Magnetospheres, Habitability, and Direct Detection of Extrasolar Planets

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Introduction

In last decade, exciting discovery of extrasolar planets

- ~500 planets
- Most are indirect detection via optical signature from host star

“Do there exist many worlds, or is there but a single world? This is one of the most noble and exalted questions in the study of Nature.”—St. Albertus Magnus, *De Caelo et Mundo* (13th century)
The Next Step

Detecting $\Rightarrow$ characterizing:

- What are their properties?
- Implications for habitability of planets still to be discovered?

Magnetospheric emissions are a potential means for both detecting and characterizing planets.

Lazio et al. (arXiv:0903.0873, “Magnetospheric Emission from Extrasolar Planets”)

Outline

• Review/primer of planetary magnetospheres and magnetospheric emissions

1. \( \tau \) Boo b

2. Blind Survey of the Solar Neighborhood

3. HD 80606b: The Extreme Planet

• Future
Planetary Magnetic Fields

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

• So what?
  – Magnetic field ⇒ Composition
  – Rotation period
    • Difficult to determine by other means
    • Defined by magnetic field for solar system giant planets
  – Existence of satellites
  – Atmospheric retention
  – Habitability

Planetary-scale magnetic fields
Earth, Jupiter, Saturn, Uranus, & Neptune (Mercury)
Planetary Magnetospheres

- 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
Magnetospheres and Habitability

Solar wind particles (with suprathermal velocities) deflected at magnetosphere

- Protects the atmosphere — thermal vs. nonthermal escape
  - Thermal: Does molecular thermal velocity exceed planetary escape velocity?
    - freshman physics problem
  - Nonthermal: collisional physics sputtering, mass loading, …
    - Water retention?

- Affects the planet's albedo
- May protect genetic material of organisms

(Shizgal & Arkos 1996, Rev. Geophys., 34, 483)
Planetary Radio Emission

- Burke & Franklin (1955) discover Jovian radio emission.
- Late 1960s/70s: Earth’s polar region recognized as radio source ($10^7$ W).
- **Voyagers**: Opens up field
- All gas giants have strong planetary magnetic fields and auroral/polar cyclotron emission.

Jupiter: Strongest at $10^{12}$ W
Planetary Radio Emission

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

Radiometric Bode’s Law

- Correlation between planetary radiated power ($P_{\text{rad}}$) and input solar wind power ($P_{\text{sw}}$)
  $$P_{\text{rad}} \sim \varepsilon P_{\text{sw}}^x$$
  - $x \sim 1$
  - $\varepsilon \sim 10^{-6}$ to $10^{-3}$


- Zarka et al. (1997) refined by adding Uranus, Neptune, and non-Io DAM.
Extrasolar Planetary Magnetic Fields?

- Star-planet interactions: Ca II H and K lines (393.3, 396.8 nm)
  HD 179949b: 0.84 $M_J$ planet in 3.1 d orbit; (Shkolnik et al. 2003, 2008)

- No auroral UV emission from HD 209458b
  $M < 0.01$ to $0.1 M_J \Rightarrow B < 0.1 B_J$ (France et al. 2010)

- Inflated hot Jupiter radii = Ohmic dissipation?
  HD 209458b, HD 189733b, and Tres-4b
  $\Rightarrow B \sim 2.5 B_J$ (Batygin & Stevenson 2010)

- Asymmetric transit properties?
  WASP-12b $\Rightarrow B \sim 0.25 B_J$ (Lai et al. 2010)
Predicting Extrasolar Planetary Radio Emission

Greissmeier et al. 2007

Frequency

$\Phi [Jy=10^{-26} \text{Wm}^{-2}\text{Hz}^{-1}]$
“Nothing New Under the Sun”

• “A Search for Extra-Solar Jovian Planets by Radio Techniques” (Yantis, Sullivan, & Erickson 1977)

• Soon after recognition that Saturn also an intense radio source
  Earth, Jupiter, Saturn

• “A Search for Cyclotron Maser Radiation from Substellar and Planet-like Companions of Nearby Stars (Winglee, Dulk, & Bastian 1986)
• Radiometric laws indicate $\tau$ Boo b is a good candidate ($\sim 0.1 \, \text{Jy near } 50 \, \text{MHz}$?)
• 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
τ Boo b

- 3 epochs, with upper limits ~ 135–300 mJy
- τ Boo b could be quite luminous, but only if beamed into quite narrow solid angle
- $P_{\text{rad}} < 10^{16}$ W
  - $S \sim 120$ mJy @ 74 MHz
  - $P_{\text{Jupiter}} \sim 10^{12}$ W
- Future instruments require $S < 25$ mJy

$L((\{x_t\} | P_{\text{rad}}, \Omega, \nu_c) = \Pi [1 - p(x > x_t | s)]$
Other Observations

- GMRT observations
  - Stars with confirmed extra-solar planets: τ Boo, 70 Vir, 55 Cnc, HD 162020, HD 174949 @ 150 MHz (Winterhalter, Majid, Lazio, et al.)
  - τ Boo @ 150 MHz (Hallinan et al.)
  - HD189733b @ 244 and 614 MHz (Lecavelier des Etangs et al.)

- UTR-2
  Stars with confirmed extra-solar planets @ 25 MHz (Zarka et al.)

- GBT
  HD 189733 b @ 320 MHz (Smith et al.)
Blind Search of the Solar Neighborhood

- Radial velocity method is easier with stable stellar lines
- Stellar activity declines with age
- Known extrasolar planets may be poor sample for magnetospheric emissions!
VLA Low-frequency Sky Survey (VLSS)

- 74 MHz ($\lambda$4 meters)
- $\delta > -30^\circ$
- $\sigma \sim 100$ mJy
- 80" resolution
# Blind Search of the Solar Neighborhood

<table>
<thead>
<tr>
<th>Catalog</th>
<th>Total Number</th>
<th>Magneto Subset</th>
<th>Median Age (Gyr)</th>
<th>Distance (pc)</th>
<th>Stacked σ (mJy)</th>
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<tbody>
<tr>
<td>NStars</td>
<td>664+1676</td>
<td>252+249</td>
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<td>24.4</td>
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<tr>
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<td>GCS-age</td>
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<tr>
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<td>656</td>
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<td>23.0</td>
<td>4.8</td>
</tr>
</tbody>
</table>

From catalogs of nearby stars, select
- F, G, K stars
- Age < 3 Gyr
- Distance <~ 40 pc
### Blind Search of the Solar Neighborhood

<table>
<thead>
<tr>
<th>Sample</th>
<th>Flux Density (3σ, mJy)</th>
<th>Luminosity (erg/s)</th>
<th>Stellar Wind Amplification Factors</th>
<th>K.E. * Jupiter</th>
<th>M.E. * Jupiter</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$v$</td>
<td>$n$</td>
<td>$B$</td>
</tr>
<tr>
<td>NStars</td>
<td>17</td>
<td>$9 \times 10^{23}$</td>
<td>1.7</td>
<td>9.8</td>
<td>2.4</td>
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<td>SPOCS-age</td>
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<td>$1.1 \times 10^{24}$</td>
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<td>1.6</td>
<td>6.7</td>
<td>2.0</td>
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<tr>
<td>GCS-eage</td>
<td>14</td>
<td>$5.8 \times 10^{23}$</td>
<td>2.2</td>
<td>30</td>
<td>3.6</td>
</tr>
</tbody>
</table>
**Lighthouse-like Brown Dwarfs**

- Low-mass stars, brown dwarfs can be strong radio emitters
- Break the Benz-Güdel relation
  - Radio luminosity far higher than expected given X-ray luminosity
  - cm wavelengths vs. dam wavelengths for Jupiter
- Extrasolar planets?
- VLA has 25 yr of observations …

TVLM 513-46546 (Hallinan et al. 2007)
Searching for Anomalous Exoplanet Emission

HD 3651

ρ CrB
Anomalous Exoplanet Emission?

HD 219828
- No candidate (SNR = 2.9)
- Possibly affected by strong, nearby source
HD 80606b

- G5 star
- 4 M\textsubscript{J} planet, 111-day orbit
- \( e = 0.93 \) (!)
- 2007 November 20 periastron passage
- 330 MHz (\( \lambda \)90 cm), 1400 MHz (\( \lambda \)20 cm)
HD 80606b

330 MHz – 1.7 mJy (3σ)

1400 MHz – 48 µJy (3σ)
HD 80606b

- $3.94 \pm 0.11 \, M_J$ planet
- $0.98 \pm 0.03 \, R_J$
- 111-day orbit
- $e = 0.93$
- $T = 39$ hr (rotation period)
- $\nu \sim 55 - 90$ MHz

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Luminosity</th>
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<tbody>
<tr>
<td>1425 MHz</td>
<td>$2.7 \times 10^{23}$ erg/s</td>
</tr>
<tr>
<td>330 MHz</td>
<td>$2.3 \times 10^{24}$ erg/s</td>
</tr>
<tr>
<td>$\sim 50$ MHz</td>
<td>$&lt; \sim 10^{23}$ erg/s</td>
</tr>
</tbody>
</table>

Future =? few mJy
- EVLA-lo @ 70 MHz
- LOFAR @ 60 MHz
Summary

- Radio emission from planetary magnetospheres driven by stellar wind interaction, possible means of detection or studying of extrasolar planets

1. $\tau$ Boo b
   - $< 10^{23}$ erg/s, unless beaming angle $<< 1.6$ sr

2. Blind Survey of the Solar Neighborhood
   - Average planet in solar neighborhood has $L < 10^{24}$ erg/s

3. HD 80606b: The Extreme Planet
   - Current observations at too high of a frequency
   - Next generation approach $10^{23}$ erg/s at 50 MHz?