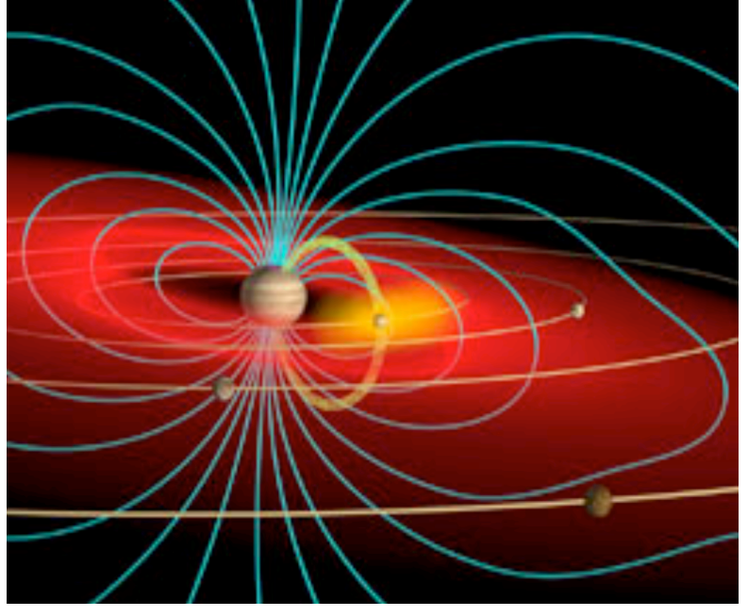

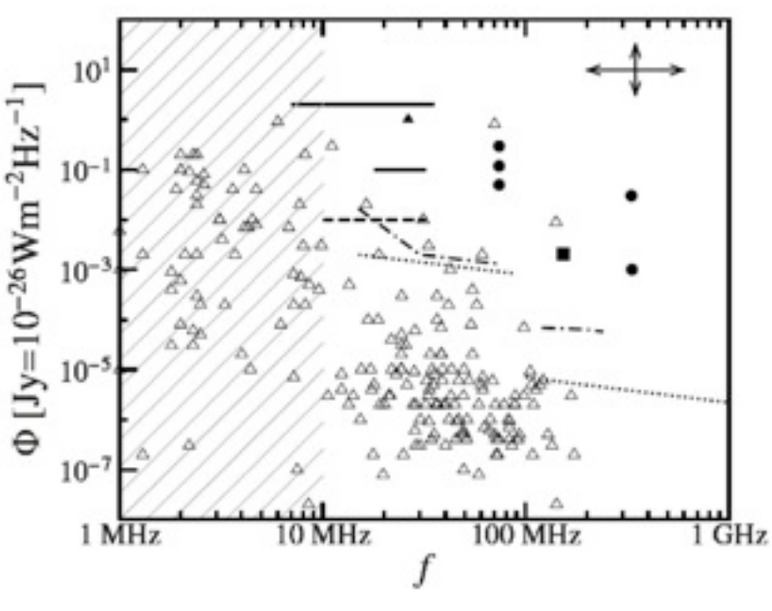

Planetary Science with LOFAR

and more

Philippe Zarka

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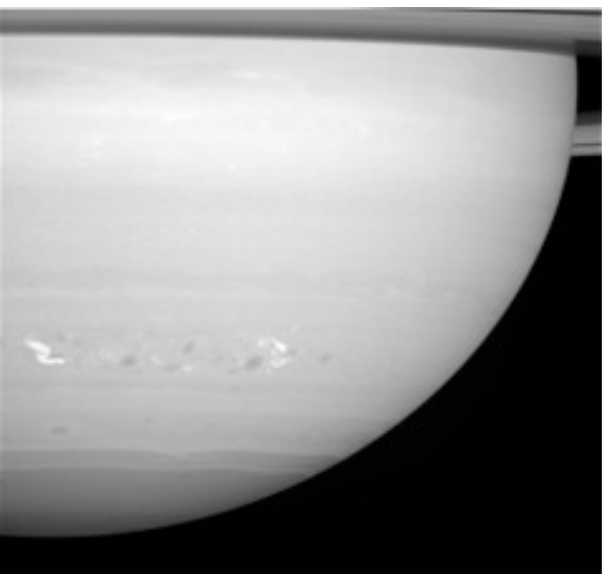
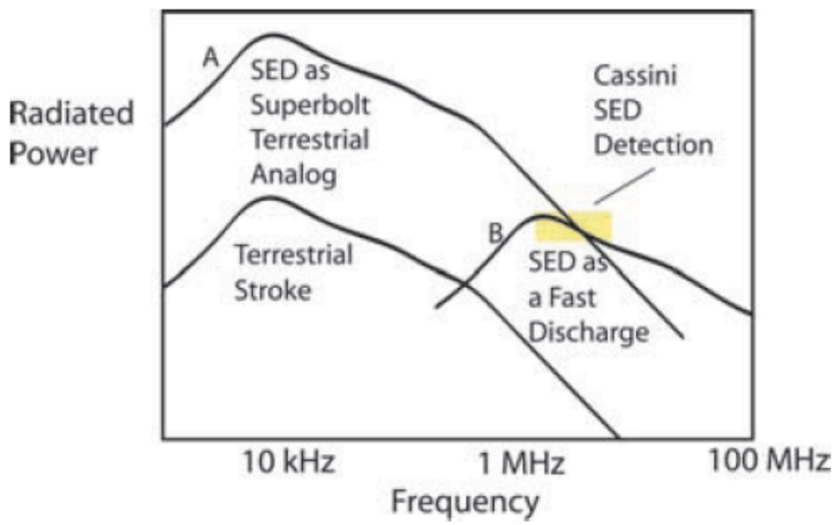
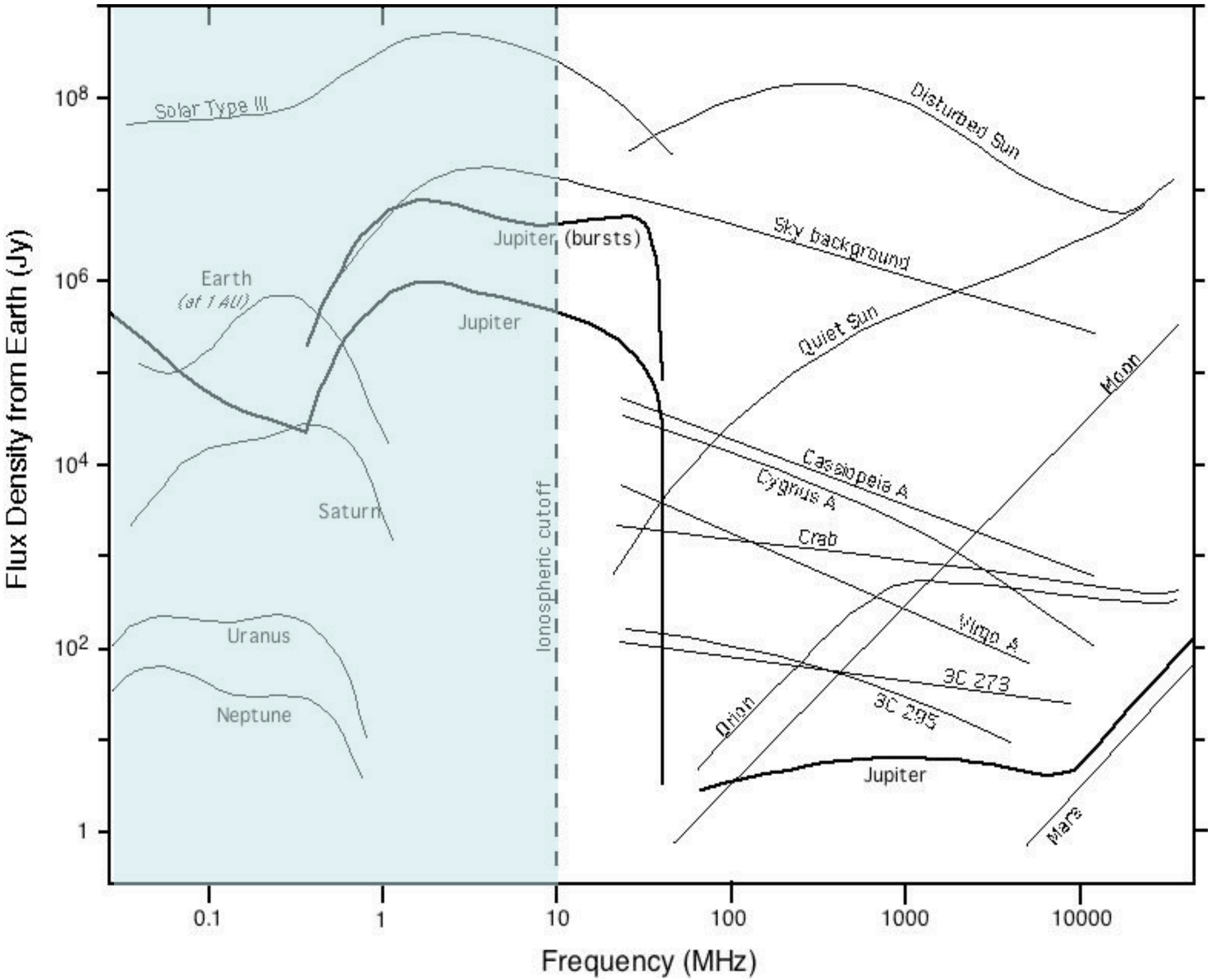
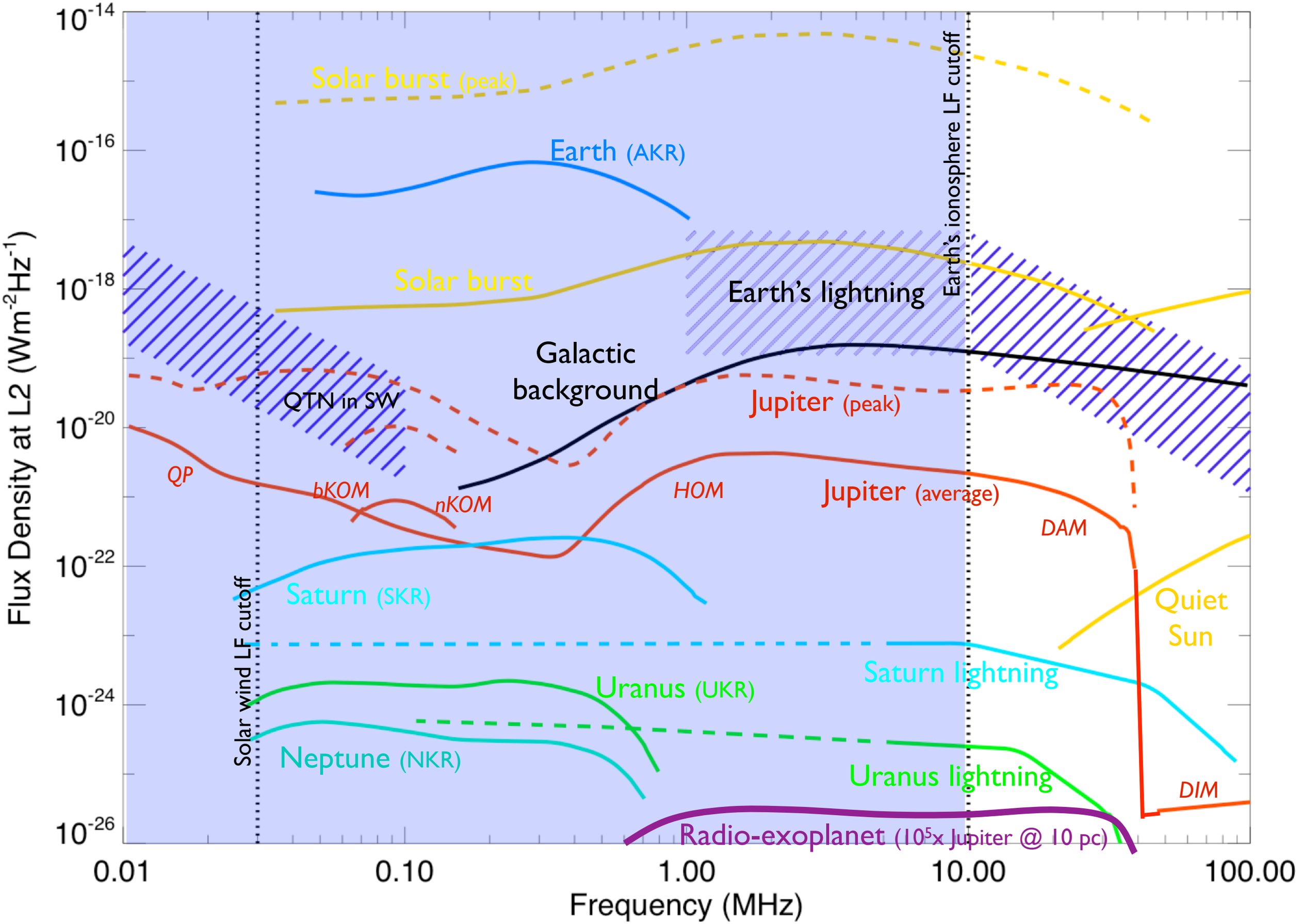




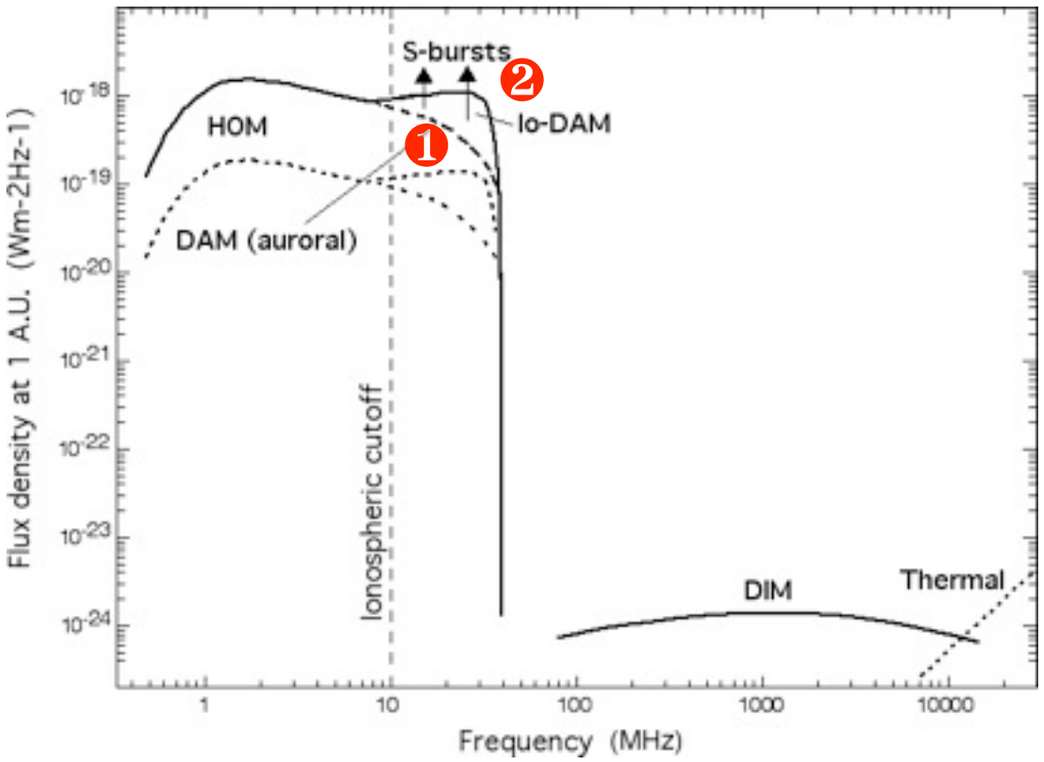

Flux Density from Earth (Jy)
10^8
10^6
10^4
10^2
1
Solar Type III
Disturbed Sun
Sky background
Jupiter (bursts)
Earth
(at 1 AU)
Jupiter
Quiet Sun
Moon
Cassiopeia A
Cygnus A
Crab
Saturn
Virgo A
3C 273
3C 295
Orion
Uranus
Neptune
Jupiter
Mars
Ionospheric cutoff
0.1
1
10
100
1000
10000
Frequency (MHz)

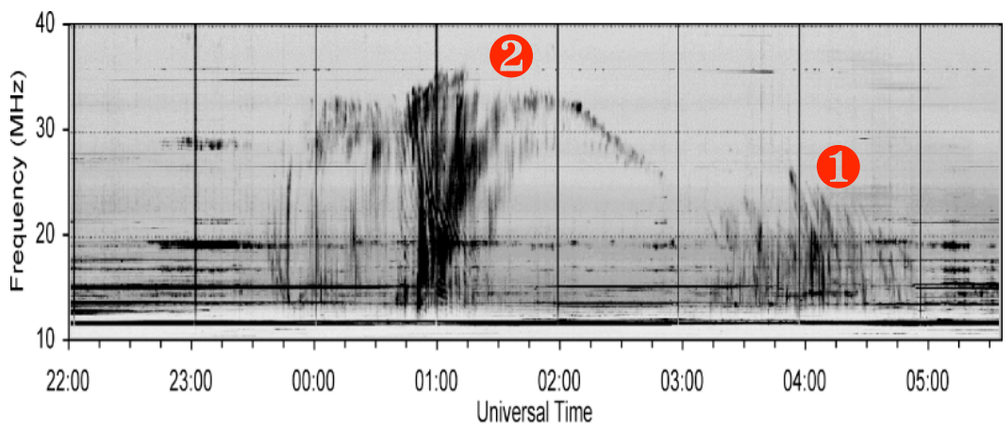

Flux Density at L2 (Wm^{-2}Hz^{-1})
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
0.01
0.10
1.00
10.00
100.00
Frequency (MHz)
Solar burst (peak)
Earth (AKR)
Solar burst
Earth's lightning
Earth's ionosphere LF cutoff
Galactic background
QTN in SW
Jupiter (peak)
QP
bKOM
nKOM
HOM
Jupiter (average)
DAM
Saturn (SKR)
Solar wind LF cutoff
Quiet Sun
Saturn lightning
Uranus (UKR)
Neptune (NKR)
Uranus lightning
DIM
Radio-exoplanet (10^5x Jupiter @ 10 pc)

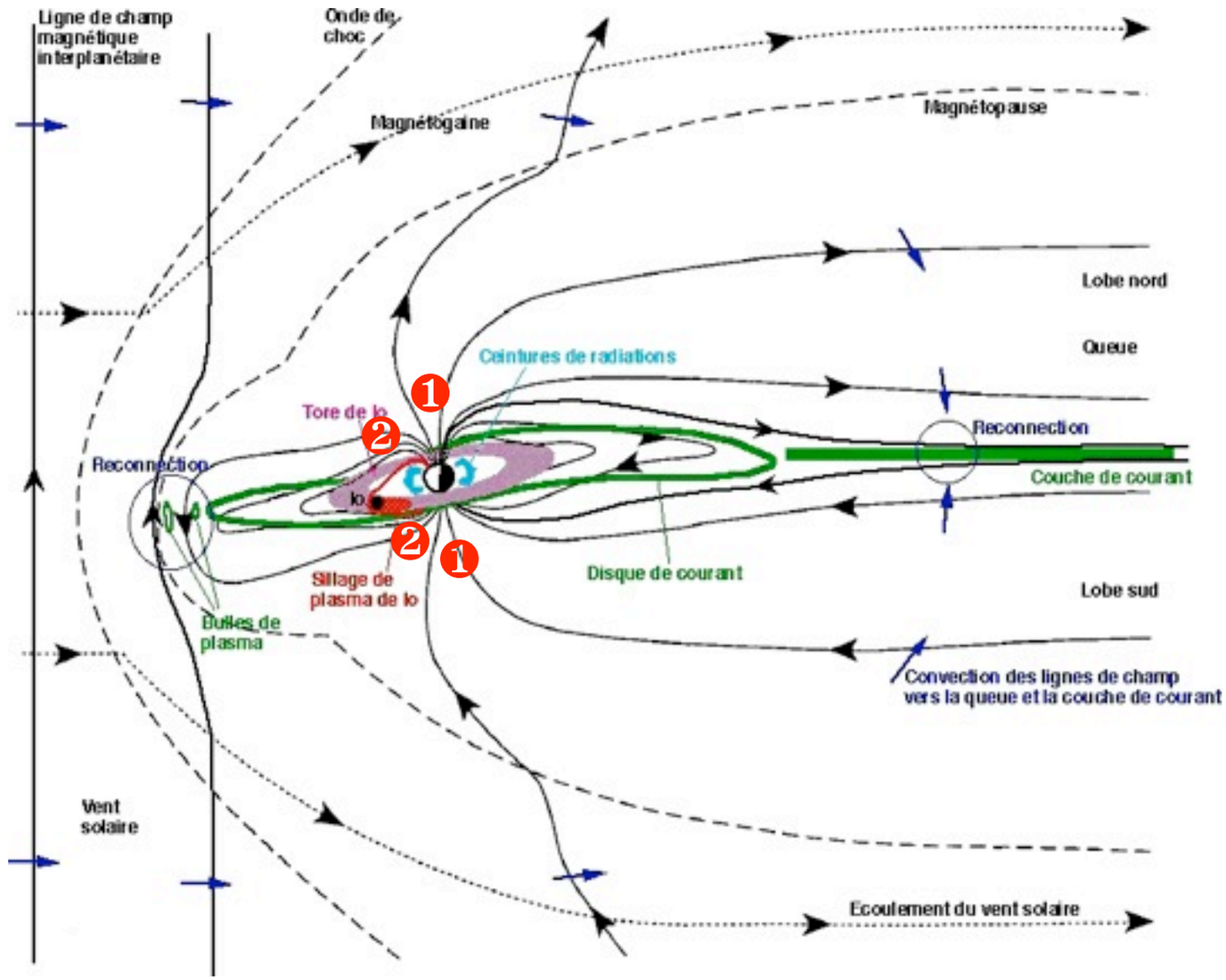
	Jupiter LF	Jupiter HF	Exoplanets	Lightning
What do we know ?				
What don't we know ?				
What can we learn with LOFAR ?				

Jupiter LF : What do we know ?

- Radio emission discovered in 1955
- Most intense planetary emission (T_b > 10^{15} K)
- Studied for 55 years, Ground-based + S/C instruments, ~no angular resolution !
- Various components due to various sources of accelerated electrons in magnetosphere
- Sharp cutoff at 40 MHz

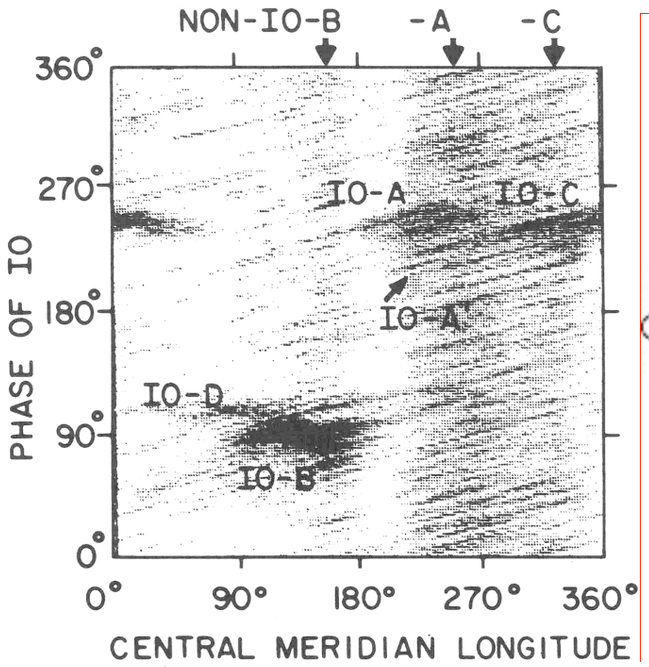


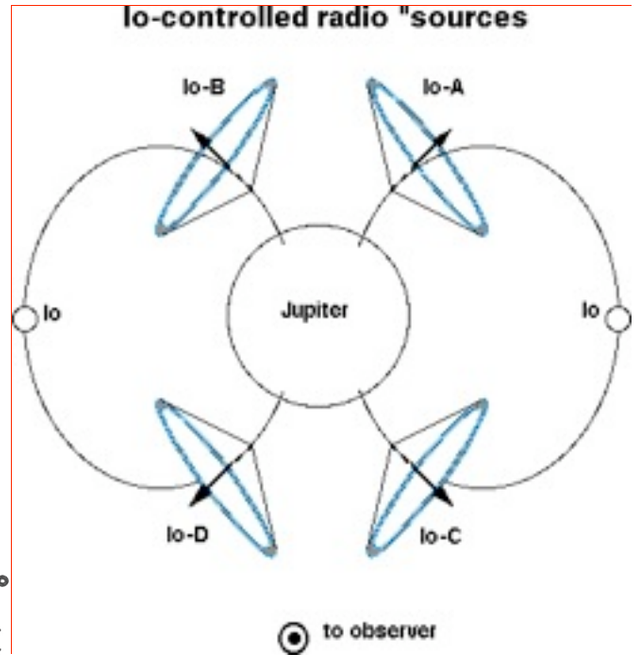


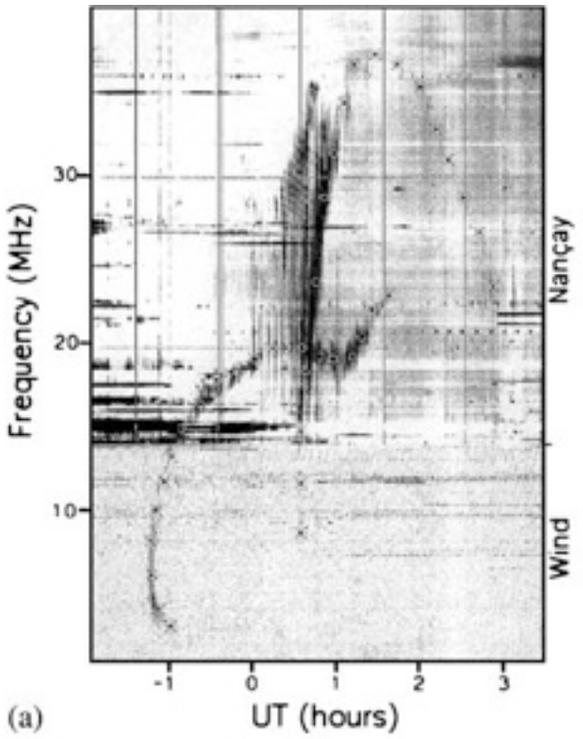


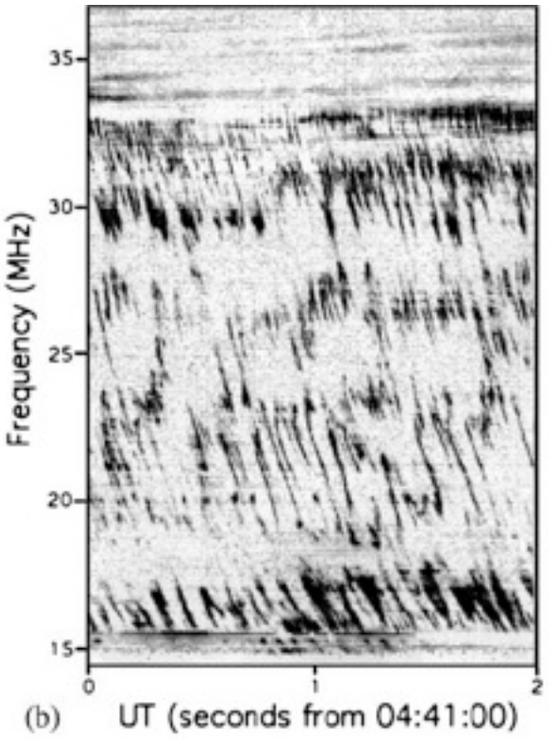
Jupiter LF : What do we know ?

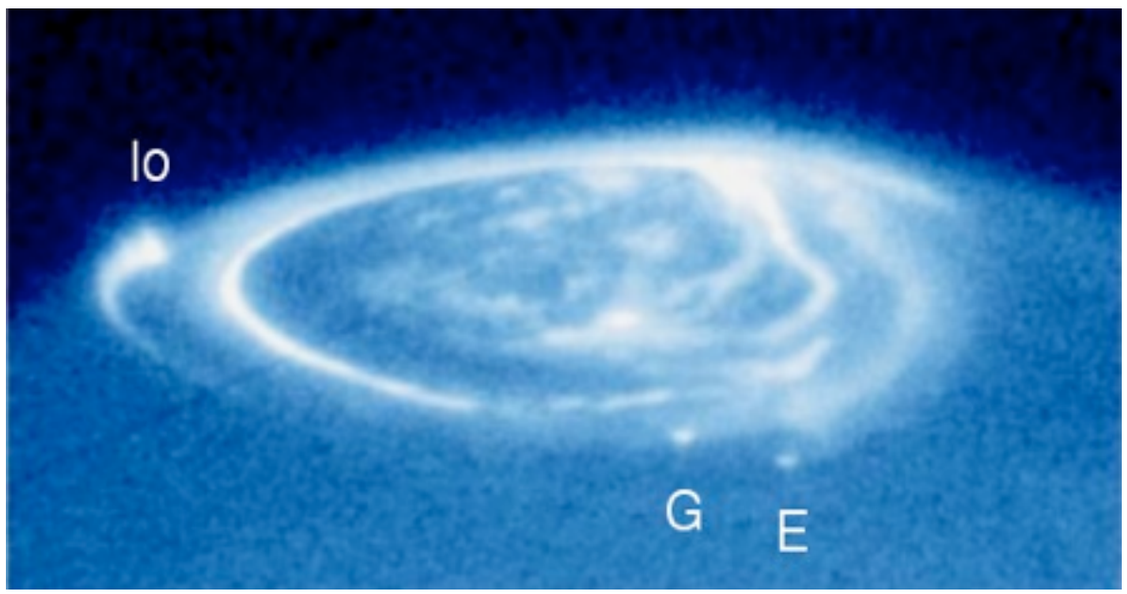
- Above 10 MHz, Io-controlled & Io-independent emissions, L- and S- bursts, correlated with UV main oval & bright spot

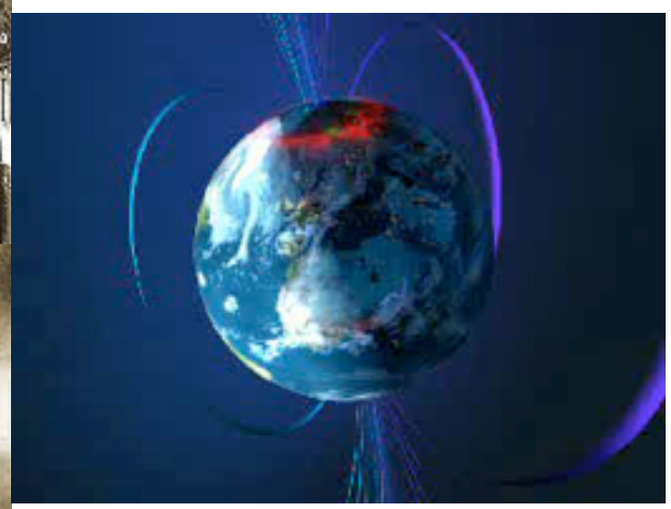






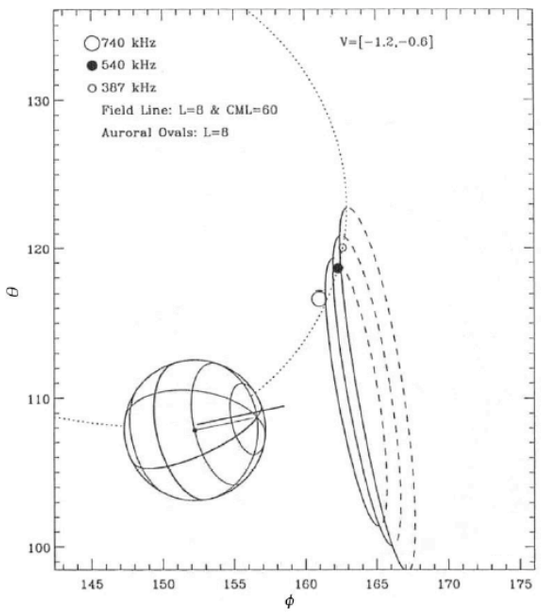


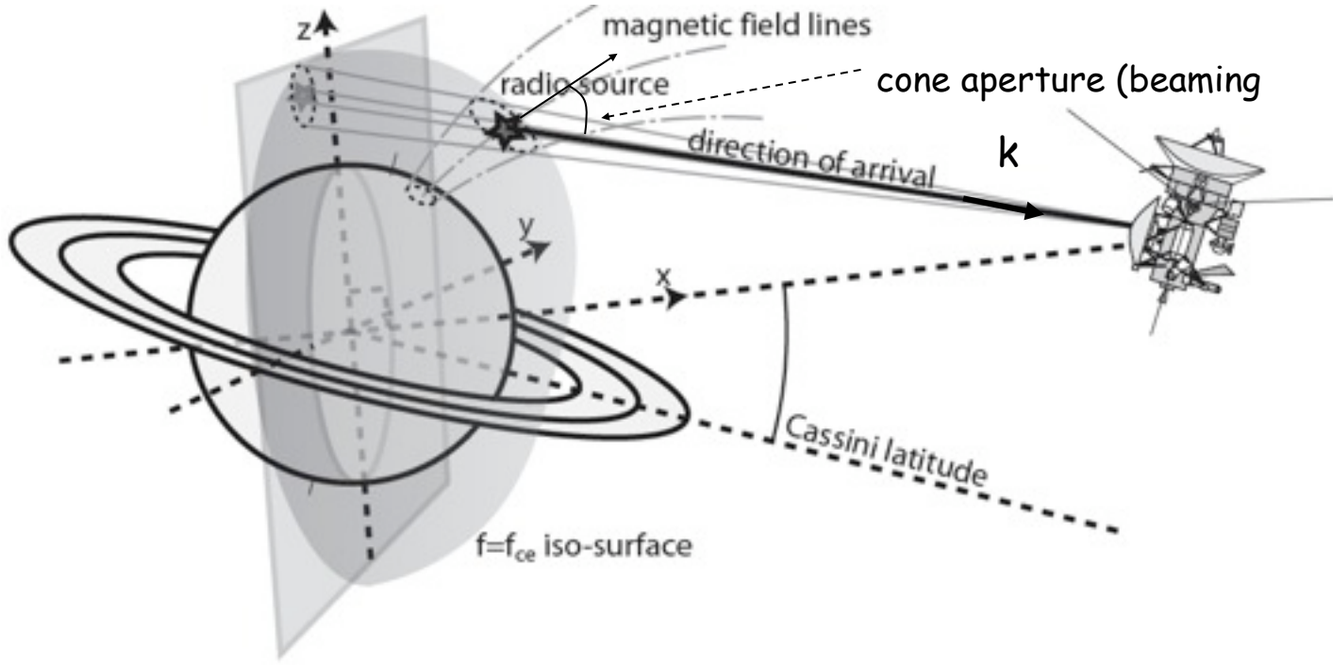


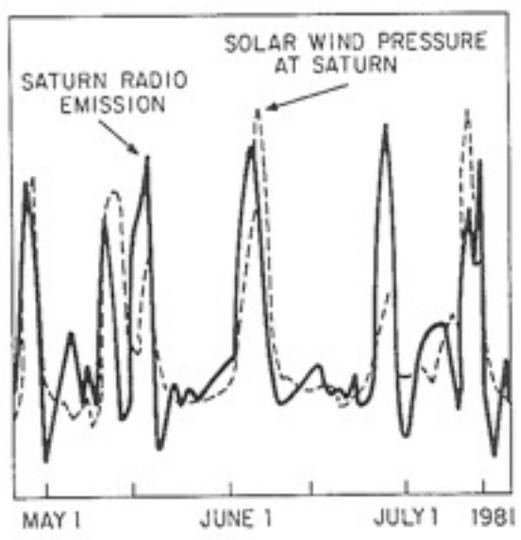


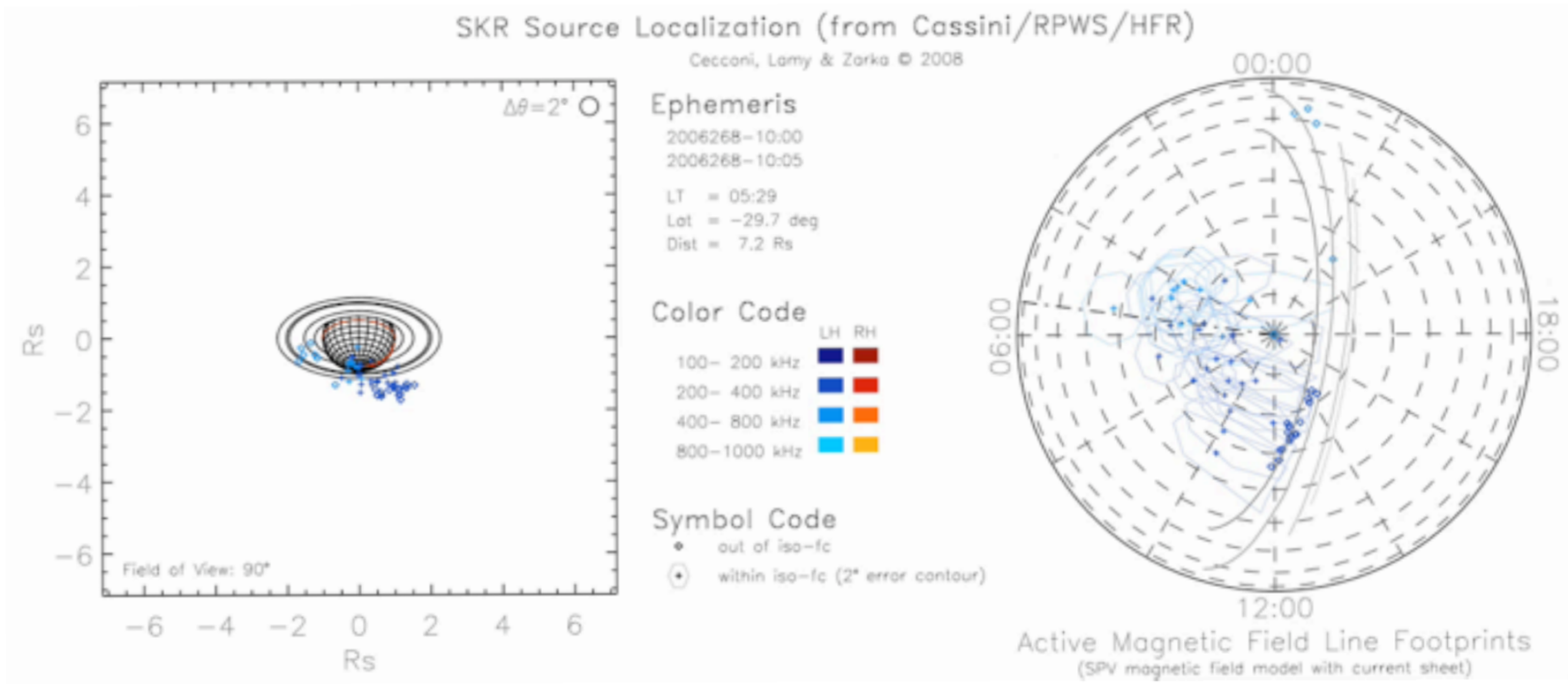
Jupiter LF : What do we know ?

- Observations : emission intense, $f \sim f_{ce}$, broadband, elliptical, X-mode, narrow beaming, correlation/UV, /SW, various modulations



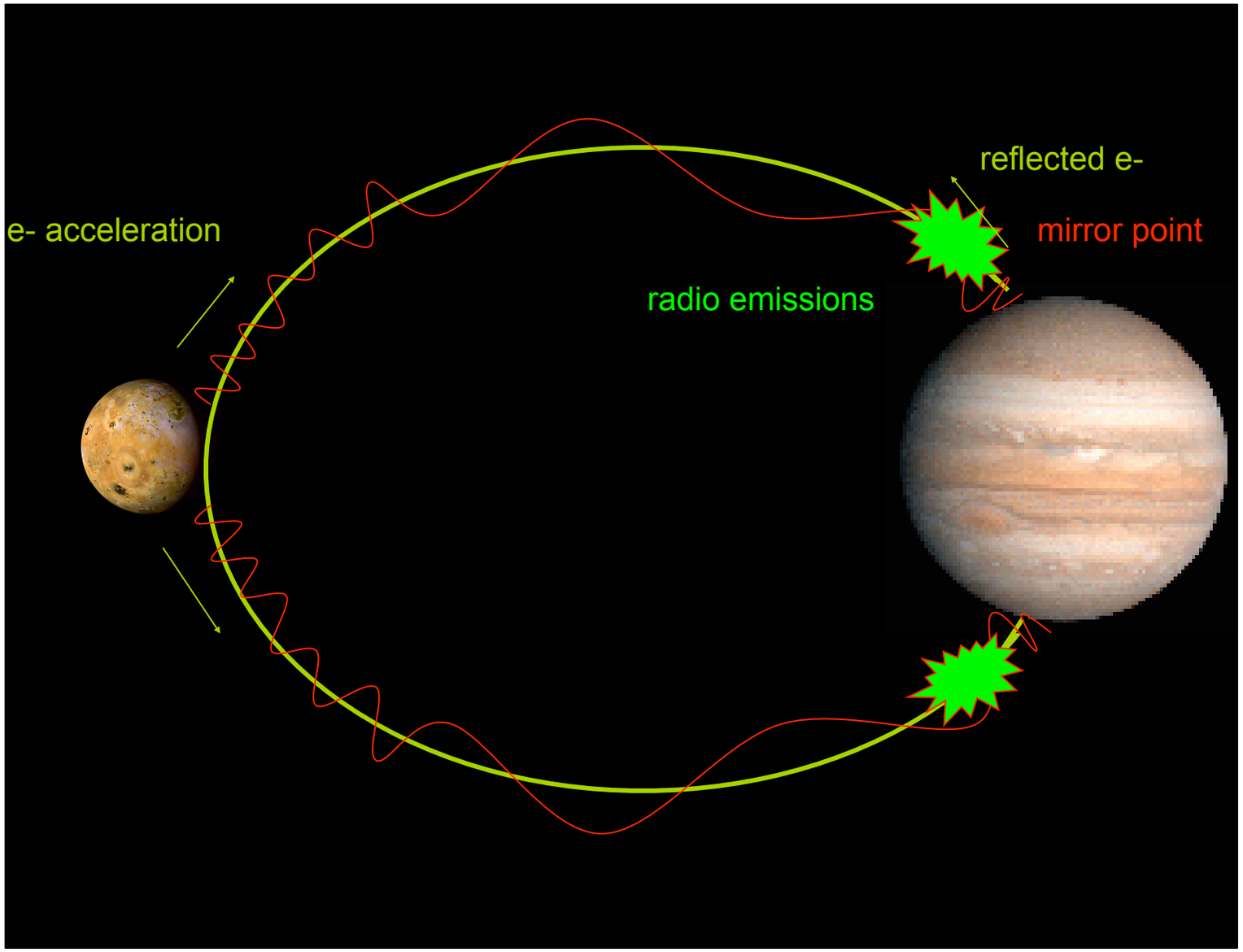


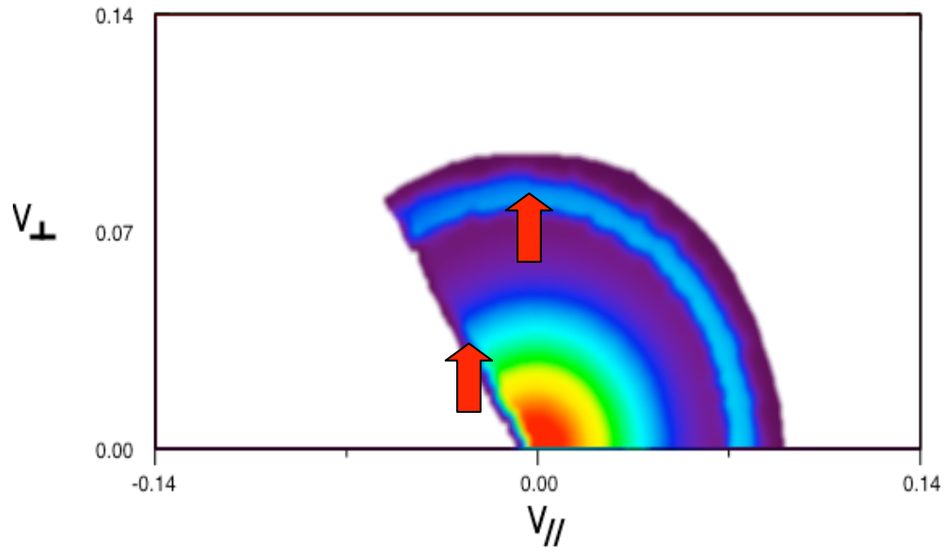




Jupiter LF : What do we know ?

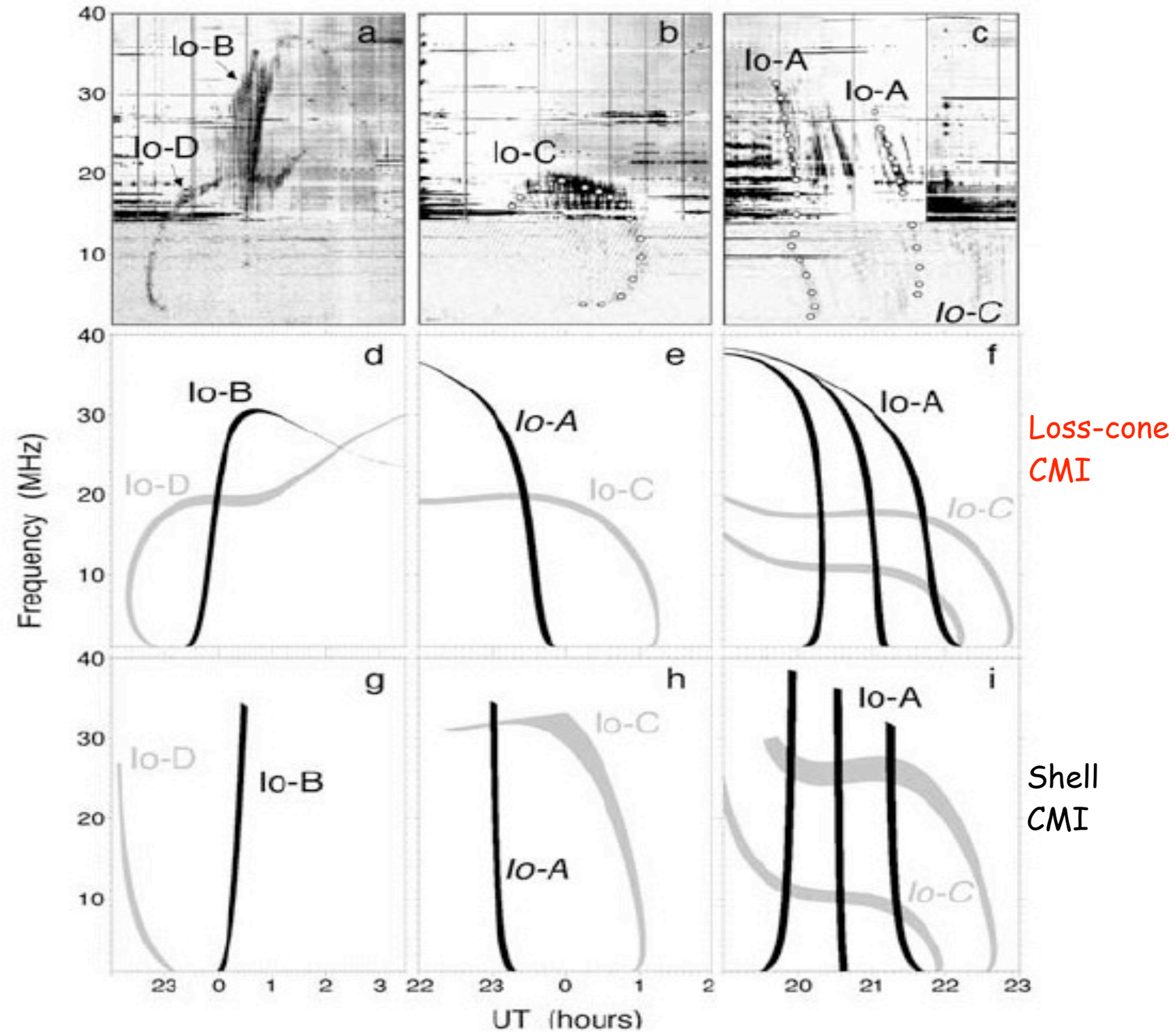
- Theory : coherent CMI (all auroral radio emissions) → strong B, $f_{pe} << f_{ce}$, accelerated/ unstable (keV) electrons → direct emission, of up to 1-5% of e- energy





Jupiter LF : What do we know ?

- ExPRES modelling → oblique emission → ≠ Earth



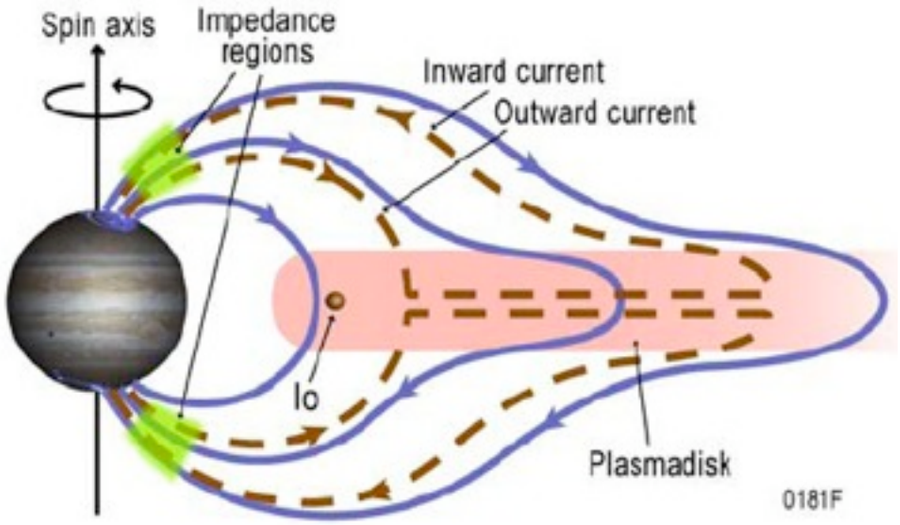
Loss-cone CMI

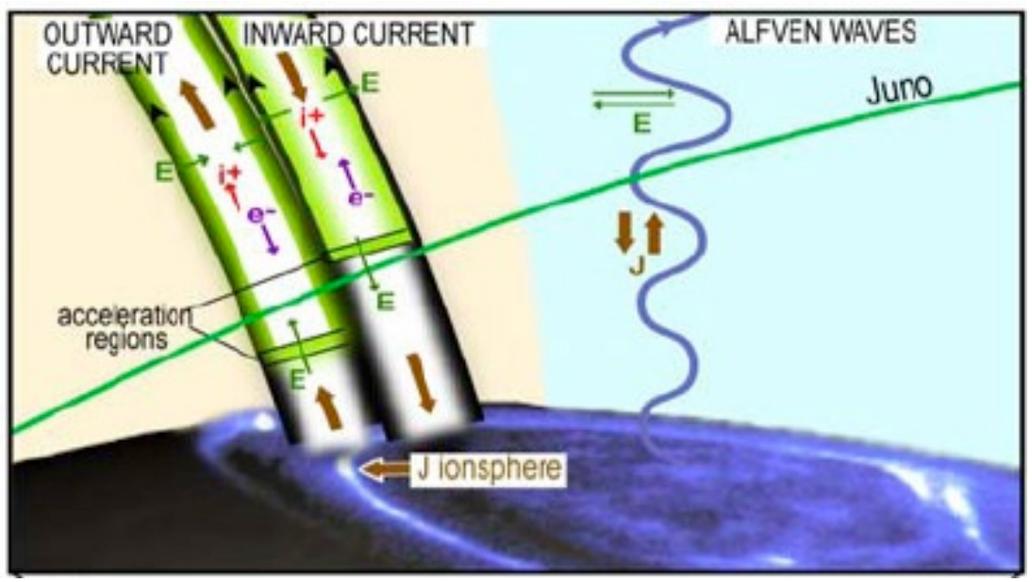
Shell CMI

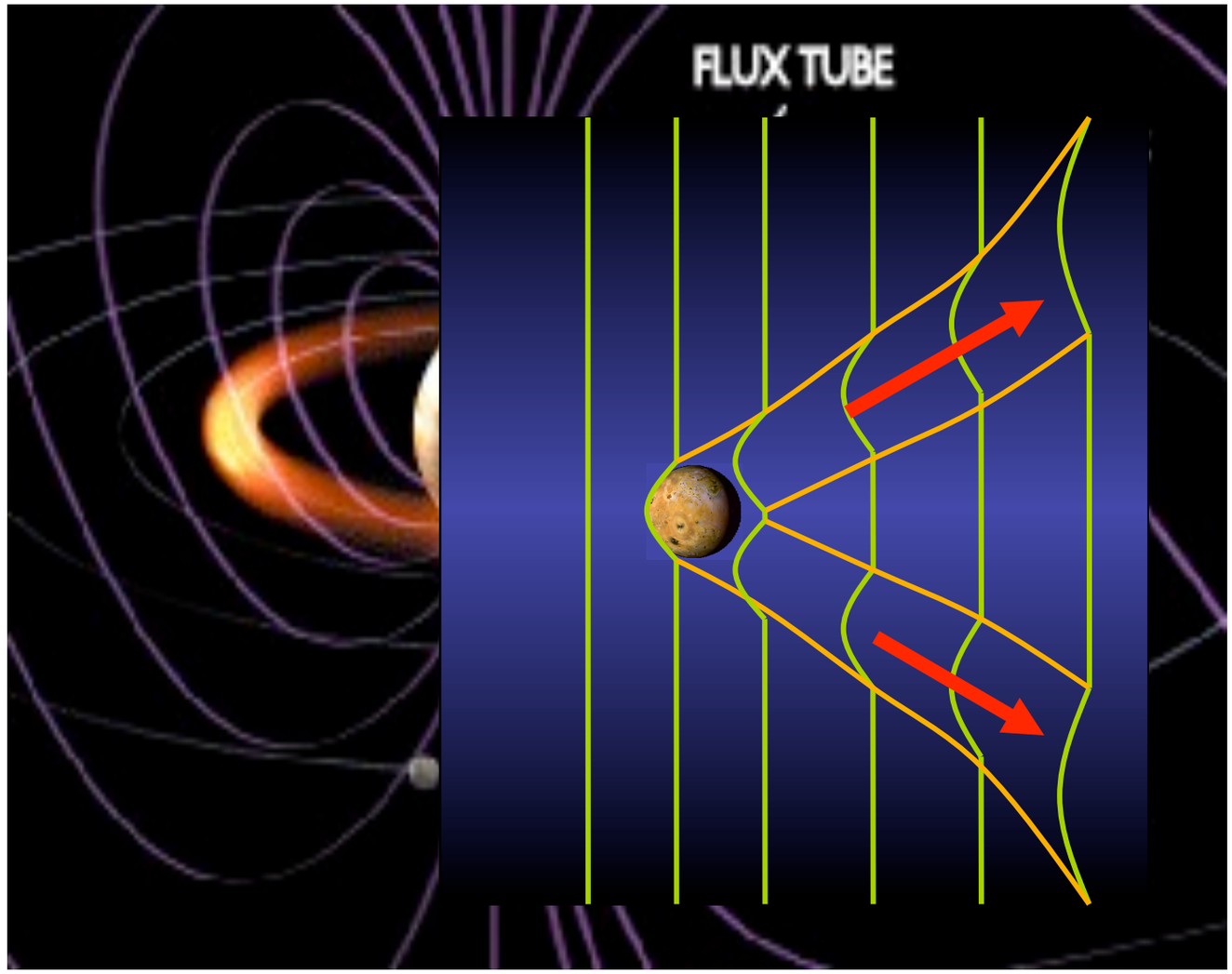
Jupiter LF : What do we know ?

→ sources of acceleration ?

- Main oval: corotation breakdown + SW/MS interaction (latter dominant for other magnetized planets)
- Io: currents / Alfvén waves



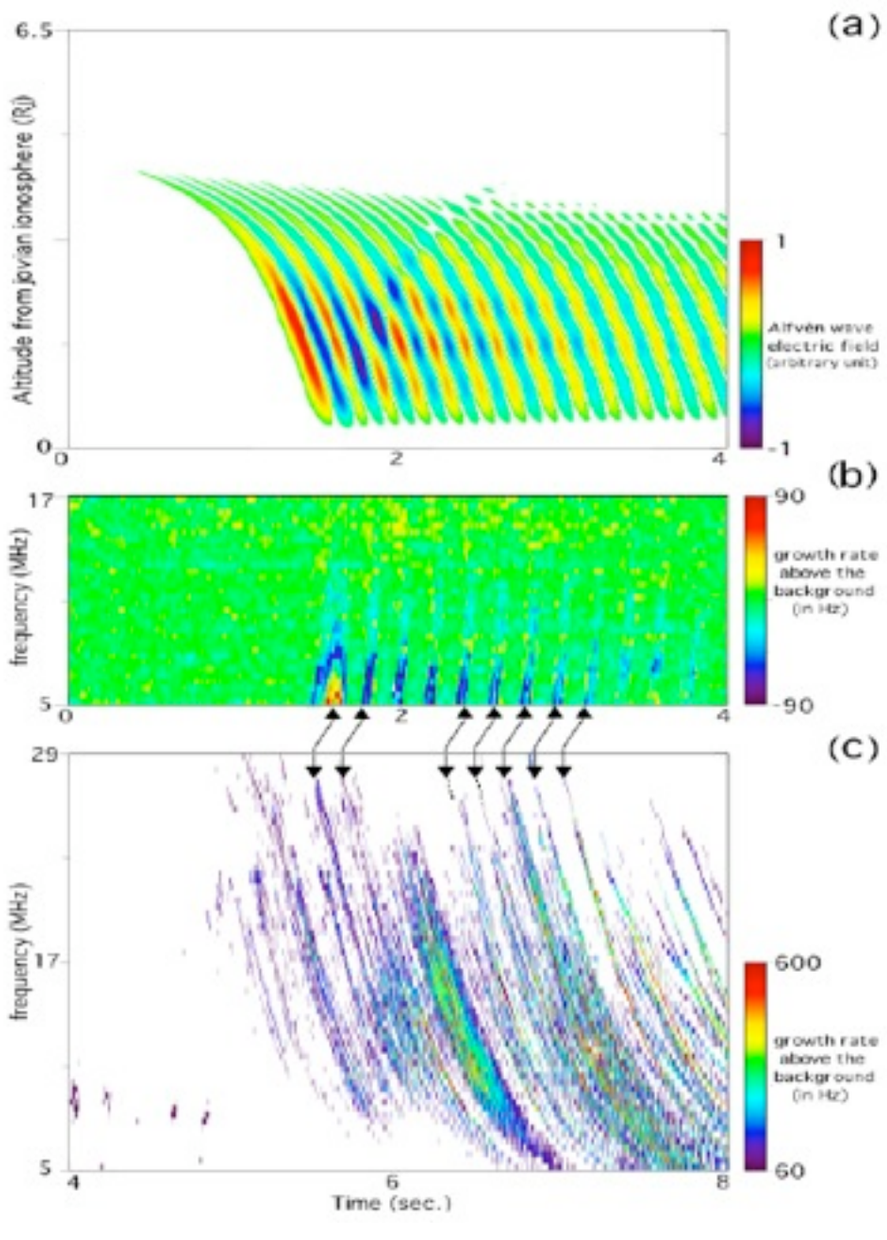


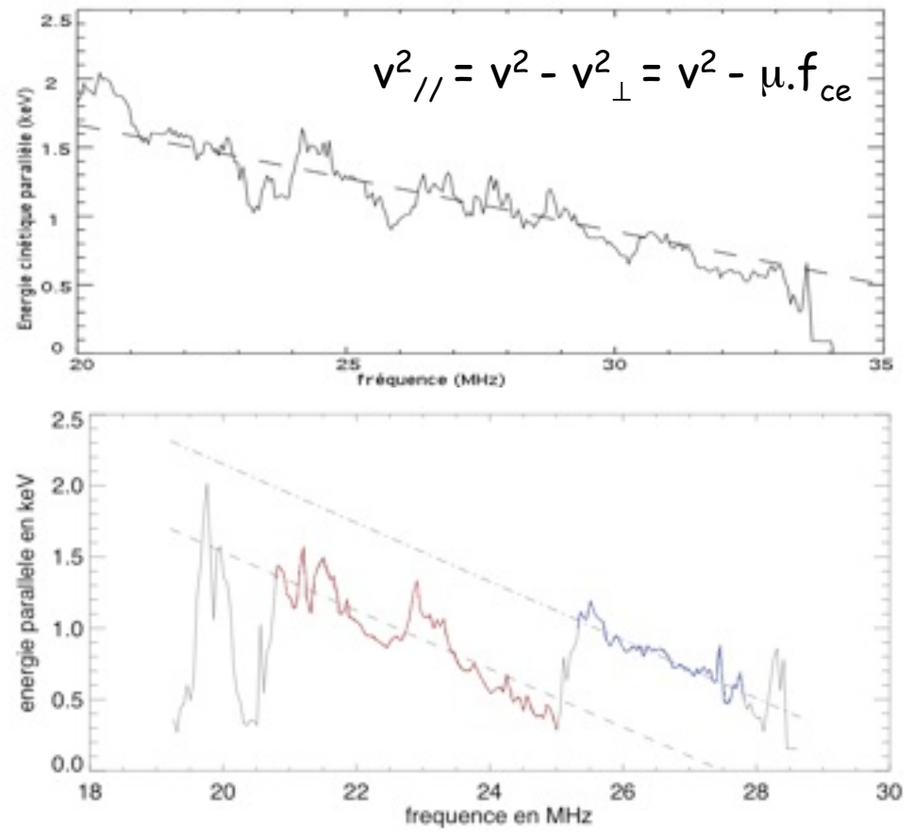


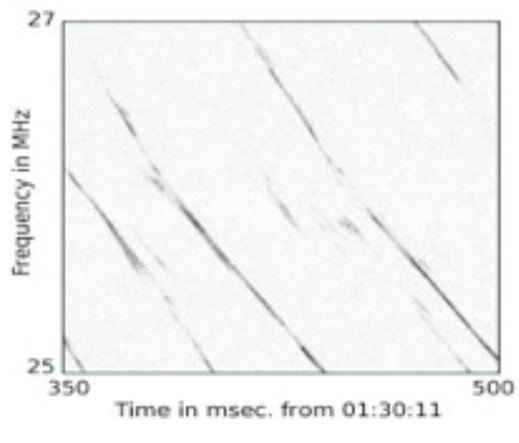
Jupiter LF : What do we know ?

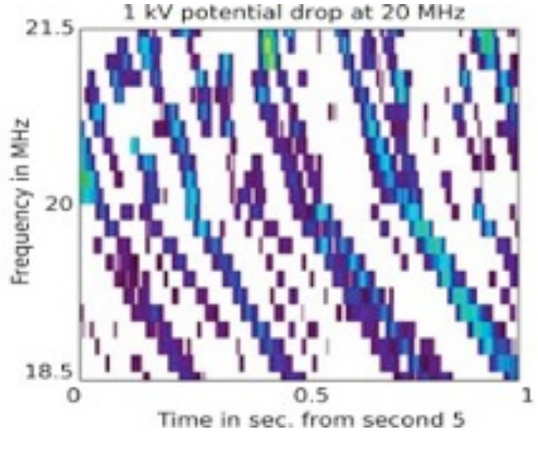
→ sources of acceleration ?

- Main oval: corotation breakdown + SW/MS interaction (latter dominant for other magnetized planets)
- Io: currents / Alfvén waves, field-aligned potential drops (DL's)



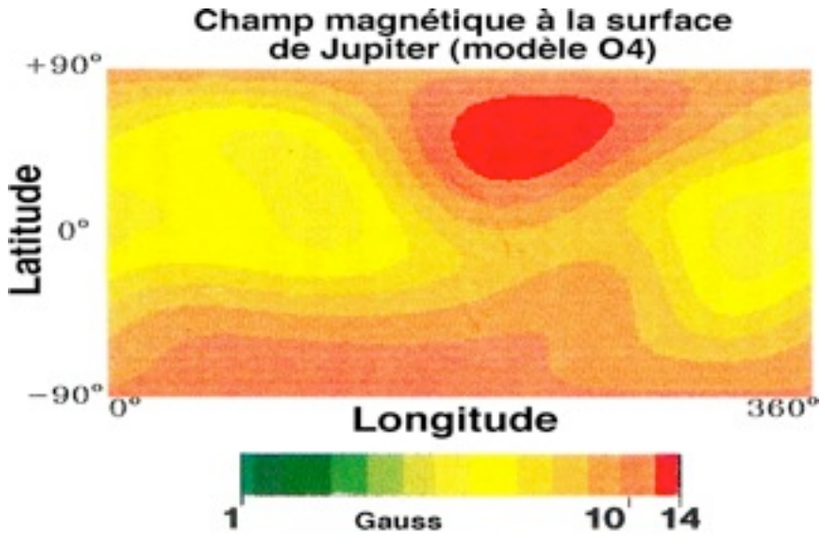


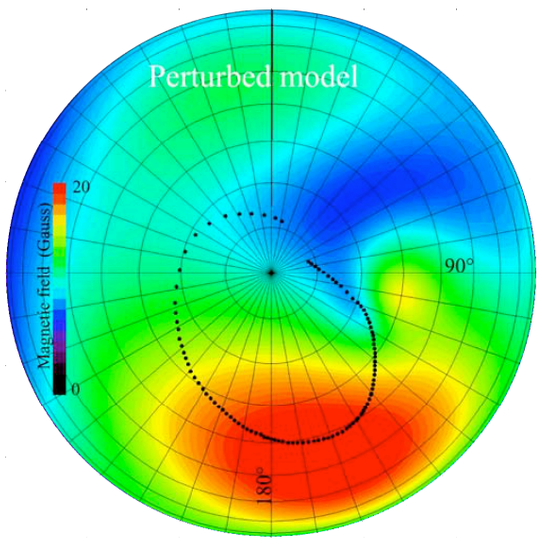


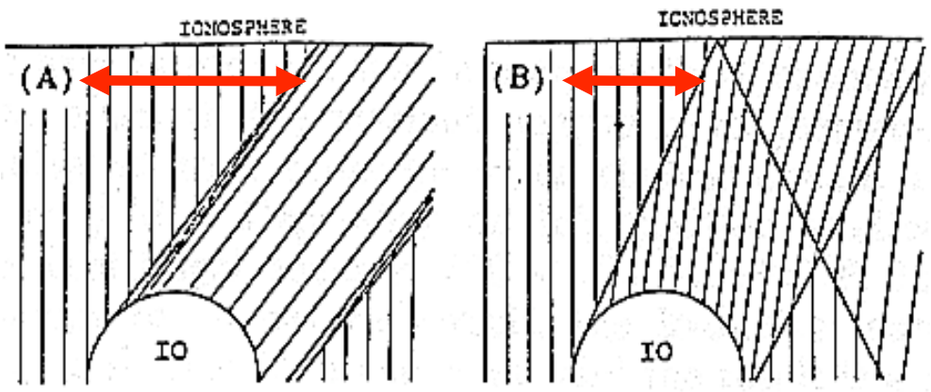


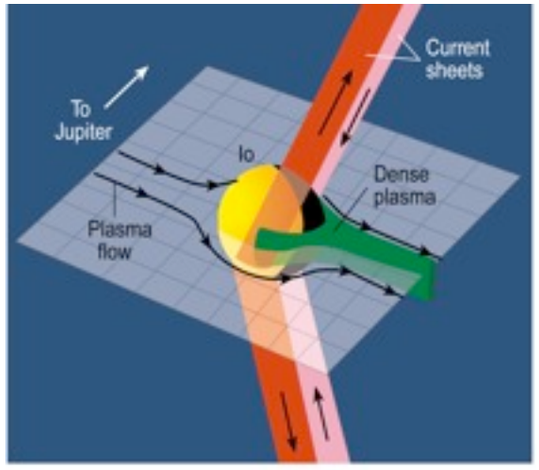
Jupiter LF : What don't we know ?

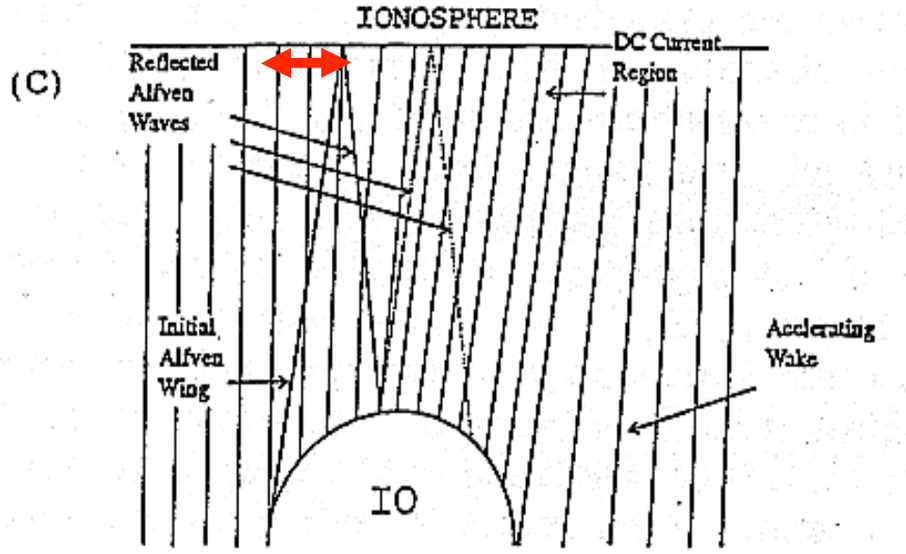
- Magnetic field model (before JUNO !) → constrains all modeling efforts
- Physics of satellite-MS interaction (existence/intensity of radio signatures, Alfvén "lead" angle)
- Physics of radio emission process (radio beaming angle)
- Direct confimation of S-bursts theory → general implications











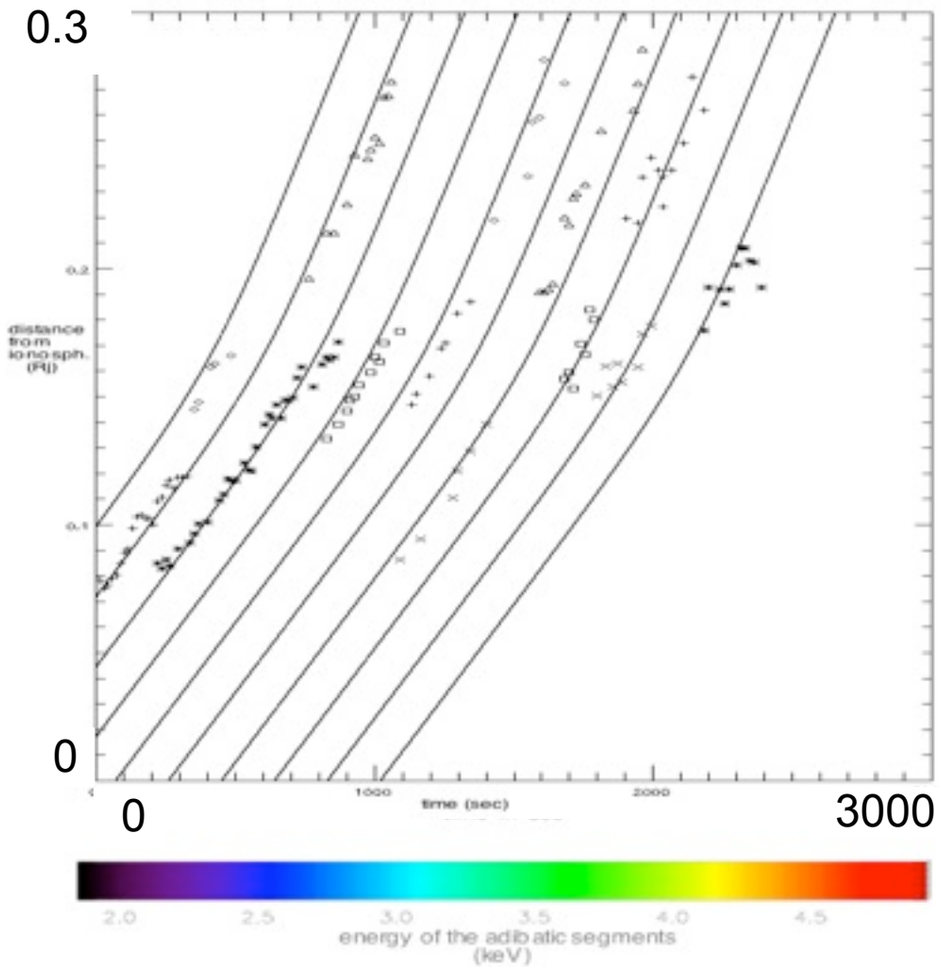
Jupiter LF : What can we learn with LOFAR ?

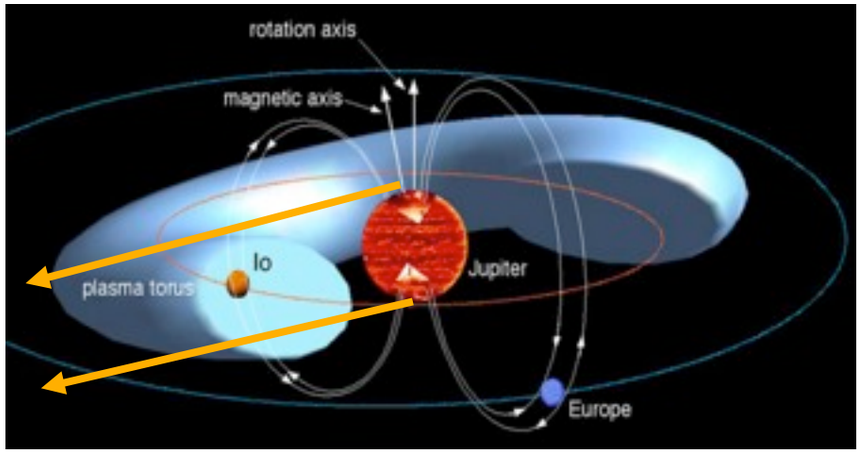
- Surface magnetic field mapping
- Physics of Io(E,G) - Jupiter interaction
- Radio beaming angle
- Electron bunches & electric fields along Io flux tube

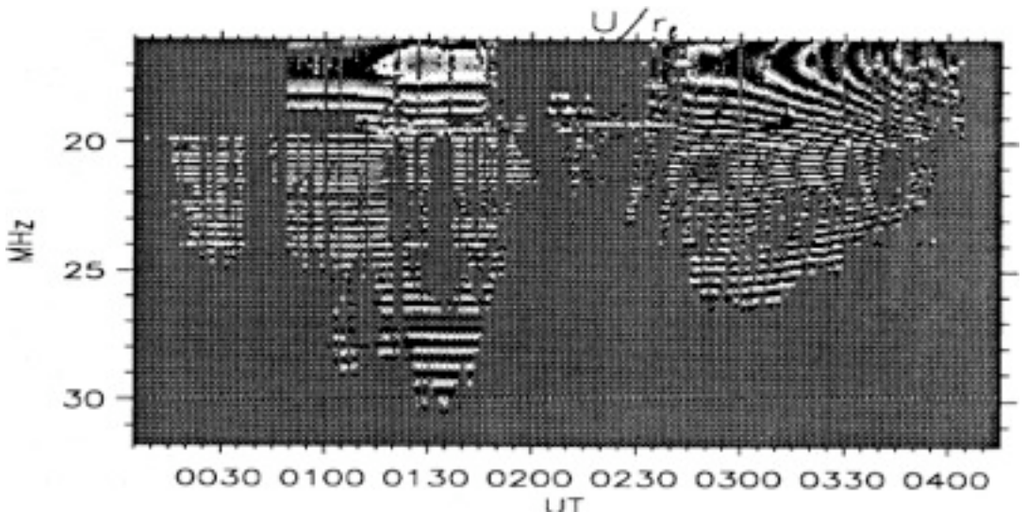
+

- Propagation effects through Io's torus (Faraday rotation, diffraction fringes)
- Multi-wavelength correlations (Radio, UV, IR, X)

→ Need for high resolution (1-2") fast (msec's) imaging below 40 MHz !







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Fast radio imaging of Jupiter's magnetosphere at low-frequencies with LOFAR

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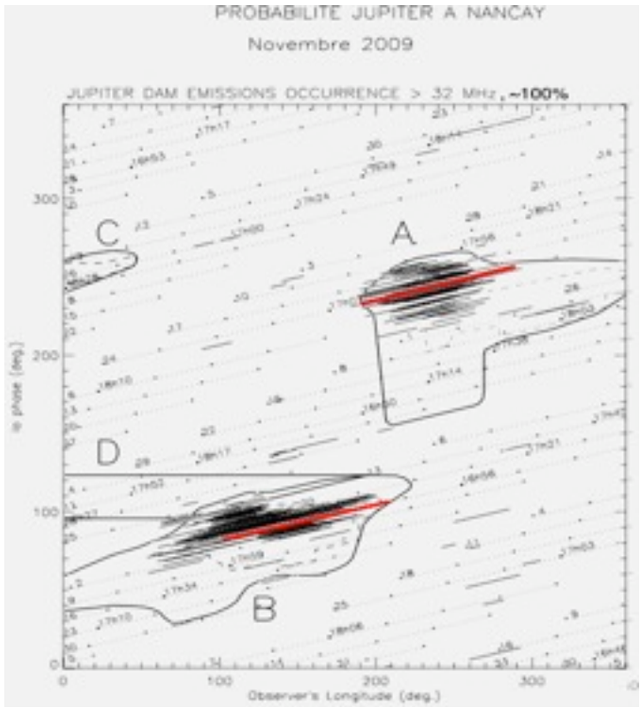
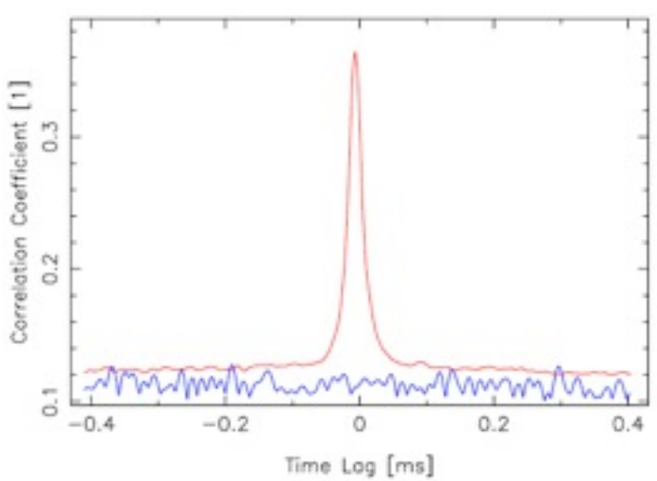
Accepted 3 September 2004

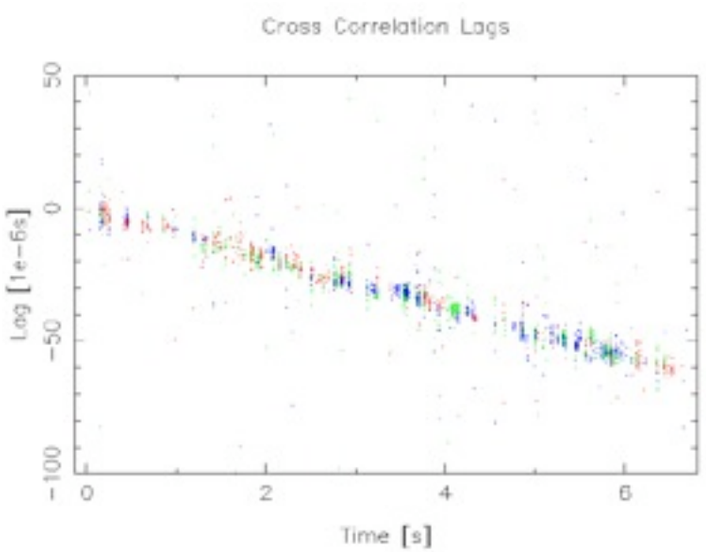
+ a dozen papers by Hess et al. 2007-2010

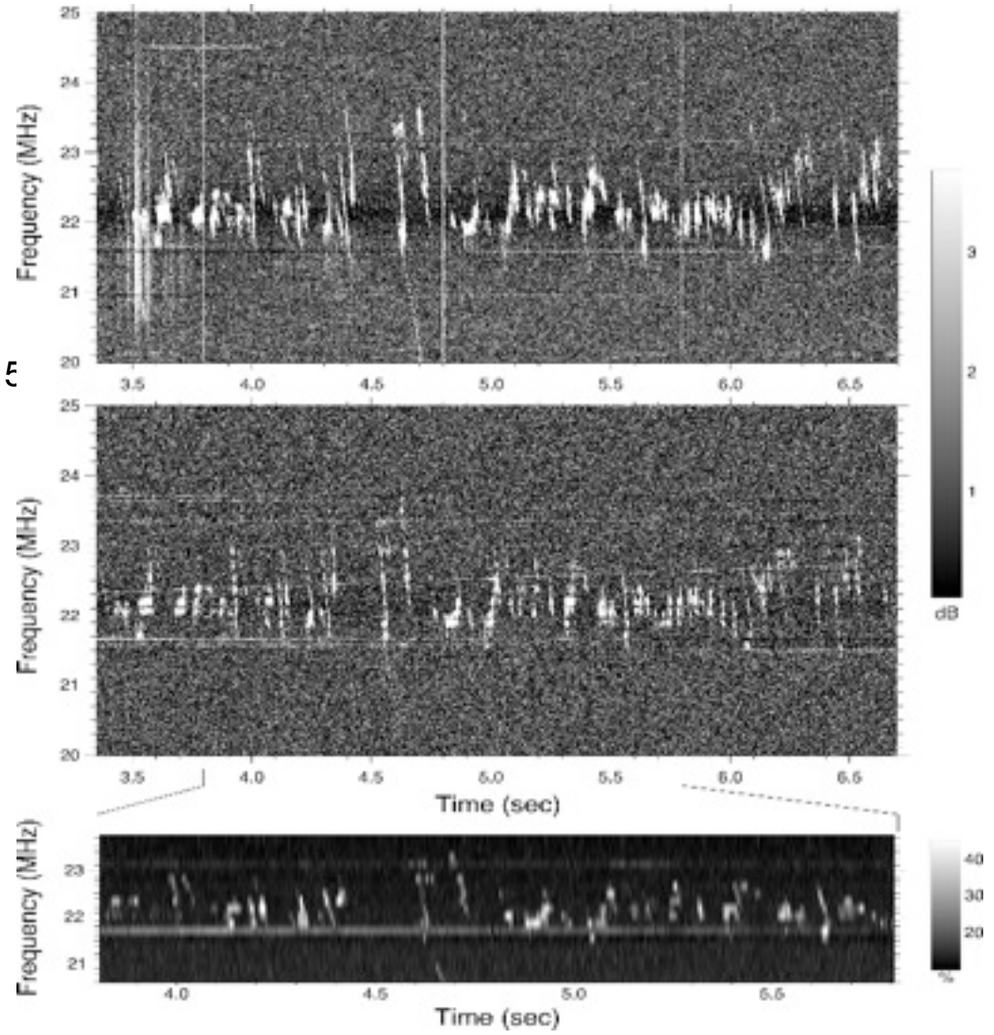
Jupiter LF : commissionning observations

- Intense emission, detectable by single station
- Predicted ephemeris for Io-Jupiter activity
- Early long baselines Nançay-ITS observations ~ 21-24 MHz → correlation fringes measured, stability > 1 sec timescale, clock drift



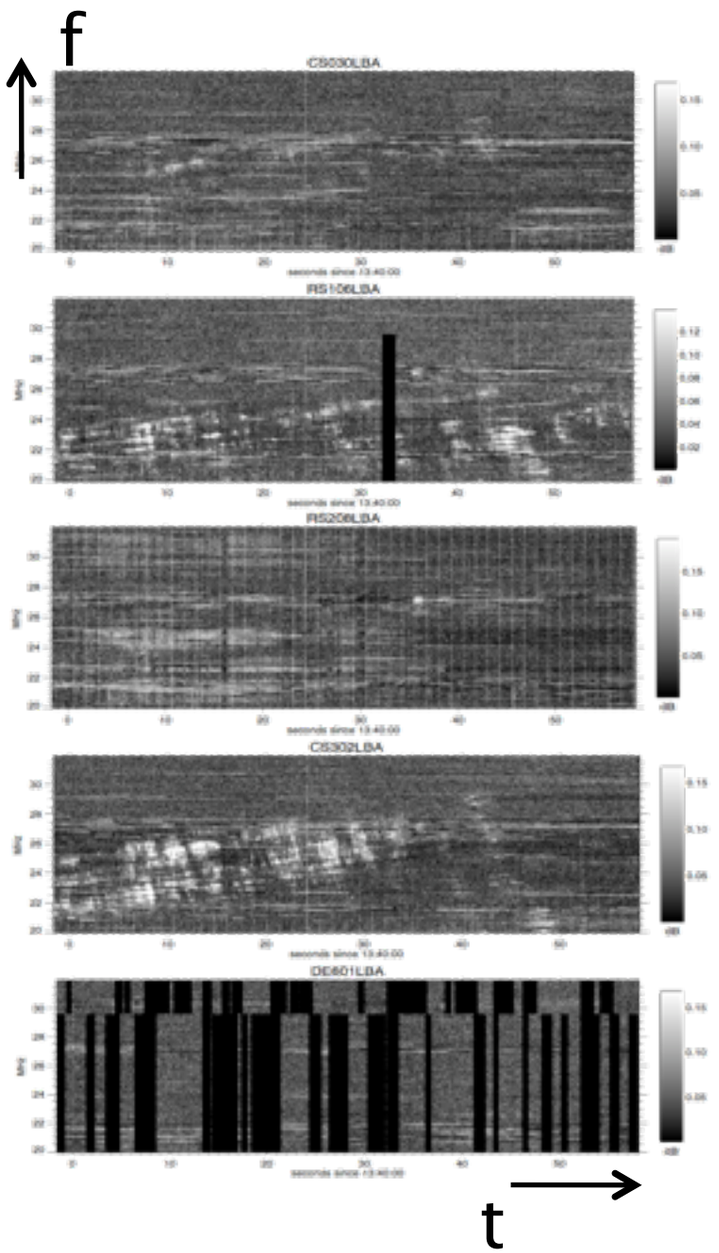


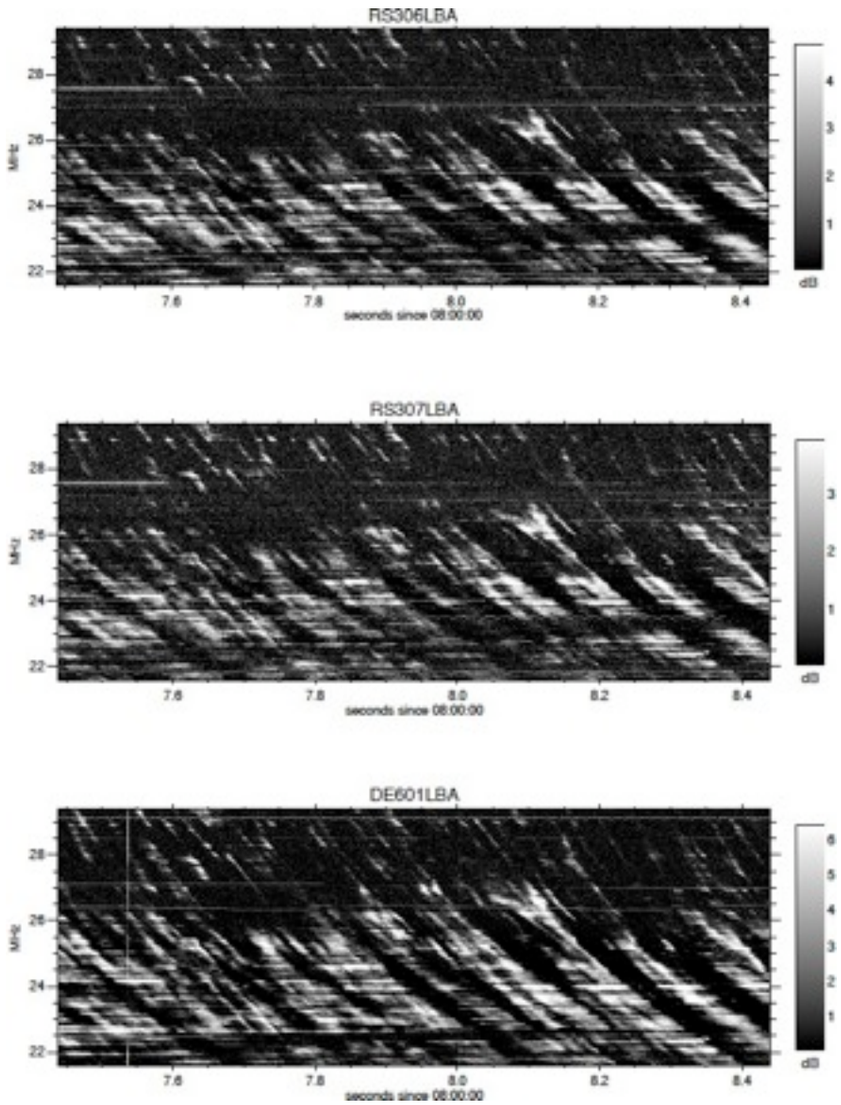




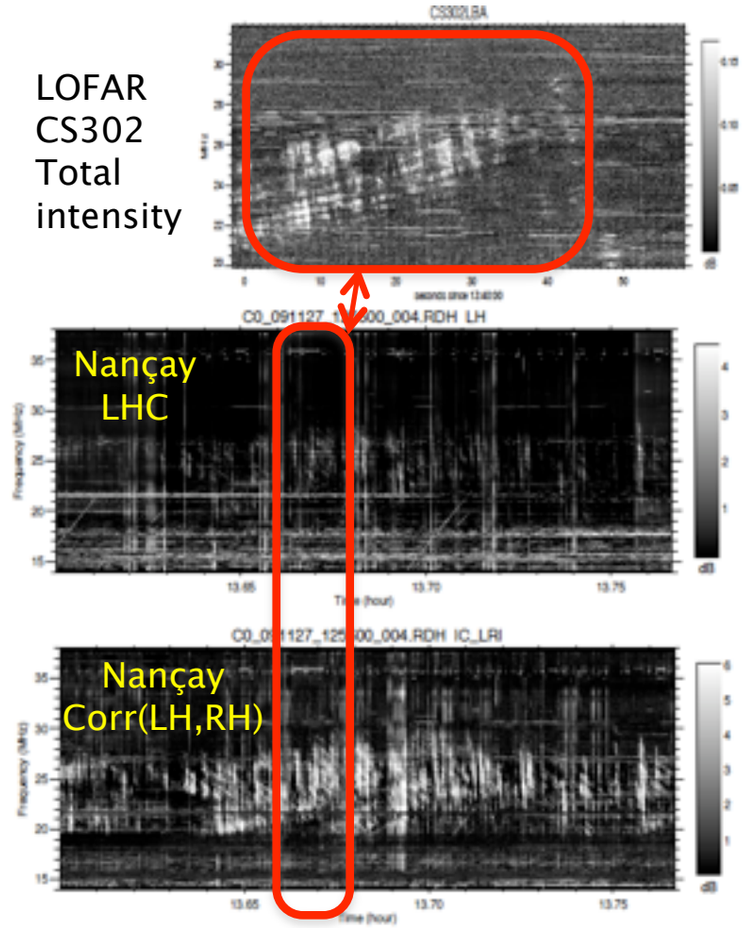
Jupiter LF : commissionning observations

- More recent observations since 2009 → debugging, characterizing LOFAR <30 MHz
- TBD: correlation station-to-station → synthesize coherent TAB, polarization calibration (/Nançay)





Jupiter's radio bursts detected by 3 LOFAR stations (3/6/2010). The correlation of these signals, depending on ionospheric density fluctuations, is a step of the commissionning of the coherent Tied-Array mode of LOFAR



Observations // Nançay decameter array

A&A 471, 1099–1104 (2007)
DOI: 10.1051/0004-6361:20077204

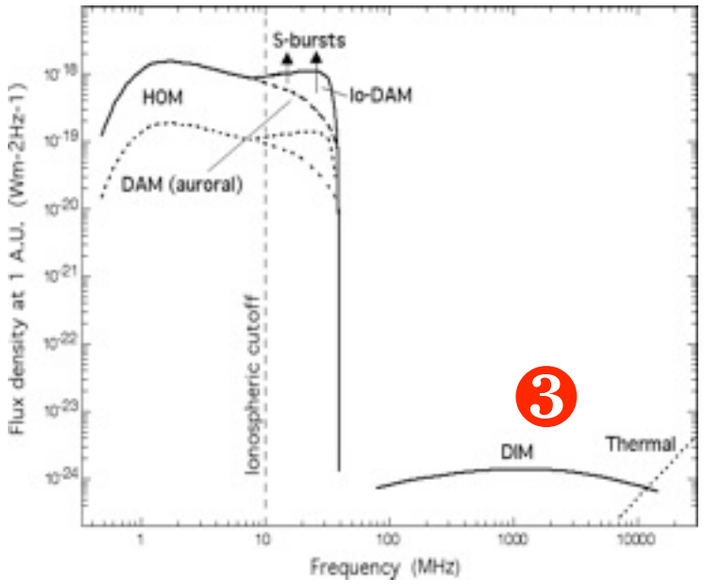
Astronomy & Astrophysics

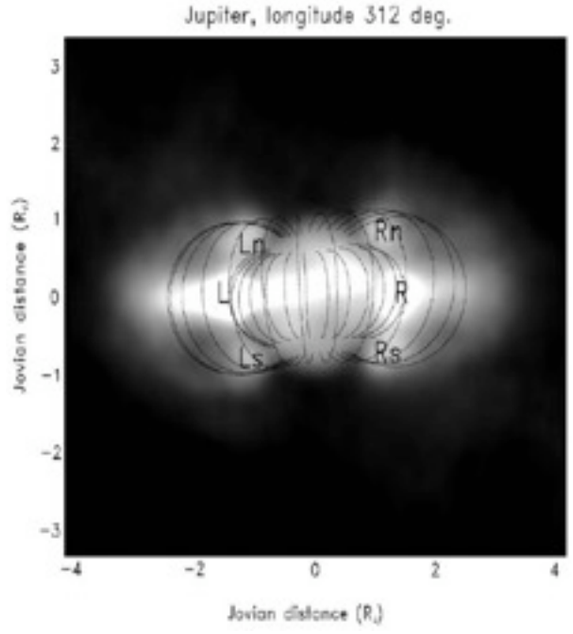
VLBI observations of Jupiter with the initial test station of LOFAR and the Nançay decametric array

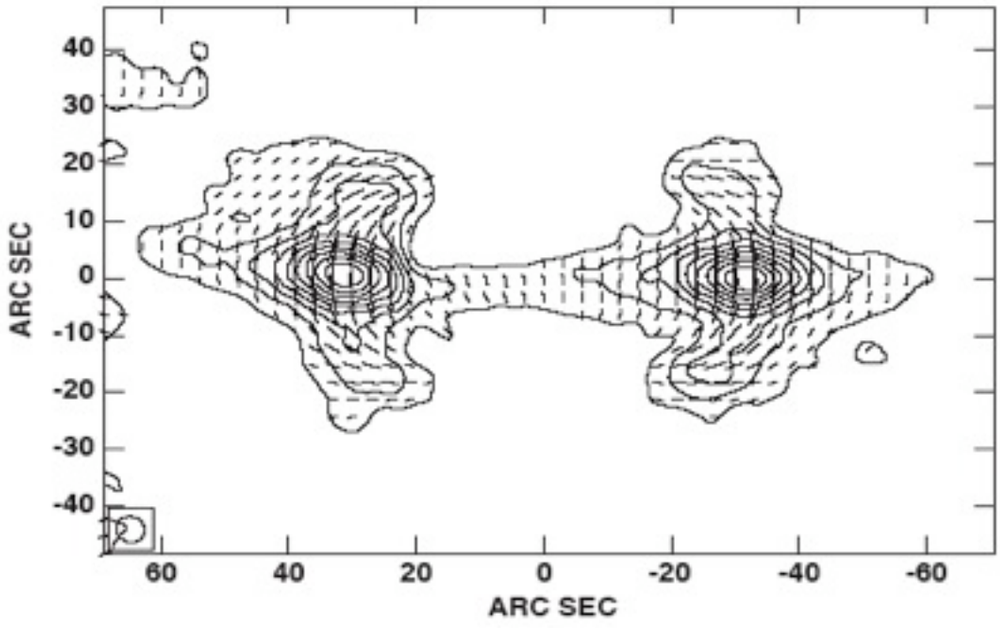
A. Nigl[1], P. Zarka[2], J. Kuijpers[1], H. Falcke[3], L. Bähren[3], and L. Denis[2]

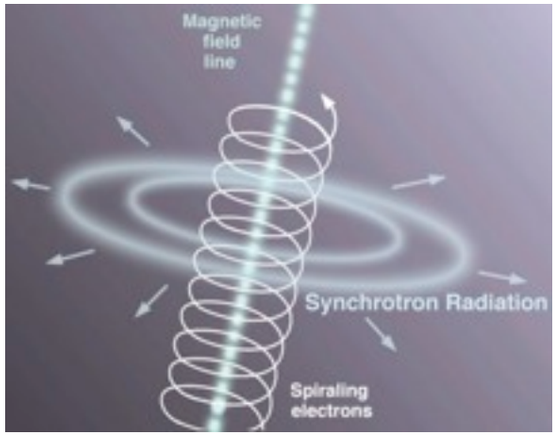
Jupiter HF : What do we know ?

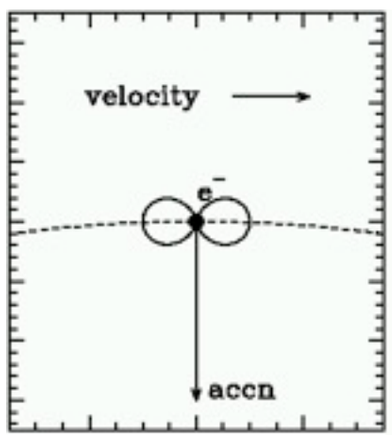
- Weaker continuum emission > 40 MHz
- Incoherent synchrotron, from MeV e- in radiation belts
- Linear polarization, perpendicular to B, beamed in a narrow forward cone (Γ^{-1})
- Slow variations /t (including correlated with SL9 impact)

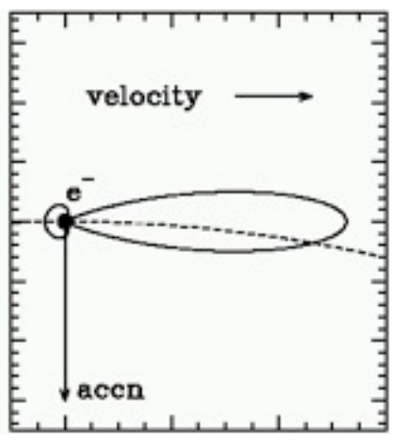


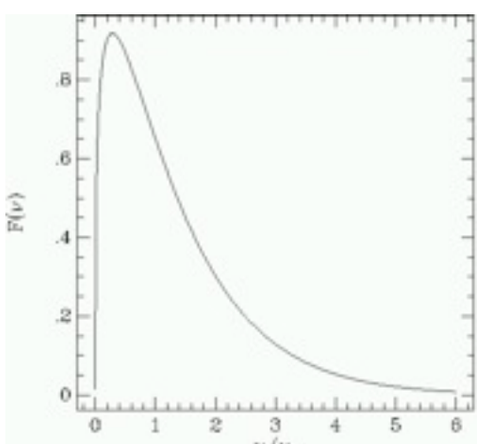






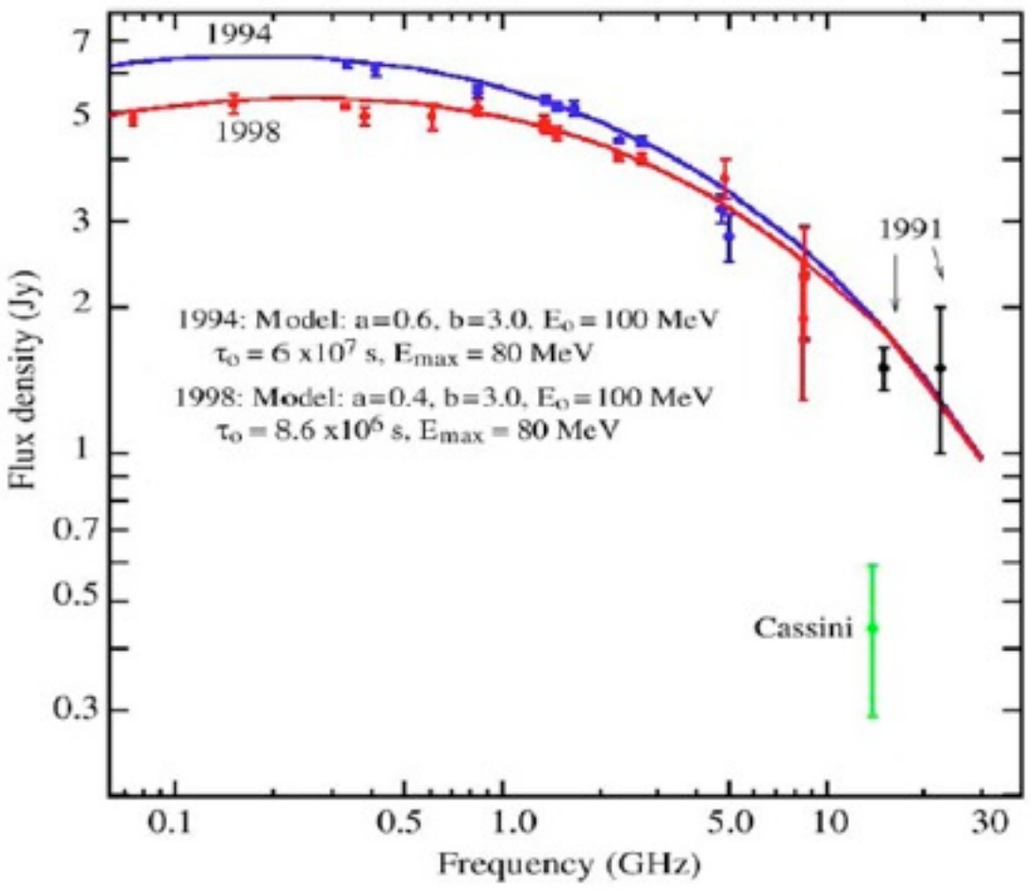


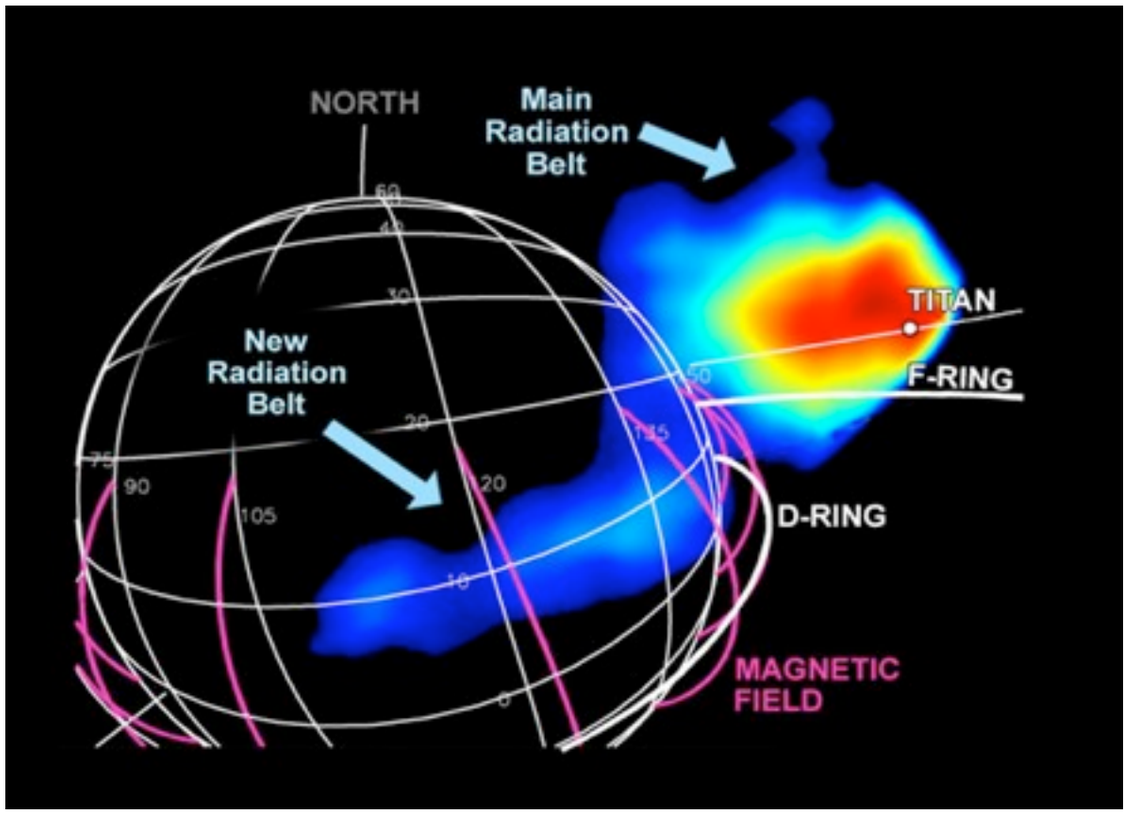




Jupiter HF : What don't we know ?

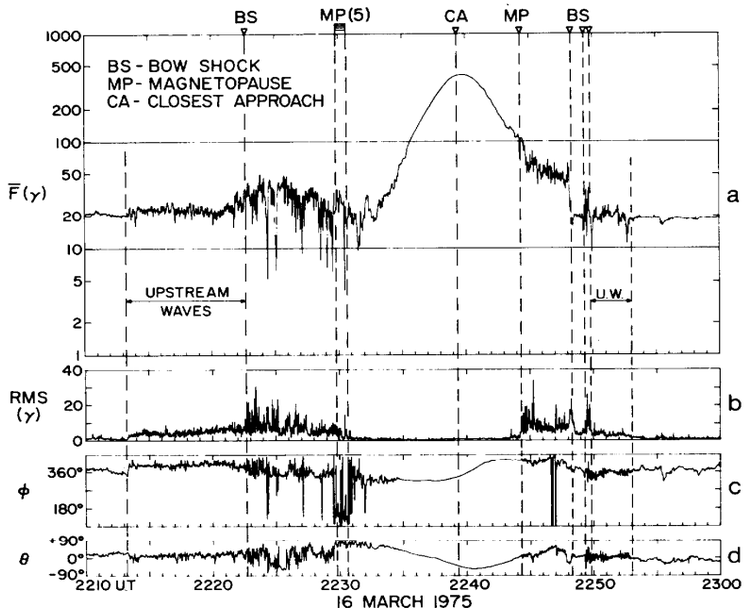
- Low energy end of electrons spectrum
- Time variations, especially related to solar wind
- Existence at other planets (Saturn, Mercury ?)



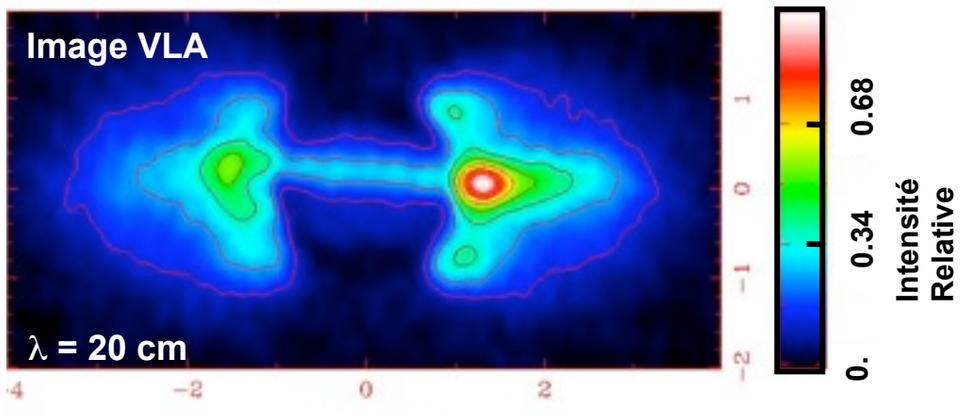


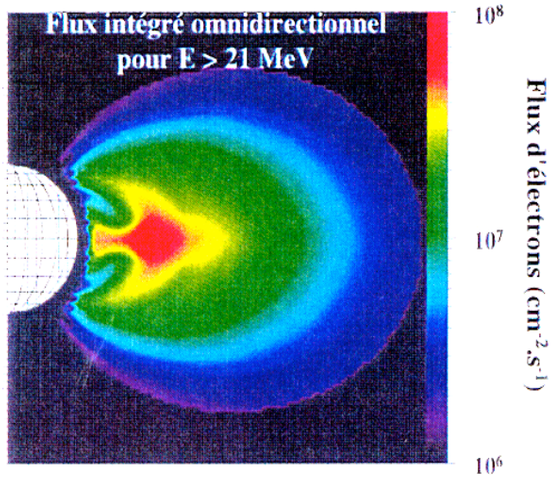
Jupiter HF : What can we learn with LOFAR ?

- High resolution LF imaging at large $\delta f/f$ (low energy e-) → origin + transport of energetic e- in Jupiter's inner radiation belts : pitch-angle scattering by PW, coulomb scattering, interaction with dust ?
- Variation / t & solar wind
- Existence at Saturn ? Mercury ?

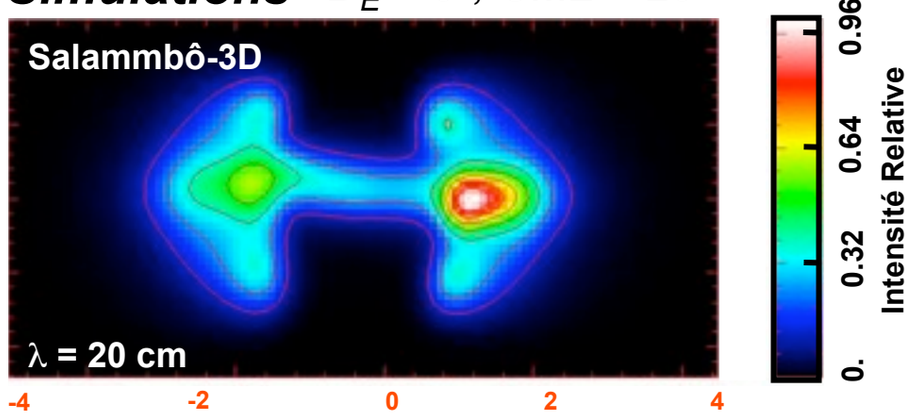


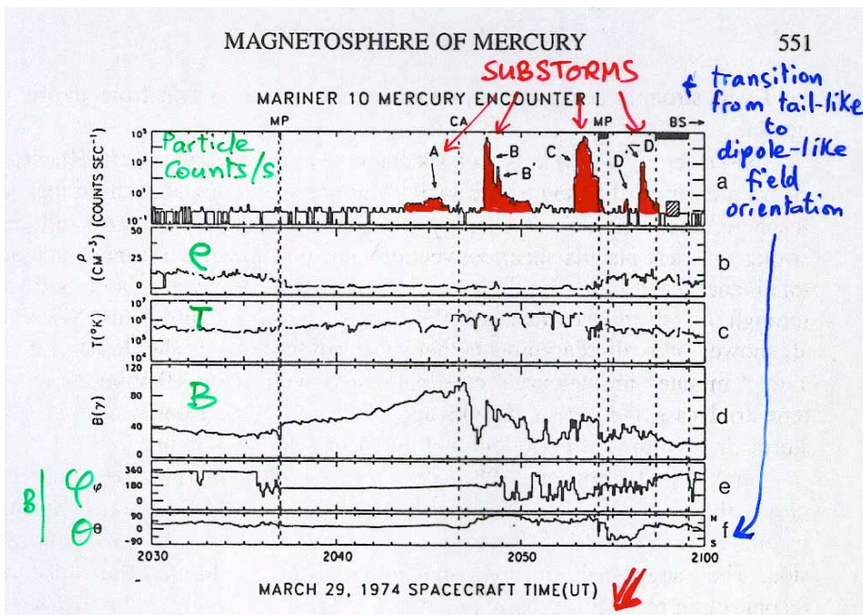
$D_E = 0^0$, $CML = 20^0$





Simulations $D_E = 0^0$, $CML = 20^0$





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LOFAR and Jupiter's radio (synchrotron) emissions

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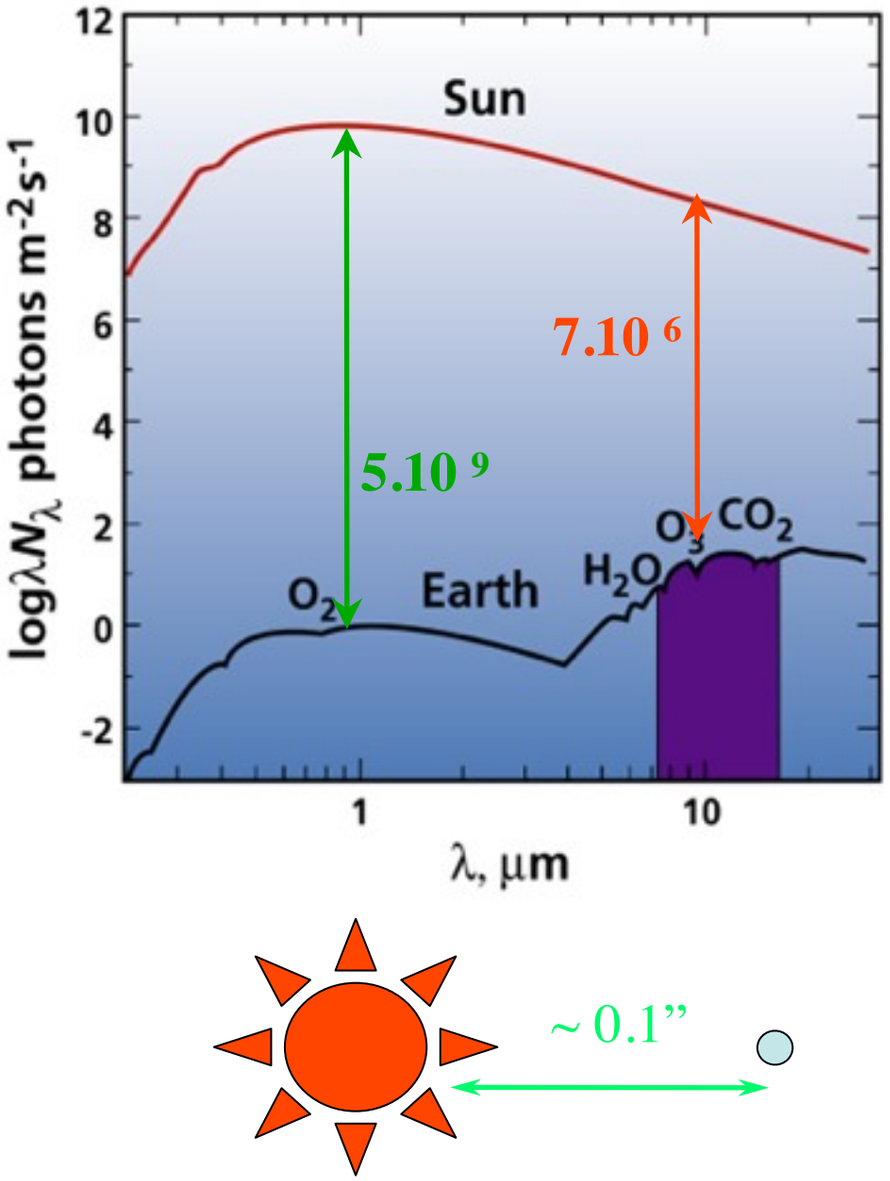
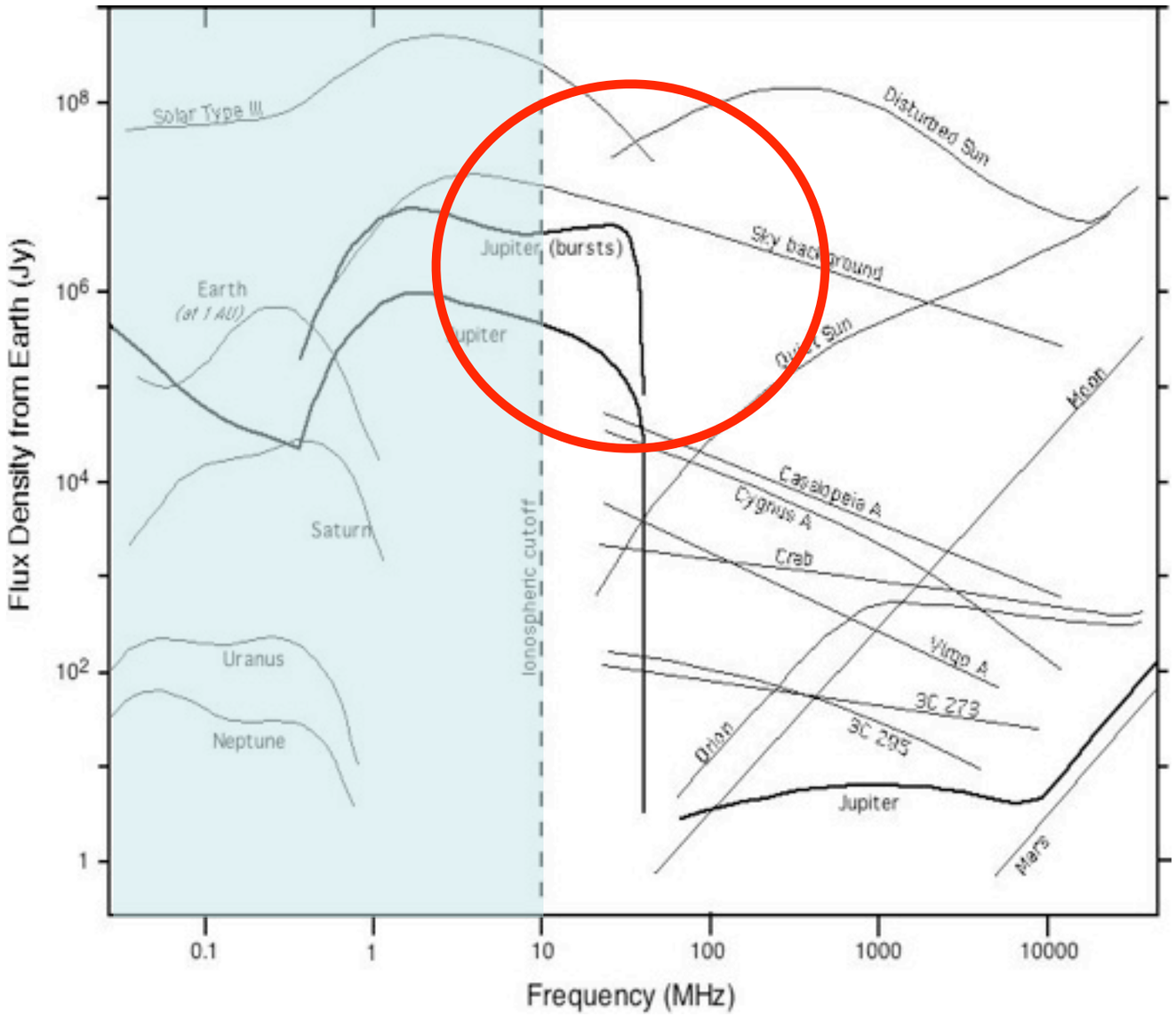
Accepted 3 September 2004

Exoplanets : What do we know ?





Exoplanets : What do we know ?

- Very weak emission if any

Maximum distance for Nσ 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
$A_e = 10^4$ m² (~NDA)	0.003	0.05	0.01	0.2	0.04	0.7
$A_e = 10^5$ m² (~UTR-2)	0.01	0.2	0.03	0.6	0.1	2.2
$A_e = 10^6$ m² (~LOFAR77)	0.03	0.5	0.1	2.	0.4	7.

(distances in parsecs)

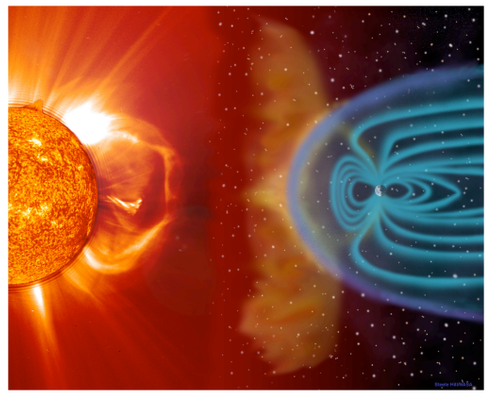
Exoplanets : What do we know ?

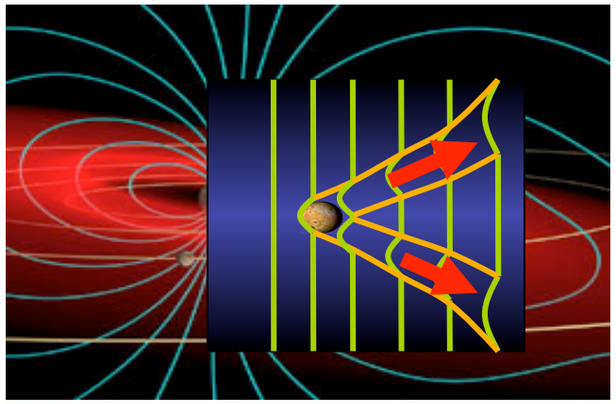
- Electron acceleration → emission level not predictable from first principles
- Various flow/obstacle engines
- "Universal" scaling law → observe hot Jupiters

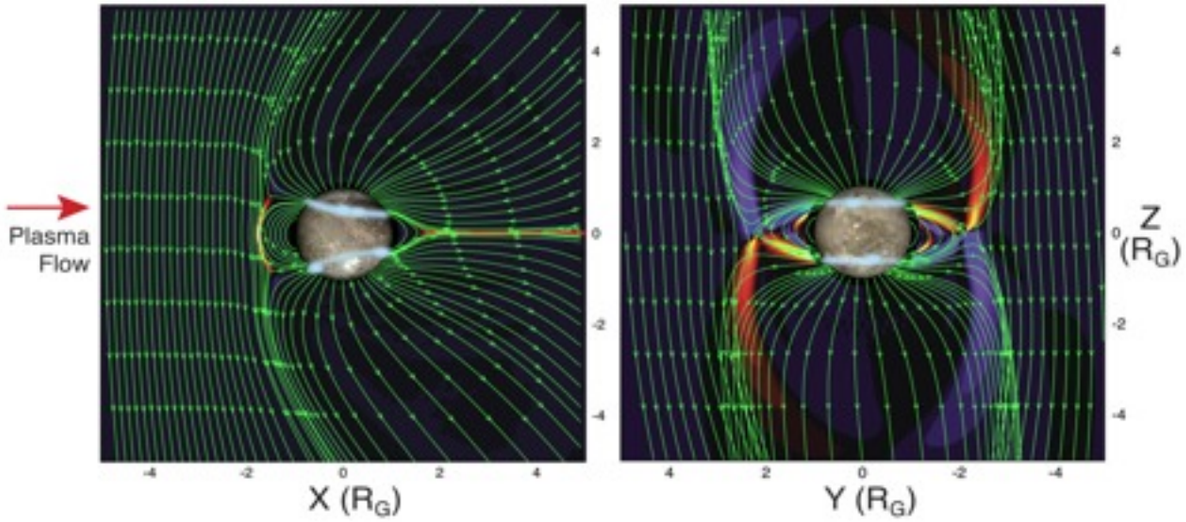
Obstacle \ Flow	Weakly/Not magnetized *(Solar wind)*	Strongly magnetized *(Jovian magnetosphere)*
Weakly/Not magnetized *(Venus, Mars, Io)*	No Intense Cyclotron Radio Emission	Unipolar interaction → Io-induced Radio Emission,
Strongly magnetized *(Earth, Jupiter, Saturn, Uranus, Neptune, Ganymede)*	Magnetospheric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

$$P_d = \varepsilon P_m$$

$$\varepsilon = 0.1 - 0.2$$



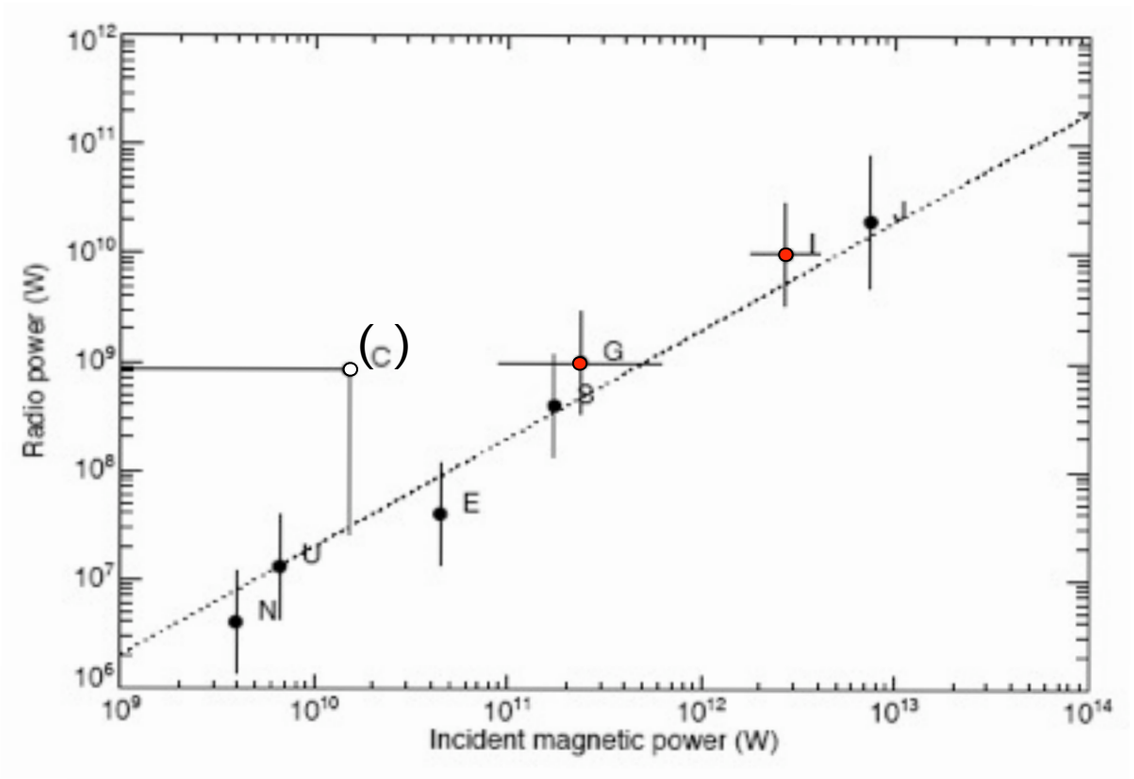


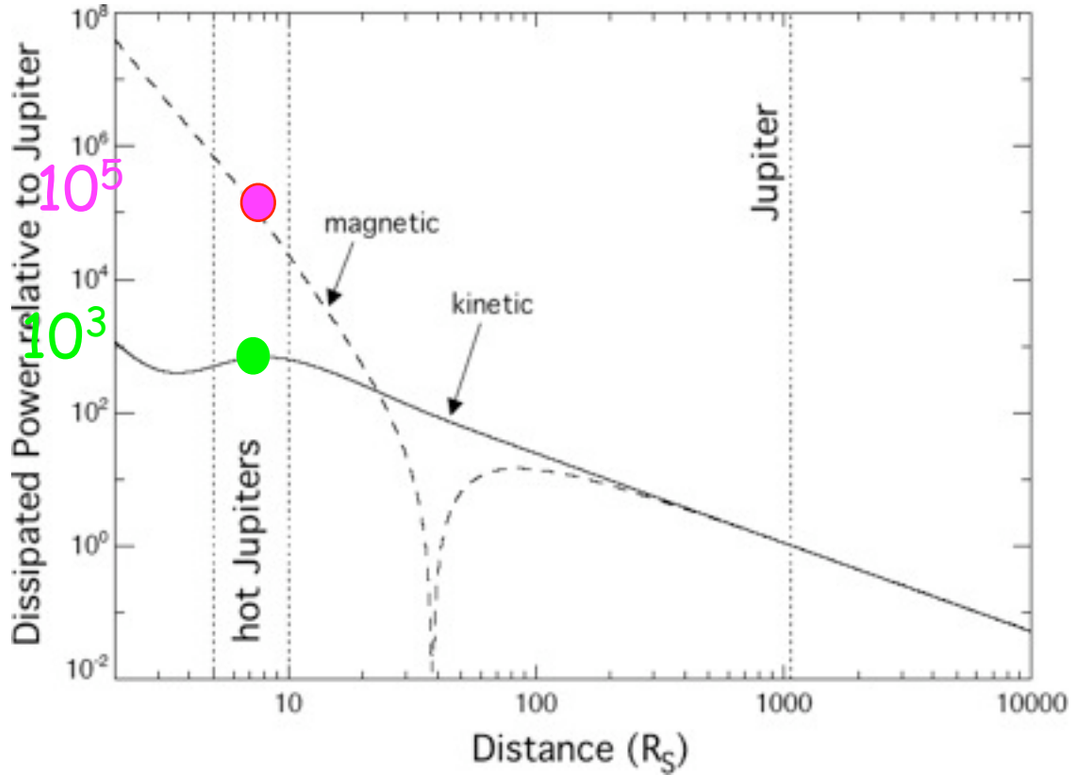


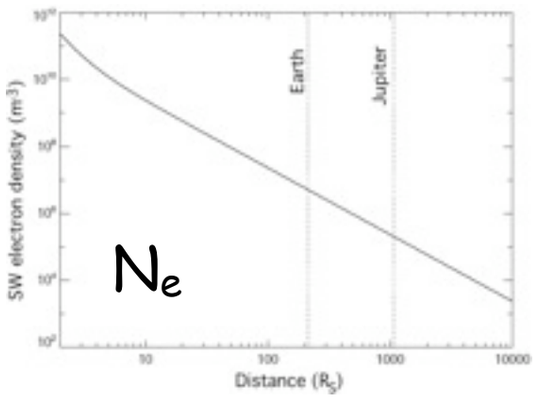
Exoplanets : What do we know ?

- Electron acceleration → emission level not predictable from first principles
- Various flow/obstacle engines
- "Universal" scaling law → observe hot Jupiters

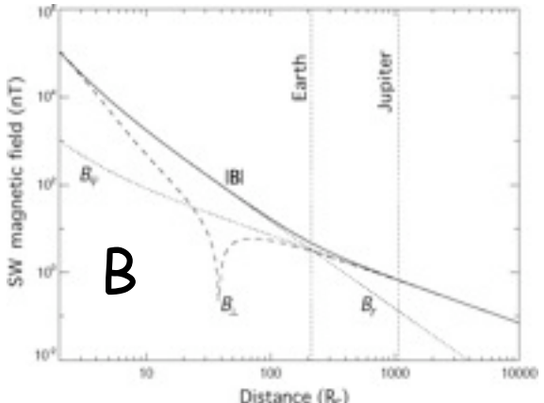
$P_{Radio} \propto P_d \sim \eta \times P_m$ $\eta \sim 2\text{-}10 \times 10^{-3}$



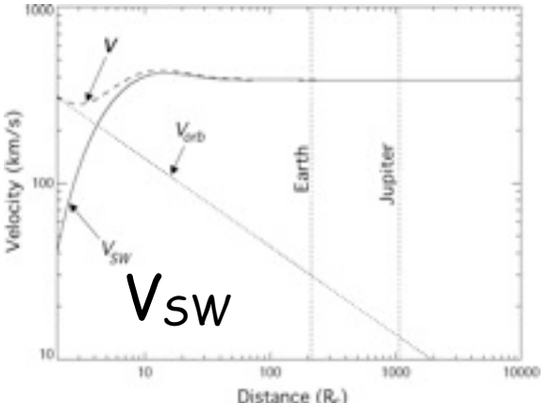




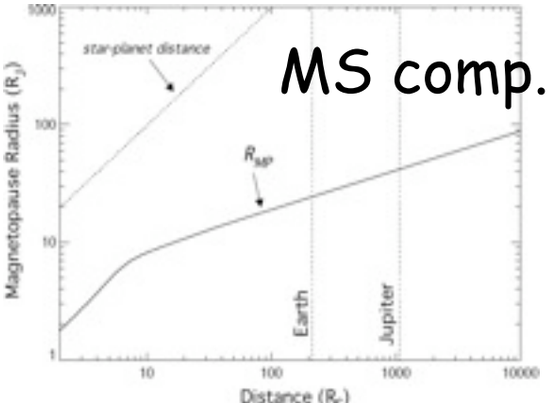
N_e



B



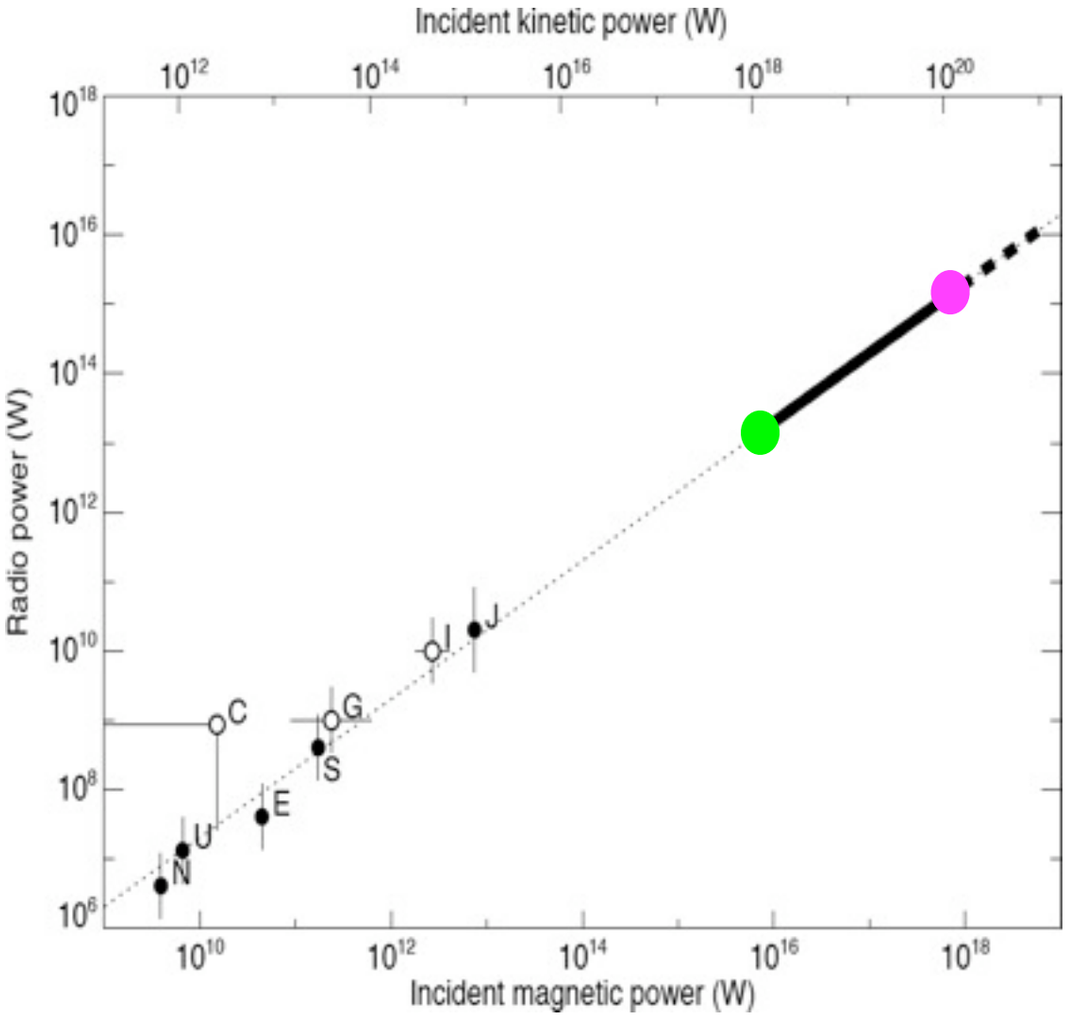
V_{SW}



MS comp.

Exoplanets : What do we know ?

- Electron acceleration → emission level not predictable from first principles
- Various flow/obstacle engines
- "Universal" scaling law → observe hot Jupiters



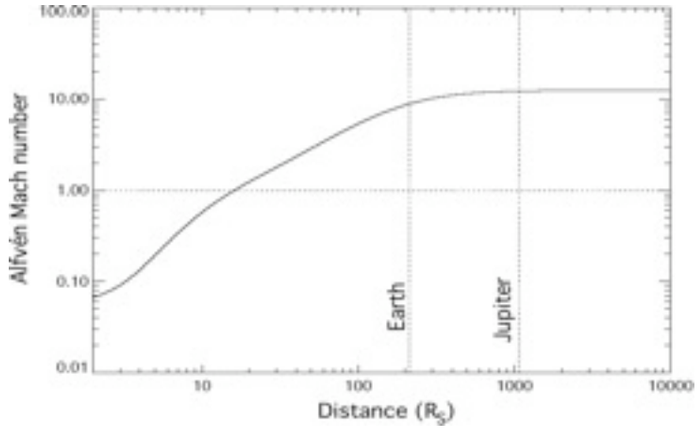
$\zeta = 10^5$

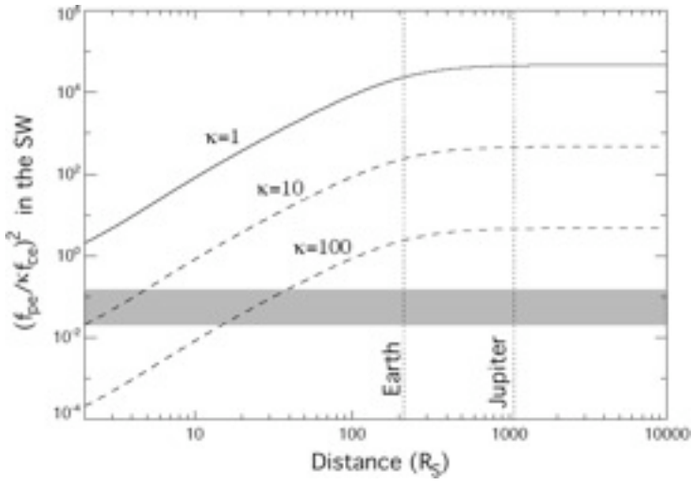
	$b\,\tau = 10^6$ *(1 MHz, 1 sec)*		$b\,\tau = 2\times10^8$ *(3 MHz, 1 min)*		$b\,\tau = 4\times10^{10}$ *(10 MHz, 1 hour)*	
	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz
$A_e = 10^4$ m^2 *(~NDA)*	1	16	3	59	13	220
$A_e = 10^5$ m^2 *(~UTR-2)*	3	50	11	190	40	710
$A_e = 10^6$ m^2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

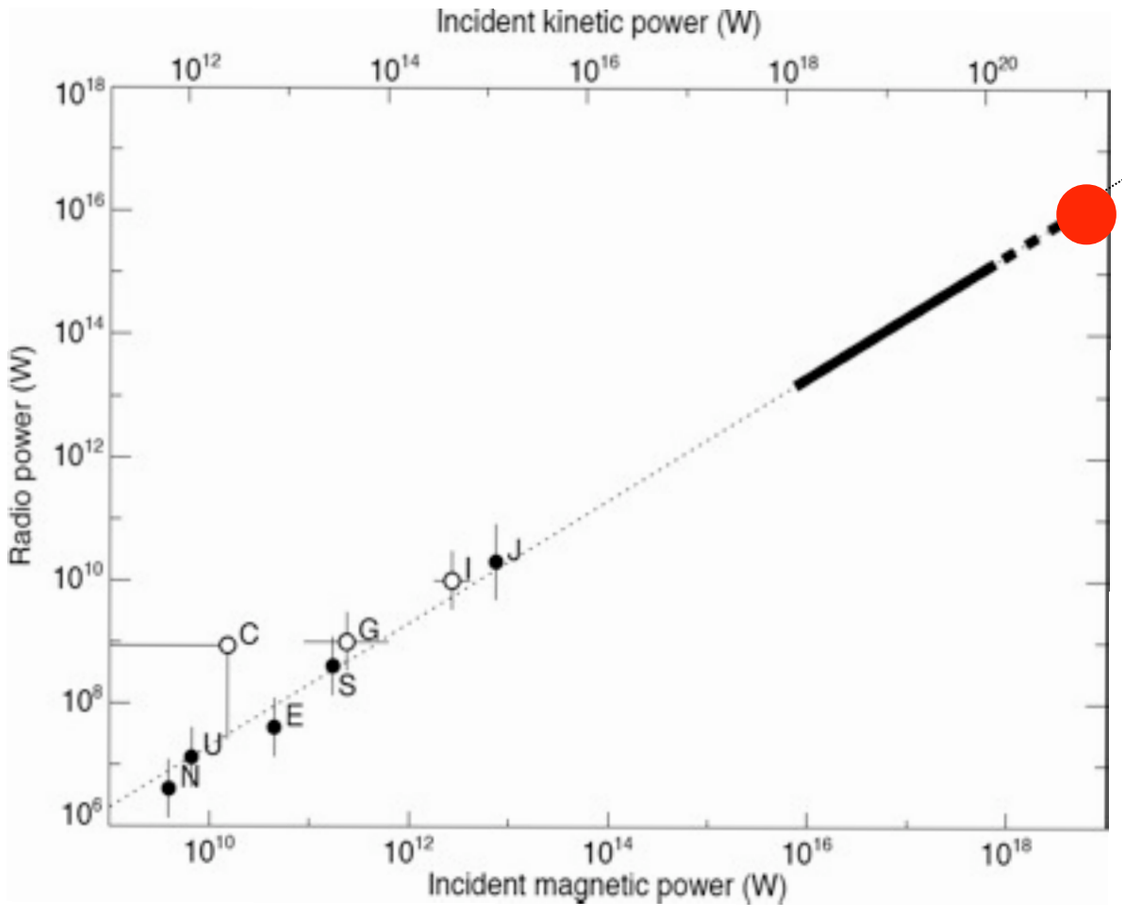
Exoplanets : What do we know ?

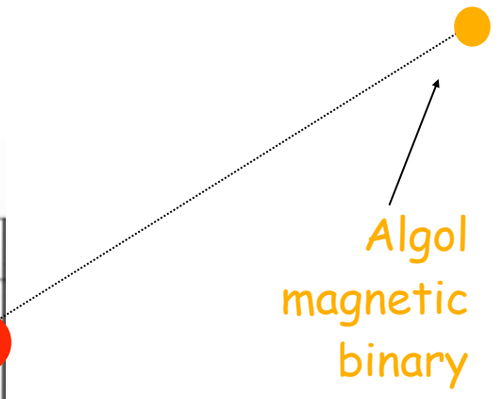
- Planetary magnetic fields ? (scaling laws, effect of spin-orbit locking)

$\omega\downarrow$ $\qquad$ $\mathcal{M} \propto \omega^{\alpha}$ $\qquad$ $\frac{1}{2} \leq \alpha \leq 1$ $\qquad$ $\rightarrow \mathcal{M}\downarrow$ (B decay) ?





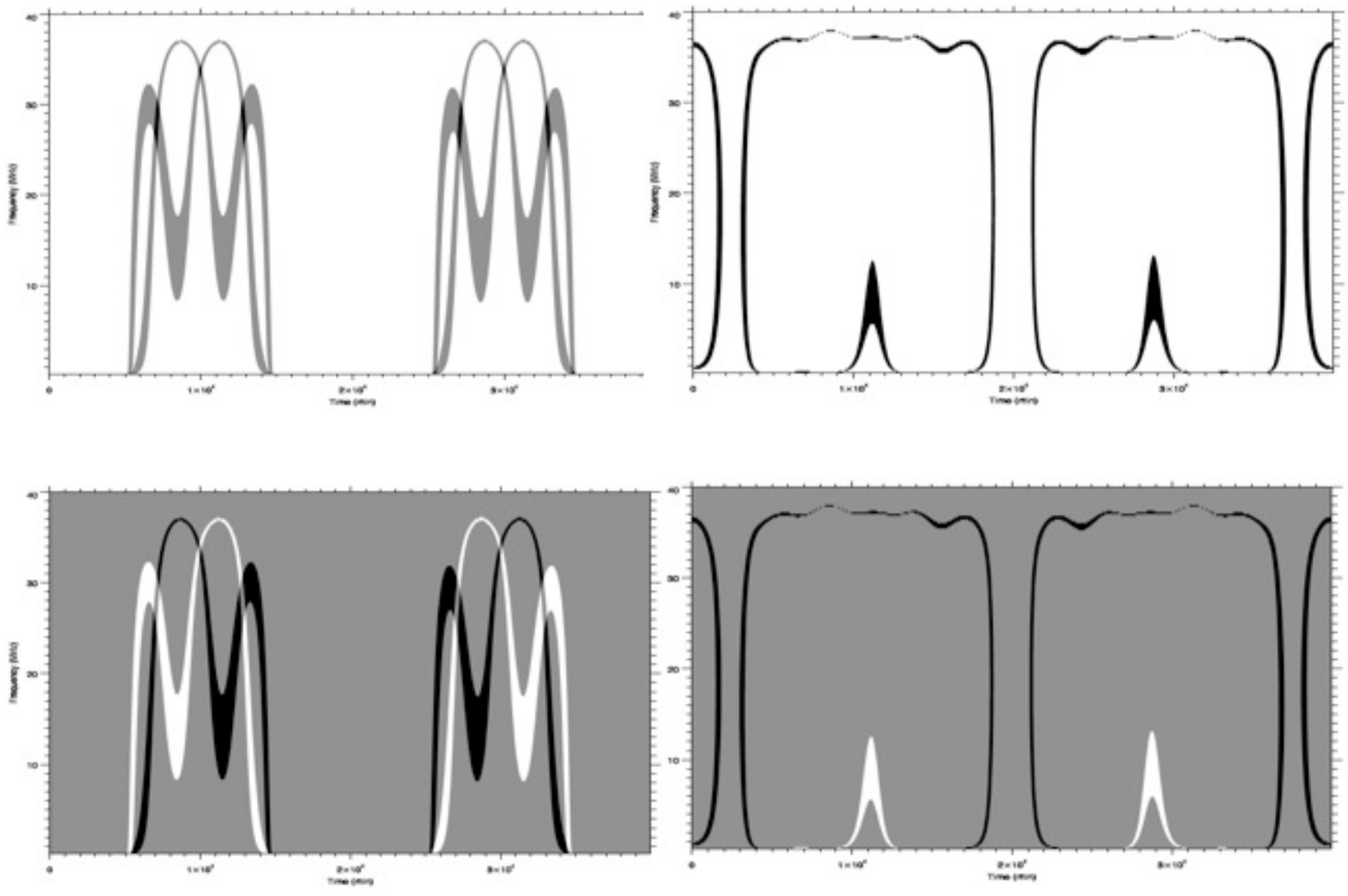




Exoplanets : What do we know ?

- Various detailed effects (role of stellar age, CME, SW estimates via Fx, SW modeling, effect of IS scintillations, M estimates, B*-p topology)

- ExPRES modelling



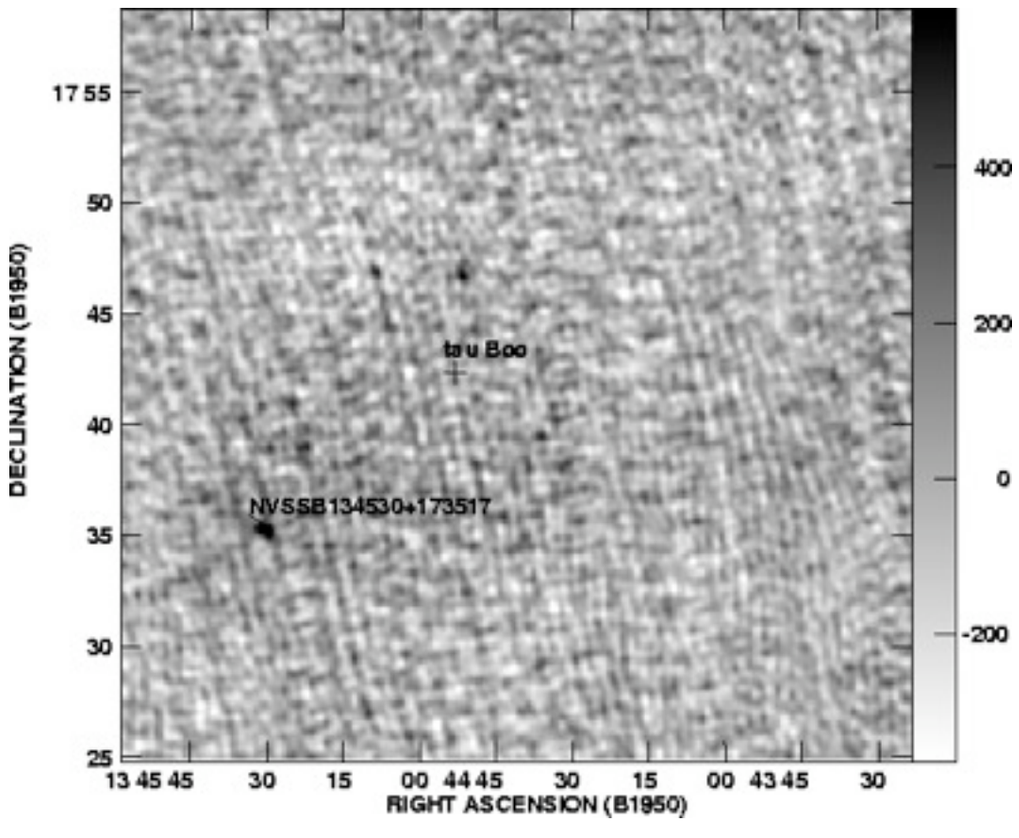
i = 0° i = 30°

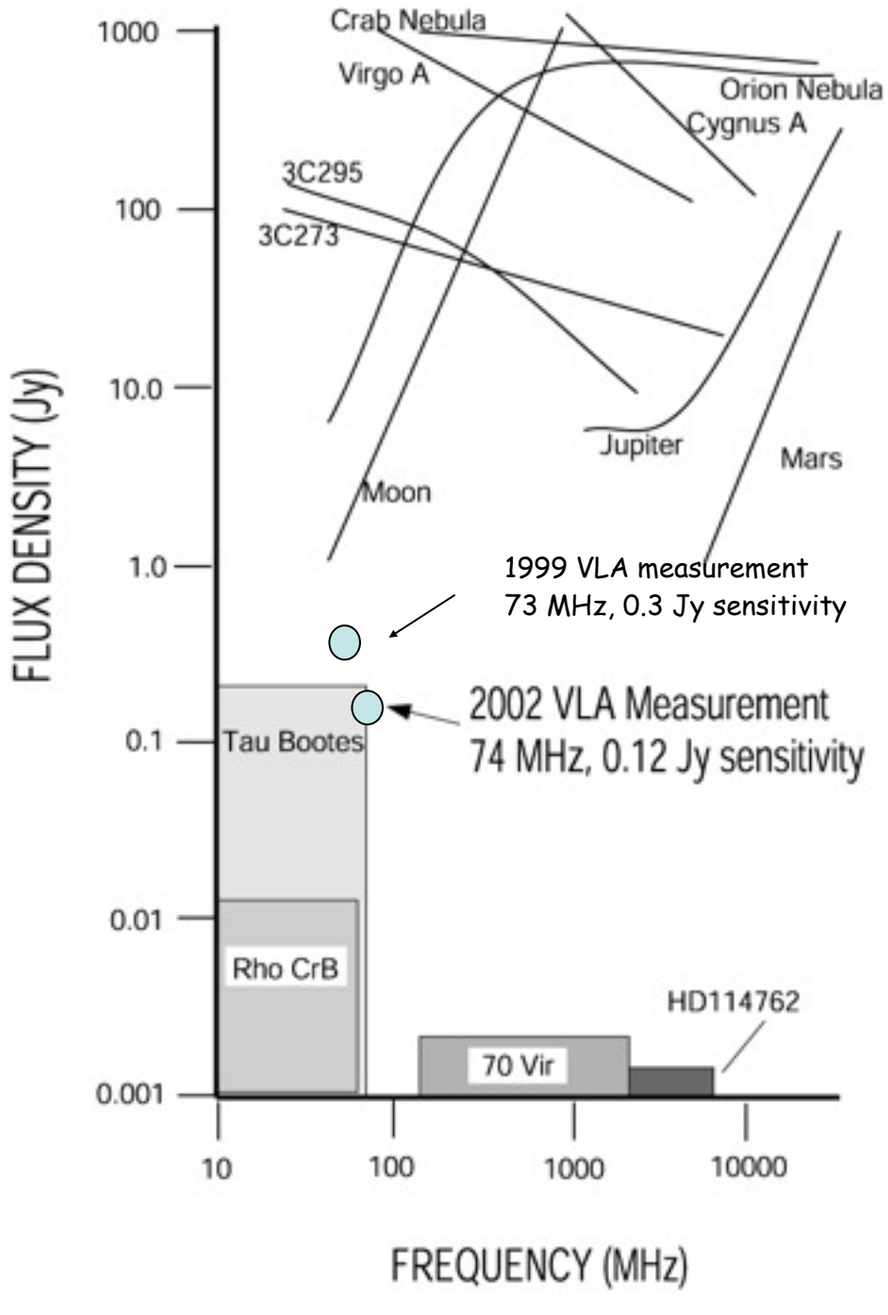
Exoplanets : What do we know ?

- Observations at VLA @74, 333, 1465 MHz : Tau Boo

Winglee et al. (1986), Bastian et al. (2000), Farrell et al. (2003, 2004), Lazio & Farrell (2007), Lazio et al. (2010)

→ no detection (but low A_{eff} / high frequency)





Exoplanets : What do we know ?

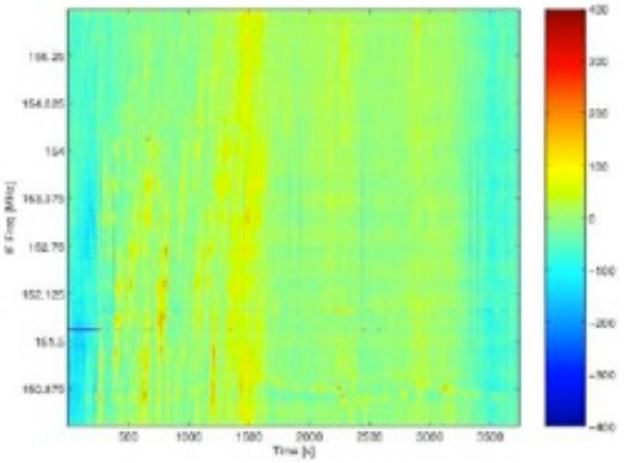
- Observations at GMRT

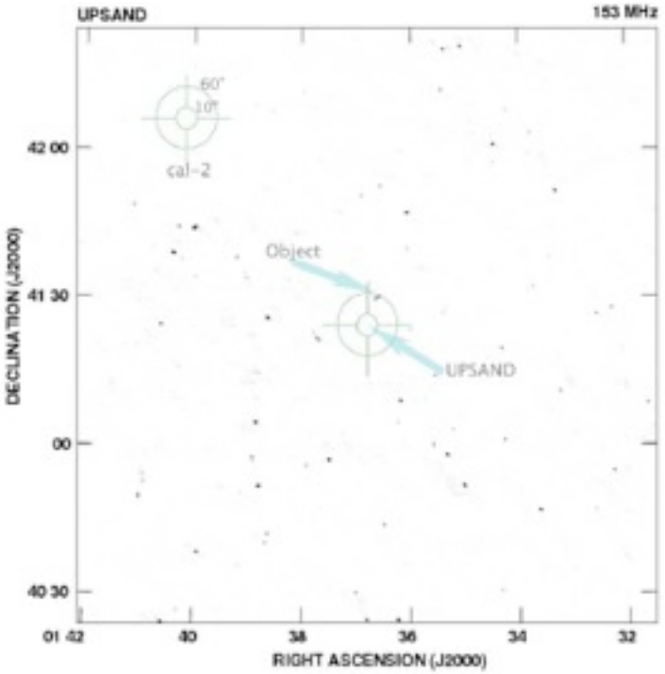
@ 153 MHz (Winterhalter et al., 2006; Majid et al., 2006; George and Stevens, 2007, 2008) : Tau Boo, Ups And

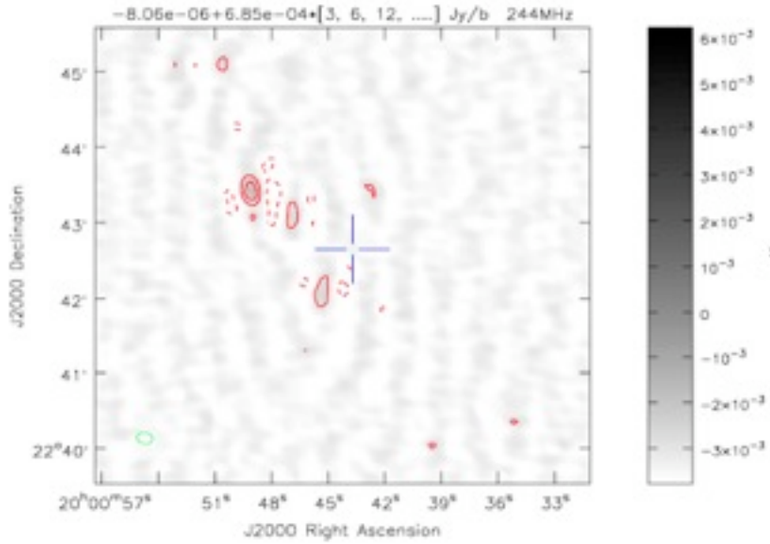
→ no detection (strongly polluted data, high frequency)

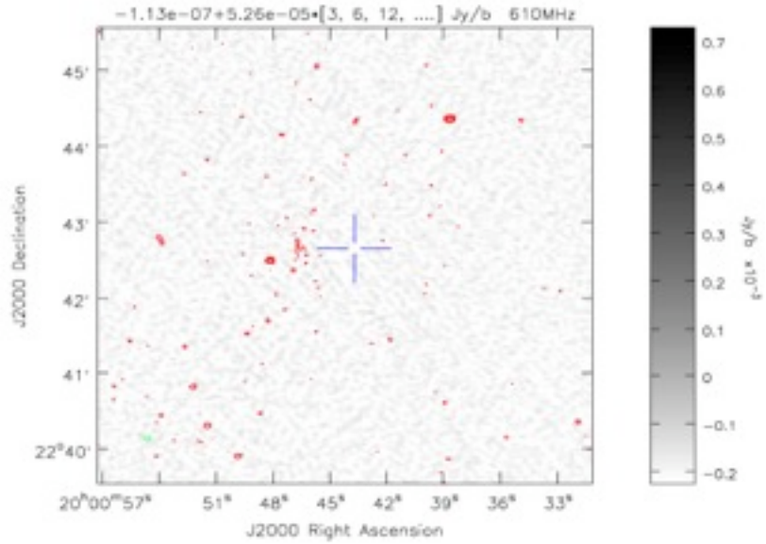
@ 244 & 614 MHz (Lecavelier des Etangs et al., 2009) search for anti-transits of 189733

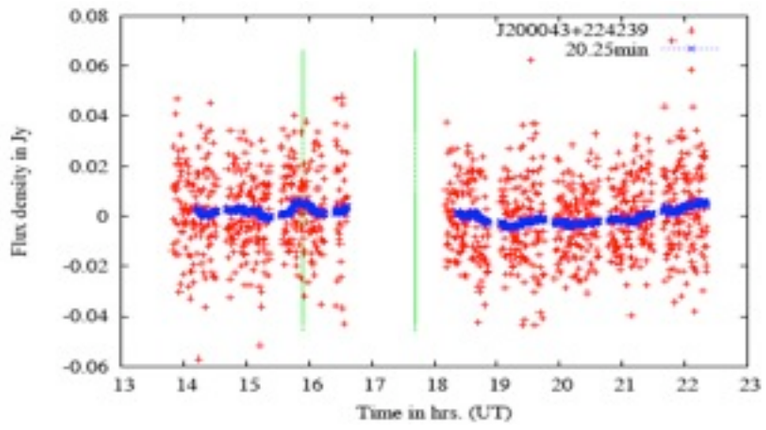
→ no detection in spite of << mJy sensitivity

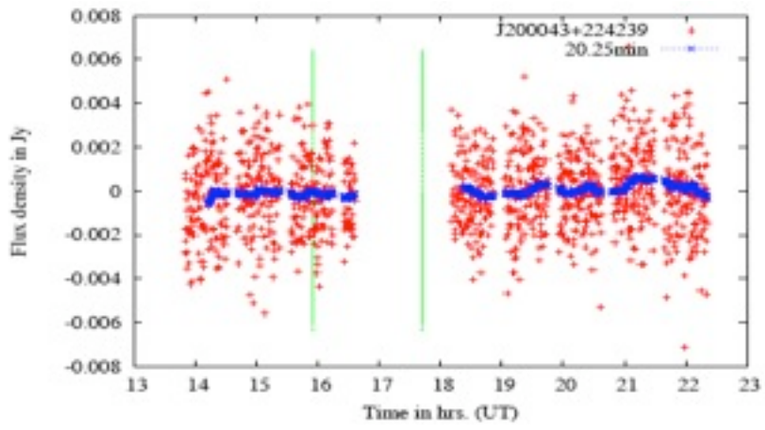












→ Unlikely to detect synchrotron emission from extrasolar planets: upper estimates

~ a few nJy, vs expected sensitivity ≤ microJy

Exoplanets : What do we know ?

- Observations at UTR-2 (12-32 MHz, ~40 targets, Zarka et al.)

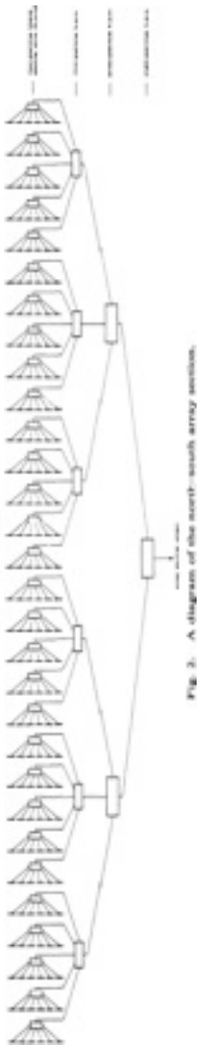
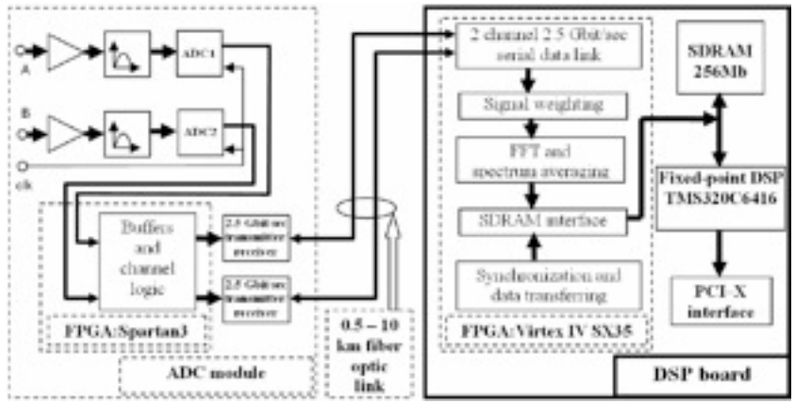
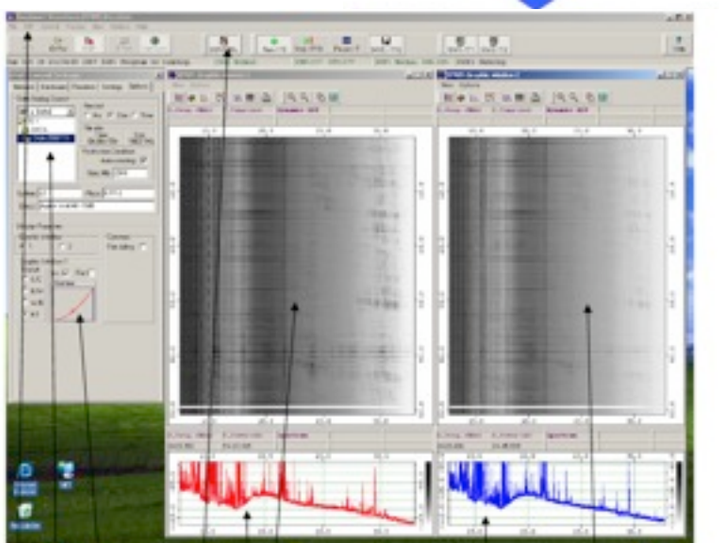


Fig. 2. A diagram of the north–south array section.

Fig. 3. A diagram of the east–west array section.





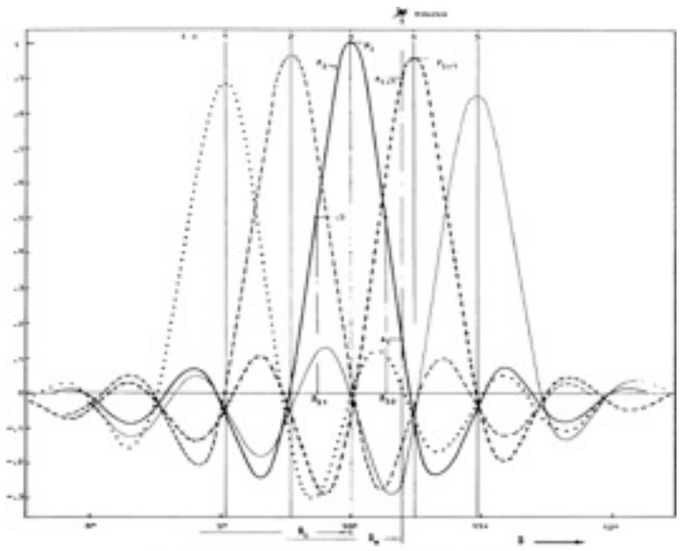


Fig. 5. Five-beam pattern of the north–south array.

Exoplanets : What don't we know ?

- If radio emission exists, intensity, frequency range, dynamic spectrum, variations ...

  everything !

  → turn Theory into Reality

Exoplanets : What can we learn with LOFAR ?

Interests:

- Direct detection → (validation of predictive scaling laws, planet-star distinction via polarization & periodicity)
- Exoplanetary magnetic fields → (internal structure models, scaling laws)
- Comparative magnetospheric physics (+ star-planet interactions, stellar wind strength / X flux, age, activity, CME …)
- Planetary rotation period → (testing spin-orbit coupling)
- Possible access to orbit inclination
- Possible discovery of intense radio-exoplanets

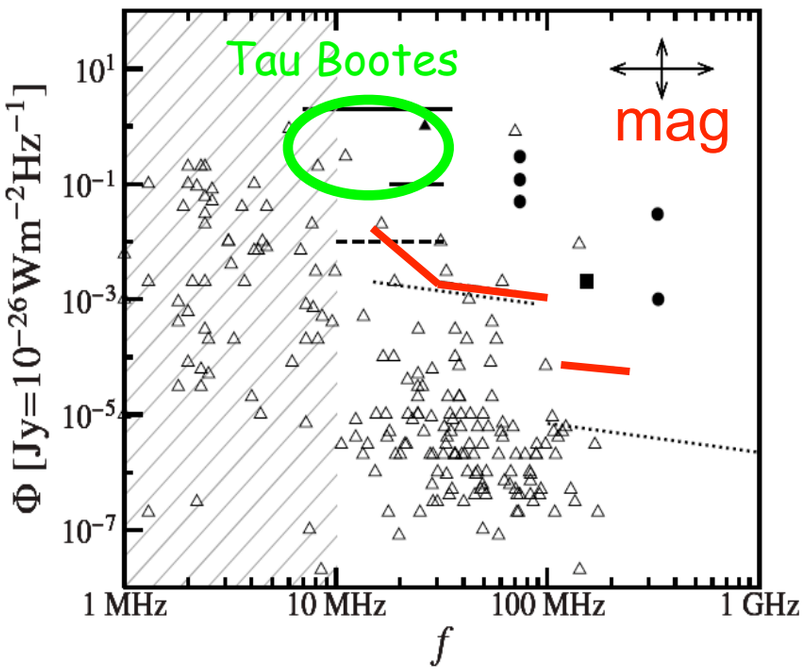
+

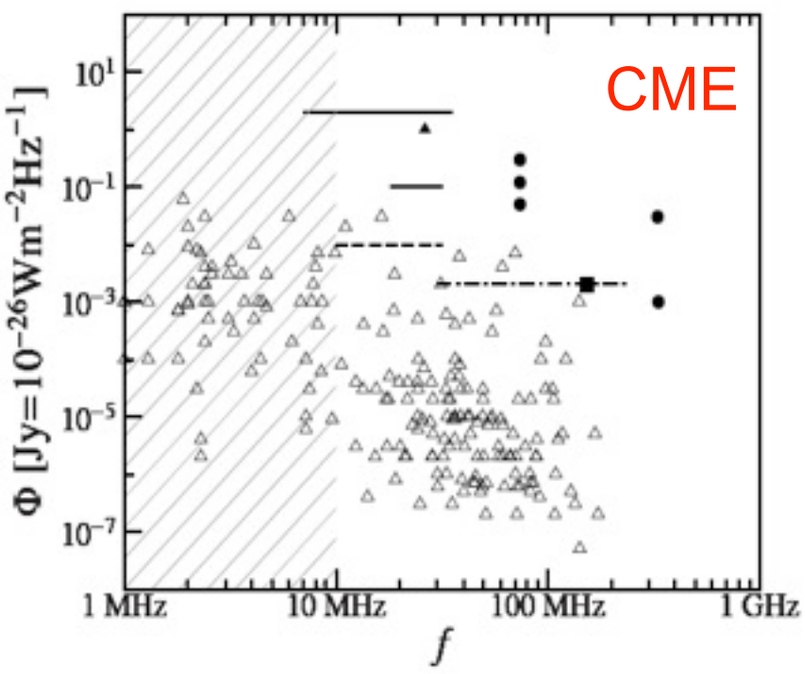
Planetary protection (versus atmospheric escape & cosmic ray bombardment)

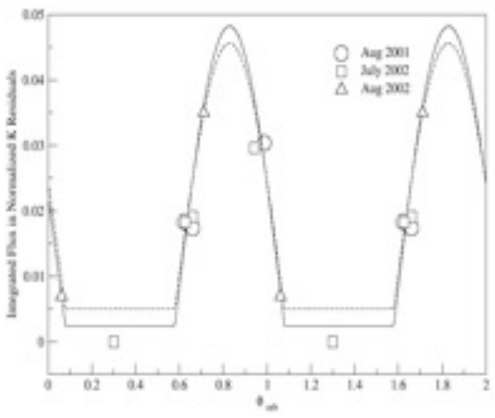
Exoplanets : What can we learn with LOFAR ?

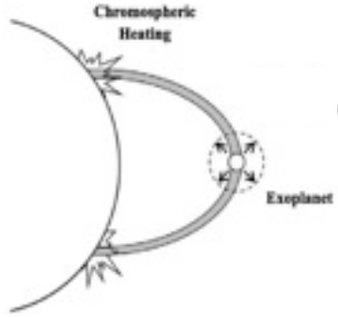
- Detection of ONE radio exoplanet would represent a major advance !

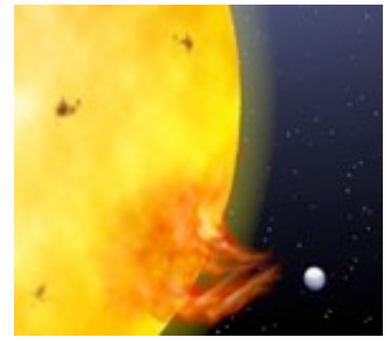
→ how to select targets ? ~predictions / census of HJ, magnetic stars, chromospheric activity, COROT targets, + all nearby stars & selected magnetic stars (red dwarfs...)



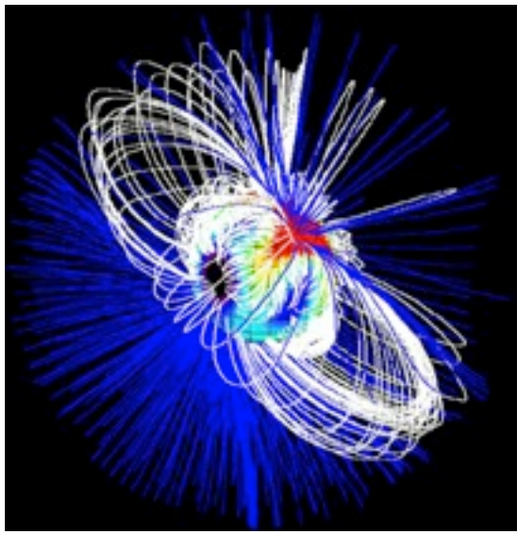






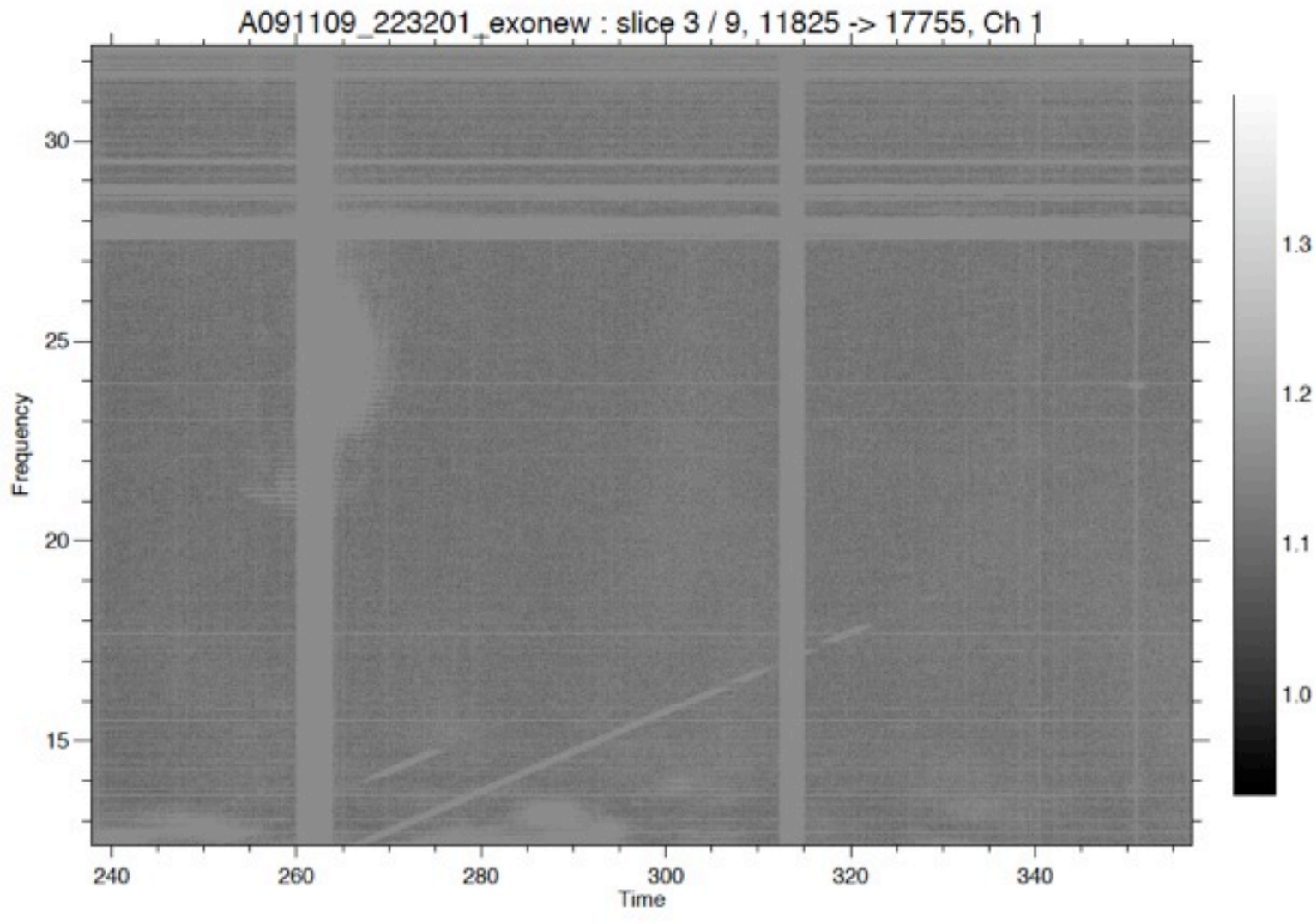


Tau Boo : 5-10 *G* (10^{-4} T)
HD 76151 : ~10 *G*
HD 189733 : >50 *G*
HD 171488 : 500*G*



Exoplanets : What can we learn with LOFAR ?

→ Requires deep RFI mitigation



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The radio search for extrasolar planets with LOFAR

W.M. Farrell[a,*], T.J.W. Lazio[b], P. Zarka[c], T.J. Bastian[d], M.D. Desch[a], B.P. Ryabov[e]

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Plasma interactions of exoplanets with their parent star and associated radio emissions

Philippe Zarka*

A&A 475, 359–368 (2007)
DOI: 10.1051/0004-6361:20077397

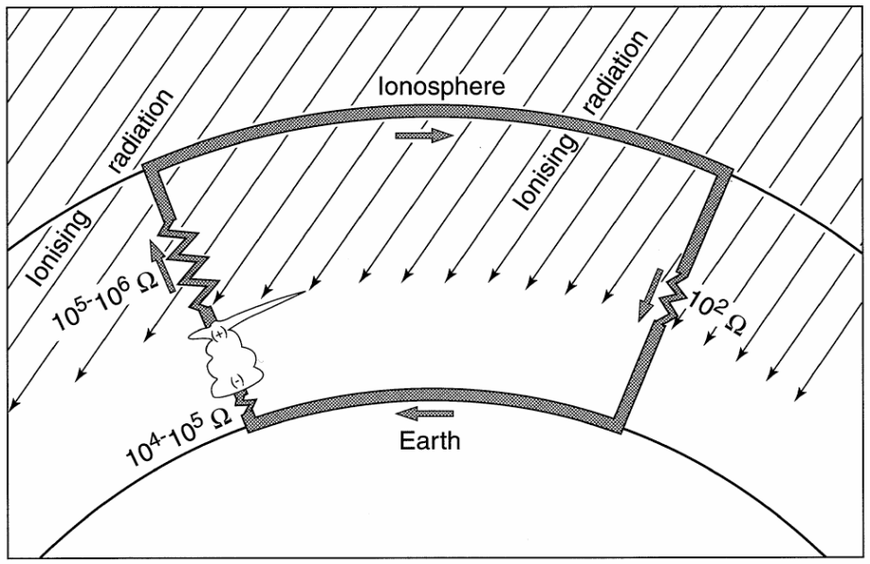
Astronomy & Astrophysics

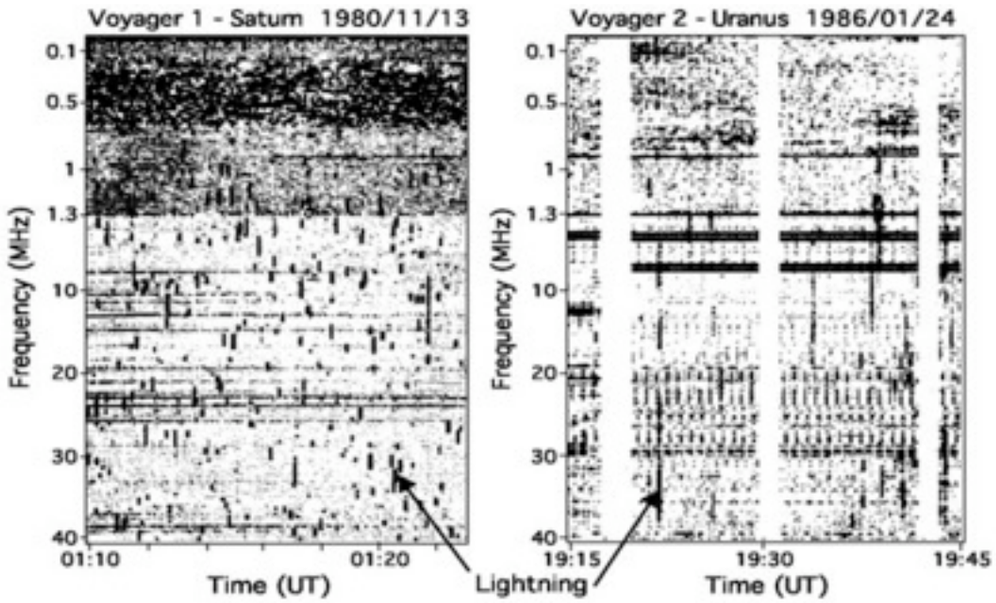
Predicting low-frequency radio fluxes of known extrasolar planets⋆,⋆⋆

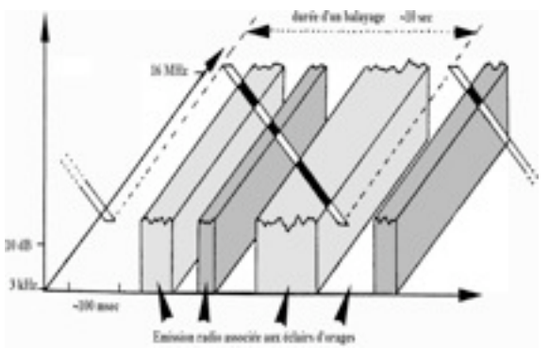
J.-M. Grießmeier[1], P. Zarka[1], and H. Spreeuw[2]

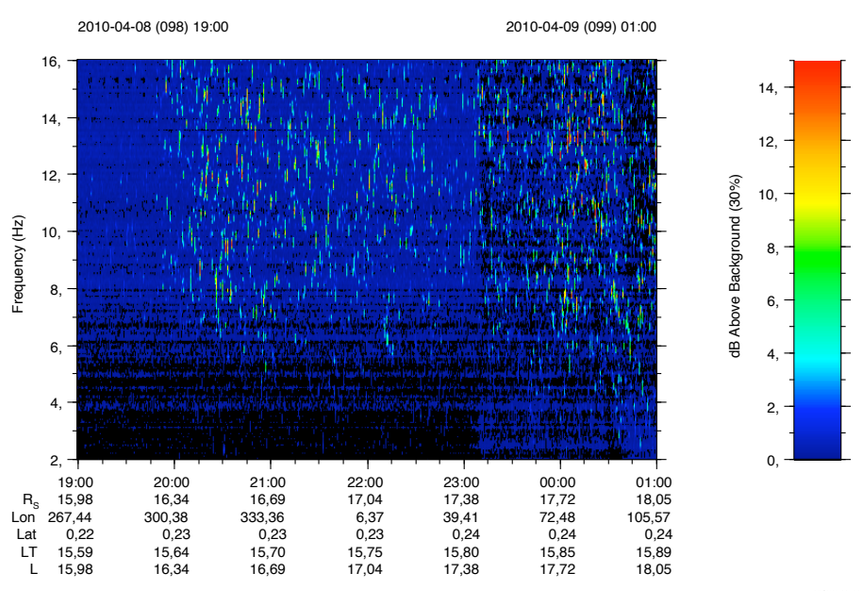
Lightning : What do we know ?

- Antenna radiation (current discharge), from small-scale charging, large-scale charge separation, E-field build-up
- Spectrum 1/f-1/f^4 (depends on Stroke duration, path tortuosity, distance)
- Flash duration & distribution, correlation/optical flashes & storms









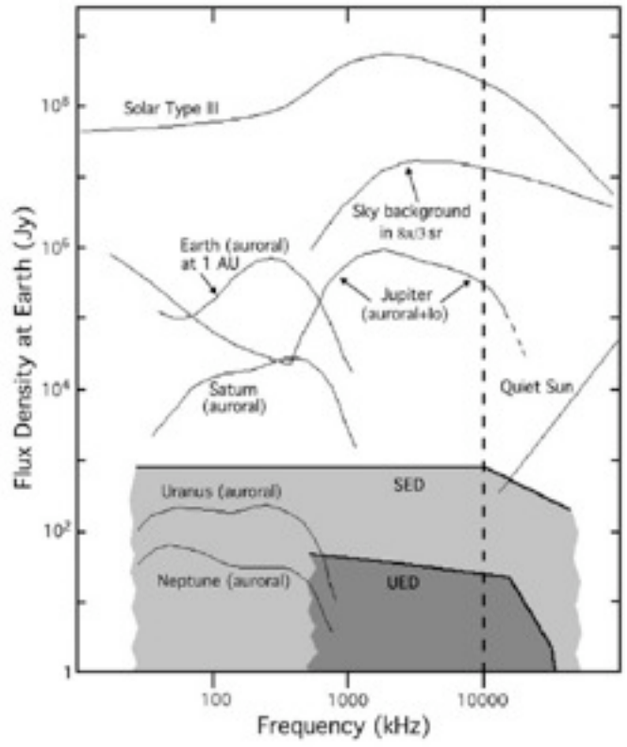
Lightning : What do we know ?

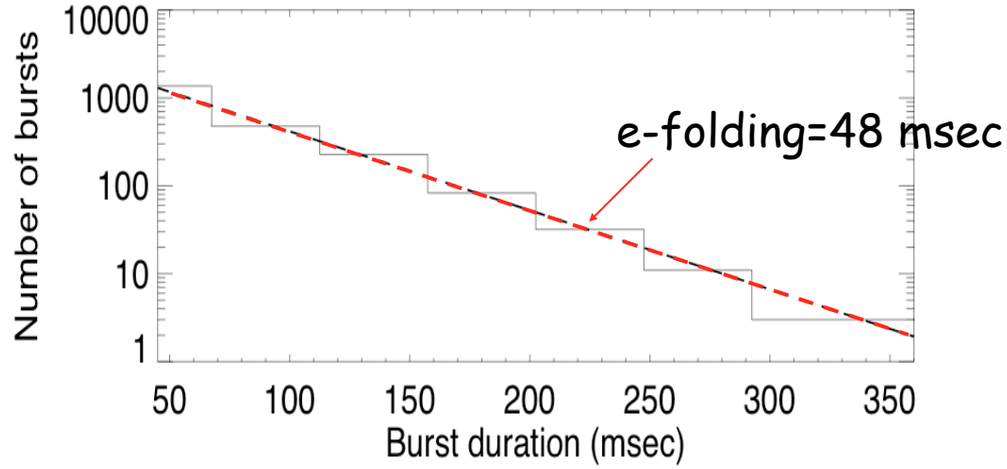
- Saturn & Uranus lightning occurrence, intensity, duration
- Meteorology @ Saturn (SED) with Cassini, ionospheric density

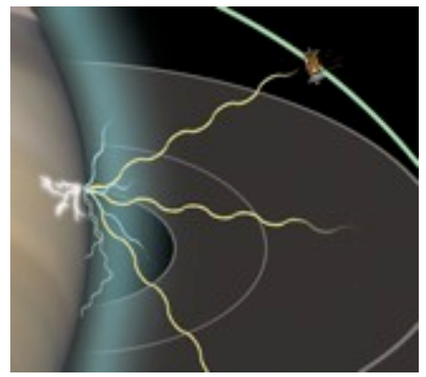
SED
- a few events/minute
- 30 to 300 msec
- ≤20 kHz to ≥40 MHz
- ~0.1 to 100 W/Hz

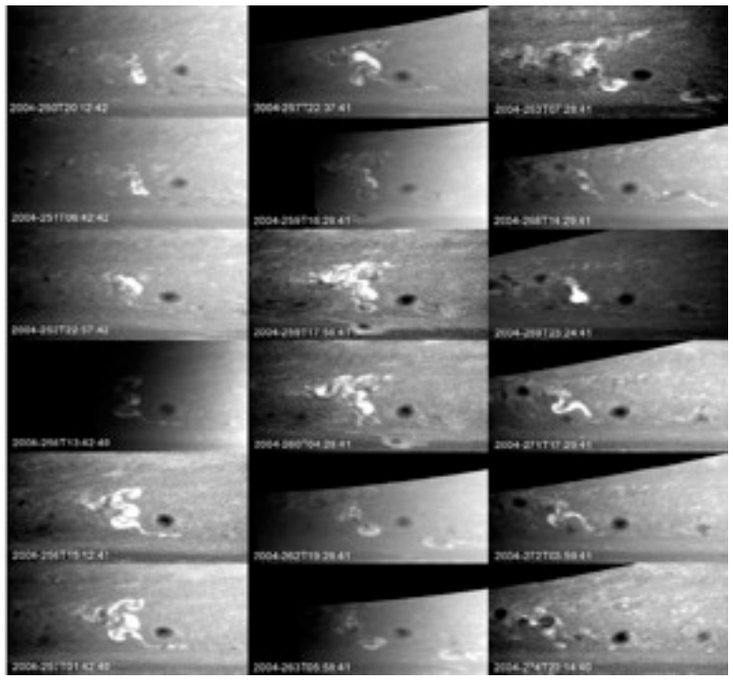
→ ~0.4 to 400 Jy @ Earth

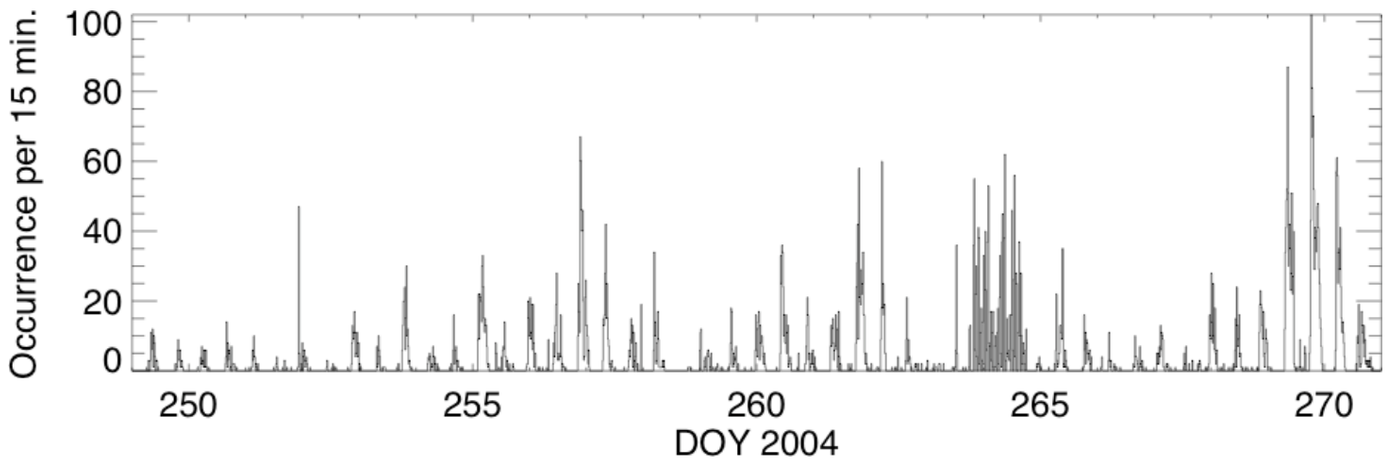
UED
- spectrum in ~f^{-1}
- ~0.3 to 25 Jy @ Earth







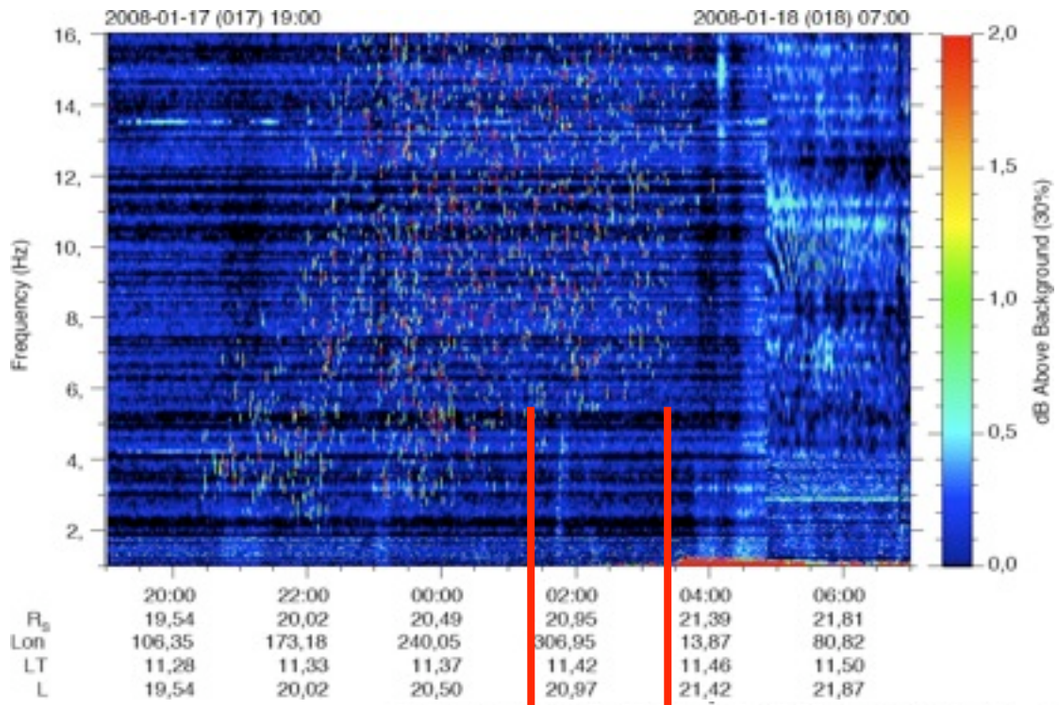


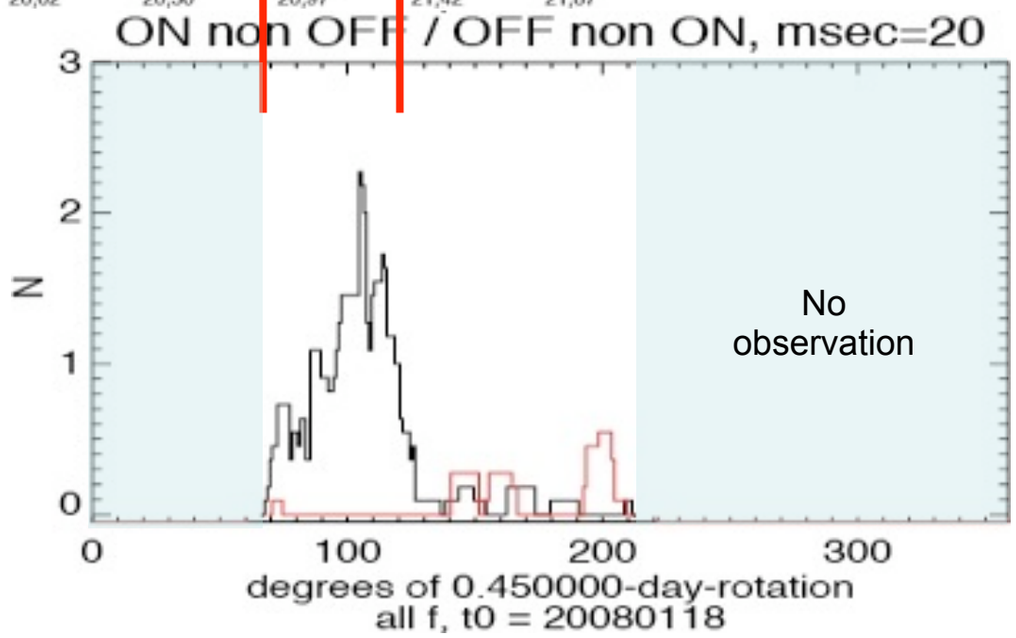


Lightning : What do we know ?

- SED detection at UTR-2, monitoring by Cassini until 2017 !

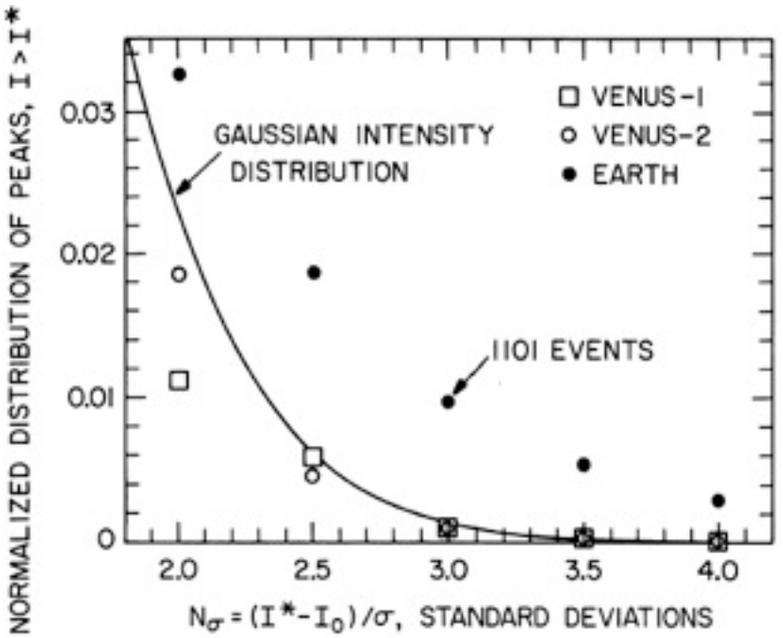
Saturn's lightning

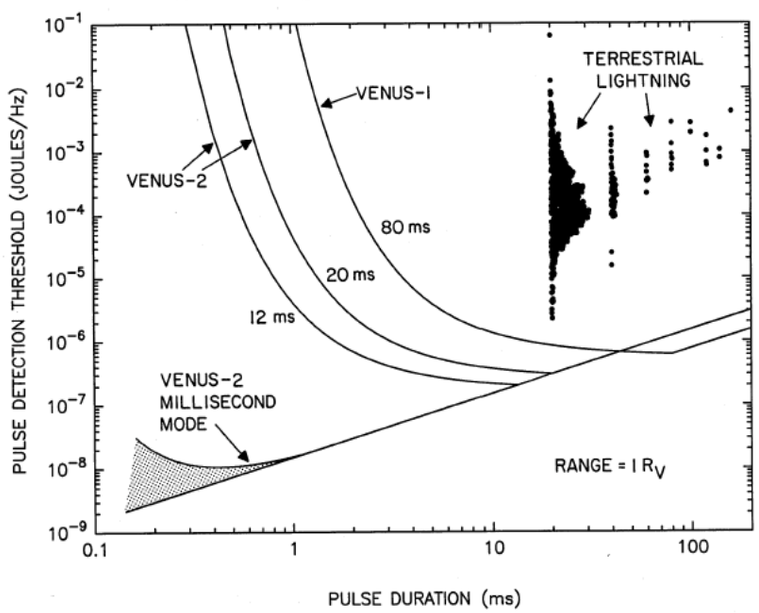


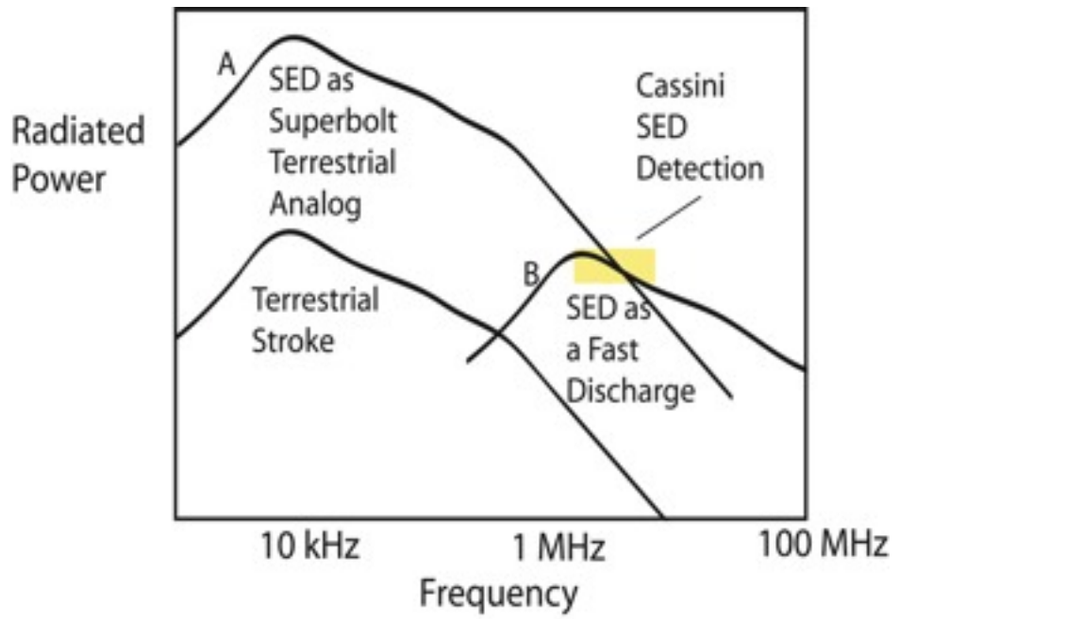


Lightning : What don't we know ?

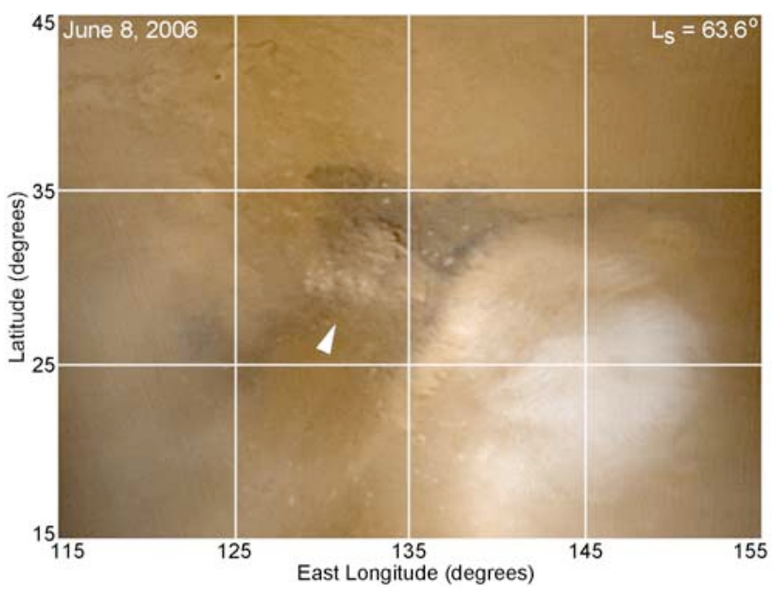
- Stroke duration at planets other than Earth → energy ?
- Existence (& properties) at Venus ?
- Dust-devils (& properties) @ Mars ?
- Transient ? existence (& properties) at J, N ?







Flux observed about 10 MHz for Saturn's lightning (SED – in yellow) and the two possible interpretations (A) and (B).



Lightning : What can we learn with LOFAR ?

Interests :

- Comparative lightning physics (electrification processes, atmospheric dynamics & cloud structure, geographical and seasonal variations …)

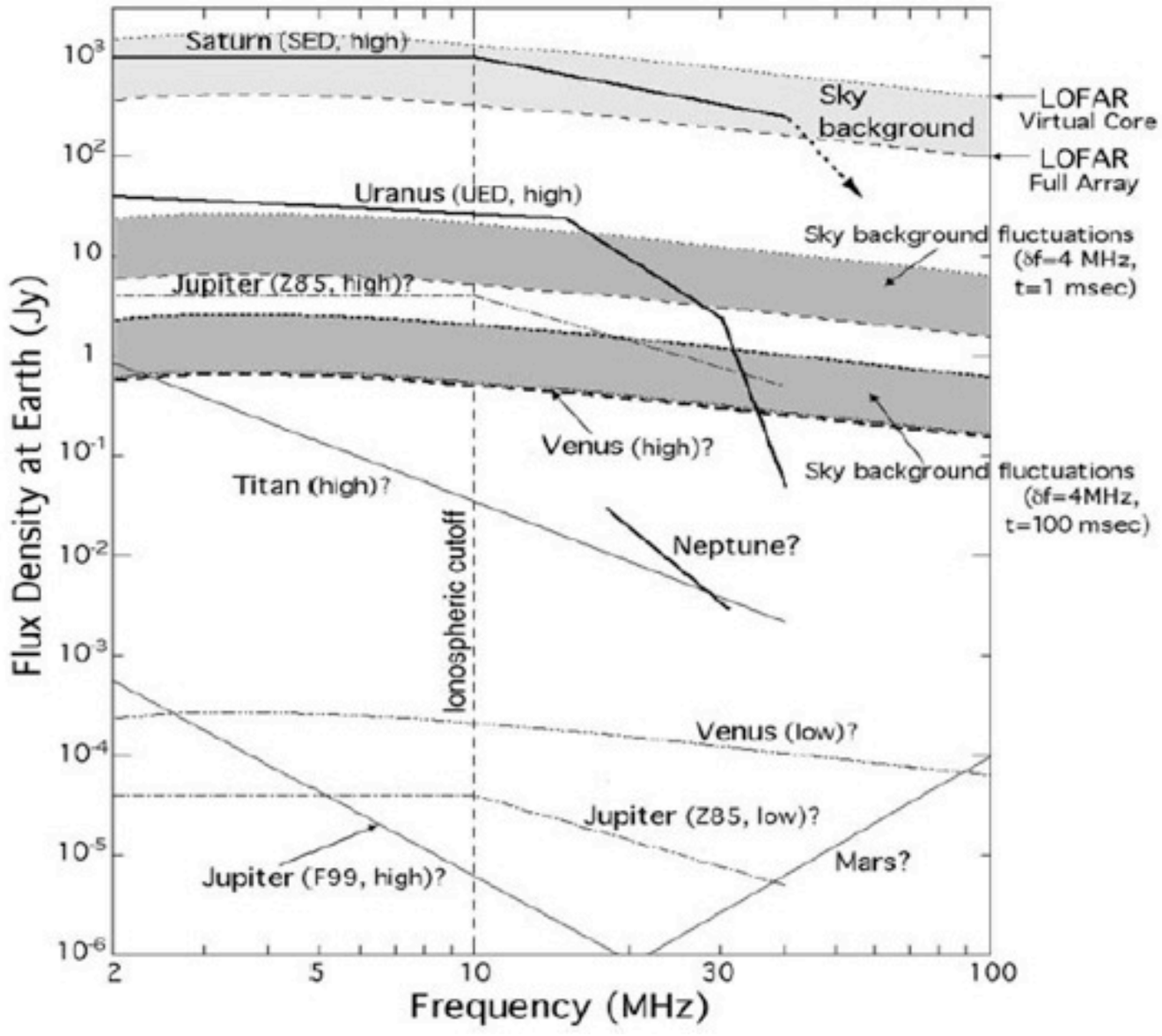
→ role in the atmospheric chemistry (production of non-equilibrium trace organic constituents, potentially important for biological processes)

- Comparative planetary meteorology (/Earth), correlation with optical / IR surveys

+

- not @Titan or @exoplanets !
- broadband TAB observations
- no need for high resolution imaging (as 2nd step only)

Planet	$Ø_{eq}$ (km)	a (ua)	$Ø_{eq\text{-}max}$ (")
Venus	12140	0.72	60.5
Mars	6790	1.52	17.9
Jupiter	142600	5.20	46.8
Saturne	120200	9.54	19.4
Titan	5150	9.54	0.8
Uranus	49000	19.18	3.7
Neptune	50200	30.06	2.4



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Study of solar system planetary lightning with LOFAR

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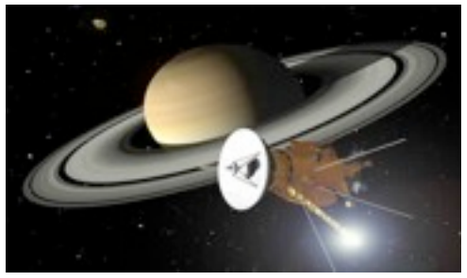
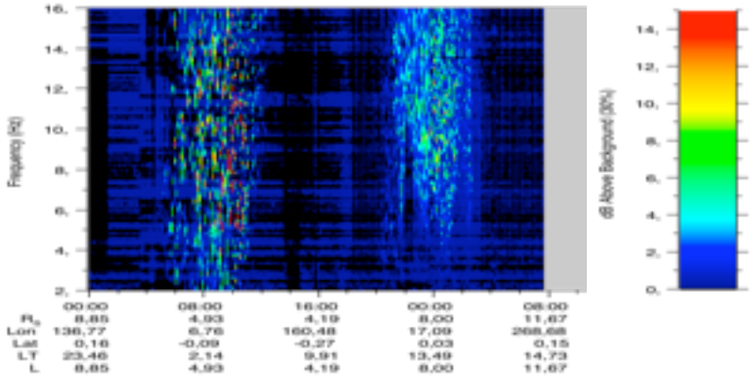
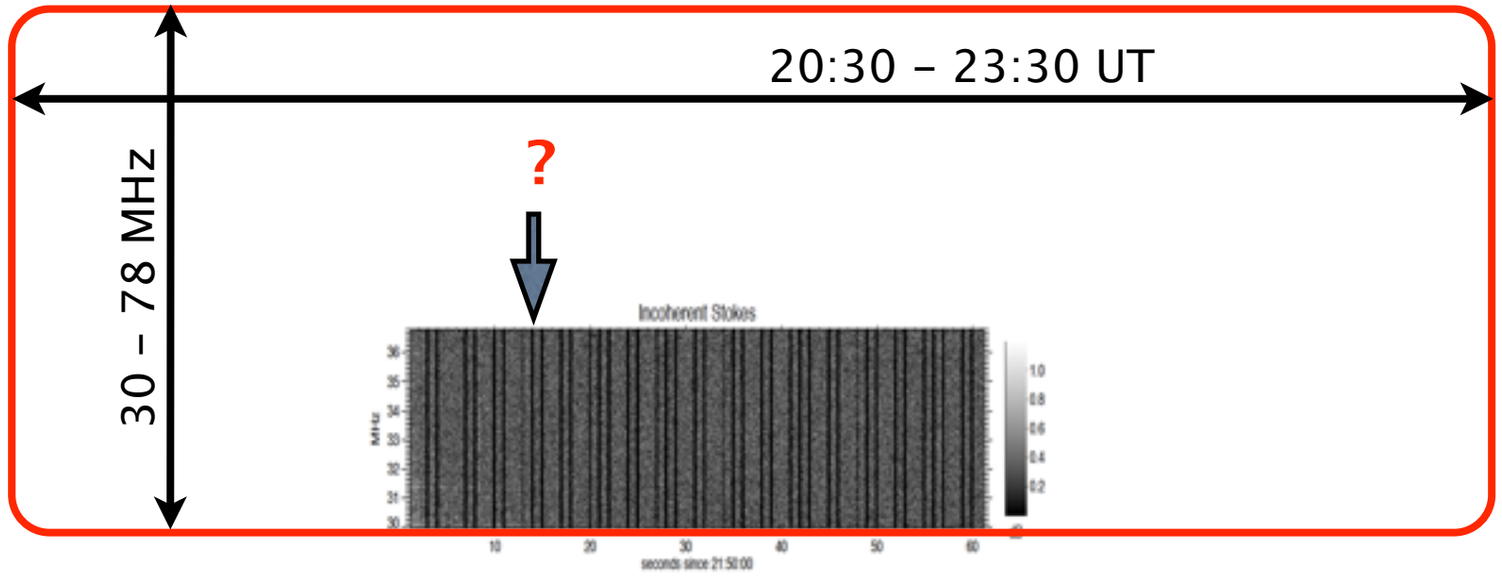
Accepted 3 September 2004

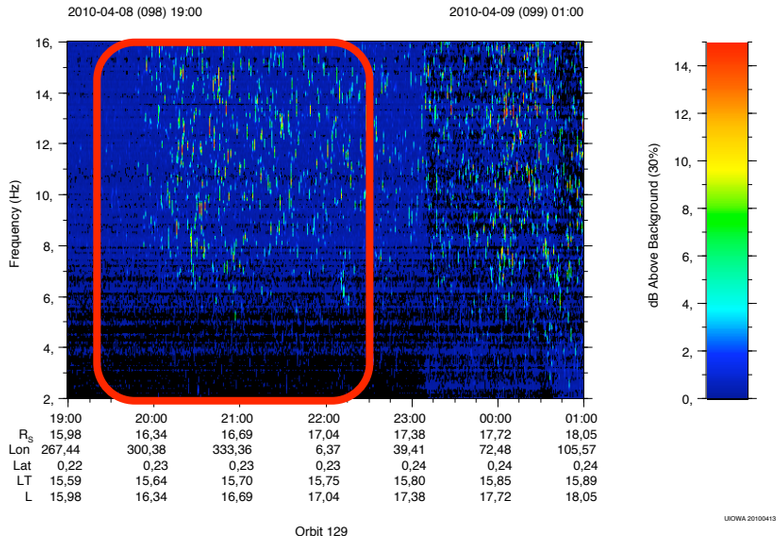
Lightning : commissionning Observations

- Cassini-predicted 3hr observations → SED activity catched









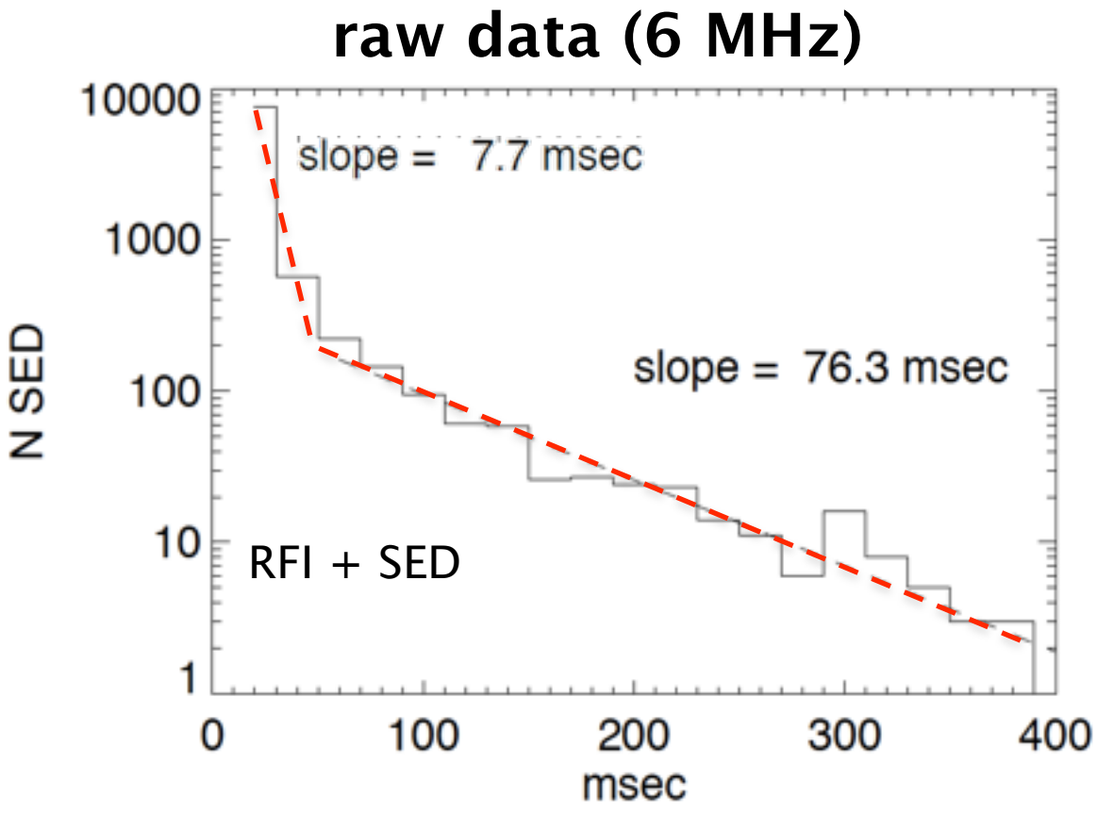
$\sigma_{sky} = 2kT_{sky}/(A (b\,\tau)^{1/2})$ $\quad T_{sky} \sim 1.15\times10^{8}/f^{2.5}$ & $A_{1\ Station} \sim 48\lambda^2/3$

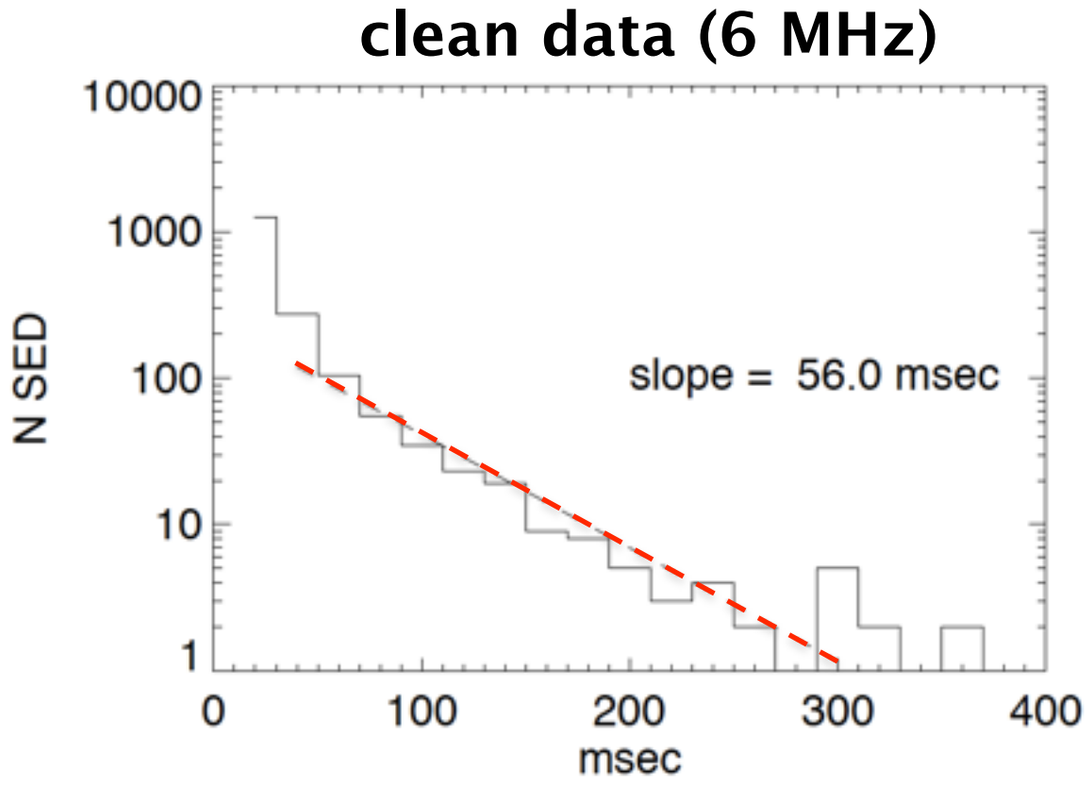
Nb of Stations	f	b	τ	σ_{sky}
1 station	30 MHz	195 kHz	82µs	10^4 Jy
10 stations	30 MHz	6 MHz	20ms	37 Jy

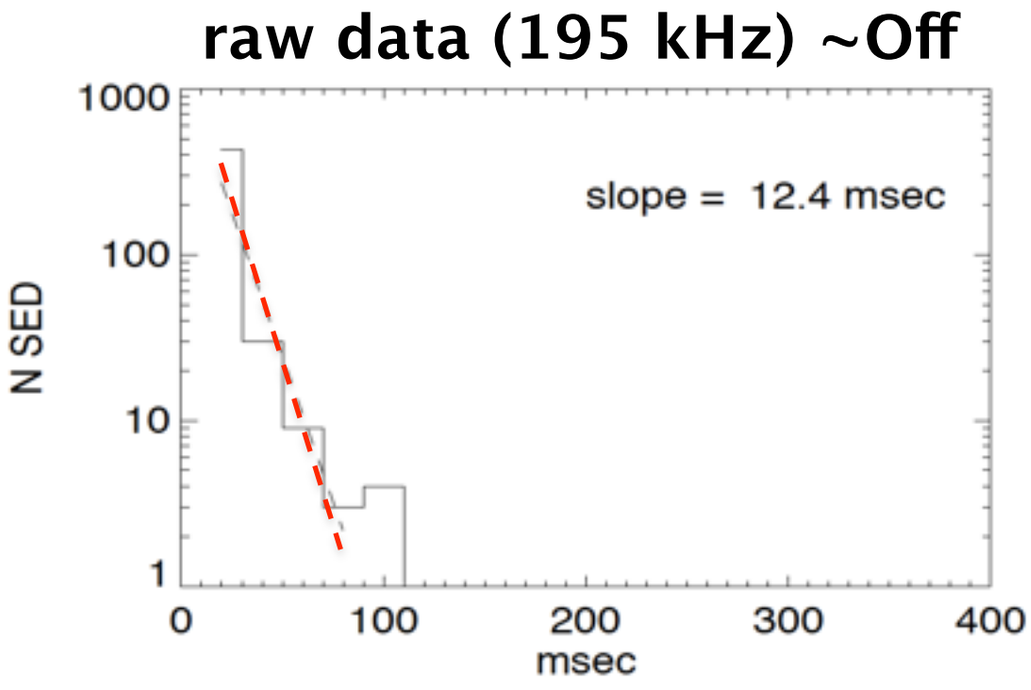
SED @ Earth ~ 10–1000 Jy $\quad$ (1 Jy = 10^{-26} W.m^{-2}.Hz^{-1})

Lightning : commissionning Observations

- Ongoing analysis → spectrum & time profile → energy ?

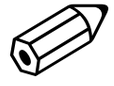
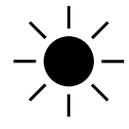






Correlations with Cassini in progress ...

Conclusions

	Jupiter LF	Jupiter HF	Exoplanets	Lightning
What do we know ?				
What don't we know ?				
What can we learn with LOFAR ?				

Conclusions

- Planetary and exoplanetary objectives :

  → require challenging observations

  → time demanding

  → very high interest : first radio-exoplanet ? Jupiter (& Io) as archetypes of auroral and flow-obstacle physics ; lightning @ all solar system planets

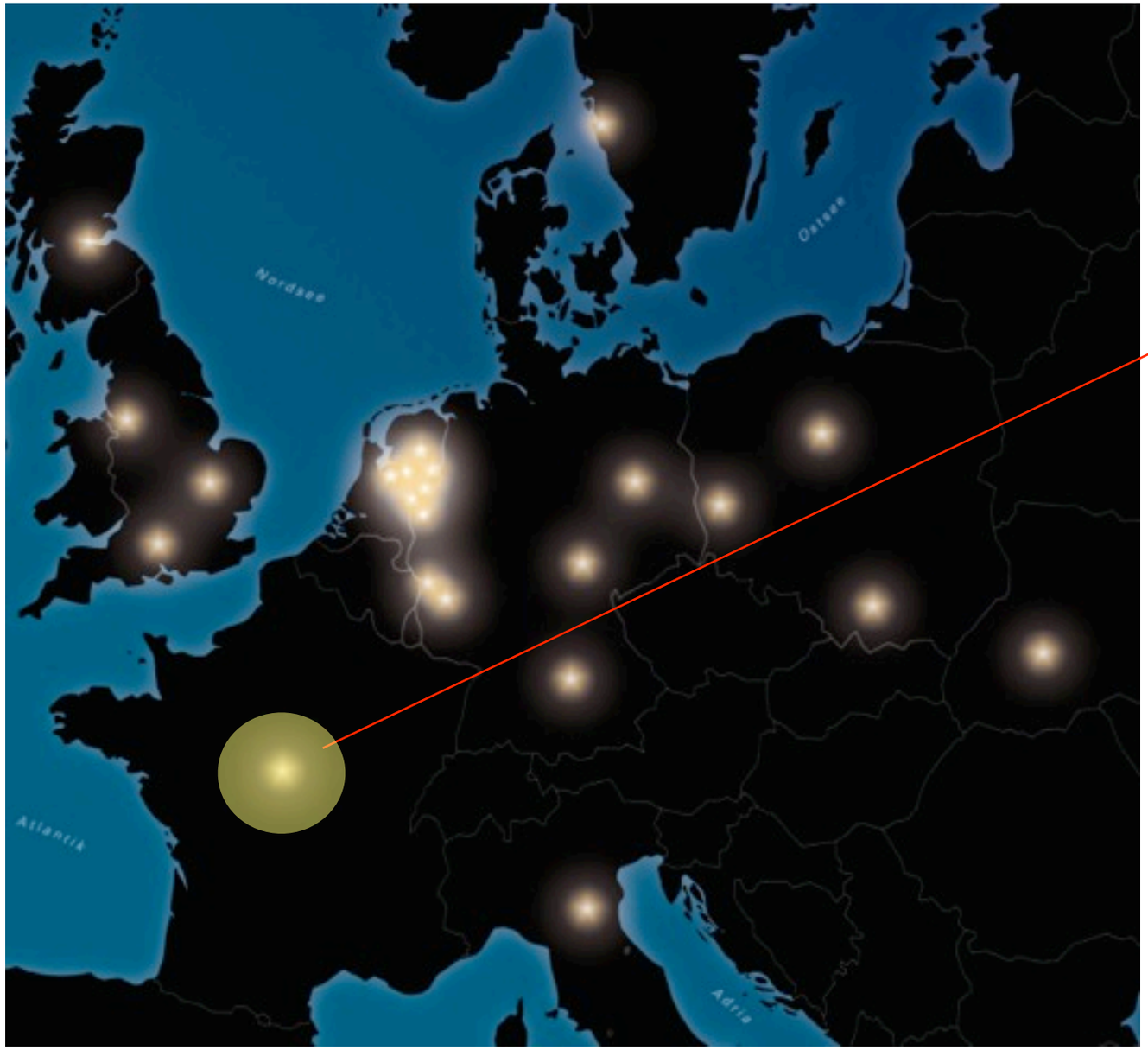
- Targeted observations (TAB primarily & Jupiter imaging) + piggybacking

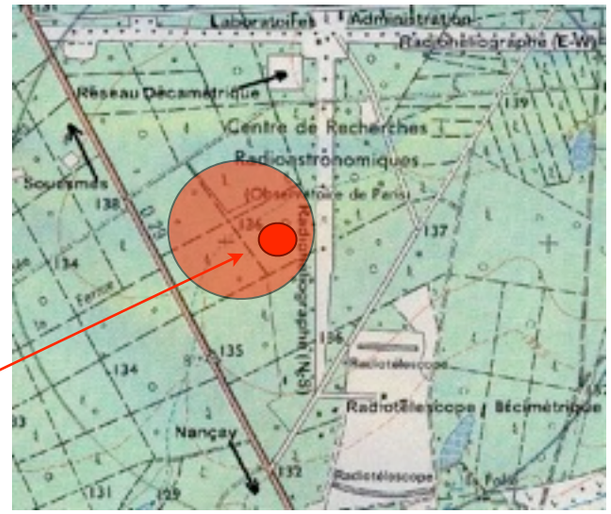
- Composition of TKP/PWG :

  - P. Zarka, J.-M. Griessmeier, W. Majid, H. Spreeuw, D. Stam, G. Woan, I. dePater, G. Hallinan, S. Hess (members)

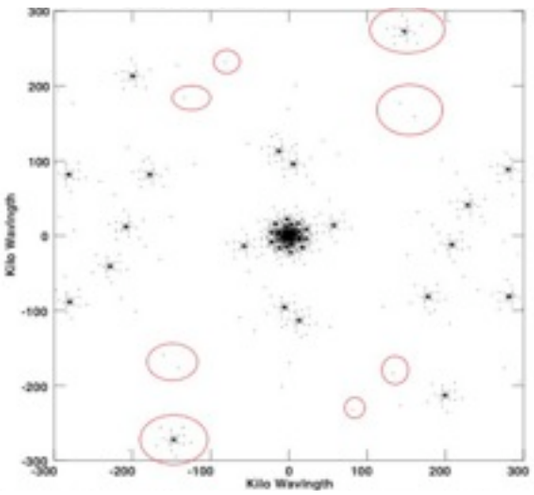
  - J. Girard, T. Bastian, E. Seran, A. Hatzes, J. Nichols [, V. Ryabov, V. Kolyadin] (associate members)

LOFAR super station in Nançay



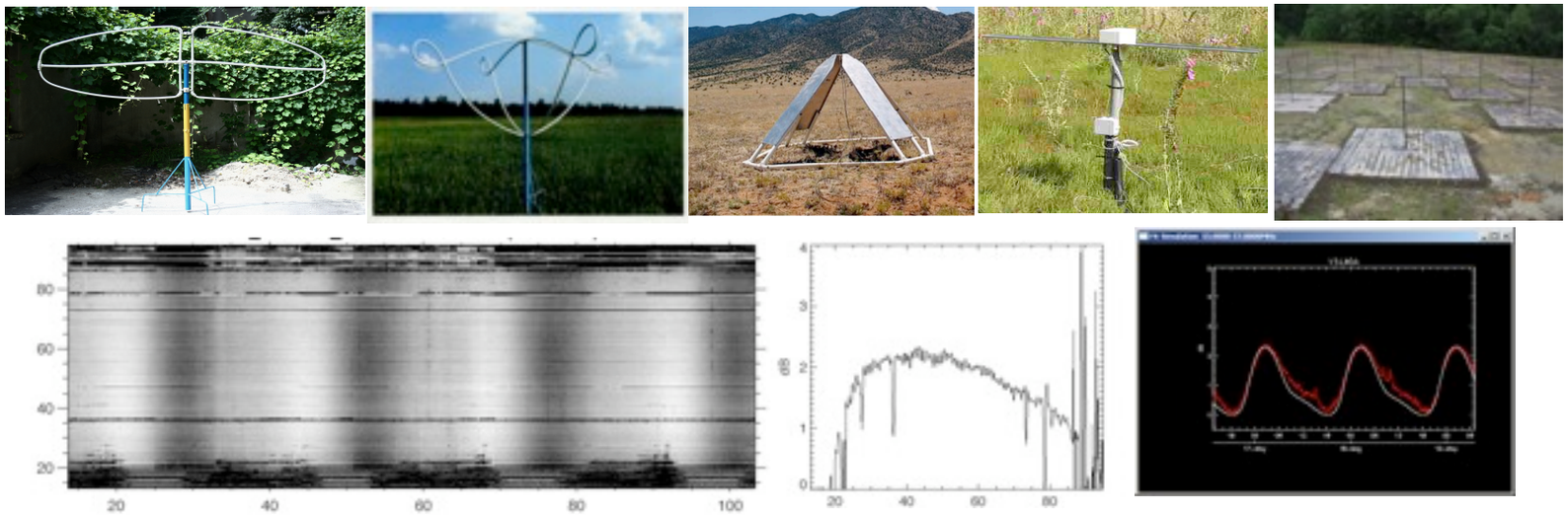


instantaneous (u,v) coverage

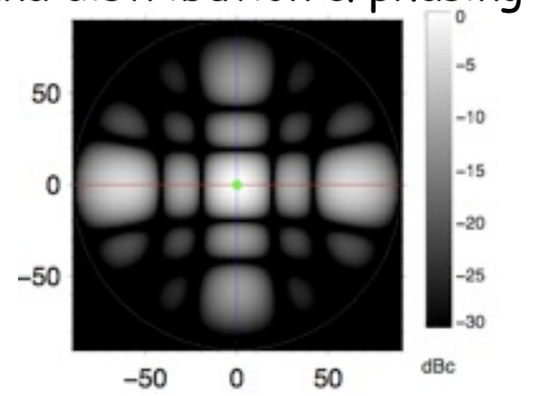


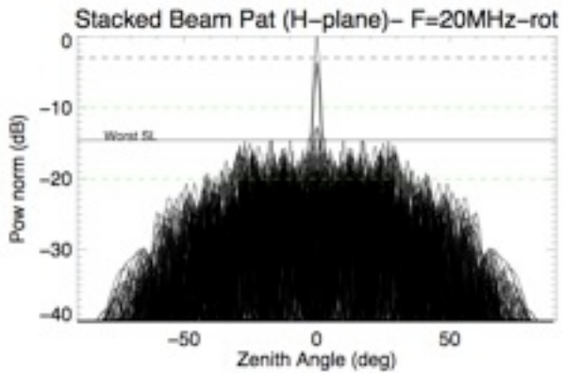
LOFAR super station in Nançay

Antenna selection and tests

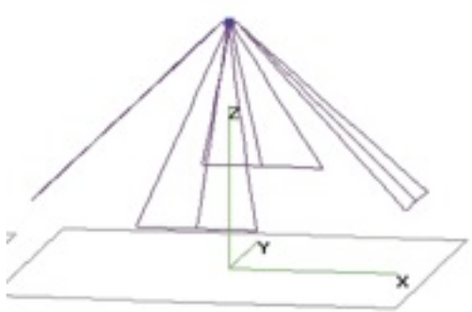


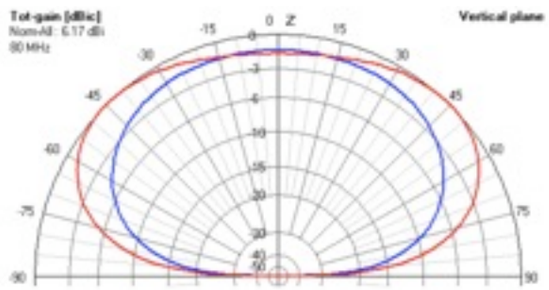
Antenna distribution & phasing



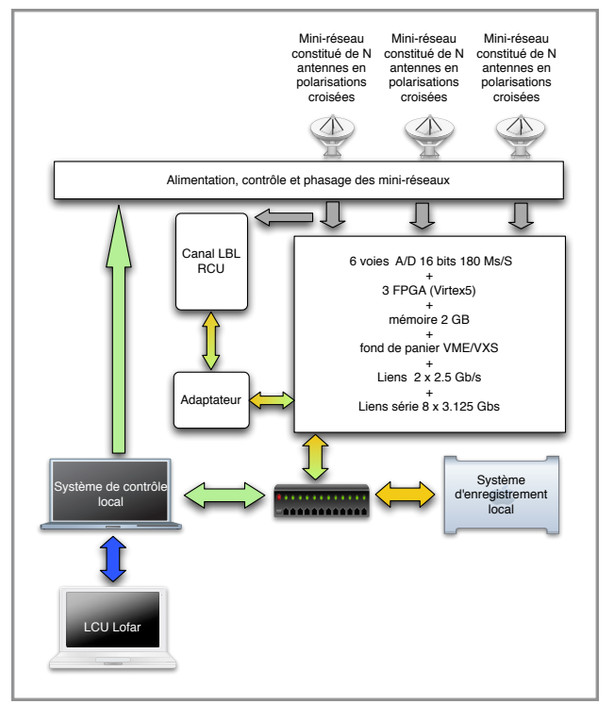


NEC simulations

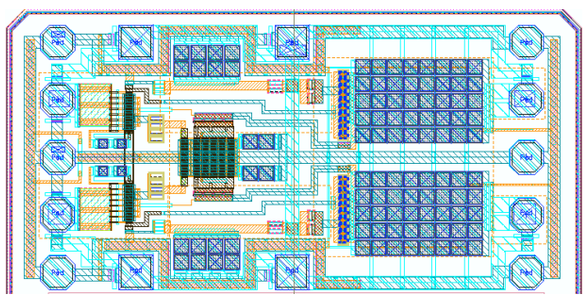


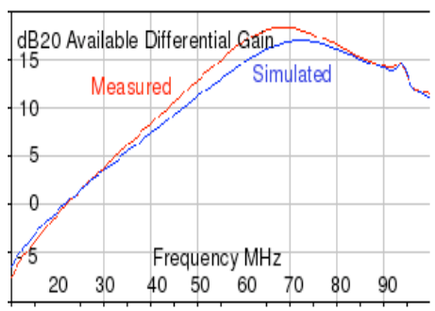


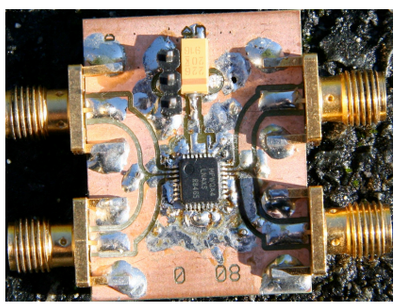
Test receiver



Antenna amplifier concept, simulation, layout







- need for your scientific inputs !