Looking for Magnetospheric Radio Emissions from Young Hot Exoplanets

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Why are we looking for exoplanets?
Background and recent status on exoplanet discoveries

Why are the radio observations important for exoplanet?
Some key properties in physics and dynamics can be revealed by Radio Emission only.

How do we find the radio signals of exoplanets?
It is a better way to “see” an exoplanet directly by its Radio Emission.

What have we learned from previous attempts?
Previous attempts, ongoing projects and future plans.
Giordano Bruno (1584)

“Thus is the excellence of God magnified and the greatness of his kingdom made manifest; He is glorified not in one, but in countless suns; not in a single earth, a single world, but in a thousand thousand, I say in an infinity of worlds.”
First planet confirmed orbiting a Sun-like star was a gas giant with an orbital period of 4.2 days. Surface temperature estimated 1000°C → “Hot Jupiter”

Nobody expected to find giant planets so close to their stars!!

Planet formation theories had to be completely rewritten to make these strange new worlds. And the fun was just beginning…
The more planetary systems we found, the stranger they became.

- Ultra short-period/Close-in planet
- Extreme physics properties
- Compact orbital configuration
- Multiplicity of planets and their hosts
Amazing Exoplanets

We know of a world that is evaporating away before our eyes.

WASP-12b
~ 1.1 days

We know of a world that is a diamond bigger than the Earth.

55 Cancri e
~ 0.7 days
~ 2 Re
~ 8 Me

1/3 planet's mass would be carbon
Some planets have three suns in the sky---91 Aquarii b
Amazing Exoplanets

Kepler-36: Two Neptune-like planets orbiting very close to each other

~13.8 & 16.2 days

7:6 MMR
Amazing Exoplanets

Kepler-11: Compact system of 6 transiting planets

TRAPPIST-1: A compact mini-Solar system of 7 planets
total confirmed exoplanets: 3777 with masses: ~1280
http://exoplanetarchive.ipac.caltech.edu/ 2018/08/20

Most effective method so far
The Galaxy is filled with planets, what’s the next step?

**The “Kepler Revolution”**

- We need more methods to reveal more details in physics and dynamics of exoplanet systems, i.e. from “Detecting to Characterizing”
- While habitable exoplanets attract much more public attention.

There is more than one planet per star in the Galaxy. Cassan et al., 2012
Tuomi et al., 2014

Small planets are more common than large planets. Howard et al., 2011
Wittenmyer et al. 2011
Fressin et al., 2013
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How do we find exoplanets and what can we learn?

Two main detection methods: mass, radius, orbit elements

1. Transit (mini-eclipses)
2. Radial velocity “Doppler wobble”
Planetary-scale magnetic fields

Earth, Jupiter, Saturn, Uranus, & Neptune

- Produced by rotation of conducting fluid
  - Earth: liquid Fe core
  - Jupiter & Saturn: metallic H2
  - Uranus & Neptune: salty oceans

- Planetary magnetic field immersed in solar wind.

- Solar wind is high-speed plasma with embedded magnetic field.

- Pressure from solar wind impacts and deforms planetary magnetic field.

- Magnetosphere
  
  *Large objects, e.g., Jovian magnetosphere is 5x diameter of full Moon*
Radio emission will tell us more about the planet.

- **Information on planetary magnetosphere:**
  - Intensity of magnetic field,
  - Plasma density in the magnetosphere
  - Rotation of conducting fluid
  - Thermal state and composition of planetary interior.

- **A new method to find exoplanet around active stars.** (while optical observation prefers quiet stars)

- **Information on planetary rotation**
  (modulation of the emission with rotation frequency and tilt)

- **Existence of satellites and their orbit information**

- **Habitability**

(Hess & Zarka 2011)
Seeking for **habitable exoplanets** is one of the most important science aims in the next & next & next decades.

- Cosmic Dawn
- New Worlds
- Physics of the Universe

**New Worlds**
Seeking nearby, habitable planets

- Nearly 500 extrasolar planets now detected - extraordinarily rapid progress
  - Huge range of properties exhibited, surprisingly different from those in our own solar system
  - Many ongoing approaches seek new “Earths” – potentially habitable rocky planets with liquid water and oxygen
  - New techniques being developed
- Kepler data adds over 300 “candidates” to the list, including many less than twice the size of Earth
- Next great step forward: understand frequency of different types of planets and lay scientific and technical groundwork to inform future strategies for detailed study of nearby Earth-like planets
Seeking for **habitable exoplanets** is one of the most important science aims in the next & next & next decades. However, a “habitable planet” is not simply a planet living within the “habitable zone”!
The existence of a suitable magnetic field is one of the most crucial requirements to the habitability of an exoplanet!

- **Stellar properties:**
  \[
  m_V = 11.05 \\
  M_\ast = 0.12 M_\odot \\
  R_\ast = 0.15 R_\odot \\
  T_\ast = 3042 K
  \]

- **Planetary properties:**
  \[
  P = 11.1855 \text{ days} \\
  M_p = 1.27 M_e
  \]
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Search for exoplanet’s radio emissions

Solar wind provides energy source
1. Kinetic energy carried by solar wind
2. Magnetic energy carried by solar wind
4. Coronal mass ejection (CME) impact

All gas giants in the Solar system have strong planetary magnetic fields and auroral/polar cyclotron emission.

Jupiter: Strongest at $10^{12}$ W
Radiometric Bode’s Law

- Good correlation between planetary radiated power ($P_{\text{rad}}$) and input solar wind power ($P_{\text{sw}}$)

\[ P_{\text{rad}} \sim \varepsilon P_{\text{sw}}^x \]

\[ x \sim 1 \]

\[ \varepsilon \sim 10^{-6} \text{ to } 10^{-3} \]


- Zarka et al. (1997) refined by adding Uranus, Neptune, and extended to exoplanets (Zarka et al 2007).

Search for exoplanet’s radio emissions
Search for exoplanet’s radio emissions

- Interactions between charged stellar wind and magnetic field of close-in giant planet may produce radio emissions detectable by large radio telescopes on the ground. (Zarka 2011)

- Cyclotron Maser Instability (CMI) (Treumann 2006). Planet-star contrast ~1@ 50MHz while in visible ($10^{-9}$) or infrared ($10^{-6}$)

- May not be possible for Jupiter analog due to galaxy radio background, but feasible for young hot Jupiters.

Frequency: ~$10^{-250}MHz$, intensity: ~$0.1\mu Jy - 1 Jy$

Zarka, 2014
Outlines

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previous attempts

- “A Search for Extra-Solar Jovian Planets by Radio Techniques” (Yantis, Sullivan, & Erickson 1977)
- “A Search for Cyclotron Maser Radiation from Substellar and Planet-like Companions of Nearby Stars” (Winglee, Dulk, & Bastian 1986)

Blind Search of the Solar Neighborhood
no detection
Various predictions suggest that τ Boo b is a good candidate (~100 mJy near 50 MHz).

VLA can observe at 74 MHz with sub-Jansky sensitivity.

$1 \text{ Jy} = 10^{-26} \text{ W/m}^2/\text{Hz}$

3 epochs between 1999 and 2003, with upper limits ~135–300 mJy.
previous attempts

- **UTR-2**: no detection
  Stars with confirmed extra-solar planets @ 25 MHz with 100 mJy and 1500 mJy sensitivities (Zarka et al. 1997; Ryabov et al. 2004)

- **VLA**: no detection
  - tau Boo @ 74 MHz with 100 mJy sensitivity (Farrell et al. 2003, 2004)
  - HD 80606 @ 330 MHz and 1465 MHz with resp. 1.7 mJy and 0.048 mJy sensitivities (Lazio & Farrell 2007, Lazio et al., 2010a).

- **GMRT**: no detection
  - HD 189733 @ 153, 244 and 614 MHz with resp. 2.1 mJy, 2 mJy and 0.16 mJy sensitivities (Lecavelier et al. 2009, 2011)
  - τ Boo, 70 Vir, 55 Cnc, HD 162020, HD 174949 @ 150 MHz (Winterhalter, et al 2006)
  - u And, e Eri, HD 128311 @ at 153 MHz (Winterhalter et al. 2006, George & Stevens 2007, 2008).

- **GBT**: no detection
  - HD 189733 b @ 320 MHz (Smith et al. 2009)
What have we learned?

We need:
- Lower frequency < 50 MHz
- Higher sensitivity < 1 mJy
- Better selected targets
- Young hot Jupiters
- Longer orbital phase coverage
- Full orbit period
- Polarization
- Circular polarization
- New scaling law?
- CMI detection of brown dwarf (Kao et. al. 2016)
## Ongoing programs

<table>
<thead>
<tr>
<th>Instrument name, location, and references</th>
<th>Description</th>
<th>Frequency range (MHz)</th>
<th>Effective area (m²)</th>
<th>Beam</th>
<th>Polarization</th>
<th>Maximum effective sensitivity (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDA (Nançay decameter array), France (Boisshot et al., 1980; Lecacheux et al., 2004)</td>
<td>2 × 72 helix-spiral antennas (rectangular arrays)</td>
<td>10–100</td>
<td>~2 × 4000</td>
<td>~6° × 10°</td>
<td>2 circular → 4 stokes</td>
<td>~10²</td>
</tr>
<tr>
<td>VLA (very large array), New Mexico, USA (Kassim et al., 1993; Cotton and Condon, 2002)</td>
<td>Interferometer: 27 parabolas × 25 m (Y-shape array)</td>
<td>74(±0.75), 330,…</td>
<td>~13 000</td>
<td>≥0.4′</td>
<td>2 polar.</td>
<td>10⁻¹–10⁻²</td>
</tr>
<tr>
<td>GMRT (giant meterwave radio telescope), Pune, India (Swarup, 1990)</td>
<td>30 parabolas × 45 m (core + Y-shape array)</td>
<td>(50), 150, 235,…</td>
<td>~30 000</td>
<td>0.3′</td>
<td>4 stokes</td>
<td>10⁻²–10⁻³</td>
</tr>
<tr>
<td>UTR-2 (Ukrainian T-shape radiotelescope, Mark 2), Kharkov, Ukraine (Braude et al., 1978; Konovalenko, 2000)</td>
<td>2040 dipoles (T-shape array)</td>
<td>7–35</td>
<td>~140 000</td>
<td>~30′ × 10°</td>
<td>1 linear polar. (EW)</td>
<td>10⁰–10¹</td>
</tr>
<tr>
<td>LOFAR (LOw Frequency ARray), The Netherlands (Van Haarlem et al., 2001; Kassim et al., 2004)</td>
<td>Interferometer/phased arrays of dipoles (core + stations up to ≥200 km)</td>
<td>10–240 in eight 4MHz bands</td>
<td>~10⁶ × (15/v)²</td>
<td>1.5″ × (100/v) (v in MHz)</td>
<td>4 stokes</td>
<td>≤10⁻³</td>
</tr>
</tbody>
</table>

(Zarka et al 2007)
Future plans

**FAST**
FAST will have > 70 MHz and best sensitivity around 3.0 μJy?

**SKA**
SKA1-LOW will have a sensitivity (1s) between 7 and 70 μJy across the band 50-350 MHz

Zarka, 2014
Future plans

The Farside Lunar Array: Farside Explorer

- solves RFI problem
- goes below Earth ionospheric cutoff frequency

*Proxima b* produces 6-83 mJy of auroral radio flux at frequencies of 0.3-0.8 MHz for planetary magnetic field strengths of 1-3 Be.
Thank you!