Exoplanet searches in Radio (I) : theory & searches with UTR2, GMRT and LOFAR

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- Jupiter LF radio emission are intense
Decameter-wave magnetospheric (auroral & satellite-induced) emissions
Decameter-wave magnetospheric (auroral & satellite-induced) emissions → attributed to Cyclotron-Maser Instability (CMI)

Resonance condition:

\[ \omega = \frac{\omega_c}{\Gamma} - k \parallel v \parallel \]

Growth rate:

\[ \gamma = \frac{\omega_p c^2}{8 \omega_c} \int_0^{2\pi} v^2_\perp(\theta) \nabla_{v_\perp} f(v_0, R(\theta)) d\theta \]

- Sources where strong B, \( f_{pe} << f_{ce} \), non Maxwellian keV e-
- high \( T_B \), 100% circularly polarized, narrow beaming, fine structures

[Wu, 1985; Treumann, 2006; Hess et al., 2008]
Decimeter emission from the radiation belts: synchrotron

LOFAR: $\Delta f = 127\text{-}172\ \text{MHz}$, $\Delta t = 7\text{h}$, Beam = $17.8''\times15.5''$, Pixel = $1''$, Jupiter disk = $49''$

Contours: VLA @ 15 GHz

[de Pater & Dunn, 2003]
Jupiter-Sun contrast favourable at LF radio ($CMI \gg \text{plasma emission}$)

→ radio search = natural idea, but ...
• Intense sky background + RFI + ionosphere → difficult!

• Maximum distance for $N\sigma$ sky-limited detection of a source $\zeta \times$ Jupiter:

$$d_{\text{max}} = \left(\frac{\zeta S J A_e}{2 N k T}\right)^{1/2} (b \tau)^{1/4} = 5 \times 10^{-8} (A_e \zeta)^{1/2} f^{5/4} (b \tau)^{1/4} \ [\text{pc}]$$

<table>
<thead>
<tr>
<th>$\zeta = 1$</th>
<th>$b \tau = 10^6$</th>
<th>$b \tau = 2 \times 10^8$</th>
<th>$b \tau = 4 \times 10^{10}$</th>
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<tbody>
<tr>
<td>$f = 10$ MH z</td>
<td>$f = 100$ MH z</td>
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<tr>
<td>$A_e = 10^4 m^2$</td>
<td>0.003</td>
<td>0.05</td>
<td>0.01</td>
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<td>(~NDA)</td>
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<tr>
<td>$A_e = 10^5 m^2$</td>
<td>0.01</td>
<td>0.2</td>
<td>0.03</td>
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<td>(~UTR-2, LOFAR)</td>
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<td>$A_e = 10^6 m^2$</td>
<td>0.03</td>
<td>0.5</td>
<td>0.1</td>
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<tr>
<td>(~SKA)</td>
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(distances in parsecs)

[Zarka et al., 1997]
THEORY
• General frame of flow-obstacle interaction in our Solar system (SW-MS & satellite-MS interactions, with magnetized or unmagnetized satellite = dipolar or unipolar interaction)

• Empirical radio-magnetic scaling law with \( \sim \) constant efficiency \( \varepsilon \sim 2 \times 10^{-3} \)

\[ [\text{Zarka et al., 2001 ; Zarka, 2007}] \]
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]
• B decay for spin-orbit synchronized systems?

\[ \mathcal{M} \propto \omega^\alpha \quad \text{with} \quad \frac{1}{2} \leq \alpha \leq 1 \quad \omega \downarrow \rightarrow \mathcal{M} \downarrow \quad ? \]

• Internal structure + convection models \(\rightarrow\) self-sustained dynamo

\(\rightarrow\mathcal{M}\) could remain \(\geq\) a few \(G R_J^3\)

[Sanchez-Lavega, 2004; Reiners & Christensen, 2010]

• If no strong planetary B \(\rightarrow\) giant Io-Jupiter-like interaction? (Unipolar inductor)

\( f_{pe}/f_{ce} \ll 1 \rightarrow B \sim 10-100 B_{\text{sun}} \)

\(\rightarrow\) emission \(\geq\) 30-300 MHz from 1-2 \(R_S\)

[Shkolnik et al., 2003, 2005, 2008]  
[Zarka, 2007]
• Measurement of an interacting magnetic binary (RS CVn V711 τ [Budding et al., 1998]) compatible with extrapolated scaling law
• Possible justification of scaling law

Magnetic reconnection and electron acceleration at the magnetopause?

• Computation of parallel E field (assuming $B_\ast=1\,\text{G}$)
• Number and energy of runaway electrons
• Parametrization by “efficiency” $\eta$

[Graphs showing relationships between parameters, with notes on in stellar MS and in SW, and reference to Jardine & Cameron, 2008]
• Maximum distance for $N\sigma$ sky-limited detection of a source $\zeta \times$ Jupiter:

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<tr>
<td></td>
<td>($1 , MHz$, 1 sec)</td>
<td>($3 , MHz$, 1 min)</td>
<td>($10 , MHz$, 1 hour)</td>
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<tr>
<td>$f = 10$ MH z</td>
<td>1</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>$f = 100$ MH z</td>
<td>16</td>
<td>59</td>
<td>220</td>
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<tr>
<td>$f = 10$ MH z</td>
<td>3</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>$f = 100$ MH z</td>
<td>50</td>
<td>190</td>
<td>40</td>
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<tr>
<td></td>
<td>190</td>
<td>710</td>
<td>220</td>
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<tr>
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<td>9</td>
<td>600</td>
<td>130</td>
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<tr>
<td></td>
<td>160</td>
<td>2200</td>
<td>2200</td>
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(distances in parsecs)

• turbulence $\rightarrow$ intermittency

• scintillations $\rightarrow$ radio flux $\times 100$?

[Chian et al., 2010]

[Farrell et al., 1999]
• Application of scaling laws to exoplanet census

[Lazio et al., 2004] [Griessmeier et al., 2007, 2011]
- Stellar B-fields & variable star-planet interaction (SPI)

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

- Magnetic stars: > 10^3 G

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

[Farès et al., 2010]
Internally driven radio emission of normal Jupiters around highly XUV luminous stars requires large radio fluxes due to rapid Xo rotation (1-3h).
• Predicting radio dynamic spectra from CMI modelling for various SPI scenarios
- imaging cannot resolve *-Xo or WD-Xo or WD-WD systems
- t-f morphology reveals system’s physical parameters
- successful loss-cone driven CMI modelling of Jupiter’s radio emissions:
  → ExPRES code

[Hess et al., 2008, 2010, 2013]
• Star-Exoplanet case: interaction scenario (auroral or unipolar inductor emission) [Hess & Zarka, 2011]

Xo-induced radio emission in stellar B field

exoplanet emission: full oval
• Star-Exoplanet case: interaction scenario (auroral or unipolar inductor emission)

[Hess & Zarka, 2011]
• 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 possible / easy post-detection)

• Model predictions easy to scale to any frequency range (depends on magnetic fields involved)

• $\geq$ a few 10’s MHz, LF cutoff becomes negligible except very close to the star & at low inclination (~occultation)
• Magnetic WD - Non-Magnetic WD systems in synchronous rotation to explain ultrashort period (P<10 min) X-ray sources with antiphase optical emission
→ unipolar inductor interaction ~ Io-Jupiter
→ X-ray emission at footpoints = heating on magnetic WD + optical emission by irradiation of the non-magnetic WD
• P decrease consistent with power radiation via unipolar induction

[Willes & Wu, 2004]
• Unipolar inductor CMI radio emission from WD-WD & WD-exoplanet systems
  → broadband emission up to 100 GHz + absorption bands, X mode dominant
  → bursts (~10 s for WD-WD systems, ~10 min for WD-Xo systems)
  → duty cycle ~ a few % (due to beaming)
  → order of magn. predictions (density of 1 keV loss-cone e- ×10 → S ×10⁴)
  → higher power in WD-WD systems due to higher magnetic moment

Flux density spectra @ 100 pc with 1 keV e-

[Flux density spectra graphs]

[Willes & Wu, 2004]
• Limited unipolar inductor lifetime due to spin(of magnetic WD)-orbit coupling
  $\rightarrow \sim 10^4$ years for WD-WD
  (system lifetime $\sim 10^6$ years due to gravitational radiation emission)
  $\sim 1\%$ detection probability per unipolar inductor phase
  $\rightarrow \sim 10^{7-9}$ years for WD-Xo with $P_{\text{orbital}}=10-30$ h.

[Willes & Wu, 2004, 2005]
→ Radio emission up to 100 GHz, 100% circularly polarized bursts, modulated at the orbital period

→ 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)

[Willes & Wu, 2004, 2005]

• Generalized unipolar inductor analysis, with non-zero $X_0$ resistivity (self-consistent model)

[Laine, 2013]
• Synchrotron emission from radiation belts

- Stable emission, allowing for long integration times, but weak
- Jupiter’s synchrotron emission $\sim 100 \text{ Jy @ 1 AU at 1 GHz} \rightarrow 0.0025 \mu\text{Jy @ 1 pc}$
- SKA1-Low sensitivity $\sim 2kT/[A(b\tau)^{1/2}] \sim 10 \mu\text{Jy}$
  
  with $A/T \sim 1000$, $b=10 \text{ MHz}$, $\tau=1 \text{ hr}$

$\rightarrow$ detectability of $1000\times$ Jupiter at pc range only

[de Pater, 2004; Zarka, 2004]
• Interest of low-frequency radio observations of exoplanets: immense!

→ Direct detection
→ Measurement of B
   ⇒ constraints on scaling laws & internal structure models
→ Planetary rotation period ⇒ tidal locking?
→ Possible access to orbit inclination
→ Existence / orbital period of satellites?
→ Comparative magnetospheric physics: theoretical frame ready

→ Magnetosphere limits atmospheric erosion by the solar wind & CME

→ Magnetosphere limits destruction of O₃ by cosmic rays

[Griessmeier et al., 2004; Khodachenko et al., 2006...]
OBSERVATIONS
• Limited angular resolution ($\lambda/D$) ⇒ no imagery (of the target)
→ (1) detect a signal, (2) star or planet?
→ discriminate via emission polarization + periodicity (orbital)
• Observations at VLA at 74, 330, 1465 MHz
  τ Boo, HD 80606 → no detection
  (but low $A_{\text{eff}}$ / high frequency)

[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** (40 h, ~0.4 mJy) → no detection

[Hallinan et al., 2013]

→ RFI ? $B_{planet} < 50 G$ ? 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]
• Inferred limits (from J. Lazio)

![Graph showing planetary magnetic field strength against frequency with data points from various sources: UTR-2 [Ryabov et al., 2004], VLA, GBT, GMRT, Lazio et al., 2010, Lecavelier et al., 2013].
• 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]
• Observations with LOFAR, 30-250 MHz, imaging + tied-array beams → a few targets observed in cycle 0  (Zarka et al., 30h, Lazio et al., 30h)
Next?

exoplanet.eu: 16 known Xo systems < 10 pc, ~235 < 50 pc, ~360 < 100 pc ...
1-10 Xo per 1hr x 10° field
100’s of Xo confirmed / candidates in ~10° Kepler field
40 stars up to 5 pc, 1000 up to 10 pc ...
coordinated obs. (UTR-2, ZD polarimetric imaging, UV-X ...)

~700 Xo systems
DISCUSSION
• Interest of low-frequency radio observations of exoplanets: immense!

→ Direct detection
→ Measurement of B

⇒ constraints on scaling laws & internal structure models

→ Planetary rotation period ⇒ tidal locking?
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→ Comparative magnetospheric physics: theoretical frame ready

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[Griessmeier et al., 2004; Khodachenko et al., 2006...]
• Inferred limits (from J. Lazio)

![Graph showing planetary magnetic field strength vs. frequency for UTR-2, VLA, GBT, and GMRT. The graph includes data from Ryabov et al. (2004), Lazio et al. (2010), and Lecavelier et al. (2013).]
- Jupiter’s radio spectrum & timescales
Some requirements for SKA searches of Xo MS and/or SPI radio emissions

→ Must significantly improve / LOFAR (if no detection)

- High sensitivity: mJy - 10's μJy at timescales from sec to hours
  
  flux density limited by emission processes and distance
  
  timescales limited by narrow beaming / visibility window of expected emission
  
  Jupiter decameter emission @ 10 pc peaks at \( \sim 25 \) μJy (sec - min timescale)
  
  \( 3 \) μJy (hour timescale)

- Broad frequency range, from 50 MHz to \( \gg \) GHz

- Broad instantaneous frequency coverage

- Circular / Full polarization

- Need to observe many targets many hours
  
  \( 5\)°x\( 5\)° FoV, multi-beam (several fields) capability ?, high duty cycles,
  
  coordinated programs (EoR, transients ?), commensal obs. ?)
• Some requirements for SKA searches of Xo MS and/or SPI radio emissions

  → Must significantly improve / LOFAR (if no detection)

- SKA1-low baseline design essentially Ok
  (hierarchical distribution of log-per. dipoles)
- 50-100 km max. baselines: low enough confusion, peeling... ?
  → high dynamic range observations needed
- RFI mitigation (very low RFI level @ SKA-Low site)
- Imaging 5°x5° field(s) at ~1 sec time resolution + multi-timescales search
- Multi-beam (multi-field) capability in SKA-Low ?
- Go to frequencies < 50 MHz ?

• Synergies with cool / dwarf / flaring stars studies (with possible strategies for post-flare exoplanet search, VLBI observations...), & with SETI