A stringent upper limit to 18cm radio emission from the extrasolar planet system \( \tau \) Boötes

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ABSTRACT

Context. It has been speculated for many years that some extrasolar planets may emit strong cyclotron emission at low radio frequencies in the range 10-100 MHz. Despite several attempts no such emission has yet been seen.

Aims. The hot Jupiter system \( \tau \) Boötes is one of the nearest (d=15 pc) exoplanets known to date. The gravitational influence of this massive hot Jupiter (M=8 M\(_{\text{Jup}}\)) has locked the star-planet system, making the star rotate in P\sim 3.3 days, similar to the orbital period of the planet. From the well established correlation between stellar rotation and radio luminosity, it is conceivable that the \( \tau \) Boötes system emits strong radio emission at significantly higher frequencies than currently probed, which we aimed to investigate with this work.

Methods. We observed \( \tau \) Boötes with the Westerbork Synthesis Radio Telescope (WSRT) at a frequency of 1.7 GHz, for 12 hours in spectral line mode, reaching a noise level of 42 \( \mu \)y/beam at the position of the target.

Results. No 18cm radio emission is detected from \( \tau \) Boötes, resulting in a 3\( \sigma \) upper limit of 0.13 mJy, corresponding to a 18cm radio luminosity of \(< 3.7 \times 10^{28} \text{ erg s}^{-1} \text{ Hz}^{-1}\). We observe \( \tau \) Boötes to be two orders of magnitude fainter than expected from the stellar relation between radio luminosity and rotation velocity.

Conclusions. This implies that either the \( \tau \) Boötes system is underluminous in the radio compared to similar fast-rotating stars, or that we happened to observe the target during a low state of radio emission.

Key words. Extrasolar planets

1. Introduction

It has been speculated for many years that some extrasolar planets may emit strong cyclotron emission at low radio frequencies in the range 10-100 MHz (Winglee et al. 1988; Zarka et al. 1997; Farrell et al. 1999; Bastian et al. 2000; Zarka et al. 2001; Lazio et al. 2004; Stevens 2005; Griessmeier et al. 2005; Zarka 2006, 2007). During magnetic storms, our own Jupiter can outshine the sun at these frequencies by several orders of magnitude. These storms are caused by the interaction of the magnetic fields of Jupiter, Io, and charged particles in the solar wind - causing the cyclotron radiation. It is expected that for those exoplanets that orbit their parent star at very short orbital distances (hot Jupiters, a\approx 0.05 AU), this interaction is so intense that their low frequency radio emission can be seen with current-day radio telescopes. Despite several attempts no such emission has yet been seen, making it an appealing science objective for the new low-frequency radio telescope LOFAR (Farrel et al. 2004).

\( \tau \) Boötes is one of the nearest (d=15 pc) exoplanets known to date. The F7V star (M = 1.3 M\(_{\text{Sun}}\), R=1.331 R\(_{\text{Sun}}\)) is orbited by a hot Jupiter with \( m \sin i = 3.9 \text{ M}_{\text{Jup}} \) with a period of P\approx 3.3 days (Butler et al., 1997). Spectropolarimetric observations of the host star reveals differential rotation with periods between 3.0 and 3.7 days from the equator to the poles. It implies that the planet is synchronized with the star’s rotation at intermediate latitudes (Catala et al. 2006). The chromospherically active star is also found to produce X-rays at a luminosity of \( 6.8 \times 10^{28} \text{ erg s}^{-1} \) (Kashyap, Drake, & Saar 2008). Recently, Brogi et al. (2012) have shown that the planet orbits the star at an inclination of 44.5\pm 1.5\(^{\circ}\), by detecting the signature of orbital motion in the spectrum of the planet.

Lazio & Farell (2007) observed \( \tau \) Boötes at 74 MHz (\( \lambda=4.0 \) m) with the Very Large Array, resulting in an upper limit of 150 mJy, constraining the low-frequency cyclotron radiation from the system. The scaling law from Zarka et al. (2001) predicts a 74 MHz flux density of 1 Jy for this system. However, it is expected that fast-rotating stellar systems should also produce radio emission at higher frequencies. e.g. Stewart et al. (1988) present a relation between 8.4 GHz (\( \lambda=3.6 \) cm) peak luminosities and the rotational velocity of 51 late-type F, G, and K stars - including both single stars (giants, sub-giants and dwarf stars) and active components of close binary-systems, \( \log_{10}[L/(R/R_{\text{Sun}})^2] = 12.0 + (2.5 \pm 0.5) \log_{10} v \) \( \text{(1)} \)

where \( L \) is the peak radio luminosity of the star (in \( \text{erg s}^{-1} \text{ Hz}^{-1} \)), \( R \) is the stellar radius, and \( v \) is the rotational velocity (in km s\(^{-1}\)). For \( \tau \) Boötes this would imply a peak luminosity in the 3–60 mJy range. To our knowledge the star has never been observed at these high frequencies, and only the 1.4 GHz (\( \lambda=21 \) cm) NVSS survey (Condon et al. 1998) provides a 5\( \sigma \) upper limit of 2.5 mJy. We therefore observed \( \tau \) Boötes with the Westerbork Synthesis Radio Telescope (WSRT) at 18cm targeting its conceivable high-frequency emission. Section 2 describes the observations and data reduction, and section 3 the results and discussion.

2. Observations and data reduction

\( \tau \) Boötes was observed for 12 hours in spectral line mode in the L band (18 cm) with the Westerbork Synthesis Radio Telescope (WSRT) on September 3, 2011. The maxi-short configuration with an integration time per visibility point of 60 sec was
Table 1. Details of the WSRT observations

| Source   | τ Boötis             |
|----------|-----------------------|
| RA (J2000) | 13 47 15.74340 *      |
| DEC (J2000) | +17 27 24.8552 *    |
| Configuration | Maxi-short          |
| Date          | Sept 03, 2011         |
| Duration (hours) | 12.0                |
| ν range (MHz) | 1640 - 1786          |
| Number of IFs | 8                   |
| Channels per IF | 128                |
| Bandwidth (MHz) | 20                  |
| Channel width (kHz) | 156.25            |
| Polarisations | XX, YY               |
| Beam size     | 61.9" × 14.5"        |
| Weighting     | robust               |
| Theoretical rms noise | 20 µJy beam⁻¹ |

* van Leeuwen 2007.

3. Results and Discussion

The resulting image is shown in Figure 1, with the position of τ Boötis marked by the cross. The system is not detected, resulting in a 3σ upper limit of 0.13 mJy. This indicates that its 18cm radio luminosity, at <3.7×10¹³ erg Hz⁻¹ sec⁻¹ during the observations was significantly lower than the stellar peak luminosity, found of stellar systems with similar equatorial rotation velocities. The radio and rotational period of τ Boötis indicate a rotational velocity at the equator of ∼20 km sec⁻¹. From the stellar rotation–radio luminosity relation of Stewart et al. (1988) at 8.4 GHz, as given in Eq. 1, τ Boötis is expected to have a peak 8.4 GHz luminosity of 3.8×10¹⁵ erg sec⁻¹ Hz⁻¹, corresponding to a flux density of 13 mJy (between 3 and 60 mJy when taking into account the uncertainty of the relation). Slee et al. (1987) and references therein indicate that these stars have generally flat spectra with Fν ∝ ν₀.₃, meaning that at 18 cm (1.6 GHz) the expected flux should be more than 60% of that at 8.4 GHz, corresponding to >2–40 mJy. The 3σ upper limit is therefore a factor 15–300 lower than peak fluxes for similar fast-rotating stars.

These observations imply that either the τ Boötis system is underluminous in the radio compared to similar fast-rotating stars, or that we happen to observe the target during a low state of radio emission. The latter is in line with flaring nature of the emission during which the radio luminosity can vary by more than an order of magnitude on time scales of days to weeks (e.g. Slee et al. 1987). Note that 8 stars in the Stewart et al. (1988) sample have meaningful upperlimits, implying that they were not observed during a high state of activity. Taking into account that all stars were observed typically ten times, it implies that they are on average flaring for ∼20% of the time. A more intense monitoring program is required to show this for τ Boötis.

That τ Boötis is underluminous at radio frequencies is less clear if the well known correlation between the radio and X-ray luminosities of magnetically active stars (e.g. Güdel 2002) is considered. According to this relation, the X-ray luminosity of τ Boötis of 6.8 × 10²⁸ erg sec⁻¹ (Kashyap, Drake, & Saar 2008) points to a radio luminosity of 10¹³⁻¹⁴ erg sec⁻¹ Hz⁻¹, corresponding to an expected flux density at about the level of the 3σ upper limit of our observations. Note that it may appear that, since Jupiter exhibit cyclotron bursts in narrow, low-frequency bands, and similar behaviour is expected for hot Jupiters, this could explain the absence of emission from tau Bootis. However, in this study we proved the broad-band high-frequency component expected to come from the host star, not from the planet.

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Fig. 1. WSRT 1640 - 1786 MHz primary beam corrected image of the τ Boötes field. Contours at [1, 2, 4, 8, 16] × 4σ_m are overlaid. The location of τ Boötes is marked in red. The beam size is 61.9′′ × 14.5′′.