

Planetary Magnetospheres

Philippe Zarka

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

- 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

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

⇒ quasi-neutrality

& $E \cdot B = 0$ ($\Delta\phi$ conserved along B lines,
= electric equipotentials)

- **Acronyms**

SW = solar wind

MS = magnetosphere

MP = magnetopause

B = magnetic field

- 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 ?

• Solar Wind

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

$$V \sim 400/r^{2/7} \text{ km/s} \quad T \sim 2 \times 10^5 / r^{2/7} \text{ K}$$

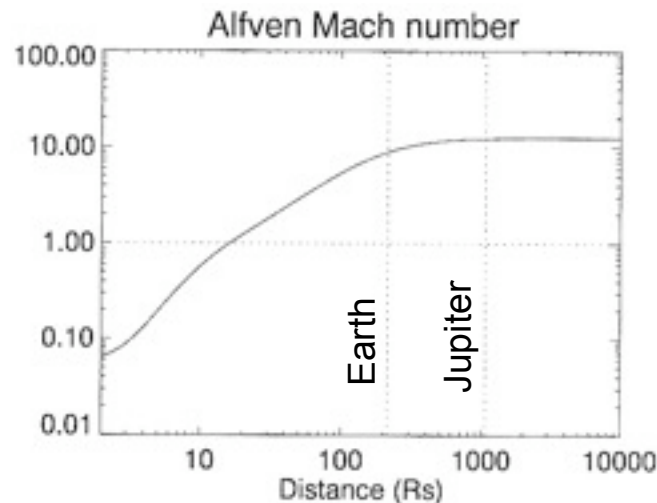
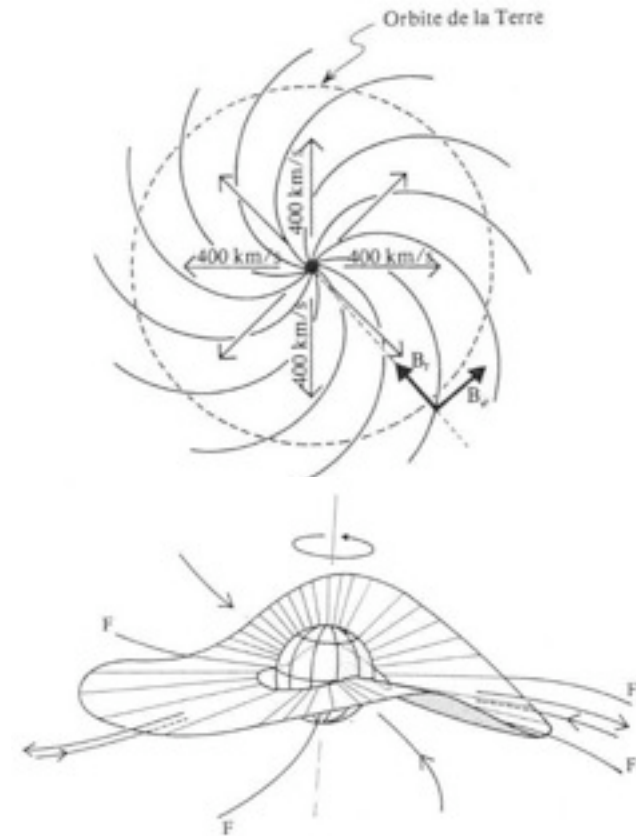
$$N = 5/r^2 \text{ cm}^{-3}$$

$$B_r = 3/r^2 \text{ nT}$$

$$B_\phi = B_r \Omega r / V = 3/r \text{ nT}$$

$$V_S \sim 60/r^{1/7} \text{ km/s}$$

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

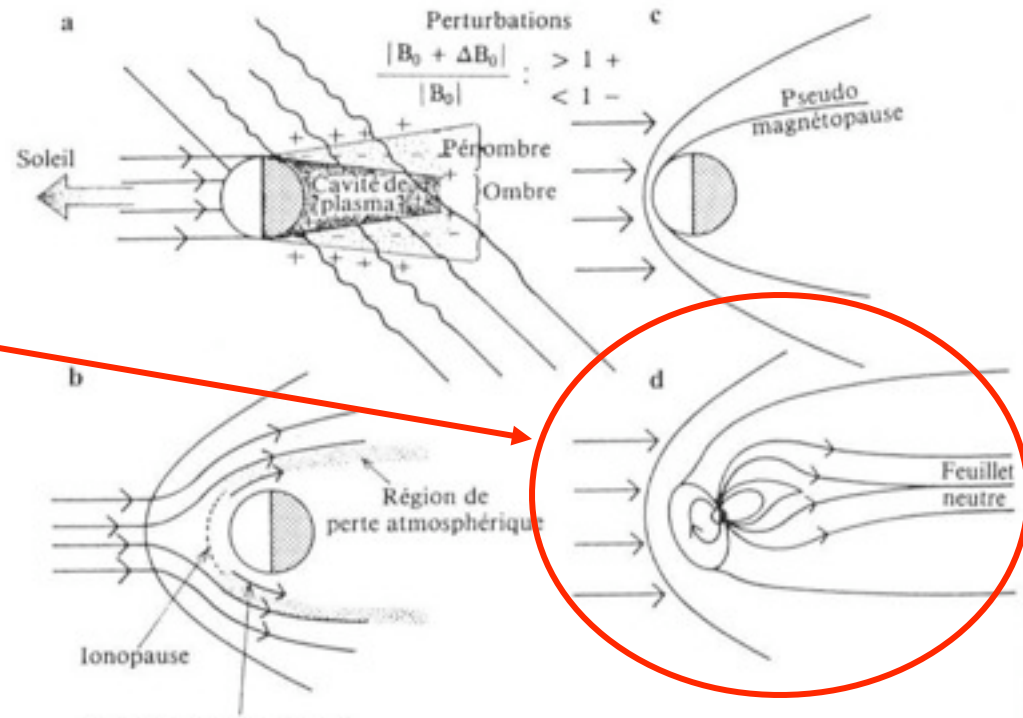


- CIR, CME, more shocks away from the Sun (SW radial evolution)

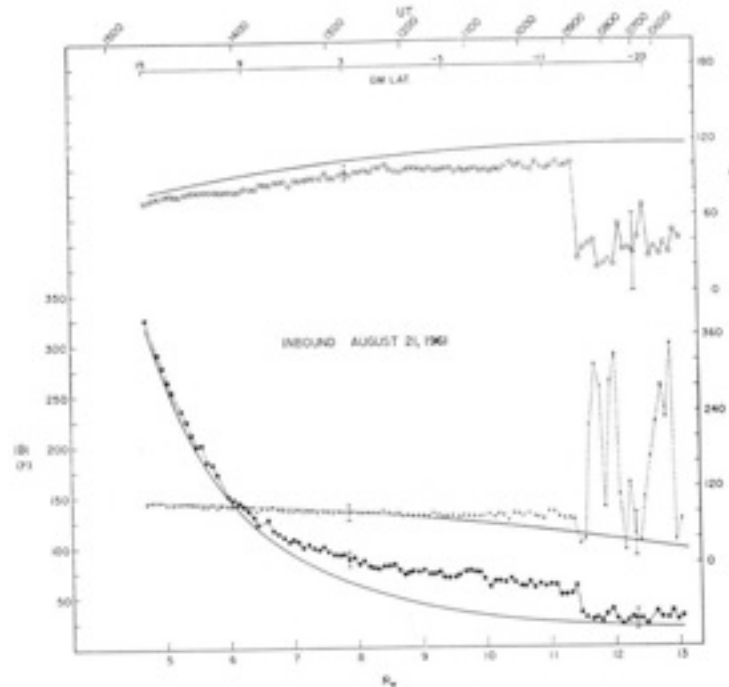
• Solar Wind - Obstacle interaction

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

- 1st case $\Rightarrow$ abrupt boundary
in planetary B = MP



[Lepping, 1986]



[Cahill & Patel, 1967]

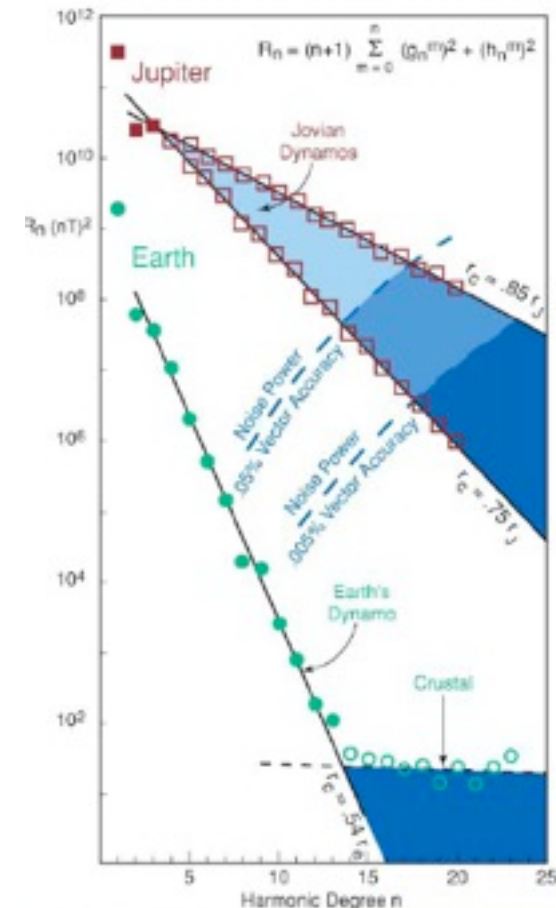
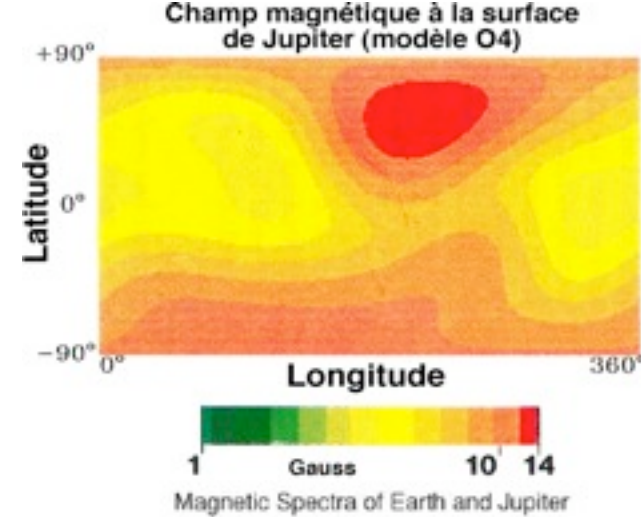
- Solar Wind / Solar Wind - Obstacle interaction
- Planetary Magnetic Fields
- Magnetospheric Boundaries
- Plasma Sources
- Plasma Circulation
- Role of Ionosphere
- Current Generators
- Aurorae (and satellite induced emissions)
- Exoplanetary Magnetospheres ?

• Planetary Magnetic Fields

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

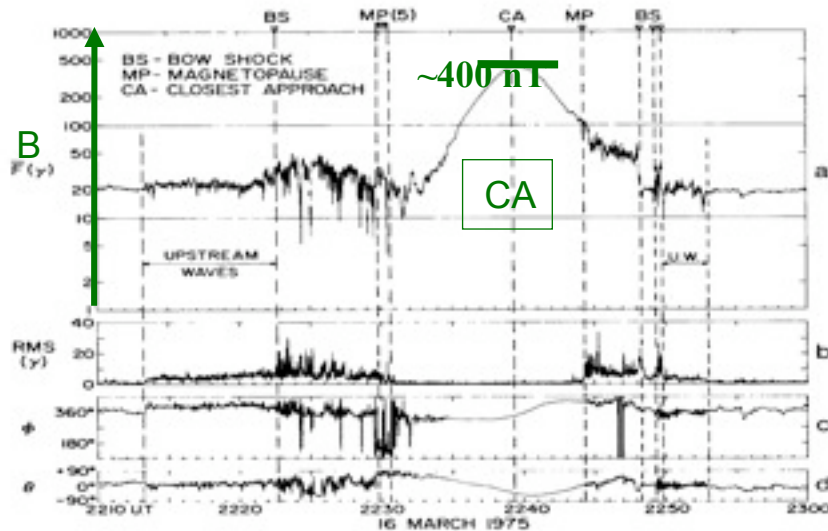
Planète	Terre	Jupiter	Jupiter	Saturne	Uranus	Neptune
R_p (km)	6378	71372	71372	60330	25600	24765
Modèle	IGRF 2000	O6	VIT4	Z3	Q3	O8
g_1^0	-0.29615	+4.24202	+4.28077	+0.21535	+0.11893	+0.09732
g_1^1	-0.01728	-0.65929	-0.75306	0	+0.11579	+0.03220
h_1^1	+0.05186	+0.24116	+0.24616	0	-0.15685	-0.09889
g_2^0	-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^1 dipolaire ($G \cdot R_p^3$)	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]



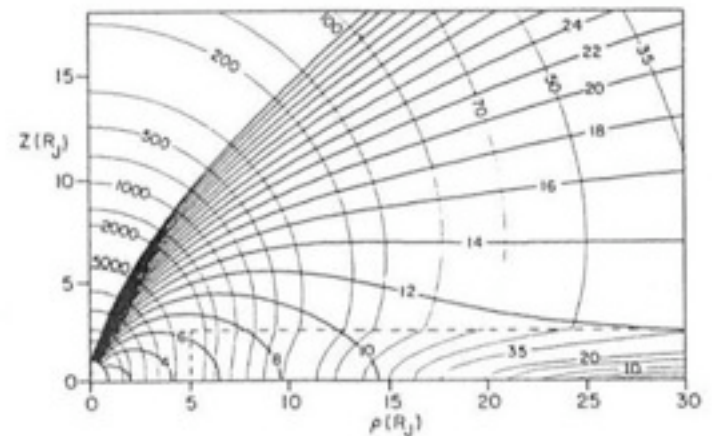
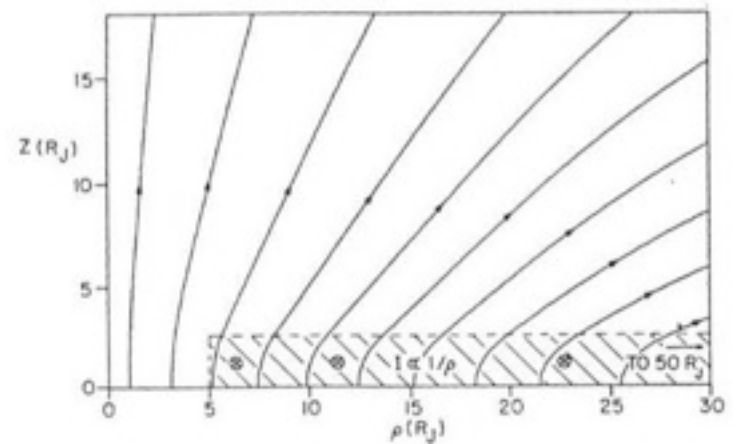
• Planetary Magnetic Fields [cont'd]

- weak dipolar field @ Mercury, $\sim 10^\circ$ tilt



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

- ring current (magnetodisc) @ Jupiter & Saturn



[Acuña et al., 1983]

- 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 ?

• Magnetospheric Boundaries

- Pressure equilibrium : $P_{SW} = KNmV^2\cos^2\chi = P_{MS} = B_T^2/2\mu_0$

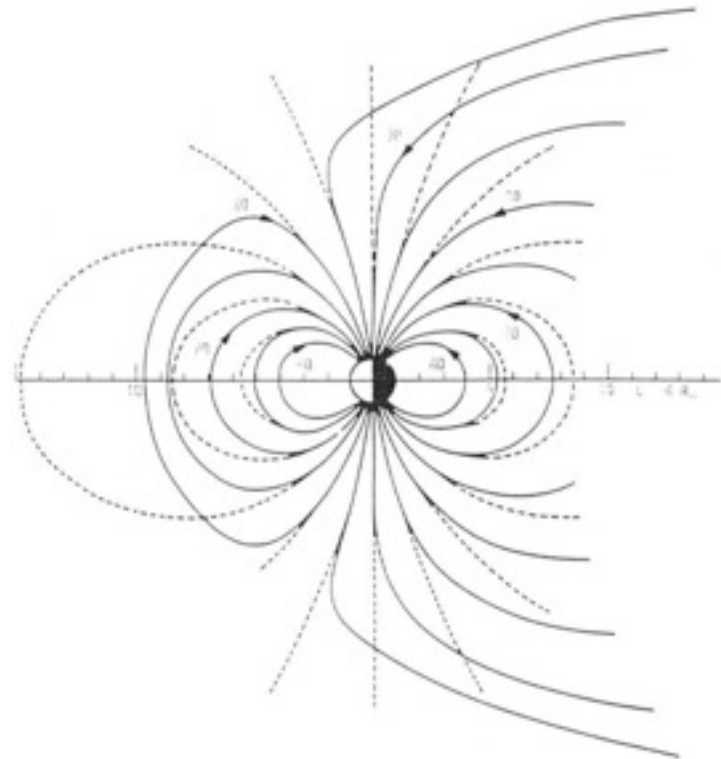
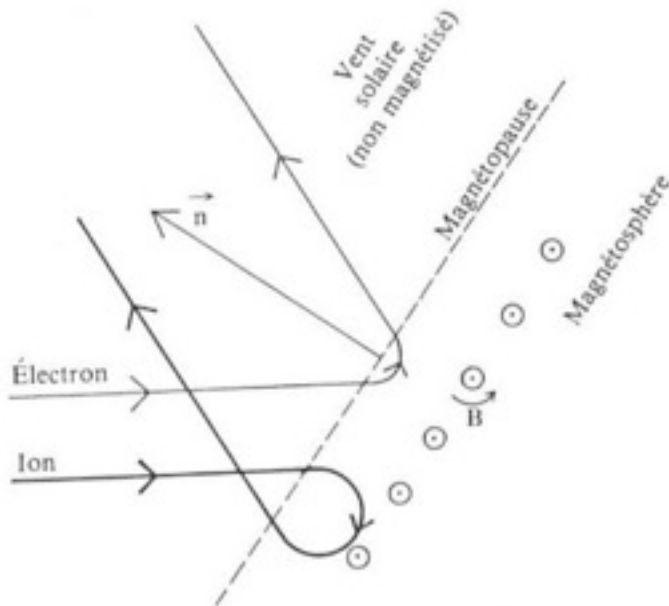
with $B_T = B_P + B_C = 2 B_P$ at MP nose

$K = 1-2$

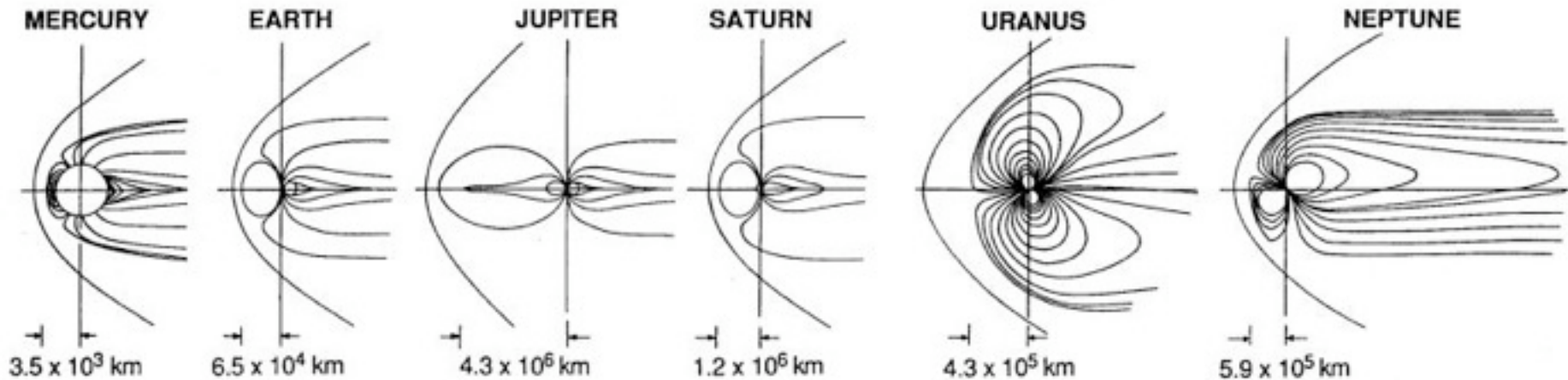
$\Rightarrow$ MP shape

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

$R_{MP} = (2 B_{eq}^2/\mu_0 KNmV^2)^{1/6}$



• 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

size of Sun
(to scale with
magnetospheres)

- magnetic field lines
- axis of rotation
- orientation of magnetic field
- solar wind

Jupiter

Saturn

Jovian Magnetopause Subsolar Standoff

Voyager 1 & 2

$|Z_{JSM}| < 20 R_J$

Slope = -0.22

$\log_{10}(R_N) [R_J]$

$\log_{10}(P_{sw}) [\text{inPa}]$

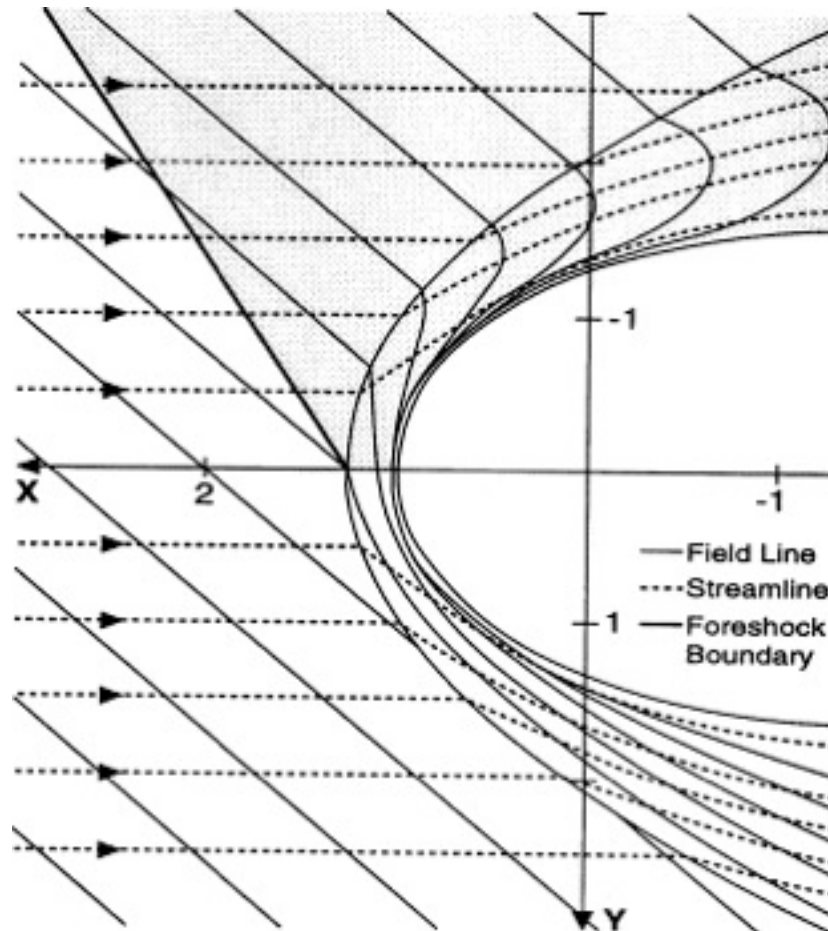
[Huddleston et al., 1998]

Uranus

Neptune

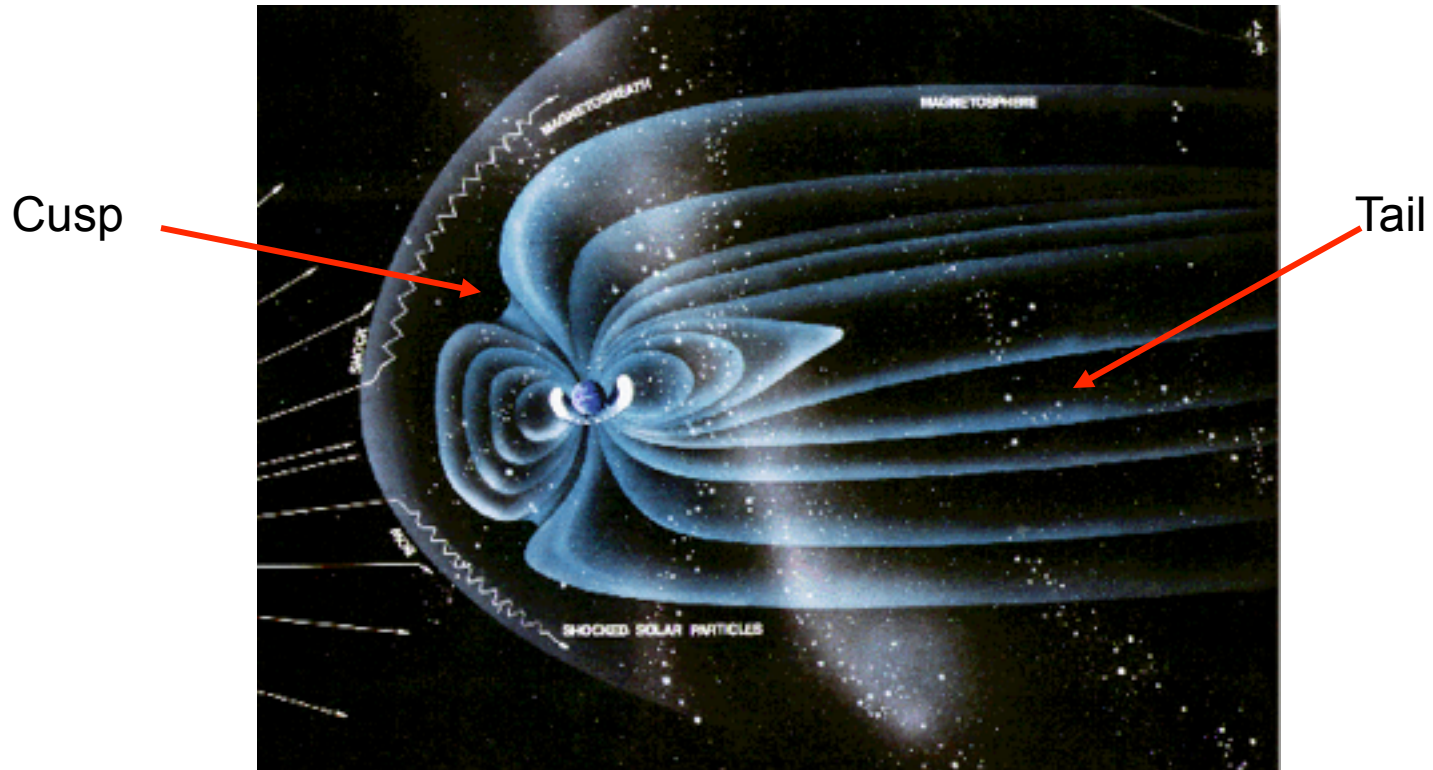
• Magnetospheric Boundaries [cont'd]

- supersonic / super-Alfvénic flow $\Rightarrow$ bow shock ahead of MP
- in magnetosheath : slowed flow ($V:4$ for $M_A \gg 1$)
 $\Rightarrow$ B draping / pile-up ($|\mathbf{V}| \cdot |\mathbf{B}| = c^2$)

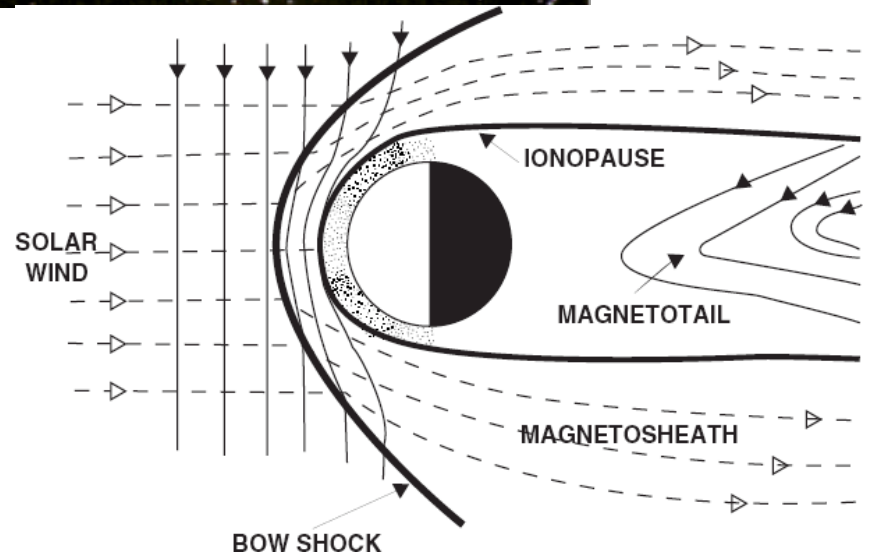


[Spreiter et al., 1966]

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



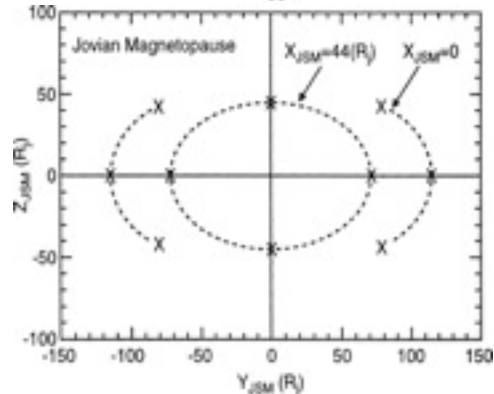
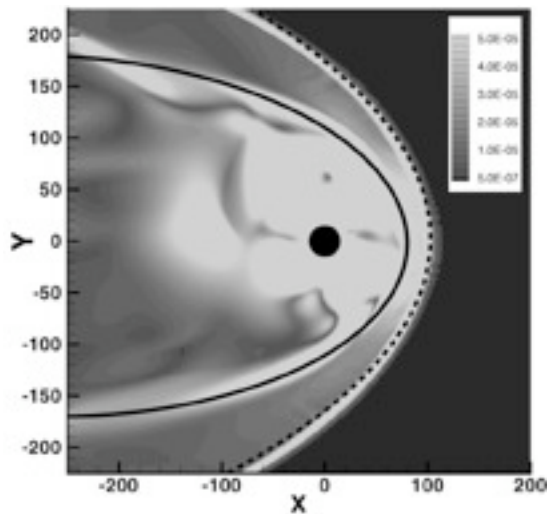
- if no intrinsic B field
⇒ induced MS, bow shock,
B draping, tail
No cusp



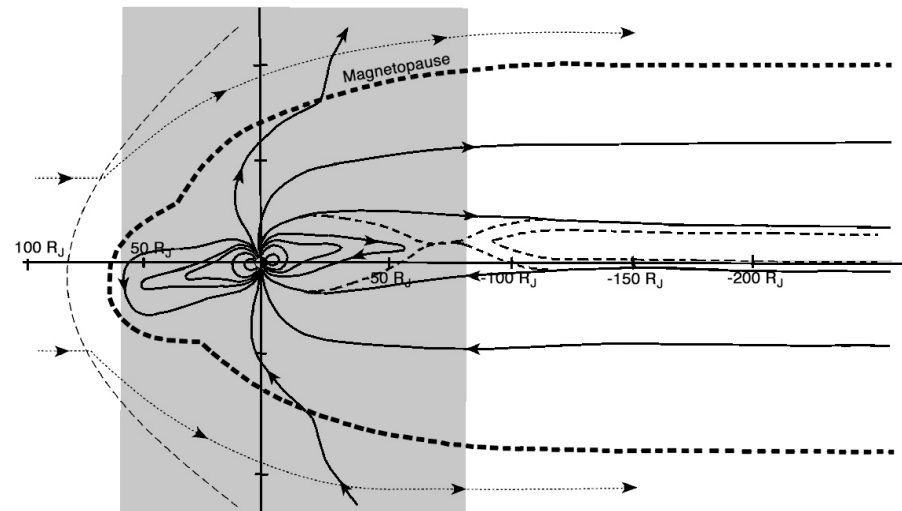
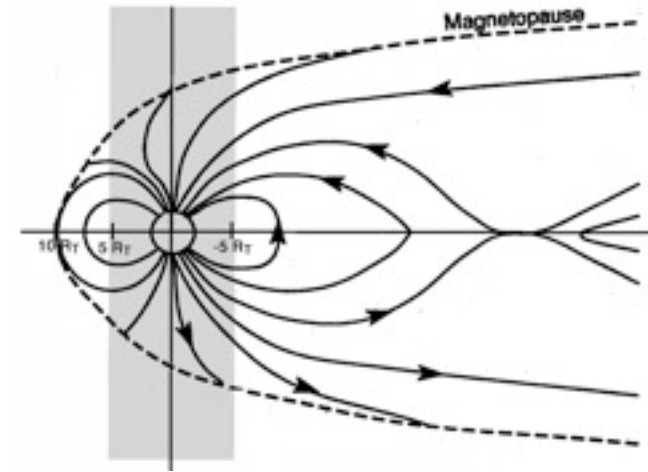
• Magnetospheric Boundaries [cont'd]

- Earth bow shock : $R = 25 R_E / (1 + 0.8 \cos \theta)$ thickness $\sim 40\%$ of MP
- Jupiter : MP closer to BS (thickness $\sim 15\%$)

$\Rightarrow$ equatorial flattening due mass loading (Io)



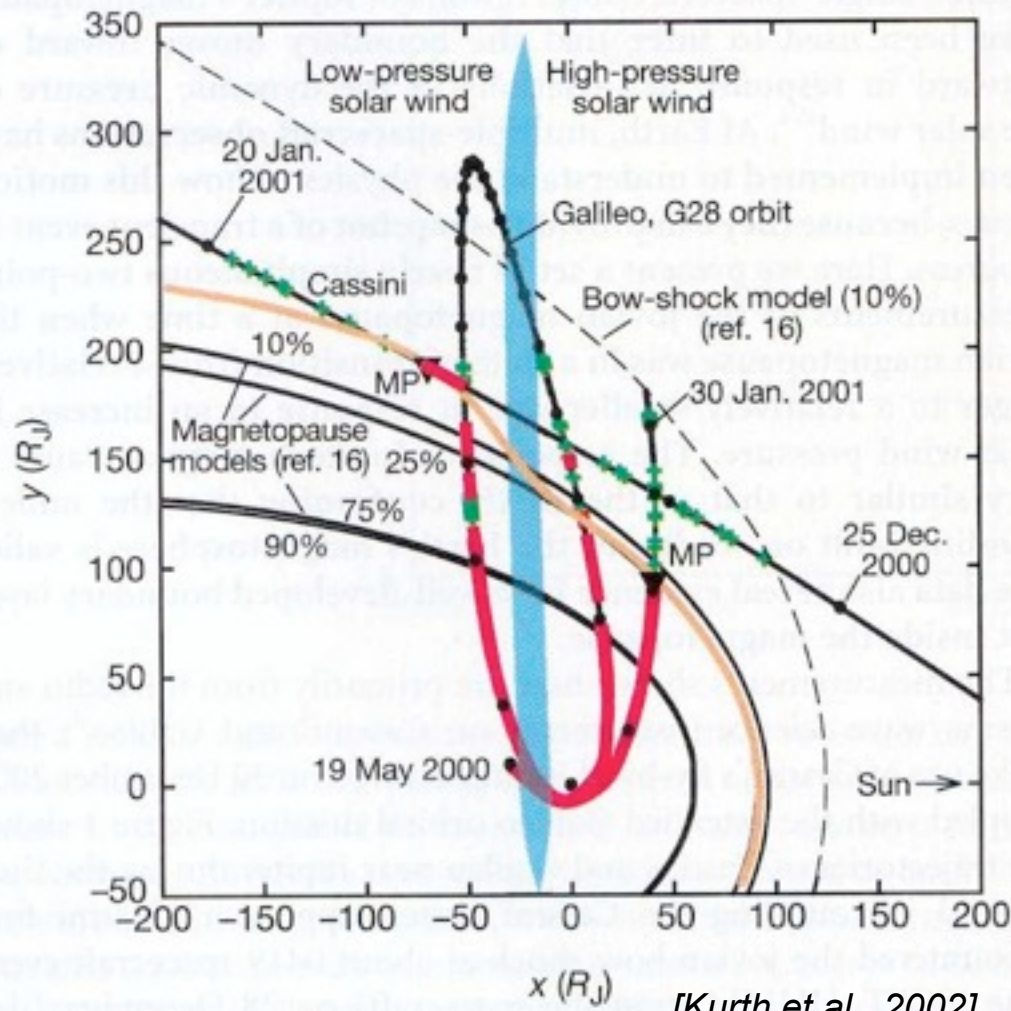
[Joy et al., 2002; Russell, 2004]



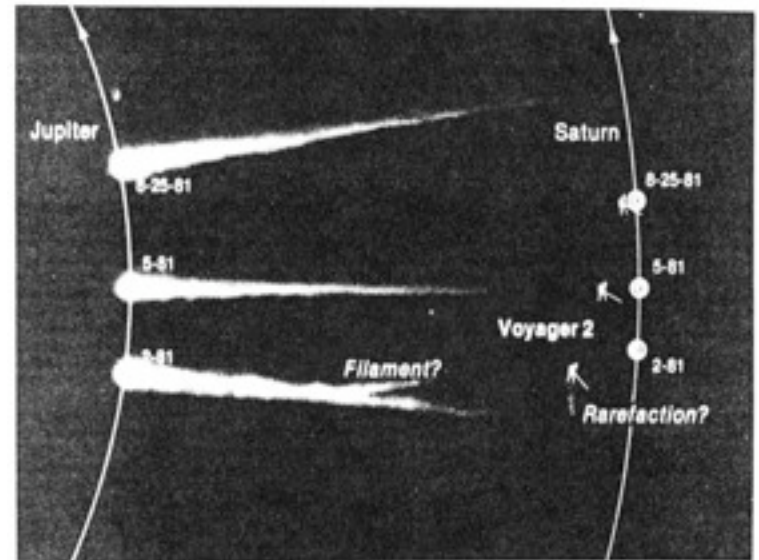
[Courtesy R. Prangé]

• 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]

- 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 ?

• Plasma Sources

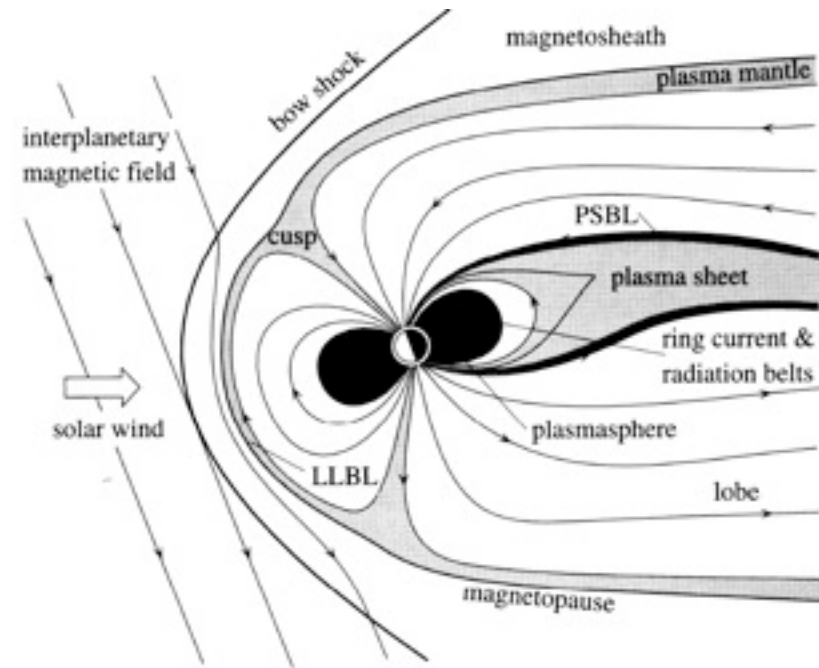
- SW : cusp + diffusion/reconnection across MP

H & He, $T \sim 100$ eV

$\sim 1\%$ of SW flow

10^{26} ions/s @ Earth

10^{28} ions/s @ Jupiter



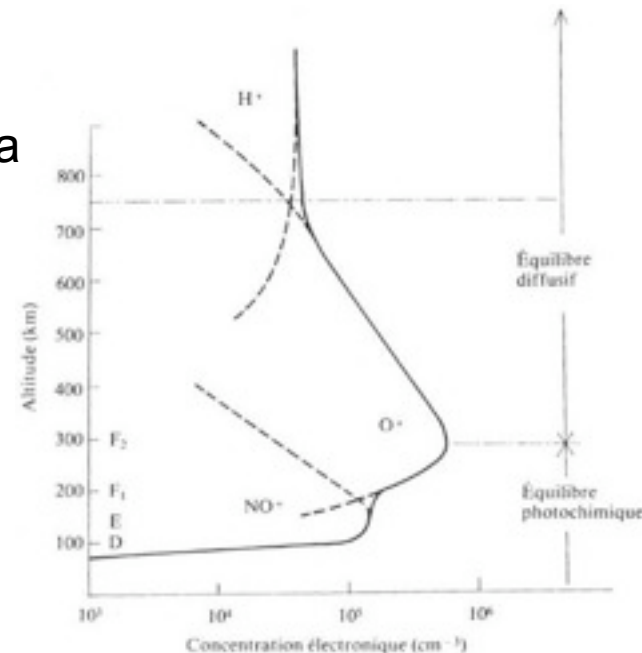
- Ionosphere : vertical diffusive equilibrium of cold plasma

$T \sim 0.1 - 1$ eV

$N = N_0 \exp(-(z-z_0)/2H)$

10^{26} N & O ions/s @ Earth

10^{28} H ions/s @ Jupiter



- **Plasma Sources** [cont'd]

- Satellites :

- Io (volcanism)

- 3×10^{28} S & O ions/s

- $\Rightarrow$ plasma torus [*Bagenal, 1994*]

- Titan (atmospheric escape)

- 10^{26} H & N ions/s

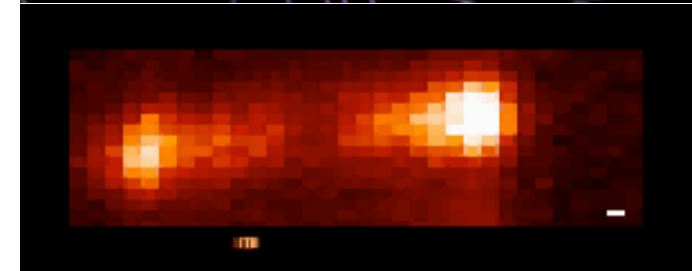
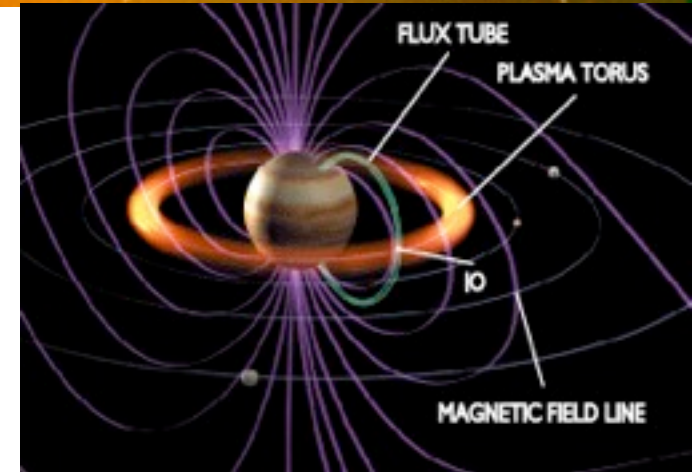
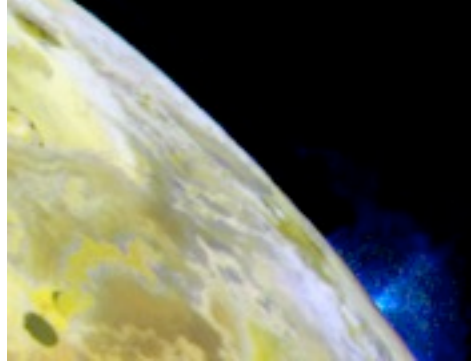
- (+C ?) [*Sittler et al., 2005*]

- Enceladus (exosphere, plumes)

- source & sink ?

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

- Icy satellites (or Mercury's) surface : sputtering

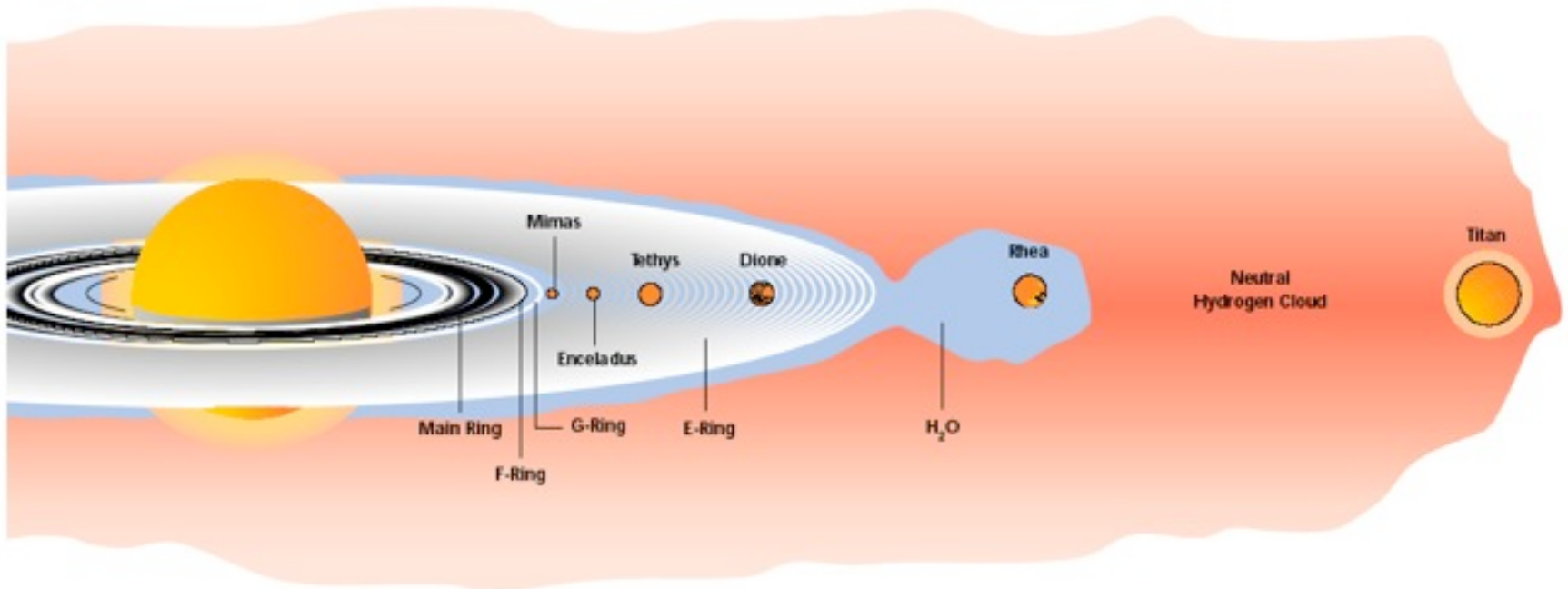


- **Plasma Sources** [cont'd]

- 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 $\sim 10^{10}$ kg @ Jupiter, $\sim 10^7$ kg @ Earth

- 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 ?

• Plasma Circulation

- Closed MS

$$V_{SW} \parallel MP$$

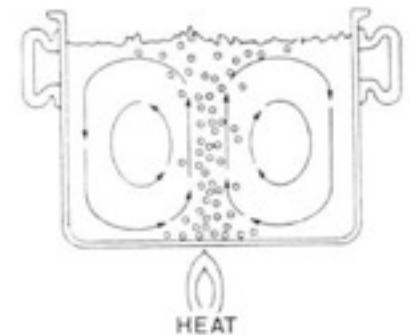
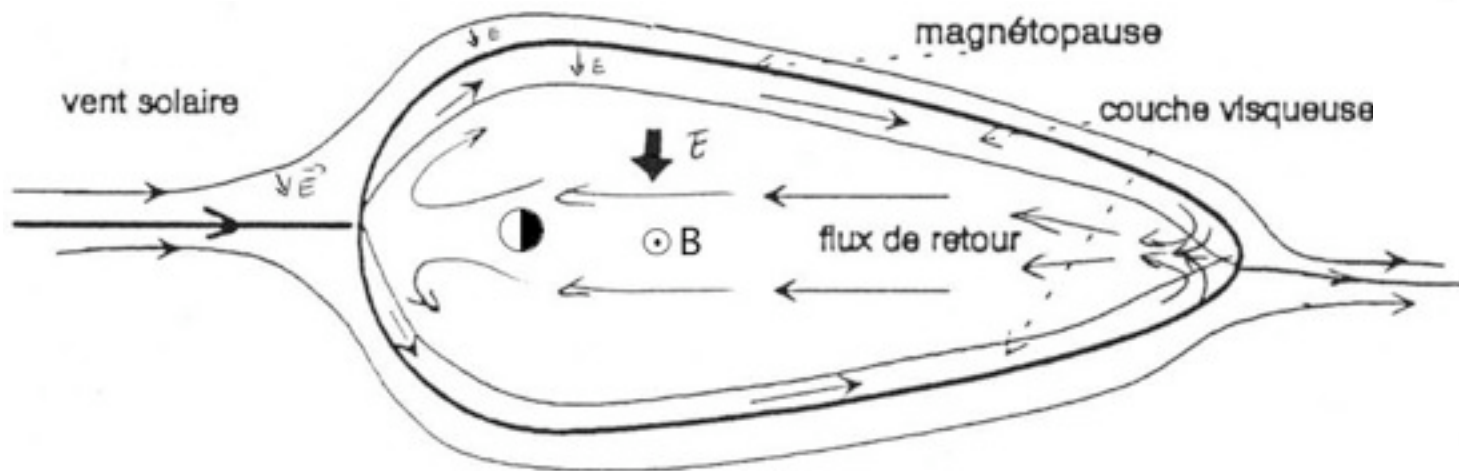
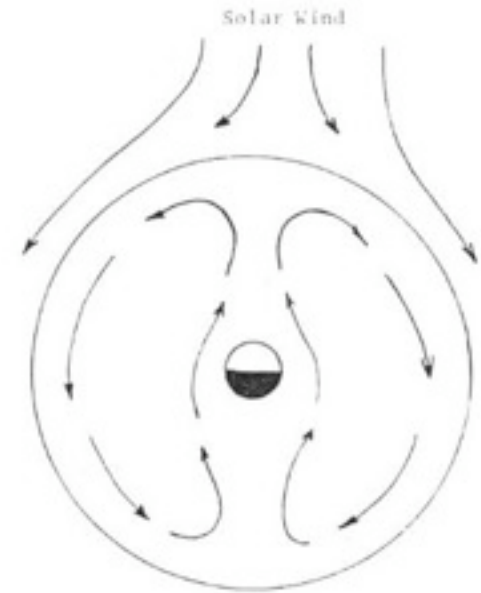
equipotential flow lines

no plasma penetration

MS electrically insulated from outside SW

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

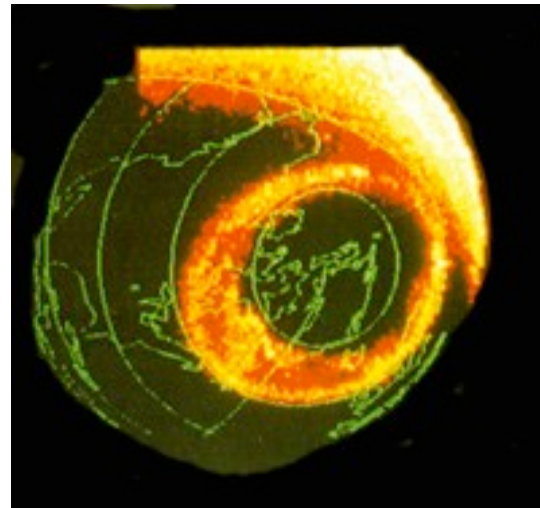
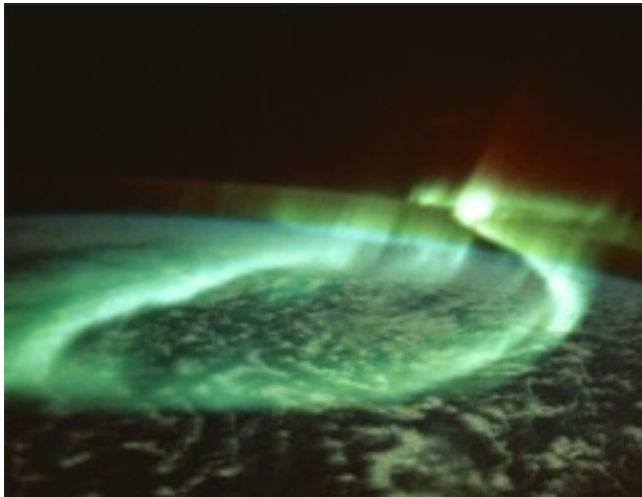
⇒ 2 convection cells



• Plasma Circulation [cont'd]

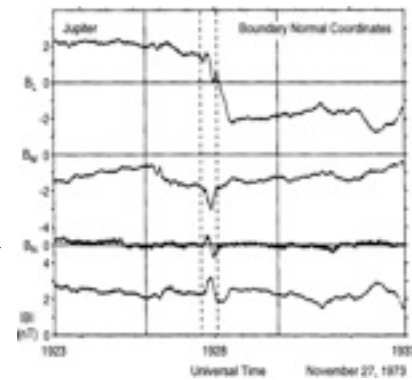
Ok / circulation observations at Earth BUT

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



- **Plasma Circulation** [cont'd]

- Open MS



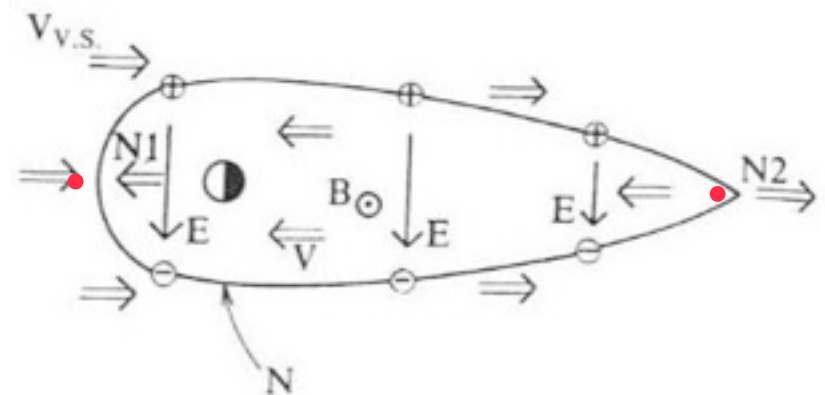
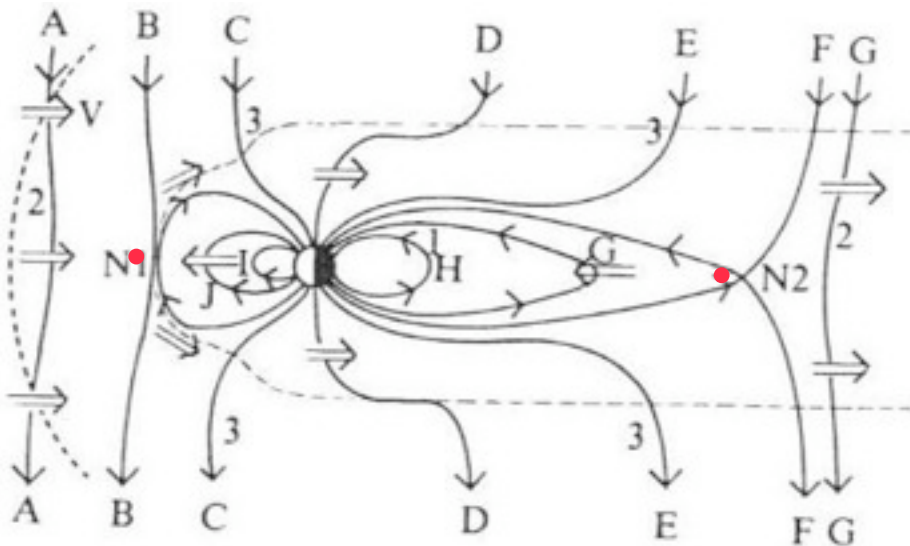
B reconnection at MP (stationary ? patchy ? $\rightarrow B_N \neq 0$) when $B_z \parallel B_P$

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

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

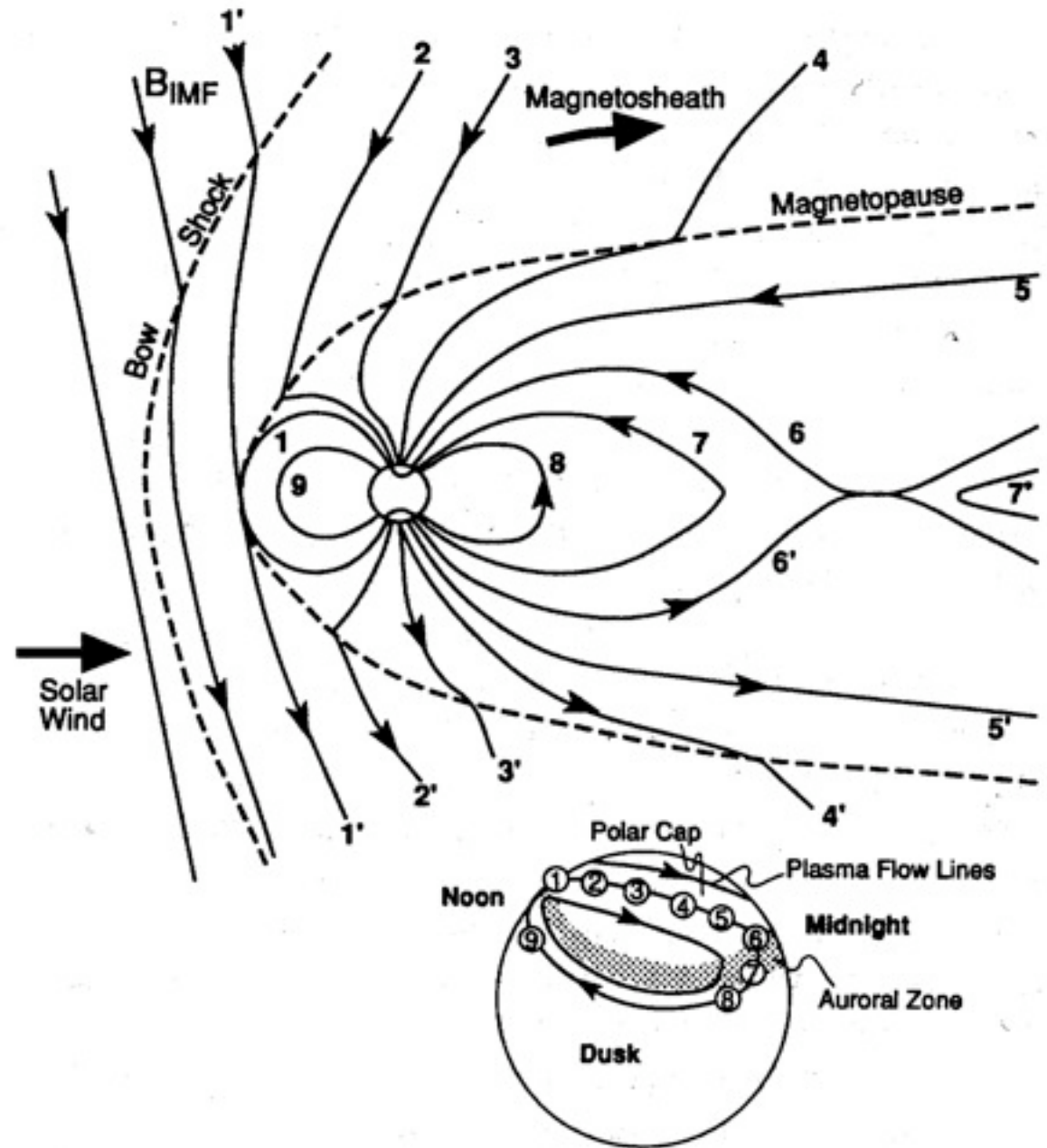
Neutral (X) line at equator

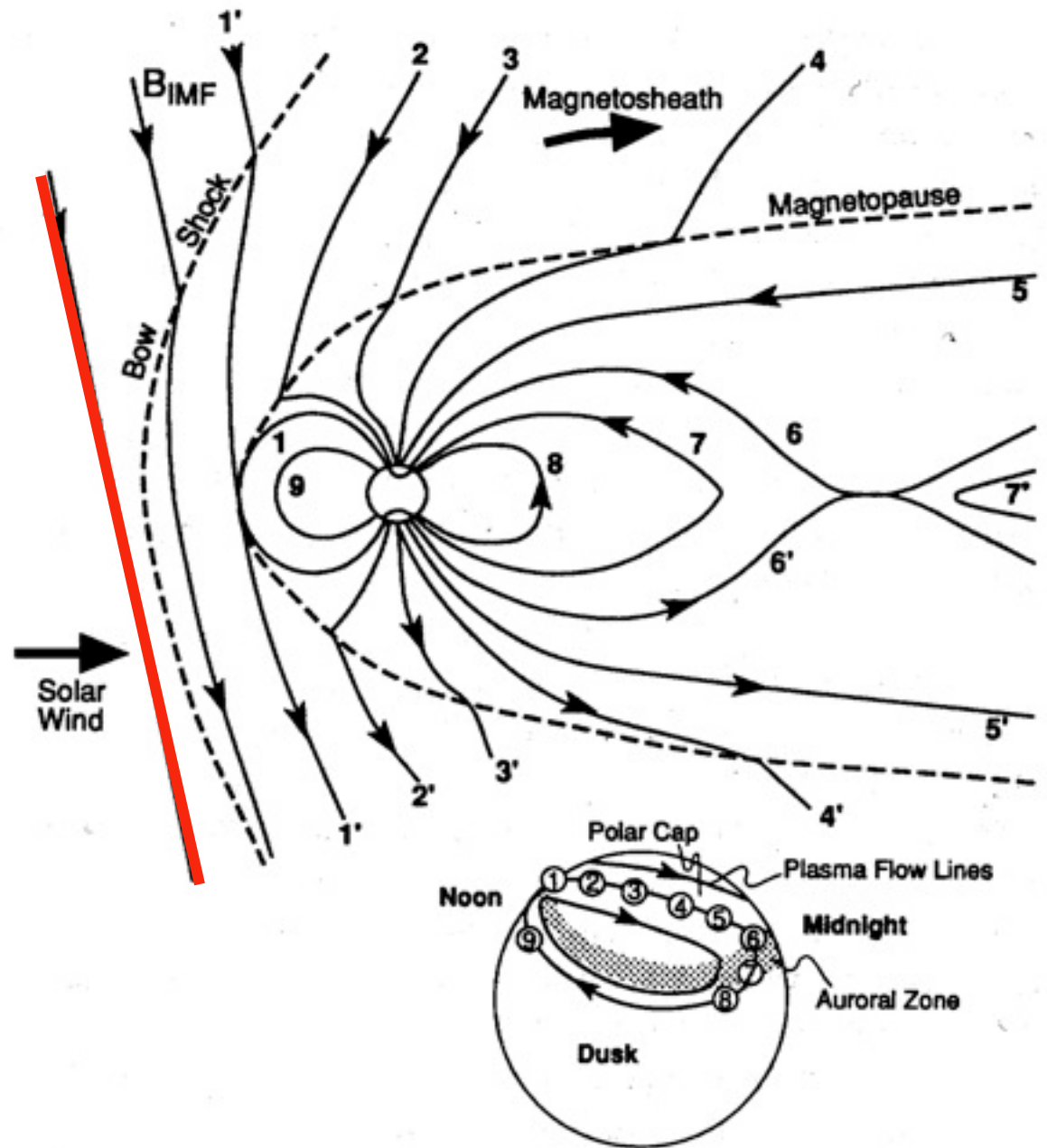
Penetration of plasma in MS $\Rightarrow$ no more equipotential

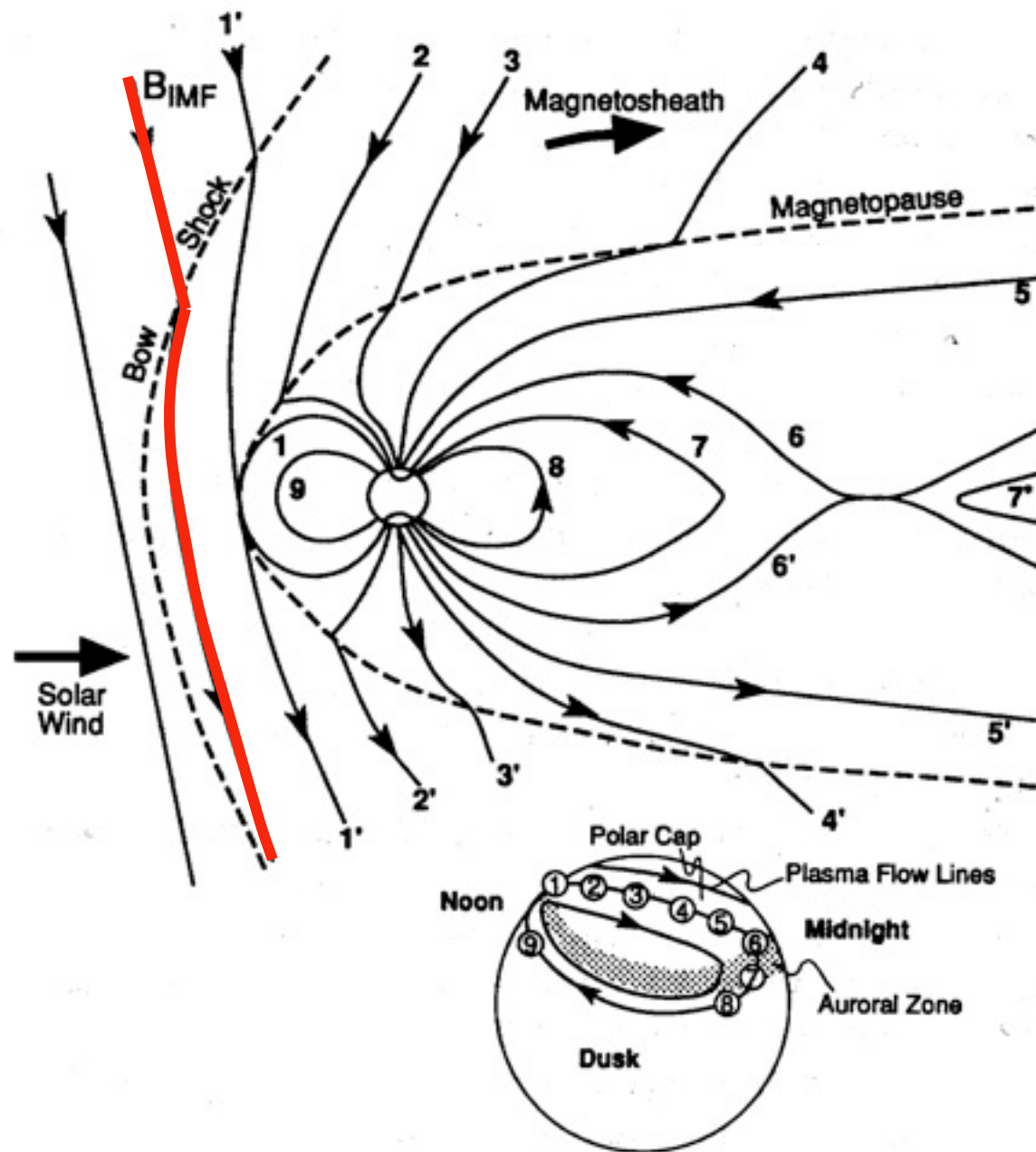


[Dungey, 1961]

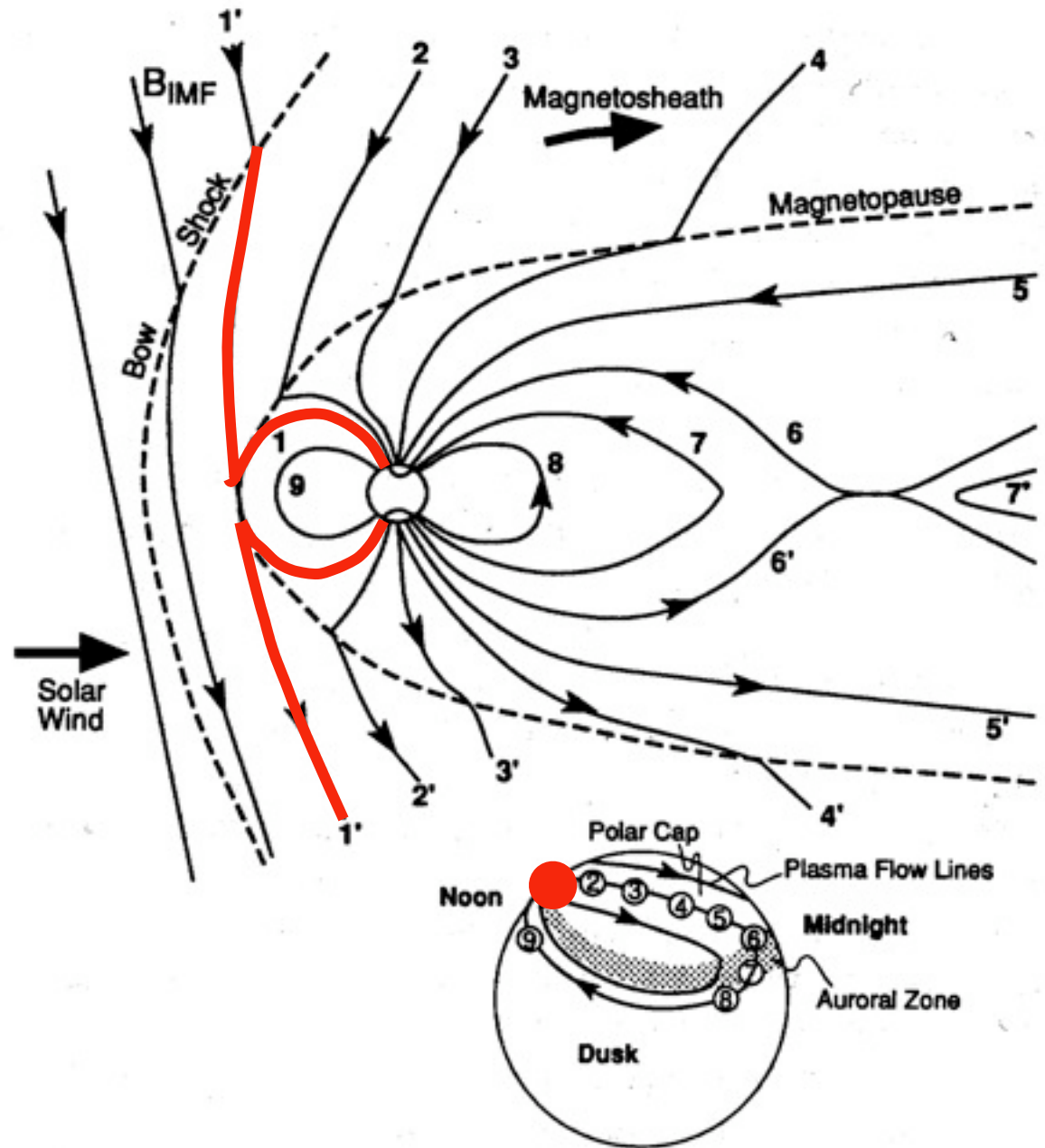
**cycle de
circulation du
plasma et du
champ
magnétique
dans la
magnétosphère
terrestre**

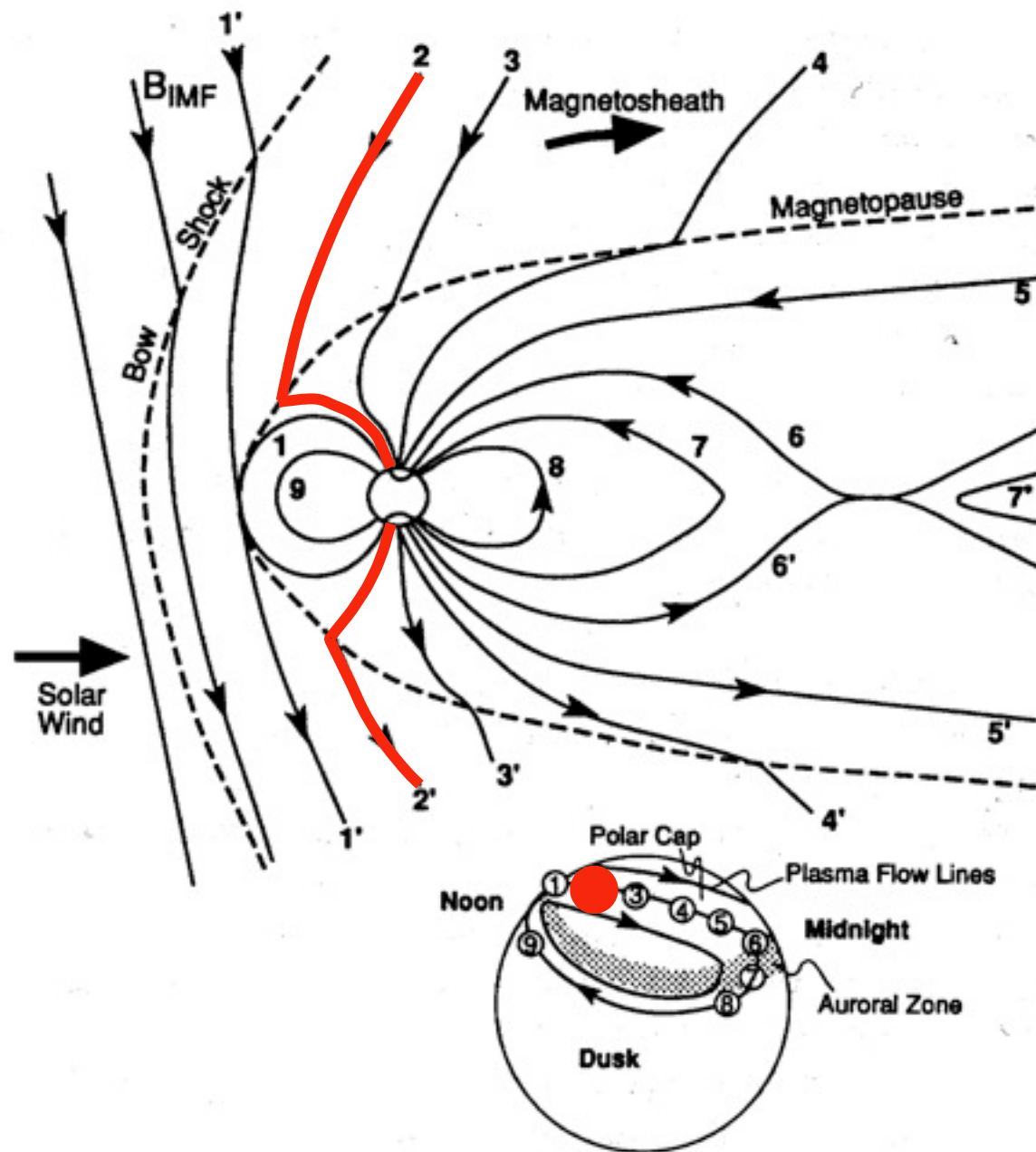


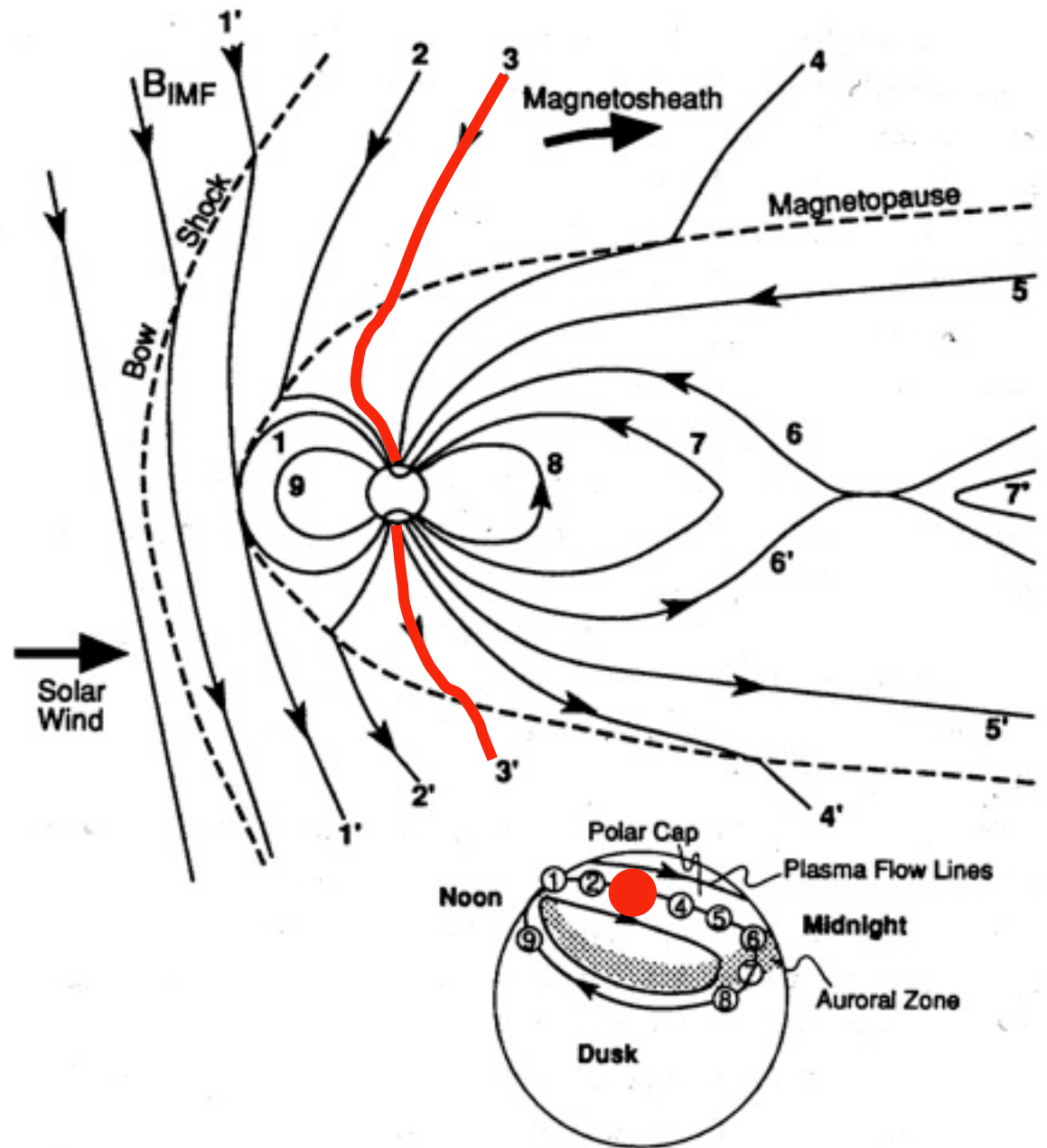




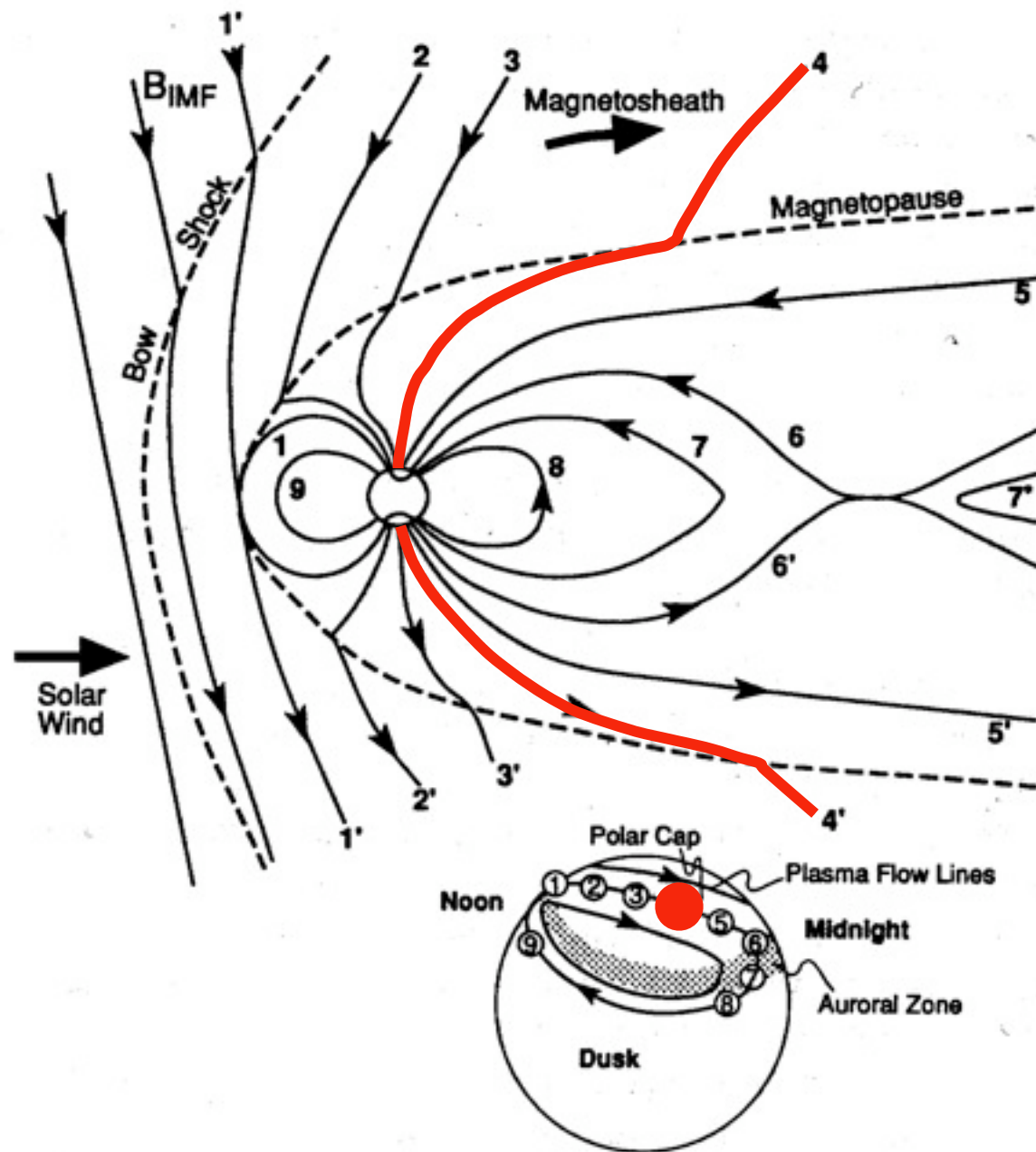
**1^{ère} reconnection
(côté jour) = début
du cycle**

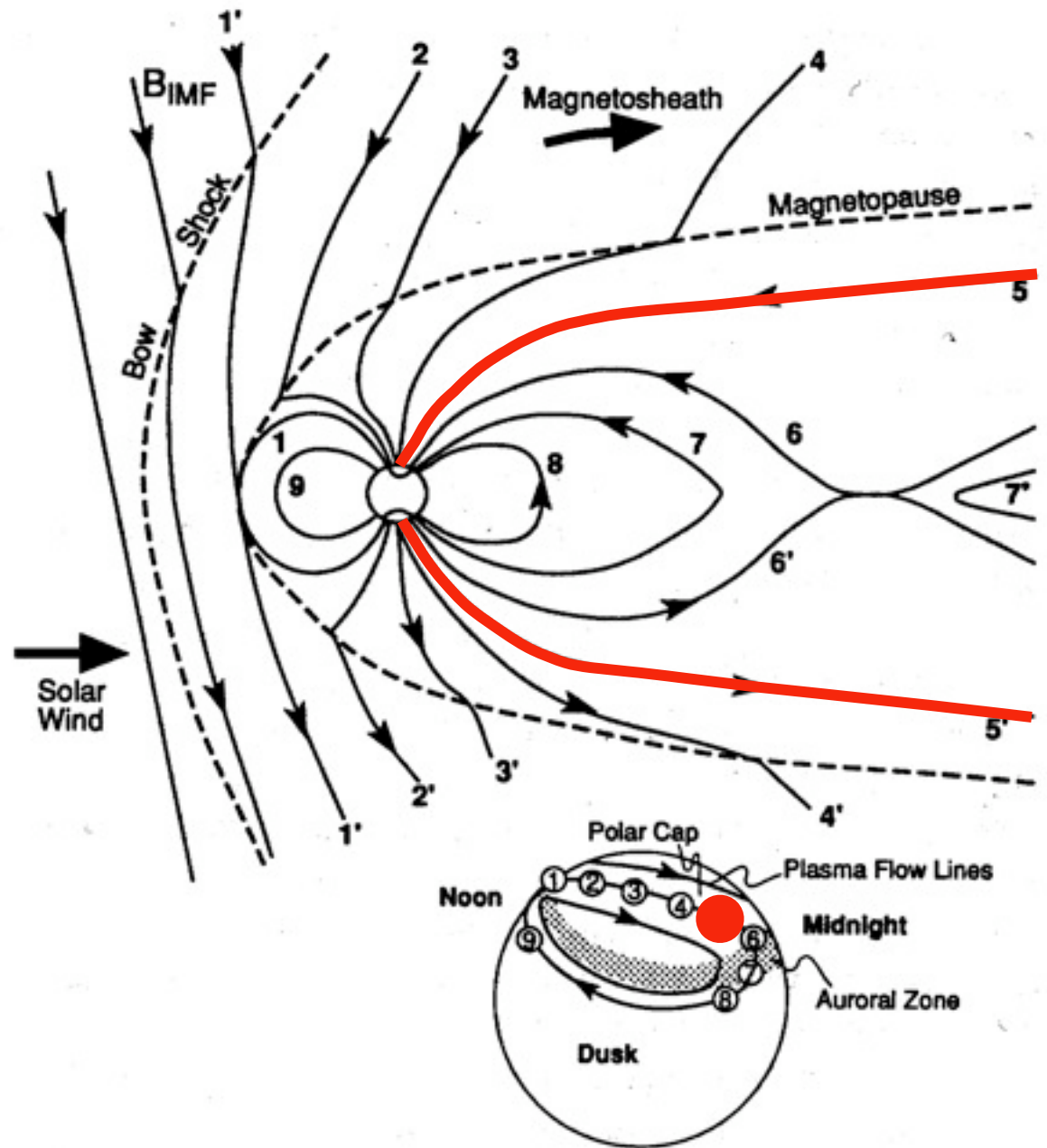




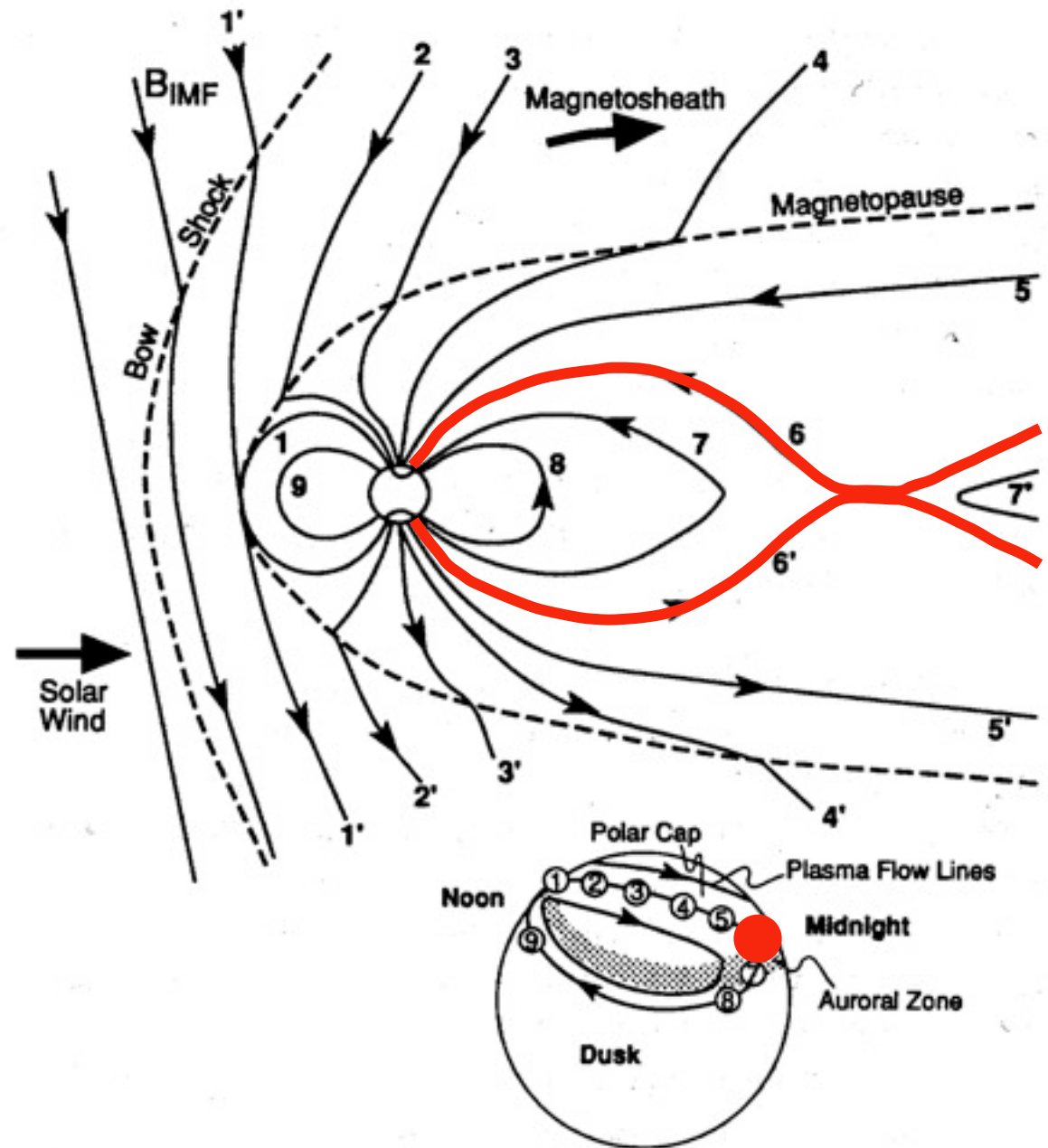


transport
au-dessus
des pôles

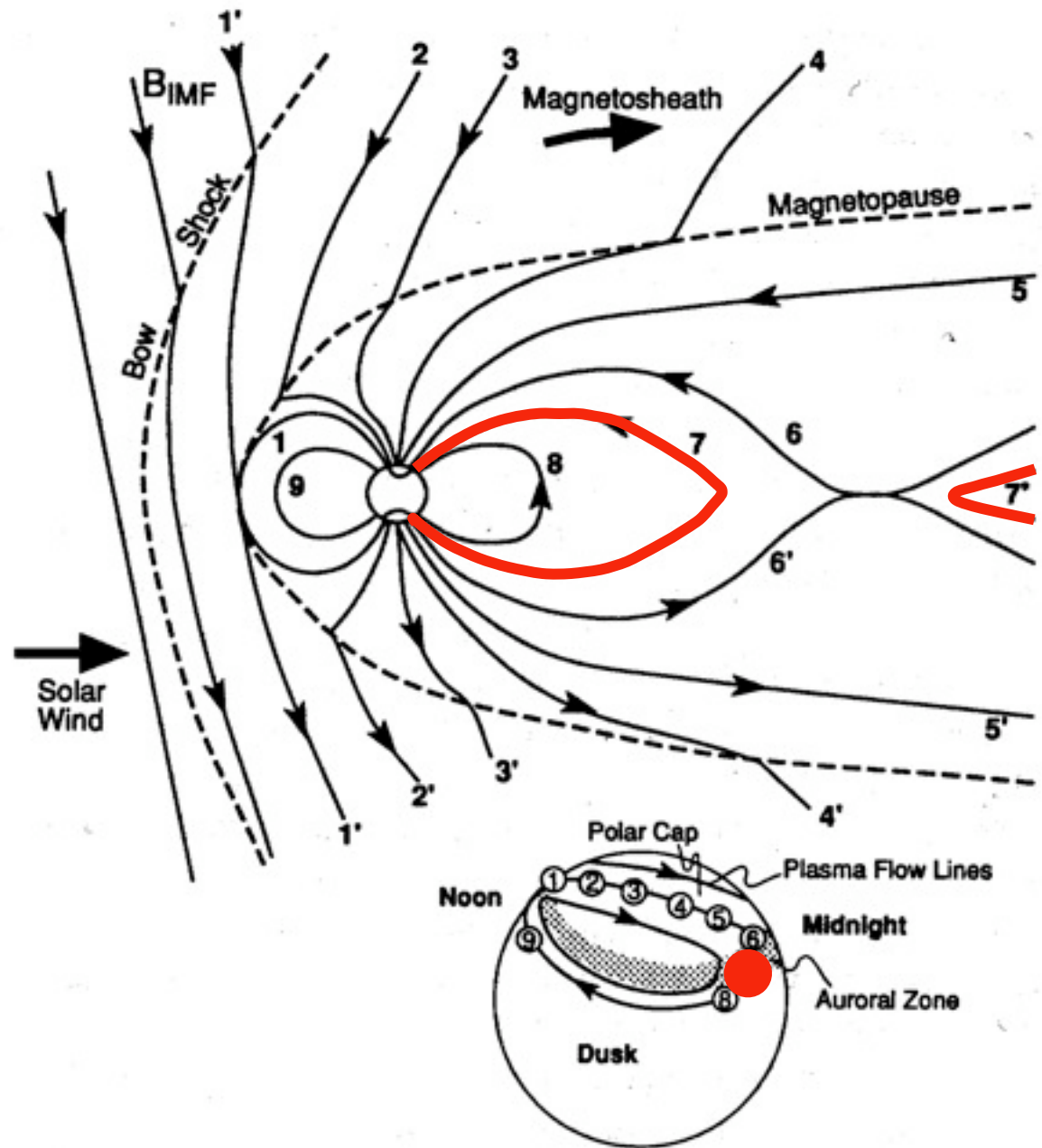




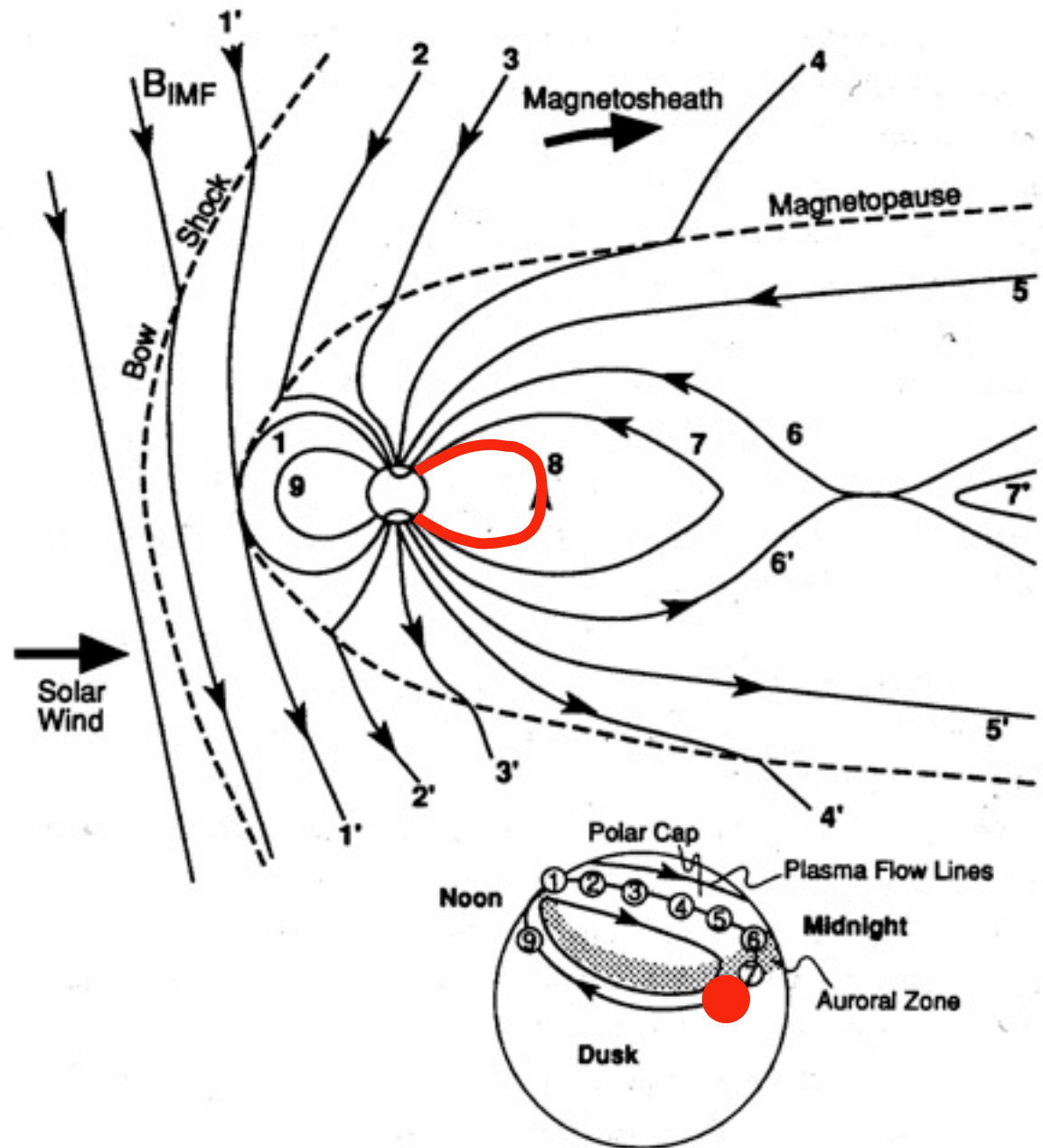
**2ème reconnection
(côté nuit)**



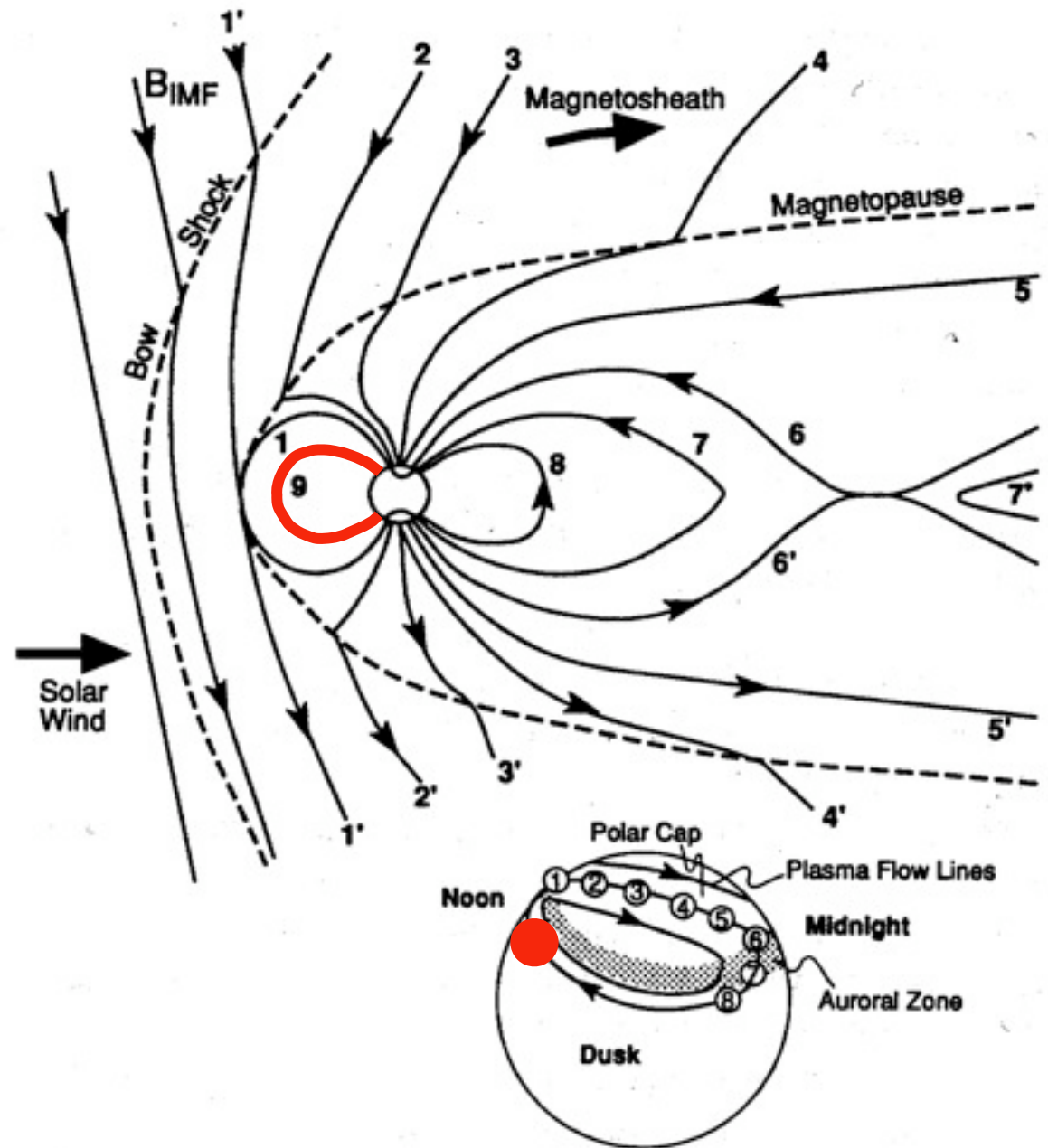
éjection d'une
bulle de plasma
(plasmoïde)
vers la queue



et retour d'une
boucle de champ
magnétique
vers le côté "jour"



**= un sous-orage
magnétosphérique**



• Plasma Circulation [cont'd]

- Solar Convection in MS [antisolar above the poles]

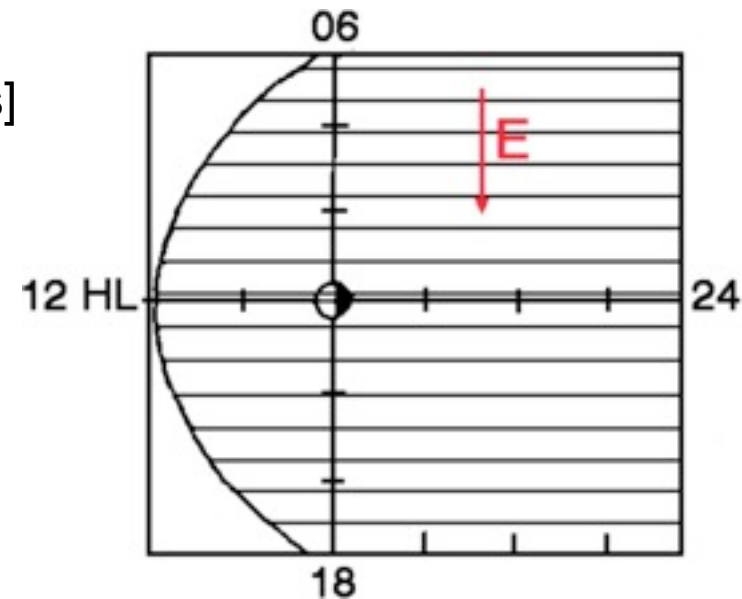
$$E = -V \times B \sim \varepsilon V_{SW} \times B_{SW} \quad (\text{dawn} \rightarrow \text{dusk})$$

$$\varepsilon = 0.1-0.2$$

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

$$\sim 50 \text{ kV @ Earth}$$

$$\sim 1 \text{ MV @ Jupiter}$$



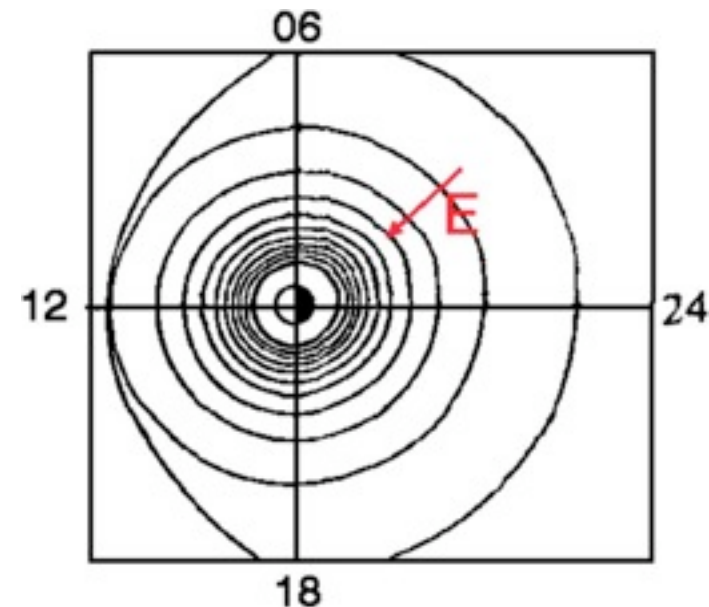
- Corotation

$$E = \Omega R \times B \quad (\text{radial})$$

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

$$\sim 90 \text{ kV @ Earth}$$

$$\sim 400 \text{ MV @ Jupiter}$$

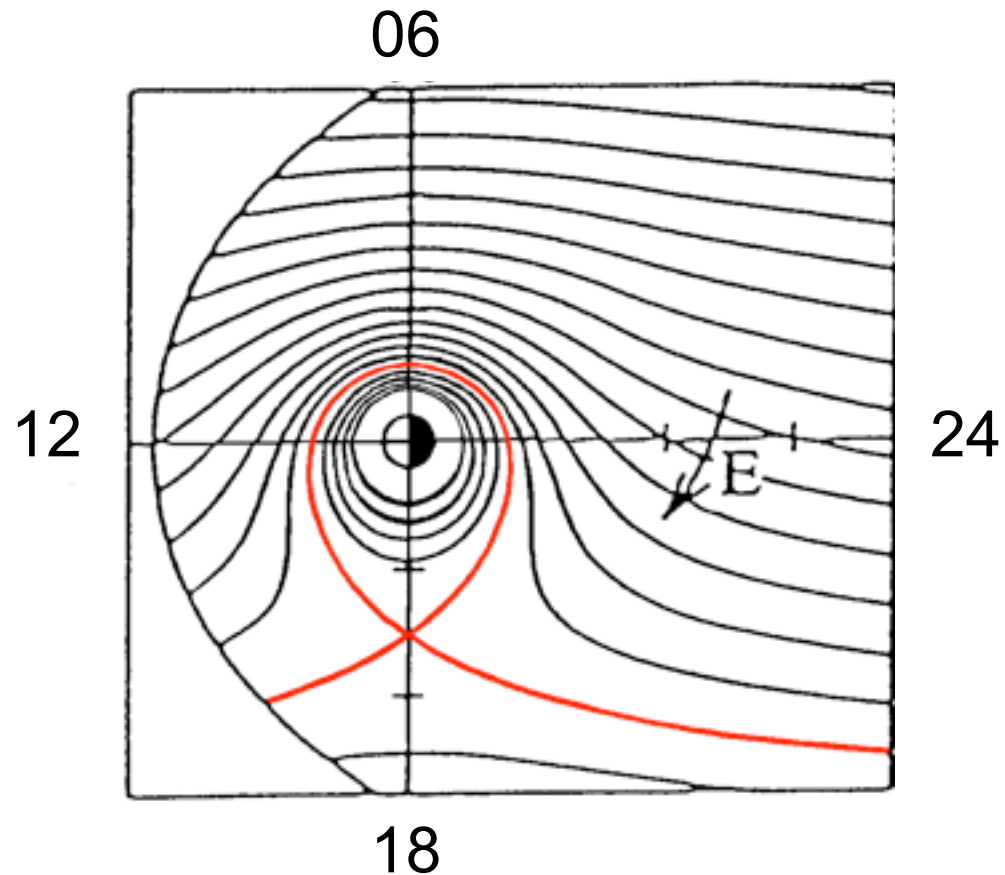


- **Plasma Circulation** [cont'd]

- Global circulation = Convection + Corotation

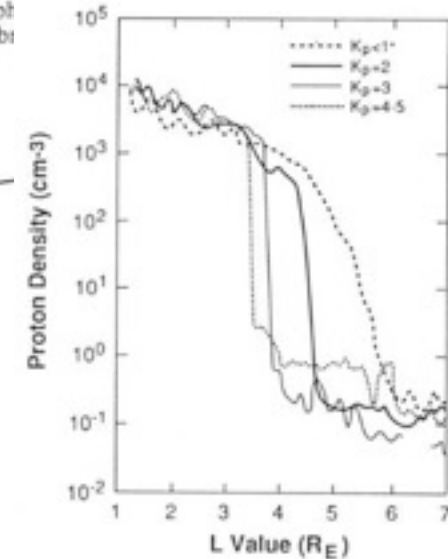
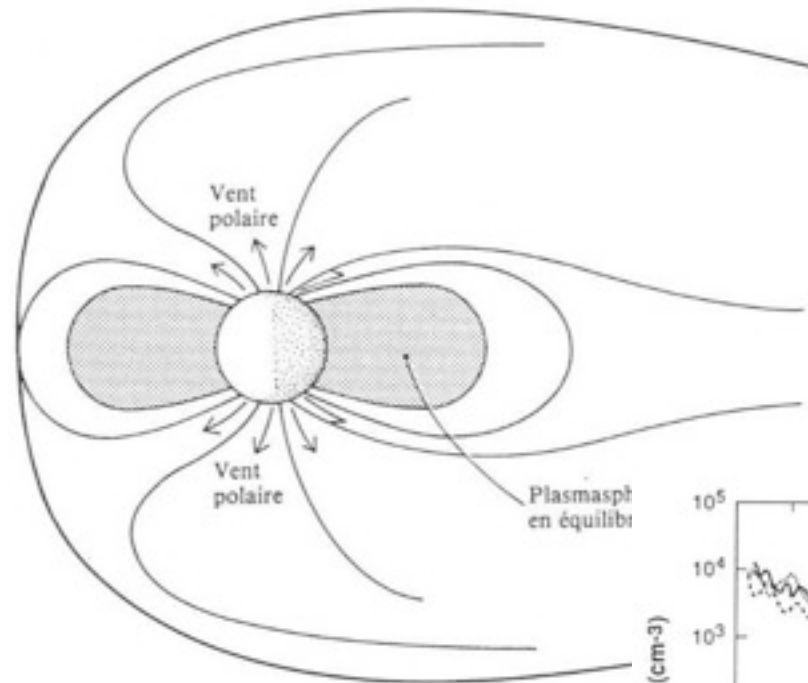
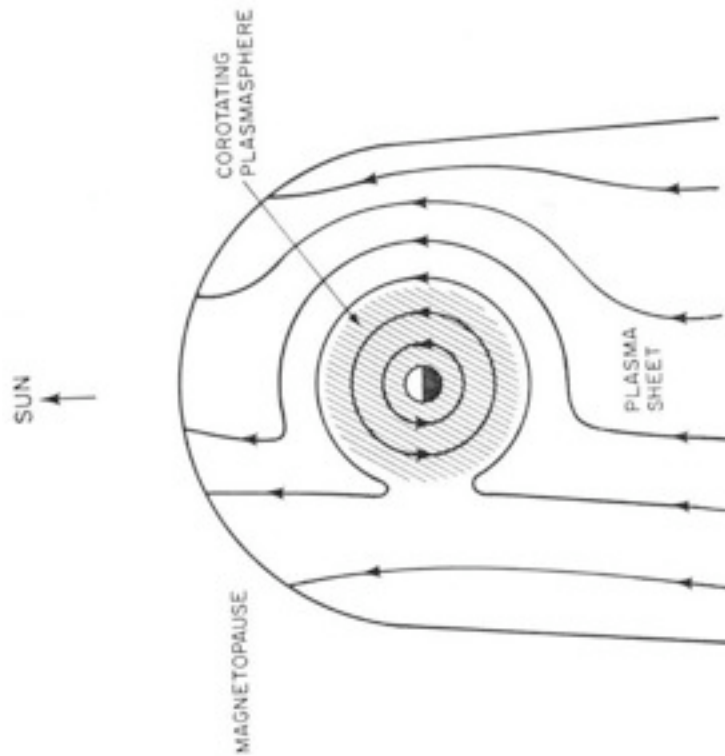
Equipotentials = flow lines

Stagnation point at LT = 18 h



• Plasma Circulation [cont'd]

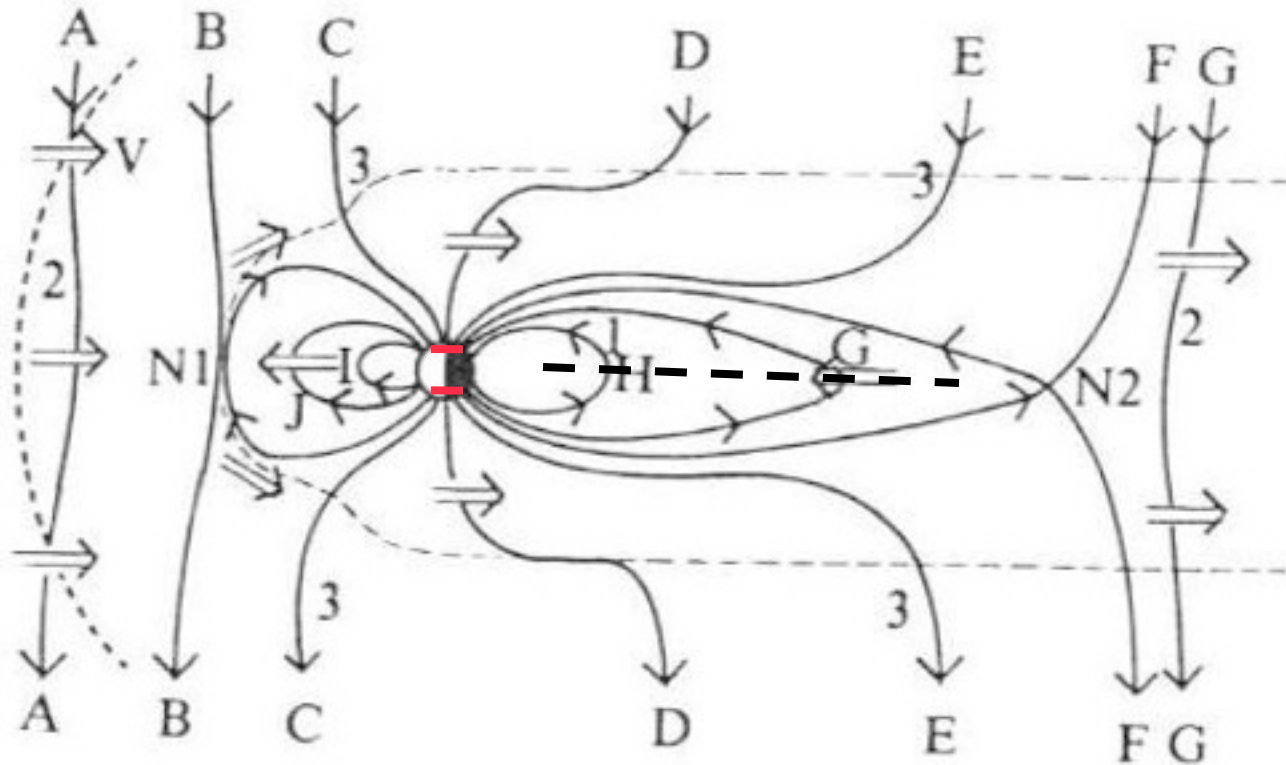
- Plasmasphere = permanently closed field lines, corotation dominated



- **Plasma Circulation** [cont'd]

- Auroral oval = limit open/closed field lines

= projection of equatorial neutral line on ionosphere

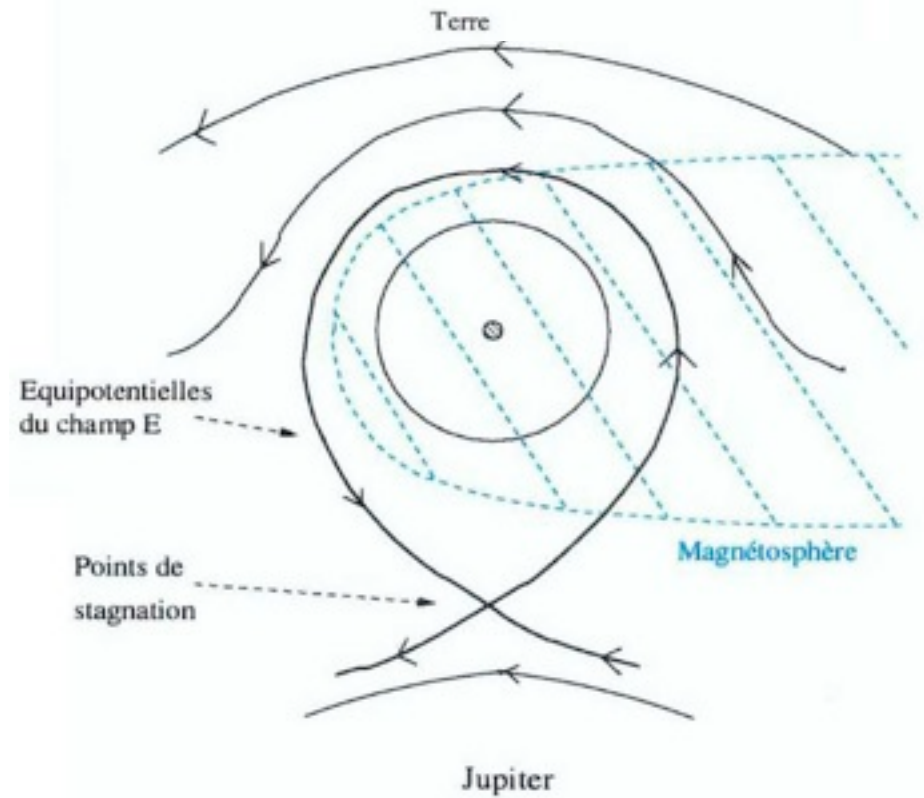
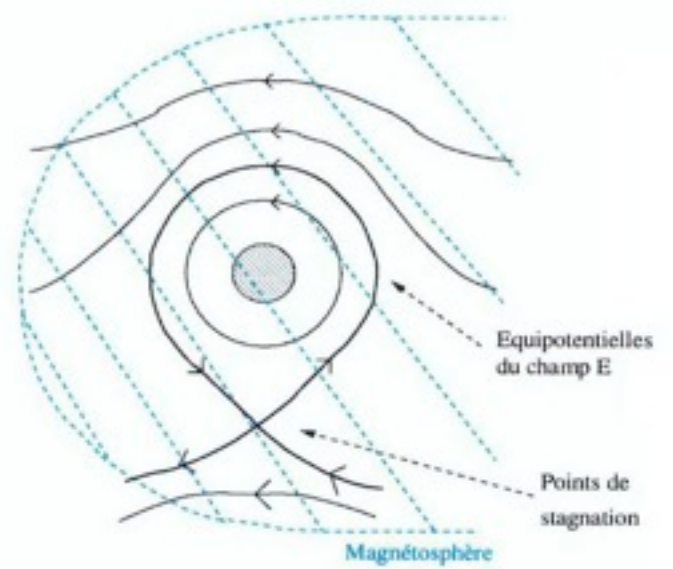
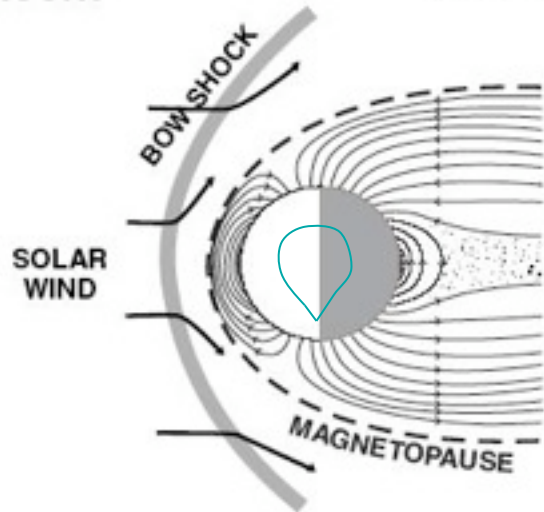


- Tail = MS antisolar extension, plasma convected to neutral plasma sheet - - -, stores / releases energy and magnetic flux

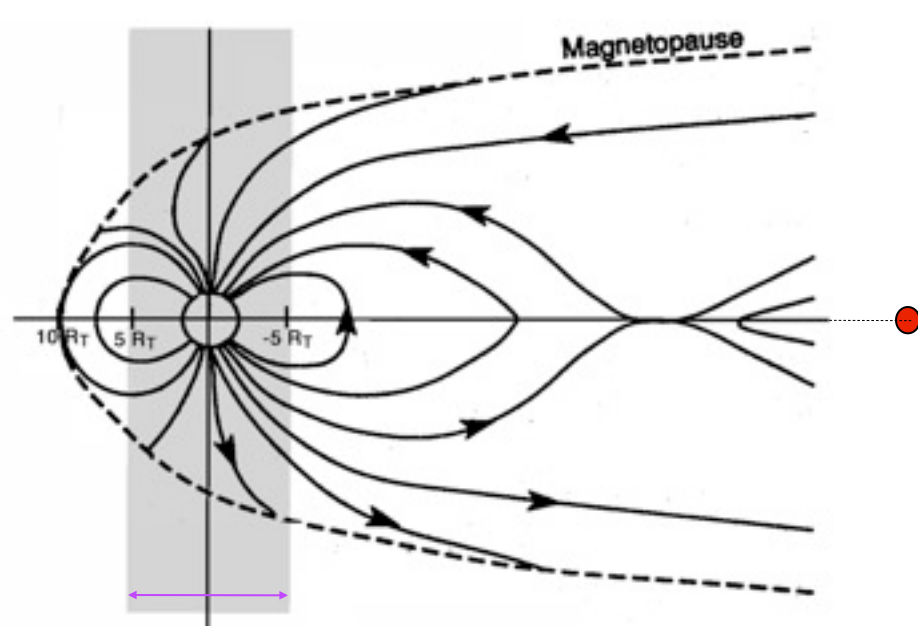
- Plasma Circulation [cont'd]

MERCURY

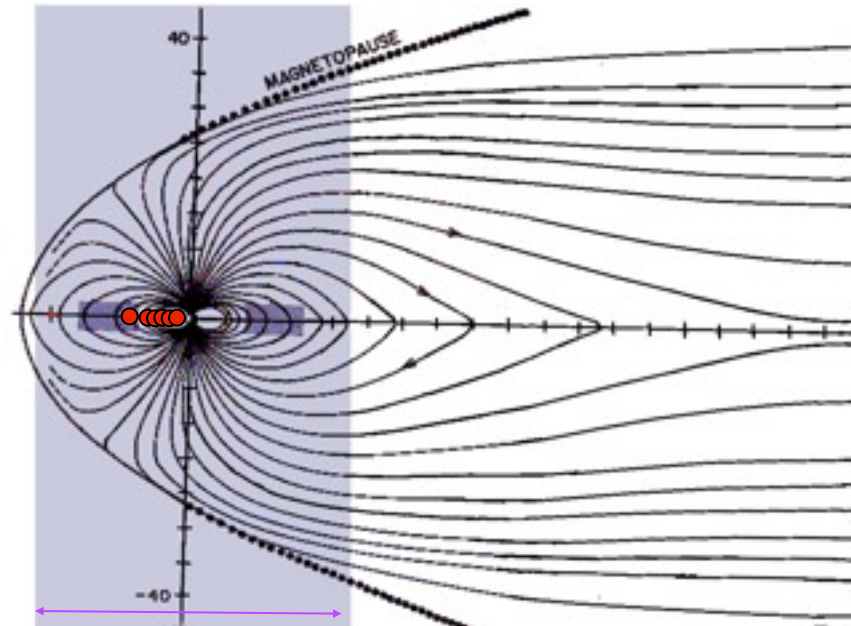
DIAMETER OF EARTH



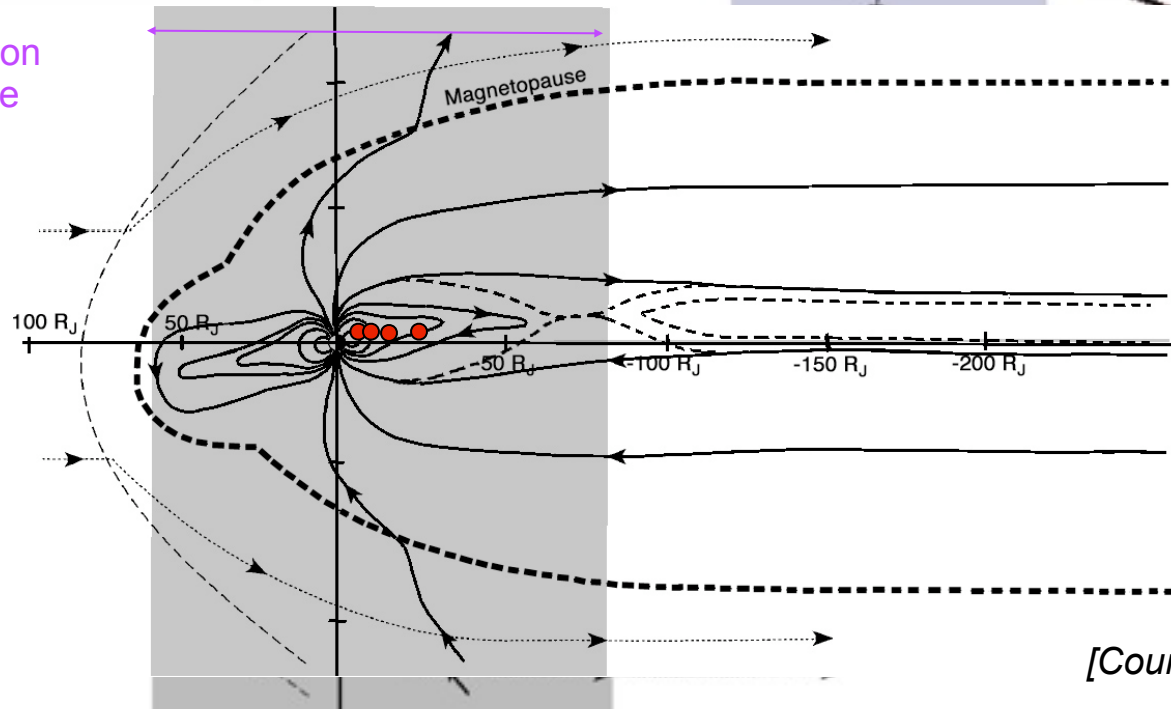
EARTH



SATURN



corotation region
plasmasphere



JUPITER

[Courtesy R. Prangé]

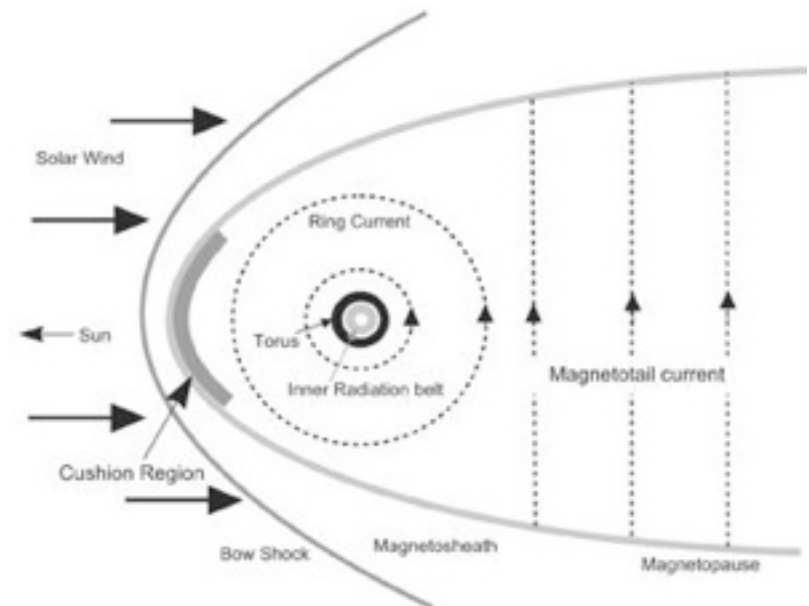
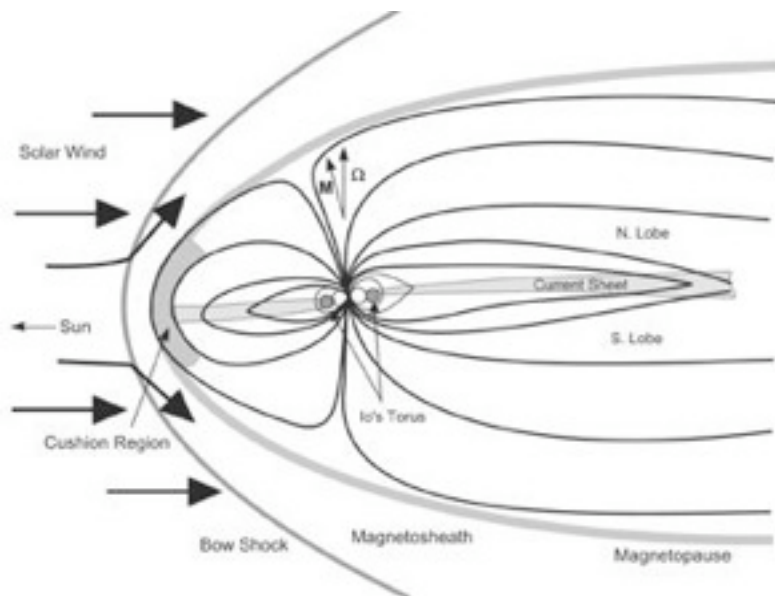
• Plasma Circulation [cont'd]

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

Planet	R_p [km]	Ω [rads/s]	G_{surf} [ms^{-2}]	$R_{\text{synch}}/R_{\text{planet}}$	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

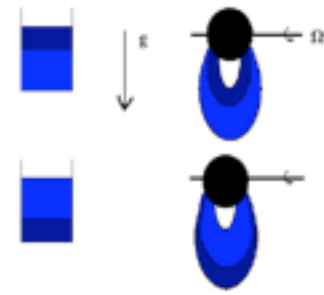


• Plasma Circulation [cont'd]

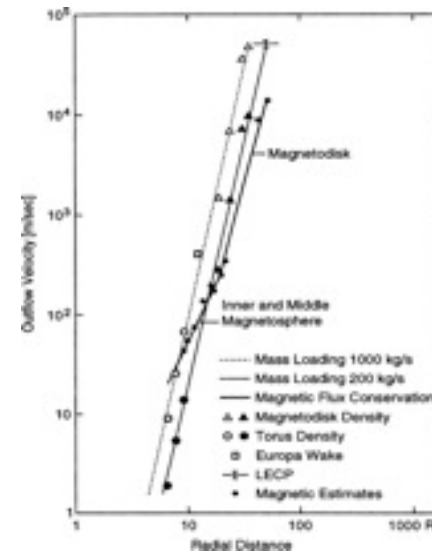
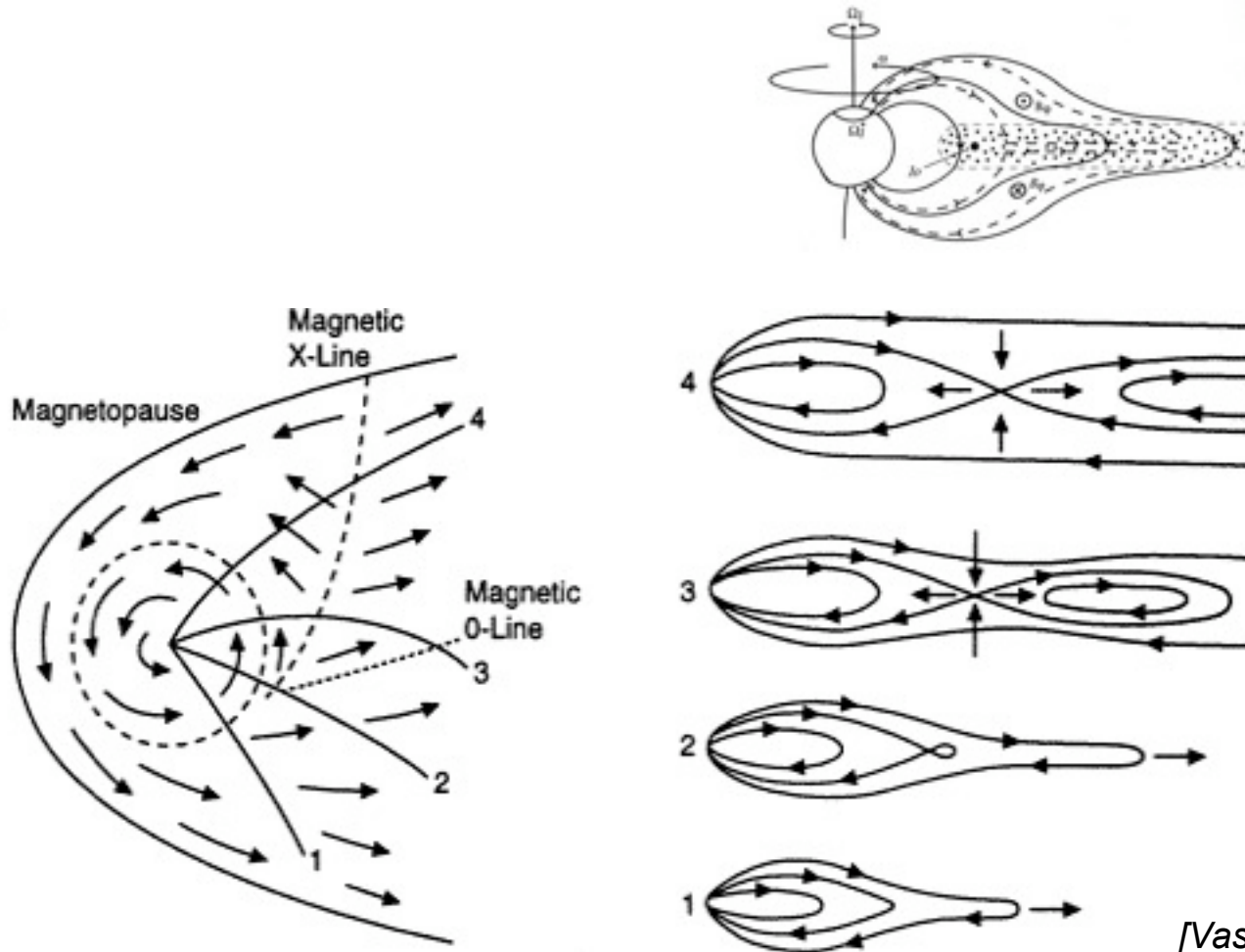
- Jupiter : outward radial transport (centrifugal interchange instability)

⇒ Vasyliunas cycle ~ rotation driven Dungey cycle

⇒ origin of auroral oval ?



[André, 2006]

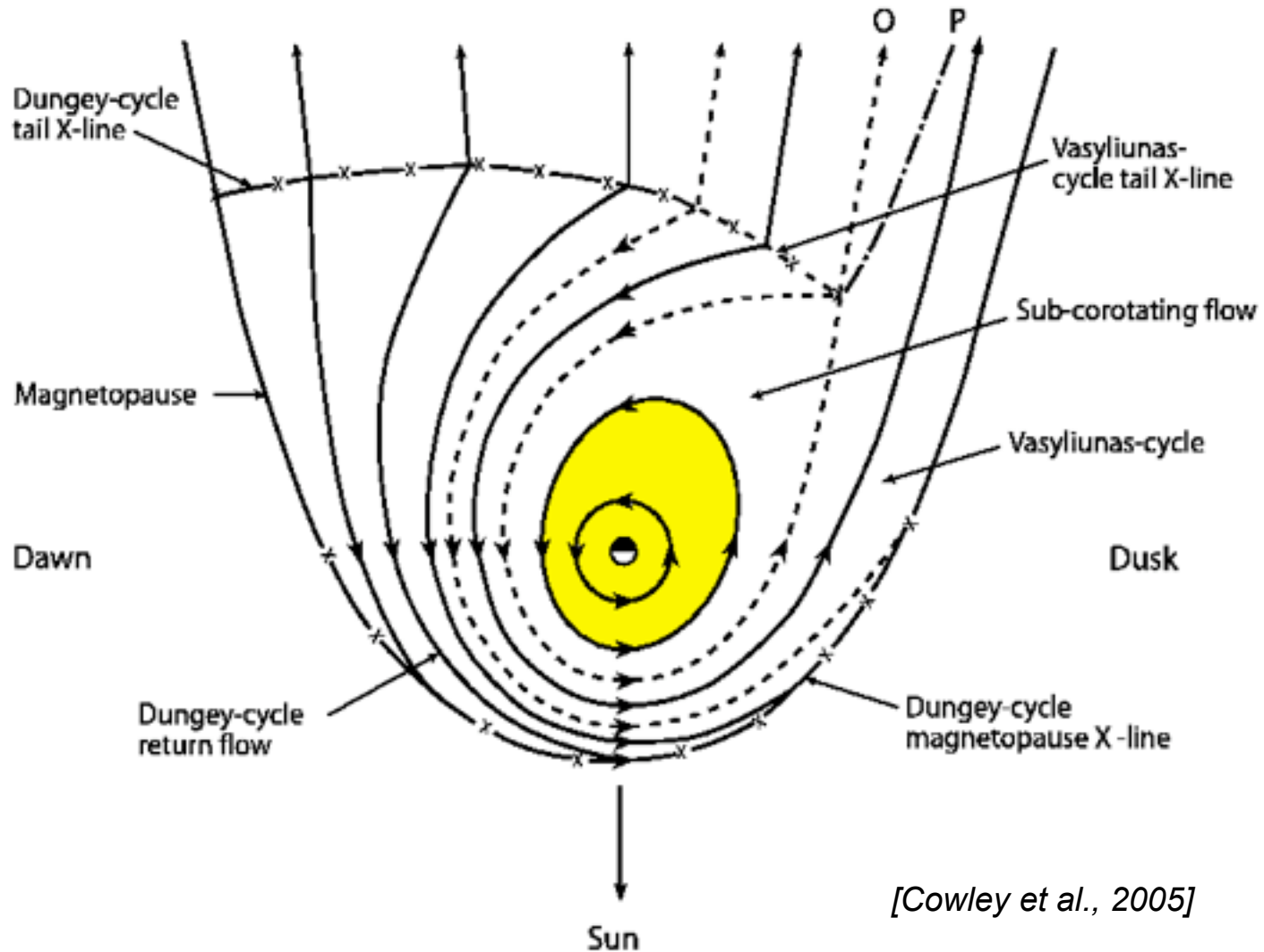


[Russell, 2001]

[Vasyliunas, 1983]

- **Plasma Circulation** [cont'd]

- Saturn : « intermediate » circulation ?

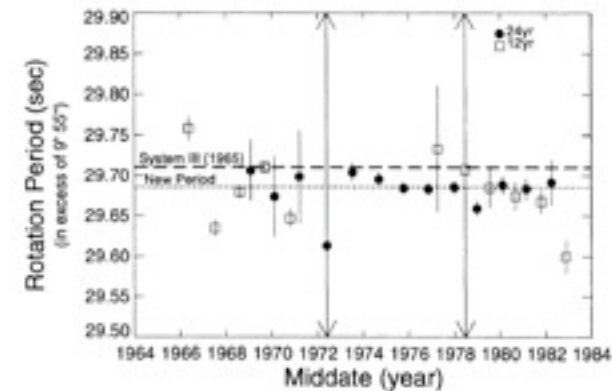


- **Plasma Circulation** [cont'd]

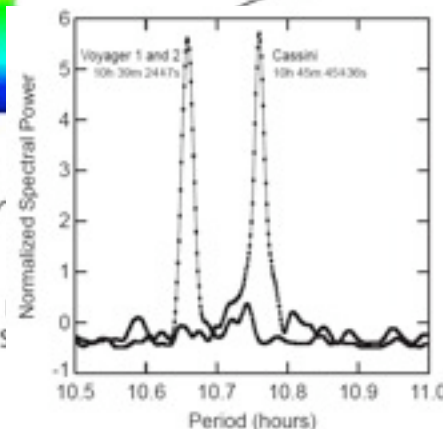
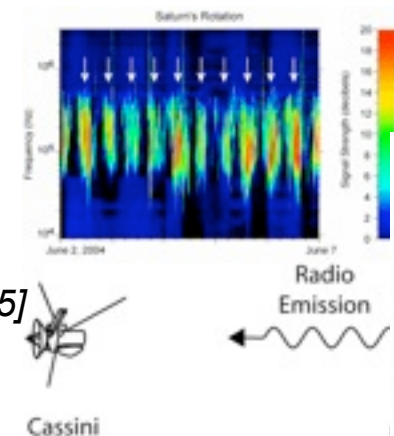
- Earth dominated by convection
 ⇒ little/no rotational signature in magnetospheric phenomena (e.g. AKR)

- 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]



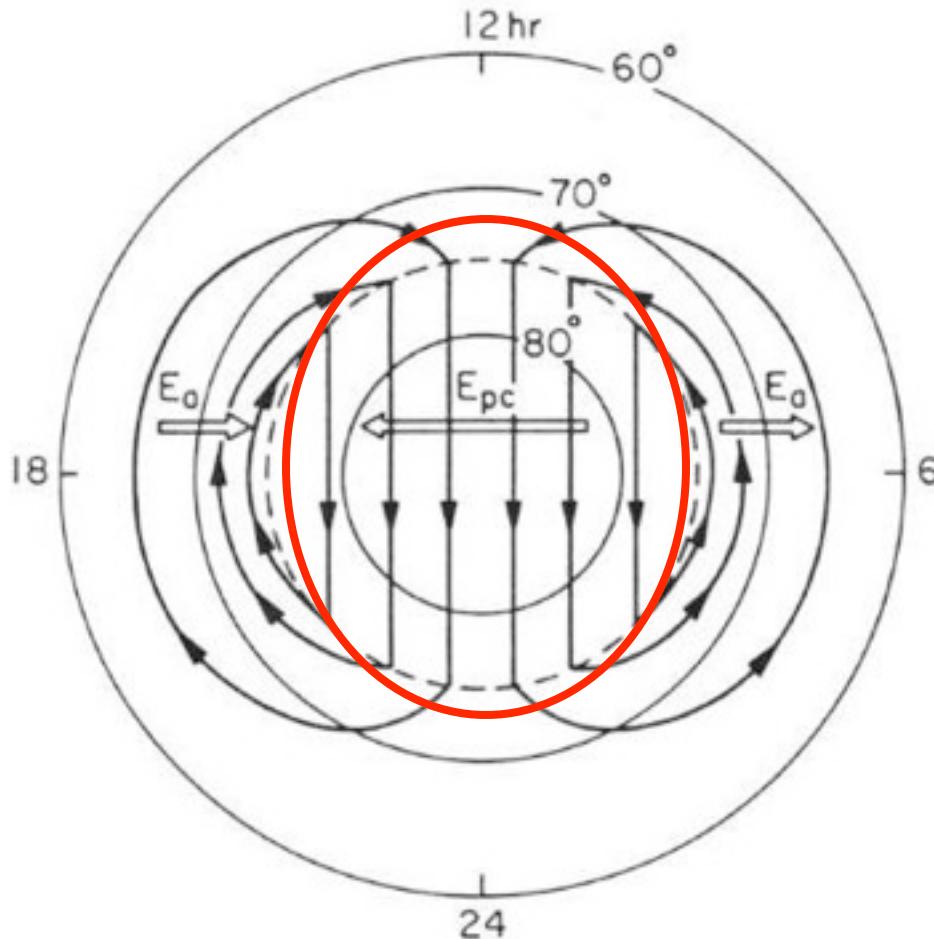
Independent of B tilt ! (at 1st order, except Uranus & Neptune)

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

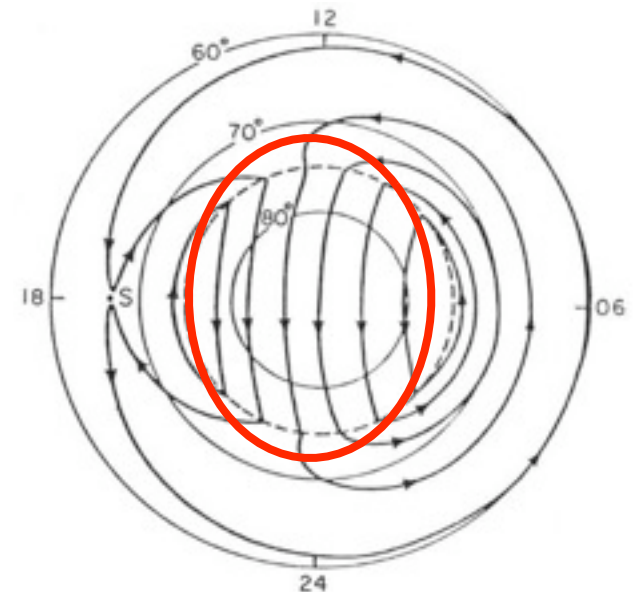
• Role of Ionosphere

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

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



+ corotation



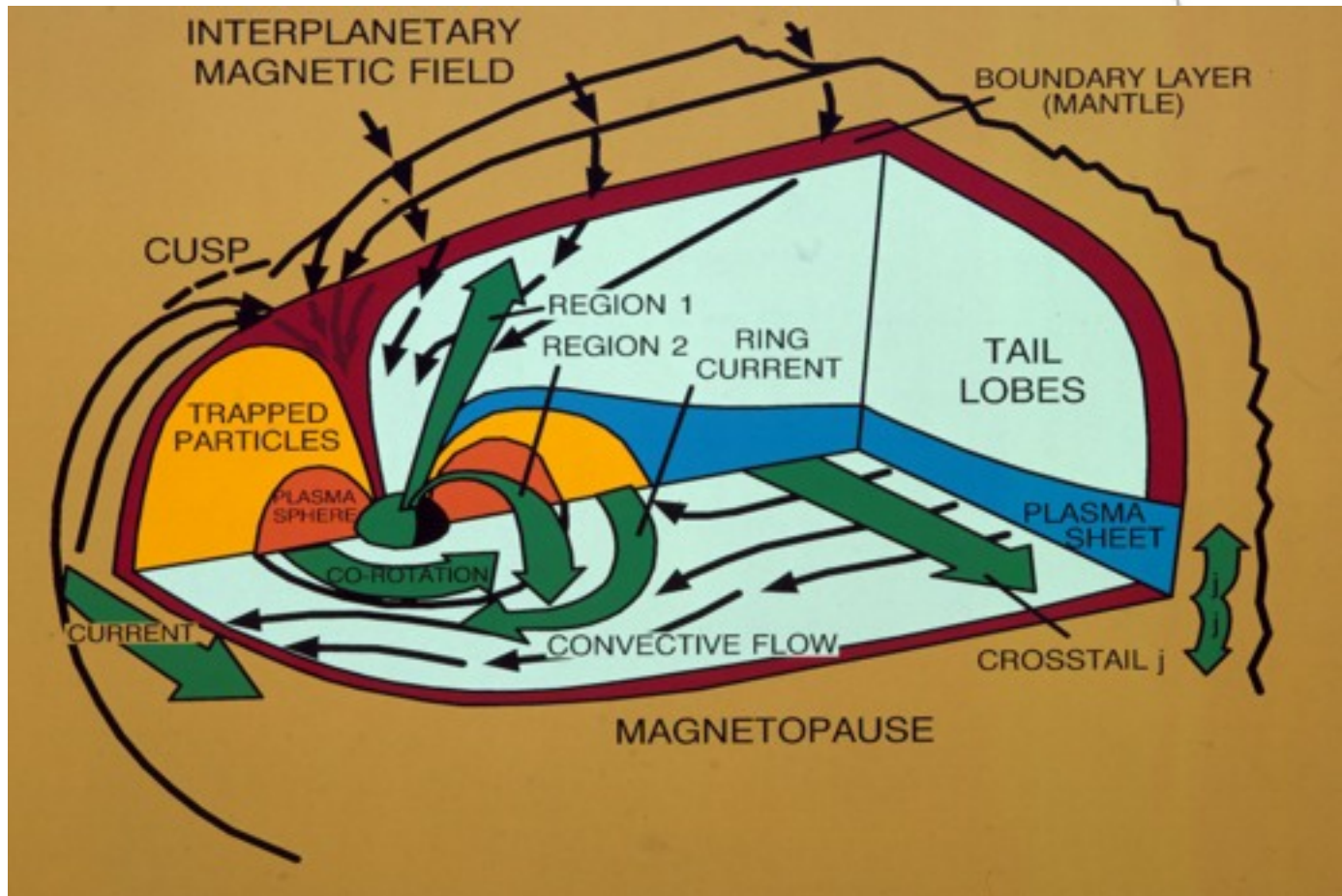
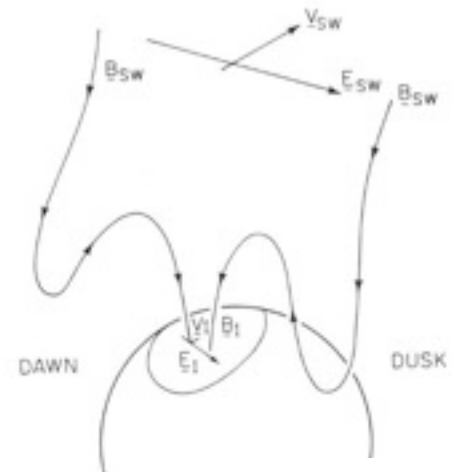
- currents closure (in sputtered/vaporized regolith @ Mercury ? [Slavin, 2004])

- 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 ?

- **Current Generators**

$$\nabla \cdot \mathbf{J} = 0$$

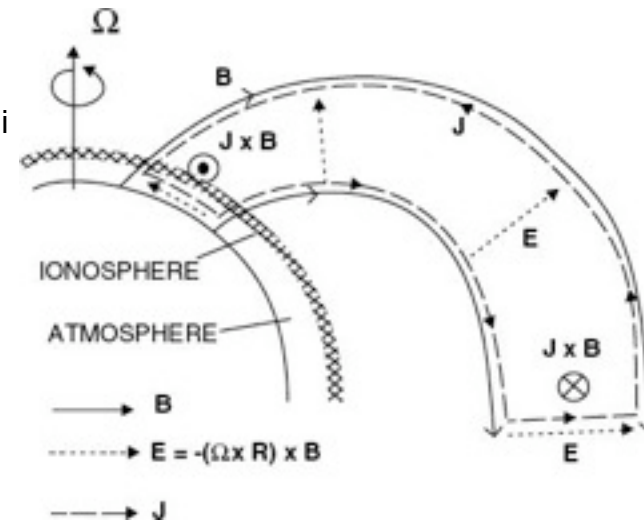
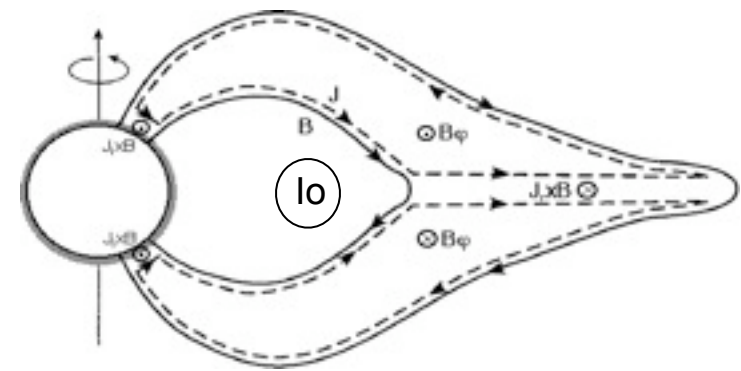
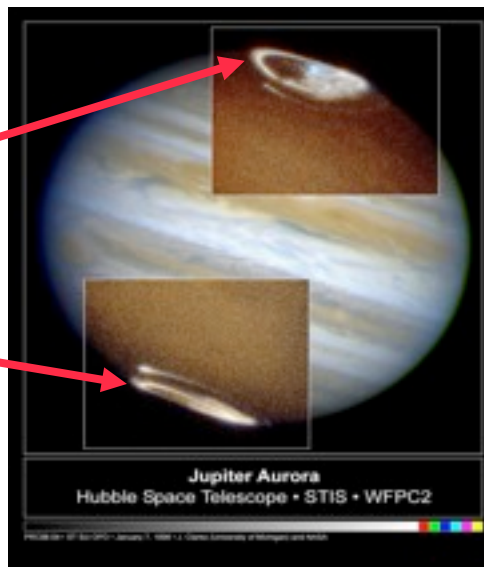
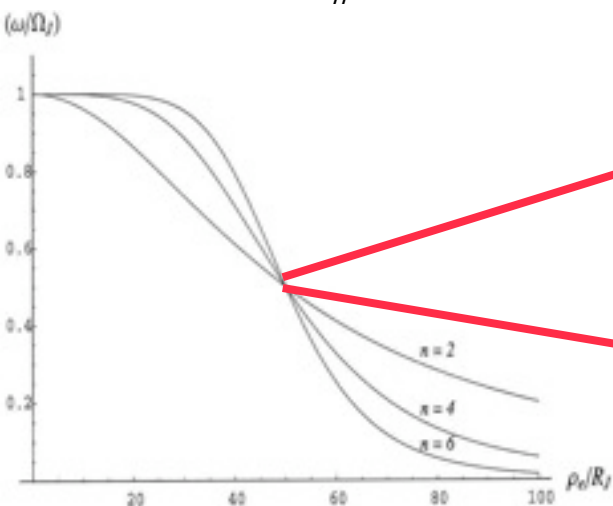
- SW / MS interaction : « region 1 » currents @ Earth
driven by $\Delta\phi$ (dawn $\rightarrow$ dusk) $\propto V_{SW} \times B_{SW}$



• Current Generators [cont'd]

- radial diffusion from Io $\Rightarrow J_r$
- plasma acceleration (corotation) by $J_r \times B_{MS}$
(+ slowing down MS plasma due to mass loading)
at expense of ionospheric plasma momentum via $J_i \times B_i$
- $\nabla \cdot J = 0 \Rightarrow J_i = J_r B_i / B_{MS} \sim 2R^3 J_r \leq \sigma_i E_i \sim \sigma_i \Omega B_e / R^{1/2}$
 $\Rightarrow$ Ok as long as $J_r \leq \sigma_i \Omega B_e / 2R^{7/2}$
- Corotation breakdown at 20-50 R_J

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



[Bagenal, 1989]

[Cowley & Bunce, 2001]

• Current Generators [cont'd]

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

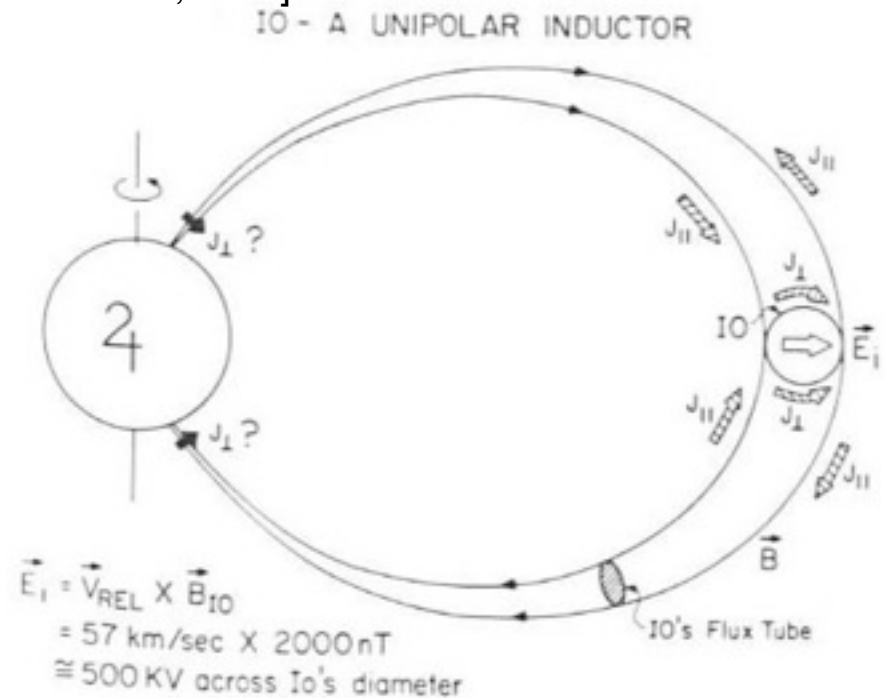
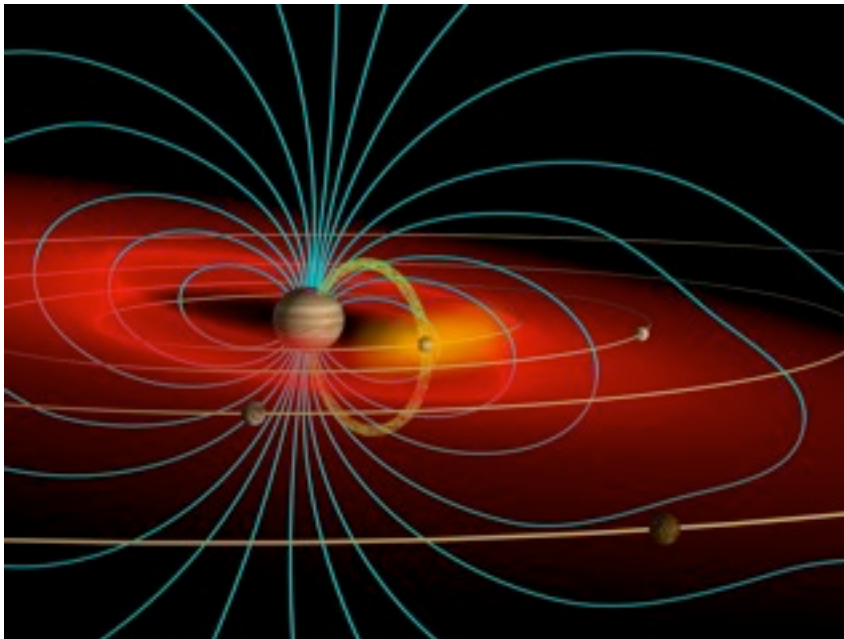
$$\mathbf{E} = -\mathbf{V} \times \mathbf{B}_J \quad \text{with} \quad \mathbf{V} = \mathbf{V}_{\text{corot}} - \mathbf{V}_K \quad (=57 \text{ km/s @ Io})$$

$$\Delta\phi \sim 2 R_{\text{sat}} E \quad (=4 \times 10^5 \text{ V @ Io})$$

Flow dominated by magnetic energy $B_J^2/2\mu_0$

$M_A < 1$ (no bow shock)

[1 case of TransAlfvénic shock @ Europa with Galileo ? *Kivelson, 2005*]



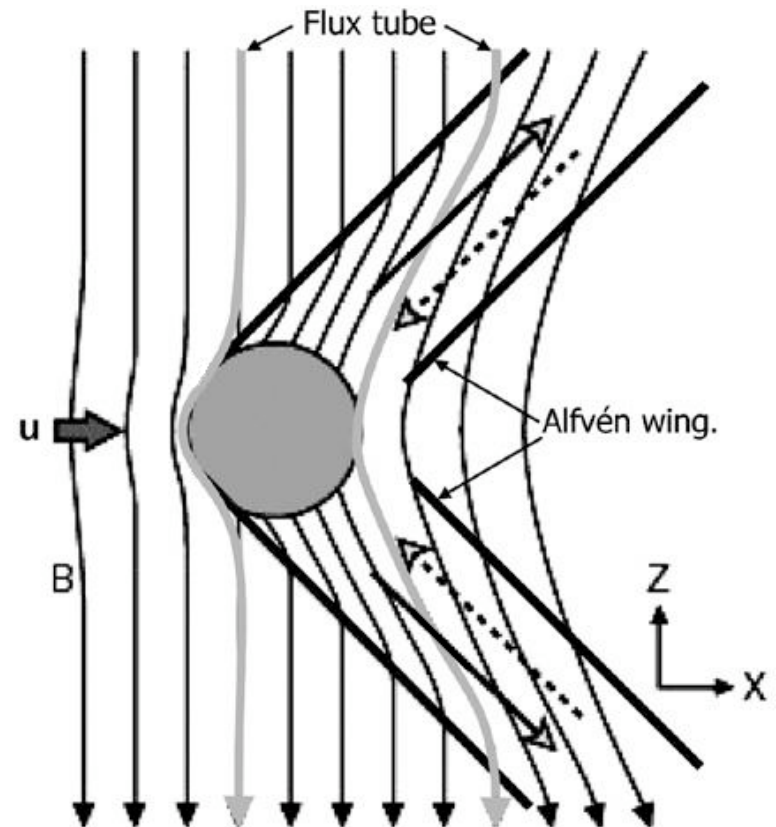
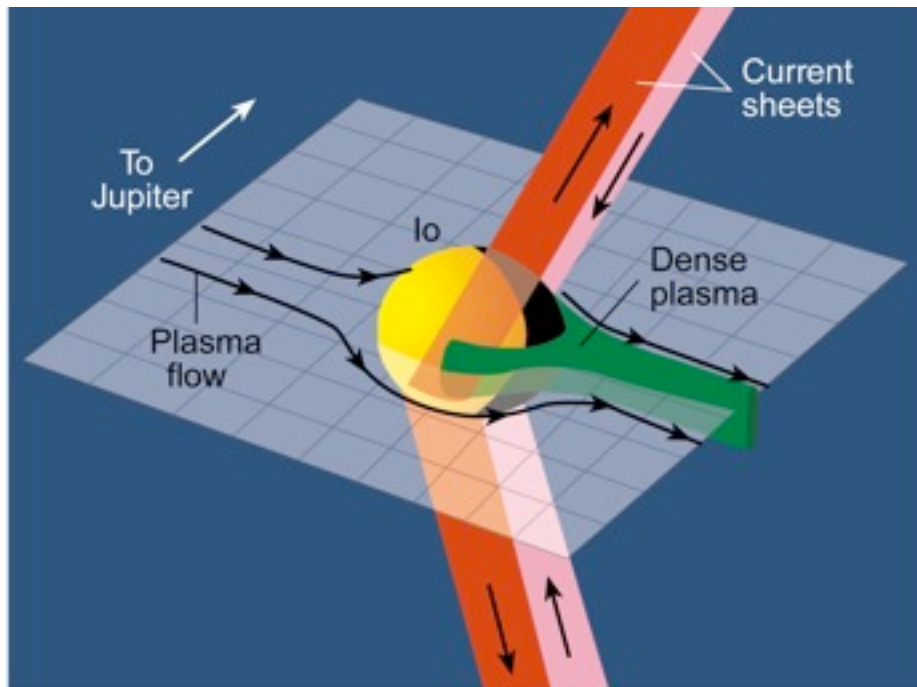
[*Piddington & Drake, 1968; Goldreich & Lynden-Bell, 1969*]

• Current Generators [cont'd]

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

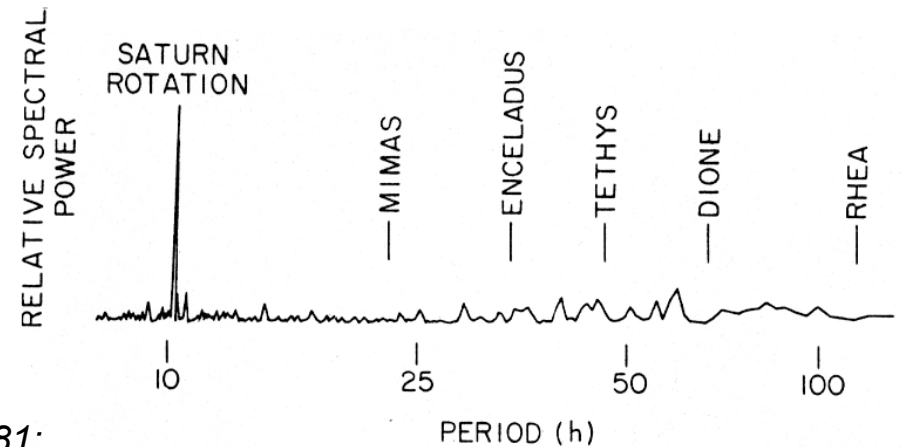
in Jupiter's ionosphere (if $M_A \ll 1$, no $j_\perp$ in MS, $2\int_{B\text{-line}} ds/V_A \ll \int_{\text{flow}} ds/V$ (= unipolar inductor)

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



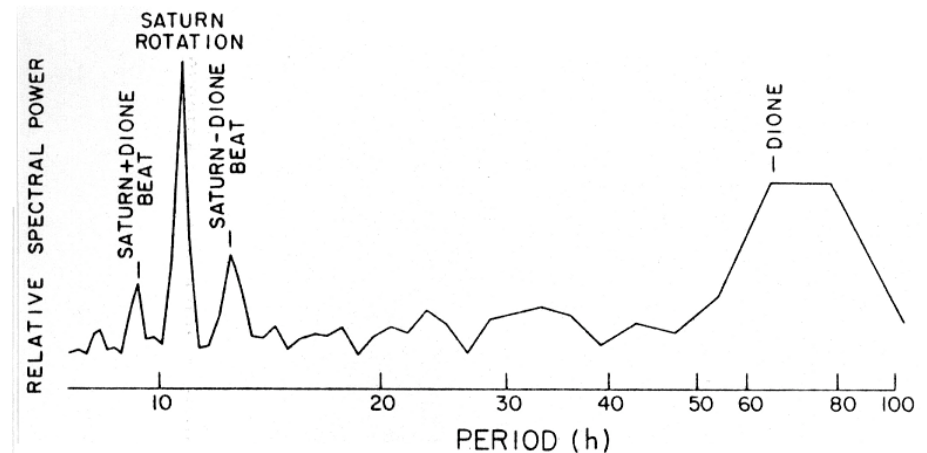
[Kivelson et al., 2004]

• Current Generators [cont'd]



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

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

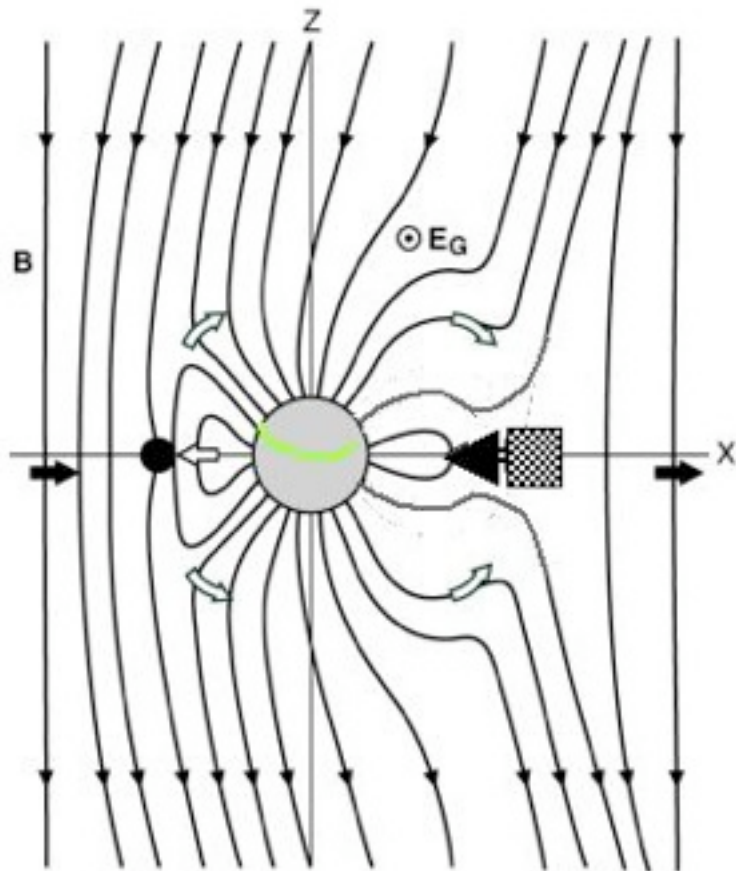


SKR @ 59 kHz, 10-18 Nov. 1980

- Dione interaction with Saturn MS ?
- Enceladus ? (exosphere, B draping [Dougherty et al., 2005])
- Titan, Rhea ? (alternatively super/sub-Alfvénic interaction [Ledvina et al., 2004], induced radio emissions ? [Menietti et al., 2007])

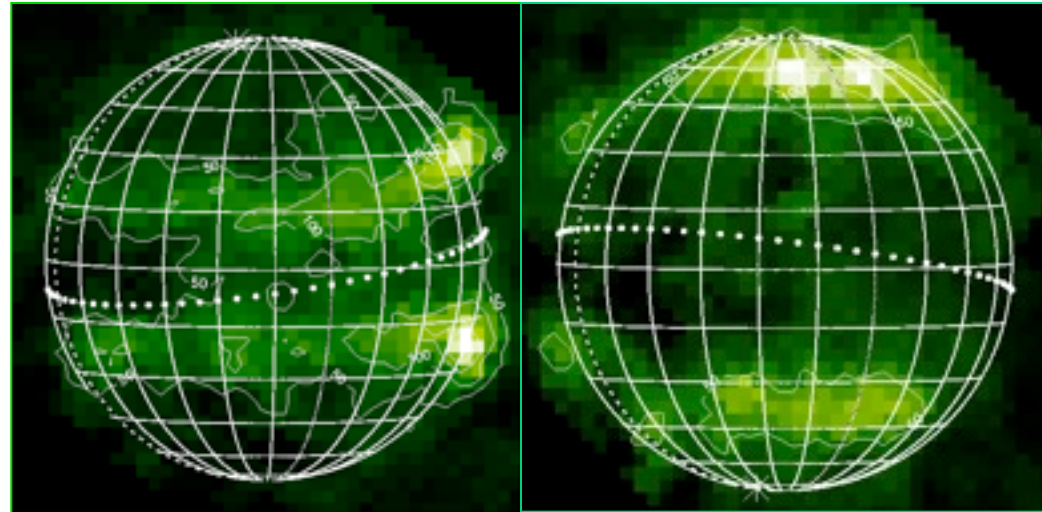
- **Current Generators** [cont'd]

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



- ➡ Torus Plasma Flow
- ⇨ Ganymede's Magnetospheric Flow
- Upstream Reconnection Line
- Downstream Reconnection Line

— open-closed boundary



Downstream / Upstream

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

- In all cases :

$$P_{\text{dissipated}} \sim B_J^2 / 2\mu_0 V k\pi R_{\text{obstacle}}^2$$

[Zarka et al., 2001, 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 ?

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

- Source = 1-10 keV electrons $\Rightarrow$ acceleration required

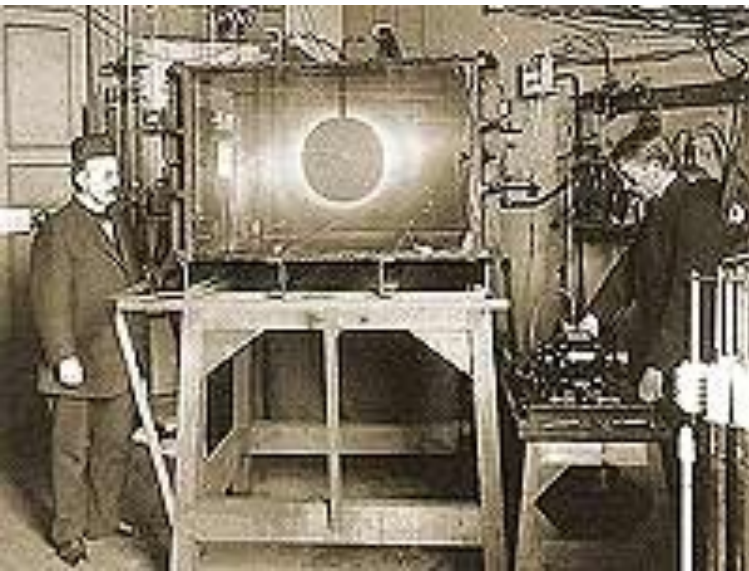
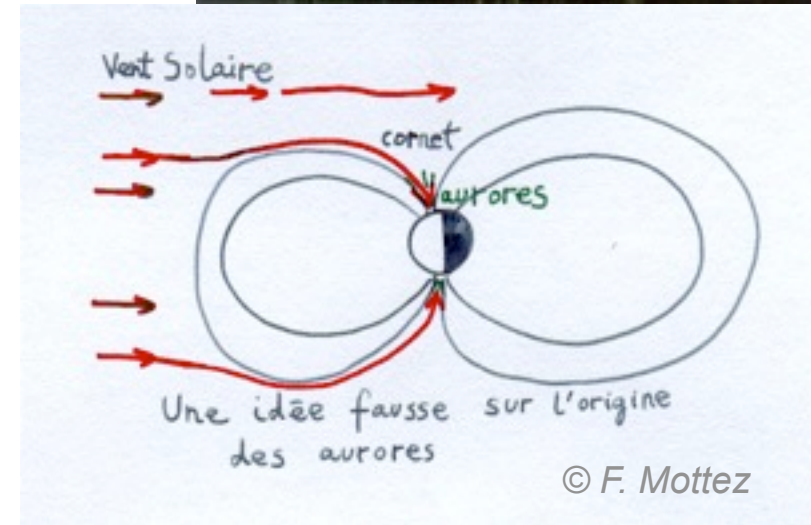
- Strong currents + low plasma density [Knight, 1972]

- Reconnection + dipolarization (adiabatic)

- Compressions, $E_{\parallel}$, waves ...

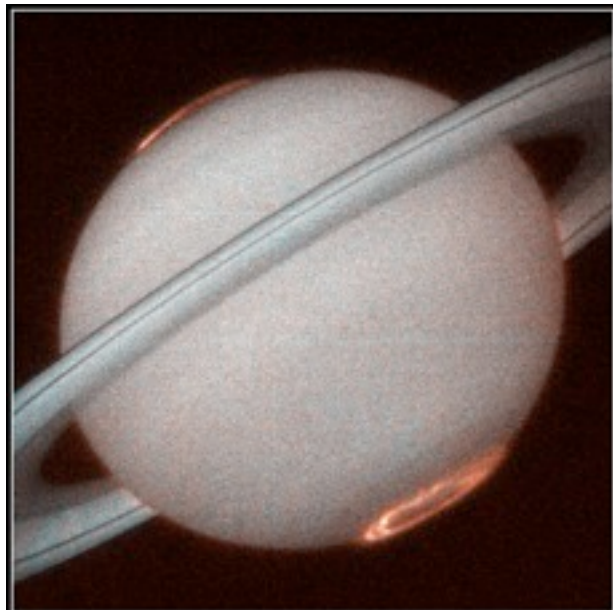
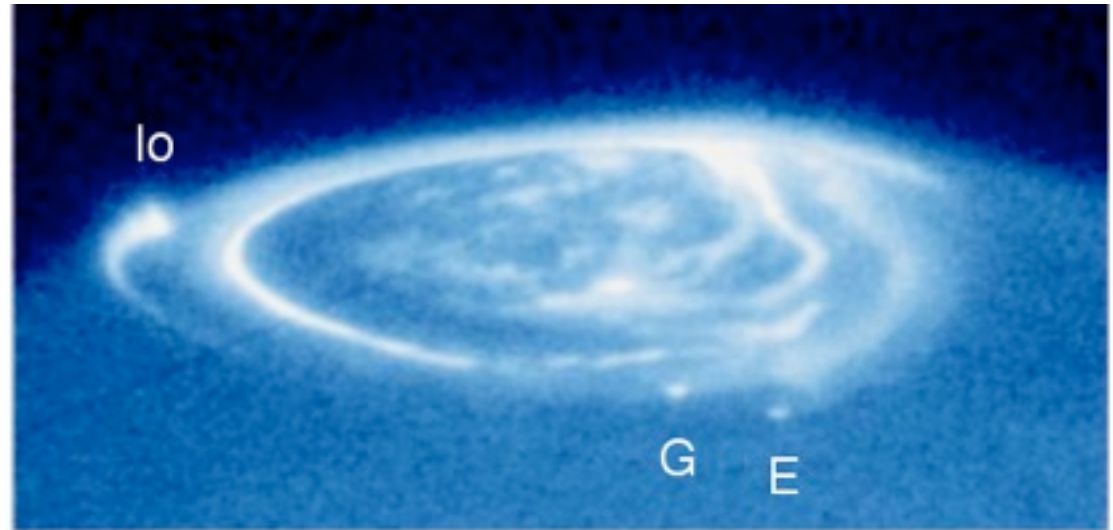
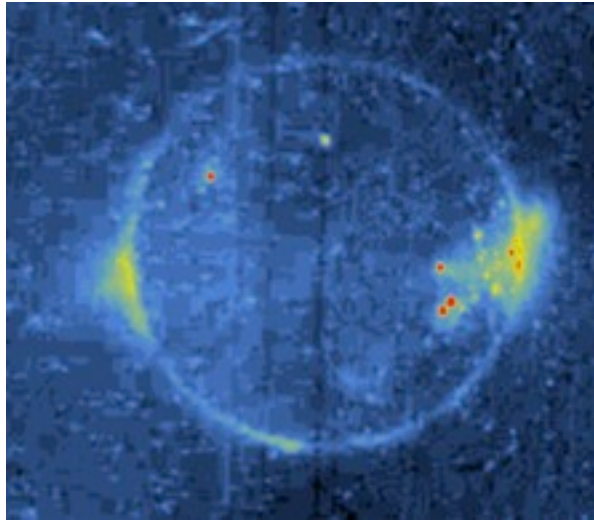
- $\Rightarrow$ UV, IR, radio emissions

- $\neq$ direct precipitation of SW in polar cusps

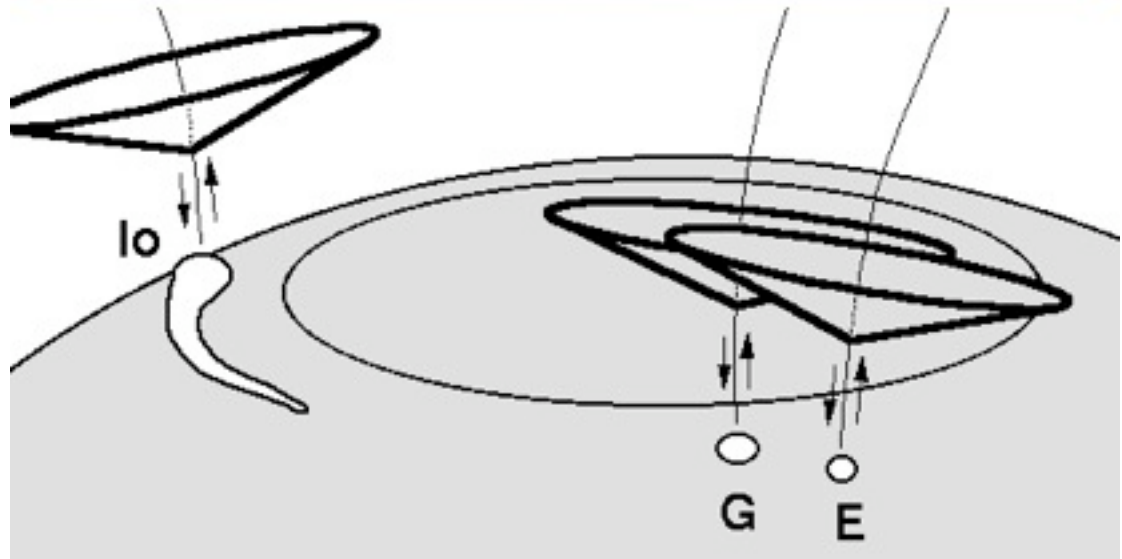


[Birkeland, 1910]

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



Saturn Aurora HST • STIS
PRC98-05 • ST ScI OPO • January 7, 1998 • J. Trauger (JPL) and NASA

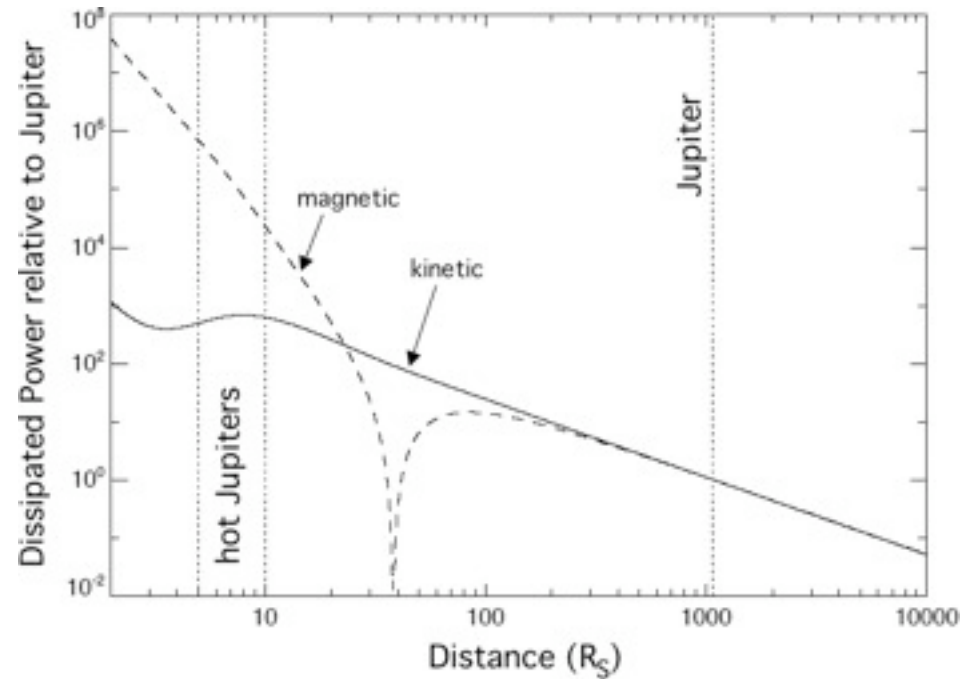
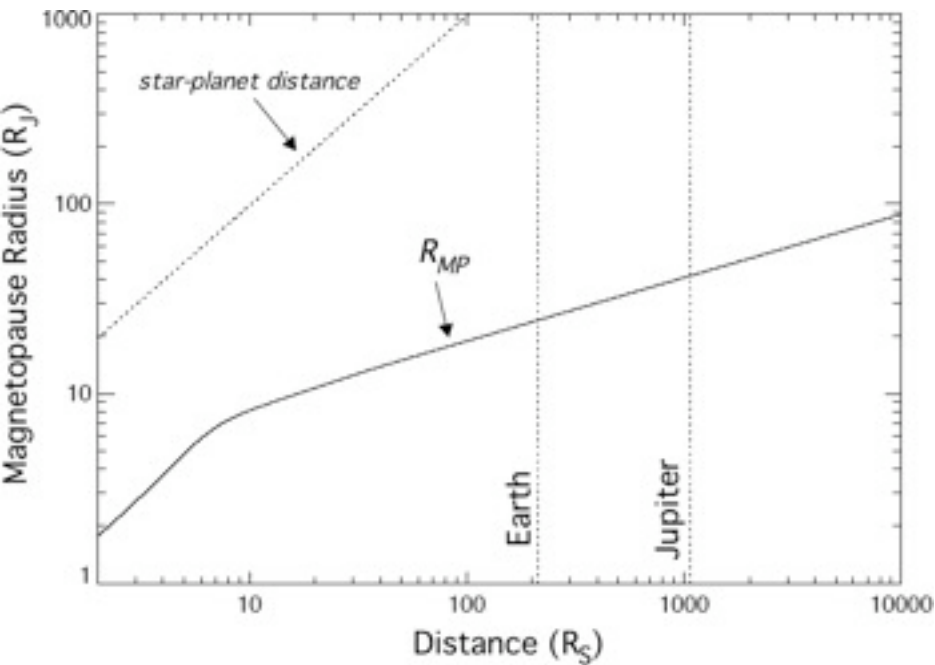


[Clarke, Prangé...]

- 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 ?

• Exoplanetary Magnetospheres ?

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



[Zarka et al., 2001, 2006]

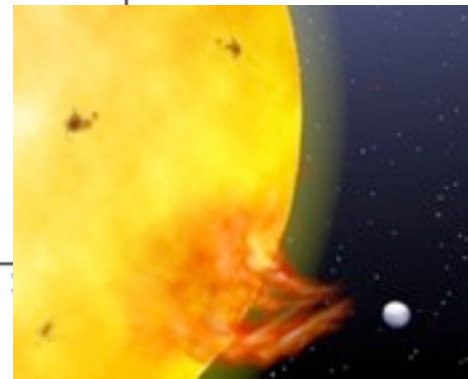
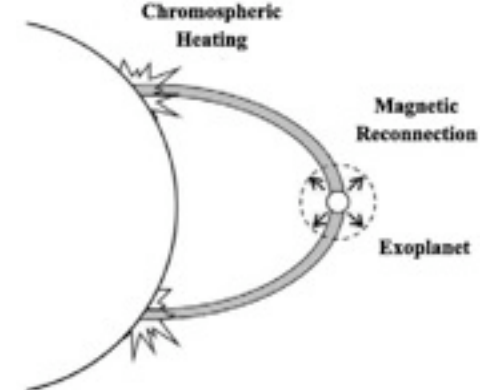
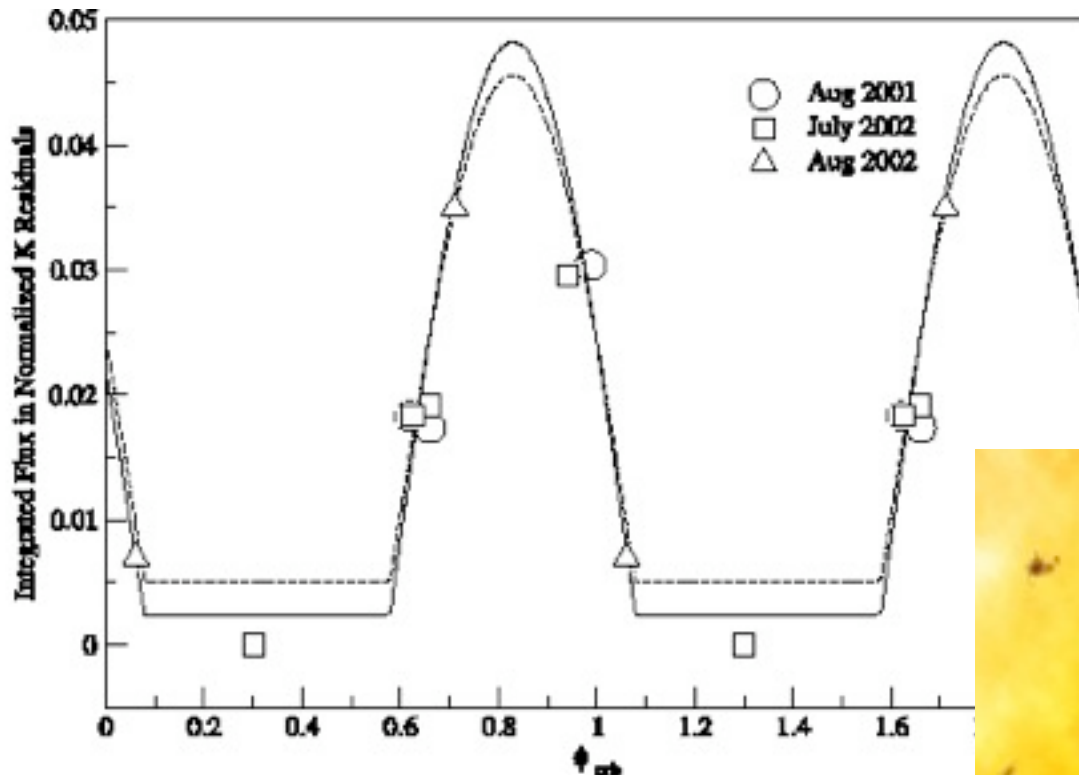
• Exoplanetary Magnetospheres ? [cont'd]

- 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 ?