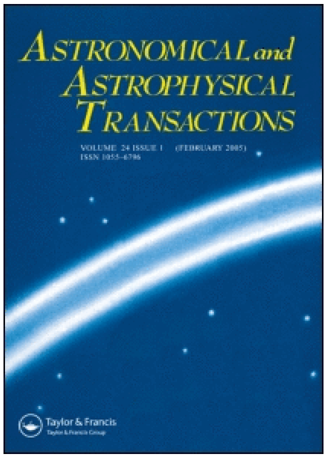

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# A scenario for impulsive stellar flares

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# A SCENARIO FOR IMPULSIVE STELLAR FLARES

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The scenario of an impulsive stellar flare is proposed: the optical continuum pulse arises in the dense atmospheric layers which are close to the region of the primary energy release, then perturbation propagates along one or several giant arches for 1–3 min, and a gas-dynamic process is developing on a large area in the other base of the arch (or several arches).

KEY WORDS Stellar flares, theory

Many observations of flares on UV Cet-type stars are now available at different spectral ranges. Most of the flare data consist of UBV-photometry, showing flare light curves with time resolution of tens of seconds obtained during special observations with moderate telescopes.

We shall consider only those flare events with total durations of 1–20 min and U-band impulsive light curves: in particular, their fast rising phase to light maximum and only a portion of their slow decay, but involving large emission fluxes. We deal with events of moderate power with maximal increase in the U-band from $1^m$ to $3^m$.

We propose here a possible scenario of the spatial and temporal development of these events (Figure 1). Let us suppose that at flare onset a powerful primary energy release takes place. It is located in one or several low-lying loops. We assume that the primary energy releases occurs above the chromosphere, but at low heights, and that the primary process affects low-lying layers up to the upper photosphere with little effect at coronal levels. For instance, it may propagate down by protons with energies $E \geqslant 10\,\text{MeV}$ or by electrons with $E \geqslant 100\,\text{keV}$, accelerated by the pinch-effect or other mechanisms.

The impulsive optical continuum emission, forming between the chromosphere and photosphere, may be close to equilibrium radiation. For $T = 2 \cdot 10^4\,K$, since the emission arises from a rather dense region, its area will be small, $S \leqslant 10^{18}\,\text{cm}^2$. It seems possible that such an emission source expands with velocities of the order of hundreds of km/s. Subsequently, the thermal disturbance propagates along one or several coronal loops, affects a large area in the remote from the primary source part of the loop and there leads to considerable gas-dynamic motions. Kostjuk and Pikel'ner (1974) pioneered the modern analysis of the

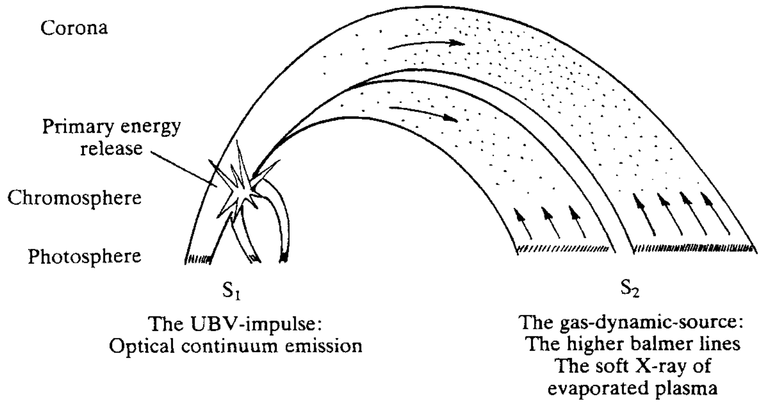

**Figure 1.**

secondary process during solar flares. Later their ideas for solar flares have been developed further in several papers (see reviews by Fisher, 1986; Katsova and Livshits, 1988 and references therein). During the course of ten years we have developed a gas-dynamic model for stellar flares on red dwarf stars (e.g. Katsova, Kosovichev, Livshits, 1981).

General features of this consideration are the following: primary energy release occurs above the chromosphere; plasma is heated strongly in the upper chromospheric layers. When the energy flux reaches the deeper layers of chromosphere, a downward-moving shock wave forms. The gas behind this radiative shock wave front is compressed by about a factor of 100, and a thin emission source with $T = 10^4$ K and hydrogen atom density of about $10^{15}$ cm$^{-3}$ forms. Let us refer to this source as a "low-temperature condensation."

Moreover, the impulsive influence on the chromosphere leads to the evaporation of hot gas toward the coronal part of loops. It can be accompanied by the appearance of soft X-ray radiation. This "evaporation" process is directly observed on the Sun.

Thus, in this scenario the observed optical continuum emission (for instance, in the U-band flare light curve, as shown on Figure 2 for YZ CMi, observed by Doyle *et al.*, 1988) can be separated into two parts: (1)—impulsive component, and (2)—the hydrogen recombination radiation from the low-temperature condensation region, which appears 1 minute after (1) and has a broader time-profile. The second maximum in the U-band is often coincident with the maximum of hydrogen line emission, and accounts for about 20% of the continuum intensity. The appearance of a secondary maximum in flare light curves is a common feature. The first component is observed to be (Panov *et al.*, 1988) somewhat bluer than that of recombination radiation from a gas condensation with $T = 10^4$ K. This is based on computations of hydrogen radiation in a low-temperature condensation. A notable feature of spectral observations is the small slope of the Balmer decrement at the time of maximum of $H_5$–$H_9$ line emissions.

Our model makes it possible to compute the range of physical parameters of emission source, and to explain the appearance of quoted decrements. For the

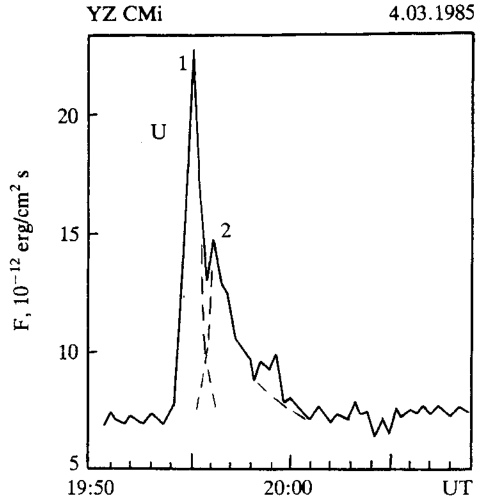

**Figure 2.**

flare on YZ CMi on 1985 March 4 (see Figure 2), Katysheva and Katsova (1990) find that typical values of physical parameters in the flaring source are the following: temperature $T \approx 12{,}000$ K, electron density $n_e \approx 3 \cdot 10^{13}$ cm$^{-3}$ and optical depth at the L$\alpha$-line centre $\tau(\mathrm{L}\alpha) \approx 2 \cdot 10^6$. Similar physical characteristics of the emitting source are derived from an analysis of Balmer decrements of this flare and some others, given by Katsova (1990). It is a necessary consequence of the model that the optical continuum emission appears at the time when the slope of the Balmer decrement becomes less steep, independently of the values of the source parameters. This may be due to the fact that the less steep Balmer decrement arises when the Balmer emission is blocked (i.e. the optical depth of the $H_{10}$-line becomes equal to 1). As LTE conditions are approached, continuum emission occurs. In a number of cases, it can lead to the appearance of a secondary maximum on the descending part of the U-band light curve, and more seldom on the B- and V-bands. A separation of the optical continuum emission is shown on Figure 2. Assuming that the lines are formed in low-temperature condensations, we find that the intensity of the optical continuum at the U-band accounts for about 10%–20% of the total intensity at the time of maximum line emission. It should be noted that if the area of the gas-dynamic source $S_2$ turns out to be large enough, up to $10^{19}$ cm$^2$, then the area $S_1$ is a factor of up to 10 less because the temperature of the optical continuum source is a factor of 2–2.5 greater.

In conclusion it is worthwhile to note that the proposed advanced development of the gas-dynamic model is due to the following recently observed features:

1. the gas-dynamic model predicts that the formation of shock waves moving down into the chromosphere must be accompanied by a short burst in far-UV-lines ($T > 10^5$ K). A burst with the expected intensity and duration in the CIV-line has been observed by the ASTRON satellite. However it did not occur just at U-band flare onset, as expected, but 50 seconds later (Burnasheva

*et al.*, 1989, Katsova, Livshits, 1989). This delay can be interpreted as the results of the propagation of a thermal wave along the length of a loop $10^{10}$ cm long with a velocity of 2000 km/s. Such a velocity is typical for thermal waves on the Sun.

2. the weak correlation or anticorrelation of the soft X-ray emission flare time profile with that of the U-band (Ambruster *et al.*, 1989) and the closer correlation of soft X-ray and H$\gamma$-line profiles (Butler *et al.*, 1989) are well established observations. The soft X-ray emission of both stellar flares and solar ones arises as a result of the gas-dynamic processes, namely, during evaporation of hot plasma into a coronal loop. The soft X-ray radiation during both the primary energy release and the optical continuum pulse is weak enough, because the value of $S_1$ is small, and the X-ray emission is absorbed when it comes out from the region between the photosphere and chromosphere, where the column density is greater than $\Delta\xi = n\,\mathrm{d}z = 2 \cdot 10^{19}\,\mathrm{cm}^{-2}$. Thus, a closer connection between the soft X-ray emission and the hydrogen line emission from a low-temperature condensation is a natural consequence of the theory.

Why is this scenario appropriate for flares of moderate power only, with $\Delta U = 1^{\mathrm{m}}$–$3^{\mathrm{m}}$? Weak fast flares can occur in small-scale low loops and do not expand in large coronal loops, or the first pulse during such a flares can be lacking. Let us call such events "true gas-dynamic" flares. Our gas-dynamic model explained the shortest observed flares (Schwartzman *et al.*, 1988) and related the minimal duration of events to the characteristic time of development of a gas-dynamic process—several tenths of a second, that is, close to the ratio of the height scale to the sound speed.

Most energetic flares are complicated as a rule, with possible repeated realization of the process of primary energy release. For a single primary energy release, during large flares this process can be distinguished by the penetration of a powerful disturbance, propagating from one base to the other, into deep layers, up to the upper photosphere. Then, the level of the optical continuum emission during the second pulse can be as high as on the first one and the flux ratio of the optical continuum to the line emission remains approximately the same for both pulses.

The following questions are of particular interest: (i) whether these flares are accompanied by impulsive soft X-ray emissions; and (ii) whether the Balmer decrement becomes less steep during the course of these events.

The proposed scenario allows us, at least in principle, to derive the temporal profiles of emission lines during the gas-dynamic phase of stellar flares. A further test would be to search for Doppler shifts of X-ray lines.

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