Extrapolating to "Hot Jupiters"

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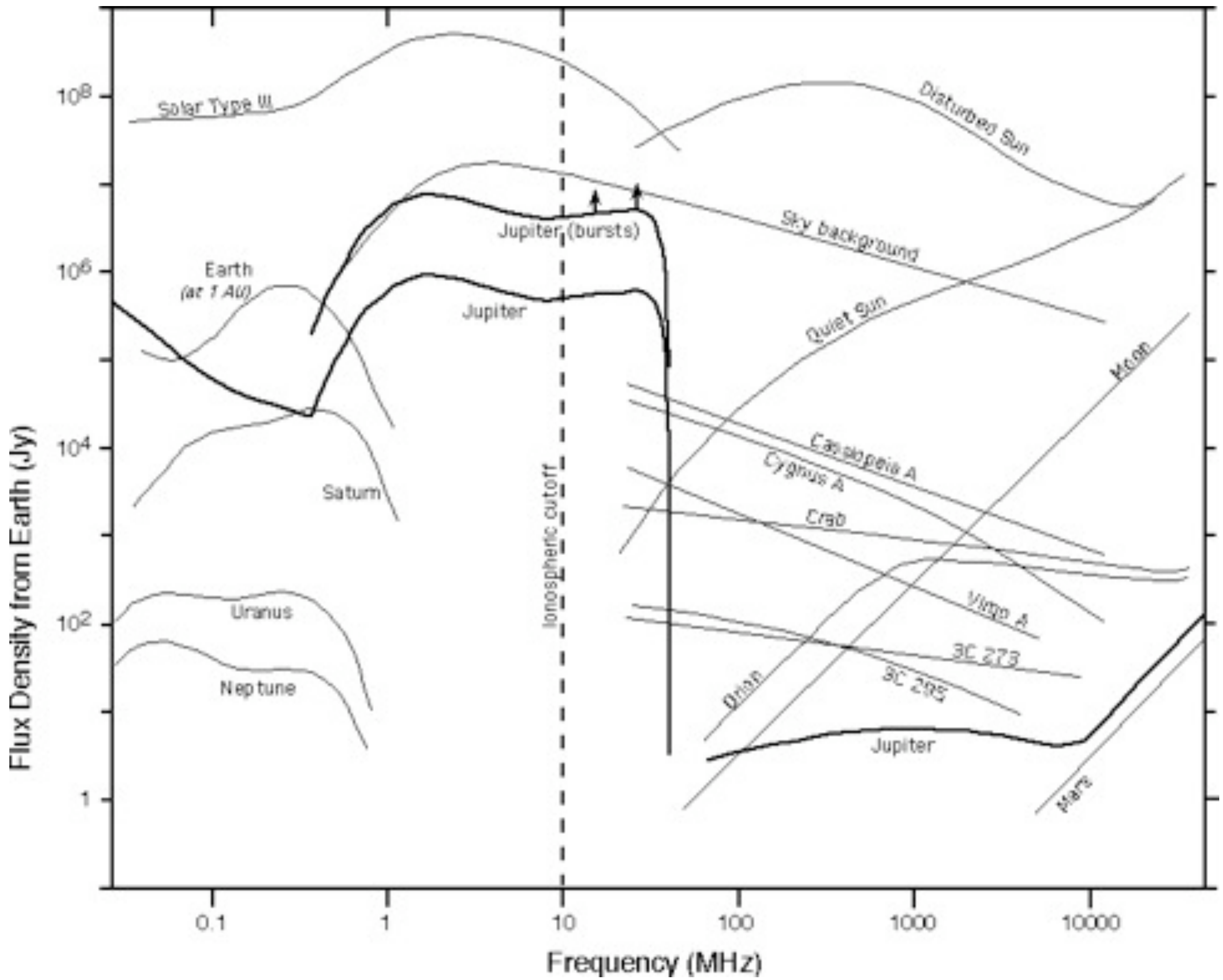
- Spectra of typical radio sources
- Sky background $T \sim 1.15 \times 10^8/f^{2.5}$
- Solar and planetary emissions very intense



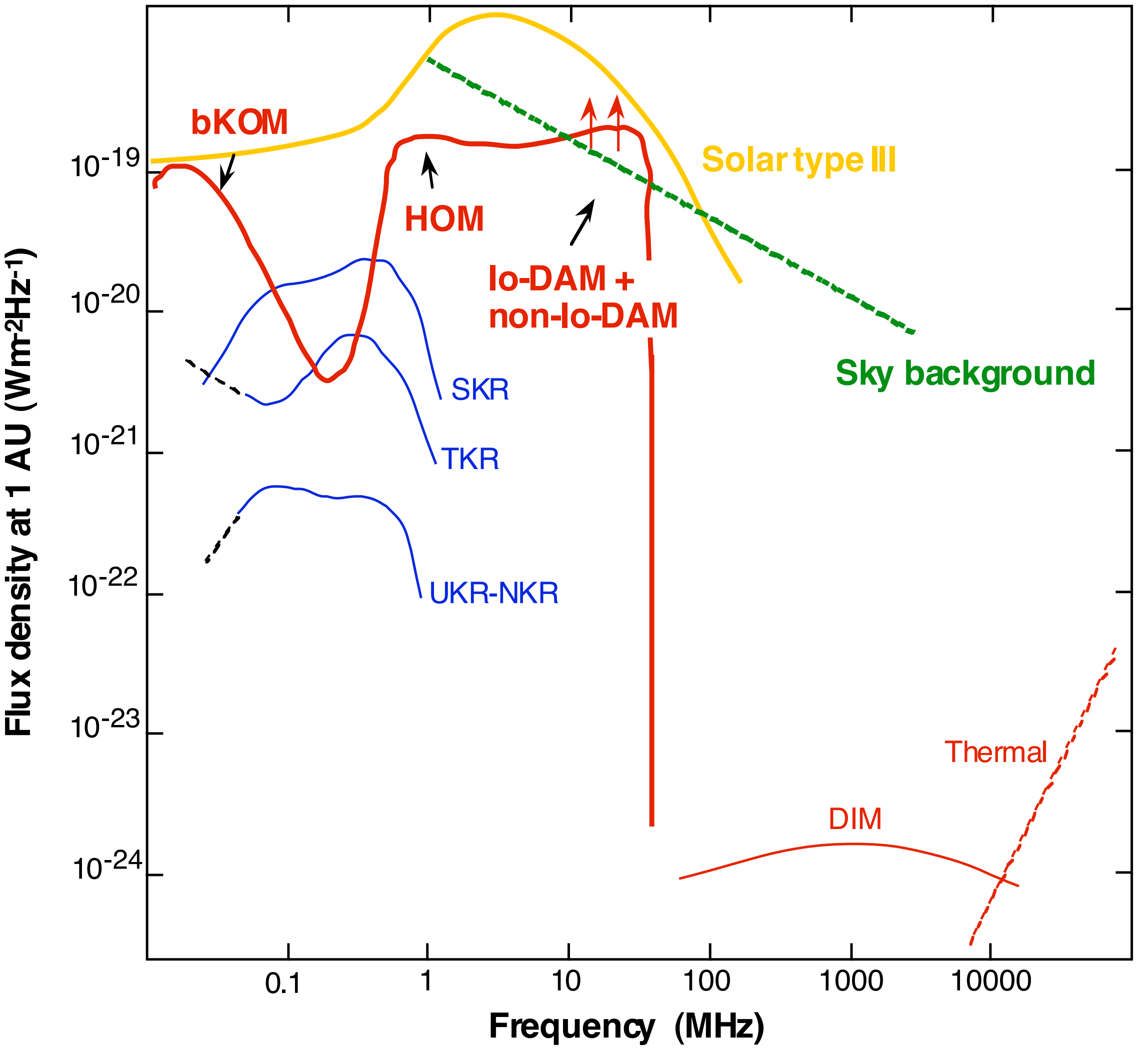
- **Radio emissions from magnetized planets**

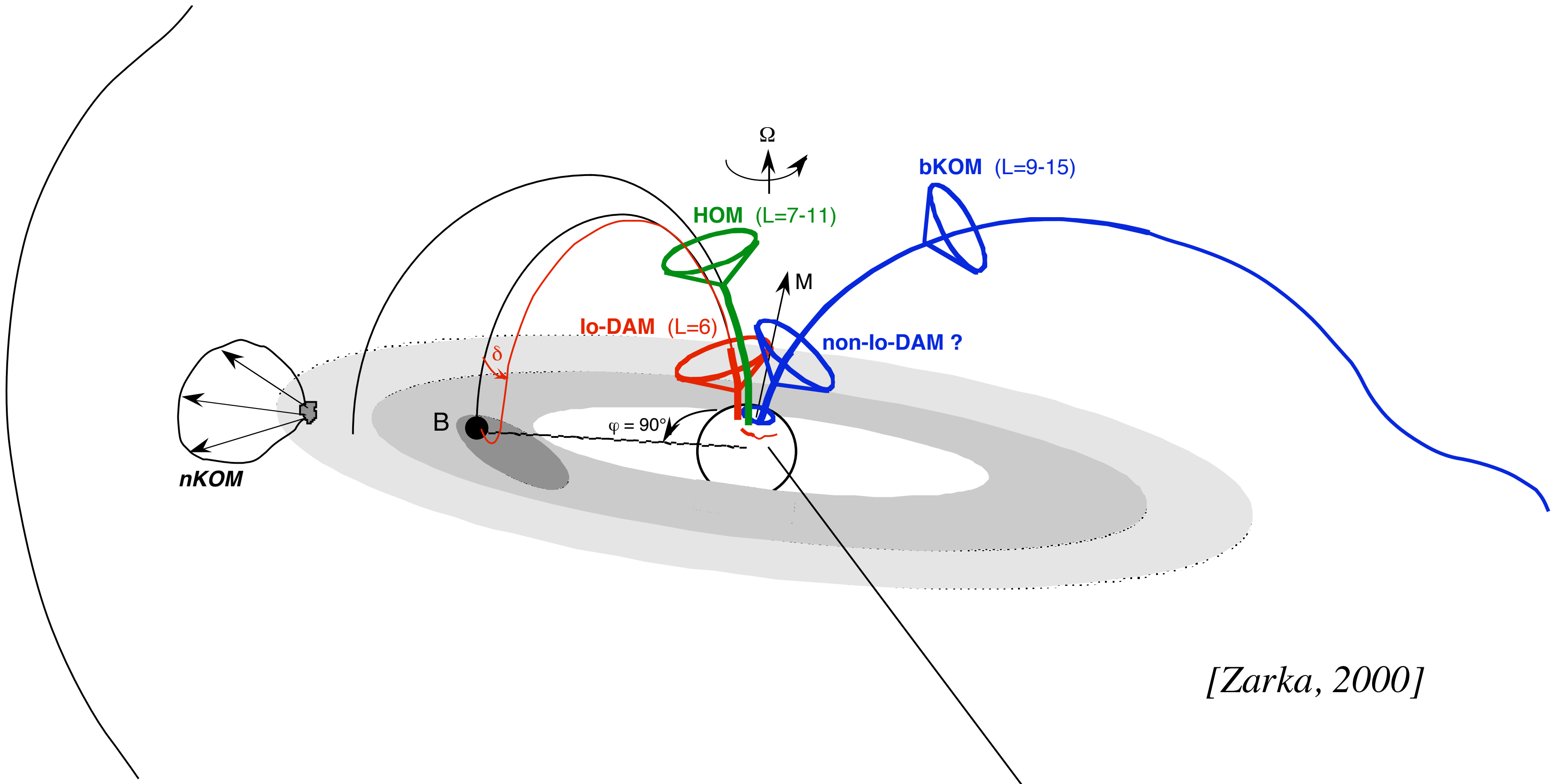
- 1955 : discovery of Jovian DAM

- 1960's : discovery of Earth's AKR/TKR

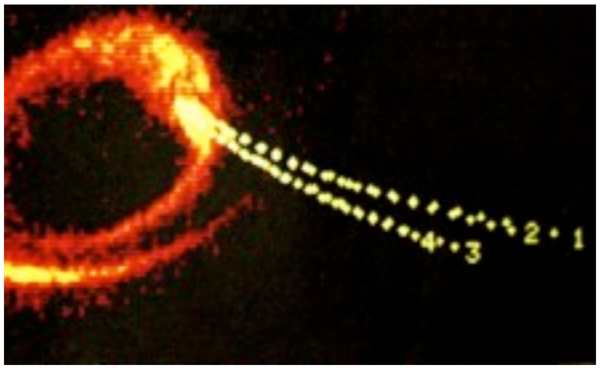
- 1970's-80's : Voyager era
⇒ SKR, UKR, NKR

⇒ all gas giants strongly magnetized





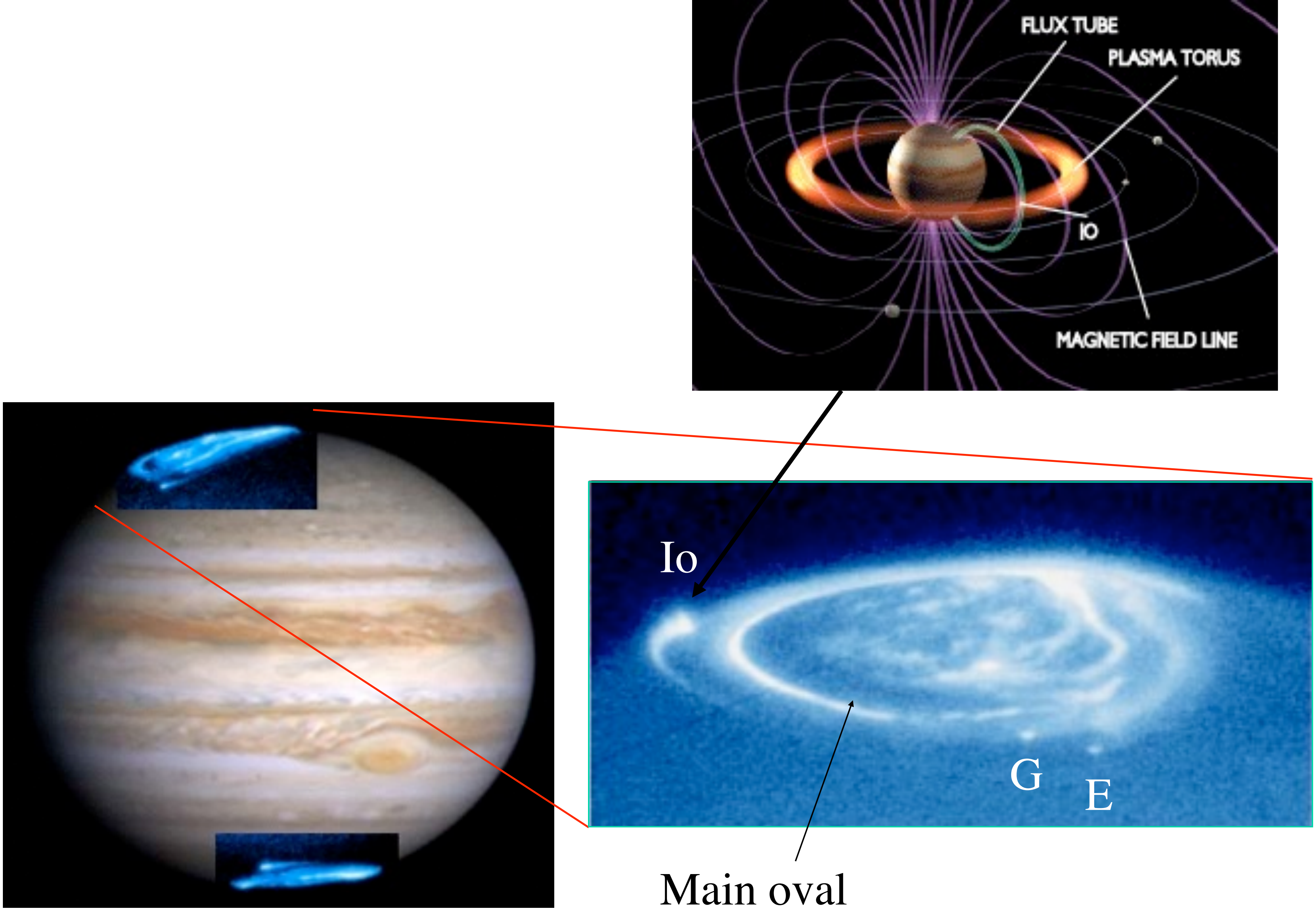
[Zarka, 2000]



[DE-2, Huff et al., 1988]

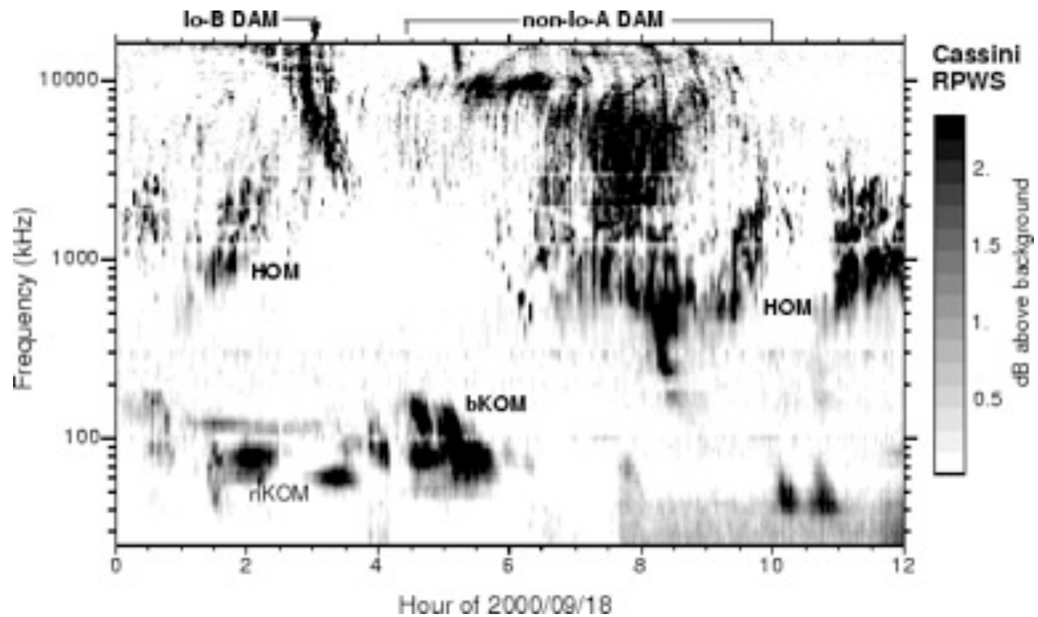
- 5 radio planets
- ≥6 LF (KOM-DAM) radio components (×2)

(auroral/polar + Io-driven)



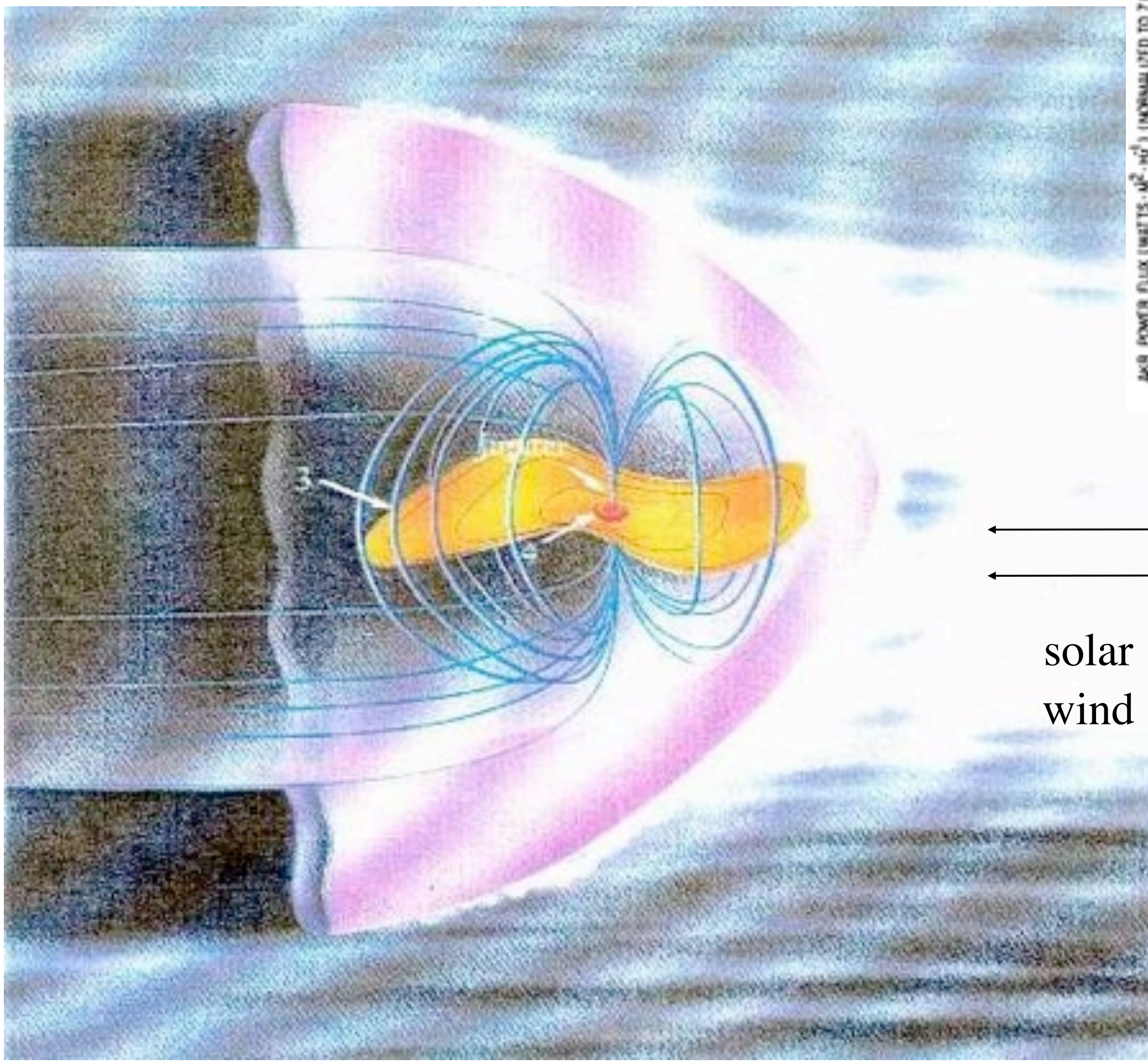
UV (H_2, Lyman-α) *[Prangé et al., 1996]*

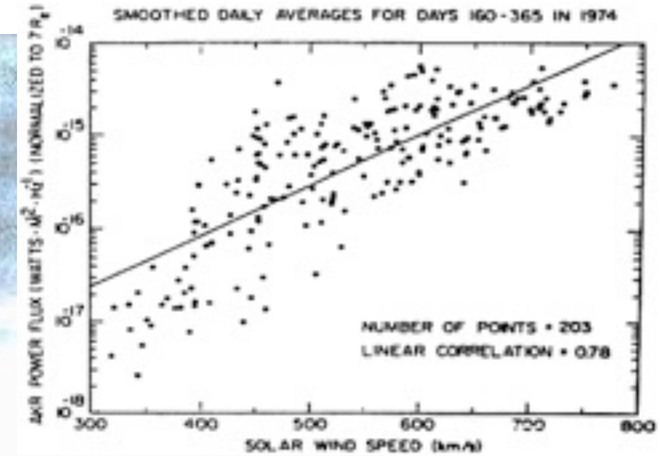
Planetary Radio Emissions



[Zarka et al., 2001]

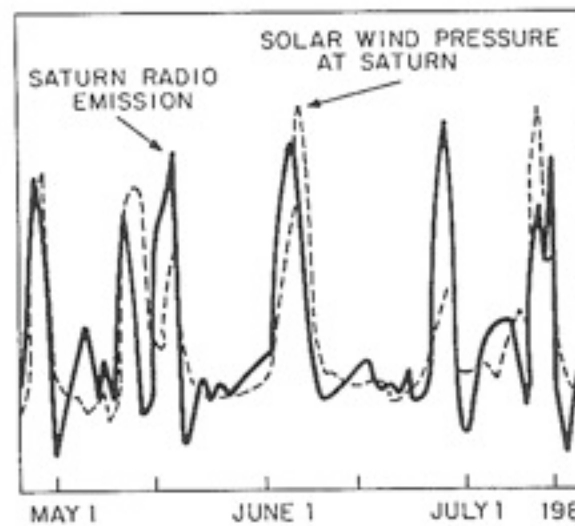
- nonthermal cyclotron emission "bursts"
- ($f \sim f_{ce}$)
- broadband ($\Delta f \sim f$)
- very intense ($T_B > 10^{15-20}$ K, $P \geq 10^{7-11}$ W, 1% of auroral input power in CMI radio radiation)
- contrast / Sun ~1
- anisotropic beaming (cone 1.1-1 sr / B) ⇒ rotation modulation
- circular / elliptical polarization
- Theory = Cyclotron Maser Instability (B, keV e-, $f_{pe} << f_{ce}$ in source)





[Gallagher and d'Angelo, 1979]

solar
wind

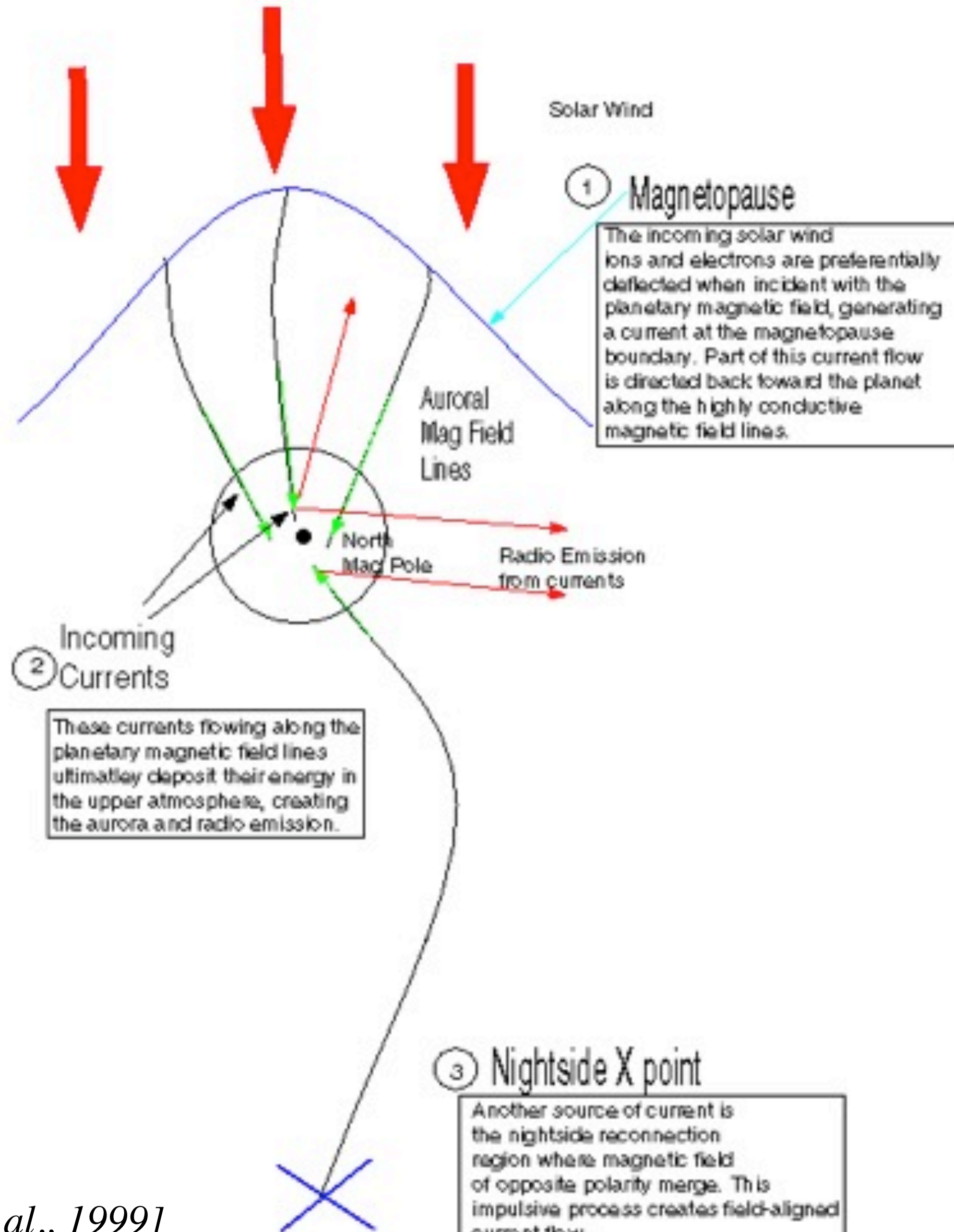


[Desch, 1981, 1982]

- Strongly solar wind driven (rotation also very important at Jupiter)

⇒ magnetic reconnection (tail, magnetopause nose) ?

⇒ magnetospheric compressions ?



[Farrell et al., 1999]

Can we detect extrasolar planets in the LF radio range ?   (< 100 MHz)

Interests :

- planetary rotation period

- remote / comparative diagnostic of magnetospheric processes (B, radio flux, energy output)

- possible discovery of "intense" radio-exoplanets

- Maximum distance of detectability

$$d_{max} = (\alpha\ S_j\ A_e / 2\ n\ k\ T_s)^{1/2} \times (b\ \tau)^{1/4}$$

$\sim 10^{-18}$ $Wm^{-2}Hz^{-1}$ (10^8 Jy)
from 1 AU distance
(25 μ-Jy from 10 pc, peak ≥ ×10 ~mJy)

~3

$\sim 2\times10^4$ K @ 30 MHz
(10^3 K @ 100 MHz,
3×10^5 K @ 10 MHz)

⇒ for α =1 : $d_{max}\ (pc) = 2.5\ 10^{-6}\ A_e^{1/2}\ (b\tau)^{1/4}$

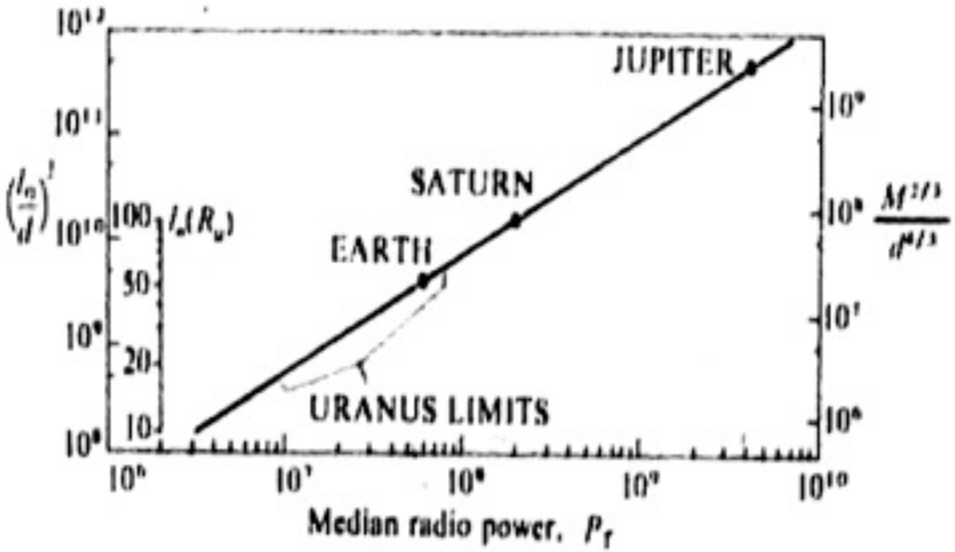
	$b\ \tau = 10^6$ (1 MHz, 1 sec)	**$b\ \tau = 2\times10^8$ (3 MHz, 1 min)**	**$b\ \tau = 4\times10^{10}$ (10 MHz, 1 hr)**
$A_e = 10^4\ m^2$ (Nançay)	**0.013**	**0.05**	**0.17**
$A_e = 10^5\ m^2$ (Kharkov)	**0.040**	**0.15**	**0.55**

- Prediction of planetary radio flux from first principles not doable

$\Rightarrow$ heuristic scaling laws ?

"kinetic" radio scaling law ...

$$P_{radio} \propto M^{2/3} d^{-4/3} (N^{2/3} V^{7/3})$$



[Desch and Kaiser, 1984]

M = planetary magnetic dipole moment

d = Sun-planet distance

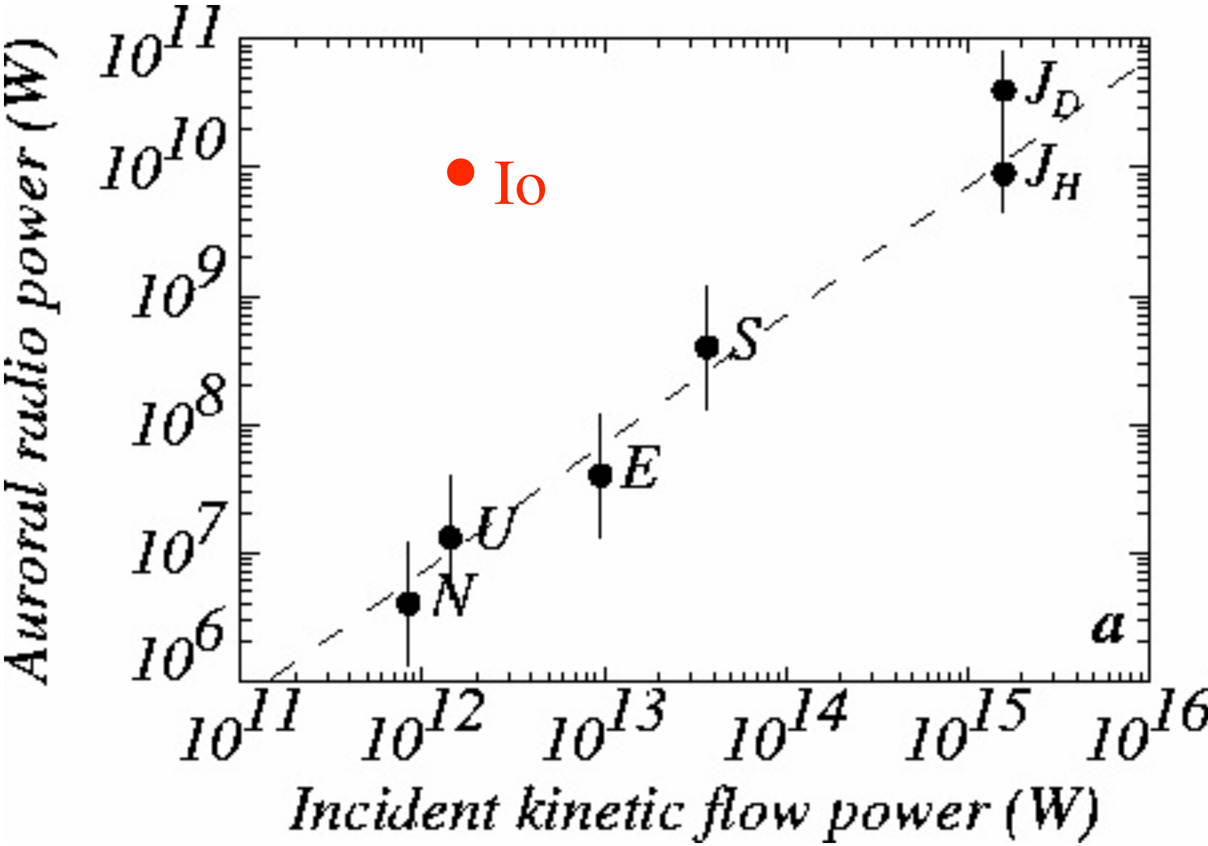
(**N**=solar wind density at 1 AU, **V**=bulk velocity)

$\Rightarrow$ *predictions for Uranus (1986)*

… extended to Uranus & Neptune, Jovian HOM/non-Io-DAM (mostly SW driven)

$$P_{radio} = 2S\Omega R^2\Delta f \propto P_{RAM} = (N_o/d^2)\, m_p\, V^3\, \pi R_{mp}^2$$

⇒ >99% correlation, slope ~1, $\propto$ ~7×10^{-6}



[Zarka, 1992]

- Note that Io-induced emission does not fit

Table 1: Average flux density, beaming, bandwidth and power of planetary radio emissions.

	Earth (auroral)	Jupiter (auroral)		***Jupiter (Io-induced)***	Saturn (auroral)	Uranus (auroral)	Neptune (auroral)
Name of radio component	TKR	*HOM*	DAM	***Io-DAM***	SKR	UKR	NKR
Average flux density S^a ($Wm^{-2}Hz^{-1}$)	5×10^{-21}	10^{-19}	10^{-19}	$\sim10^{-19}$	2×10^{-20}	4×10^{-22}	2×10^{-22}
Radio beam "effective" solid angle Ω (sr)	0.5 – 1.	*1. – 2.*	0.5 – 1.	***0.1 – 0.2***	0.5 – 1.	~1.	~1.
Average spectrum width Δf (MHz)	0.2 – 0.4	*1 – 2*	10 – 20	***10 – 20***	0.4 – 0.8	~0.7	~0.5
Average radio power P_r (W)	4×10^{7}	9×10^{9}	4×10^{10}	$\sim10^{10}$	4×10^{8}	1.3×10^{7}	4×10^{6}
Power normalized to Earth's case $P_r / P_{r,e}$	1	*~200*	1000	***~250***	10	~0.3	0.1

[a] S = average flux density normalized to a 1 AU distance (see text for the way S is computed).

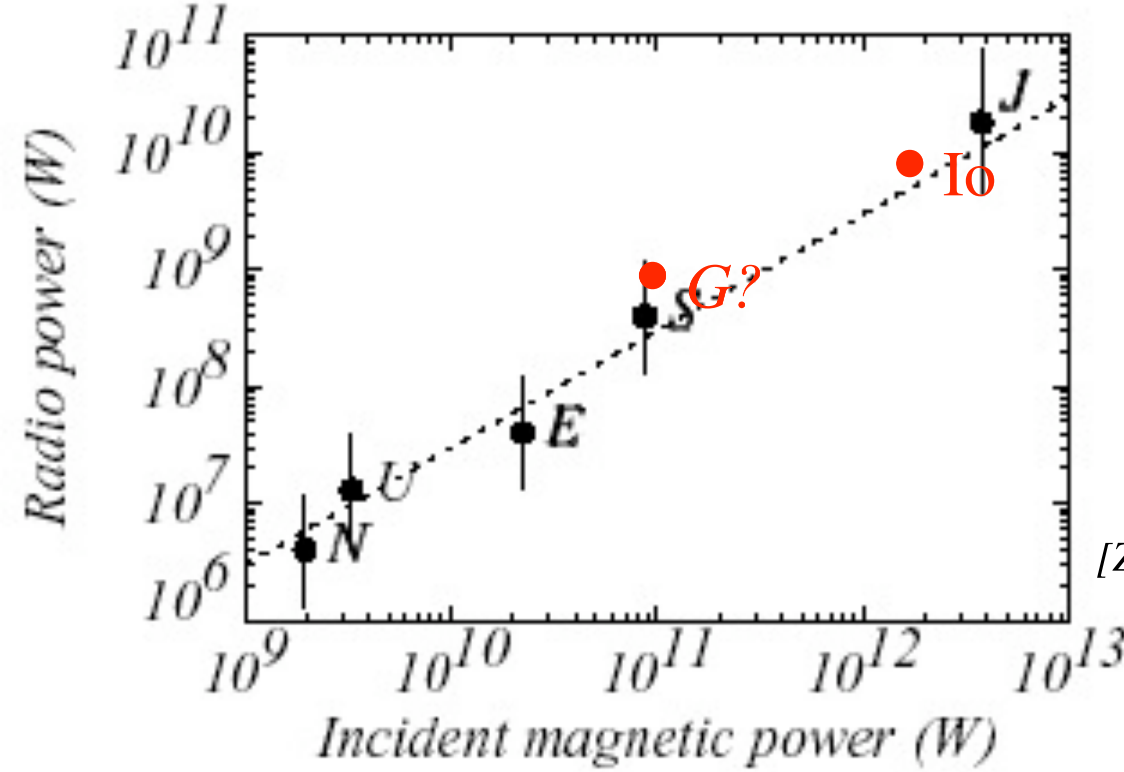
Table 2: Radiated power of auroral radio emissions, incident solar wind power on magnetosphere, and corresponding efficiencies.

	Earth (auroral)	Jupiter (auroral)		Saturn (auroral)	Uranus (auroral)	Neptune (auroral)
Name of radio component	TKR	*HOM*	DAM	SKR	UKR	NKR
Average radio power P_r (W)	4×10^{7}	$\mathit{9\times10^{9}}$	4×10^{10}	4×10^{8}	1.3×10^{7}	4×10^{6}
Planetary radius R_p (km)	6378	*71400*	71400	60330	26200	24760
Orbital radius (AU)	1.	*5.2*	5.2	9.6	19.2	30.1
Magnetic dipole moment ($G.R_p^3$)	0.31	*4.3*	4.3	0.21	0.23	0.14
Computed R_{mp} (R_p)	10	*43*	43	19	25	24
Measured R_{mp} (R_p)	10	*60*	60	20	18	23
Solar wind incident kinetic (ram) power P_{ram} (W)	9.6×10^{12}	$\mathit{1.6\times10^{15}}$	1.6×10^{15}	3.7×10^{13}	1.4×10^{12}	8.4×10^{11}
"radio-to-kinetic" efficiency α ($\times10^{-6}$)	4.2	*5.6*	25	10.8	9.2	4.8
"radio-to-magnetic" efficiency β ($\times10^{-3}$)	1.8	*2.4*	10.7	4.6	3.9	2.1

"magnetic" radio scaling law

$$P_{radio} \propto P_{IMF} = (B_\perp^2/2\mu_o)\, V\, \pi R_{obs}^2$$

⇒ >99% correlation, slope ~1, ∝ ~3×10^{-3} (in SW magnetic energy density = kinetic / 400, both vary in d^{-2} beyond ~1 AU)



[Zarka et al., 2001]

- Io (and Ganymede?) fit well, considering Jovian magnetospheric incident magnetic power ! (NB: dissipated power of Io-Jupiter electrodynamic circuit ~magnetic energy flux on obstacle)

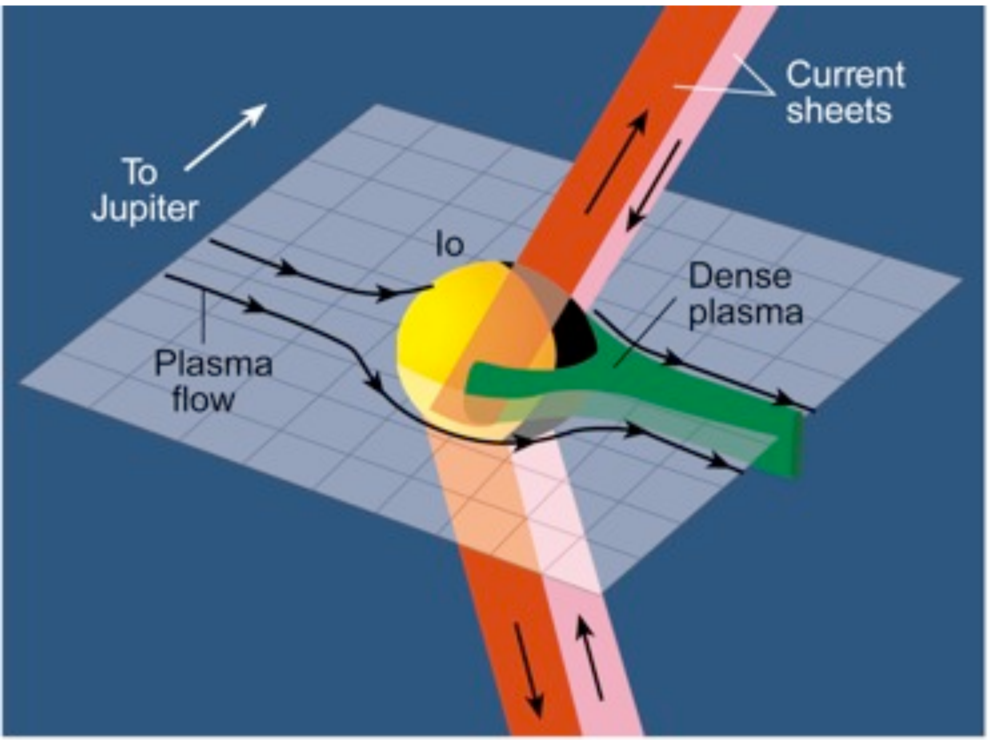
Generalization : α ?

• Auroral radio emissions driven by Solar Wind / Magnetosphere interaction

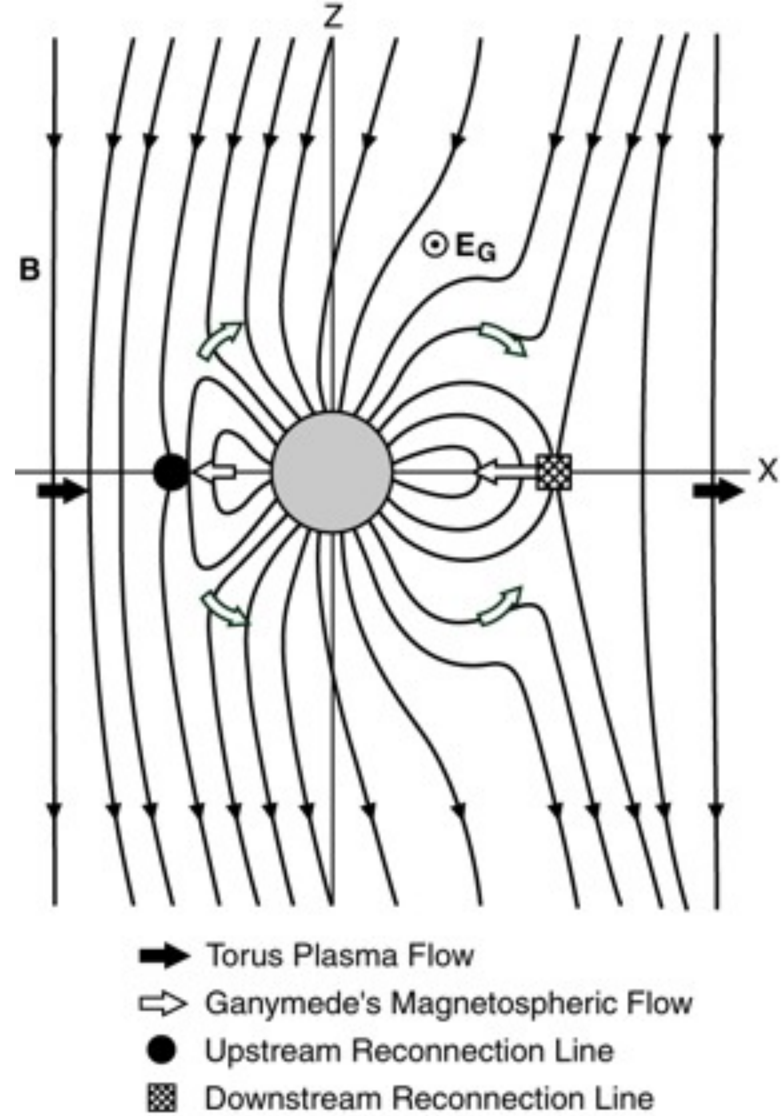
• Satellite induced radio emission(s) driven by Magnetosphere / Satellite interaction

⇒ in both cases → flow-obstacle interaction → keV e- → cyclotron radio emission near magnetized body

• In spite of complex chain of processes, existence of scaling laws in our solar system :

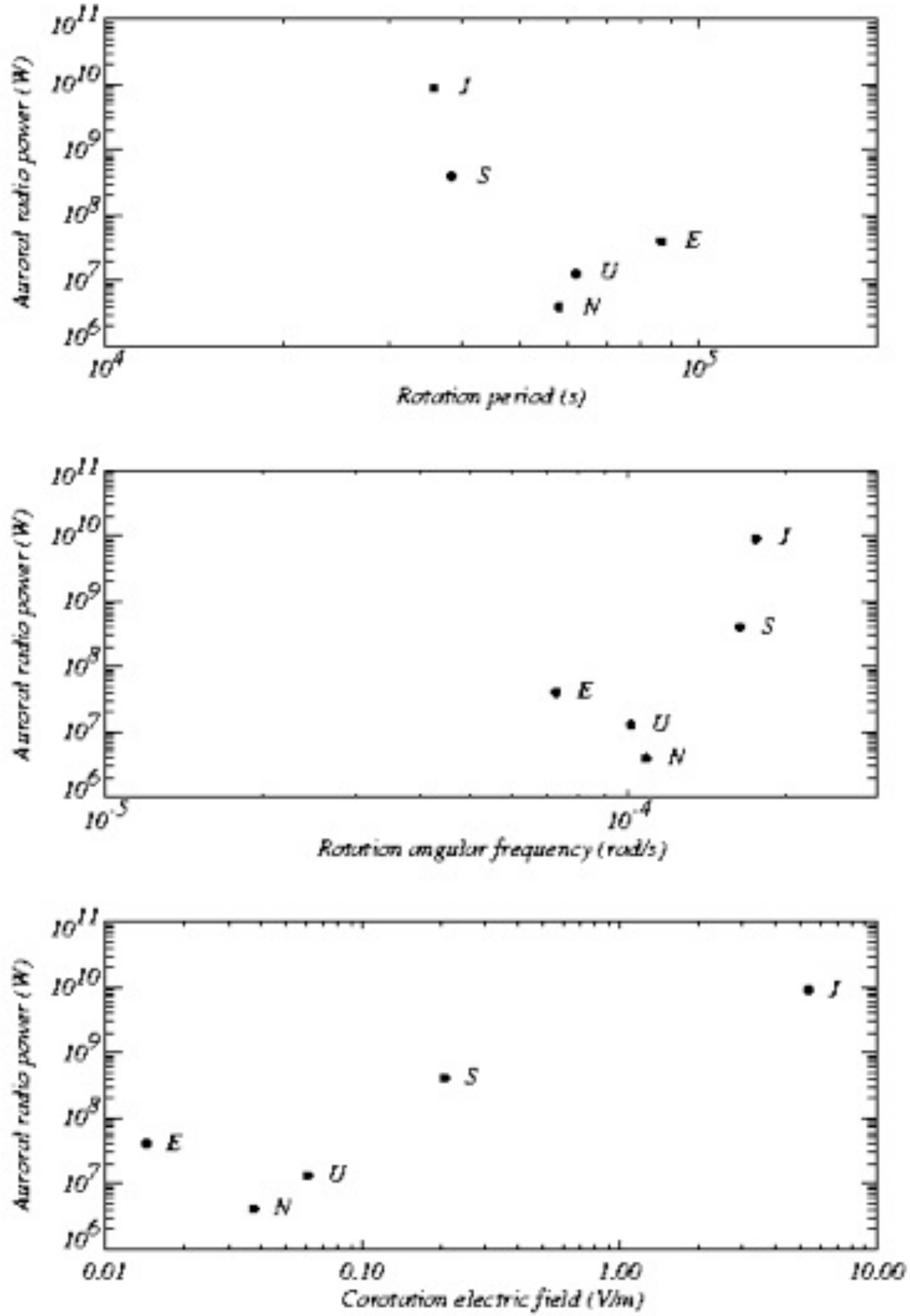


Io-Jupiter : Alfvèn waves

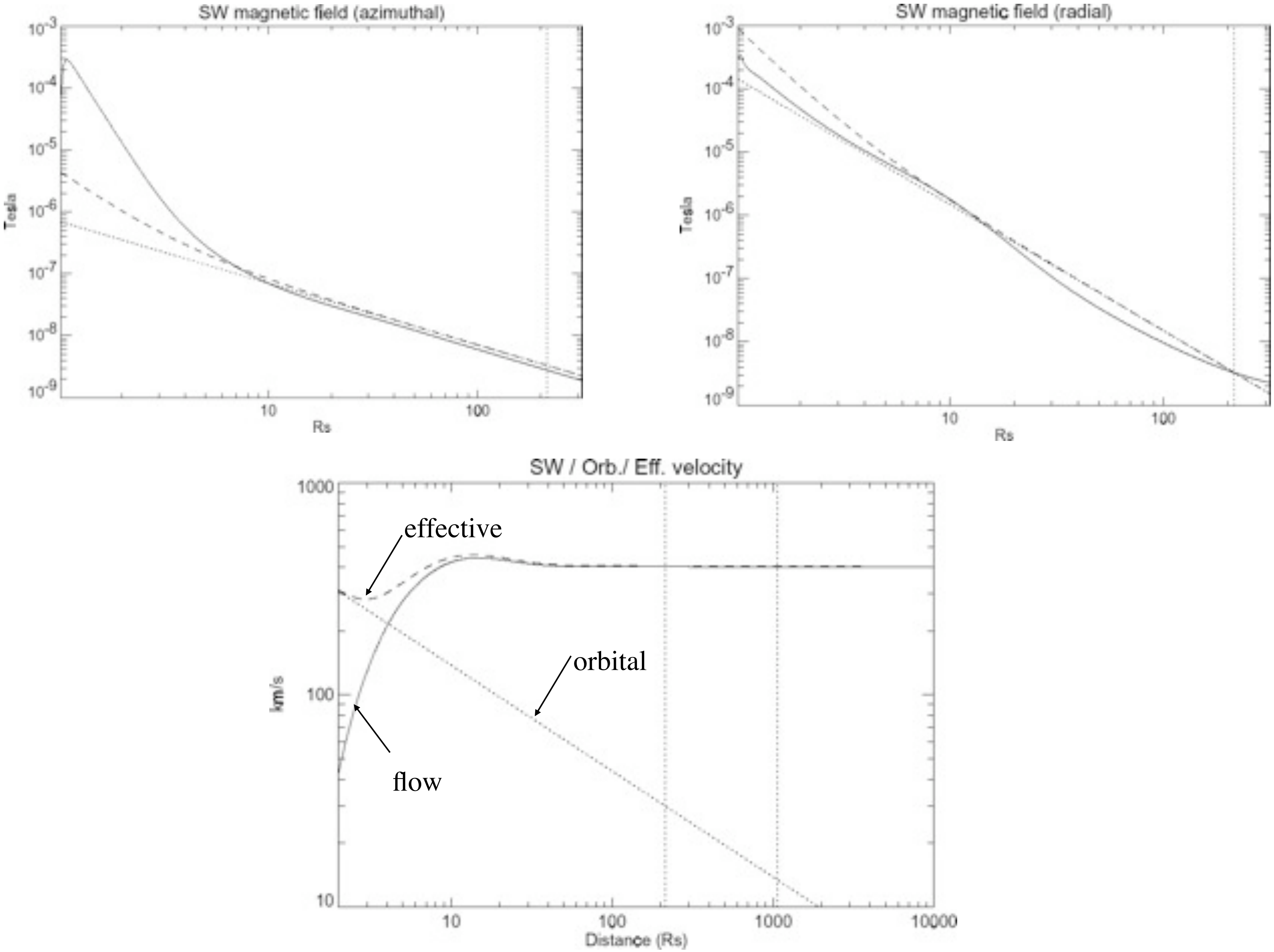


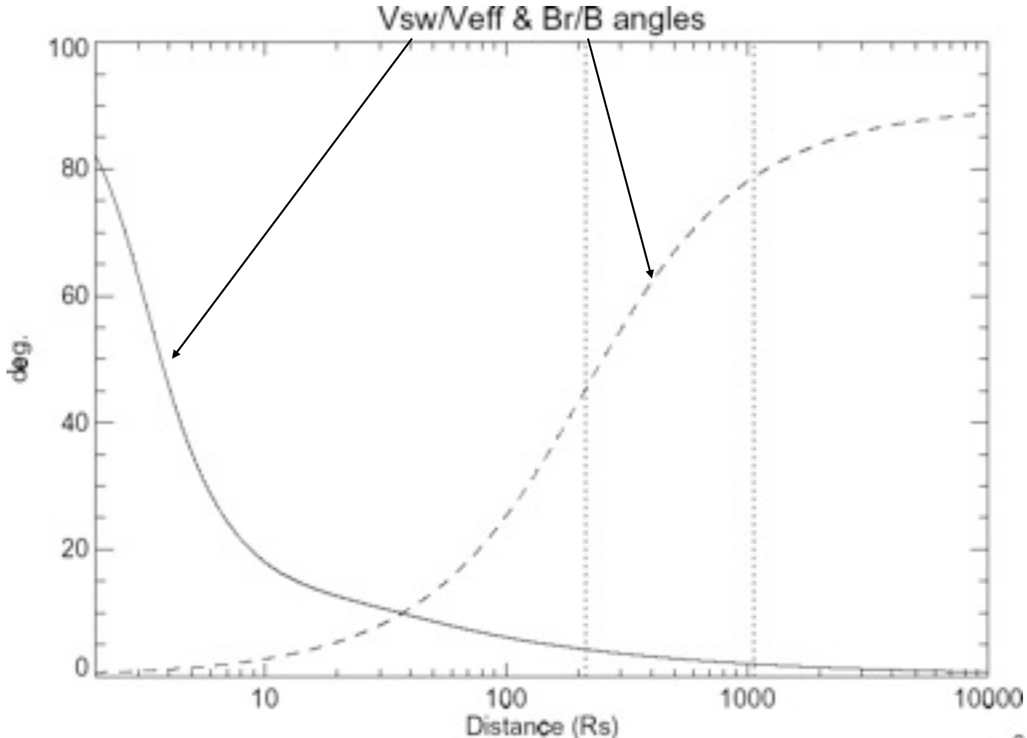
Ganymede-Jupiter : magnetic reconnection

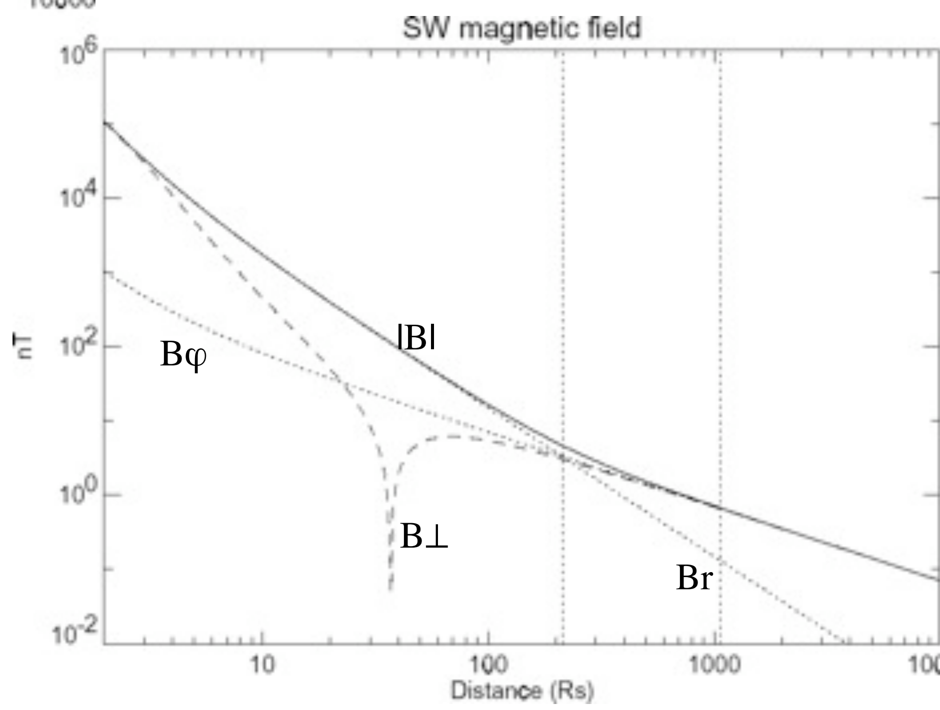
• No correlation between Radio power and rotation



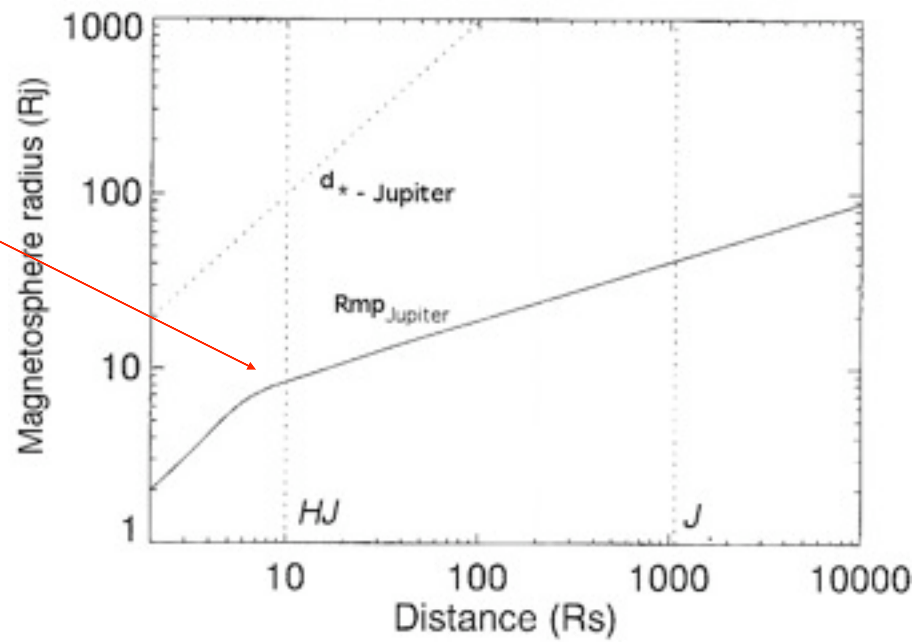
Extrapolation of kinetic and magnetic radio scaling laws

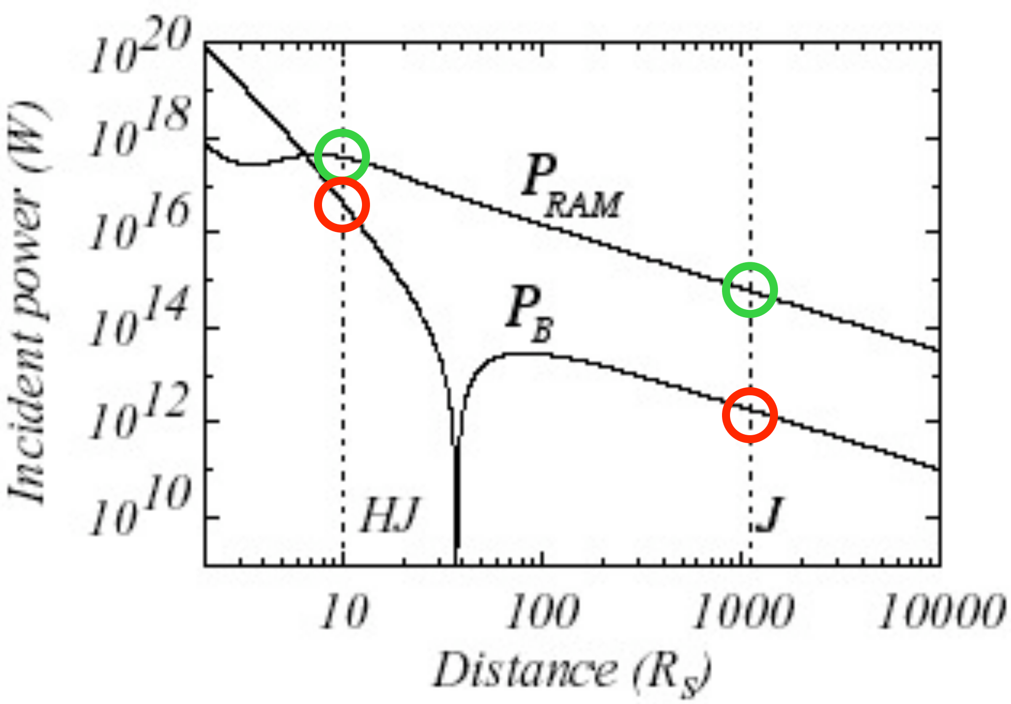



Vsw/Veff & Br/B angles
deg.
Distance (Rs)


SW magnetic field
nT
|B|
Bφ
B⊥
Br
Distance (Rs)

• magnetospheric shrinking





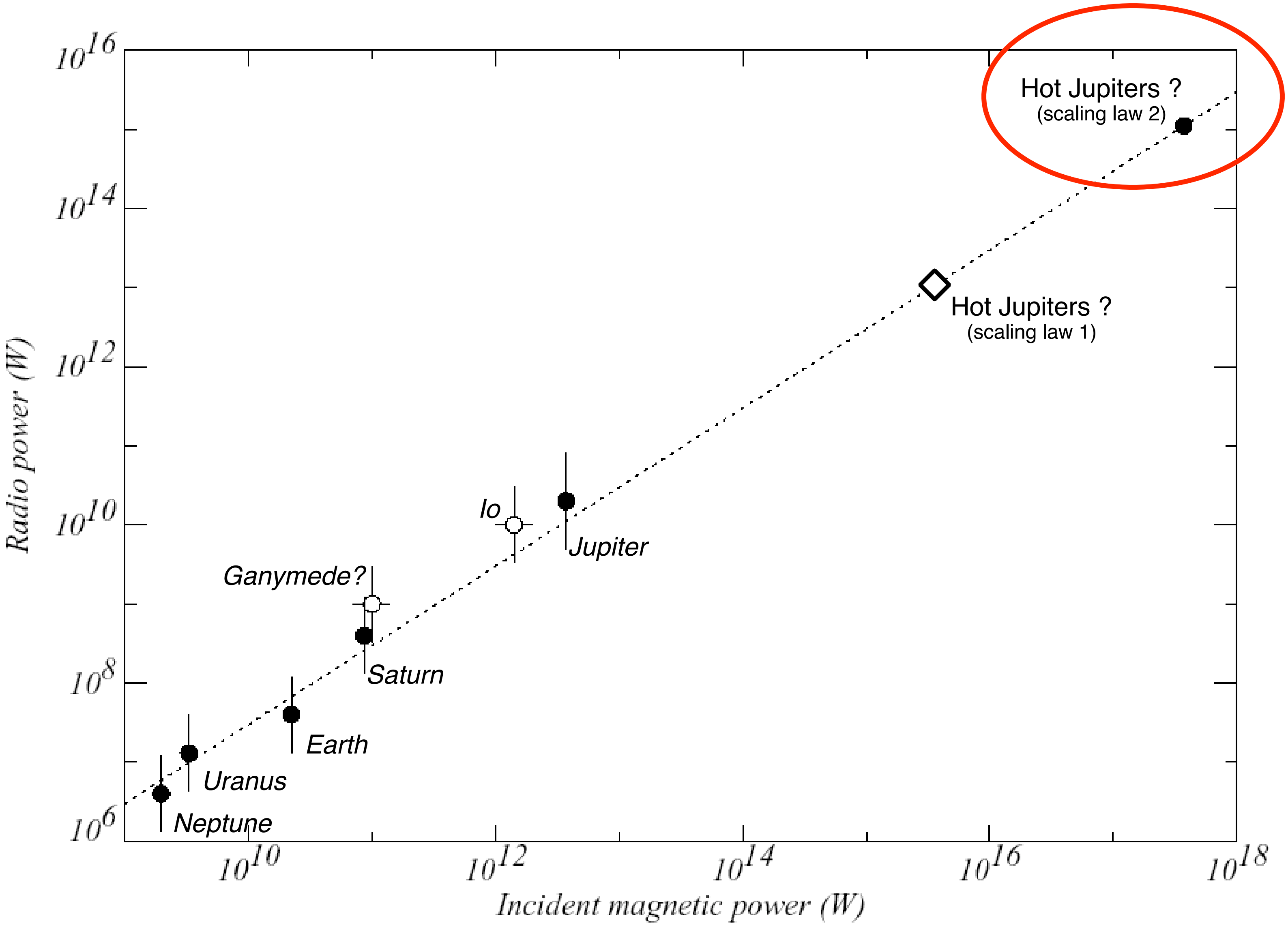
• **increased power for Hot Jupiters**

⇒ 10^3 × to

10^5 × Jupiter's flux

- same for radio flux ?

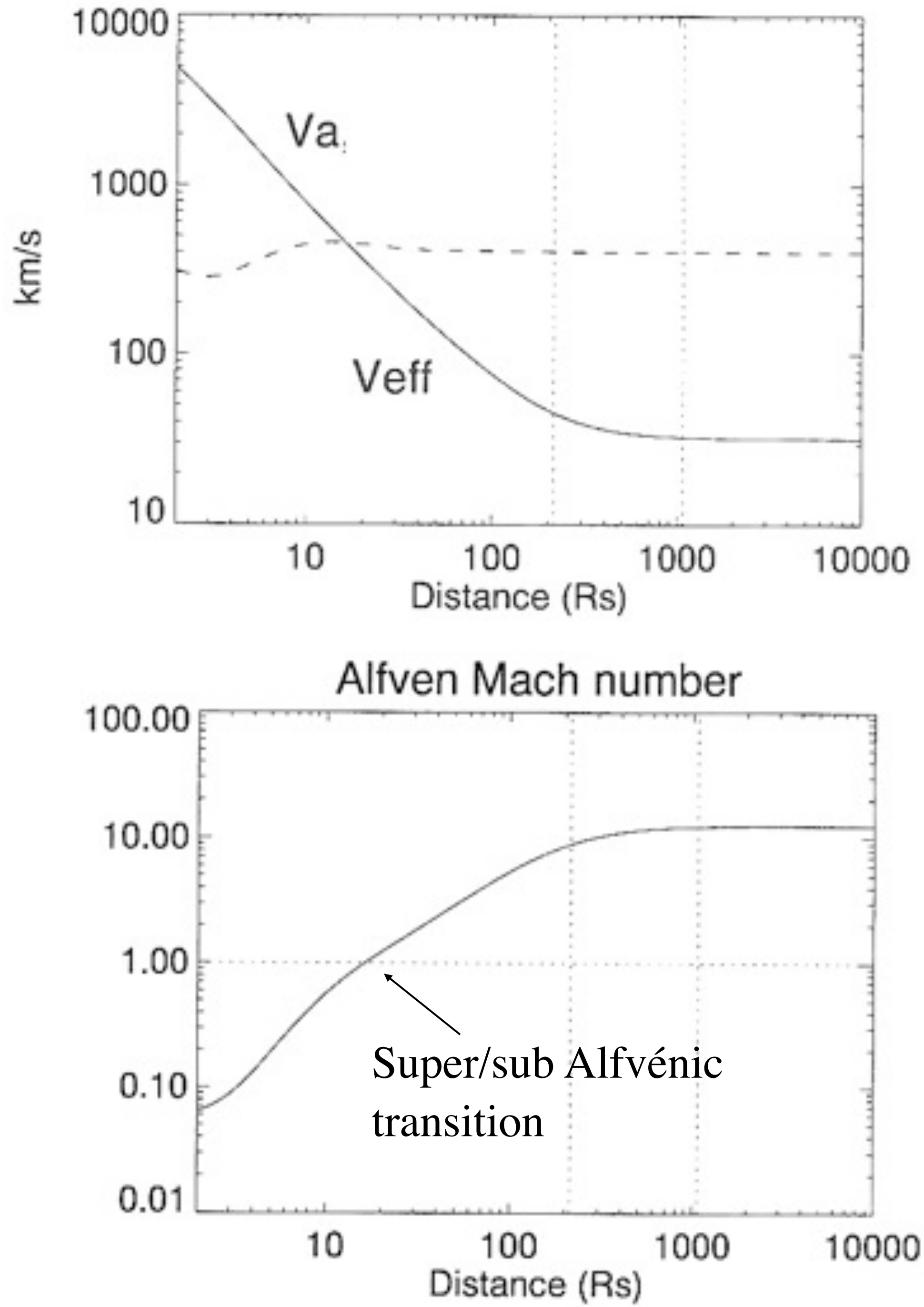
  except if unexpected "saturation" mechanism



If planet not magnetized ?

• HJ in sub/trans-Alfvénic regime

⇒ giant analogous of Io(planet)-Jupiter(star) interaction ?



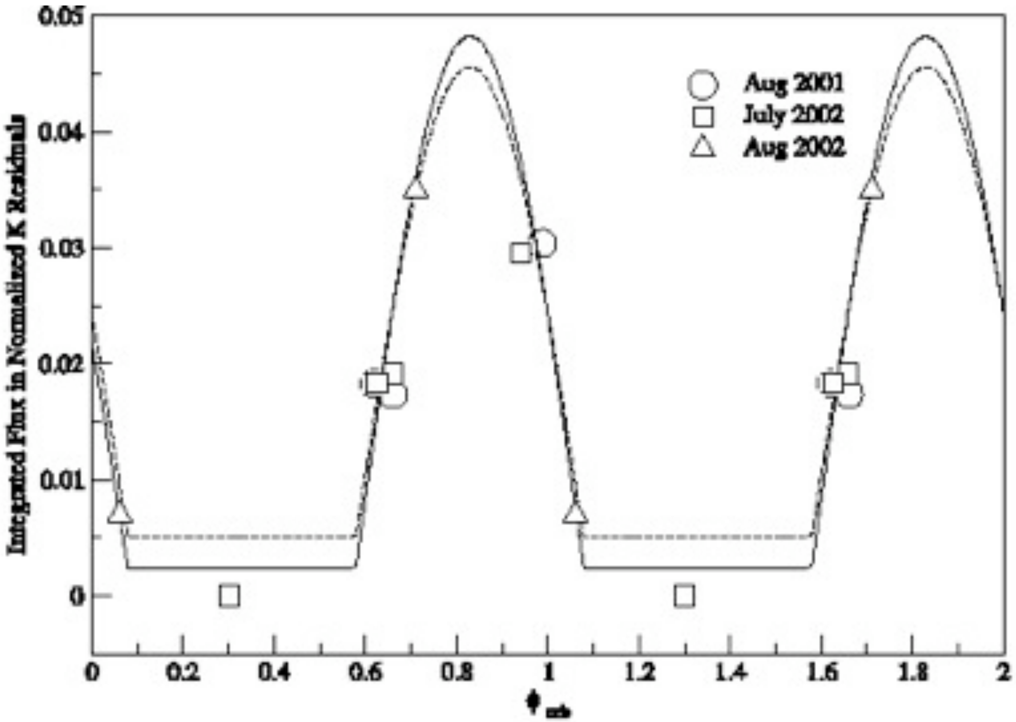
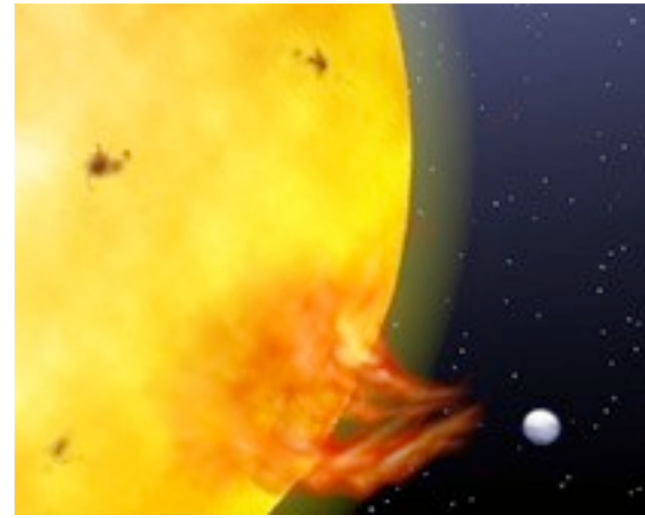
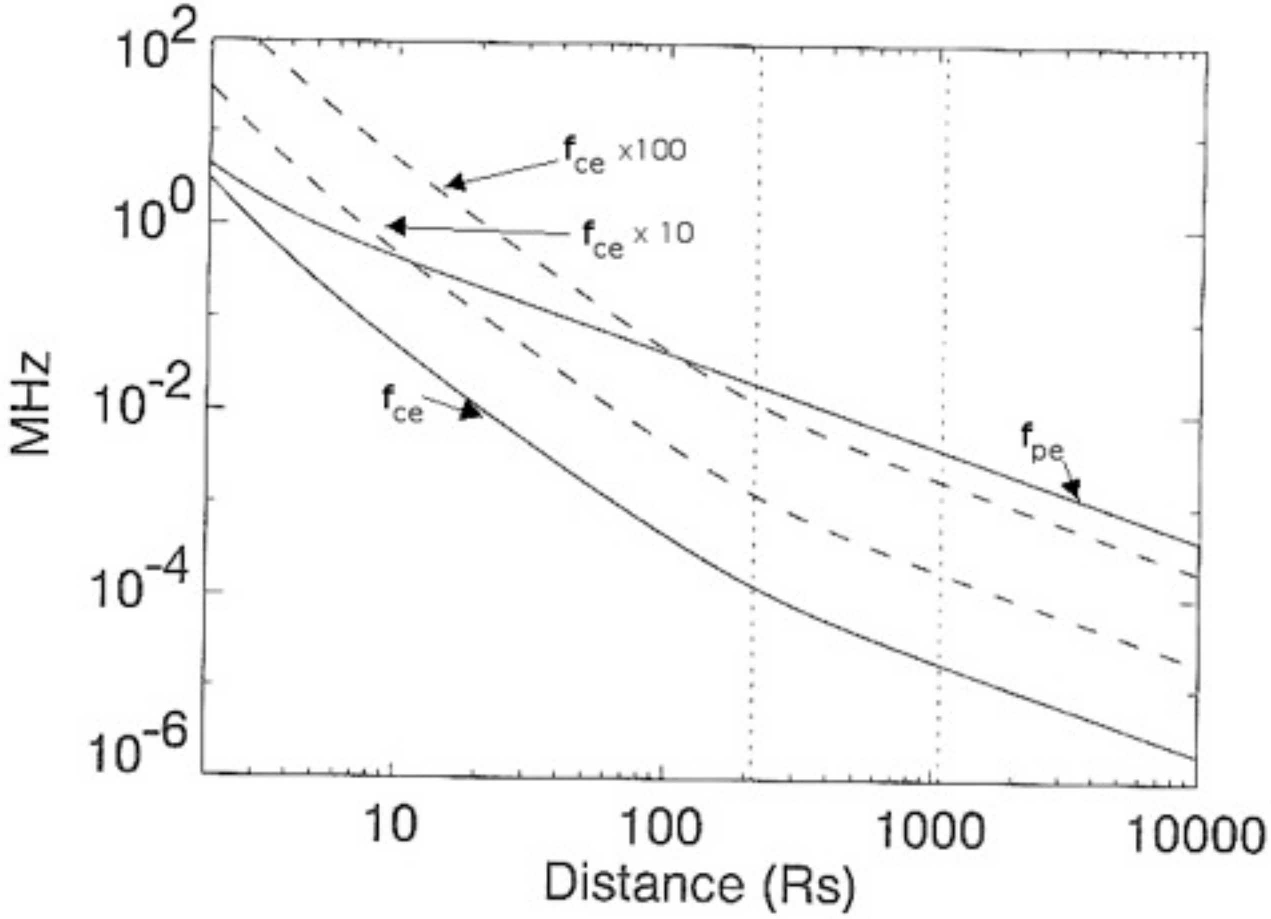


FIG. 6.—Integrated flux of the nine K-line residuals taken from a normalized mean spectrum. The minimum flux was set to zero and all others scaled accordingly. The size of the points is the size of the error bars. The solid line is the best-fit bright-spot model discussed in the text with the spot at a latitude of 30° and stellar inclination angle $i = 87°$. The dashed line is a model with $i = 83°$. Units of the integrated flux are in equivalent angstroms relative to the normalization level, which is approximately 1/3 of the stellar continuum.



[Shkolnik et al., 2003]

• but f_{pe}/f_{ce} in solar corona not favourable to Cyclotron Maser Instability except in strongly magnetized regions (loops …)



⇒ exoplanetary driver of strongly magnetic radio flaring stars ? (check for periodicities !)

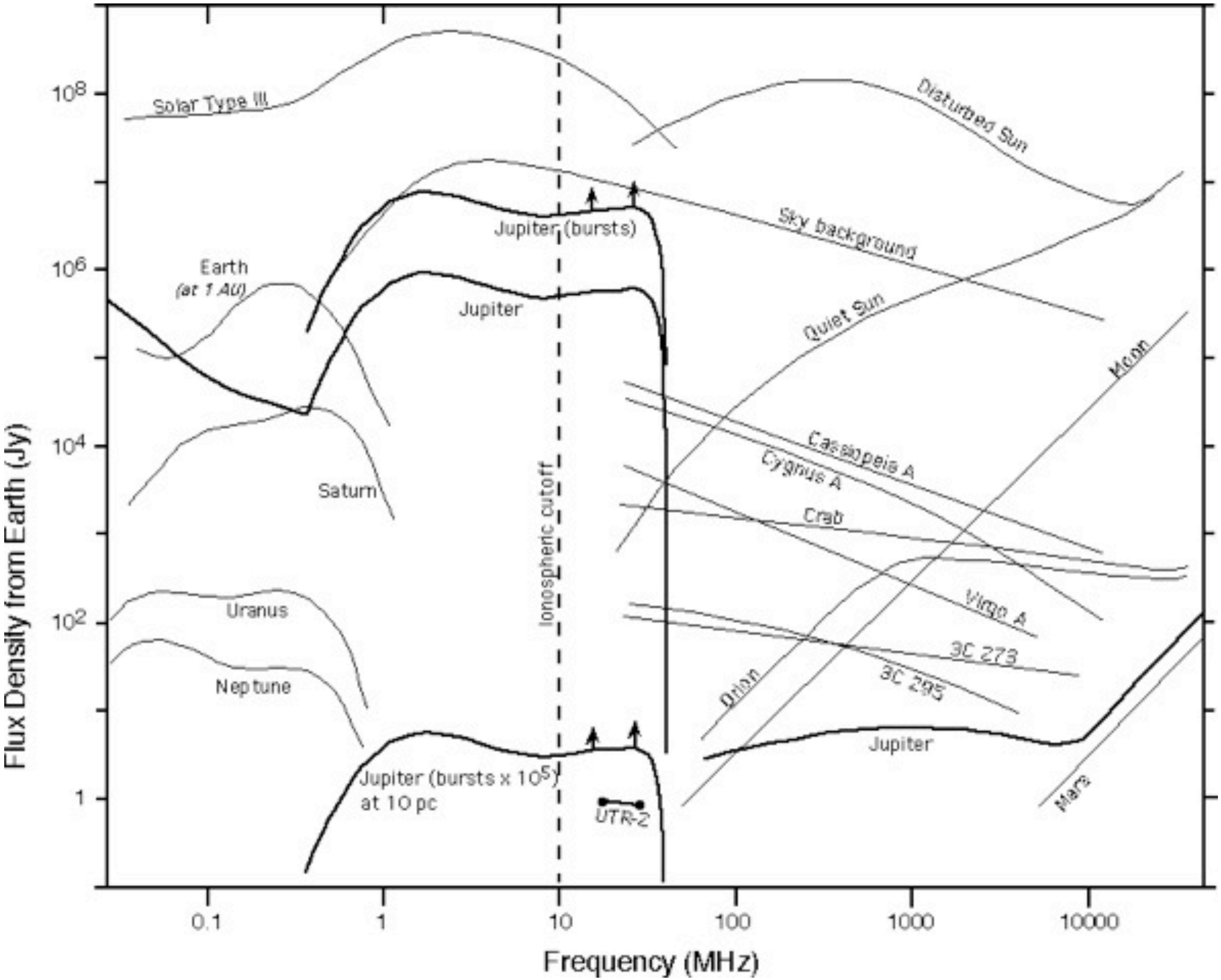
- Maximum distance of detectability : Hot Jupiters

$\Rightarrow$ for $\alpha = 10^5$

	$b\,\tau = 10^6$ (1 MHz, 1 sec)	$b\,\tau = 2\times10^8$ (3 MHz, 1 min)	$b\,\tau = 4\times10^{10}$ (10 MHz, 1 hr)
$A_e = 10^4$ m^2 (Nançay)	**4**	**16**	**54**
$A_e = 10^5$ m^2 (Kharkov)	**13**	**47**	**174**
$A_e = 10^6$ m^2 (LOFAR)	**41**	**158**	**537**

\+ Stellar type $\Rightarrow$ P_{SW} up to $\times 10^{2\text{-}3}$

\+ Scintillations $\Rightarrow$ P_{radio} up to $\times 10^2$



Flux Density from Earth (Jy)
Frequency (MHz)
10^8
10^6
10^4
10^2
1
0.1
1
10
100
1000
10000
Solar Type III
Disturbed Sun
Sky background
Jupiter (bursts)
Earth
(at 1 AU)
Jupiter
Quiet Sun
Moon
Cassiopeia A
Cygnus A
Crab
Saturn
Ionospheric cutoff
Uranus
Neptune
Virgo A
3C 273
3C 295
Orion
Jupiter
Jupiter (bursts x 10^5)
at 10 pc
UTR-2
Mars

• *Extrapolation of kinetic radio scaling law to a dozen HJ*

+ heuristic scaling law for planetary magnetic fields

("Blackett-like" : $M \propto m^{1-2.5}\ \omega^{0.5-1}$ ω = 10-100 hours)

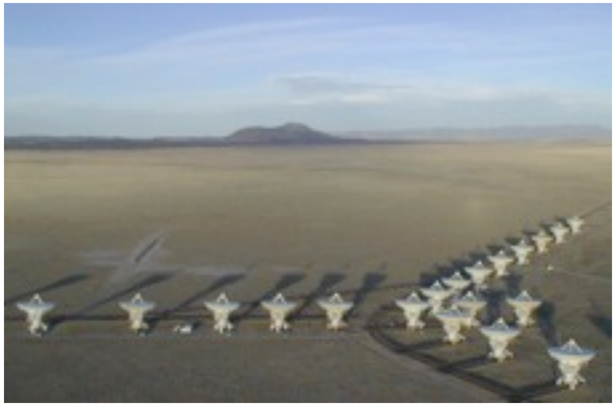
$\Rightarrow$ *estimates of f_{ce} and radio flux*

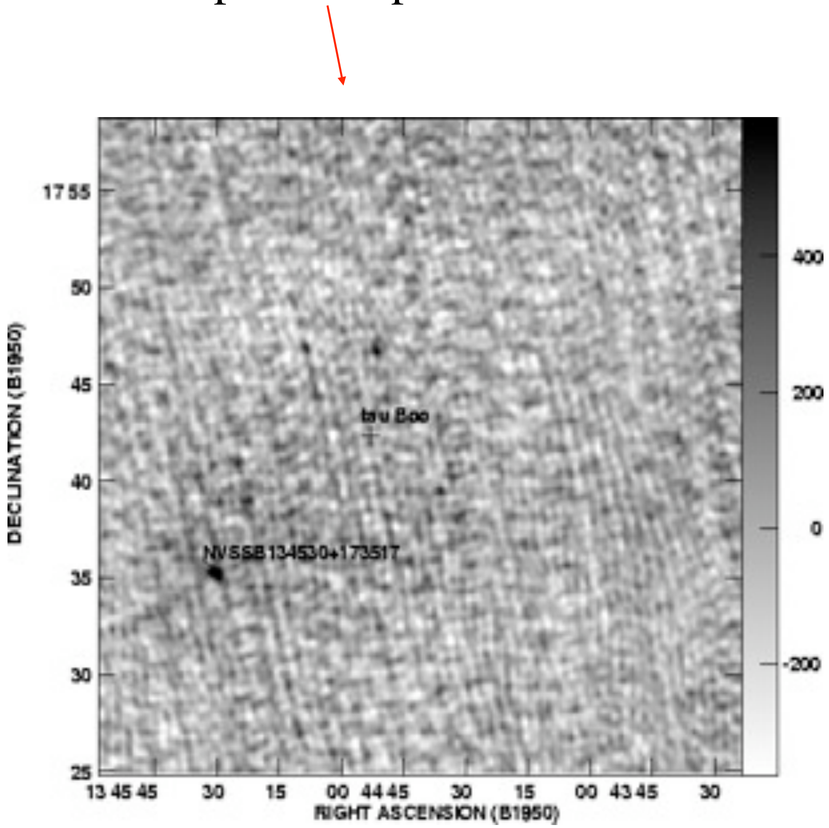
$\Rightarrow$ *Tau Bootes best "high frequency" candidate*

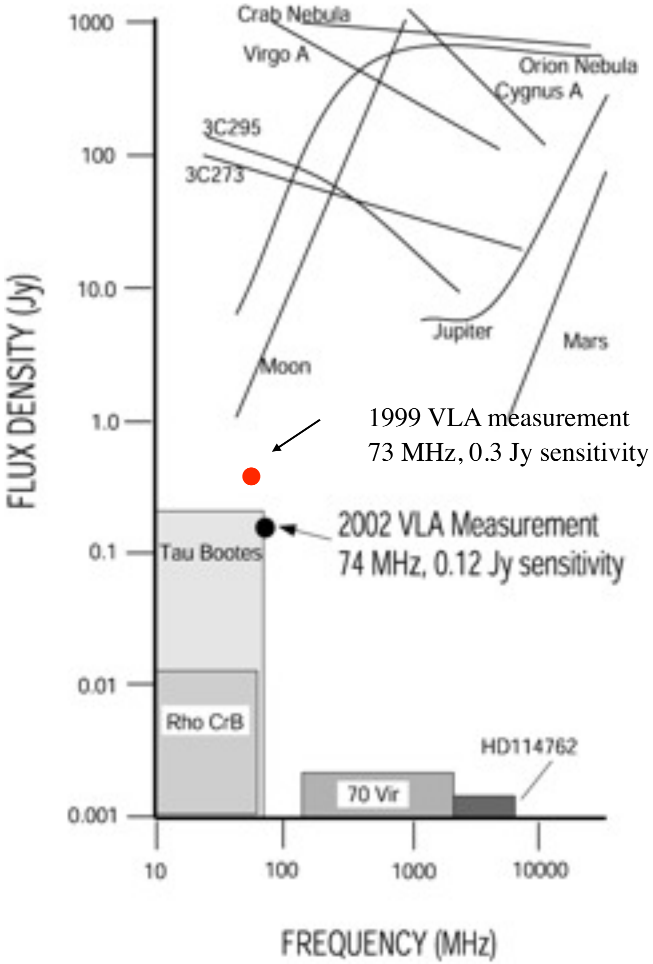
	mj	d (AU)	2π/ω (hr)	s (ly)	fc (MHz)	Radio Power (W)	S (milliJy)
51 Peg	0.47	0.05	101	50	0.7	1×10^{11}	0.012
						4×10^{13}	3.9
υ And	0.68	0.06	110	54	1.1	1×10^{11}	0.007
						5×10^{13}	2.4
55 Cnc	0.84	0.1	351	44	0.5	4×10^{10}	0.007
						8×10^{12}	1.5
ρ CrB	1.1	0.2	10	54	27	2×10^{11}	3×10^{-4}
						6×10^{13}	0.13
16CygB	1.5	1.72	10	72	46	2×10^{10}	2×10^{-5}
						4×10^{12}	0.003
47 UrMaj	2.8	2.11	10	46	130	3×10^{10}	2×10^{-5}
						6×10^{12}	0.004
τ Bootes	3.9	0.05	79	49	28	1×10^{12}	0.003
						8×10^{14}	2.2
70 Vig	6.6	0.4	10	59	545	4×10^{11}	4×10^{-5}
						2×10^{14}	0.023
HD114762	10.0	0.3	10	91	1090	1×10^{12}	2×10^{-5}
						8×10^{14}	0.015

[Farrell et al., 1999]

- Observations of Tau Bootes with the VLA
  - → 27 × 25m antennas : A_{eff} ~ 13000 m^2
  - → ≤1.5 MHz band at 73-74 MHz
  - → ≥0.4' beam
  - → 2 polar
  - → spatial maps







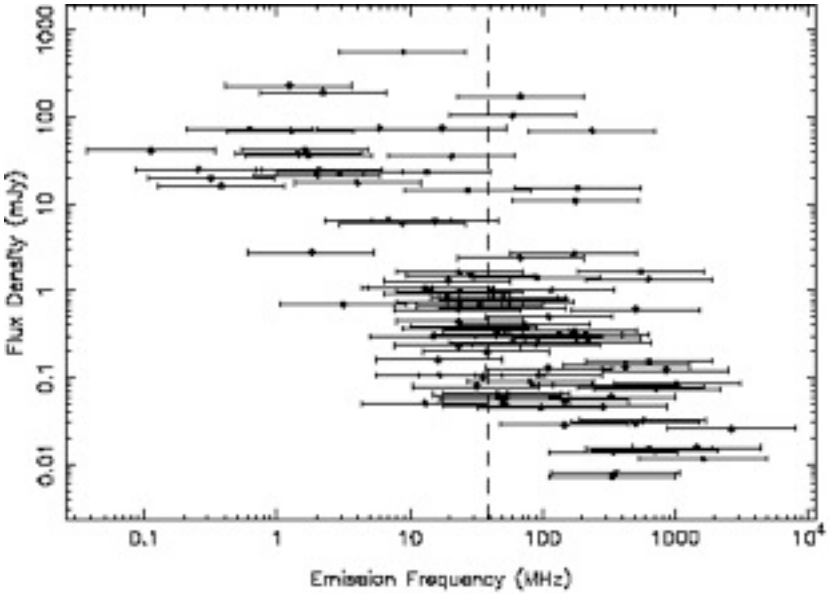


Fig. 1.— The predicted "burst" flux densities for the 106 known extrasolar planets vs. the characteristic emission frequency based on the radiometric Bode's law of equations (3) and (4). The horizontal bars indicate the assumed ranges for the emission frequencies, allowing for the statistical variations in the planetary magnetic moments. The expected *burst* flux densities are obtained by assuming that increases of roughly a factor of 100 can be obtained by larger stellar wind loading of the planet's magnetosphere. The vertical dashed line indicates the approximate cutoff frequency for Jupiter.

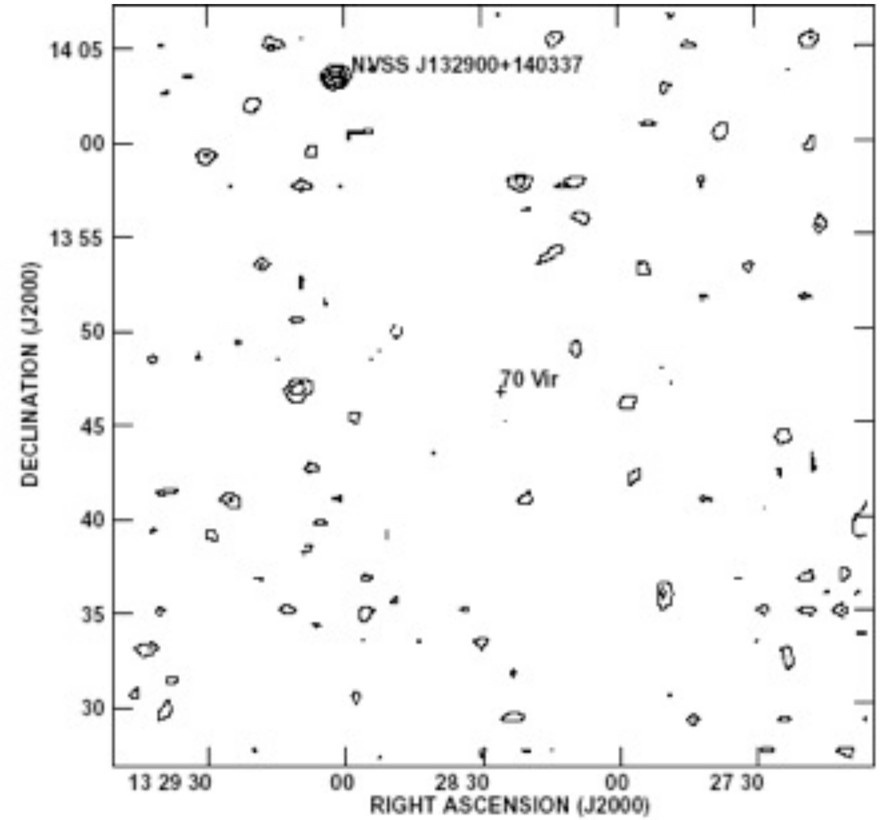


Fig. 2.— The field around 70 Vir at 74 MHz, illustrating the typical field observed. The noise level is 0.13 Jy beam^{-1}, with a $25'' \times 25''$ beam. The contours are 0.13 Jy $\text{beam}^{-1} \times -3, 2, 3, 4, 5, 7.07$, and 10. The position of 70 Vir is marked by a cross. Also indicated is the radio source NVSS J132900+140337, likely to be an extragalactic radio source.

[Lazio et al., 2003]

- **LOFAR : the LOw Frequency ARray**

→ Interferometer of phased arrays

→ $A_e \sim 10^6$ m^2 (250 000 m^2 "core" + ~100 "stations")

→ wide-field (a few °s) imagery with 1"-10" angular resolution

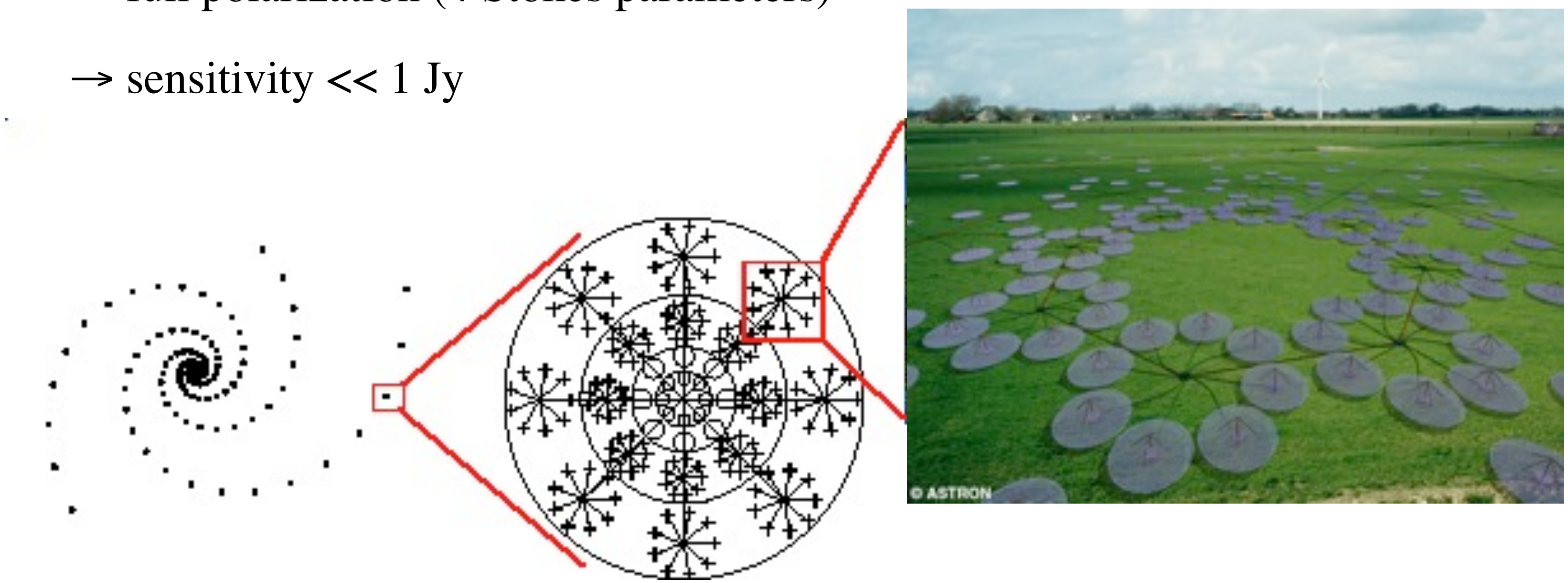
→ 32 MHz ⊂ 10-220 MHz

→ fully digital, resolutions down to 1 kHz × 1 msec / spectral maps

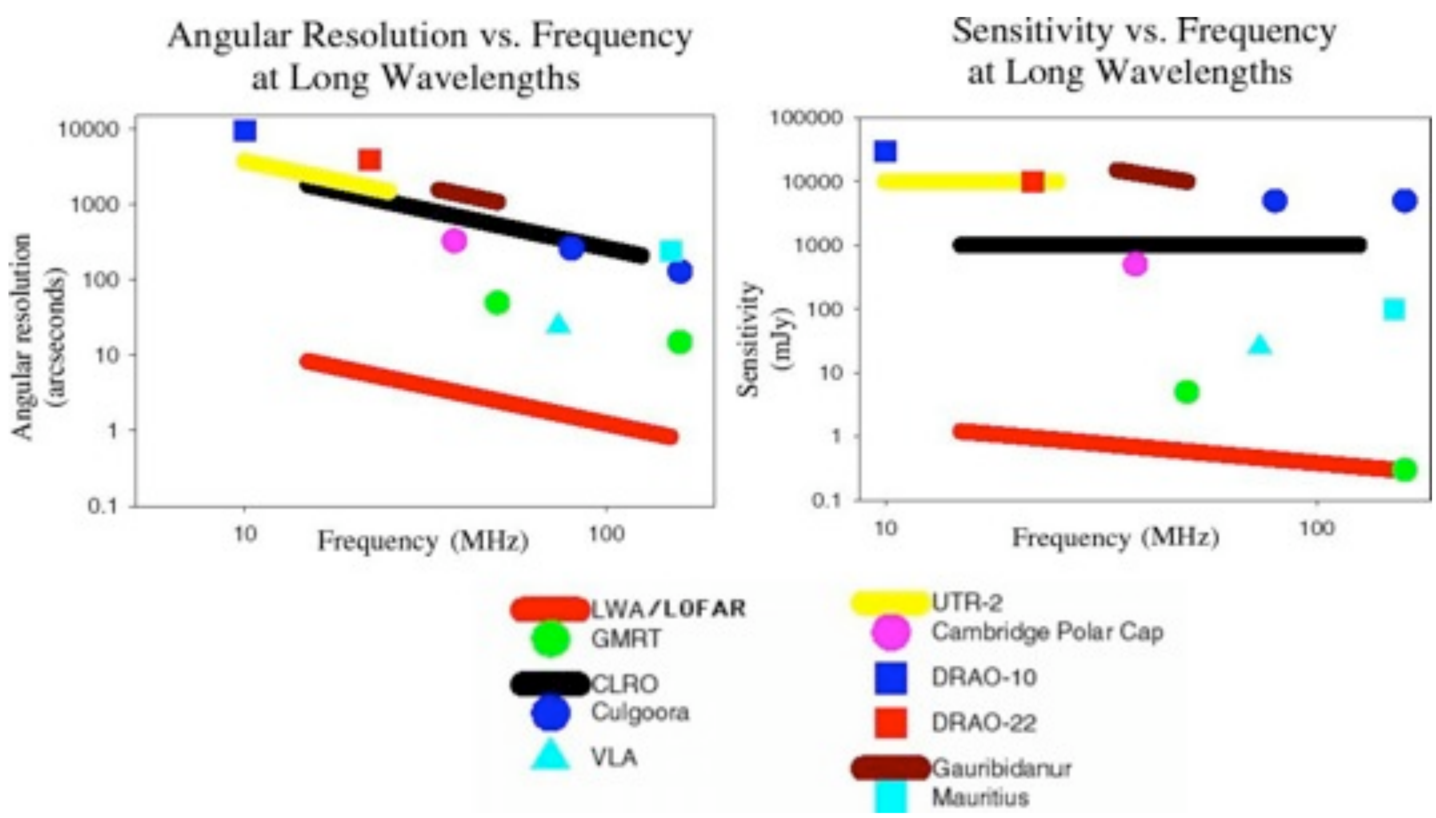
→ multi beam (up to 8 simultaneously)

→ full polarization (4 Stokes parameters)

→ sensitivity << 1 Jy



Frequency	Effective Area	Sensitivity (mJy/4 MHz)		Resolution		Beamsize	
(MHz)	(m2)	Array	VC	Array (”)	VC (’)	Array (’)	VC (°)
15	1.3×10^6	98	400	12	41	1260	90
30	3.3×10^5	68	280	6.2	21	650	90
75	5.2×10^4	46	190	2.5	8.3	250	90
120	3.3×10^5	2.4	10	1.5	5.2	160	23
200	1.2×10^5	2.2	9	0.9	3.1	95	23



• large dynamic range

• narrow beam ⇒ low "confusion"

• built-in RFI mitigation techniques + ionospheric correction

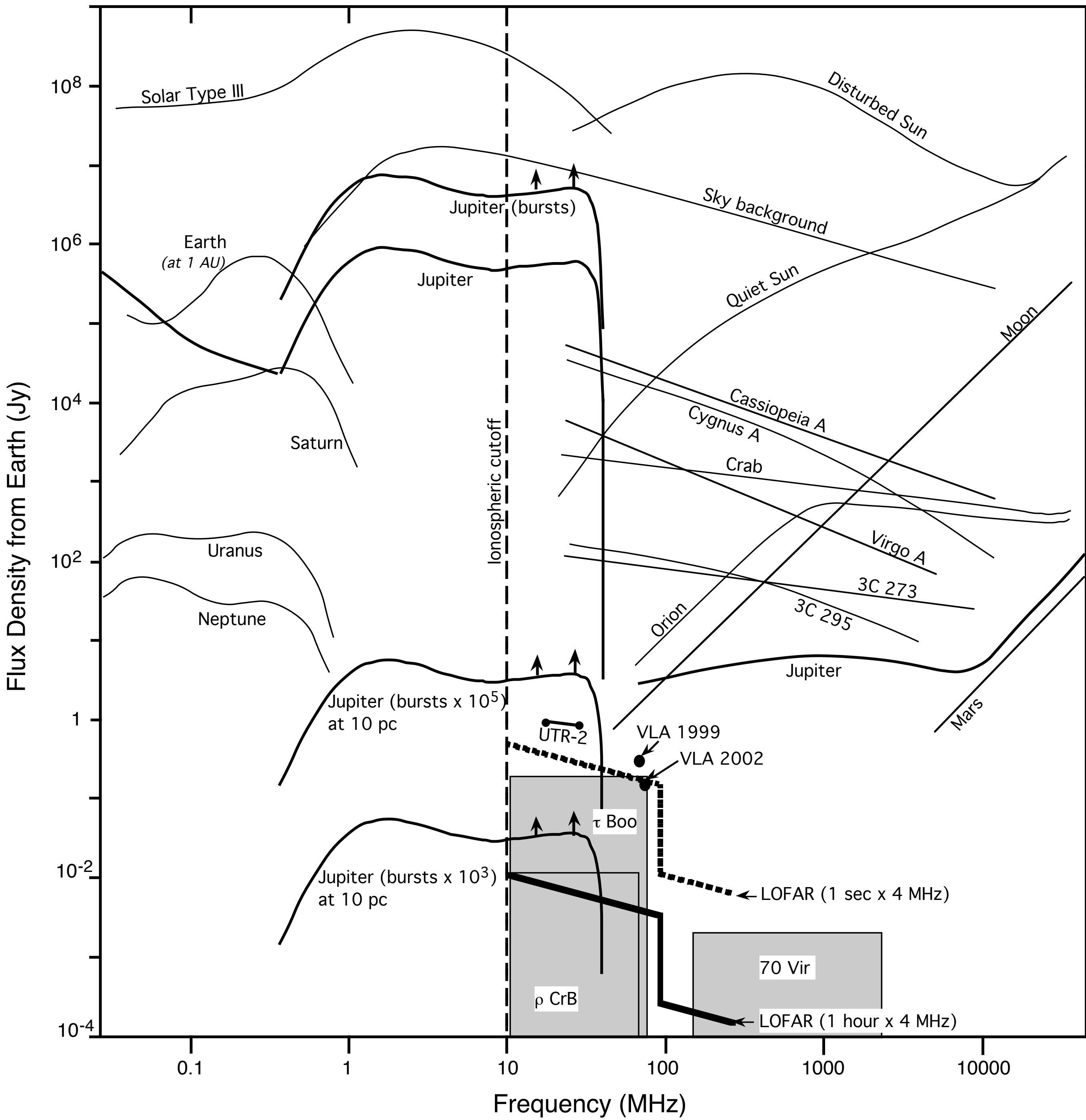
⇒ effective clean broad bandwidth & high sensitivity

• total flux detection of hot jupiters ⇒ polarization ?

• orbital motion through radio

astrometry ? ⇒ more distant planets

Operations will start in 2006-07 ...


Solar Type III
Disturbed Sun
Sky background
Jupiter (bursts)
Earth
(at 1 AU)
Jupiter
Quiet Sun
Moon
Saturn
Ionospheric cutoff
Cassiopeia A
Cygnus A
Crab
Virgo A
3C 273
3C 295
Orion
Uranus
Neptune
Jupiter
Mars
Jupiter (bursts x 10^5)
at 10 pc
UTR-2
VLA 1999
VLA 2002
τ Boo
Jupiter (bursts x 10^3)
at 10 pc
LOFAR (1 sec x 4 MHz)
70 Vir
ρ CrB
LOFAR (1 hour x 4 MHz)
Flux Density from Earth (Jy)
Frequency (MHz)
10^8
10^6
10^4
10^2
1
10^-2
10^-4
0.1
1
10
100
1000
10000

References

- W. M. Farrell, M. D. Desch, and P. Zarka : *On the possibility of coherent cyclotron emission from extrasolar planets,* J. Geophys. Res., 104, 14025-14032, **1999**.

- P. Zarka, 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**.

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with possible resign of 1/3 of all CNRS laboratory directors