Planet-Star Plasma Interactions and Possible Radio Emission

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- Remote observation of exoplanetary magnetospheres ?

- Planetary radio emissions properties & energy source

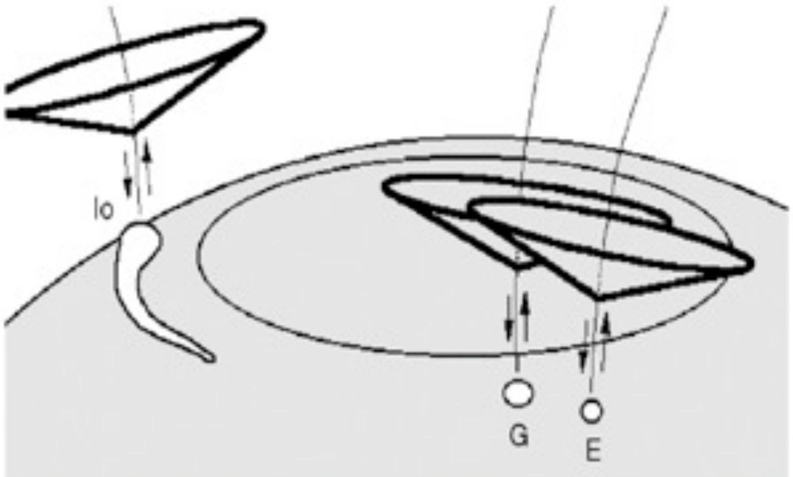
  in Planet-Star plasma interactions

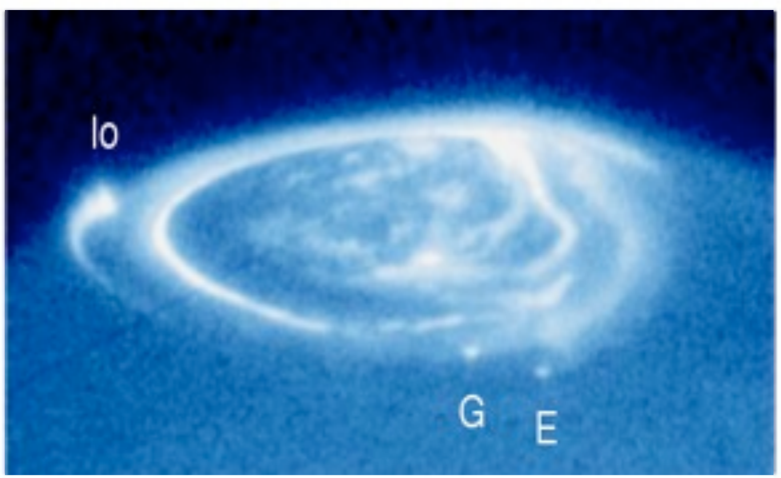
- Scaling laws and Extrapolation to hot Jupiters

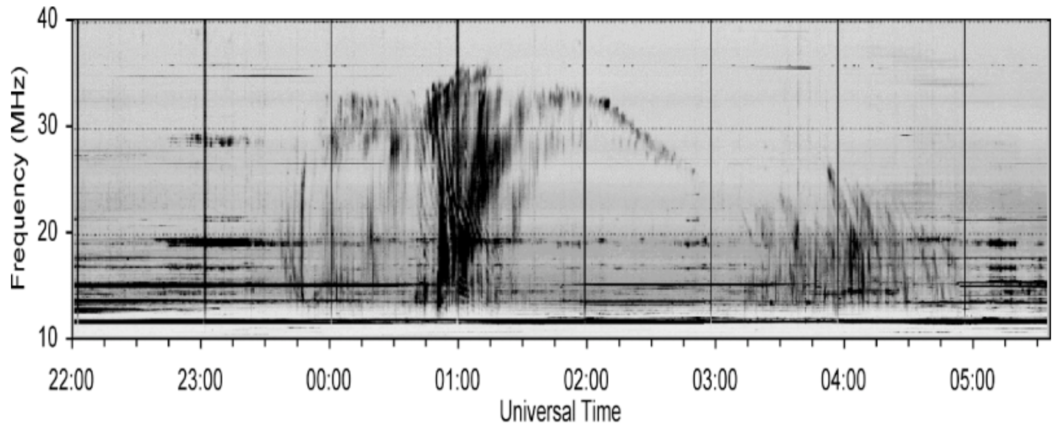
- Observations …

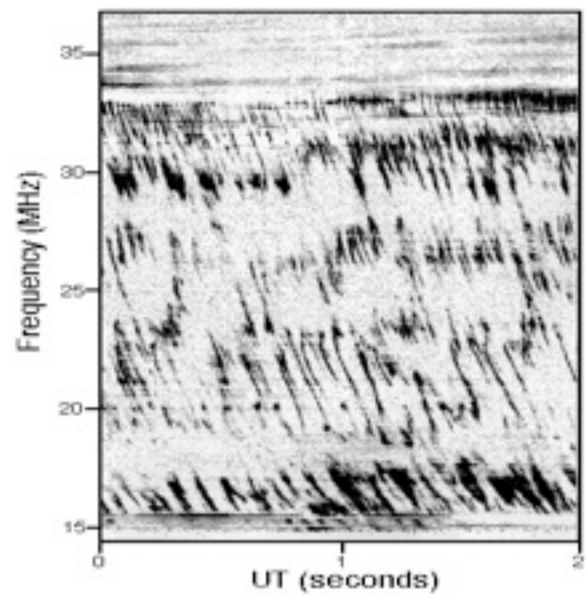
[Zarka, P., Plasma interactions of exoplanets with their parent star and associated radio emissions, Planet. Space Sci., 55, 598-617, 2007]

Electromagnetic signatures : aurorae (UV,IR,optical) & radio emissions



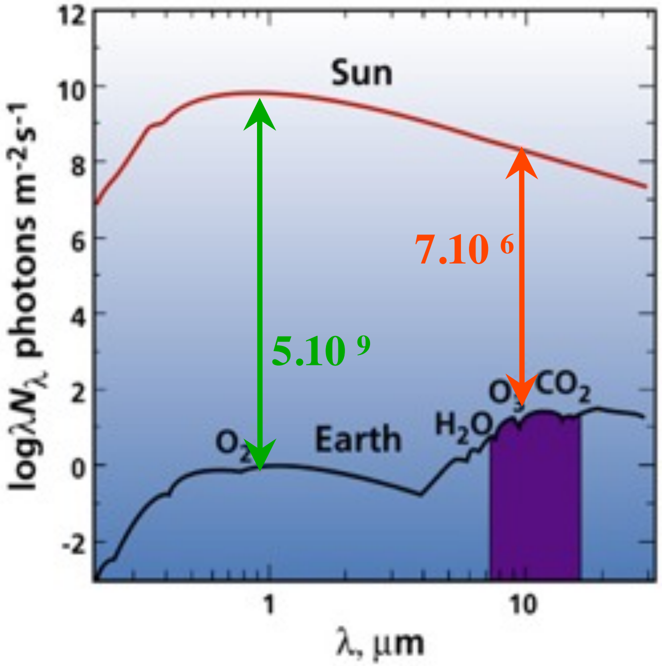


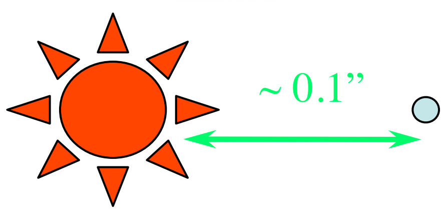




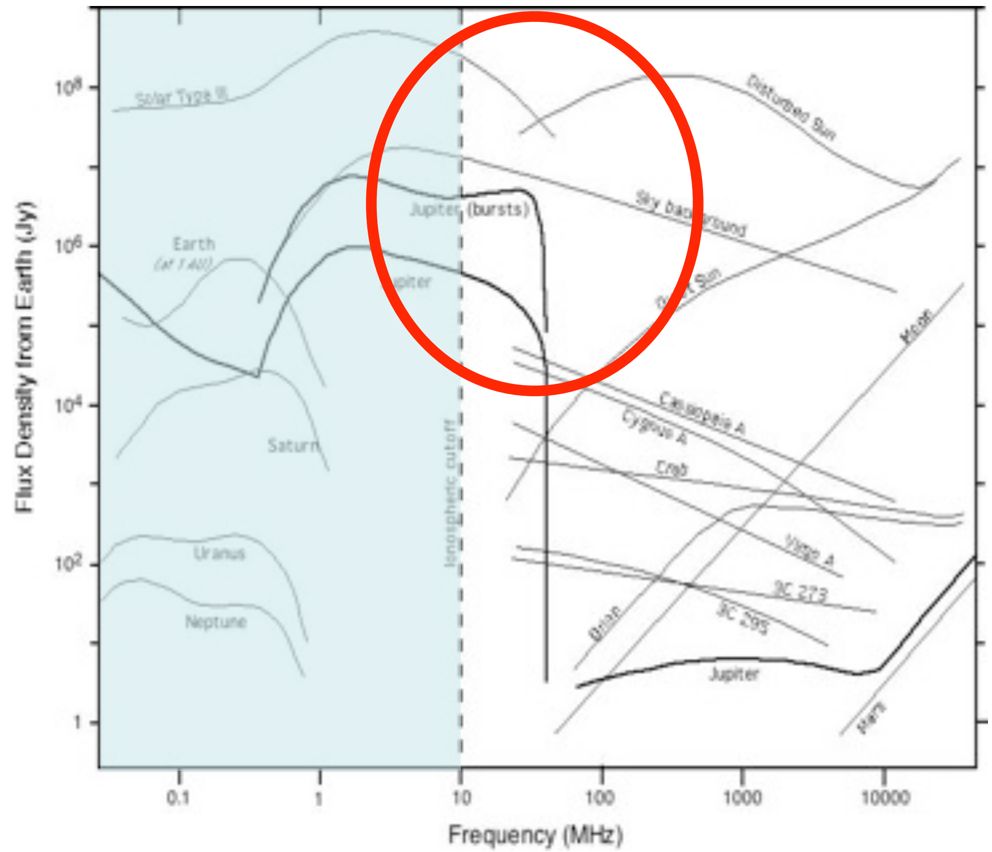
Detectability at stellar distances ?

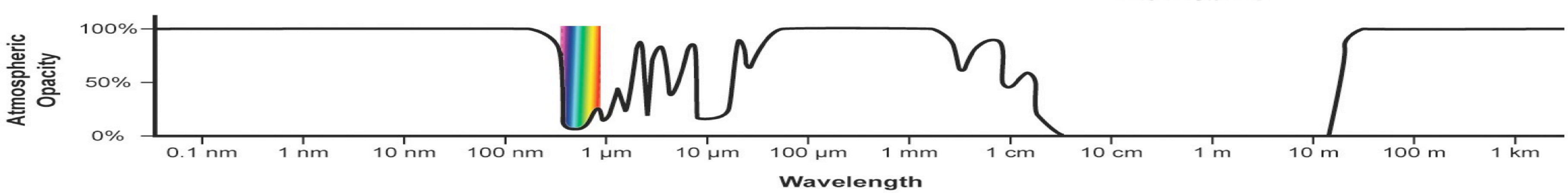
Star/planet proximity
→ contrast





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





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]

Radio detectability

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

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

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

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

[Zarka, 2007 ; and references therein]

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, 2007 ; and references therein]

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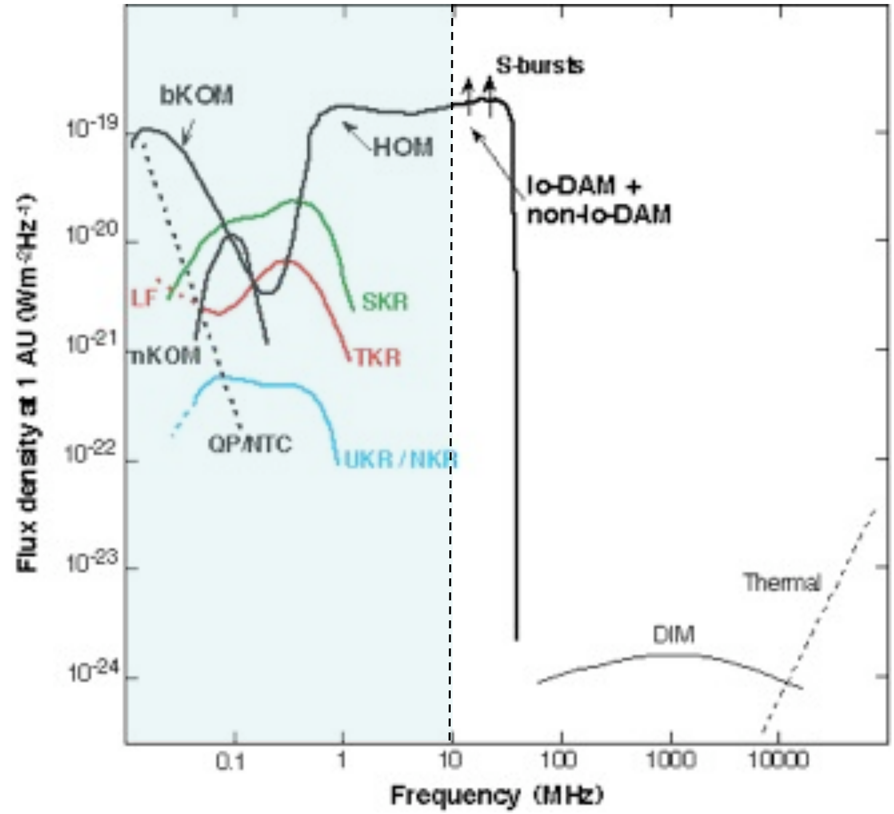
Auroral radio emissions properties

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



[Zarka, 1998]

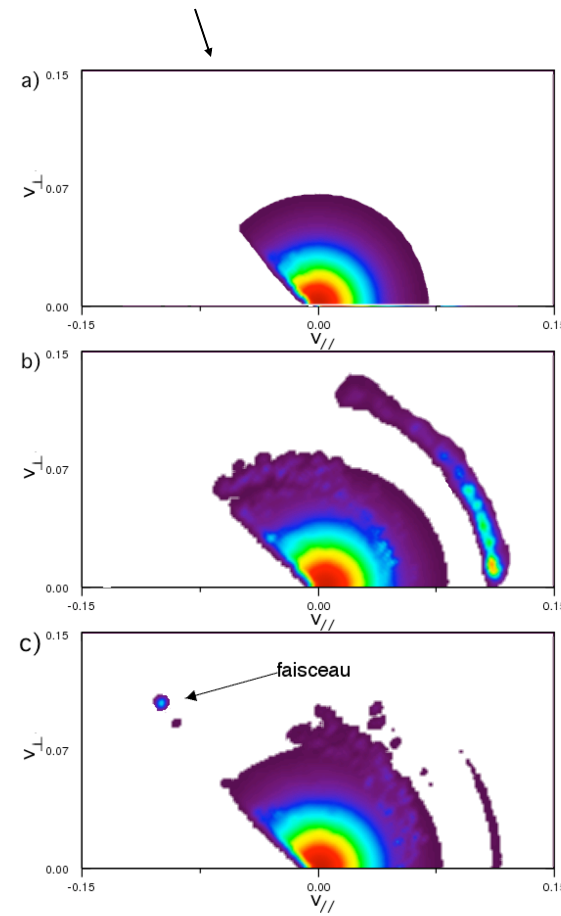
Auroral radio emissions generation

- 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

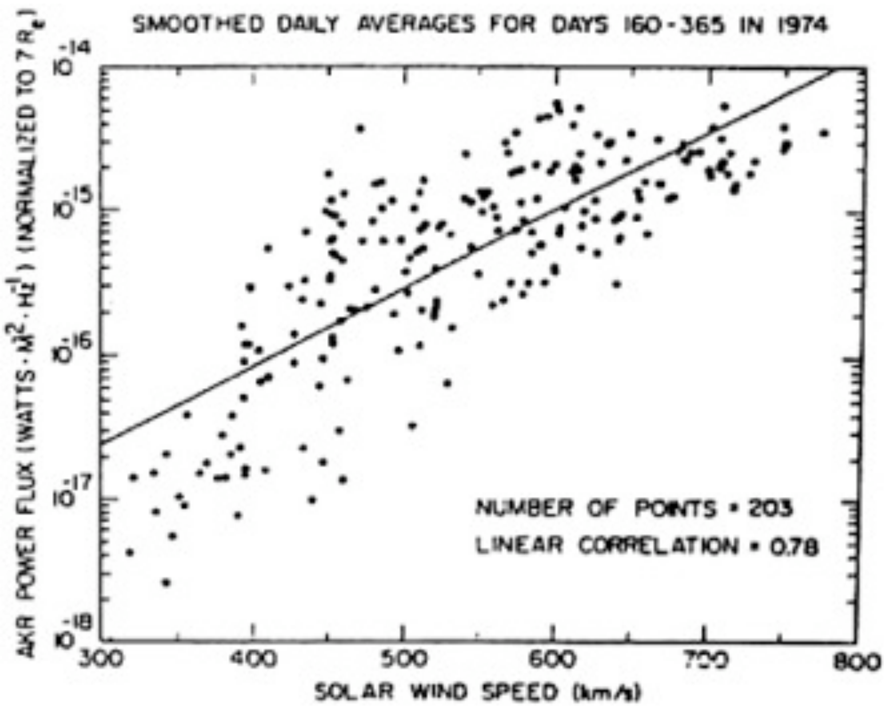
→ direct emission at $f \sim f_x \approx f_{ce}$, at large angle /B

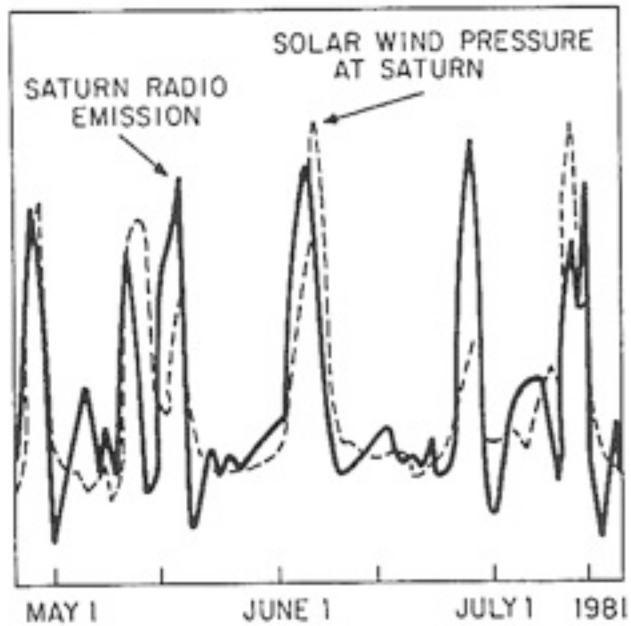
up to 1-5% of e- energy in radio waves, bursts



Emission intensity not predictable from first principles

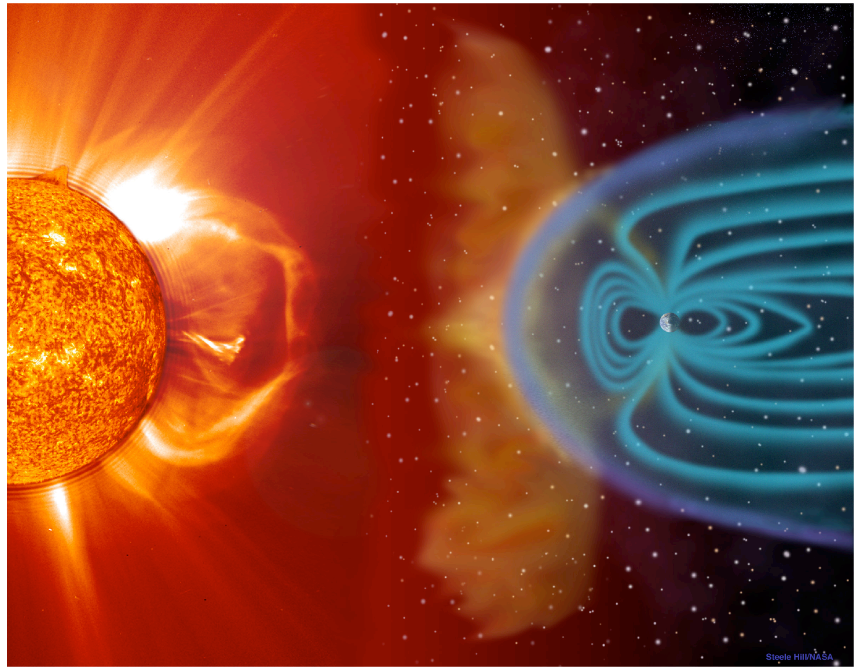
Strong correlation between Solar Wind (P, V...) and auroral radio emissions





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

Energy sources : solar wind - magnetosphere interaction



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

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

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

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

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

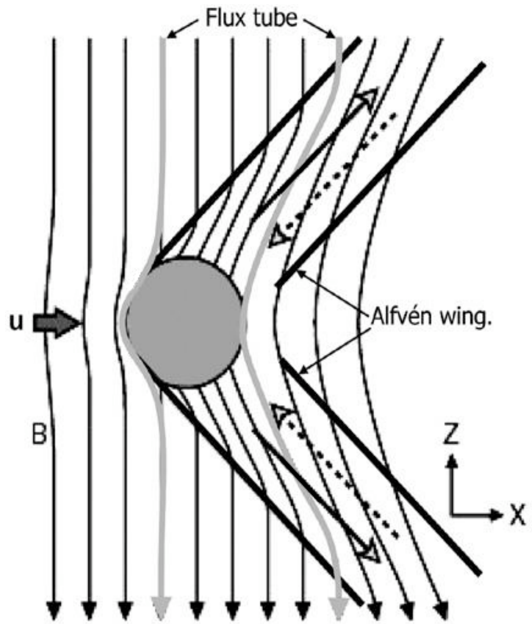
Energy sources : unipolar interaction

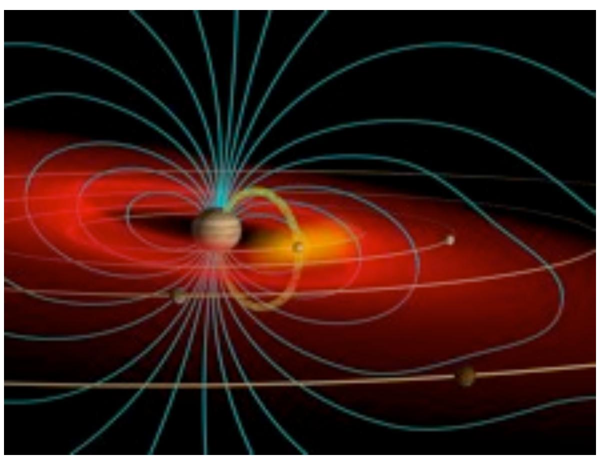
• Io-Jupiter : Alfvén waves & currents

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

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

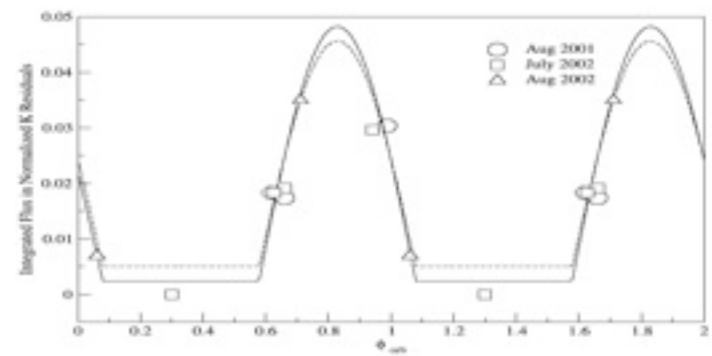
$M_A \leq\ (\ \varepsilon = (1+M_A^{-2})^{-1/2}\ )\ \leq 1$

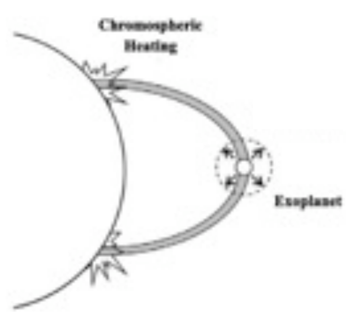


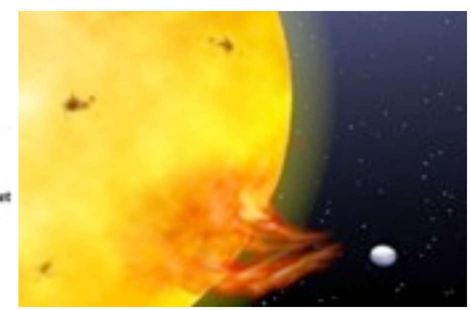


[Neubauer, 1980 ; Saur et al., 2004]

Chromospheric hot spot on HD179949 & υ And ?



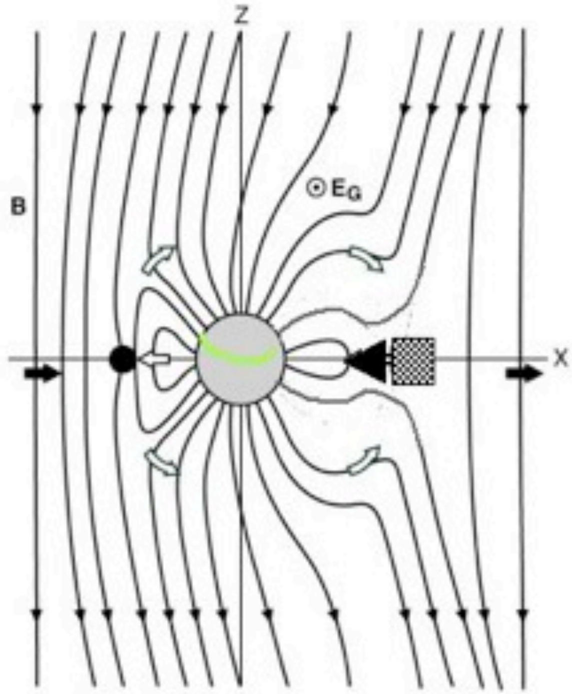


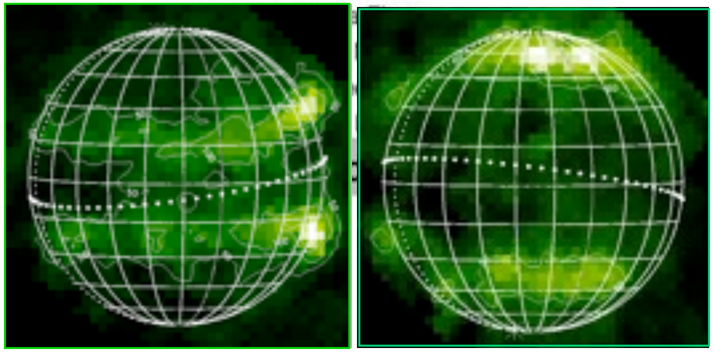


[Shkolnik et al. 2003, 2004, 2005]

Energy sources : dipolar interaction

• Ganymede-Jupiter : reconnection





Downstream Upstream

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

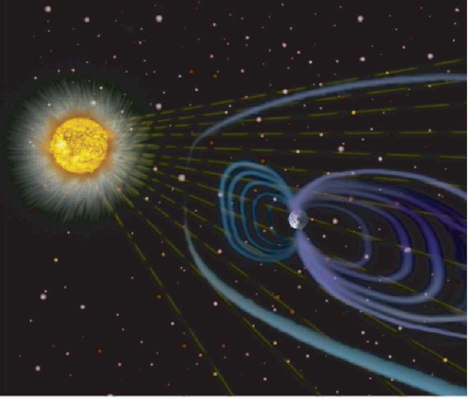
$P_d = \varepsilon\ K\ VB_\perp^2/\mu_o\ \pi R_{MP}^2$

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

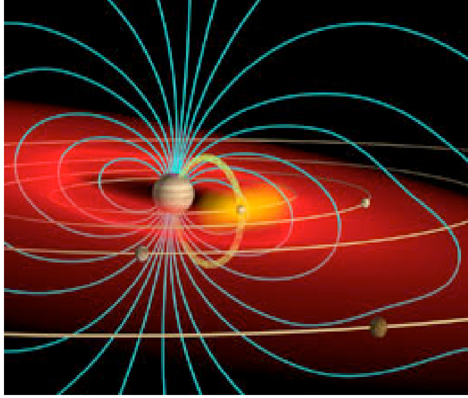
$\varepsilon \sim 0.1 - 0.2$

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

$\varepsilon \sim 0.2 \pm 0.1$



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

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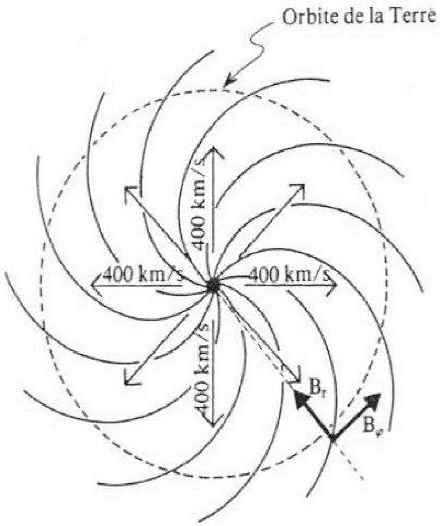
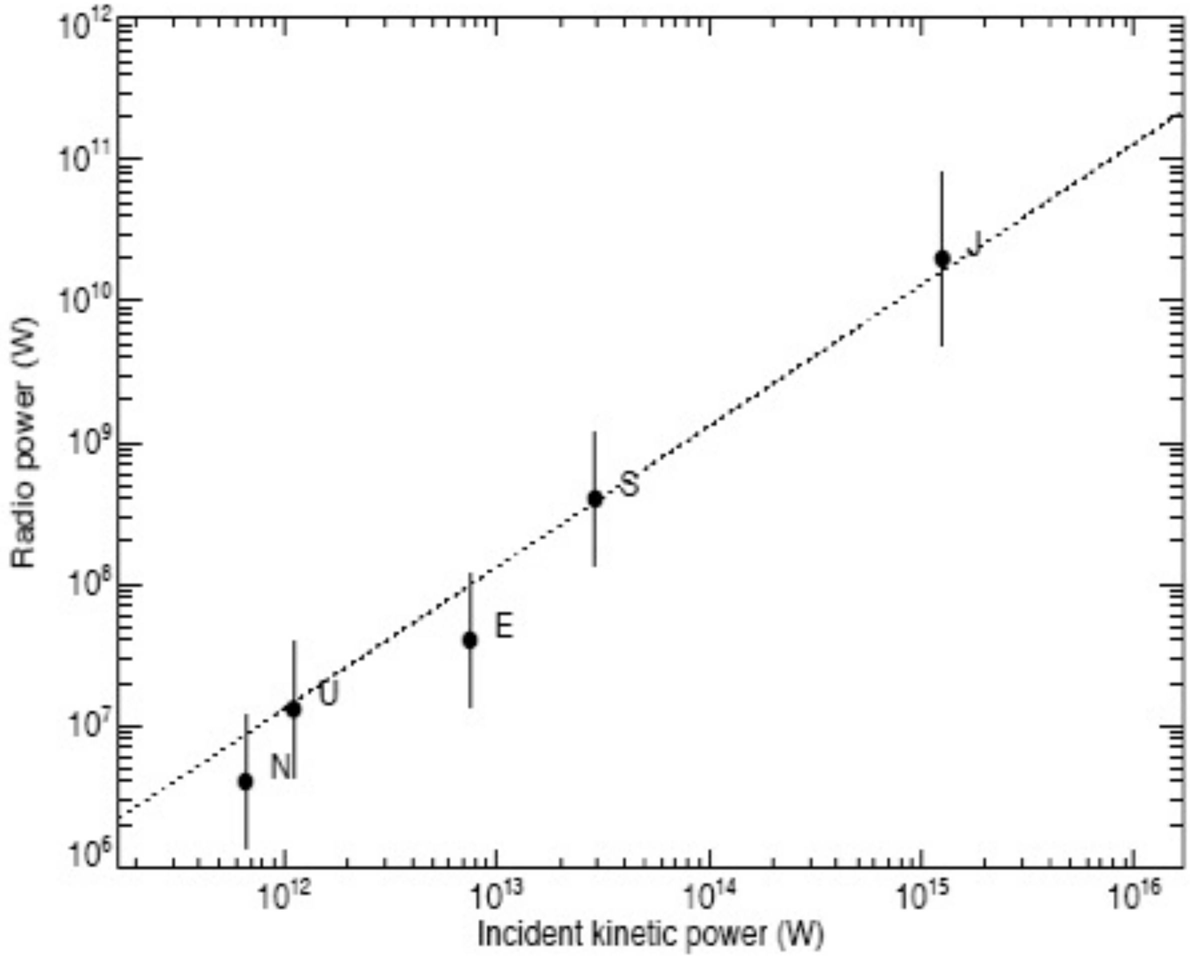
« Radio-kinetic Bode's law » (auroral emissions)

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





Solar Wind expansion

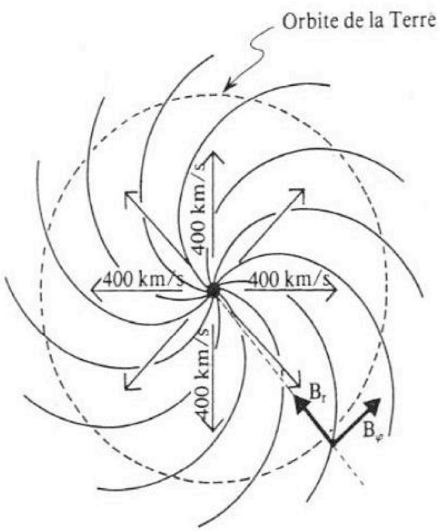
$V \sim c^{te}$

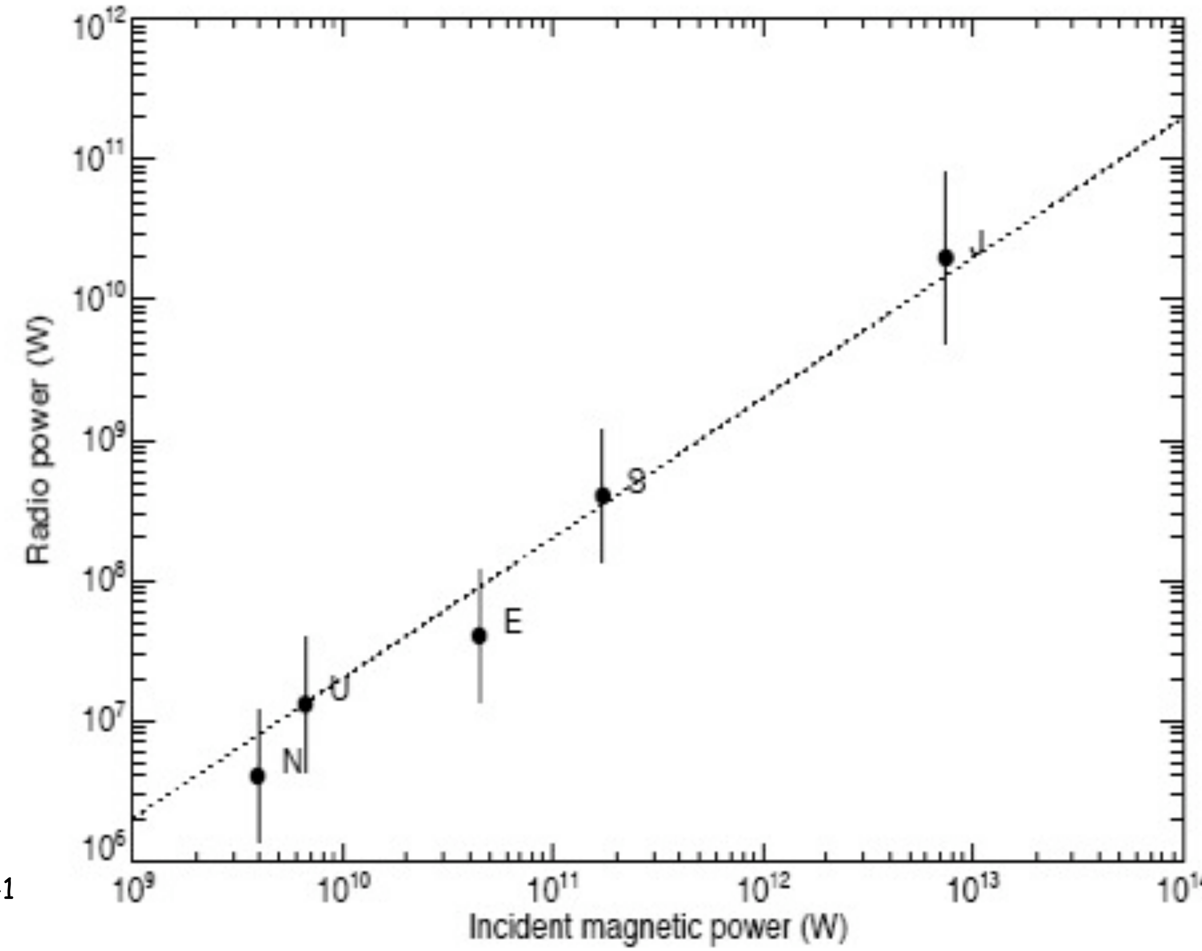
$N \sim d^{-2}$ (mass conservation)

[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)

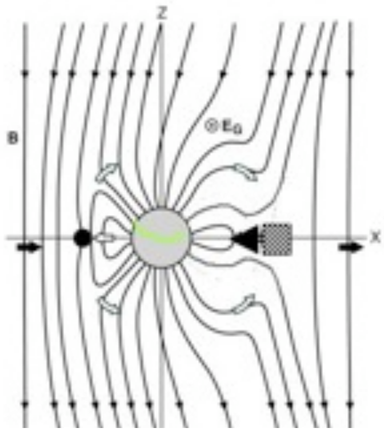
$B\varphi \sim d^{-1}$ ($B_R/B\varphi = V/\Omega d$) → $B \sim d^{-1}$

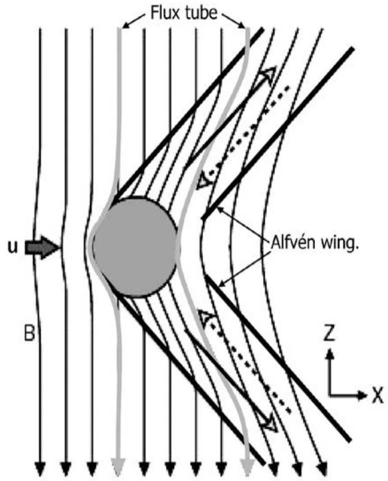
(beyond Jupiter orbit, $B \sim B\varphi$)

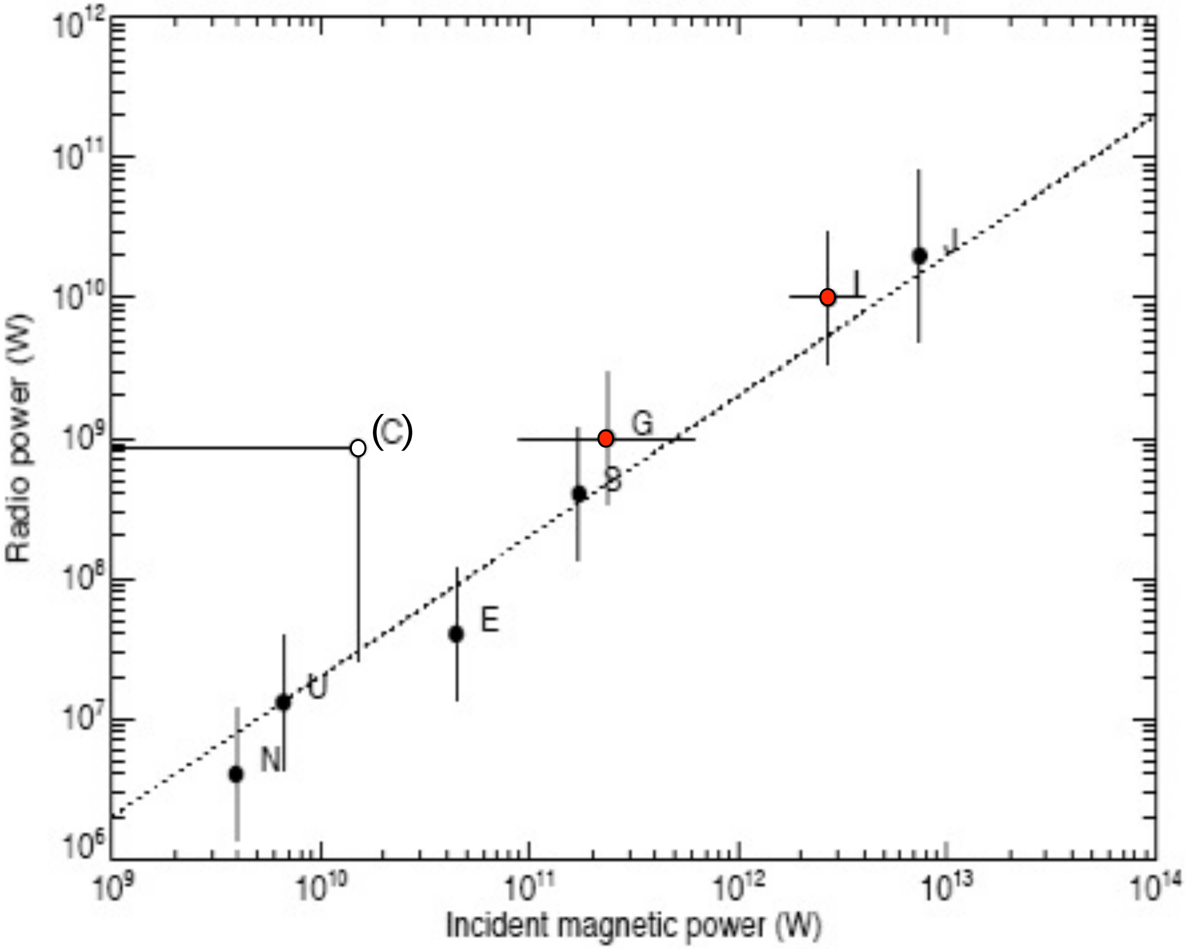
[Zarka et al., 2001]

« 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]

Exoplanets

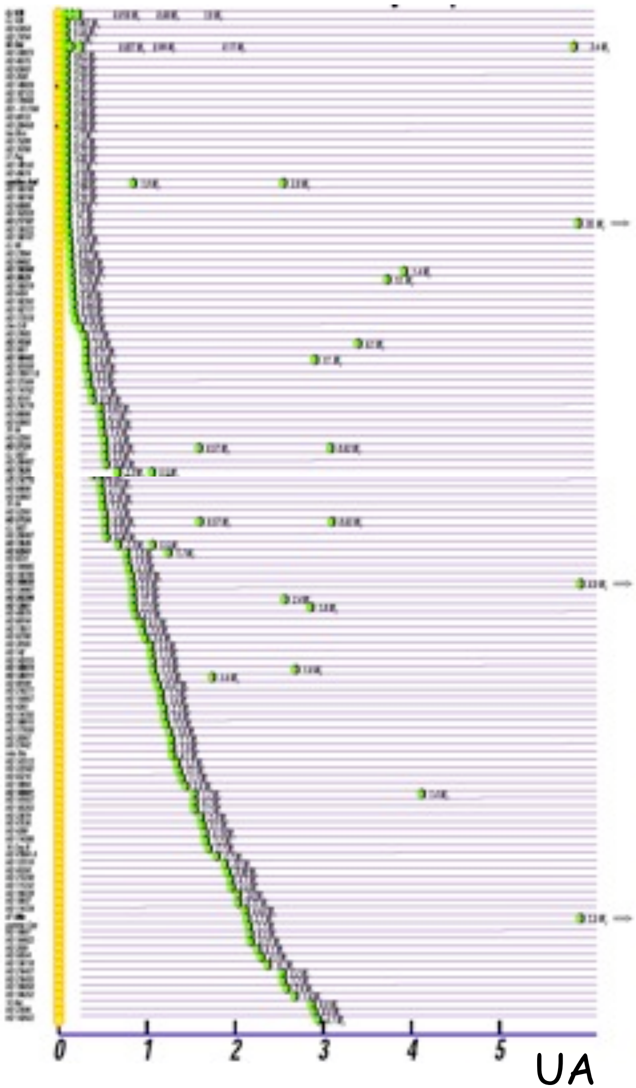
353 exoplanets (in 298 systems) [as of 18th july 2009]

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

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

→ >60 « hot Jupiters »

with periastron @ ~5-10 R_S



[exoplanet.eu]

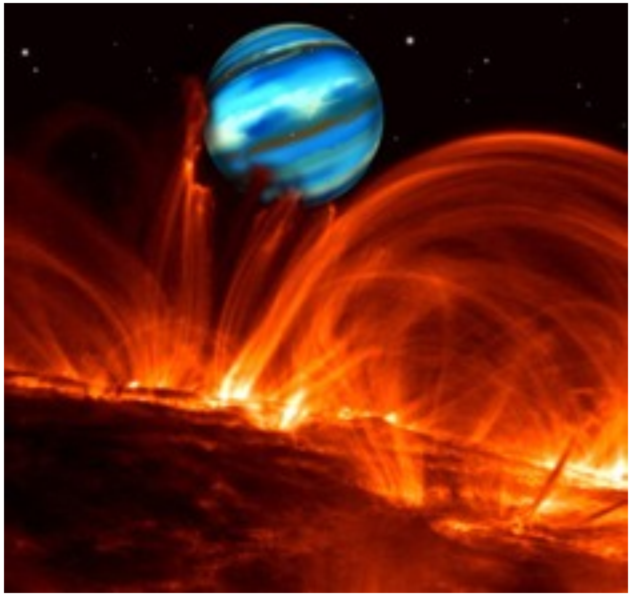
Large-scale stellar magnetic fields

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

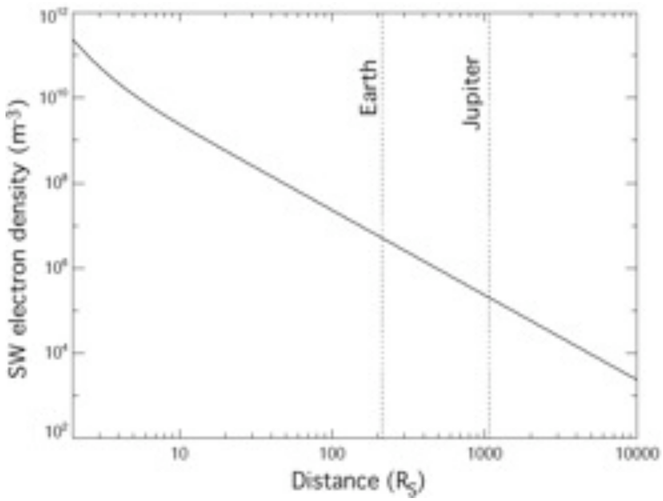
HD 171488 : 500G

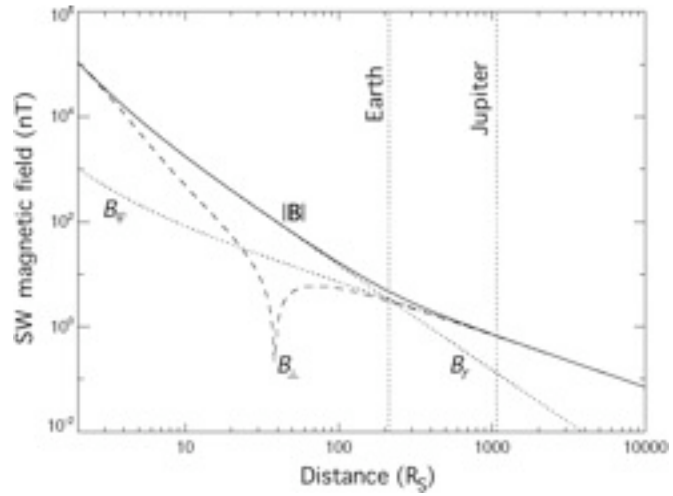
...

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

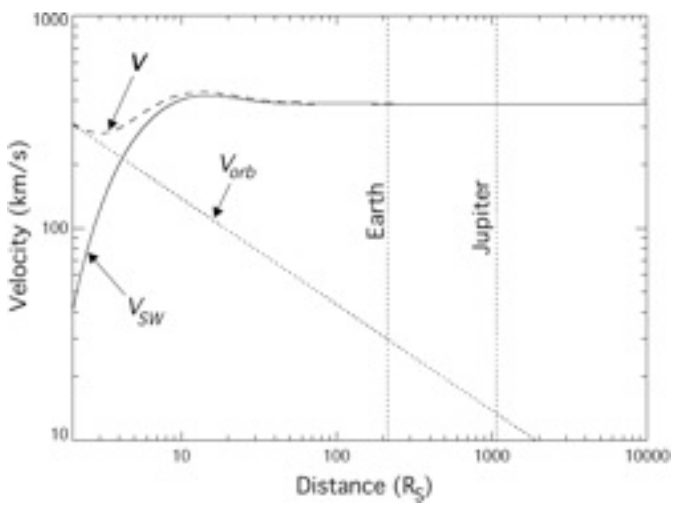
Modelling a magnetized hot Jupiter orbiting a Solar type star

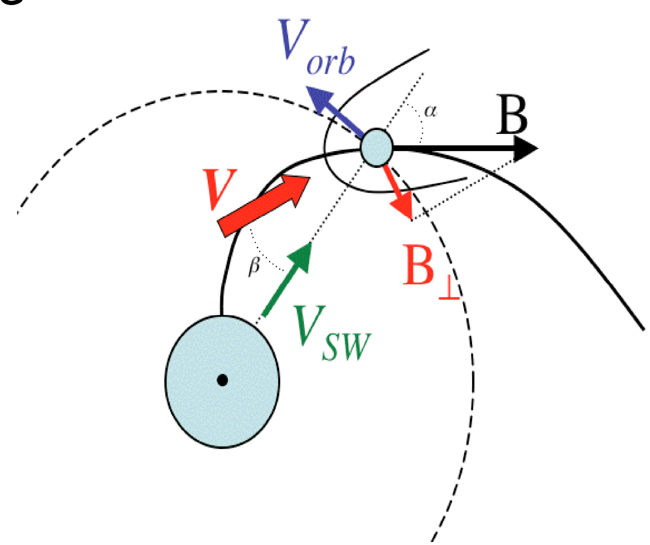
- Ne & B variations in Solar corona and interplanetary medium





- Solar wind speed in the planet's frame





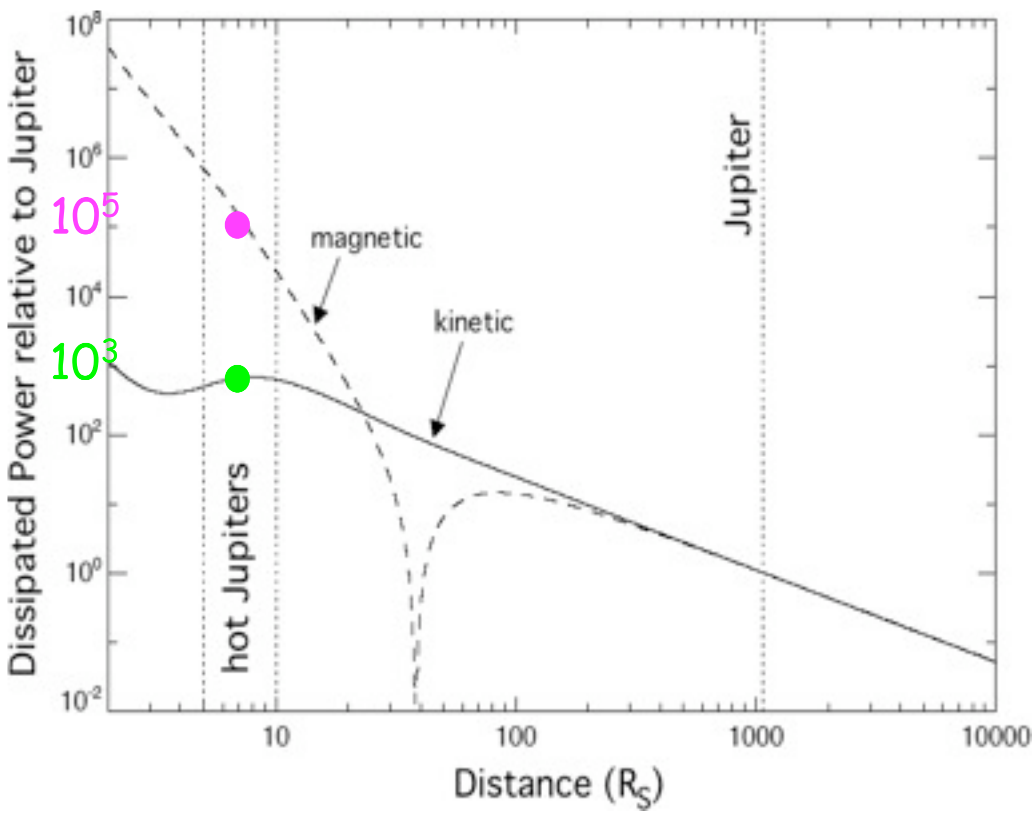
[Zarka et al., 2001, 2007]

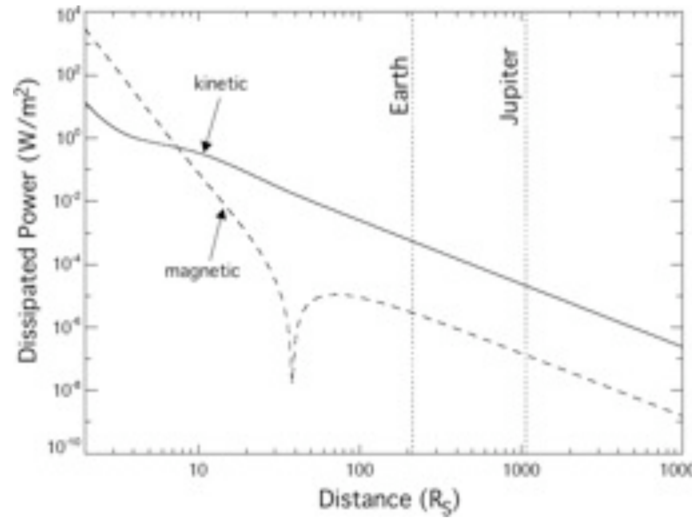
Modelling a magnetized hot Jupiter orbiting a Solar type star

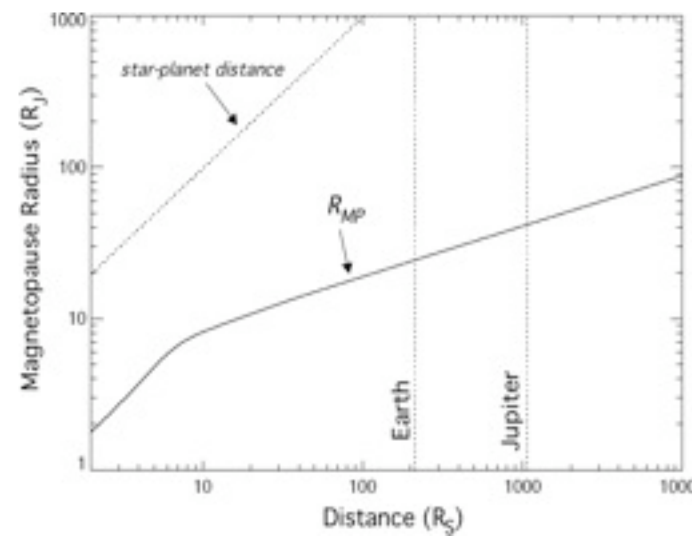
→ Dissipated power per unit area of the obstacle

→ Magnetospheric compression

→ Total dissipated power on obstacle

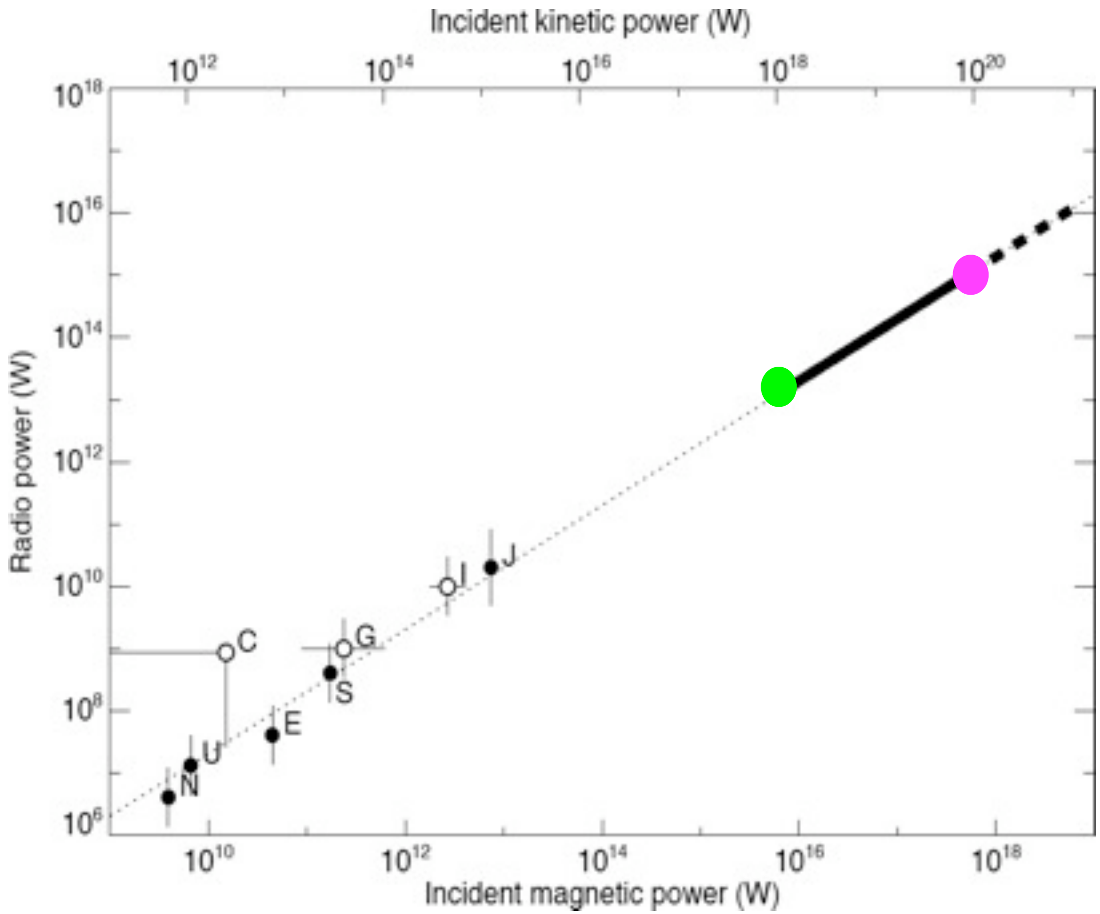






[Zarka et al., 2001, 2007]

and applying the generalized radio-magnetic Bode's law

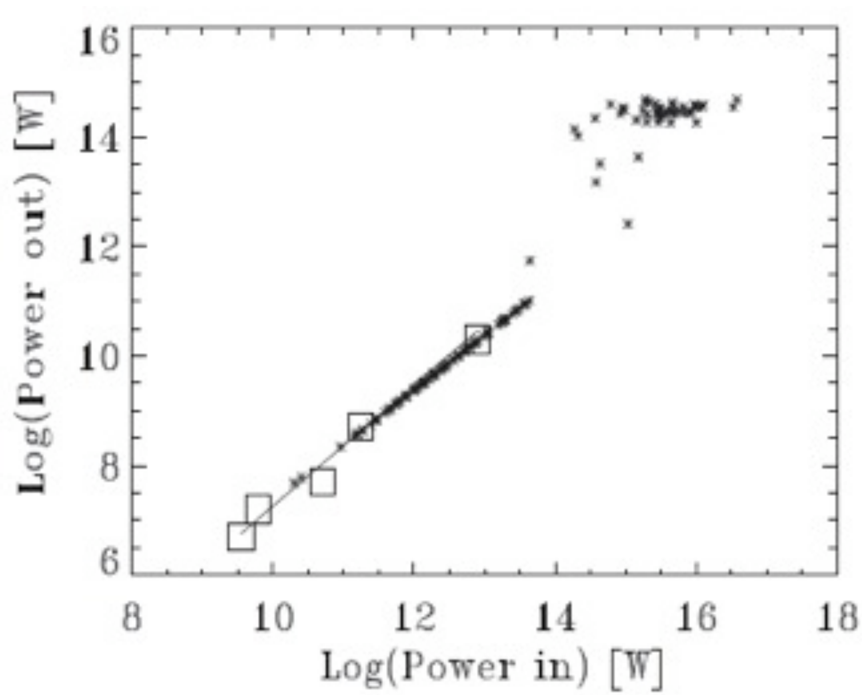


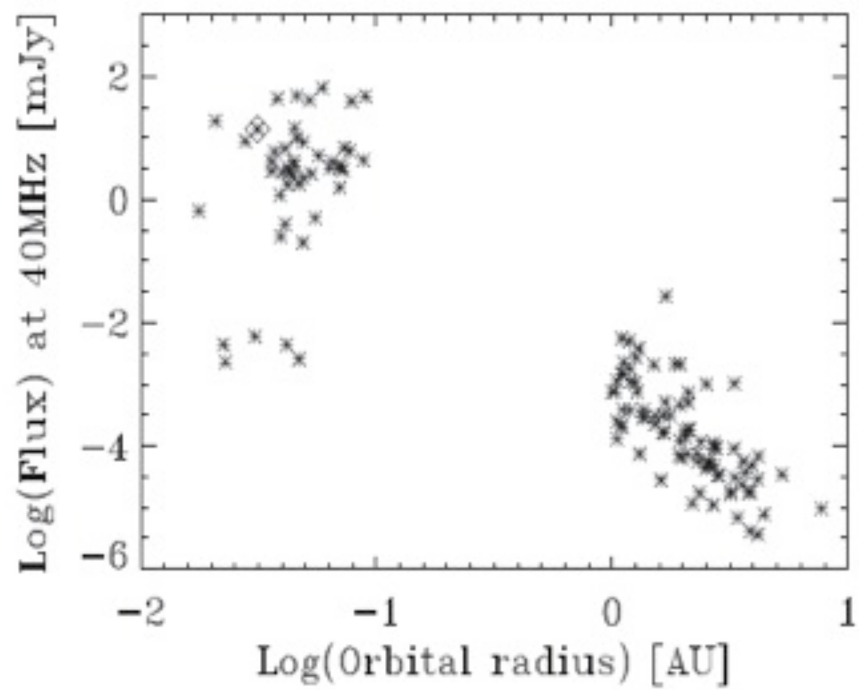
- Extrapolations of Radio-kinetic/magnetic Bode's laws → $P_{Radio} = P_{Radio\text{-}J} \times 10^{3\text{-}5}$
- if no "saturation" nor planetary magnetic field decay

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

Magnetic reconnection and electron acceleration at the magnetopause ?

- Computation ofparallel E field (assuming B_*=1G)
- Number and energy of runaway electrons
- Parametrization by “efficiency” η





[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) → $\omega\downarrow$

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

UPPER LIMIT OF MAGNETIC FIELDS IN HOT JUPITERS

Planet	M (M_J)	P_{orb} (days)	R (R_J)	M_D (G m^3)	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

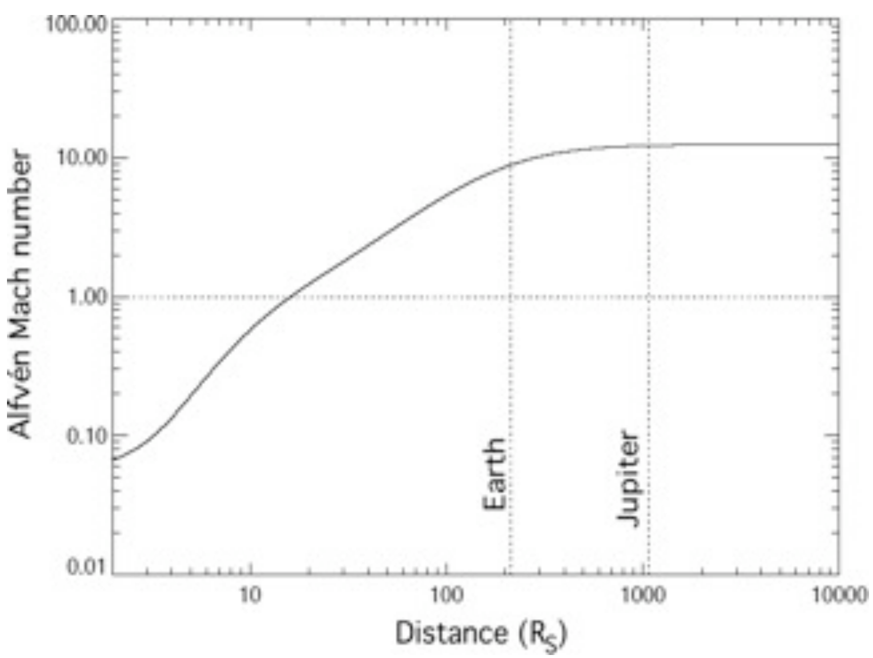
- Internal structure + convection models

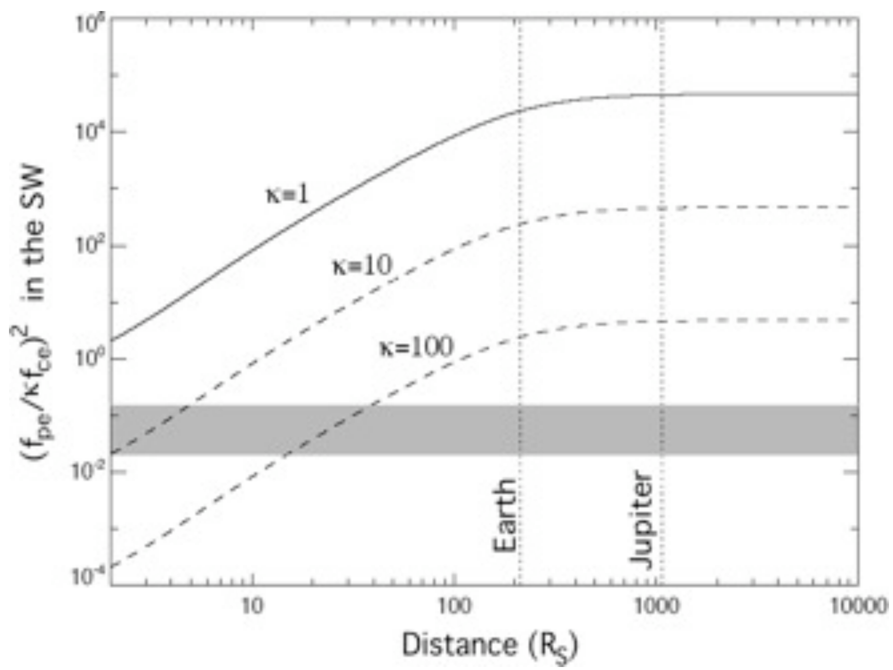
→ self-sustained dynamo → $\mathcal{M}$ may remain ≥ a few G.R_J^3

[Sanchez-Lavega, 2004]

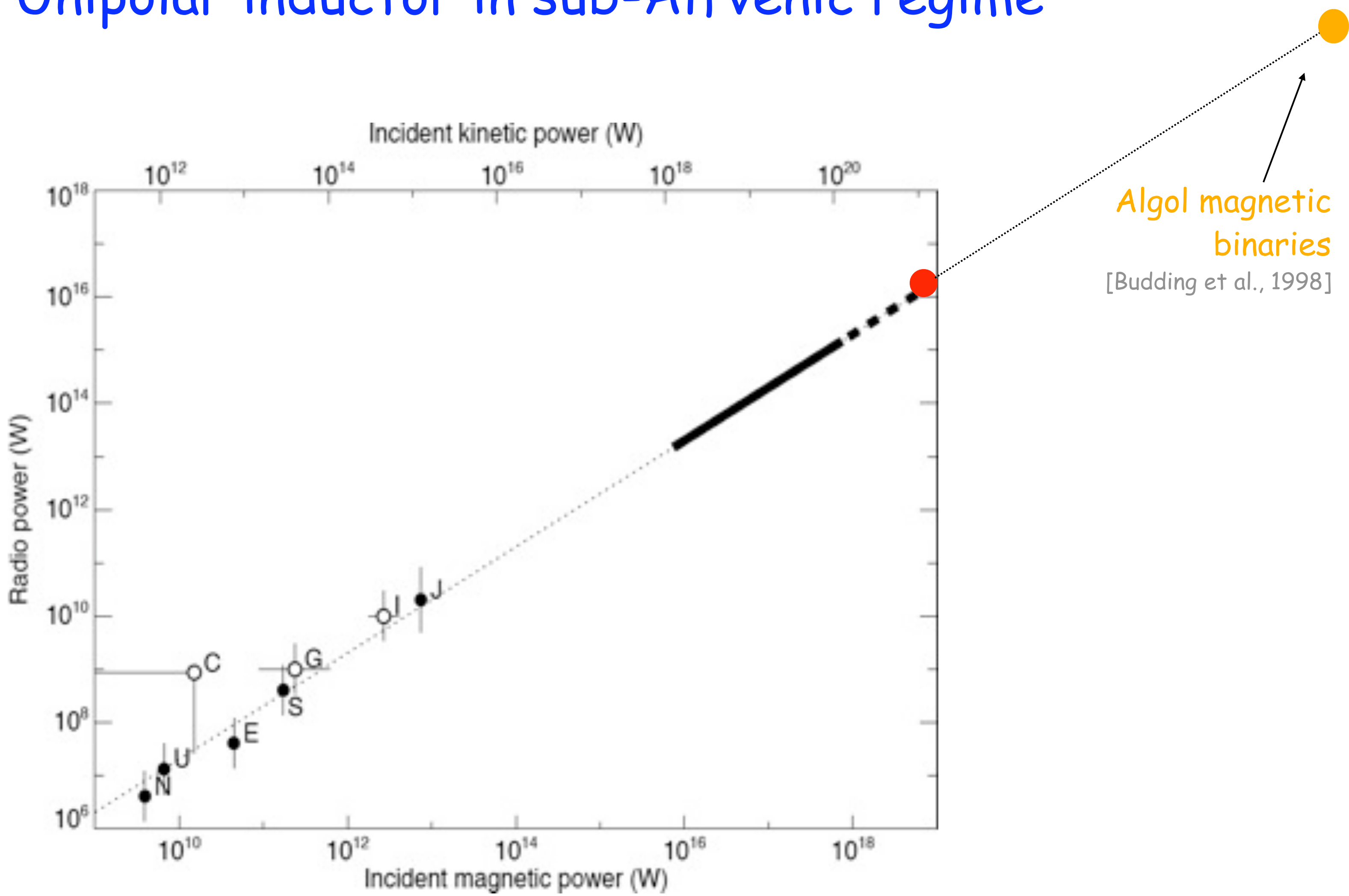
Unipolar inductor in sub-Alfvénic regime

- 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



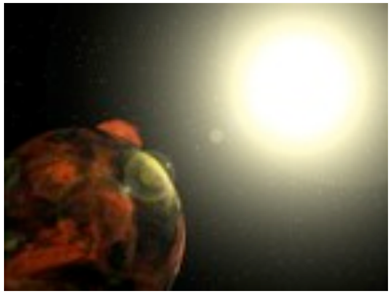
• Extrapolation / Radio-magnetic Bode's law

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

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

[Zarka, 2007]

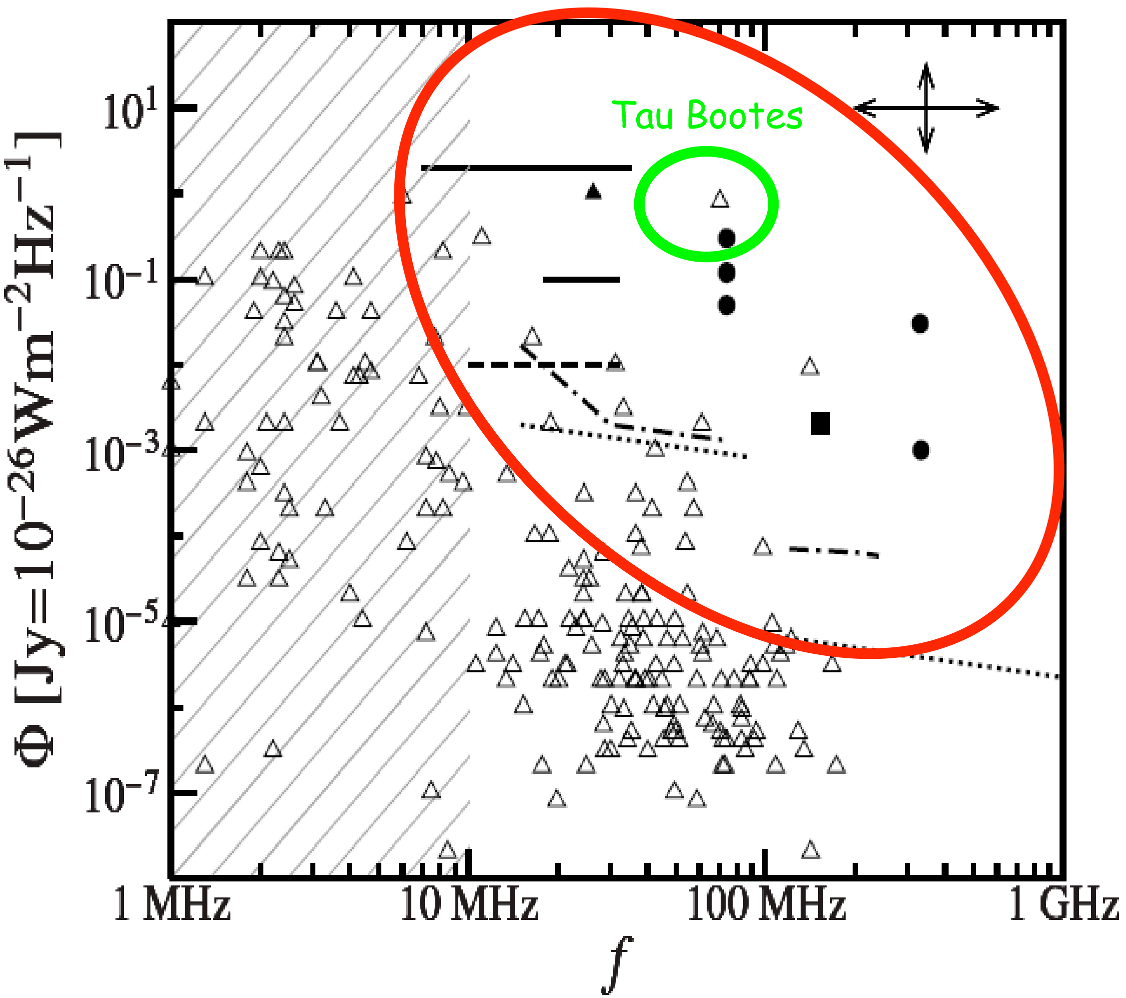
Maximum distance of detectability of 10^5 α Jupiter's radio emissions



	$b\,\tau = 10^6$ (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)

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]

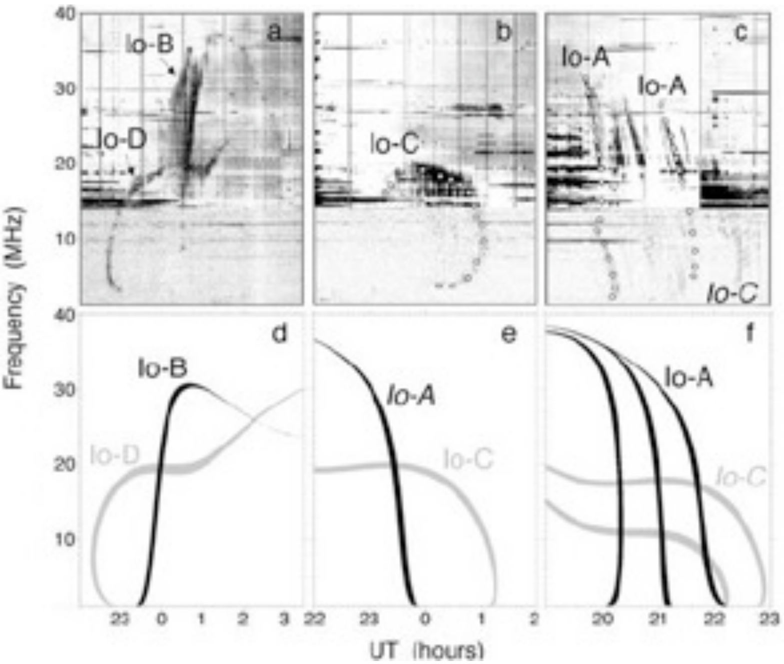
- Role of (frequent) Coronal Mass Ejections

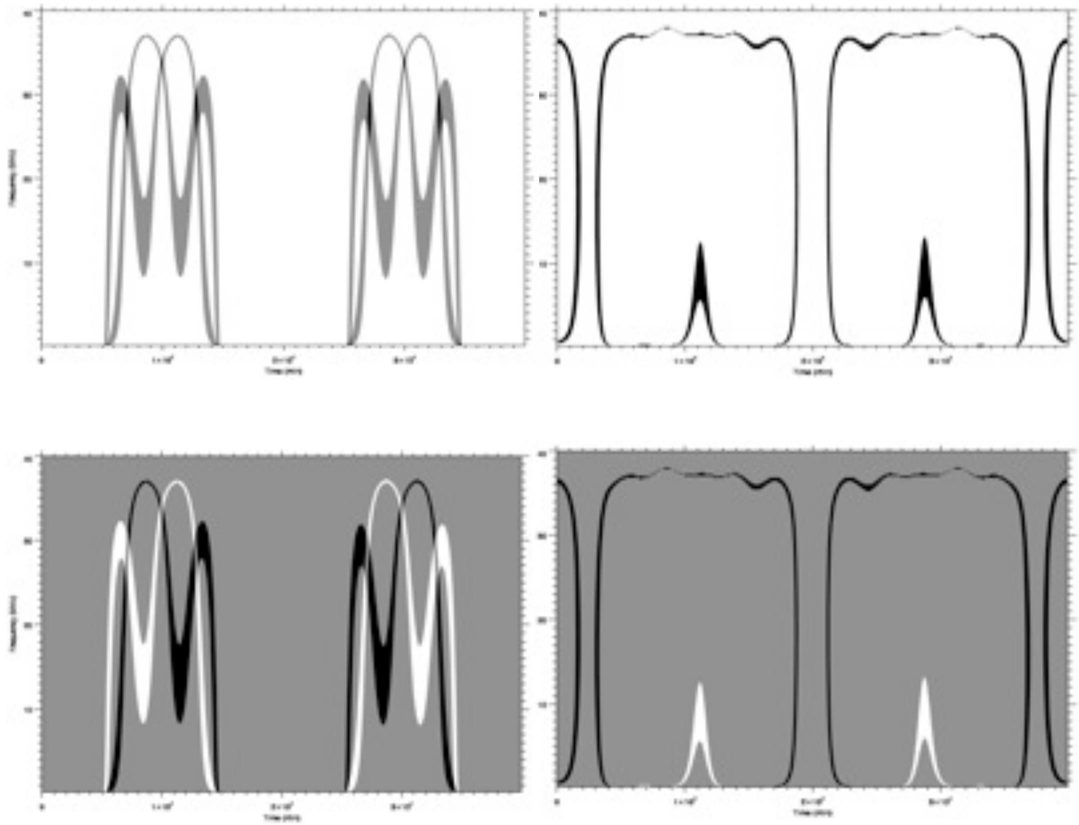
[Khodachenko et al., 2006]

- Application of unipolar inductor model to white dwarfs systems

[Willes and Wu, 2004, 2005]

Dynamic spectrum modeling : from Jupiter to exoplanets





i = 0°

i = 30°

[Hess et al., 2008]

[Hess & Zarka, in preparation]

- Remote observation of exoplanetary magnetospheres ?
- Planetary radio emissions properties & energy source

  in Planet-Star plasma interactions
- Scaling laws and Extrapolation to hot Jupiters
- 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 ?

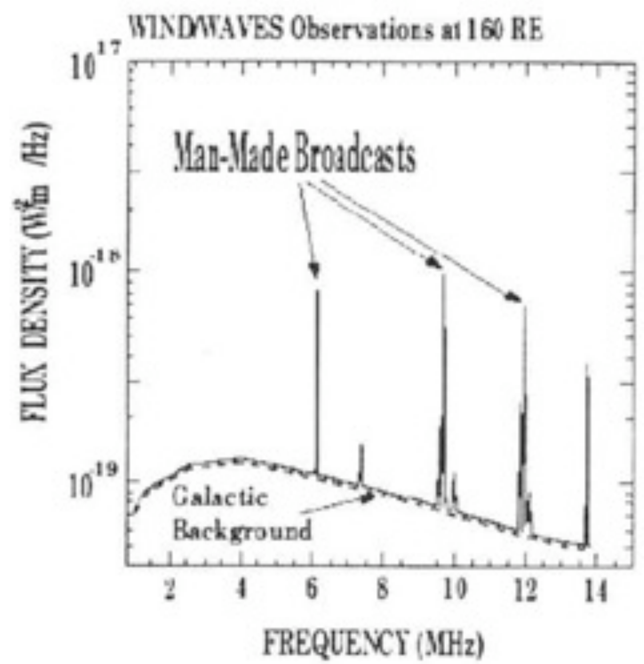
  → discriminate via emission polarization (circular/elliptical)

  + periodicity (orbital)

  → search for Jovian type bursts ?

- Very bright galactic background ($T_b \sim 10^{3-5}$ K)
- RFI (natural & anthropic origin) →
- Ionospheric cutoff ~ 10 MHz, and

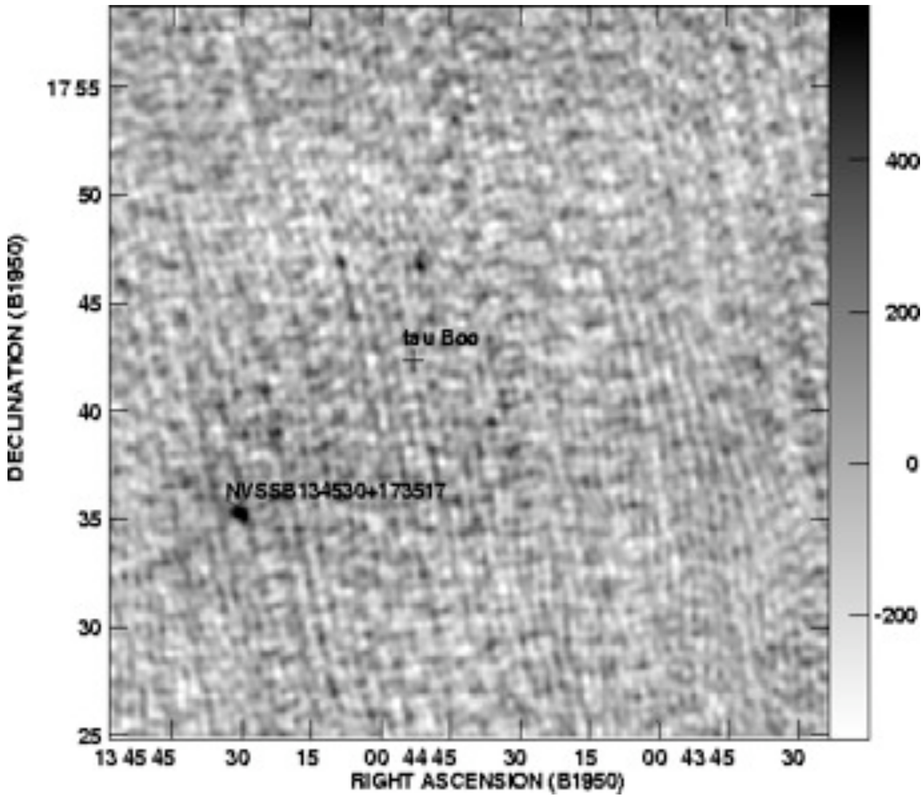
  perturbations ≤30-50 MHz
- IP/IS scintillations

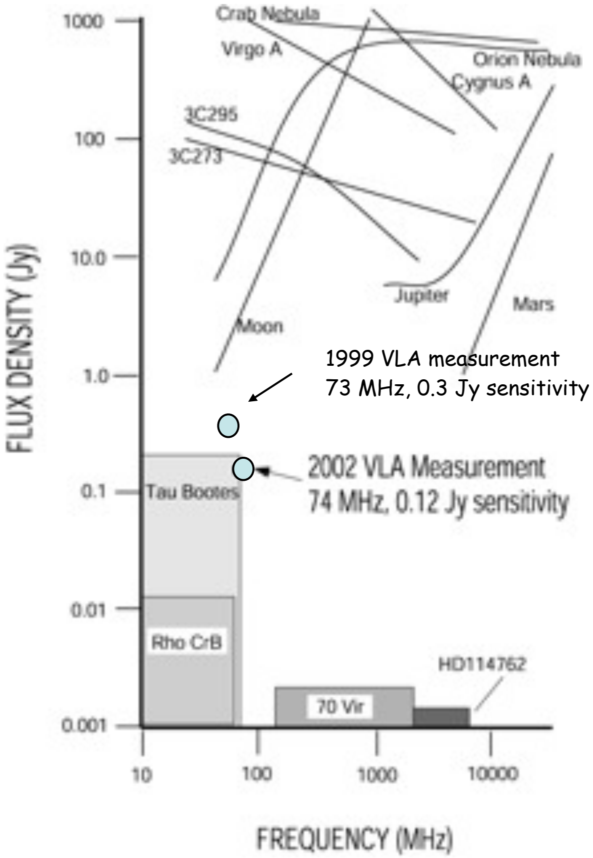


• VLA

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

Very Large Array

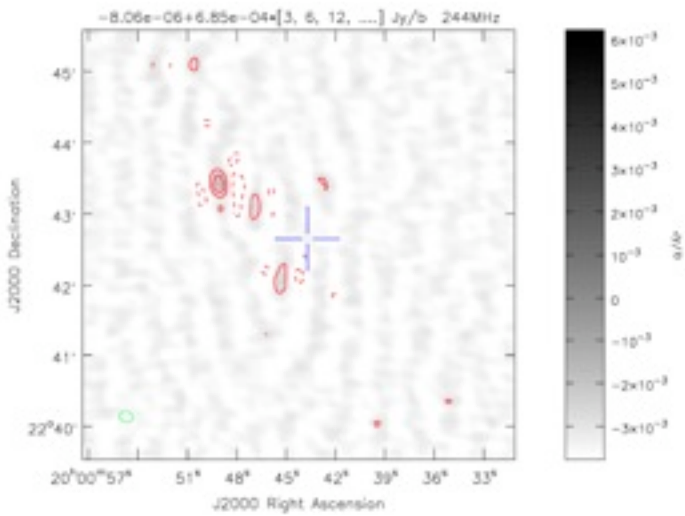


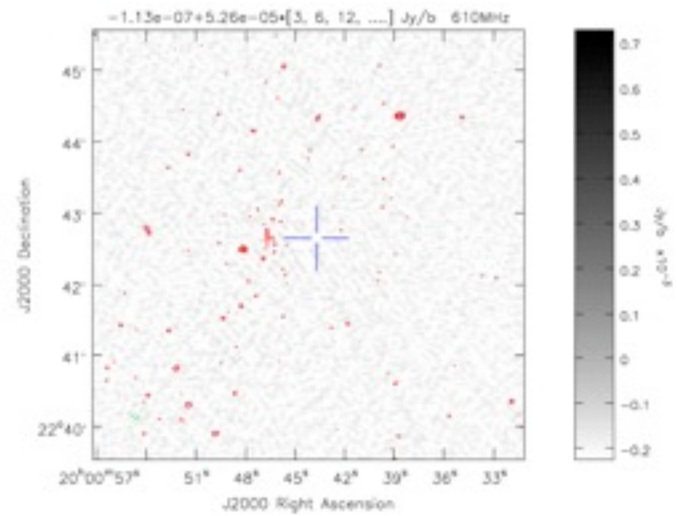


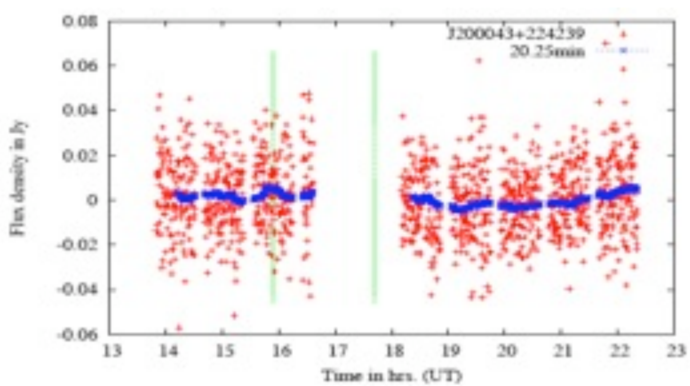
[Bastian et al., 2000 ; Farrell et al., 2003, 2004; Lazio & Farrell, 2007]

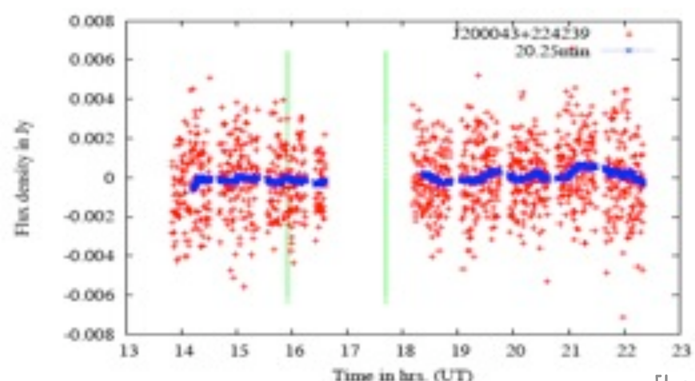
• GMRT

- 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



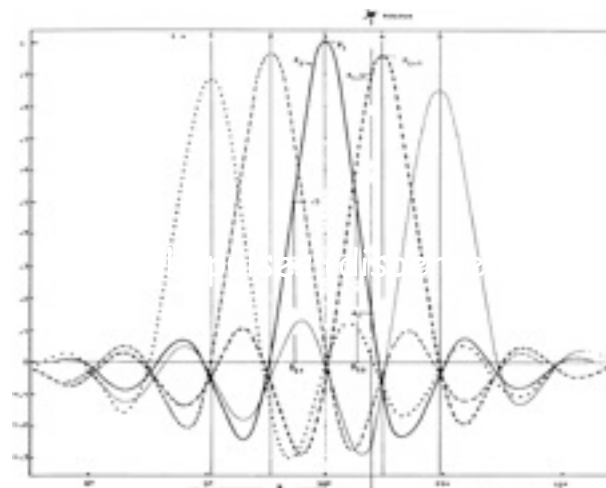






[Lecavelier et al., 2009]

• UTR-2



- 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 analysis of 1-sec survey images
- Targeted observations of all known exoplanets + all stars within 10 pc, with emphasis on :
  - hot jupiters with « good » predicted frequency range & flux density (Tau Boo, HD 192263 ...)
  - Corot planets (HD46375...)
  - Planets orbiting magnetized stars (Tau Boo, Ups And, HD189733 ...)
  - Selected magnetic stars (red dwarfs ...)

To be continued …