SEARCH FOR RADIO EMISSIONS FROM EXTRASOLAR PLANETS: THE OBSERVATION CAMPAIGN

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Abstract

Using the new 150 MHz receivers of the Giant Meterwave Radiotelescope (short "GMRT") in India, we have searched for radio emissions from a sub-set of known "hot Jupiters". We have selected five targets based on the expected flux density and the level of background noise. No observation of these targets has been attempted previously at these frequencies with the sensitivity and aperture offered by GMRT. Calibrations with GMRT at 150 MHz have confirmed the noise floor to be 3 mJy over a 5 MHz bandwidth. The noise floor is well below the expected flux levels from the targets.

This paper will describe the campaign, and present the preliminary results.

1 Introduction

Non-thermal, low-frequency radio emissions have been observed for decades from planets in our solar system. Below a certain cut-off frequency (approximately 40 MHz in the case of Jupiter) the emissions are thought to be, at least in large part, cyclotron-maser emissions from unstable keV electron distributions precipitating in the auroral regions of magnetized planets.. The intrinsic power radiated by Jupiter in this frequency regime is several hundred Giga-Watt, and the power is supplied by some combination of the average solar wind and impulsive solar events such as coronal mass ejections (in addition, the planet's interaction with its moon Io contributes a significant and distinguishable part

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to the power profile). The emissions produced consist of burst from a few seconds to over an hour in duration, at frequencies close to the local electron cyclotron frequency. At and above the cut-off frequency, synchrotron emission from trapped energetic electrons dominate, but the power level is several orders of magnitude lower than that below the cut-off.

The generation mechanism of the emission below the cut-off is so effective that brightness temperatures of 10^{15} to 10^{20} K are achieved, yielding a Jupiter/Sun contrast of ≥ 1, for a quiet sun (i.e., no Type II bursts). However, early studies that scaled the Jupiter emissions to an arbitrary distance of 10 parsecs distance concluded that the flux density levels at Earth would be very low, much too low to allow detection [Gary and Gulkis, 1974].

More recently, about 150 planets outside the solar system have been discovered with (optical) radial velocity measurements, and their orbital elements determined. Different from the Jupiter - Sun geometry, many of the planets are very close to their primary (< 0.1 AU in many cases), and thus they find themselves in a much stronger stellar wind than Jupiter. The energy input into a magnetosphere so close to a star is orders of magnitude larger than that experienced by Jupiter. Expecting that the radiated power is proportional to the power input from the stellar wind (but with unknown conversion efficiency), emissions from such “hot Jupiters” are perhaps strong enough to allow detection from Earth. Our observation strategy is thus to concentrate on known extrasolar planetary systems that contain “hot Jupiters”, targeting those for which we estimate the highest flux (see next section).

2 Selection of Targets

Recent theoretical studies by, for example, Desch and Kaiser [1984], Zarka et al. [2001], and others, have proposed scaling ‘laws’ to estimate the radio power (P_r) emitted from solar (stellar) wind driven cyclotron emissions:

$$P_r \propto \left(\frac{m}{m_j}\right)^{1.33} \left(\frac{a}{a_j}\right)^{-1.60} (4 \times 10^{11})\,\mathrm{W}$$

where the subscript ’j’ refers to Jupiter, ’m’ to the mass, and ’a’ to the distance of the planet to its star. It should be noted that the parameters in the above equation are empirical ones determined using the radio planets in our solar system. In addition, the crucial exponents are evolving in the literature, and so the above relation is a rough estimate, an indication perhaps, at best.

Working from the full list of extra-solar planets, the targets of observation were selected (Table 1) based on the expected flux level using the above formula, and variations of Blackett’s ’law’ (an empirical expression relating the planet’s magnetic field to its mass), yielding a minimum flux (Flux1), and a maximum flux (Flux2) expected at Earth [e.g., Lazio et al., 2004]. Also considered and desired were high galactic latitude to decrease background noise, and close distance (d in parsec) to decrease sensitivities to some model assumptions.

The expected range for the electron cyclotron frequency (f_{ce}) is an important consideration used to determine if the observation frequency is below the cut-off frequency described in the introduction. However, the uncertainties in the parameters were such that our estimates for f_{ce} were not believable, and we did not consider the cut-off frequency in our first observations reported here.

Table 1: Extrasolar planetary systems observed in early 2005

Name	M(Jup)	a(AU)	d(pc)	Flux1(mJy)	Flux2(mJy)	Gal Lat
Tau Bootes	5.2	0.05	15.6	717.8	4446.8	-73.9
HD 162020	2.4	0.21	4.7	43.6	123.6	59.6
HD 179949	1.2	0.04	27.0	211.1	310.3	15.8
70 Virginis	9.3	0.48	18.1	1.6	17.9	-74.1
Upsilon Andromedae	0.9	0.06	13.5	147.3	170.8	20.7

3 The Giant Meterwave Radio Telescope (GMRT)

The Giant Meterwave Radio Telescope (GMRT), located near Pune, India, is the largest fully steerable telescope operating at meter wavelengths (Figure 1). Currently, its lowest operating frequency is 150 MHz.

We conducted a series of observations at the GMRT during the observatory's Cycle 7 observing period. Our observations were carried out over three days in March 2005 with a center radio frequency near 150 MHz. During the first two days (Mar 7 and 8) we collected both interferometric as well as pulsar mode (phased array mode) data on a number of sources simultaneously. In interferometric mode, we used 22 of the 30 antennas, excluding one or two extreme antennas in each arm as well as four antennas that were not operating at 150 MHz. On March 16, we recorded exclusively in pulsar mode. In this mode, we only used the central square array (CSQ) because of their phase stability over long durations and the nature of the pulsar mode data stream, which unlike interferometric mode, rules out post-correlation phase corrections.

3.1 Observation Strategy

As described above (Table 1), we selected five extra-solar primary targets. Flux calibration and monitoring were carried out by observing strong, well understood sources in an OFF-ON-OFF mode, with a cycle time of five minutes, both at the start and the end of each observing session. For this purpose we chose the strong radio-loud quasar sources 3c286, 3c298, 3c353, and 1830–36. In addition to flux calibration we performed regular phase calibrations of the array by selecting strong nearby phase calibrators based primarily on our previous experience at GMRT and the VLA. Phase calibrations were carried for five minutes before and after observing each target source. In pulsar mode we also observed a number of pulsars in order to better understand the caveats of the instrument and our analysis techniques.

Figure 1: GMRT consists of 30 individual 45 meter dish antennas, with a collecting area of nearly 50 000 m^2*. The array is spread over a distance of 25 km, arranged in a Y pattern for the outlying arm antennas, and a concentration of 12 antennas in a central square.*

Our strategy for detecting radio emission from extra-solar planets is to look for both large scale emission (in time and frequency), as well as short burst-like emission as observed in the case of Saturnian and Jovian emission. Our test calibrations have shown, however, that at both scales, there are significant contributions from other background sources, including Radio Frequency Interference (RFI), which may, in effect hide the desired signal. For this reason, we have taken care to spend about 25% of our observing time on calibration runs in various modes to better understand the GMRT instrument and our data.

At the expense of some loss in overall sensitivity, we divided the CSQ array into two subarrays. One subarray was then pointed to the desired source (extra-solar planet or pulsar), while simultaneously the second subarray was pointed about five degree away from the source in a cold piece of the sky as determined from archived maps at nearby frequencies.

4 Preliminary Results: Radio Maps and Dynamic Spectra

In interferometric mode, we have measured the visibility function along each baseline, which moves along tracks in the u-v plane as the earth rotates. The sky brightness, or map, is obtained by the process of deconvolution, using the visibility function. This process involves using the CLEAN algorithm. We have used the AIPS (Astronomical Image Processing Software) package to reduce our data and obtain preliminary maps of our target's field of view. Our current maps have sensitivities at the level of 3–10 mJy. With removal of RFI and further CLEANing, we expect our sensitivity to be improved by at least factor of 5–10 for each of our maps.

Our best radio map so far, shown in Figure 2, is of the Upsilon Andromeda region at 153 MHz.

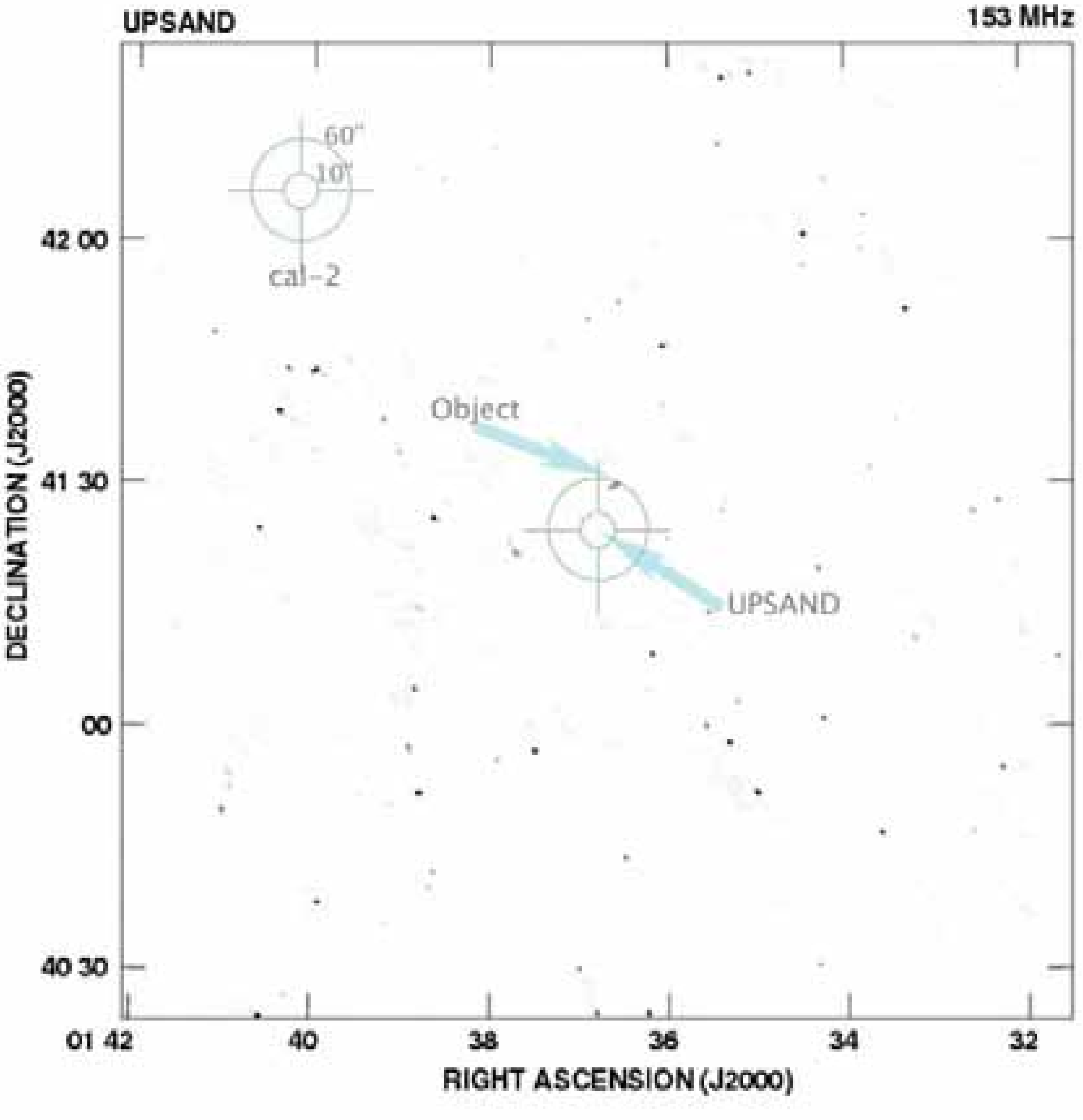

Figure 2: Radio map of the Upsilon Andromeda region at 153 MHz. The data was integrated for 1 hour over a 5 MHz bandwidth. The beam size is about 60 arc-seconds (circles). The RMS noise in this map is 3 mJy. The dark spots are well-cataloged radio sources, including a compact object at the edge of the beam.

The RMS noise in this map is 3 mJy, and even though the source was estimated to produce hundreds of mJy, no emission is seen within the circle. This suggests that either the source is much weaker, or that the observing frequency is above the upper cut-off frequency, or both. Another possibility is that the emissions are strongly beamed, away from the Earth's direction.

Yet another possibility is that the emissions could be quasi-periodic bursts of short duration, and as such might be integrated away with the hour-long staring as was done to produce the map. In a different, albeit standard approach we calculate emission intensity as a function of both radio frequency and time at various frequency and time resolutions. These dynamic spectra are then corrected for both bandpass shape as well as gain variations, per our calibration data. We next apply an RFI removal algorithm to mask out pixels that are determined to be caused by RFI. The cleaned spectra are then dedispersed with a number of trial dispersion measures and integrated along the frequency axis. We then carry out a power search algorithm for events above a certain threshold. This analysis is repeated for data obtained with the off-source subarray. The results are then compared to veto signals that are common in both data sets. This technique provides a powerful measure of vetoing 'signals' that are seen in both dynamic spectra. We are currently fine tuning our analysis algorithms with recorded pulsar data [see Majid et al., 2005 (this issue)].

Figure 3 shows a preliminary result of these techniques applied to our March 2004 (DOY 209) observation of Upsilon Andromeda (upsand). The first 3 minutes or so represent the OFF-SOURCE region (represented in Figure 2 by cal–2), with very low flux levels (blue). During the ON-SOURCE there is structure seen with significant levels of flux, with some dispersion (i. e. it is not quite vertical). The last few minutes are again OFF-SOURCE, with low flux levels indicated by the blue color.

While tantalizing, we point out that the analyses of this data is far from complete, and the apparent structure in the dynamic spectrum is likely due to RFI and/or source confusion. More analyses are needed to develop robust RFI excision algorithms and better characterize the observed features.

The analysis of the other four targets is still in progress, but the radio maps, with typical RMS noise levels of 7 mJy, have not shown any indications of emissions.

5 Summary

We have reported on our continuing attempts to detect low frequency emissions from the magnetosphere of five known extrasolar planets, so-called hot Jupiters, using the Giant Meterwave Radio Telescope's new 150 MHz capability. The five planetary systems observed in March 2005 were Tau Bootes, HD 162020, HD 179949, 70Virginis, and Upsilon Andromedae.

The analyses of the data is still ongoing, but some preliminary results are radio maps and dynamic spectra at unpresidented low noise levels in this frequency range. Especially for the Upsilon Andromeda map, the 3 mJy noise level is an order of magnitude lower than

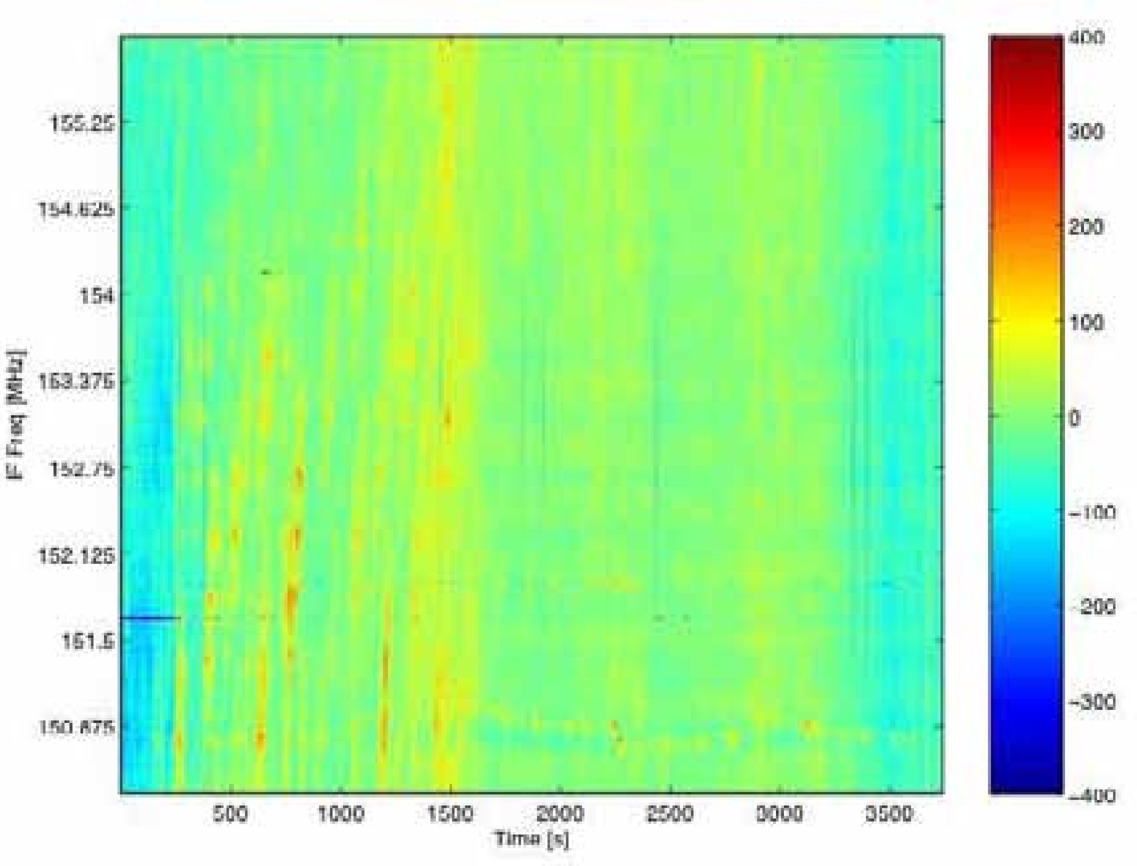

Figure 3: Dynamic spectrum of the Upsilon Andromeda region at 153 MHz. Near the left and right edges the array is looking to the OFF-SOURCE position, and the flux levels are very low (blue). In between, however, at the ON-SOURCE position, high levels of flux are observed. This probably due to RFI. Time resolution is 512 μsec; Spectral resolution is 15-31 kHz; The beam size is 7'.

previous attempts [e. g., Bastian et al., 2000]. Even so, there are no indications in the maps of magnetospheric emissions, despite some model predictions that the flux seen at Earth should be on the order of a hundred mJy (UpsAnd). Perhaps 150 MHz is too high a frequency, i. e., perhaps the cut-off frequency is below 150 MHz. To solve this problem we need to wait until GMRT has installed the planned 50 MHz capability, or LOFAR comes online [e. g., Farrell et al., 2003].

An interesting result is that the dynamic spectra of Upsilon Andromeda showed strong flux variations when on-source, but nothing when off-source. In principle, this should rule out local RFI, but the GMRT system and its environment are sufficiently complex to suspect RFI anyway. One way to reduce the uncertainty is by repeating the observations: Should we see the same or similar patterns we may have a signal from UpsAnd.

Acknowledgments

We are thankful for the support from NASA's Jet Propulsion Laboratory, from The National Center for Radio Astrophysics near Pune, India, and from the International Space Science Institute in Bern, Switzerland.

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