Multi-frequency long-term monitoring of the ultracool dwarf TVLM 513-46546

Antoaneta Antonova,[1] John Gerard Doyle,[2] Gregg Hallinan,[3]
Aaron Golden,[3] Stephen Bourke[3,4]

[1] Department of Astronomy, Faculty of Physics, University of Sofia, Bulgaria
[2] Armagh Observatory, College Hill, Armagh, N. Ireland
[3] Centre for Astronomy, National University of Ireland, Galway, Ireland
[4] Joint Institute for VLBI in Europe, Dwingeloo, The Netherlands
tony@phys.uni-sofia.bg

(Conference poster. Accepted on 08.01.2010)

Abstract.
Recently, observations of three ultracool dwarfs have shown that the emission is in fact due to the electron cyclotron maser instability operating in the low plasma density, high magnetic field strength regions above the poles of a large-scale magnetic field, i.e. it is similar to that of the magnetized planets in the Solar system. The M8.5 dwarf TVLM 513-46546 is one of the most studied radio emitting dwarfs. It has been found to display periodic pulses of 100% circularly polarized radio emission, the periodicity of the bursts being consistent with the rotational period of the dwarf as confirmed by optical I band observations . Here we present a systematic review and analysis of all observations of TVLM 513-46546 conducted in the radio X and C bands, including our latest VLA and Arecibo observations.

Key words: pulsars: general — radiation mechanisms: non-thermal — radio continuum: stars — stars: activity — stars: low-mass, brown dwarfs — stars: magnetic fields

Дългосрочни наблюдения на ултра-хладната звезда-джудже TVLM 513-46546 в няколко честоти

Антоанета Антонова, Джон Джерард Дойл, Грег Халинан,
Аарон Голден, Стивън Бърк

Неотдавна, радио наблюдения на три ултра-хладни джуджета показаха, че радиоизлъчването всъщност се дължи на механизма електронен циклотронен мазер, опериращ в районите с висок интензитет на магнитното поле и ниска плазмена плътност, намиращи се над полюсите на глобално магнитно поле, т.е. подобно на излъчването от магнетизираните планети от Слънчевата система. Звездата TVLM 513-46546, джужде от спектрален клас M8.5, е еднин от най-изследваните ултра-хладни обекти, активни в радиодиапазона. Неговото излъчване се характеризира с периодични, 100% кръгово поляризирани пулсации. Периодът на пуслациите е съвместим с периода на околоосно въртене на джуджето, което бе потвърдено чрез наблюдения в оптичният филтър I. Тук ние представяме систематичен обзор и анализ на всички радионаблюдения на TVLM 513-46546, включително нашите последни наблюдения с радиотелескопите VLA и Arecibo.

1 Introduction

In recent years, ultracool dwarfs (UCDs) have unexpectedly been confirmed as a new class of radio sources. Thus far, 12 dwarfs of spectral class M7 - L3.5, including two binary systems, have been detected in the radio domain (Berger et al. [2006], Phan-Bao et al. [2007], Antonova et al. [2008]).

Initially, the detection of variable, broadband radio emission with low net circular polarization suggested incoherent gyrosynchrotron radiation due to a population of electrons spiraling in the magnetic field of the ultracool dwarf (Berger et al. [2002], Osten et al. [2006]. Yet, some of these sources exhibit bright 100% circularly polarized pulses with a periodicity, consistent with the rotational period of the dwarf (Hallinan et al. [2007], Hallinan et al. [2008], Lane et al. [2007]. Such characteristics suggest an alternative mechanism - the electron cyclotron maser (ECM) instability.

Here we present a systematic review and analysis of all observations of TVLM 513-46546 conducted in the radio X and C bands, including our latest NRAO Very Large Array (VLA)[5] observations of the M8.5 dwarf TVLM 513-46546 (TVLM 513) together with re-analysis of VLA observations of the same dwarf taken in April 2007 by Bergter et al. [2008].

2 Observations

In Table 1, we present the basic observational characteristics of the TVLM 513 data sets. The fluxes and periodicities marked with * are taken from the referenced in the last column sources. The rest are derived from our re-analysis of the data.

Table 1: A summary of the radio observations for TVLM 513

Date of . observ.	Instr./ Freq. (GHz)	Integr. time (h)	Average flux (μmJy)	Period (h)	Data first reported:
23. 09. 2001	VLA 8.4	2	308±16*	no	Berger [2002]
24. 01. 2004	VLA 4.8	10	228±11*	no	Osten et al. [2006]
-	VLA 8.4	10	284±13*	no	-
13. 01. 2005	VLA 4.9	5	405±18*	≈2*	Hallinan etal. [2006]
-	VLA 8.4	5	396±16*	≈2*	-
20. 05. 2006	VLA 4.8	10	368±16*	1.96*	Hallinan et al. [2007]
-	VLA 8.4	10	464±9*	1.96*	-
20. 04. 2007	VLA 8.4	8	353±14*	1.96	Berger et al. [2008]
01. 06. 2007	VLA 8.4	8	318±9	1.95957	paper in prep.
16 –18. 05. 2008	Arec. 4.3 – 5.0	3×3	–	1.958	paper in prep.

3 Results and discussion

The mean fluxes derived from each of the observations are shown in Table 1. The 2001 observations of TVLM 513 were too short for a periodicity serch. However, Berger [2002] reported a highly circularly polarized flare. In 2004, Osten et al. [2006] conducted VLA observations of the same dwarf with time-sharing between 3 frequencies. Because of this, searching for periodicities in

[5] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

the light curves was not possible. However, in several of the scans (at both frequencies) highly polarized bursts can be seen. The analysis of the 2005 observations by Hallinan etal. [2006], suggested both rotational modulation of the signal and the ECM mechanism as the source of the emission. The period was estimated to be ~ 2 h. During the May 2006 observations short, extremely bright and 100% circularly polarized pulses were detected. These, together with the confirmation (via simultaneous photometrical I band observations) that the periodicity is due to the rotation of the dwarf, conclusively confirmed the coherent nature of the emission.

In June 2007 TVLM 513 was detected with a mean flux level of 318 ± 9 μJy. This flux is $\approx 100\mu$Jy lower than the one found in 2005 and 2006, yet it is similar to that reported by Berger [2002]. Inspection of the light curve of TVLM 513 revealed a number of bright, highly polarized bursts of short duration, similar to the May 2006 observations of the same dwarf. The Lomb-Scargle periodogram revealed a clear periodicity in the signal (Figure 1), with two peaks at frequencies ~ 0.5 hr^{-1} and ~ 1 hr^{-1}, corresponding to a period of $\approx$1.96 hours, as is the case for the January 2005 and May 2006 data. In addition, we have an inter-pulse – an aperiodic event, confirming that the detected periodical emission does not exclude the presence of random flare events. Flares have been reported in the optical, UV and X-ray bands as well as in spectral lines such as H α on several UCDs(Liebert et al. [2003], Fuhrmeister & Schmitt [2004]).

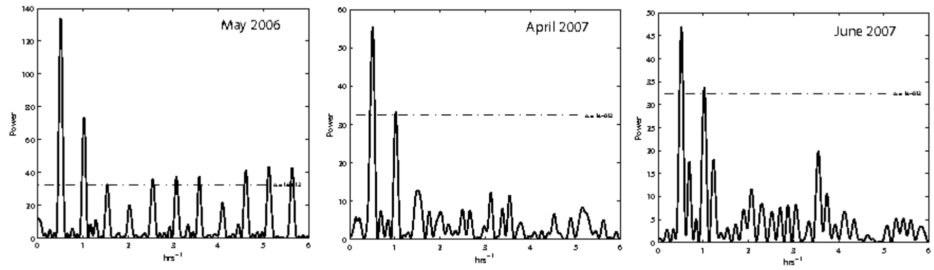

Fig. 1: Lomb-Scargle periodogram for the April and June 2007 datasets, plus for comparison the May 2006 data. For each dataset, the false alarm probability is given.

Data was also obtained in April 2007 for TVLM 513 by Berger et al. [2008]. However, these authors did not report a periodicity, thus this data was obtained from the archive and reduced in a similar manner as the June 2007 data. The the Lomb-Scargle periodogram for the April 2007 data is also shown in Figure 1 and for comparison, the Lomb-Scargle periodogram for the May 2006 data. The periodicity in all three datasets is unquestionable, with a Lomb-Scargle false alarm probability $<< 10^{-12}$.

The April and June observations are second and third epoch observations of pulsed radio emission from TVLM 513, thus suggesting that the emission mechanism is stable on long times scales. From previous observations we know that the rotation period is ≈1.96 hr (Hallinan et al. [2006], Lane et al. [2007]). Using this period we find excellent agreement between the April and June 2007 datasets suggesting (i) that the pulse locations are stable remaining confined to a narrow range of rotational phase (although they may vary in intensity and duration) and (ii) that a more accurate period may be derived based on these two datasets. The stability of the field structure has major implications with the pulsed emission giving vital information on the characteristic size and topology of magnetic fields in ultracool dwarfs.

The similarity between the two datasets (April and June 2007) suggests that the magnetic field structures are stable on timescales of at least 6 weeks for this UCD. Such information on the magnetic field is crucial to understanding the means by which persistent levels of ECM emission are sustained in the magnetospheres of UCDs. This persistent generation of ECM emission in turn, implies the presence of stable electric fields, which are somehow generated and sustained within the magnetosphere of the ultracool dwarf. Such electric fields may be a fundamental source of electron acceleration, and hence radio emission, for plasma trapped in a large-scale magnetic field.

Since there was less than 6 weeks between the April and June observations of TVLM 513, we were able to extract a more accurate period of 1.95957 for the rotation of the dwarf. Figure 2 shows the Stokes I and Stokes V light-curve (here we plot two phases for clarity) from the June 2007 (solid line) and April 2007 data (dotted line) phase folded to a period of 1.95957 ± 0.00007 hours. Note the excellent agreement between the positive and negative polarities. In the bottom panel of Figure 2 we show the results for Stokes V where the phase is 1.95950 hrs (left panel) and 1.95964 hrs (right panel), i.e. shifted by ± 0.00007 hrs.

In 2008 we observed TVLM 513 over 3 succesive nights, using the Wideband Arecibo Pulsar processor (WAPP) backend of the Arecibo telescope spanning the range of 4300 - 5300 MHz. As a result we can report the detection of pulses on each of the nights and the highest intensity radio emission yet detected from an ultracool dwarf in excess of 20 mJy. A short duration structure in the periodic pulses has yielded brightness temperatures 10^{15} K (Figure 3). Although a significant variability is present in the amplitude of the periodic pulses, they remain stable in phase and morphology.

There is significant evidence of the presence of double-peaked structure in many of the pulses. Also, the pulses show temporal broadening with increasing frequency (Figure 3) which is reminiscent of the inverted-V electron precipitation associated with the auroral kilometric radiation detected at high latitudes in the Earth's magnoetosphere (Green et al. 1979). This may prove to be a key signature to electron cyclotron emission from stellar and substellar magnetosheres. However, further Arecibo observations of TVLM 513 as well as other pulsing dwarfs are required to investigate the ubiquity of this phenomena.

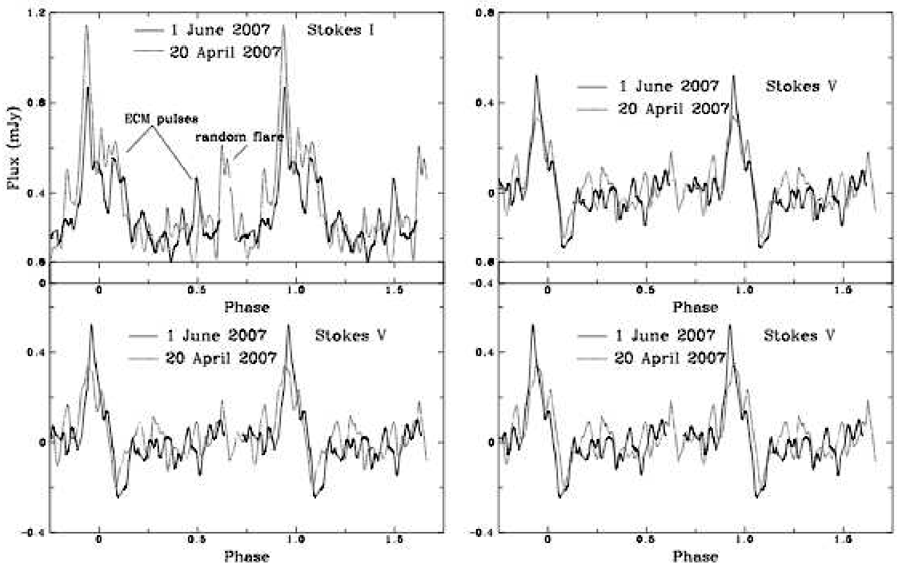

Fig. 2: In the top two panels we have the Stokes I and V from June 2007 (solid line) and April 2007 (dotted line) phase folded with a period of 1.95957 hrs from 20 April 2007 00:15 UT. In the bottom panel we show the results for Stokes V where the phase is shifted by ±0.00007 hrs; 1.95950 hrs (left panel) and 1.95964 hrs (right panel). In the top left panel, we label the stable ECM burst region and the random flare event.

4 Conclusions

Using data taken 42 days apart, we have established to a high degree of accuracy the lack of evolution in the morphology of the periodic light curves, although changes in the structure of the pulses are observable from one rotation to the next. Nevertheless, the overall pulse interval does still occur (within a few minutes) at the same orbital phase. However, observations at a higher cadence and frequency resolution are required in order to investigate the location, extent, and morphology of the sub-pluses which are clearly observable in each burst interval (e.g. the preliminary results from our 2008 Arecibo observations). Phase connecting both datasets, gives a more accurate period of 1.95957 hours. Ongoing photometric monitoring observations should yield sufficiently accurate rotation period enabling us to phase connect these data to the earlier observations of TVLM 513.

Acknowledgements. A.Antonova gratefully acknowledges the support of the Scientific Research Fund of St. Kl. Ohridski University of Sofia (grant No. 80/2009). Armagh Observatory is grant-aided by the N. Ireland Dept. of Culture, Arts & Leisure. GH and AG gratefully acknowledge the support of

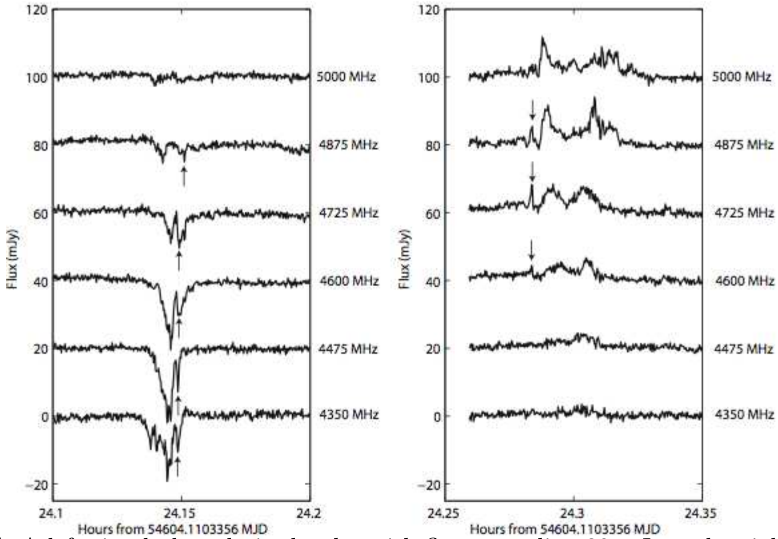

Fig. 3: A left circularly polarized pulse with flux exceeding 20 mJy and a right circularly polarized pulse exceeding 15 mJy detected on 18 May 2008 with the Arecibo telescope. The presence of structure with duration ~ 5 s and bandwidth < 375 MHz(arrows) can be used to place a lower limit on the brightness temperature of the emission of 10^{15} K.The temporal broadening from lower to higher frequencies and double peaked structure of the pulses may prove to be characteristic to the pulsed emission fron ultracool dwarfs.

Science Foundation Ireland (grant No. 07/RFP/PHYF553). JGD thanks the Leverhulme Trust for support.

References

Antonova, A., Doyle, J. G., Hallinan, G., Bourke, S. & Golden, A. 2008 *A&A, 487, p.317-322*

Berger, E. 2002, *ApJ, 572, p.503-513*

Berger, E. 2006, *ApJ, 648, p.629-636*

Berger, E., Gizis, J. E., Giampapa, M. S., Rutledge, R. E., Liebert, J., Martín, E., Basri, G., Fleming, T. A., Johns-Krull, C. M., Phan-Bao, N. & Sherry, W. H., 2008 *ApJ, 673, p.1080-1087*

Fuhrmeister, B. & Schmitt, J.H.M.M., 2004, *A&A, 420, p.1079-1085*

Hallinan, G., Antonova, A., Doyle, J. G., Bourke, S., Brisken, W. F. & Golden, A. 2006 *ApJ , 653, p.690-699*

Hallinan, G., Bourke, S., Lane, C., Antonova, A. Zavala, R. T., Brisken, W. F., Boyle, R. P., Vrba, F. J., Doyle, J. G. & Golden, A. 2007 *ApJ, 663, p.L25-L28*

Hallinan, G., Antonova, A., Doyle, J. G., Bourke, S., Lane, C. & Golden, A. 2008 *ApJ, 684, p.644-653*

Lane, C., Hallinan, G., Zavala, R. T., Butler, R. F., Boyle, R. P., Bourke, S., Antonova, A., Doyle, J. G., Vrba, F. J. & Golden, A. 2007 *ApJ, 668, p.L163-L166*

Liebert, J., Kirkpatrick, J.D., Cruz, K.L., Reid, I.N., Burgasser, A., Tinney, C.G. & Gizis, J.E., 2003, *AJ, 125, p.343-347*

Osten, R. A., Hawley, S. L., Bastian, T. S. & Reid, I. N. 2006, *ApJ, 637, p.518-521*

Phan-Bao, N., Osten, R. A., Lim, J., Martín, E. L. & Ho, P. T. P. 2007, *ApJ, 658, p.553-556*