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On the Origin of Large X-ray Flares on RS CVn Subgiants

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Abstract. We carried out the gas-dynamic simulation of physical processes in giant loops during decay phase of long-duration X-ray flares on active late-type stars, in particular, UX Ari. Soft X-rays arise in dense, very hot giant loops ($n = (1-4) \cdot 10^{11}$ cm^{-3}, $T \approx 100$ MK and the area $S \approx 8 \cdot 10^{21}$ cm^2) and last as long as the plasma is heated in the upper part of the loop system. Commonly an analysis of such events suggests that the total flare energy is provided by the magnetic energy in a loop volume. It is required magnetic field strengths as much as 1–3 kG, i.e. photospheric values of the magnetic field strength in the corona. Powerful events in giant loops can be a result of reconnection of large-scale magnetic fields. We estimate the energy of the current component of the magnetic field occurring after perturbation of a steady-state MHD configuration. Two cases are considered: stretching out of the global and large-scale magnetic fields by the stellar wind or by CME. In both situations this energy turns out to be enough to provide the energy for large prolonged stellar flares in all the streamer belt around the star or in its part.

1. Introduction

During last ten years powerful flares on active late-type stars have been observed with satellites GINGA, EUVE, ROSAT, ASCA and BeppoSAX. These observations were carried out in the soft X-ray and EUV spectral ranges. The most of these powerful prolonged flares are registered on late-type subgiants which are the components of the RS CVn binaries (Graffagnino et al. 1995; Osten & Brown 1999) as well as on the active young G star AB Dor (Güdel et al. 1999, Maggio et al. 2000).

While impulsive flares lasting less than 100 s usually occur on red dwarfs, phenomena on subgiants discussed here can last one day and more. The plasma temperature in flare maxima exceeds $100 \cdot 10^6$ K, and high values of the temperature and the emission measure $EM \approx 3 \cdot 10^{54}$ cm^{-3} keep for many hours. The energy release in the soft X-rays of such flares comes to $10^{35} - 10^{37}$ erg, that exceeds the energy release of the most powerful solar events for 5–6 orders of magnitude.

In the last papers concerning analysis of long-term X-ray flares one is supposed that their energy is provided by transformation of the magnetic field energy in emitting region into other forms. Otherwise, in order to estimate this energy, we use as for impulsive flares the expression $E_{\rm tot} = (B^2 - B_0^2) \cdot V_{\rm loop}/(8\pi)$, where B, B_0 are magnetic field strengths at the end and at the beginning of a process, the volume $V_{\rm loop}$ for long-term flares is adopted to be equal to the loop volume (Maggio et al. 2000). This formula gives that the strength B is a few kG, that is absolutely unacceptable for magnetic fields in coronae of considered stars. Consideration of this contradiction initiated our work.

2. Modelling of the Soft X-ray Flare Decay

We present here the first results for the flare on UX Ari on 1997, August 28–30, registered not only the soft X-ray emission, but also the hard one in spectral range $h\nu > 20$ keV (Pallavicini & Tagliaferri 1998). Authors estimated the total energy release of this flare in the soft X-rays larger than $6 \cdot 10^{36}$ erg. The temperature T and the emission measure EM_V in this flare were presented by Pallavicini & Tagliaferri (1998) only for three exposures: at the maximum, at the temperature decrease and the end of the flare. To provide a definite modelling, we adopt that values of the temperature fall into a middle of each exposure.

The binary system UX Ari consists of two component: the primary is the G5 V star with the radius $R_{G5} = 0.93\ R_\odot$ and the secondary is the K0 subgiant with the radius $R_{K0} = 4.7\ R_\odot$. The gravity force on the subgiant surface is quite low, $g_{K0} = 880$ cm c^{-2}; it is about 30 times weaker than solar one. The photometric period of rotation is very close to an orbital one: $P_{orb} = 6.438^d$.

The second RS CVn binary analyzed here briefly as a sample of a superflare is BH CVn = HR 5110 (F2 IV + K2 IV); its parameters are $P_{orb} = 2.61^d$, the mass ratio is $M_2/M_1 = 0.54$ and the adopted value of M_1 is 1.5 $M_\odot$.

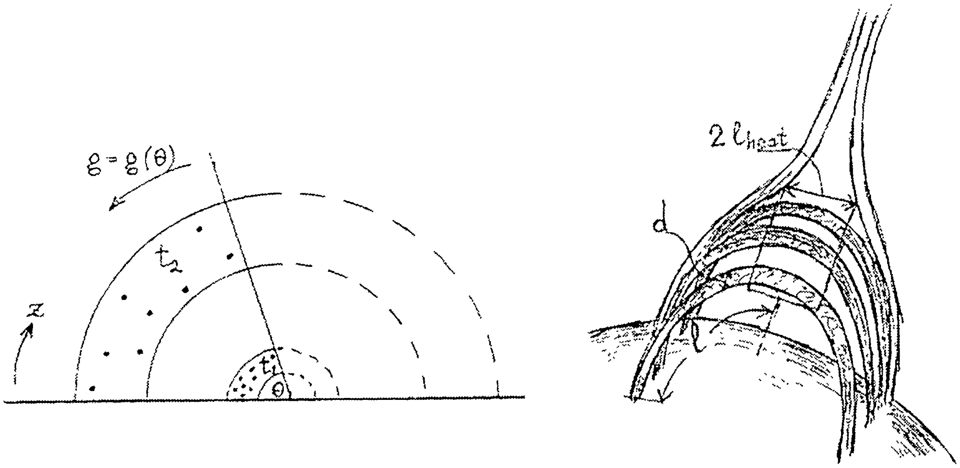

Figure 1. Left panel – a schema of the loop for two moments. g is the gravity depending on the angle θ. Right panel – the system of giant coronal loops. d is a diameter of each loop, 2 l – loop's length, 2 l_{heat} – heated part of loop.

By analogy with dynamic flares on the Sun, we suppose that during long-duration stellar flares giant loops are formed, and their subsequent evolution is due to a delivery of the energy into the coronal part of the loop. Using an solar experience (Getman & Livshits 2000), we'll consider a gas-dynamic stage of the flare, when the magnetic field does not already effect on the developing process, except the confinement of a plasma inside the magnetic loop and a fact that the thermal conduction becomes anysotropic one. At this dynamic phase a ratio of the gas pressure to the magnetic one in giant loops (at large coronal heights) $\beta = 8\pi p/B^2$ becomes to be greater than 1.

The X-ray flare source is modelled by the heating of the fixed mass of the gas. We solve the one-dimensional gas-dynamic equations taking into account the gravity (varies with height), the thermal conduction and radiative losses. The heating near the top of the giant loop was distributed over the time and space (along the mass lagrangian coordinate). The process substantially depends on the prolonged heating near the top of the loop, which is given in the following form:

$$H = H_0 \cdot \exp\left\{-\left(\frac{s - s_m}{s_1}\right)^2\right\} \cdot \exp\left\{-\left(\frac{t - t_2}{t_1}\right)^2\right\},$$

where H_0 is the maximal heating in erg g^{-1} s^{-1}, s_m is the Lagrangian coordinate of the loop top, s_1 is the characteristic spatial scale, t_1 is the characteristic heating decay time, t_2 is the rise time of heating. The heating function included also an additional heating which is equal numerically to radiative losses of the plasma at initial moment, and it never exceeds 10% of the maximal heating.

The previous code for solar flares was modified in order to carry out computations for stellar conditions of various gravity and higher energy of the process. In particular, for values of the temperature above $20 \cdot 10^6$ K, the radiative loss function was changed according to the expression $L(T) = 10^{-24.73}\,T^{0.25}$ erg cm^3 s^{-1}, obtained from the calculations by Mewe et al. (1995).

The plasma is able to expand and to shrink in the giant loop of the semi-circle shape (see Fig. 1). Evolution of the coronal loop can not explain sharp rise of the soft X-ray radiation and its slow decay, therefore during modelling we were forced either to compute the growth phase separately from the decay phase or to restrict motions of the plasma velocities no more than 10 km/s. As a rule, the results obtained by these approaches for the decay phase are in close agreement.

The initial model for given calculations is: the temperature in the isothermal hydrostatic loop $T = 20 \cdot 10^6$ K, the density at the loop base $n = 4 \cdot 10^{11}$ cm^{-3} and the semi-length $l = 2 \cdot 10^5$ km.

Fig. 2 represents the dependence of the temperature at the top of the loop, the emission measure of the hot gas with $T > 50 \cdot 10^6$ K and the length of the semi-loop on the time. These calculations are made with $H_0 = 4.5 \cdot 10^{13}$ erg/(g $\cdot$ s), $t_1 = 5^h$, $t_2 = 0.5^h$. The length of the semi-loop reaches the solar radius, increasing by a factor of 3.5. Within 5 hours after the beginning the density changes along the loop from $n = 3.5 \cdot 10^{11}$ cm^{-3} at the base to $n = 7 \cdot 10^{10}$ cm^{-3} at the top.

Thus, the first conclusion is that the long-duration X-ray emission is a consequence of prolonged heating of the upper part of the loop. This agrees with results of Betta et al. (1997).

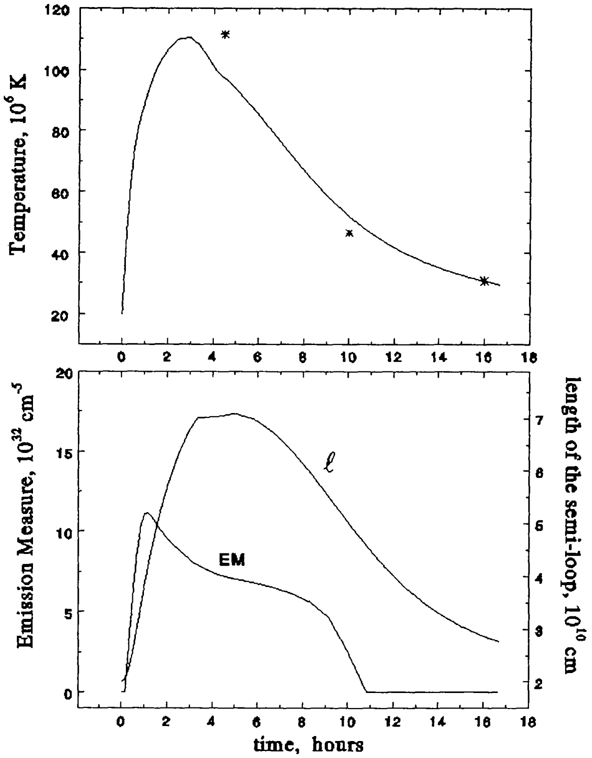

Figure 2. Temporal behaviour of the temperature at the top of the loop, the emission measure and the length of the half of the loop. Asterisks (*) represent values of the temperature derived by Pallavicini & Tagliaferri (1998) from flare observations on UX Ari

The total energy injected into one half of the loop during 15 hours is equal to $H_f = 6.2 \cdot 10^{14}$ erg cm^{-2} In order to get the observed value of the volume emission measure and the total flare energy we have the corresponding computed values for one loop to multiply by an "effective" flare area : $EM_V = S_1 \cdot EM_l$ and $E = S_2 \cdot H_f$. For the UX Ari flare we obtain $S_1 \approx S_2 \approx 8 \cdot 10^{21}$ cm^2. This estimation of the area of the large long-duration flare is quite reliable. Unfortunately, till now modelling does not allow to find a diameter of loops and their number independently of one another.

Modelling of the superflare on HR 5110 leads to similar results (the length of the semi-loop is $l = 8 \cdot 10^{10}$ cm), but the heating function decays slower as compared to the UX Ari flare.

3. The Magnetic Field as the Energy Source for Large X-Ray Flares

The energy and the size of the flare under consideration are very high. Reconnection of large-scale magnetic fields rather than local ones can provides the energy of such powerful prolonged events.

First of all, we can consider the global (dipole) magnetic field stretched out by a stellar wind. To estimate the energy of the current component of the magnetic field we use the steady-state solution presented by Koutchmy & Livshits (1992). The energy of this field can be obtained by integration over the volume out of the sphere with the radius R, then

$$E = 2\frac{m^2}{3\,R^3}\left(1 - \frac{2\,Re_m + 2}{(Re_m + 2)^2}\right) \approx 2\frac{m^2}{3\,R^3},$$

where Re_m – magnetic Reynolds number. The value E at large Re_m distributes in two among the energy of the dipole field $m^2/(3\,R^3)$ and the energy of the additional current component. If to introduce the value of the magnetic field near the pole of the dipole B_*, we can rewrite the result as $E \approx (1/3)\,B_*^2\,R_*^3$, (see also Veselovsky 1999 for the heliosphere).

The more real is a situation when flares occur in the large-scale magnetic fields of large activity complexes on the stars. The energy of such phenomena can be estimated if to approximate the magnetic field by a flat (two-dimensional) dipole. Using the solution by Somov & Syrovatskii (1974), similar calculations give the estimation of the energy $E = (9/8)B_y^2\zeta^3$, where B_y – the magnetic field in the loop, ζ – a distance from the 2D-dipole to the loop top; ζ is close to an extension of the loop system along the neutral line of the large-scale magnetic field. For fields of tens of G and large scales of loop systems, we obtain naturally the energy $E \leq 10^{32}$ erg on the Sun and up to 10^{37} erg on late-type subgiants, that is enough for development of these non-stationary events.

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