Pergamon
www.elsevier.com/locate/asr
Available online at www.sciencedirect.com
SCIENCE DIRECT•
doi: 10.1016/S0273-1177(03)00326-0

NEW MODELLING OF A LARGE LONG-DURATION X-RAY FLARE ON UX ARI

I.M. Livshits[1], M.A. Livshits[1], and R. Pallavicini[2]

[1] *Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation, Russian Academy of Sciences, 142190 Troitsk, Moscow Region, Russia*
[2] *INAF–Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, I-90134 Palermo, Italy*

ABSTRACT

We have carried out a new gas-dynamic simulation of the physical processes occurring in a fixed amount of plasma confined in coronal loops heated in the top. We chose the solution which explains both the time behaviour of the temperature and the energetics of the X-ray emission of a long-duration X-ray flare observed by BeppoSAX on UX Ari. This analysis makes it possible to obtain the length of the loop and the distribution of the temperature and density along the loop (with $T_{max} \approx 100$ MK and $n_e = (1-3) \cdot 10^{11}$ cm^{-3}), as well as to estimate the X-ray flare area $S \approx 10^{22}$ cm^2. Franciosini et al. (2001) have developed a time-dependent model of magnetic reconnection for the decay phase of the same flare. Our gas-dynamic solution corresponds to reconnection of middle-scale magnetic fields which in the model by Franciosini et al. (2001) corresponds to a degree n of the Legendre polynomial close to 5. The magnetic field strength is estimated to be about 100 G near the loop top. We argue that the shrinkage-effect plays a more important role during large long-duration X-ray stellar flares than in solar two-ribbon flares. © 2003 COSPAR. Published by Elsevier Ltd. All rights reserved.

INTRODUCTION

During the past decade several powerful long-duration flares on active late-type stars have been observed at X-ray and EUV wavelengths by GINGA, EUVE, ROSAT, ASCA and BeppoSAX. Most of these powerful events originated on subgiant components of the RS CVn binaries as well as on active young K-type stars like AB Dor (Graffagnino et al. 1995, Osten & Brown 1999, Pallavicini & Tagliaferri 1999; Güdel et al. 1999, Maggio et al. 2000).

While impulsive flares lasting less than a few hundred seconds usually occur on red dwarfs, the flares discussed here can last one day and longer. The plasma temperature at flare maximum exceeds $100 \cdot 10^6$ K, and emission measure as high as $EM \approx 3 \cdot 10^{54}$ cm^{-3} are observed. The energy release in soft X-rays in these powerful flares reaches $10^{35} - 10^{37}$ ergs, exceeding the energy release of the most powerful solar events for 5–6 orders of magnitude.

X-ray observations of a large flare on UX Ari lasting for about 1 day were presented by Franciosini et al. (2001), who modelled successfully this flare by using the two-ribbon flare model developed by Poletto et al. (1988). They applied an approach elaborated earlier for the solar case, which assumes that a disruptive event opens an arcade of loops. The open field lines are then driven towards a current sheet formed above the magnetic inversion line, where they reconnect at progressively higher altitudes, forming a growing system of loops. The magnetic energy released in the reconnection process provides the continuous heating responsible for the X-ray emission during the flare.

The model by Poletto et al. (1988) assumes that along meridional planes closed field lines below the neutral point are described by Legendre polynomials P_n of order n while above the neutral points the magnetic field is radial (higher values of n imply smaller regions). By estimating the rate of magnetic energy release due

Adv. Space Res. Vol. 32, No. 6, pp. 1181–1186, 2003
© 2003 COSPAR. Published by Elsevier Ltd. All rights reserved
Printed in Great Britain
0273-1177/$30.00 + 0.00

to reconnection and by assuming that a fraction q (constant throughout the flare) is re-emitted in the X-ray band the observed soft X-ray light curve of this flare can be successfully reproduced. However, the solution is not unique and different magnetic field parameters, corresponding to values $n = 3$, 5, 9 and 17, can fit the observations equally well. In order to discriminate between these various possibilities, one can use the temporal behaviour of the physical parameters of the X-ray source. The temperature and emission measure profiles are available from Figure 5 of Franciosini et al. (2001). Therefore, we propose here to use the information on the flaring source derived from the X-ray light curves to get in formation on the strength of the magnetic field in the flare loop.

MODELLING OF THE SOFT X-RAY FLARE DECAY

Recently we developed an approach which allowed us to explain the general features of the long-duration stellar X-ray events on the basis on the gas-dynamic modelling of the evolution of giant coronal loops (Livshits I. & Livshits M. 2002). This approach is an extension to the stellar case of the gas-dynamic modelling developed earlier by us for long-duration solar flares. Our approach is different from that developed by Jakimiec et al. (1992) and, more recently, by Reale et al. (2002) who modelled stellar flares by using the Palermo-Harvard hydrodynamic code.

From an investigation of the general features of large long-duration solar flares Livshits et al. (2002) concluded that during the decay phase of X-ray flares, after the temperature maximum, the plasma evaporating from the chromospheric to the coronal part of a loop decreases significantly. This means that during the decay phase the temporal behaviour of the physical parameters of the plasma – temperature, density and velocity – are mostly determined by the heating and its temporal variation. Therefore, for long-duration stellar flares it is possible to restrict our consideration to the case of a pure coronal event with a fixed mass of the gas in the loop.

Let's emphasize that if to adopt that the long-lived X-ray loops exist during solar flares, so it requires, first of all, to maintain the energy balance: the plasma inside the loop tends to cool fast and the loop starts to shrink catastrophically; for prolonged stellar flares in the EUV-range the energy balance was considered by Katsova et al. (1999). If the required heating is provided, then the motions of coronal loops as a whole as well as plasma motions inside them can be explained by variations of the heating function with appropriate initial and boundary conditions.

Thus, we suppose that during long-duration stellar flares giant loops are formed, and their subsequent evolution is due to the input of energy into the coronal part of the loops. We do not specify the mechanism of plasma heating. It is an external on-going process which heats the plasma confined inside the loop. The heating is due to the reconnection process, but the energy is transferred into the loop by some poorly understood mechanism that could be either accelerated particles or shock waves. At present, even for solar flares the nature of the heating mechanism is far from being understood.

The magnetic field confines the plasma inside the magnetic loop and provides anisotropy of the thermal conduction (heat propagates along magnetic field lines). We model the decay phase of the flare at phases when the ratio of the gas pressure to the magnetic one $\beta = 8\pi p/B^2$ approaches the value 1 in giant loops at large coronal heights or even greater (for $T = 100 \cdot 10^6$ K, $n = 10^{11}$ cm^{-3} and B=100 G the value β is equal to 7).

We model the X-ray flare on UX Ari observed by BeppoSAX on 1997, August 28-30 (Franciosini et al. 2001). The binary system UX Ari consists of two components: the primary is the G5 V star with radius $R_{G5} = 0.93\ R_\odot$ and the secondary is a K0 subgiant with radius $R_{K0} = 4.7\ R_\odot$. The gravity at the surface of the subgiant is quite low, $g_{K0} = 880$ cm c^{-2}, i.e. about 30 times weaker than solar. The photometric period of rotation is very close to the orbital one: $P_{orb} = 6.438^d$.

The X-ray flare source is modelled by the heating of a fixed amount of gas. We solve the one-dimensional gas-dynamic equations by taking into account gravity (which varies with height), thermal conduction and radiative losses (see Livshits & Livshits 2002 for details). The heating near the top of the giant loop is distributed over time and space (along the mass Lagrangian coordinate). The process basically depends on the prolonged heating near the top of the loop, which has the following form:

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

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 of heating, t_1 is its rise time and t_2 is the characteristic heating decay time. The heating function includes also an additional heating term which is equal to the radiative losses of the plasma at the flare start and never exceeds 10% of the maximum heating.

The code originally developed by us for solar flares (Getman & Livshits 2000) was modified in order to carry out computations under stellar conditions of various gravities and higher energy release. 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 or to shrink in a giant loop of semi-circular shape (see Figure 1). The modelling of the coronal loop cannot explain simultaneously the sharp rise of the soft X-ray radiation and its slow decay; therefore during modelling we were forced either to compute the rise phase separately from the decay phase or to restrict plasma motions to velocities of no more than 10 km/s. As a rule, the results obtained by these two approaches are in close agreement for the decay phase.

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

Figure 2 shows the time dependence of the temperature at the top of the loop, as well as the time behaviour of the emission measure of the hot gas with $T > 50 \cdot 10^6$ K and the length of the semiloop. These calculations are made with $H_0 = 1.5 \cdot 10^{13}$ erg/(g · s), $t_1 = 0.83^h$, $t_2 = 13.3^h$. We model here only the decay phase of the flare (the positive values of time in Figure 2).

This computation shows that the process of plasma heating in the loop up to temperatures around 100 MK is accompanied by an increase of the length of the semiloop by a factor of 3.5 (assuming that its cross-section remains unchanged). In the solution presented in Figure 2 the fast shrinkage of the loop after the temperature maximum is weak; however, if heating at the rise phase occurs faster, then the maximum temperature exceeds 100 MK and the shrinkage effect is stronger.

The crucial point for the choice of the solution shown in Figure 2 with respect to others with lower densities is the fact that it must be able to explain simultaneously the temporal profile of the temperature and the energetics of the flare event. Indeed, in order to get the observed value of the volume emission measure and the total flare energy we have to multiply the computed values for one loop by an "effective" flare area: $EM_V = S_1 \cdot EM_l$ and $E = S_2 \cdot H_f$ (here H_f is the energy injected near the loop top through 1 cm^2). In the selected solution, from the comparison of the observed and computed emission measure of the semiloop we obtain $S_1 \approx 10^{22}$ cm^2. This choice of the numerical simulation corresponds to a total heating which is close to 10^{15} erg cm^{-2} during 24 hours. Therefore we obtain that S_2 is close to S_1. The energy of the process providing the observed X-ray radiation is around 10^{37} ergs.

Note that within 1 hour after the beginning of the observations the density changes along the loop from $n_e = 3 \cdot 10^{11}$ cm^{-3} at the base to $n_e = 7 \cdot 10^{10}$ cm^{-3} at the top.

DISCUSSION

It is interesting to compare the conclusions by Franciosini et al. (2001) with those derived from our analysis. The gas-dynamic modelling allows us to determine the size of the loops and the density of the plasma near the flare maximum when the temperature is close to 100 MK. The comparison of the inferred values with those given for four possible solutions by Franciosini et al. (2001) shows that the solution for the degree of the Legendre polynomial n=5 agrees with the results of the gas-dynamic modelling. Such a conclusion can be obtained by comparing the electron densities n_e for various n given in Table 3 of Franciosini et al. (2001) with the mean value of the density along the loop in our modelling.

Large prolonged stellar flares represent the most powerful ones in a sequence of flares in activity complexes on the Sun. Reconnection of large-scale fields occur in these events at scales typical for such activity complexes. Processes like two-ribbon flares are quite common and they occur not only on the Sun, but also on late-type subgiants in systems of giant loops. Prior to the X-ray observations it was not possible to predict precisely the values of the temperature and maximum energy of such events which are determined by the evolution of magnetic fields on the active star. Note that the strengths of these fields can be estimated in two ways: firstly, during the flare the hot plasma should be confined inside the loops; secondly, both the magnetic energy released in the reconnection process and the energy required to support the gas-dynamic

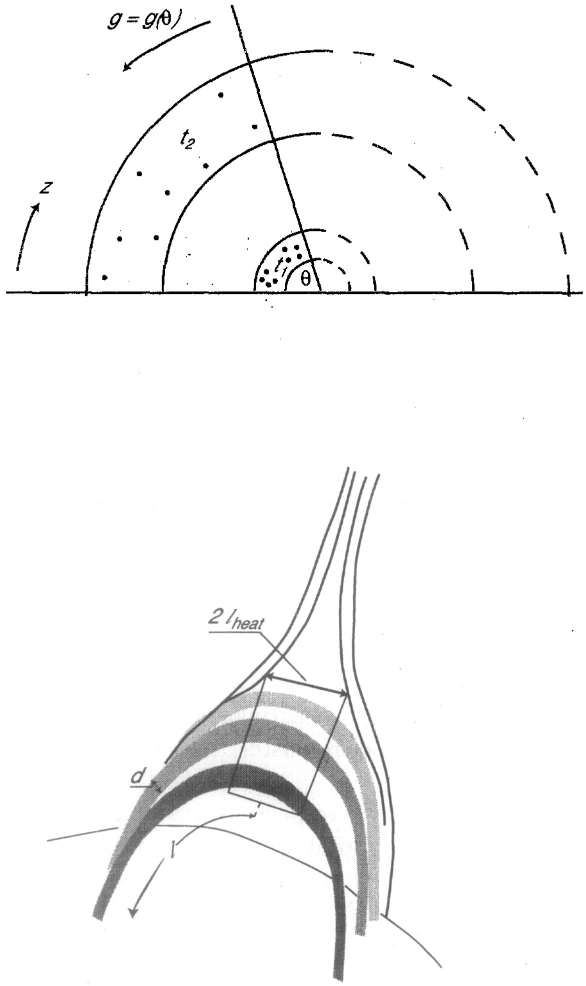

Fig. 1. The upper part of the figure represents schematically the loop at times t_1 and t_2. g is the gravity which depends on the angle θ, i.e. varies with the height above the base of the corona. The lower part of the figure is a system of giant coronal loops. d is the diameter of each loop, $2\ l$ is the loop length, $2\ l_{heat}$ is the heated part of the loop.

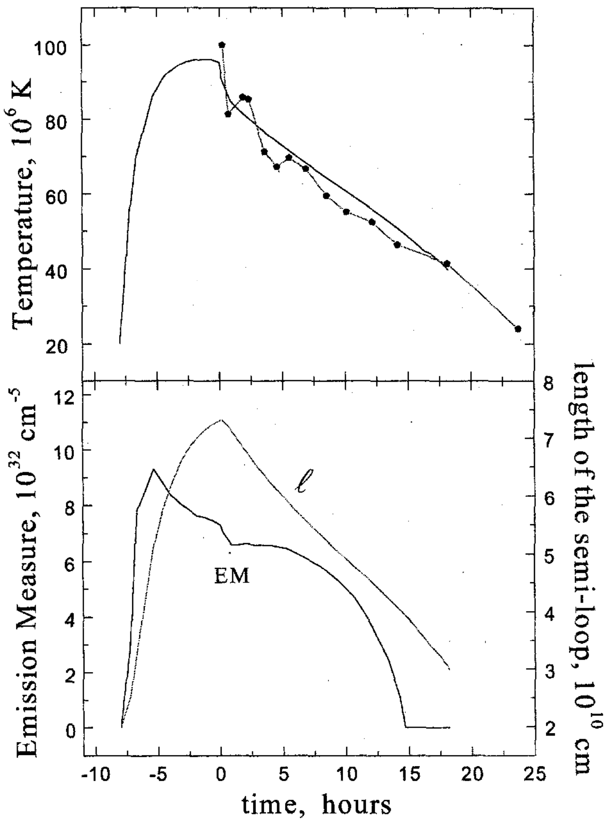

Fig. 2. Time behaviour of the temperature at the top of the loop, of the emission measure and the semilength of the loop. Points represent values of the temperature obtained by Franciosini et al.(2001) from X-ray flare observations on UX Ari. The zero-point of a horizontal axis corresponds to the start of the X-ray observations.

process can be calculated for this flare. Both these ways lead to an estimate of the magnetic field at the top of the flaring loop of about 100 G.

There are some differences in these two approaches of modelling stellar flares. In the Poletto et al. (1988) model used by Franciosini et al. (2001) reconnection has an essential role, while in the present model it is an external on-going process, which just provides the "heating" to the loop(s). Besides, we chose the simplest case for the evolution of the coronal loop. The long-duration X-ray emission arises here in the course of the process with minimal energy that corresponds to the shrinking of the coronal loop during the decay phase. The reason for such a choice was the similar time behaviour of the temperature and of the emission measure in the decay phase of this stellar flare and that of flares in complexes of activity on the Sun (see Figure 6 in Livshits et al. 2002).

For "dynamic" flares (Svestka et al. 1995) or large-scale coronal restructuring on the Sun the temperature begins to decrease significantly when the emission measure is still rising. The X-ray light curve for such events has a maximum, a sharp decrease and a subsequent gradual long-duration decay; these features of both the EM and T behaviour as well as the shape of the X-ray flare light curve distinguish coronal dynamic phenomena from flares occurring in complexes of activity. The latter are characterized by a long-duration decay just after the maximum. Namely these features allows us to regard long-duration X-ray flares on subgiants as a more energetic analog of flares in complexes of activity on the Sun (but not "dynamic" flares).

We note that the properties of our final model are close to those proposed by Poletto et al. (1988), when reconnection occurs at progressively higher altitudes, forming a growing system of loops. Densities of the plasma in these continuously forming loops diminish progressively. Therewith, dense loops which arise in the first stages of the flares give the main contribution to the soft X-ray radiation. The slow rate of cooling of the plasma inside flare loops is associated with some shrinkage of such structures. On the Sun, when the reconnection process starts and the reconnection site reaches a sufficient height, the shrinkage effect is observable (Forbes & Acton 1996). The plasma temperature in the shrinking X-ray loops is high enough but it never exceeds $20 \cdot 10^6$ K. Nevertheless, serious shrinkage has never been observed, especially in a large-scale loop system in the solar flares in the complex of activity. From the other hand, the plasma temperature close to the peak of the UX Ari flare reaches $100 \cdot 10^6$ K and the size of the stellar flare loops is large. It allows us to suppose that the shrinkage effect should manifest itself during such powerful prolonged X-ray stellar flares.

Our simple gas-dynamic modelling is able to describe observations of long-duration X-ray flares on different active stars (Livshits I. & Livshits M. 2002). It gives some evidence for a more significant role of the shrinkage-effect on these stars in comparison with the Sun. If this actually occurs, then accelerated particles of moderate energies are confined and even re-accelerated in the shrinking loop system. Therefore, hard (above 10 keV) X-ray radiation should be observed near the peak of large flares. Such radiation has indeed been detected by BeppoSAX in some cases. For the UX Ari flare Franciosini et al. (2001) found that the ratio between the hard ($\geq$ 10 keV) and the soft (0.1-10 keV) X-ray flux is ~ 0.2 at the flare peak.

ACKNOWLEDGEMENTS

This work was supported by Grants of Russian Foundation for Basic Research NN 02-02-17286, 01-02-17693, 01-02-16307 and of INTAS No 2000-840. We are grateful to COSPAR for allowing us to present this work at the General Assembly even in the absence of the two main authors. We are thankful to the referees for useful remarks which helped us to improve the paper.

REFERENCES

Forbes, T.G. & Acton, L.W. Reconnection and field line shrinkage in solar flares, *ApJ*, **459**, 330 (1996)

Franciosini, E., Pallavicini, R. & Tagliaferri, G. BeppoSAX observation of a large long-duration X-ray flare from UX Arietis, *Astron. Astrophys.*, **375**, 196 (2001)

Getman, K.V., & Livshits, M.A. Solar flares with long soft X-ray decays: energy balance in giant loops, *Astronomy Reports*, **44**, 255 (2000)

Graffagnino, V.G., Wonnacott, D. & Schaeidt, S. HR5110 superflare: an interbinary flare identified?, *Monthly Notices of Royal Ac.Soc.*, **275**, 129 (1995)

Güdel, M., Linsky, J., Brown, A. & Nagase, F. Flaring and quiescent coronae of UX Arietis: results from ASCA and EUVE campaigns, *ApJ*, **511**, 404 (1999)

Jakimiec, J., Sylwester, B., Sylwester, J., Serio, S., Peres, G., & Reale, F. Dynamics of flaring loops. II. Flare evolution in the density-temperature diagram, *Astron. Astrophys.*, **253**, 269 (1992)

Katsova, M.M., Drake, J.J., & Livshits, M.A. New insights into the large 1993 July 15-17 flare on AU Mic: the first detection of post-eruptive energy release on a red dwarf star. *ApJ*, **510**, 986 (1999)

Livshits, I.M., & Livshits, M.A. Origin of prolonged X-ray on active late-type stars, *Astronomy Reports*, **46**, 327 (2002)

Livshits, I.M., Badalian, O.G. & Belov, A.V. Common features in the development of prolonged, powerful solar X-ray flares. *Astronomy Reports*, **46**, 597 (2002)

Maggio, A., Pallavicini, R., Reale, F. & Tagliaferri, G. Twin X-ray and the active corona of AB Dor observed with BeppoSAX, *Astron. Astrophys.*, **356**, 627 (2000)

Mewe, R., Kaastra, J.S. & Liedahl, D.A. *Legacy*, **6**, 16 (1995).

Osten, R., & Brown, A. EUV photometry of RS Canum Venaticorum systems: four megaseconds, *ApJ*, **515**, 746 (1999).

Pallavicini, R., & Tagliaferri, G. Stellar coronae with BeppoSAX, in Highlights of X-ray astronomy, B. Aschenbach and M.J. Freyberg (Eds.), MPE Report 272, 378 (1999)

Poletto, G., Pallavicini, R. & Kopp, R.A. Modeling of long-duration two-ribbon flares on M dwarf stars *Astron. Astrophys.*, **201**, 93 (1988)

Reale, F., Bocchino, F., Peres, G. Modelling non-confned coronal dynamics and X-ray diagnostics, *Astron. Astrophys.*, **383**, 952 (2002)

Svestka, Z., Farnik, F., Hudson, H.S., Uchida, Yu., Hick, P., Lemen, J.R. Large-scale active corona phenomena in Yohkoh SXT images. I. Post-flare giant arches rising with constant speed, *Solar Phys*, **161**, 331 (1995).

E-mail addresses: maria@sai.msu.ru, pallavic@astropa.unipa.it

Manuscript received ; revised ; accepted 13 February 2003.