Exoplanet searches in Radio: Theory & Observations from UTR-2 to LOFAR/SKA

P. Zarka

LESIA, Observatoire de Paris, CNRS, UPMC, Université Paris Diderot, 92190 Meudon, philippe.zarka@obspm.fr
- Jupiter LF radio emission are intense ⇒ discovery & measure of B field (~10G) and rotation period (~10h)
- ∃ similar Terrestrial emissions, ≤1 MHz (B ~ 0.5G)
- Radiation belts emission = synchrotron
- Auroral emissions = Cyclotron-Maser (CMI) : f=f_{ce}, keV e-, high T_B, circular polar., narrow beaming, t-f variability
- Contrast Jupiter - Sun ~ 1 → radio search!
• Intense sky background (+ RFI + ionosphere) → detection difficult

• Maximum distance for Nσ sky-limited detection of a source ζ x Jupiter:

\[
d_{\text{max}} = \left(\frac{\zeta S_J A_e}{2NkT}\right)^{1/2} (b\tau)^{1/4} = 5 \times 10^{-8} (A_e \zeta)^{1/2} f^{5/4} (b\tau)^{1/4} \quad [\text{pc}]
\]

<table>
<thead>
<tr>
<th>ζ = 1</th>
<th>(b\tau = 10^6) (1 MHz, 1 sec)</th>
<th>(b\tau = 2 \times 10^8) (3 MHz, 1 min)</th>
<th>(b\tau = 4 \times 10^{10}) (10 MHz, 1 hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f = 10) MHz</td>
<td>(f = 100) MHz</td>
<td>(f = 10) MHz</td>
<td>(f = 100) MHz</td>
</tr>
<tr>
<td>(A_e = 10^4) m² (~NDA)</td>
<td>0.003</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>(A_e = 10^5) m² (~UTR-2, LOFAR)</td>
<td>0.01</td>
<td>0.2</td>
<td>0.03</td>
</tr>
<tr>
<td>(A_e = 10^6) m² (~SKA)</td>
<td>0.03</td>
<td>0.5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

(distances in parsecs)

[Zarka et al., 1997]
THEORY
• General frame of flow-obstacle interaction in our Solar system: magnetic reconnection, Alfvén waves, Unipolar interaction

• Empirical radio-magnetic scaling law with \( \sim \)constant efficiency \( \varepsilon \sim 2 \times 10^{-3} \)
Extrapolation to hot Jupiters:
• Magnetospheric radio emission up to $10^5$ Jupiter
• Unipolar inductor emission up to $\geq 10^6$ Jupiter at $\geq 30$-300 MHz, but requires $B^* \geq 10$-100B

[Zarka et al., 2001; Zarka, 2007]
• Measurement of an interacting magnetic binary (RS CVn V711 τ) compatible with extrapolated scaling law [Zarka, 2010]

• Controversial optical SPI detection [Shkolnik, 2003-5-8]

[Graphic with data points plotting radio power vs. incident kinetic power and magnetic binary image]
- Internally driven radio emission of normal Jupiters around highly XUV luminous stars → large radio fluxes requires rapid Xo rotation (1-3h) [Nichols, 2011, 2012]
The maximum distance for $N\sigma$ sky-limited detection of a source $\zeta \times \text{Jupiter}$:

<table>
<thead>
<tr>
<th>$\zeta = 10^5$</th>
<th>$b = 10^6$ (1 MHz, 1 sec)</th>
<th>$b = 2 \times 10^8$ (3 MHz, 1 min)</th>
<th>$b = 4 \times 10^{10}$ (10 MHz, 1 hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f = 10$ MHz</td>
<td>1</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>$f = 100$ MHz</td>
<td>16</td>
<td>59</td>
<td>220</td>
</tr>
</tbody>
</table>

| $A_e = 10^4$ m$^2$ | $f = 10$ MHz | 3 | 11 | 40 |
| ($\sim\text{NDA}$) | 50 | 190 | 710 |

| $A_e = 10^5$ m$^2$ | $f = 10$ MHz | 9 | 160 | 130 |
| ($\sim\text{UTR-2, LOFAR}$) | 160 | 600 | 2200 |

| $A_e = 10^6$ m$^2$ | $f = 10$ MHz | 9 | 160 | 130 |
| ($\sim\text{SKA}$) | 160 | 600 | 2200 |

(distsances in parsecs)

- $\text{turbulence} \rightarrow \text{intermittency}$  
- $\text{scintillations} \rightarrow \text{radio flux } \times 100$?
• Predicting radio dynamic spectra from CMI modelling for various SPI scenarii
  - no imaging → t-f morphology reveals physical parameters
  - successful loss-cone driven CMI modelling of Jupiter’s radio emissions :
    → Meudon ExPRES code

[Hess et al., 2008, 2010, 2013]
• Star-Exoplanet case: parameters (stellar/exoplanet B tilt/offset, orbit inclination), planetary and stellar rotation, planetary orbital period ...

[Hess & Zarka, 2011]

• Study of typical cases (specific modeling post-detection)

• Model predictions scalable to any frequency range (depends on B involved)

• ≥ a few 10’s MHz, LF cutoff becomes negligible except very close to the star & at low inclination (~occultation)
• White dwarf-planet unipolar interaction explains ultrashort period (P<10 min) X-ray sources with antiphase optical emission: X-Ray emission by heated footpoints on magnetic WD + optical emission by irradiation of the companion

• P decrease consistent with power radiation via unipolar induction
• System lifetime due to gravitational radiation emission

• CMI radio emission?
  → may reveal Earth-like planets in close orbit around WD (= remnants of main sequence stars with planet surviving the stellar expansion phase and back in stable orbit)
• Interest of low-frequency radio observations of exoplanets: immense!

→ Direct detection, discovery?
→ Measurement of B (only way!)
    ⇒ constraints on scaling laws & internal structure models
→ Planetary rotation period ⇒ tidal locking?
→ Possible access to orbit inclination
→ Existence / orbital period of satellites?
→ Comparative (exo)planetary magnetospheric physics = NEW FIELD, theoretical frame ready, we are leading it

→ Magnetosphere favours habitability (limits atmospheric erosion by solar wind & CME, limits destruction of O$_3$ by cosmic rays)

[Griessmeier et al., 2004; Khodachenko et al., 2006...]

• Synchrotron emission from radiation belts: stable but weak (a few nJy @ 1 pc)
PREDICTIONS
Application of scaling laws to exoplanet census → target selection

[Lazio et al., 2004]  [Griessmeier et al., 2007, 2011]
• Unipolar inductor CMI radio emission from WD-exoplanet systems
  → broadband emission up to 100 GHz (+ absorption bands), 100% circularly polarized bursts (X mode dominant), modulated at the orbital period
  → orbital period modulation: bursts (~10 min), a few % duty-cycle (beaming)
  → order of magnitude predictions (N_e of 1 keV loss-cone e- ×10 → S ×10^4)
  → Limited unipolar inductor lifetime due to spin-orbit coupling

Flux density spectra @ 100 pc with 1 keV e-

[Log [S] (Jy) vs. Log_{10}[f] (GHz) for different values of n_e (10^8, 10^9, 10^10 cm^-3)

[Willes & Wu, 2004, 2005]
• Stellar B-fields & variable star-planet interaction (SPI)

- Solar B field:
  - large-scale $\sim 1 \, G$
  - mag. loops $\sim 10^3 \, G$
  (few % of surface)

- Magnetic stars: $> 10^3 \, G$

- $\tau$ Boo: 5-10 $G$ ($10^{-4} \, T$)
- HD 76151: $\sim 10 \, G$
- HD 189733: $> 50 \, G$
- HD 171488: 500$G$

[Farès et al., 2010]

[HD189733]
OBSERVATIONS
• Observations at VLA at 74, 330, 1465 MHz
  τ Boo, HD 80606 → no detection (low $A_{\text{eff}}$, 'HF')

[Winglee et al., 1986; Bastian et al., 2000; Farrell et al., 2003, 2004; Lazio & Farrell, 2007; Lazio et al., 2010]
• Observations at GMRT at 153 MHz

**Ups And, ε Eri, HD 128311 → no detection**

[Winterhalter et al., 2006; Majid et al., 2006; George and Stevens, 2007, 2008]

τ Boo (> 4M_J, ~0.05 AU, 16 pc, P=79.5h) : 40 h, ~0.4 mJy

→ no detection

[Hallinan et al., 2013]

→ RFI ? \( B_{\text{planet}} < 50 \text{G} \) ? (!) emission too weak ?
• Observations at GMRT at 153 MHz, 244, 614 MHz → anti-transits of HD189733b, HD209458b

HAT-P-11b

[Lecavelier et al., 2009, 2011]

HAT-P-11, 153 MHz unconfirmed in 2010

[Lecavelier et al., 2013]
Last minute information:
Recent A&A paper by Sirothia et al.
Several candidate radio exoplanets in GMRT 150 MHz survey.
To be followed, confirmed, but very encouraging.
• Observations at UTR-2, 10-30 MHz dual beam, $\delta f=4$ kHz, $\delta t=20$ msec

[Ryabov et al., 2004, 2010; Zarka et al., in prep]
• Inferred limits (from J. Lazio)

![Graph showing planetary magnetic field strength vs. flux density and frequency. The graph includes data points for UTR-2, VLA, GBT, and GMRT. The references are Ryabov et al., 2004; Lazio et al., 2010; and Lecavelier et al., 2013.]
• Observations with LWA, 10-88 MHz
256 antennas, dual beam,
mJy sensitivity

[Hallinan et al.]

HJUDE – Hot Jupiter Detection Experiment with the LWA ⇒ 5000 hours

A volume-limited survey of known HJs

<table>
<thead>
<tr>
<th>Planet</th>
<th>$d$ (pc)</th>
<th>$a$ (AU)</th>
<th>$P_{\text{orb}}$ (d)</th>
<th>$M$ ($M_J$)</th>
<th>Coordinates (J2000)</th>
<th>Best month</th>
<th>Num. days</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ And b</td>
<td>13.49</td>
<td>0.059</td>
<td>4.62</td>
<td>1.4</td>
<td>$01^h37^m +41^d24^m$</td>
<td>Sep</td>
<td>37</td>
</tr>
<tr>
<td>$\tau$ Boo b</td>
<td>15.62</td>
<td>0.048</td>
<td>3.31</td>
<td>6.5</td>
<td>$13^h47^m +17^d27^m$</td>
<td>Mar</td>
<td>43</td>
</tr>
<tr>
<td>HD 189733 b</td>
<td>19.45</td>
<td>0.081</td>
<td>2.22</td>
<td>1.13</td>
<td>$20^h01^m +22^d43^m$</td>
<td>Jun</td>
<td>29</td>
</tr>
<tr>
<td>HD 187123 b</td>
<td>48.26</td>
<td>0.042</td>
<td>3.10</td>
<td>&gt; 0.51</td>
<td>$19^h47^m +34^d25^m$</td>
<td>Jun</td>
<td>31</td>
</tr>
<tr>
<td>HD 209458 b</td>
<td>49.63</td>
<td>0.047</td>
<td>3.52</td>
<td>&gt; 0.69</td>
<td>$22^h03^m +18^d53^m$</td>
<td>Ang</td>
<td>32</td>
</tr>
</tbody>
</table>

- Hot Jupiters likely to be tidally locked:

<table>
<thead>
<tr>
<th>Planet</th>
<th>$d$ (pc)</th>
<th>$a$ (AU)</th>
<th>$P_{\text{orb}}$ (d)</th>
<th>$M$ ($M_J$)</th>
<th>Coordinates (J2000)</th>
<th>Best month</th>
<th>Num. days</th>
</tr>
</thead>
<tbody>
<tr>
<td>55 Cnc b</td>
<td>12.34</td>
<td>0.116</td>
<td>14.65</td>
<td>&gt; 0.84</td>
<td>$08^h53^m +28^d20^m$</td>
<td>Dec</td>
<td>30</td>
</tr>
<tr>
<td>$\rho$ CrB b</td>
<td>17.24</td>
<td>0.226</td>
<td>39.84</td>
<td>&gt; 1.06</td>
<td>$16^h01^m +33^d18^m$</td>
<td>Apr</td>
<td>30</td>
</tr>
<tr>
<td>70 Vir b</td>
<td>17.99</td>
<td>0.484*</td>
<td>116.60</td>
<td>&gt; 7.46</td>
<td>$13^h28^m +13^d47^m$</td>
<td>Mar</td>
<td>30</td>
</tr>
<tr>
<td>HD 195019 b</td>
<td>38.52</td>
<td>0.137</td>
<td>18.20</td>
<td>&gt; 3.58</td>
<td>$20^h28^m +18^d46^m$</td>
<td>Jun</td>
<td>30</td>
</tr>
<tr>
<td>HD 114762 b</td>
<td>38.65</td>
<td>0.363*</td>
<td>83.89</td>
<td>&gt;11.68</td>
<td>$13^h12^m +17^d31^m$</td>
<td>Mar</td>
<td>30</td>
</tr>
<tr>
<td>HD 38529 b</td>
<td>39.28</td>
<td>0.131*</td>
<td>14.31</td>
<td>&gt; 0.86</td>
<td>$05^h47^m +01^d10^m$</td>
<td>Nov</td>
<td>30</td>
</tr>
<tr>
<td>HD 178911 Bb</td>
<td>42.59</td>
<td>0.345*</td>
<td>71.48</td>
<td>&gt; 7.29</td>
<td>$19^h09^m +34^d36^m$</td>
<td>Jun</td>
<td>30</td>
</tr>
<tr>
<td>HD 37605 b</td>
<td>43.98</td>
<td>0.261*</td>
<td>54.23</td>
<td>&gt; 2.86</td>
<td>$05^h40^m +06^d04^m$</td>
<td>Nov</td>
<td>30</td>
</tr>
</tbody>
</table>

* Sources with eccentricities greater than 0.1.
• Observations with LOFAR, 26-62 MHz, imaging + TAB

[Zarka et al.]

→ 5 targets observed 30h in cycle 0

UPS AND, 2013-02-27, 2h, ISB @ 56 MHz : image = 4096x4096 pixels (5") = 6° x 6°

(u,v) ≤ 5000 wavelengths, CSclean (CASA)
• Observations with LOFAR, 26-62 MHz, imaging + TAB

[Zarka et al.]

17 targets to be observed 17h in cycle 1
NEXT ?
LOFAR:
- Search for transients, « naïve approach »: Images (t), Visibilities (t)
- Search for transients: less naïve approach: FT (image pixels),
  Compressed Sensing ⇒ (2D + t) sparse recovery
- Circular / Full polarization

- 1000's candidates
- Time variability due to narrow beaming / visibility
- Need to observe large sample at low frequencies (< 100 MHz)
  to overcome geometrical selection effects ⇒ long duty-cycles
- Commensal observations

OLWA
- all sky LWA
**NenuFAR :**

- In standalone mode, compact array with very high sensitivity
- 10-88 MHz bandwidth, 2 full-band beams + 256 pixels maps within a broad FoV (8°-60°)^2
- National instrument ⇒ possibility of very high duty-cycles (e.g. Kepler field) (including observations in // with LOFAR)
- Very high FoM for exoplanet search

<table>
<thead>
<tr>
<th>Radio Array</th>
<th>Freq. range (MHz)</th>
<th>Effective area (m^2)</th>
<th>N polar.</th>
<th>% of obs. time</th>
<th>Figure of Merit (FoM)</th>
<th>Field of View (°^2)</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTR-2 (2040 dipoles)</td>
<td>10-32</td>
<td>~143 000</td>
<td>1</td>
<td>5-10%</td>
<td>157-315</td>
<td>0.25 - 7</td>
<td>30’</td>
</tr>
<tr>
<td>VLA 27 dishes (25 m Ø)</td>
<td>73-74.6</td>
<td>~2 000</td>
<td>2</td>
<td>1-5%</td>
<td>&lt;1</td>
<td>68</td>
<td>25”</td>
</tr>
<tr>
<td>GMRT 30 dishes (45 m Ø)</td>
<td>149-157</td>
<td>~30 000</td>
<td>2</td>
<td>1-2%</td>
<td>5-10</td>
<td>5</td>
<td>20”</td>
</tr>
<tr>
<td>LOFAR low : 48 stations × 48/96 dip.</td>
<td>30-80</td>
<td>100 000 – 14 000</td>
<td>2</td>
<td>5%</td>
<td>180 (60)</td>
<td>10-300</td>
<td>5''-0.9''</td>
</tr>
<tr>
<td>LOFAR high : 48 st. × 48/96 × 16 dip.</td>
<td>110-250</td>
<td>70 000 – 20 000</td>
<td>2</td>
<td>5%</td>
<td>180 (60)</td>
<td>4-30</td>
<td>0.6''-0.3''</td>
</tr>
<tr>
<td>LSS 48 × 19 dipoles</td>
<td>15-85</td>
<td>47 000 – 4 000</td>
<td>2</td>
<td>20%</td>
<td>384</td>
<td>70-2000</td>
<td>3.8°-0.7°</td>
</tr>
</tbody>
</table>

- Possible synergies with complementary instruments : LF radio (UTR-2, GURT, OLWA), ZD spectropolarimetry (cf. above), UV-X * luminosity …
SKA-LOW

→ Must significantly improve / LOFAR (if no detection)

• Jupiter decameter emission @ 10 pc peaks at \( \sim 25 \, \mu\text{Jy} \) (sec - min timescale) / 3 \( \mu\text{Jy} \) (hour timescale), (x20 if planet at \( \sim 1 \, \text{AU} \))

• SKA-low sensitivity: mJy - 10's \( \mu\text{Jy} \) at timescales from sec to hours
→ no more need of scaling laws, \( \sim \)Jupiter detectable at 10s of pc

• SKA-low baseline design essentially Ok: broad freq. range \( \geq 50 \, \text{MHz} \), broad instantaneous coverage, full polar, 50-100 km baselines, radio quiet site (multi-beam capability ?)

FAST ?

LOFAR on the Moon ?
• Synergies with white / brown / cool dwarfs & flaring stars studies (cf. above)

VLA : RMS noise \( \sim 1.6 \mu \text{Jy/beam} \)

→ Brown dwarfs pulses discovered at GHz frequencies
→ Periodic pulses (~2 h), 100% circularly polarized, \( T_B > 10^{15} \) K, \( |B| \sim 2 \text{ kG} \)

- from dwarfs to planets (X, H-alpha, T, rotation, transition to stable B geometries)
- lower mass planets more frequent around M dwarfs (habitable?)
- stellar bursts (~type II/III), cause planetary auroras, atmospheric loss
- similar obs. techniques and emission levels (star-planet discrimination via orbital period & polarization)
THIS IS POTENTIALLY A HIGH VISIBILITY HIGH «RETURN» SUBJECT ...