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A stringent upper limit to 18 cm radio emission from the extrasolar planet system τ Boötis
(Research Note)

A. Stroe, I. A. G. Snellen, and H. J. A. Röttgering

Leiden Observatory, Leiden University, Postbus 9513, 2300 RA Leiden, The Netherlands
e-mail: snellen@strw.leidenuniv.nl

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 τ Boötis is one of the nearest (d = 15 pc) exoplanets known to date. The gravitational influence of this massive hot Jupiter ($M \sim 6\,M_{\rm jup}$) 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 τ Boötis system emits strong radio emission at significantly higher frequencies than currently probed, which we aimed to investigate with this work.
Methods. We observed τ Boötis with the Westerbork Synthesis Radio Telescope (WSRT) at a frequency of 1.7 GHz. for 12 h in spectral line mode, reaching a noise level of 42 μJy/beam at the position of the target.
Results. No 18 cm radio emission is detected from τ Boötis, resulting in a 3σ upper limit of 0.13 mJy, corresponding to a 18 cm radio luminosity of $<3.7 \times 10^{13}$ erg s^{-1} Hz^{-1}. We observe τ Boötis 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 τ Boötis 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. planetary systems – radio continuum: stars

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, $a \sim 0.05$ 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).

τ Boötis is one of the nearest (d = 15 pc) exoplanets known to date. The F7V star ($M = 1.3\,M_{\rm Sun}$, $R = 1.331\,R_{\rm Sun}$) is orbited by a hot Jupiter with $m \sin i = 3.9\,M_{\rm Jup}$ with a period of $P = 3.31$ 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 6.8×10^{28} erg s^{-1} (Kashyap et al. 2008). Recently, Brogi et al. (2012) have shown that the planet orbits the star at an inclination of $44.5 \pm 1.5°$, by detecting the signature of orbital motion in the spectrum of the planet.

Lazio & Farell (2007) observed τ Boötis 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,

$$\log_{10}[L/(R/R_{\rm Sun})^{2.5}] = 12.0 + (2.5 \pm 0.5)\log_{10} v \qquad (1)$$

where L is the peak radio luminosity of the star (in erg s^{-1} Hz^{-1}), R is the stellar radius, and v is the rotational velocity (in km s^{-1}). For τ Boötis 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 5σ upper limit

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	Sep. 03, 2011
Duration (h)	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	$61.9'' \times 14.5''$
Weighting	robust
Theoretical rms noise	20 μJy beam^{-1}

Notes. [*] van Leeuwen (2007).

of 2.5 mJy. We therefore observed τ Boötis with the Westerbork Synthesis Radio Telescope (WSRT) at 18 cm targeting its conceivable high-frequency emission. Section 2 describes the observations and data reduction, and Sect. 3 the results and discussion.

2. Observations and data reduction

τ Boötis was observed for 12 h 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 s was used. Two polarisations (XX and YY) and eight spectral windows (IFs) of 20 MHz bandwidth and 128 channels each, were recorded. The resulting frequency coverage ranged from 1640 MHz to 1786 MHz.

The data set was reduced using the Common Astronomy Software Applications (CASA). It was flagged automatically for autocorrelations and shadowing and then manually for Radio Frequency Interference (RFI). Antenna RT5 was used as testbed for a new receiver, did not record interferometric data and was thus flagged. Two calibrators were also observed for 30 min each: 3C 147 before and CTD93 after the observation of τ Boötis. Their flux densities were set on the Perley-Butler (2010) scale to 19.43 Jy and 4.41 Jy at 1665 MHz (18 cm), respectively. The data was corrected for bandpass and gain variations, flagging channels 0 to 4 and 101 to 128 because of the roll-off of the bandpass. The data for the science target was split and underwent several rounds of phase only self-calibration and one round of amplitude and phase self-calibration.

The sidelobes from two bright galaxies affected region centred on the target source and were removed using the peeling technique (Noordam 2004). The brightest source could not be removed completely most probably due to an imperfect model that does not capture the extended emission correctly. The image was produced using robust weighting set to 0.0 (Briggs 1995) and was cleaned manually using clean boxes, yielding a synthesized beam of $61.9'' \times 14.5''$. Taking into consideration the 50% data lost from flagging, the theoretical rms was 20 μJy beam^{-1}. The observed rms noise $\sigma_{\rm obs}$ is composed of

two contributions: the thermal noise, $\sigma_{\rm th}$, caused mainly by the telescope electronics and galactic background, and the confusion noise, $\sigma_{\rm conf}$, that mostly affects the central part of the field of view. Considering the two contributions to be uncorrelated:

$$\sigma_{\rm obs} = \sqrt{\sigma_{\rm th}^2 + \sigma_{\rm conf}^2}. \tag{2}$$

The measured rms noise at the edges of the image in areas free of emission was 32 μJy beam^{-1}, whereas in the centre it reaches 42 μJy beam^{-1}. A confusion noise of roughly 27 μJy beam^{-1} added in quadrature to the noise at the edges of the field can account for the higher rms value at the centre.

The image was corrected for the primary beam attenuation, leading to an rms value within a 4 arcmin square region centred on the position of τ Boötis of 42.6 μJy beam^{-1} with a maximum of 131.8 μJy beam^{-1}. Therefore, we can pose a 5 sigma upper of 0.21 mJy^{-1} limit on the radio flux of τ Boötis at 18 cm.

3. Results and discussion

The resulting image is shown in Fig. 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 18 cm radio luminosity, at $<3.7 \times 10^{13}$ erg Hz^{-1} s^{-1} during the observations was significantly lower than the stellar peak luminosity found of stellar systems with similar equatorial rotation velocities. The radius and rotational period of τ Boötis indicate a rotational velocity at the equator of ~20 km s^{-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 to have a peak 8.4 GHz luminosity of 3.8×10^{15} erg s^{-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 $F_\nu \propto \nu^{0\pm0.3}$, 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 very 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 6.8×10^{28} erg s^{-1} (Kashyap et al. 2008) points to a radio luminosity of 10^{13-14} erg s^{-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
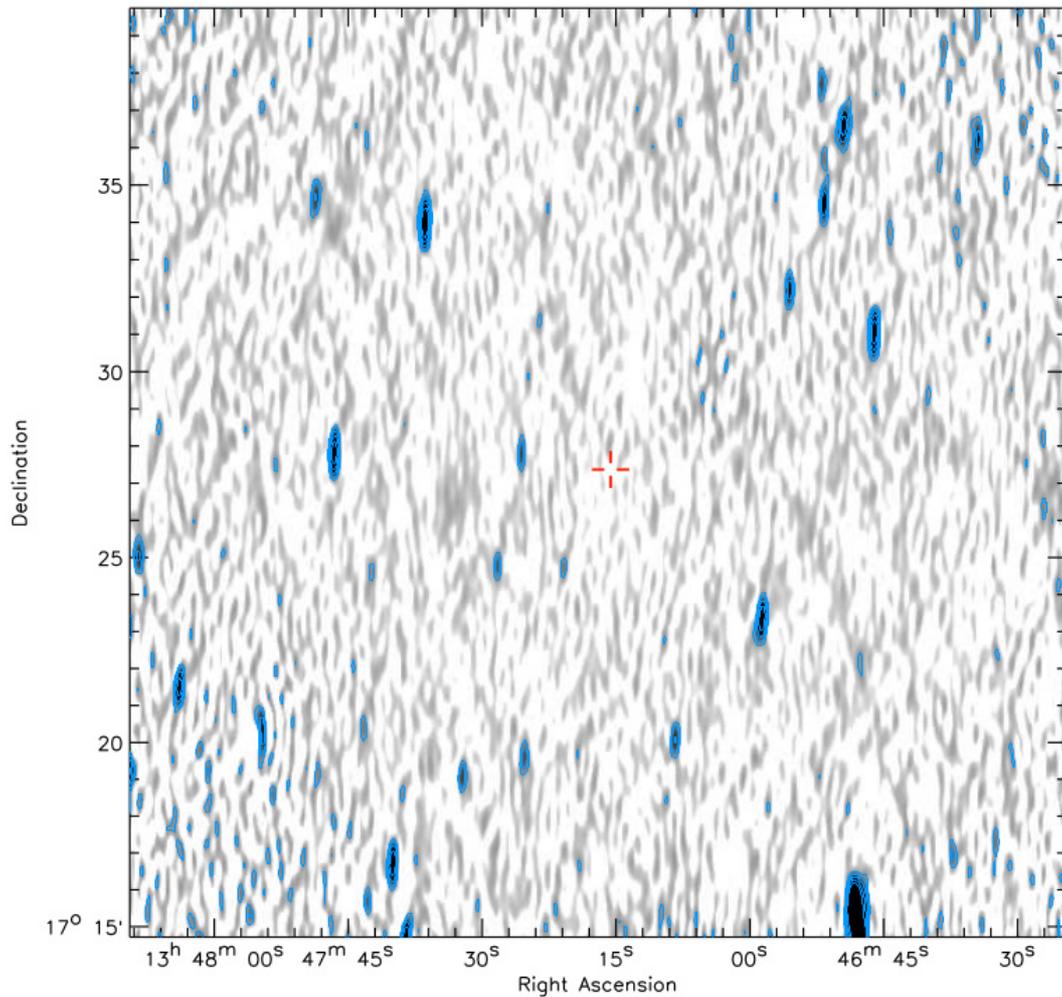
Fig. 1. WSRT 1640–1786 MHz primary beam corrected image of the τ Boötis field. Contours at $[1, 2, 4, 8, 16] \times 4\sigma_{rms}$ are overlaid. The location of τ Boötis is marked in red. The beam size is $61.9'' \times 14.5''$.

probed the broad-band high-frequency component expected to come from the host star, not from the planet.

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