ORIGIN OF THE BLUE CONTINUUM RADIATION IN THE FLARE SPECTRA OF dMe STARS

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Calculations of the emission spectrum of a homogeneous plane layer of pure hydrogen plasma taking into account nonlinear effects (the influence of bremsstrahlung and recombination radiation of the layer itself on its Menzel factors) \(^9\) show that the blue component of the optical continuum during the impulsive phase of large flares on dMe stars originates from the near-photospheric layers \(^1\). The gas behind the front of a stationary radiative shock wave propagating in the red dwarf chromosphere toward the photosphere is not capable of generating the blackbody radiation observed at the maximum brightness of the flares.

Keywords: red dwarf stars: flares: models of flares: plane layer: impulsive heating

1. Introduction. Grinin and Sobolev \(^1\) were the first to show that the optical continuum emission during the impulsive phase of large flares on dMe stars arises in the “transition region between the chromosphere and the photosphere.” The near-photospheric layers are heated by beams of high-energy (\(\approx 10\) MeV) protons \(^2\) or/and (\(\approx 100\) keV) electrons \(^4\). The initial energy fluxes (“at the upper boundary of the flare region” \(^2\)) in the proton and electron beams are \(F_0 \approx 10^{11} - 10^{12}\) erg cm\(^{-2}\) s\(^{-1}\) and \(F_0 \approx 3 \cdot 10^{11}\) erg cm\(^{-2}\) s\(^{-1}\), respectively.

Katsova et al. \(^5\) and Livshits et al. \(^6\) were the first to examine the hydrodynamic response of the chromosphere of a red dwarf to impulsive heating by a high-power beam of accelerated electrons (a low-energy cutoff \(E_1 = 10\) keV, a spectral index \(\gamma = 3\), \(F_0 = 10^{12}\) erg cm\(^{-2}\) s\(^{-1}\)). In solving a single-temperature \(^3\) system of gas dynamics equations “with the given boundary and initial conditions and the calculated loss and heating functions“ \(^5\), they found that two disturbances “propagate downward and upward“ \(^5\) “from the formed zone of high pressure“ \(^6\). The disturbance propagating toward the photosphere (“downward“ \(^5\)) “is described in subsequent times by a solution of the type of the second-kind temperature wave \(^7\).“ “The latter is characterized by a subsonic-velocity propagation of the thermal wave [temperature jump]“ \(^6\), “in front of which a [non-stationary] shock wave ...“ develops \(^5\).

In these papers \(^5\) it was assumed that a region of thickness \(\Delta z \approx 10\) km between the temperature jump and the shock front (referred to below as a chromospheric condensation)

\(^1\)The brief version of this article has been published in the Proceedings of the conference in honor of the 100th birthday of Academician V. V. Sobolev (St. Petersburg, September 21–25, 2015), pp. 219–221.

\(^2\)In the part examining the nature of the optical continuum of stellar flares, the study \(^6\) gives a brief discussion of work of Katsova et al. \(^5\).

\(^3\)\(T_e = T_i\), where \(T_e\) is the electron temperature and \(T_i\) is the ion one.
is the source of quasi-blackbody radiation at wavelengths around 4500 Å (see Fig. 4 in [5] and identical Fig. 8 in [6]). Katsova et al. [5] and Livshits et al. [6] note (pp. 162—163 in [5] and p. 281 in [6]) that the physical parameters of the chromospheric condensation ($N_H \approx 2 \cdot 10^{15}$ cm$^{-3}$, $T_e = T_{ai} = T \approx 9000$ K, where $T_{ai}$ is the atom-ion temperature) are in the range of the parameters of a plane layer in the model of Grinin and Sobolev [1] ($N_H \sim 10^{15} - 10^{17}$ cm$^{-3}$, $T \sim 5000 - 20000$ K, $\Delta z \sim 10^6 - 10^8$ cm). Here $N_H$ is equal to the sum of the hydrogen atom and proton concentrations. The chromospheric condensation [5], however, lies at a height of $\approx 1500$ km [5, 6] above the level of the quiescent photosphere of a red dwarf, i.e., much higher than the homogeneous plane layer [1].

The non-stationary shock wave [5] propagates in the partially ionized gas of the chromosphere of a red dwarf toward the photosphere at a velocity of up to $\sim 100$ km/s (see Eqs. (A1), (A2) and Fig. 7 in [6]). The electron and atom-ion components of the chromospheric plasma are heated differently behind the shock front [5] i.e., it is true that the atom-ion temperature of the post-shock gas [5] is considerably higher than its electron temperature:

$$T_{ai} \gg T_e$$  \hspace{1cm} (1)

(with the exception of the dense layers near the photosphere [1]). As a result, the region between the temperature jump and the shock front [5] is, in fact, a two-temperature region.

In [9] the emission spectrum of a two-temperature ($6$ eV $\leq T_{ai} \leq 12$ eV, $0.8$ eV $\leq T_e \leq 1.5$ eV) motionless homogeneous plane layer of pure hydrogen plasma ($3 \cdot 10^{14}$ cm$^{-3} \leq N_H \leq 3 \cdot 10^{16}$ cm$^{-3}$) has been calculated taking into account the influence of bremsstrahlung and recombination radiation of the layer itself on its Menzel factors. This layer is located behind the front of a stationary plane-parallel radiative shock wave (we use a frame of reference in which the shock front is at rest). In [9] the value of $N_H$ at which the intensity of the continuum spectrum approaches the Planck function was determined.

From the start we have assumed that the optical depth in the resonance transition in the center of the layer, $\tau_{12}^D$, is approximately equal to $10^7$. The corresponding layer thickness, $\mathcal{L}$, was introduced according to this condition (p. 2 and Eq. (53) in [9]). The transition from a transparent gas to a gas whose continuum emission is close to the Planck function was, however, subsequently examined for the layer of a fixed thickness $\mathcal{L}$ (see the first paragraph in section 7 in [9]). We have also assumed (the last paragraph in section 8) that radiative cooling of the partially ionized gas heated at the front of a stationary shock wave can create a zone that is responsible for the blue component of the optical continuum of stellar flares.

The present paper shows that the blackbody radiation observed at the maximum brightness of strong flares on dMe stars (the blue component of the optical continuum) originates from the deep (near-photospheric) layers [1]. Various approaches for explaining the spectral

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4 The velocities of the flow are subsonic for electrons, but supersonic for the ions and atoms [8].
observations are analyzed for this purpose: the model of Grinin and Sobolev [1], the model of a second-kind temperature wave [5, 6], and the model of a plane-parallel radiative shock wave propagating with a constant velocity in the red dwarf chromosphere toward the photosphere.

2. Continuous spectrum. We will show that the calculated intensities of continuous radiation from two- [9] and single-temperature [1] homogeneous plane layers are similar if:

(a) the electron temperature lies in the range $0.8 \text{ eV} \leq T_e \leq 1.5 \text{ eV}$, and

(b) the optical depth at a resonance transition is

$$\tau_{12}^D = \frac{k_{12}^D L}{2} \sim 10^7$$

or more. Here $k_{12}^D$ is the absorption coefficient at the center of the Doppler core of the $L_\alpha$ line (the value of $k_{12}^D$ is defined by Eq. (53) in [9]).

Since $\tau_{12}^D \gg 1$, photons leave the plasma in the far wings of the spectral line (p. 6 in [9]). For this reason the mean escape probability, $\theta_{12}$, for a photon of the resonance transition is independent of the atom-ion temperature of the gas:

$$\theta_{12} \approx \left( \frac{B_{21} \mathcal{E}_0}{\Delta \omega_{21}^D} \right)^{3/5} \left( \tau_{12}^D \right)^{3/5}, \quad \tau_{12}^D \propto \frac{1}{\sqrt{\pi \Delta \omega_{21}^D}} \propto T_{ai}^{-1/2}$$

(see Eqs. (55), (53), and (43) in [9]). Here $B_{21}$ is the corresponding Stark broadening parameter, $\mathcal{E}_0$ is the Holtsmark field strength, and $\Delta \omega_{21}^D$ is the Doppler half-width. Thus, the Menzel factors and, therefore, the intensity of the continuous radiation from the layer [9] do not explicitly depend on the atom-ion temperature.

Solution of the balance equations for the populations of the levels shows [9] that the Menzel factors differ little from unity so that the source function $S_\nu \approx B_\nu(T_e)$. This result remains true when $T_{ai} = T_e = T$. Grinin and Sobolev [1] begin with the assumption of thermodynamic equilibrium in the dense gas of a stellar flare: $S_\nu = B_\nu(T)$ (Eq. (9) in [1]).

Taking into account that the Gaunt factors for bremsstrahlung and photoionization absorption in the optical range are on the order of unity (e.g., [10], pp. 16–18) and that the number $k_{max}$ of attainable atomic levels is high, we find that the radiation intensities calculated using Eq. (25) in [9] and Eq. (9) in [1] are close, with

$$I_\nu \approx B_\nu(T) \cdot (1 - e^{-\tau_\nu}),$$

where

$$\tau_\nu = \chi^{(b)}_\nu \mathcal{L} \left[ 1 + \frac{2Ry}{T} \sum_{j=k}^{k_{max}} e^{\beta_j} \right], \quad \beta_j \equiv \frac{Ry}{j^2T},$$

5A weak dependence of the Menzel factors on $T_{ai}$ is caused by the parameter $b_{kn'}$ in Eq. (56) of study [9].

6For an electron density $N_e \approx 10^{15} \text{ cm}^{-3}$, the number of the level defining the boundary of the visible continuum is 13 (the Inglis-Teller relation).
Figure 1. The emission spectrum of a homogeneous plane layer of thickness $L = 10$ km [9] for $T_{ai} = T_e = T$. The dashed curves correspond to 0.8 eV and the smooth curves, to 1 eV. The Roman numerals correspond in increasing order to $N_H = 2 \cdot 10^{15} \text{ cm}^{-3}$, $N_H = 7 \cdot 10^{15} \text{ cm}^{-3}$, and $N_H = 3 \cdot 10^{16} \text{ cm}^{-3}$.

$\kappa_{\nu}^{(b)}$ is the bremsstrahlung absorption coefficient (see Eq. (29a) in [9]). The sum is taken over all levels for which the threshold photoionization frequency $\nu_j \leq \beta_k T/h$; then $h \nu \geq \beta_k T$.

Katsova et al. [5] and Livshits et al. [6] give the following physical parameters of the source of quasi-blackbody radiation at wavelengths around 4500 Å: $\Delta z \approx 10$ km, $N_H \approx 2 \cdot 10^{15} \text{ cm}^{-3}$, $T \approx 9000$ K $\sim$ 0.8 eV. It is easy to see that the corresponding single-temperature ($T_{ai} = T_e$) homogeneous plane layer cannot generate the small Balmer jump (the bottom curve of Fig. 1). Evidently, this layer also cannot explain the blue continuum radiation observed at the maximum brightness of strong flares, since the gas inside the layer [5] is transparent in the continuous spectrum (the optical depth at wavelength $\lambda = 4170$ Å is $\tau_{4170} \sim 0.02 \ll 1$ [9]).

On the other hand, emission from a denser gas with the same layer thickness can explain well both the observed color indices of strong flares and the small size of the Balmer jump [1].

In order to verify these statements, let us calculate the value of $\tau_{4500}$ for a homogeneous plane layer with $S_\lambda = B_\lambda(T)$. Table 1 shows the results. The equilibrium electron concentration, $N_{e}^{\text{eq}}$, is calculated according to the Saha equation. The values of $k_{\text{max}}$ and $\tau_{4500}$ are obtained from Eq. (12) in [9] and Eq. (5) of the present article, respectively. From this table,

It is evident that the exponent “-39” in Eq. (4) of study [1] should read “-39,” and the temperature $T$ should be raised to a power of “-1/2.”

Here, as in [5] [6], we use the model of a homogeneous plane layer to calculate the radiation intensity from the chromospheric condensation [5]. The validity of such approach is not discussed in this paper.
Table 1. Physical parameters of the plasma inside the layer with $S_\lambda = B_\lambda(T)$

| $N_H$, cm$^{-3}$ | $T$, K | $L$, km | $N_e^{eq}$, cm$^{-3}$ | $k_{max}$ | $\tau_{4500}$ |
|-----------------|--------|--------|---------------------|------|----------|
| $10^{15}$       | 9000   | 10     | $1.99 \cdot 10^{14}$| 16   | $2.2 \cdot 10^{-2}$ |
| $2 \cdot 10^{15}$ | 9000   | 10     | $2.91 \cdot 10^{14}$| 15   | $4.7 \cdot 10^{-2}$ |
| $10^{16}$       | 9000   | 10     | $6.8 \cdot 10^{14}$ | 14   | 0.255    |
| $10^{17}$       | 9000   | 10     | $2.2 \cdot 10^{15}$ | 12   | 2.65     |

it follows that the layer with $N_H = 2 \cdot 10^{15}$ cm$^{-3}$, $T = 9000$ K generates the blackbody-like continuum in the blue-visible region of the spectrum at $L \gtrsim 215$ km$^2$.

In the model [5] the formation of the chromospheric condensation with the necessary thickness $\Delta z \approx 10$ km occurs only when the shock front enough widely separates from the temperature jump (see Fig. 8 in [6]). At earlier times the geometric thickness of the gas layer [5] $\Delta z < 10$ km, since the temperature jump moves at a subsonic velocity. The plane layer with a smaller thickness $L$ is still more transparent in the optical continuum.

We note that for the layer with $T = 0.8$ eV and $L = 10$ km, a comparatively small Balmer jump can be obtained only for a near-photospheric concentration $N_H = 3 \cdot 10^{16}$ cm$^{-3}$ (see the lower curve labeled III in Fig. 1). A slight increase in temperature ($T = 1$ eV) leads to a reduction in the required concentration (see the top curve for $N_H = 7 \cdot 10^{15}$ cm$^{-3}$).

The homogeneous plane layer with $N_H = 3 \cdot 10^{16}$ cm$^{-3}$, $T = 1$ eV, and $L = 10$ km provides the blue continuum radiation from a stellar flare (the top curve in Fig. 1). Fig. 2 also demonstrates that for $T = 1.2$ eV, $N_H = 3 \cdot 10^{16}$ cm$^{-3}$, and the layer thickness $L = 20$ km, the emission lines are entirely “sunk” in the continuous spectrum. These concentrations, temperatures, and thicknesses of the blackbody radiation sources lie within the range of parameters for a pure hydrogen plasma layer in the model of Grinin and Sobolev [1]. In a study of the fine time structure of two flares on AD Leo, Lovkaya [11] has found that at the maximum brightness these two flares radiated as absolute black bodies with temperatures of approximately 1.2 and 1.12 eV. Based on a detailed colorimetric analysis, Zhilyaev et al. [12] have determined a temperature $T \approx 1.16$ eV for the blackbody radiation at the peak of a strong flare on the red dwarf EV Lac. The authors [11] have found (p. 354) that the homogeneous plane layer with $N_H = 10^{16}$ cm$^{-3}$, $\Delta z = 1.5 \cdot 10^6$ cm, and $T = 11000$ K generates the energy distribution in the continuum, which is in close agreement with the energy distribution in the continuous spectrum at the maximum brightness of another flare on EV Lac.

Therefore, a homogeneous plane layer with the parameters corresponding to the chromospheric condensation [5] (the model of Katsova et al.), as opposed to a dense layer in the model of Grinin and Sobolev [1], cannot explain the continuous spectrum of stellar flares.

\footnote{$\tau_{4500} \approx 4.7 \cdot 10^{-3} \cdot 215 \approx 1.$}

\footnote{See also Appendix in the present article.
3. **Stationary radiative shock wave.** In [9] it was assumed that radiative cooling of the gas behind the front of a *stationary* plane-parallel shock wave propagating in the red dwarf chromosphere toward the photosphere is capable of creating a zone with near-photospheric concentration $N_H = 3 \cdot 10^{16} \text{ cm}^{-3}$ (this value corresponds to the value of $N_H$ of the source of the blue continuum radiation at $T_e = 1 \text{ eV}$ in the framework of the homogeneous plane layer model). Here we clarify the conditions under which this is possible.

Fadeyev and Gillet [13], Bychkov *et al.* [14] have calculated the profile of a stationary plane-parallel *radiative* shock wave with detailed accounting for elementary processes in the post-shock plasma: the electron impact ionization, the triple recombination, the electron impact excitation and de-excitation, etc.\(^{11}\) The following parameters were chosen in [14] for the unperturbed gas: the total concentration of ions and atoms $N_0 = 10^{12} \text{ cm}^{-3}$, a temperature $T_0 = 3000 \text{ K}$, and a *magnetic field* $H_0 = 2 \text{ G}$. The magnetic field is oriented perpendicular to the gas velocity [14]. The plasma flows through the discontinuity surface at a velocity of $u_0 = 60 \text{ km/s}$ (we use a frame of reference in which the shock front is at rest).

Let us take $N_0 = 10^{14} \text{ cm}^{-3}$ for the unperturbed chromosphere of a dMe star and retain the other parameters of the gas *without modification*. Immediately after the discontinuity for the same shock velocity $u_0$ we have: $N_1 \approx 3.9 \cdot 10^{14} \text{ cm}^{-3}$, $T_{ai1} \approx 1.03 \cdot 10^5 \text{ K} \approx 8.86 \text{ eV}$, $T_{el1} \approx 7.42 \cdot 10^3 \text{ K} \approx 0.64 \text{ eV}$, and $H_1 \approx 7.8 \text{ G}$ (the atoms and ions are heated at the shock front along the Rankine-Hugoniot adiabat and the electrons, along the Poisson adiabat). Here the ionization state of the unperturbed gas is calculated via the solution of the system\(^{\text{11}}\)

\(^{11}\)In [14] the numerical calculations have been performed for two-levels atoms and ions.
of the Saha equations; the ionization of metals is taken into account (for more details, see pp. 651–653 in [14]). Clearly, $T_{ai1} \gg T_{e1}$ (see also paragraph 4 in the introduction to this article). In these calculations we use a reduced value of the pre-shock gas temperature ($3000 \, \text{K}$ instead $\sim 5000 \rightarrow 8000 \, \text{K}$). In the present problem, however, the Mach number is quite high ($M_0 = u_0/v_{s0} \approx 10.3 \gg 1$, where $v_{s0}$ is the adiabatic sound speed), so the time “history” of radiative cooling of the post-shock gas should not depend too strongly on the background temperature $T_0$.

Calculations [14] show that the optical depth in the Ly $- \alpha$ line in the cooling region of the post-shock gas is $\tau_{12} \sim 10^7$ ($\tau_{12}$ is reckoned from the discontinuity surface). The authors [9] have shown that $\tau_{12}$ depends weakly on the concentration of the hydrogen atoms in the post-shock plasma (see Eqs. (2)–(3) in [9]). Thus, under the conditions of the chromosphere of a red dwarf, we can set $\tau_{12} \sim 10^7$ in a first approximation (as in section 2 of study [9]).

A two-temperature ($T_{ai1} > T_e$) plane layer of thickness $L$ can be treated as the simplest approximation for the radiative cooling region behind the front of a stationary plane-parallel shock wave. For concreteness we assume that $\tau_{12}$ is the optical depth at the point $L/2 + l$, where $l$ is the geometric size of the region where the electron temperature $T_e$ is raised by the elastic collisions of electrons with ions and atoms [13, 14]. Since $L \gg l$ [13, 14], we will assume that $\tau_{12} \approx \tau_{12}^p$ (see also the paragraph six of introduction to the present article).

With increasing $N_H$ in the cooling region of the post-shock plasma, the geometric thickness $L$ of the emitting plane layer decreases. In fact, for $N_H = 3 \cdot 10^{16} \, \text{cm}^{-3}$, $T_e = 1 \, \text{eV}$, and $T_{ai} = 8 \, \text{eV}$ (an estimate), according to Eq. (2) we obtain that

$$L = \frac{2\tau_{12}^p}{k_{12}^p} \sim 2 \cdot 10^7 \cdot \left[4\pi^{3/2} \sqrt{\frac{m_H}{m_e}} \frac{a_0^2}{E_{21}} \frac{\sqrt{\frac{\text{Ry}}{T_{ai}}} N_{gr}}{f_{12}} \right]^{-1} \approx 500 \, \text{m}^{12}$$

(6)

Here $m_H$ is the hydrogen atom mass, $m_e$ is the electron mass, $a_0$ is the Bohr radius, $E_{21}$ is the excitation energy of the second level of the hydrogen atom, $f_{12} \approx 0.416$ (the absorption oscillator strength for the transition $1 \rightarrow 2$), and $N_{gr}$ is the concentration of atoms in the ground state (here, for concreteness, we assume that $N_{gr} \approx 2 \cdot 10^{16} \, \text{cm}^{-3}$). It is clear that $L \propto \sqrt{T_{ai}}$, so that a reduction in the atom-ion temperature in Eq. (6) leads to a drop in $L$.

According to study of Lovkaya [11], the linear sizes of the flares on AD Leo at the maximum brightness are approximately $10^9 \, \text{cm}$ (see p. 609 in [11]). Since $L$ is much less than $10^9 \, \text{cm}$, our assumption [9] regarding the origin of the blue continuum radiation is not confirmed.

4. Additional remarks. Sobolev and Grinin [15] assume that the line spectrum of

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12 It is assumed here that there is no connection between the increasing in $N_H$ and the change in the magnetic field $H$ during all non-stationary radiative cooling of the post-shock gas.

13 The brief version of this article is available via the ADS Article Service in the Proceedings of Cool Stars 9: http://adsabs.harvard.edu/abs/1996ASPC..109..629S.
stellar flares is formed in the chromospheric layers where “gas-dynamic effects caused by the rapid release of energy play an extremely important role” [5]. In the present article it has been shown that the homogeneous plane layer of pure hydrogen plasma with the parameters obtained by Katsova et al. [5] is transparent in the optical continuum. This result is in agreement with [15]. Thus, the model [5] can explain (qualitatively) the increased intensity of the hydrogen emission lines in the spectra of stellar flares.

In the gas-dynamic calculations [16, 17] Kowalski has increased the energy flux in the electron beam to \( F_0 = 10^{13} \text{ erg cm}^{-2} \text{s}^{-1} \) (a low-energy cutoff \( E_1 = 37 \text{ keV} \)). The author [17] believes that “the ... optical continuum radiation [during the impulsive phase of stellar flares] originates from the chromospheric condensation with [electron] densities as high as \( N_{e,\text{max}} \approx 5.6 \times 10^{15} \text{ cm}^{-3} \), \( T \approx 12800 \text{ K} \) and from non-moving ... dense \( (N_e \approx 10^{15} \text{ cm}^{-3} \), \( T \sim 10.000 \text{ K} \)) layers below the chromospheric condensation” [17] (only \( \approx 25\% \) of the blue continuum radiation is produced in these layers [17]).

The calculations of Grinin et al. [4], which contradict the viewpoint [16, 17], were not discussed in [16, 17]. As justification for raising \( F_0 \) to \( 10^{13} \text{ erg cm}^{-2} \text{s}^{-1} \), it was pointed out [16] that “non-thermal ... deka-eV electrons” rapidly lose their energy during interactions with the chromosphere of a red dwarf and, for this reason, cannot heat the deep layers of the star’s atmosphere. But in [4] the energy losses of high-energy electrons through ionization of atoms and Coloumb interactions with free electrons are taken into account (see Eqs. (1) and (2) in [4]). In addition, \( F_0 = 10^{13} \text{ erg cm}^{-2} \text{s}^{-1} \) is two orders of magnitude greater than the value of \( F_0 \) usually used in gas-dynamic models of solar flares (see Somov et al. [18]). At the same time, with \( F_0 = 10^{11} - 10^{12} \text{ erg cm}^{-2} \text{s}^{-1} \) and the same beam parameters [17], it has not been possible to reproduce the optical continuum spectrum of stellar flares [17].

Therefore, Kowalski’s conclusion regarding the nature of \( \approx 75\% \) [17] of the blue continuum radiation is not sufficiently substantiated.

The plasma behind the front of a stationary radiative shock wave moves at a subsonic velocity relative to the discontinuity surface. In addition, as the post-shock plasma radiates, the velocity of the gas flowing out of the discontinuity, \( u(t) \), decreases because the gas becomes denser. From the standpoint of a laboratory observer, however, the velocity of the gas, \( u'(t) \), is equal to \( u_0 - u(t) \). As a result, the line core of the emission line of the post-shock plasma should be shifted as a whole in the direction of motion of the shock front. It is interesting to note that the H\( \alpha \) line profile in the spectrum of a flare on dM5.6e (see Fig. 7a in Eason et al. [19]) has a Doppler core that is shifted to the blue, rather than red (see also subsection 5.3 in [9]). The gas behind the front of a shock wave propagating in the partially ionized chromosphere upward can generate this radiation.

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\(^{14}\)The full text of the article is available via the ADS Article Service: http://adsabs.harvard.edu/abs/1993ARep...37..182G, http://adsabs.harvard.edu/abs/1993ARep...37..187B.

\(^{15}\)Here we have in mind the problem of return current.
5. Model of a second-kind temperature wave. Katsova et al. \[5\] and Livshits et al. \[6\] do not take into account the inequality $T_{ai} \gg T_e$ in the post-shock chromospheric plasma of stellar and solar flares, and this is a fundamental deficiency of their models \[5, 6\]. As it follows from pp. 3666—3667 and Fig. 1 in \[20\], Katsova and Livshits do not dispute this statement. (“We apply the two-temperature approximation where the electrons and ions are heated differently behind the shock front” (p. 3667 in \[20\]).)

6. Conclusion. Let us summarize the astrophysical results obtained in this paper.

(a) It has been demonstrated that the blue continuum radiation observed at the maximum brightness of large flares on dMe stars originates from the near-photospheric layers \[1\].

(b) It has been shown for the first time that the homogeneous plane layer with the parameters corresponding to the chromospheric condensation \[5\], as opposed to the denser layer in the model \[1\], cannot explain the optical continuum spectrum of stellar flares.

Our conclusions are based on an analysis of three different approaches to explaining the spectral observations using the model of a homogeneous plane gas layer. In \[1\] this layer is located in the “transition region between the chromosphere and the photosphere.” In the gas-dynamic calculations \[5\], a single-temperature ($T_e = T_{ai} = T$) plane layer corresponds to the chromospheric condensation formed by a second-kind temperature wave. Finally, in the model of a stationary plane-parallel shock wave propagating in the partially ionized chromosphere of a red dwarf toward the photosphere, a two-temperature ($T_{ai} \neq T_e$) gas layer is the simplest approximation for the radiative cooling region. We note that this model differs from the models \[5, 6\]. In fact, Katsova et al. \[5\] and Livshits et al. \[6\] introduce a “system of [partial differential] equations of one-dimensional gravitational gas dynamics” \[5\] taking into account the thermal conductivity (Fourier’s law), while the authors \[13, 14\] consider a system of ordinary differential equations with detailed accounting for non-stationary radiative cooling in the post-shock plasma.\[17\]

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\[16\] In order to avoid misunderstandings, we recall that the “opposite” situation occurs in the EUV part of solar and stellar flares; i.e., the electron temperature of the plasma is considerably higher than the ion temperature: $T_e \gg T_i$ (see Somov et al. \[15\]).

\[17\] The thermal conductivity and the gravitational acceleration are not taken into account.
APPENDIX\textsuperscript{18}

- To calculate the radiation intensity from the chromospheric condensation \cite{5}, Katsova \textit{et al.} \cite{5} and Livshits \textit{et al.} \cite{6} use the \textit{modified} Eq. (9) from paper by Grinin and Sobolev \cite{1}:

\[ I_\text{fl} = B_\lambda(T) \cdot (1 - e^{-\Delta\tau_\lambda}), \]

(7)

where the value of \(\Delta\tau_\lambda\) is equal to

\[ \int a(T, p_e)p_e d\xi; \]

(8)

\(p_e\) is the electron pressure, “\(a(T, p_e)\) is taken in accordance with the tables of \cite{21}, \(\xi\) is a Lagrangian variable: \(d\xi = -N_\text{H} dz\) \cite{5}’. The integration is carried out “over the complete high-density region \textit{for different times}” (p. 163 in \cite{5}).\textsuperscript{19}

Bode’s tables \cite{21} contain data for \textit{homogeneous} plasma whereas the chromospheric condensation \cite{5} is rather \textit{inhomogeneous}. Therefore, Eq. (8) is incorrect. Moreover, this Eq. cannot be used in the calculations of the radiation intensity from a \textit{plane layer}. The solution of this problem is the replacement of \(\Delta\tau_\lambda\) in Eq. (7) with \(\tau_\lambda\) (as in Table 1).

- The physical parameters of the condensation \cite{5} are close to the parameters of the \textit{reversing layer} of an A0 star (see Allen \cite{22}, § 103). Using the absorption coefficient for such plasma \cite{21}, let us calculate the optical depth at wavelength 5000 Å, \(\tau_\text{Bode}_{5000}\), at \(\Delta z = 10\) km:

\[ \tau_\text{Bode}_{5000} \approx 10^{0.97} \cdot \mu \text{Ar} \cdot N_a \Delta z \approx 0.03 \sim 10^{-2} \ll 1. \]

(9)

Here \(\mu\) is the molecular weight of the gas without the electrons and metals (\(\mu \approx 1.235 \text{ [22]}\)), \text{Ar} is the unified atomic mass unit, \(N_a\) is the total number density of atoms (\(N_a \approx 1.585 \cdot 10^{15} \text{ cm}^{-3} \text{ [22]}\)). One can see that \(\tau_\text{Bode}_{5000}\) coincides in order of magnitude with \(\tau_{4500}\) (Table 1) at \(N_\text{H} = 2 \cdot 10^{15} \text{ cm}^{-3}\) and \(T \approx 9000\) K. Note that the value of \(N_\text{H}\) inside the chromospheric condensation \cite{5} is \textit{strictly less} than \(10^{16} \text{ cm}^{-3}\) for all values of \(\xi\) (in particular for \(\xi = 10^{21} \text{ cm}^{-2}\) corresponding to \(\Delta z = 10^6 \text{ cm}\) at \(N_\text{H} = 10^{15} \text{ cm}^{-3} \text{ [5]}\)).

- Katsova \textit{et al.} \cite{5} (p. 163) and Livshits \textit{et al.} \cite{6} (p. 281) state that the optical radiation from the \textit{plane layer} with \(N_\text{H} = 2 \cdot 10^{15} \text{ cm}^{-3}\), \(T \approx 9000\) K, \(\Delta z = 10\) km provides the color indices, which are “in a good agreement with the observed blue-white radiation” \cite{6} of a stellar flare (\(U - B = -1, B - V = 0.5\) \cite{5} \cite{6}).

\textsuperscript{18}This part of the article is published only in \textit{astro-ph.SR}.

\textsuperscript{19}Eq. (7) corresponds to that on p. 281 in \cite{6}; see also Eq. (4) in \cite{6}.
In the present article it has been demonstrated that this layer is *transparent* in the optical continuum. As it follows from [1], the opacity of the gas beyond the Balmer jump is a necessary condition for explaining the color indices at the maximum brightness of large stellar flares. Therefore, the *real* values of $U - B$ and $B - V$ for the layer [5] are *not in the blue-visible region*. In addition, the published color indices [5] do not correspond the color indices at the peaks of strong flares: $U - B \approx -1.0$ and $B - V \approx 0.2$ (p. 300 in [23]; $U - B = -0.91 \pm 0.02$ and $B - V = 0.0 \pm 0.02$ (Zhilyaev et al. [12]).

- Again, Katsova *et al.* [5] (p. 163) and Livshits *et al.* [6] (p. 281) state that the layer [5] provides the value of the Balmer jump $D \approx 0.8$ (“in accordance with Grinin and Sobolev [1]”). Here the value of the Balmer jump “is determined by the formula

$$D = \log \frac{I_{\nu>\nu_2}}{I_{\nu<\nu_2}},$$

where $I_{\nu>\nu_2}$ and $I_{\nu<\nu_2}$ are the radiation intensities immediately after and immediately before the jump” [1]. In reality, as it follows from Fig. 3, the value of $D \approx 0.8$ for the layer with thickness $\sim 10^8$ cm $\sim 10^3$ km ($T \approx 9000$ K, $N_H = 10^{15}$ cm$^{-3}$).

**References**

1. V. P. Grinin and V. V. Sobolev, Astrophysics **13**, 348 (1977). DOI: 10.1007/BF01006610
2. V. P. Grinin and V. V. Sobolev, Astrophysics **28**, 208 (1988). DOI: 10.1007/BF01004071
3. V. P. Grinin and V. V. Sobolev, Astrophysics **31**, 729 (1989). DOI: 10.1007/BF01012732
4. V. P. Grinin, V. M. Loskutov, and V. V. Sobolev, Astron. Rep. **37**, 182 (1993).
5. M. M. Katsova, A. G. Kosovichev, and M. A. Livshits, Astrophysics **17**, 156 (1981). DOI: 10.1007/BF01005196
6. M. A. Livshits, O. G. Badalyan, A. G. Kosovichev, and M. M. Katsova, Solar Phys. **73**, 269 (1981).
7. P. P. Volosevich, S. P. Kurdyumov, L. N. Busurina, and V. P. Krus, U.S.S.R. Comput. Math. Math. Phys. **3**, 204 (1963). DOI: 10.1016/0041-5553(63)90131-9
8. S. B. Pikel’ner, Izv. Krymsk. Astrofiz. Observ. **12**, 93 (1954).
9. E. Morchenko, K. Bychkov, and M. Livshits, Astrophys. Space Sci. **357**, article id. 119 (2015). arXiv:1504.02749
10. V. V. Ivanov, Transfer of Radiation in Spectral Lines. U.S. Department of Commerce, National Bureau of Standards, Washington (1973).

\[\text{arXiv:1504.00000G}\]
Figure 3. "Balmer jump $D$ as function of the temperature $T$ [(10³ K)] for different thickness $z_0$ of the emitting region: a) $N_H = 10^{15}$ cm$^{-3}$, b) $N_H = 10^{16}$ cm$^{-3}$ (Grinin and Sobolev 1). In 1 the emission of negative hydrogen ions at $T < 10^4$ K is taken into account.
11. M. N. Lovkaya, Astron. Rep. 57, 603 (2013). DOI: 10.1134/S1063772913080040

12. B. E. Zhilyaev, M. V. Andreev, A. V. Sergeev, et al., Astron. Lett. 38, 793 (2012). DOI: 10.1134/S1063773712120079

13. Yu. A. Fadeyev and D. Gillet, Astron. Astrophys. 368, 901 (2001). arXiv:astro-ph/0101165

14. O. M. Belova, K. V. Bychkov, E. S. Morchenko, and B. A. Nizamov, Astron. Rep. 58, 650 (2014).

15. V. V. Sobolev and V. P. Grinin, Astrophysics 38, 15 (1995). DOI: 10.1007/BF02113956

16. A. F. Kowalski, S. L. Hawley, M. Carlsson, et al., Solar Phys. 290, 3487 (2015).

17. A. F. Kowalski, In: A. G. Kosovichev, S. L. Hawley, and P. Heinzel, eds. Solar and Stellar Flares and their Effects on Planets; Proceedings IAU Symposium No. 320, 2015. 259 (2016).

18. B. V. Somov, S. I. Syrovatskii, and A. R. Spektor, Solar Phys. 73, 145 (1981).

19. E. L. E. Eason, M. S. Giampapa, R. R. Radick, et al., Astron. J. 104, 1161 (1992).

20. M. M. Katsova and M. A. Livshits, Solar Phys. 290, 3663 (2015). arXiv:1508.00254

21. G. Bode, Kontinuierliche Absorbtion von Sternatmosphären. Sternwarte, Kiel (1965).

22. C. W. Allen, Astrophysical Quantities, 3rd ed. University of London, The Athlone Press, London (1973).

23. V. P. Grinin, In: L. V. Mirzoyan et al., eds. Flare Stars in Star Clusters, Associations and the Solar Vicinity; Proceedings IAU Symposium No. 137, 1989. 299 (1990).