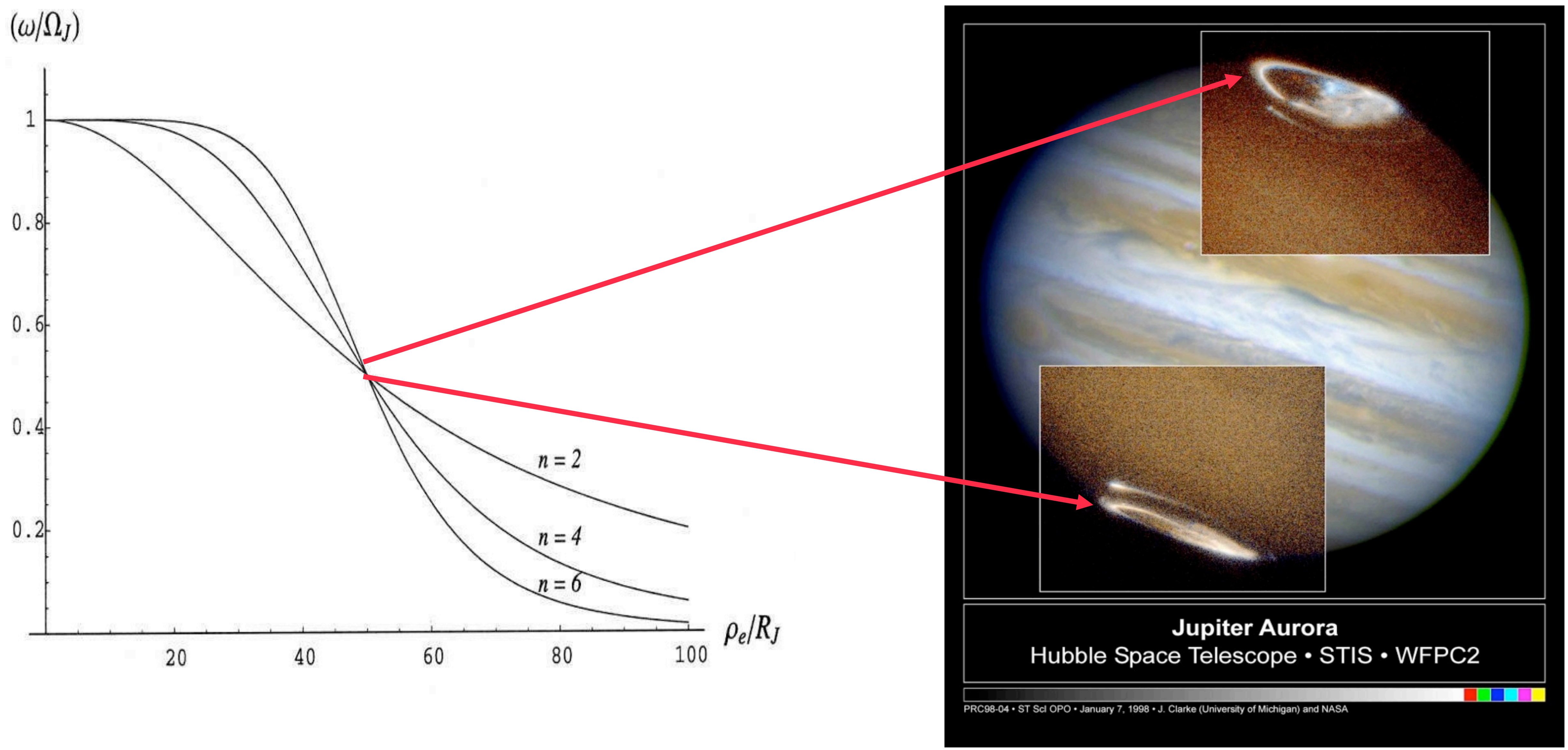




[Bagenal, 1989]

- Corotation breakdown at 20-50 R_J

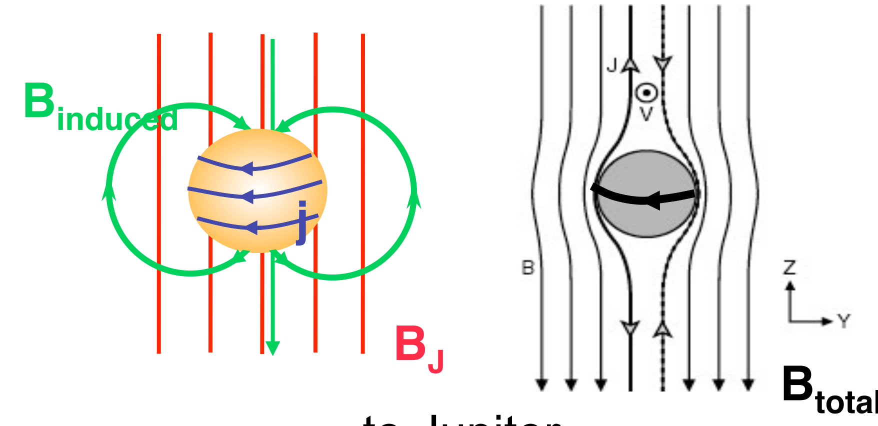
  $\Rightarrow J_{//}$ max $\Rightarrow$ main auroral oval at Jupiter



[Cowley & Bunce, 2001]

- **Magnetosphere-Satellites coupling**

- Unmagnetized satellite / MS interaction (Io, Europa, Enceladus...)



to Jupiter →

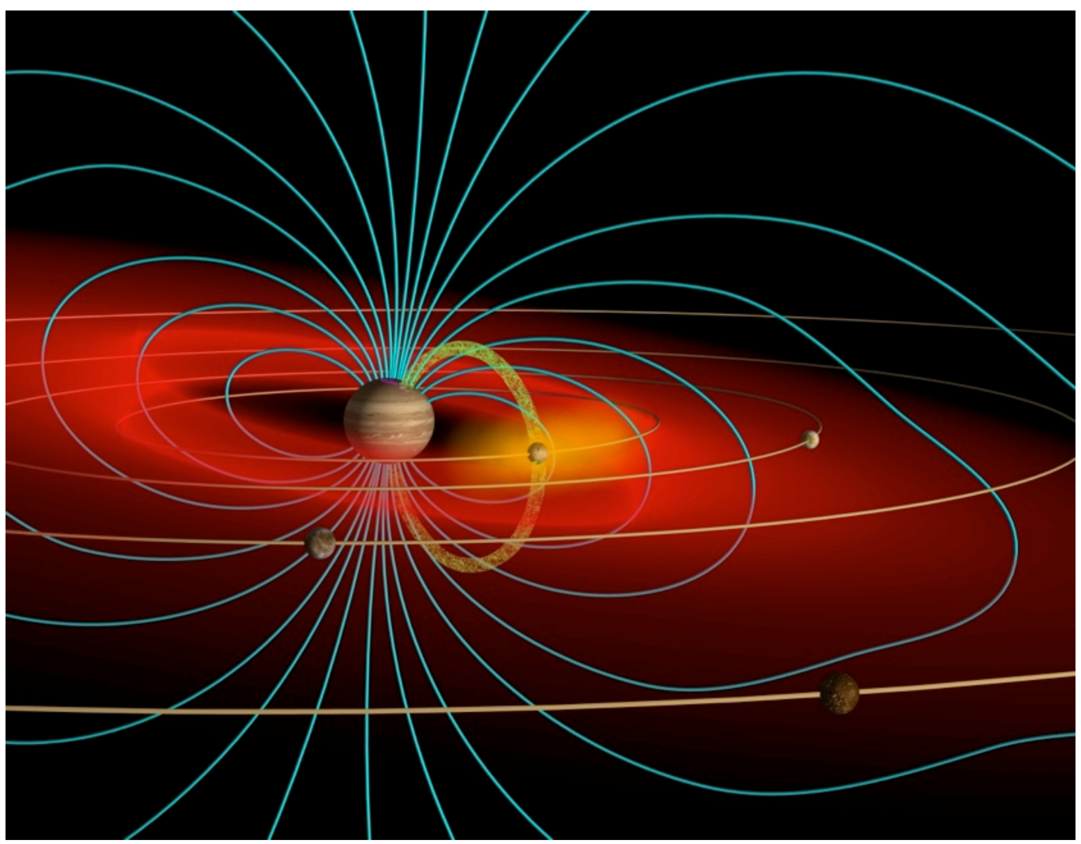
$\Rightarrow$ Induced field

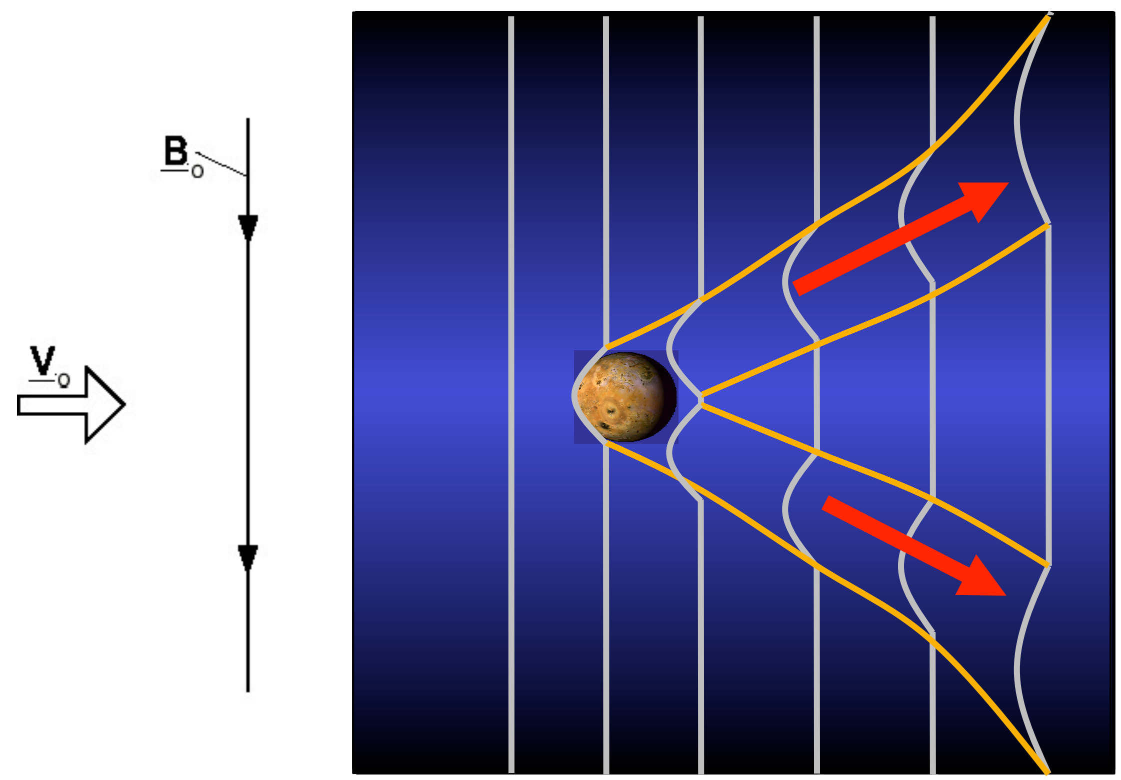
$E = -V \times B_J$ with $V = V_{corot} - V_K$ (=57 km/s @ Io)

$\Delta\phi \sim 2\ R_{sat}\ E$ (=4x10^5 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, Saur et al., 2002, Khurana, 2009]





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

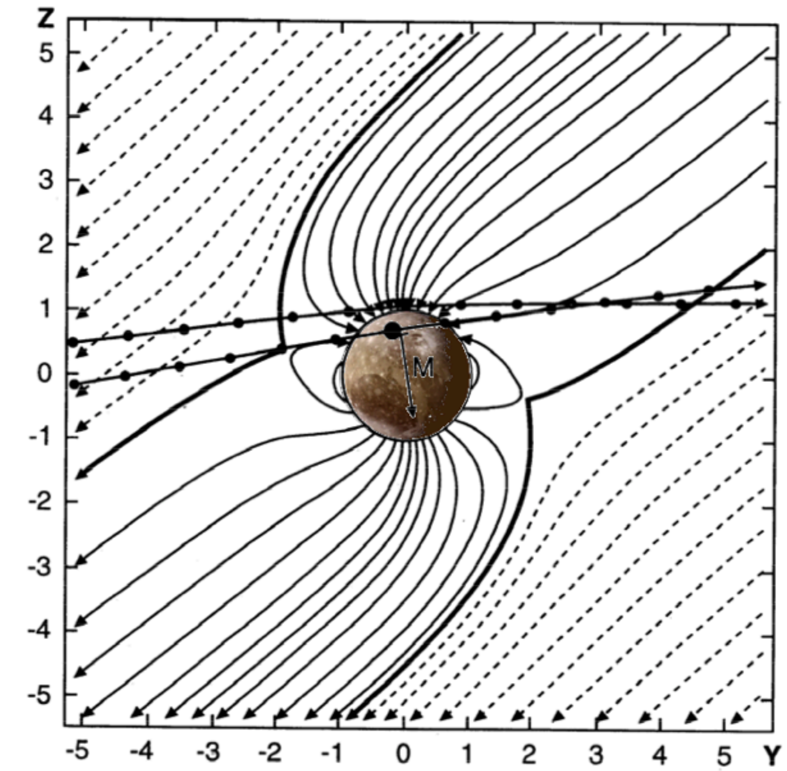
($\varepsilon \sim M_A \sim 0.15$)

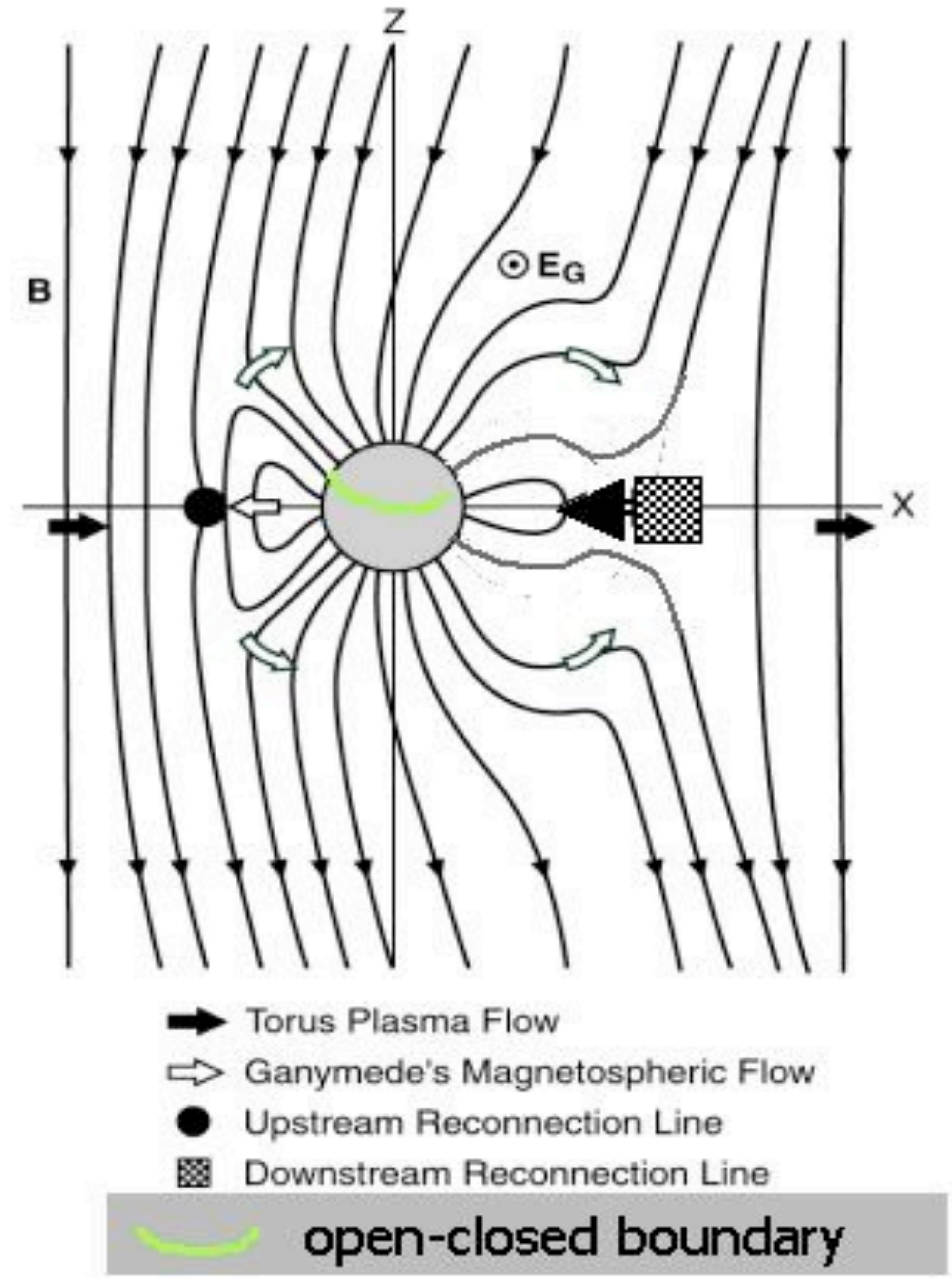
• **Magnetosphere-Satellites coupling**

- Magnetized satellite / MS interaction (Ganymede, ~100 nT)

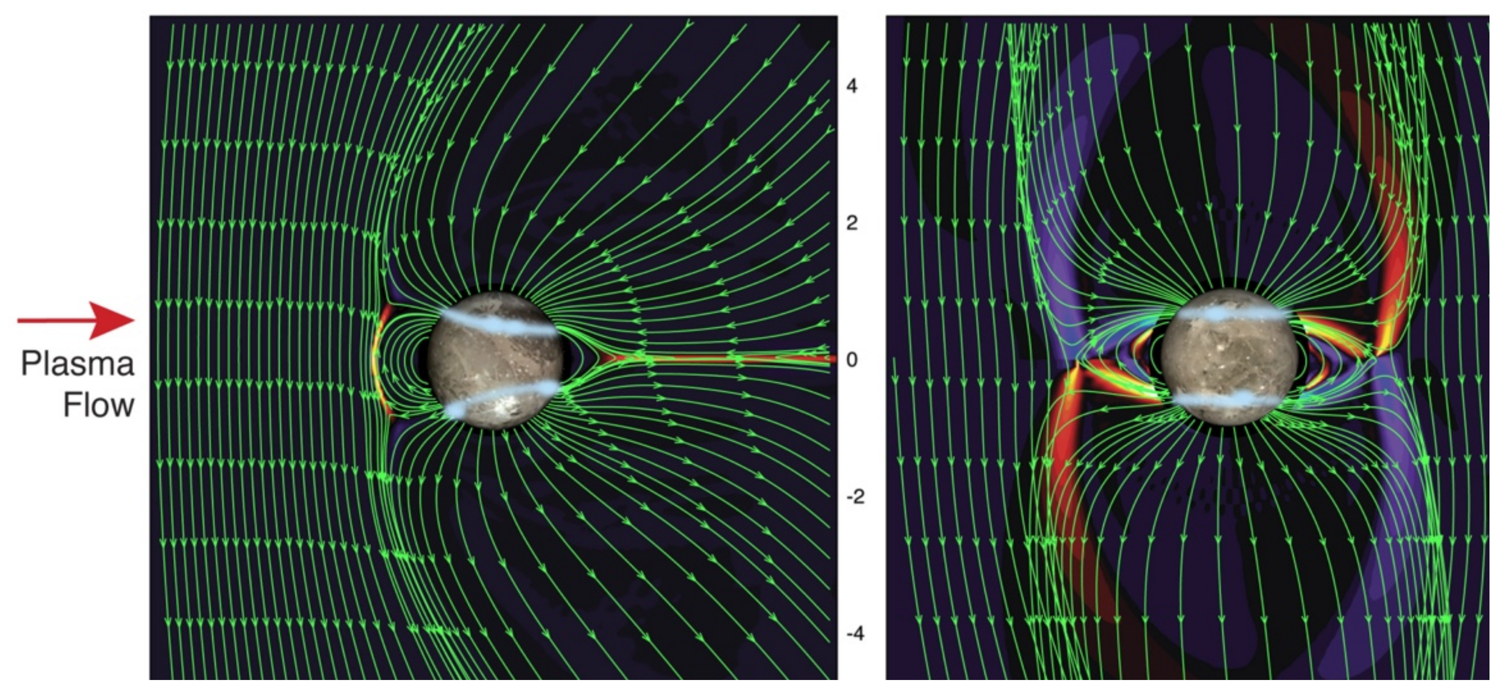
⇒ B reconnection

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





[Kivelson et al., 2004]

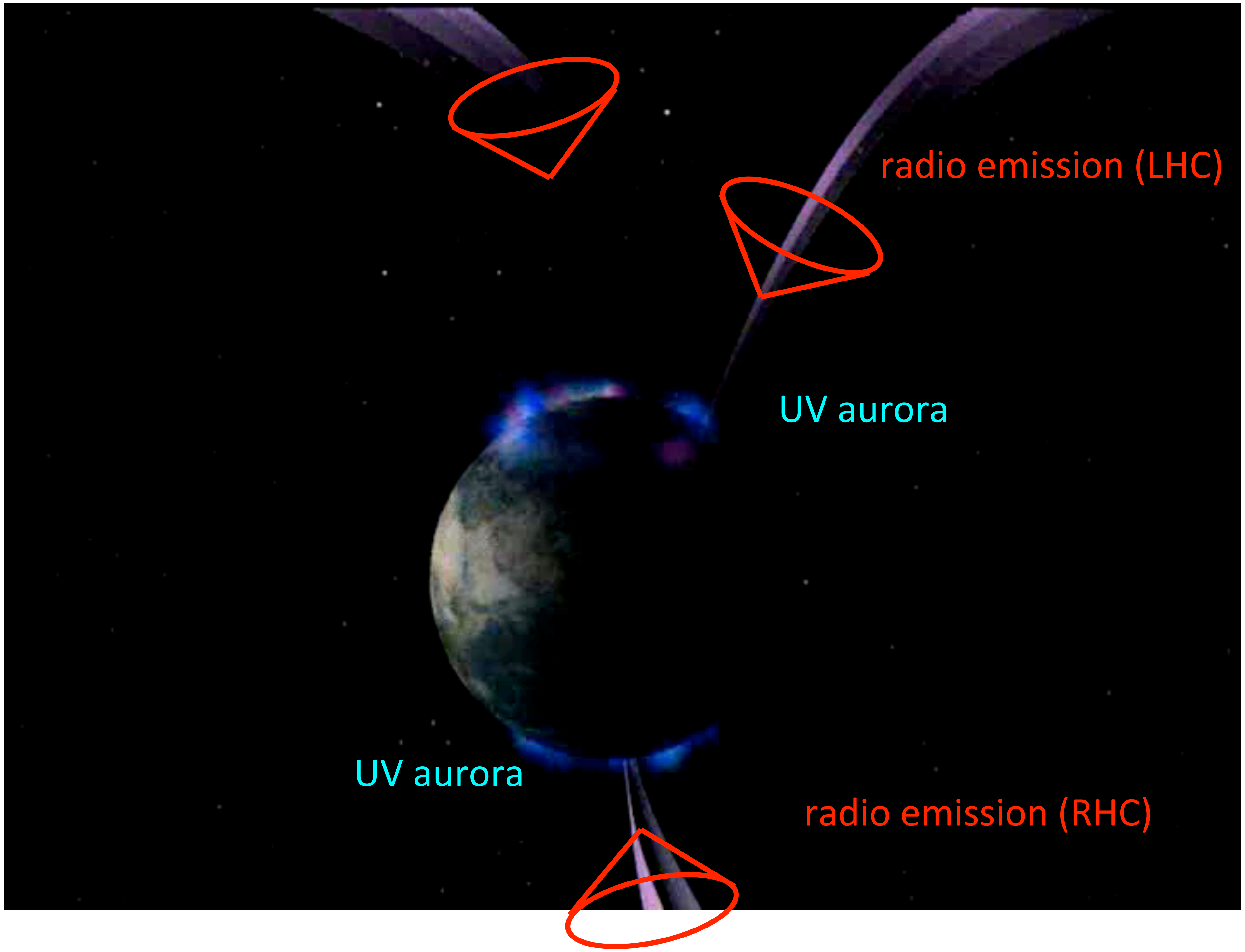


Dissipated powed :

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

($k = \cos^4(\theta/2) = 1$; $\varepsilon \sim 0.15$)

Aurora and radio emissions



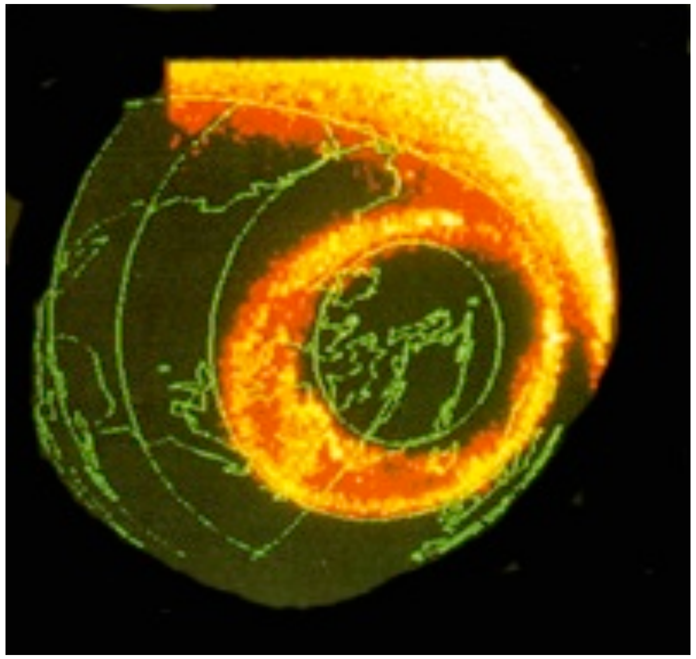
• **Aurora : short wavelengths**

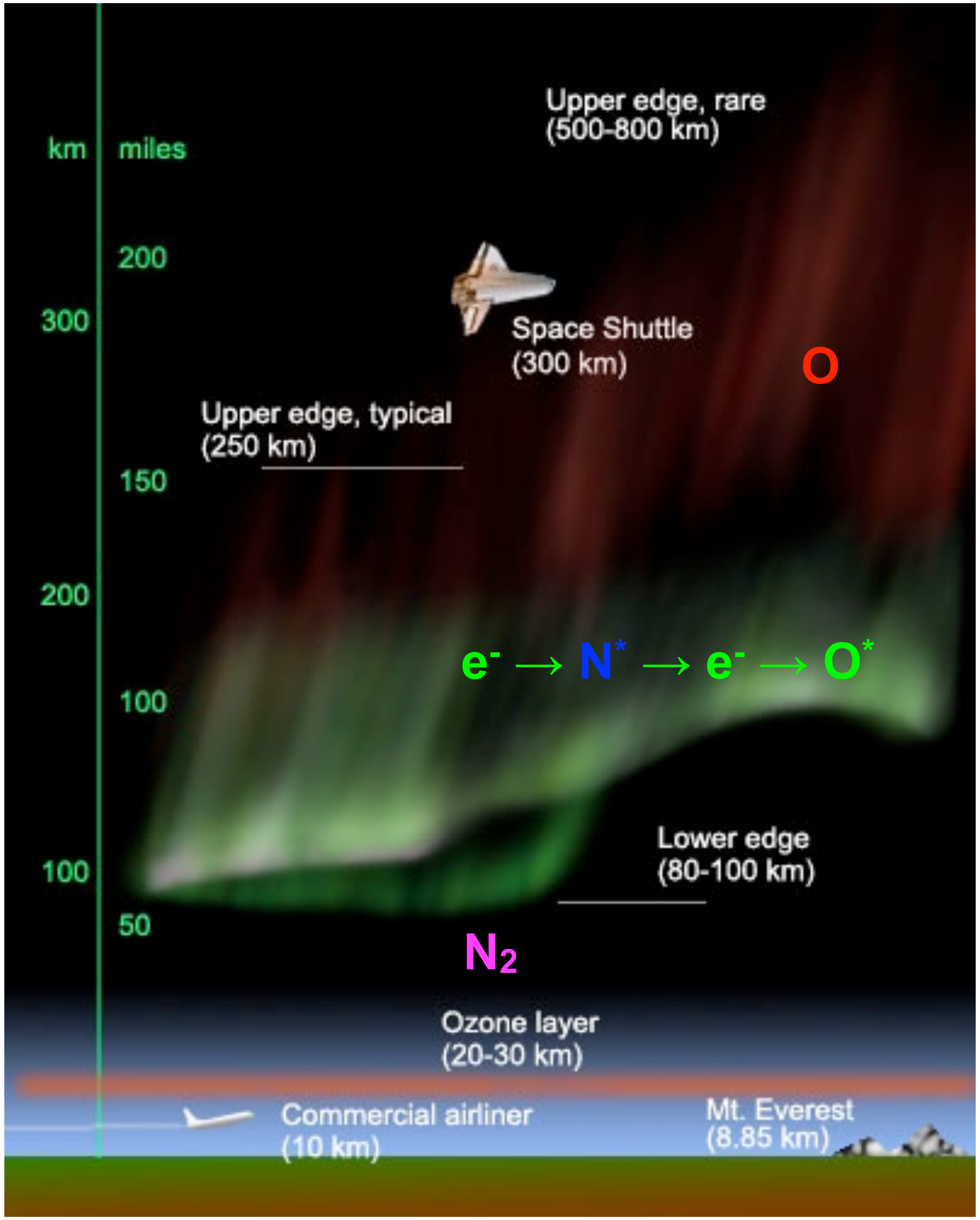
- strong currents + low plasma density ⇒ e- acceleration 1-100 keV

[Knight,1972]

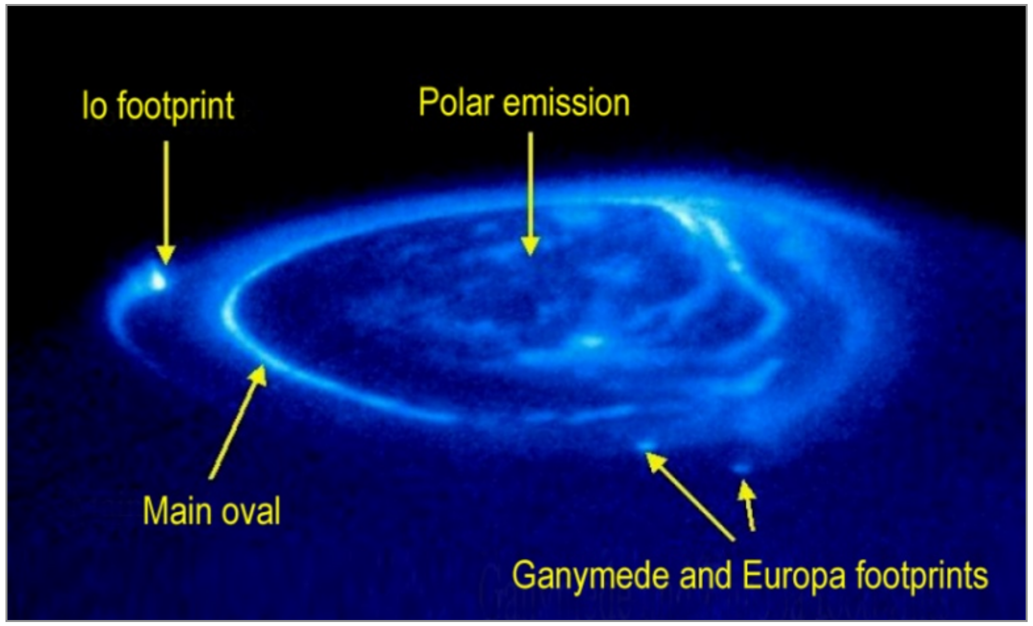
- collisions, excitation de-excitation ⇒ aurora

- Earth : visible (O, N, N_2)

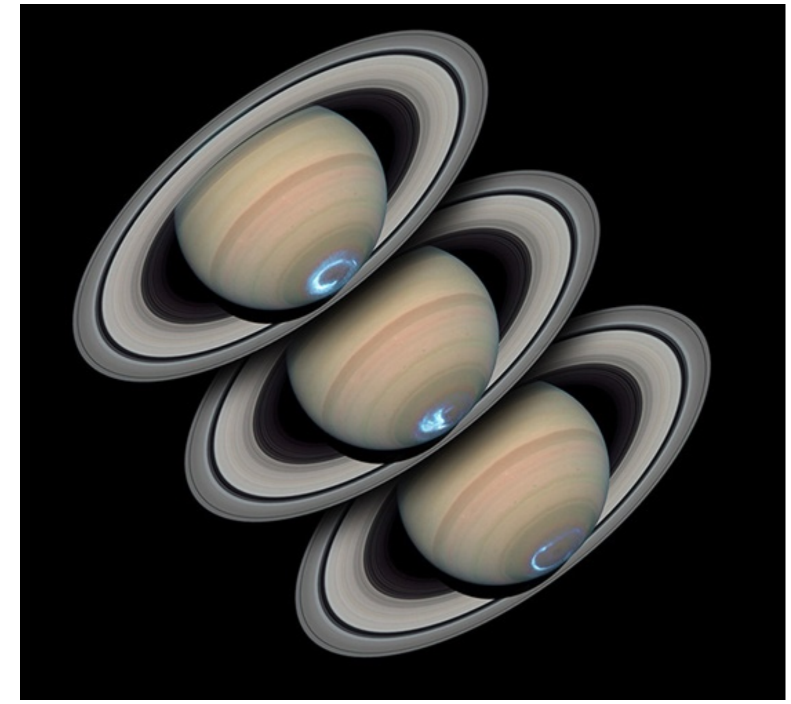




- Jupiter, Saturn : UV (H, H_2)

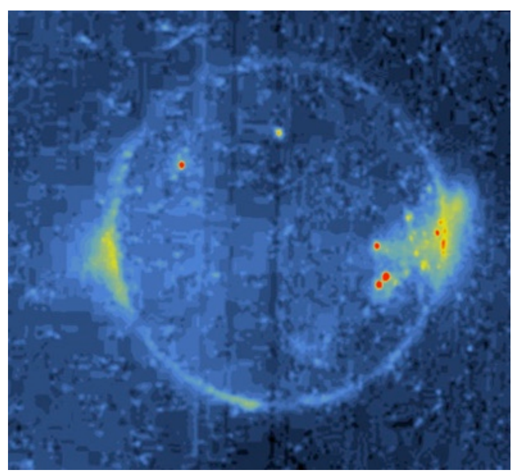


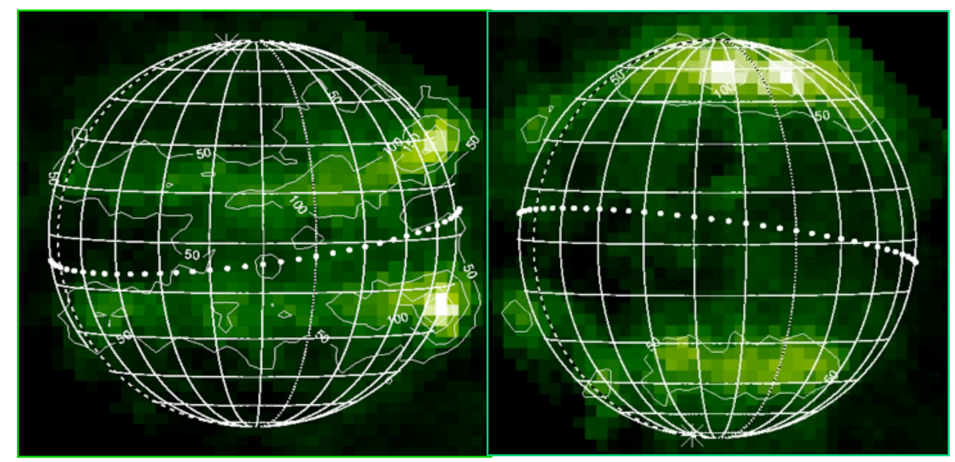
[Clarke et al., 2002]



- Io, Ganymede

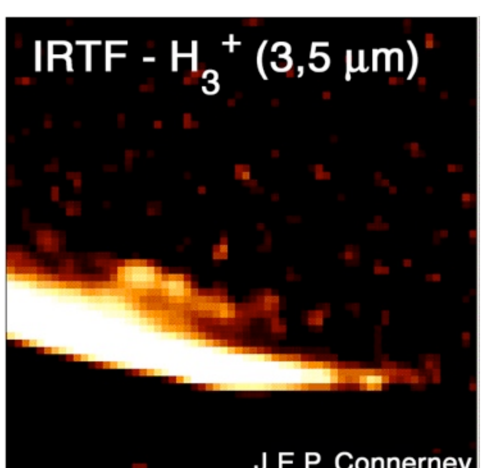
[Roesler et al., 1999; Geissler et al., 1999; Feldman et al., 2000]

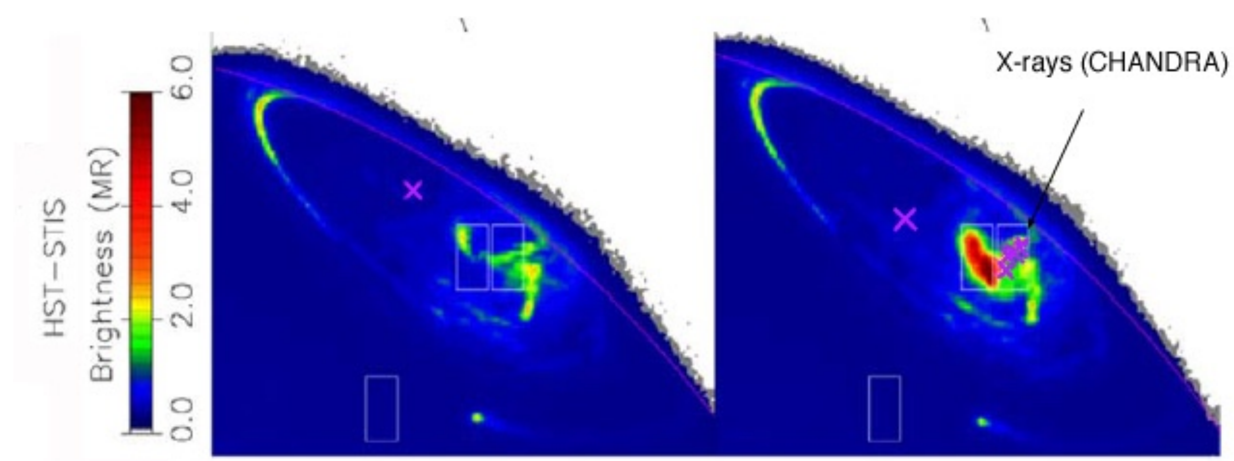




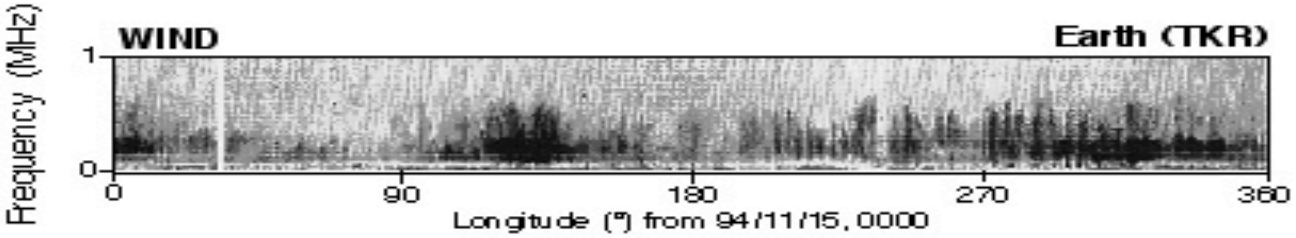
Downstream Upstream

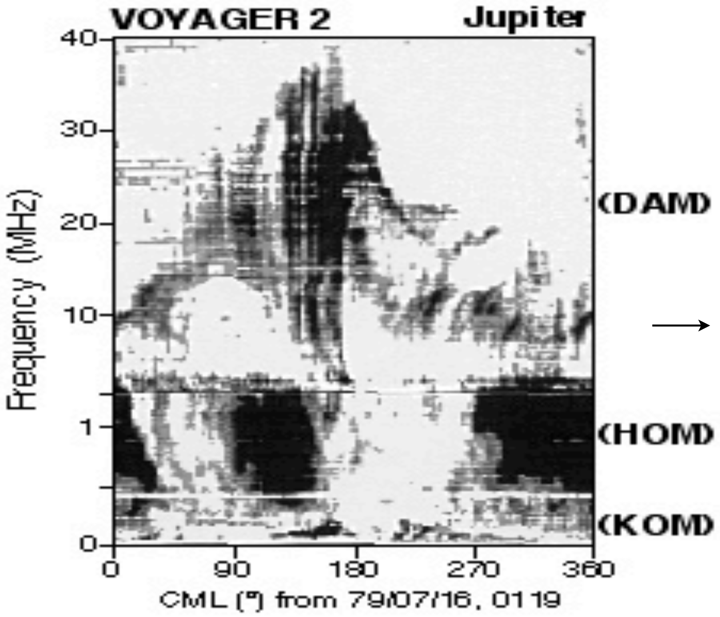
- IR and X emissions (Jupiter)

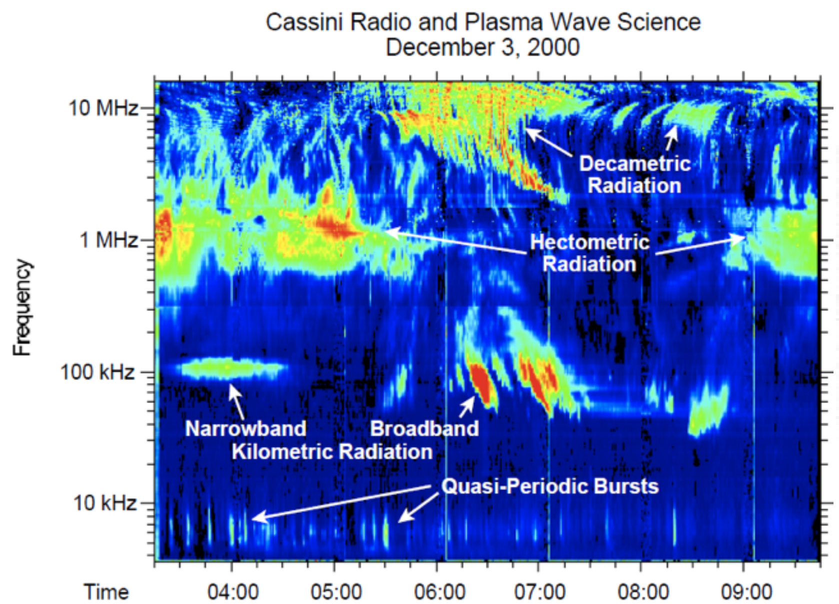


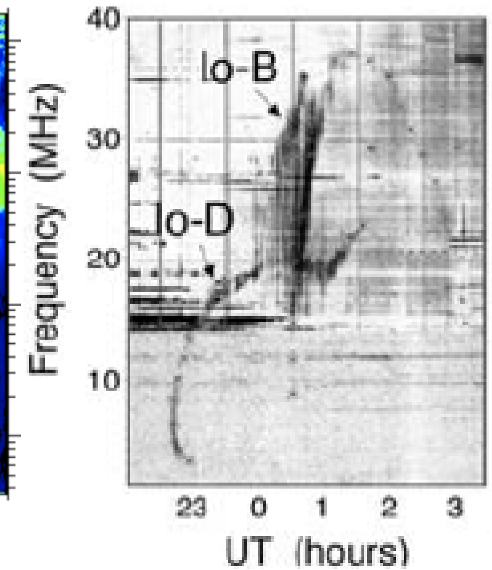


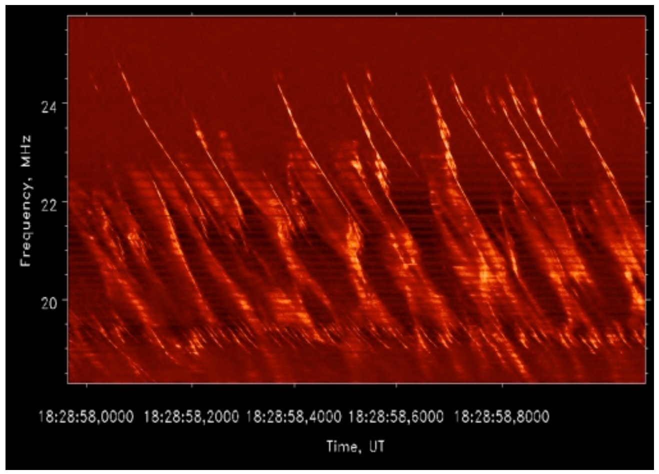
• Aurora : radio emissions



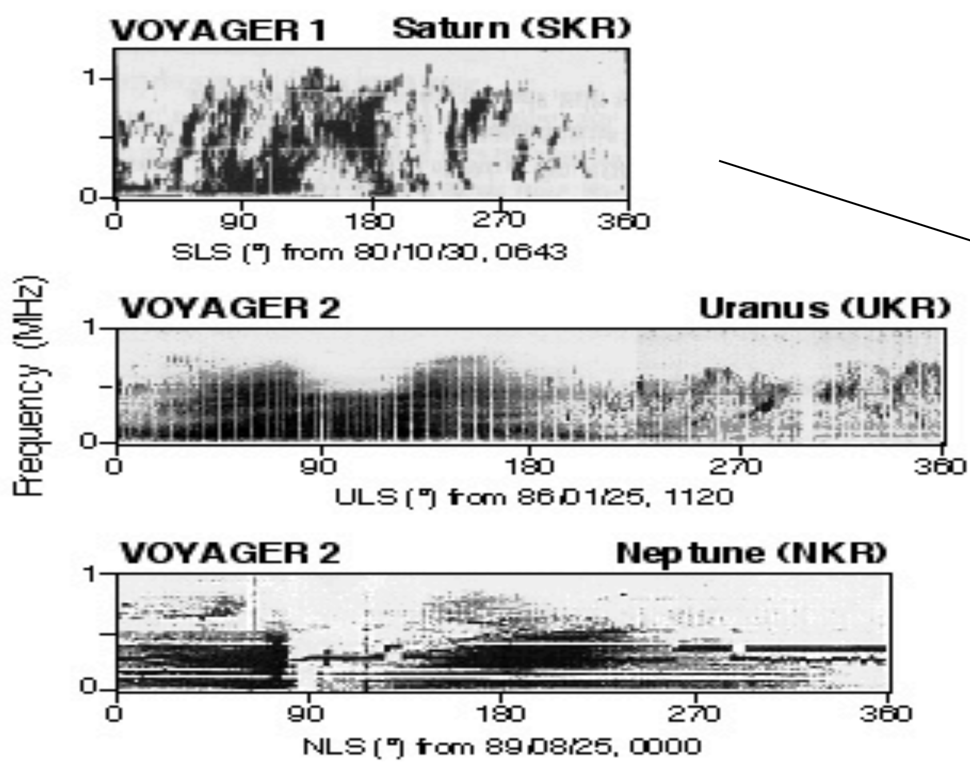


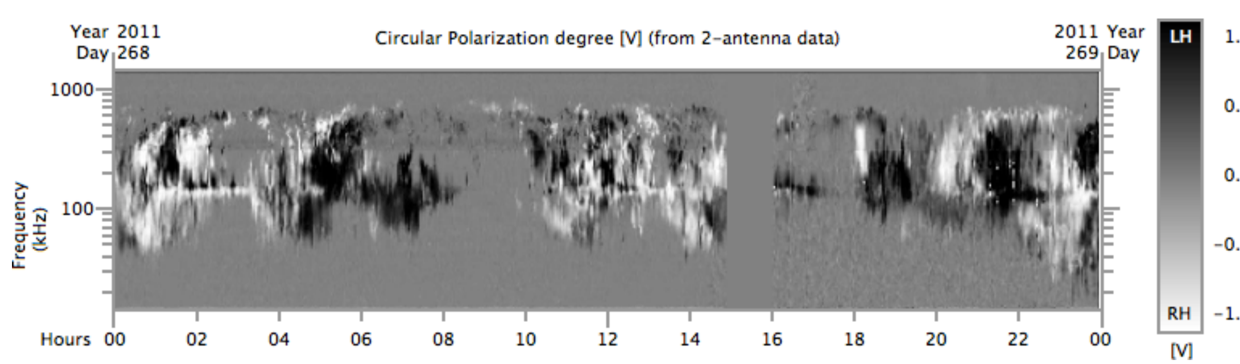






[Queinnec & Zarka, 1998; Hess et al., 2008; Ryabov et al., 2014]

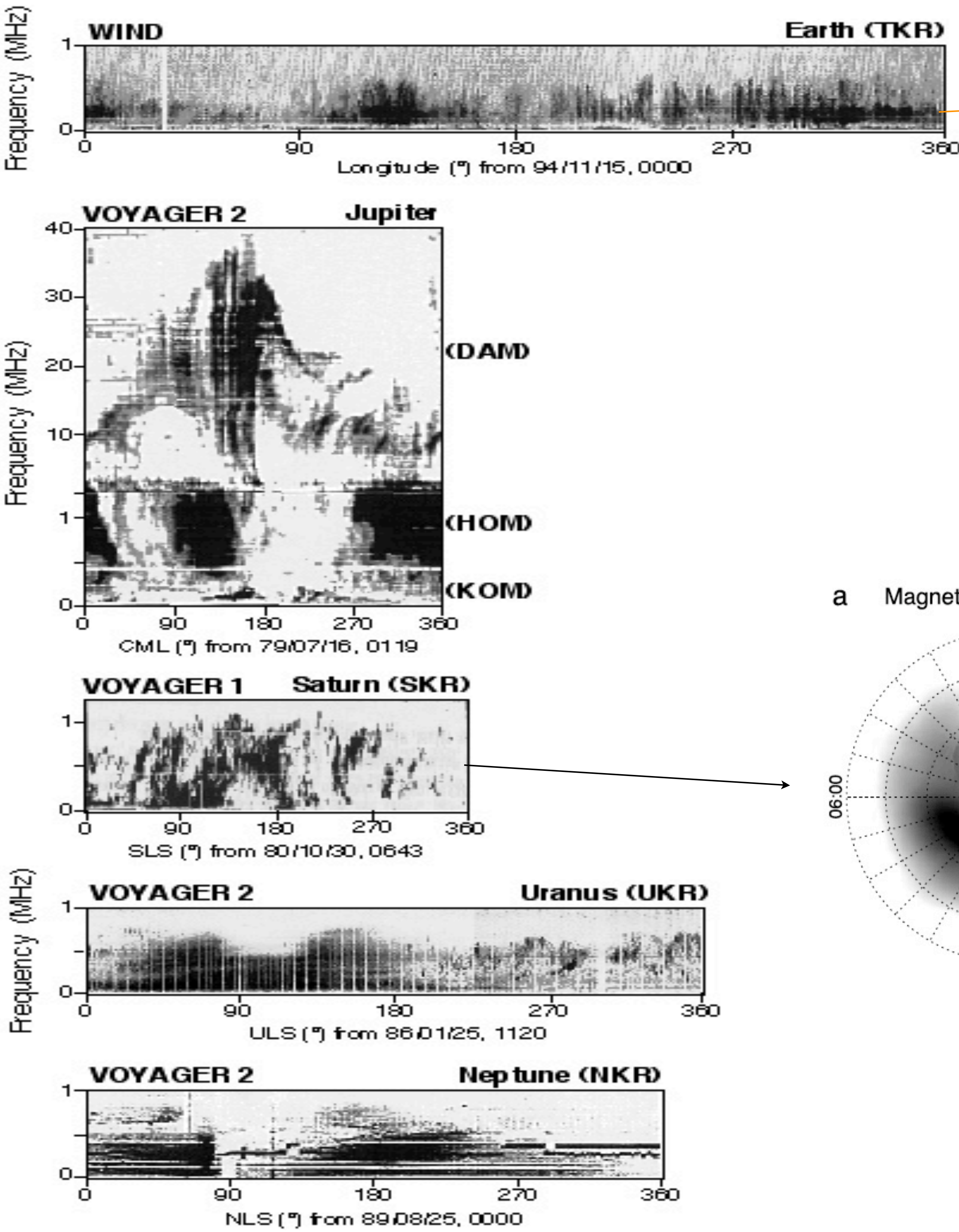




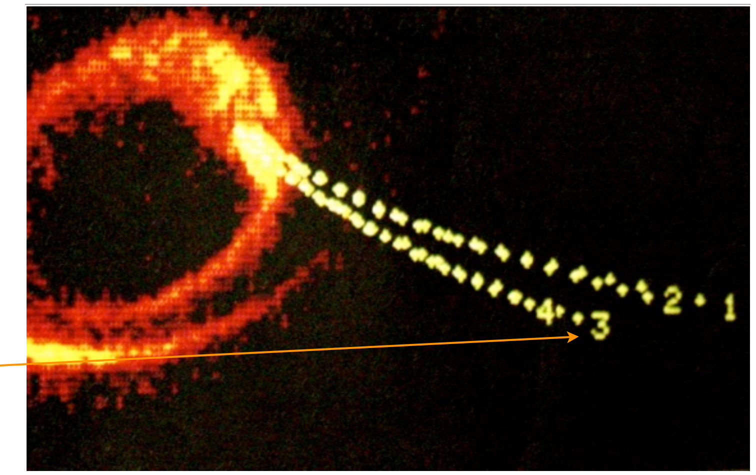
[Lamy et al., 2008]

[Zarka, 1998]

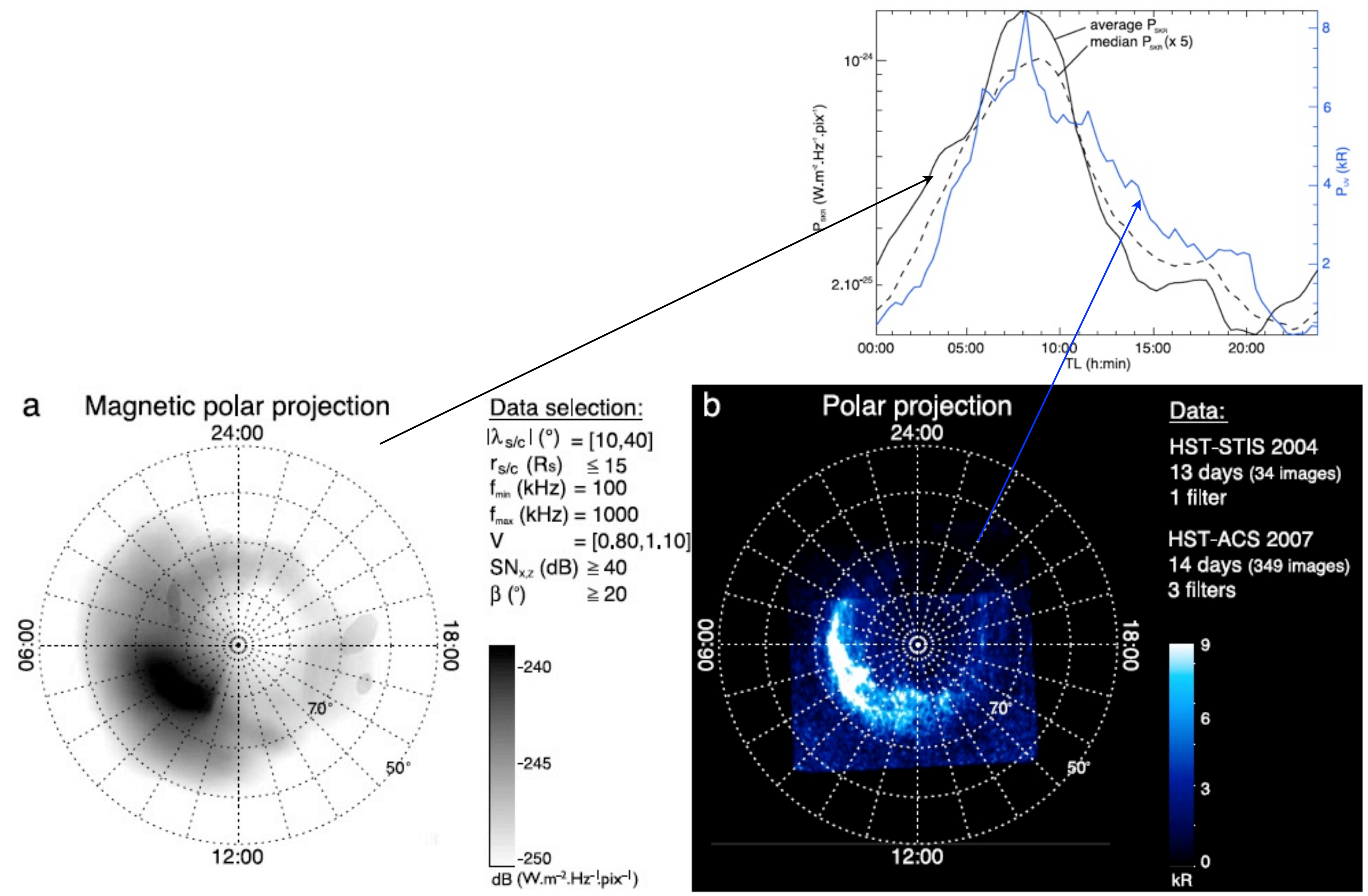
• Aurora : radio - UV correlations



[Zarka, 1998]



[Huff et al., 1988]



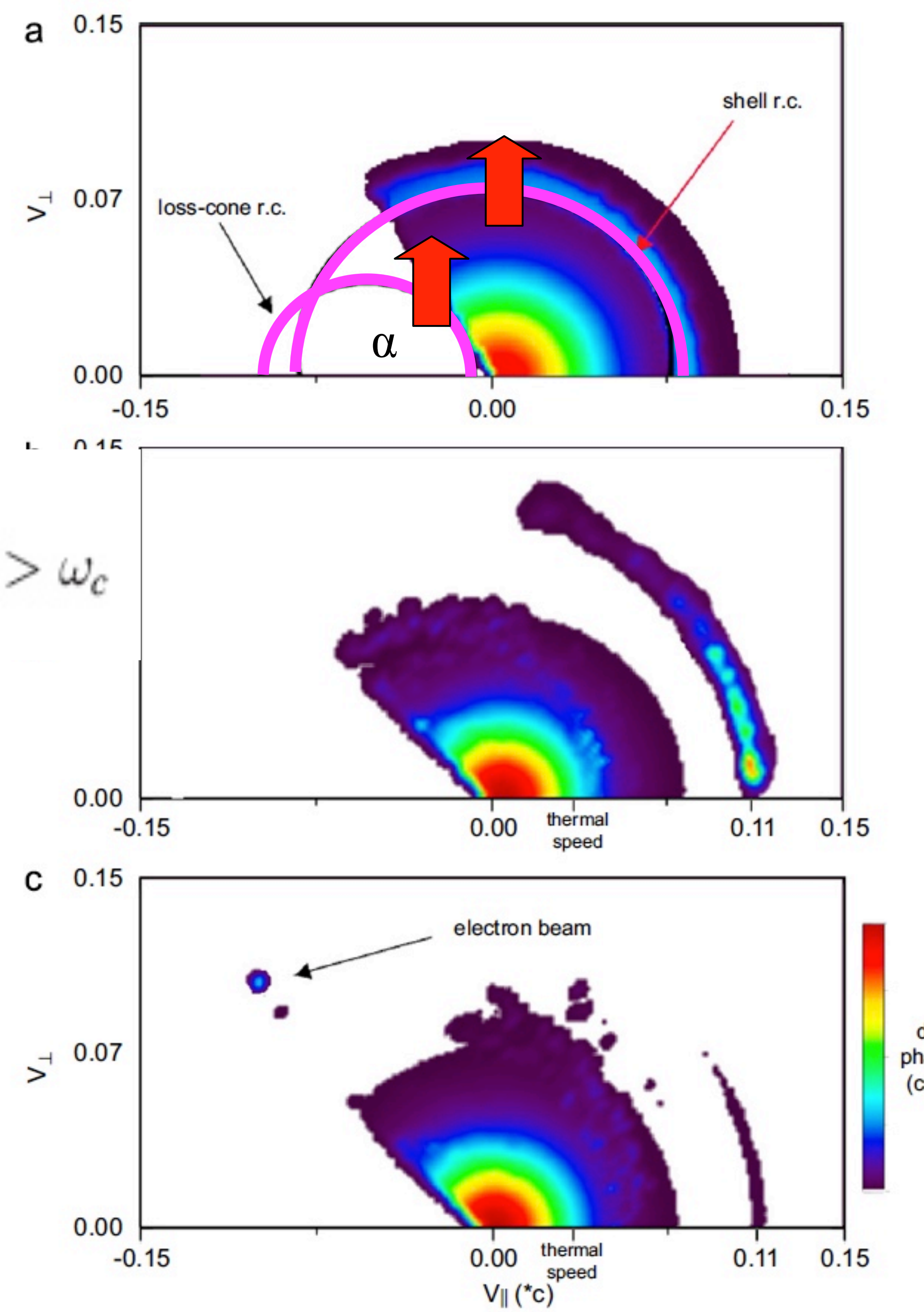
[Lamy et al., 2009]

• **Radiation mechanism : the Cyclotron Maser Instability**

- Highly magnetized medium ($f_{pe} << f_{ce}$)
- keV electrons

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

$$\gamma = \frac{\omega_p^2 c^2}{8\omega_c}\int_0^{2\pi} v_\perp^2(\theta)\nabla_{v_\perp} f(\mathbf{v}_0, \mathbf{R}(\theta))d\theta \textit{ with } \omega > \omega_c$$



[Wu, 1985 ; Treumann, 2006 ; Hess et al., 2008]

→ broad frequency range ($f \sim f_{ce} \propto |B|$)

→ intense ($T_B \sim 10^{15\text{-}20}$ K)

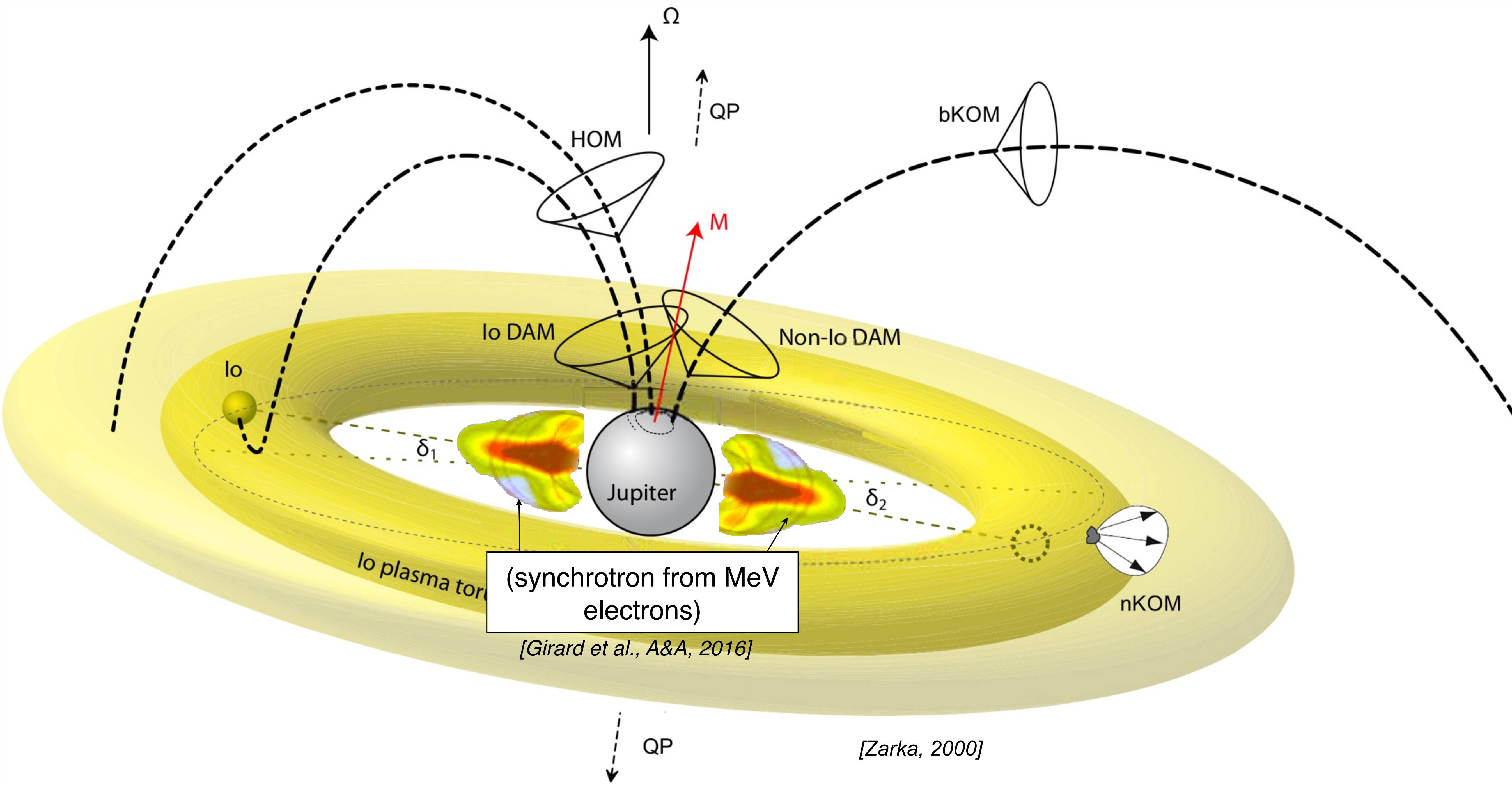
→ sporadic (msec-hour)

→ anisotropic (widely open hollow cone)

→ circularly/elliptically polarized (X mode)

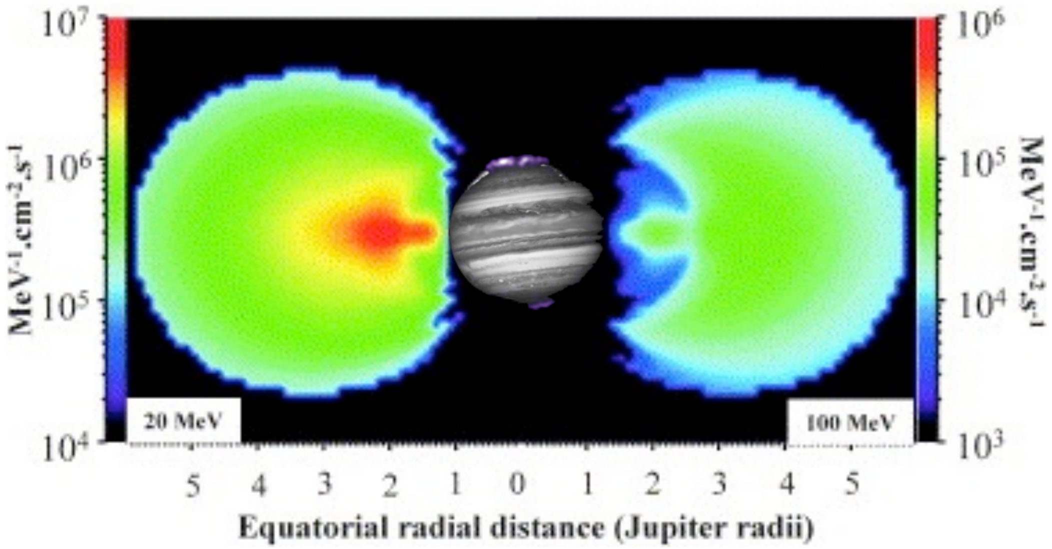
- loss-cone (α) : $V_{//o} = c.\cos\theta = V/\cos\alpha \Rightarrow \theta = \cos^{-1}(V/c.\cos\alpha) < 90°$ (θ↓ for V or f↑)
- horseshoe/shell ($E_{//}$) : $V_{//o} = c.\cos\theta \sim 0$ θ ~ 90° (∀ f) intensity ↑ with V

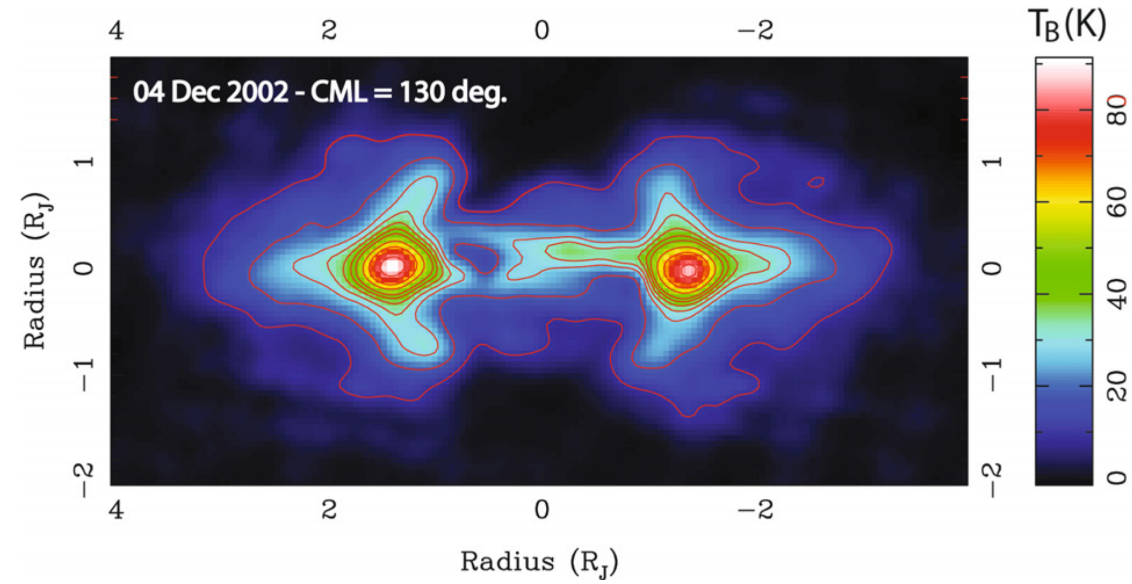
Radiation belts



- MeV ions and electrons ⇒ synchrotron emission

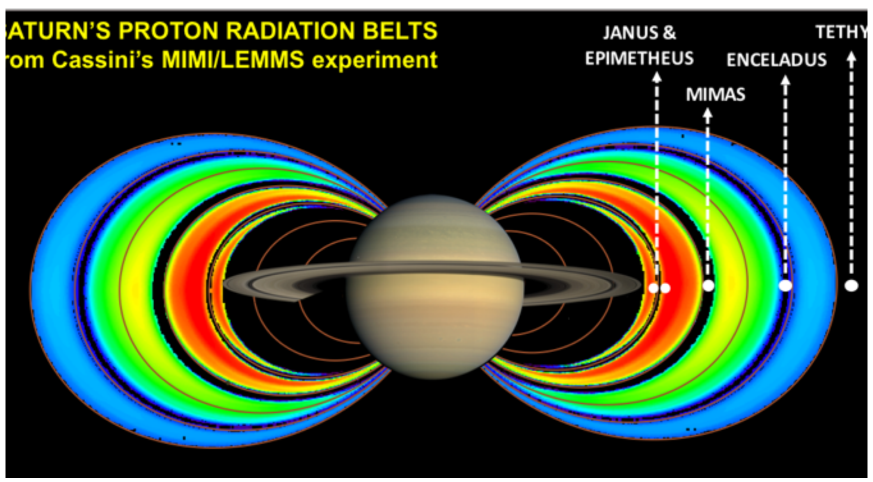
Jupiter





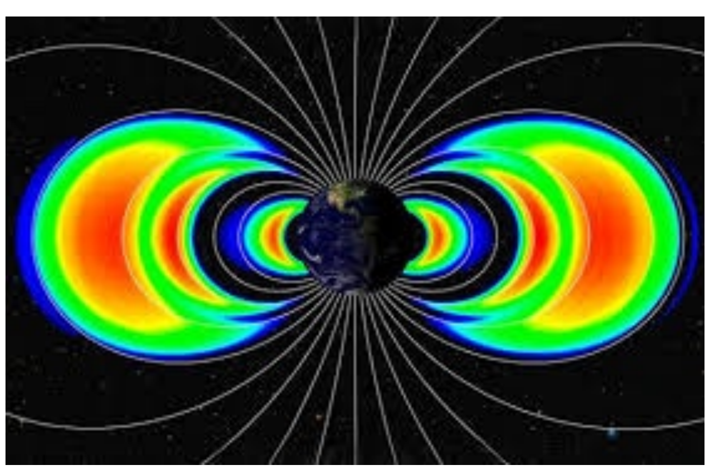
[Santos-Costa 2009; Nenon 2018]

Saturn



?

Earth



⇒ Rapid losses in internal belt due to strong plasma wave-particle interactions ?

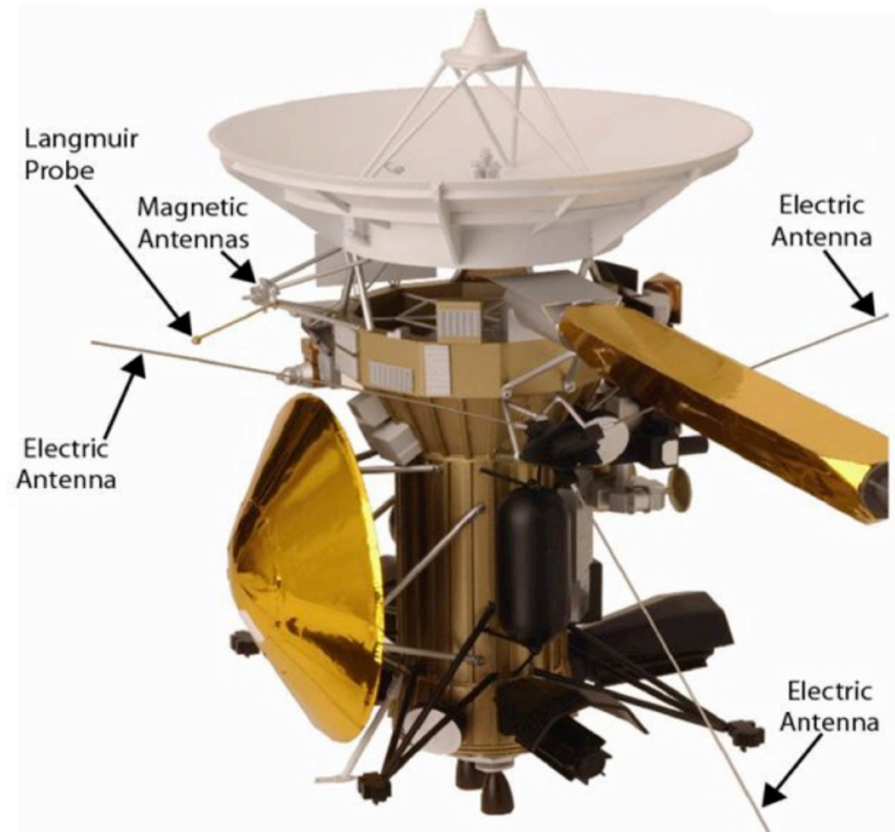
- no radiation belt at Mercury ?
- Uranus ? Neptune ?

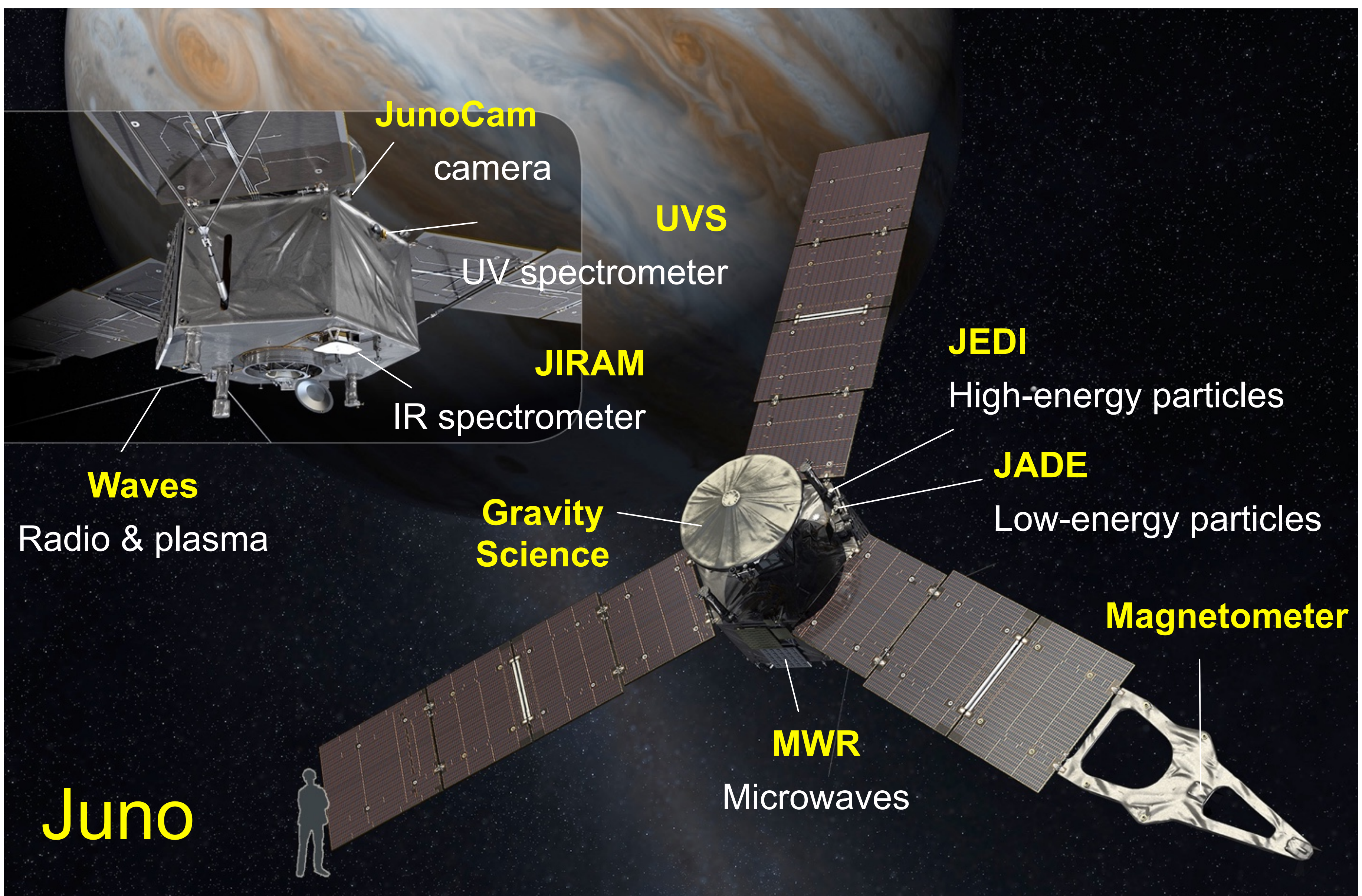
Radio Observations
&
Simulations

- **S/C wave & particles instrumentation**

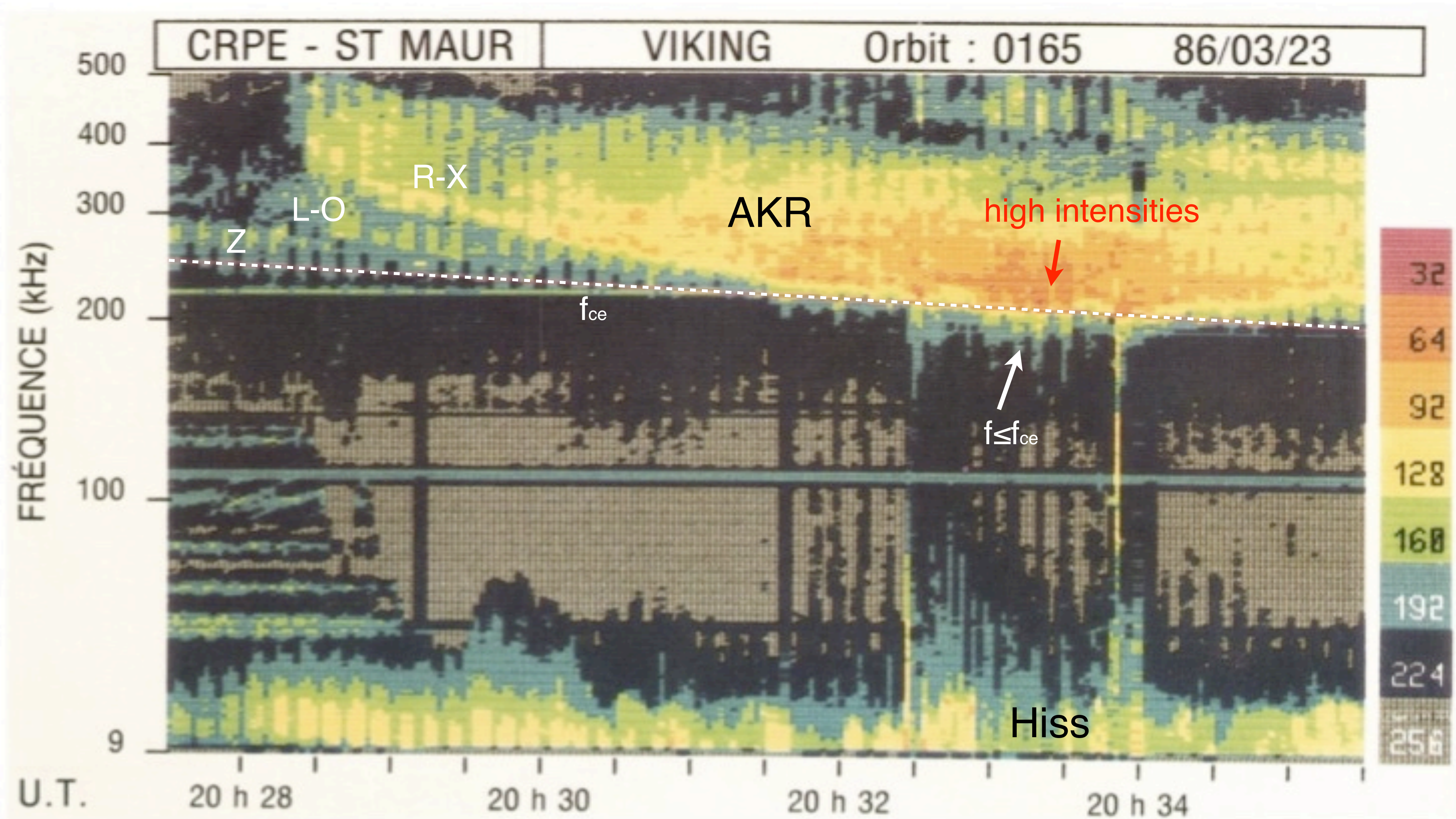
  - Cassini : RPWS (radio & plasma waves), CAPS, INMS (thermal plasma), MIMI (energetic plasma & ENA)

  + ISS (Imaging), UVIS, VIMS, CIRS (UV/IR spectro-imagers), MAG (magnetometer), RSS (radio science), CDA (dust)



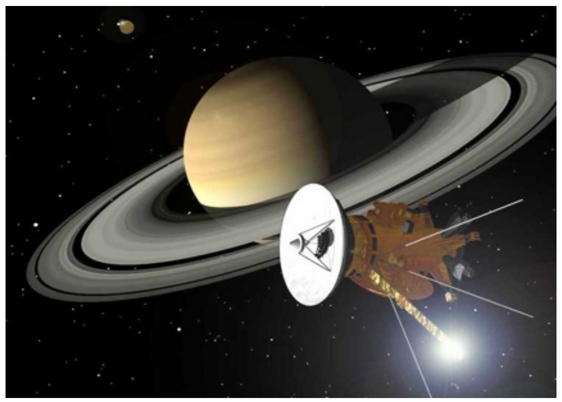


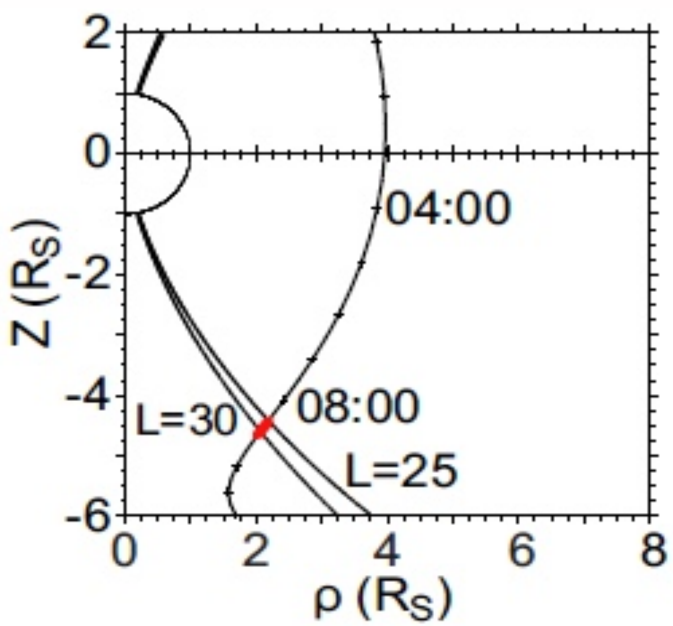
• **In-source measurements : Earth (Viking)**

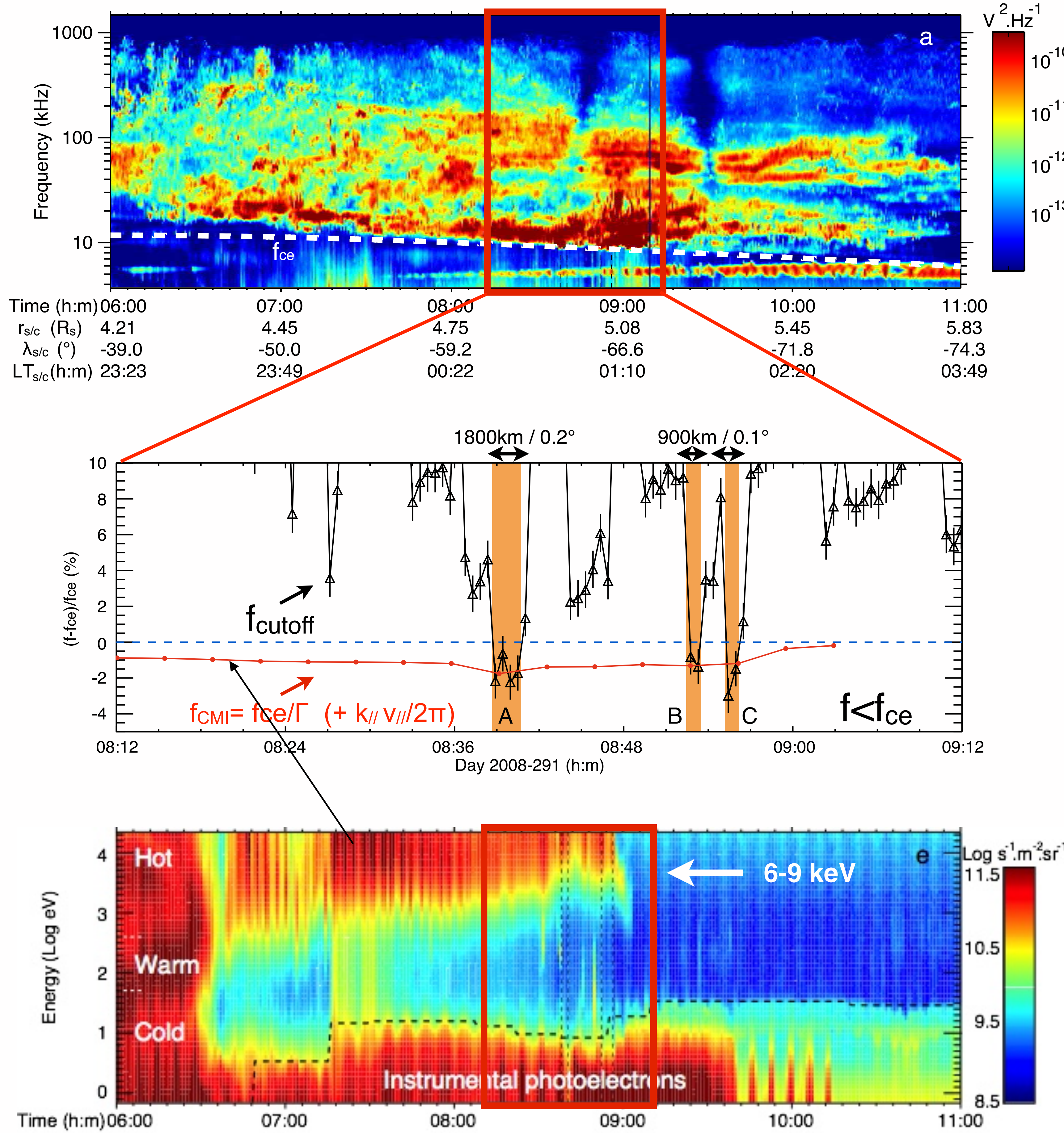


[de Féraudy et al., 1988 ; Bahnsen et al., 1989 ; Roux et al., 1993]

• In-source measurements : Saturn (Cassini)

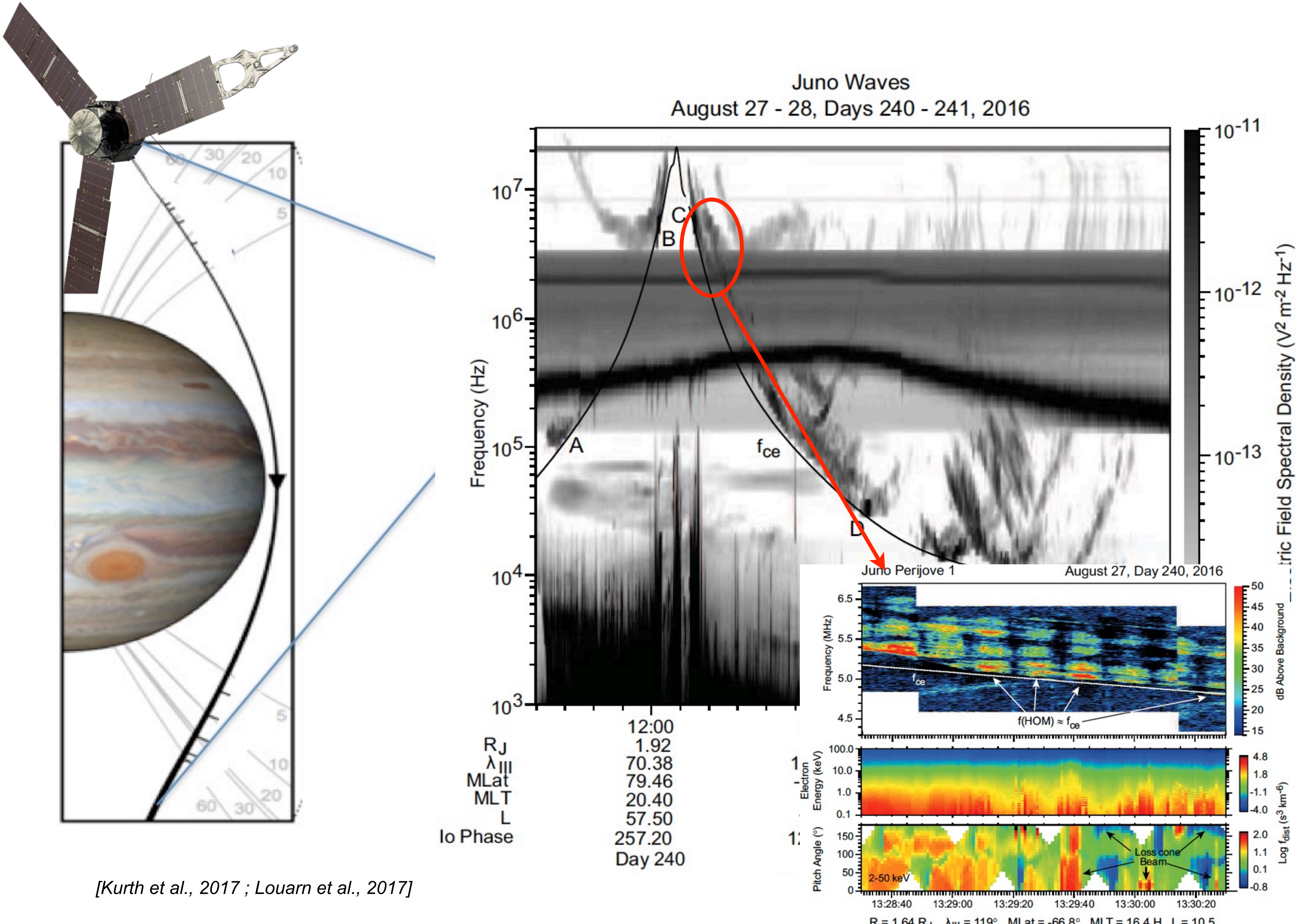






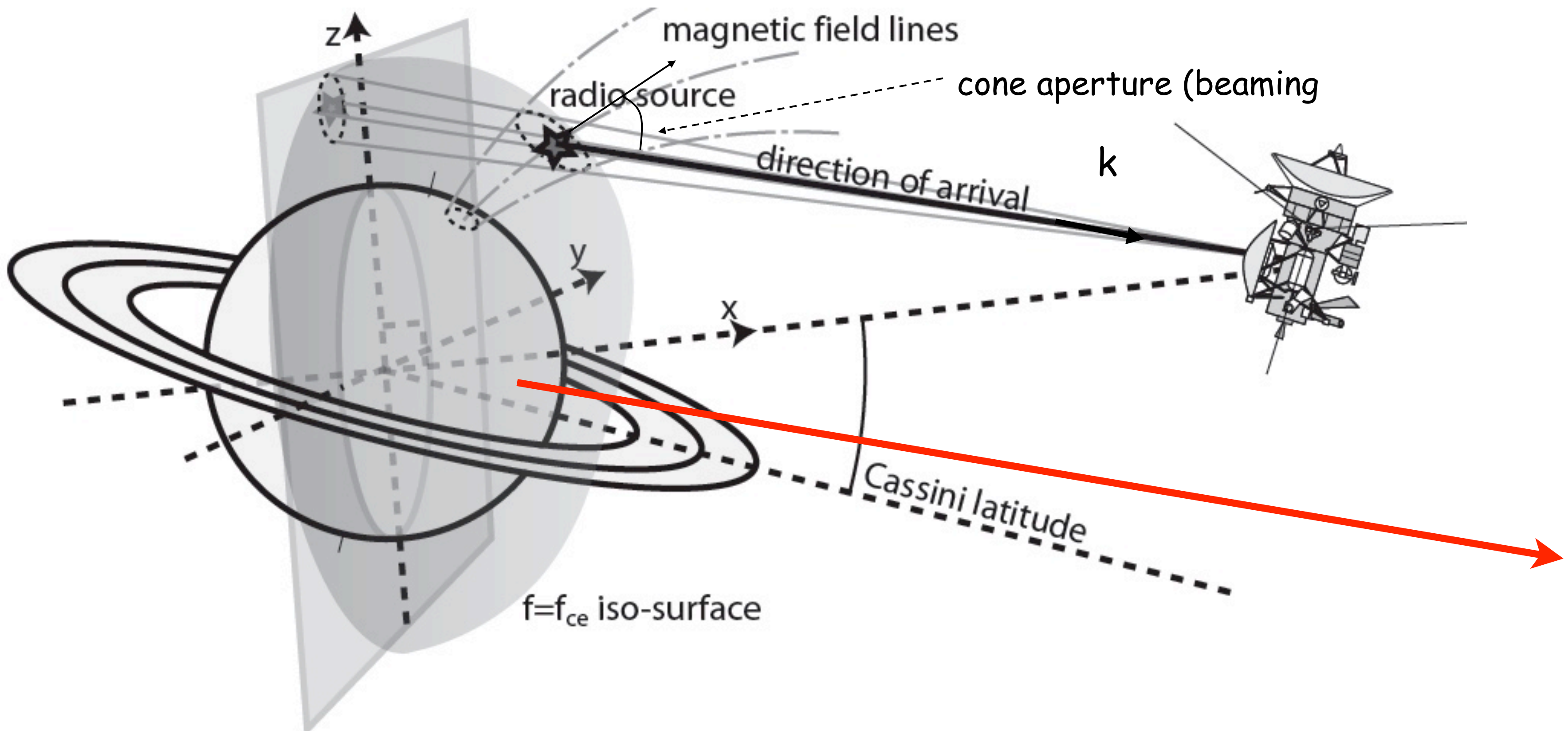
[Lamy et al., 2010, 2011]

• In-source measurements : Jupiter (Juno)

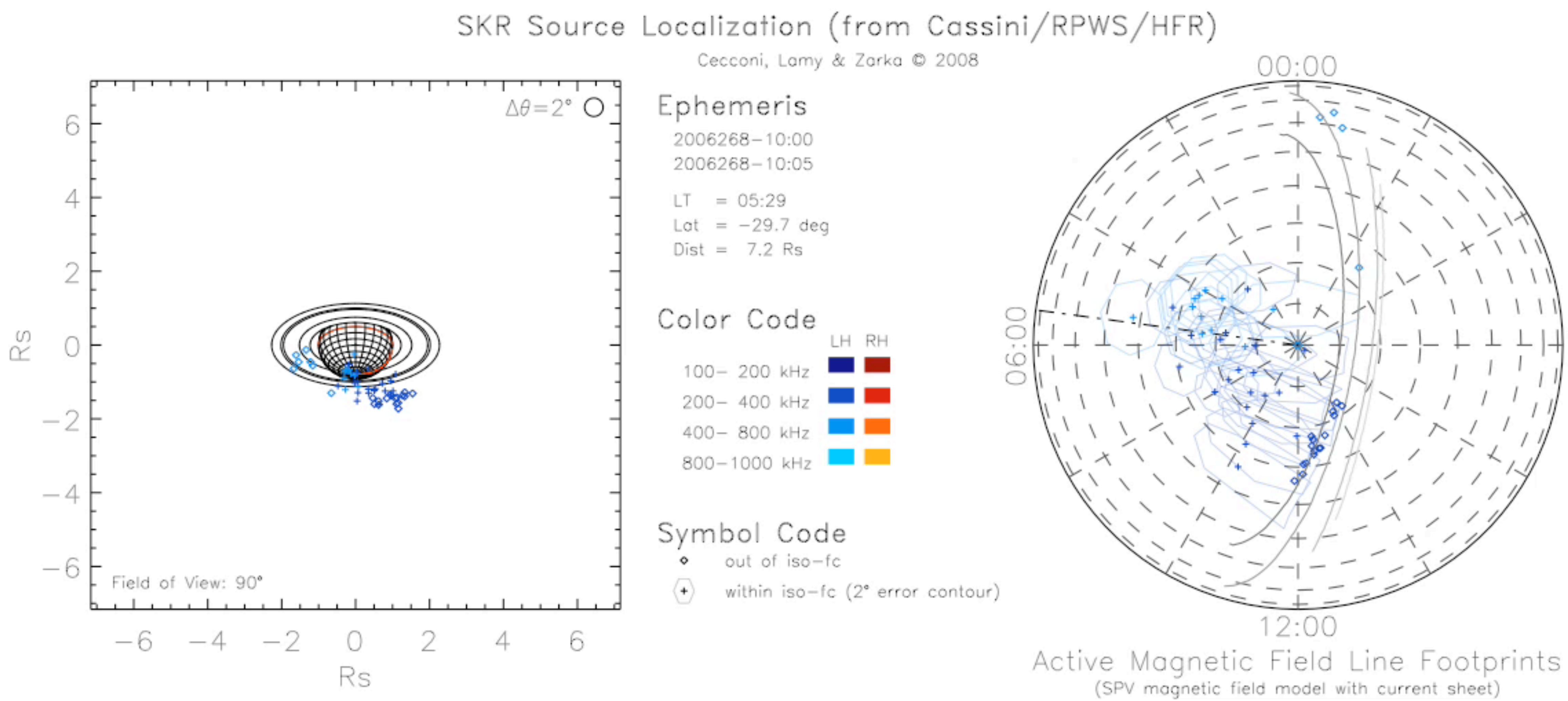


[Kurth et al., 2017 ; Louarn et al., 2017]

• Remote measurements : Saturn (Cassini/RPWS goniopolarimetry)

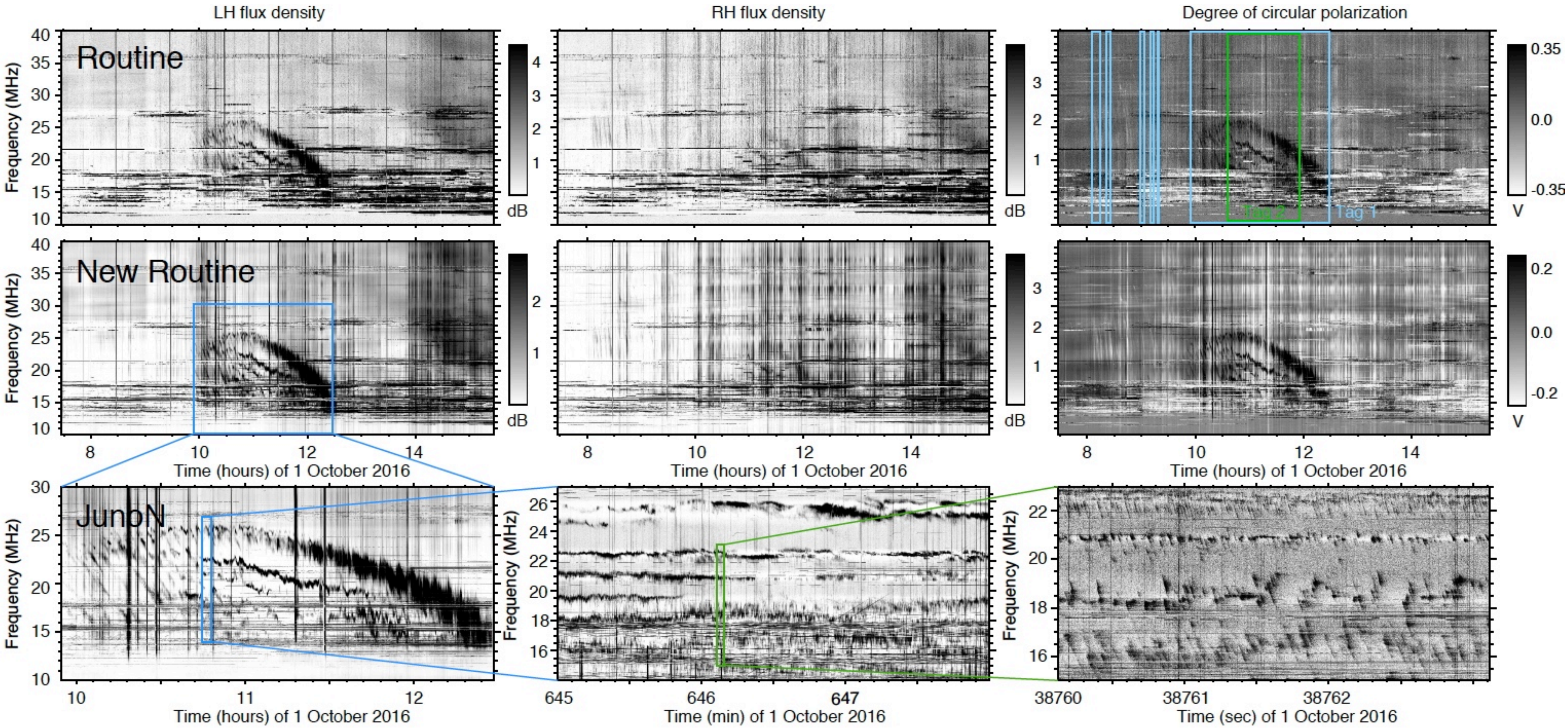


[Cecconi et al., 2009]



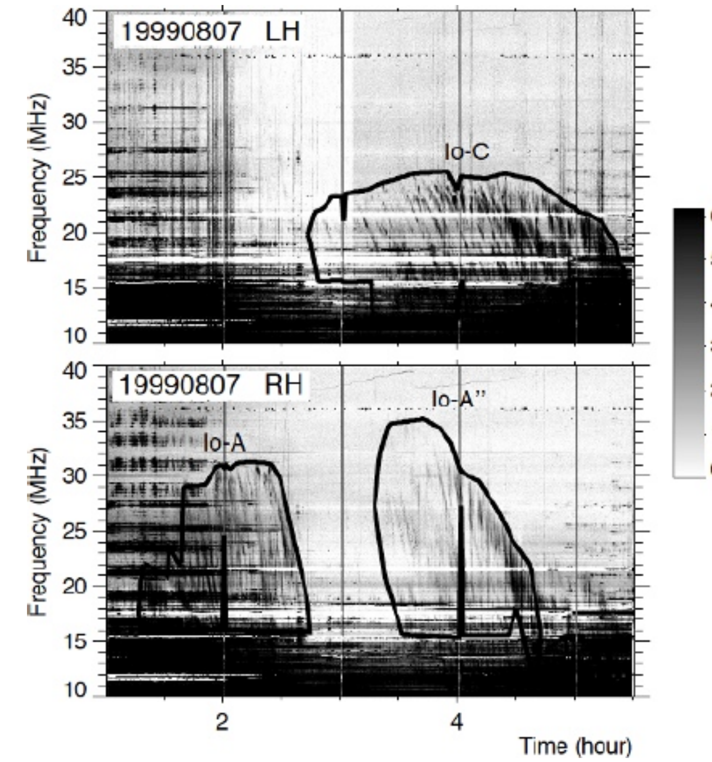
• **Remote measurements : Jupiter (Nançay)**

[Lamy et al., 2017]

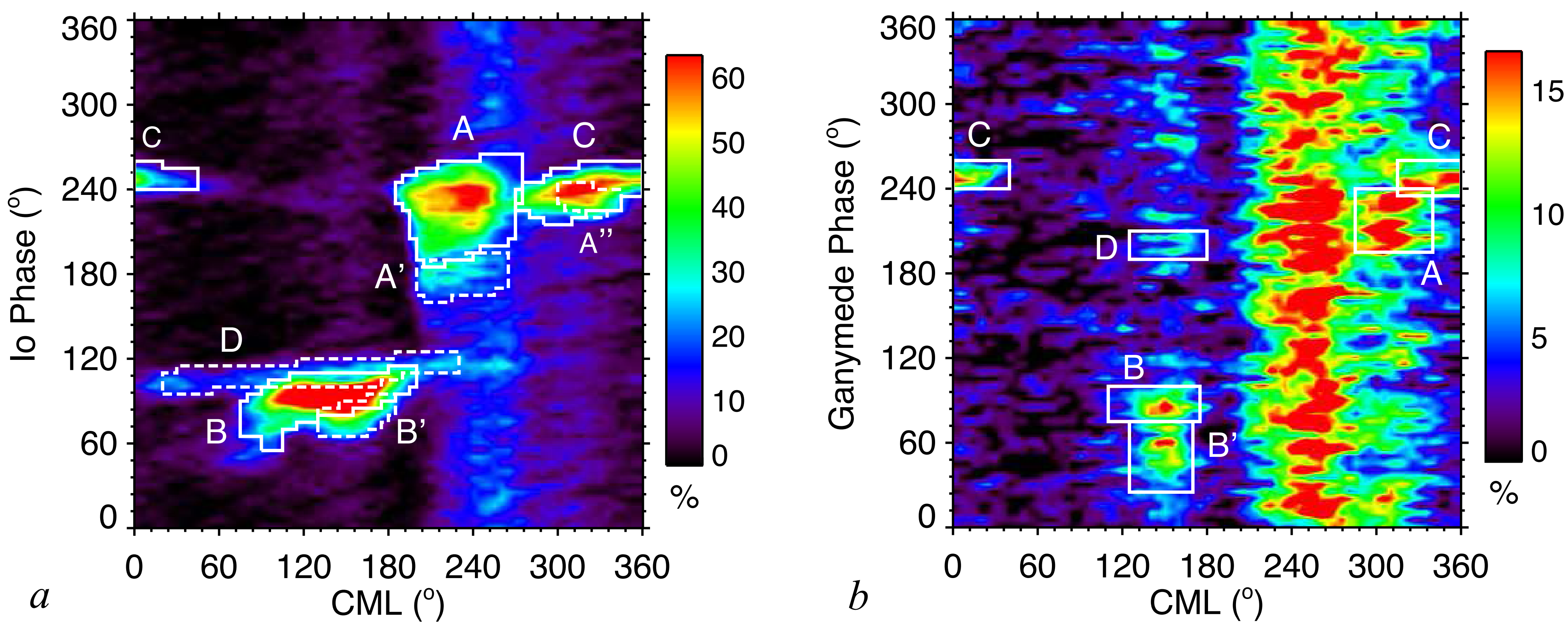


- emission catalog over 30+ years ⇒ statistical studies

[Marques et al., 2017]

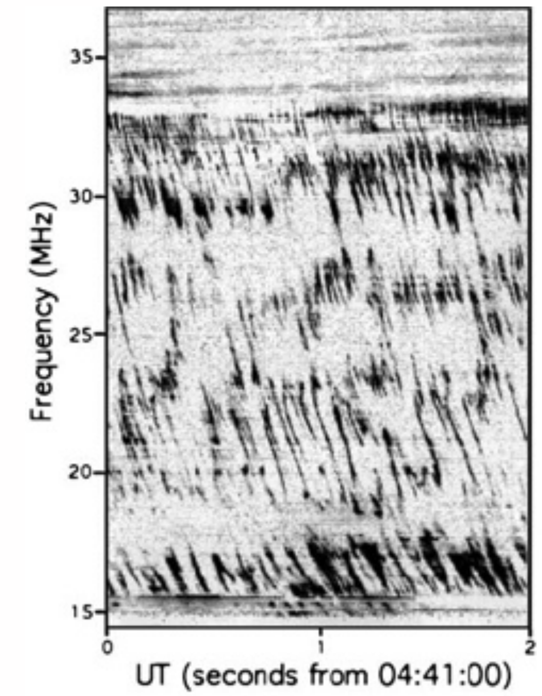


- detection (+ energetics) of Ganymede-Jupiter radio emissions *[Zarka et al., 2018]*



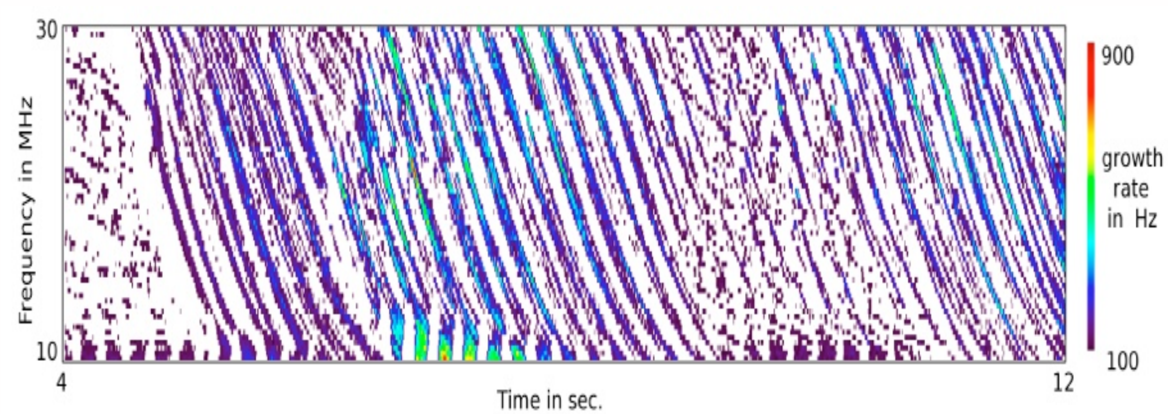
- high time-frequency measurements ⇒ S-bursts ⇒ microphysics

[Queinnec & Zarka, 2001 ; Zarka, 2004]

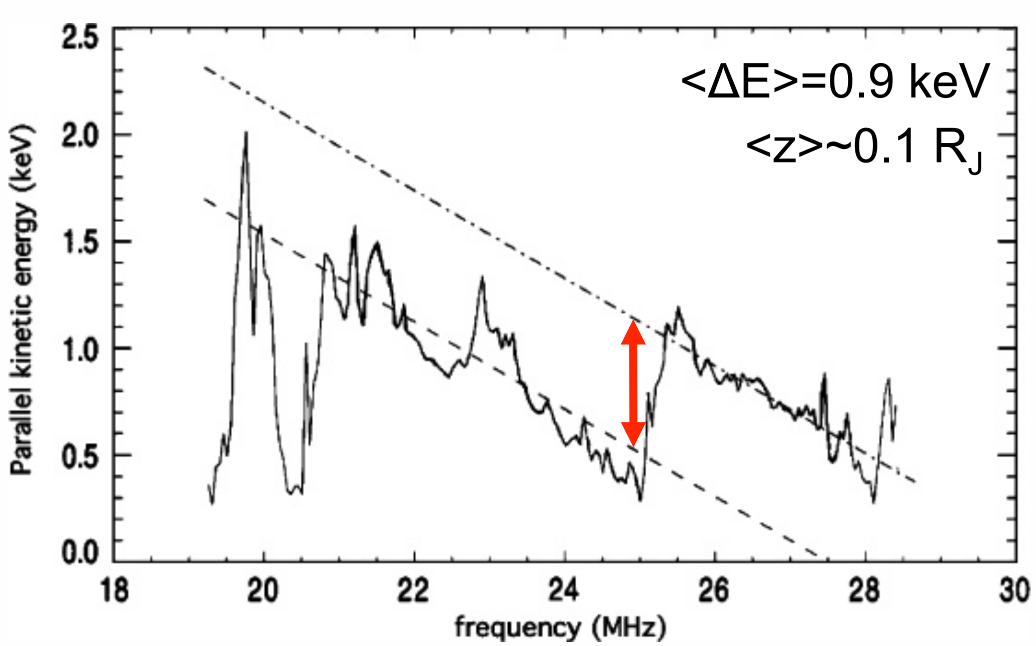


- loss-cone driven (oblique) CMI emission from
  Alfvén waves acceleration of electrons

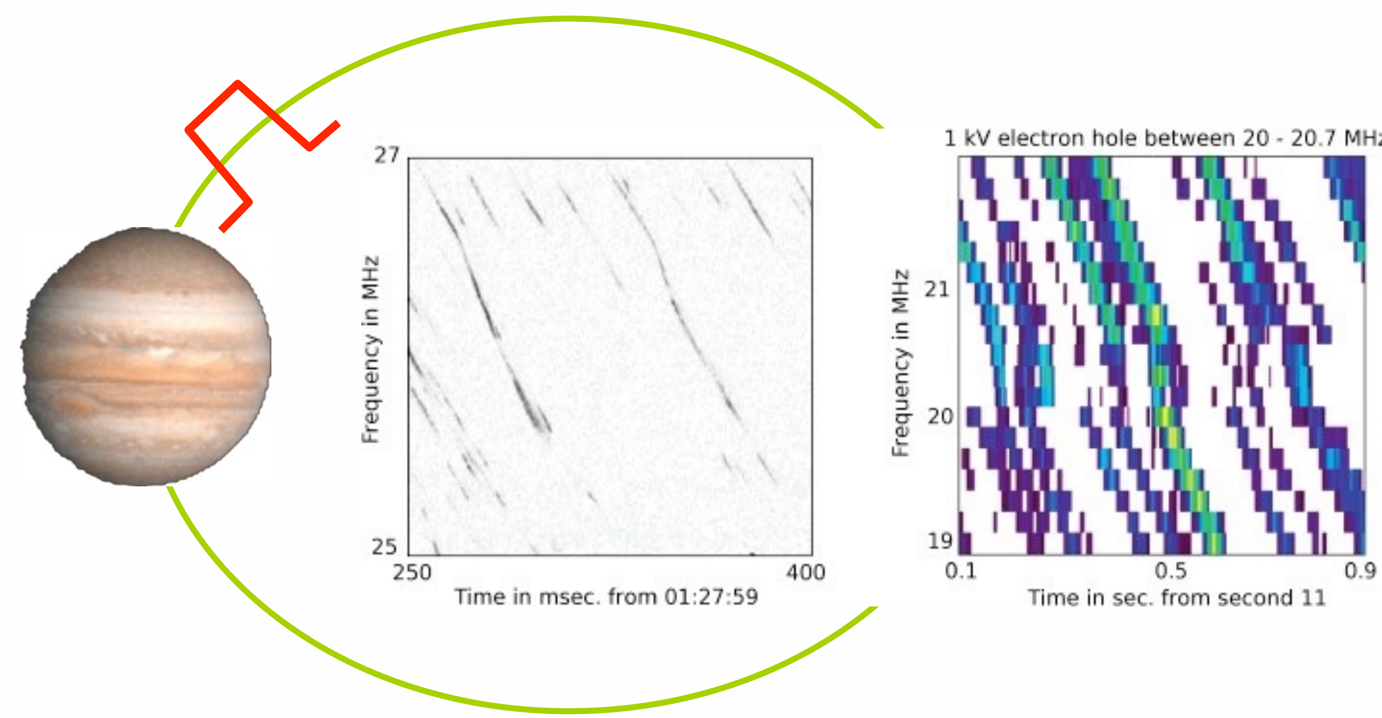
*[Su et al. 2006,
Hess et al., 2007a]*



- discovery of kV double-layers / electron & ion holes along IFT

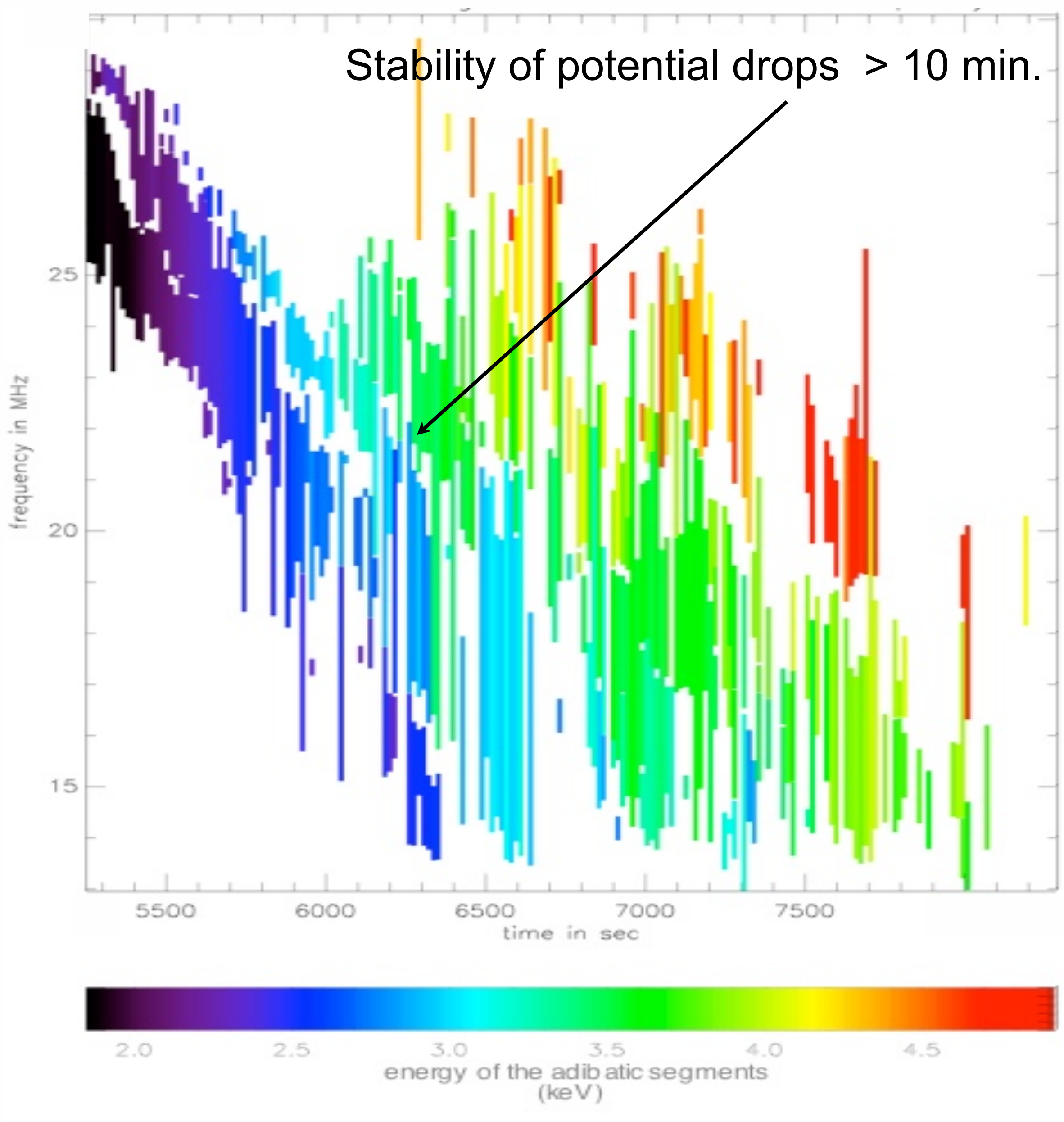


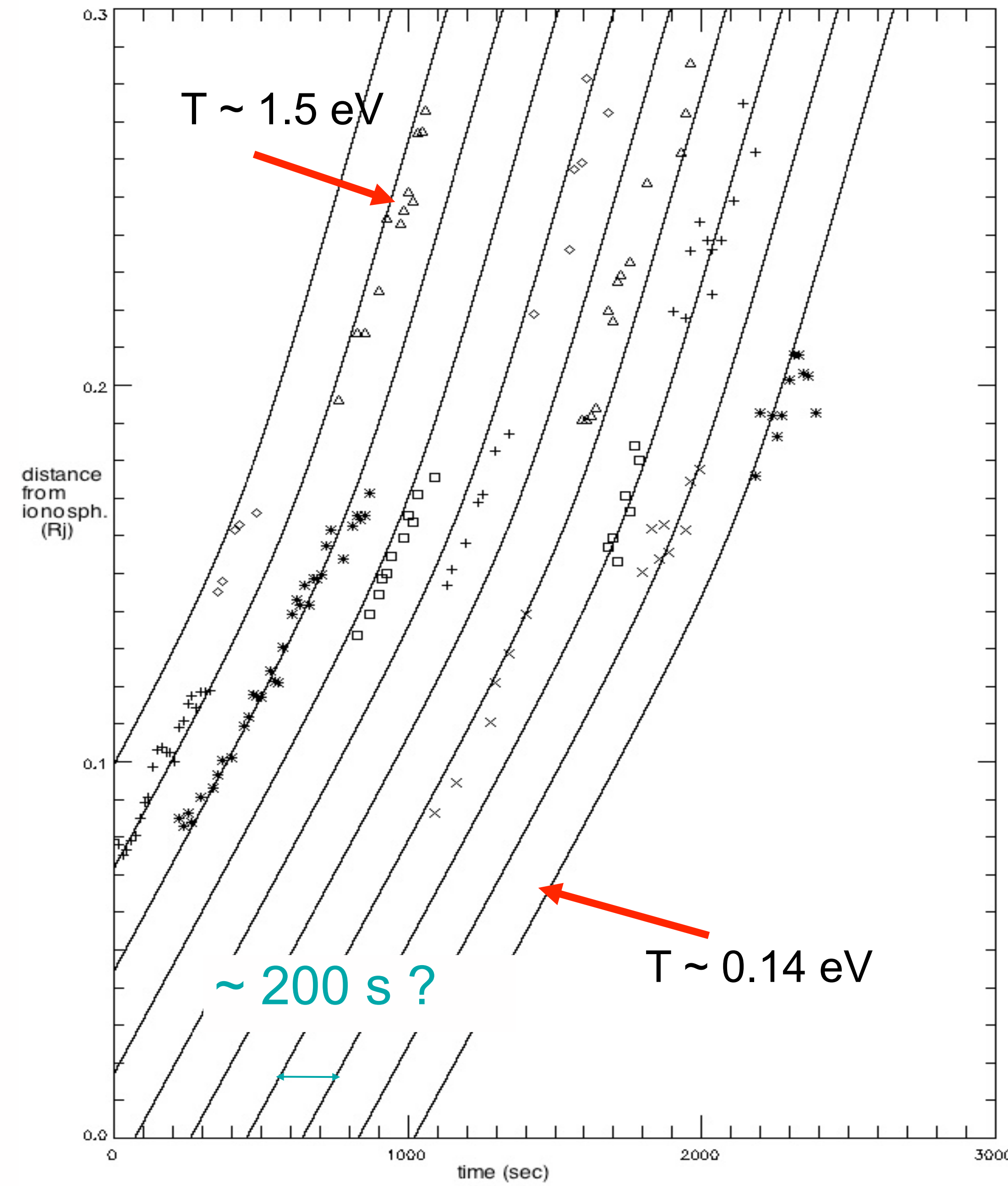
[Hess et al, 2007b]



[Hess et al,, 2009a]

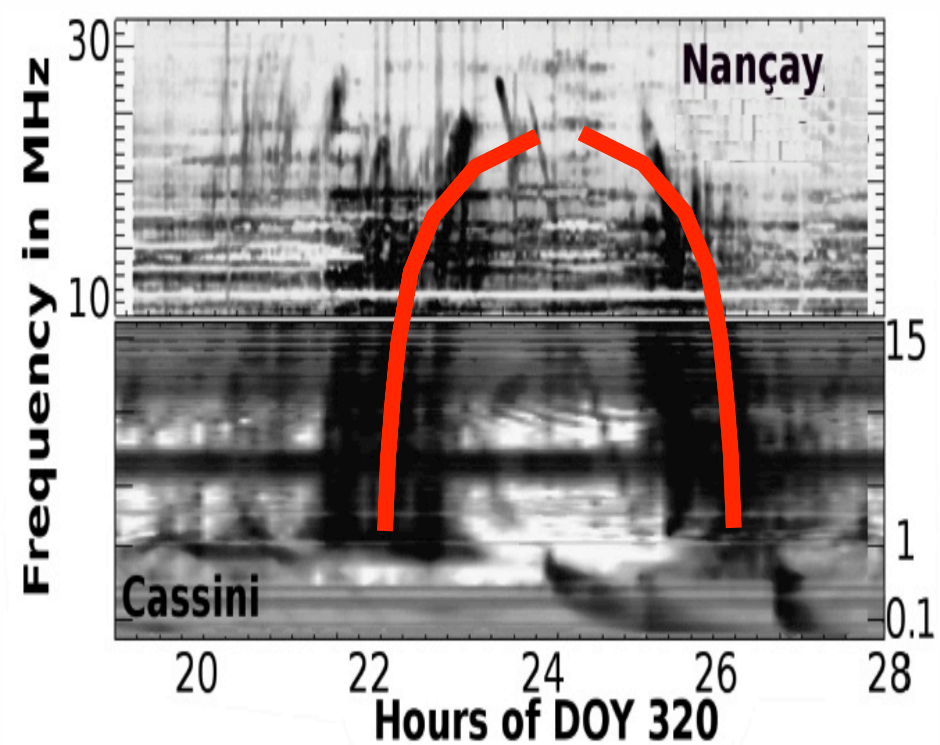
- DL motion along the IFT at the local plasma sound velocity



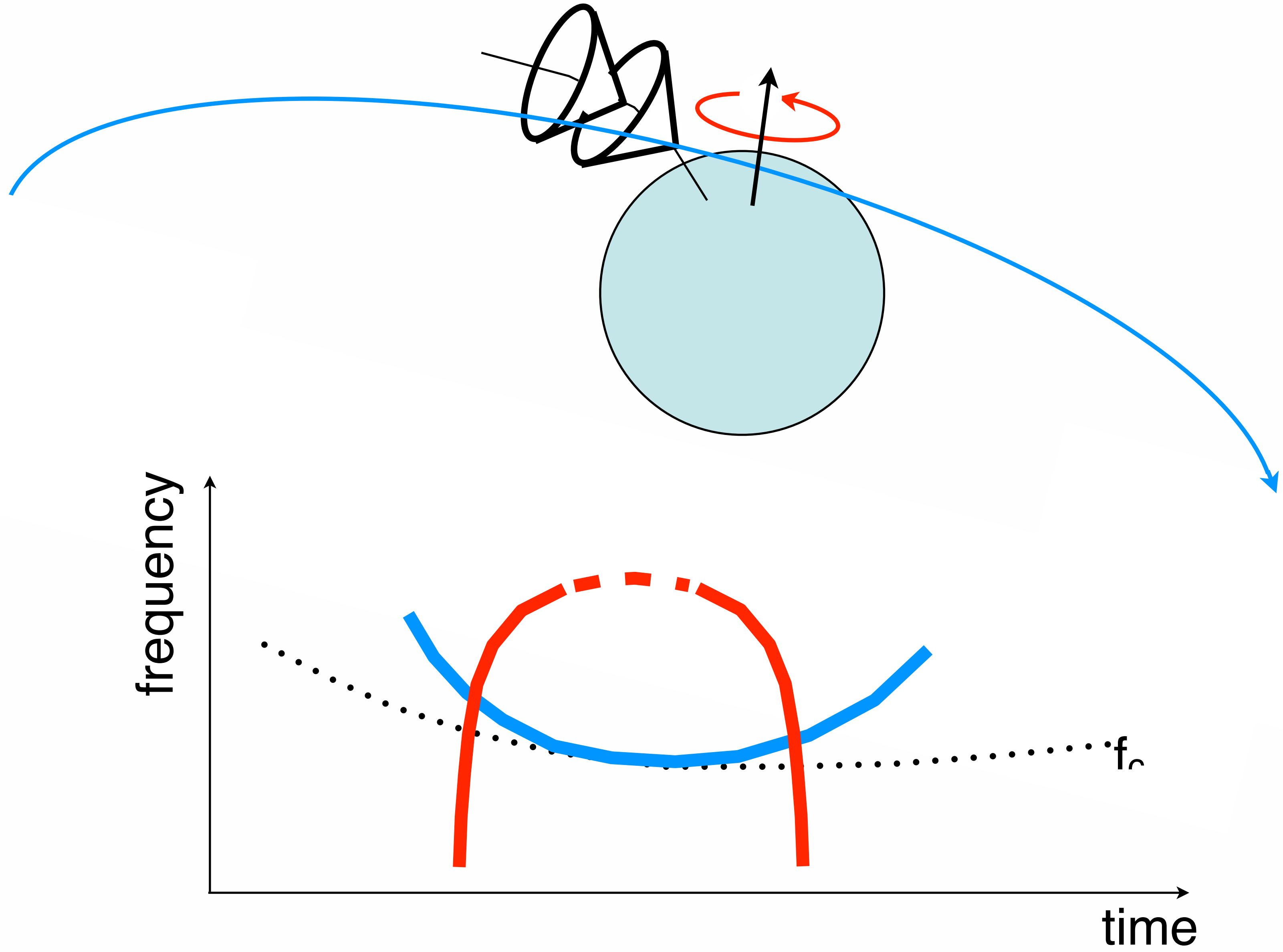


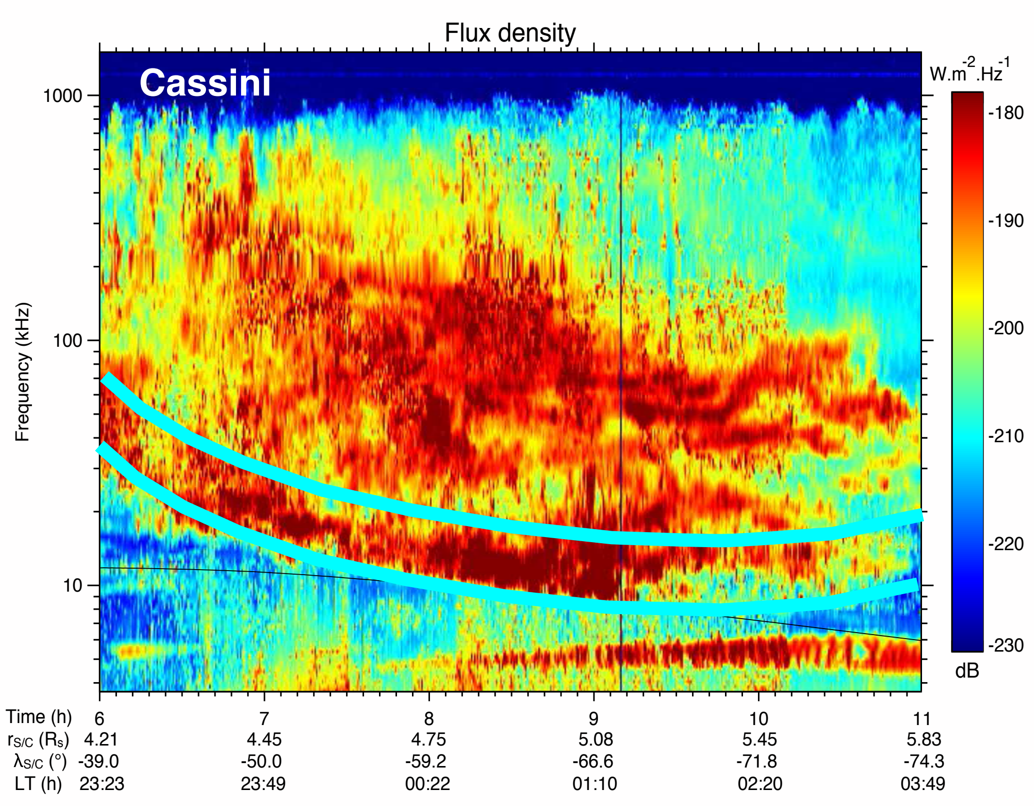
[Hess et al, 2009b]

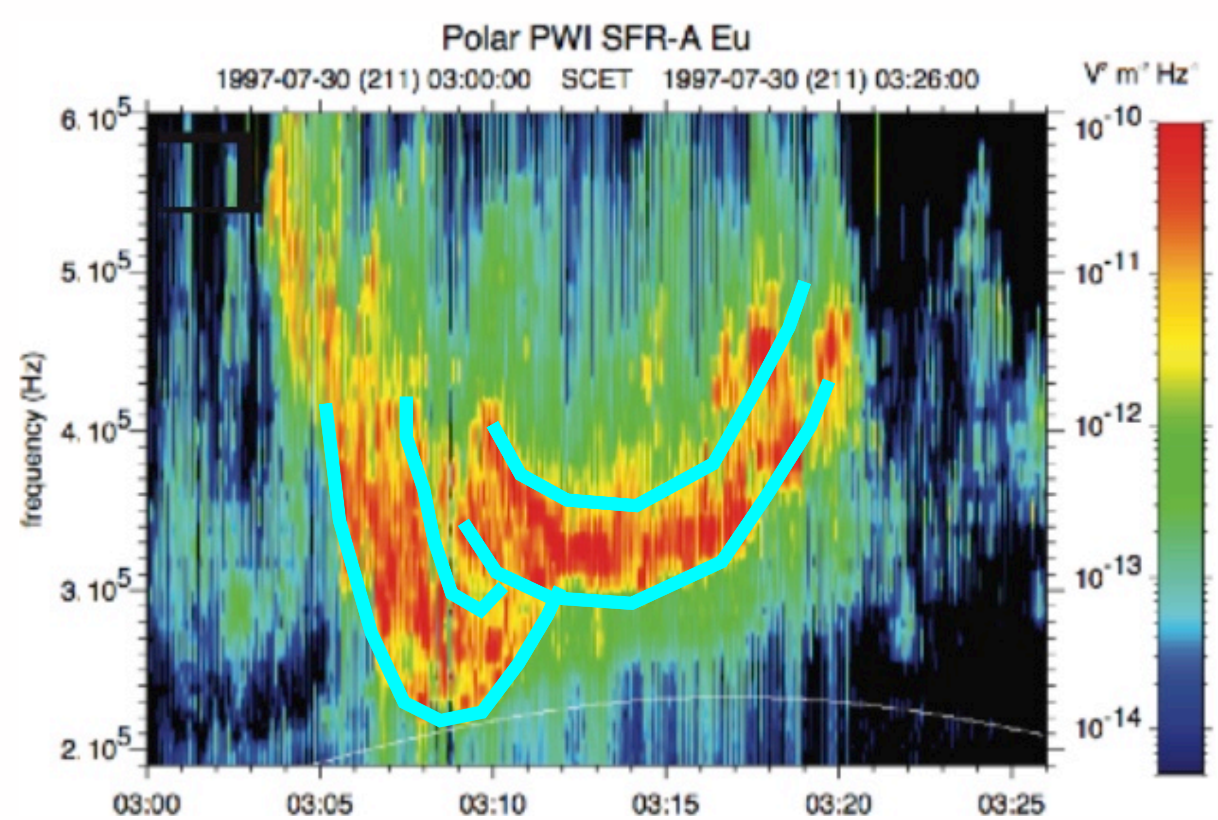
• **Time-frequency radio arcs**



[Hess et al., 2014]







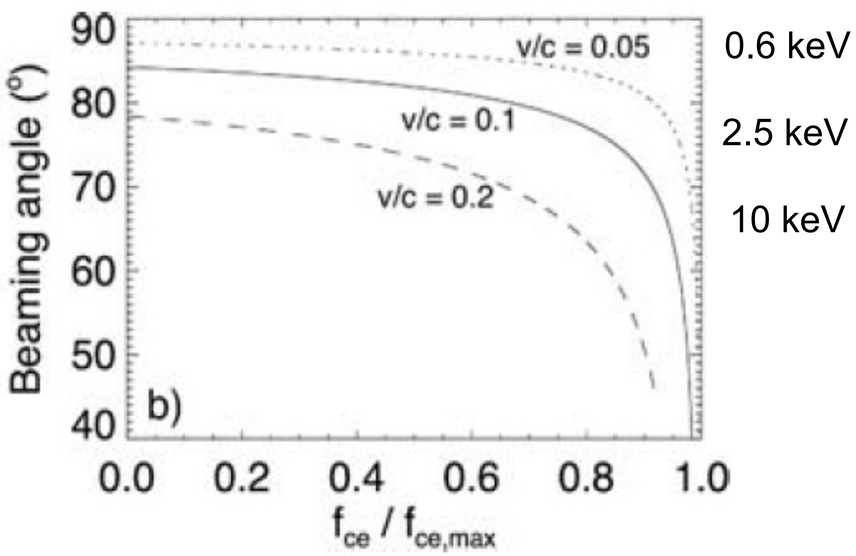
• **Time-frequency radio arcs & simulations (ExPRES)**

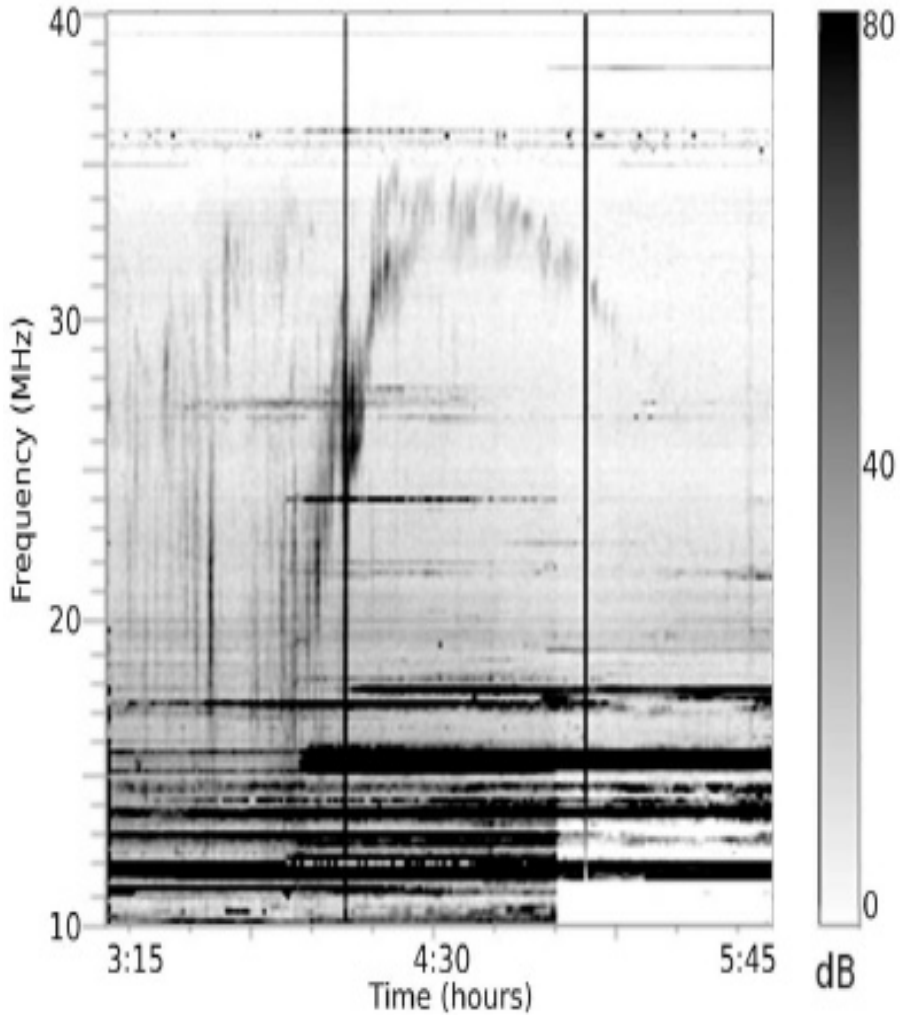
- Exoplanetary & Planetary Radio Emissions Simulator

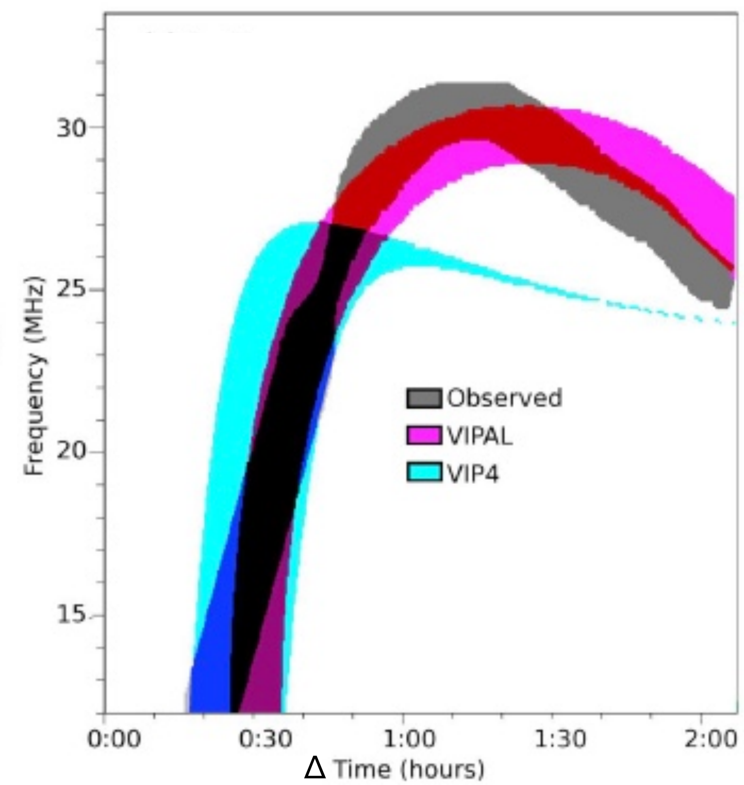
→ Inputs: source(s) field line, B model, CMI, df/dv⊥ (loss-cone/shell, e- energy), cone thickness δθ, observing geometry

→ Outputs: occurrence & polarization sense (t,f)

loss-cone beaming





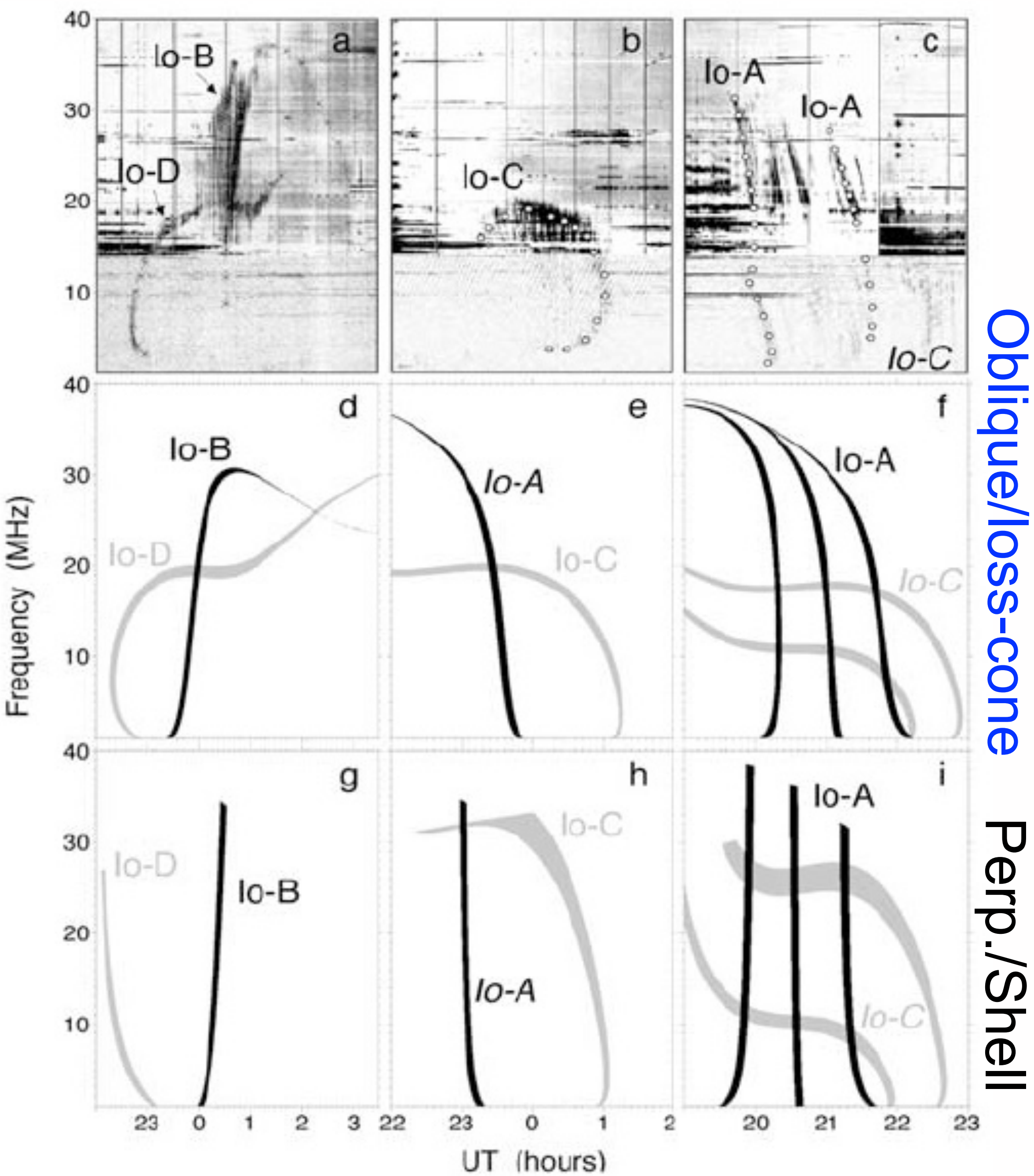


[Hess et al., 2008, 2011]

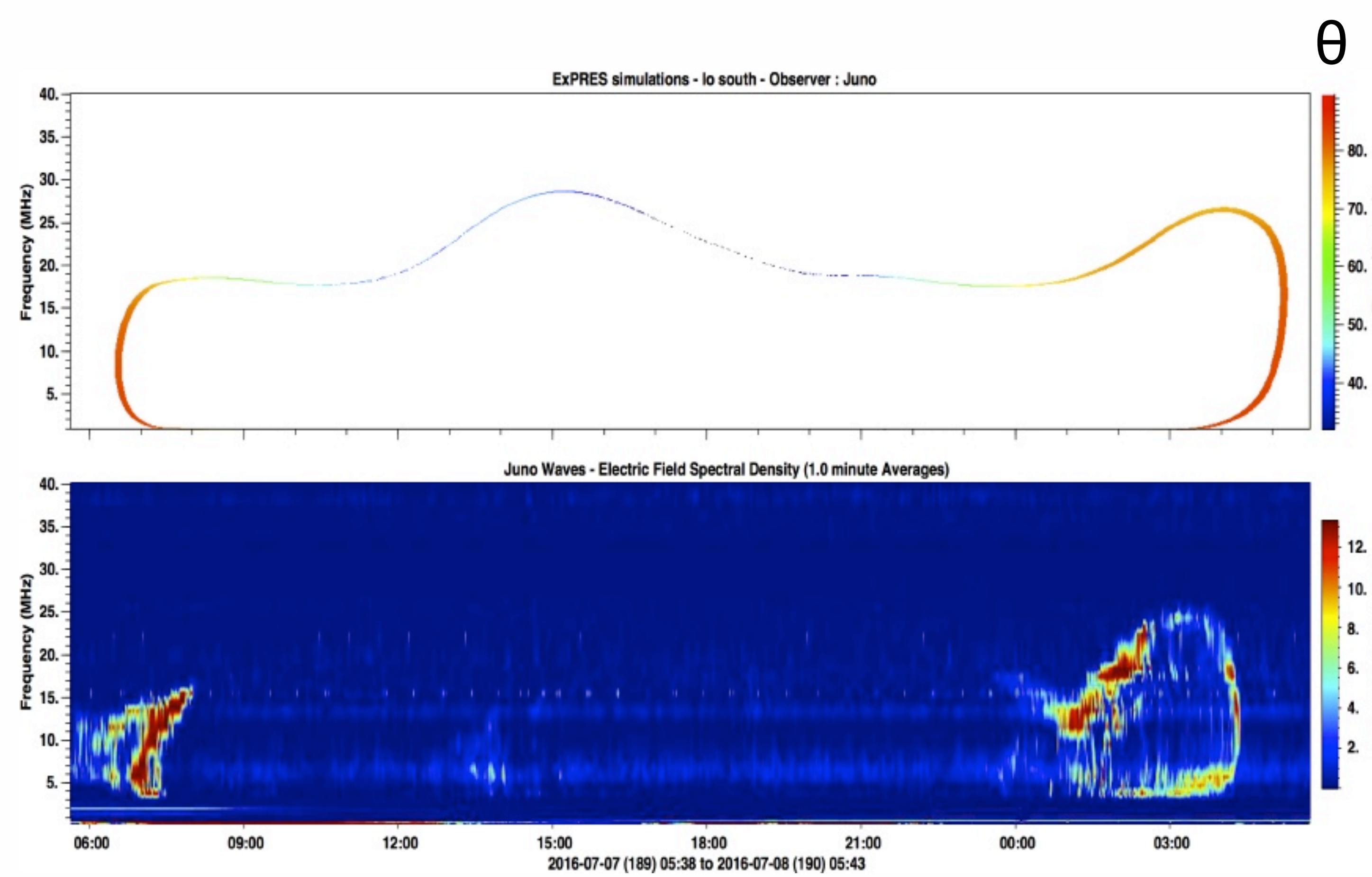
- Favours loss-cone driven (oblique) CMI for Io-Jupiter arcs

Nançay observations

Juno/Waves observations



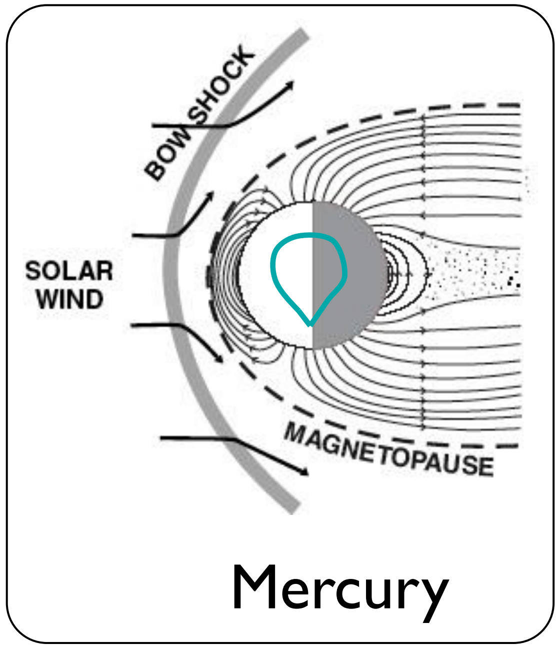
[Hess et al., 2008, 2011]

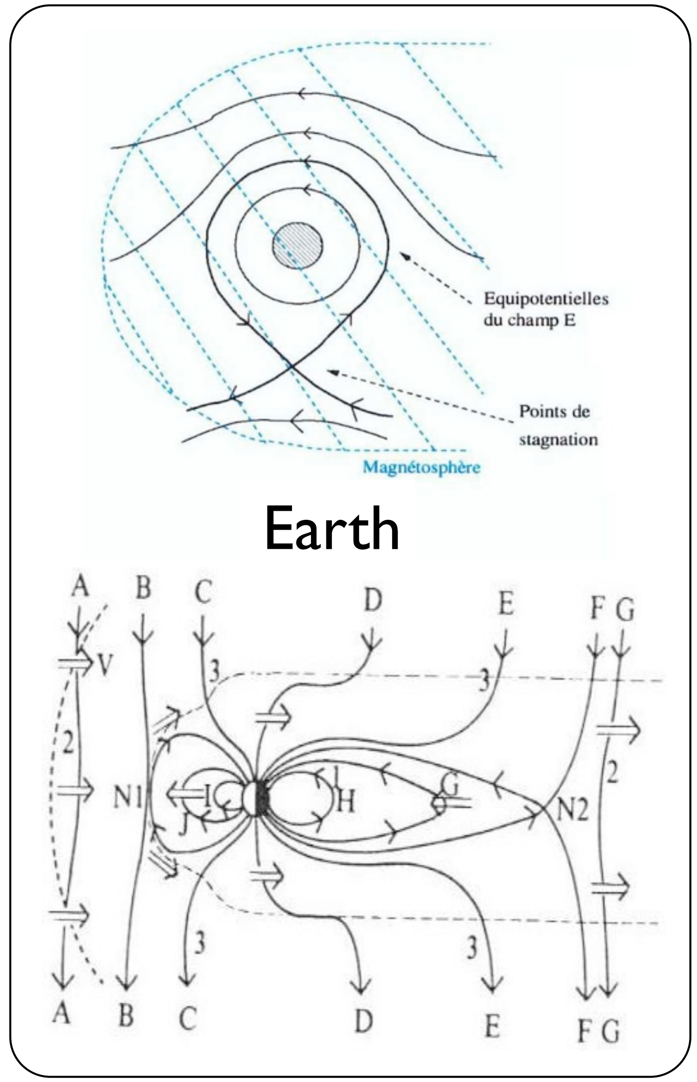


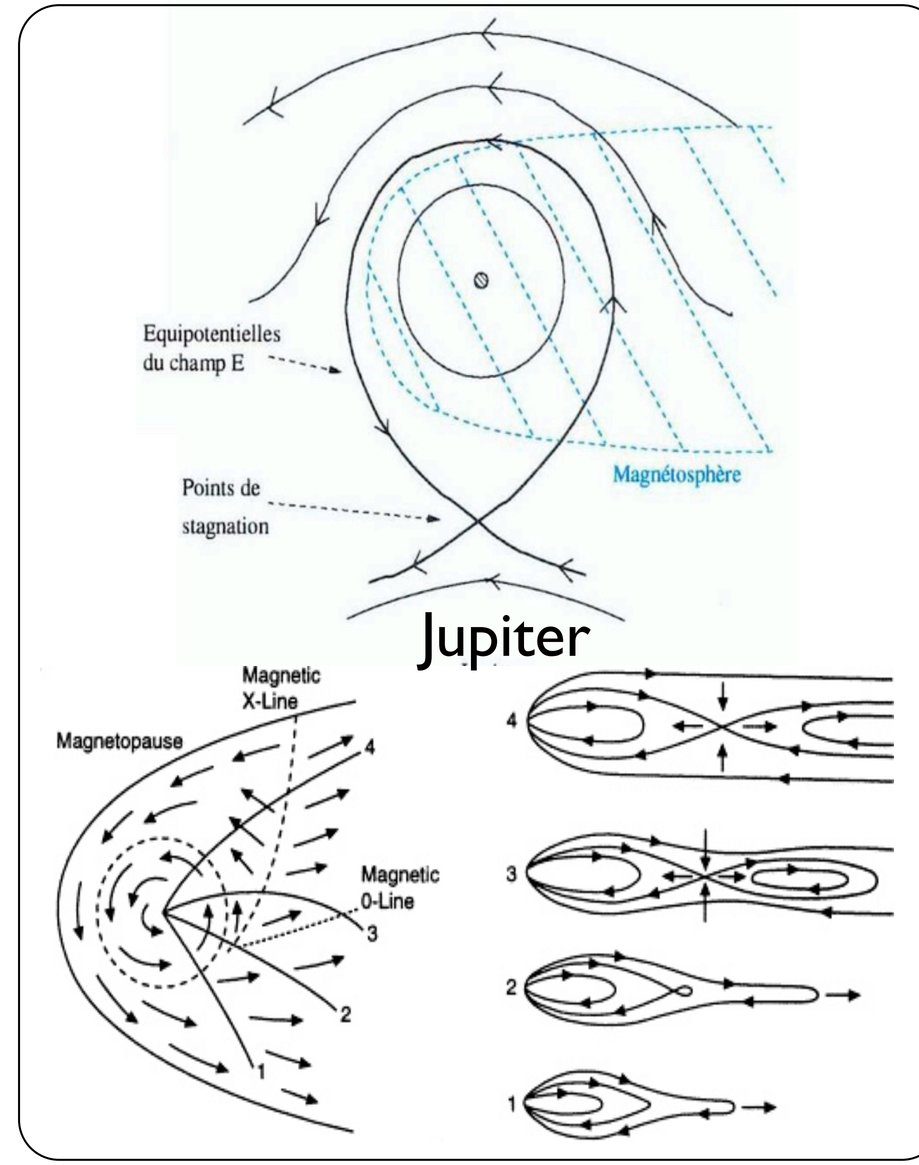
[Louis et al. 2017]

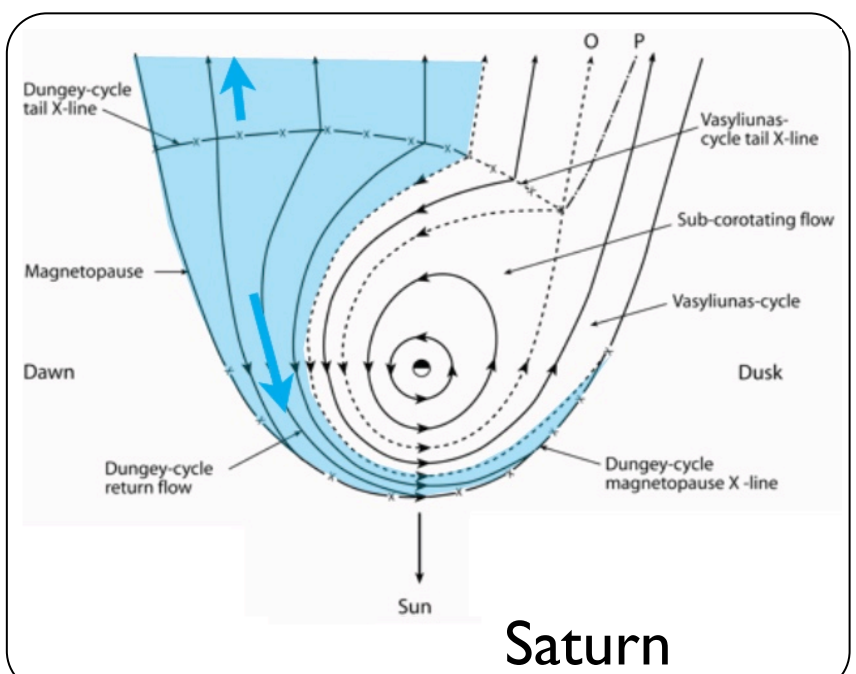
Application to Exoplanets

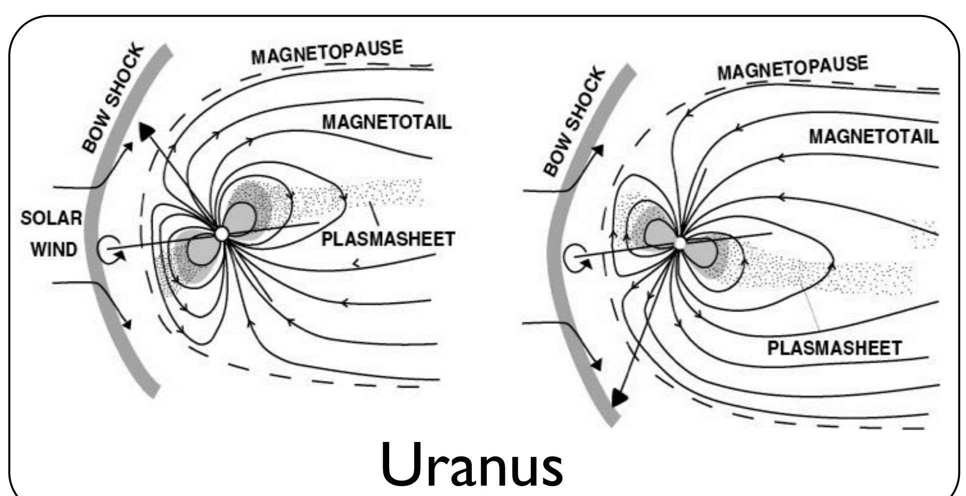
• **Magnetospheric structure & dynamics strongly different at each planet**

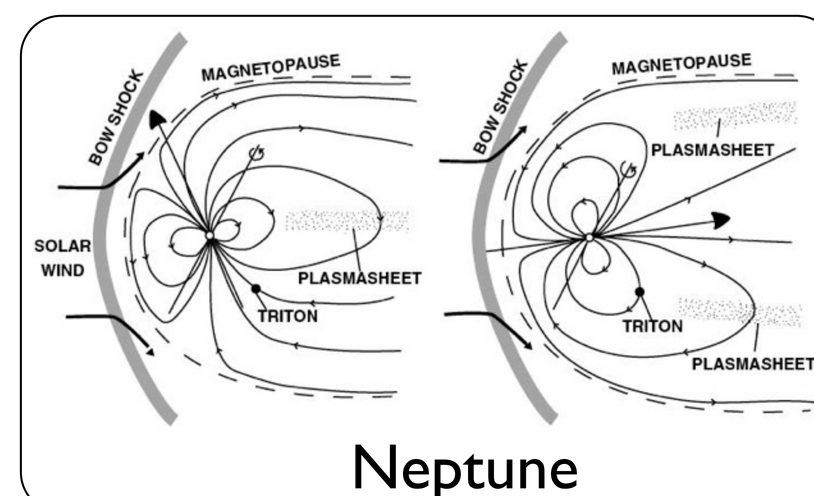






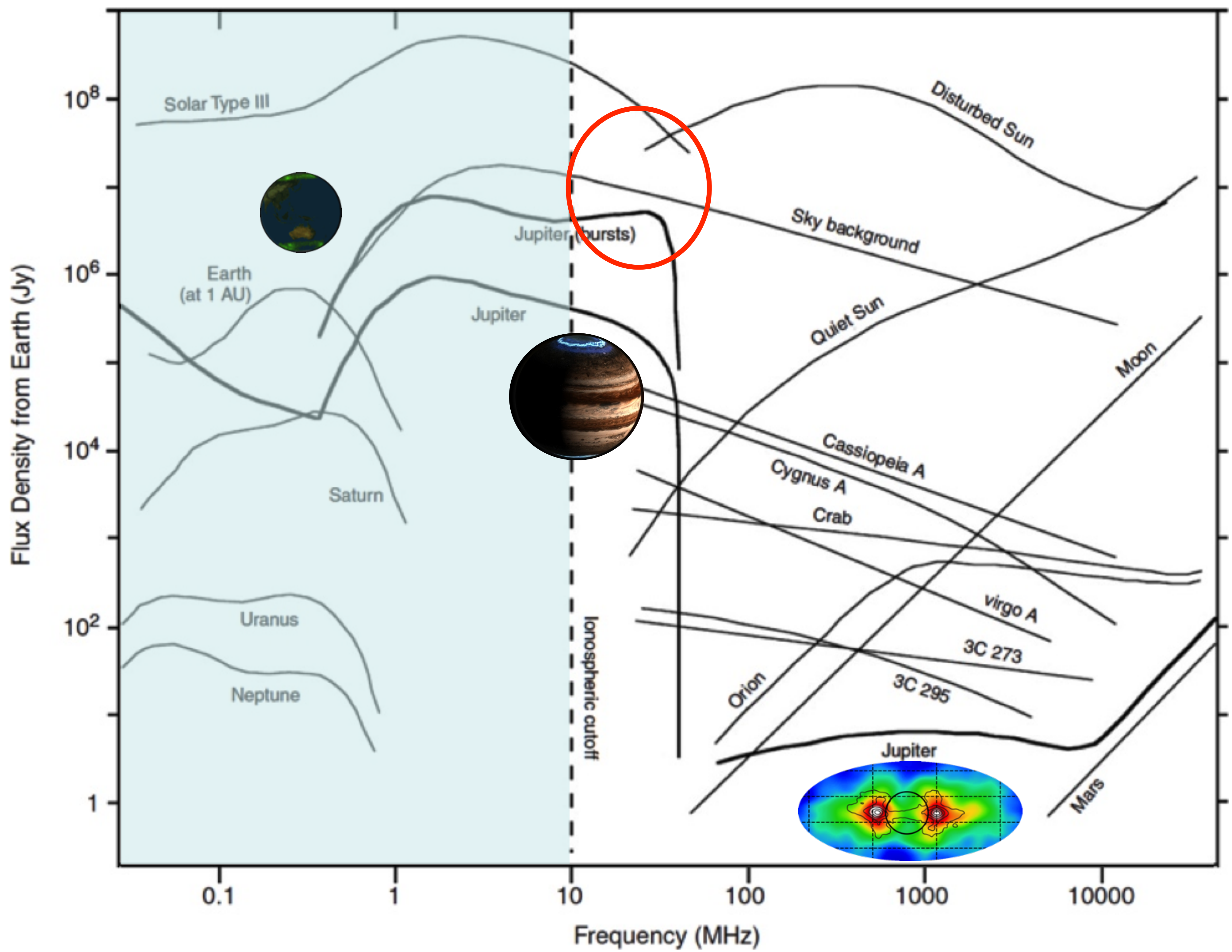






→ need for comparative exo-magnetospheric physics

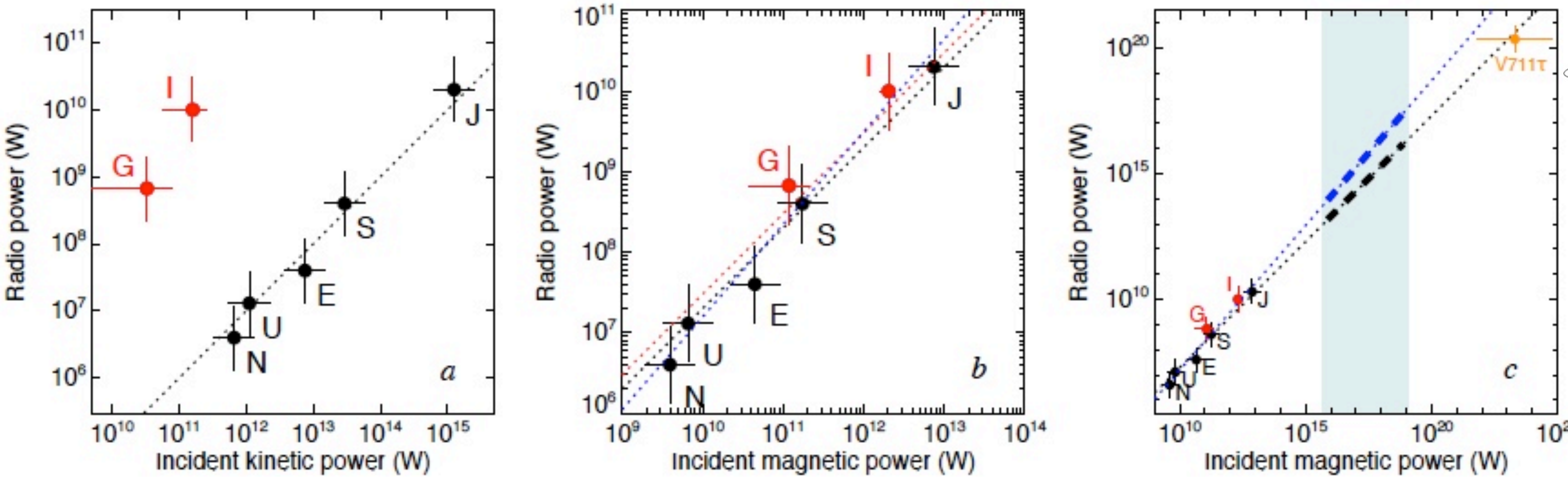
• **Magnetospheric radio emissions ?**



[Zarka, 2010]

- detectable from exoplanets ? → Jupiter at ≤ 0.2 pc with LOFAR

• **Radio-magnetic scaling law** → predicted intensities



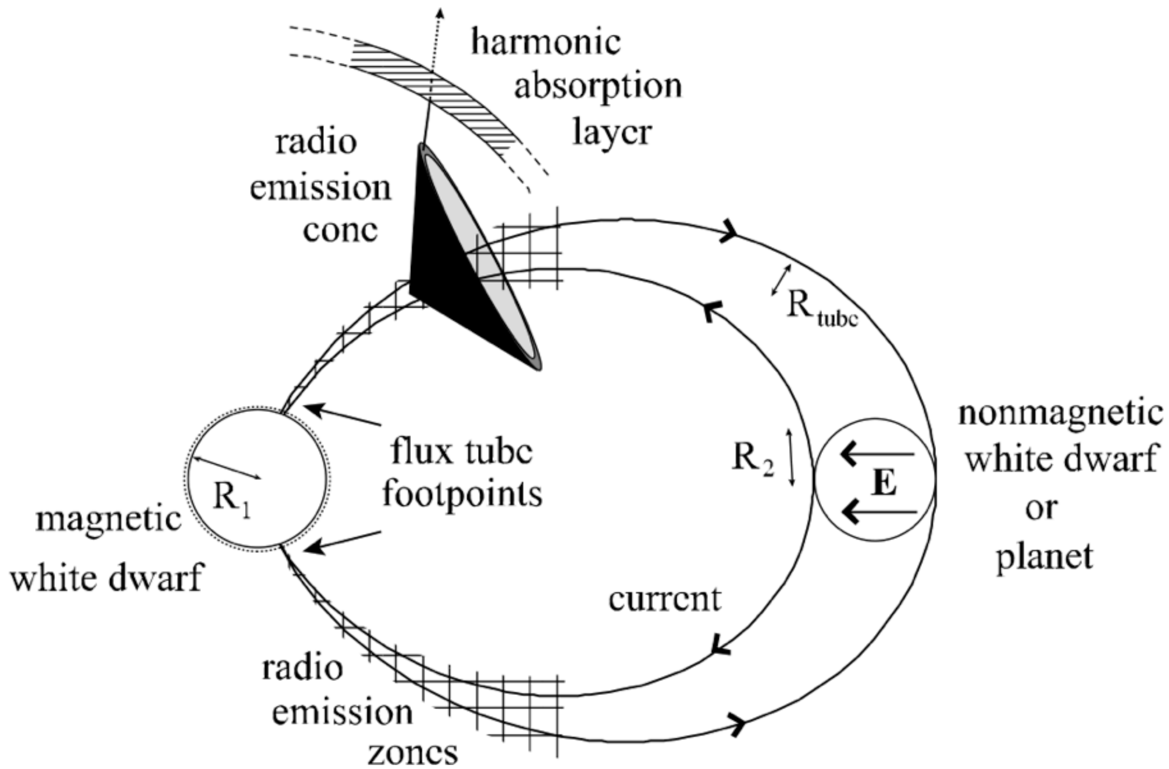
$$P_d = \varepsilon \, (V_{flow} B_\perp^{\,2}/\mu_o) \, \pi R_{obs}^{\,2}$$

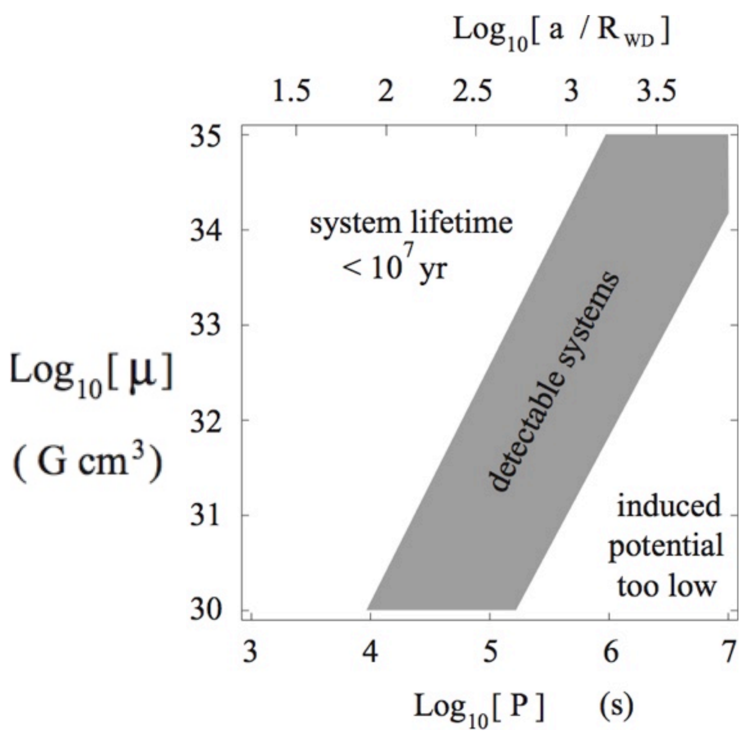
$$P_r = \beta \, (V_{flow} B_\perp^{\,2}/\mu_o) \, \pi R_{obs}^{\,2} = \beta \, P_d / \varepsilon$$

$$\beta = 2\text{-}10 \times 10^{-3}$$

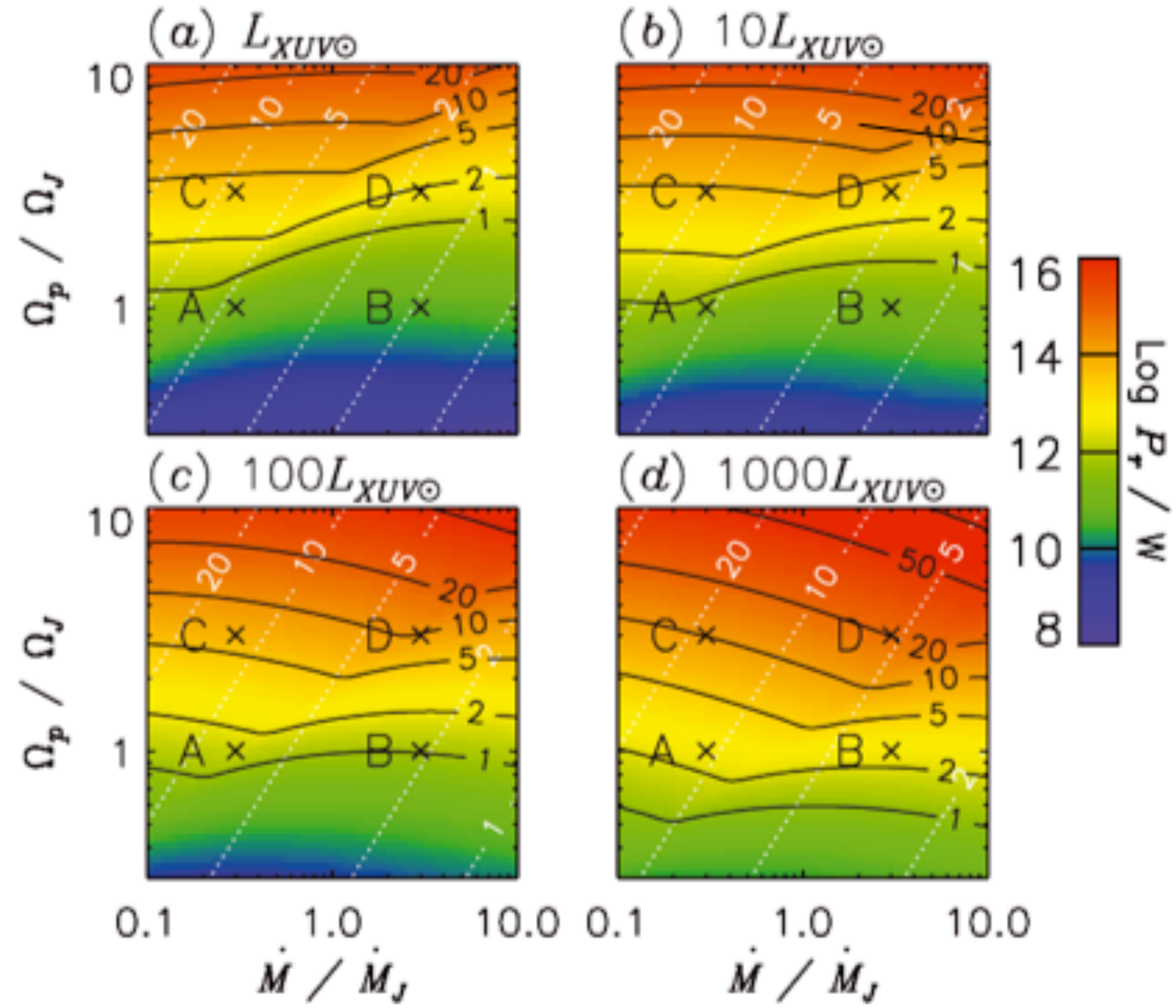
hot Jupiters : magnetospheric and induced emission

[Zarka et al., 2001 ; Zarka, 2007, 2018]





[Willes & Wu, 2004, 2005]



[Nichols, 2011, 2012]

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

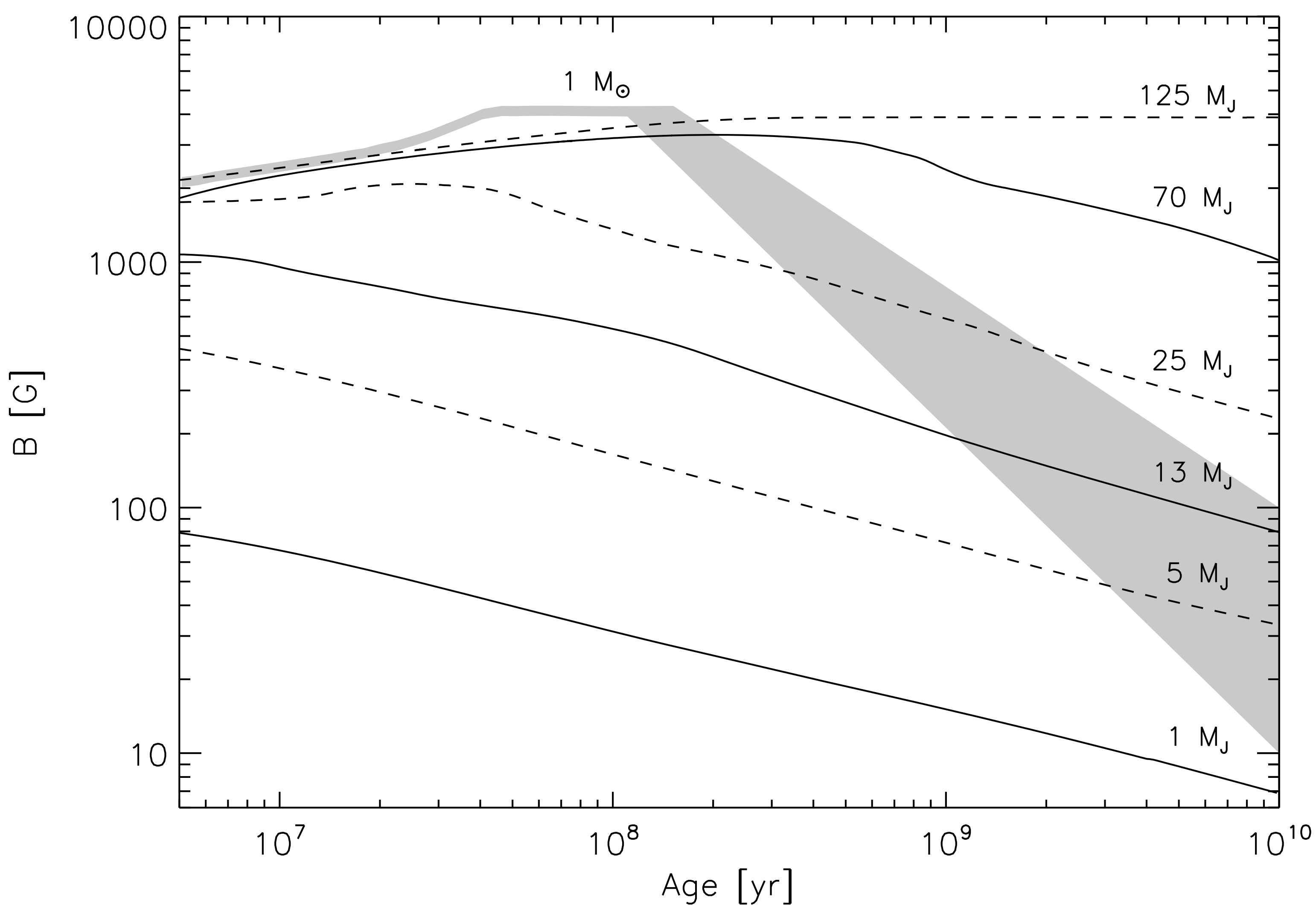
  - Hot Jupiters ⇒ Spin-orbit synchronisation (tidal forces) ⇒ ω↓
    but $M \propto \omega^{\alpha}$ with $½ \leq \alpha \leq 1$ ⇒ M↓ (B decay) ?

  - Internal structure + convection models
    ⇒ self-sustained dynamo ⇒ M could remain ≥ a few $G.R_J^3$

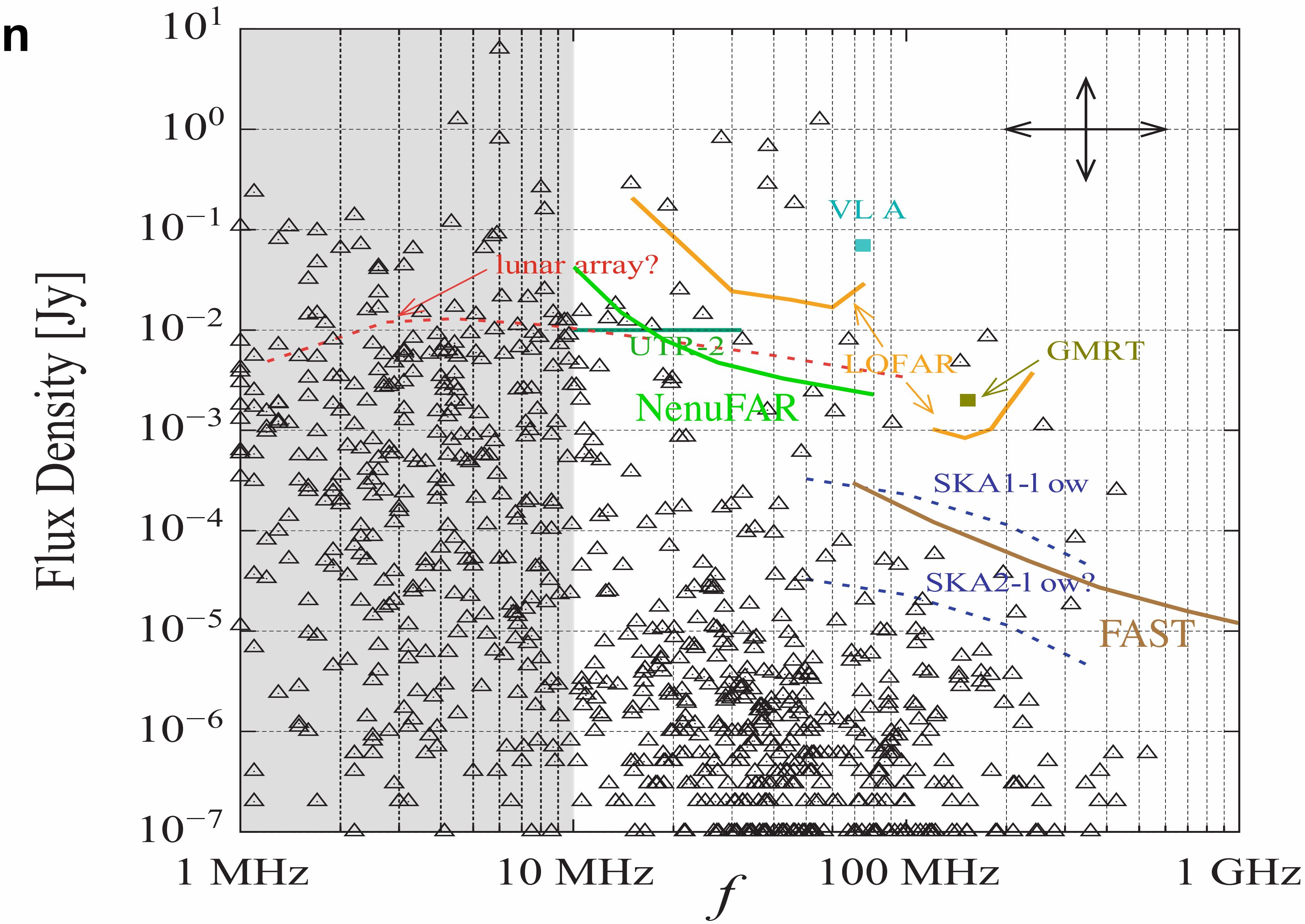
[Sanchez-Lavega, 2004]

  - More favourable predictions for fast rotators

[Reiners & Christensen, 2010]



• **Prospects for radio detection**

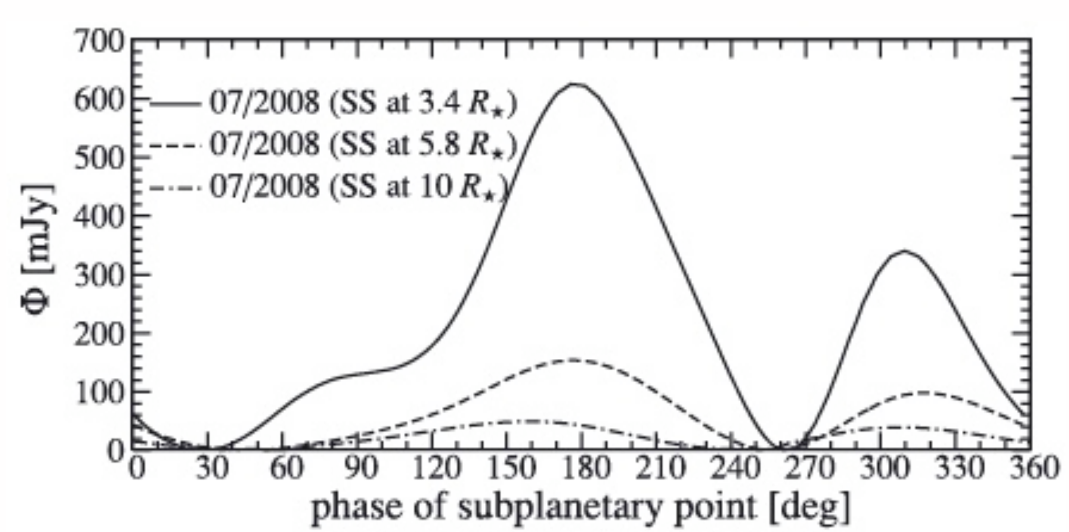


[Grießmeier et al., 2011; Grießmeier, 2018]

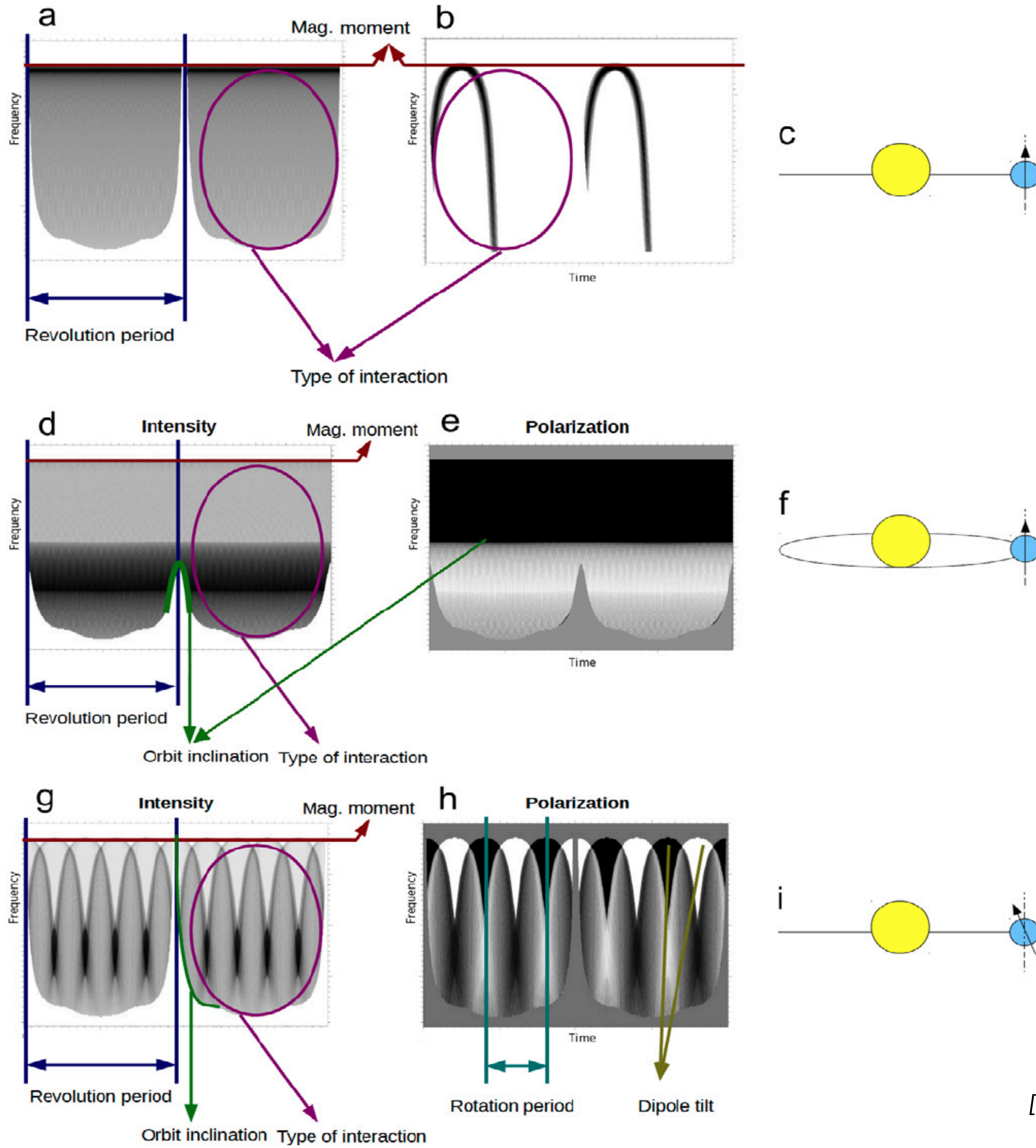
- Weak expected signal requires large instruments
- Star-Planet discrimination : polarization (circular) + periodicities (rotation, orbital)

- Variable SPI for HD 189733 ?

[Farès et al., 2010]



- **ExPRES simulations**

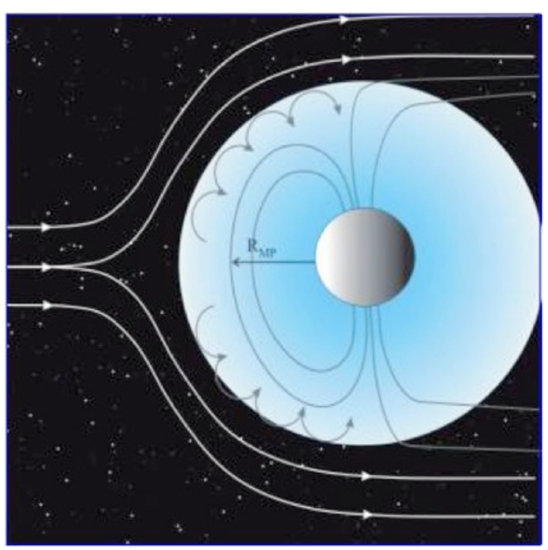


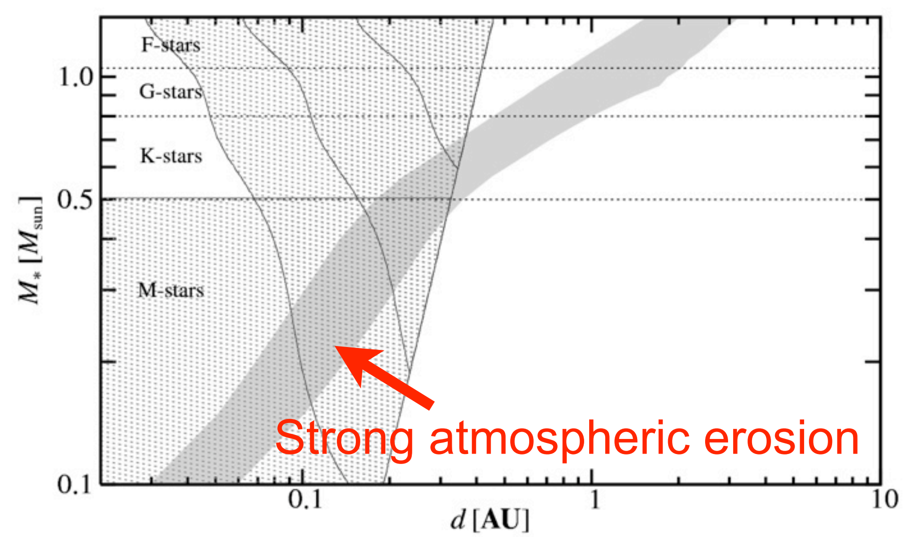
[Hess & Zarka, 2011]

• **What can we learn ?**

- Planetary |B| & tilt ⇒ dynamo ⇒ planetary interior structure
- Planetary rotation ⇒ spin-orbit locking ?
- Presence of satellites
- Orbit inclination
- Star-Planet plasma Interactions : type, energetics

⇒ comparative exo-magnetospheric physics, exo-space weather





[Griessmeier et al., 2004 ; Khodachenko et al., 2006]

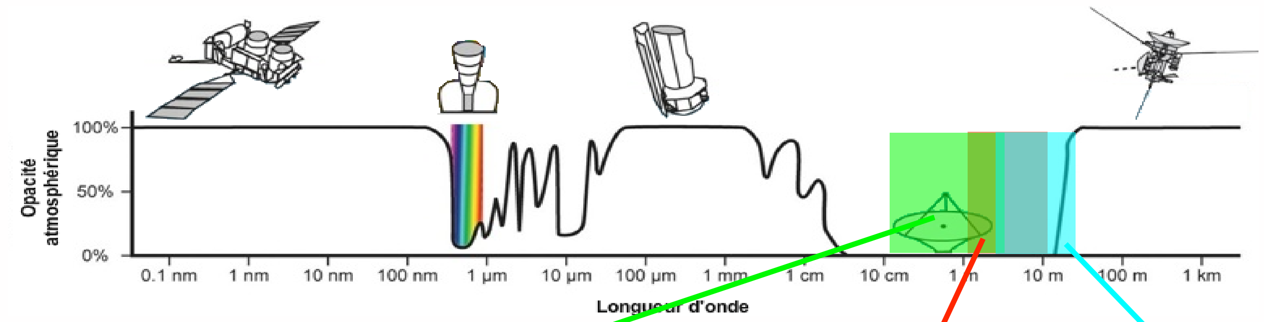
- implications for exobiology (magnetosphere limits atmospheric erosion by SW and CME, cosmic ray bombardment)

Perspectives

- **Planetary / magnetospheric space missions**

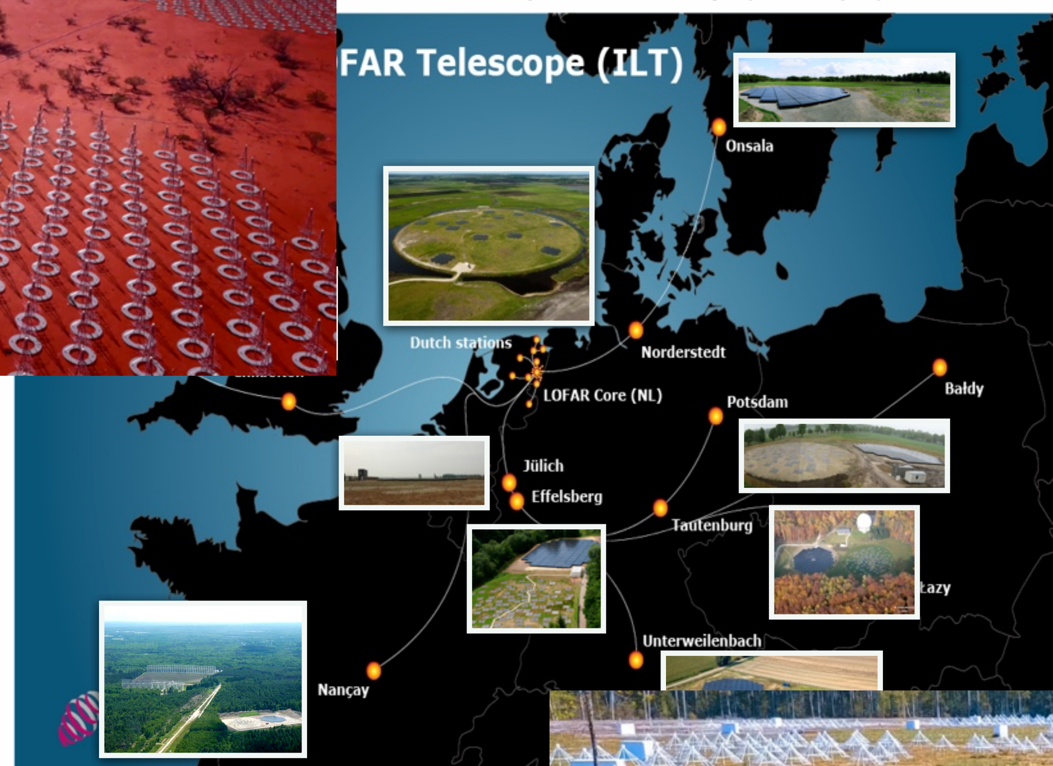
    - ongoing : Juno, Maven, Cluster, Themis
    - incoming : BepiColombo, Juice
    - projects : Uranus/Neptune ...

• **Present / Future large low-frequency radiotelescopes**



SKA ≥50 MHz (Aus)

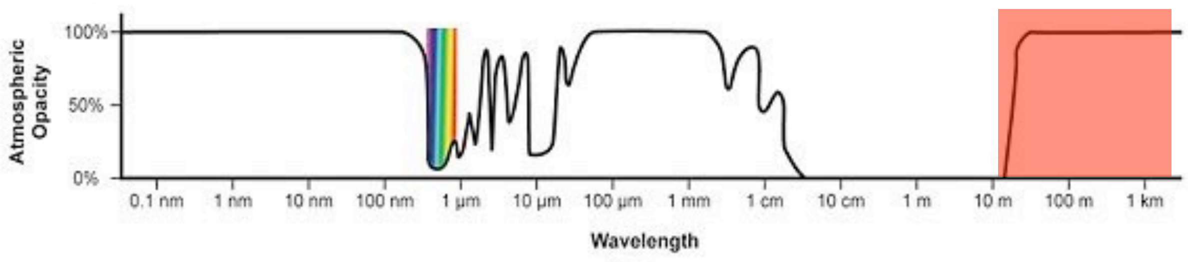
LOFAR 30-250 MHz (NL, Eu)

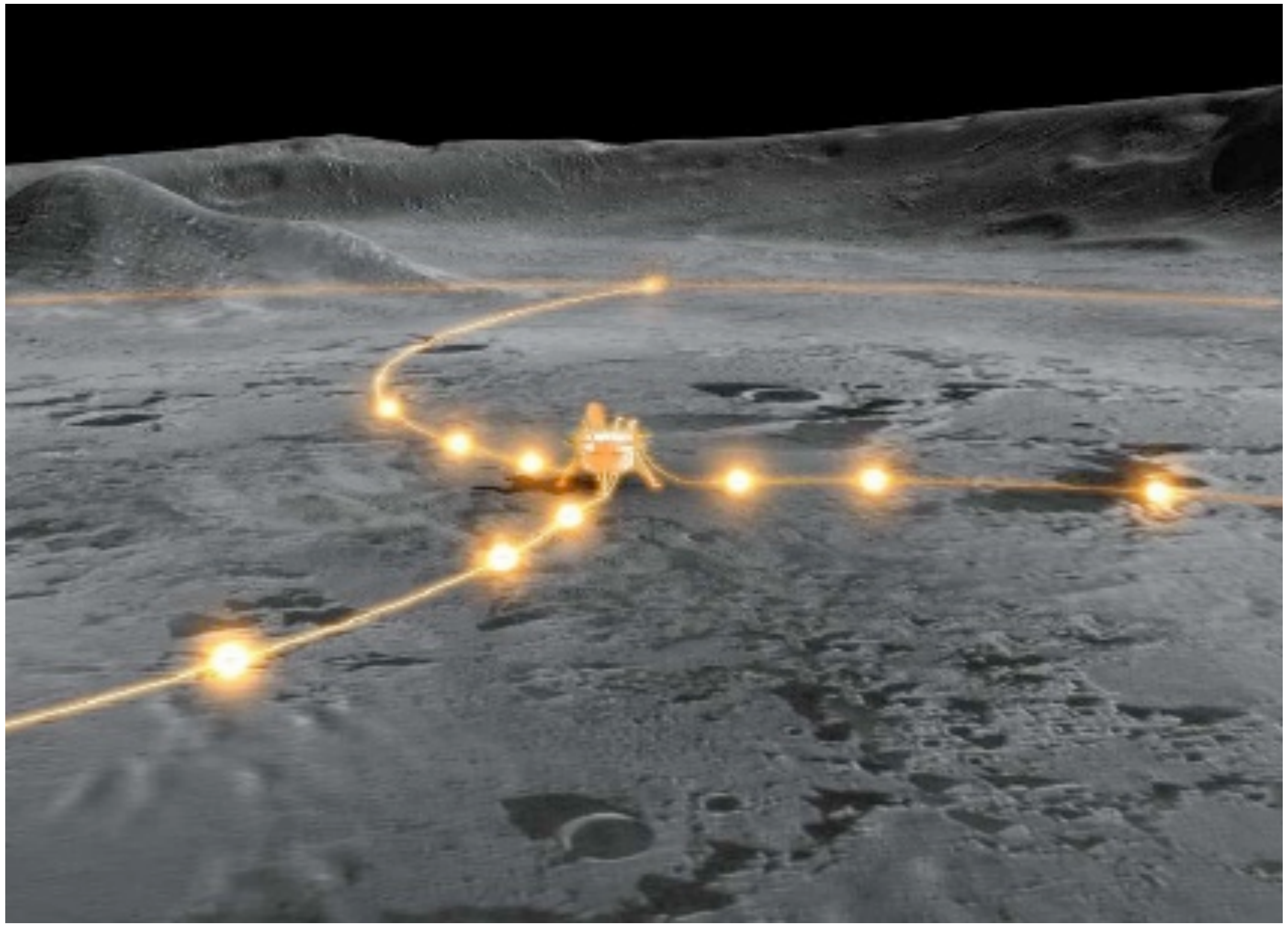


NenuFAR 10-85 MHz (Fr)

• **Moon- / space-based low-frequency radiotelescopes**

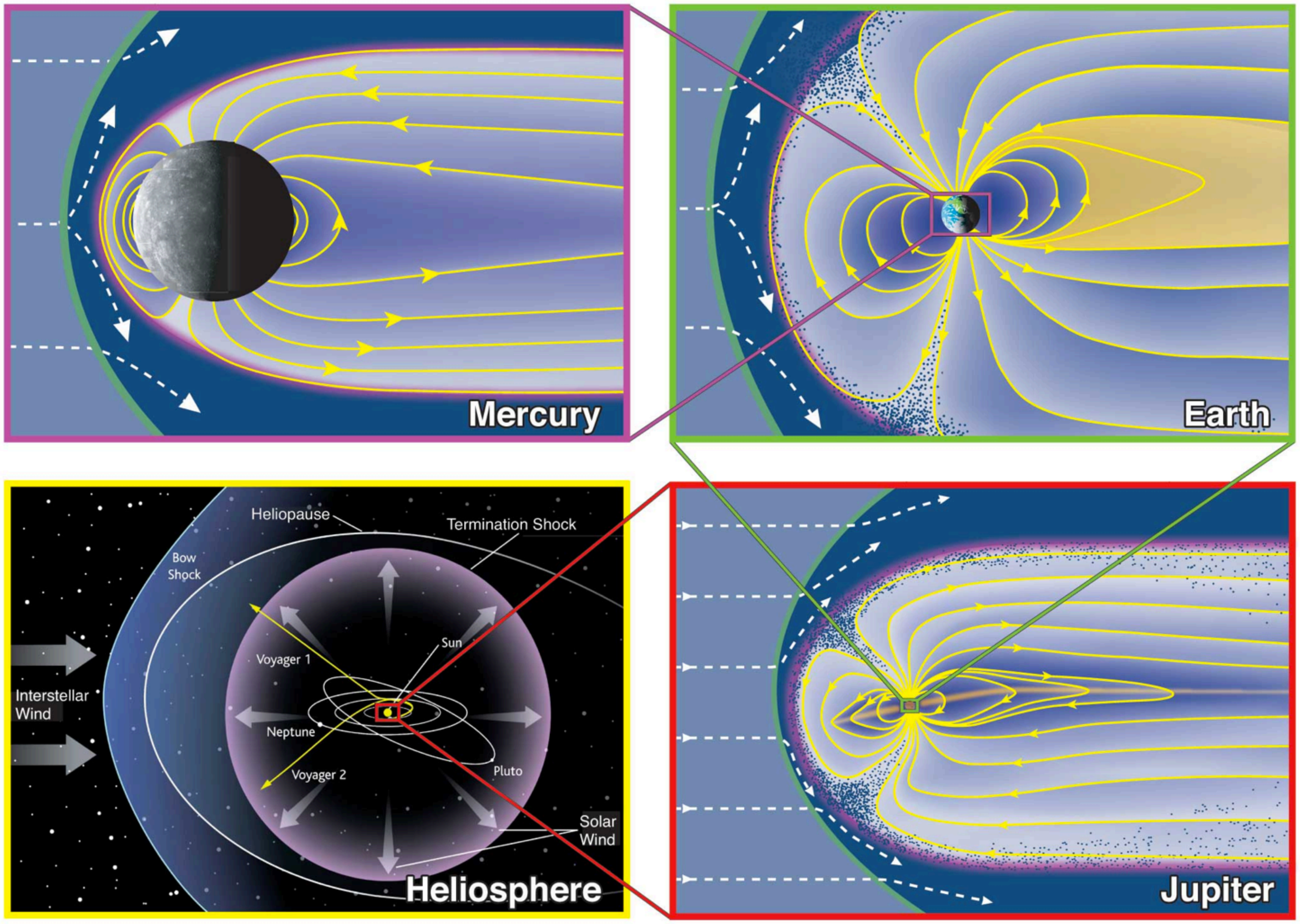
~ No ionosphere, low RFI level (farside, night) → range ≤ 30 MHz accessible



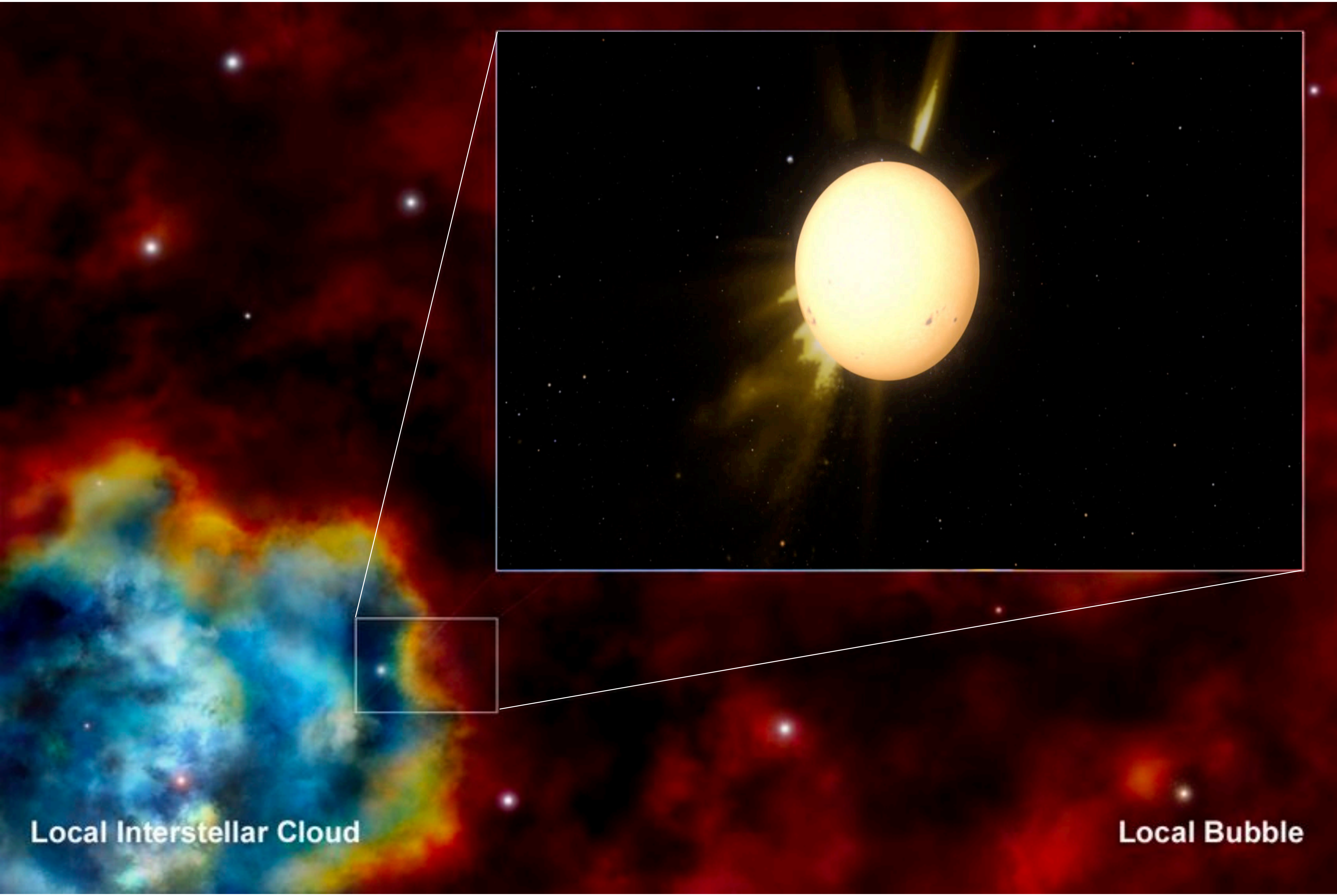


• **Magnetospheres**

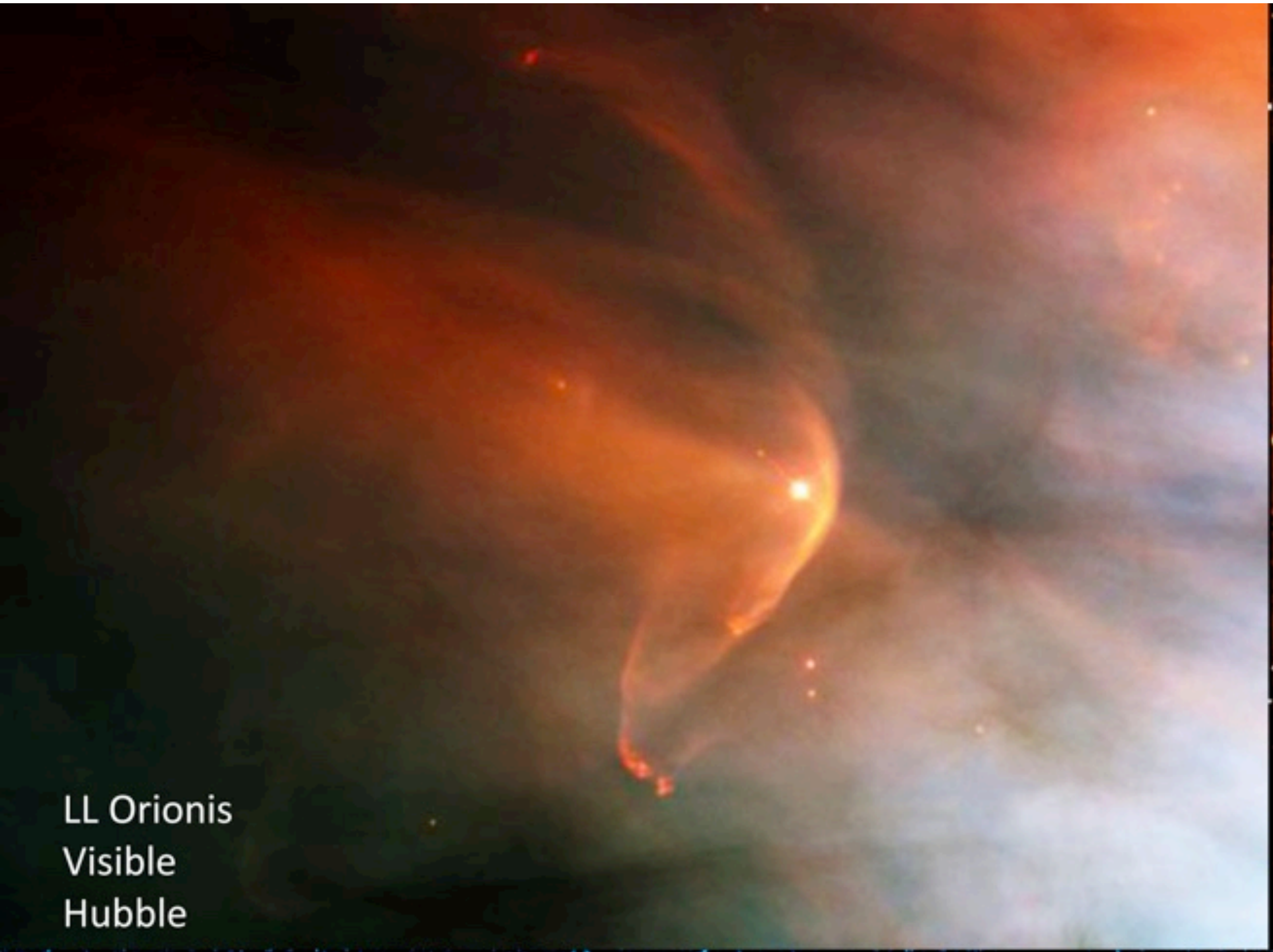
- Plasma physics laboratories
- Large diversity of scales and plasma environments
- "Ground truth" for astrophysical applications

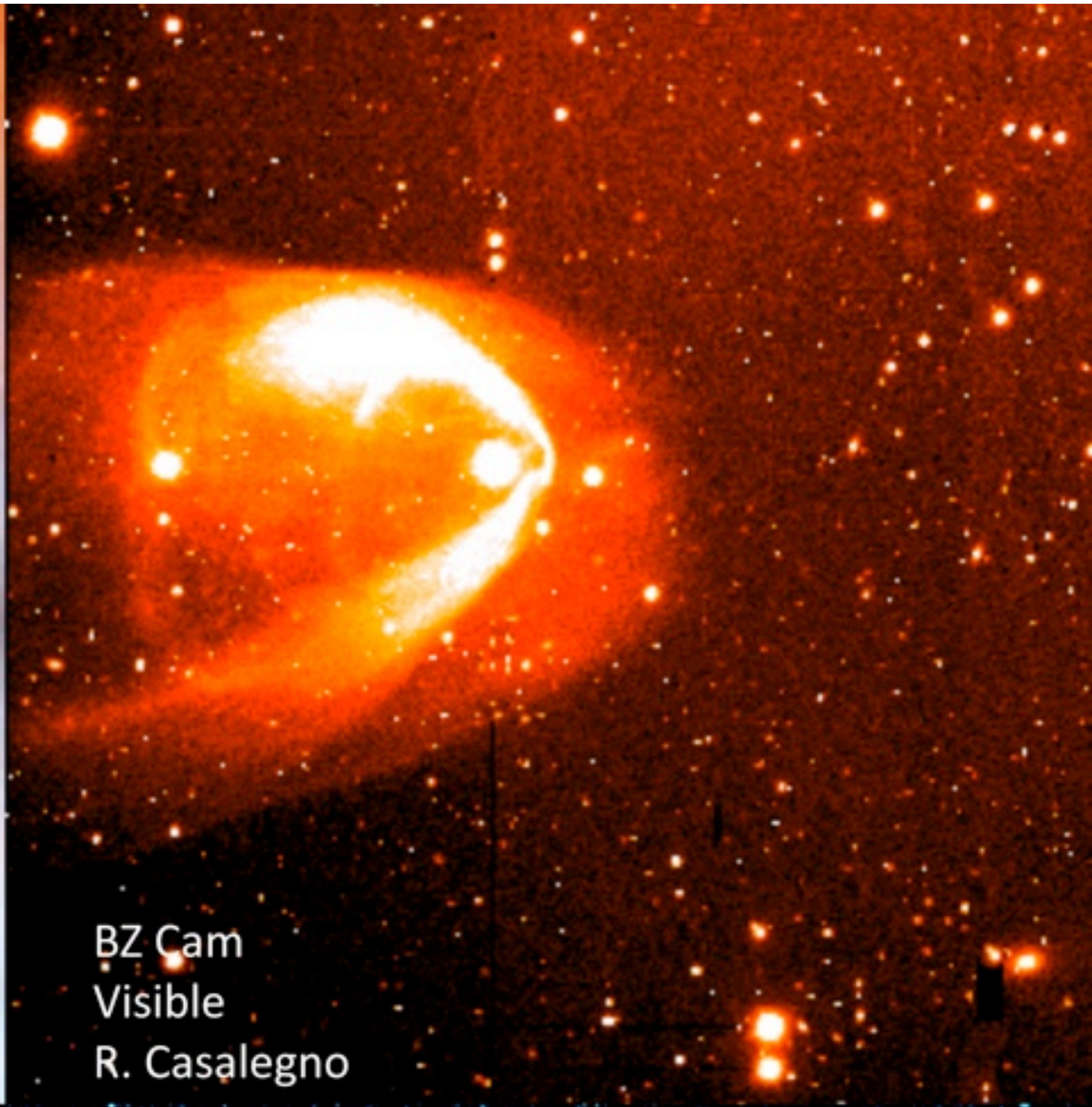


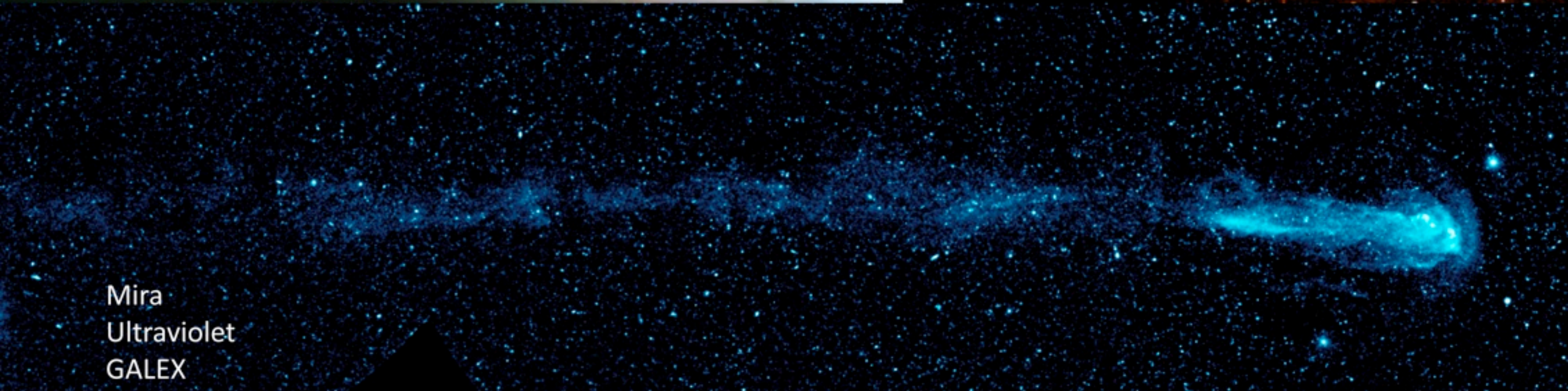
- **Heliosphere**



• **Astrospheres**







Merci.