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Slowly Varying Component of Radio Emission from TVLM 513-46546 and Continuous Sources of High Energy Electrons in the Coronae of UltraCool Stars

V. V. Zaitsev[a], * and A. V. Stepanov[b], **

[a]*Institute of Applied Physics, Russian Academy of Sciences, Nizhniy Novgorod, Russia*

[b]*Central Astronomical Observatory, Russian Academy of Sciences, Pulkovo, St. Petersburg, Russia*

**e-mail: za130@appl.sci-nnov.ru*

***e-mail: stepanov@gao.spb.ru*

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Abstract—It is shown that a source generating a slowly varying or quiet component of radio emission from ultracool stars such as the brown dwarf TVLM 513-46546 can be the gyrosynchroton radiation from the magnetic loops system distributed quasi-uniformly over the star's surface. Such a model explains the low modulation of the flux and makes it possible to understand the pumping mechanism of magnetic loops by high energy electrons. The main parameters of magnetic loops and which part of the star's surface is the emission source are determined using the information on microwave radiation from the brown dwarf TVLM 513-46546.

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1. INTRODUCTION

Ultracool stars such as brown dwarfs, i.e., stars of a spectral class later than M7, are differed from other stars of later spectral classes by their significantly higher activity in the radio frequency band. According to (Rutledge, 2000; Ravi, 2011), their ratio between radio luminosity and X-ray luminosity is higher by approximately four orders than for stars of spectral classes from F to M < 7 (Guedel, 1993). One of the most famous representatives of ultracool stars is the brown dwarf TVLM 513-46546.

TVLM 513-46546 is characterized by two components of microwave radiation. One component is characterized by a high brightness temperature $\geq 10^{11}$ K (Hallinan, 2007), it is totally polarized, and it is generated in the magnetosphere most probably continuously. The repeatability of the radio emission with the period of the star's rotation round its axis confirms this (Fig. 1).

In this case the source is characterized by a narrow radiation pattern and occupies a small area $S \ll 2.4 \times 10^{18}$ cm^2 with respect to the visible area of the brown dwarf's surface $S_* \approx 1.5 \times 10^{20}$ cm^2.

The second component, which is called *quiescent* is characterized by a brightness temperature of about 10^9 K (Osten, 2006; Berger, 2008) and a small degree of circular polarization (<15%); and it is seen to continuously demonstrate weak modulation with a period close to the period of the star's rotation, i.e., approximately 2 hours (Fig. 2).

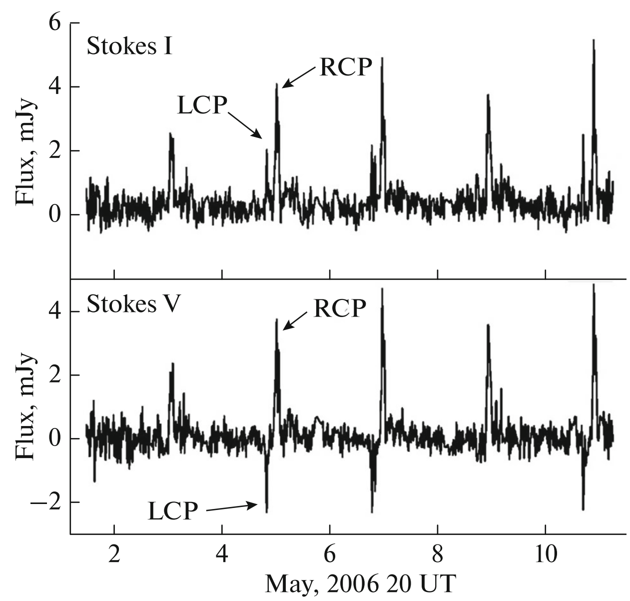

Fig. 1. Light curves of brown dwarf TVLM 513-46546 at frequency 8.44 GHz detected in two channels (Stokes parameters I and V). Period of radiation pulses appearing coincides with period of star's rotation, 1.96 hours (Hallinan, 2007).

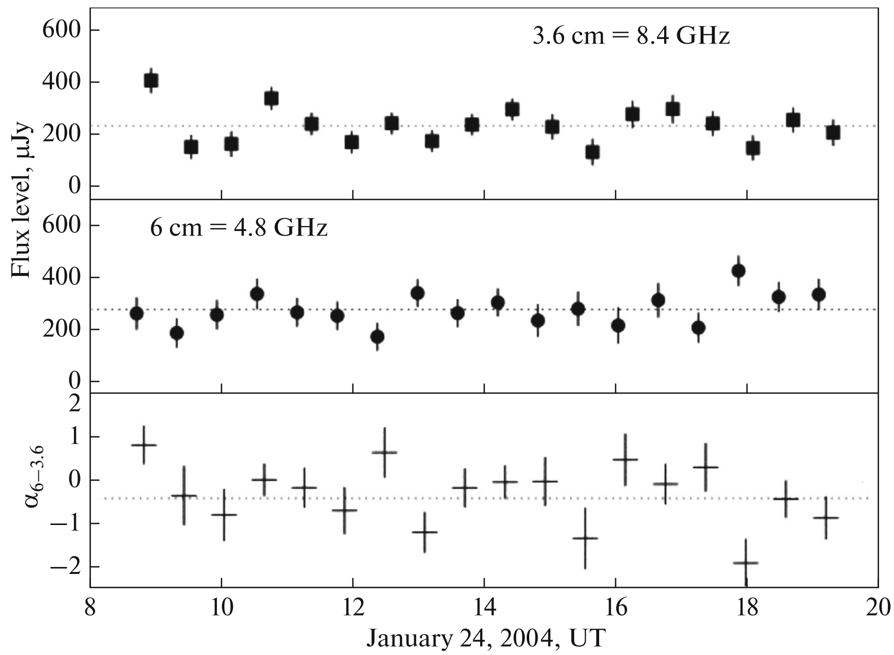

Fig. 2. Variations of radio emission from brown dwarf TVLM 513-46546 at 4.8 and 8.4 GHz. Bottom panel shows spectrum index variation in range 1.4–4.8 GHz (Osten, 2006).

The weak modulation of the quiet component under the star's rotation means that the respective sources are distributed uniformly in the TVLM 513-46546 atmosphere and their total area can be comparable with the area of the brown dwarf's surface. In addition, the respective sources of radio emission should be added continuously by energetic particles to compensate the losses caused by particles precipitation into the loss cone and to provide the observed brightness temperature.

A totally polarized component with a high luminance temperature and narrow directional pattern is usually interpreted based on the electron cyclotron maser (Yu, 2011) or on plasma mechanism of radiation (Zaitsev, 2016). As for the slowly varying or quiet component, we assume that it appears due to the gyro-synchrotron radiation of moderately relativistic electrons in the magnetic fields of the brown dwarf (White, 1989). Moreover, as a rule the radiation is suggested in the dipole magnetic field of the star and the parameters of fast electrons are postulated (number density n_e and spectrum factor δ) without discussing their origin. In addition some properties of the quiet component of radio emission make it possible to conclude more correctly on the source parameters and its distribution in the corona of the brown dwarf.

2. OBSERVATION DATA

The quiet radio emission of the brown dwarf TVLM 513-46546 in the microwave wavelength demonstrates practically invariable performances for a multiyear period of observation, which means that this component is stable on a temporal scale of several years (Berger, 2008). The quiet component was investigated at VLA on January 24, 2004 and the following radio emission fluxes at wavelengths of 20, 6, and 3.6 cm (Osten, 2006) were obtained:

$$F(20\text{ cm}) = 260 \pm 46\mu\text{ Jy},$$
$$F(6\text{ cm}) = 284 \pm 13\mu\text{ Jy},$$
$$F(3.6\text{ cm}) = 228 \pm 11\mu\text{ Jy}.$$

The degree of circular polarization at wavelengths of 3.6 and 6 cm is V/I < 15%. The spectral index determined in (Berger, 2008) $F_\nu \sim \nu^\alpha$ for the wavelength of 20–6 cm has a wide range; it is positive on average and equal to $\alpha = 0.1 \pm 0.2$ For 6–3.6 cm the spectral index is negative and is equal to $\alpha = -0.4 \pm 0.1$. $\alpha = -0.4 \pm 0.1$. A change in the sign of the spectral index means that the spectrum of quiet emission has a maximum and the maximum frequency ν_{max} is in the range of (Osten, 2006) ν_{max} = 1.4–4.8 GHz (i.e., λ = 20–6 cm). A change of the frequency index's sign in the gyrosynchrotron mechanism means that the radiation mode transits from an optically thick mode to an optically thin one. In other words the source of radiation in the range 4.8–8.4 GHz is most probably optically thin and it is important for further estimations.

The information collected by the Chandra ACIS-S3 spacecraft shows that the quiet radio emission from the brown dwarf TVLM 513-46546 is accompanied by soft X-ray radiation in the energy range 0.3–2 keV

(Berger, 2008) and it means that the hot plasma with a temperature of $T \approx 10^7$ K can be in the source of the radio emission. The luminosity of the X-ray radiation in the mentioned range is $L_x \approx 8.5 \times 10^{24}$ erg s^{-1}, which corresponds to the emission measure ME $\approx 1.8 \times 10^{48}$ cm^{-3}.

3. SOURCE MODEL AND ORIGIN OF HIGH ENERGY ELECTRONS

In the work (Zaitsev, 2016), the coherent mechanism of radio emission is examined in order to explain the origin of the totally polarized component of radio emission from the brown dwarf TVLM 513-46546 with a high brightness temperature. It is shown that a hot extended plasma can form in magnetic loops appearing in the brown dwarfs' atmosphere due to photospherical convection. The electric currents generated in magnetic loops by photosphere convection heat the plasma and lift the depressed atmosphere; and as a result, the following condition is true at coronal levels $\nu_p > \nu_c$ needed for implementing the plasma mechanism. Here ν_p and ν_c are the plasma and electron gyro-frequency, respectively. The idea of coronal magnetic loops as the source of radio emission is attractive since, in coronal loops, a long-lived mechanism of storage them by high energy electrons due to the generation of inductive electric fields under the oscillations of electric current is implemented (Zaitsev, 2016). As a result the long-term generation of intensive radio emission is maintained. Since for continuously generating the quiet component by the gyrosynchrotron mechanism the source of high temperature electrons is required, we assume that this component also appears in the coronal magnetic loops, which have different characteristics with respect to the sources of the intensive component and are distributed quasi-uniformly over the brown dwarf's surface (Fig. 3).

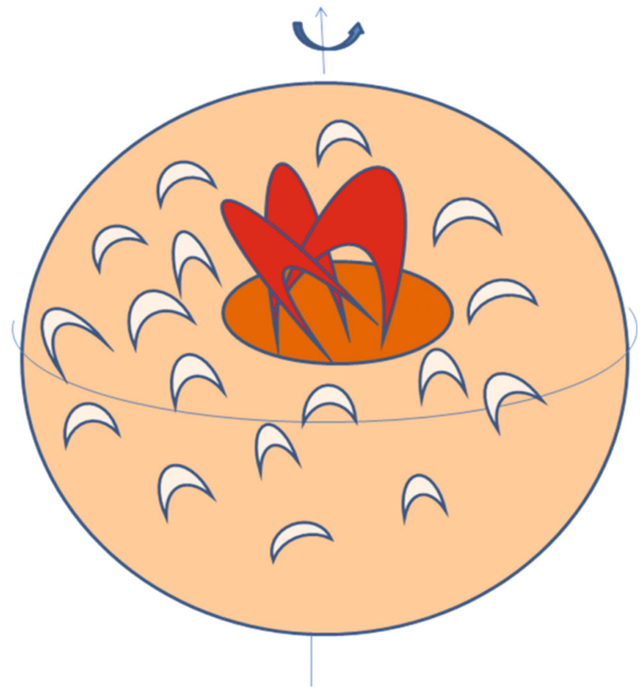

Fig. 3. Active area generating intensive totally polarized component of radio emission (in central part of picture) and distributed sources generating quiet component of radio emission.

Let us use the information on radio emission flux of the quiet component at frequency ν = 8.4 GHz, for which the source is optically thin. For the power-series distribution of high temperature electrons with the energy spectrum factor δ the flux of the gyrosynchrotron radiation from an optically thin source at frequency ν can be presented as follows (Dulk, 1985):

$$F_\nu = 3.3 \times 10^{-24} \times 10^{-0.52\delta} (\sin\vartheta)^{-0.43+0.65\delta} \times \left(\frac{\nu}{\nu_c}\right)^{1.22-0.9\delta} (n_e d)\, B \frac{S}{R^2} \text{ erg cm}^{-2}\,\text{s}^{-1}\,\text{Hz}^{-1}. \quad (1)$$

Here ϑ is the angle between the magnetic field and the direction toward the observer, $\nu_c = 2.8 \times 10^6 B$ is electrons' gyro-frequency, B is the magnetic field, n_e is the number density of energetic electrons in the source, d is the source's thickness in the projection to the observer, S is the visible area of the source, and R is the distance to the source. For the brown dwarf TVLM 513-46546, the distance is R = 10.6 pc = 3.26 × 10^{19} cm.

For the maximum frequency ν_{peak} in the spectrum of gyrosynchrotron radiation and polarization degree r_c, we use the following formulas (Dulk, 1985):

$$\nu_{\text{peak}} = 2.72 \times 10^3 \times 10^{0.27\delta} (\sin\vartheta)^{0.41+0.03\delta} \times (n_e d)^{0.32-0.03\delta} B^{0.68+0.03\delta}, \quad (2)$$

$$r_c = 1.26 \times 10^{0.035\delta} \times 10^{-0.071\cos\vartheta} \left(\frac{\nu}{\nu_c}\right)^{-0.782+0.545\cos\vartheta}. \quad (3)$$

Formulas (1) and (3) are true for the angle range $\vartheta = 20°$–$80°$ and for the optical thickness $\tau_\nu = \kappa_\nu d < 1$, where

$$\kappa_\nu = 1.4 \times 10^{-9-0.22\delta} (\sin\vartheta)^{-0.09+0.72\delta} \left(\frac{\nu}{\nu_c}\right)^{-1.30-0.98\delta} \frac{n_e}{B}. \quad (4)$$

For the model of the quiet component source presented in Fig. 3, let us determine the visible area of the source in the following way:

$$S \approx N_{\text{loop}} l d, \quad (5)$$

where N_{loop} is the number of magnetic loops (elementary sources of radio emission) on the visible semisphere and d and l are the typical thickness and length of a separate loop.

According to the observed (Osten, 2006) spectrum index of optically thin radiation $\alpha = -0.4 \pm 0.1$ from the relationship $\alpha = 1.22 - 0.90\delta$, it is possible to determine (from (1)) the spectrum index of high energy electrons and from there to find the index of optically thin radio emission $\delta \approx 1.8 \pm 0.1$; i.e., the electron spectrum is sufficiently rigid. If we assume that $\vartheta \approx 80°$, which is probable for the examined model of the source, from formula (3) for the degree of circular polarization, it is possible to determine the magnetic field in the coronal magnetic loops—the sources of gyrosynchrotron radiation. If we assume that $\delta = 2, r_c = 0.15, \nu = 8.4 \times 10^9$ Hz, we obtain that $B \approx 1.07 \times 10^2$ G. The determined values of the magnetic field and of the spectrum index of high energy electrons jointly with the condition on optically thin sources at a frequency of 8.4 GHz, i.e., $\tau_{8.4} = \kappa_{8.4} d < 1$, impose constraints on the value $n_e d$, which determines the radio emission flux (1): $n_e d \leq 2 \times 10^{16} \text{cm}^{-2}$. Formula (2) gives the same value for the maximum frequency if we assume that $\nu_{\text{peak}} \leq 1.4$ GHz. The presented estimations correspond to the energy spectrum index of high energy electrons $\delta \approx 1.8 \pm 0.1$. This does not mean that such a spectrum index is maintained for any energy. For example, the information on hard X-ray radiation from the Sun shows that the spectrum of high temperature electrons has a sharp knee under energies of several hundreds of keV and becomes softer, which corresponds to the rise in the spectrum index δ. This is confirmed by the results presented in (Zaitsev, 2016), where the formation of magnetic loops in the corona of the brown dwarf TVLM 513-46546 caused by the photosphere convection is examined and the upper energy limit of fast electrons accelerated by inductive electric fields in magnetic loops, which is not higher than 1.5 MeV (see below), is determined. That is why we consider that the δ value, which we use for estimations, is acceptable by considering the approximate character of formulas (1)–(4) for gyrosynchrotron radiation. Assuming $d \approx 2 \times 10^8$cm and $l \approx (2.5–5) \times 10^9$cm, we obtain the total area of all elementary sources $S \approx (0.5–1.0) \times 10^{18} N_{\text{loop}}$. Substituting this value in formula (1) for the radio emission flux, we obtain the relationship between the radio emission flux and the number of magnetic loops

$$F_{\nu=8.4} = 228 \pm 11\ \mu Jy \approx 2.28 \times 10^{-27} \text{erg/cm}^2 \text{s Hz}$$
$$= (2.28–5.6) \times 10^{-45} (n_e d) N_{\text{loop}}\ \text{erg/cm}^2\ \text{s Hz}.$$

From here we determine $N_{\text{loop}}(n_e d) \approx (0.5–1.0) \times 10^{18}$ and by considering $n_e d \leq 2 \times 10^{16} \text{cm}^{-2}$, we obtain the number of loops ensuring the required radio emission flux $N_{\text{loop}} \approx 25–50$. Note that 15–30% of the star's surface is covered by sources. The plasma concentration n_e in the elementary sources—magnetic loops can be estimated according to the soft X-ray radiation that accompanies the radio emission of the quiet component by assuming that the source of the X-ray radiation are the magnetic loops filled by hot plasma with temperature $T \approx 10^7$ K. The total volume of the hot plasma that generates soft X-ray radiation is $V \approx \pi d^2 l N_{\text{loop}}/4 \approx (2–8) \times 10^{27}$ cm^3. In this case from the condition $\text{ME} = n^2 V \approx 1.8 \times 10^{48}$ cm^{-3}, we determine concentration n of the thermal plasma in the magnetic loops $n \approx (1.4–3) \times 10^{10}$ cm^{-3}. We determine the concentration of high temperature particles from the condition of the optically thin source at the frequency 8.4 Hz, $n_e d \leq 10^{16} \text{cm}^{-2}$, which gives $n_e \leq 5 \times 10^7$ cm^{-3}.

4. DISCUSSION

As a source generating a slowly varying or quiet component of radio emission from the brown dwarf TVLM 513-46546, we examine the gyrosynchrotron emission from the system of magnetic loops distributed quasi-uniformly over the star's surface. Such a model explains the weak modulation of the flux of the radio emission under the star's rotation and makes it possible to understand the pumping mechanism of magnetic loops by high energy electrons (Zaitsev, 2016). This mechanism is connected with the oscillation of the electric current in the magnetic loop as an equivalent electric circuit. The generation of the electric current is driven by the electromotive force in the loop footpoint appearing due to the interaction of the photosphere convection with the loop's magnetic field. Under the electric current oscillations, the inductive electric field is arised, which accelerates the electrons. The photosphere convection maintains the continuous self-oscillation process (Zaitsev, 2017) ensuring the long-term pumping of the magnetic loop by the high temperature electrons. The estimations presented in (Zaitsev, 2017) show that under currents of 7×10^9 A the self-oscillations are accompanied by the generation of inductive electric fields with an intensity of $E \approx 7 \times 10^{-4}$ V cm^{-1}. In such an electric field the electrons in the loop's scale receive an energy of 0.7–1.5 MeV. In this case the stationary numder density of energetic electrons depends on the ratio between the accelerating field E and the Dreicer field E_D and on the velocity of the particles' diffusion into the loss cone. In our case $E/E_D \approx 0.1$, which gives $n_e \leq 10^8$ cm^{-3}. This does not contradict the estimations presented above according to the radio emission flux. The question arises on why the coherent mechanisms of radiation—electron cyclotron maser and plasma mechanisms—are not implemented in the sources of a slowly changing component. The electron cyclotron maser mechanism is not efficient due to the moderate magnetic field in the loops because the cyclotron frequency is significantly lower than the plasma frequency and the respective increments are lower than the instability threshold. As for the plasma mechanism, the respective radiation cannot fall into the frequency band of the performed observations at VLA. Another reason can be as follows: the loss cone is filled totally due to the energetic electrons' diffusion under Coulomb collisions. As a result the instability increments in the plasma waves become lower than the excitation threshold. This problem should be examined separately.

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