325 MHz LARGE ARRAY OBSERVATIONS OF ULTRACOOL DWARFS
TVLM 513-46546 AND 2MASS J0036+1821104

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ABSTRACT

We present 325 MHz (90 cm wavelength) radio observations of ultracool dwarfs TVLM 513-46546 and 2MASS J0036+1821104 using the Very Large Array (VLA) in 2007 June. Ultracool dwarfs are expected to be undetectable at radio frequencies, yet observations at 8.5 GHz (3.5 cm) and 4.9 GHz (6 cm) have revealed sources with >100 μJy quiescent radio flux and >1 mJy pulses coincident with stellar rotation. The anomalous emission is likely a combination of gyrosynchrotron and cyclotron maser processes in a long-duration, large-scale magnetic field. Since the characteristic frequency for each process scales directly with the magnetic field magnitude, emission at lower frequencies may be detectable from regions with weaker field strength. We detect no significant radio emission at 325 MHz from TVLM 513-46546 or 2MASS J0036+1821104 over multiple stellar rotations, establishing 2.5σ total flux limits of 795 μJy and 942 μJy, respectively. Analysis of an archival VLA 1.4 GHz observation of 2MASS J0036+1821104 from 2005 January also yields a non-detection at the level of <130 μJy. The combined radio observation history (0.3 GHz to 8.5 GHz) for these sources suggests a continuum emission spectrum for ultracool dwarfs that is either flat or inverted below 2–3 GHz. Further, if the cyclotron maser instability is responsible for the pulsed radio emission observed on some ultracool dwarfs, our low-frequency non-detections suggest that the active region responsible for the high-frequency bursts is confined within two stellar radii and driven by electron beams with energies less than 5 keV.

Key words: brown dwarfs – radio continuum: stars – radiation mechanisms: non-thermal – stars: activity – stars: low-mass – stars: magnetic field

1. INTRODUCTION

Ultracool dwarfs (UCDs) describe a subsection of stellar objects located on the boundary between more massive stars and sub-stellar bodies such as gas giant planets. It includes fully convective, very low mass stars (M7 and lower) and all brown dwarfs, X-ray and Hα intensity (typical proxies for magnetic activity) for UCDs is weak, dropping substantially after spectral class M7 (Liebert et al. 1999; Audard et al. 2007). Radio emission is expected to be undetectable at the μJy level, based on empirical X-ray scaling laws (Guedel & Benz 1993; Benz & Guedel 1994), and the assumption that highly neutral UCD atmospheres are incapable of sustaining magnetic stresses which pervade the atmospheres of solar-type stars. However, a growing number of UCDs have been discovered that display significant emission at centimeter wavelengths and suggest the presence of persistent kilogauss-scale magnetic fields (Berger et al. 2001; Burgasser & Putman 2005; Hallinan et al. 2008; Osten et al. 2009). Furthermore, the quiescent radio emission is nearly constant from spectral types M0 to L5 (Berger et al. 2005; Berger 2006). It appears that, for at least some UCDs, the typical indicators of magnetic activity are not well correlated with decreased radio flux.

Radio emission from these peculiar UCDs is typically broad band and unpolarized with high brightness temperature (108–109 K) during quiescence, and can exceed 1011 K with nearly 100 mJy during bursts (Berger 2002; Antonova et al. 2008; Hallinan et al. 2008). There is also evidence of long-term radio variability (Antonova et al. 2007). The assumed radiation mechanism was initially incoherent gyrosynchrotron (Berger 2002; Berger et al. 2005) from populations of mildly relativistic electrons with a power-law energy distribution. However, the high brightness temperature and high circular polarization seen during burst events suggested a coherent radiation mechanism such as the cyclotron maser instability (CMI; Melrose et al. 1984; Wingee 1985). First suggested by Hallinan et al. (2006), CMI has also been used to describe burst emission from the polar, low-density–high magnetic field regions of magnetized planets (Zarka 1998; Ergun et al. 2000), Algol (Mutel et al. 1998), and late-type flare stars (Bingham et al. 2001; Kellett et al. 2002). The CMI model may also explain the quiescent emission, possibly created via depolarization of persistent maser sources (Hallinan et al. 2006; Littlefair et al. 2008; Yu et al. 2011).

The exact mechanism(s) responsible for UCD radio emission (flaring on the top of a quiescent background) is unclear, but it is likely due to a combination of both gyrosynchrotron emission and CMI. The emission frequency for each mechanism scales directly with the local magnetic field strength, emitting at the electron cyclotron frequency (Ωce, MHz = 2.8 · BG). Gigahertz radio observations then require kilogauss-scale fields, while detectable radio emission may exist at megahertz frequencies from regions of weaker field strength (~116 G at 325 MHz). A vast majority of UCD observations have been limited to gigahertz frequencies where radio instruments are historically the most sensitive. Constraining the full spectral profile with addition of low-frequency observations may provide valuable information that allows one to distinguish between the suggested emission processes, as well as reveal key differences in the atmospheres of UCDs compared with high-mass M dwarfs.

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Further, as UCDs are uniquely placed on the boundary between stars and sub-stellar objects, low-frequency measurements also provide a guide for future observations of extrasolar planets.

2. TARGET HISTORY

TVLM 513-46546 (hereafter TVLM513) is a spectral type M9 dwarf with mass equaling 0.09 M$_{\odot}$ and age $> 1$ Gyr (Reid et al. 2000). Radio emission from this nearby source ($\sim 10.6$ pc; Dahn et al. 2002) was first detected by Berger (2002). Berger’s observations at 8.5 GHz revealed both persistent stellar emission and occasional (2%-10% duty cycle) pulses with flux densities exceeding 1 mJy. Detected bursts were highly circularly polarized and lasted multiple minutes. Both the persistent and burst emission features were later confirmed by Osten et al. (2006), Hallinan et al. (2006), Hallinan et al. (2007), Berger et al. (2008), Forbrich & Berger (2009), and Doyle et al. (2010) through observations at 8.5 GHz and 4.9 GHz. Further, Hallinan et al. (2007) and Lane et al. (2007, optical) detected a pulse periodicity of $\sim 2$ hr, consistent with the stellar rotation rate. Osten et al. (2006) made a 5$\sigma$ detection of TVLM513 at 1.4 GHz and it is undetected at lower frequencies at sensitivity levels similar to the GHz detections (Antonova2007).

2MASS J0036+1821104 (2M0036, onward) is a L3.5 brown dwarf with mass $\sim 0.06-0.074$ M$_{\odot}$ (Schweitzer et al. 2001), age $> 0.8$ Gyr (Burrows et al. 2001), and is located at 8.8 pc (Dahn et al. 2002). Radio observations at 8.5 GHz by Berger (2002) revealed quiescent emission with occasional bursts, similar to those witnessed on TVLM513. Subsequent measurements at 4.9 GHz by Hallinan et al. (2008) revealed strong ($5 \times$ the quiescent level) circularly polarized pulses, lasting 5–20 minutes and with a 3 hr period corresponding to the stellar rotation rate. However, observations at 8.5 GHz by Berger et al. (2005) and Forbrich & Berger (2009) detected no significant activity over multiple stellar rotation periods, indicating a possible absence of periodicity above 4.9 GHz. To date, there are no published observations of 2M0036, below 4.9 GHz.

3. OBSERVATIONS AND DATA REDUCTION

Radio observations of UCDs TVLM513 and 2M0036, were conducted 2007 June 24–26 using the NRAO Very Large Array (VLA). Each source was observed for $\sim 10.5$ hr (10 s integration) using 2 $\times$ 6.25 MHz bands centered at 327.5 MHz and 321.6 MHz. Each frequency band was split into 15 spectral channels for the purpose of radio frequency interference removal and to mitigate bandwidth smearing. At observation time, the array utilized 23, 25 m antennas positioned in A configuration (maximum baseline $\sim 35$ km), resulting in a $\sim 2.5$ deg field of view and $\sim 6'' \times 5''$ angular resolution. The radio flux density scale was set using amplitude calibrator 3C 286 (assumed 24.49 Jy at 327.5 MHz). Phase calibration and the receiver bandpass correction was performed using standard sources 1513+236 and 0042+233 for TVLM513 and 2M0036, respectively. Measurements of each UCD and its corresponding phase calibrator were intertwined, performing 2 $\times$ 30 minute primary target scans followed by a 5 minute calibrator scan, then repeating.

Data reduction and imaging were performed using both AIPS$^6$ and Obit$^7$ software packages. The visibility data were calibrated using standard AIPS tasks. Automated data flagging, visibility self-calibration, and imaging were performed in Obit. Light curves of TVLM513 and 2M0036, were made in both total (Stokes I) and circularly polarized (Stokes V) flux using AIPS task DFTPL.

For comparison with published 1.4 GHz quiescent emission observations of TVLM513, we analyzed VLA archival data from 2005 January 10 which contained an $\sim 8$ hr observation of 2M0036. The data consisted of 2 $\times$ 50 MHz bands centered on 1465 MHz and 1385 MHz obtained in the BnA hybrid configuration (maximum baseline $\sim 21.2$ km north–south and 12.2 km east–west). Amplitude and phase offsets were determined using calibrators 3C 147 (assumed 21.39 Jy at 1465 MHz) and 0042+233. Data editing, calibration, and imaging were performed using standard AIPS routines.

4. RESULTS

4.1. TVLM513

We observe no significant unpolarized or circularly polarized radio emission associated with TVLM513 over the 10.5 hr observation. The position of TVLM513 is well determined ($<1''$), based on closely spaced radio (Berger et al. 2008) and infrared (Cutri et al. 2003) detections and estimates of TVLM513’s proper motion (Schmidt et al. 2007). Given the positional accuracy, we report a 2.5$\sigma$ non-detection limit to the total (Stokes I) and circularly polarized (Stokes V) quiescent radio flux. These limits are 795 $\mu$Jy for I and 743 $\mu$Jy for V. The relationship between our 2.5$\sigma$ upper limit for TVLM513 and previously measured peak flux density values is shown in Figure 1 (scaled to 10.6 pc) and listed in Table 1.

Previous observations of TVLM513 indicate a pulse period of $\sim 1.96$ hr (Hallinan et al. 2006; Lane et al. 2007). To search for burst emission and any potential periodicity, we constructed light curves at the known position of TVLM513 in both unpolarized and circularly polarized intensity with time resolutions between 10 s and 10.5 hr. We detect no

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$^6$ Astronomical Image Processing System, release 31DEC10.  
$^7$ Obit is developed and maintained by Bill Cotton at The National Radio Astronomy Observatory in Charlottesville, Virginia, USA and is made available under the GNU General Public License, version 1.1.269-6-64b.
Table 1
Measurement Summary Listing Observing Frequency $\nu$ in GHz, Observation Length $\tau$ in hr, and the Recorded Flux $S$ in $\mu$Jy

| Source   | Date     | $\nu$ | $\tau$ | $S$         | Reference                      | Notes |
|----------|----------|-------|--------|-------------|-------------------------------|-------|
| TVLM513  | 2008 Mar 30    | 8.5   | 7      | 539 $\pm$ 19 | Forbrich & Berger (2009)      |        |
|          | 2007 Jul 26    | 8.4   | 8      | 318 $\pm$ 9  | Doyle et al. (2010)           | Burst |
|          | 2007 Jul 26    | 0.3   | 10     | <795         | Current work                  |        |
|          | 2007 Jul 1     | 8.5   | 9      | 208 $\pm$ 18 | Berger et al. (2008)          |        |
|          | 2007 Apr 20    | 8.5   | 8      | 353 $\pm$ 14 | Current work                  | Burst |
|          | 2007 Apr 20    | 8.5   | 8      | ...          | Hallinan et al. (2007)        |        |
|          | 2007 Feb 12    | 0.6   | 4      | <225         | Antonova (2007)               | GMRT  |
|          | 2006 May 20    | 8.4   | 10     | 464 $\pm$ 9  | Current work                  | Burst |
|          | 2006 May 20    | 8.4   | 8      | ...          | Hallinan et al. (2006)        | Burst |
|          | 2005 Jan 13    | 8.4   | 5      | 396 $\pm$ 16 | Hallinan et al. (2006)        | Burst |
|          | 2004 Jan 24    | 8.4   | 4      | 228 $\pm$ 11 | Osten et al. (2006)           |       |
|          | 2004 Jan 24    | 4.9   | 4      | 284 $\pm$ 13 | Current work                  |       |
|          | 2004 Jan 24    | 1.4   | 4      | 260 $\pm$ 46 |                     |       |
|          | 2001 Sep 23    | 8.5   | ...    | 980 $\pm$ 40 | Berger (2002)                 | Burst |

| 2M0036   | 2008 Mar 30    | 8.5   | 7      | 144 $\pm$ 22 | Forbrich & Berger (2009)      |       |
|          | 2007 Jun 24    | 0.3   | 10     | <942         | Current work                  |       |
|          | 2007 Jun 24    | 0.3   | ...    | <4100        | Current work                  |       |
|          | 2006 Sep 24    | 4.9   | 12     | 241 $\pm$ 14 | Hallinan et al. (2008)        | Burst |
|          | 2006 Sep 24    | 4.9   | ...    | >500         | Current work                  |       |
|          | 2005 Jan 10    | 4.9   | 8      | 152 $\pm$ 9  | Berger et al. (2005)          |       |
|          | 2005 Jan 10    | 1.4   | 8      | <130         | Berger et al. (2005)          |       |
|          | 2002 Sep 28    | 8.5   | 8      | 134 $\pm$ 16 | Berger et al. (2005)          |       |
|          | 2002 Sep 28    | 4.9   | 8      | 259 $\pm$ 19 |                           |       |
|          | 2001 Sep 9     | 8.5   | 3      | 327 $\pm$ 14 | Berger (2002)                 | Burst |
|          | 2001 Sep 9     | 8.5   | ...    | 720 $\pm$ 40 |                           | Burst |
|          | 2001 Sep 23    | 8.5   | 2      | 135 $\pm$ 14 |                           |       |

Notes. Measurements are made using the VLA unless noted otherwise.

significant variation to the measured radio intensity on any timescale. Also, no periodicity was found within the noise over $\sim$5 stellar rotations, performing both a blind period search and by folding the flux values at the expected period. Light curves of the circularly polarized flux with 10 s and 5 minute temporal resolution along with the corresponding Lomb–Scargle periodogram of the 10 s measurements are shown in Figure 2. Our 325 MHz non-detection implies a pulse flux density upper limit of 3.5 mJy (Stokes $I$) assuming a 5% duty cycle. High-frequency observations by Berger et al. (2009) and Hallinan et al. (2007) observe pulse duty cycles in the range of 2%–10%.

4.2. 2M0036

We searched the anticipated location of 2M0036, for polarized and unpolarized radio emission at observation frequencies of 325 MHz and 1.4 GHz. The position of 2M0036, is known to an accuracy smaller than each of the synthesized beams (see Section 3) and is therefore well constrained. No significant radio emission was observed at either frequency. Our 325 MHz non-detection establishes a 2.5$\sigma$ upper limit on the quiescent flux $<942 \mu$Jy in total intensity (Stokes $I$) and $<870 \mu$Jy in circularly polarized (Stokes $V$) intensity for the 10.5 hr observation. The non-detection at 1400 MHz ($<130 \mu$Jy in Stokes $I$, $<95 \mu$Jy Stokes $V$, 2.5$\sigma$) sets an upper limit on the quiescent flux that is slightly lower than the predicted

![Figure 2](image-url)
extrapolation from higher frequencies when assuming a flat spectrum (see Figure 3).

No notable burst activity in the 325 MHz total flux or polarized flux measurements was observed on timescales from 10 s to 10.5 hr. The corresponding burst flux density upper limit is 4.1 mJy (Stokes I) assuming a 5% duty cycle. We also detect no periodicity in the measured flux over >3 stellar rotations, assuming a stable rotation rate of 3.08 hr (Hallinan et al. 2008). A light curve of the 325 MHz circular polarization measurements folded at the expected pulse period and a Lomb–Scargle periodogram of 10 s resolution data are shown in Figure 4. A similar flux variability search using the 1.4 GHz observation periodogram of 10 s resolution data are shown in Figure 4. A solid line indicates the 5 minute median value of the 10 s measurements. Bottom: a Lomb–Scargle periodogram of the 10 s resolution circularly polarized flux values. Dashed lines indicate false alarm probabilities of 0.01 (99%), 0.1 (90%), and 0.5 (61%).

![Figure 3](image)

**Figure 3.** Peak luminosity of 2M0036, from all published observations, scaling the measured radio flux density to a distance of 8.8 pc. Indicators are the same as in Figure 1. See Table 1 for specific radio measurements and author sources.

A similar flux variability search using the 1.4 GHz observation periodogram of 10 s resolution data are shown in Figure 4. A solid line indicates the 5 minute median value of the 10 s measurements. Bottom: a Lomb–Scargle periodogram of the 10 s resolution circularly polarized flux values. Dashed lines indicate false alarm probabilities of 0.01 (99%), 0.1 (90%), and 0.5 (61%).

The CMI mechanism is quenched if the relativistic RX-mode cutoff frequency exceeds the cyclotron frequency. This constraint can be written in terms of an upper limit on the plasma β, the ratio of electron plasma to cyclotron frequencies (Mutel et al. 2006),

$$\beta = \frac{\omega_{ce}}{\Omega_{eqc}} < \sqrt{\frac{\gamma - 1}{\gamma}},$$

with \(\gamma\) representing the electron beam Lorentz factor. For \(\gamma - 1 \ll 1\), this can be recast as

$$\beta \sim 5 \times 10^{-3} \cdot \frac{n_e}{B_G E_{keV}} < 1,$$

where \(n_e\) is the electron density per cubic centimeter, \(B_G\) is the magnetic field in Gauss, and \(E_{keV}\) is the beam energy in keV.

By assuming a magnetic field configuration, an electron density profile, and a mean beam energy, this constraint can be mapped to a coronal volume for which the CMI mechanism is viable. We assume a dipole field with surface equatorial field strength \(B_0 = 5\) kG, consistent with estimates of 3 kG at the 8 GHz source altitude (Reiners & Basri 2007; Hallinan et al. 2008) but below the maximum of 10 kG based on dynamo models (Browning 2008). The electron density profile is more problematic. Stellar coronal loop models suggest either a low-order power law or exponential dependence with radial distance, with a scale height of order the loop size (Rosner et al. 1978; Collier Cameron 1988). We assume an example surface electron density \(n_e = 10^9\) cm\(^{-3}\) (Fludra et al. 1999; Yu et al. 2011) and an exponential dependence with a density scale height equal to the stellar radius.

Figure 5(a) illustrates the masing criteria (β) in a model UDC magnetosphere for 100 keV electron beams. Presumably, the periodic bursts observed on UCDs are generated in an active region extending along a corotating field line and emitting at a frequency consistent with the local magnetic field strength.

![Figure 4](image)

**Figure 4.** Top: measured radio flux (Stokes V) at the position of 2M0036, folded with a period of 3.08 hr. Dots represent the 10 s resolution radio intensity. A solid line indicates the 5 minute median value of the 10 s measurements. Bottom: a Lomb–Scargle periodogram of the 10 s resolution circularly polarized flux values. Dashed lines indicate false alarm probabilities of 0.01 (99%), 0.1 (90%), and 0.5 (61%).
Detections at both 8.5 GHz and 4.9 GHz imply an active region extending to at least 1.5 stellar radii. This is consistent with estimates from 2M0036, by Hallinan et al. (2008). Lower frequency observations probe larger radii, hence the highest observation frequency where \( \beta < 1 \) and pulsed emission is absent defines the region’s uppermost vertical extent. Assuming observations of 2M0036 and TVLM513 are typical of all UCDs and that the year-long history of pulse activity on TVLM513 continued throughout our 325 MHz observations (i.e., nearly 100% pulse duty cycle), the absent pulse emission at 1.4 GHz continued throughout our 325 MHz observations (i.e., nearly 100% pulse duty cycle). This is consistent with a flat gyrosynchrotron spectrum with indication of the total (Stokes I) and circularly polarized (Stokes V) flux were made on timescales between 10 s and 10.5 hr. While strong continuous emission and multi-minute, circularly polarized pulses were previously recorded at 4.9 GHz and 8.5 GHz, no significant emission was measured at 325 MHz. We set 2.5\( \sigma \) total flux limits of 795 \( \mu Jy \) and 942 \( \mu Jy \) for TVLM 513-46546 and 2MASS J0036+1821104, respectively, for the quiescent emission over 10.5 hr, consistent with a flat gyrosynchrotron spectrum with a potential spectral break near 2–3 GHz as indicated by Osten et al. (2006). Furthermore, we observe no significant variation in the 325 MHz radio flux at the expected location of each source. The absence of variable radio flux from TVLM 513-46546 below 1.4 GHz suggests that pulse emission from these UCDs (assuming a CMI electron acceleration model) originates from a source region confined below two stellar radii and/or is driven by electron beam energies less than a few keV.

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REFERENCES

Antonova, A. 2007, PhD thesis, The Queen’s Univ. Belfast
Antonova, A., Doyle, J. G., Hallinan, G., Bourke, S., & Golden, A. 2008, A&A, 487, 317
