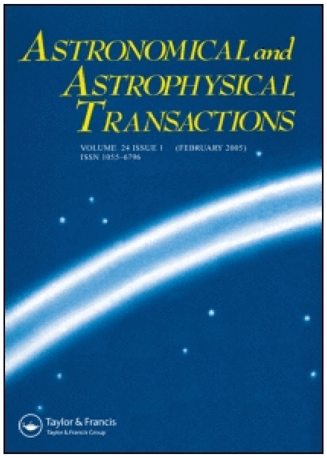

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MODELLING LONG DURATION X-RAY FLARES ON THE UX Ari LATE-TYPE SUBGIANT

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Modelling of the gas-dynamic process in giant coronal arches for interpretation of the large prolonged X-ray flare on subgiant UX Ari with less than solar gravity is carried out. The case where plasma is heated near the top of the giant loop is considered taking into account the thermal conduction and radiative losses. The observational duration of the soft X-ray flare radiation and peculiar features of the temporal behaviour of the temperature can be explained if this process is developed under prolonged heating in giant loops with densities more than 10^{11} cm^{-3}. The model of the X-ray flare source, agreeing with the observed value of the emission measure, includes around 8 loops lifting up to heights around 10^{11} cm, i.e. more than 0.2 R_*. It is proposed than the energy of such non-stationary phenomena is supplied from the large-scale (global) magnetic fields, and these flares are not a result of evolution of local magnetic fields as happens during impulsive stellar flares.

KEY WORDS Late-type stars, stellar activity, X-ray flares, magnetic fields

1 INTRODUCTION

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

While impulsive flares lasting less than 100 s usually occur on red dwarfs, the phenomena on subgiants discussed here can last a day or more. The plasma temperature at the flare maxima exceeds 100×10^6 K, and high values of the temperature and the emission measure persist for many hours. The energy release in the soft X-rays of such flares comes to 10^{35}–10^{36} erg, that exceeds the energy release of the most powerful solar events by 4–5 orders of magnitude.

To analyze the data of these huge prolonged phenomena the Palermo–Harvard 1D-hydrodynamic model of plasma confined in a coronal loop (PH code) is often used (Peres *et al.*, 1982). It is well developed and applied to an interpretation of observations of solar and stellar flares lasting about 100 s (Reale *et al.*, 1993; other references are in Betta *et al.*, 1997). These authors used a few additional suppositions, in some cases they include a scaling law for coronal loops in framework of the gas-dynamic consideration.

Taking into account the experience of analysis of analogous phenomena on the Sun, we decided to come back to the pure gas-dynamic approach for interpretation of data on powerful prolonged stellar flares. Since gas-dynamic processes are developed more effectively when the gravity is smaller, we carry out this modelling first for the K0 subgiant, a component of UX Ari binary.

This paper contains a brief discussion of the X-ray flare observations on UX Ari and the gas-dynamic numerical modelling of this event, that allows us to estimate the physical conditions in the X-ray flare source. A new idea about the origin of the flare energy in such events is discussed.

2 SOME OBSERVATIONAL DATA OF LONG DURATION FLARES ON UX ARI

Prolonged flares in the UX Ari binary occur more often than in other RS CVn systems. One such non-stationary event on this star was registered with the *ASCA* satellite on 1994, August 29 during the growth and the maximum of the X-ray flare; the maximal temperature was $T_{\max} = 220 \times 10^6$ K and the emission measure was $EM = 310^{54}$ cm^{-3} (Güdel *et al.*, 1999). Then, three flares with durations of 5.2, 23.0 and 21.5 hours were detected in 1995, November 9, 20 and 22 during the long-term monitoring with the Extreme Ultraviolet Explorer (Osten and Brown, 1999). Note that the whole period 1995, November 19–25 can be considered as a single prolonged non-stationary process on this star.

During one of the most powerful flares on UX Ari on 1997, August 28–30 not only the soft X-ray emission was registered, but also the hard emission in the spectral range $h\nu > 20$ keV (Pallavicini and Tagliaferri, 1998). The authors estimated the total energy release of this flare in the soft X-rays to be larger than 6×10^{36} erg that is comparable with the energy release of a one-day flare registered by *GINGA* satellite on this star (Tsuru *et al.*, 1989).

Modelling of the most powerful phenomena faces great problems.

During the flare on UX Ari on 1997, August 29, lasting more than 24 hours and when a hard X-ray emission of 20–100 keV was found, it became possible to observe all the stages of the flare process in different energy channels. This allowed us to determine the physical conditions in the flare source quite reliably. Unfortunately, the temperature T and the emission measure EM_V in this flare were presented by Pallavicini and Tagliaferri (1998) only for three exposures: at the maximum, for the temperature decrease and at the end of the flare. To provide a definite modelling, we adopt that the values of the temperature fall into the middle of each exposure.

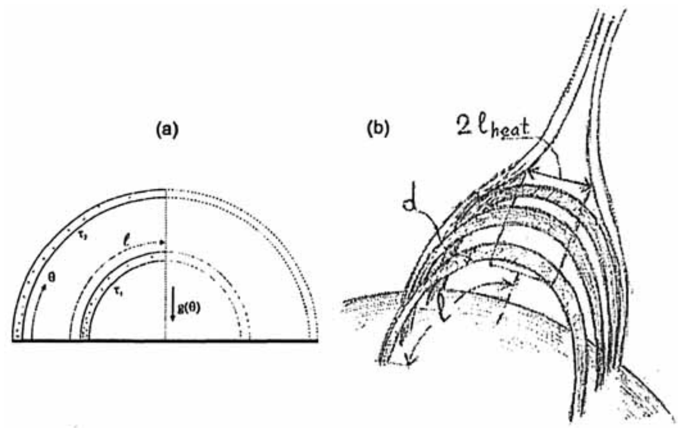

Figure 1 (a) – the sketch of half the loop at two times; (b) – the scheme of the loop system.

The binary system UX Ari consists of two component: the primary is the G5 V star with radius $R_{G5} = 0.93R_{\odot}$ and the secondary is the $K0$ subgiant with radius $R_{K0} = 4.7R_{\odot}$. 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 the orbital one: $P_{orb} = 6.438^d$. For more information on this system see the catalog by Strassmeier *et al.* (1988).

3 MODELLING THE SOFT X-RAY FLARE DECAY

Our simulation is concerned with flares with a long decay of soft X-ray emission (LDF). Such events observed on the Sun were studied by Z. Svestka and colleagues (they called them dynamic flares, see Svestka *et al.* (1995) and references therein). For an explanation of observational data an idea on the post-eruptive energy release was proposed. It is supposed here that the coronal mass ejection opens magnetic force lines, and then this magnetic configuration returns to its initial state.

According to Getman and Livshits (1999, 2000), the first active phase of LDF consists of a few subsequent elementary acts of reconnection in the vertical current sheet. Then the dynamic stage of the process begins when one (or several) giant coronal loop is formed and the energy input into its top provides an expansion and lifts up the loop and its soft X-ray radiation for a prolonged time. During this dynamic phase the ratio of the gas pressure to the magnetic one in giant loops (at large coronal heights) $\beta = 8\pi p/H^2$ becomes greater than 1.

A numerical code for simulation of LDFs on the Sun was developed by Getman and Livshits (1999, 2000). Indeed, the energy balance in the giant loop (in the shape of semi-circle, see Figure 1) was analyzed by solving the one-dimensional gas-dynamic equations taking into account the gravity (which varies with height), the thermal conduction and radiative losses. The heating near the top of the giant loop was distributed over 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:

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

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 X-ray flare source is modelled by the heating of the fixed mass of the gas. The boundary conditions are the following: the pressure at the foot and at the top of the loop is temporally constant; the temperature at loop's foot is fixed and a heat flux at both boundaries is absent. The initial conditions correspond to the isothermal hydrostatic loop with these parameters: the number density at the bottom, the temperature there ($T > 10^6$ K) and the length of the semi-loop. This dynamic phase of the LDF was investigated more elaborately to get the best fit with the values derived from observations.

The previous code for solar LDFs by Getman 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 20×10^6 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 choice of values for free parameters of this modelling was the following: first of all, for the chosen parameters of the heating function we modelled the temperature behaviour at the decay phase of the X-rays. The value H_0 mainly defines the maximum value of the temperature for a given LDF and the value t_2 defines the temperature decay rate.

In general, we carried out the modelling with initial densities from $2 \cdot 10^{10}$ to 5×10^{11} cm^{-3}, with an initial semi-length of the loop $l = (0.5\text{–}5) \times 10^{10}$ cm and heat fluxes varied in wide ranges. For these processes, the total energy of which doesn't exceed 10^{37} erg, the loop top temperature turns out to be in the ranges of (10–200) $\times 10^6$ K. For similar initial models two sets of solutions can be separated, with a weak and strong loop expansion. The behaviour of the temperature in this powerful long decay flare on UX Ari can be understood only in the case of the strong loop expansion with the initial number density (3-5) $\times 10^{11}$ cm^{-3}.

Thus, plasma heated near the top of the loop is expanded. Then after the maximum of heating, the expansion of the giant loop changes to compression. For the powerful processes considered such a change goes on differently in diluted and dense loops. In the first case which can be referred to as coronal evolution, it happens smoothly and the temporal behaviour of the temperature is presented as a part of the parabola. In the second case the slow expansion changes to fast compression, accompanied by a sharp, almost exponential temperature decrease. That or another type of solution is obtained when the density in the loop turns out

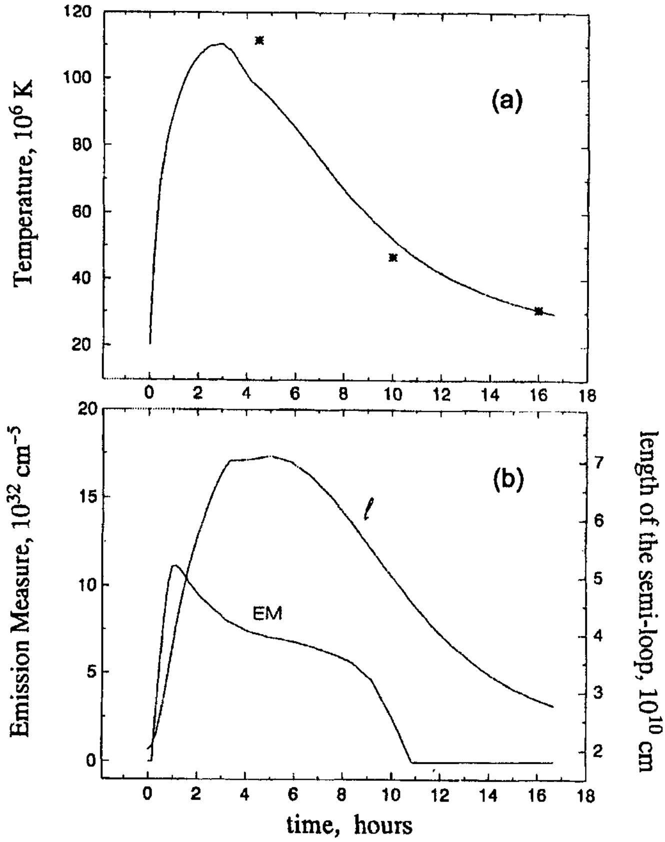

Figure 2 Temporal profiles of the temperature at the top of the loop (a), the emission measure of the hot gas with $T > 50 \times 10^6$ K and the length of the semi-loop (b). Three observational values of the temperature are marked by asterisk. The emission measure is referred to one half of the loop.

to be greater or less than the value 4×10^{11} cm^{-3}; (this density corresponds to the initial model with the temperature $20 \cdot 10^6$ K and the semi-length $l = 2 \times 10^5$ km and depends only weakly from these values). Figure 2 represents the dependence of the temperature at the top of the loop, emission measure of the hot gas with $T > 50 \times 10^6$ K and the length of the semi-loop from the time. These calculations are made with $H_0 = 4.5 \times 10^{13}$ erg g^{-1} s^{-1}, $t_1 = 0.5^h$, $t_2 = 5^h$ and heating of a quarter of the loop nearby its top. We were able to get an agreement between modelled and observed shapes of the dependencies $T(t)$ for such a minimal density, which is in one order of magnitude greater than that in large LDFs on the Sun. The length of the semi-loop reaches the solar radius. 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.

For the interpretation of flare data, the following simple scheme can be considered. Let the flare source consist of the set of m loops with the length of 2 l each (see Figure 1b). Then the volume emission measure can be represented as:

$$EM_V = S_1 EM_l = 2m\, d^2 \int_0^l n_e^2\, \mathrm{d}l,$$

where d is the loop diameter. EM_V is derived from X-ray observations, and

$$EM_l = \int_0^l n_e^2\, \mathrm{d}l$$

is taken out as a result of our modelling.

The value of the total energy of the process E is:

$$E = S_2 H_f = 2ml_{\mathrm{heat}}\, d \iint H\, \mathrm{d}s\, \mathrm{d}t,$$

where l_{heat} is the length of the heated part of the loop (this value is taken as a parameter at the beginning of the process). The value of summary heating is an integral over the Lagrangian coordinate s and over the time: $H_f = \iint H\, \mathrm{d}s\, \mathrm{d}t$ (in terms of cm^{-2}) is received as a result of the program.

The simulation is carried out for the wide interval of initial densities at the top of the loop. Note that on the one hand the value l_{heat} must not be very small, otherwise strong non-linear effects arise during heat propagation; and on the other hand it must not be very large, otherwise H_f greatly increases with the same value of H_0. According to different physical suppositions the value l_{heat} must be close to d, but some difference of the value l_{heat}/d from 1 can arise due to features of the loop top heating and geometric factors. On comparing the simulated results with observational values of the energy E and the volume emission measure EM_V, results of calculations with close values of S_1 and S_2 (i.e. l_{heat} and d) are preferable.

This modelling allows us to describe the variation of the temperature (Figure 2) and leads to a maximum of the values of emission measure of the semi-loop $EM_l \approx 1.1 \times 10^{33}$ cm^{-5} and integral heating $H_f = 6.2 \times 10^{14}$ erg cm^{-2} for the moment $t = 16^h$. The final solution was chosen in the case when parameters S_1 and S_2 are close to each other, i.e. $l_{\mathrm{heat}}/d \approx 1$.

From our solution $l = 7 \times 10^{10}$ cm (see Figure 2) and by choice the value of parameter $l_{\mathrm{heat}} \approx 0.28l$ we obtain $d = 2 \times 10^{10}$ cm and $m \approx 8$.

4 ENERGY SOURCE FOR LONG DECAY FLARES

The energy of the flare under consideration is very high. In order to provide such an amount of the energy it is necessary that oppositely directed magnetic fields with a strength of 1.6×10^3 G annihilate in a whole volume occupied by the system of giant coronal loops ($V \approx EM_V/n^2 \approx 6 \times 10^{31}$ cm^3). Fields with such strength cannot exist in the outer stellar atmosphere, in particular in the inner corona. Therefore the reconnection of local magnetic fields is unable to provide the necessary energy for LDFs. It makes sense to consider analogous processes in large-scale magnetic fields.

The energy deposited in the heliospheric current sheet can be estimated from the following. Indeed, the *global* magnetic field at the minimum of the solar activity is close to a dipole whose axis is close to the rotational one. The force lines of interplanetary magnetic field follow the radial direction at large distances from the Sun. The sources of such a field in the outer corona and distant parts of heliosphere can be simply represented as a superposition of the fields of the solar dipole and a thin ring current in equatorial area. Of course, it is supposed that the solar (or stellar) wind is effective enough to take force lines from the corona away.

In this case, according to Veselovsky (1999), the energy saved in this current is equal in the order of magnitude to the dipole field energy which is in the layers above the beginning of the wind outflow. The integral along the volume from the solar dipole field energy for $r > R_\odot$ is equal to $B_\odot^2 R_\odot^3/3$. If the field near the solar poles is $B_\odot = 1\,G$, the current energy is 1.1×10^{32} erg. Notice that integration of the solar wind from the Source Surface does not change this estimate. In this case the current dissipates in the corona, in the streamer belt. That's why it is not accidental that the energy of this current in the heliosphere estimated in such a way is close to the upper limit of the energy of non-stationary processes on the Sun.

The stellar wind from the active component of the UX Ari binary is apparently more powerful than solar one. For the $K0$ subgiant radius 4.7 $R_\odot$ and the field on the dipole axis 10 G, we have an estimate of the current energy more than 10^{36} erg. Nowadays magnetic fields with the dipole-type structure on active late-type stars are beginning to be measured, and their strengths turn out to be tens of G. That's why there is a possibility of explanation of the energy input into giant flare loops due to the dissipation of currents in a circumstellar envelope nearby the active subgiant.

Still, the most possible reason for the appearance of powerful prolonged flares is the reconnection of the large-scale magnetic fields near the magnetic equator. Here the size of large hills of the magnetic field may be smaller but field strengths are essentially higher compared with the global parameters of the star: the areas of polar regions and the magnetic field strength therein. This follows from the observations of large spots in the photosphere of subgiants which are components of RS CVn binaries and from the existence of active complexes and of active longitudes in them. The link of long duration flares with transients (Coronal Mass Ejections) which often appear on the Sun above the neutral line of large-scale magnetic field can be considered as an argument in support of this point of view. It is obvious that for binary systems we cannot exclude the effects of interaction between magnetospheres. Indications of the existence of powerful plasma effects in active subgiant surroundings in the above mentioned systems' structure can be obtained from radio observations.

5 CONCLUSIONS

The modelling of the gas-dynamic process in giant coronal loops allows us to describe the duration of the soft X-rays and the peculiar features observed in the temporal behaviour of the temperature both in weak and in the most powerful prolonged flares on active late-type stars. The temporal dependencies of the temperature as well as the emission measure, derived from observations of large LDFs, testifies that this process develops in very dense coronal loops ($n = 10^{11}$–10^{12} cm^{-3}). In the UX Ari flare on 1997, August 29 such dense loops lifted up to heights of 10^{11} cm, i.e. more than $0.2R_*$. These powerful events are interpreted here in the framework of a model of a set of 8–10 loops, but not of a one-loop model.

In contrary to the Palermo–Harvard 1D-hydrodynamic code, we consider only the pure gas-dynamic process, without including a statistical scaling law for coronal loops into the set of gas-dynamic equations. Therefore in each solution we obtain an intrinsic dependence of the temperature at top of the loop on the emission measure, $T_{\rm top}(\sqrt{EM})$.

In order to interpret the observational behaviour of $T_{\rm top}(\sqrt{EM})$ we consider the soft X-rays as a sum of the radiation of a set of isolated loops which are forming at different stages of the active phase of long-duration flares.

Strictly speaking this consideration is concerned with a dynamic phase of LDFs. The active phase of LDFs can be investigated with an analogous approach when X-ray data with high temporal resolution become available.

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