Planet - Star Plasma Interactions

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References:


• Interest of LF radio observations of exoplanets

• Theoretical predictions
  - planetary radio emissions
  - energy sources
  - scaling laws
  - extrapolation to exoplanets

• Conclusion
• Interest of LF radio observations of exoplanets

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• Conclusion
Obstacles to direct exoplanet detection

$\Rightarrow$ contrast & proximity star/planet

\[ \log_{10} N_{\lambda} \text{ photons m}^{-2} \text{s}^{-1} \]

\[ \lambda, \mu m \]

\[ \text{Sun} \]

\[ \text{Earth} \]

\[ \text{O}_2 \]

\[ \text{H}_2\text{O} \]

\[ \text{O}_3 \]

\[ \text{CO}_2 \]

\[ 7 \times 10^6 \]

\[ 5 \times 10^9 \]

\[ \sim 0.1 \text{ arcsec} \]
Atmospheric transparency

Gamma-rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio Waves observable from Earth.

Long-wavelength Radio Waves blocked.
Interest of Radio observations

• A low frequencies, thermal spectrum in $\lambda^{-2}$ (Rayleigh-Jeans)

• A very low frequencies, solar and planetary spectra $\neq$ thermal

• «Plasma» processes $\Rightarrow$ Contrast Sun/Jupiter $\sim 1$!
Limitations of Radio observations

- Limited angular resolution ($\lambda/D$)

- Very bright galactic background ($T_b \sim 10^{3-5}$ K)

- RFI (natural & anthropic origin)

- Ionospheric cutoff $\sim 10$ MHz,
  perturbations $\leq 30-50$ MHz,
  scintillations IP/IS
**Sensitivity of observations**

- **Galactic radio background**: $T \sim 1.15 \times 10^8 / \nu^{2.5} \sim 10^{3.5} \text{ K (10-100 MHz)}$

  $\rightarrow$ statistical fluctuations \[ \sigma = \frac{2kT}{A_e(b\tau)^{1/2}} \]

  $\rightarrow N = s / \sigma$ \quad with \quad $s = \zeta S_J / d^2$

  \[ S_J \sim 10^{-18} \text{ Wm}^{-2}\text{Hz}^{-1} \quad (10^8 \text{ Jy}) \quad \text{à 1 UA} \]

- **Maximum distance for $N\sigma$ detection of a source $\zeta$ x Jupiter**:  

  \[ d_{\text{max}} = \left( \frac{\zeta S_J A}{2NkT} \right)^{1/2}(b\tau)^{1/4} \]

  $\Rightarrow d_{\text{max}} \text{ (pc) } = 5 \times 10^{-8} \left( A_e \zeta \right)^{1/2} f^{5/4} (b\tau)^{1/4} \]
⇒ $\zeta = 1$

<table>
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<tr>
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<td>$f = 100$ MHz</td>
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| $A_e = 10^4$ m²  | 0.003 | 0.05 | 0.01 | 0.2 | 0.04 | 0.7 |
| $A_e = 10^5$ m²  | 0.01  | 0.2  | 0.03 | 0.6 | 0.1  | 2.2 |
| $A_e = 10^6$ m²  | 0.03  | 0.5  | 0.1  | 2.  | 0.4  | 7.  |

(distances in parsecs)
• Interest of LF radio observations of exoplanets

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  - planetary radio emissions
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• Conclusion
Solar Wind - Magnetosphere Interaction ...
Aurorae
Radio emissions
Properties of radio emissions

• $f \sim f_{ce}$, $\Delta f \sim f$

• $T_B > 10^{15}$ K

• circular/elliptical polarization (X mode)

• very anisotropic beaming (conical, $\Omega \ll 4\pi$ sr)

• variability /t (bursts, rotation, solar wind...)

• correlation radio / UV

• radiated power: $10^6$-$10^{11}$ W
Generation of radio emissions

• **Coherent cyclotron emission**: 2 conditions within sources:
  - low $\beta$ magnetized plasma ($f_{pe} \ll f_{ce}$)
  - energetic electrons (keV) with non-Maxwellian distribution

$\rightarrow$ high magnetic latitudes
$\rightarrow$ direct emission at $f \sim f_x \approx f_{ce}$

• **Acceleration of electrons**:
  - interactions $B/\text{satellites} \rightarrow E_{\parallel}$
  - MS compressions
  - magnetic reconnections
Strong correlation between Solar Wind (P, V...) and auroral radio emissions
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Solar Wind - Magnetosphere Interaction

- Kinetic energy flux on MS cross-section:
  \[ P_C \sim N \pi V^2 \pi R_{MP}^2 \]
  \[ N = N_0/d^2 \quad N_0 = 5 \text{ cm}^{-3} \text{ m} \sim 1.1 \times m_p \]

- Poynting flux of IMF on MS cross-section:
  \[ P_B = \int_{MP} (E \times B/\mu_o).dS \]
  \[ E = -V \times B \rightarrow E \times B = VB_{\perp}^2 \rightarrow P_B = B_{\perp}^2/\mu_o V \pi R_{MP}^2 \]

Magnetopause radius \( R_{MP} \) from pressure equilibrium:
\[ V \sim c^t e \]
\[ N \sim d^{-2} \quad \text{(mass conservation)} \]
\[ B_R \sim d^{-2} \quad \text{(magnetic flux conservation)} \]
\[ B_\phi \sim d^{-1} \quad (B_R/B_\phi = V/\Omega d) \rightarrow B \sim d^{-1} \]
(behind Jupiter orbit, \( B \sim b_\phi \))

\[ \rightarrow B^2 \text{ varies as } NV^2 \text{ thus } P_C \text{ varies as } P_B \]

\[ \rightarrow P_C/P_B \sim 170 \text{ beyond } 1 \text{ UA} \]
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Satellite - $B_{Jupiter}$ interaction
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Dipolar interaction

- Magnetic reconnection
  (e.g. Ganymede-Jupiter)

\[ P_d = \varepsilon K V B_\perp^2/\mu_0 \pi R_{MP}^2 \]

Efficiency \( \varepsilon \sim 0.1-0.2 \)

\( K= \sin^4(\theta/2) \) ou \( \cos^4(\theta/2) \) 0 or 1

\[ \rightarrow P_d = \varepsilon P_B \]
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Unipolar interaction

- Interaction via Alfvén waves & currents
  (e.g. Io-Jupiter)

\[ \phi = E \times 2R_{\text{obs}} = V \times B_\perp \times 2R_{\text{obs}} \]

\[ P_d = \varepsilon' \frac{V B_\perp^2}{\mu_0 \pi R_{\text{obs}}^2} \]

\[ \varepsilon' = (1+M_A^{-2})^{-1/2} \quad M_A \leq \varepsilon' \leq 1 \]

\[ \rightarrow P_d = \varepsilon' P_B \]
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• Conclusion
Radio-kinetic Bode’s law » (auroral emissions)

\[ P_{\text{Radio}} \sim \eta_1 \times P_C \quad \text{with} \quad \eta_1 \sim 10^{-5} \]

[Desch and Kaiser, 1984 ; Zarka, 1992]
« Radio-magnetic Bode's law » (auroral emissions)

\[ P_{\text{Radio}} \sim \eta_2 \times P_B \quad \text{with} \quad \eta_2 \sim 2 \times 10^{-3} \]
« Generalized radio-magnetic Bode’s law » (all emissions)

\[ P_{\text{Radio}} \sim \eta \times P_B \quad \text{with} \quad \eta \sim 2-10 \times 10^{-3} \]
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~250 exoplanets (in ~200 systems) 16% with $a \leq 0.05$ UA (10 Rs)

24% with $a \leq 0.1$ UA

→ ~40 « hot Jupiters » with periastron @ ~5-10 $R_S$

**Magnetic field at Solar surface:**

→ large-scale $\sim 1$ G ($10^{-4}$ T)

→ magnetic loops $\sim 10^3$ G,

over a few % of the surface

**Magnetic stars:** $> 10^3$ G
Modelling of a hot Jupiter (magnetized) orbiting a Solar type star

- Electron density in Solar corona

![Graph showing electron density in Solar corona](image)
• Solar wind speed in the planet's frame
- Interplanetary magnetic field
- Dissipated power per unit area of the obstacle
- Magnetospheric compression
• Total dissipated power on obstacle
• Extrapolation / Radio-kinetic Bode’s law \[ P_{\text{Radio}} = P_{\text{Radio-J}} \times 10^3 \] [Farrell et al., 1999, 2004]

• Extrapolation / Radio-magnetic Bode’s law \[ P_{\text{Radio}} = P_{\text{Radio-J}} \times 10^5 \] [Zarka et al., 2001, 2005]

except if there is a « saturation » mechanism
**Planetary magnetic field decay?**

- Radio detection $\rightarrow f > 10$ MHz $\rightarrow B_{\text{max-surface}} \geq 4$ G

- Jupiter: $m = 4.2 \ G R_J^3$, $B_{\text{max-dipole}} = 8.4$ G, $B_{\text{max-surface}} = 14$ G, $f_{\text{max}} = 40$ MHz

- Spin-orbit synchronisation (tidal forces) $\rightarrow \omega \downarrow$

- But $m \propto P_{\text{sid}} \alpha \ -1 \leq \alpha \leq -\frac{1}{2} \rightarrow m \downarrow$ (B decay)?

<table>
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<th>Upper Limit of Magnetic Fields in Hot Jupiters</th>
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<tbody>
<tr>
<td>Planet</td>
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<tr>
<td>--------</td>
</tr>
<tr>
<td>HD 179949b$^a$ ........</td>
</tr>
<tr>
<td>HD 209458b ........</td>
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<tr>
<td>$\tau$ Boo b$^a$ ........</td>
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<td>OGLE-TR-56b ......</td>
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- Internal structure + convection models

  $\rightarrow$ self-sustained dynamo  $\rightarrow m$ could remain $\geq$ a few $G R_J^3$

[Sanchez-Lavega, 2004]
• Unipolar inductor in sub-Alfvénic regime
  (as for Io-Jupiter)
But radio emission possible only if $\frac{f_{pe}}{f_{ce}} \ll 1$

$\Rightarrow$ intense stellar B required ($\kappa = 10-100 \times B_{\text{Sun}}$)

$\Rightarrow$ emission $\geq 30-250$ MHz from 1-2 $R_S$
Extrapolation / Radio-magnetic Bode's law

\[ P_{\text{Radio}} = P_J \times 10^5 \times \left(\frac{R_{\text{exo-ionosphere}}}{R_{\text{magnetosphere}}}\right)^2 \times \left(\frac{B_{\text{star}}}{B_{\text{Sun}}}\right)^2 \]

\[ = P_{\text{Radio-J}} \times 10^6 \]
\[ \Rightarrow \zeta = 10^5 \]

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<td>1</td>
<td>3</td>
<td>13</td>
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<td>16</td>
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<td>220</td>
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<td>11</td>
<td>40</td>
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<td>50</td>
<td>190</td>
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<td>( f = 100 \text{ MH}z )</td>
<td>160</td>
<td>600</td>
<td>2200</td>
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(distances in parsecs)
Other published studies ...

- Possibilities for radio scintillations ⇒ burts $P_{\text{radio}} \times 10^2$
  [Farrell et al., 1999]

- Estimates of exoplanetary $m$ (scaling laws - large planets better) $\rightarrow f_{ce}$ & radio flux
  [Farrell et al., 1999; Griessmeier et al., 2004]

- $F_x$ as wind strength estimator
  [Cuntz et al., 2000; Saar et al., 2004, Stevens, 2005]

- Stellar wind modelling (spectral type spectral, activity, stellar rotation)
  [Preusse et al., 2005]

- Time evolution of stellar wind and planetary radius (young systems better)
  [Griessmeier et al., 2004; Stevens, 2005]

- Role of (frequent) Coronal Mass Ejections
  [Khodachenko et al., 2006]

- Application of unipolar inductor model to white dwarfs systems
  [Willes and Wu, 2004, 2005]
• Predictions for the whole exoplanet census
  ➡ radio-kinetic extrapolation

  [Lazio et al., 2004]

  ➡ radio-magnetic + CME extrapolations

  [Griessmeier, Zarka, Spreeuw, 2007]
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• Conclusion
• The Radio Search for Extrasolar Planets is worth pursuing!

• Objectives

  → Direct detection (planet-star distinction via polarization & periodicity)
  → Planetary rotation period
  → Measurement of $B \Rightarrow$ constraints on scaling laws & internal structure models
  → Comparative magnetospheric physics (star-planet interactions)
  → Discovery tool (eventually) ?

• Ongoing observations at UTR-2, GMRT, VLA

• Future observations with : LOFAR, ALMA, SKA ... and from the Moon ?