Interactions plasmas étoile-planète
Implications & détectabilité

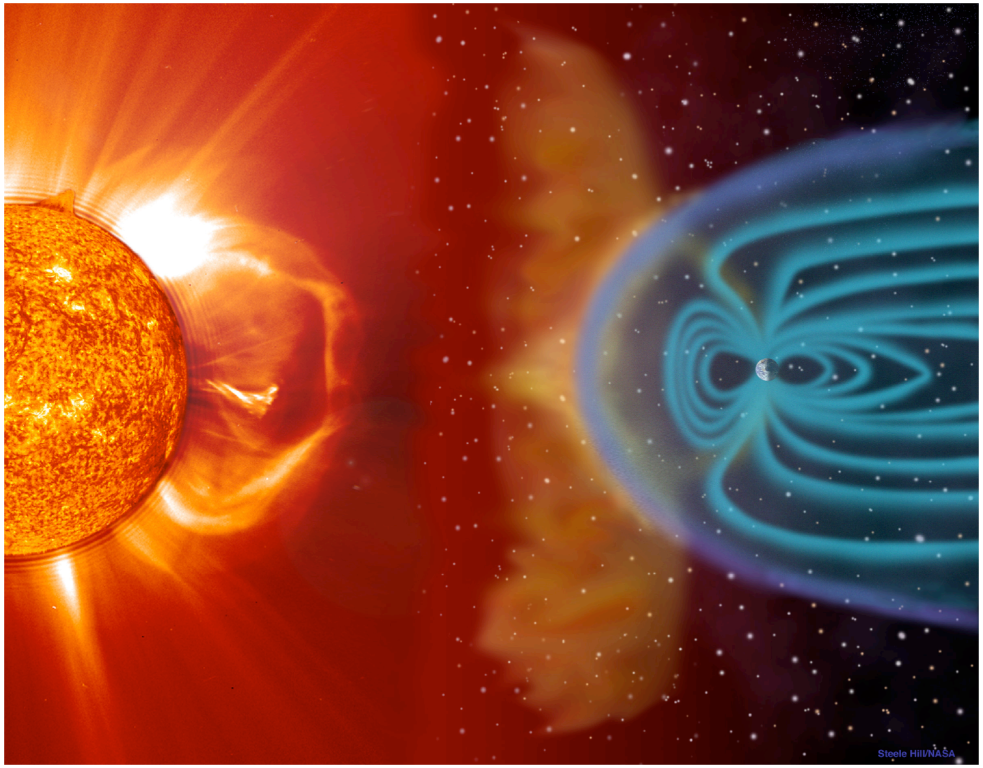
Philippe Zarka

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

- Interactions plasmas étoile-planète
- Signatures électromagnétiques
- Détectabilité radio
- Propriétés des émissions radio planétaires
- Lois d'échelle
- Implications pour les jupiters chauds
- Observations

- Interactions plasmas étoile-planète
- Signatures électromagnétiques
- Détectabilité radio
- Propriétés des émissions radio planétaires
- Lois d'échelle
- Implications pour les jupiters chauds
- Observations

Solar wind - magnetosphere interaction



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

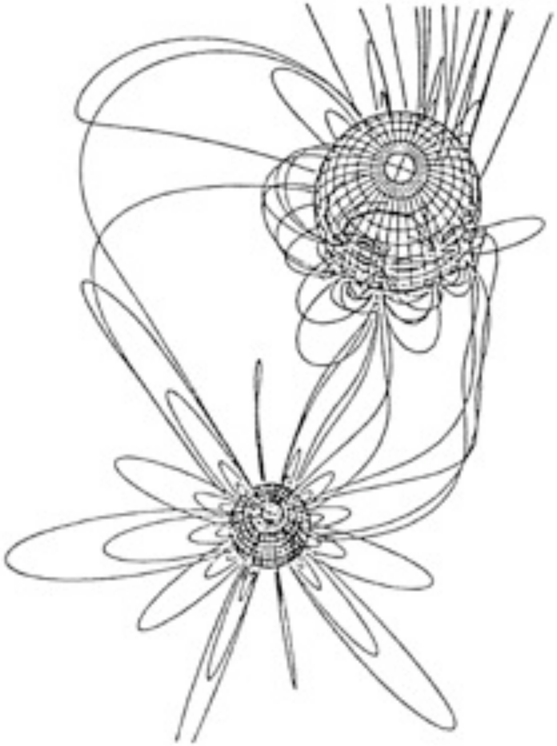
  $N=N_o/d^2$ $N_o=5\ cm^{-3}$ $m \sim 1.1 \times m_p$

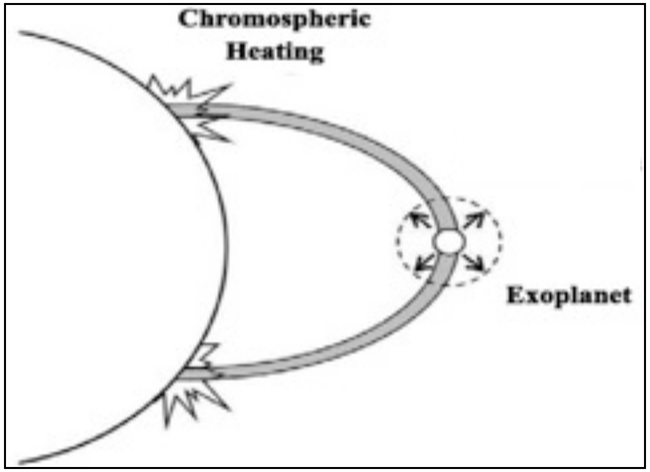
- Poynting flux of B_{IMF} on obstacle cross-section : $P = \int_{obs} (\mathbf{E}\times\mathbf{B}/\mu_o).\mathbf{dS}$

$\mathbf{E}=-\mathbf{V}\times\mathbf{B} \rightarrow \mathbf{E}\times\mathbf{B} = VB_\perp^2$ $B_\perp \sim d^{-1/-2}$ $\rightarrow$ $P_m = B_\perp^2/\mu_o \; V \; \pi R_{obs}^2$

[Akasofu, 1981, 1982; Zarka et al., 2001, 2007]

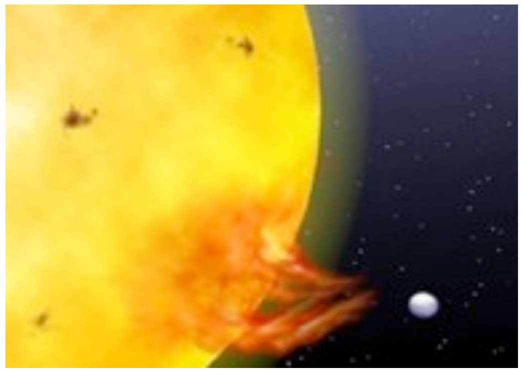
Dipolar & Unipolar interactions

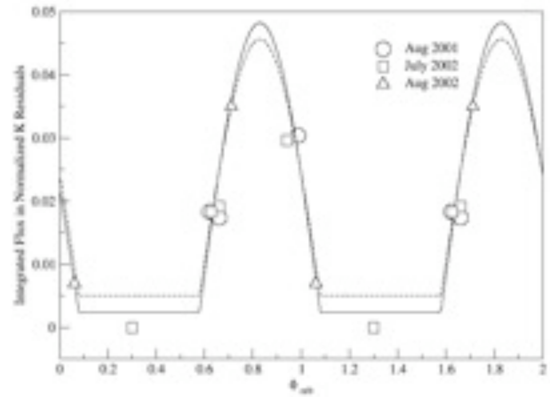




Dipolar & Unipolar interactions

- Chromospheric hot spot on HD179949 + υ And



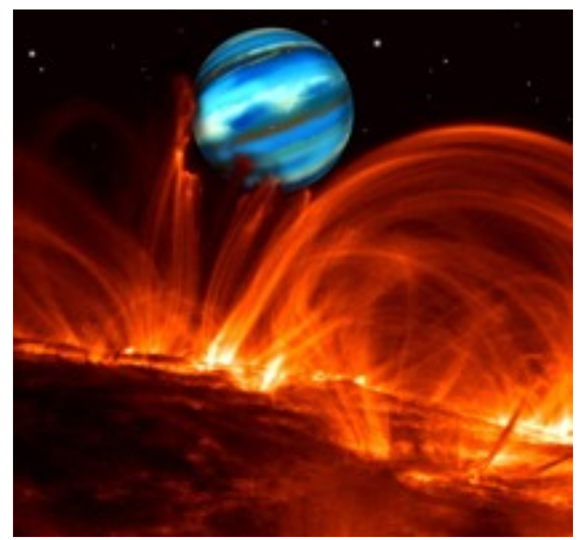


[Shkolnik et al. 2003, 2004, 2005]

- Large-scale stellar magnetic fields

(ESPaDOnS@CFHT & NARVAL@TBL)

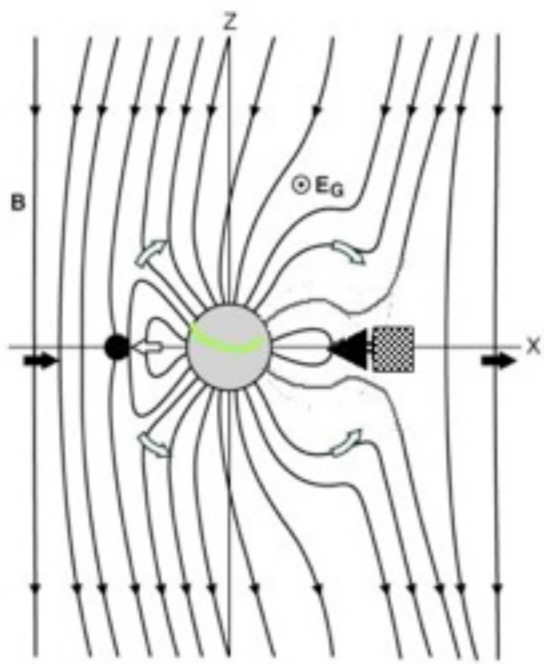
Tau Boo : 5-10 G
HD 76151 : ~10 G
HD 189733 : >50 G
HD 171488 : 500G
...

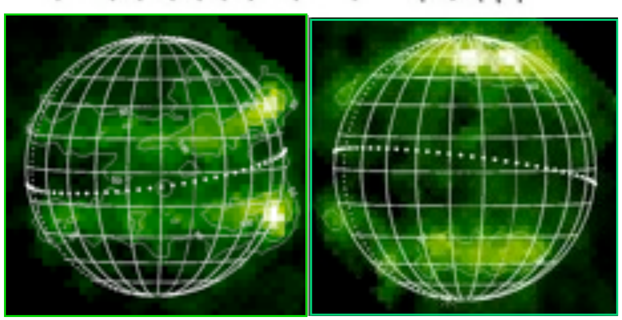


[Catala et al., 2007; Donati et al., 2007, 2008]

Dipolar & Unipolar interactions

- Ganymede-Jupiter : reconnection
- Io-Jupiter : Alfvén waves & currents

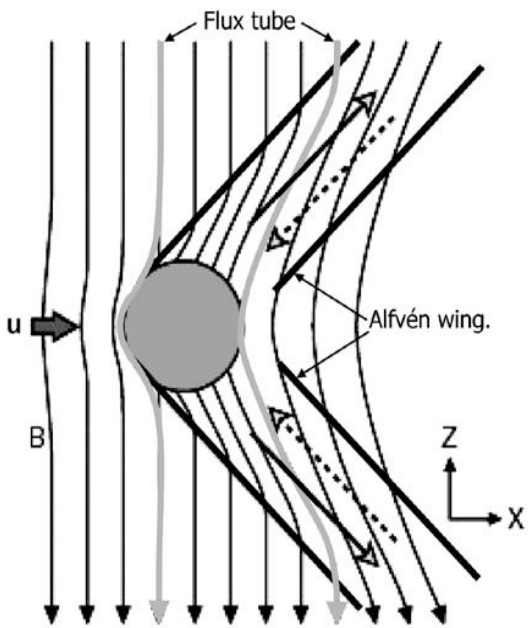


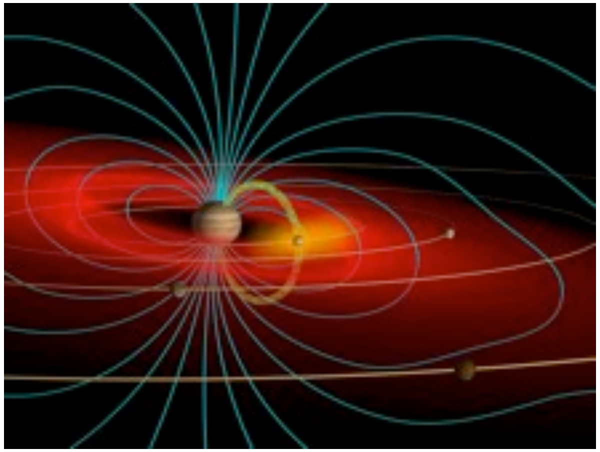


Downstream Upstream

$P_d = \varepsilon\, VB_\perp^2/\mu_o\, \pi R_{obstacle}^2$

$\varepsilon \sim 0.2 \pm 0.1$



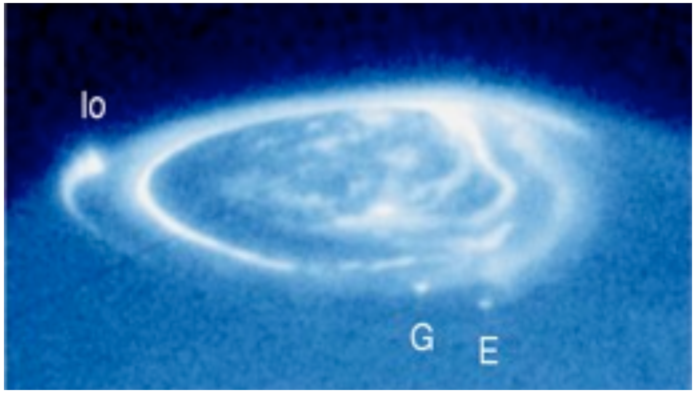


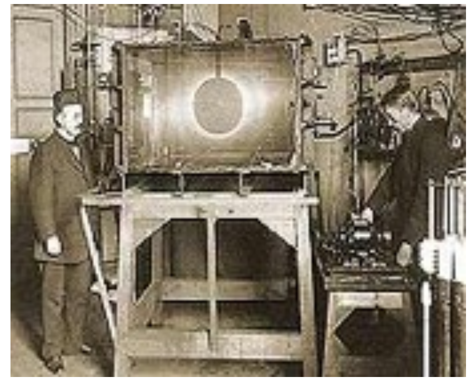
[McGrath et al., 2002; Kivelson et al., 2004; Saur et al., 2004]

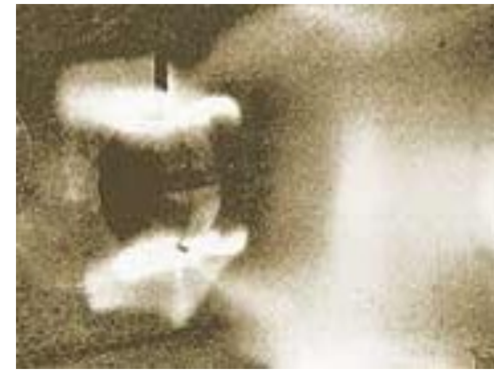
- Interactions plasmas étoile-planète
- Signatures électromagnétiques
- Détectabilité radio
- Propriétés des émissions radio planétaires
- Lois d'échelle
- Implications pour les jupiters chauds
- Observations

Electromagnetic signatures : optical (UV) …

• Aurora





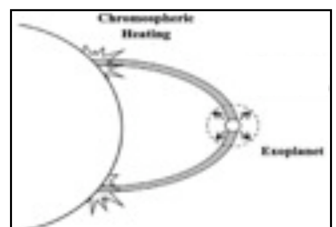


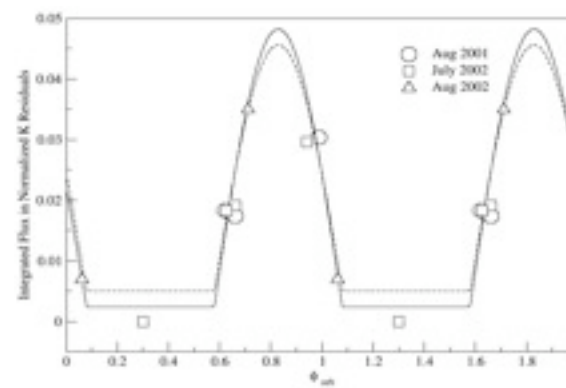
[Birkeland, 1910]

• Chromospheric hot spots

→ unipolar or dipolar interaction ?

→ power budget ? spot phase ?



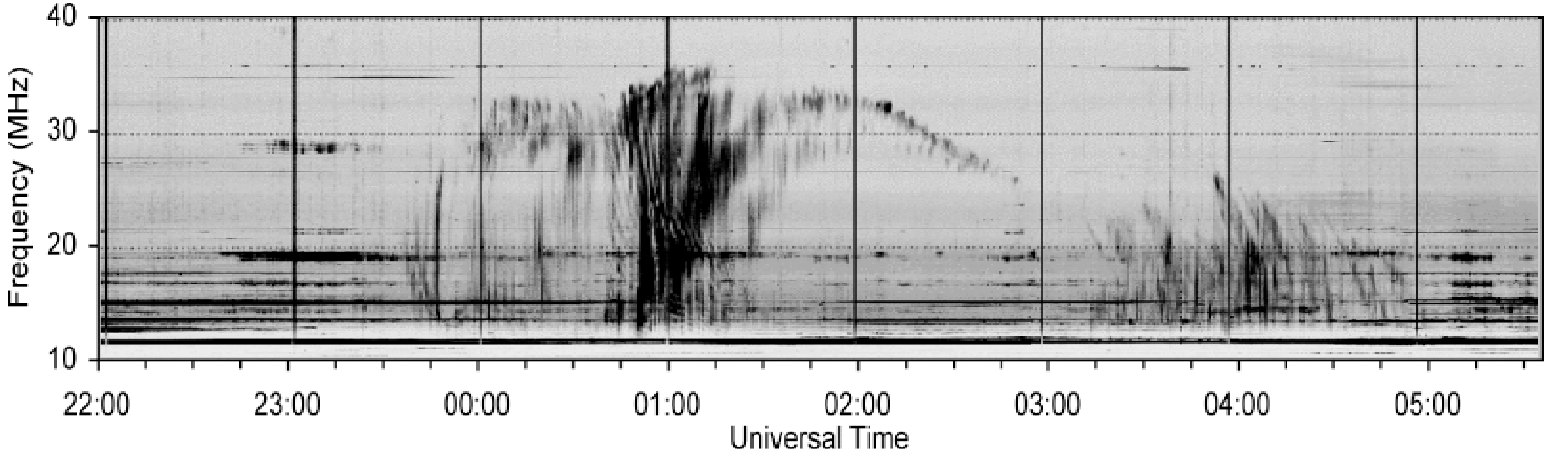


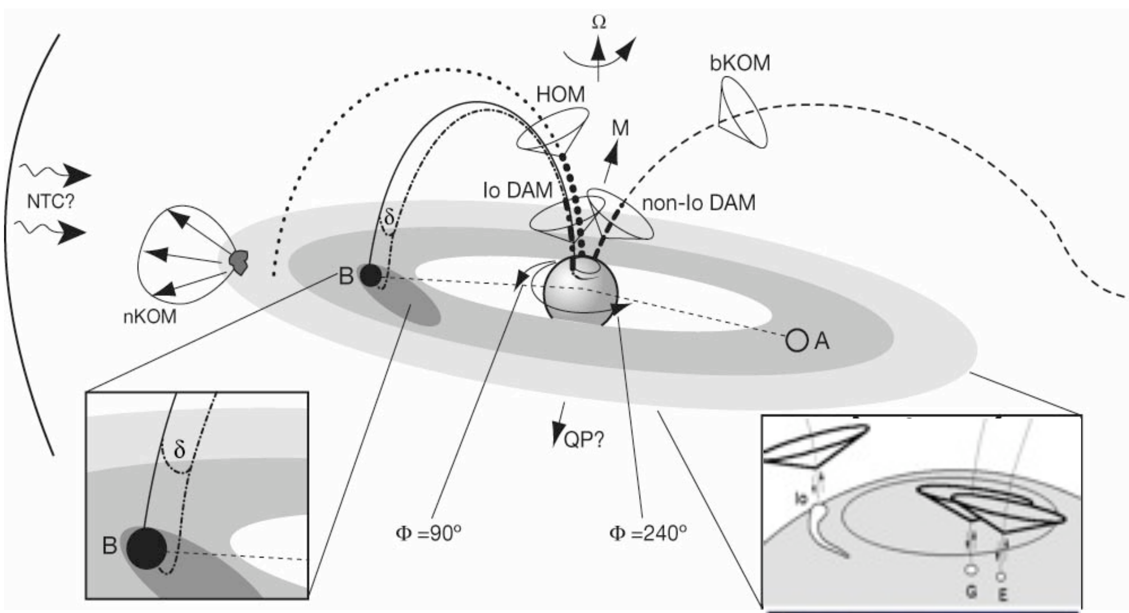
[Preusse et al., 2006; Shkolnik et al., 2005, 2008; Zarka, 2007]

• Super-flares ?

[Rubenstein & Schaefer, 2000 ; Schaefer et al., 2000]

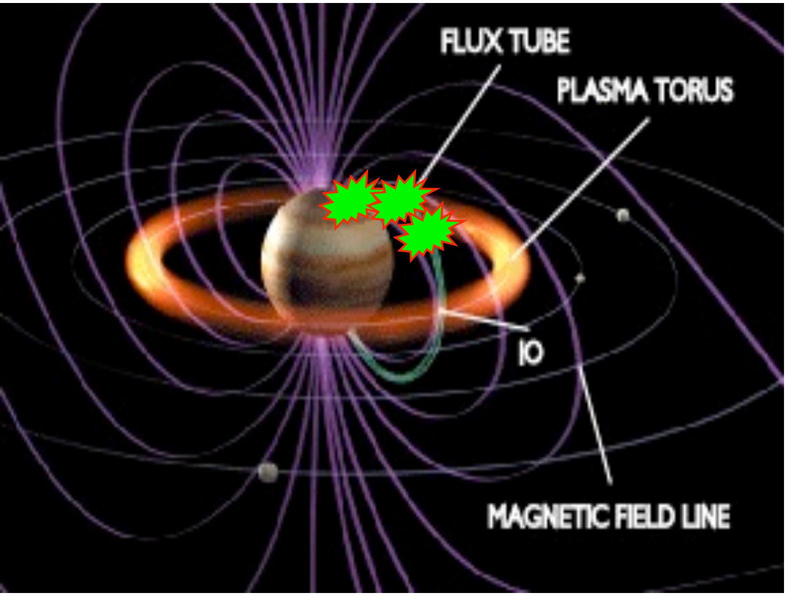
… and radio emissions …

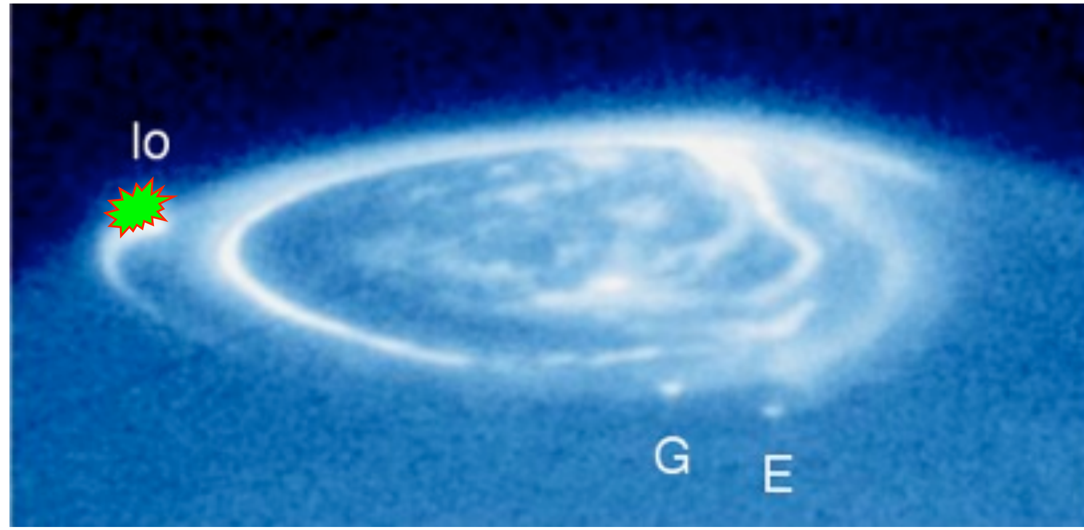


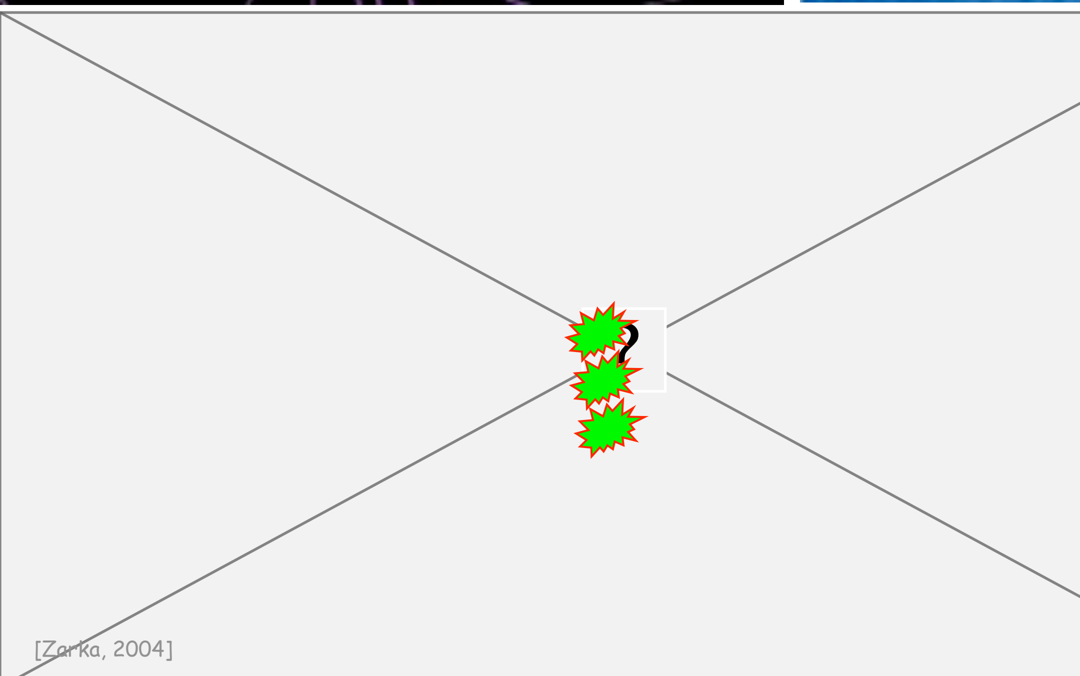


[Zarka, 2004]

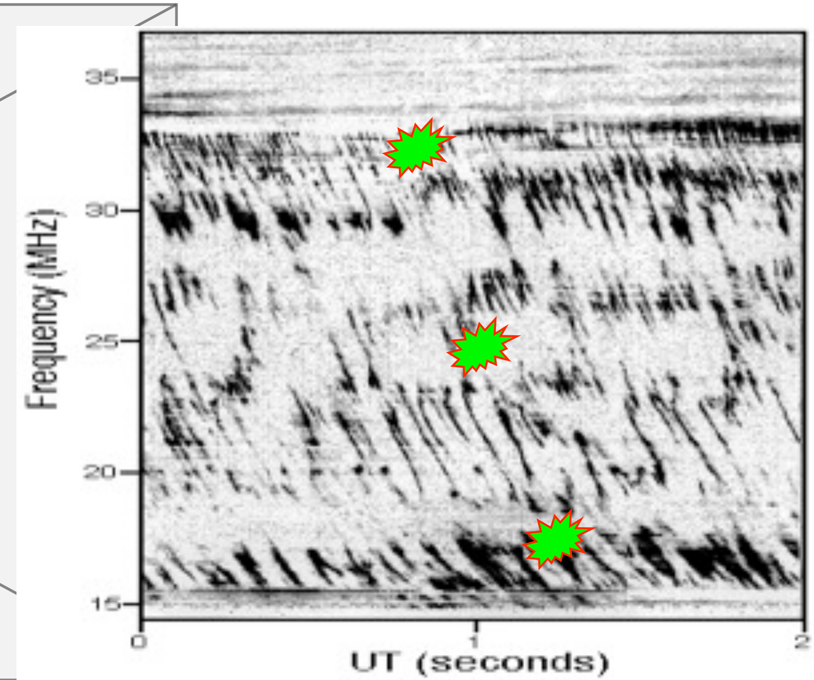
… including from Io-Jupiter electrodynamic interaction

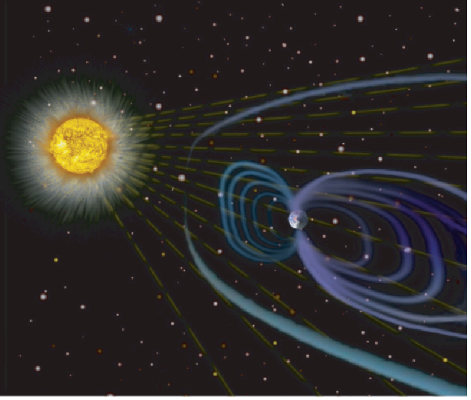




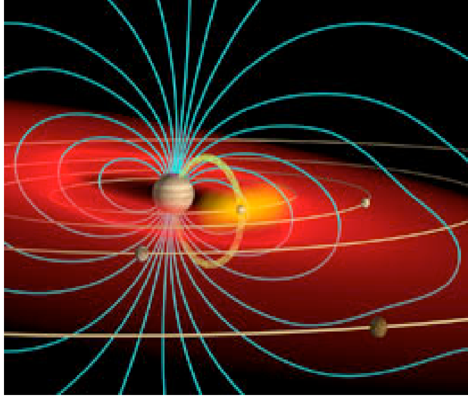


[Zarka, 2004]





Radio emissions from flow-obstacle interactions

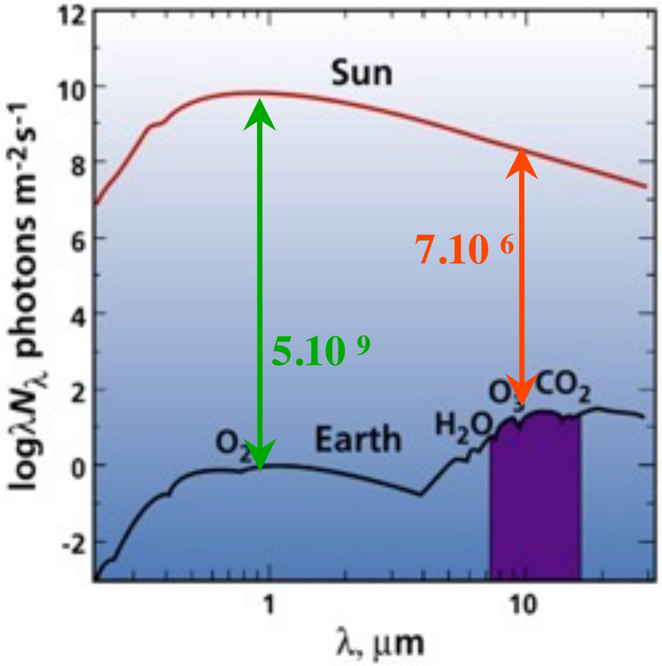


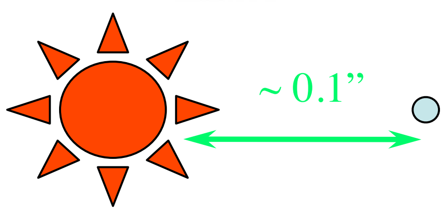
Obstacle \ Flow	Weakly/Not magnetized *(Solar wind)*	Strongly magnetized *(Jovian magnetosphere)*
Weakly/Not magnetized *(Venus, Mars, Io)*	No Intense Cyclotron Radio Emission	<u>Unipolar interaction</u> → Io-induced Radio Emission,
Strongly magnetized *(Earth, Jupiter, Saturn, Uranus, Neptune, Ganymede)*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

- Interactions plasmas étoile-planète
- Signatures électromagnétiques
- Détectabilité radio
- Propriétés des émissions radio planétaires
- Lois d'échelle
- Implications pour les jupiters chauds
- Observations

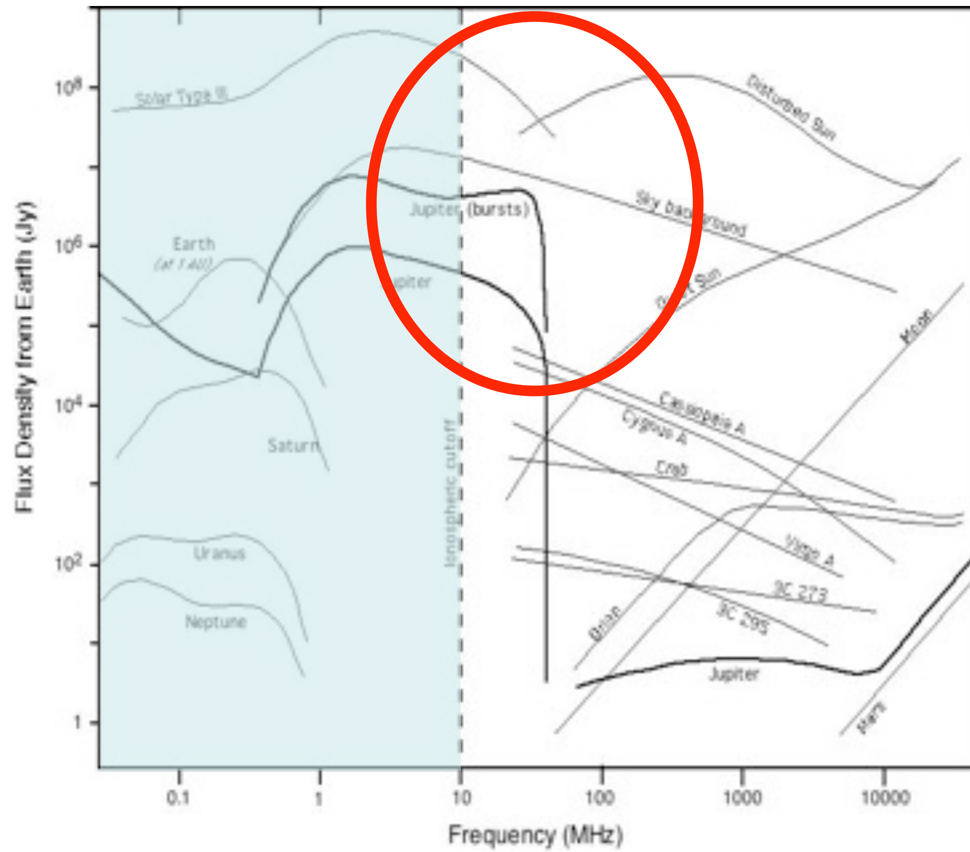
Interest of LF radio observations for direct detection

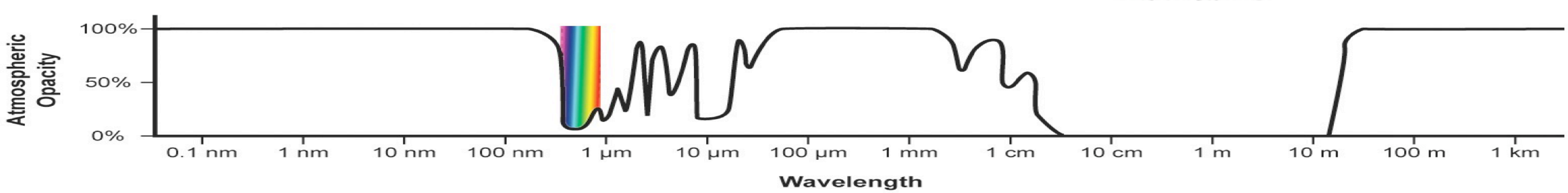
Star/planet proximity
→ contrast





Intense non-thermal radio emissions :
« Plasma » processes
→ Contrast Sun/Jupiter ~1 !





Sensitivity of observations

- Galactic radio background: $T \sim 1.15 \times 10^8 / \nu^{2.5} \sim 10^{3-5}$ 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

- Maximum distance for $N\sigma$ detection of a source ζ x Jupiter :

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

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

[Zarka et al., 1997]

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.

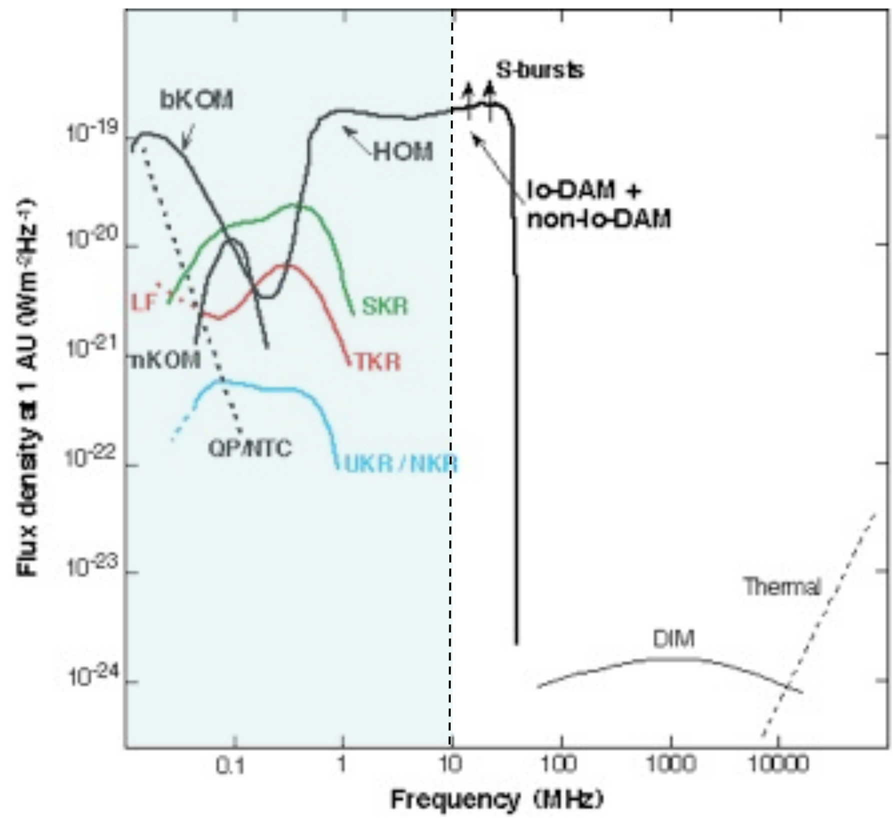
(distances in parsecs)

[Zarka et al., 1997]

- Interactions plasmas étoile-planète
- Signatures électromagnétiques
- Détectabilité radio
- Propriétés des émissions radio planétaires
- Lois d'échelle
- Implications pour les jupiters chauds
- Observations

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



[Zarka, 1998]

Generation of « auroral » radio emissions

- Coherent cyclotron emission : 2 conditions within sources :

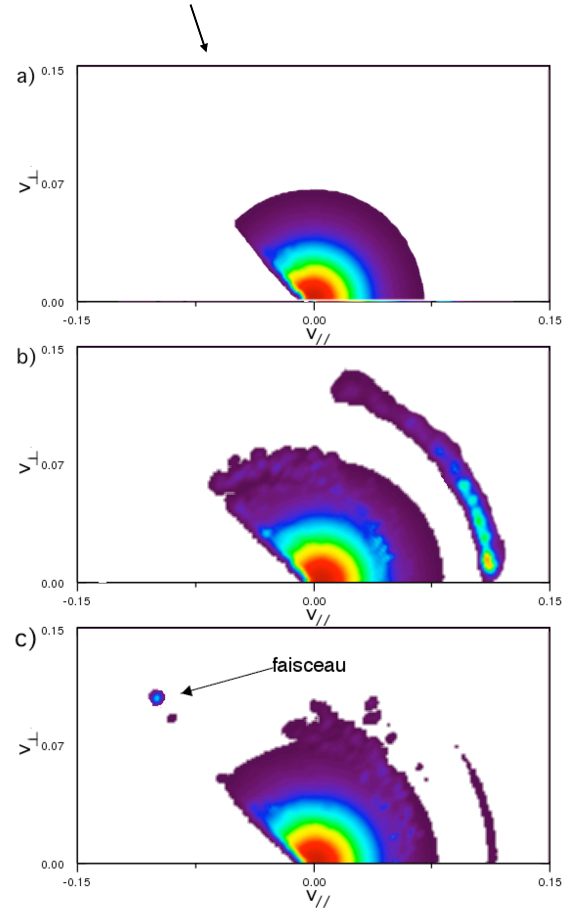
  - low β magnetized plasma ($f_{pe} \ll f_{ce}$)

  - 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



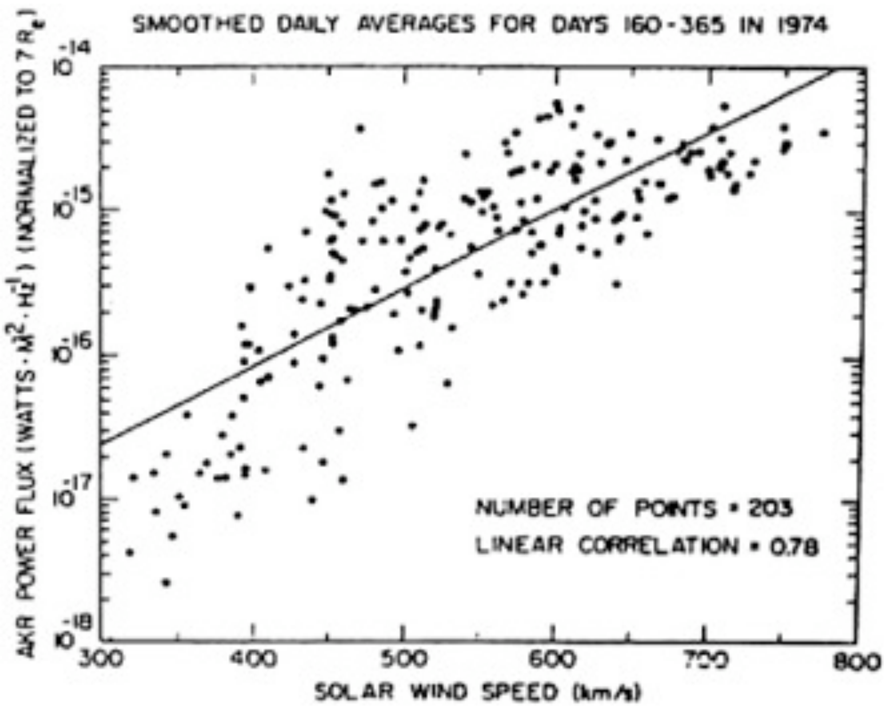
- Acceleration of electrons :

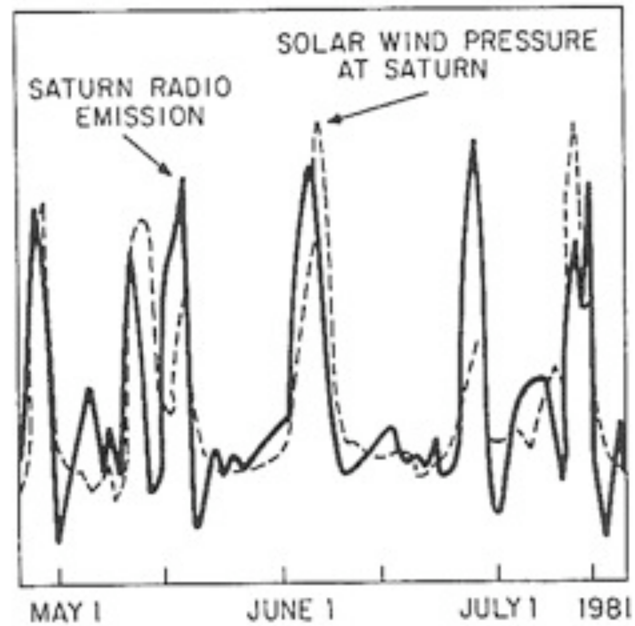
  - magnetic reconnections

  - MS compressions

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

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



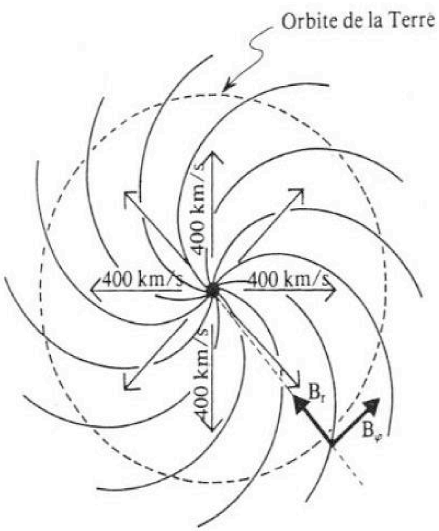


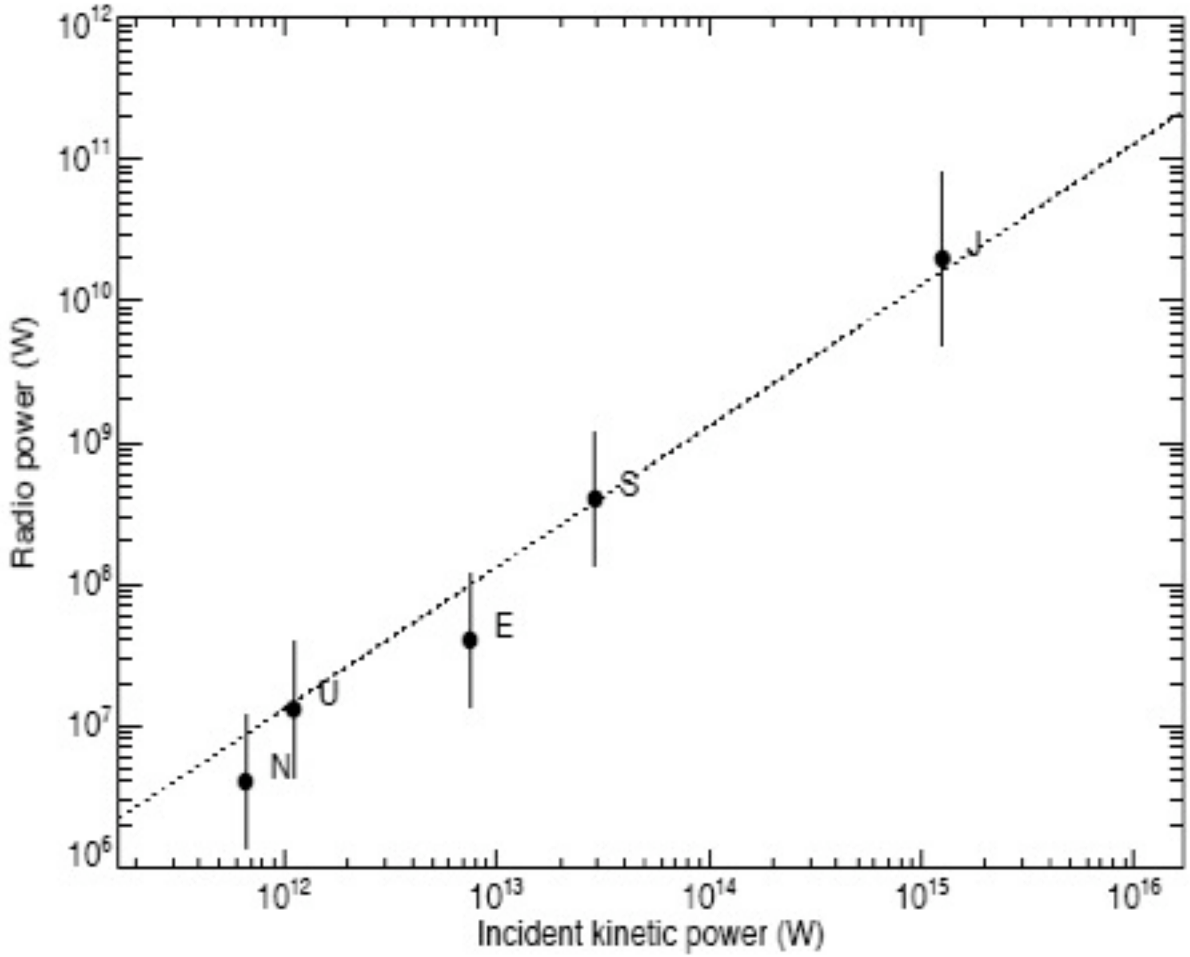
[Desch, 1981; *Gallagher and d'Angelo*, 1981]

- Interactions plasmas étoile-planète
- Signatures électromagnétiques
- Détectabilité radio
- Propriétés des émissions radio planétaires
- Lois d'échelle
- Implications pour les jupiters chauds
- Observations

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

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





Solar Wind expansion

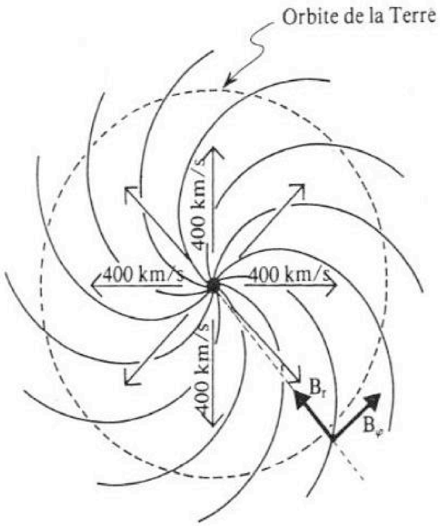
$V \sim c^{te}$

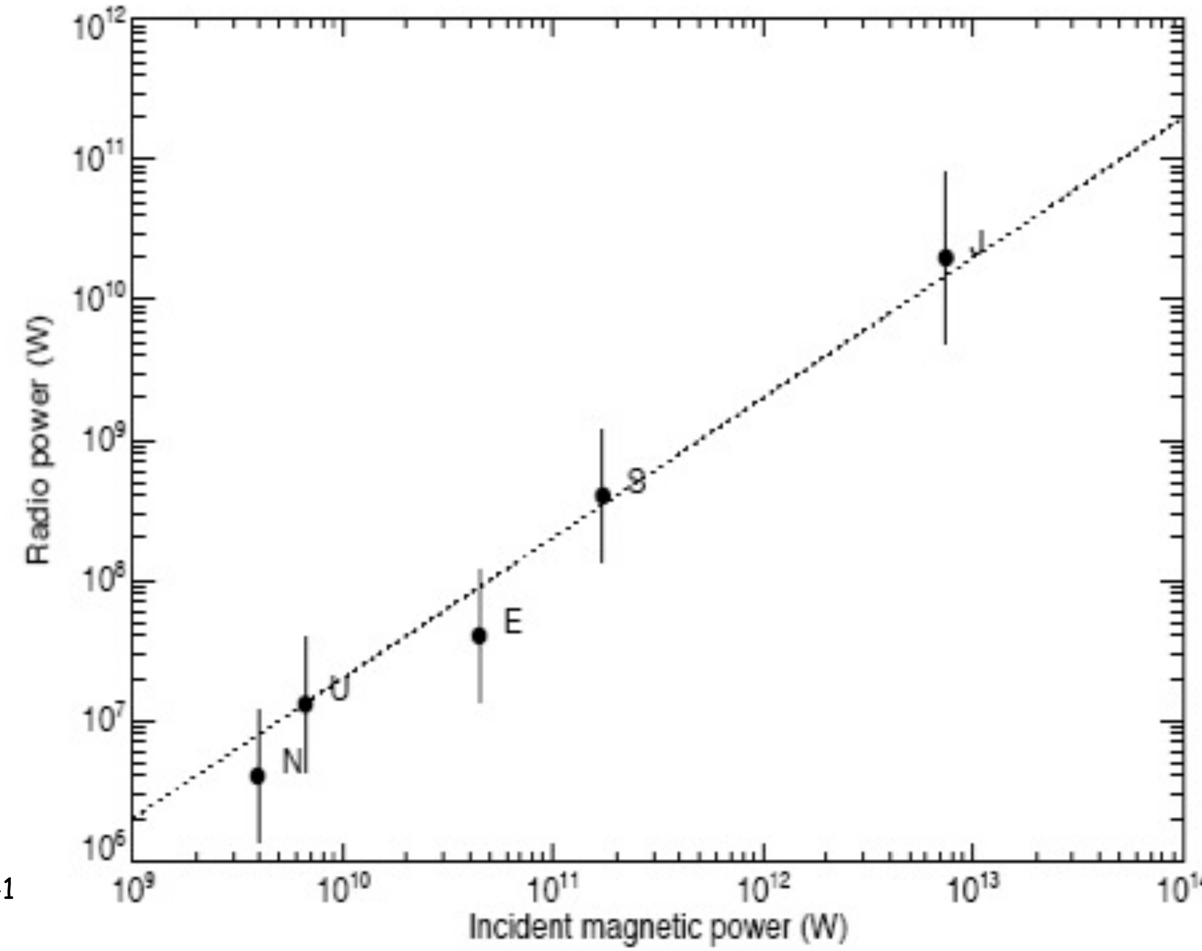
$N \sim d^{-2}$ (mass conservation)

[Desch and Kaiser, 1984 ; Zarka, 1992]

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

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





Solar Wind expansion

$V \sim c^{te}$

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

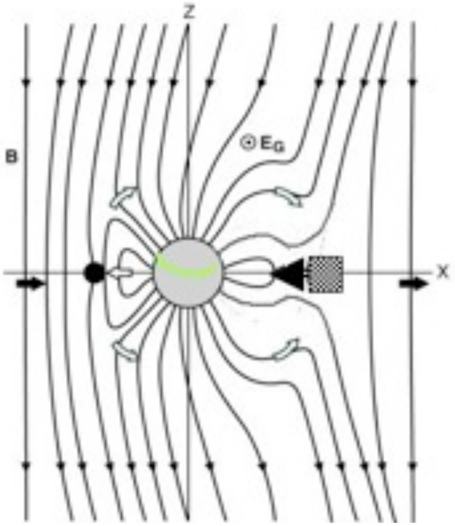
$B_R \sim d^{-2}$ (mag flux conservation)

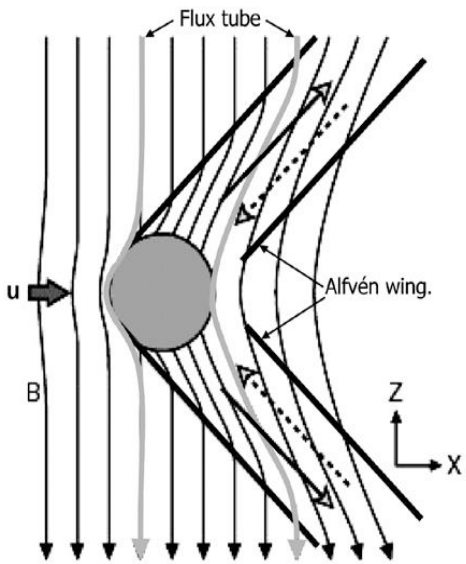
$B\varphi \sim d^{-1}$ ($B_R/B\varphi = V/\Omega d$) $\rightarrow B \sim d^{-1}$

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

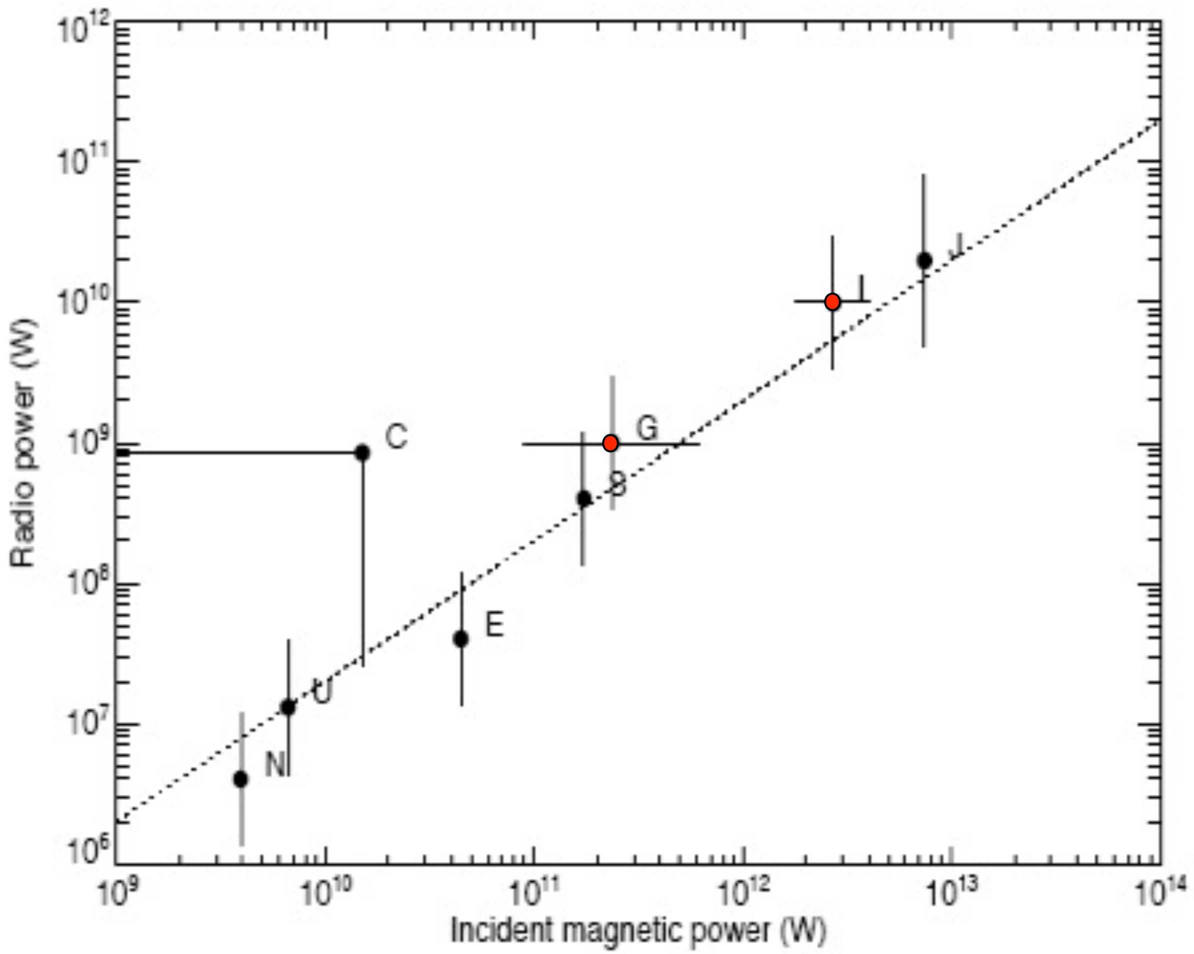
[Zarka et al., 2001]

« 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]

- Interactions plasmas étoile-planète
- Signatures électromagnétiques
- Détectabilité radio
- Propriétés des émissions radio planétaires
- Lois d'échelle
- Implications pour les jupiters chauds
- Observations

Exoplanets & Star data

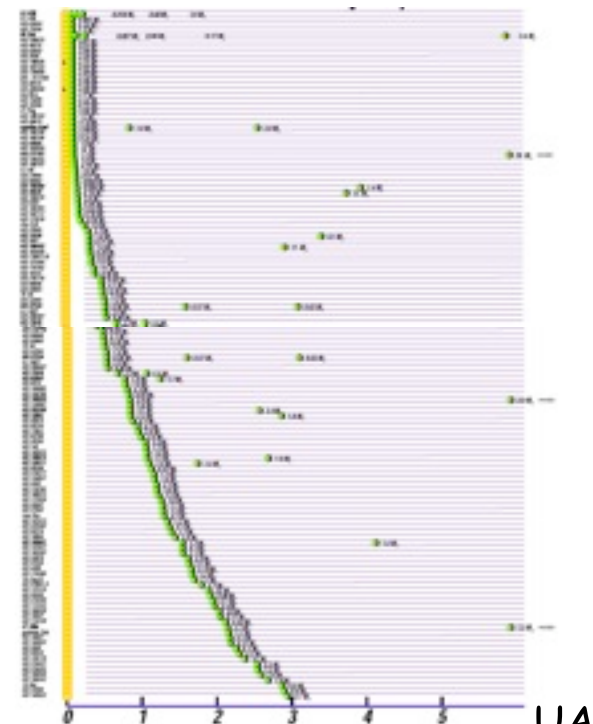
>350 exoplanets (in >260 systems)

~70 with $a \leq 0.05$ AU = 10 Rs (20%)

~100 with $a \leq 0.1$ AU (30%)

→ >50 « hot Jupiters »

with periastron @ ~5-10 R_S



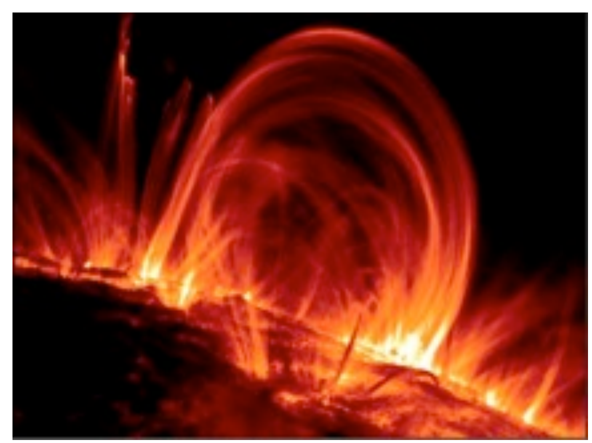
exoplanet.eu

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

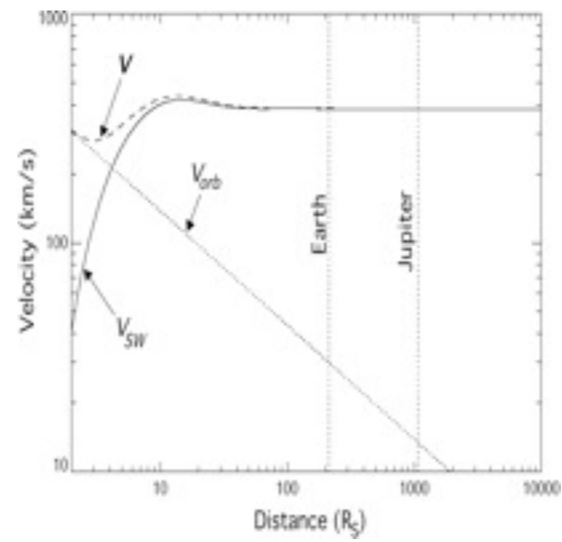
Modelling a magnetized hot Jupiter orbiting a Solar type star

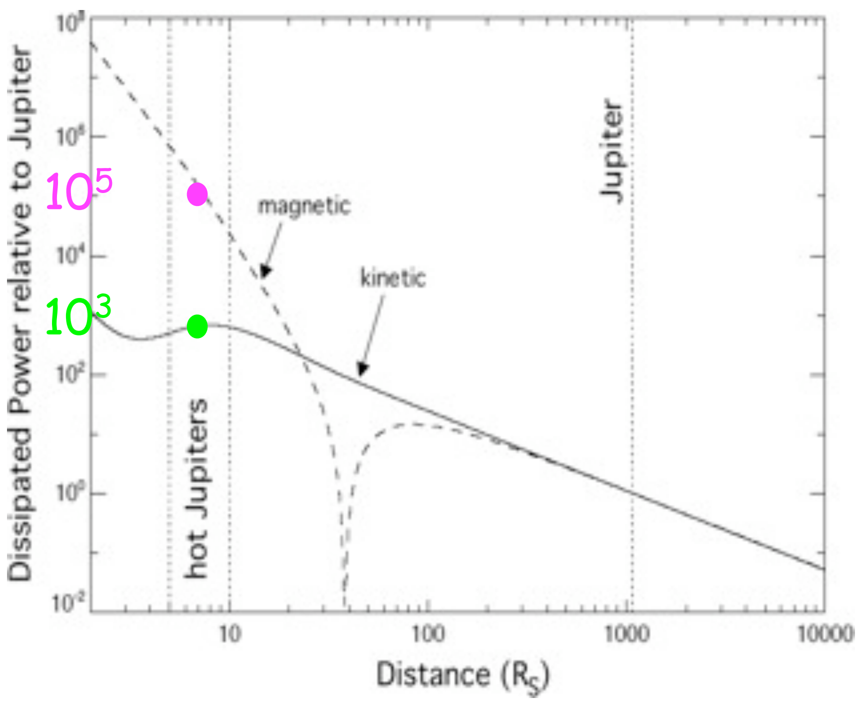
- Ne & B variations in Solar corona and interplanetary medium
- Solar wind speed in the planet's frame

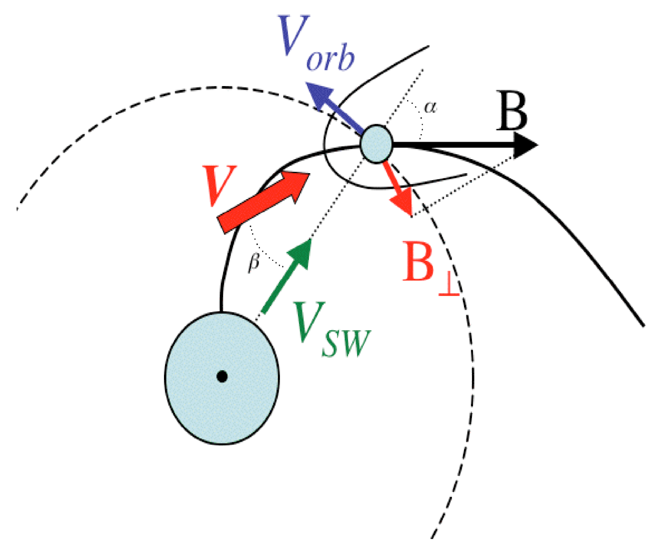
  → Dissipated power per unit area of the obstacle

  → Magnetospheric compression

  →Total dissipated power on obstacle

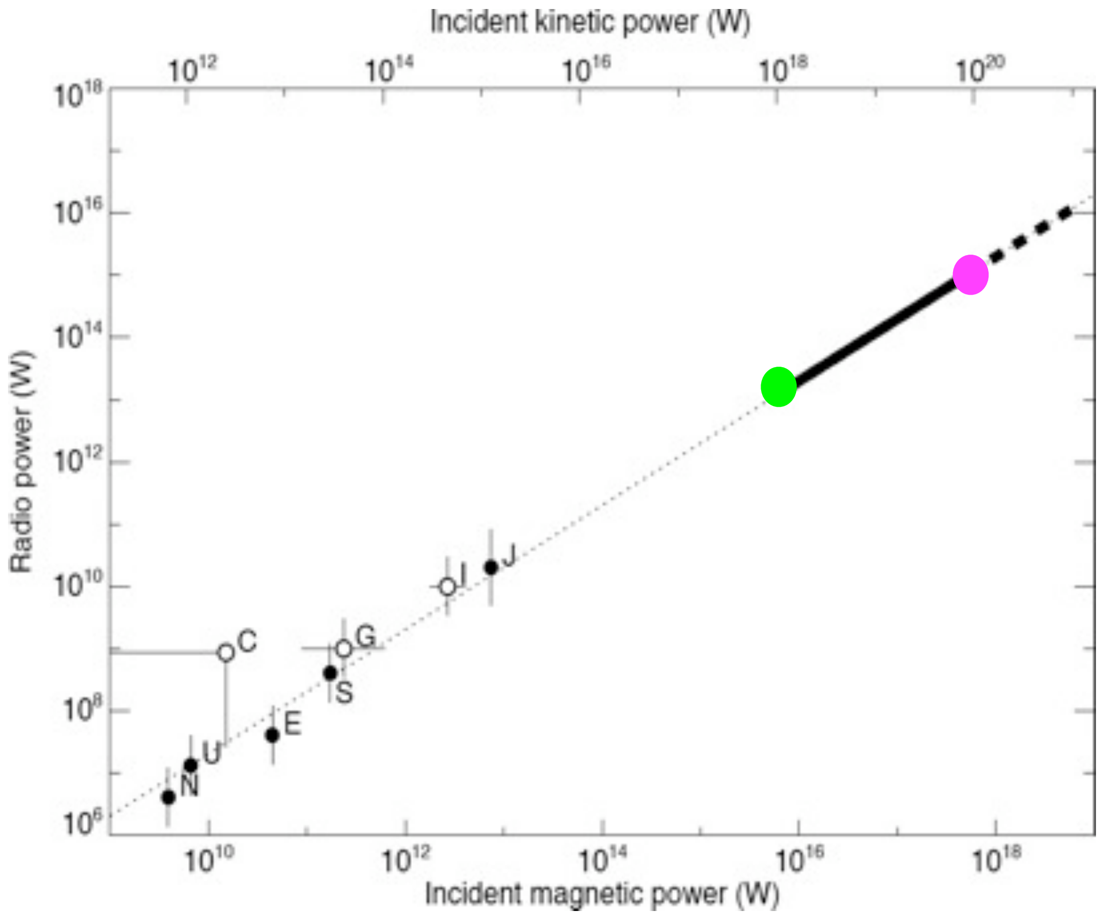






[Zarka et al., 2001, 2005]

+ Scaling law

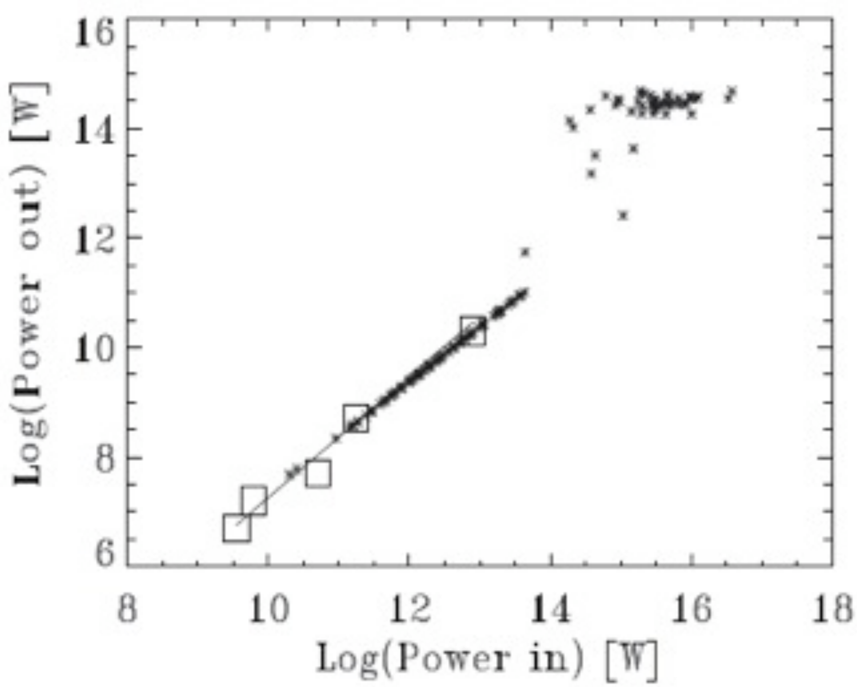


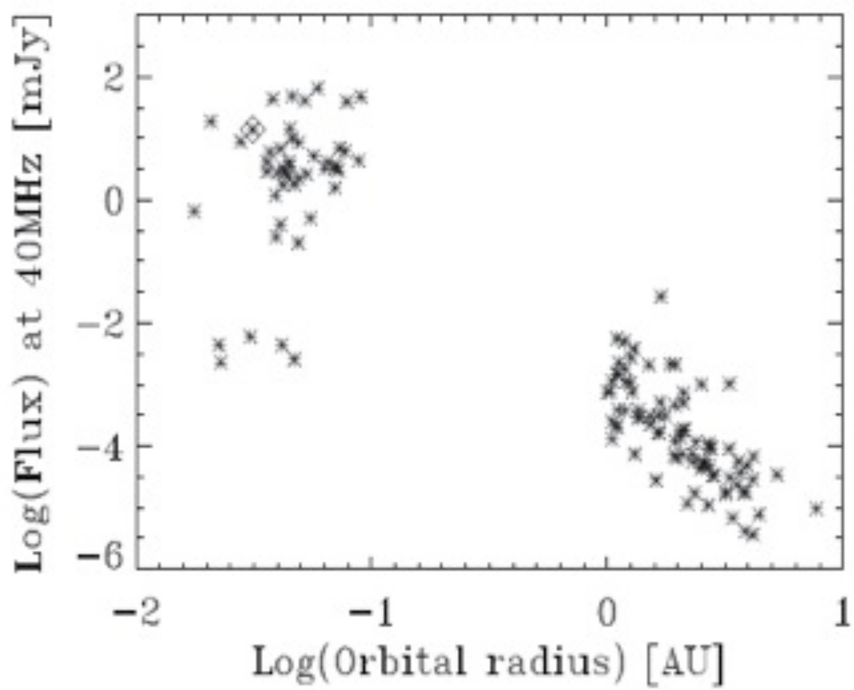
- Extrapolations of Radio-kinetic/magnetic Bode's laws → $P_{Radio} = P_{Radio\text{-}J} \times 10^{3-5}$
- if no "saturation" nor planetary magnetic field decay

[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, $B_{max\text{-}surface} = 14$ G, $f_{max} = 40$ MHz
- But Spin-orbit synchronisation (tidal forces) → ω↓

and $\mathcal{M} \propto P_{sid}^{\alpha}$ $-1 \leq \alpha \leq -\frac{1}{2}$ → $\mathcal{M}$↓ (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

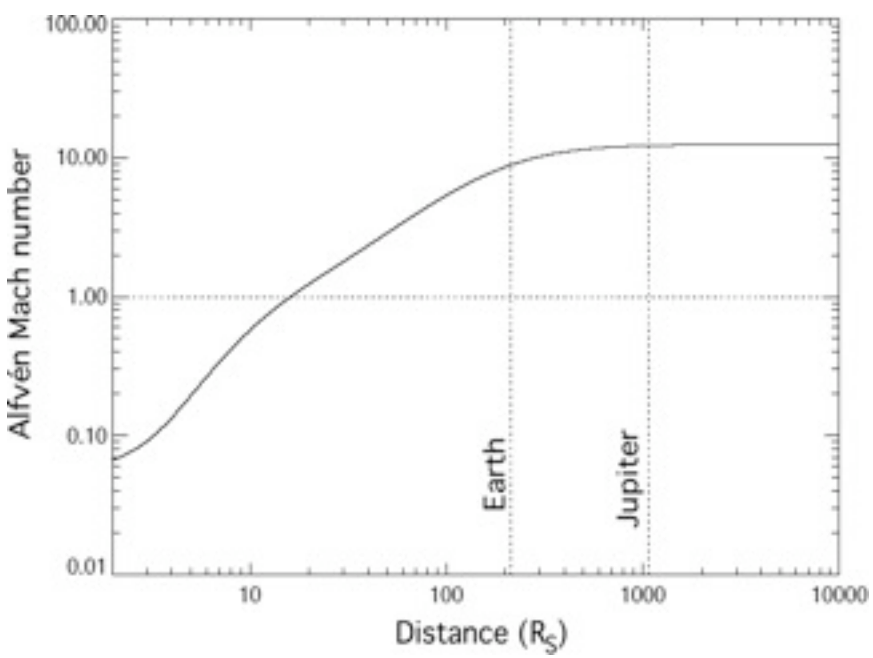
[Sanchez-Lavega, 2004]

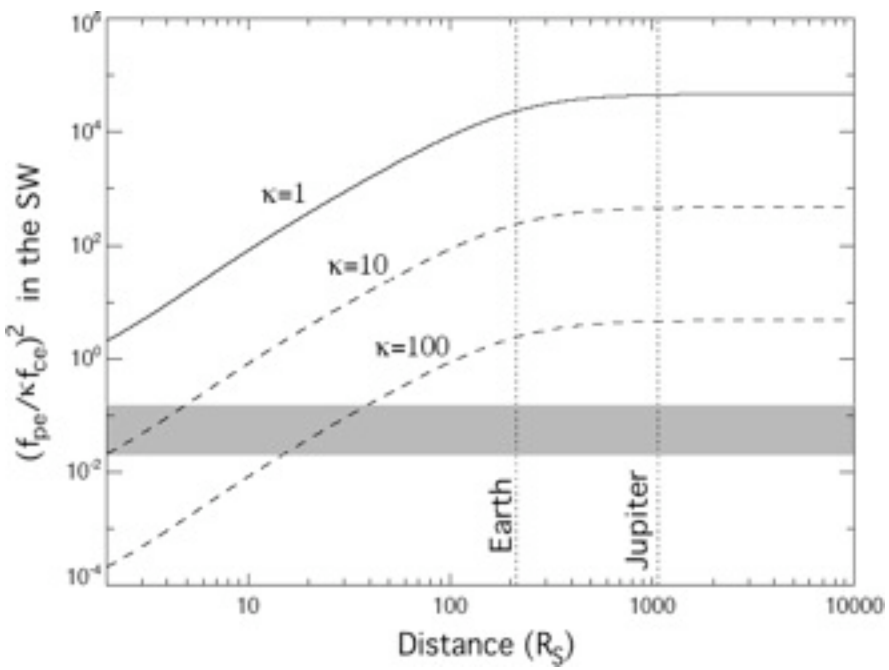
Unipolar inductor in sub-Alfvénic regime

- Similar to Io-Jupiter case
- But radio emission possible only if $f_{pe}/f_{ce} \ll 1$

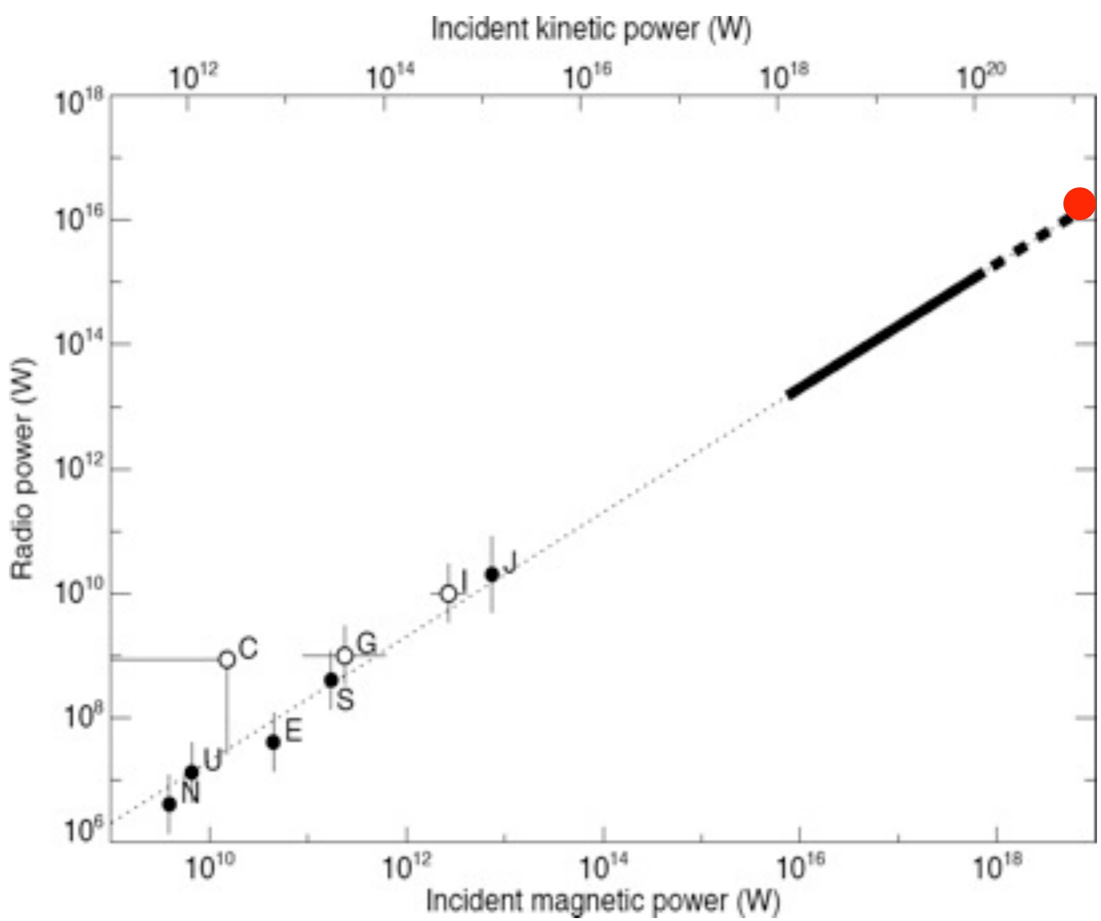
  → intense stellar B required (10-100 x B_{Sun})

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





Unipolar inductor in sub-Alfvénic regime



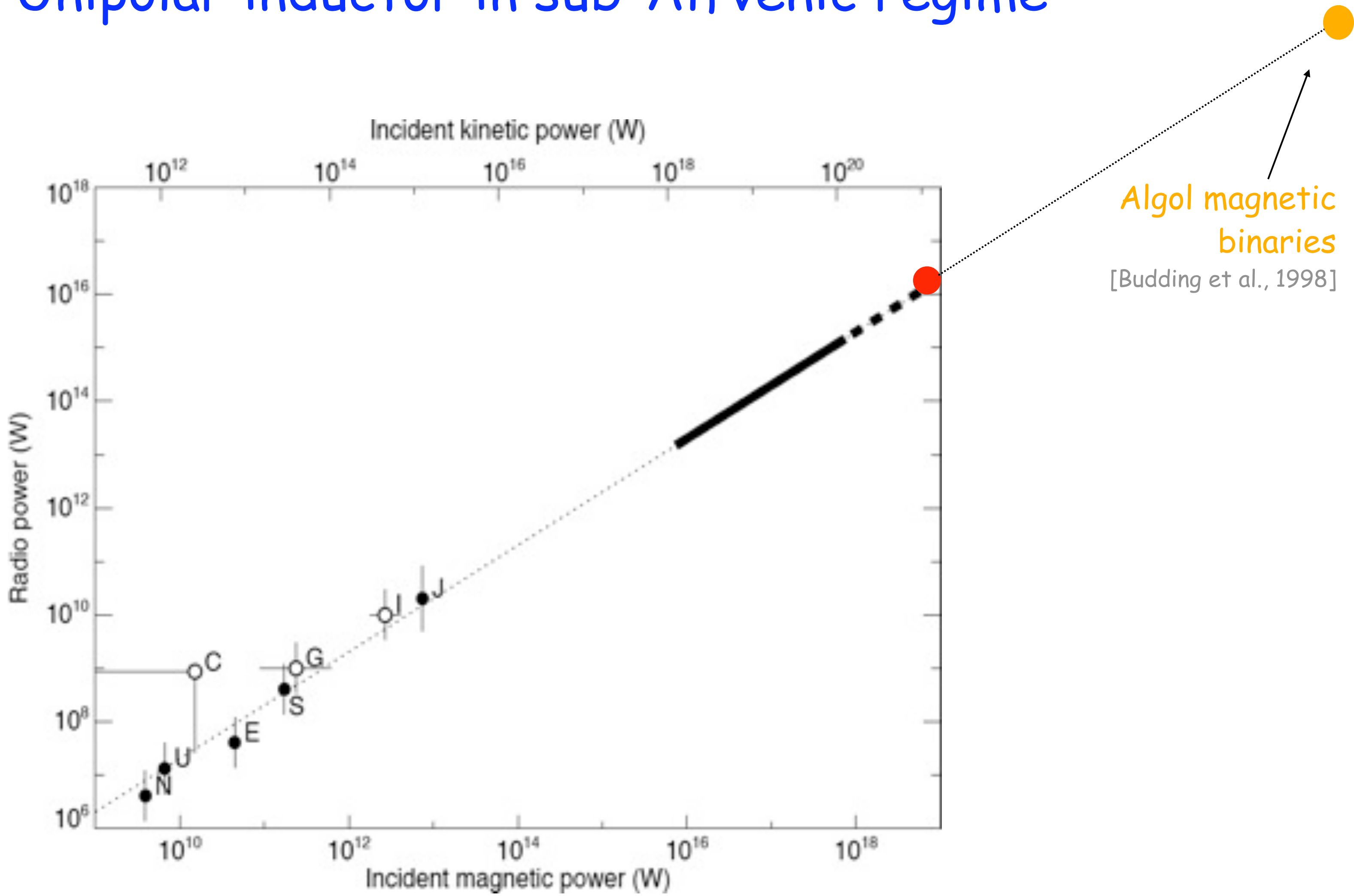
- Extrapolation / Radio-magnetic Bode's law

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

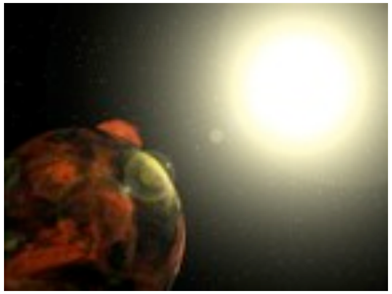
= up to $P_{Radio\text{-}J} \times 10^6$

[Zarka, 2007]

Unipolar inductor in sub-Alfvénic regime



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)

[Zarka, P., Plasma interactions of exoplanets with their parent star and associated radio emissions, Planet. Space Sci., 55, 598-617, 2007]

Other studies ...

- Possibilities for radio scintillations $\Rightarrow$ 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)

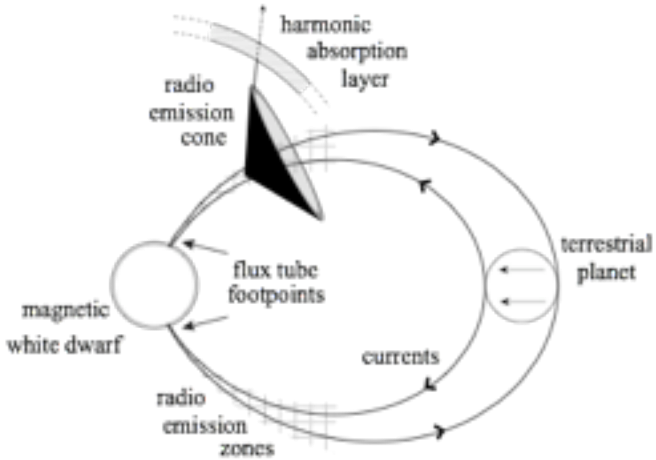
[Griessmeier et al., 2004 ; Stevens, 2005]

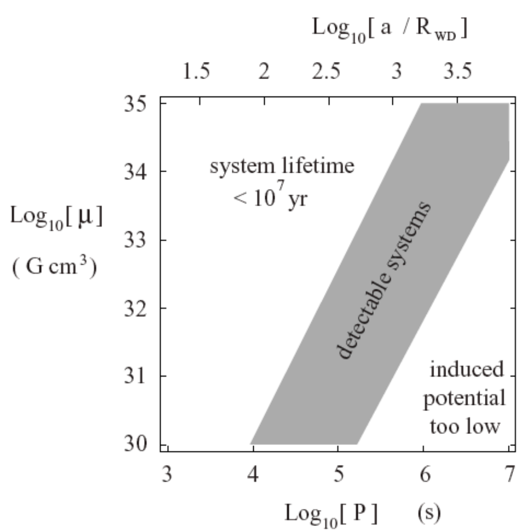
- Role of (frequent) Coronal Mass Ejections

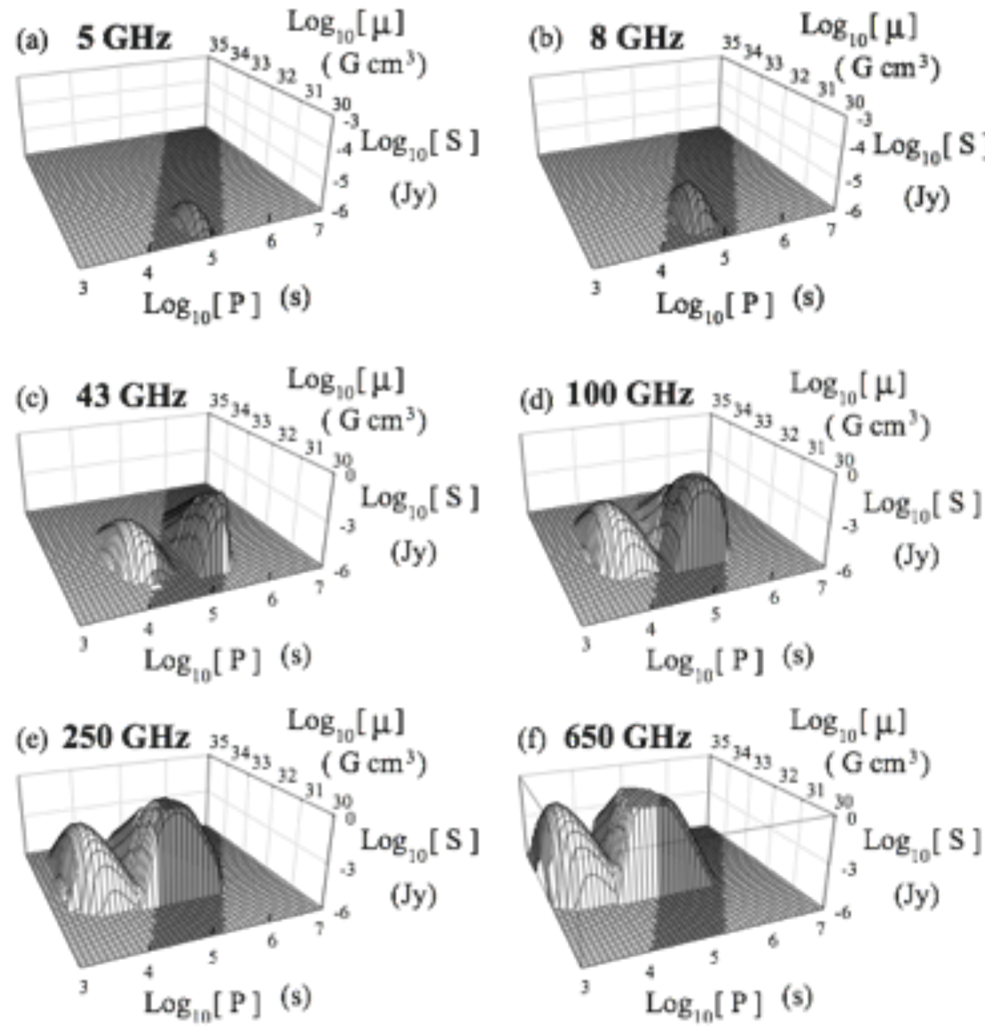
[Khodachenko et al., 2006]

• Application of unipolar inductor model to white dwarfs systems

[Willes and Wu, 2004, 2005]

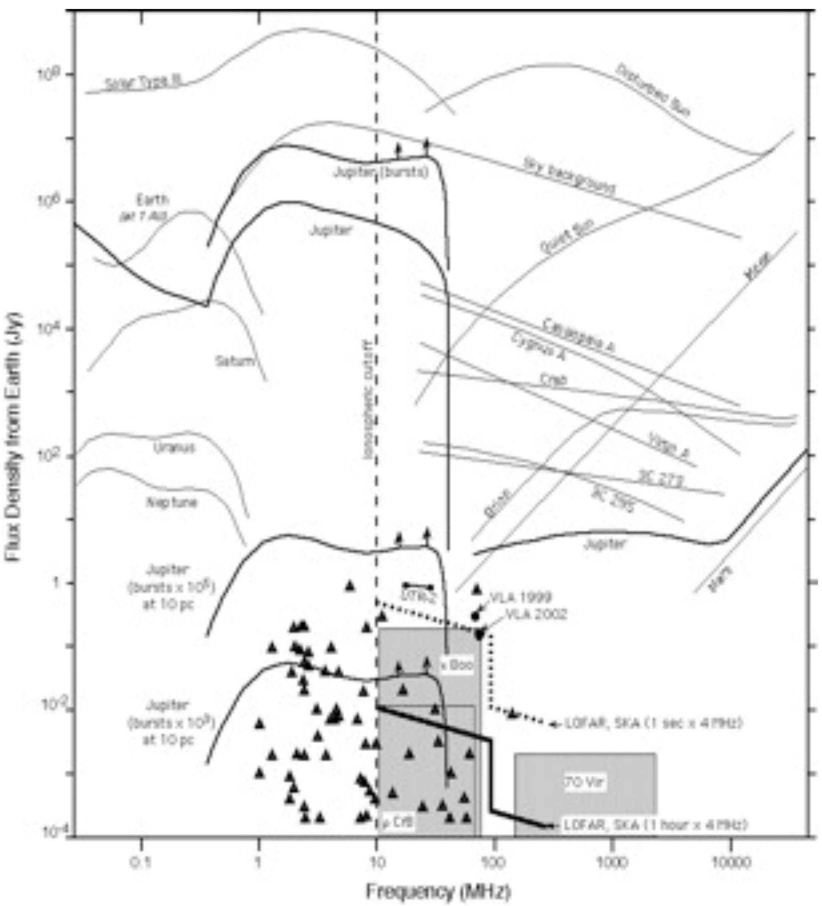


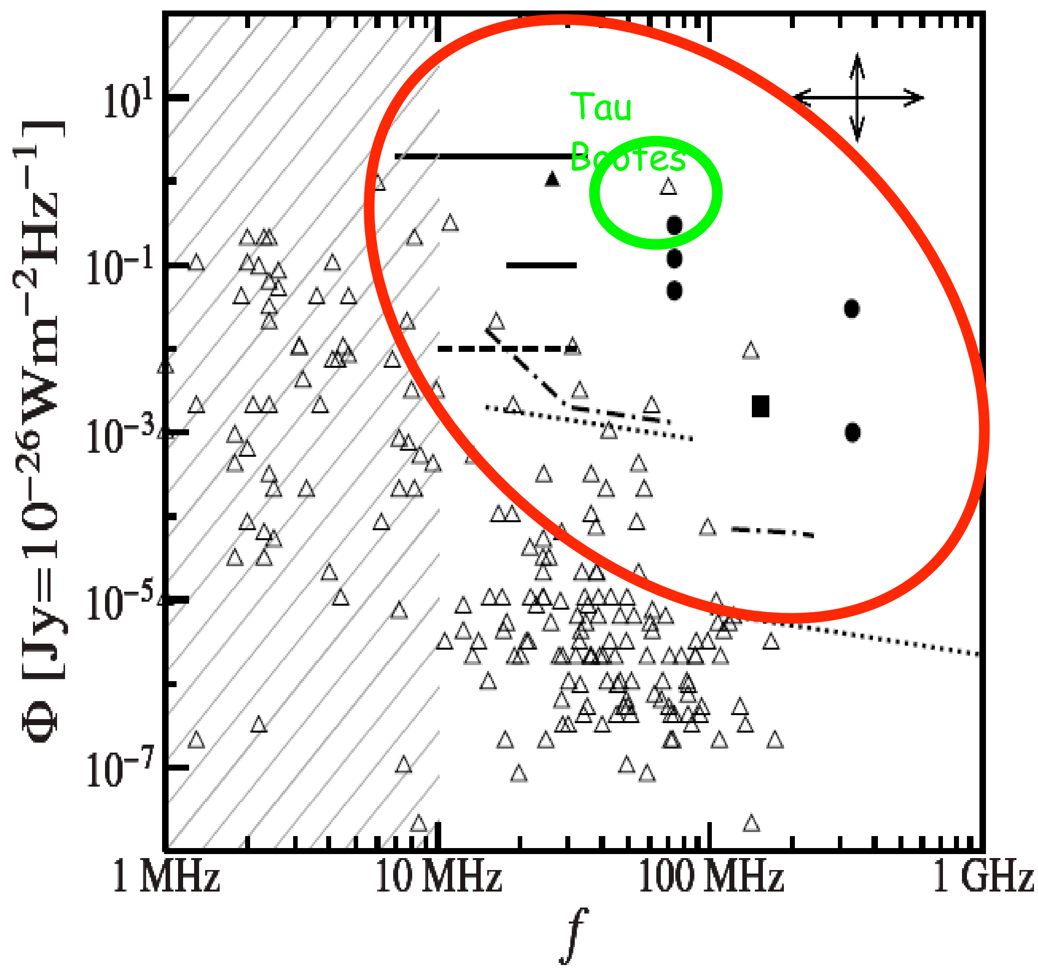




saturated loss-cone driven cyclotron-maser emission

Predictions for the whole exoplanet census





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

- Interactions plasmas étoile-planète
- Signatures électromagnétiques
- Détectabilité radio
- Propriétés des émissions radio planétaires
- Lois d'échelle
- Implications pour les jupiters chauds
- Observations

Low-Frequency radio observations

- Limited angular resolution (λ/D) : 1 UA à 1 pc = 1 " ⇒ no imagery

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

  → discriminate via emission polarization (circular/elliptical)

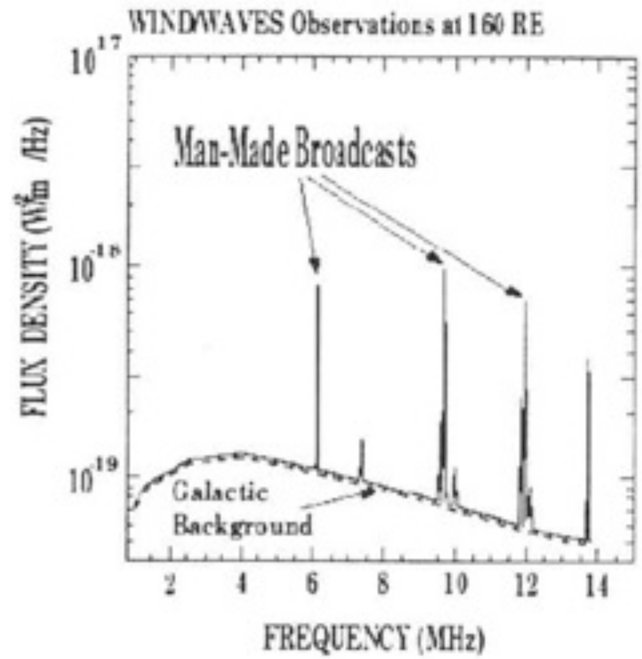
  + periodicity (orbital)

  → search for Jovian type bursts ?

- 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



Low-Frequency radio observations

- Interest

→ Planetary rotation period ⇒ tidal locking ?

→ Possible access to orbit inclination

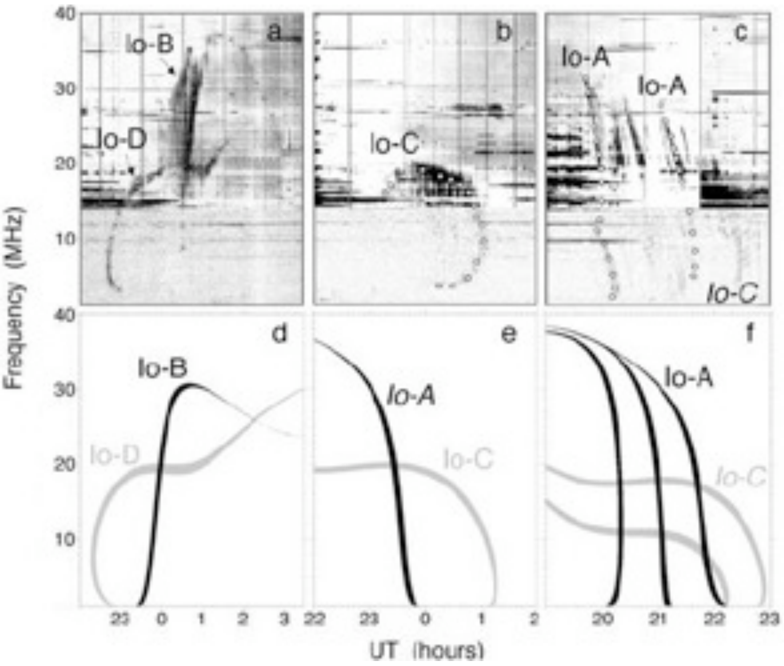
→ Measurement of B ⇒ contraints on scaling laws & internal structure models

→ Comparative magnetospheric physics (star-planet interactions)

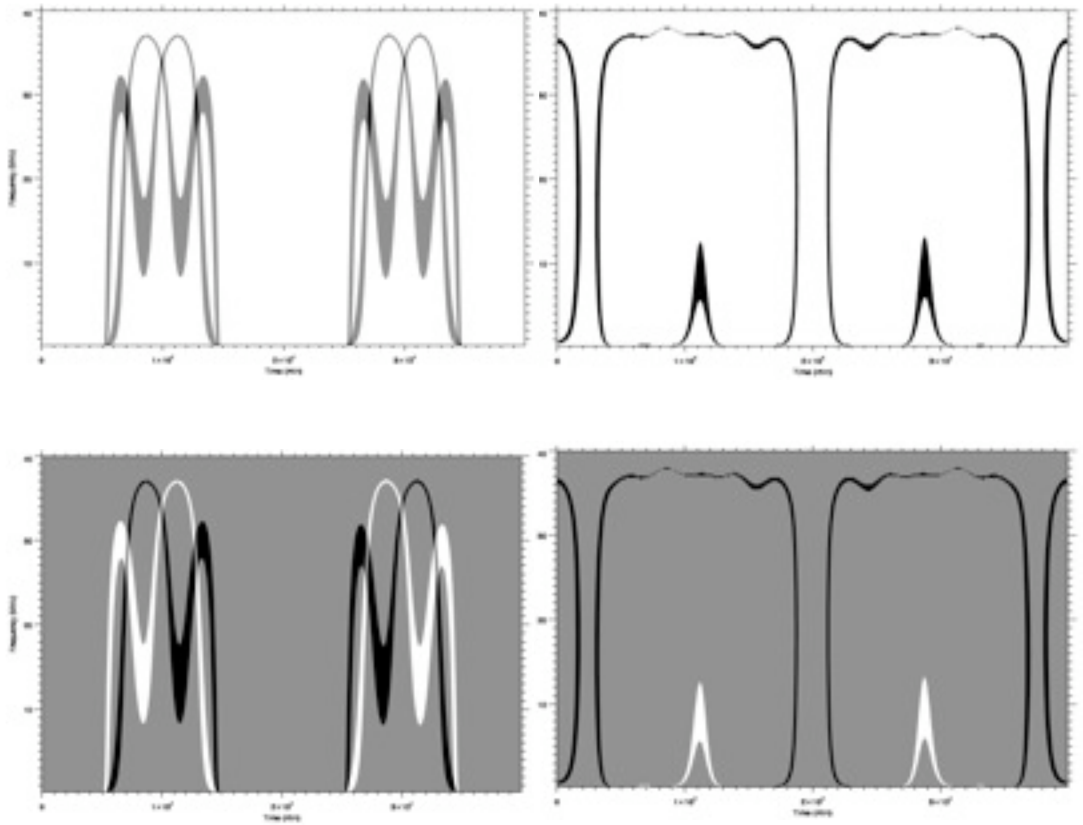
→ Discovery tool (search for more planets) ?

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

Dynamic spectrum modeling : from Jupiter to exoplanets



[Hess et al., 2008]



i = 0°

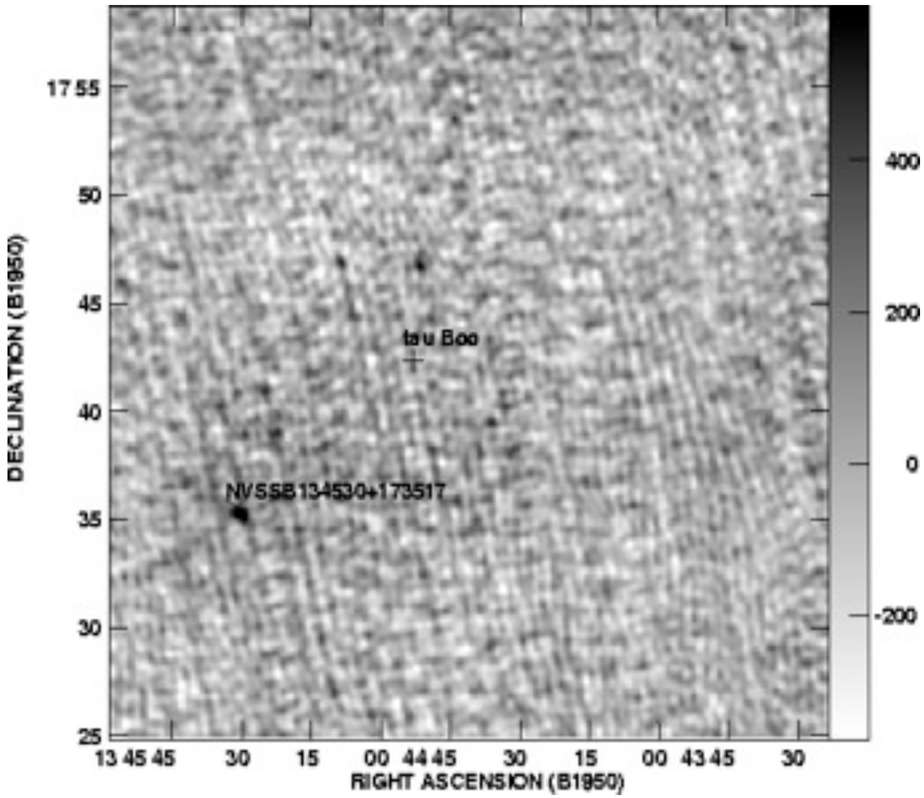
i = 30°

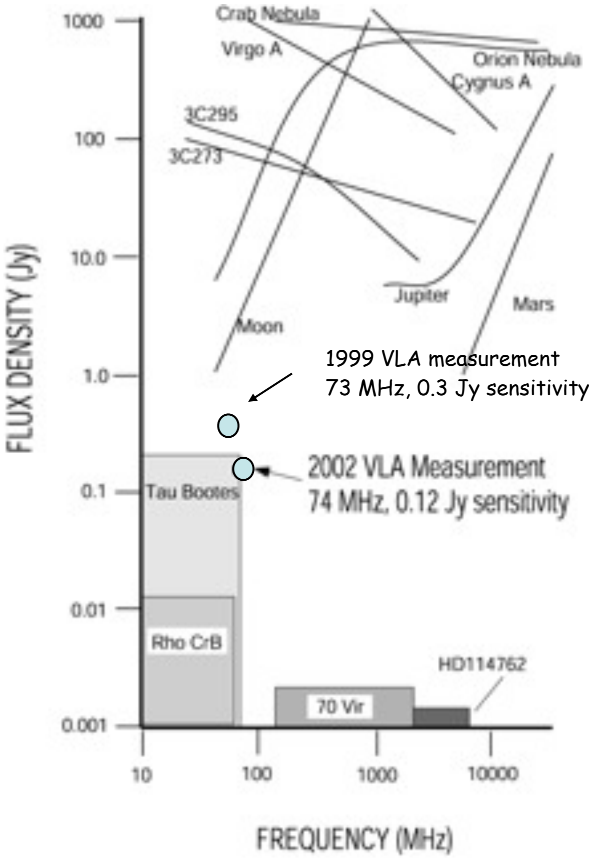
[Hess & Zarka, in preparation]

• VLA

- f ~ 74 MHz
- target Tau Bootes
- epochs 1999 - 2003
- imaging
- ~0.1 Jy sensitivity

Very Large Array

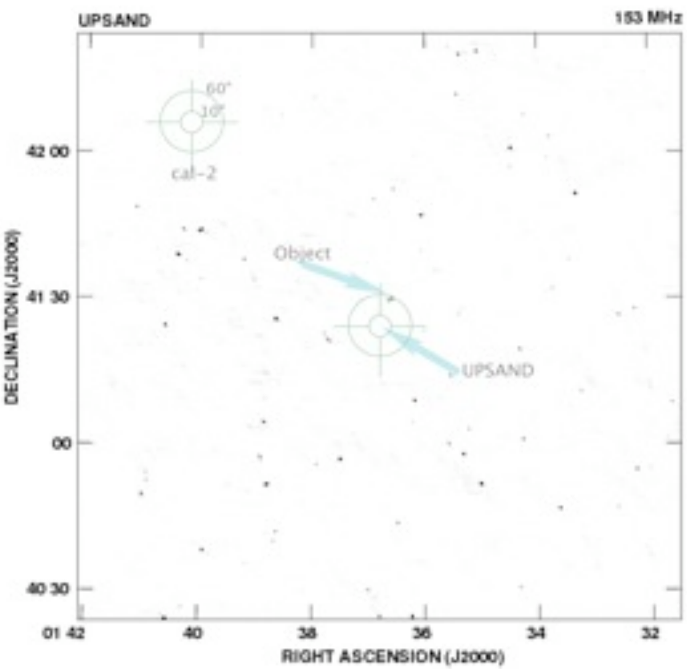


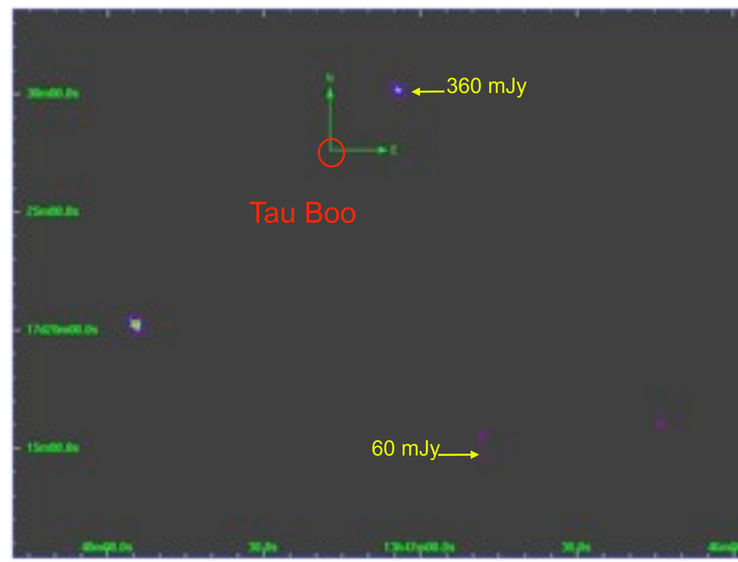


[Bastian et al., 2000 ; Farrell et al., 2003, 2004; Lazio & Farrell, 2007]

• GMRT

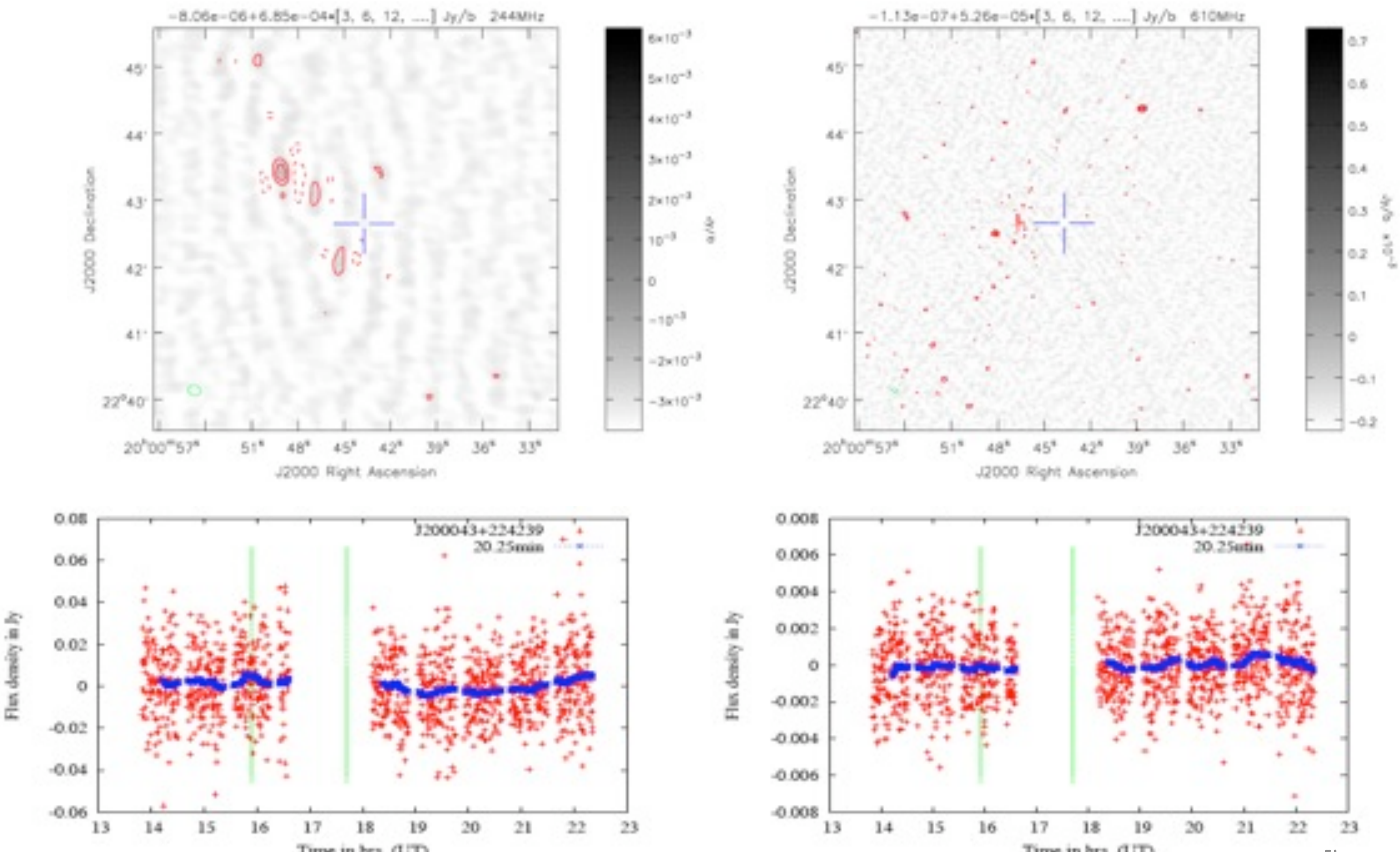
- f ~ 153 MHz
- several targets (Tau Boo, Ups And...)
- epochs 2005 - 2007
- imaging + tied array mode
- sensitivity ~ a few mJy





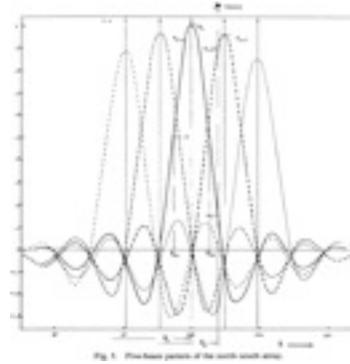
[Winterhalter et al., 2005 ; George and Stevens, 2007 ; ...]

- GMRT
    - f ~ 244 & 614 MHz
    - target HD 189733
    - epoch 2008 (anti-transit)
    - imaging + tied array beam
    - <<1 mJy sensitivity

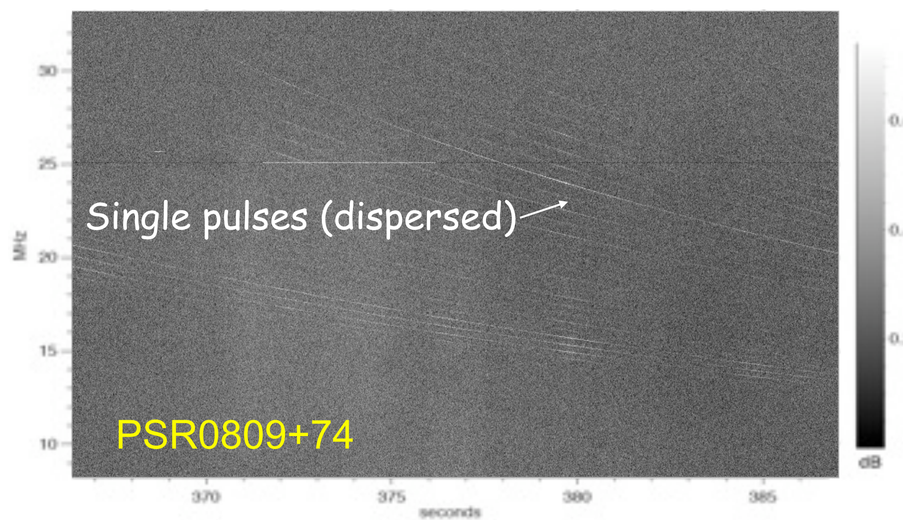


[Lecavelier et al., 2009]

• 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]

• LOFAR

- 30-250 MHz
- Epoch 2009+
- Sensitivity ≤ mJy
- Imaging + tied array beams (≥8)
- Built-in RFI mitigation & ionospheric calibration

➔ Exoplanet search part of "Transients" KP

LOFAR observations (>2010)

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

  ⇒ source identification by coordinates (exoplanet)

  ⇒ flux, polarization, frequency & bandwidth ?

  ⇒ flag / switch to Tied-Array mode observations

- <u>Targeted observations</u>

⇒ All known exoplanets (V_r, transits…) : presently >350 candidates

Special emphasis on

- close-in exoplanets (Hot Jupiters) with « good » predicted frequency range & flux density (τ Boo, HD192263…)
- 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 …)

A suivre ...