THE MODEL OF THE IMPULSIVE PHASE OF STELLAR FLARES

V.P.GRININ[1] and V.V.SOBOLEV[2]

[1]Crimean Astrophysical Observatory, 334413,
p/o Nauchny, USSR
[2]Leningrad State University, 198904, St. Petergoff, USSR

ABSTRACT. The arguments in favour of that the primary heating of the gas at the impulsive phase of stellar flares is caused by charged particles of higher energies than in the solar flares are given. It is shown that the model of the deep heating by high energy protons ($E \simeq 10$ MeV) or electrons ($E \simeq 100$ keV) with taken into account of the radiative transfer in flare region explane the main properties of the optical continuum of the flare.

INTRODUCTION. The general similarity of the flares on UV Ceti - -type stars and on the Sun has been noted at the last time by many authors and was reflected in the models of stellar flares (see review by Kodaira, 1983). Here we want to stress one important difference: the gas emitting in the optical continuum even in the strongest solar flares is optically thin (Machado and Rust, 1974), whereas at maximum light of strong stellar flares its optical thickness beyond Balmer jump may be very large. This fact was noticed first in the paper by authors (Grinin and Sobolev, 1977, paper I), where it was shown that the optical flares are localized in dense layers of atmosphere: $n_H \simeq 10^{15} - 10^{17}$ cm^{-3}. This conclusion is confirmed by observations of quasi-black-body radiation in flares of YZ CMi (Mochnacki and Zirin, 1980; Kaler at al. 1982), BY Dra (Chugainov, 1987) and some other stars. It means that the primary heating agent penetrates in deeper layers (in the units of column density) of stellar atmosphere then in the solar flares.

We showed recently (Grinin and Sobolev, 1988a) that the protons of the energy $E \simeq 10$ MeV can provide the gas heating with the parameters mentioned above. On the basis of other arguments the proton heating in stellar flares was suggested also by Van den Oord (1988). Hereinafter we give the results of the model calculations of proton heating and compared them with the data of optical observations. The role of the fast electrons is discussed too.

THE PROTON MODEL OF DEEP HEATING. We considered the thermal equilibrium in the dense part of an atmosphere of red dwarf assumed that the quasi-stationary proton beam has the initial energy spectrum $N(E_0) \sim E_0^{-\gamma}$ at $E_0 \geqslant E_1$. The energy deposition in a thick target at the depth x: $q_p(x)$ is due to ionizations and coulomb collisions (Emslie, 1978) and is considered without taking into account the changes of particle trajectories at the scattering. The additional source of heating is the optical and UV-radiation of the flare itself. For the correct accounting of this factor we considered the radiative transfer in LTE plane-parallel approximation. So, the equation of the thermal equilibrium in our model is non-linear:

$$q_p(x) = 4\pi\int\left[B_\nu(x) - \bar{I}_\nu(x)\right]\alpha(x)\,d\nu \qquad (1)$$

where B - the Planck function, $\bar{I}$ - the mean intensity of radiation, α - the absorption coefficient per unit volume - include the free-bound and free-free transitions of hydrogen atoms and H^-.

The equation (1) were solved by iterative method (see for details Grinin and Sobolev, 1988b) at the assumptions: 1) the gas pressure P = const during the heating; 2) the initial distribution of the atoms is determined by the barometric low: $n_H(x) = n_H(0)\exp(bx)$ and $n_H(0) = 10^{14}$ cm^{-3} at x = 0. We did not considered the upper layers of the flare (in which the emission lines are formed predominantly) and did not taken into account the radiative losses in the spectral lines because they are weak usually in comparison with the flare continuum at maximum light (Kodaira, 1983).

The main parameters of the typical model of strong stellar flare are shown in Figure 1.

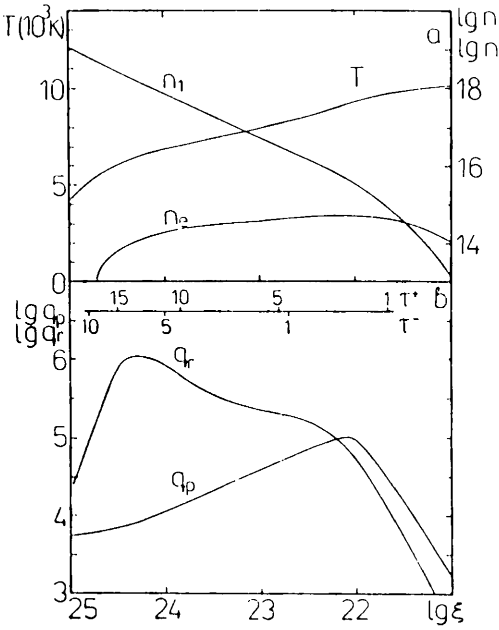

Figure 1. a - the temperature (T), electron (n_e) and neutral atom (n_1) number densities as a function of the column density ξ in the model: E_1 = 5 MeV γ = 3 and F(0) = $5\cdot10^{11}$ erg/cm^{2}s at b = 10^{-6} cm^{-1}.

b - the energy deposition by protons (q_p) and by radiation of the flare (q_r) in erg/cm^3·s in the same model. The optical depths scale beyond (τ$^+$) and before (τ$^-$) Balmer jump are shown.

From Fig. 1 it can be seen that in deep layers the radiative heating significantly prevails the primary heating by the particles. This property is typical for the models in which the optical thickness of the flare in continuum $\tau \gg 1$ (realized at the energy flux in the beam $F(0) > 3 \cdot 10^{11}$ erg/cm^2·s). The radiation of such flares has a small Balmer jump and is quasi-black-body. Its temperature increases at the transition from the center to the limb flares.

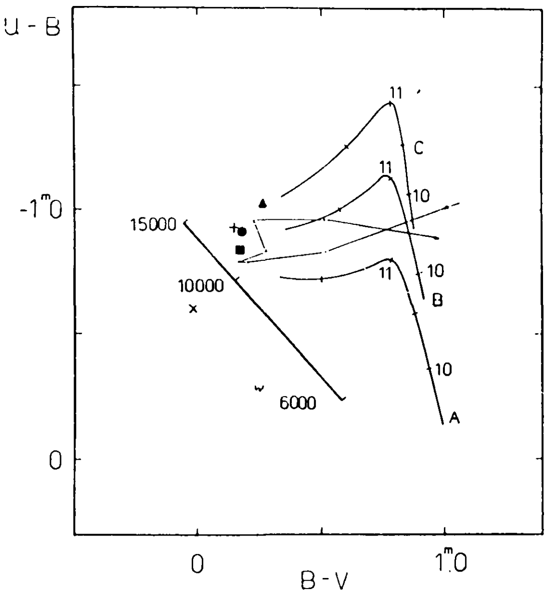

Figure 2. The theoretical two-colour diagram for the set of the models: A,B,C - correspond to E_1 = 10, 5 and 3 MeV at $\gamma = 3$. The values of lg F(0) are shown along theoretical lines. The mean values of colour indexes of strong flares of UV Ceti (x), EV Lac (+), YZ CMi (•), AD Leo (▲) and CN Leo (■) at maximum light - from Moffett (1974) and Chugainov (1982) observations. Thin line shows the evolution of colours in strong flare of BY Dra from Chugainov (1987).

On the Fig. 2 the theoretical two-colour diagram is shown. Its special feature is the concentration of theoretical lines in the region of the colour indexies: $U - B \simeq -0\overset{m}{.}8 \div -1\overset{m}{.}0$ and $B - V \simeq 0\overset{m}{.}2 \div 0\overset{m}{.}3$. The existence of such region on two-colour diagram is well known also from photoelectric observations of strong stellar flares (Moffett, 1974; Cristaldi and Rodonó, 1975, Chugainov, 1982; see Fig. 2). This important observational fact has been discussed widely in the literature and interpreted in favour of hot gas ($T \gtrsim 10^5$ K) emission (Mullan, 1976; Gershberg, 1978; Chugainov, 1982; Kodaira, 1983). However as it was mentioned in paper I, such point of view disagrees with the flare spectra at maximum light (intensive "low-temperature" Balmer and Ca II emission lines and very rare weak He II lines). The model of deep heating gives the alternative interpretation of this fact and agrees with the property of flare spectra mentioned above.

THE ROLE OF THE FAST ELECTRONS.

a) Non-relativistic electrons. In the case of the solar flares the bulk of accelerated electrons has non-relativistic energy: $E \simeq 10$ keV. This electrons are stopped in chromospheric layers and heated up to 10^7 K. From this region the energy transfers into deep layers by conductivity or in shock front. This two-step mechanism of heating has been realized in the models of stellar flares by Katsova et al. (1981) and Cram and Wood (1982). In the first paper the flare model with parameters of electron beam: $E_1 = 15$ keV, $\gamma = 3$ and $F(0) = 10^{12}$ erg/cm^2·s is calculated and the both mentioned above mechanisms of energy transfer are taken into account. The comparison of their model with ours shows that the parameters of the flare with two-step heating by electrons are about the same as in the proton model with the parameters: $E_1 = 3$ MeV, $\gamma = 3$ and $F(0) = 10^{11}$ erg/cm^2.s (according to Fig. 2 the colours of such flare are: $U - B \simeq - 1^m_.5$ and $B - V \simeq 0^m_.7$). It means that the direct heating of deep layers of atmosphere by high-energetic particles is about 10 times more effective compared with two-step mechanism of heating by non-relativistic electrons.

b) Sub-relativistic electrons. The role of fast electrons will be essentially higher if they have harder energetic spectrum ($\gamma < 3$) then in strongest solar flares. At the same energy fluxes F(0) the energy deposition in 1 cm^3 by electrons with energy E will be the same as in the case of protons with the energy $E(m_p/m_e)^{1/2} \simeq 50E$ (Syrovatskii and Shmeleva, 1972). Therefore the calculated above models are applicable at the first approximation to the case of the primary heating by sub-relativistic electrons ($E > 100$ keV).

CONCLUSION. At present it is not possible to say what of these two cases is realized on the flare stars. But in both cases the more energetic particles then in the solar flares are neded. The model calculations show that the primary heating by charged particles and the heating by radiation of the flare are the main source of the optical stellar flares.

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