Chapter 3

Search for Cyclotron Maser Emission from Extrasolar Planets

3.1 Introduction

Radio frequency cyclotron maser radiation is emitted by all five of our solar system’s magnetized planets. By analogy, extrasolar planets are also expected to be a source of non-thermal radio emission. For the emission to occur, a planet must be magnetized and exposed to a source of energetic (keV) electrons, such as a stellar wind. The electrons’ interaction with the planet’s magnetic field creates anisotropy in the energy distribution of the electrons. This allows resonance between electrons spiraling in the magnetic field and circularly polarized waves to amplify the waves and produce coherent emission. Using two empirical models, the “Radiometric Bode’s Law” and a variation on that law by Zarka, we predicted radio fluxes and cyclotron frequencies for the full catalog of known extrasolar planets. Four target planets were selected for observations with the Arecibo radio telescope. These planets were observed at 327 MHz in 15 hours of observations over the course of nine days in July, 2004.

To date, extrasolar planets have been discovered and studied using the radial velocity technique almost exclusively. In radial velocity searches, spectroscopic observations of the parent star’s reflex motion as it is orbited by one or more planets are used to determine each planet’s orbital period and radius and to place a lower limit on the planet’s mass.

The detection of cyclotron maser radiation would be the first detection of radio
emission from an extrasolar planet and only the second direct detection of an extrasolar planet at any wavelength. (The first direct detection was of a planet transiting HD 209485. Spectroscopic observations of the parent star during transit revealed sodium absorption lines from the planet’s atmosphere. However, only a tiny fraction of planets will have observable transits; a larger number of extrasolar planets should be detectable by their radio emission.)

The detection of non-thermal radio emission from an extrasolar planet would tell us that the planet is magnetized and, therefore, that it houses an electrically conducting fluid core, enabling more detailed analysis of the planet’s composition. The presence of a magnetic field is also important because it has been suggested that a planet must have a magnetic field in order to be habitable; functioning as a shield from cosmic rays, the magnetic field prevents high-energy particles from damaging nascent cells and genetic material.

Cyclotron maser emission also provides information about a planet’s rotation rate which cannot be obtained from the radial velocity technique. This is, in fact, the definitive method by which the rotation rates of gas planets within our own solar system are measured.

More information about the planet’s magnetosphere can be obtained from an analysis of the emission’s polarization (expected to be either 100% circular or elliptical) as described in Bastian, Dulk, & Leblanc (2000). Through analysis of the sense of circular polarization, the emission can be localized to one or both of the planet’s hemispheres. The detection of elliptical polarization can be used to place a limit on the plasma density in the magnetosphere.

Cyclotron maser emission also provides a means by which to detect satellites orbiting extrasolar planets. In our solar system, Jupiter’s radio emission is mod-
ulated by its moon Io. The energetic electrons required for the cyclotron maser come in this case not from the solar wind, but from the interaction between Io and Jupiter’s magnetosphere. The detection of such a periodic modulation in the extra-solar planet’s radio emission could similarly indicate the presence and revolution period of of a satellite about that planet.

3.2 Observations and Analysis

The four target planets were observed as shown in Table 3.1. Observations were made on seven different days in the period from July 19, 2004 to July 27, 2004. A typical observation lasted for between one and three hours, and all were made at 327 MHz over a 50 MHz bandwidth using the Wide-Band Arecibo Pulsar Processor (WAPP) with 256 frequency channels and a 128 µs sampling rate. Targets were selected using flux predictions as described in Section 3.4.2. Approximately ten minutes of off source observations were also included on each day of observing.

Dynamic spectra were prepared using the filterbank routine from Duncan Lorimer’s SIGPROC data analysis suite (Lorimer, 2001). Time resolution was degraded from 128 µs to 0.1 s, sufficient for the search for cyclotron maser emission. Data were normalized as in Section 2.2.
Table 3.1. Table of Observations

<table>
<thead>
<tr>
<th>Object</th>
<th>MJD</th>
<th>Duration</th>
<th>RA</th>
<th>Dec</th>
<th>N</th>
<th>W</th>
<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ Boo</td>
<td>53205.9</td>
<td>120 min</td>
<td>13:47:16.0</td>
<td>17:27:24</td>
<td>18:40–18:55</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>70 Vir</td>
<td>53206.9</td>
<td>120 min</td>
<td>13:28:26.0</td>
<td>13:46:49</td>
<td>17:35–17:40, 18:10–18:30</td>
<td>17:40–18:00</td>
<td>1</td>
</tr>
<tr>
<td>τ Boo</td>
<td>53207.9</td>
<td>120 min</td>
<td>13:47:16.0</td>
<td>17:27:24</td>
<td>—</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>HD 114762</td>
<td>53209.7</td>
<td>165 min</td>
<td>13:12:20.1</td>
<td>17:31:2</td>
<td>—</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>HD 114762</td>
<td>53212.7</td>
<td>165 min</td>
<td>13:12:20.1</td>
<td>17:31:2</td>
<td>—</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>HD 114762</td>
<td>53213.7</td>
<td>10 min</td>
<td>13:12:20.1</td>
<td>17:31:2</td>
<td>—</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>HD 128311</td>
<td>53213.7</td>
<td>70 min</td>
<td>14:36:00.6</td>
<td>09:44:47.5</td>
<td>—</td>
<td>—</td>
<td>1</td>
</tr>
</tbody>
</table>

Note. — Four sources were observed at 327 MHz over the course of ten days. Observation durations are approximate and include up to ten minutes of off-source time. RA and Dec are given in J2000 coordinates. Times in the columns headed W and N are AST and denote start time and duration of narrow and wide signals, as described in Section 3.3. A 1 in the “Day” column indicates that observations were made on a weekday, when RFI is expected to be more prevalent. A 2 indicates that observations were made on a weekend.
3.3 Results

No detections were made above approximately 0.6 Jy (5σ). However, future analysis employing the methods discussed in Chapter 2 could search the data more sensitively, to a limit of $\frac{1}{\sqrt{N}}$ of the single-pixel upper limit, where $N$ is the number of points included in the filter or group. We also note that some signals deserving further analysis were observed. We group these signals into two categories: wide drifting signals, occupying more than about 2 MHz of the band, and narrow drifting signals, occupying about 200 kHz of the band. Representative signals are shown in Figures 3.1 and 3.2.

The wide signal shows a regular modulation which suggests the signal is of artificial origin. In Figure 3.3, we present a five-minute dynamic spectrum of 70 Vir (left), which displays a wide drifting signal, and 50 second time series averaged over 15 frequency channels around 340 MHz from the same dynamic spectrum (right).

We note, however, that wide drifting signals are seen only in observations of 70 Virginis. While observations of both Tau Boo and 70 Virginis display narrow drifting signals, neither signal is seen in any off-source observation or from any other source.

These signals were observed in 19 of the 49 dynamic spectra from 70 Vir (38%), 3 of the 49 dynamic spectra from Tau Boo (6%), and in no dynamic spectra for the other sources, HD 114762 and HD128311. The last three columns of Table 3.1 describe when and for how long the signals were observed. In the column headed W, we list the times during which the wide signals were observed in Atlantic Standard Time (AST). The column headed N provides this information for narrow signals. If the observation was made on a weekday, it is denoted with a 1 in the
Figure 3.1: Narrow drifting signal in a 5-minute dynamic spectrum on 70 Virginis.
Figure 3.2: Wide drifting signal in a 5-minute dynamic spectrum on 70 Virginis.
Figure 3.3: 50 seconds of the dynamic spectrum on the left are averaged over 15 channels around 340 MHz to produce the time series shown on the right.

last column. A 2 in the last column means that the observation was made on the weekend. RFI is expected to be highest during the day on weekdays. Our signals show no such correlation.

3.4 Models

3.4.1 The Qualitative Picture

The quantitative models discussed in Section 3.4.2 are empirical models based on observations of the radio-loud planets within our solar system. Therefore, we preface the quantitative models with a qualitative description of some representative cases.

The five magnetized planets in our solar system (Earth, Jupiter, Saturn, Neptune, and Uranus) display such a diversity of radio profiles that it is difficult to sketch an accurate picture of “typical” emission.

Neptune, for instance, displays episodes of intense, narrowband radio emis-
sion. Each approximately hour-long episode is marked by a battery of bursts with timescales under 30 ms. In addition to these rapid radio bursts, Neptune also emits long-duration broadband emission (Warwick et al., 1989). Uranus’ radio emission also contains both “smooth” and ”bursty” components (Warwick et al., 1986).

Jupiter’s emission, perhaps the most complex and best-studied, contains kilometric (30 kHz - 300 kHz), hectometric (0.3 - 3 MHz), and primarily Io-controlled decametric components (3 - 30 MHz). It is characterized by long-duration (≈ 1 minute) and frequency-drifting short duration bursts (≈ 1 ms) bundled into emissions episodes that can last a few hours (Gurnett et al., 2002).

In every case, the particulars of the emission are closely tied to structure within the planet’s magnetic field and solar activity, including solar wind density and velocity and the magnitude of the interplanetary magnetic field at the planet’s location (Barrow, Genova, & Desch, 1986). These properties vary on all timescales; the solar wind displays both a quasi-stationary state, which varies on time scales from days to months, and a transient state, in which the smooth quasi-stationary wind is punctuated every day or so by shorter-duration activity associated with coronal mass ejections (Neugebauer, 1991).

### 3.4.2 The Quantitative Picture

Target sources were selected based on their predicted flux using the two versions of the “Radiometric Bode’s Law” presented in Farrell, Desch, & Zarka (1999) and shown in Equations 3.1 and 3.2. These relations combine Blackett’s law, which describes the dependence of a planet’s magnetic moment on its rotation rate and mass, with spacecraft measurements of radio emission from the solar system’s magnetized planets. The first model is calibrated using measurements from Saturn,
Jupiter and Earth; the second model also includes Uranus and Neptune.

Since little is known about the extrasolar planets and their environments, the predictions rest on a number of assumptions. First, we assume that the magnetization of the extrasolar planets scales with mass and rotation frequency as the magnetization of our solar system’s gaseous planets does (Farrell, Desch, & Zarka, 1999). We also assume that the parent stars produce stellar winds similar to our sun’s and that the planetary dipole moments scale as $M \sim \omega m^{5/3}$, where $\omega$ is the planet’s rotation rate and $m$ is the planet’s mass.

Flux predictions for our five target planets are presented in Table 3.4.2. The predicted cyclotron frequency, at which cyclotron maser emission peaks, is represented by $\nu_c$. Predicted flux densities $f_I$ and $f_{II}$ are also shown.

In Model I, radio power from a magnetized planet goes as

$$P_I = \left( \frac{\omega}{\omega_j} \right)^{0.58} \left( \frac{m}{m_j} \right)^{0.98} \left( \frac{d}{d_j} \right)^{-1.17} 4 \times 10^9 \text{ W}$$

(3.1)

where $d$ is the distance between the star and the planet and the subscript $j$ indicates the value for Jupiter.

After Zarka et al. (1997), Farrell, Desch, & Zarka (1999) include radio power from Uranus and Neptune and decametric radiation from Jupiter in their second empirical model (Model II), giving:

$$P_{II} = \left( \frac{\omega}{\omega_j} \right)^{0.79} \left( \frac{m}{m_j} \right)^{1.33} \left( \frac{d}{d_j} \right)^{-1.60} 400 \times 10^9 \text{ W}.$$  

(3.2)

A lower limit on the flux density incident at Earth is found by assuming isotropic emission (spherically symmetric beaming):

$$F_{I,II} = \frac{P_{I,II}}{4\pi s^2 \Delta \nu} \text{ Wm}^{-2}\text{Hz}^{-1}$$

(3.3)
Table 3.2. Planet Data and Predicted Parameters

<table>
<thead>
<tr>
<th>Object</th>
<th>$m$</th>
<th>$2\pi/\omega$</th>
<th>$d$</th>
<th>$D$</th>
<th>$\nu_c$</th>
<th>$f_I$</th>
<th>$f_{II}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(m_j)$</td>
<td>(h)</td>
<td>(AU)</td>
<td>(pc)</td>
<td>(MHz)</td>
<td>(mJy)</td>
<td>(mJy)</td>
<td>(mJy)</td>
</tr>
<tr>
<td>τ Boo</td>
<td>4.13</td>
<td>79.5</td>
<td>0.05</td>
<td>15.6</td>
<td>7</td>
<td>0.01</td>
<td>8</td>
</tr>
<tr>
<td>70 Vir</td>
<td>7.44</td>
<td>10</td>
<td>0.48</td>
<td>18.11</td>
<td>158</td>
<td>$1 \times 10^{-4}$</td>
<td>0.08</td>
</tr>
<tr>
<td>HD 114762</td>
<td>11.03</td>
<td>10</td>
<td>0.35</td>
<td>40.57</td>
<td>304</td>
<td>$3 \times 10^{-5}$</td>
<td>0.02</td>
</tr>
<tr>
<td>HD 128311</td>
<td>2.63</td>
<td>10</td>
<td>1.06</td>
<td>16.6</td>
<td>27</td>
<td>$2 \times 10^{-4}$</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Note. — Mass ($m$), star-planet distance ($d$) and Earth-star distance ($D$) from the California and Carnegie Planet Search Team: http://exoplanets.org. In cases where $d < 0.1$ AU, it is assumed that the planet is tidally locked to its parent star; hence, its rotation period is equal to its revolution period. In all other cases, we estimate the rotation period to be 10 hours, after Farrell, Desch, & Zarka (1999). HD 114762 has been provisionally classified as a brown dwarf by Schneider in the Extra-Solar Planets Encyclopedia: http://www.obspm.fr/encycl/encycl.html.

where $\Delta \nu$ is the emission bandwidth, equal to half the cyclotron frequency $\nu_c$, as in Farrell, Desch, & Zarka (1999)

$$\nu_c = 5600 \times M \times \text{kHz.}$$  \hspace{1cm} (3.4)

3.5 Discussion

No signals of astronomical origin were detected from any of the four target sources. However, the results of this search may inform the methods of future searches from radio emission from extrasolar planets. The unusual interference found in
observations of 70 Vir underscores the importance of a sound technique by which to discriminate between RFI and signals of astronomical origin. We suggest more frequent switching between source and off-source. For future observations at 1420 MHz, the new ALFA system could also be used to identify terrestrial interference, as such RFI will generally appear in all seven beams; a weak astronomical signal will only appear in one beam.

Furthermore, the signal is expected to be transient: therefore, additional observations increase our chances of catching an episode of cyclotron maser activity. The sensitive dependence of radiated power on stellar wind speed means that a small, temporary change in the activity of the parent star could bring the cyclotron maser emission up to detectable levels (Farrell, Desch, & Zarka, 1999).

Low-frequency instruments like LOFAR will also increase the likelihood of detecting nonthermal emission from extrasolar planets, as they operate closer to the expected frequency of maximum emission. However, observations at higher frequencies are also worthwhile: if a planet is significantly more magnetized than assumed in the model, the peak frequency of its cyclotron maser emission will be raised accordingly. For this reason, it is worthwhile to observe a large sample of planets; such a sample is more likely to include a highly magnetized planet that would be detectable at the frequencies at which Arecibo is most sensitive.
REFERENCES


Neugebauer, M. 1991, Science, 252, 404


Appendix A

Selected Arecibo Observations of Extrasolar Planets

Here we present a selection of dynamic spectra from the July, 2004 observations of extrasolar planets made at the Arecibo Observatory, as described in Chapter 3. Spectra are identified by source name, MJD and scan number, a sequential identifier for each 5-minute scan. Both wide and narrow signals are seen in spectra from 70 Virginis; Tau Boo shows the narrow signal. Dynamic spectra of HD 114762 and HD 1128311, which show neither signal type, are shown as well. The top panel shows the average spectrum for the 5-minute scan. The right panel shows the scale factor by which each spectrum was adjusted to match the levels of the average spectrum.