JVL Observations of Young Brown Dwarfs

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Abstract

We present sensitive 3.0 cm JVL radio continuum observations of six regions of low-mass star formation that include twelve young brown dwarfs (BDs) and four young BD candidates. We detect a total of 49 compact radio sources in the fields observed, of which 24 have no reported counterparts and are considered new detections. Twelve of the radio sources show variability in timescales of weeks to months, suggesting gyrosynchrotron emission produced in active magnetospheres. Only one of the target BDs, FU Tau A, was detected. However, we detected radio emission associated with two of the BD candidates, WL 20S and CHLT 2. The radio flux densities of the sources associated with these BD candidates are more than an order of magnitude larger than expected for a BD and suggest a revision of their classification. In contrast, FU Tau A falls on the well-known correlation between radio luminosity and bolometric luminosity, suggesting that the emission comes from a thermal jet and that this BD seems to be forming as a scaled-down version of low-mass stars.

Key words: ISM: jets and outflows – radio continuum: stars – stars: formation – stars: individual (FU Tau) – stars: pre-main sequence

1. Introduction

Brown dwarfs (BDs) are intriguing objects whose masses lie in between the mass of planets and the mass of stars. They are supposed to burn deuterium in their interiors, thus having a mass larger than 13 $M_{\text{Jup}}$, but their mass is not large enough to drive stable hydrogen burning (where stable means sufficient to maintain thermodynamic equilibrium), corresponding to masses smaller than about 75 $M_{\text{Jup}}$. The main difference between BDs and stars is that BDs are not supported by thermal pressure, as they do not have sufficient internal heating, but are instead supported by electron degeneracy pressure. Thus, from the point of view of their internal structure, BDs are more similar to giant planets than to stars. However, there is currently a debate about how to define the borderline separating BDs and planets. While the traditional view is the aforementioned condition of deuterium burning for BDs (IAU definition 2003), this has been questioned by several authors such as Chabrier et al. (2007; 2014). These authors present counter-examples that do not fulfill the deuterium-burning criterion and propose that a better criterion could be the formation mechanism: while BDs and stars are most likely formed through collapse of a protostellar core (as opposed to a disk), planets are most likely formed through the “core accretion” model in a protoplanetary disk (Pollack et al. 1996).

Therefore, it is crucial to test from a solid observational base that BDs indeed form in a similar way as low-mass stars. Recently, a number of statistical studies of BDs and young stellar objects (YSOs) in the Class II/III stages (according to the evolutionary scheme of Adams et al. 1987) seem to indicate that the formation mechanism of BDs cannot be easily distinguished from the formation of stars (e.g., Bayo et al. 2011; Luhrman 2012; Scholz et al. 2012a; Alves de Oliveira et al. 2013; Downes et al. 2014). Most of these studies aim at sampling the IMF down to the substellar regime, or studying the spatial distributions of stars and BDs. Other studies have compared accretion properties of low-mass YSOs with those of BDs, finding that they are consistent with a common formation mechanism (e.g., Muzerolle et al. 2005; Downes et al. 2008; Alcalá et al. 2014). The presence of disks in stars as well as in BDs also points to a common formation mechanism (e.g., Scholz et al. 2006; Ricci et al. 2014). An additional and crucial complementary study to test if BDs form as low-mass stars should come from studying their centimeter emission, as YSOs are known to emit at these wavelengths either through free–free emission from thermal radio jets when they are very young or through gyrosynchrotron emission from active magnetospheres later in their evolution (e.g., Feigelson & Montmerle 1999; Dzib et al. 2015).

The YSOs emitting gyrosynchrotron emission are typically in the Class II or later stages, and their emission is highly time variable (e.g., Dzib et al. 2013, 2015; Pech et al. 2016). On the other hand, thermal radio jets are non-variable and associated typically with more embedded YSOs (in the Class 0/I stage, e.g., Beltrán et al. 2001; Ward-Thompson et al. 2011; Carrasco-González et al. 2012). In particular, this last possibility is especially compelling because signs of outflows have been clearly found in BDs, both as optical jets (e.g., Whelan et al. 2009, 2014; Joergens et al. 2012) and as molecular outflows (e.g., Phan-Bao et al. 2011, 2014; Monin et al. 2013; Palau et al. 2014). However, BDs have rarely been detected at centimeter wavelengths (e.g., Krishnamurthi et al. 1999; Güdel 2002; Osten & Jayawardhana 2006), but this could be due to a lack of sensitivity of the instruments used in earlier works. Actually, recent studies have shown that the new capabilities of the VLA allow the detection of very faint sources that are associated with proto-BD candidates (Morata et al. 2015). Thus, they are candidate thermal radio jets driven by substellar objects.

In this paper, we present deep observations with the Jansky VLA toward six BDs associated with known indicators of outflows and with no published detection in the radio continuum. Our main aim is to study the nature of their centimeter emission and compare it to the emission typically

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1 http://home.dtm.ciw.edu/users/boss/definition.html
found in YSOs. In Section 2, we describe the observations. In Section 3, we present the detections, and in Section 4 we discuss our detections in the context of the well-known properties of centimeter emission from YSOs.

2. Observations

The observations were made as part of project 14B-230 with the Karl G. Jansky Very Large Array of NRAO\(^2\) centered at the rest frequency of 9.9 GHz (3.0 cm) during 2014 October, November, and December. At that time, the array was in its C configuration, providing a maximum baseline of 3.4 km and an angular resolution of \(\sim 2''\) at the wavelength of 3.0 cm. The field of view is taken to be the full width at half power of the primary beam (4/6 at the observing wavelength), although, in the case of sources that are bright enough, imaging can be made outside of this region. The phase centers of the six regions observed are given in Table 1. In this table, we also list the number of times each region was observed (from 3 to 5 times), the synthesized beam and the rms of the final image, and the amplitude and gain calibrators.

The digital correlator of the JVLA was configured in 32 spectral windows of 128 MHz width divided into 64 channels with spectral resolution of 2 MHz each. The total bandwidth was about 4 GHz in a dual-polarization mode. The half-power full width of the primary beam is 4/6 at 3 cm.

The data were analyzed in the standard manner using the CASA (Common Astronomy Software Applications) package of NRAO, although for the stages of component fitting and image contouring, we used the AIPS (Astronomical Image Processing System) package. We used the ROBUST parameter of CLEAN set to 2, in order to obtain a better sensitivity at the expense of losing some angular resolution. In Table 2, we list the sources detected with their counterparts (when they exist), the positions, total flux densities, and notes on the time variability, angular extent, and nature of the sources. The counterparts were searched using the SIMBAD (The Set of Identifications, Measurements, and Bibliography for Astronomical Data) database. The 12 sources that have significant variability over the period of observations exhibit maximum variations (taken to be the ratio between the maximum and minimum flux densities observed considering all epochs) that go from factors of 1.5 to 3.7.

3. Comments on Individual Sources

3.1. FU Tau

FU Tau is a young, wide BD binary system. Its components show a projected angular separation of 5''7 (or 830 au at a distance of 145 pc, see below) with a position angle (PA) of \(\sim 145^\circ\) (Luhman et al. 2009). The NW component, FU Tau A, has a spectral type of M7.25, corresponding to a mass of \(M_{\text{NW}}\), while the SE component, FU Tau B, has a spectral type of M9.25, corresponding to a mass of \(M_{\text{SE}}\) (Luhman et al. 2009). Monin et al. (2013) detected a molecular outflow associated with FU Tau, but given the angular resolution of 11'' that of the IRAM 30 m telescope observations, they could not establish which of the two components of the FU Tau binary was producing it. As optical forbidden line emission, a reliable tracer of the shocks caused by outflow activity, has been detected in the spectrum of FU Tau A (Stelzer et al. 2010). Monin et al. (2013) assumed that this component is the driving source of the molecular outflow.

We adopted, as the distance and proper motions of FU Tau, the average values of the nearby stars V773 Tau (Torres et al. 2012) and HP Tau (Torres et al. 2009). This gives an adopted distance of 145 pc and proper motions of \(\mu_\alpha \cos \delta = 15.5 \text{ mas} \text{ yr}^{-1}\) and \(\mu_\delta = -19.7 \text{ mas} \text{ yr}^{-1}\), respectively. Figure 1 shows the radio continuum emission we detected with the positions of FU Tau A and B, after correction by the proper motions. As can be seen in the figure, the radio emission coincides with component FU Tau A, and this supports the proposition of Monin et al. (2013) that this is the source driving the molecular outflow.

3.2. MHO 5

This very low-mass star was detected by Briceño et al. (1998). It has a spectral type of M6.2. Its estimated mass is \(90 \, M_{\text{Jup}}\) (Muzerolle et al. 2003), just above the hydrogen-burning limit. Phan-Bao et al. (2011) reported an associated bipolar CO outflow with an estimated outflow mass of \(7.0 \times 10^{-7} \, M_{\odot}\) and a mass-loss rate of \(9.0 \times 10^{-10} \, M_{\odot} \text{ yr}^{-1}\).

We did not detect a radio source associated with MHO 5 at the 3-\(\sigma\) level of 12 \(\mu\)Jy. Of the five sources detected in the field, the only one with a counterpart is associated with 2MASS J04322946+1814002. This radio source is moderately time

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variable (showing a maximum-to-minimum flux density ratio of 1.6 along the five epochs of observation) and very bright, with an average flux density of ~67 mJy. Based on its infrared properties, Gutermuth et al. (2009) classified it as a Class II YSO. However, Dzib et al. (2015) found no evidence of proper motions; a result that favors an extragalactic nature for the source. In Figure 2, we present the radio continuum spectrum of MHO 5. It shows flux density rising with frequency and is
consistent with an optically thick synchrotron source. We tentatively propose that this source is an extragalactic high frequency peaker (HFP; Dallacasa et al. 2000). Similar sources have been found in other regions of star formation (e.g., Rodríguez et al. 2014a; Dzib et al. 2015).

### 3.3. MMS 6-main

MMS 6-main is the brightest and the most compact submillimeter continuum source in the Orion MMS 6 region (Takahashi et al. 2009). A compact molecular outflow lobe (∼1000 au) associated with MMS 6-main and having an estimated outflow mass of $3.3 \times 10^{-4} M_\odot$ and a mass-loss rate of $4.4 \times 10^{-6} M_\odot\text{yr}^{-1}$ was reported by Takahashi & Ho (2012).

The mm sources MMS 6-main and MMS 6-NE (Takahashi et al. 2009) coincide with two of the radio sources that we detected (see Figure 3). MMS 6-main was detected previously at 3.6 cm with a very similar flux density (0.15 mJy; Reipurth et al. 1999) to our detection. To our knowledge, this is the first centimeter detection of MMS 6-NE. This is an extensively studied region and of the 13 radio sources detected in the primary beam, 11 have previously reported counterparts (see Table 2).

There are two BDs in the field observed: TKK 755 and 2MASS J05351294-0502086, with spectral types of M7.75 and M6.5 (Peterson et al. 2008), respectively. We did not detect associated radio sources with them at a 3-σ upper limit of 16 μJy.

### 3.4. ISO-Oph 32

This star, also known as 2MASS J16262189-2444397, has a spectral type of M6.5 (Manara et al. 2015). This corresponds to a mass of $\sim 70 M_\text{Jup}$, at the hydrogen-burning limit. We did not detect an associated source at the 3-σ level of 10 μJy.

### 3.5. ISO-Oph 102

Our main goal in this field was the BD ISO-Oph 102. This object has a spectral type of M6 and a mass of $60 M_\text{Jup}$ (Ricci et al. 2012). We did not detect an associated radio source at a 3-σ upper limit of 9 μJy.

However, in the field we detected two interesting sources. The first is WL 20S, a BD candidate (Alves de Oliveira et al. 2010) that we detected with a flux density of $326 \pm 55 \mu Jy$ (Figure 4). This source was previously detected using the VLA with flux densities of $220 \pm 16 \mu Jy$ and $236 \pm 28 \mu Jy$ at 4.5 and 7.5 GHz, respectively (Dzib et al. 2013). As discussed by Dzib et al. (2013), the radio source is associated with component WL 20S and not with either of the other two more massive components of the triple system (WL 20E and WL 20W; see Figure 4). The 2.7 mm dust emission is associated with WL 20S and WL 20W (Barsony et al. 2002).
Figure 2. Radio spectrum of the source 2MASS J04322946+1814002, located in the MHO 5 region. The data points at 323 and 608 MHz are from Ainsworth et al. (2016), while the data points at 1.4, 4.5, and 9.9 GHz are from Condon et al. (1998), Dzib et al. (2015), and this paper, respectively.

Figure 3. JVLA 3.0 cm continuum contour image of the MMS 6 region. The contours are $-4, -3, 3, 4.5, 6, 8, 10, 12, 15$, and $20$ times $4.60 \mu$Jy beam$^{-1}$, the rms of the image. The half-power contour of the synthesized beam of the image is shown in the bottom left corner. The $+$ symbols mark the positions of the mm sources MMS 6-main and MMS 6-NE from Takahashi et al. (2009).
The other interesting radio source detected in the field is associated with SR 12 (Struve & Rudjøbing 1949). This is a T Tau binary (Simon et al. 1987) with K4 and M2.5 components (Gras-Velázquez & Ray 2005), that are separated by 0.21 (Kuzuhara et al. 2011). This angular separation corresponds to a physical separation of 29 au at a distance of 137 pc (Ortiz-León et al. 2017). This T Tau binary, also known as SR 21AB, has associated the exoplanet candidate SR 12C, with an estimated mass of $\sim 1.3 M_{\text{Jup}}$ (Kuzuhara et al. 2011). SR 12C appears projected by $\sim 8^\prime$7 ($\sim 1200$ au at a distance of 137 pc) to the south of SR 12AB and is the widest-separation substellar companion candidate to a T Tau binary currently known (Kuzuhara et al. 2011).

The radio source was previously detected using the VLA with flux densities of 160 ± 37 $\mu$Jy and 87 ± 12 $\mu$Jy at 4.5 and 7.5 GHz, respectively (Dzib et al. 2013). There are no reported optical or infrared individual positions for the stars in this binary system, and we could not determine which of the stars the radio emission is associated with (Figure 5). The extrasolar planet is not detected at a 3-$\sigma$ upper limit of 24 $\mu$Jy. This relatively large noise is due to the primary beam correction applied to this region, which is far ($\sim 2^\prime$5) from the phase center.

3.6. LS-RCrA 1

Our main goal in this field was the BD 2MASS J19013357-3700304, with a spectral type M6.5 (Fernández & Comerón 2001; Barrado y Navascués et al. 2004). We did not detect an associated radio source at a 3-$\sigma$ upper limit of 10 $\mu$Jy. In the field, we detected the source CHLT 2 (see Figure 6), a BD candidate (Feigelson et al. 1998). This source was first detected at radio wavelengths by Brown (1987) and is sometimes referred to as Brown 5. Since then, it has been detected in several radio studies of the core of the Corona Australis molecular cloud (e.g., Suters et al. 1996; Forbrich et al. 2006; Choi et al. 2008; Miettinen et al. 2008; Liu et al. 2014). The radio source is time variable, with centimeter flux densities ranging from 0.2 mJy (Forbrich et al. 2006) to 4.4 mJy (Suters et al. 1996). However, it did not show evidence of variability in the five epochs that we observed it in. From measurements at 3.5 and 6.2 cm, Choi et al. (2008) determined a spectral index of $-1.3 \pm 0.3$ for year 1996 and of $+1.06 \pm 0.13$ for year 2005. A highly negative spectral index rules out a free–free nature for the emission (Rodríguez et al. 1993). For observations made in 1986 and 1992, Suters et al. (1996) determined spectral indices in the range of $-0.28 \pm 0.30$ to $+1.05 \pm 0.17$. In at least one epoch, the source showed evidence of circular polarization (Choi et al. 2009).
CHLT 2 is associated with a faint \((K = 16.4)\) near-infrared source that would be a BD if it laid in the CrA cloud and was \(< 10^7\) year old (Feigelson et al. 1998). Miettinen et al. (2008) note that their radio properties, in particular their persistent strong emission, do not support the BD classification. Liu et al. (2014) propose that this source is a radio galaxy.

4. Discussion

There are twelve young BDs and four young BD candidates in the six fields imaged. We detected only one BD and two BD candidates. The small number of detections precludes a firm statistical conclusion, but this result suggests that BD candidates have larger radio flux densities than the BDs.

Morata et al. (2015) have recently discussed the expected radio luminosity for young BDs. Extrapolating the well-known correlation between radio luminosity and bolometric luminosity (their Figure 5), one estimates that, for the BD region, the expected luminosity is roughly bracketed by \(S_{3.6 \text{ cm}} \approx 10^{-4.0 \pm 0.5} \text{ mJy kpc}^2\). Assuming that the 3.6 cm flux density is similar to the 3.0 cm flux density that we measured, and because FU Tau A is at a distance of 145 pc, we find that for this source, \(S_{3.6 \text{ cm}} \approx 10^{-3.7} \text{ mJy kpc}^2\), in the range of the equation given above. A similar agreement is obtained for IC348-SMM2E (Palau et al. 2014; see below).

To depict this more clearly, we have updated the figure of Morata et al. (2015), showing the relation between radio luminosity and bolometric luminosity with our new observations (Figure 7). To create the figure, we have assumed a range of bolometric luminosities from 0.19 \(L_\odot\) (Luhman et al. 2009) to 0.01 \(L_\odot\) for FU Tau A. This last luminosity is estimated by using the relation between Spectral Type (ST) and effective temperature given by Baraffe et al. (2015). For an ST M7.25 for FU Tau A (Luhman et al. 2009), the corresponding effective temperature is 2700 K. We then converted the effective temperature to luminosity by using the relation of Luhman et al. (2003, their Figure 8). It should be noted, however, that because FU Tau A is overluminous for its effective temperature (Scholz et al. 2012b), this lower limit is uncertain. For the case of IC348-SMM2E, we used the bolometric luminosity estimated by Palau et al. (2014) and the new deep 3.3 cm observations reported in Forbrich et al. (2015), where the source was detected for the first time at this wavelength. We note that Forbrich et al. (2015) estimate a spectral index of 0.4 for IC348-SMM2E, suggesting a thermal radio jet. The results of Rodríguez et al. (2014b) are also consistent with a positive spectral index. Figure 7 shows that the confirmed BDs FU Tau A and IC348-SMM2E follow the well-known relation between radio luminosity and bolometric luminosity very well, suggesting that this relation extends down to the BD regime and that at least these two BDs seem to have formed as a scaled-down version of low-mass stars. Indeed,
FU Tau has previously been proposed to be an example of star-like formation, based on its isolated position, its wide companion, its disk, and its outflow (e.g., Luhman et al. 2009; Stelzer et al. 2010).

In contrast, the radio luminosities of the sources associated with the candidate BDs are much larger than expected. In the case of WL 20 S (assuming a distance of 140 pc; Ortiz-León et al. 2017), we obtain $S_{3.6 \text{ cm}} \approx 10^{-2.2} \text{ mJy kpc}^2$, while for CHLT 2 (assuming a distance of 130 pc; Neuhäuser & Forbrich 2008), we obtain $S_{3.6 \text{ cm}} \approx 10^{-2.0} \text{ mJy kpc}^2$. These radio luminosities are more than an order of magnitude larger than expected. We show this more clearly in Figure 7, where we used the same strategy as in the case of FU Tau A to estimate the bolometric luminosity of WL 20 S, for which we assumed that the ST should be M6.5 or later, while for CHLT 2 the bolometric luminosity is estimated to be $0.006 L_\odot$, assuming a spectral type M9 (adopted by Miettinen et al. 2008). Considering that the radio luminosity–bolometric luminosity relation seems to hold for the confirmed BDs discussed above, our results for WL 20 S and CHLT 2 suggest that these two candidates might instead be background sources of a different nature.

5. Conclusions

The high sensitivity of the Jansky VLA allows the detection of faint, previously unreported sources in regions of star formation. The main results of our study can be summarized as follows.

1. We observed six regions with young BDs associated with outflows. We detected a total of 49 compact sources of which 24 are new detections.

2. The only bona fide BD that we detected is FU Tau A. Its radio luminosity is consistent with the extrapolation of the radio luminosity–bolometric luminosity correlation down to the substellar regime. Assuming that the centimeter emission from FU Tau A comes from a faint thermal jet, our findings indicate that the radio luminosity–bolometric luminosity correlation seems to extend to the BD regime, supporting the view that BDs form as a scaled-down version of low-mass stars.

3. We detected radio sources in association with two BD candidates (WL 20S and CHLT 2) in the regions studied. Their radio luminosities are more than an order of magnitude larger than expected from the radio
luminosity–bolometric luminosity correlation, questioning the BD classification.

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