Planetary Magnetospheric Structure

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Rencontres de Blois - 2006

- Solar Wind / Solar Wind - Obstacle interaction
- Planetary Magnetic Fields
- Magnetospheric Boundaries
- Plasma Sources
- Plasma Circulation
- Role of Ionosphere
- Current Generators
- Aurorae (and satellite induced emissions)
- Exoplanetary Magnetospheres ?

• **Foreword**

High plasma conductivity

⇒ B frozen-in

⇒ E = -VxB (0 in plasma frame)

⇒ quasi-neutrality

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

= electric equipotentials)

• **Acronyms**

SW = solar wind

MS = magnetosphere

MP = magnetopause

B = magnetic field

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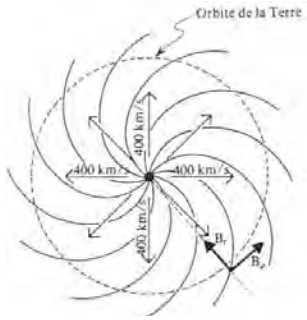
• Solar Wind



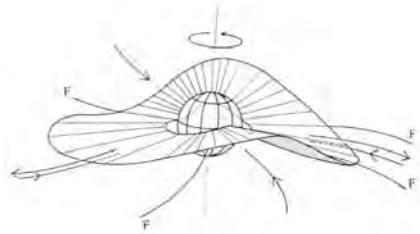
- dominated by bulk energy density : $NmV^2/2$
- carries away solar B rooted in the Sun ⇒ ballerina skirt
- SW parameters at planetary orbits (r in AU) :

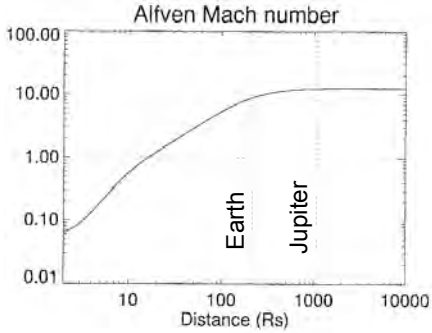
$V \sim 400/r^{2/7}$ km/s $T \sim 2\times10^5/r^{2/7}$ K

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

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

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



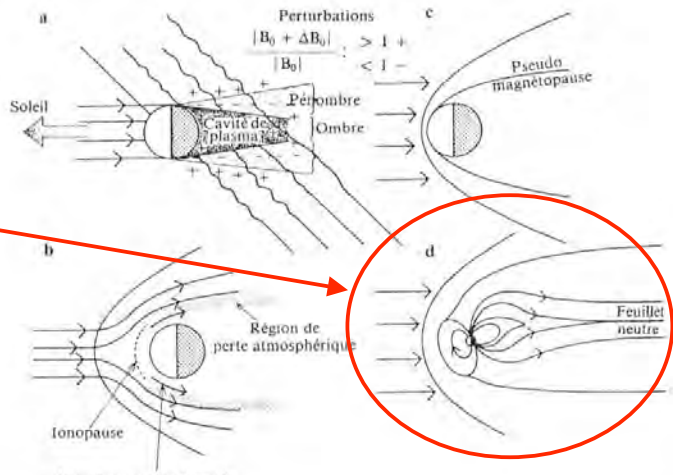


- CIR, CME, more shocks away from the Sun (SW radial evolution)

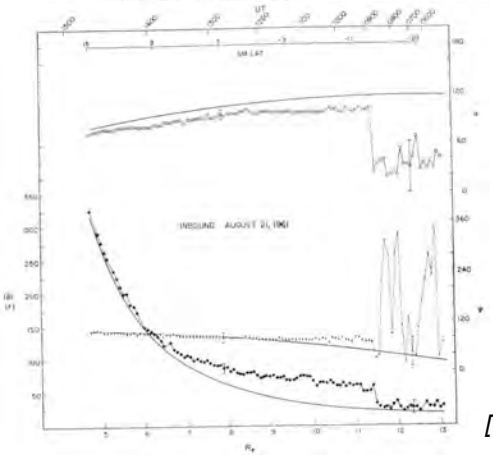
• Solar Wind - Obstacle interaction

- depends on presence of obstacle's :
  - intrinsic large-scale B
  - ionosphere
  - conductivity

-1st case ⇒ abrupt boundary
  in planetary B = MP



[Lepping, 1986]



[Cahill & Patel, 1967]

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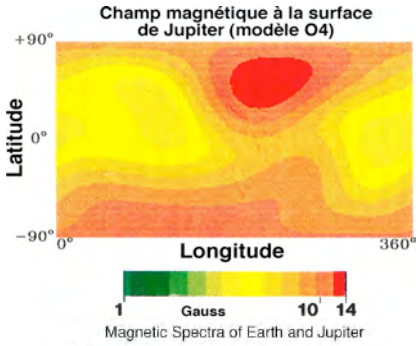
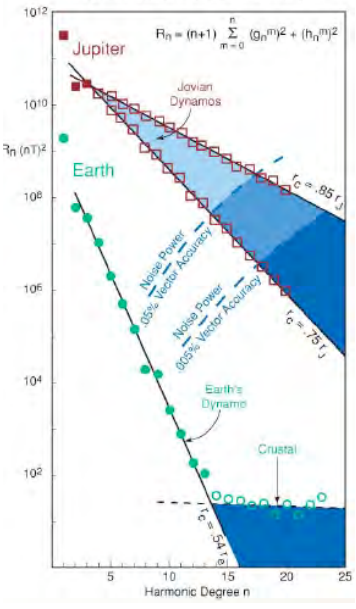
• Planetary Magnetic Fields

- dipole + high-order terms
- known up to n~14 at Earth, n≤4 at other planets
- measurements : MAG in-situ, teledetection (IR, radio)



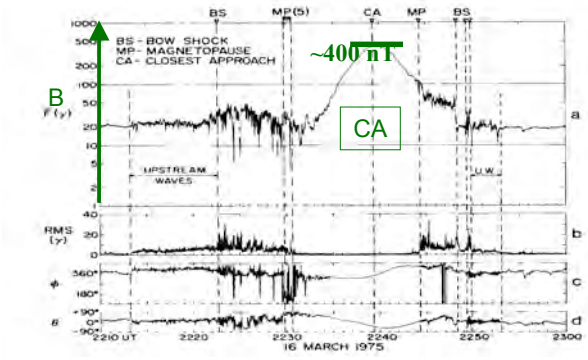


Planète	Terre	Jupiter	Jupiter	Saturne	Uranus	Neptune
R_P (km)	6378	71372	71372	60330	25600	24765
Modèle	IGRF 2000	O6	VIT4	Z3	Q3	O8
g_1^0	−0.29615	+4.24202	+4.28077	+0.21535	+0.11893	+0.09732
g_1^1	−0.01728	−0.65929	−0.75306	0	+0.11579	+0.03220
h_1^1	+0.05186	+0.24116	+0.24616	0	−0.15685	−0.09889
g_2^0	−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

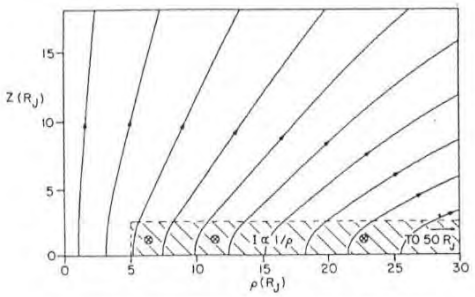
[adapted from Ness, 1992]

• **Planetary Magnetic Fields** [cont'd]

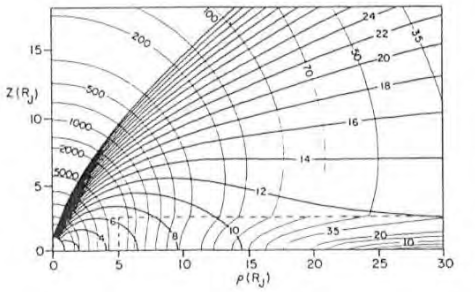
- weak dipolar field @ Mercury, ~10° tilt



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



- ring current (magnetodisc) @ Jupiter & Saturn



[Acuña et al., 1983]

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• Magnetospheric Boundaries

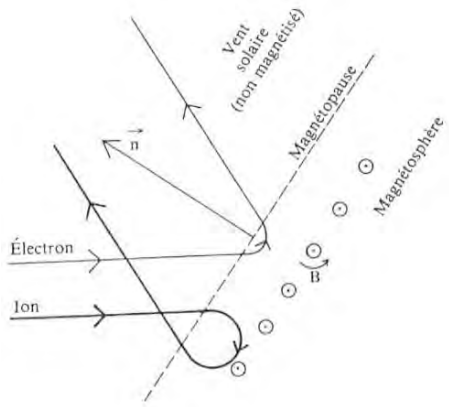
- Pressure equilibrium : $P_{SW} = KNmV^2\cos^2\chi$ = $P_{MS} = B_T^2/2\mu_o$

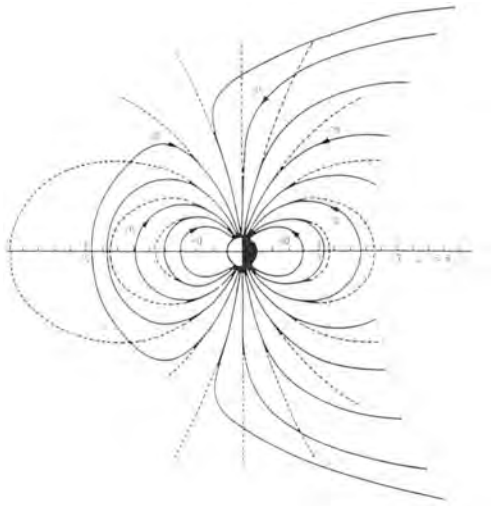
  with $B_T = B_P + B_C = 2\,B_P$ at MP nose K = 1-2

  ⇒ MP shape

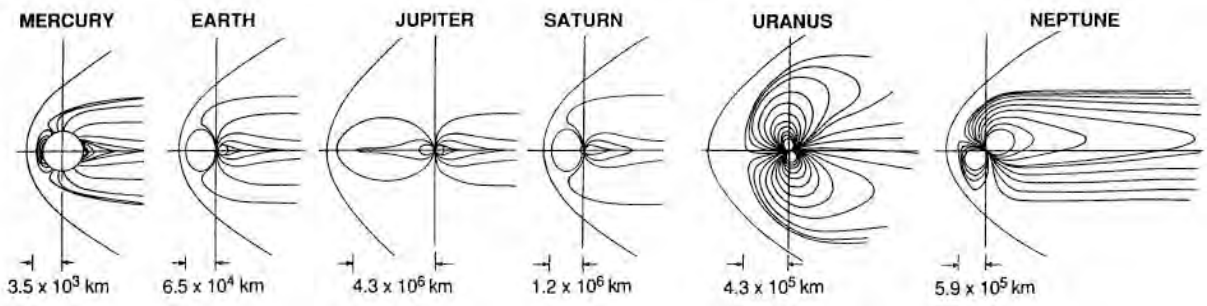
- MP sub-solar point (dipolar field : $B_P = B_{eq}\,(1+3\cos^2\theta)/R^3$) :

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





• Magnetospheric Boundaries [cont'd]



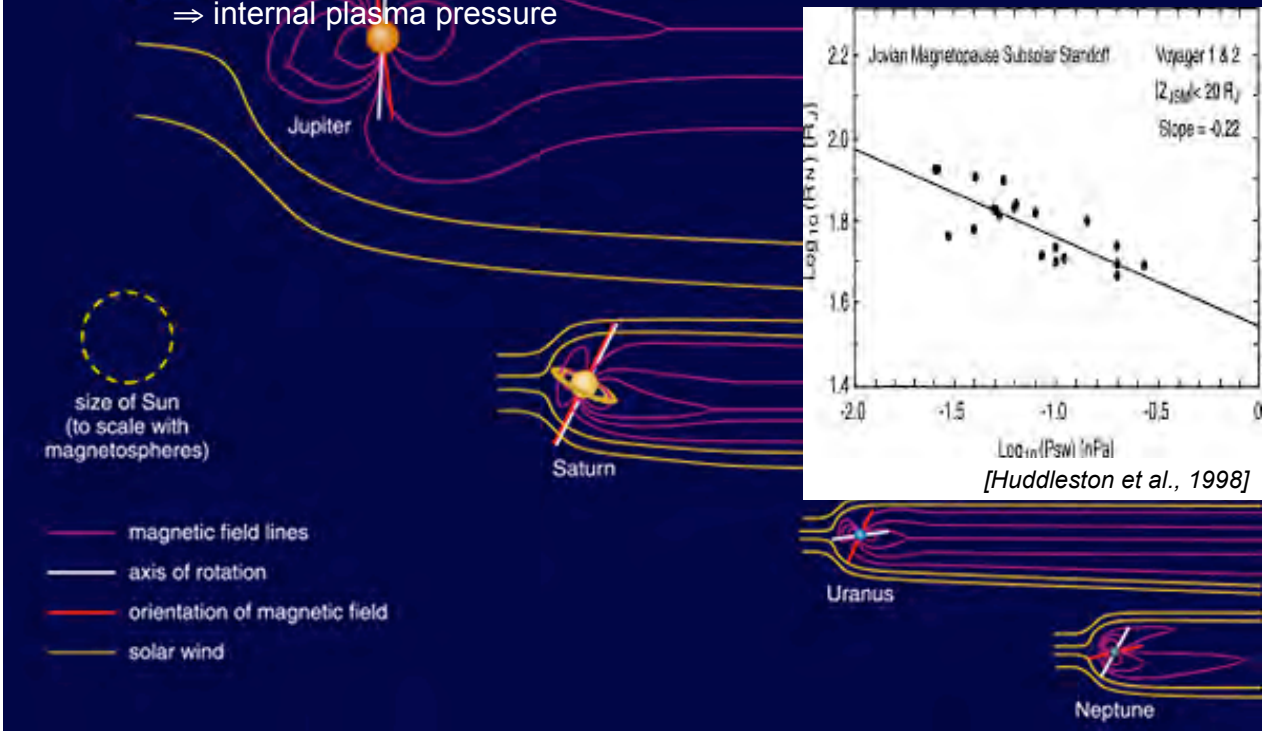
	Mercure	Terre	Jupiter	Saturne	Uranus	Neptune
R_P (km)	2 439	6 378	71 492	60 268	25 559	24 764
D orbitale (UA)	0.39	1	5.2	9.5	19.2	30.1
M_{dip} (G.km^3)	5.5×10^7	7.9×10^{10}	1.6×10^{15}	4.7×10^{13}	3.8×10^{12}	2.2×10^{12}
Champ à l'équateur B_e (G)	0.003	0.31	4.3	0.21	0.23	0.14
Inclinaison [B,Ω] (°) et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

• **Magnetospheric Boundaries** [cont'd]

- Jupiter's MS larger and more compressible ($R_{MP} \propto P_{SW}^{-1/4.5}$)

⇒ internal plasma pressure

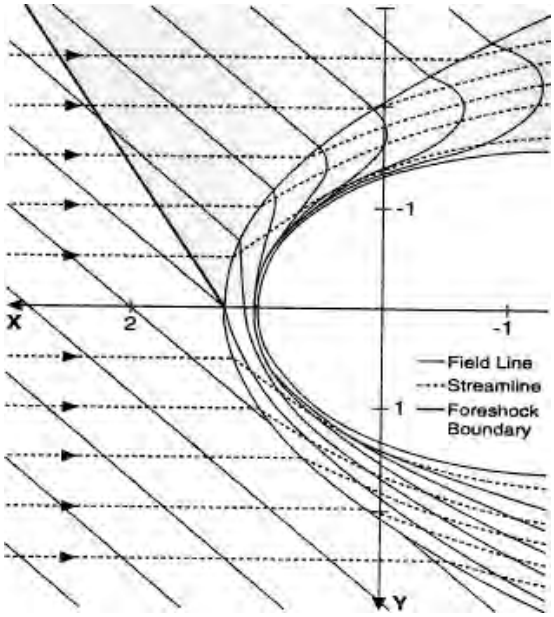


[Huddleston et al., 1998]

• **Magnetospheric Boundaries** [cont'd]

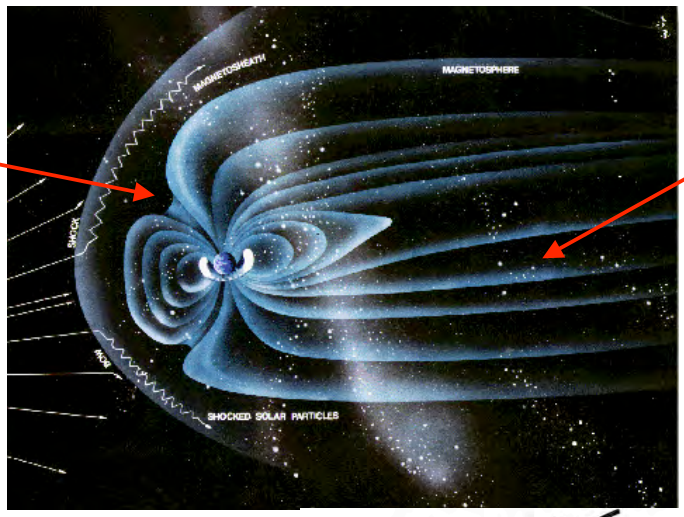
- supersonic / super-Alfvénic flow ⇒ bow shock ahead of MP
- in magnetosheath : slowed flow (V:4 for $M_A >> 1$)

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



[Spreiter et al., 1966]

• **Magnetospheric Boundaries** [cont'd]

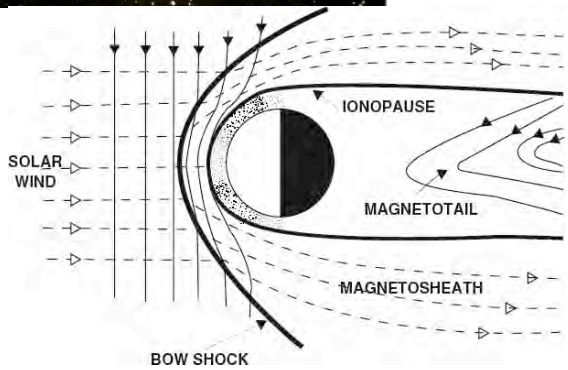


- if no intrinsic B field

  ⇒ induced MS, bow shock,

  B draping, tail

  No cusp

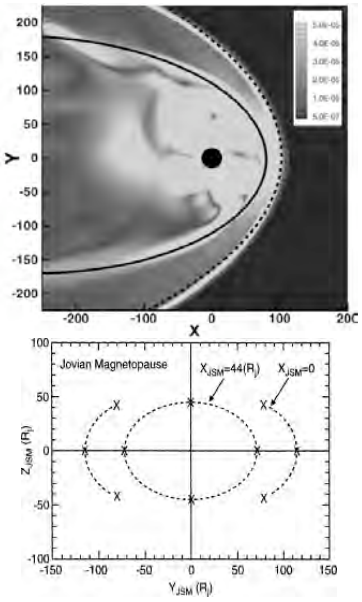


• **Magnetospheric Boundaries** [cont'd]

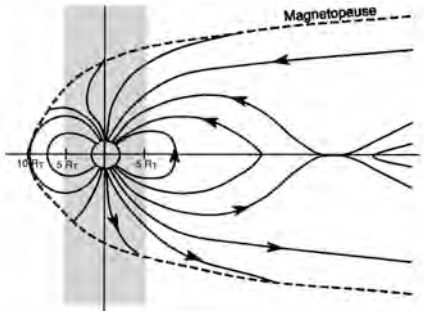
- Earth bow shock : R = 25 R_E/(1+0.8cosθ) thickness ~40% of MP

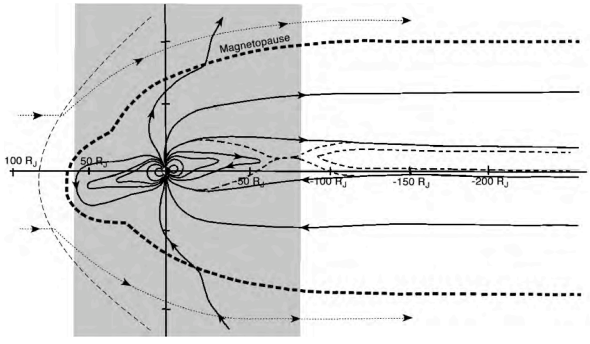
- Jupiter : MP closer to BS (thickness ~15%)

  ⇒ equatorial flattening due mass loading (Io)



[Joy et al., 2002; Russell, 2004]





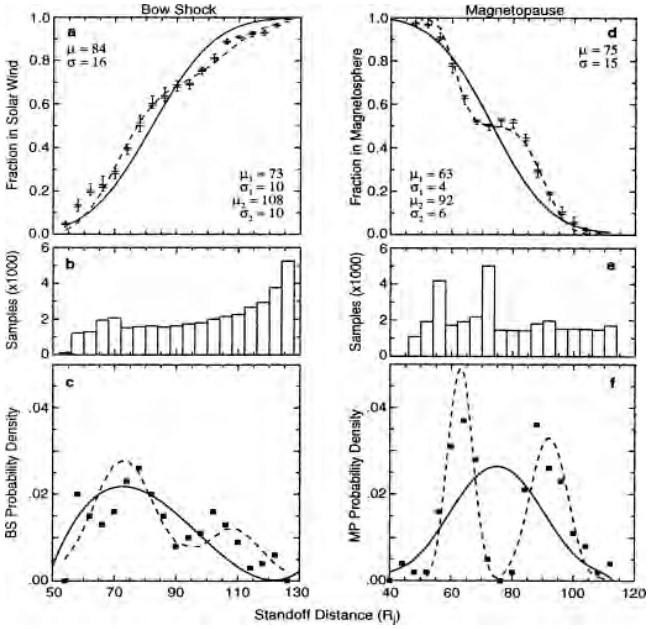
[Courtesy R. Prangé]

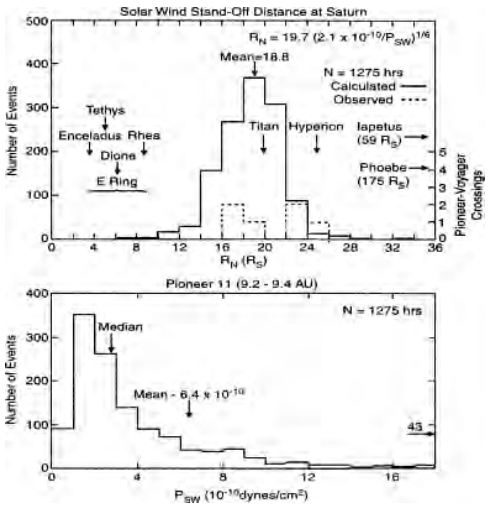
• **Magnetospheric Boundaries** [cont'd]

- 2 states of compression of Jupiter MS, not related to 2 states of P_{SW}

  ⇒ variability of MS mass-loading ?

- Saturn ?



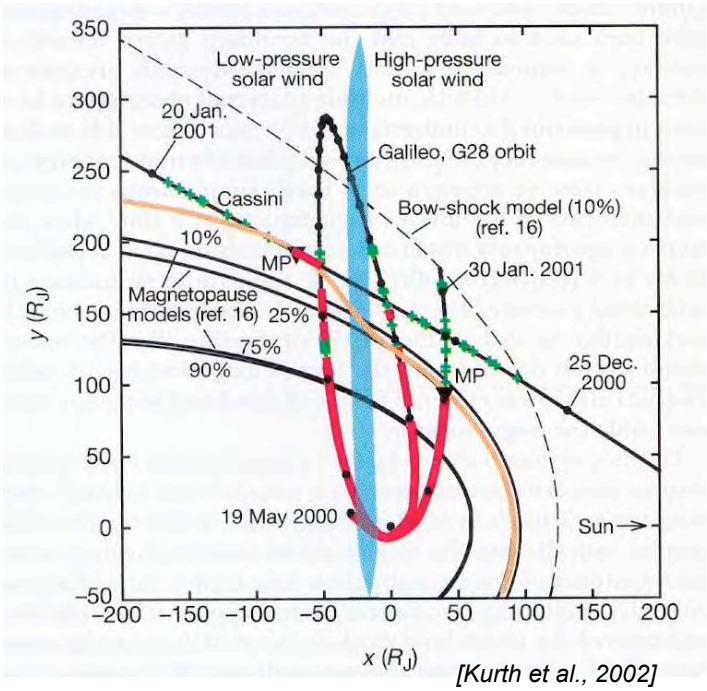


[Joy et al., 2002; Russell, 2004]

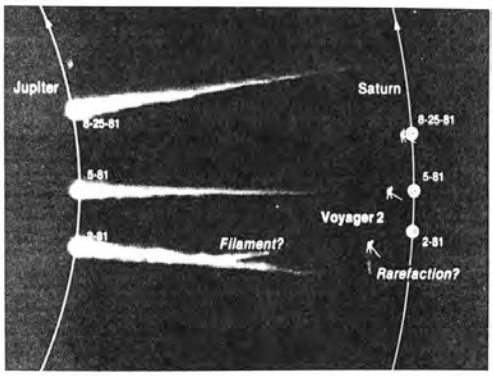
• **Magnetospheric Boundaries** [cont'd]

- on-going MS compression measured by Cassini + Galileo

- Jovian magnetotail extent (≥5 AU) measured by Voyager



[Kurth et al., 2002]



[Desch, 1983]

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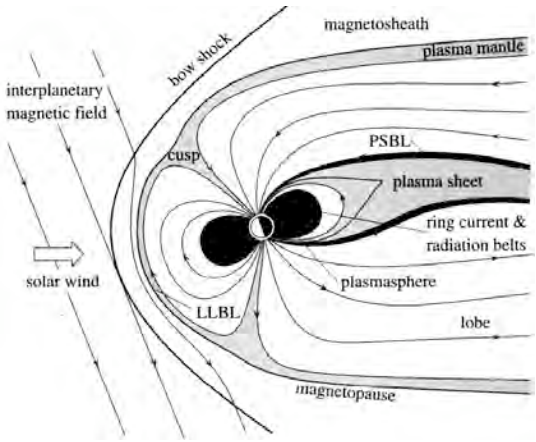
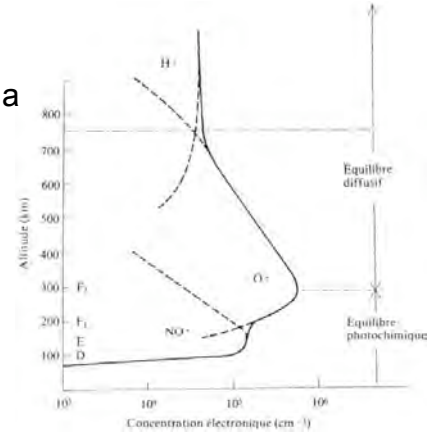
• Plasma Sources

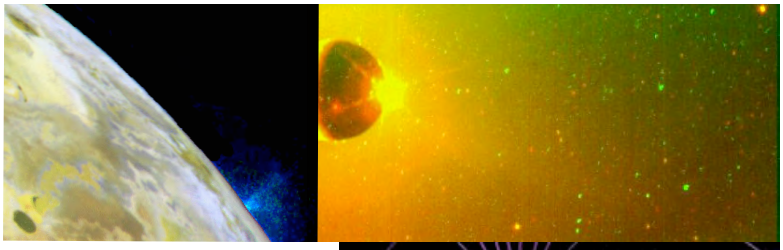


- <u>SW</u> : cusp + diffusion/reconnection across MP
  - H & He, T~100 eV
  - ~1% of SW flow
  - 10^{26} ions/s @ Earth
  - 10^{28} ions/s @ Jupiter

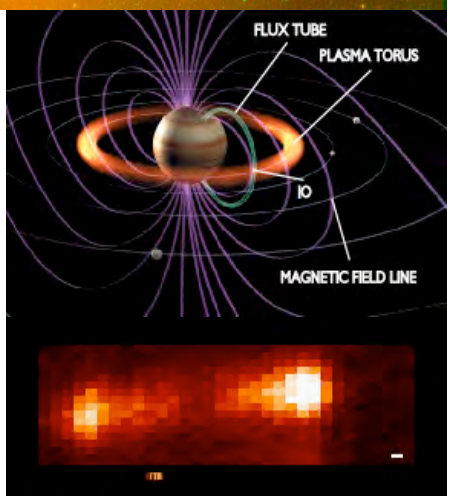


- <u>Ionosphere</u> : vertical diffusive equilibrium of cold plasma
  - T~0.1-1. eV
  - $N = N_o \exp(-(z-z_o)/2H)$
  - 10^{26} N & O ions/s @ Earth
  - 10^{28} H ions/s @ Jupiter

• **Plasma Sources** [cont'd]



- Satellites :



Io (volcanism)

$3x10^{28}$ S & O ions/s

⇒ plasma torus *[Bagenal, 1994]*

Titan (atmospheric escape)

10^{26} H & N ions/s

(+C ?) *[Sittler et al;, 2005]*

Enceladus (exosphere, plumes)

source & sink ?

[Dougherty et al., 2005 ; Jones et al., 2006]

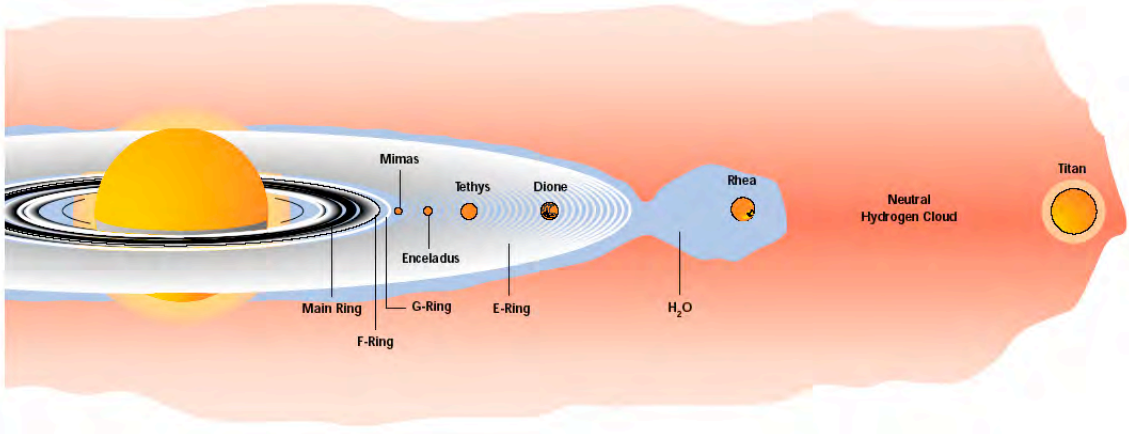
Icy satellites (or Mercury's) surface : sputtering

• **Plasma Sources** [cont'd]

- Rings (sputtering / photo-dissociation + ionisation)

water ions, O^+, O_2^+ *[Young et al., 2005 ; Bouhram et al., 2006]*

up to 10^{28} ions/s *[Richardson & Jurac, 2005 ; Hansen et al., 2005]*



- Plasma reservoirs : boundary layers, plasma/current sheet, radiation belts

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

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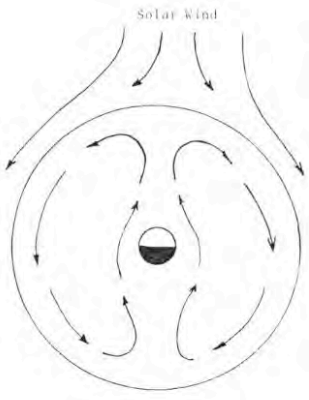
• **Plasma Circulation**



- <u>Closed MS</u>

  V_{SW} // MP

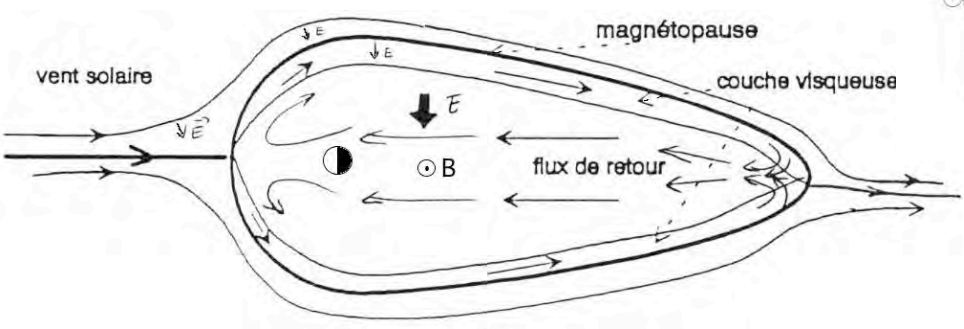
  equipotential flow lines

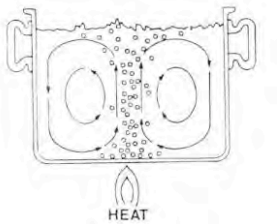
  no plasma penetration

  MS electrically insulated from outside SW

  Internal plasma entrained by friction (a few ρ_{Li})

  ⇒ 2 convection cells

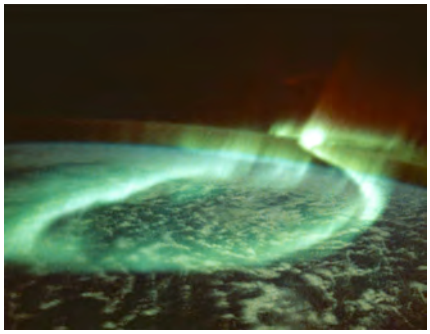


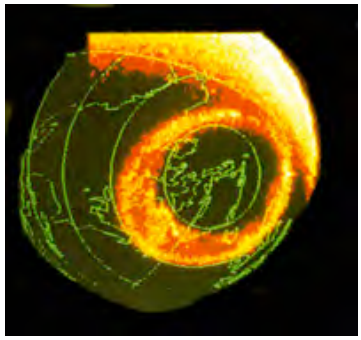


• **Plasma Circulation** [cont'd]

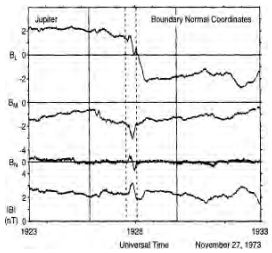
Ok / circulation observations at Earth <u>BUT</u>

- energetic plasma inside MS
- large scale E (dawn → dusk) inside MS
- quasi permanent circumpolar aurora (∅ = 10°-20°, UV + radio)
- SW control (B_z) of MS activity





• **Plasma Circulation** [cont'd]



- <u>Open MS</u>

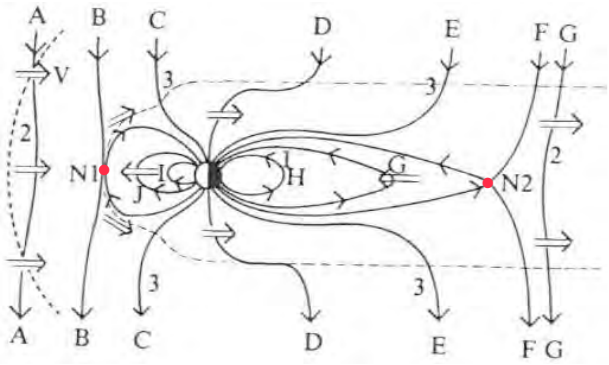
B reconnection at MP (stationary ? patchy ? → $B_N \neq 0$) when B_z // B_P

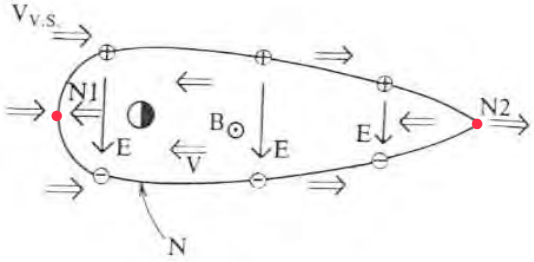
(MS closed or high-latitude reconnection when B_z anti// B_P)

Transport of B line to tail, reconnection, dipolarization (= Dungey cycle)

Neutral (X) line at equator

Penetration of plasma in MS ⇒ no more equipotential





[Dungey, 1961]

• **Plasma Circulation** [cont'd]

- Solar Convection in MS [antisolar above the poles]

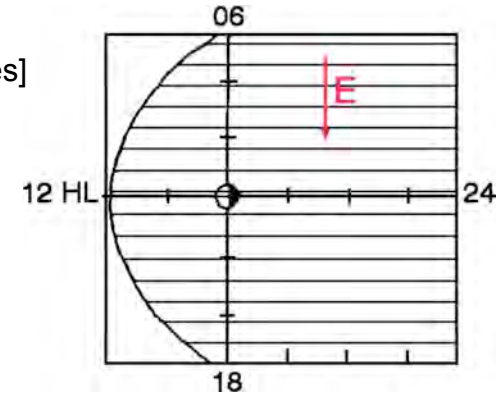
E = -VxB ~ ε V_{SW} x B_{SW} (dawn → dusk)

ε = 0.1-0.2

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

~ 50 kV @ Earth

~ 1 MV @ Jupiter



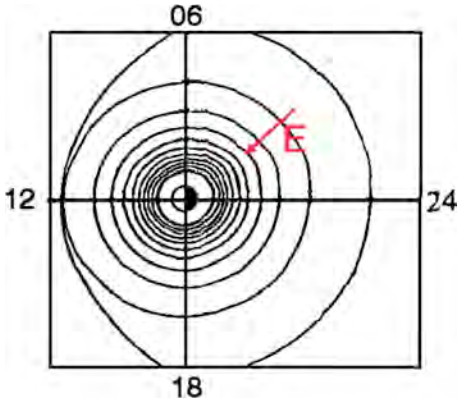
- Corotation

E = ΩR x B (radial)

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

~ 90 kV @ Earth

~ 400 MV @ Jupiter

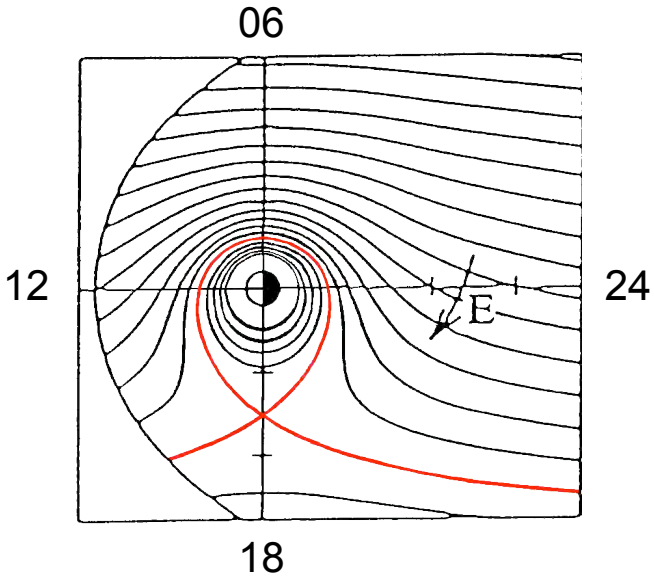


• **Plasma Circulation** [cont'd]

- Global circulation = Convection + Corotation

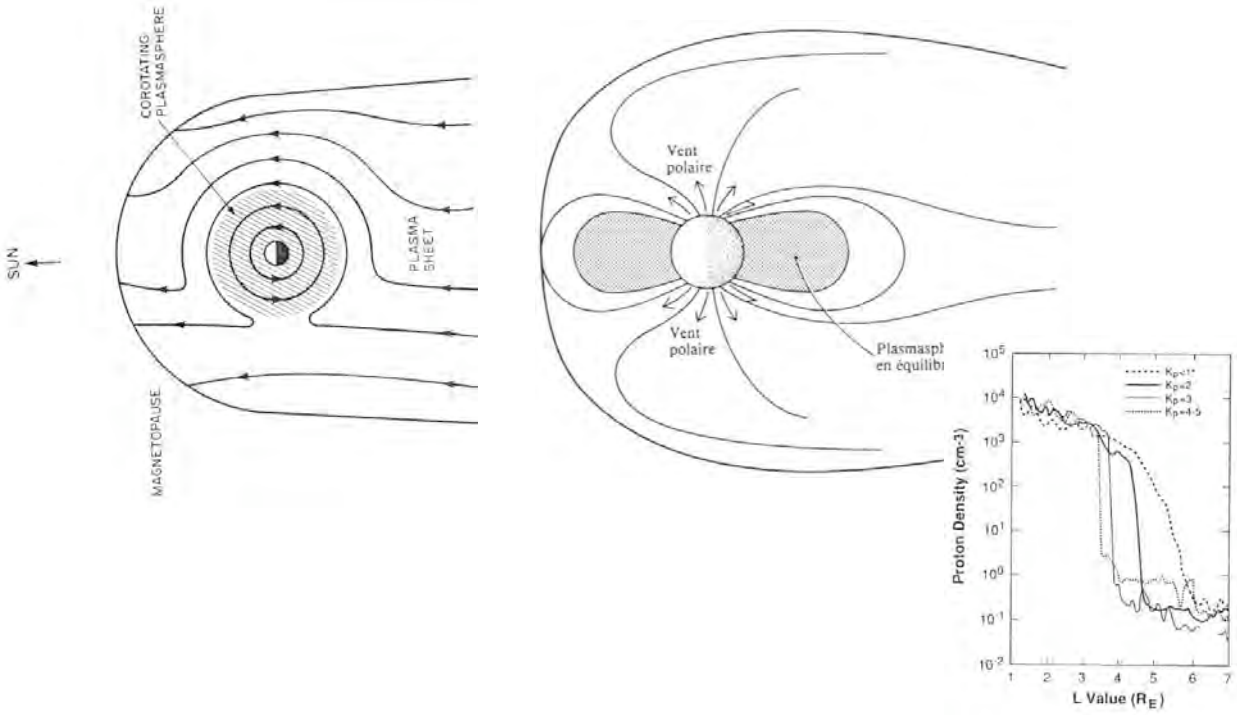
Equipotentials = flow lines

Stagnation point at LT = 18 h



• **Plasma Circulation** [cont'd]

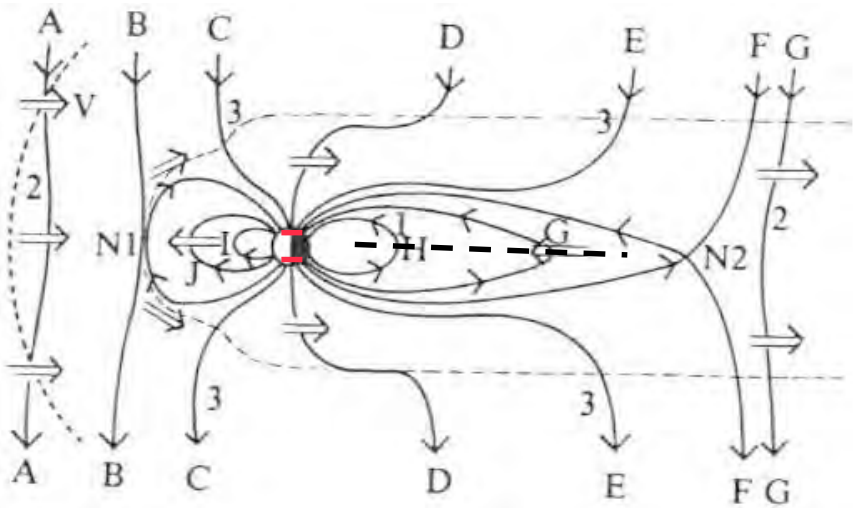
- Plasmasphere = permanently closed field lines, corotation dominated



• **Plasma Circulation** [cont'd]

- Auroral oval = limit open/closed field lines

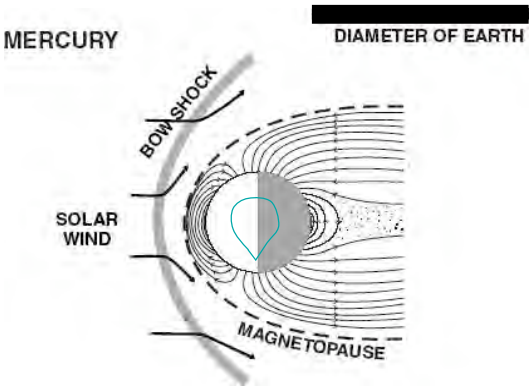
= projection of equatorial neutral line on ionosphere

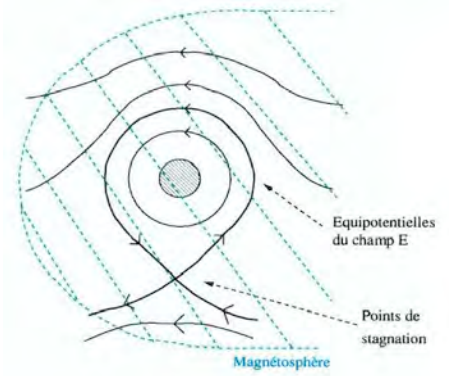


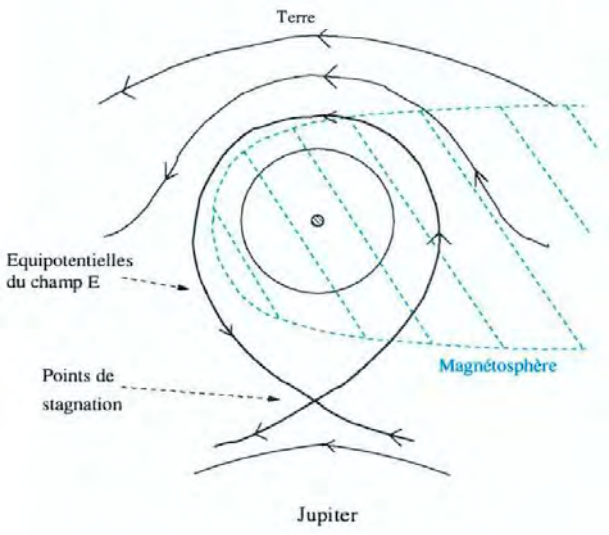
- Tail = MS antisolar extension, plasma convected to neutral plasma sheet - - -,

stores / releases energy and magnetic flux

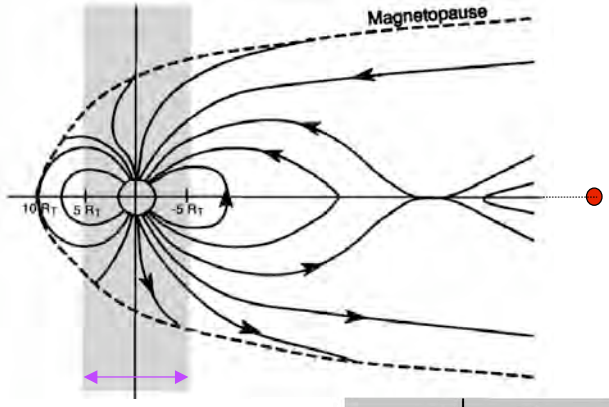
• **Plasma Circulation** [cont'd]





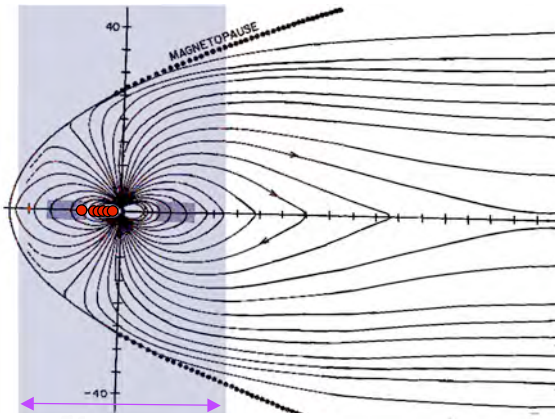


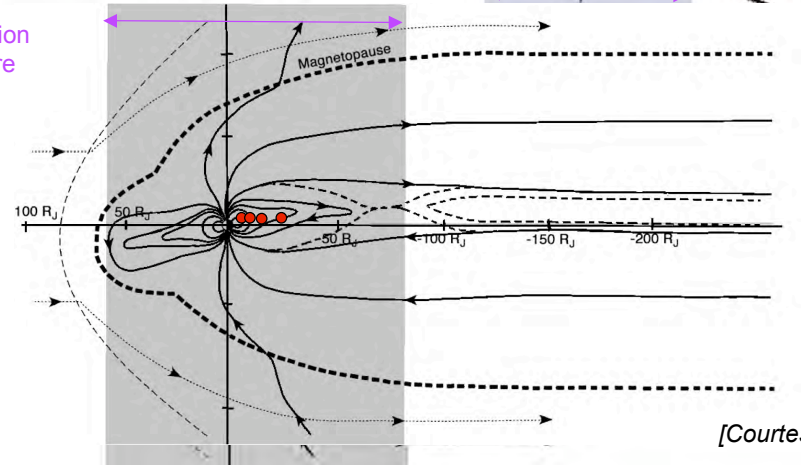
EARTH



corotation region
plasmasphere

SATURN





JUPITER

[Courtesy R. Prangé]

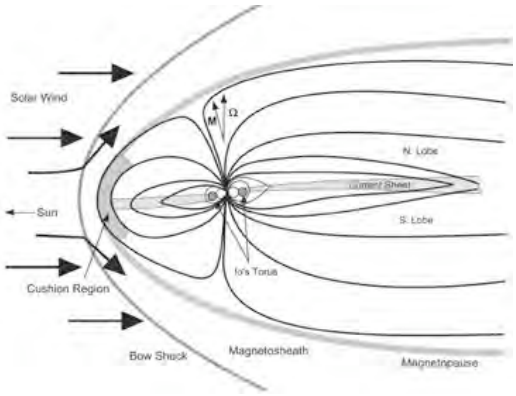
• **Plasma Circulation** [cont'd]

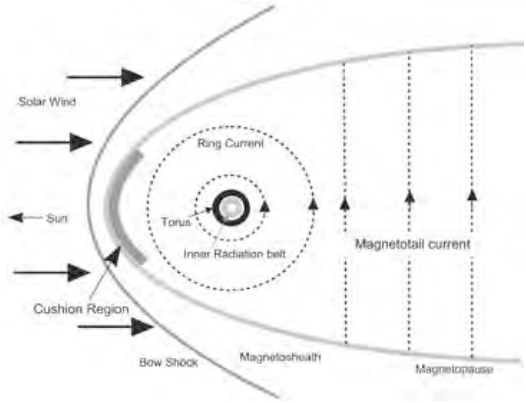
- Plasma sources vs Synchronous orbit (where $F_{centrifugal} = F_{gravitation}$)

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

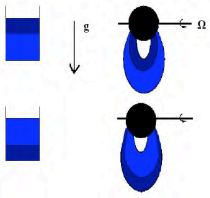
[Russell, 2004]

- At Jupiter : extended current disk





• **Plasma Circulation** [cont'd]

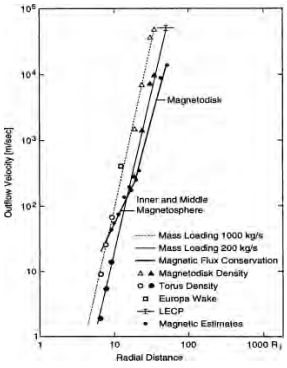


[André, 2006]

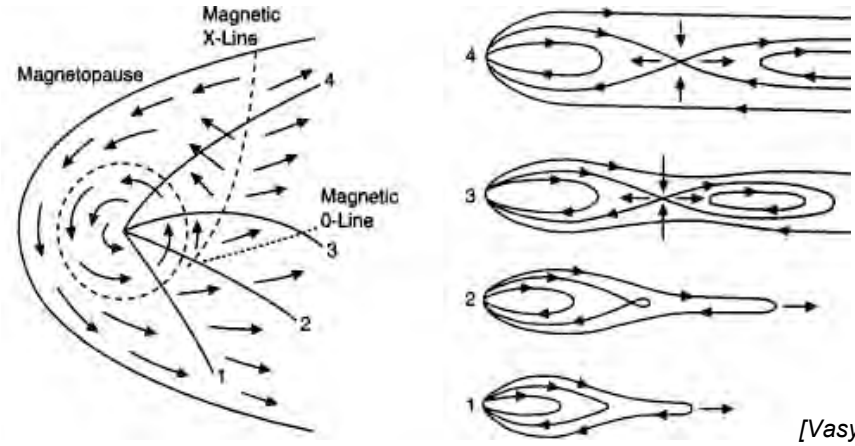
- Jupiter : outward radial transport (centrifugal interchange instability)

⇒ Vasyliunas cycle ~ rotation driven Dungey cycle

⇒ origin of auroral oval ?



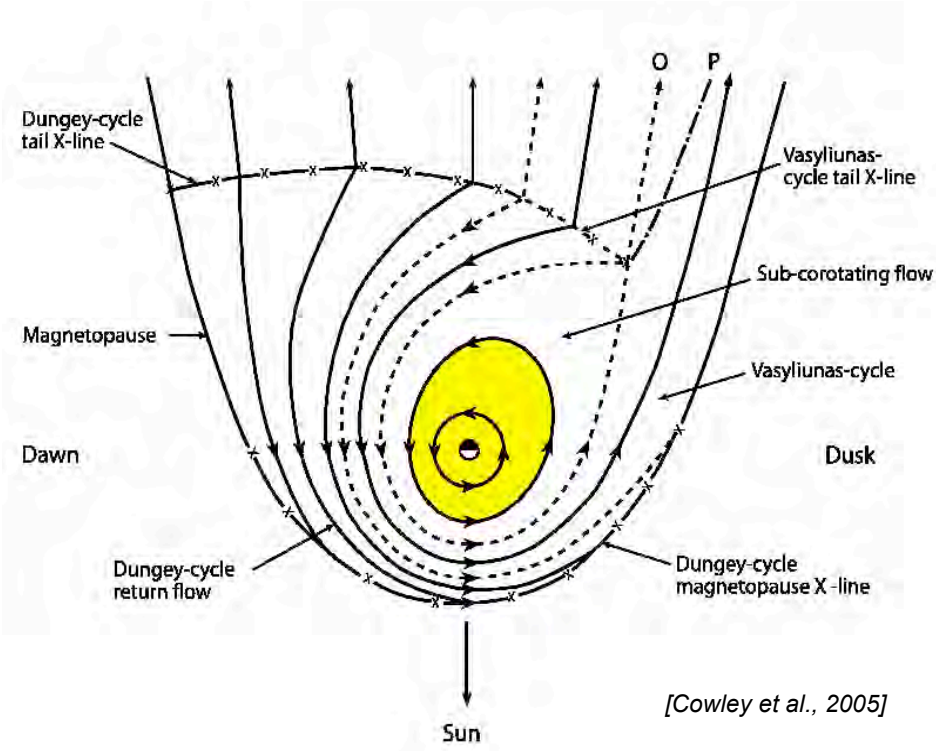
[Russell, 2001]



[Vasyliunas, 1983]

• **Plasma Circulation** [cont'd]

- Saturn : « intermediate » circulation ?

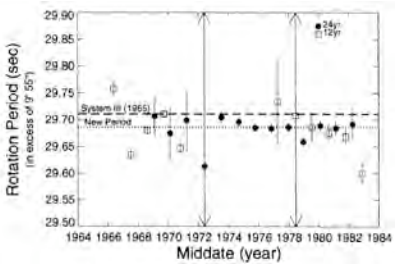


[Cowley et al., 2005]

• **Plasma Circulation** [cont'd]

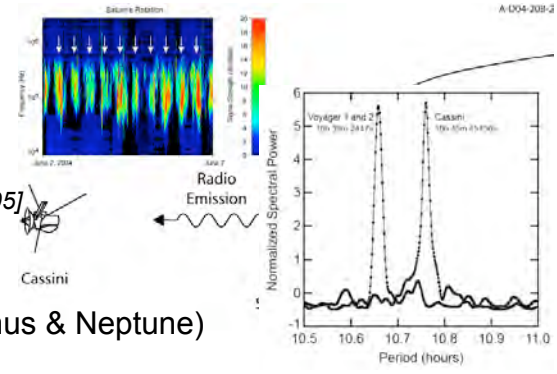
- Earth dominated by convection
  ⇒ little/no rotational signature in magnetospheric phenomena (e.g. AKR)

- Same (even more so) expected for Mercury



- Jupiter dominated by corotation
  ⇒ many magnetospheric phenomena
  (particle flux, radio emissions…)
  reveal a strong rotational signature
  ⇒ measurement of rotation period to 10^{-6} accuracy *[Higgins et al., 1997]*

- Saturn = intermediate situation :
  corotation and convection compete
  ⇒ corotational signatures, with fluctuations
  (e.g. variable radio period) *[Cecconi & Zarka, 2005]*



Independent of B tilt ! (at 1st order, except Uranus & Neptune)

- Solar Wind / Solar Wind - Obstacle interaction
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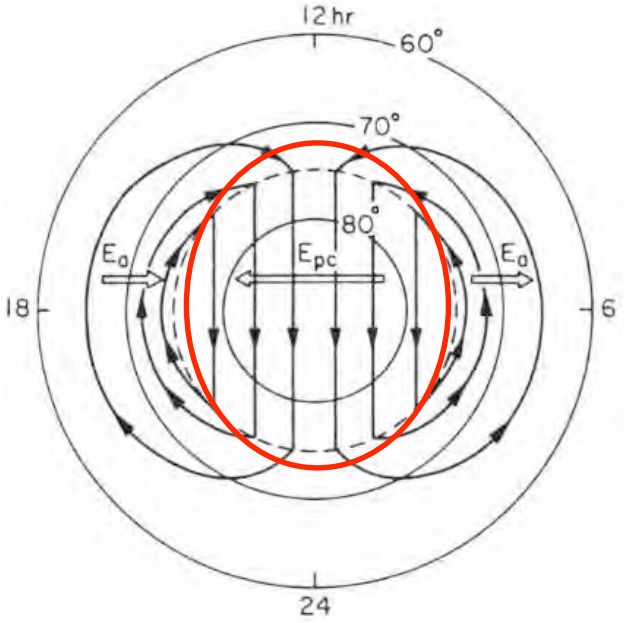
- Plasma Circulation
- Role of Ionosphere
- Current Generators
- Aurorae (and satellite induced emissions)
- Exoplanetary Magnetospheres ?

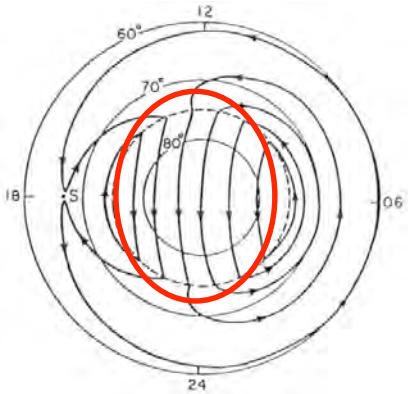
• Role of Ionosphere

- mapping of MS and SW $\Delta\phi$ (via equipotential B lines)

$\Rightarrow$ high-latitude convection cells : $E_i >> E_{MS}$, $V_i << V_{MS}$



+ corotation



- currents closure (in sputtered/vaporized regolith @ Mercury ? *[Slavin, 2004]*)

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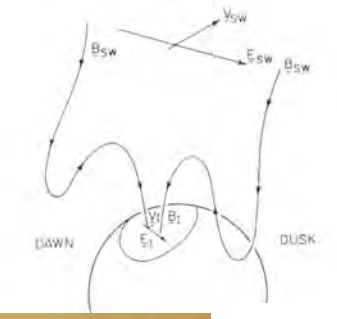
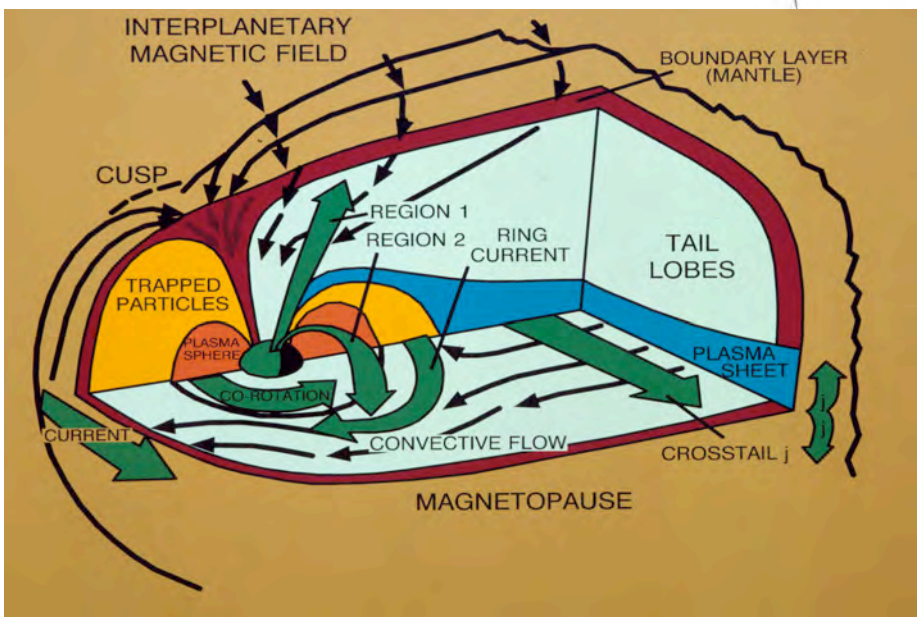
• **Current Generators**

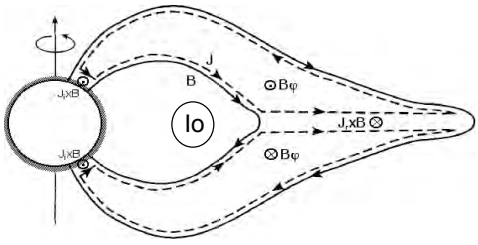
$\nabla . J = 0$



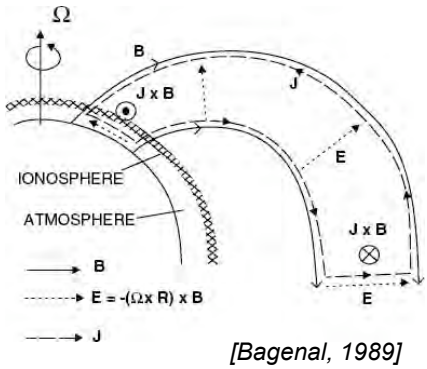
- <u>SW / MS interaction</u> : « region 1 » currents @ Earth
driven by $\Delta\phi$ (dawn → dusk) ∝ V_{SW} x B_{SW}



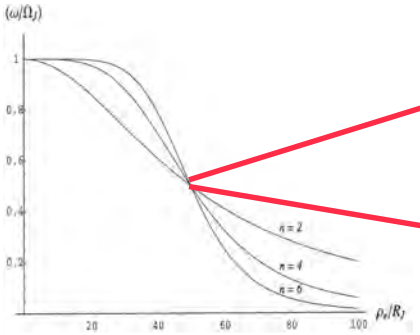
• **Current Generators** [cont'd]

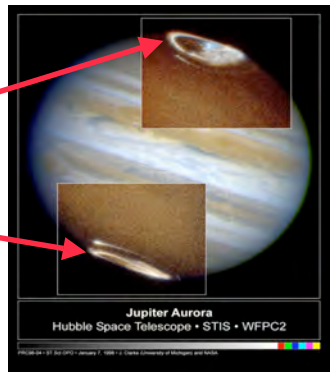


- radial diffusion from Io ⇒ J_r
- plasma acceleration (corotation) by J_r x B_{MS}
  (+ slowing down MS plasma due to mass loading)
  at expense or ionospheric plasma momentum via J_i x B_i
  $\nabla.J = 0 \Rightarrow J_i = J_r B_i/B_{MS} \sim 2R^3 J_r \leq \sigma_i E_i \sim \sigma_i \Omega B_e/R^{1/2}$
  $\Rightarrow$ Ok as long as $J_r \leq \sigma_i \Omega B_e/2R^{7/2}$
- <u>Corotation breakdown</u> at 20-50 R_J
  $\Rightarrow J_{//}$ max $\Rightarrow$ main auroral oval at Jupiter



[Bagenal, 1989]

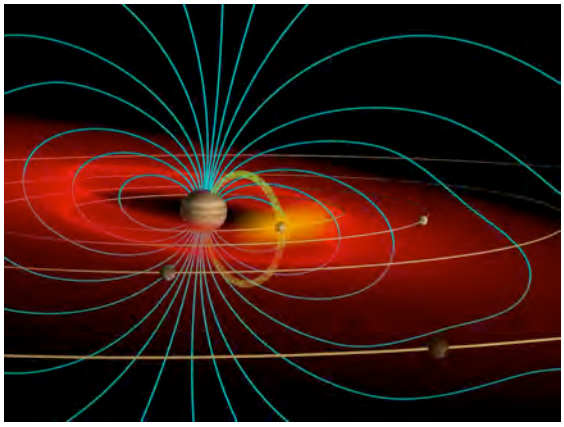


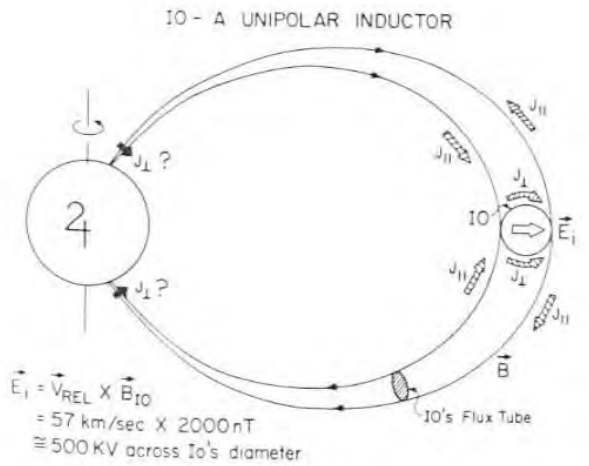


[Cowley & Bunce, 2001]

• **Current Generators** [cont'd]

- <u>Unmagnetized satellite / MS interaction</u> *[Saur et al., 2004]* :
  $E = -V \times B_J$ with $V=V_{corot}-V_K$ (=57 km/s @ Io)
  $\Delta\phi \sim 2 R_{sat} E$ (=4x10^5 V @ Io)
  Flow dominated by magnetic energy $B_J^2/2\mu_o$
  $M_A < 1$ (no bow shock)
  [1 case of TransAlfvénic shock @ Europa with Galileo ? *Kivelson, 2005*]





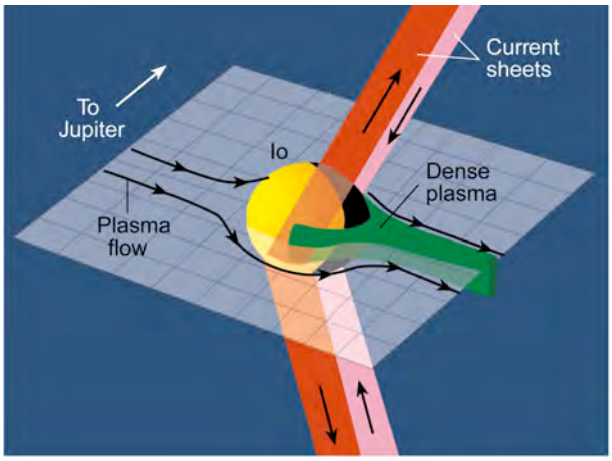
[Piddington & Drake, 1968; Goldreich & Lynden-Bell, 1969]

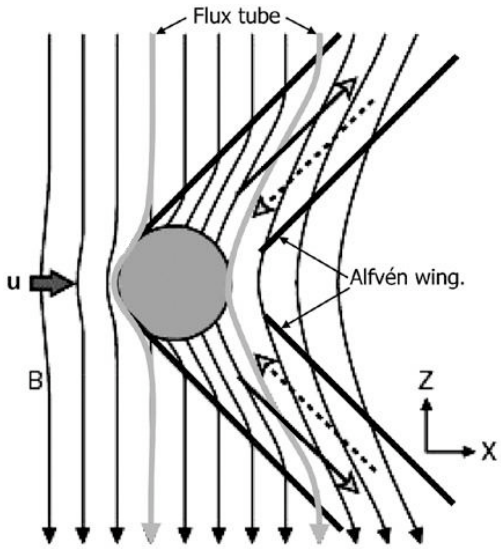
• **Current Generators** [cont'd]

- Current induced by E (a few 10^6 A) closes

  in Jupiter's ionosphere (if $M_A<<1$, no $j_\perp$ in MS, $2\int_{B\text{-line}} ds/V_A << \int_{flow} ds/V$ (= unipolar inductor)

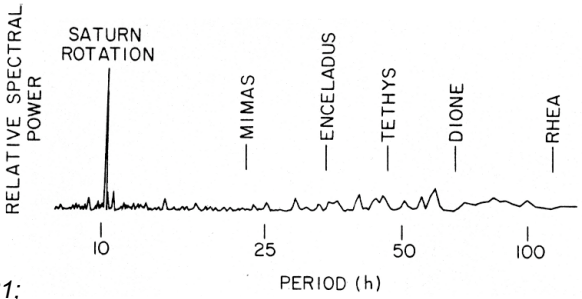
  in Jupiter's magnetosphere (if $M_A<1$, $j_\perp$ in MS, $2\int_{B\text{-line}} ds/V_A \geq \int_{flow} ds/V$ (= Alfvén wings)





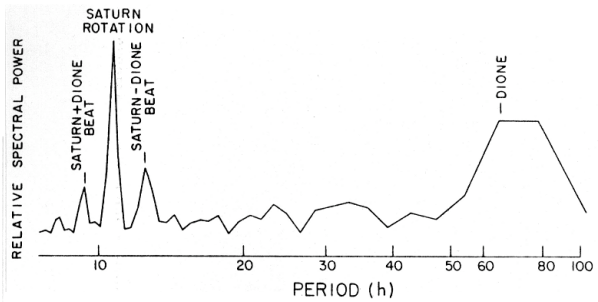
[Kivelson et al., 2004]

• **Current Generators** [cont'd]



SKR @ 174 kHz, 28 Oct. - 18 Dec. 1980

[Desch & Kaiser, 1981; Kurth et al., 1981]

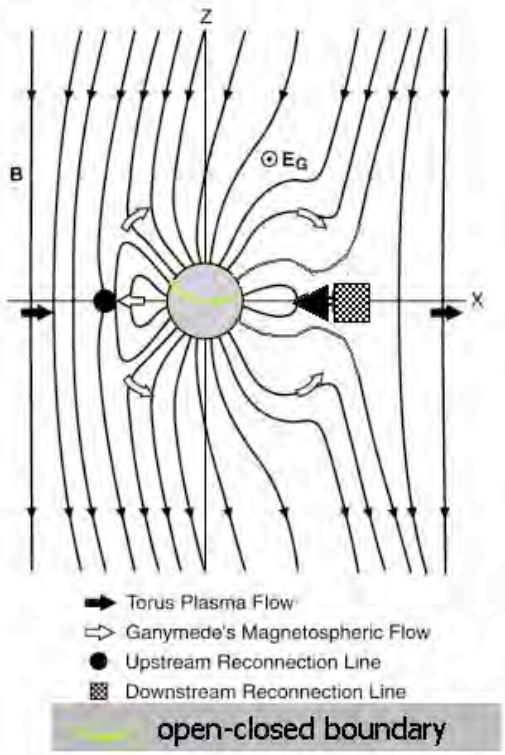


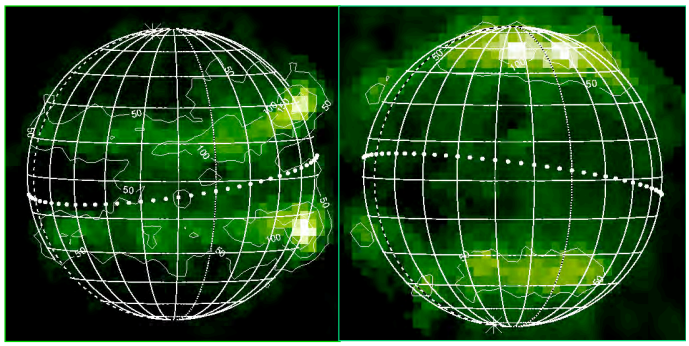
SKR @ 59 kHz, 10-18 Nov. 1980

- Dione interaction with Saturn MS ?
- Enceladus ? (exosphere, B draping *[Dougherty et al., 2005]*)
- Titan ? (alternatively super/sub-Alfvénic interaction *[Ledvina et al., 2004]*)

• **Current Generators** [cont'd]

- Magnetized satellite / MS interaction *[Kivelson et al., 2004]* : B reconnection





Downstream / Upstream
[McGrath et al., 2002 ; Feldman et al., 2000]

- In all cases :

$P_{dissipated} \sim B_J^2/2\mu_o \; V \; k\pi R_{obstacle}^2$

[Zarka et al., 2001, 2006]

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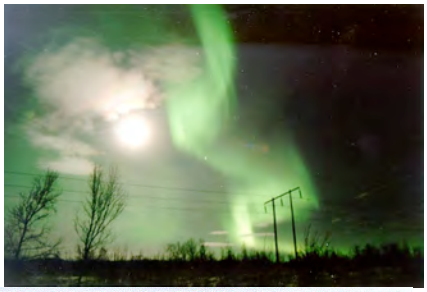
• **Aurorae (and satellite-induced emissions)**



- Source = 1-10 keV electrons ⇒ acceleration required

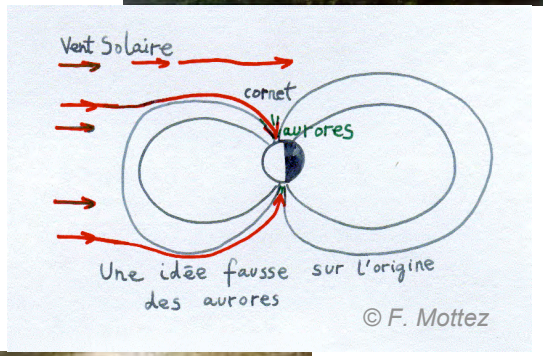
  Strong currents + low plasma density *[Knight, 1972]*

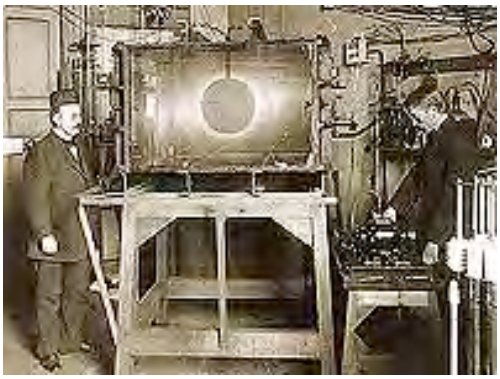
  Reconnection + dipolarization (adiabatic)

  Compressions, $E_{//}$, waves …

  ⇒ UV, IR, radio emissions

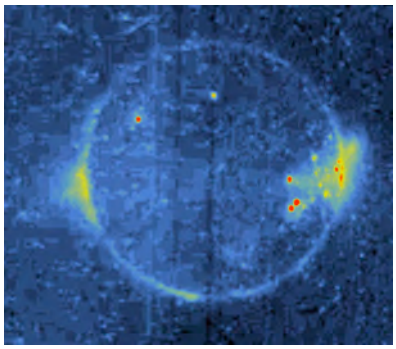
  ≠ direct precipitation of SW in polar cusps

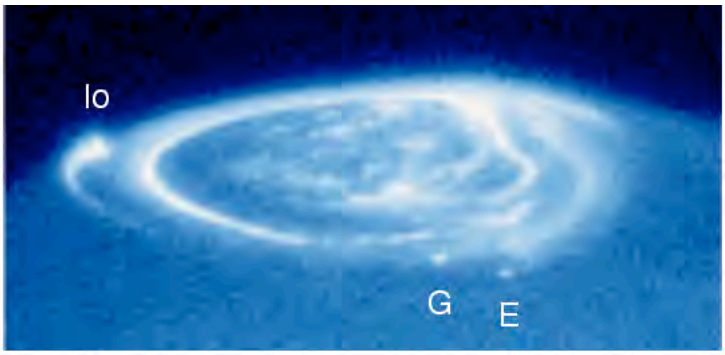


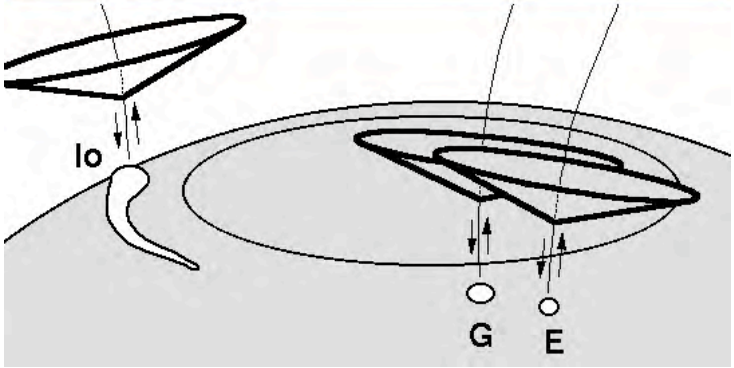


[Birkeland, 1910]

• **Aurorae (and satellite-induced emissions)** [cont'd]







[Clarke, Prangé…]

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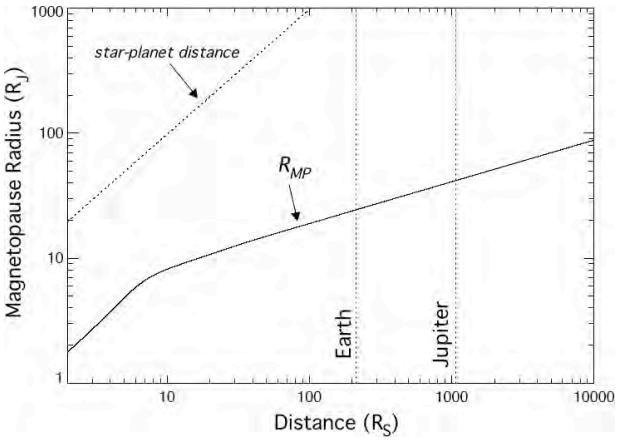
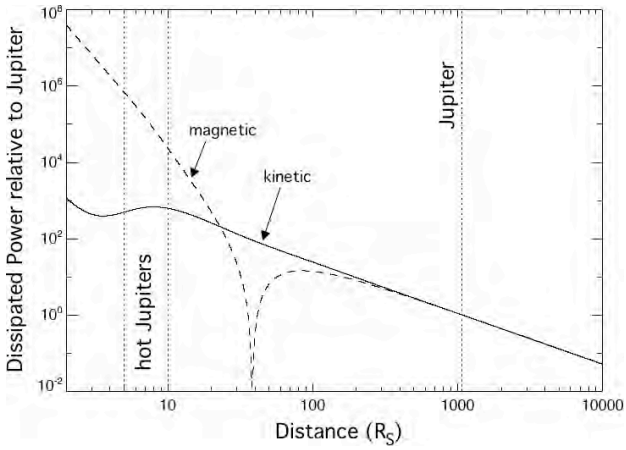
• **Explanetary Magnetospheres ?**

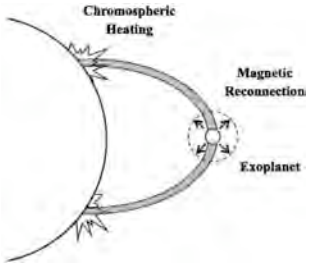
- high SW pressure ⇒ compressed MS
- high SW power input ⇒ very energetic MS ⇒ intense e.m. emissions ?





[Zarka et al., 2001, 2006]

• **Explanetary Magnetospheres ?** [cont'd]

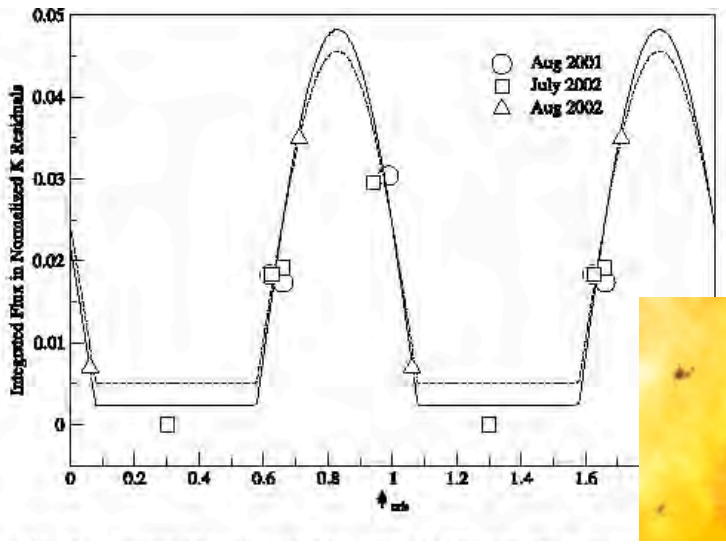


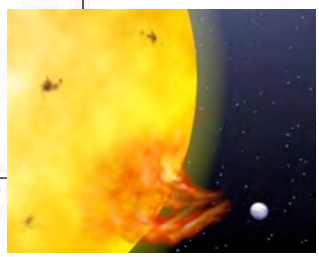
- reconnection with stellar B

  (~ magnetic binaries, Ganymede-Jupiter) *[Ip et al., 2004]*

  or giant Io-Jupiter like interaction (M_A<1 for hot Jupiters) *[Zarka, 2006]*

  ⇒ cf. observations by *[Shkolnik et al., 2003, 2005]*





Conclusions

- Variety of magnetospheric structures
  (function of SW strength, mass-loading…)
- Comparative approach of magnetospheres essential
- Saturn especially interesting because « intermediate »
- Prospects for exoplanets
- How can one do so much with so little mass ?
- Come on, it's not soooooo complicated after all !