Optical Continuum of Powerful Solar and Stellar Flares

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The powerful optical continuum of solar and stellar flares is hard to explain within the concept of the gasdynamic response of the chromosphere to the impulsive heating. It requires too large amount of accelerated particles, in contradiction with the hard X-ray observations. The resolution of this trouble is to take into account the absorption of the short wavelength radiation of the hot flaring plasma by the optical emission source, i.e. the low temperature condensation. Our estimates show that this can help to explain the origin of the optical continuum of powerful impulsive flares on the Sun and red dwarfs and superflares on the young G stars.

1 Introduction

A large amount of the multi-wavelength observations of solar flares as well as the optical and X-ray observations of flares on red dwarfs have been analysed in the last years; non-stationary events with the total energy exceeding that of the most powerful phenomena on the Sun by 2–3 orders of magnitude were detected on some late-type low-mass stars by the *Kepler* spacecraft. This required a new analysis of the data on the stellar flares. Particularly, this refers to the possibility of the generation of the powerful continuous optical radiation of the superflares.

Theoretical investigation of the problem concerning the flares on red dwarfs was carried out in a series of papers by Grinin and Sobolev [8, 9, 10, 11].

It is clear that the heating by the accelerated particles, mainly electrons, should be accompanied by the gasdynamic motions. This dynamic response of the dense layers of the atmosphere was considered for the first time by Kostiuk and Pikelner [13] and later was considered in a numerous number of papers dedicated to the flares on the Sun and the stars [14, 7, 6, 2, 12, 3].

The optical emission in the gasdynamic model is known to originate in the dense low-temperature condensation between the front of the downward moving shockwave and the heating front. The plot of the density $n = n_{\mathrm{H\,I}} + n_{\mathrm{H\,II}}$ for several instants of a powerful solar flare is given in the left panel of Fig. 1. The density is seen to reach quite high values of the order 10^{15} cm^{-3} in a time of about 10 s.

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Although the aforementioned theoretical works were confirmed by the observations in various aspects, it still remains unclear: are such models able to account for the optical continuum arising in powerful flares on the Sun (and the stars)? In the present work an attempt is made to answer this question and find the conditions for the optical continuum in a flare to arise.

2 Method of solution

In the gasdynamic model the optical radiation arises in a peculiar low-temperature gas condensation. Can the radiation of the condensation give a contribution to the continuum? In order to answer this question, we made use of the calculation [2]. This *gasdynamic* calculation provides the gas density, the temperature, the ionization degree and some other parameters as functions of the column density ξ [cm^{-2}] (the gas is assumed to be pure hydrogen). In the right panel of Fig. 1 the thin solid line represents the electron density in the condensation (other lines will be explained later).

The lower boundary of the condensation (the right one in the figure) is a shock wave through which the undisturbed gas flows into the condensation and heats. This explains the high ionization at the lower boundary. The condensation is limited from above by the hot gas which also heats it due to the thermal conductivity. This explains the high ionization at the upper boundary. The ionization is low in the middle part of the condensation.

Given the density, the temperature and the electron number density, one can calculate the spectrum of the radiation emerging from the condensation. We performed such a calculation by the method described in [15], namely we solved the equations of radiative transfer and statistical equilibrium in the condensation

$$\mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu, \tag{1}$$

$$\sum_{j \neq i} n_i R_{ij} = \sum_{j \neq i} n_j R_{ji}. \tag{2}$$

It turned out that such a condensation gives no contribution to the continuum. However, it should be noted that the system of equations solved in [2] did not include either the equations of statistical equilibrium or the charge conservation law. Therefore, after solving the equations (1)–(2), it may turn out that the ion density is not equal to the electron density, i.e. the electroneutrality of the medium may be violated. And this is actually the case. In the right panel of Fig. 1 the thin solid line represents the electron density in the condensation which was taken from the gasdynamic calculation, and the dashed line represents the ion density which is obtained from the solution of the equations (1)–(2). In order to enforce the electroneutrality, one should add one more equation to the system, namely:

$$n_p = n_e, \tag{3}$$

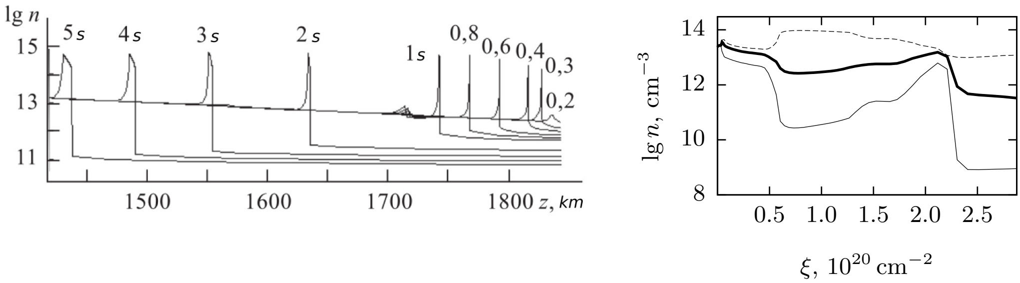

Figure 1: *Left.* The response of the solar atmosphere to the impulsive heating by the non-thermal electrons with the energy flux 10^{11}erg/cm^2/s and sufficiently hard spectrum which corresponds to a powerful solar flare [3]. *Right.* Thin solid line: electron number density in the gasdynamic model. Dashed line: corresponding number density of the ions. Thick solid line: electron and ion number density in case of electroneutrality concerned. The column density ξ is counted from the top of the condensation.

and the electron density should be calculated from the new system of equations instead of being taken from the gasdynamic model. The plot of the electron number density obtained in such a way is represented in the right panel of Fig. 1 by the thick solid line. It is clear from the comparison of this line with the thin solid one that the gasdynamic calculation tends to underestimate the electron density along with the optical depth of the gas in the continuum. Hence, the amount of the continuous radiation is also decreased.

Concerning the impossibility of explaining the optical continuum, we draw attention to one more factor which was not taken into account in [2], namely the irradiation of the condensation by the short-wavelength emission of the hot plasma filling the magnetic loop during the flare. This plasma has the temperature of the order 10^7 K and radiates in XEUV and SXR spectral regions. For a M2 class flare one can use the differential emission measure (DEM) provided by the CHIANTI package [5, 4]. Unfortunately, analogous data for the most powerful solar flares are absent for different reasons, therefore we assumed that for such flares the DEM(T) is an order of magnitude larger than that given in CHIANTI for a M2 class flare and calculated the spectrum of the gas with the density 10^9 cm^{-3} (Fig. 2). Note that this is the spectrum of the coronal gas only, therefore the flux in the He II 304 Å line can be underestimated.

First of all let us consider a simplified problem. Suppose there is a layer of hydrogen of a finite width with a given density and temperature (we call this temperature "initial"). The layer is irradiated by the photosphere. Moreover, in the layer there are artificial sources of heat which, along with the photospheric radiation and the radiation of the layer itself, maintain the given (initial) temperature. These artificial sources are introduced in order not to consider the evolution of the whole process in time, but instead to use the gasdynamic solution (or its analogue) for a certain instant. In other words, we replace the non-stationary problem with a stationary one. It is justified since beginning with approximately the time of 2 s, the evolution of the condensation is

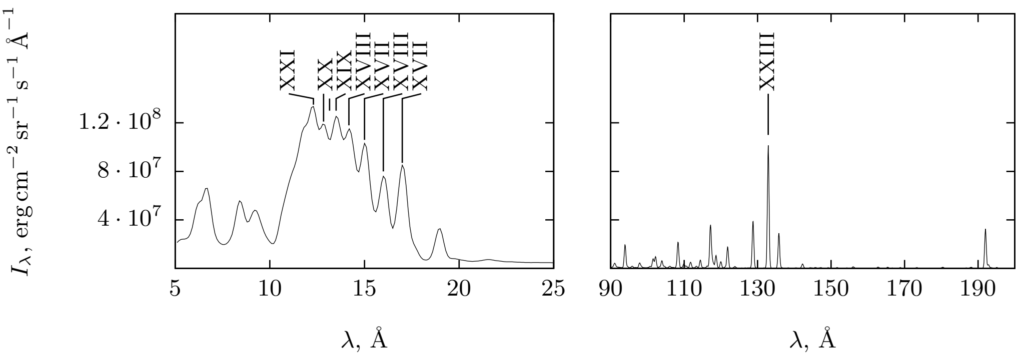

Figure 2: Two parts of the spectrum of the hot flaring plasma. The numbers indicate the ionization stage of the iron atom emitting the relevant line.

essentially quasi-stationary and its structure changes little with time (of course, up to a certain time). In fact, the parameters of the condensation depend on the time. In particular, the temperature is determined by the equation of energy. But taking into account the above consideration, we eliminate the dependence on the time, and in order to maintain the temperature at a given level, we introduce the artificial heat sources. Thus, we assume the validity of the condition of radiative equilibrium with the additional heat source in the layer. This condition takes the form

$$4\pi \int \eta_\nu d\nu = q + \int d\Omega \int I_\nu \chi_\nu d\nu, \tag{4}$$

where η_ν, χ_ν are the emissivity and opacity, and q is the power of the artificial sources. From this relation we find the power of the artificial sources

$$q = 4\pi \int \eta_\nu d\nu - \int d\Omega \int I_\nu \chi_\nu d\nu. \tag{5}$$

So, solving the equations (1)–(4) with the numerical values of q found from the equation (5), we obtain the populations of the atomic levels, the ionization degree and the temperature in the condensation, the latter being equal to the initial temperature. Now in order to take into account the X-ray source, we have to solve the equations (1)–(4) with *the same* sources q, but the upper boundary condition in the equation of radiative transfer should correspond to the X-ray emission falling on the condensation from above. As a result, we obtain the new populations, ionization degree and the new temperature which is higher than the initial one. We also calculate the spectrum of the radiation emerging from the condensation and can compare it with the spectrum of the quiet Sun to see if any additional continuum arises in the condensation and how large it is. Let us compare the specific intensity at the disc center of the radiation emerging from the condensation I_c and the radiation of the

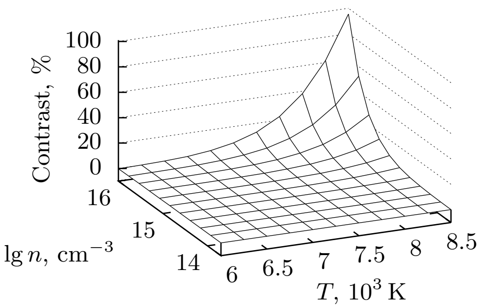

Figure 3: Contrasts in per cents for various values of the density and temperature of the condensation.

photosphere $I_{\rm p}$ at the wavelength 4500 Å. Let us term the quantity $(I_{\rm c} - I_{\rm p})/I_{\rm p}$ the contrast.

In our calculations we represent the condensation as a finite homogenous layer of the width 50 km as in the gasdynamic solution. The density and the initial temperature are varied in the ranges from 5×10^{13} to 10^{16} cm^{-3} and from 6000 to 8500 K, respectively. The plot of the contrasts is shown in Fig. 3.

It is seen that the high contrasts (>10%) are reached only at high densities ($\sim 10^{15}$ cm^{-3}) and temperatures ($\sim$8500 K).

Taking into account the external radiation in the gasdynamic response of the chromosphere to the heating should change the physical conditions inside the condensation. Namely, at the beginning of the process, when the condensation is tenuous, the external radiation should prevent the strong cooling (and hence the decrease of the ionization degree) in the middle of the condensation. But by the end of the non-thermal particle heating (approximately in 10 s after the onset of the response) the condensation would propagate quite deep and its density would increase while the temperature throughout it would still be high due to the "preliminary" heating by the X-rays. This provides the generation of the optical continuum. In other words, the optical thickness of the condensation at the wavelength 4500 Å becomes $\gtrsim 0.03$.

3 Conclusions

The general idea of the relation between the origin of the optical continuum and the impact of the accelerated particles on the atmosphere which was put forward by Grinin and Sobolev is of current interest. The further development of the gasdynamic model with account of the absorption of the short-wavelength radiation is desired. Following this way may probably help to understand the emergence of the powerful optical continuum. Note that the radiation of the condensation is most likely related to the blue continuum whereas the lower-temperature red continuum can arise as a consequence of the irradiation of the upper photosphere by the soft X-rays from the large cloud of the hot plasma which forms during a flare (as it is stated in [1]).

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