Radio bursts from Solar System planets and Extrasolar planets

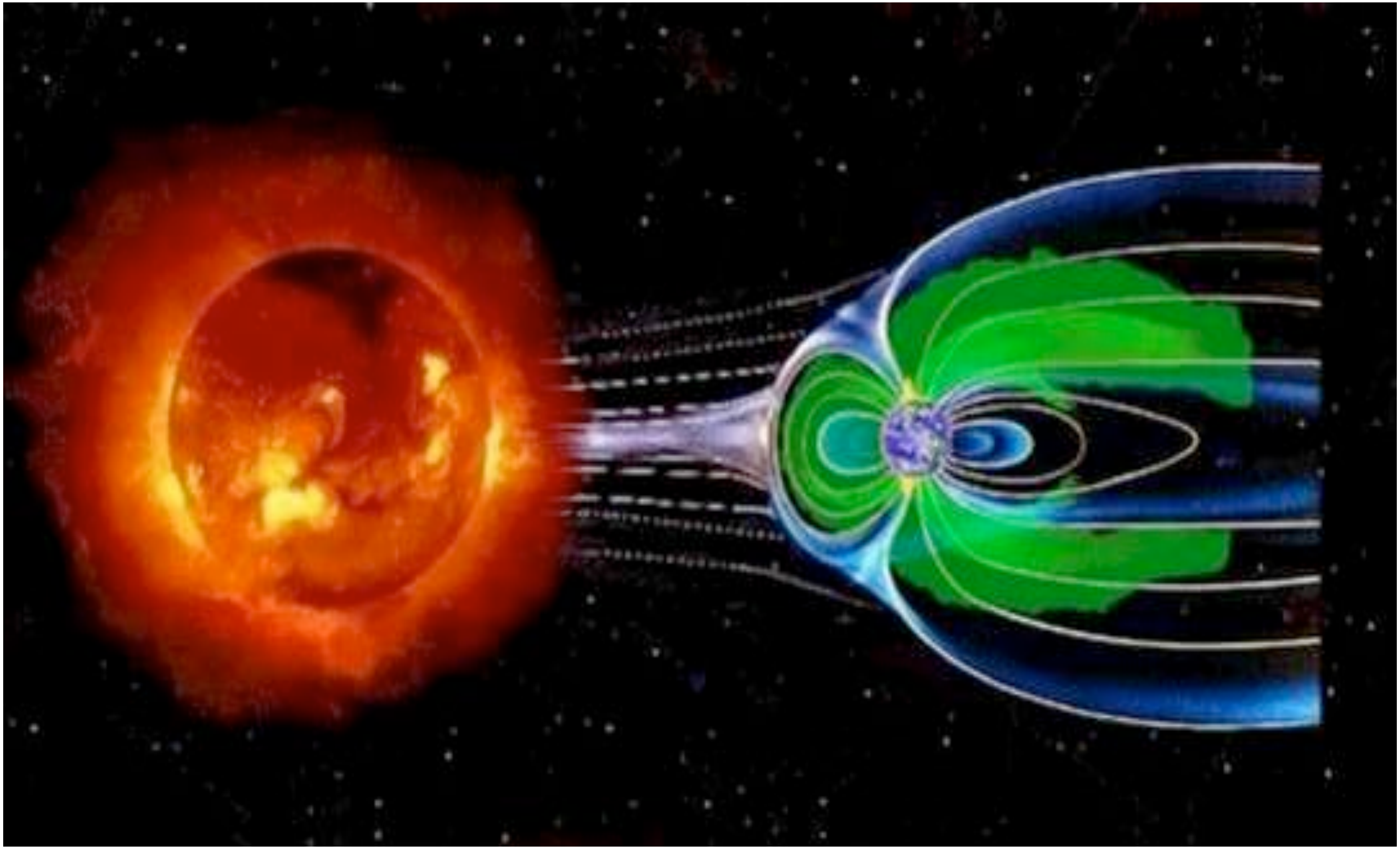
Philippe Zarka

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

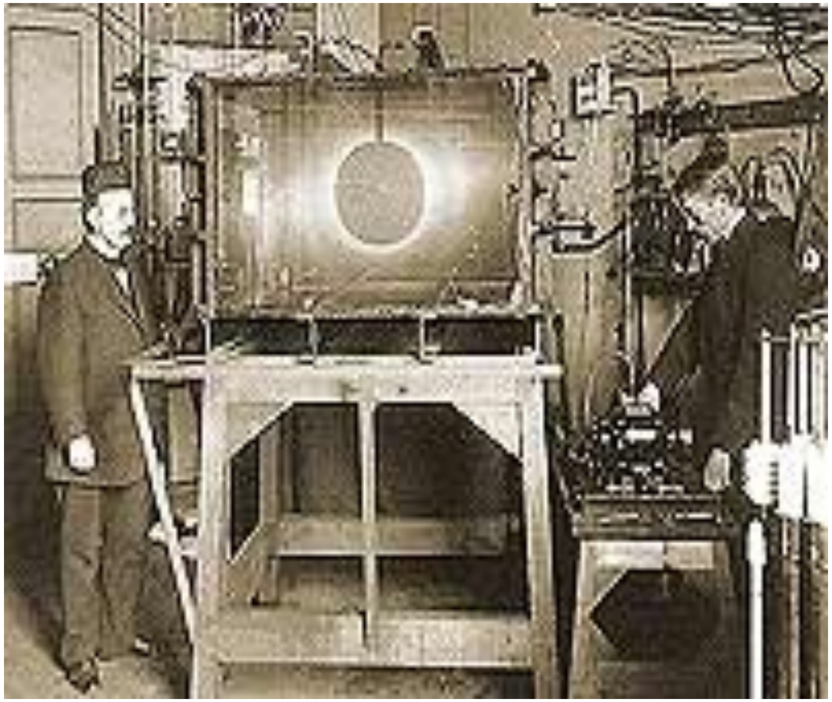
LF planetary radiosources : plasma phenomena

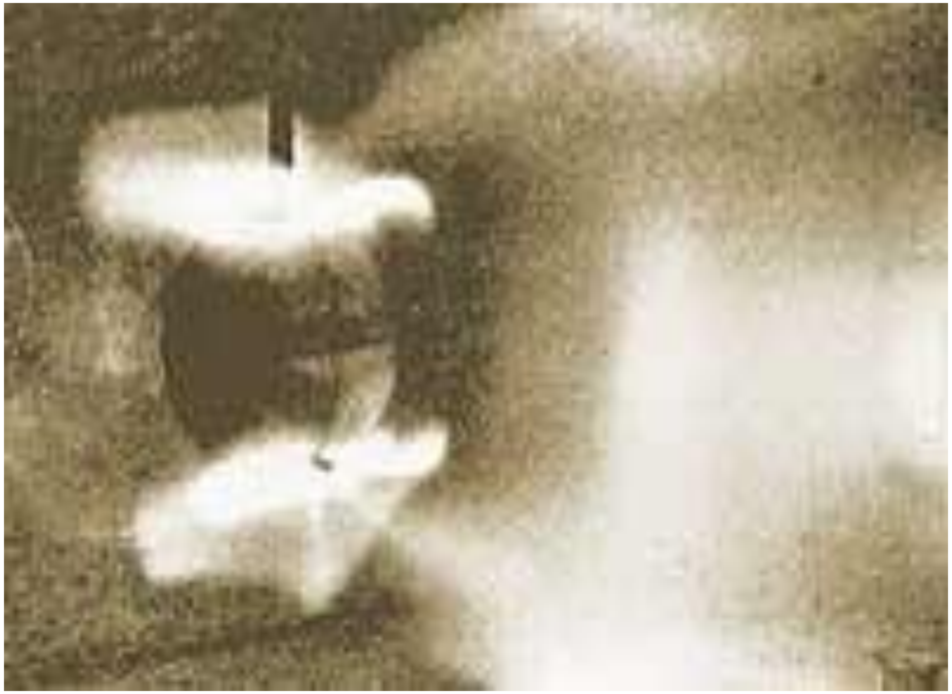
Radio component	**Planet**	**Frequency**	**Radiation process**
Radiation belts	J	<100 MHz - GHz	Synchrotron (incoherent)
Auroral	E J S U N	10's kHz - 10's MHz	Cyclotron Maser (coherent)
Satellite induced	J (I,G,C?) S?	100's kHz - 10's MHz	Cyclotron Maser (coherent)
Lightning	E (J) S U (N)	kHz - 10's MHz	Antenna radiation (current discharge)
VLF e.m. (NTC, nKOM…)	E J S U N	≤10's – 100 kHz	Mode conversion e.s.→ e.m. Instabilities ~f_{pe}, f_{UH} ?

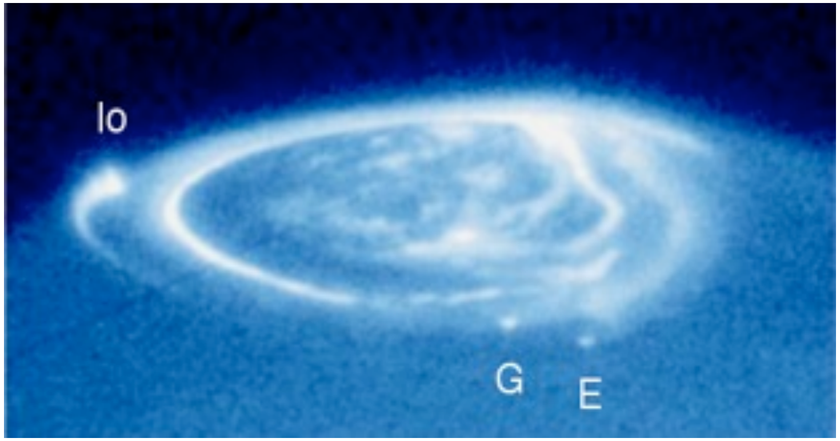
Solar wind - magnetosphere interaction



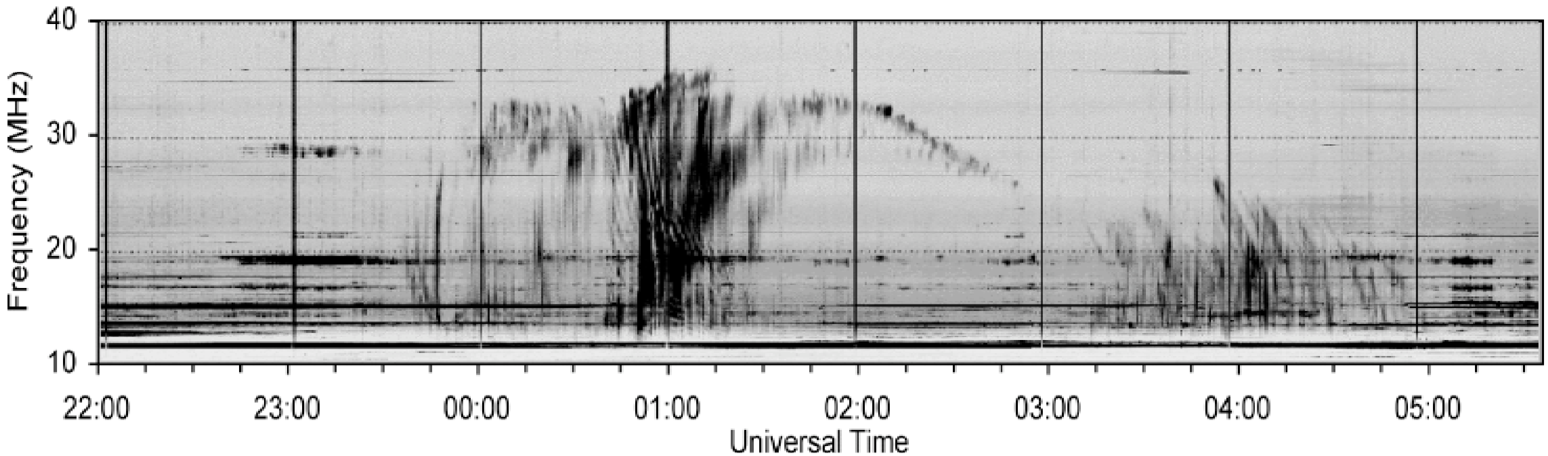
Aurora …

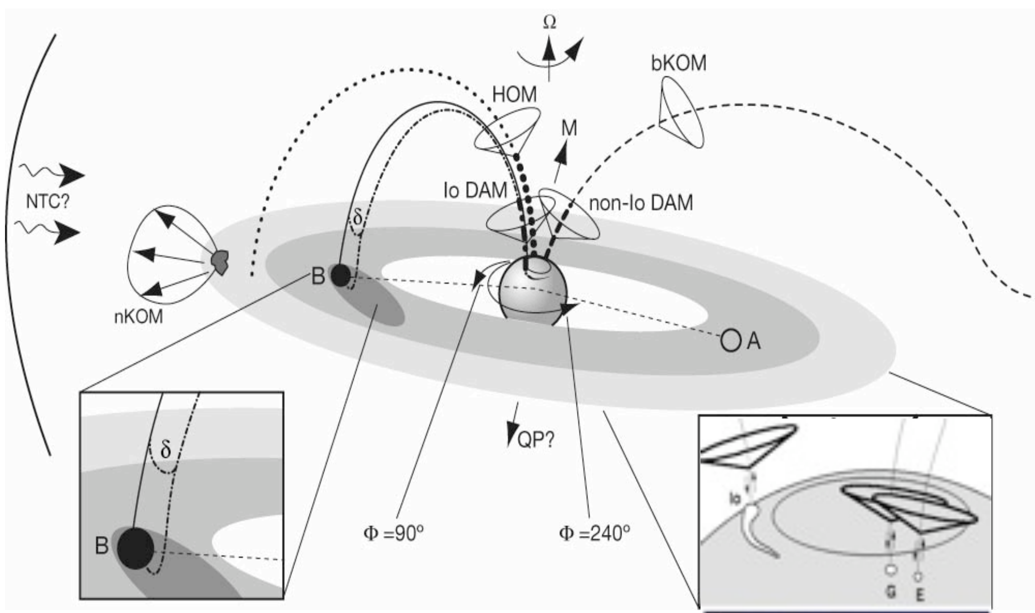




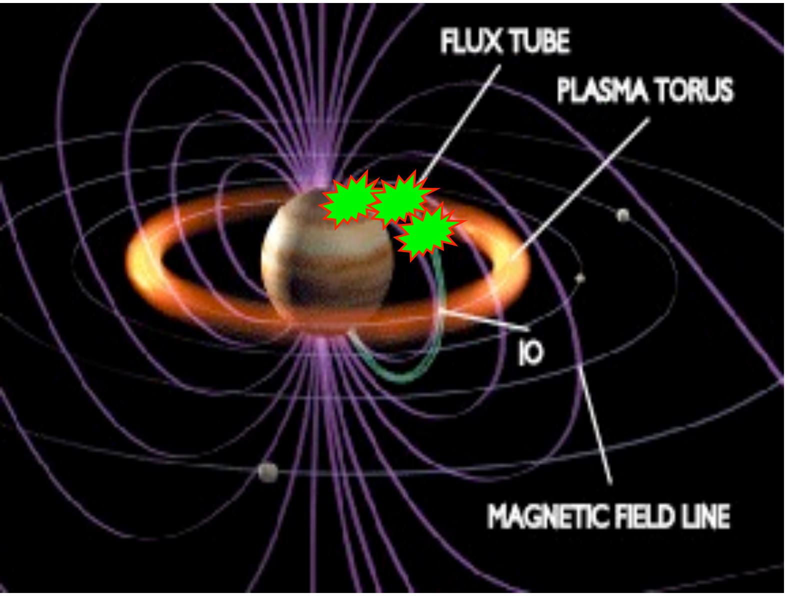


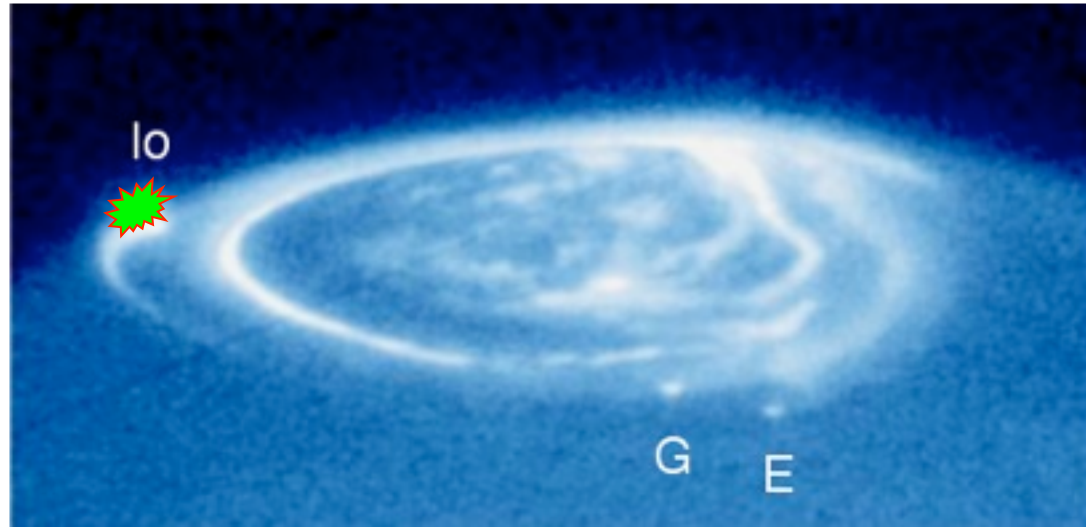
… and radio emissions

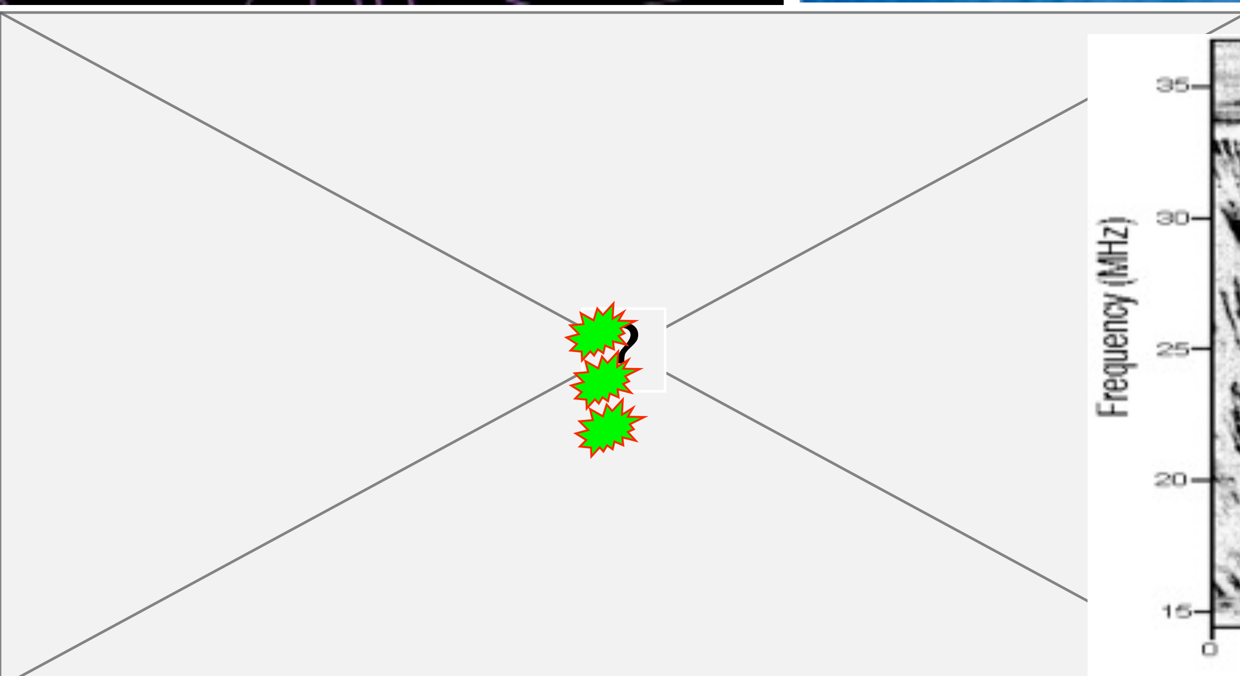


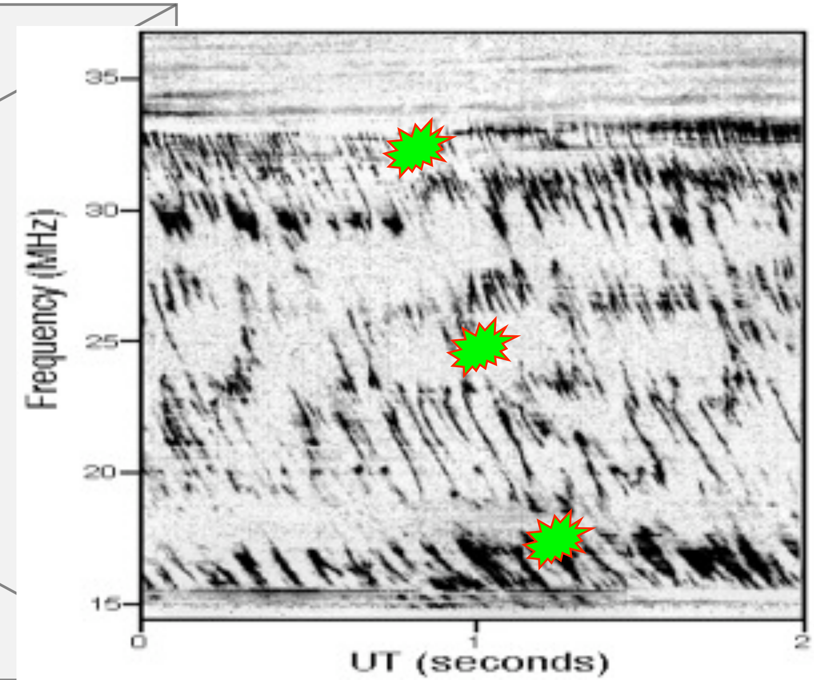


Io-Jupiter electrodynamic interaction and radio bursts



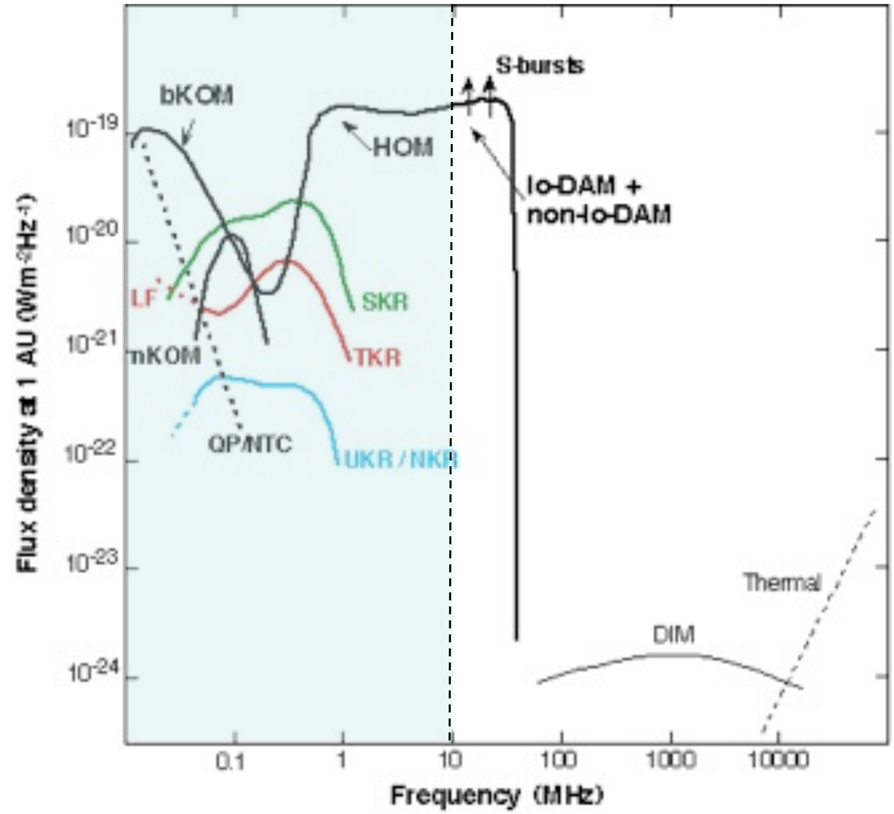






Properties of « auroral » radio emissions

- sources where B, $f_{pe} \ll f_{ce}$, keV e- → generally high latitude
- very intense : $T_B > 10^{15}$ K
- $f \sim f_{ce}$, $\Delta f \sim f$
- circular/elliptical polarization (X mode)
- very anisotropic beaming (conical ~30°-90°, $\Omega \ll 4\pi$ sr)
- variability /t (bursts, rotation, solar wind, CME…)
- correlation radio / UV
- radiated power : 10^{6-11} W



Generation of « auroral » radio emissions

- Coherent cyclotron emission : 2 conditions within sources :

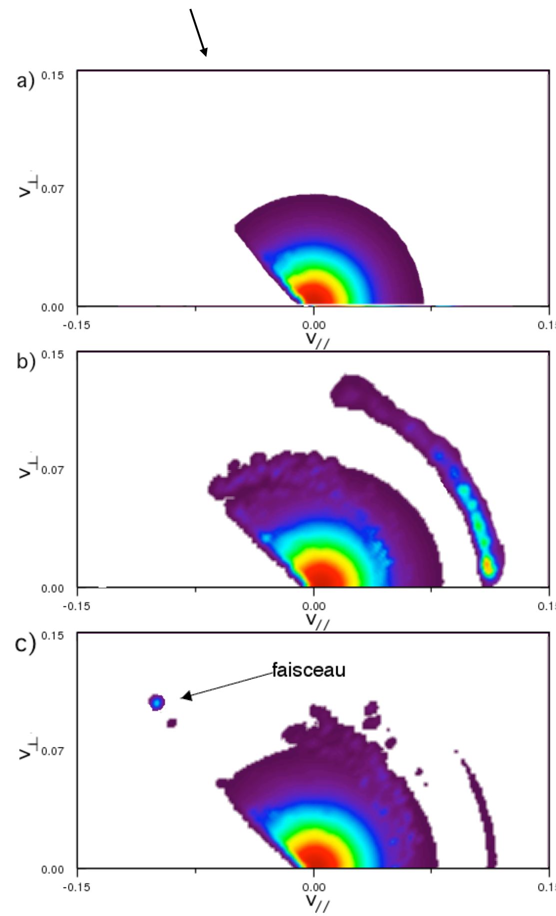
  - low β magnetized plasma ($f_{pe} \ll f_{ce}$)

  - energetic electrons (keV) with non-Maxwellian distribution

→ high magnetic latitudes

→ direct emission at $f \sim f_x \approx f_{ce}$, at large angle /B

up to 1-5% of e- energy in radio waves, bursts



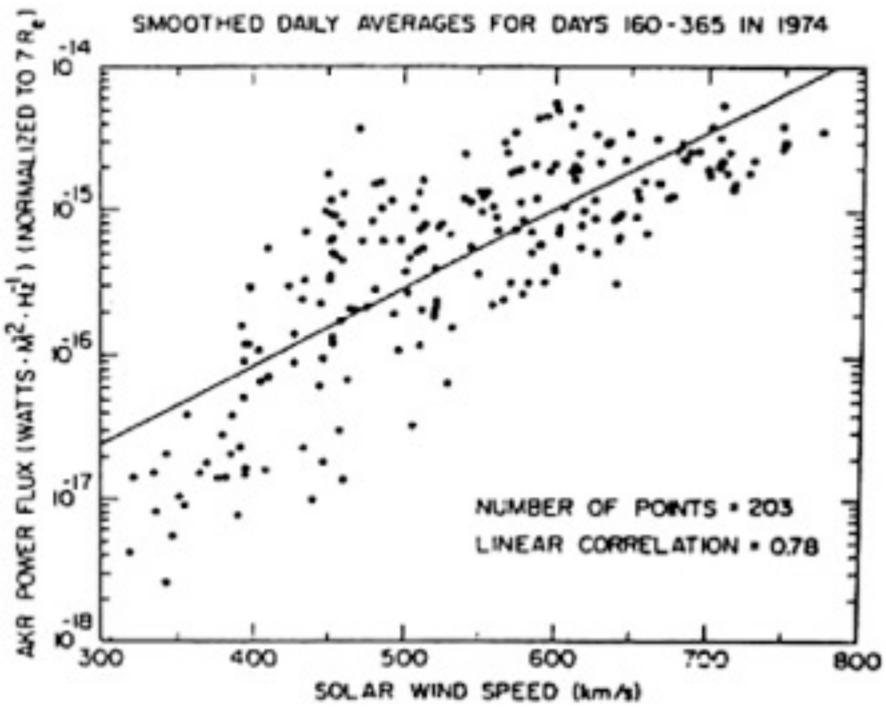
- Acceleration of electrons :

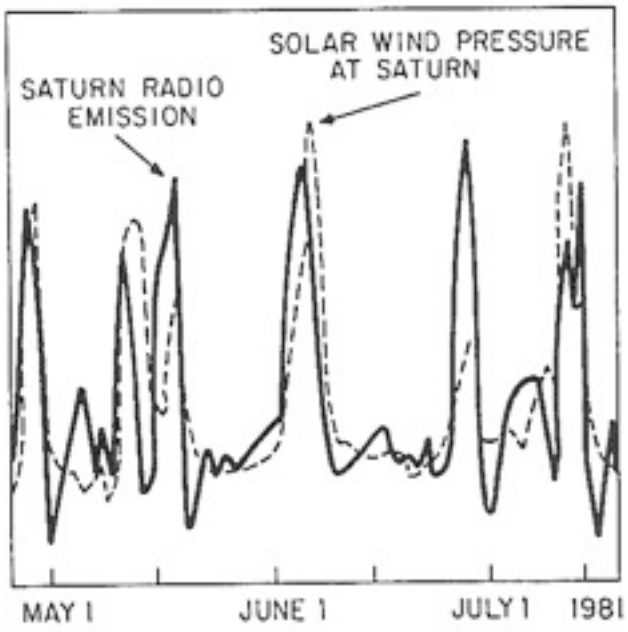
  - magnetic reconnections

  - MS compressions

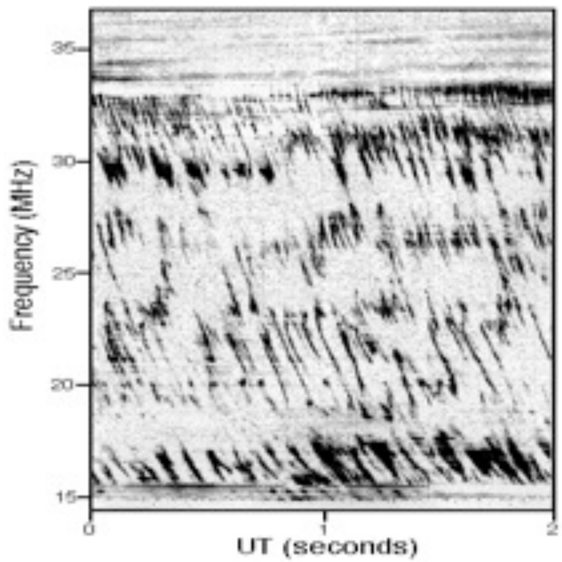
  - interactions B/satellites → $E_{//}$

Strong correlation between Solar Wind (P, V…) and auroral radio emissions





Electron bunches & electric fields along Io flux tube

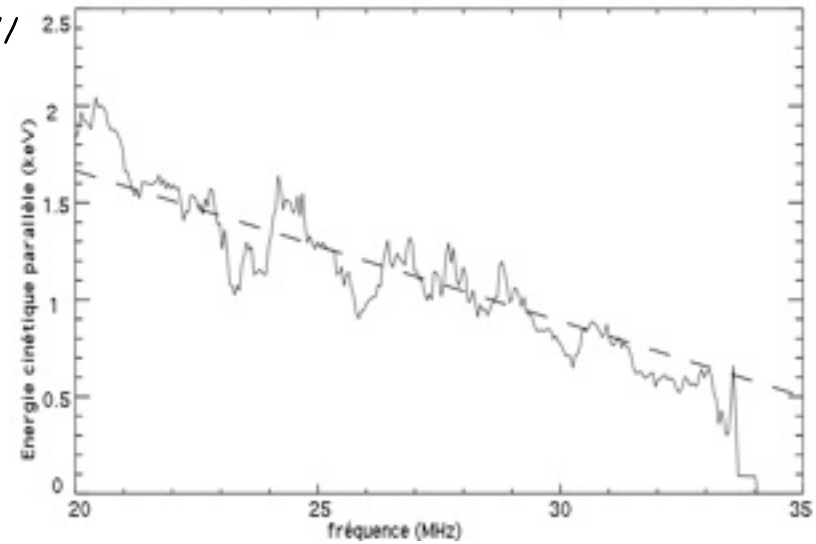


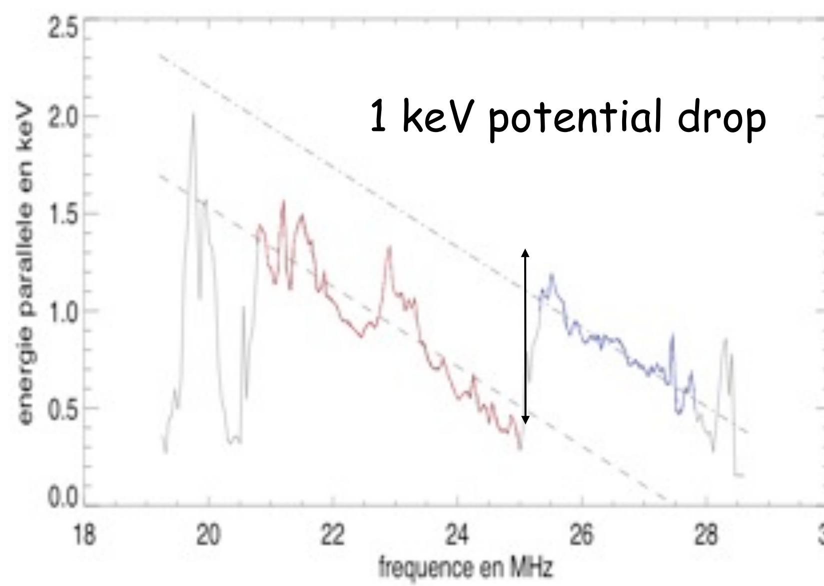
e- adiabatic motion

$\rightarrow v^2_{//} = v^2 - v^2_{\perp} = v^2 - \mu . f_{ce}$

[Hess et al., 2007]

$v^2_{//}$

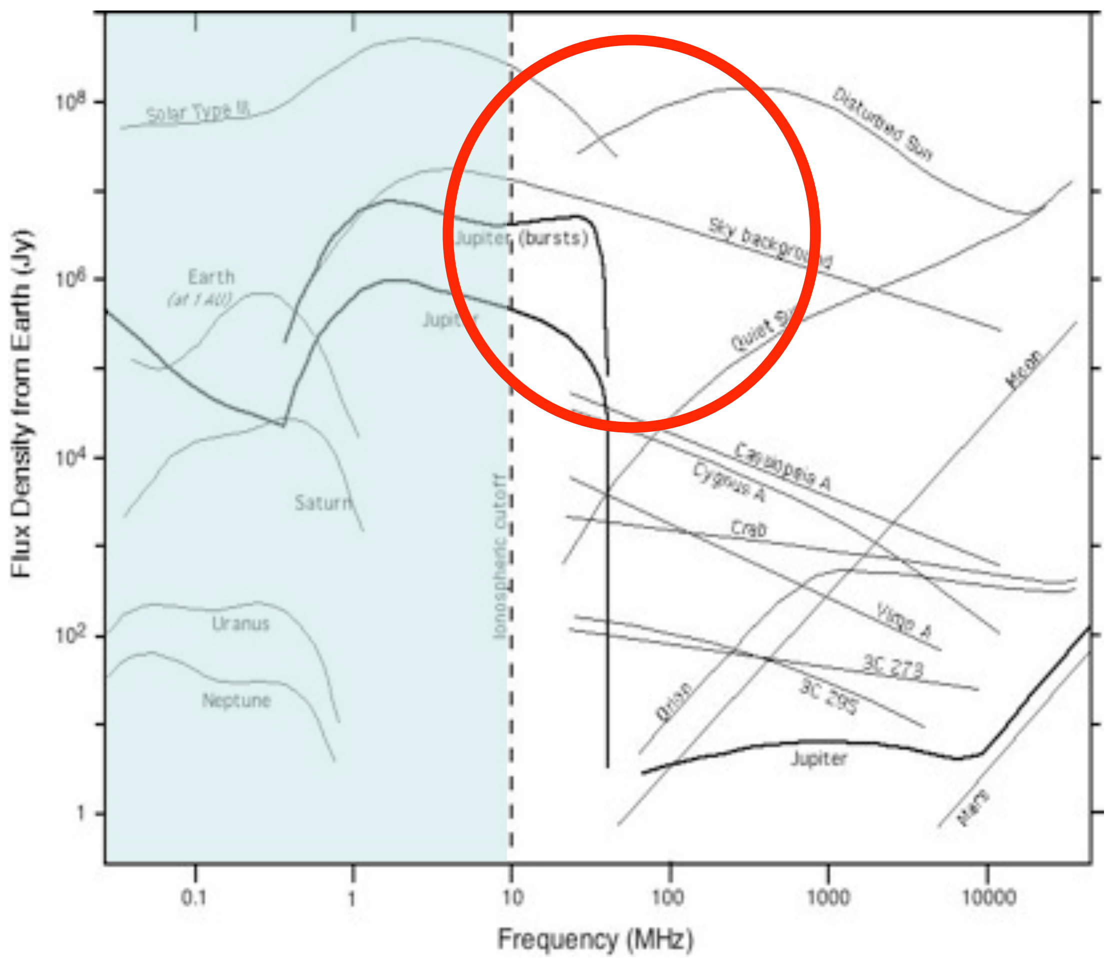




f_{ce}

Interest of Radio observations

« Plasma » processes ➔ Contrast Sun/Jupiter ~1 !



Sensitivity of observations

• <u>Galactic radio background</u>: $T \sim 1.15 \times 10^8 / \nu^{2.5} \sim 10^{3\text{-}5}$ K (10-100 MHz)

→ statistical fluctuations $\sigma = 2kT/A_e(b\tau)^{1/2}$

→ $N = s / \sigma$ with $s = \zeta\, S_J / d^2$

$S_J \sim 10^{-18}$ Wm^{-2}Hz^{-1} (10^8 Jy) à 1 UA

• <u>Maximum distance for Nσ detection of a source ζ x Jupiter</u> :

$$d_{max} = (\zeta S_J A/2NkT)^{1/2}(b\tau)^{1/4}$$

$$\Rightarrow \quad d_{max}\,(pc) = 5\times10^{-8}\,(A_e\,\zeta)^{1/2}\, f^{5/4}\,(b\tau)^{1/4}$$

Maximum distance of detectability of Jupiter's radio emissions

	$b\tau = 10^6$ (1 MHz, 1 sec)		$b\tau = 2\times10^8$ (3 MHz, 1 min)		$b\tau = 4\times10^{10}$ (10 MHz, 1 hour)	
	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz
$A_e = 10^4\ m^2$ (~NDA)	0.003	0.05	0.01	0.2	0.04	0.7
$A_e = 10^5\ m^2$ (~UTR-2)	0.01	0.2	0.03	0.6	0.1	2.2
$A_e = 10^6\ m^2$ (~LOFAR77)	0.03	0.5	0.1	2.	0.4	7.

(distances in parsecs)

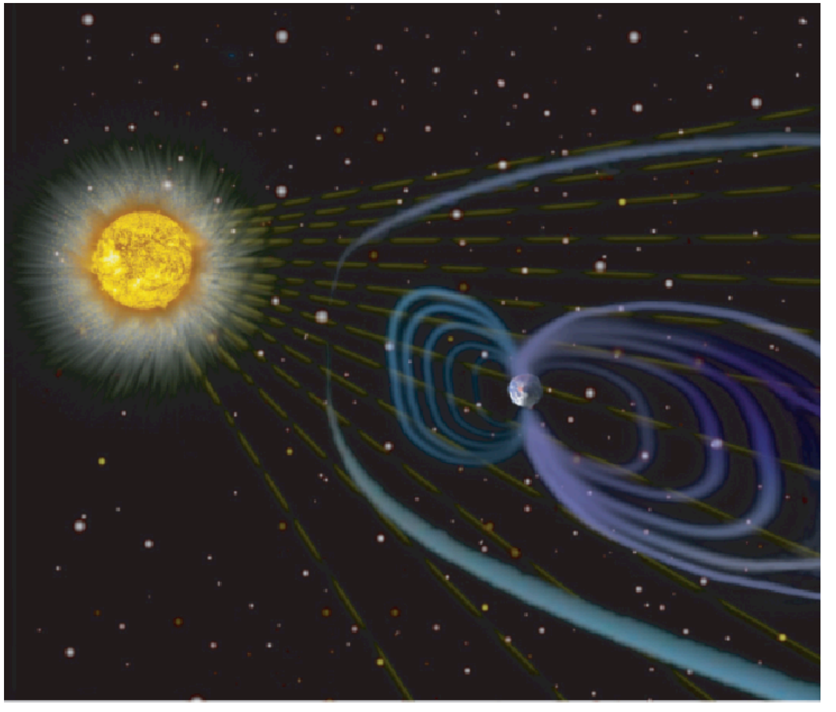
Radio emission from exoplanets ?

Theory

- Zarka, P., Plasma interactions of exoplanets with their parent star and associated radio emissions, Planet. Space Sci., 55, 598-617, 2007 (not a review paper).

- Zarka, P., R. A. Treumann, B. P. Ryabov, and V. B. Ryabov, Magnetically-driven planetary radio emissions and applications to extrasolar planets, Astrophys. Space Sci., 277, 293-300, 2001.

Flow-obstacle interaction

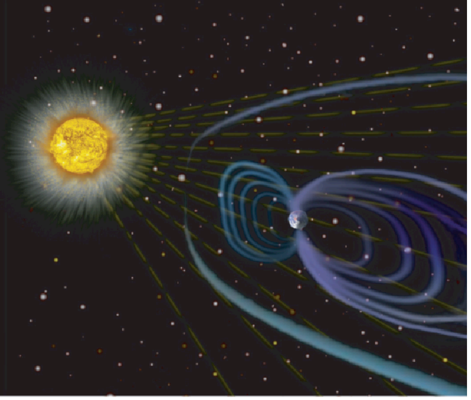


- Kinetic energy flux on obstacle cross-section : $P_k \sim \; NmV^2 \, V \; \pi R_{obs}{}^2$

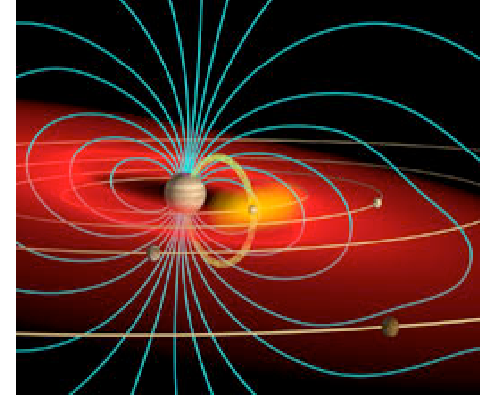
  $N = N_o/d^2 N_o = 5 \text{ cm}^{-3}$ $\quad m \sim 1.1 \times m_p$

- Poynting flux of B_{IMF} on obstacle cross-section : $P = \int_{obs} (\mathbf{E} \times \mathbf{B}/\mu_o).\mathbf{dS}$

$\mathbf{E} = -\mathbf{V} \times \mathbf{B} \rightarrow \mathbf{E} \times \mathbf{B} = VB_\perp{}^2 \quad \rightarrow \quad P_m = B_\perp{}^2/\mu_o \; V \; \pi R_{obsP}{}^2$



Flow-obstacle interactions



Flow / Obstacle	Weakly/Not magnetized *(Solar wind)*	Strongly magnetized *(Jovian magnetosphere)*
Weakly/Not magnetized *(Venus, Mars, Io)*	No Intense Cyclotron Radio Emission	<u>Unipolar interaction</u> → Io-induced Radio Emission,
Strongly magnetized *(Earth, Jupiter, Saturn, Uranus, Neptune, Ganymede)*	<u>Magnetospheric Interaction</u> → Auroral Radio Emissions : E, J, S, U, N,	<u>Dipolar interaction</u> → Ganymede-induced Radio Emission

Solar Wind expansion

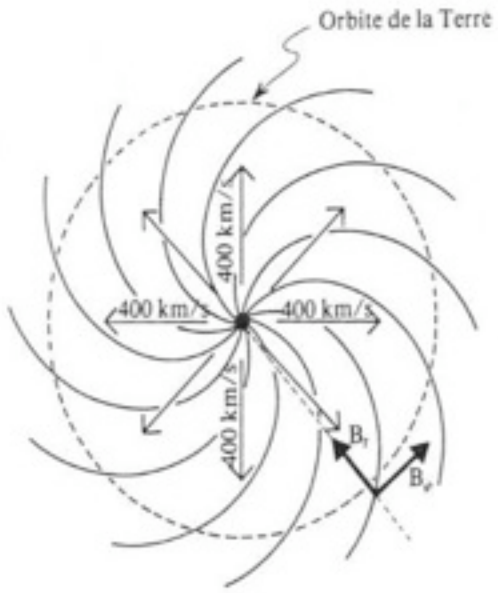
$V \sim c^{te}$

$N \sim d^{-2}$ (mass conservation)

$B_R \sim d^{-2}$ (magnetic flux conservation)

$B\varphi \sim d^{-1}$ $(B_R/B\varphi = V/\Omega d) \rightarrow B \sim d^{-1}$

(beyond Jupiter orbit, $B \sim B\varphi$)

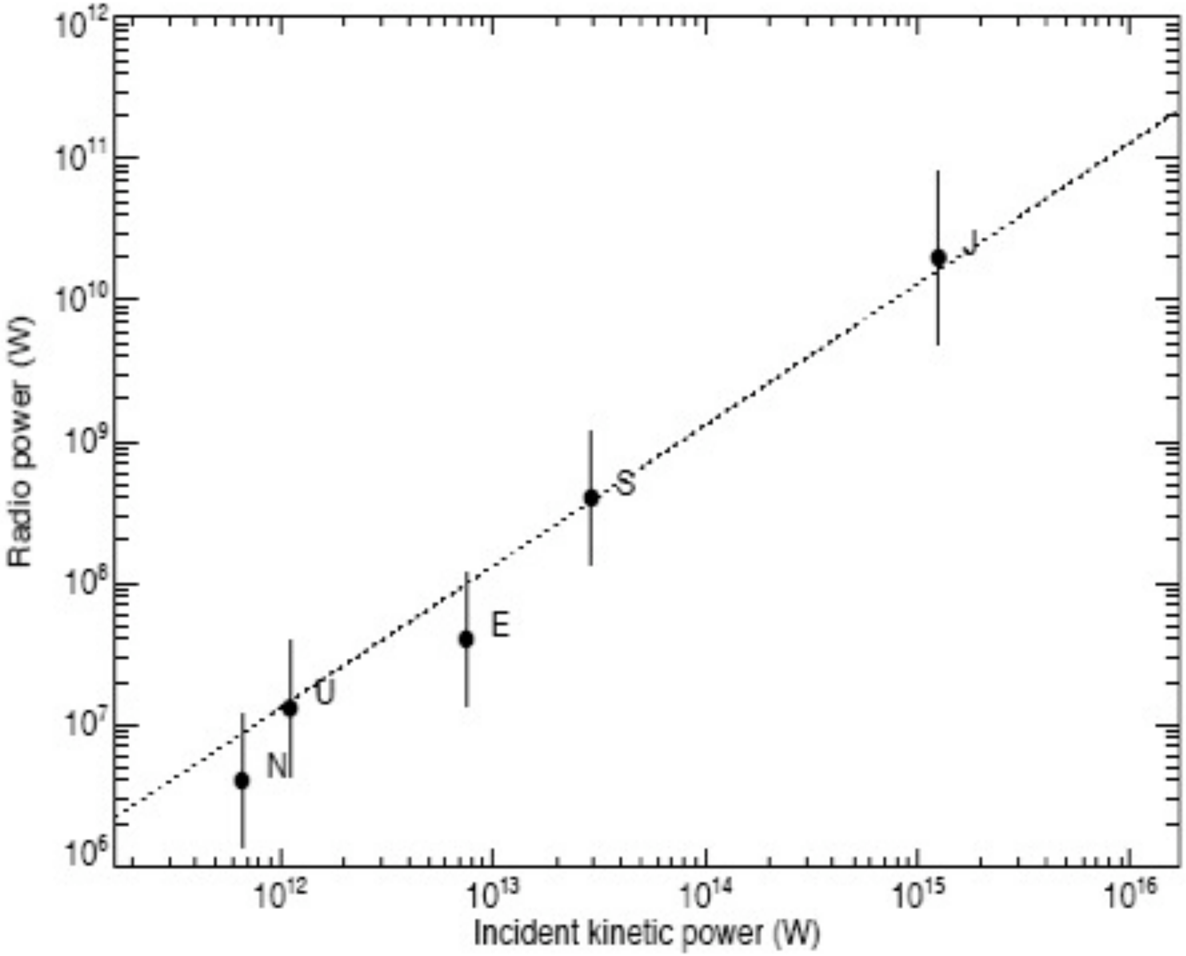


→ B^2 varies as NV^2 thus P_C varies as P_B

→ $P_C / P_B \sim 170$ beyond 1 UA

« Radio-kinetic Bode's law » (auroral emissions)

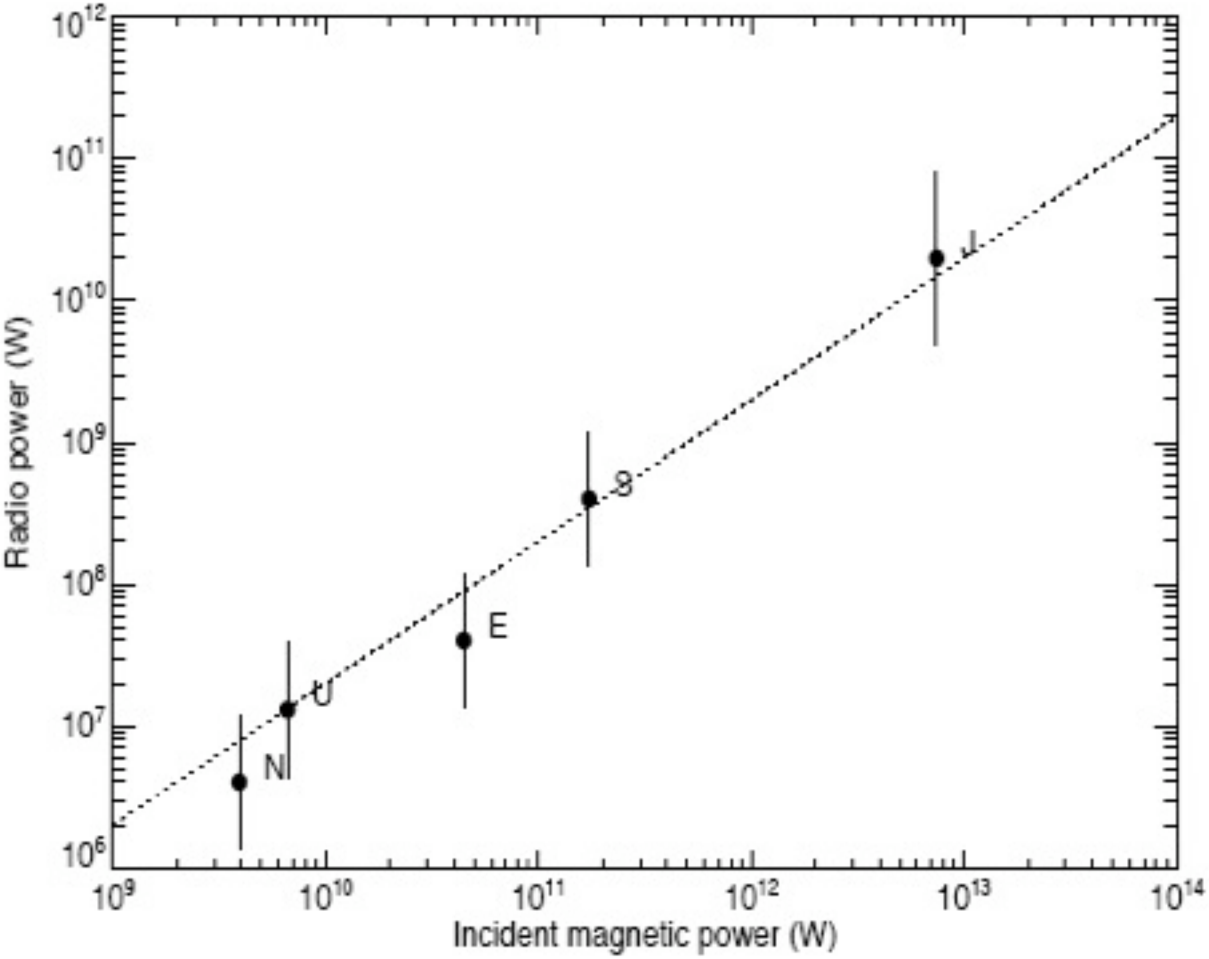
$P_{Radio} \sim \eta_1 \times P_C$ with $\eta_1 \sim 10^{-5}$



[Desch and Kaiser, 1984 ; Zarka, 1992]

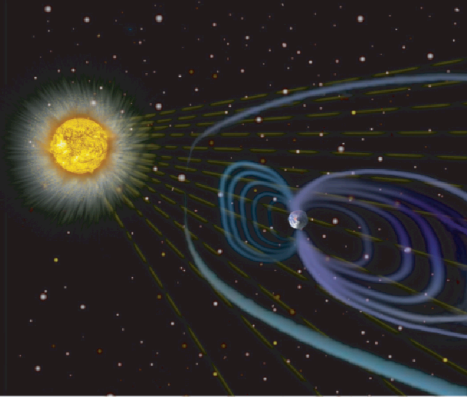
« Radio-magnetic Bode's law » (auroral emissions)

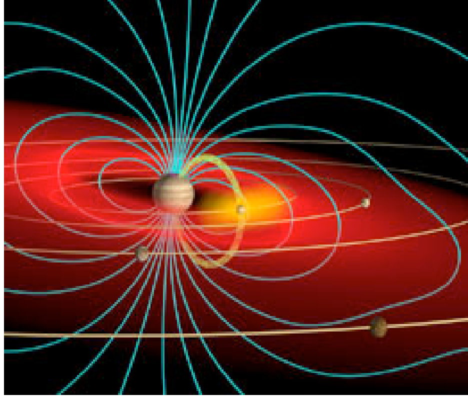
$P_{Radio} \sim \eta_2 \times P_B$ with $\eta_2 \sim 2\times10^{-3}$



[Zarka et al., 2001]

Flow-obstacle interactions





Obstacle \ Flow	Weakly/Not magnetized *(Solar wind)*	Strongly magnetized *(Jovian magnetosphere)*
Weakly/Not magnetized *(Venus, Mars, Io)*	No Intense Cyclotron Radio Emission	<u>Unipolar interaction</u> → Io-induced Radio Emission,
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Dipolar interaction

- Magnetic reconnection

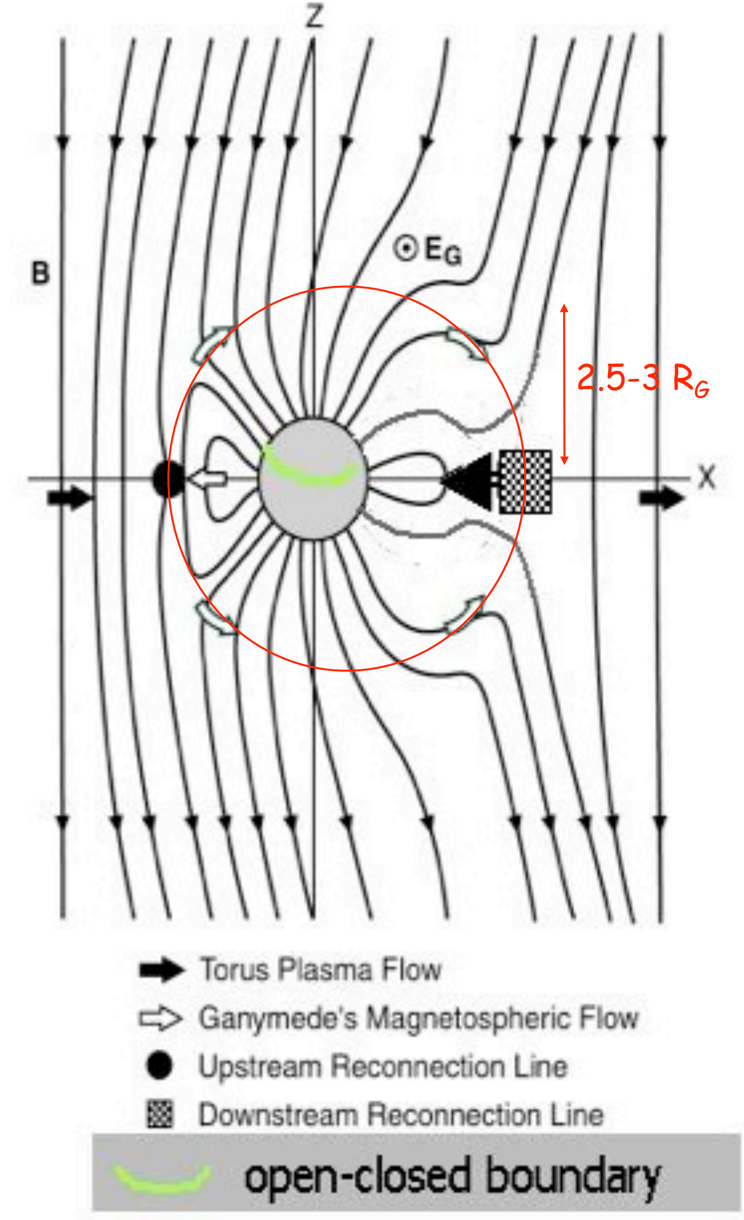
  (e.g. Ganymede-Jupiter)

$P_d = \varepsilon\ K\ V B_\perp^2/\mu_o\ \pi R_{MP}^2$

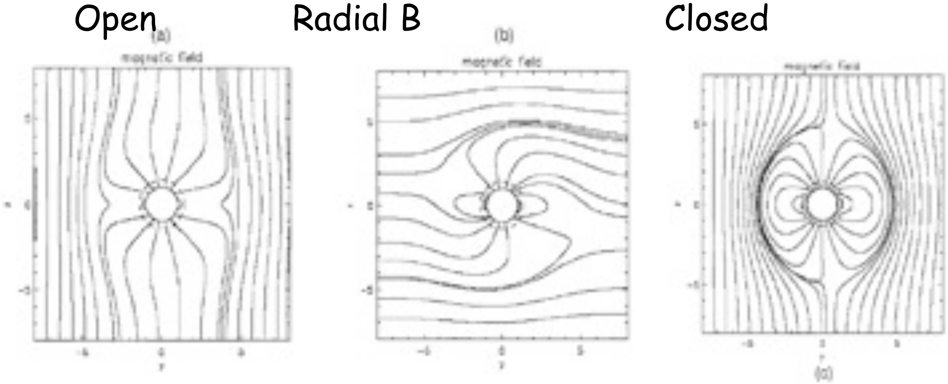
Efficiency $\varepsilon \sim 0.1\text{–}0.2$

K= $\sin^4(\theta/2)$ ou $\cos^4(\theta/2)$ 0 or 1

→ $P_d = \varepsilon\ P_B$



Open Radial B Closed



Unipolar interaction

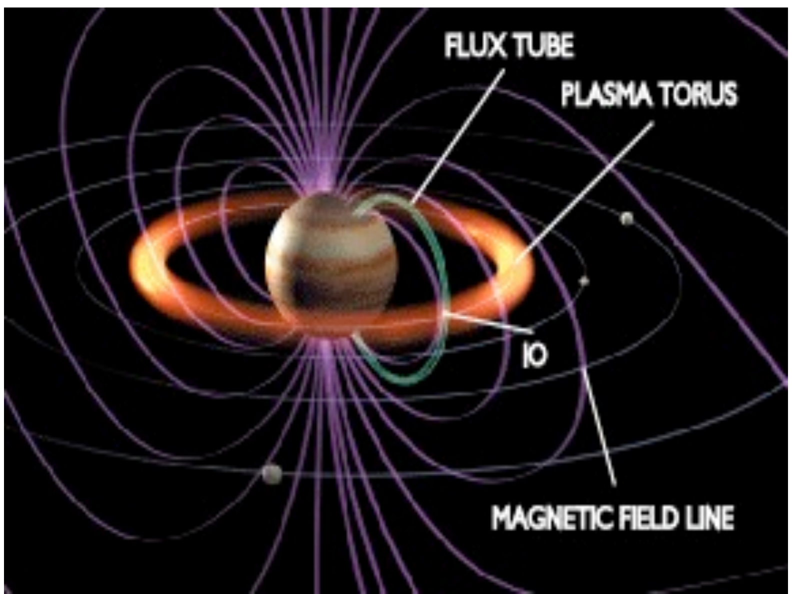
- Interaction via Alfvén waves & currents

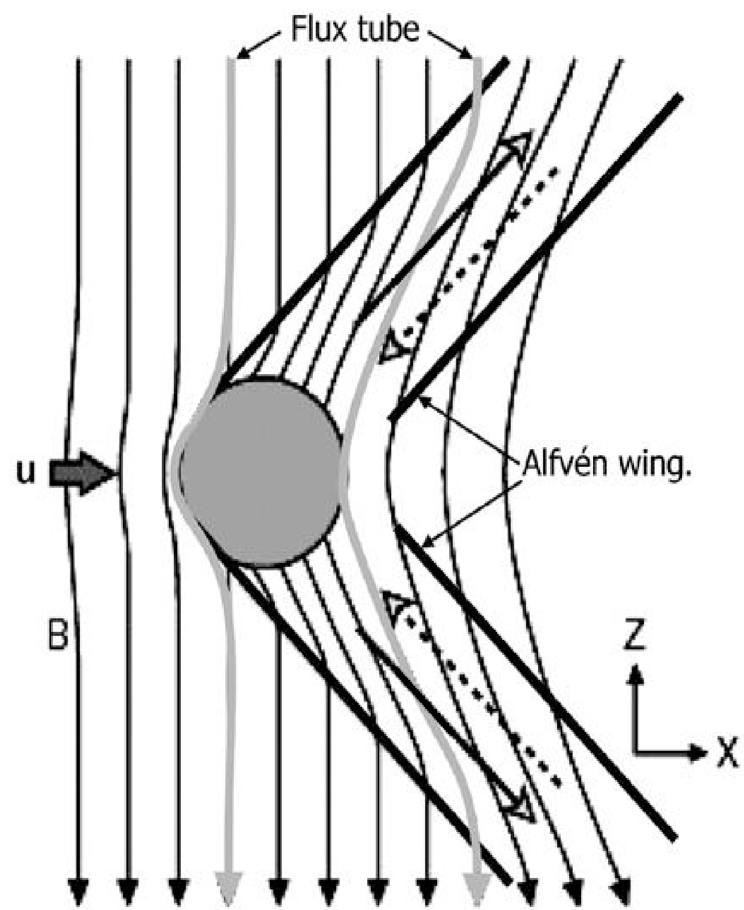
(e.g. Io-Jupiter) $\phi = E\times 2R_{obs} = V\times B_{\perp}\times 2R_{obs}$

$P_d = \varepsilon' VB_{\perp}^2/\mu_o \pi R_{obs}^2$

$\varepsilon' = (1+M_A^{-2})^{-1/2}$ $M_A \leq \varepsilon' \leq 1$

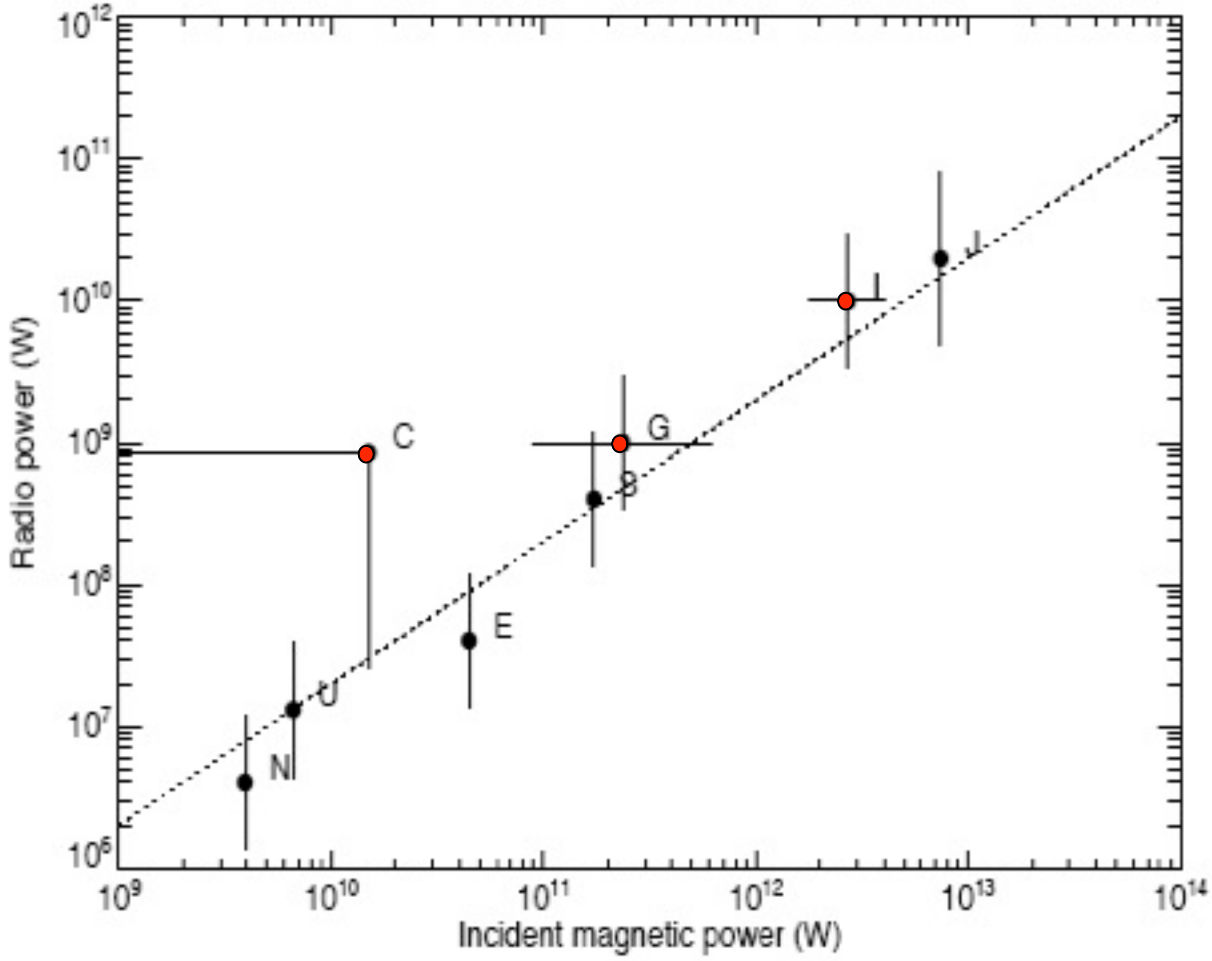
→ $P_d = \varepsilon' P_B$





« Generalized radio-magnetic Bode's law » (all emissions)

$P_{Radio} \sim \eta \times P_B$ with $\eta \sim 2\text{-}10 \times 10^{-3}$



[Zarka et al., 2001, 2005]

Exoplanets & Star data

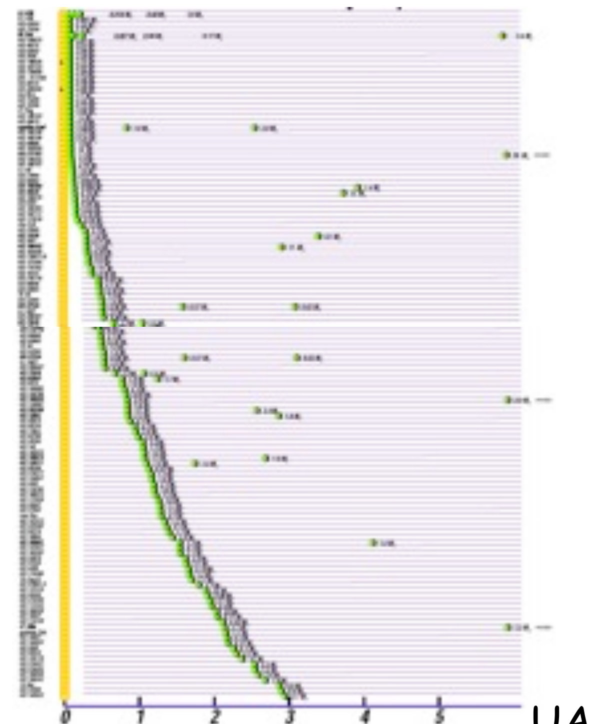
~330 exoplanets (in ~260 systems)

60 with $a \leq 0.05$ AU = 10 Rs (18%)

93 with $a \leq 0.1$ AU (28%)

→ >50 « hot Jupiters »

with periastron @ ~5-10 R_S



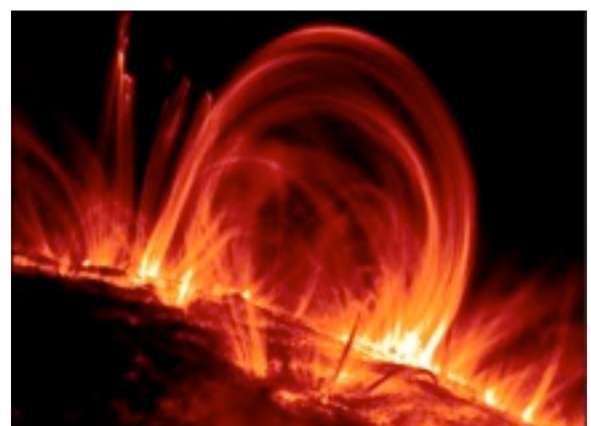
exoplanet.eu

Magnetic field at Solar surface :

→ large-scale ~1 G (10^{-4} T)

→ magnetic loops ~10^3 G,

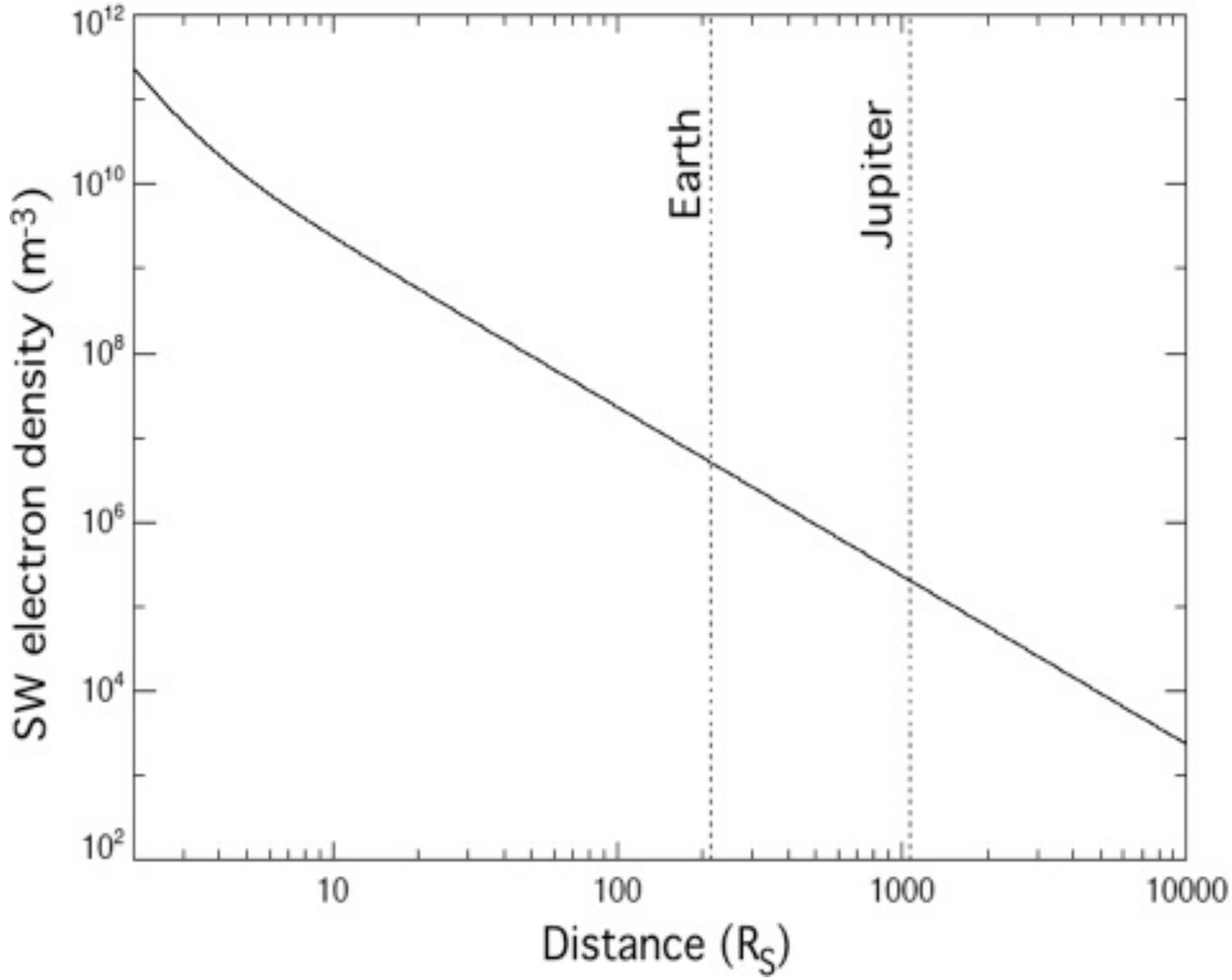
over a few % of the surface



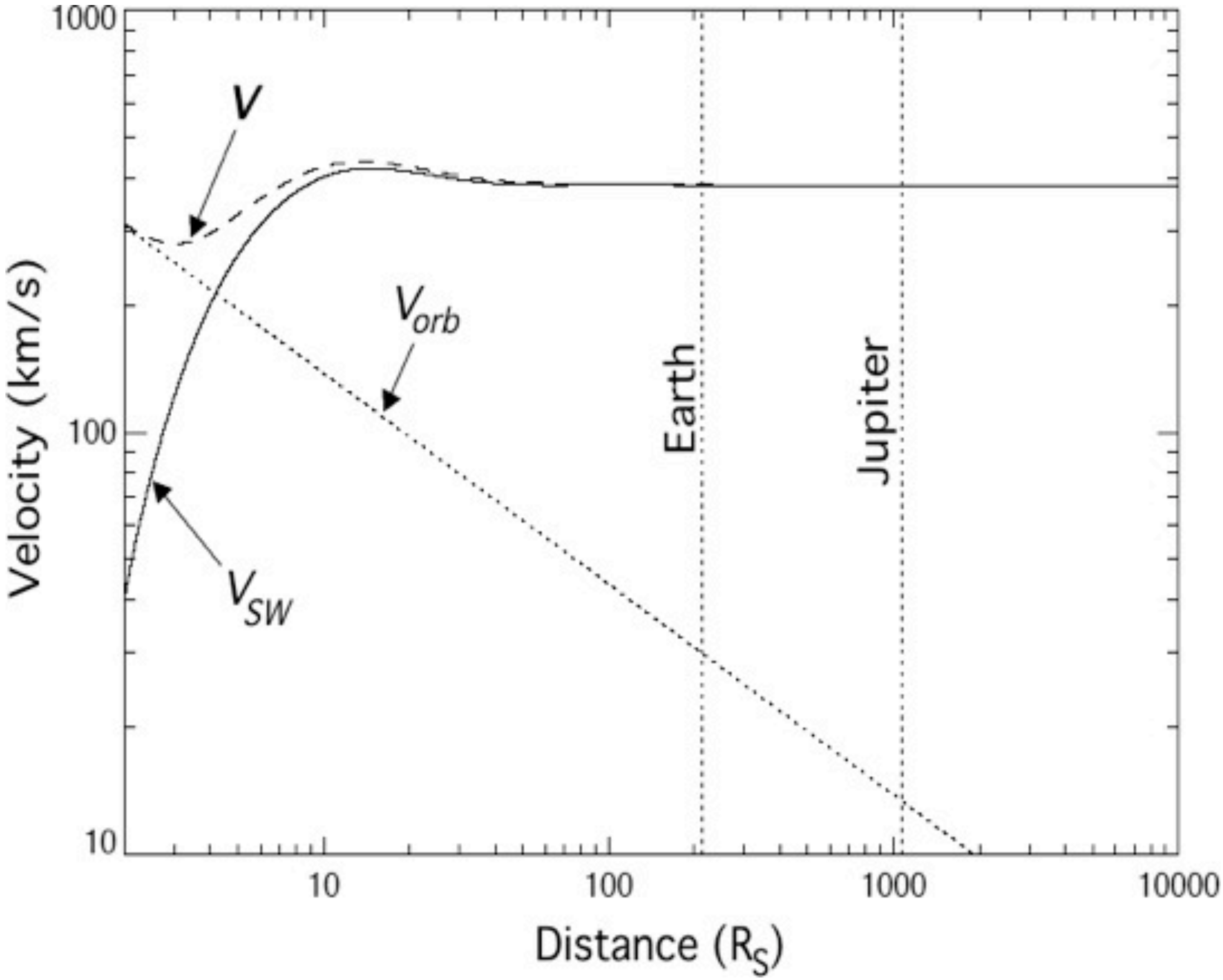
Magnetic stars : > 10^3 G

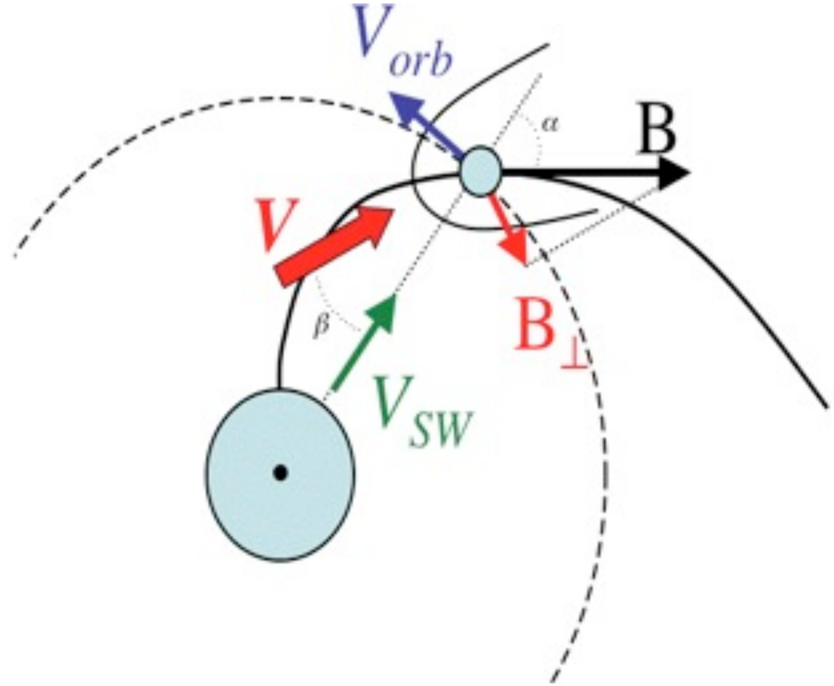
Modelling of a hot Jupiter (magnetized) orbiting a Solar type star

- Electron density in Solar corona

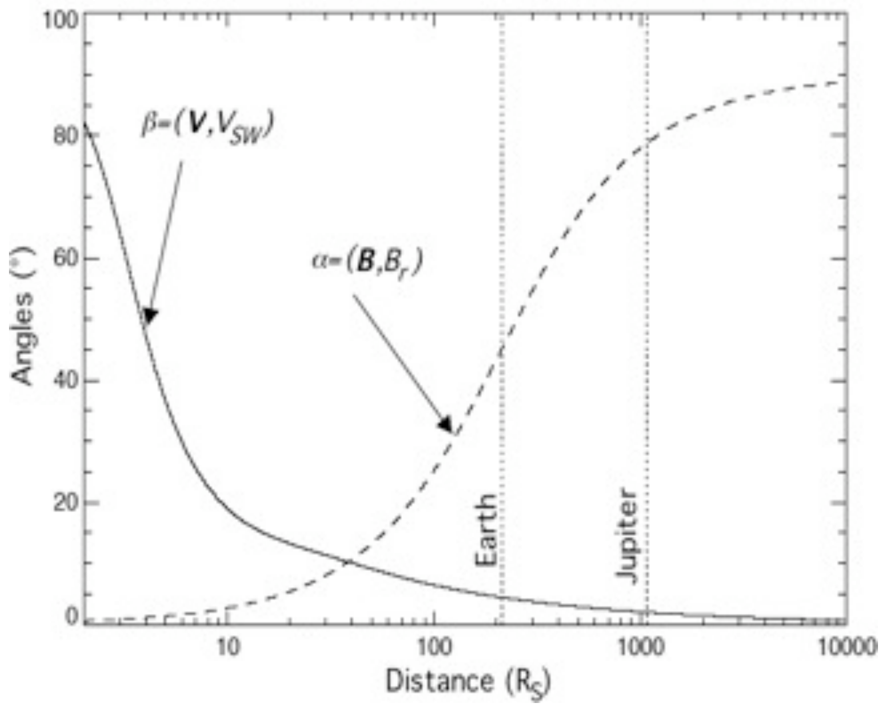


- Solar wind speed in the planet's frame



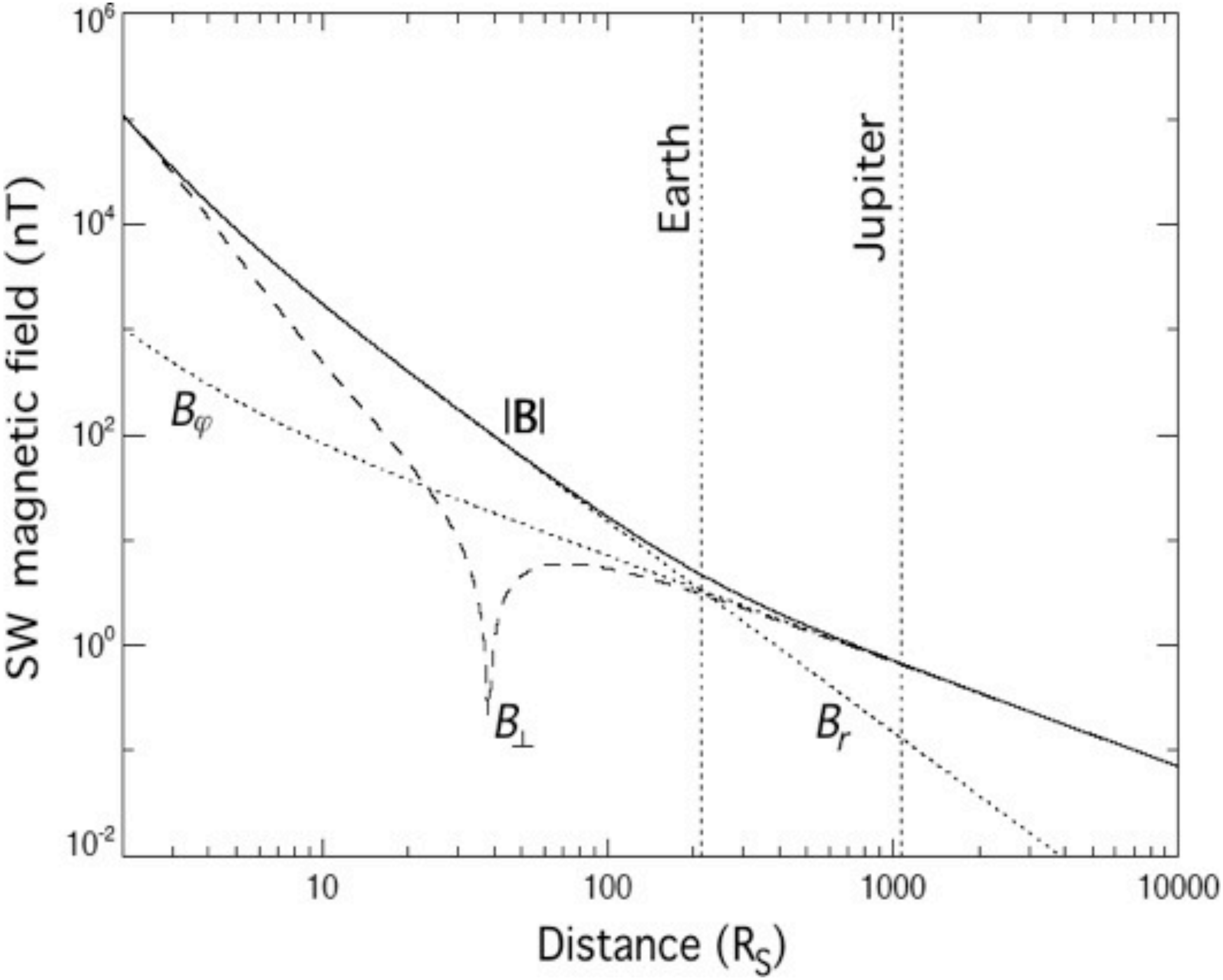


V_orb
α
B
V
β
B_⊥
V_SW

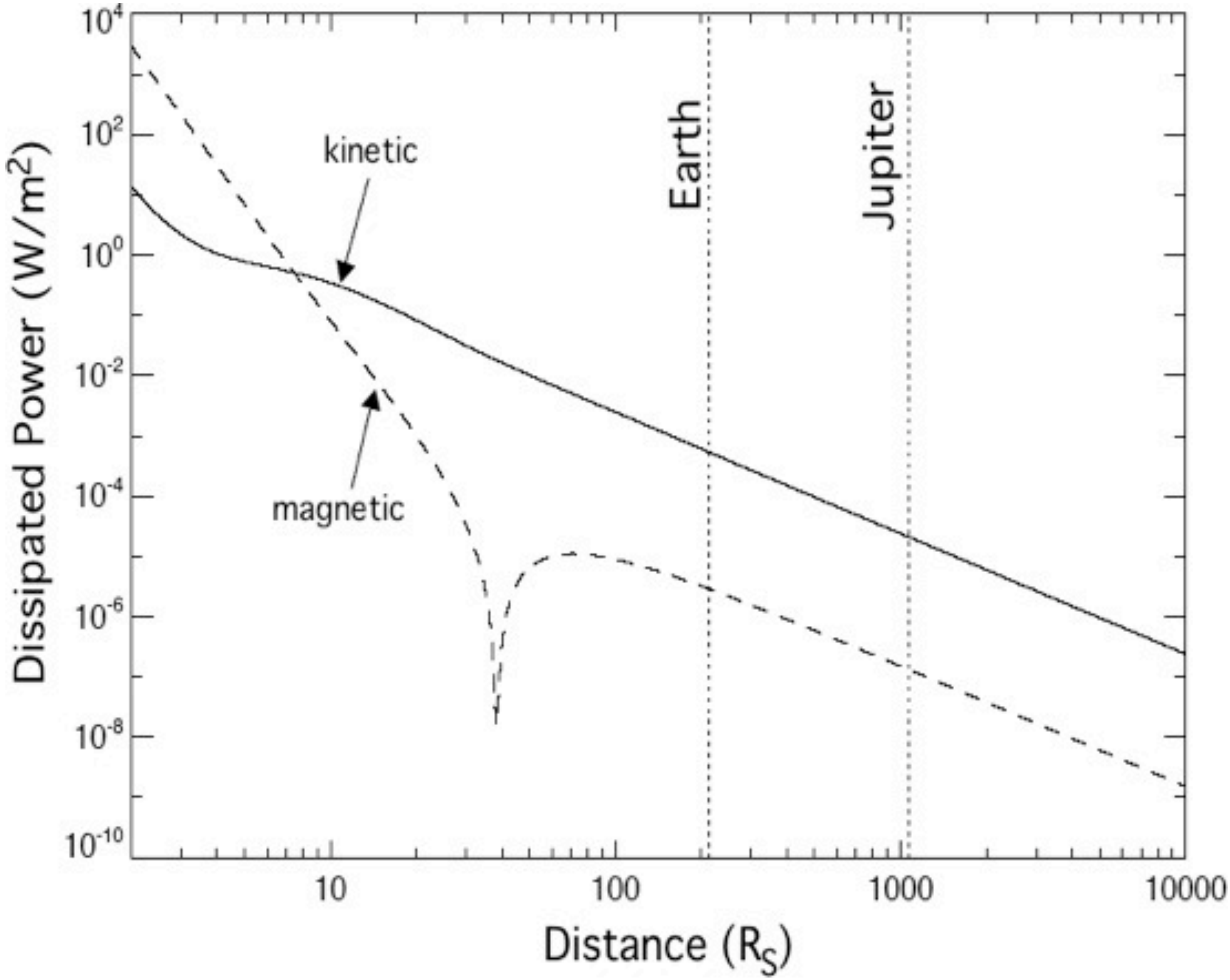


β=(V,V_SW)
α=(B,B_r)
Earth
Jupiter
Angles (°)
Distance (R_S)
0
20
40
60
80
100
10
100
1000
10000

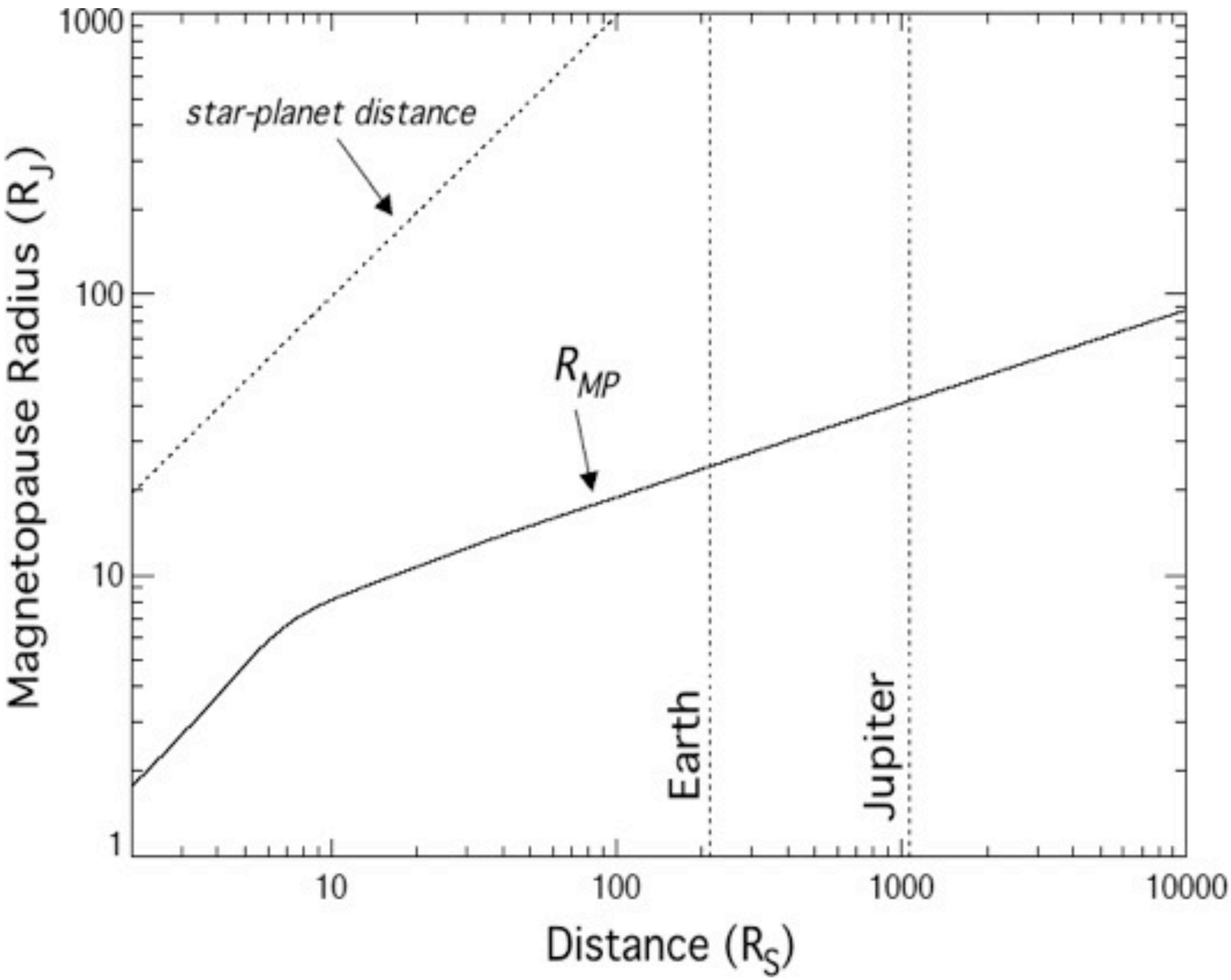
• Interplanetary magnetic field



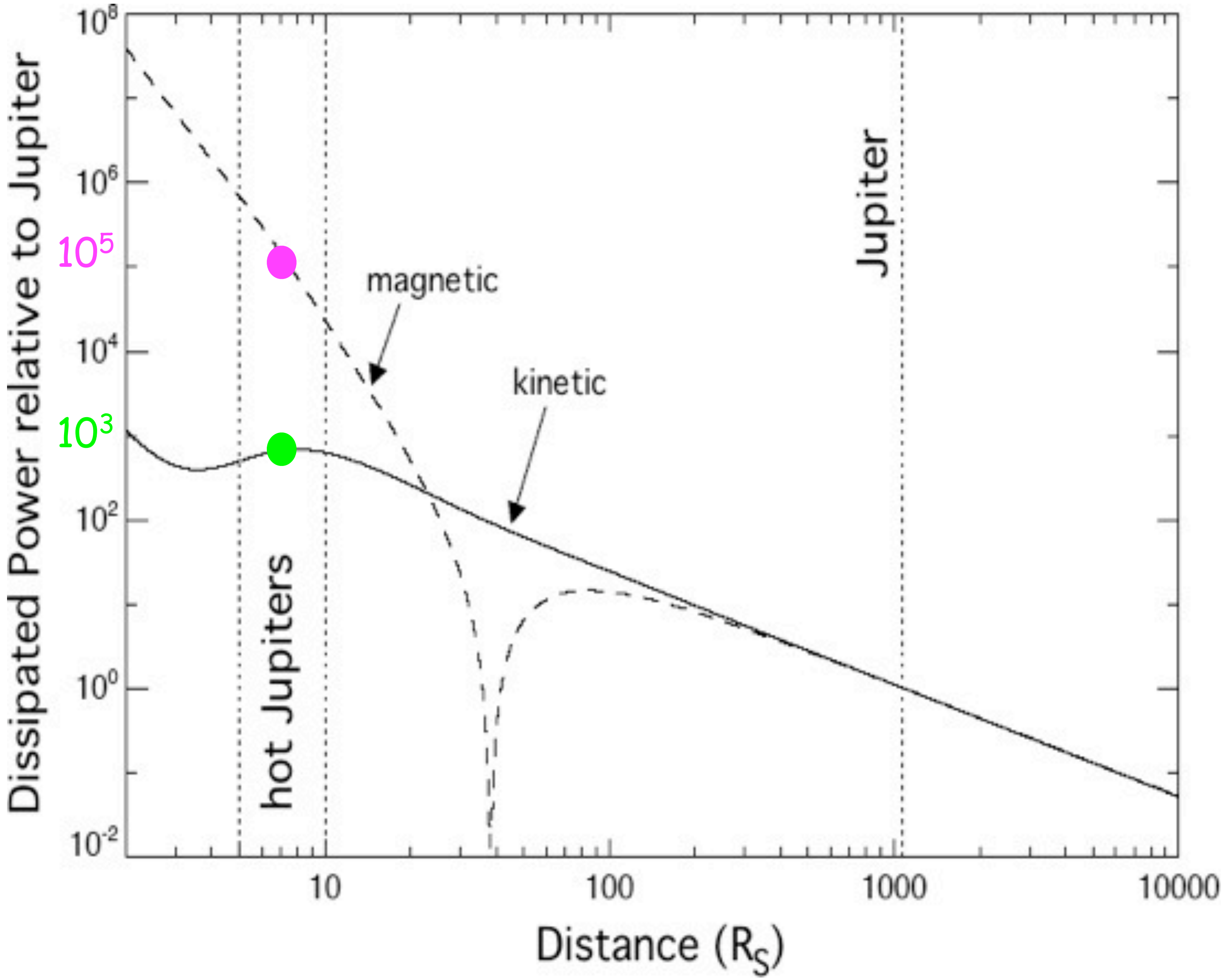
• Dissipated power per unit area of the obstacle



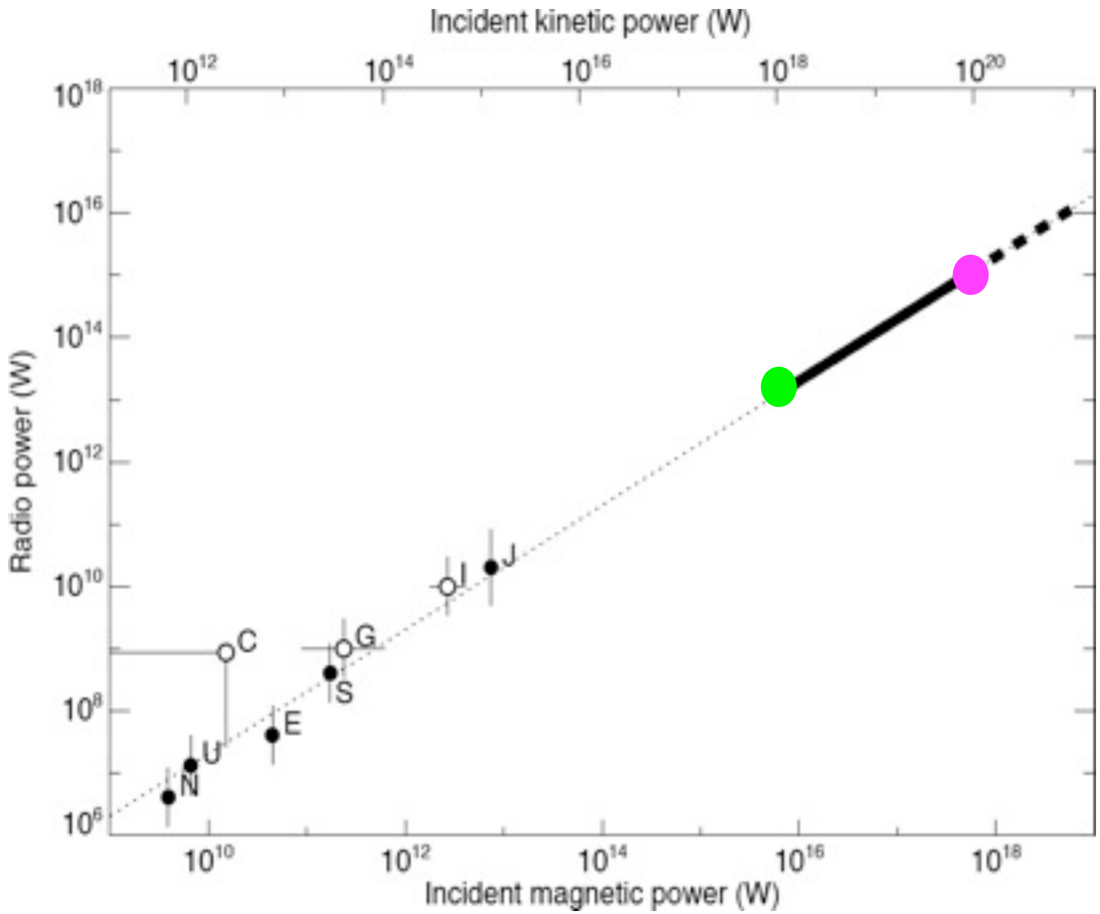
• Magnetospheric compression



- Total dissipated power on obstacle



Scaling laws

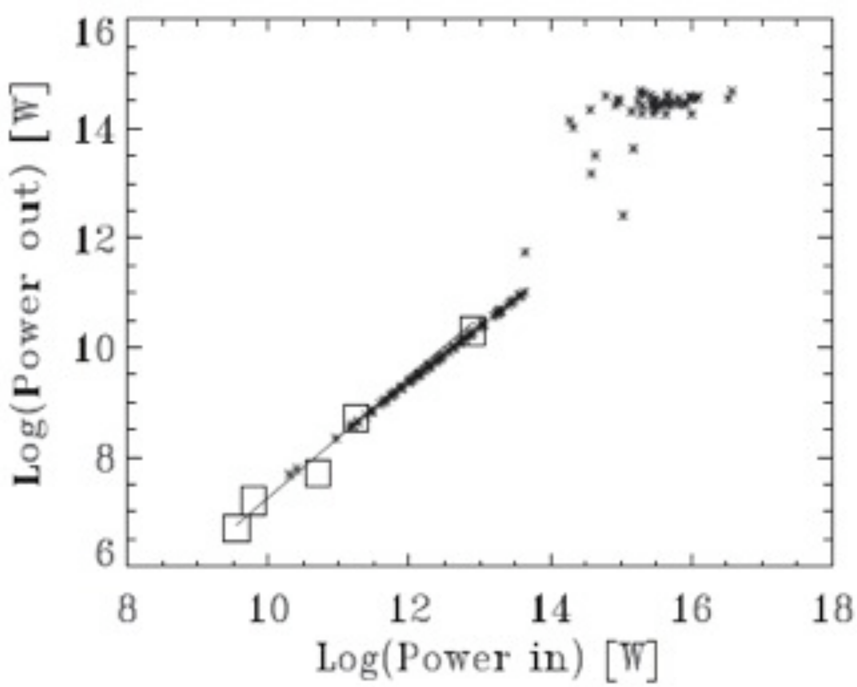


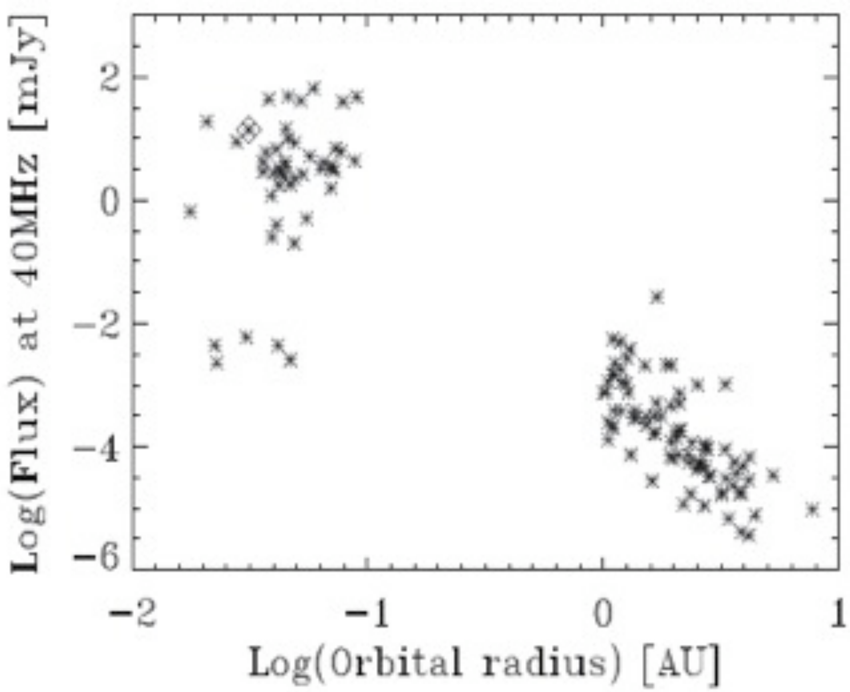
- Extrapolations of Radio-kinetic/magnetic Bode's laws → $P_{Radio} = P_{Radio\text{-}J} \times 10^{3\text{-}5}$
- if no "saturation" nor planetary magnetic field decay

[Farrell et al., 1999, 2004 ; Zarka et al., 2001, 2005]

Magnetic reconnection and electron acceleration at the magnetopause

B*=1G, η=10%





[Jardine & Collier-Cameron, 2008]

Planetary magnetic field decay ?

- Radio detection → f > 10 MHz → $B_{max\text{-}surface} \geq 4$ G
- Jupiter : $\mathcal{M} = 4.2\ G.R_J^3$, $B_{max\text{-}dipole} = 8.4$ G, $B_{max\text{-}surface} = 14$ G, $f_{max} = 40$ MHz
- Spin-orbit synchronisation (tidal forces) → ω↓
- But $\mathcal{M} \propto P_{sid}^{\alpha}$ $-1 \leq \alpha \leq -\frac{1}{2}$ → $\mathcal{M}$↓ (B decay) ?

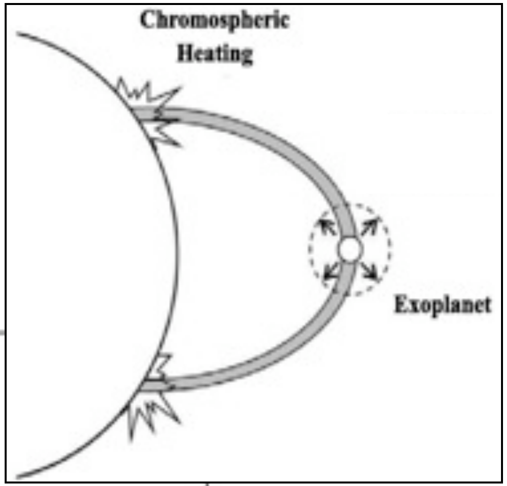
Upper Limit of Magnetic Fields in Hot Jupiters

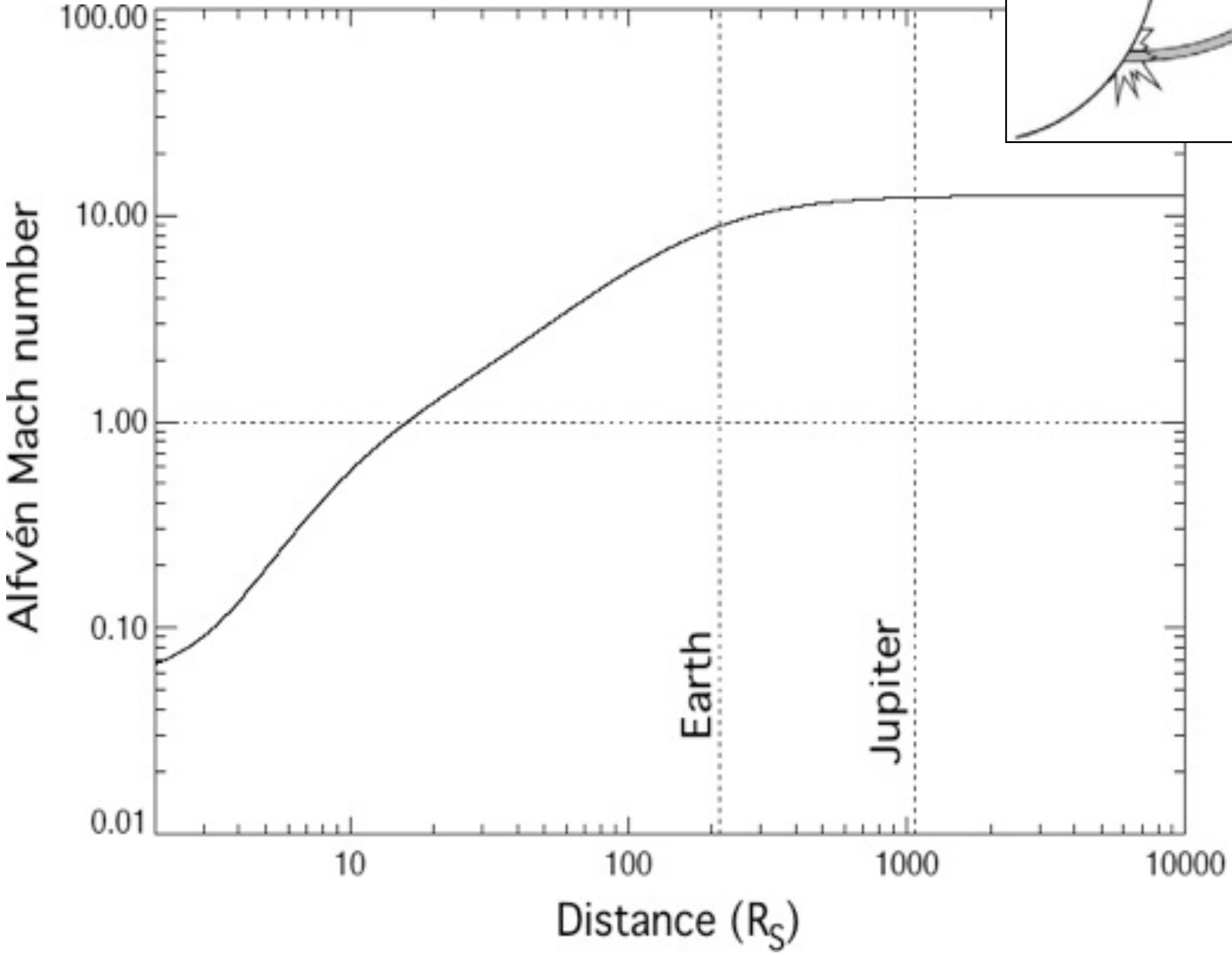
Planet	M (M_J)	P_{orb} (days)	R (R_J)	M_D (G m³)	B_s (G)
HD 179949b[a]	0.84	3.093	1.3	1.1×10^{24}	1.4
HD 209458b	0.69	3.52	1.43	0.8×10^{24}	0.8
τ Boo b[a]	3.87	3.31	1.3	1.6×10^{24}	2
OGLE-TR-56b	0.9	1.2	1.3	2.2×10^{24}	2.8

- Internal structure + convection models
  → self-sustained dynamo → $\mathcal{M}$ could remain ≥ a few $G.R_J^3$

[Sanchez-Lavega, 2004]

• Unipolar inductor in sub-Alfvénic regime
(as for Io-Jupiter)

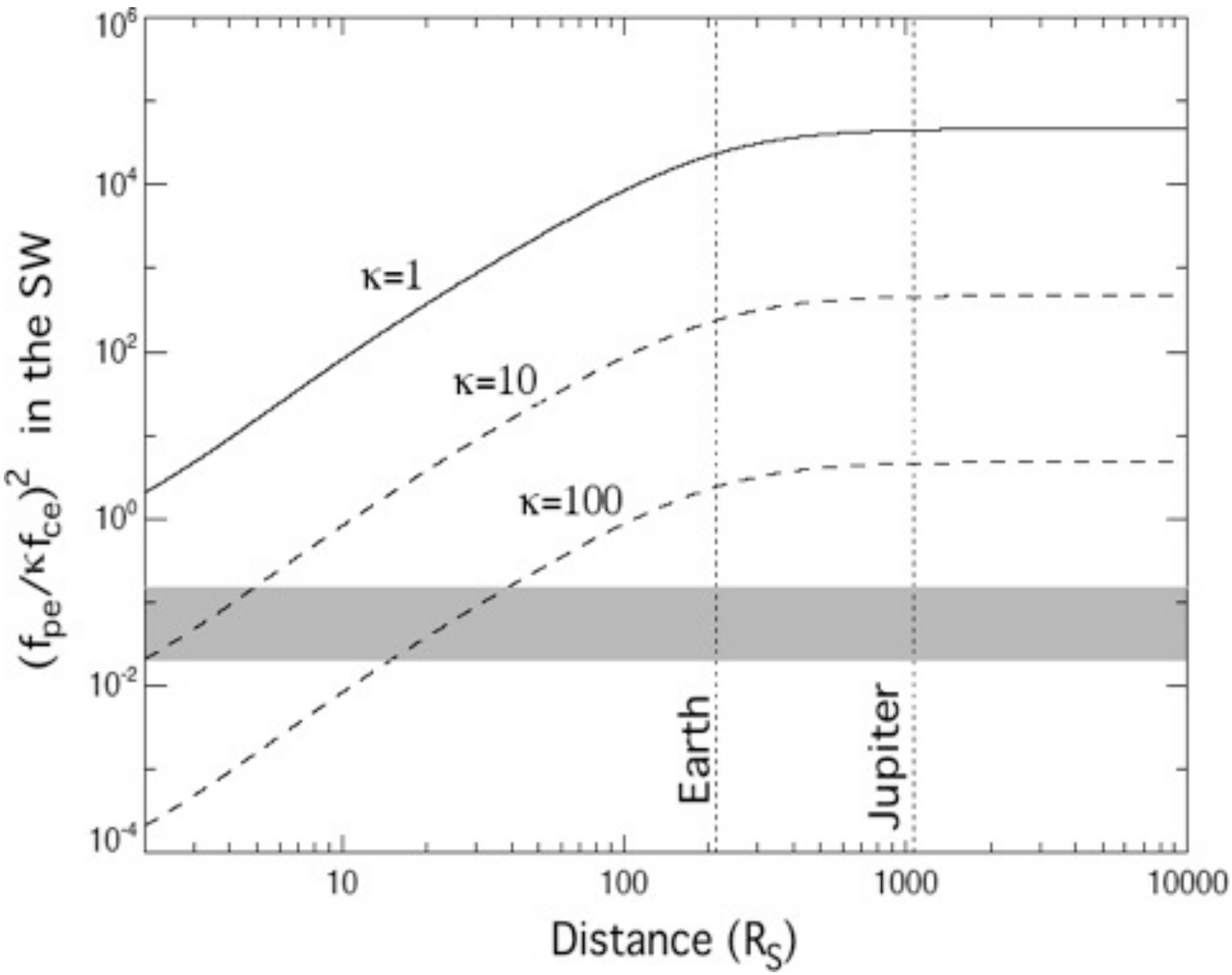




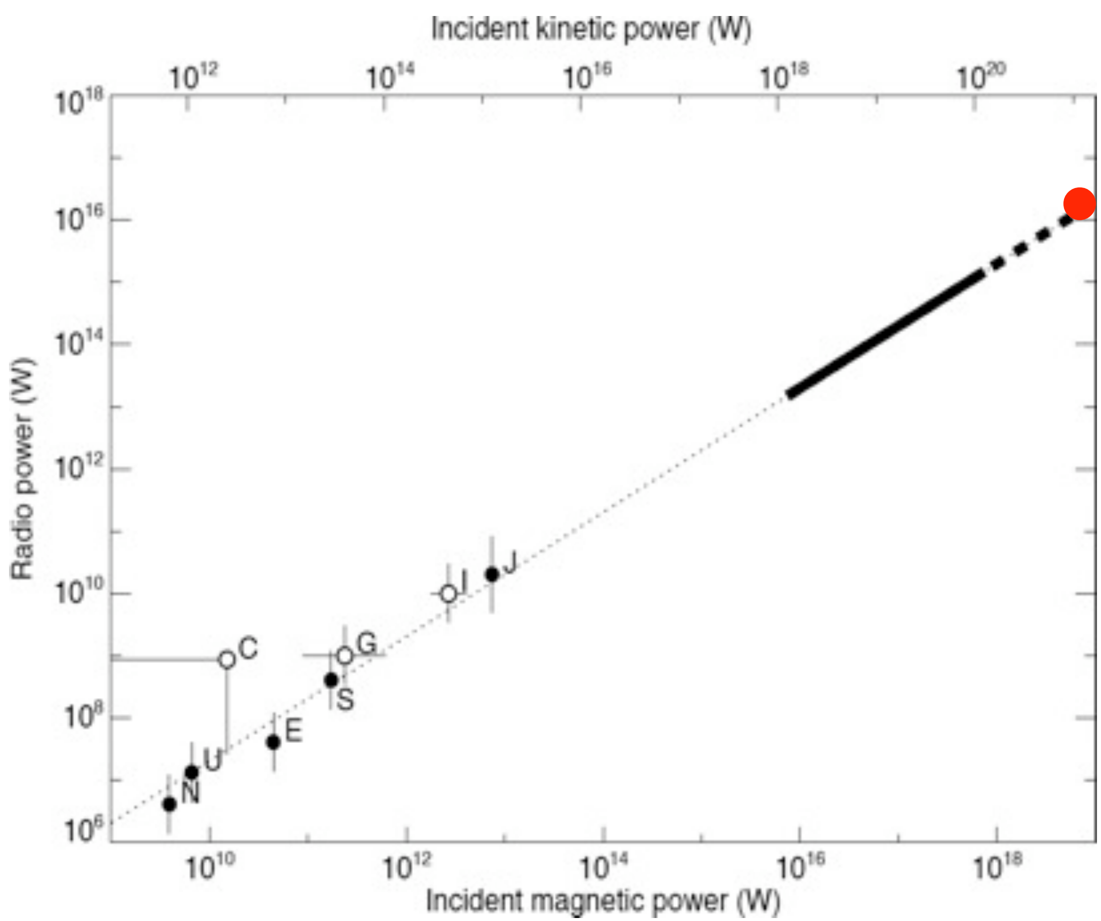
- But radio emission possible only if $f_{pe}/f_{ce} \ll 1$

  → intense stellar B required (κ = 10-100 x B_{Sun})

  → emission ≥ 30-250 MHz from 1-2 R_S



Unipolar inductor in sub-Alfvénic regime

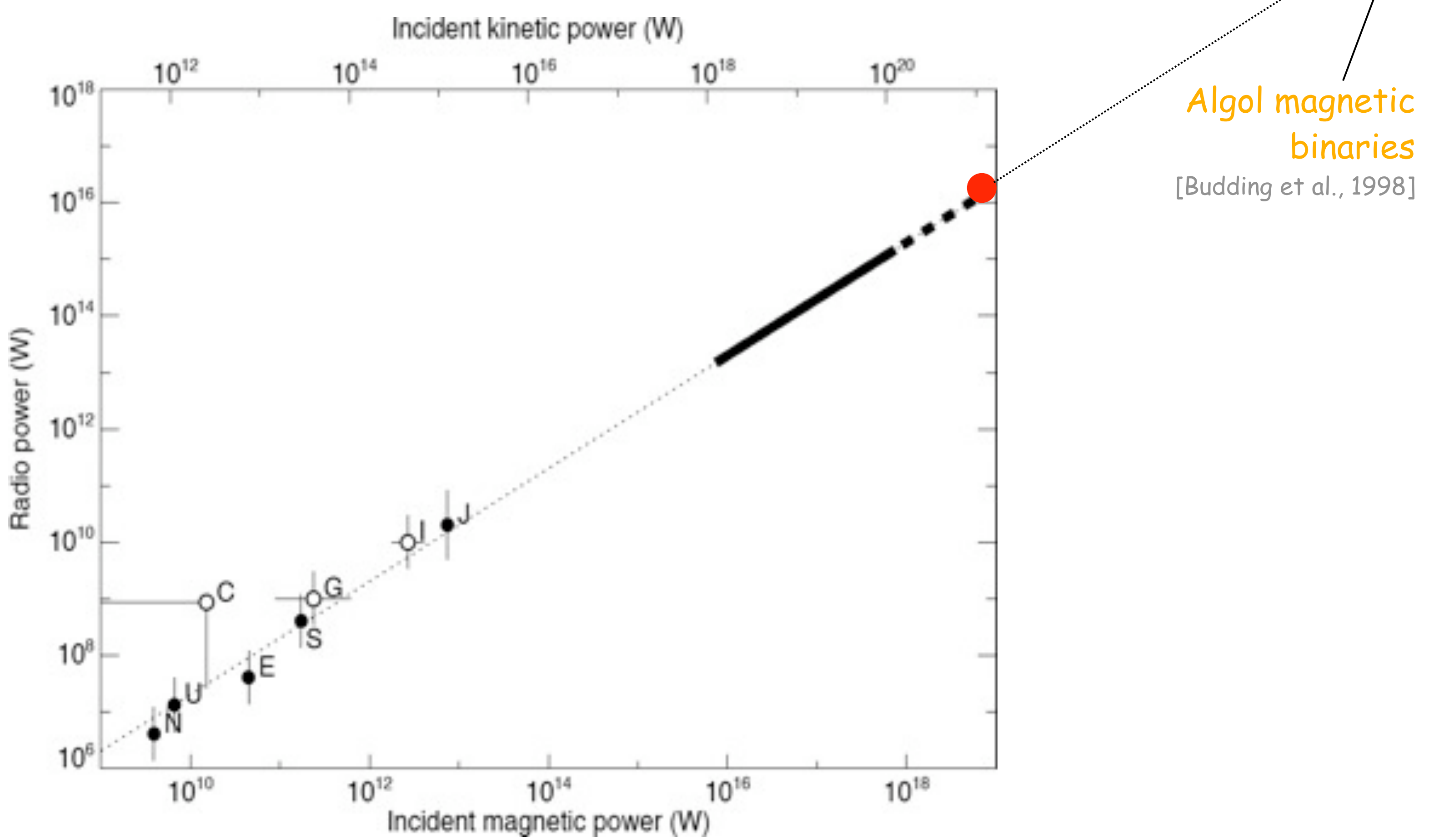


- Extrapolation / Radio-magnetic Bode's law

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

[Zarka, 2007]

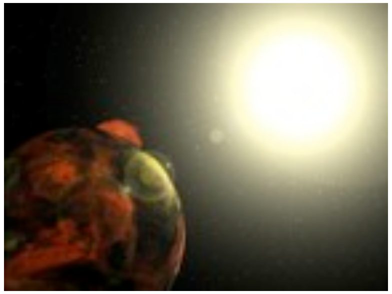
Unipolar inductor in sub-Alfvénic regime



Algol magnetic binaries

[Budding et al., 1998]

Maximum distance of detectability of 10^5 α Jupiter's radio emissions



	$b\tau = 10^6$ (1 MHz, 1 sec)		$b\tau = 2\times10^8$ (3 MHz, 1 min)		$b\tau = 4\times10^{10}$ (10 MHz, 1 hour)	
	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz
$A_e = 10^4\ m^2$ (~NDA)	1	16	3	59	13	220
$A_e = 10^5\ m^2$ (~UTR-2)	3	50	11	190	40	710
$A_e = 10^6\ m^2$ (~LOFAR77)	9	160	33	600	130	2200

(distances in parsecs)

Other studies ...

- Possibilities for radio scintillations ⇒ burts $P_{radio} \times 10^2$

[Farrell et al., 1999]

- Estimates of exoplanetary $\mathcal{M}$ (scaling laws - large planets better) → f_{ce} & radio flux

[Farrell et al., 1999 ; Griessmeier et al., 2004]

- F_x as wind strength estimator

[Cuntz et al., 2000 ; Saar et al., 2004, Stevens, 2005]

- Stellar wind modelling (spectral type spectral, activity, stellar rotation)

[Preusse et al., 2005]

- Time evolution of stellar wind and planetary radius (young systems better)

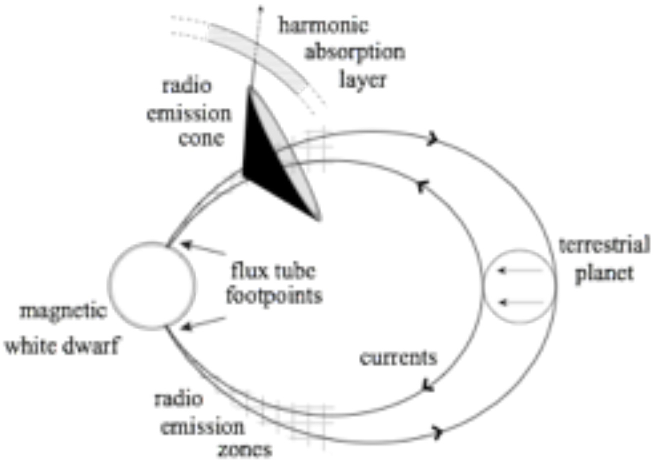
[Griessmeier et al., 2004 ; Stevens, 2005]

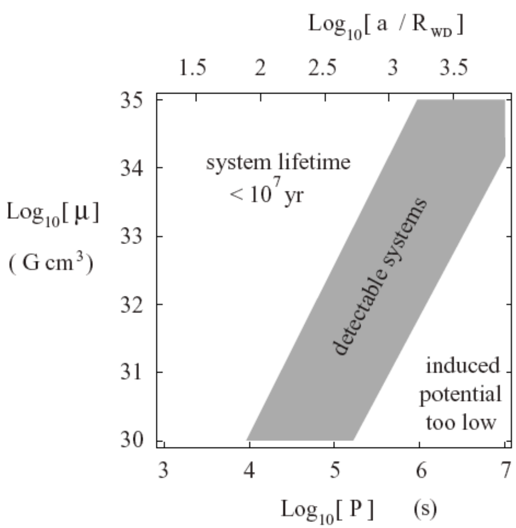
- Role of (frequent) Coronal Mass Ejections

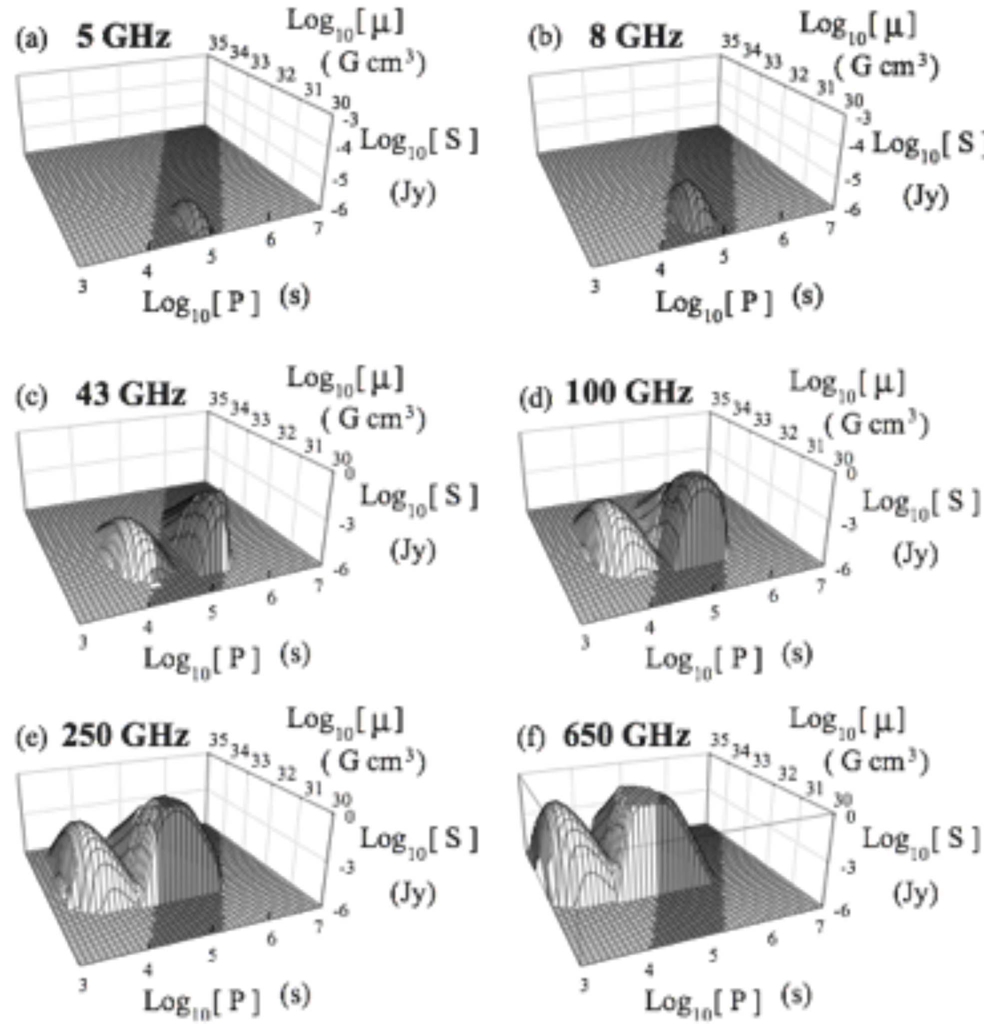
[Khodachenko et al., 2006]

- Application of unipolar inductor model to white dwarfs systems

[Willes and Wu, 2004, 2005]



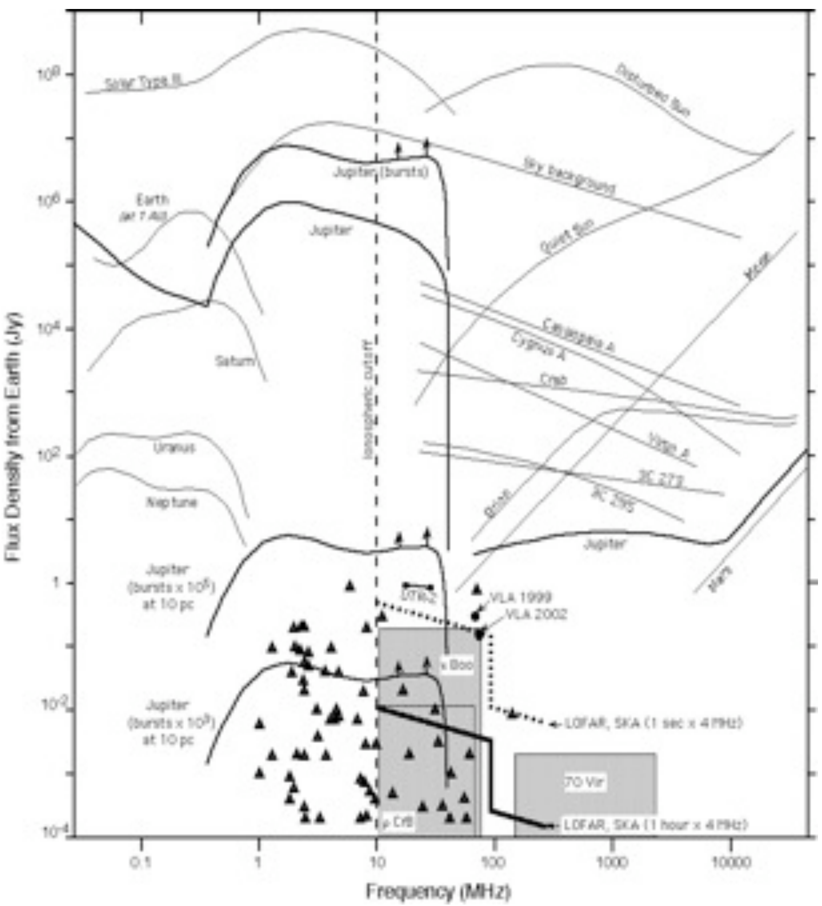


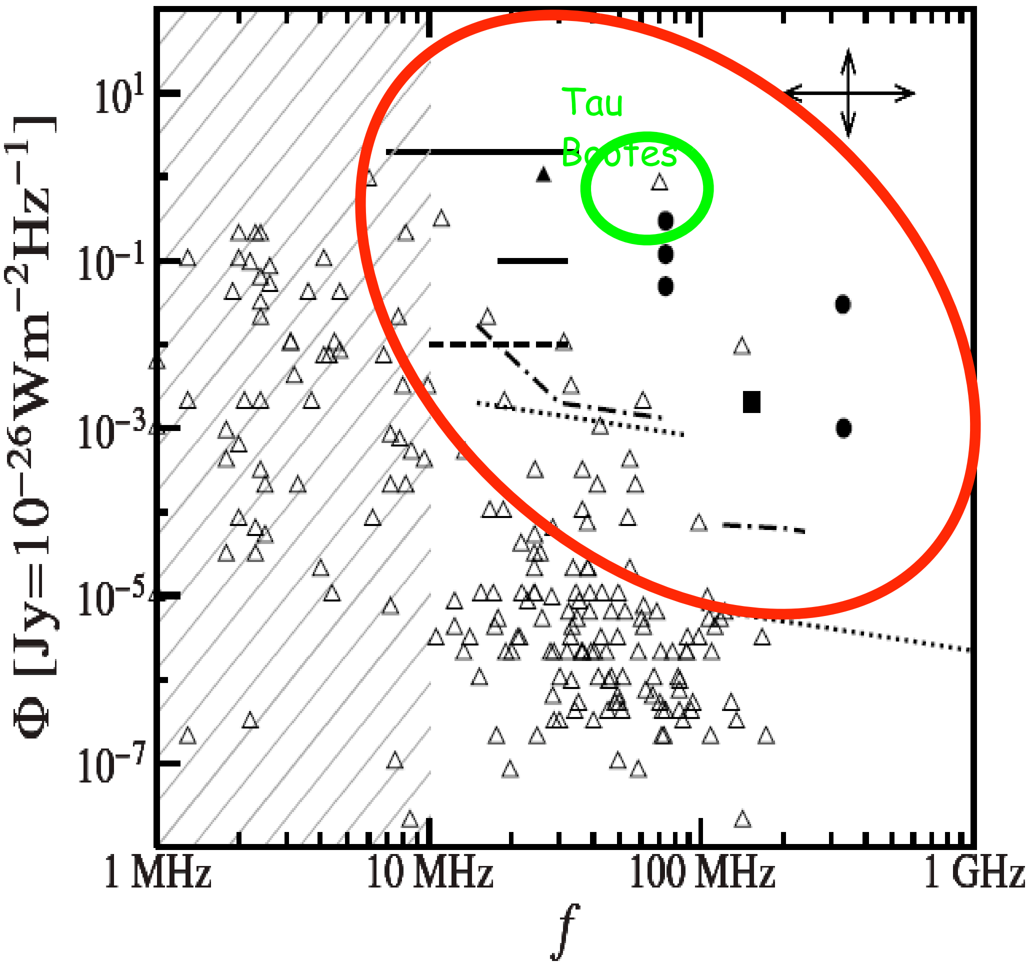


saturated loss-cone driven cyclotron-maser emission

[Willes & Wu, 2004, 2005]

Predictions for the whole exoplanet census





[Lazio et al., 2004; Zarka, 2004; Griessmeier et al. 2007]

Low-frequency radio observations & objectives

1 UA à 1 pc = 1 " ⇒ planet & star not resolved

→ Direct detection of a Jovian like emission / burst

→ Planet-Star distinction via polarization (circular/elliptical) & periodicity (orbital ?)

→ Planetary rotation period ⇒ tidal locking ?

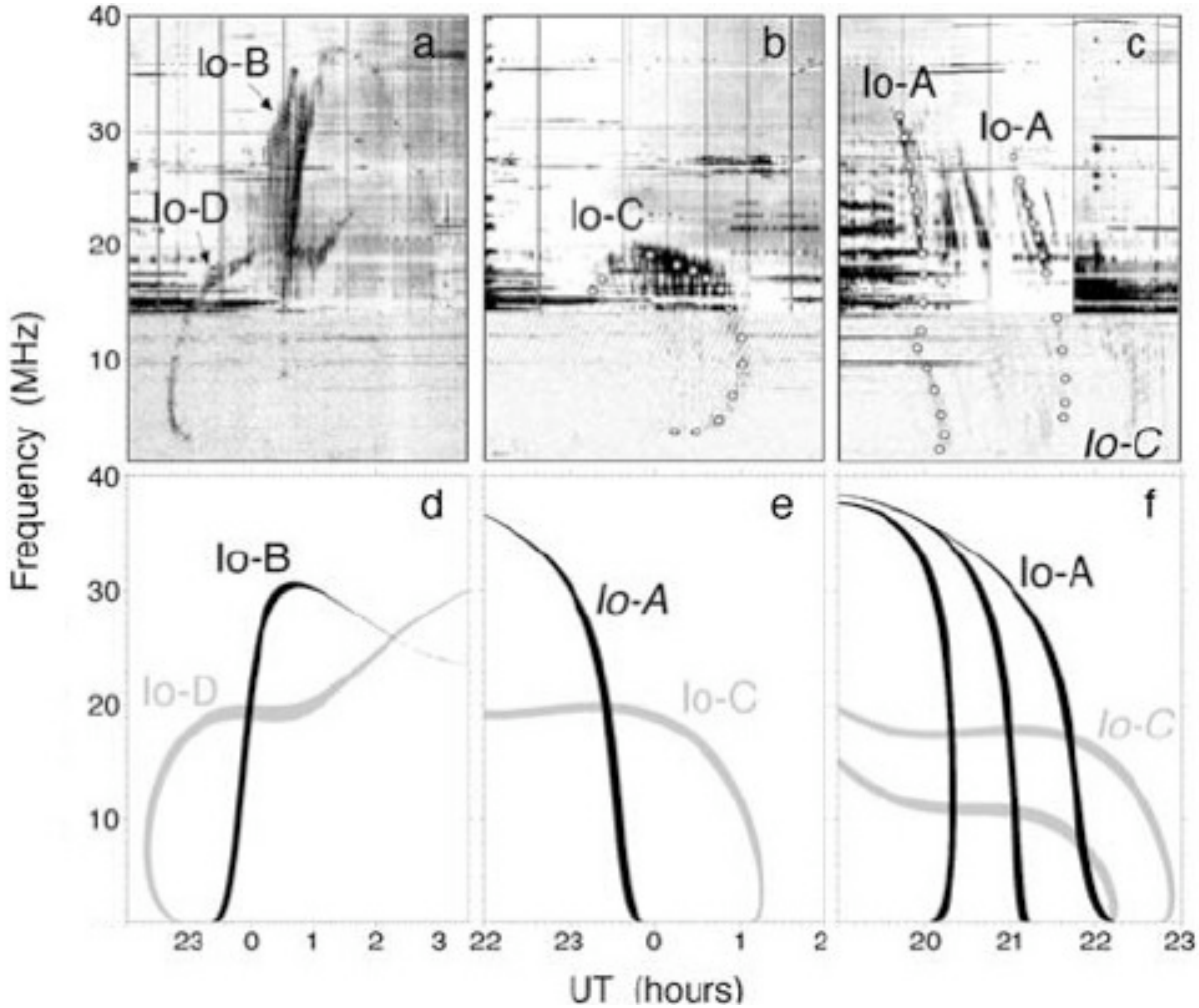
→ Measurement of B ⇒ contraints on scaling laws & internal structure models

→ Comparative magnetospheric physics (star-planet interactions)

→ Discovery tool (search for more planets) ?

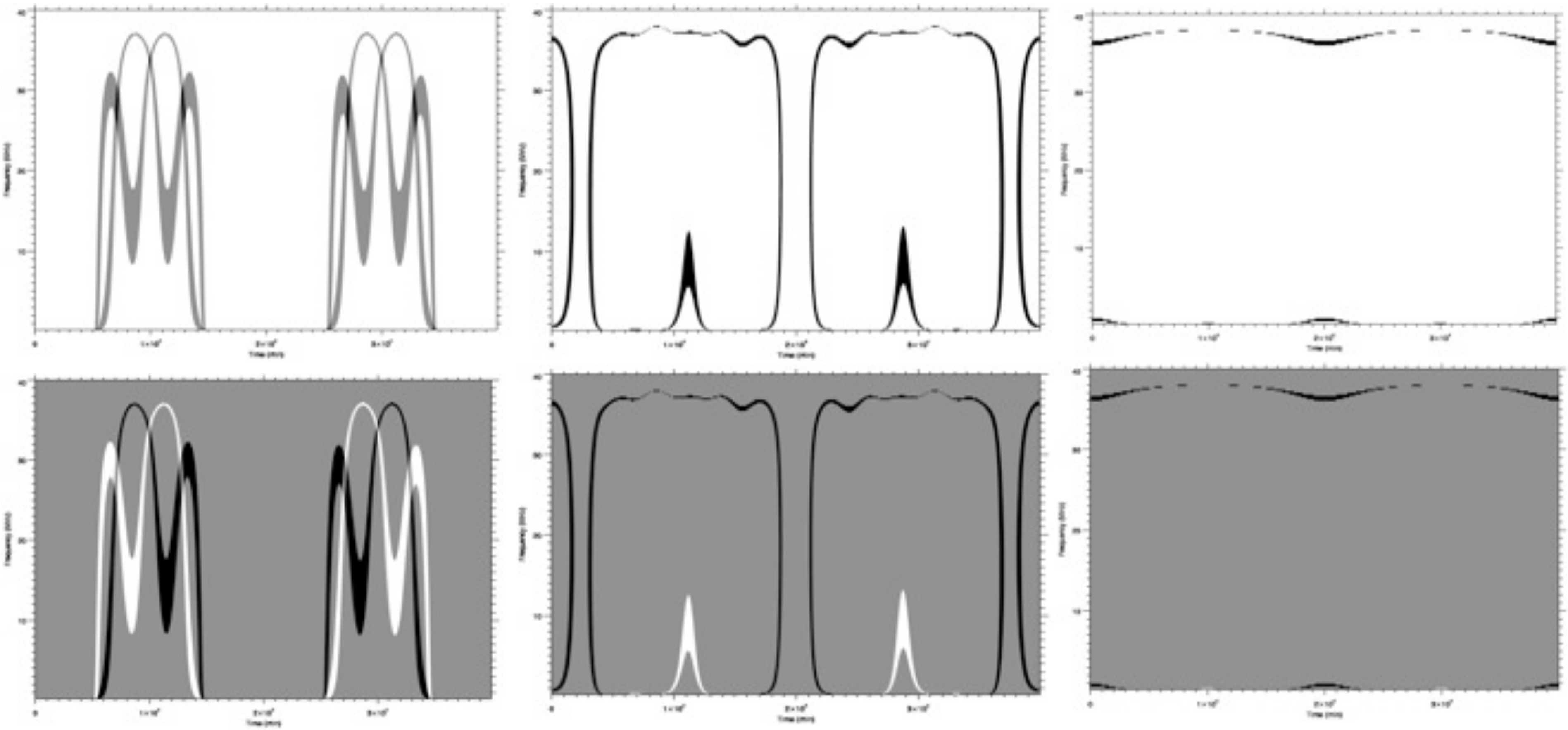
[Zarka et al., 1997 ; Farrell et al., 2004]

Dynamic spectrum modeling : from Jupiter …



[Hess et al., 2008]

Dynamic spectrum modeling : … to exoplanets



orbit inclination = 0° 30° 45°

Radio emission from exoplanets ?

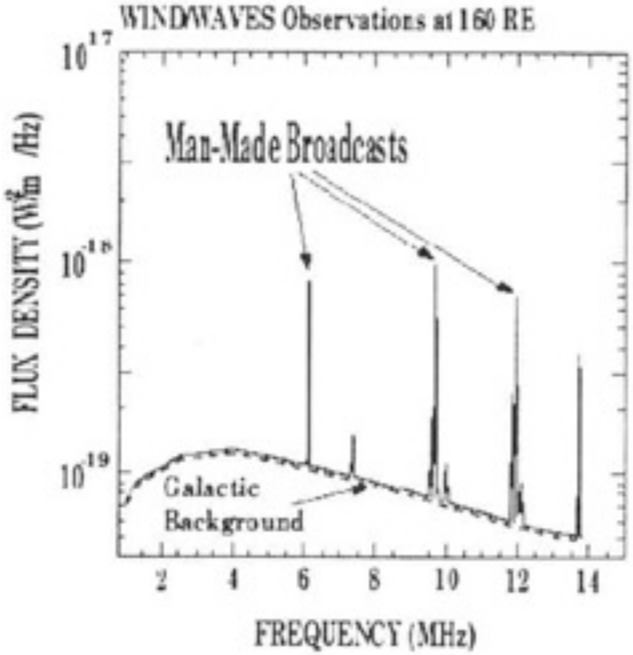
Observations

Limitations of Radio observations

- Limited angular resolution (λ/D)
- Very bright galactic background (T_b ~10^{3-5} K)
- RFI (natural & anthropic origin)
- Ionospheric cutoff ~ 10 MHz,

  perturbations ≲30-50 MHz,

  scintillations IP/IS



LF radio observations

Instrument Name & Location	Description	Frequency range (MHz)	Effective area (m^2)	Beam	Polarisation	Maximum effective sensitivity (Jy)
NDA (Nançay Decameter Array), France	2x72 helix-spiral antennas (rectangular arrays)	10 - 100	~2 x 4000	~ 6° x 10°	2 circular → 4 Stokes	$\sim 10^2$
VLA (Very Large Array), New Mexico, USA	Interferometer : 27 parabolas x 25m ∅ (Y-shape array)	74, 330, ...	~13000	≥ 0.4'	2 polar.	$<10^{-2}$
GMRT (Giant Meterwave Radio Telescope), Pune, India	30 parabolas x 45m ∅ (core + Y-shape array)	150, 235, ...	~30000	0.3'	4 Stokes	$<10^{-3}$
UTR-2, Kharkov, Ukraine	2040 dipoles (T-shape array 1 km x 2 km)	7 - 35	~140000	~30' x 10°	1 linear polar. (EW)	10^0
LOFAR (Low Frequency Array), The Netherlands	Interferometer / Phased arrays of dipoles (core + stations up to >100 km)	10 - 240	$\sim 10^6 \times (15/\nu)^2$	~1.5" x(100/ν) [ν in MHz]	4 Stokes	$<10^{-3}$

1 UA à 1 pc = 1 " ⇒ no imagery

→ (1) detect a signal, (2) star or planet ?

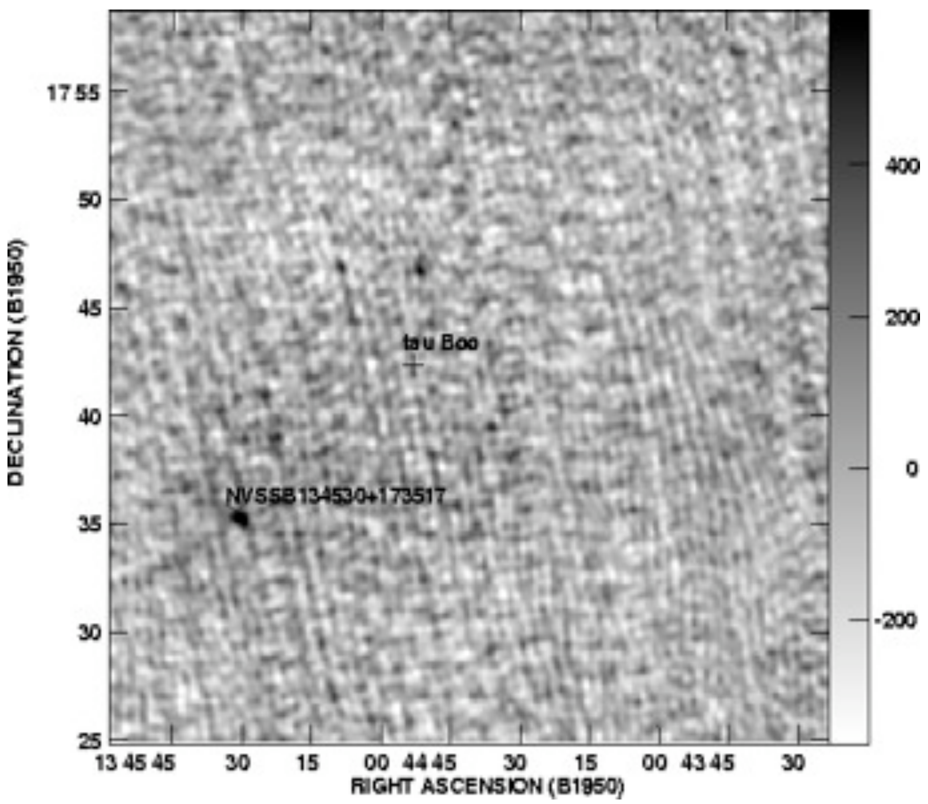
→ discriminate via emission polarization (circ./elliptical) + periodicity (orbital)

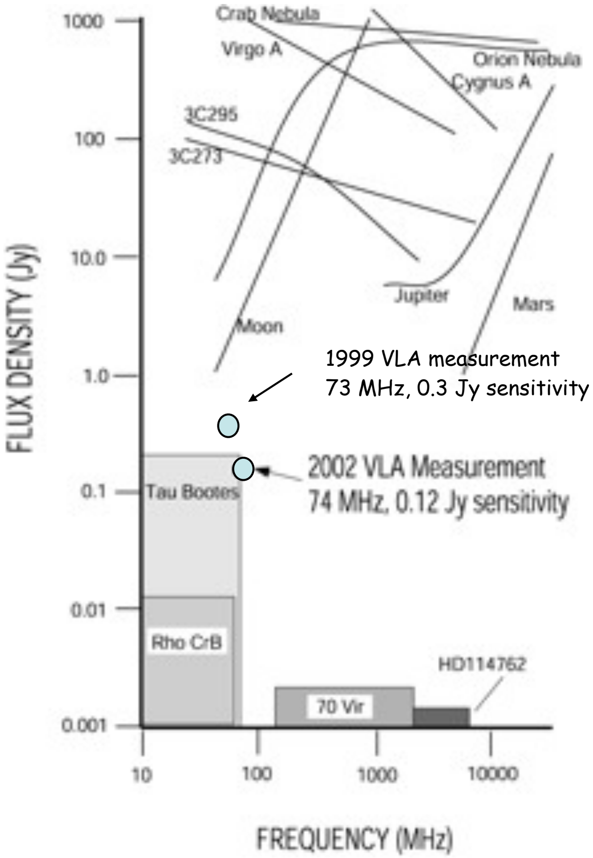
→ search for Jovian type bursts ?

• VLA

- f ~ 74 MHz
- target Tau Bootes
- epochs 1999 - 2003
- imaging

Very Large Array

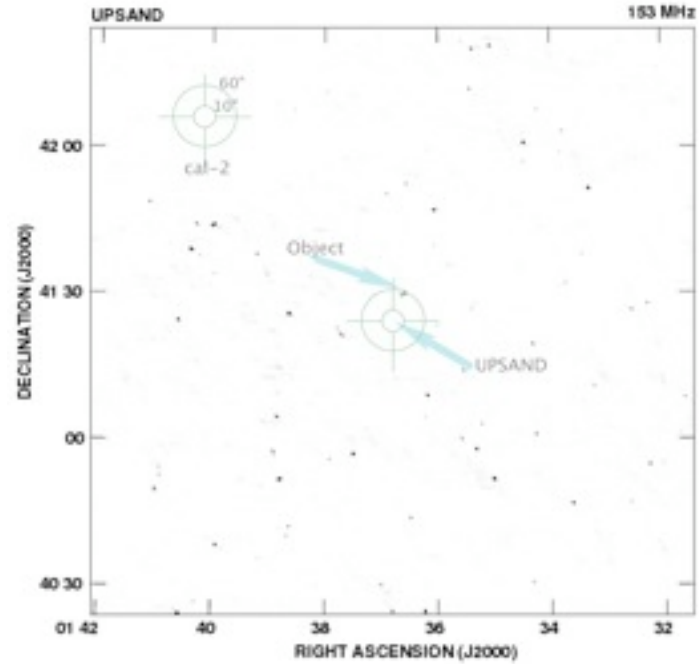


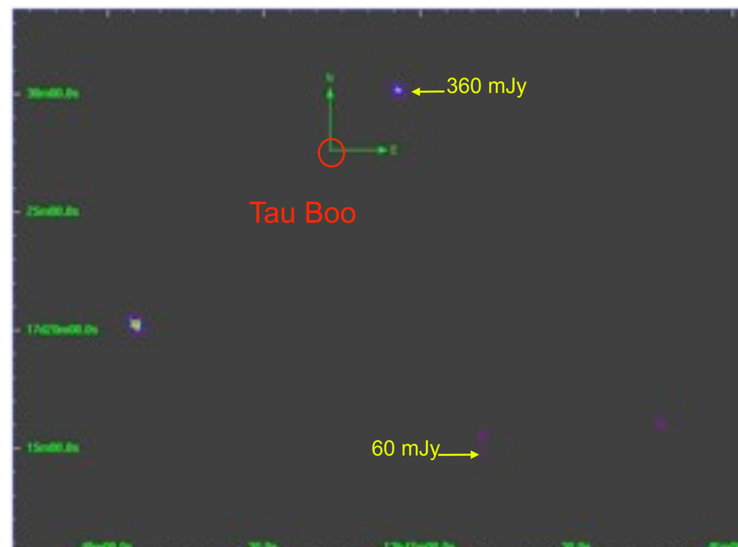


[Bastian et al., 2000 ; Farrell et al., 2003, 2004; Lazio & Farrell, 2007]

- GMRT

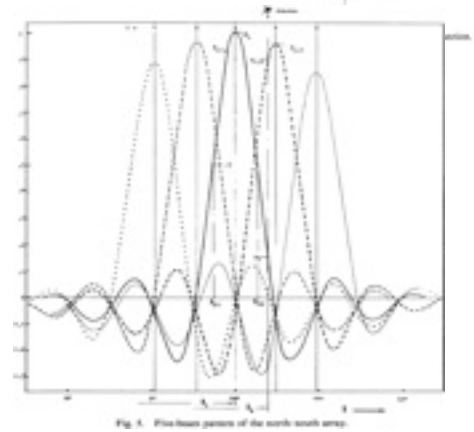
- f ~ 153 MHz
- several targets (Tau Boo, Ups And...)
- epochs 2005 - 2007
- imaging + tied array mode
- sensitivity ~ a few mJy

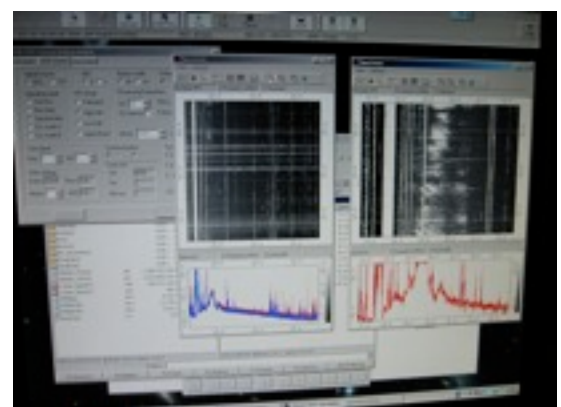




[Winterhalter et al., 2005 ; George and Stevens, 2007 ; ...]

• UTR-2

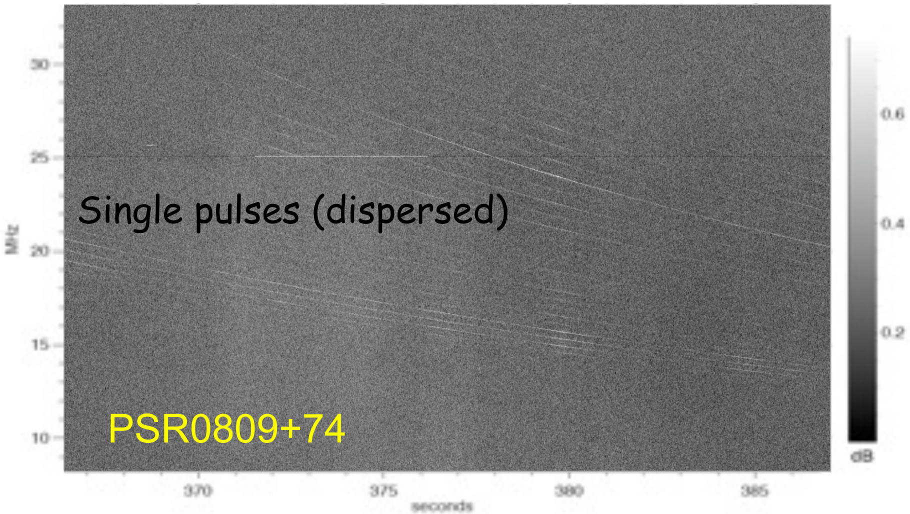




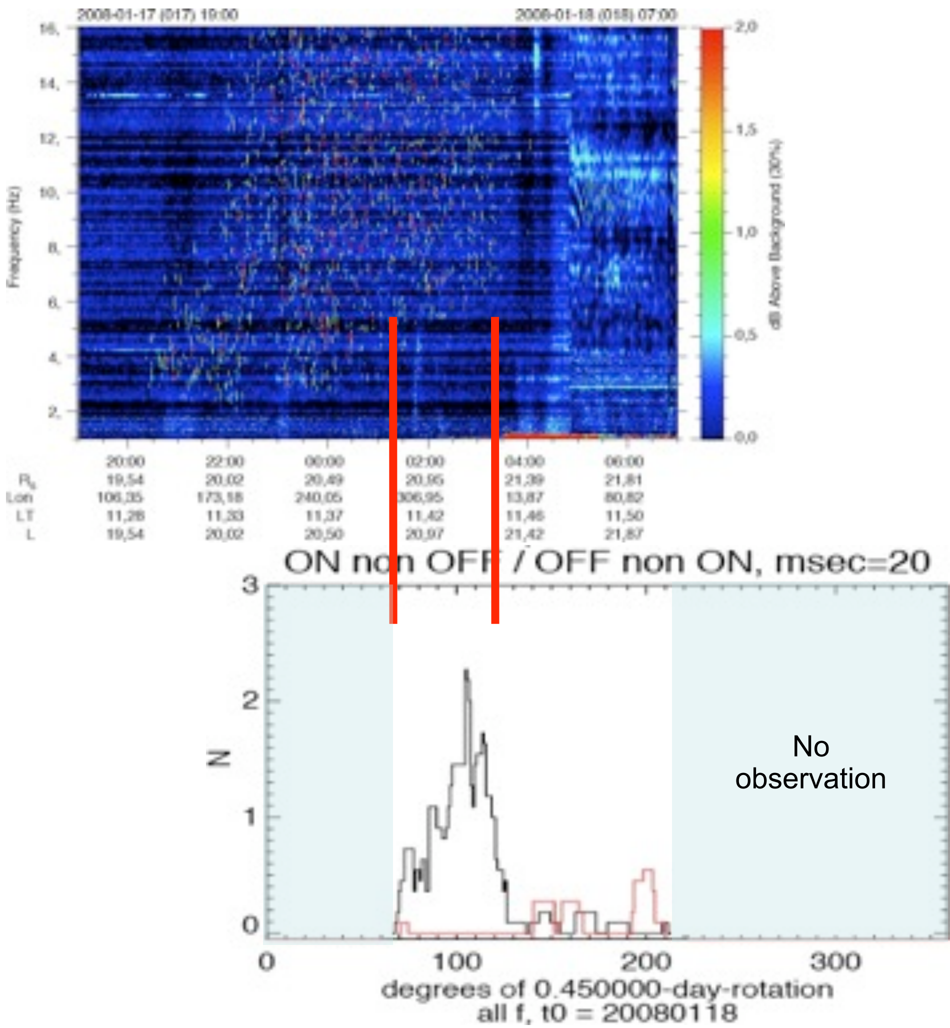
- f ~ 10-32 MHz
- a few 10's targets (hot Jupiters)
- epochs (1997-2000) & 2006-2008+
- Simultaneous ON/OFF (2 tied array beams)
- sensitivity ~1 Jy within (1 s x 5 MHz)
- t,f resolution (~ 10 msec x 5 kHz)
- RFI mitigation

[Zarka et al., 1997 ; Ryabov et al., 2004]

- UTR-2



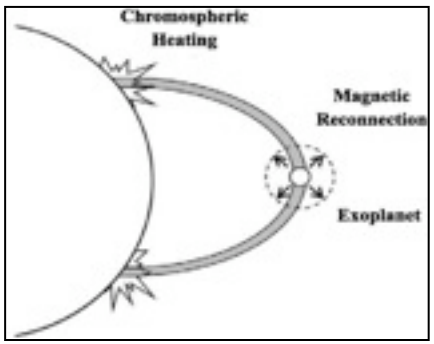
Saturn's lightning

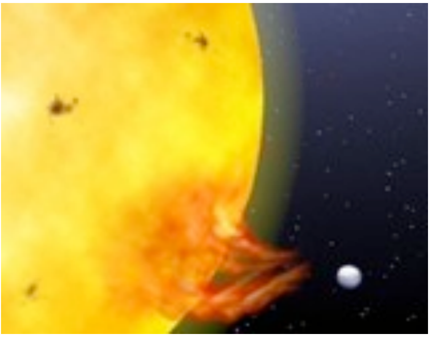


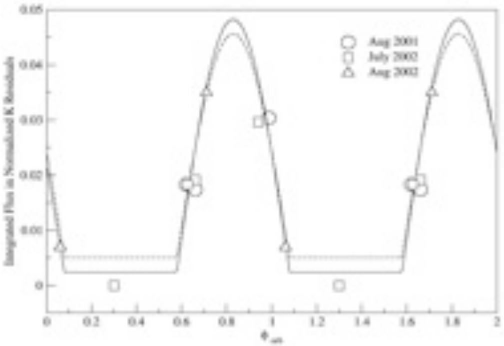
Optical observations

• Super-flares ? [Rubenstein & Schaefer, 2000 ; Schaefer et al., 2000]

• Chromospheric hot spot (optical) on HD179949 + υ And [Shkolnik et al. 2003, 2004, 2005]







➡ unipolar or dipolar interaction ?

➡ hot spot 60° ahead of sub-planetary point (P=3.1d)

→ Ok wrt "backwards" Alfén waves propagation in the stellar wind [Preusse et al., 2006]

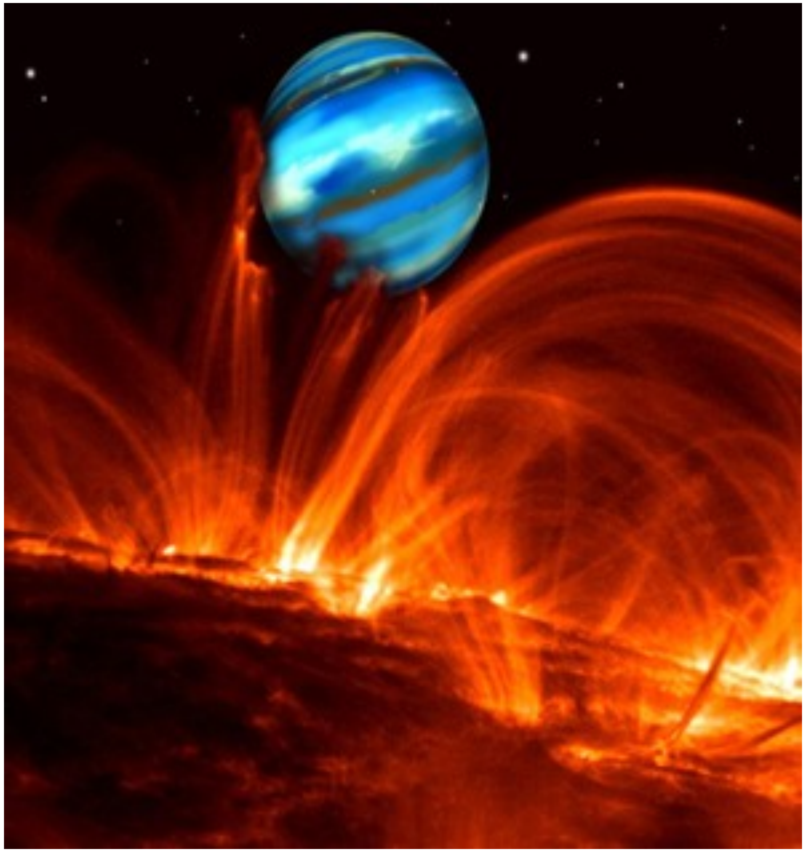
➡ $P_{spot} > 10^{19}$ W but $P_d = 0.15 \times 10^{15} \times \pi R_J^2$ W → energy crisis ?

→ larger obstacle or wind strength + stellar B ? (F_X ~10× solar)

[Shkolnik et al., 2005 ; Zarka, 2007]

ESPaDOnS spectropolarimeter @ CFHT

- Magnetic field of Tau Bootes [Catala et al., 2007]



- LOFAR

- 30-250 MHz
- Epoch 2009+ (solar max. !)
- Sensitivity ≤ mJy
- Imaging + tied array modes
- Built-in RFI mitigation & ionospheric calibration

➔ Exoplanet search part of “Transients” KP

➔ Candidate exoplanets + all close-by stars

Planets / Exoplanets Observations

- <u>RSM + Piggybacking on Surveys (≥ 1 sec)</u>

⇒ source identification by coordinates (vicinity of solar sys. planet, exoplanet)

⇒ flux, polarization, frequency & bandwidth ?

⇒ flag / switch to Tied-Array mode observations (exoplanets, lightning)

or fast imaging / TBB capture (Jupiter, lighting)

- <u>Targeted observations</u>

⇒ All known exoplanets (V_r, transits…) : presently >300 candidates

Special emphasis on

- close-in exoplanets (Hot Jupiters) with « good » predicted frequency range & flux density (τ Boo, HD192263…) [Griessmeier et al., 2007]
- Planets orbiting magnetized stars (τ Boo, υ And, HD189733…)
- COROT-monitored targets (HD46375…)

⇒ All observable stars closer than 10 pc (Gl 581…)

⇒ Selected magnetic stars (red dwarfs …) [tbd]