Continuum and Line Emission of Flares on Red Dwarf Stars: Origin of the Blue Continuum Radiation

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There are two types of models that explain the appearance of the quasi-blackbody radiation during the impulsive phase of stellar flares. Grinin and Sobolev [1] argue that this component of the optical continuum is formed in “the transition layer between the chromosphere and the photosphere.” Katsova et al. [4] have “raised” the source of the white-light continuum up to the dense region in the perturbed chromosphere. In the present contribution (the main paper is published in “Astrophysics” [9]), we show that the statement in [4] is erroneous.

1 Introduction

Grinin and Sobolev [1] were the first who showed that the quasi-blackbody spectrum at the flare’s maximum brightness is formed near the photosphere. Heating of the deep layers is due to the high energy proton or/and electron beams with the initial energy flux $F_0 \approx 10^{12}$ erg cm^{-2}s^{-1} and $F_0 \approx 3 \times 10^{11}$ erg cm^{-2}s^{-1}, respectively [2, 3].

Katsova et al. [4] calculated the first gas dynamic model of the impulsive stellar flares (the energy flux in the electron beam $F_0 = 10^{12}$ erg cm^{-2}s^{-1}). According to this model, the blue component of the optical continuum is formed in a chromospheric condensation. The condensation is located between a temperature jump and the front of the downward shock (the temperature wave of the second kind [5]). The physical parameters of this source of white-light continuum ($N_H \approx 2 \times 10^{15}\,\mathrm{cm}^{-3}$, $T \approx 9000\,\mathrm{K}$, and thickness $\Delta z \approx 10$km) lie in the range of the layer parameters in the model by Grinin and Sobolev [1] ($N_H \sim 10^{15}{-}10^{17}\,\mathrm{cm}^{-3}$, $T \sim 5000{-}20000\,\mathrm{K}$, and $\Delta z \gtrsim 10$ km). Here, N_H is equal to the sum of the proton and atom concentrations. However, the condensation is formed at height of about 1500 km above the quiescent photosphere of a red dwarf, i.e. in the upper chromosphere.

The downward shock [4] propagates through *a partially ionized gas* of the red dwarf chromosphere. The flow speed is subsonic for the electron component of the plasma but this speed is hypersonic for the ion-atom component [6]. Therefore, both ions and atoms are heated more intensively than electrons

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at the shock front. Thus, the region between the temperature jump and the front of the downward shock is, in fact, *two-temperature* ($T_{ai} \gg T_e$) [7]. Here, T_{ai} is the ion-atom temperature, and T_e is the electron one.

2 Emission spectrum of a two-temperature layer

Morchenko et al. [7] calculated the emission spectrum of a homogeneous pure hydrogen layer with $6\,\mathrm{eV} \leq T_{ai} \leq 12\,\mathrm{eV}$ and $0.8\,\mathrm{eV} \leq T_e \leq 1.5\,\mathrm{eV}$. The layer density lies in the range $3 \times 10^{14}\,\mathrm{cm}^{-3} \leq N_H \leq 3 \times 10^{16}\,\mathrm{cm}^{-3}$.

Initially, we assume that the Lyman-α optical depth in the center of the layer, τ_{12}^D, is approximately equal to 10^7 (see Eq. (1) in [7]). However, at values of $N_H \sim 10^{16}\,\mathrm{cm}^{-3}$ the layer thickness, $\mathcal{L}$, is *small* ($\tau_{12}^D \propto N_1 \mathcal{L}$ – see Eq. (53) in [7]). Here, N_1 is the concentration of the ground state atoms. Therefore, we consider the transition from the transparent gas to the gas whose emission is close to the Planck function under conditions when $\mathcal{L}$ is fixed (see the first paragraph of Sect. 7 in [7]).

The following elementary processes were taken into account: the electron impact ionization, excitation, and de-excitation, the triple recombination, the spontaneous radiative recombination, the spontaneous transitions between discrete energy levels. We consider the influence of the layer's radiation (bremsstrahlung and recombination) on the occupation of atomic levels. It is necessary as the flare luminosity is stronger in the optical range than that of the quiescent atmosphere of the whole star.

We take into account the scattering of line radiation in the framework of the Biberman–Holstein approximation [8]. Since $\tau_{12}^D \gg 1$, photons escape the flare plasma in the distant line wings [7]. The following asymptotic formula is valid for the resonance transition:

$$\theta_{12} \approx \left(\frac{\mathcal{B}_{21} \mathcal{E}_0}{\Delta \omega_{21}^D} \right)^{3/5} \frac{1}{(\tau_{12}^D)^{3/5}}. \tag{1}$$

Here, $\mathcal{B}_{21}$ is the Stark broadening parameter, $\mathcal{E}_0$ is the Holtsmark field strength, and $\Delta\omega_{21}^D$ is the Doppler width.

Our calculations [7] have shown that the Menzel factors do not differ from unity at values of $\tau_{12}^D \sim 10^7$ and higher. Moreover, the two-temperature 10 km layer with $N_H = 3 \times 10^{16}\,\mathrm{cm}^{-3}$, $T_{ai} = 10\,\mathrm{eV}$, $T_e = 1\,\mathrm{eV}$ generates the blue continuum radiation (the optical depth at wavelength $\lambda = 4170$ Å, τ_{4170}, is approximately equal to 6).

We also *proposed* that the non-stationary radiative cooling of the gas behind the downward stationary shock can produce an equilibrium region, which is responsible for the quasi-blackbody radiation during the impulsive phase of stellar flares (the last sentence in [7]).

3 Origin of the blue continuum radiation

The model [4] includes the one-temperature ($T_{ai} = T_e = T$) source of the white-light continuum. Let us investigate the applicability of the calculations [7] for a one-temperature layer with $\tau_{12}^D \gtrsim 10^7$. It is true that

$$\tau_{12}^D \propto \frac{1}{\sqrt{\pi}\Delta\omega_{21}^D} \propto {T_{ai}}^{-1/2}. \quad (2)$$

Therefore, the mean photon escape probability, θ_{12}, as well as the Menzel factors of the layer do not depend on the ion-atom temperature. Thus, at $T_e = T_{ai} = T$ numerical results [7] remain valid.

Then it is true that the 10 km layer with the parameters from the model by Katsova et al. [4] is *transparent* in the optical continuum (see the lower curve designated to "I" in Fig. 2 from [7]): $\tau_{4170} \ll 1$, Q.E.D.

In the paper [9] we briefly discuss the theoretical possibility of the origin of the blue continuum radiation behind the downward stationary shock with *radiative cooling*. Based on a simple estimate, it is shown that the Planck emission is formed only under conditions when the gas flows from the viscous jump on a small distance (approximately five hundred meters). Thus, our hypothesis [7] is not confirmed.

Finally, we hold that the quasi-blackbody spectrum during the impulsive phase of stellar flares is formed in the deep layers [1, 10].

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