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VARIABLE RADIO EMISSION FROM THE YOUNG STELLAR HOST OF A HOT JUPITER

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ABSTRACT

We report the discovery of variable radio emission associated with the T Tauri star, V830 Tau, which was recently shown to host a hot Jupiter companion. Very Large Array observations at a frequency of 6 GHz reveal a detection on 2011 May 1 with a flux density $919 \pm 26\ \mu$Jy, along with non-detections in two other epochs at <66 and $<150\ \mu$Jy. Additionally, Very Long Baseline Array observations include one detection and one non-detection at comparable sensitivity, demonstrating that the emission is nonthermal in origin. The emission is consistent with the gyro-synchrotron or synchrotron mechanism from a region with a magnetic field $\gtrsim$30 G and is likely driven by an energetic event such as magnetic reconnection that accelerated electrons. With the limited data we have, we are not able to place any constraint on the relationship between the radio emission and the rotational or orbital properties of V830 Tau. This is the first detection of radio emission from a non-degenerate star known to host an exoplanet.

Key words: planets and satellites: magnetic fields – stars: activity – stars: magnetic field – stars: pre-main sequence

1. INTRODUCTION

High-energy processes, including those that produce radio emission, are an important diagnostic of stellar magnetospheres and the influence of those magnetospheres on accretion, planet formation, and even habitability (Feigelson & Montmerle 1999; Feigelson et al. 2002; Güdel 2002; Abrevaya et al. 2012; Osten & Wolk 2015). Of the thousands of known exoplanets, hot Jupiters represent the best opportunity to study the interaction between star and exoplanet due to their close proximity, which creates amplified stellar wind flux and potentially an enhanced exoplanet magnetosphere that could stimulate strong radio emission such as that seen in Jovian decametric bursts (Zarka et al. 2015).

Aside from the first discovered exoplanets found orbiting a pulsar (Wolszczan & Frail 1992), however, none of the known exoplanets or their stellar hosts has been detected at radio wavelengths. The absence of stellar host detection is partly due to selection effects in the optimal exoplanet search methods that select against the most active stars, which are those most likely to produce radio emission (Güdel 2002). Primarily, however, it is a result of the very low luminosity of thermal emission from ordinary stars at radio wavelengths. Exoplanet emission is even more challenging because of the likely weaker magnetic field strengths in these bodies. While Jupiter is the brightest low-frequency radio source in the solar system, when moved to a distance of 10 pc, its flux density falls below that of the faintest radio source ever detected. Nevertheless, hot Jupiters have been considered promising targets because of their proximity to the host star and possibly higher magnetic field strengths. Numerous searches at long radio wavelengths have been carried out without clear evidence of detection of either star or exoplanet (e.g., Farrell et al. 2003, 2004; Lazio & Farrell 2007; Lecavelier Des Etangs et al. 2009; Lazio et al. 2010; Hallinan et al. 2013; Sirothia et al. 2014; Winterhalter et al. 2015).

The recent discovery of a hot Jupiter companion to V830 Tau has raised the possibility of studying an exoplanet associated with a young, active system (Donati et al. 2015, 2016). V830 Tau is a non-accreting solar-mass T Tauri star located at 150 pc (Torres et al. 2009). Its age is estimated from pre-main-sequence evolutionary tracks to be ~2 Myr (Siess et al. 2000). V830 Tau has been observed in the framework of the Magnetic Topologies of Young Stars & the Survival of close-in massive Exoplanets (MaTYSSE)[11] program, which focuses on the role of the magnetic field in the formation of stars and planets using high-resolution optical spectropolarimetry. The star was first observed with the Echelle SpectroPolarimetric Device for the Observation of Stars (ESPaDOnS; Donati 2003) at the Canada–France–Hawaii Telescope (CFHT) on top of Mauna Kea in 2014 December.

The large-scale magnetic topology at the stellar surface was modeled from a time series of total intensity and circular polarization profiles, while unpolarized intensity velocity profiles showed a hint of residual periodic signal after the large velocity jitter from the rotation-modulated spot pattern was removed (Donati et al. 2015). A more intensive observing campaign was repeated during the following season, from 2015 November to December using CFHT/ESPaDOnS, its twin Narval on Telescope Bernard Lyot (TBL), and the Gemini Remote Access to CFHT ESPaDOnS Spectrograph (GRACES; Chene et al. 2014). These new data confirmed the presence of a

[11] http://matysse.irap.omp.eu

hot Jupiter in a 4.93 day orbit around this 2 Myr T Tauri star (Donati et al. 2016). This discovery is important for the implication of formation and migration timescales of giant planets in close orbits around solar-type stars and for the potential impact of young hot Jupiters on the early architecture of planetary systems.

The rotation properties of the host star were also accurately derived from Doppler imaging data, including a constraint on the differential rotation. V830 Tau has a rotation period of 2.741 days (in agreement with Grankin 2013) and a differential rotation rate between the equator and pole of 0.0172 ± 0.0014 radians per day. Concerning the large-scale structure of the surface magnetic field, Zeeman Doppler imaging allowed derivation of a field with a topology that is dominated by a dipole having an average unsigned flux of 350 G. The reconstructed brightness map of V830 Tau shows that about 12% of the surface is covered by cool spots and bright plages over a wide range of latitudes, and that the stellar spin axis is tilted by 55° with respect to the line of sight (Donati et al. 2015, 2016).

In this paper, we describe the analysis of archival Karl G. Jansky Very Large Array (VLA) and Very Long Baseline Array (VLBA) observations of V830 Tau. In Section 2, we present the observations and demonstrate a detection of variable radio emission from V830 Tau. In Section 3, we discuss these observations in the context of known emission for T Tauri stars and the properties of V830 Tau, in particular. We also consider optimal methods for direct or indirect detection of the exoplanet through radio techniques.

2. OBSERVATIONS AND RESULTS

2.1. Very Large Array

VLA observations of V830 Tau were conducted on three separate epochs in spring 2011. Statistics on variability and spectral index from these observations were summarized in Dzib et al. (2015) as part of a large survey. Total integration on V830 Tau was approximately 4 minutes per epoch. The VLA was in its B configuration for these observations, leading to synthesized beam sizes of ~1 arcsec. All observations were obtained in a dual-polarization wideband continuum mode providing a total of 2 GHz of bandwidth, with 1 GHz of bandwidth centered at 4.5 and 1 GHz of bandwidth centered at 7.5 GHz. Absolute flux calibration was provided with a short observation of 3C 147. Amplitude and phase gain calibration was provided with observations of the compact source J0403+2600. Data were calibrated, flagged, and imaged using standard methods in the CASA package.

Figure 1 shows the full field surrounding V830 Tau from 2011 May 01. V830 Tau is clearly detected at the phase center of the image. V830 Tau was not detected on 2011 February 25. On 2011 April 12, we fitted a source at the position of V830 Tau that is nominally significant but given the presence of other peaks of comparable brightness in the map, we also treated this epoch as a non-detection. Two bright sources to the southeast of V830 Tau appear to be the dual radio lobes associated with an active galactic nucleus. Figure 2 shows narrow-field images centered on V830 Tau from all three epochs. Table 1 summarizes the observational results.

We also computed a Stokes V image for epoch 2011 May 1, in which no source is detected with a 3σ upper limit of 66 μJy, or ~7% of the peak flux density of V830 Tau. Imaging separately the upper- and lower-frequency windows of V830 Tau we measure a spectral index $\alpha = 0.1 \pm 0.1$ for $S \propto \nu^{\alpha}$. We find no statistical difference in the flux density of V830 Tau if we split the data into two-minute segments.

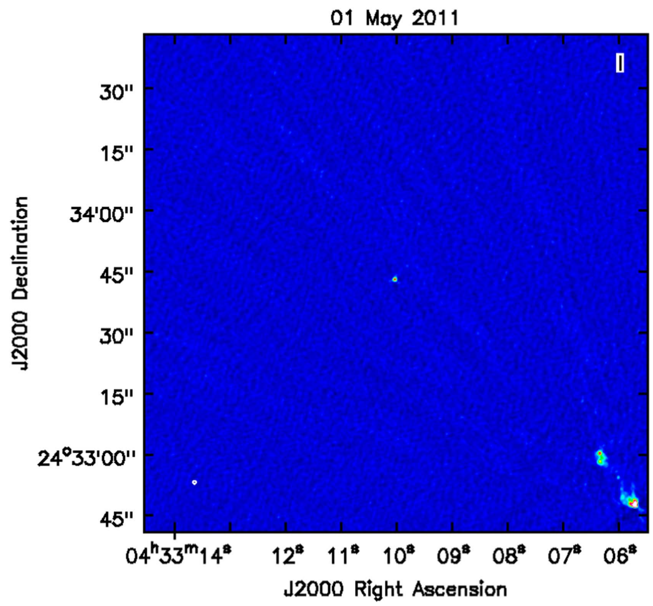

Figure 1. V830 Tau on 2011 May 1 in a wide-field image. V830 Tau is at the center of the image. A bright, likely extragalactic source is located to the southeast of V830 Tau. The synthesized beam is shown in the lower left.

2.2. Very Long Baseline Array

V830 Tau was also observed with the VLBA on two epochs as part of the Gould's Belt Distances Survey (GOBELINS). Details of the observational strategy and calibration are presented in papers describing results for the Ophiuchus cloud from the same survey (Ortiz-León et al. 2016). The data were obtained at a sky frequency of 8.4 GHz with a recording bandwidth of 256 MHz in right and left circular polarizations. Rapid phase switching to the compact calibrator J0426+2327 was used to correct for short timescale atmospheric phase fluctuations. Additionally, J0435+2532, J0429+2724 and J0438+2153 were observed every ~50 minutes to correct for the phase gradient over the sky in the region of the target. The data were calibrated using standard fringe-finding strategies, achieving images with an rms flux density of ~40 μJy and a synthesized beam of ~1 mas. V830 Tau was detected in only one epoch (2015 September 11) with a flux density of 501 ± 75 μJy in a synthesized beam of 1.8×0.8 mas. The lack of detection in the other epoch further confirms the high variability of the source. The results are summarized in Table 1.

3. ANALYSIS AND DISCUSSION

V830 Tau is clearly detected with the VLA on 2011 May 1 with a flux density of 919 ± 26 μJy and with the VLBA on 2015 September 11 with a flux density of 501 ± 75 μJy. Source fitting at the position of V830 Tau on 2011 April 12 reveals a marginal detection with a flux density ~150 μJy; however, there are other features in the image with similar flux densities, so we treat this as a non-detection. We find no VLA detection on 2011 February 25 at a 3σ threshold of 66 μJy and no VLBA

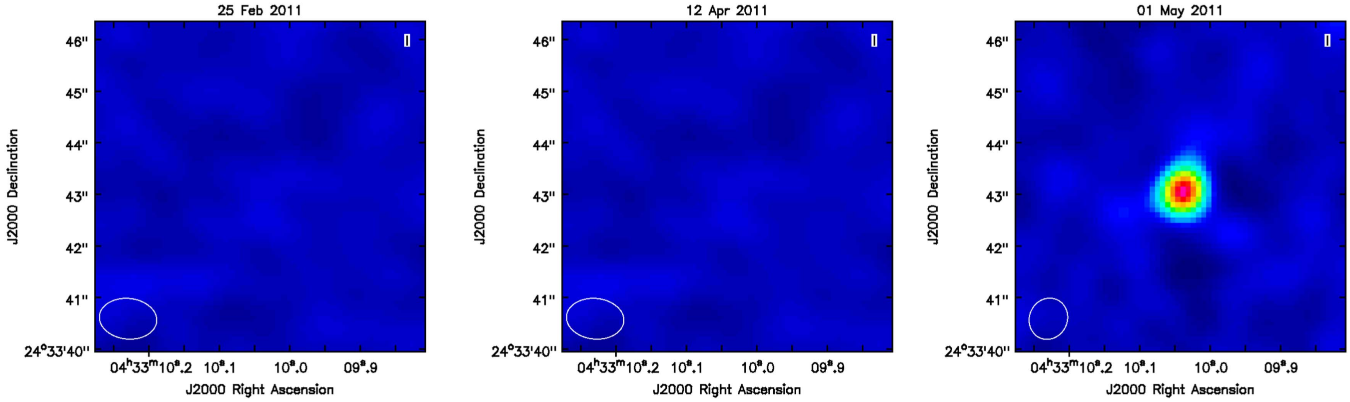

Figure 2. Images from each of the three VLA epochs, zoomed in on V830 Tau. The synthesized beam is shown in the lower left.

detection on 2014 August 31 at a 3σ threshold of 117 μJy. These non-detections are consistent with the one reported observation in the literature, an upper limit of 110 μJy at 3.6 cm from VLA observations in 1994 (Chiang et al. 1996). Together, these results demonstrate that V830 Tau is strongly variable on a timescale of weeks with an amplitude of variability greater than $10\times$.

V830 Tau is associated with a weak X-ray source, 1RXS J043309.8+243359, with a luminosity $L_X \sim 10^{30}$ erg s^{-1} – 5.7×10^{30} erg s^{-1} (Voges et al. 1999; Scelsi et al. 2007). The radio/X-ray luminosity correlation for stars, $L_X/L_R \approx 10^{15\pm1}$, has been shown to be valid over 10 orders of magnitude and a wide range of active sources including the Sun, M dwarfs, and young stellar objects (Güdel 2002). We estimate a radio flux density of ~40–200 μJy given the range of X-ray measurements. Taking into account the non-simultaneous nature of the radio and X-ray measurements and the order of magnitude scatter in the correlation, we consider our radio results to be consistent with the Güdel–Benz relationship.

The radio and X-ray properties of V830 Tau are consistent with those of other T Tauri stars. Many T Tauri stars are known to be bright and variable in the radio. For instance, GMR-A was observed to vary by more than a factor of $20\times$ at wavelengths from 2 cm to 3 mm (Bower et al. 2003). Monitoring of the Orion, Taurus, and other regions has identified young stellar objects with mJy flux densities, many of them variable (Garay et al. 1987; Felli et al. 1993; Carkner et al. 1997; AMI Consortium et al. 2012; Kounkel et al. 2014; Dzib et al. 2015). X-ray and radio luminosity and variability have been shown to be correlated in GMR-A and in other T Tauri stars. We note that Ortiz-León et al. (2016) showed that T Tauri radio emission typically breaks into nonthermal and thermal emitters. V830 Tau clearly falls into the nonthermal category.

We infer that the emission mechanism is gyro-synchrotron or synchrotron radiation from a power-law distribution of relativistic particles in a strong magnetic field based on several lines of evidence. One, the VLBA detection demonstrates a nonthermal origin for emission with the brightness temperature $T_b \gtrsim 1.3 \times 10^7$ K. Two, the spectral index $\alpha \approx 0$ is consistent with the partially optically thick component of gyro-synchrotron or synchrotron radiation (Dulk 1985). Three, the absence of circular polarization is consistent with the emission mechanism not originating from the cyclotron mechanism or a coherent emission mechanism, which are known to produce circular polarization fractions as high as 100% (Smith et al. 2003). Four, the average stellar magnetic dipole field inferred for optical spectropolarimetry of $B \approx 350$ G leads to a cyclotron frequency of ~1 GHz, well below the frequency of our detections. Variations in the field strength in the magnetosphere, however, could lead to regions where the cyclotron frequency is significantly higher.

Further, we can show that there is consistency between the stellar model and gyro-synchrotron/synchrotron parameters. V830 Tau is compact in the VLBA observations with a source size that is equal to or smaller than the beam size $\sim 50 R_\odot$ or 0.3 AU. Further, given the observed brightness temperature lower limit, synchrotron radiation from a power-law distribution of electrons requires a magnetic field $B \gtrsim 30$ G (Güdel 2002), consistent with the spectropolarimetric magnetic field average. Therefore, we see good consistency between the observed stellar size, magnetic field strength, and the observed radio emission during the high or flaring state. In the quiescent or low state where we do not detect V830 Tau, we can only place an upper limit on $T_b < 6 \times 10^5$ K. The detections likely occur in a flaring state that is the result of electron acceleration via magnetic reconnection or other processes, that produces a nonthermal high-energy tail for the electron energy distribution.

From these data, we cannot infer whether the emission arises from the star, the hot Jupiter, or an interaction between the two, although stellar emission is the most likely explanation. Future observations, however, may be able to detect the role of the hot Jupiter on the radio emission. We consider several possibilities.

The non-thermal radio emission from V830 Tau is compact and detectable with very long baseline interferometry. High-resolution imaging may be effective in separating stellar and exoplanet emission. For a semimajor axis $a = 0.057$ au, the angular separation is 0.44 mas. At long centimeter wavelengths (~3 cm), this separation will be unresolved but could potentially be detected with sufficient sensitivity and calibration accuracy. If the flat spectrum of V830 Tau persists to shorter wavelengths (~7 mm), then the angular separation of the star and exoplanet can be resolved by Earth baselines. The astrometric reflex motion of the star due to the exoplanet, on the other hand, is equal to the angular separation reduced by a factor $\sim M_p/M_\odot \approx 7.3 \times 10^{-4}$, resulting in an 0.35 μarcsec signal. Astrometry on stars has achieved ~100 μarcsec accuracy but without detection of an exoplanet companion, although numerous stellar binaries have been characterized (e.g., Bower et al. 2009, 2011; Forbrich et al. 2013; Reid & Honma 2014; Ortiz-León et al. 2016). If the presence of a hot

Table 1
VLA and VLBA Results for V830 Tau

Tel.	Epoch	UT	Beam	rms (μJy)	S (μJy)
VLA	2011 Feb 25	04:47	$1''.1 \times 0''.8$, 84°	22	<66
	2011 Apr 12	02:37	$1''.6 \times 0''.8$, 86°	34	147 ± 34
	2011 May 01	22:25	$0''.8 \times 0''.6$, −23°	26	919 ± 26
VLBA	2014 Aug 31	14:23	1.8×0.8 mas^2, −10°	39	<117
	2015 Sep 11	13:42	1.8×0.8 mas^2, −11°	40	501 ± 75

Note. Non-detections are given as 3σ upper limits.

Jupiter is indicative of a more complex planetary system with Jupiter-mass planets at large semimajor axes, then astrometric detection of that signature may be possible.

Total intensity monitoring across the radio spectrum offers promising opportunities for characterizing the stellar and exoplanet magnetosphere. We plot in Figure 3 the detected flux density as a function of stellar rotational phase, using the ephemeris from Donati et al. (2016). There is no clear trend in these sparse data with rotational phase. This is likely the result of the detections being due to flaring activity in V830 Tau, but may also be due to variable magnetospheric structure. If it is detectable, quiescent or steady, radio emission is more likely than flaring flux to show a trend with rotational phase. We also plot the mean surface magnetic field density as a function of rotational phase in Figure 3 based on the 2015 December observations. This calculation approximates the total volume-integrated magnetic energy density, albeit with an emphasis on the surface field. Synchrotron radiation is proportional to the magnetic energy density and, therefore, in the case of a uniform distribution of nonthermal particles will follow this magnetic quantity. The total variation in the computed quantity is a factor of 1.6, far less than the factor of $>10\times$ variability observed. Differential rotation and other secular effects on the magnetosphere imply that the particular profile of the magnetic field is likely to evolve on a timescale of the differential rotation $\sim$1 year. This makes clear that simultaneous and/or contemporaneous radio and spectropolarimetric is necessary to fully disentangle any effects associated with the rotational period.

We cannot make a meaningful comparison of the existing radio data with orbital phase, because the latter is only known to an accuracy of 1%. Over the $\gtrsim$4 year span of our observations, we completely lose any orbital phase information. Currently, the eccentricity of the orbit is weakly constrained to $e < 0.3$. Highly eccentric orbits in stellar binaries have been shown to produce periodic radio emission (Massi et al. 2002; Adams et al. 2011; Torres et al. 2012). Dense sampling with sensitivity to quiescent flux over multiple beat periods ($P_{\rm beat} = 6.17$ day) between the orbital and rotational periods will be necessary to discriminate between rotational and orbital effects (Fares et al. 2010). Observations over even longer time intervals are also necessary to characterize the timescale and nature of variability.

At meter wavelengths, stellar and exoplanet emission may become substantially brighter. For the star, the cyclotron frequency is 1 GHz for a mean magnetic field of 350 G, indicating the possibility for strong low-frequency emission. The magnetic field of the exoplanet, of course, is unknown. But it is not unreasonable to think that the magnetic field for a young hot Jupiter would be higher than that of an older one, just as the young stellar magnetic field is higher. The

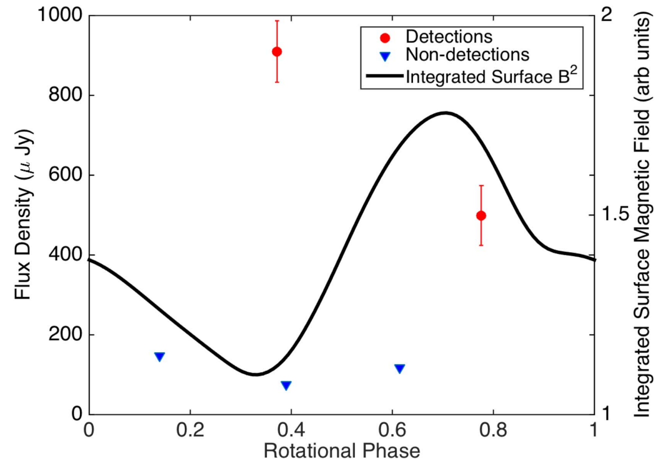

Figure 3. Radio flux density as a function of stellar rotational phase. The left y-axis shows the range of flux densities, which are plotted for VLA and VLBA detections and non-detections (3σ upper limits). The right y-axis shows the relative scaling of the integrated surface magnetic field energy, which was determined from 2015 observations and is plotted as the dark line. Differential rotation and changes in the stellar dynamo imply that only radio observations obtained within $\sim$1 year of the spectropolarimetric data are likely to be meaningfully related to the shape of the magnetic energy curve. Thus, only the VLBA detection at phase of 0.8 has a direct relationship with the magnetic energy curve.

radiometric Bode's law (Zarka et al. 2001; Lazio et al. 2004) provides a method for estimating the coherent cyclotron radio luminosity of a star–exoplanet system based on scalings observed in the solar system. We use the law to predict the median radio luminosity for a hot Jupiter orbiting a solar-type star to be $P = 3 \times 10^{21}$ erg s^{-1}, corresponding to a flux density of $\sim$1 μJy for V830 Tau at a frequency of 100 MHz. The radio flux, however, scales with the stellar wind power, likely proportional to the stellar magnetic field energy density, and with the planetary magnetic moment, which is also likely proportional to the stellar magnetic field strength. Thus, the radio power may scale as $\sim B^3$, which is 10^3–10^6 higher for V830 Tau than for the Sun. Thus, a peak flux density of $\sim$1–1000 mJy from the exoplanet at meter wavelengths is feasible for V830 Tau. Estimates of this kind are, of course, very uncertain given the absence of any exoplanet detections at radio wavelengths. GMRT observations at 323 and 608 MHz of other young stellar objects in Taurus indicate mJy flux levels that are consistent with free–free emission rather than a coherent emission process (Ainsworth et al. 2016).

The discovery of variable radio emission from V830 Tau opens a new observational window on hot Jupiter hosts and, potentially, on the star–planet magnetic interaction. For the first time, we have detected the stellar host of an exoplanet system.

Radio observations can play an important role in full characterization of the stellar magnetosphere and may ultimately be able to detect the exopolanet or star–exoplanet interactions, either directly or indirectly. Simultaneous observations over multiple cycles of the rotational and orbital periods are essential for accurate characterization and exploration of this unique system. The study of radio emission from other T Tauri stars can provide a statistical characterization of the magnetic and particle environments of young stars and, possibly, their planetary companions.

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