Radioastronomy and the study of Exoplanets

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- Remote observation of exoplanetary magnetospheres ?

- Planetary radio emissions properties & energy source

  in Planet-Star plasma interactions

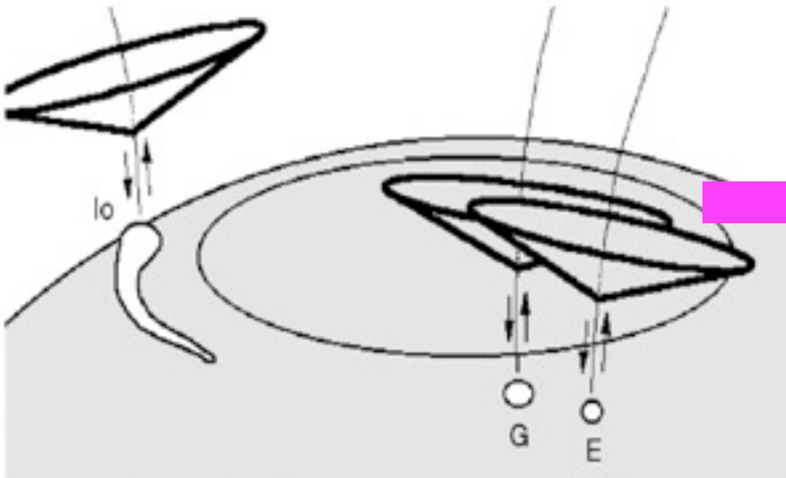
- Scaling laws and Extrapolation to hot Jupiters

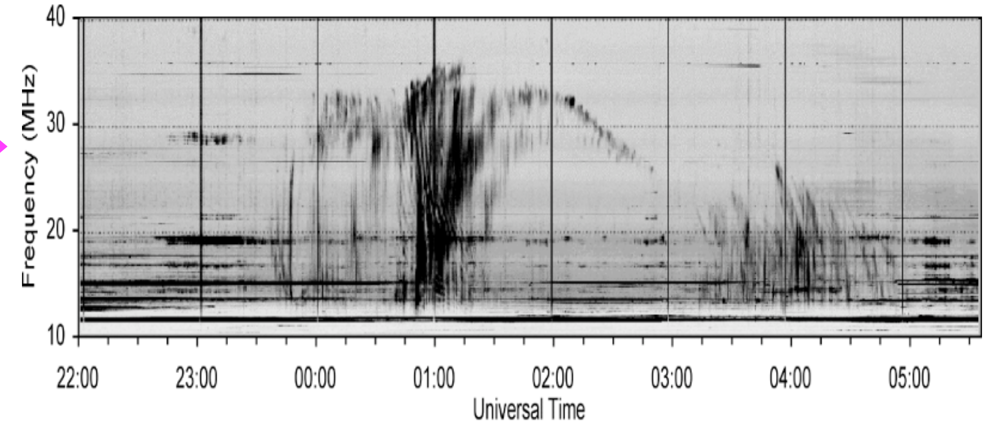
- Observations …

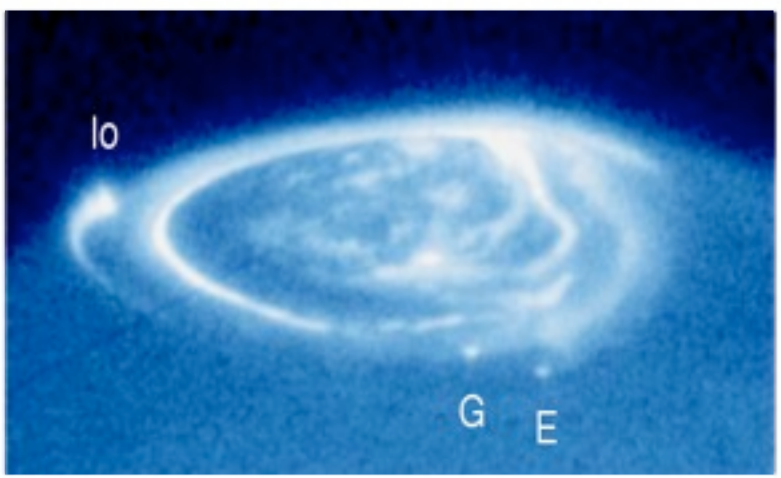
[Zarka, P., Plasma interactions of exoplanets with their parent star and associated radio emissions, Planet. Space Sci., 55, 598-617, 2007]

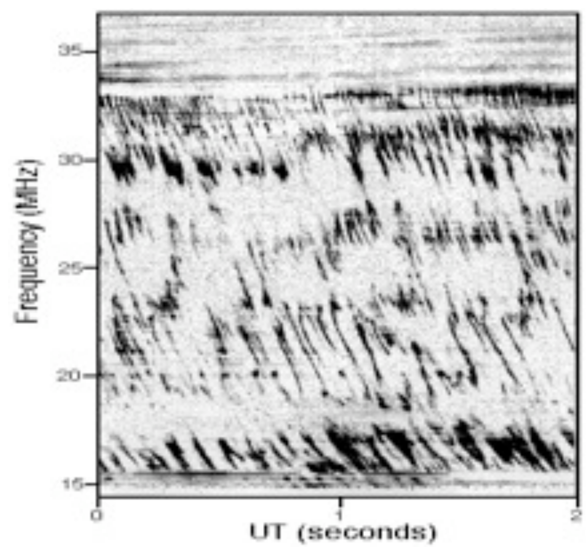
Electromagnetic signatures : aurorae (UV,IR,optical)

& radio emissions



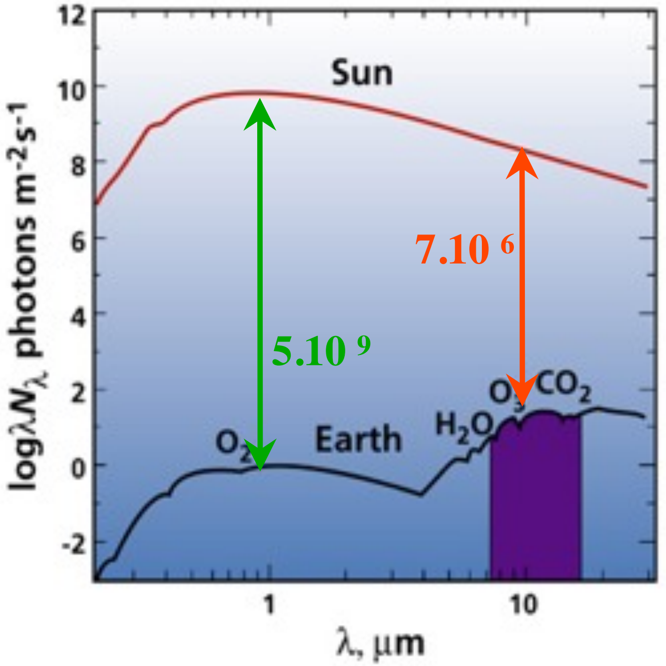


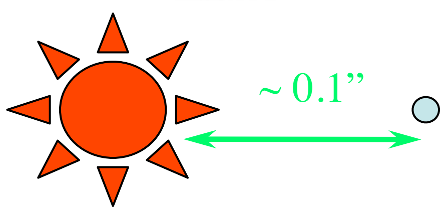




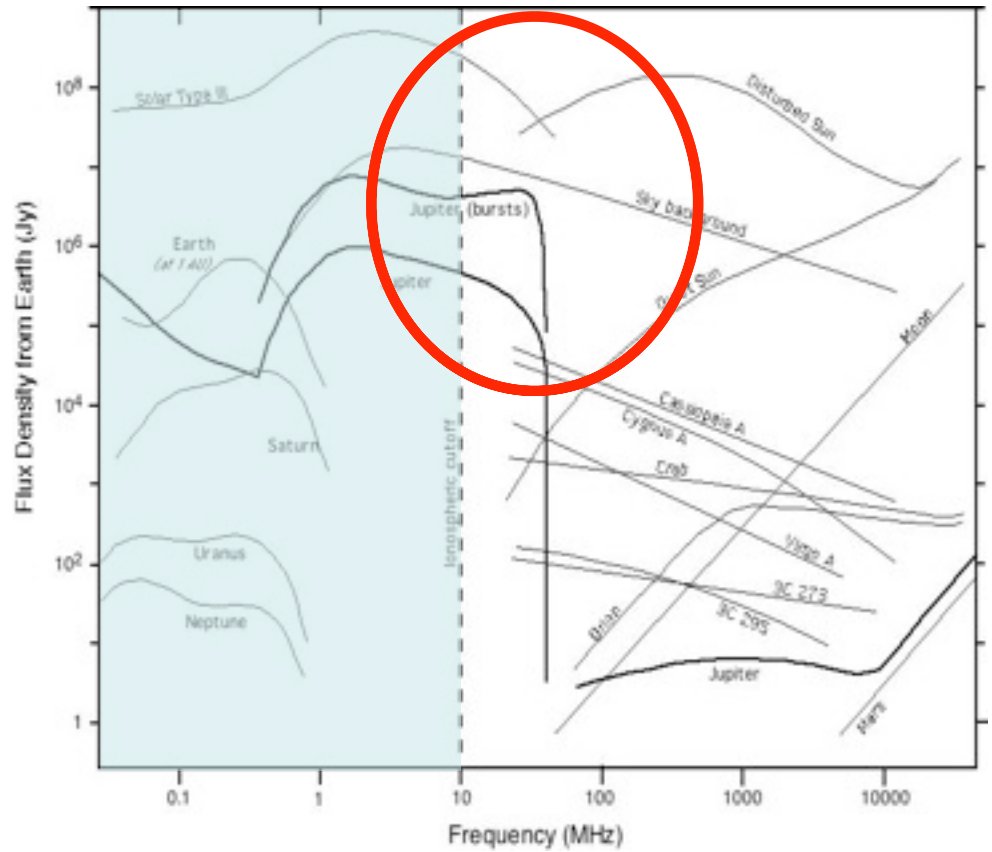
Detectability at stellar distances ?

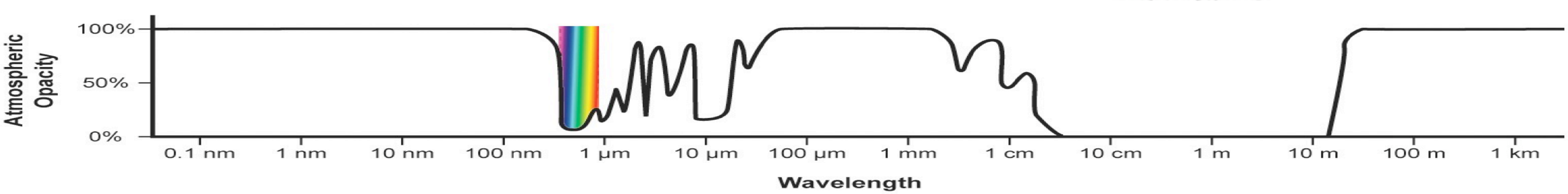
Star/planet proximity
→ contrast





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





Radio detectability

- 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 :

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

$\zeta = 1$	$b\tau = 10^6$ (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, 2007 ; and references therein]

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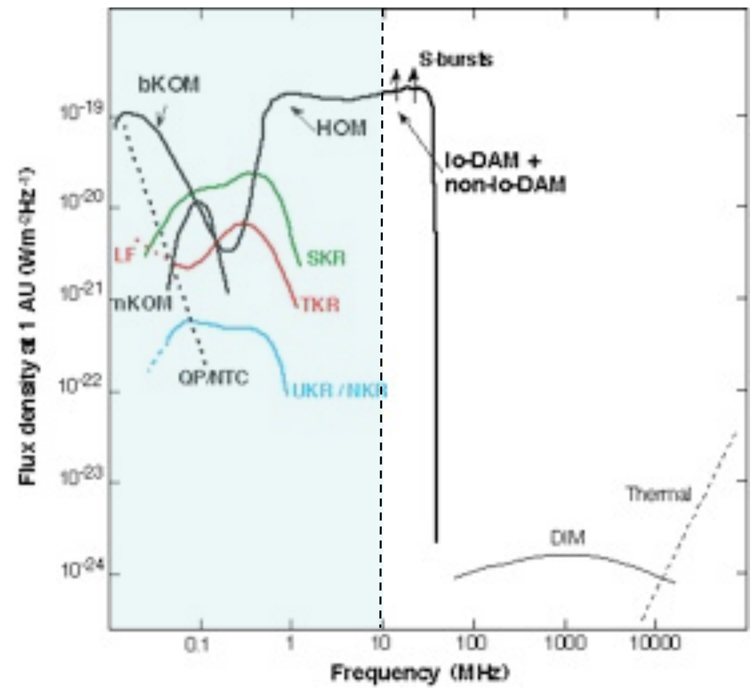
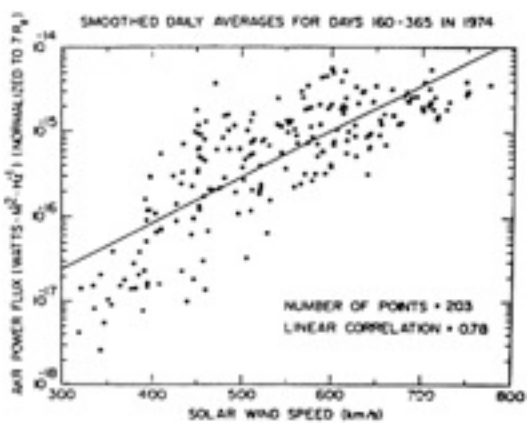
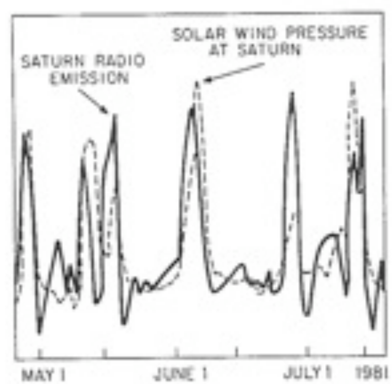
Auroral radio emissions properties

- 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, sw, CME…)
- correlation radio / UV
- radiated power : 10^{6-11} W



[Zarka, 1998]





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

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

Auroral radio emissions generation

- Coherent cyclotron emission : 2 conditions within sources :

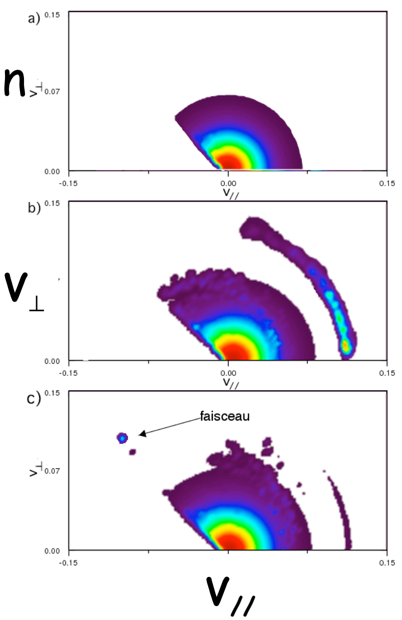
  - f_{pe} ($\propto N_e^{1/2}$) << f_{ce} ($\propto B$)

  - energetic electrons (keV) with non-Maxwellian distribution

→ high magnetic latitudes

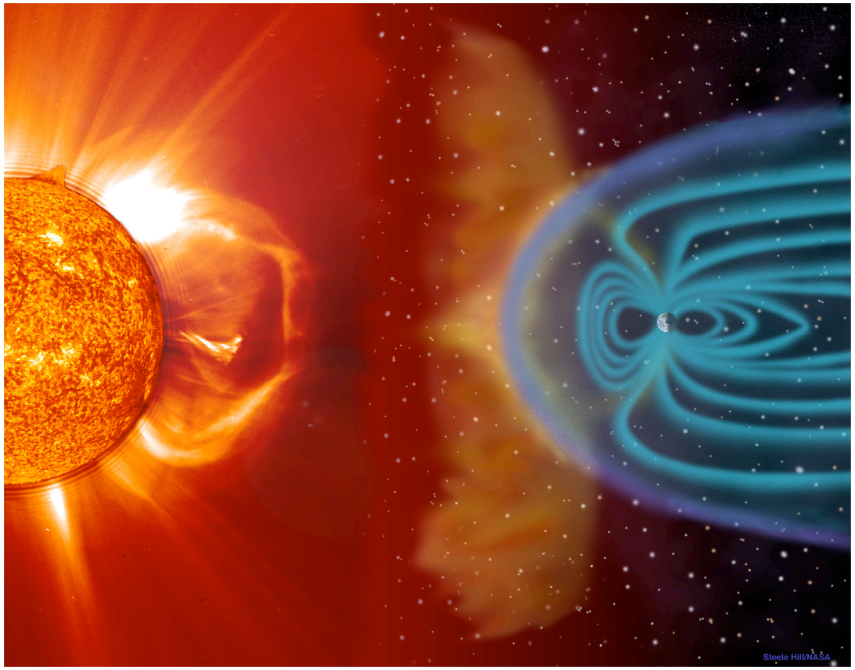
→ direct emission at $f \sim f_x \approx f_{ce}$, at large angle /B

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



Emission intensity not predictable from first principles

Energy sources : 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 : $P = \int_{obs}(\mathbf{E}\times\mathbf{B}/\mu_o).\mathbf{dS}$

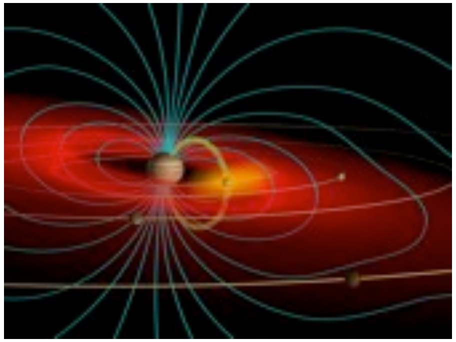
$\mathbf{E}=-\mathbf{V}\times\mathbf{B} \rightarrow \mathbf{E}\times\mathbf{B} = VB_\perp^2$ $\rightarrow$ $P_m = B_\perp^2/\mu_o\ V$

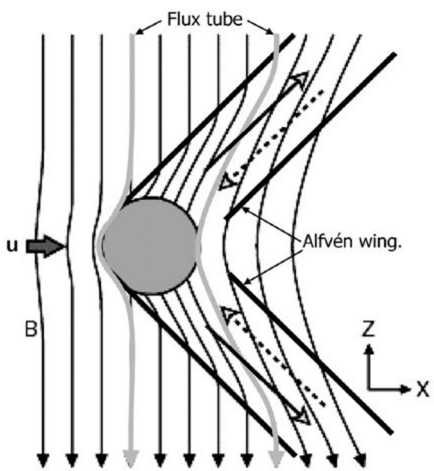
πR_{obs}^2

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

Energy sources : unipolar interaction

- Io-Jupiter : Alfvén waves & currents





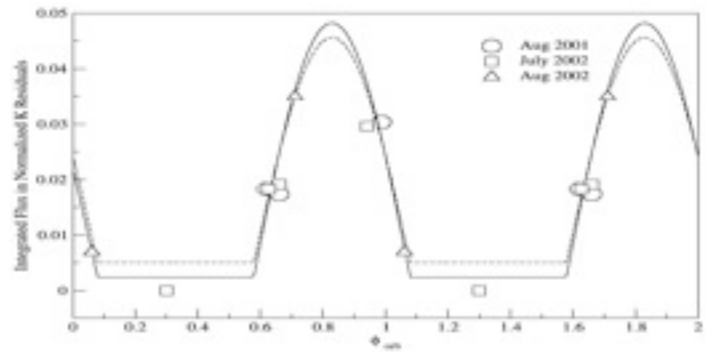
$$\phi = E \times 2R_{obs} = V \times B_{\perp} \times 2R_{obs}$$

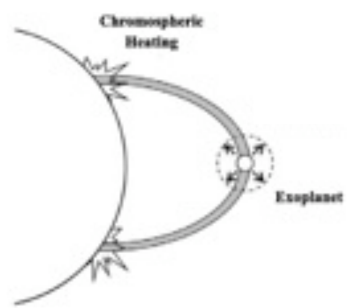
$$P_d = \varepsilon\, V B_{\perp}^2 / \mu_o\, \pi R_{obs}^2 = \varepsilon\, P_m$$

$$M_A \leq \varepsilon \leq 1$$

[Neubauer, 1980 ; Saur et al., 2004]

- Chromospheric hot spot on HD179949 & υ And ?

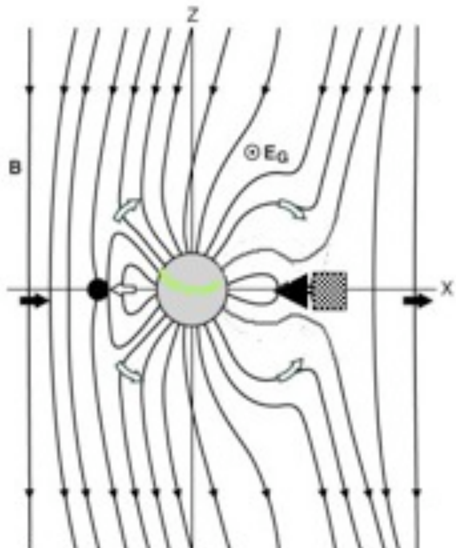


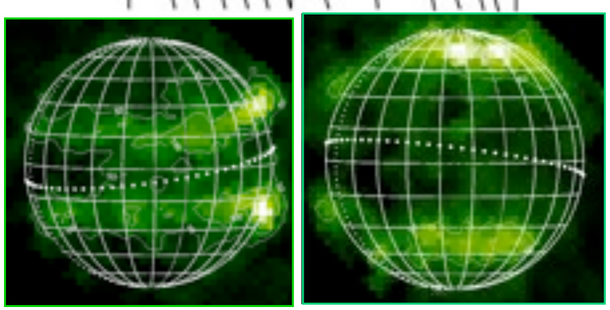


[Shkolnik et al. 2003, 2004, 2005]

Energy sources : dipolar interaction

- Ganymede-Jupiter : reconnection





Downstream Upstream

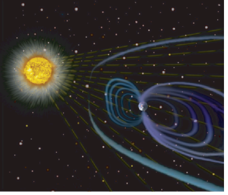
$$P_d = \varepsilon\ K\ VB_\perp^2/\mu_o\ \pi R_{MP}^2 = \varepsilon\ K\ P_m$$

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

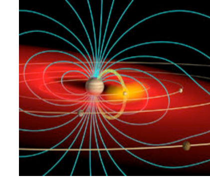
$\varepsilon \sim 0.1 - 0.2$

[McGrath et al., 2002; Kivelson et al., 1997, 2004]

- Interacting magnetized binaries or star-planet systems ?



Radio emissions from 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

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

$$\varepsilon \sim 0.2 \pm 0.1$$

[Zarka et al., 2001, 2007]

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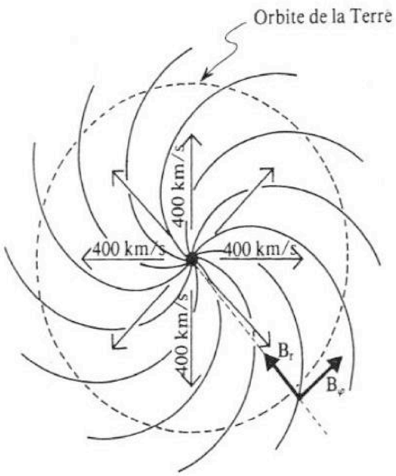
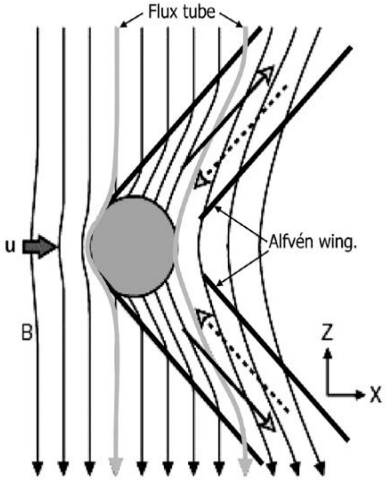
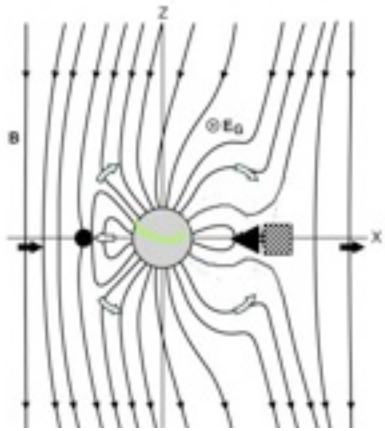
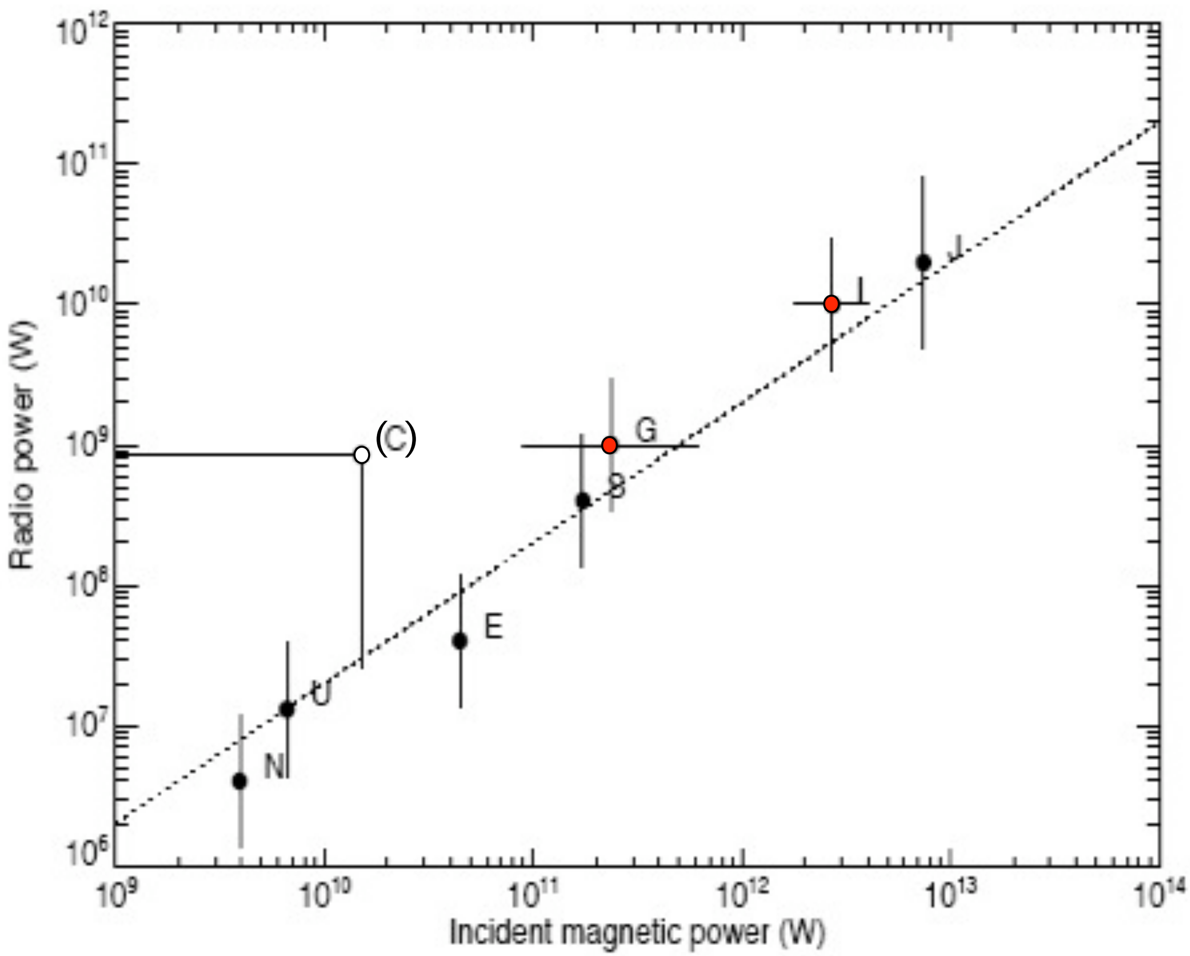
« Generalized radio-magnetic Bode's law » (all radio emissions)

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









[Zarka et al., 2001, 2005]

Exoplanets & Stellar Magnetic Fields

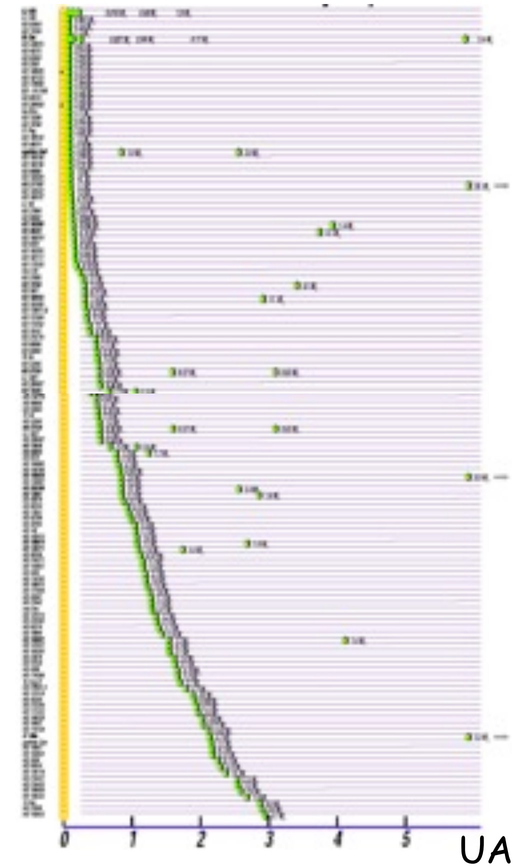
• 374 exoplanets (in >300 systems)

~110 with $a \leq 0.1$ AU (30%)

~75 with $a \leq 0.05$ AU = 10 Rs (20%)

→ « 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

• Spectropolarimeters : ESPaDOnS@CFHT
NARVAL@TBL

Tau Boo : 5-10 G

HD 76151 : ~10 G

HD 189733 : >50 G

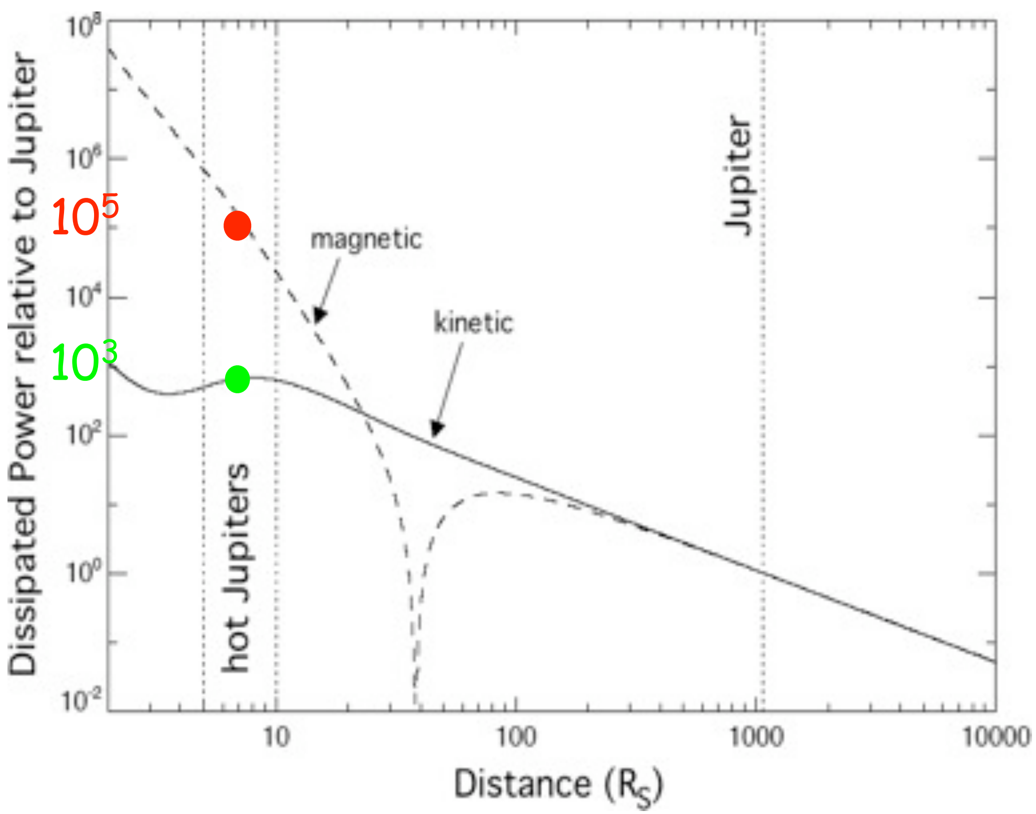
HD 171488 : 500G ...

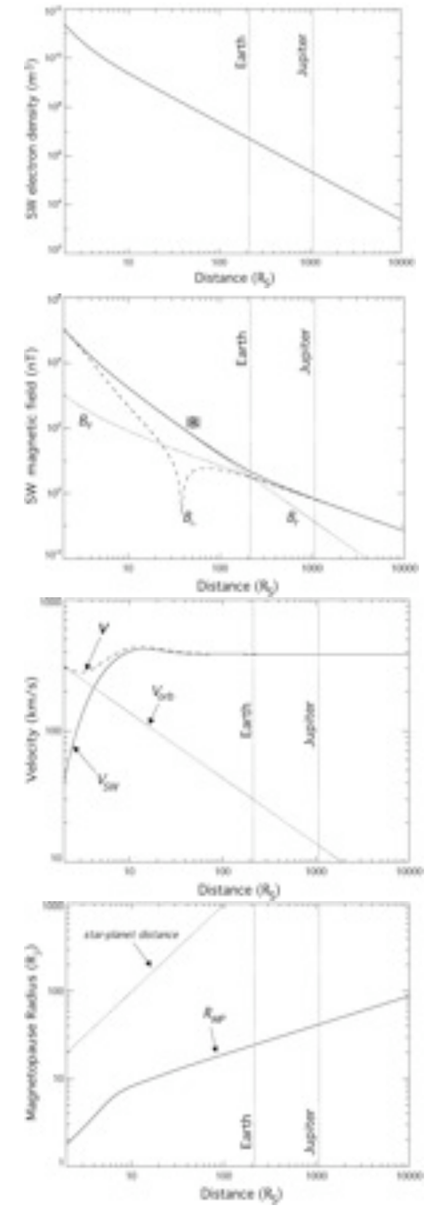
[Catala et al., 2007; Donati et al., 2007, 2008]

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
- Magnetospheric compression

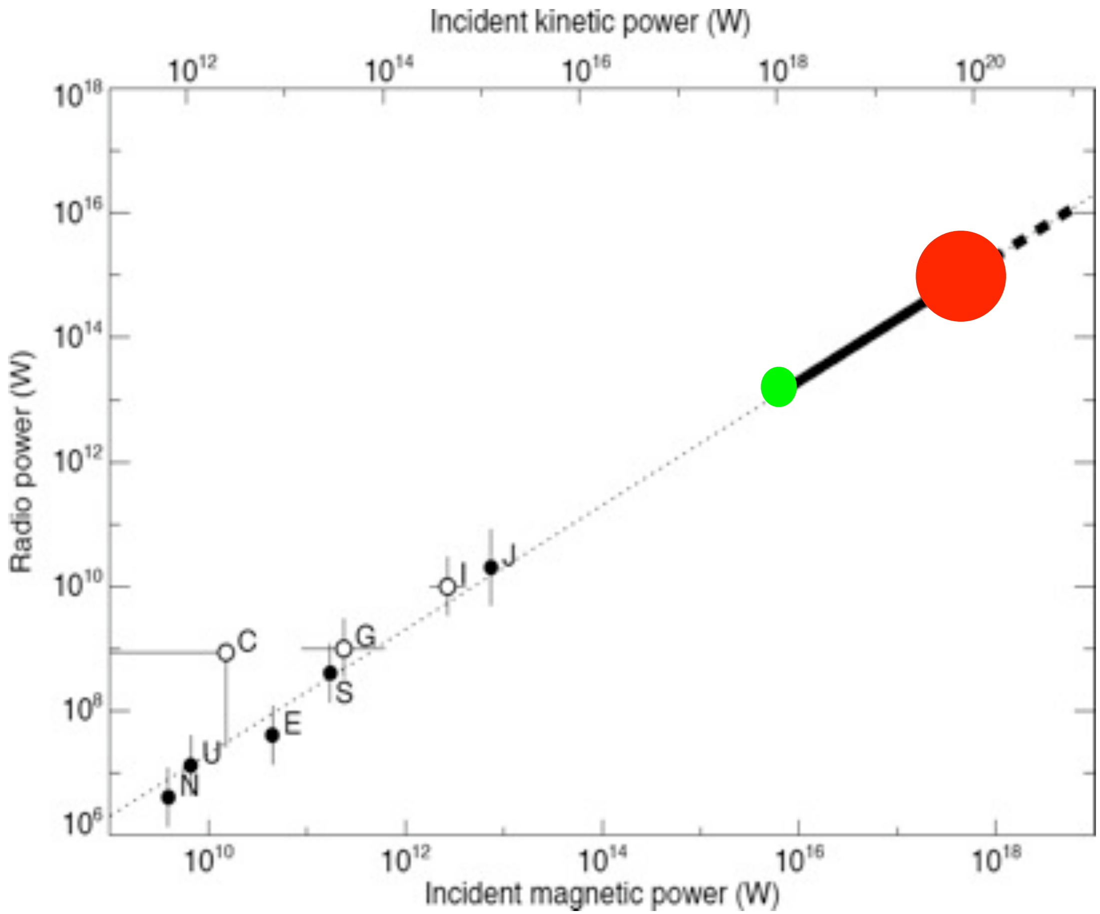
→ Total dissipated power on obstacle





[Zarka et al., 2001, 2007]

and applying the generalized radio-magnetic Bode's law



→ $P_{radio\text{-}max} = P_{Radio\text{-}J} \times 10^5$

if no "saturation" nor planetary magnetic field decay

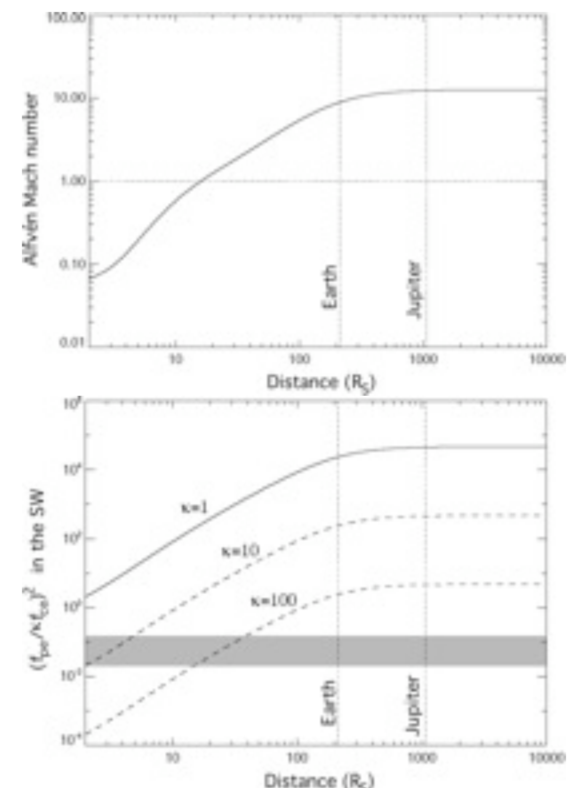
[Farrell et al., 1999, 2004 ; Zarka et al., 2001, 2007]

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) → $\omega\downarrow$

  and $\mathcal{M} \propto P_{sid}^{\alpha}$ $-1 \leq \alpha \leq -\frac{1}{2}$ → $\mathcal{M}\downarrow$ (B decay) ?

Unipolar inductor in sub-Alfvénic regime

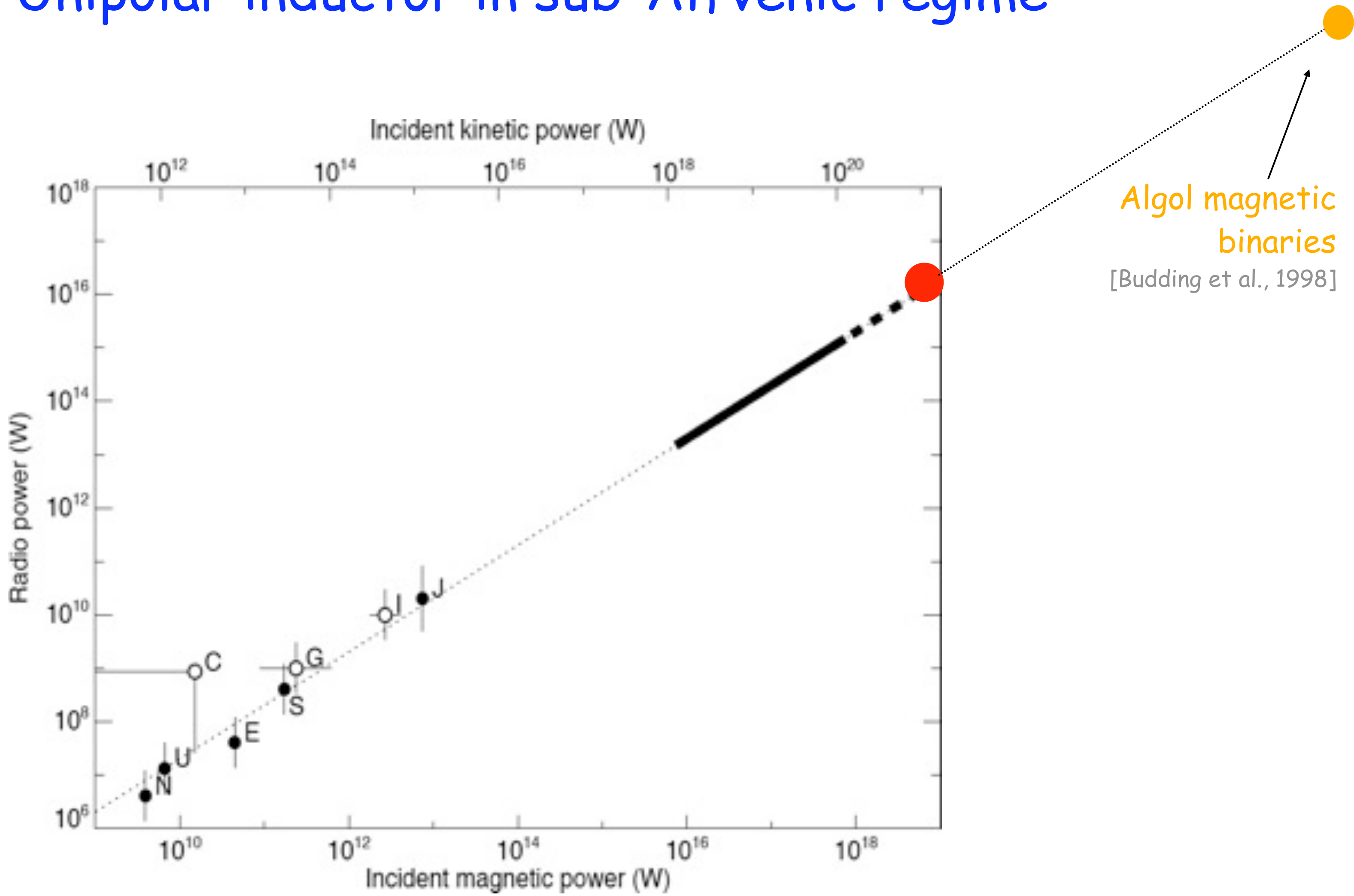


- Similarities with Io-Jupiter case
- But radio emission possible only if $f_{pe}/f_{ce} \ll 1$

  → intense stellar B required (κB_{sun} with κ=10-100)

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

Unipolar inductor in sub-Alfvénic regime

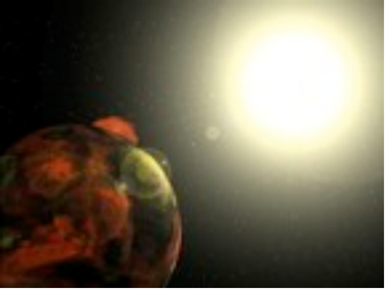


• Extrapolation / Radio-magnetic Bode's law

$\rightarrow$ $P_{radio-max} = P_J \times 10^5 \times (R_{exo-ionosphere}/R_{magnetosphere})^2 \times (B_{star}/B_{Sun})^2$

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

[Zarka, 2007]

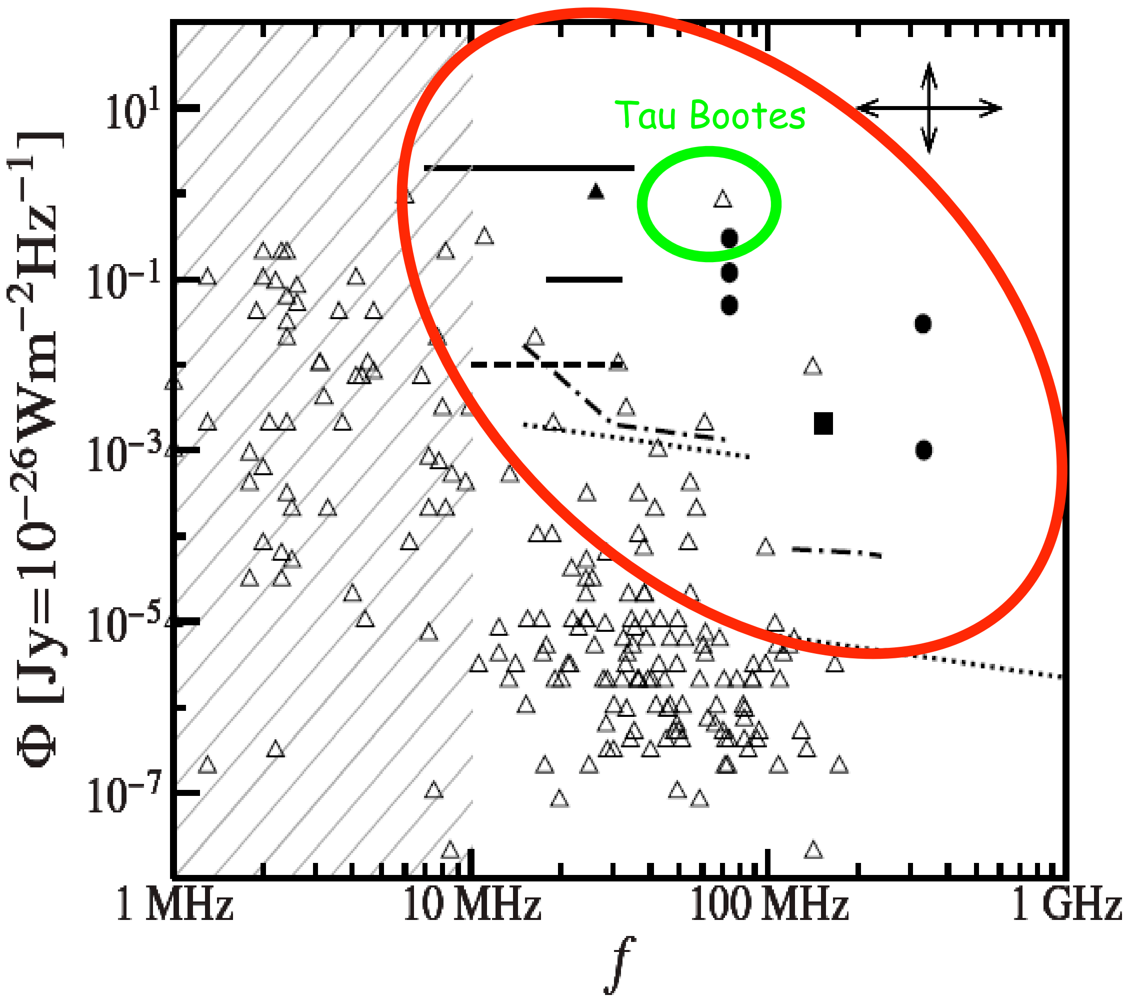


Maximum distance of detectability of 10^5 α Jupiter's radio emissions

$\zeta = 10^5$	$b\,\tau = 10^6$ *(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)

Predictions for the whole exoplanet census



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

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]
- Different solar wind conditions, Role of (frequent) Coronal Mass Ejections

  [Khodachenko et al., 2006; Griessmeier et al., 2007]
- Magnetosphere limits Atmospheric Erosion [Griessmeier et al., 2004]
- Application of unipolar inductor model to white dwarfs systems [Willes and Wu, 2004, 2005]
- Internal structure/convection models and self-sustained dynamo [Sanchez-Lavega, 2004]
- Magnetic reconnection, E-field and runaway electrons at the magnetopause ?

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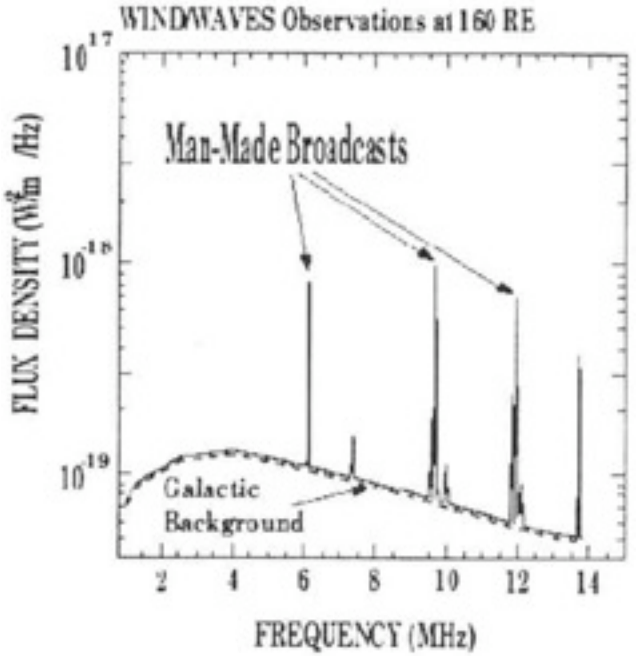
Low-Frequency radio observations

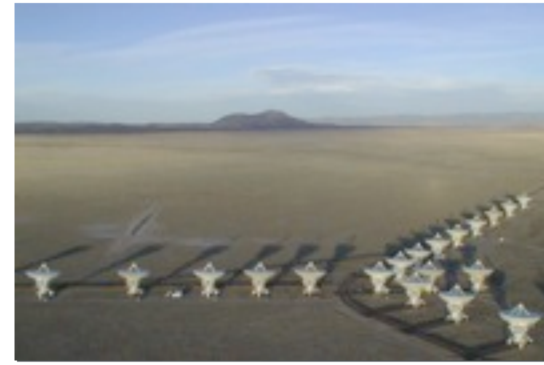
- Limited angular resolution (λ/D) : 1 UA à 1 pc = 1 " $\Rightarrow$ no imagery
  - → (1) detect a signal, (2) star or planet ?
  - → discriminate via emission polarization (circular/elliptical) + periodicity (orbital)
  - → search for Jovian type bursts ?

- Very bright galactic background (T_b ~10^{3-5} K)
- RFI (natural & anthropic origin) →
- Ionospheric cutoff ~ 10 MHz, and perturbations ≲30-50 MHz
- IP/IS scintillations

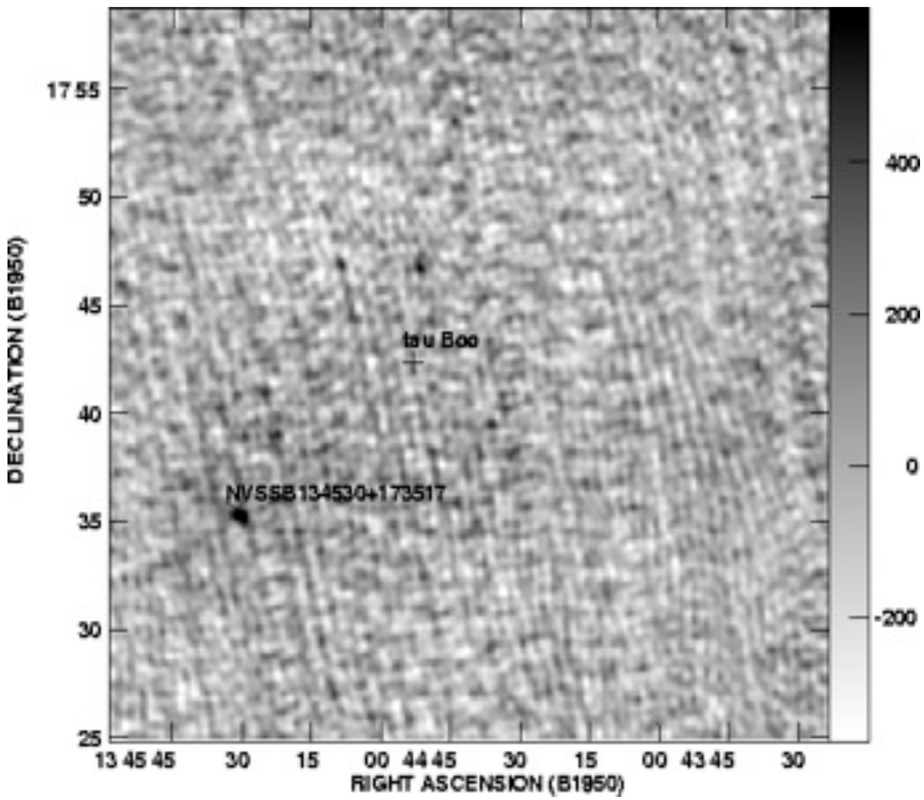


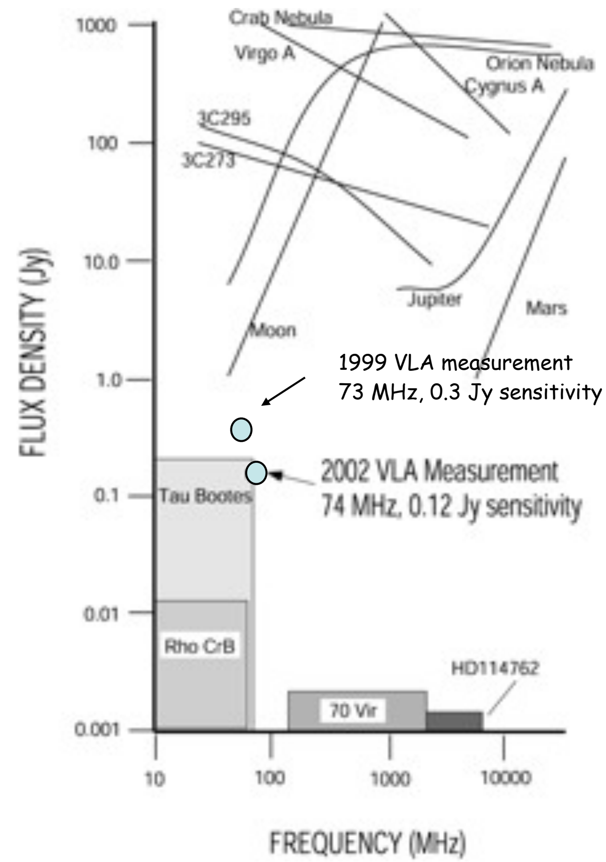
• VLA

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



Very Large Array

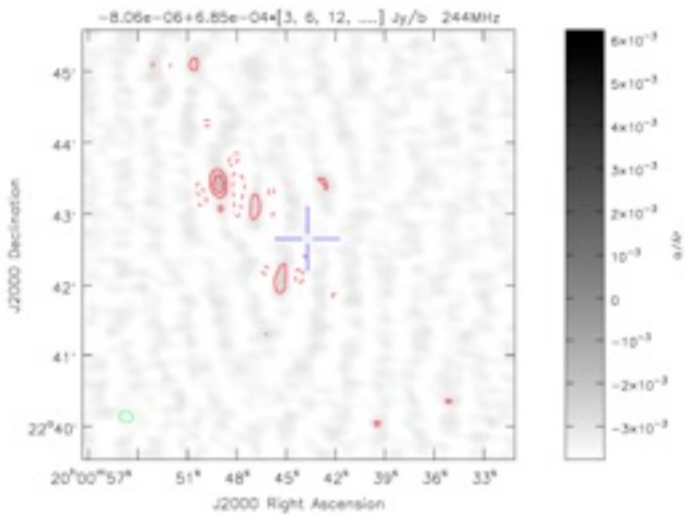


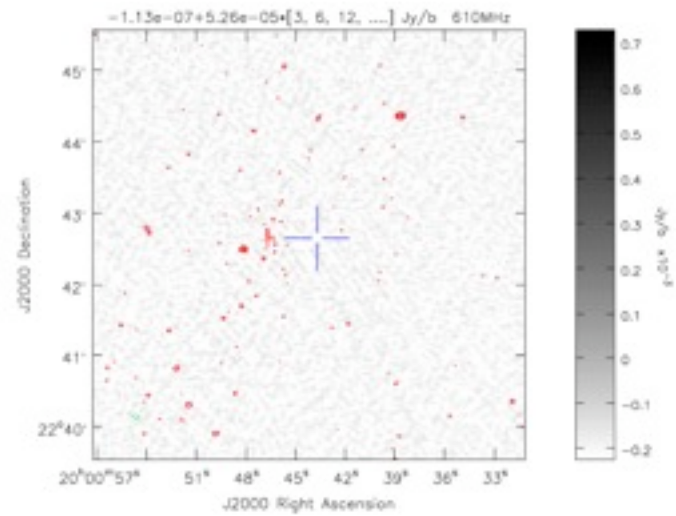


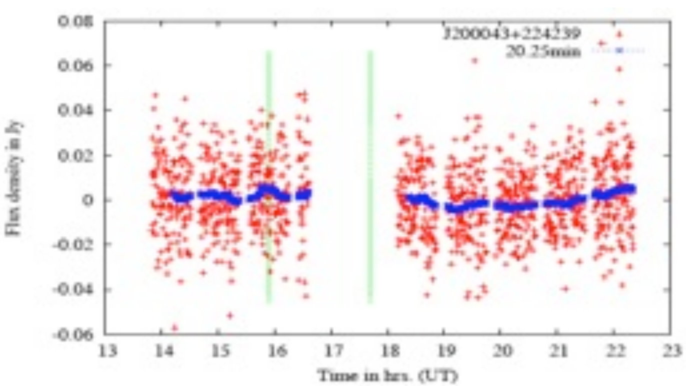
[Bastian et al., 2000 ; Farrell et al., 2003, 2004; Lazio & Farrell, 2007]

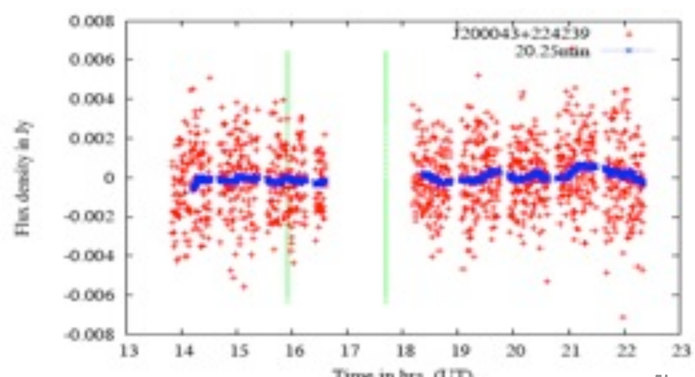
• GMRT

- f ~ 153, 244 & 614 MHz
- targets : Tauu Boo, Ups And, HD 189733
- epochs 2005-2007, 2008 (anti-transit of HD 189733)
- imaging + tied array beam
- <<1 mJy sensitivity









[Lecavelier et al., 2009]

• UTR-2

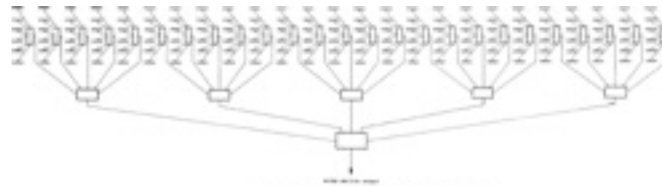


Fig. 1. A diagram of the east-west array section.

Fig. 2. A diagram of the north-south array section.

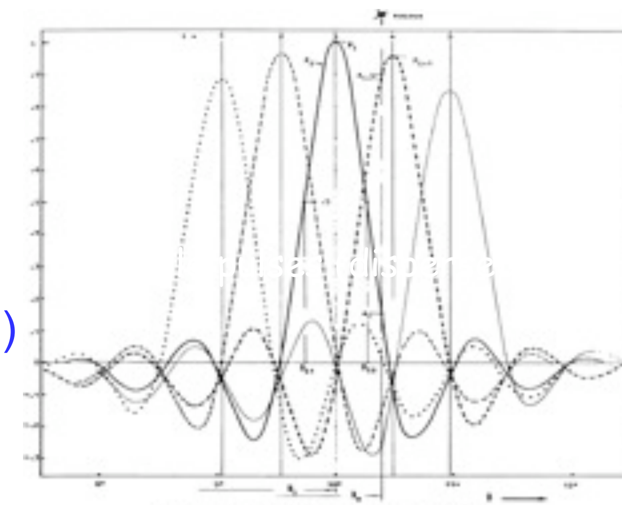


Fig. 3. Five-beam pattern of the north-south array.

- 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” Key Project

- Systematic search

  \+
- Targeted observations

Interest of low-frequency radio observations of exoplanets

→ Direct detection

→ 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, 2007 ; and references therein]