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X-RAY EMISSION FROM UTRACOOL STARS

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We study two possibilities of the origin of quiescent X-ray emission from ultracool stars using the examples of brown dwarfs TVLM 513-46546 and VB 10: (a) radiation from hot coronas and (b) radiation from a system of magnetic loops filled with a sufficiently dense hot plasma heated due to the dissipation of electric currents flowing in the loops. The parameters of the corona, as well as the parameters of the loops and their number, which are necessary for the implementation of the observed X-ray emission measure, have been determined. For the studied brown dwarfs, the generation of X-rays by a set of hot loops is energetically more favorable than in the case of a hot corona, which was also confirmed by the results of the analysis of quiescent microwave radiation from the brown dwarf TVLM 513-46546.

1. INTRODUCTION

One of the important sources of information about stellar coronas is the X-ray emission of a coronal plasma. For the first time, the X-ray emission from the corona of the active dwarf α Cen was recorded in 1977 by the HEAO-1 space observatory in the range 0.2–3.0 keV with the luminosity $L_x \approx 10^{27}$ erg $\cdot$ s$^{(-1)}$, while the radiation level remained virtually invariable for five days of observations [1]. A detailed review of the X-ray emission of stars is presented in [2]. Stars of late spectral classes K (temperature 3500–5000 K), M (brown dwarfs not earlier than subclass M 7, temperature 2000–3500 K), and L (brown dwarfs with a temperature of 1500–2000 K), despite the relatively low surface temperature, are sources of soft X-ray emission. This indicates that such stars may have hot coronas or local magnetic structures like loops filled with hot plasma. A number of characteristics of the X-ray emission of brown dwarfs were obtained using the space X-ray observatories ROSAT (0.1–2.4 keV) [3–6], Chandra (0.1–10.0 keV) [7–14], and space X-ray telescope XMM-Newton (0.1–15.0 keV) [15–17].

Flare processes on a number of M-class stars were also studied in the range 0.016–0.163 keV by the Extreme Ultraviolet Explorer (EUVE), which provided information about the parameters of coronal magnetic loops in the atmospheres of these stars [18, 19]. The analysis of the X-ray emission of the 11 dMe and dM stars closest to us (ROSAT), located at 2.4–11.0 pc away and having masses $M_*/M_\odot \approx 0.08$–0.44 and sizes $R_*/R_\odot \approx 0.1$–0.5, showed [3] that the coronas of these stars consist of two thermal components, namely, a "soft" component with the temperature $T \approx (2$–$4) \cdot 10^6$ K and a "hard" component with the temperature $T \approx 10^7$ K (hereafter the index "$\odot$" denotes the values related to the Sun). Herein, the "hard" component shows a greater instability on time scales of the order of an hour compared to the "soft" component. The authors assume that the fundamental magnetic structure of the coronas of the studied stars of late spectral classes, by analogy with the solar corona, is a system of coronal magnetic loops filled

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with hot plasma and having different pressure and temperature values. In [12, 14], based on the Chandra Observatory data, a quasi-stationary X-ray corona of the brown dwarf VB 10 (M8) with the X-ray luminosity $L_{\mathrm{x}} = (2.4\pm0.46)10^{25}$ erg/s in the range 0.2–1.5 keV was detected. It follows from Chandra/ACIS observations that 50% of the stars not earlier than the M7 subclass are characterized by the ratio between X-ray and bolometric luminosities at the level $L_x/L_{\mathrm{bol}} = 10^{-5}$. For stars of spectral classes M7–M9, $L_{\mathrm{x}}/L_{\mathrm{bol}} \approx 10^{-4}$, while for L dwarfs, $L_{\mathrm{x}}/L_{\mathrm{bol}} \approx 10^{-5}$, and only 15% of the L dwarfs have X-ray emission [20].

The previous ROSAT observations did not detect quasi-stationary coronas of ultracool stars [7] due to the insufficient sensitivity of the X-ray equipment. Based on this, an erroneous conclusion was drawn stating that the relatively low conductivity of the photospheres of ultracool stars prevents the generation of electric currents, the formation of small-scale magnetic structures such as loops, and the occurrence of the corresponding processes of magnetic reconnection and coronal heating. Later, the results of joint radio, X-ray, ultraviolet, and optical observation of the ultracool dwarf TVLM 513-46546 (spectral class M8.5) for 9 h were presented in [13]. The long-term quasi-constant X-ray emission of the dwarf in the range (0.3–2.0) keV corresponded to the temperature $T \approx 10^7$ K and was accompanied by continuous microwave radiation at a frequency of 8.46 GHz, the properties of which corresponded to the gyrosynchrotron mechanism of radio emission [21, 22]. Herein, weak modulation of the radiation flux during the star rotation [21] may witness a quasi-uniform distribution of radiation sources over the star surface. The X-ray radiation of TVLM 513-46546 was also accompanied by emission in the H_α line, which indicated that the chromosphere of the star was heated by internal sources, since the radiation energy in the H_α line was approximately twice the energy of coronal X-rays. In addition, the emission in the H_α line was localized in a region occupying about 50% of the star surface and was modulated with the star rotation period (2 h). Thus, it can be assumed that in this case there is both a uniform distribution of the sources (to which the observed microwave radiation is related) over the star surface and the presence of a local active region generating X-ray and optical radiation.

We study two possibilities of generating quasi-stationary soft X-ray emission, namely, the generation of radiation in hot coronas and in the magnetic loops formed in the corona of a brown dwarf by convective photospheric plasma flows. The parameters of X-ray coronas have been determined. The excitation of electric currents, plasma heating, and generation of X-ray emission inside the loops are also considered. The parameters of the latter and their number that are necessary for provision of the observed X-ray emission measure are determined by the example of brown dwarfs TVLM 513-46546 and VB 10.

2. OBSERVATIONAL CHARACTERISTICS OF BROWN DWARFS TVLM 513-46546 AND VB 10

Further, fully convective low-mass stars TVLMM 513-46546 and VB 10 will be considered as examples, so we present their observational characteristics.

2.1. The star TVLM 513-46546

The ultracool star TVLM 513-46546 of spectral class M8.5V has an effective photospheric temperature $T_{\mathrm{eff}} = 2200$ K, the mass $M_* = 0.07M_\odot = 1.4\cdot10^{32}$ g, and the radius $R_* = 0.1R_\odot \approx 7\cdot10^9$ cm. The free-fall acceleration on the star surface is $g = 2\cdot10^5$ cm $\cdot$ s^{-2}, i. e., approximately an order of magnitude higher than the solar one. The star TVLM 513-46546 is remote from the Earth at the distance $d \approx 10.6$ pc (1 pc $= 3.086\cdot10^{13}$ km) and is characterized by a high rotation speed $v \sin i \approx 60$ km/s (here, v is the rotation speed at the equator and i is the angle between the axis of star rotation and the direction to the observer). Quasi-constant X-ray emission in the range 0.3–2.0 keV corresponded to the source temperature $T \sim 10^7$ K, the observed flux (Chandra ACIS-S3) $F_{\mathrm{x}} \approx 6.3\cdot10^{-16}$ erg$\cdot$cm$^{-2}\cdot$s^{-1}, and the total luminosity at distance d equal to $L_{\mathrm{x}} = 4\pi d^2 F_x \approx 8.5\cdot10^{24}$ erg/s [13]. According to the radio emission data, the magnetic field in the star corona is $B \approx 100$ G [13].

2.2. The star GL752B

The ultracool star GL752B (VB 10) of spectral class M8 has an effective photospheric temperature $T_{\mathrm{eff}} = 2600$ K, the mass $M_* = 0.075 M_\odot \approx 1.5 \cdot 10^{32}$ g, and the radius $R_* \approx 0.1 R_\odot$. The free-fall acceleration on the star surface is $g = 2.1 \cdot 10^5$ cm/s^2. The star is remote from the Earth at the distance $d \approx 6.1$ pc and has a relatively low rotation speed $v \sin i \approx 6.5$ km/s. Bolometric luminosity of the star is $L_{\mathrm{bol}} \approx 10^{-3.34} L_\odot$ and the X-ray luminosity outside the flares is $L_{\mathrm{x}} \approx 10^{-5} L_{\mathrm{bol}}$. The magnetic field on the star surface $B \approx 1.3$ kG [14]. Spectral analysis of quasi-constant X-ray emission in the range 0.3–2.0 keV indicates a source temperature $T_1 \approx 3.5 \cdot 10^6$ K and the possible presence of a second component with the temperature $T_2 \approx 1.5 \cdot 10^7$ K. The X-ray current in this case is $F_{\mathrm{x}} \approx 3.7 \cdot 10^{-15}$ erg $\cdot$ cm$^{-2} \cdot$ s^{-1} and corresponds to the total luminosity $L_{\mathrm{x}} = 4\pi d^2 F_x \approx 1.5 \cdot 10^{25}$ erg/s [14].

The difference between the most brown dwarfs and other stars of late spectral classes is their relatively intense radio emission. While for stars of subclasses not earlier than M7, the ratio of luminosities in the X-ray and radio ranges is $L_{\mathrm{x}}/L_{\mathrm{R}} = 10^{15}$–$10^{16}$ Hz, for stars of subclasses later than M7, we have $L_{\mathrm{x}}/L_{\mathrm{R}} = 10^{11}$–$10^{12}$ Hz [13]. Herein, the $L_{\mathrm{x}}/L_{\mathrm{R}}$ ratio for VB 10 is an order of magnitude greater than for stars of classes M8.5 TVLM 513-46546 and LSR 1835+32 [14], which is due apparently to the low rotation speed of the star. It was shown in [14] that the $L_{\mathrm{x}}/L_{\mathrm{R}}$ ratio decreases with increasing star rotation speed. It is also noted that the magnetic activity of VB 10 is similar to the activity of the classes M0–M6 stars and notably differs from the activity of TVLM 513-46546 [14].

3. HOT CORONA AS A POSSIBLE SOURCE OF QUASI-STATIONARY X-RAY RADIATION OF BROWN DWARFS

Consider the quiescent X-ray emission of brown dwarfs assuming that this radiation is generated due to the hot corona of a star.

3.1. Parameters of X-ray coronas

If a corona with temperature T is the source of quiescent X-ray radiation of a brown dwarf, then the effective radiating volume has an order of magnitude

$$V \approx 4\pi R_*^2 H, \tag{1}$$

where

$$H = \frac{k_{\mathrm{B}} T R_*^2}{m_{\mathrm{i}} G M_*} \tag{2}$$

is the altitude scale of the inhomogeneous corona, which corresponds to the temperature T, k_{B} is the Boltzmann constant, m_{i} is the ion mass, and $G = 6.67 \cdot 10^{-8}$ cm$^3 \cdot$ g$^{-1} \cdot$ s^{-2} is the gravitational constant. If the average density of electrons (ions) in volume V is equal to $\bar{n}$, then the luminosity of the corona in the X-ray emission [3] is

$$L_{\mathrm{x}} = P(T) \bar{n}^2 V, \tag{3}$$

where

$$P[\mathrm{erg} \cdot \mathrm{cm}^3/\mathrm{s}] = 2 \cdot 10^{-27} \sqrt{T}[K] + 5 \cdot 10^{-25} \exp \sqrt{2.8 + 10^6/T[K]}. \tag{4}$$

Equations (1)–(4) make it possible to estimate the volume of the emitting coronas and the average particle density in the coronas according to the observed luminosity in the X-ray emission and coronal temperature. For the brown dwarf TVLM 513-46546, estimates give the emitting corona volume $V \approx 2.5 \cdot 10^{30}$ cm^3, the altitude scale $H \approx 4 \cdot 10^9$ cm, and the average plasma density in the corona $\bar{n} \approx 6 \cdot 10^8$ cm^{-3}. We obtain $V \approx 8.4 \cdot 10^{29}$ cm^3, $H \approx 1.4 \cdot 10^9$ cm, and $\bar{n} \approx 1.7 \cdot 10^9$ cm^{-3} for the brown dwarf VB, respectively. It can be seen that the emitting corona of VB 10 is more compact and dense, which, with almost identical masses and radii of both objects, is related to a less hot and less extended corona and a greater X-ray luminosity of the star VB 10 compared to the star TVLM 513-46546 [12, 13].

3.2. The problem of heating X-ray coronas

The problem of heating the X-ray coronas of brown dwarfs is in a sense more difficult than the problem of heating the solar corona. The fact is that due to the hot corona, the energy losses related to the thermal conductivity notably increase in the brown dwarfs considered. For example, for the star TVLM 513-46546, the radiation losses are $Q_{\mathrm{r}} \approx 3 \cdot 10^{25}$ erg/s, whereas the energy losses of the corona related to the thermal conductivity are of the order of $Q_T \approx 0.92 \cdot 10^{-6} T^{7/2} V H^{-2} \approx 4 \cdot 10^{29}$ erg/s, which significantly exceeds similar losses from the solar corona, $Q_{T\odot} \approx 10^{28}$ erg/s. This means that in order to maintain a quasi-stationary corona of the brown dwarf TVLM 513-46546, more powerful heating sources than for the Sun are required. This conclusion is also valid for the star VB 10.

There are different approaches to solving the problem of coronal heating: wave heating [23], heating due to the dissipation of electric currents [24, 25], heating by microflares [26], heating due to parametric resonance [27], and heating of the corona by heat currents from open magnetic flux tubes (class II spicules) [28]. In the latter case, the plasma inside the flux tubes is heated to a temperature of about 10^7 K by electric currents generated by an electromotive force that arises as a result of interaction of photospheric convection with the magnetic field of the flux tubes. In this case, it is possible to estimate the number of spicules needed to compensate for losses related to the thermal conductivity and maintain the X-ray corona in a quasi-stationary state. Assuming that the main role is played by the electron thermal conductivity along the magnetic field of the spicule with the thermal conductivity coefficient $\kappa_{\parallel}^{e}$, the heat current from the spicule to the corona can be estimated according to the equation

$$Q_{T_{\mathrm{sp}}}[\mathrm{erg/s}] = \kappa_{\parallel}^{e} \frac{\Delta T}{\Delta z} \pi r_0^2 \approx \frac{0.9 \cdot 10^{-6} T[K]^{7/2}}{\Delta z[\mathrm{cm}]} \pi (r_0^2[\mathrm{cm}])^2. \tag{5}$$

Here, r_0 is the magnetic flux tube radius, which can be represented by the size of the granulation cell $D \approx 10^7$ cm for M8.5 stars [29]. Then for $T = 10^7$ K, $r_0 = 10^7$ cm, and $\Delta z = 10^9$ cm we obtain $Q_{T\mathrm{sp}} \approx 10^{24}\ \mathrm{erg\,s^{-1}}$. Therefore, to compensate for radiation losses and thermal conductivity losses from the corona of the brown dwarf TVLM 513-46546, approximately $4 \cdot 10^5$ hot spicules are required, the total area of the bases of which ($1.3 \cdot 10^{20}$ cm^2) is about the surface area of the star ($6.2 \cdot 10^{20}$ cm^2). This is significantly different from the Sun, where spicules occupy about 1% of the surface. For the star VB 10, the required area of 10^6 spicules is also about 50% of the star surface. With allowance for such a striking difference from the situation on the Sun, we consider the option related to the possible contribution of hot magnetic loops to the observed X-ray emission measure of brown dwarfs.

4. MAGNETIC LOOPS AS A POSSIBLE SOURCE OF X-RAY EMISSION

The possibility of the existence of a system of coronal magnetic loops with an electric current generated by photospheric convection in the active regions of ultracool stars is considered in [22]. Using the example of the brown dwarf TVLM 513-46546, the parameters of magnetic loops, the magnitude of electric currents generated by stellar convection and the efficiency of plasma heating inside the loops were determined. We will exploit the main results of this paper to assess whether magnetic loops can be the source of the observed X-ray emission of brown dwarfs.

The transfer of energy from the center to the surface of the star in the case of brown dwarfs is related to convection. At the photospheric levels, the convection velocity for stars of late spectral classes varies from 10^4 cm/s [30] to $1.4 \cdot 10^5$ cm/s [31], according to different estimates. The size of granulation cells for M8.5 stars approximately coincides with the size of supergranulation cells and is $D \approx 1.4 \cdot 10^7$ cm [29]. Estimates show that the half-thickness of the magnetic loops at the photospheric convection velocity $V \approx 10^4$–10^5 cm/s is of the order of the granulation cell size $r_1 \approx D \approx 10^6$–$10^7$ cm. The interaction of the radial component of the photospheric convection velocity with the azimuthal component of the magnetic field of the loop leads to the appearance of an electromotive force and causes the generation of an electric current flowing from one base of the loop through the coronal part to another base and closing in dense layers of the lower atmosphere, forming a closed electric circuit [32]. The electromotive force is concentrated in the photospheric base of the loop and has a magnitude of the order of

$$\Xi = \frac{l_1}{\pi c r_1^2} \int\limits_0^{r_1} V_r B_\varphi 2\pi r \, \mathrm{d}r \approx \frac{|\bar{V}_r| \, I l_1}{c^2 r_1}, \tag{6}$$

where l_1 is the height of the section of the electric circuit in the area of action of the photospheric electromotive force, V_r is the radial component of the photospheric convection velocity in the local cylindrical coordinate system (r, φ, z) with the z axis along the axis of the loop, I is the electric current flowing along the magnetic loop through its cross section, and $B_\varphi \approx 2I/(cr_1)$ is the magnetic-field azimuthal component generated by the longitudinal current. Estimates show that the main contribution to the resistance of the circuit is made by the region of action of the photospheric electromotive force, where, due to the large concentration of neutral atoms and the influence of the magnetic field, the Cowling conductivity stipulated by ion–atomic collisions plays a crucial role. The value of the resistance is determined by the equation [32]

$$R(I) \approx \frac{1.5 l_1 I^2 F_1^2}{\pi r_1^4 c^4 n_\mathrm{e} m_\mathrm{i} \nu'_\mathrm{ia} (2 - F_1)}, \tag{7}$$

where n_e is the electron number density, ν'_ia is the effective frequency of collisions of ions with neutral atoms, and $F_1 = n_\mathrm{a}/(n_\mathrm{e} + n_\mathrm{a})$ is the relative concentration of neutral atoms. The dependence of the resistance on the magnitude of the electric current is related in this case to the prevailing contribution to the total resistance of the Cowling conductivity, which, in turn, depends on the azimuthal component of the magnetic field of the loop [33]. The stationary value of the current in the magnetic loop is determined from the condition $R(I)I = \Xi(I)$, from where at $l_1 \approx r_1$ we obtain (in CGS units) [19]

$$I \approx 0.8[|V_r| \, \pi r_1^3 c^2 n_\mathrm{e} m_\mathrm{i} \nu'_\mathrm{ia} (2 - F_1) F_1^{-2}]^{1/2}. \tag{8}$$

Effective frequency of collisions of ions with neutral atoms

$$\nu'_\mathrm{ia}[Hz] \approx 1.6 \cdot 10^{-11} F_1 (n_\mathrm{e} + n_\mathrm{a}) \sqrt{T}[E], \tag{9}$$

In the region of action of the photospheric electromotive force ($\Delta z \approx l_1$), the Joule heating power is less than the loss due to optical radiation because of the high density of the material; therefore, there is no notable plasma heating and an increase in the degree of ionization compared to photospheric conditions. In this case, in Eq. (8), the relative density of neutral atoms can be considered equal to unity ($F_1 \approx 1$). For the considered brown dwarfs in the altitude range $\Delta z \approx l_1$ the following parameter values are valid: $n_\mathrm{a} \approx 5 \cdot 10^{16}$–$10^{17}$ cm^{-3}, $n_\mathrm{e} \approx 5 \cdot 10^{9}$–$10^{10}$ cm^{-3}, and $T \approx 2200$ K. In this case, for the possible range of photospheric convection velocities $V \approx 10^4$–10^5 cm/s and the magnetic flux tube radius $r_1 \approx 10^6$–10^7 cm in the region of the photospheric electromotive force, we obtain the following estimates of the electric current: $I = 2 \cdot 10^{18}$–$2 \cdot 10^{20}$ CGS units $\approx 7 \cdot 10^8$–$7 \cdot 10^{10}$ A. Thus, electric currents in magnetic loops can reach fairly high values, which admits the formation of a hot plasma in the loops and the X-ray generation.

Consider the heating of the coronal part of magnetic loops in the atmospheres of brown dwarfs. At the coronal levels for an optically thin medium at temperatures $T > 2 \cdot 10^5$ K, hydrogen gives the main contribution to the neutral component, while the relative content of neutral atoms is determined by the equation [34, 35]

$$F = 0.32 \cdot 10^{-3} \frac{1 + T/(6T_\mathrm{H})}{\left|\frac{\bar{T}}{T_1}\right|^{2-b} \left|1 + \frac{\bar{T}}{T_1}\right|^{1+b} \sqrt{T}[K]} \exp \frac{T_\mathrm{H}}{T}, \tag{10}$$

where $T_{\mathrm{H}} = 1.58 \cdot 10^5$ K, $T_1 = 7.036 \cdot 10^5$ K, and $b = 0.748$. In the temperature range 10^6–10^7 K of interest to us, the following approximation is valid to within a few percent:

$$F \approx \frac{0.15}{T[K]}. \tag{11}$$

The rate of Joule current dissipation per unit volume of the loop, with allowance for (11), is determined by the equation [32]

$$q_J[\mathrm{erg} \cdot \mathrm{cm}^{-3} \cdot \mathrm{s}^{-1}] = \frac{j_z^2}{\sigma} + \frac{F^2 B_\varphi^2 j_z^2}{(2-F)c^2 n_{\mathrm{e}} m_{\mathrm{i}} \nu'_{\mathrm{ia}}} \approx 2.2 \cdot 10^{-9} \frac{I^4}{n^2 r_1^6 T^{3/2}}, \tag{12}$$

where all physical quantities on the right-hand side are given in CGS units.

In the coronal part of the loop, the second term in Eq. (12) gives the main contribution to the current dissipation. Despite the relatively low concentration of neutral atoms, $F \ll 1$, an effective dissipation channel related to the Cowling conductivity is switched on. This is due to a decrease in the effective conductivity of the plasma

$$\sigma_{\mathrm{eff}} = \frac{\sigma}{1 + \dfrac{F^2 \omega_{\mathrm{e}} \omega_{\mathrm{i}}}{(2-F)\nu'_{\mathrm{e}} \nu'_{\mathrm{ia}}}}, \tag{13}$$

since under the corona conditions, the last term in the denominator of Eq. (13) is much greater than unity (here, ω_{e} and ω_{i} are the gyrofrequencies of electrons and ions, respectively). In other words, the presence of a small number of neutral atoms can significantly reduce the effective conductivity compared to the classical Spitzer conductivity and thereby increase the efficiency of current dissipation.

The heating of the magnetic loop is determined by the balance of Joule dissipation, thermal conductivity, and radiation losses from the plasma. In the temperature range $10^5 < T[K] \leq 2 \cdot 10^7$, the approximate expression [36] is valid as the radiation loss function

$$q_{\mathrm{r}} \approx \chi_0 n_{\mathrm{e}}^2 T^{-1/2}, \qquad \chi_0 = 10^{-19}. \tag{14}$$

We assume that the height of the loops is less than the reduced altitude of the nonuniform atmosphere at plasma temperatures resulting from the analysis of the soft X-ray emission spectra of brown dwarfs. In this case, the plasma density can be expressed in terms of pressure and temperature, $n_{\mathrm{e}} = p/(2k_{\mathrm{B}}T)$. This assumption limits the length of the loops: $l < \pi H \cong 1.3 \cdot 10^{10}$ cm in the case of the brown dwarf TVLM 513-46546 and $l < 4.4 \cdot 10^9$ cm in the case of the brown dwarf VB 10. In the first case, the length of the loops can be comparable to the radius of the star, while in the second case the length of the loops is several times less. Taking into account the assumption made and Eqs. (12) and (14), we write the heat balance equation for a stationary magnetic loop as follows:

$$\frac{\mathrm{d}}{\mathrm{d}s} \kappa_{\mathrm{e}} T^{5/2} \frac{\mathrm{d}T}{\mathrm{d}s} = q_{\mathrm{r}} - q_J. \tag{15}$$

Here, s is the coordinate along the loop, $\kappa_{\mathrm{e}} = 0.92 \cdot 10^{-6}$, $q_{\mathrm{r}} = [\chi_0 p^2/(4k_{\mathrm{B}}^2)]T^{-5/2}$, and $q_J = 10^{-8} k_{\mathrm{B}}^2 I^4 T^{1/2}/(p^2 r_1^6)$. Equation (15) can be solved using the following boundary conditions at the base ($s = 0$) and at the top ($s = l/2$) of the magnetic loop: $T = T_0$ and $\mathrm{d}T/\mathrm{d}s = 0$ for $s = 0$, and $T = T_1$ and $\mathrm{d}T/\mathrm{d}s = 0$ for $s = l/2$. It is assumed that the temperature at the top is much higher than at the base of the loop ($T_1 \gg T_0$). The analysis of Eq. (15) makes it possible to determine the distribution of temperature and density along the loop. The values of temperature T_1 and plasma density n_1 at the top of the loop are determined by the equations (in CGS units)

$$T_1[K] \approx 2 \cdot 10^{-2} \frac{(IL)^{4/9}}{r_1^{2/3}}, \qquad n_1[ni^{-3}] = \frac{1}{3}\left(\frac{2\kappa_{\mathrm{e}}}{\chi_0}\right)^{1/2} \frac{T_1^2}{L}, \qquad L = \frac{l}{2}. \tag{16}$$

The temperature at the top of the loop is maximum and the density is minimum. Both values vary only slightly over most of the length of the loop, except for the bases near which the values quickly reach equilibrium values.

As an example, we determine the number of hot loops in the corona of the brown dwarf TVLM 513-46546, which can provide an observable X-ray emission measure. The spectrum of quiescent X-ray emission indicates the plasma temperature inside the loops, $T_1 \approx 10^7$ K. The assumption that at a given temperature the height of the loops does not exceed the reduced scale of the corona altitude imposes a constraint on the loop length: $L = l/2 \leq 6.5 \cdot 10^9$ cm. By analogy with the solar corona, we assume that the thickness of the magnetic loops with current almost does not change with the altitude and coincides with the thickness in the region of action of the photospheric electromotive force, i. e., $r_1 \approx 10^7$ cm. Then from Eqs. (16) we obtain the electric current required to heat the plasma inside the loop to the above-mentioned temperature, $I = 1.8 \cdot 10^{20}$ CGSunits $= 6 \cdot 10^{10}\ A$, as well as the plasma density $n_1 \approx 2.2 \cdot 10^{10}$ cm^{-3} and the radiation measure of an individual loop $EM_{\text{loop}} \approx 2 \cdot 10^{45}$ cm^{-3}. It can be seen that in order to provide a complete observable X-ray emission measure, it is necessary to have $N_{\text{loop}} = EM_*/(EM_{\text{loop}}) \approx 4.5 \cdot 10^2$ hot loops in the corona of a brown dwarf, where EM_* is the measure of X-ray emission of a brown dwarf. For the brown dwarf VB 10 at $r_1 \approx 10^7$ cm, $L \leq 2.2 \cdot 10^9$ cm, and $T_1 \approx 3.5 \cdot 10^6$ K we obtain $I = 1.7 \cdot 10^{10}\ A$, $n_1 \approx 8 \cdot 10^9\ cm^{-3}$, and $N_{\text{loop}} \approx 2.8 \cdot 10^4$, respectively. In the latter case, the necessary radiation measure is provided by a larger number of loops, which is related to a decrease in their length and plasma density.

5. DISCUSSION

We consider two possible origins of the quiescent X-ray emission of brown dwarfs TVLM 513-46546 and VB 10. The first is the radiation of hot quasi-homogeneous coronas with temperatures of 10^7 and $3.5 \cdot 10^6$ K, respectively. The second is the radiation of a system of magnetic loops filled with a sufficiently dense hot plasma heated due to the Joule dissipation of electric currents flowing in the loops. Electric currents in the loops are supported by an electromotive force resulting from interaction between the flows of a weakly ionized convective photospheric plasma and the magnetic field of the loops. Generation of X-ray radiation by a system of hot magnetic loops is, in our opinion, an energetically more favorable option compared to the case of a homogeneous hot corona, since the energy requirements of the heating source are significantly reduced. Indeed, when the magnetic loops are heated, the source should compensate only for the optical and X-ray emission losses, which are about $8.5 \cdot 10^{24}$ and $1.5 \cdot 10^{25}$ erg s^{-1} for the stars TVLM 513-46546 and VB 10, respectively, while when the entire corona is heated the source should also compensate for the losses related to the heat escape from the corona as a result of thermal conductivity, which are $3 \cdot 10^{28}$–$4 \cdot 10^{29}$ erg/s and exceed the radiation losses by several orders of magnitude.

The constant X-ray emission of the brown dwarf TVLM5B-46546 is also accompanied by microwave radiation, which shows stability on a time scale of several years [13]. The spectral characteristics of the microwave radiation studied using the VLA system at wavelengths of 3.6, 6.0, and 20.0 cm [21] indicate that the gyrosynchrotron radiation mechanism takes place in the brown dwarf corona. The model of a gyrosynchrotron radiation source in the form of a system of coronal magnetic loops with magnetic fields of the order of 10^2 G and subrelativistic electrons with energies of 0.7–1.5 MeV can provide the observed radiation flux 228 μJy at the frequency $\nu = 8.4$ GHz, assuming the presence of 25–50 loops with the thickness $d = 2 \cdot 10^8$ cm and a length of $5 \cdot 10^9$ cm [22]. If the thickness of the magnetic loops is of the order of the size of the granulation cells, i. e., $d = 10^7$ cm, which seems more likely, then $4 \cdot 10^2$ loops are required to explain the observed microwave radiation flux, which coincides with the number of loops needed to explain the observed luminosity in the soft X-ray emission of the brown dwarf TVLM 513-46546. This circumstance suggests that the constant X-ray and constant microwave radiation of TVLM 513-46546 have a common source — a system of coronal magnetic loops with a total number $N_{\text{loop}} \approx (4.0\text{–}4.5) \cdot 10^2$, which are filled with a hot plasma having a temperature of about 10^7 K and subrelativistic particles.

Thus, the existence of hot coronas with the temperature $T \approx 10^6$–10^7 K in brown dwarfs TVLM 513-46546 and VB 10 seems to us less likely than the existence of hot X-ray loops. We have shown that the source of thermal X-ray emission is coronal magnetic loops, the plasma of which is heated to the temperature $T \approx 10^7$ K due to the dissipation of electric currents flowing in the loops generated by the convection of the star matter. In this case, hot loops cannot be the source of corona heating, since the thermal conductivity across the magnetic field is a factor of $(\omega_\mathrm{i}\tau_\mathrm{i})^2 \approx 10^{10}$ less than along the field [28]. Here, $\omega_\mathrm{i} \approx 10^6$ s^{-1} is the gyrofrequency of ions in the magnetic field $B = 100$ G, $\tau_\mathrm{i} \approx T^{3/2}/n \approx 0.1$ s is the ion collision time (n is the plasma density in the corona). On the other hand, according to the star radio emission data, there is evidence that red dwarfs have hot coronas with $T \approx 10^7$ K (stars no later than subclass M6) [37, 38]. The mechanisms of heating the coronas of red dwarfs, whose X-ray luminosity is one or two orders of magnitude greater than the X-ray luminosity of brown dwarfs, require special research.

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