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# Mapping the Radio Coronae of Cool Stars and Brown Dwarfs

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**Abstract.** The pulsing radio emission detected from ultracool dwarfs can be used as a powerful diagnostic of magnetic field strengths and topologies at and below the substellar boundary. Studies thus far have confirmed magnetic field strengths of 3 kG for two late M dwarfs and 1.7 kG for an L3.5 dwarf, the latter being the first confirmation of kG magnetic fields for an L dwarf. Ongoing long term monitoring of the radio pulses will also investigate the stability of the associated large-scale magnetic fields over timescales  $> 1$  year. We also present the preliminary results of a lengthy radio monitoring campaign of the rapidly rotating M4 star V374 Peg, with the resulting light curves phased with magnetic maps previously obtained through Zeeman Doppler Imaging. The radio emission from V374 Peg is strongly modulated by the large scale dipolar magnetic field, with two clear peaks in the radio light curve per period of rotation, occurring when the dipolar field lies in the plane of the sky. These results provide strong evidence that the electron cyclotron maser instability plays a pivotal role in the production of quiescent radio emission from V374 Peg, representing a significant departure from the accepted model of gyrosynchrotron emission as the dominant source of quiescent radio emission from active M dwarfs.

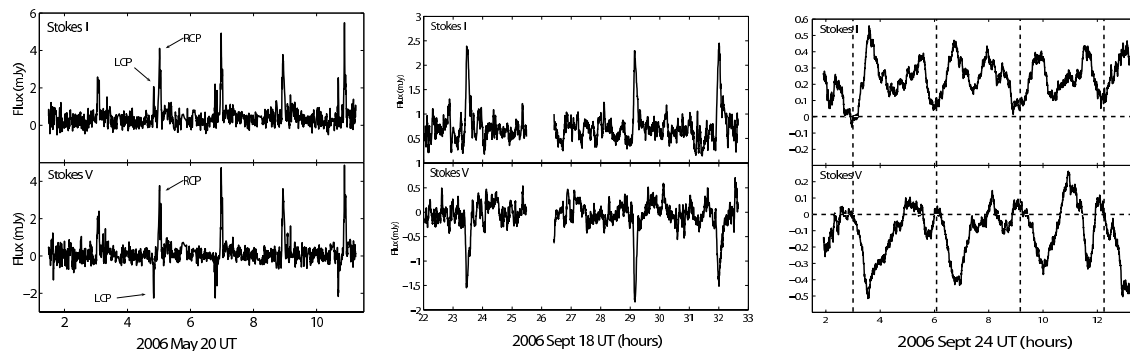
**Keywords:** Radiation Mechanisms: Nonthermal, Radio Continuum: Stars, Stars: Activity, Stars: Low-Mass, Brown Dwarfs, Stars: Magnetic Fields

**PACS:** 97.10.Jb, 97.20.Jg, 97.30.Nr, 97.20.Vs

## INTRODUCTION

In recent years, very low mass stars and brown dwarfs (collectively termed ultracool dwarfs), have unexpectedly been confirmed as a new class of radio source [1, and references therein]. We have conducted lengthy VLA monitoring campaigns of three such dwarfs, the M8.5 dwarf LSR J1835+3259 (hereafter LSR J1835), the M9 dwarf TVLM 513-46546 (hereafter TVLM 513) and the L3.5 dwarf 2MASS J00361617+1821104 (hereafter 2MASS J0036), that have revealed much on the nature of this anomalous radio emission [2, 3, 1]. The characteristics of this radio emission have proved extraordinary, particularly the periodic presence of 100% circularly polarized pulses (Figure 1). These pulses are due to narrowly beamed electron cyclotron maser (hereafter ECM) emission, the same nature of radio emission detected at kHz and MHz frequencies from the magnetized planets in our solar system ([4, 5], but requiring much more powerful kilogauss magnetic fields. All ultracool dwarfs detected thus far in the radio have also

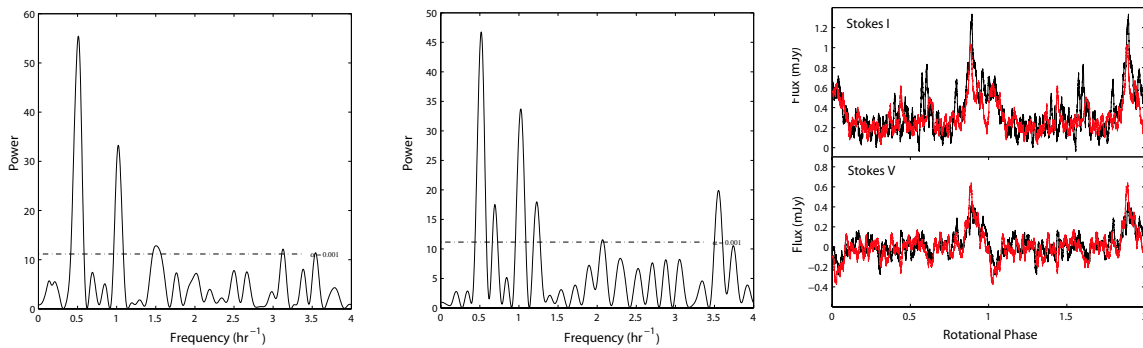
been confirmed to produce quiescent unpolarized radio emission. However, in the case of 2MASS J0036, the unpolarized radio emission is shown to be periodic, with no evidence for a quiescent, aperiodic component ([1]. Crucially, brightness temperature limitations imposed on this periodic unpolarized radio emission rule out incoherent emission mechanisms such as gyrosynchrotron radiation. The unpolarized emission from this and other ultracool dwarfs is also attributed to depolarized ECM emission, with depolarization possibly occurring due to propagation effects such as scattering. These results provide the strongest evidence to date that the ECM instability is the dominant mechanism producing radio emission in the magnetospheres of ultracool dwarfs.



**FIGURE 1.** The periodic light curves of three pulsing ultracool dwarfs. **Left:** The M9 dwarf TVLM 513. **Centre:** The M8.5 dwarf LSR J1835. **Right:** The L3.5 dwarf 2MASS J0036. Total intensity (Stokes I) and circular polarization (Stokes V) light curves are shown for each dwarf. Right circular polarization is represented by positive values and left circular polarization is represented by negative values in the Stokes V light curve.

## INVESTIGATING MAGNETIC FIELD STRENGTHS AND TOPOLOGIES FOR PULSING ULTRACOOOL DWARFS

The confirmation of the ECM instability as a source of persistent levels of broadband radio emission from ultracool dwarfs, indistinguishable in temporal and polarization characteristics from gyrosynchrotron radiation, has implications for our understanding of both stellar magnetic activity and the dynamo mechanism generating magnetic fields in fully convective stars and brown dwarfs. In-situ observations of this mechanism in operation in planetary magnetospheres have confirmed that (a) the resulting radio emission is generated at the electron cyclotron frequency denoted by  $\nu_c \approx 2.8 \times 10^6 B$  Hz, enabling extremely accurate measurement of the magnetic field strength in the source region of the pulsed emission (b) emission in the R-X mode close to perpendicular to the magnetic field in the source region is favored, yielding the polarity of the magnetic field in the source region and (c) the emission can be very narrowly beamed allowing the constraint of both source size and hence brightness temperature, as well as location. Therefore, ECM emission is a vital diagnostic tool for remote sensing of the plasma conditions as well as the magnetic field strengths and topologies of ultracool dwarfs. Indeed, radio observations have confirmed magnetic field strengths of 3kG for TVLM

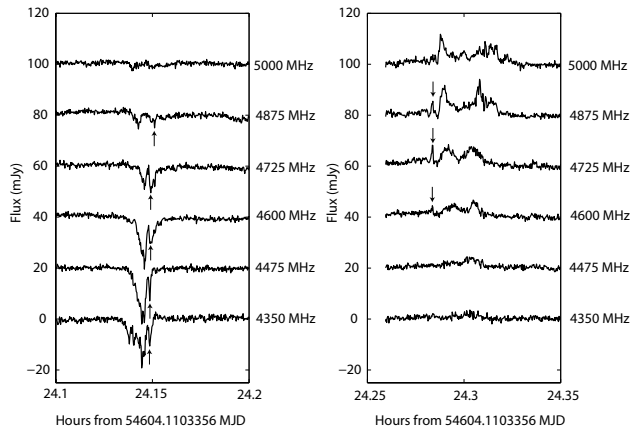


**FIGURE 2.** **Left:** Lomb-Scargle periodogram of the radio observations of TVLM 513 conducted in April 2007. **Centre:** Lomb-Scargle periodogram of the radio observations of TVLM 513 conducted in June 2007. **Right:** The data from April 2007 (black) and June 2007 (red) phase folded to a period of  $1.9596 \pm 0.0001$  hours. The same periodic signal is present in both observations and moreover the pulsed emission is stable over the six week interval between observations.

513 and LSR J1835 and field strengths of 1.7kG for 2MASS J0036, the latter being the first confirmation of kG magnetic fields for an L dwarf, establishing strong magnetic dynamo action out to spectral type L3.5 [1].

The pulsed emission can also give vital information on the stability of large-scale magnetic fields for ultracool dwarfs. Radio monitoring of a number of ultracool dwarfs has confirmed that the pulses can vary in brightness, disappear and reappear. If the magnetic field is large-scale and stable, such pulses should always be confined to a particular range of phase of rotation of the dwarf governed by the topology of the large-scale, stable magnetic field. This can be investigated through correlating the phase of the radio pulses from the various observations. If the pulses do remain confined to a narrow range of rotational phase, it confirms the presence of large-scale stable magnetic fields on timescales  $> 1$  year.

[6] did not detect a periodicity in the radio emission from TVLM 513 in observations conducted in April 2007, unlike previous observations reported by [3], and suggested that this long term variability may be associated with a change in field configuration, thereby ruling out the possibility of a stable magnetic field on timescales  $> 1$  year for this dwarf. However, we have reduced these data and confirm that the periodicity of 1.96 hours is indeed present in the data with very high significance. Therefore, the flares reported by [6], are not actually flares, but rather periodic pulses. Furthermore, we also observed TVLM 513 in June 2007, less than 6 weeks after the observations performed by [6] and phase correlation of these data confirm a very stable magnetic field configuration over this interval (Figure 2). Ongoing photometric monitoring observations should yield a rotation period of sufficient accuracy to phase connect these phased data to earlier observations of TVLM 513.



**FIGURE 3.** A left circularly polarized pulse with flux exceeding 20 mJy and a right circularly polarized pulse with flux exceeding 15 mJy detected on 2008 May 18 at the Arecibo Observatory. The presence of structure with duration  $\sim 5$  seconds and bandwidth  $< 375$  MHz (arrows) can be used to place a lower limit on the brightness temperature of the radio emission of  $10^{15}$  K. We also note the temporal broadening from lower to higher frequencies and double peaked structure of both pulses, despite originating in independent source regions. Such morphology may prove to be characteristic of the pulsed emission from ultracool dwarfs.

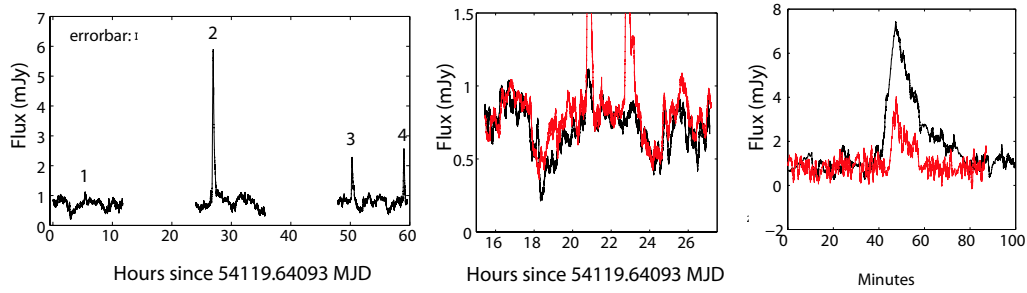
## BROADBAND DYNAMIC SPECTRA OF THE PULSED EMISSION

We have commenced observations of pulsing ultracool dwarfs using the Arecibo Observatory in an attempt to obtain broadband dynamic spectra of the periodic pulses from this new class of radio transient. The first of these observations consisted of 3 successive nights of the pulsing ultracool dwarf TVLM 513, using the Wide-band Arecibo Pulsar Processor (WAPP) backend on the Arecibo dish spanning the frequency range 4300-5300 MHz. The brightest pulsed emission detected had flux intensity in excess of 20 mJy, the highest intensity radio emission yet detected from an ultracool dwarf, and the presence of short duration structure in the periodic pulses have confirmed brightness temperatures  $> 10^{15}$  K.

While further observations are required to confidently discuss the morphology of the pulses detected from TVLM 513 in May 2008, there is significant evidence for the presence of a double-peaked structure in many of the pulses. Moreover, these double-peaked pulses are seen to temporally broaden with increasing frequency (Figure 3). This may prove to be a key signature of ECM emission from stellar and substellar magnetospheres, although further Arecibo observations of an extended sample of pulsing ultracool dwarfs, as well as continued monitoring of TVLM 513, are essential to establishing ubiquity of this phenomena.

## MAPPING THE RADIO CORONAE OF ACTIVE M DWARFS

The question arises whether ECM emission may also play a role as a source of both pulsing and quiescent radio emission from earlier type active M dwarfs, particularly in



**FIGURE 4.** **Left:** The radio light curve of V374 Peg over three nights observing in January 2007. The radio emission is periodic at the rotation period ( $p = 0.445654 \pm 0.000002$  days) with two peaks per period of rotation of the dwarf. There are 3 bursts detected over the entire observation, with a 4th marginal event. Three of the events, event 1,2 and 4, occur at the same phase of rotation of the dwarf. **Centre:** The radio light curve from V374 Peg on 2007 January 19 phased with the radio light curve from V374 Peg on 2007 January 21. The close correlation of the light curves is evident. **Right:** Event 2 (black) phased with Event 4 (red). Both bursts occur at the same rotational phase of the dwarf and share a very similar morphology.

light of the fact that radio luminosities are steadily maintained from early type M dwarfs through to late M and early L type dwarfs with no obvious demarcation indicating any change in emission mechanism [1]. Zeeman Doppler Imaging has directly confirmed that rapidly rotating, mid and late type M dwarfs do indeed possess large-scale poloidal magnetic fields, conducive to the generation of ECM emission [7]. If the ECM instability is indeed responsible for a significant fraction of the quiescent and pulsing radio emission from active dwarf stars, strong rotational modulation of the highly directive emission may be present, as has been the case for ultracool dwarfs. We have begun a radio monitoring campaign of active M dwarfs consisting of observations of sufficient duration to investigate the presence of such rotational modulation in quiescent or flare emission.

The M4 dwarf V374 Peg was selected as the first target for this campaign as it has been confirmed to possess a large-scale magnetic field with a dominant dipolar component stable over timescales  $> 1$  year [8, 9]. Most importantly, the multi-epoch ZDI observations have allowed the period of rotation of the star to be determined with sufficient accuracy to allow direct correlation of any radio light curves to the putative orientation of the large-scale magnetic field at the time of the radio observations. We present VLA monitoring observations of 12 hours each on 3 successive nights with the Very Large Array on 2007 January 19,20 and 21, covering three full periods of rotation of the star and correlate the resulting periodic light curve to the orientation of the rotating dipolar magnetic field.

The quiescent radio emission is unpolarized and clearly periodic with rotation of the star with two peaks and troughs per period of rotation of the dwarf (Figure 4). This periodic modulation is strongly correlated with the orientation of the magnetic field as determined from ZDI data, such that the peaks in emission occur when the high strength magnetic field region at base of the dominant radial component of the dipolar magnetic field, is perpendicular to our line of sight. The degree of correlation between the radio light curve on successive nights is quite extraordinary with individual structures repeating periodically with rotation of the dwarf. Such short duration periodically repeating

structures cannot be explained by occultation of emitting regions and instead clearly imply a highly directive emission mechanism.

There are 3 bursts detected over the entire observation, with a 4th marginal event. When considered individually, all 4 events possess similar characteristics to radio flares typically attributed to incoherent gyrosynchrotron emission, having low ( $< 10\%$ ) or no circular polarization. However, 3 of the events, event 1,2 and 4, occur at the same phase of rotation of the dwarf. Such events occurring at the same phase of rotation of the dwarf indicate that the transient nature of the emission, as detected terrestrially, is not due to intrinsic flaring at the source, but rather due to the inherent directivity of the emission mechanism. As has been previously shown to be the case for ultracool dwarfs, such events are more properly classified as pulses rather than flares.

These results present a significant departure from the accepted model of gyrosynchrotron emission as the dominant source of quiescent radio emission from active M dwarfs. The strong rotational modulation of both the quiescent and pulsing radio emission from V374 Peg can only be accounted for by highly directive radiation. ECM emission originating at the polar regions of the dipolar field can account for the observed periodicity in quiescent and pulsed emission, and is consistent with the observed correlation with the rotational modulation of the radio light curves and the orientation of the large-scale dipolar field relative to our line of sight.

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