Flares in Late-type Stars: X-Ray

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1 Introduction

Flare-like brightenings, similar to those observed on the Sun but on a larger energy scale, are observed in a variety of late-type stars, including classical M dwarf flare stars, RS CVn-type binaries and pre-main sequence (PMS) objects. These events, which are observable over the whole electromagnetic spectrum, are interpreted as due to rapid release of magnetic energy at the star surface. Comprehensive reviews of stellar flares have been presented by Haisch & Rodonò (1989), Pettersen (1991), Haisch et al. (1991), Pallavicini (1992a), as well as in contributions at this conference. Here I will discuss X-ray emission, with emphasis on flares on M dwarfs and RS CVn binaries.

X-ray observations are important because they provide information on the high-temperature coronal portion of the flare and, at least in principle, could give clues as to the primary energy release and particle acceleration. In the stellar case there are severe limitations of the diagnostic capabilities of X-ray observations, in comparison to the solar case. In fact, stellar flares have up to now been observed only at soft X-ray energies ($\leq$ 10 keV) where thermal processes greatly dominate over non-thermal ones (optical continuum observations have to be used in this case as a proxy for hard X-rays). Moreover, stellar X-ray observations are spatially unresolved and so far of poor spectral resolution. Thus, the observational data that are readily accessible are only light curves, average temperatures T and volume integrated emission measures $EM = \int n^2 dV$, but there is no direct information on parameters such as density, volume and detailed geometry.

2 Observations

When observed in disk-integrated soft X-rays, the Sun is an extremely variable source, and there are clear indications for both transient flare-like events and for more gradual long-term variations associated with rotational modulation and the solar activity cycle (e.g. Pallavicini 1993 and references therein). It may come as

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a surprise therefore that before *ROSAT* there were only a few X-ray flaring stars which were not part of well-established classes of flare stars like UV Ceti-type stars, RS CVn binaries and PMS objects. The best case was probably a flare observed with *EXOSAT* on the G0V star π^1 UMa (Landini et al. 1986) which released $\sim 2 \times 10^{33}$ erg in the X-ray band. Clearly, the paucity of X-ray flare detections from normal stars was due to the biased nature of most *Einstein* and *EXOSAT* observations, which were pointed primarily at known active stars.

The unbiased observations carried out by *ROSAT* during the All-Sky Survey have shown that virtually all type of late-type stars are flaring sources (Schmitt 1994), thus providing strong support to the notion that magnetic activity is widespread in the cool half of the HR diagram. During the All-Sky Survey, *ROSAT* was scanning great circles perpendicular to the ecliptic plane and each source was observed once every orbit for at least two days (or more depending on its position in the sky). Each observation therefore consisted of short snapshots (typically ~ 20 sec) separated by one orbit period (~ 90 min) over a time interval of two or more days. Flares have been detected with this technique from stars of all spectral types from F to M: several examples are given in Fleming et al. (1993) and Schmitt (1994). It is worth noting that flares have been detected in this way also from some A and B stars, although in this case it is unclear whether X-ray emission originated from the A and B primaries or rather from unseen late-type companions.

Although the *ROSAT* All-Sky Survey has allowed the detection of flares in an unbiased way, it was limited in the time coverage of the observed events except for long lived flares covering several satellite orbits. For events lasting less that ~ 1 hour, our knowledge of X-ray flare emission is still largely based on previous *Einstein* and *EXOSAT* data as well as on pointed *ROSAT* observations. The long uninterrupted observations carried out by *EXOSAT* are particularly relevant in this respect, since they were not affected by the usual data gaps associated with low-orbit satellites like *Einstein* or *ROSAT*. Observations of X-ray flares by *EXOSAT* have been reviewed by Pallavicini et al. (1990) and Linsky (1991), while *Einstein* flare observations were discussed by Haisch (1983) and Ambruster et al. (1987). The main results obtained by these satellites with regard to flare stars and RS CVn binaries are summaried separately in the following two sections.

2.1 M dwarf flare stars

Short-lived events, with typical durations of minutes to tens of minutes and integrated X-ray energies of $\sim 10^{30}$ to 10^{33} ergs, are commonly observed from late K and M dwarfs of the UV Cet and BY Dra types. These are active red dwarfs with Balmer lines in emission and evidence of strong surface magnetic activity. The light curves of these flaring events resemble strongly those of *compact* flares on the Sun, i.e. flares which are believed to occur in one or more magnetically confined loops. The average temperatures derived from the X-ray data ($\sim 2 - 4 \times 10^7$ K) are similar to those of solar flares, while the volume emission measures are several orders of magnitude larger ($\sim 10^{51} - 10^{53}$ cm^{-3}).

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The X-ray emission is typically more gradual and longer lived than the optical continuum emission, consistently with the thermal nature of the X-ray spectra. There is strong evidence that these stellar flares are scaled-up version of solar compact flares: if the physical mechanism is the same, their larger energies imply larger volumes or higher magnetic fields, or both.

In addition to short-lived events, intense long-duration events are occasionally observed from M dwarf stars. Examples are a large flare on YY Gem observed by *EXOSAT* (Pallavicini et al. 1990) and flares on CC Eri and EV Lac observed by *ROSAT* (Pan & Jordan 1994, Schmitt 1994). These flares last from a few to several hours and may release as much as $\sim 10^{34}$ erg in the soft X-ray band. Their long decay time, and sometimes also their long rise time, suggest a gradual energy release process and continued heating during the decay. If an analogy can be drawn with solar flares, these events could be the analog of solar *two-ribbon* flares, where continuous reconnection occurs as open field lines relax back to a closed lower energy configuration (see, e.g., Priest 1995). Note that this analogy is based only on the shape of the X-ray light curve, but there is no proof that the physical mechanism responsible for these long duration events is indeed the same as for solar two-ribbon flares (see discussion in Pallavicini 1992b).

2.2 RS CVn and Algol-type binaries

In contrast to flares in M dwarf stars, long duration flares lasting several hours are the norm rather than the exception for RS CVn and Algol type binaries. These X-ray flares are also much more energetic than flares on M dwarfs, and have typical X-ray energy releases of $\sim 10^{34}$ to 10^{37} erg (i.e. two to five orders of magnitude more than the total energy of the largest solar flares). RS CVn systems are close binaries usually formed by an F or G dwarf and a K subgiant, orbiting each other with periods from less that a day to about two weeks. Algol-type systems, which are nearly-contact binaries with mass transfer between the two components, behave similarly to RS CVn's with regard to the X-ray properties. A large flare on Algol, with a duration of more than 4 hours and a total energy of $\sim 10^{35}$ erg, was observed by *EXOSAT* (White et al. 1986, van den Oord & Mewe 1989) and a somewhat larger flare from the same star (lasting 4 times longer) was observed by the Japanese satellite *Ginga* (Stern et al. 1992). In both cases, the peak temperature derived from the X-ray spectra was $\sim 7 \times 10^7$ K, i.e. larger than the typical temperatures observed in M dwarf flares.

Additional examples of X-ray flares in RS CVn binaries seen by *EXOSAT* have been published by Culhane et al. (1990), White et al. (1990) and Tagliaferri et al. (1991). A flare from II Peg seen by *Ginga* is discussed by Doyle et al. (1991) while Ottmann & Schmitt (1994) and Ottmann (1995) have discussed large flares on AR Lac and Algol seen by *ROSAT*. The latter flares have peak X-ray luminosities of $\sim 2 \times 10^{32}$ erg s^{-1}, peak temperatures approaching $\sim 10^8$ K and total X-ray energies of nearly 10^{37} erg.

In some cases, extremely long flares have been reported for RS CVn binaries. For instance, Tsuru et al. (1989) reported the observation by *Ginga* of the decay phase of a large flare on UX Ari which lasted more than one day and released in the X-ray band more than 10^{37} erg. The peak temperature was 8×10^7 K and the emission measure was nearly 1×10^{55} cm^{-3}. A smaller event (with a total X-ray energy of $\sim 3 \times 10^{35}$ erg) was observed from the same star during the late decay of the major flare. Kürster (1994) reported the observation by *ROSAT* of a flare lasting 9 days from the RS CVn binary CF Tuc. If the light curve is really due to a single event, this is the longest stellar flare ever observed. This raises the question whether small short-lived events (like the ones on M dwarf stars) do exist in RS CVn stars, or whether flares in RS CVn binaries are due to mechanisms fundamentally different from those operating in dMe stars and in the Sun. Note that the much larger quiescent emission of RS CVn binaries makes it difficult to detect small flares, but at least one short lived event (with a rise time of less than 3 min) has been reported from the RS CVn binary σ^2 CrB (van den Oord et al. 1988). It is clear anyway that flares on RS CVn's last typically longer and reach much larger energies than flares on dMe stars.

3 Models

The observed parameters of stellar X-ray flares (both for M dwarf stars and RS CVn binaries) are the X-ray temperature and volume emission measure, the rise and decay time, and the X-ray luminosity and integrated X-ray energy. These can be compared with the analogous quantities measured in solar compact and two-ribbon flares (see tables published by Landini et al. 1986, White et al. 1986, van den Oord et al. 1988, Pallavicini et al. 1990, Linsky 1991). For solar flares, other quantities can also be measured, at least approximately, like the loop length L and height H, the volume V and the density n (the latter usually derived from the observed EM and V). An estimate can also be made of the minimum magnetic field stength B_{min} required to confine the flaring loop. For stellar flares, these quantities must be inferred in an indirect way and the rest of this paper will be devoted to discuss the techniques used for this purpose, and their limitations.

3.1 Order of magnitude estimates

An approximate estimate of flare density and volume can be obtained by considering a simple loop which cools by radiation and conduction, with no additional heating in the decay phase. For simplicity, I assume a semicircular loop of length L and constant cross-section, with an aspect ratio α of loop diameter to loop length (the following considerations can easily be extended to the more general case where the ratio Γ of the loop cross-section at the top and at the base is different from unity). For an ensemble of N identical loops, the volume is given by

$$V = \frac{\pi}{4} L^3 (N\alpha^2) \tag{1}$$

and the emission measure is

$$EM = \frac{\pi}{4} n^2 L^3 (N\alpha^2) \tag{2}$$

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The factor $N\alpha^2$ reflects our ignorance of the detailed geometry and is equal to 0.01 for a single loop of aspect ratio $d/L = 0.1$ (as typically observed in the Sun). In the case of an expanding loop, the expressions for V and EM must be multiplied by a factor $(\Gamma + 1)/2$. The height of the loop is given by $H = L/\pi$.

If the flare cools by radiation and conduction the observed decay time will be given by

$$\frac{1}{\tau_{obs}} = \frac{1}{\tau_r} + \frac{1}{\tau_c} \tag{3}$$

where τ_r is the radiative cooling time, τ_c is the conductive cooling time and τ_{obs} is the decay time measured from the observed light curve (more correctly, an effective decay time should be used which takes into account the variation of temperature with time, cf. van den Oord et al. 1988).

The radiative cooling time (in sec) is given by

$$\tau_r = \frac{3kT}{n\Lambda(T)} \tag{4}$$

where $\Lambda(T)$ is the radiative loss function which can be approximated as $\Lambda(T) = \Lambda_0 T^\gamma$ with $\gamma = 0.25$ for $T \geq 2 \times 10^7$ K and $\Lambda_0 = 1.86 \times 10^{-25}$ cgs units.

The conductive cooling time (in sec) is given by

$$\tau_c \sim 1.2 \times 10^{-10} \frac{nL^2}{T^{2.5}} \tag{5}$$

where I have assumed classical Spitzer conductivity.

Note that the ratio τ_r/τ_c is usually unknown and may vary from flare to flare and even in the course of the same flare. In order to determine the flare density and geometry, one has to make further assumptions on the value of this ratio.

A simple approximation (see, e.g., Haisch 1983) is to assume that the cooling mechanisms are equally important, i.e. $\tau_r \sim \tau_c$. Although this assumption is supported by some solar observations close to the flare peak, it remains poorly justified at different times during a flare and when comparing different flares. The obvious advantage is that under this assumption one can determine exactly the flare parameters n, L, and $N\alpha^2$. In fact, by equating the observed decay time to the radiative cooling time, and taking the temperature derived from spectral fits of X-ray data, one can determine the density n. This, combined with the observed EM, gives the volume V. On the other hand, by equating the conductive cooling time to the observed decay time, and using the density derived above, one can also determine the loop length L which, combined with the volume, gives also $N\alpha^2$.

A problem with this approach is that the conductive cooling time (which depends on the actual geometry and the assumed conductivity, i.e. classical or turbulent) is poorly known. An alternative approach (e.g. Pallavicini et al. 1990) is to neglect conductive losses completely, and to derive only upper limits to density (and lower limits to volume) by equating the observed decay time to the radiative cooling time. In this case it is obviously not possible to determine uniquely the loop length L and height H. These parameters can be determined only as a function of $N\alpha^2$, assuming plausible values for this quantity (e.g. $N = 1$ and $\alpha = 0.1$).

The above considerations can be put in more general terms by combining the expression for the volume emission measure (Eq. 2) with those for the radiative and conducting cooling times (Eqs. 4 and 5), and by investigating the dependence of loop height H on $N\alpha^2$. Plots of H vs. $N\alpha^2$, which depend on the temperature, emission measure and observed decay time of individual flares, have been published by White et al. (1986), van den Oord et al. (1988), and van den Oord & Mewe (1989), although with significant differences in the functional expressions adopted by different authors. Depending on which cooling mechanism dominates, one has in fact:

$$H \sim (N\alpha^2)^{-\frac{1}{3}}(\Gamma + 1)^{-\frac{1}{3}} \qquad \text{for} \;\; \tau_r \ll \tau_c \tag{6}$$

$$H \sim (N\alpha^2)(\Gamma + 1)^{-1} \qquad \text{for} \;\; \tau_r \gg \tau_c \tag{7}$$

$$H \sim (N\alpha^2)^{-1} \qquad \text{for} \;\; \tau_r = \tau_c \tag{8}$$

where I have considered the more general case in which the flaring loops have a non constant cross-section (described by the expansion factor Γ). It is clear that assuming equal radiative and conductive losses gives the minimum loop length and height, while the assumption that radiative losses dominate will give a loop length which depends only weakly on the parameter $N\alpha^2$ (for plausible values of Γ and $N\alpha^2$ the loop height will differ from the minimum value by a factor of 2, at most). Much larger uncertainties occur if the flare cools predominantly by conduction: in this case, the derived loop length and height could easily be in error by one order of magnitude or more depending on the actual geometry of the flare (even barring possible departures from classical conductivity). Note however that the large dependence on Γ predicted by Eq. 7 in the case of conductive cooling (which was reported by White et al. 1986 and van den Oord et al. 1988) virtually disappears if account is also taken of the reduction of the conductive flux at the footpoints in a tapered loop (van den Oord & Mewe 1989). In practice, the most reliable parameter is the *minimum* height derived under the assumption of equal radiative and conductive losses. Even in this case, the derived parameters could be easily in error if there is additional heating during the decay.

3.2 Quasi-static cooling

It should be evident from the previous section that in order to determine in a unique way the flare geometry (both L and $N\alpha^2$), one has to introduce an additional relationship which fixes the value of the ratio $\mu = \tau_r/\tau_c$. One such relationship is to assume $\mu = 1$, as discussed above. It has been shown by van den Oord & Mewe (1989) that a more physically meaningful case is the one in which the flare cools quasi-statically through a sequence of constant pressure loops. For a static equilibrium model, in fact, a balance exists between the various energy input and loss terms which in turns implies a constant ratio between the conductive and radiative decay times. It can be shown that for the case of

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a power-law radiative loss function $\Lambda(T) \sim T^{\gamma}$, this ratio depends only on the exponent γ and is given by $\mu = 0.18$ for $\gamma = 0.25$. Note that the low value of this ratio means that radiative cooling dominates, although conduction is not completely negligible.

For quasi-static cooling with $\mu = 0.18$ and no heating in the decay, simple analytical relationships can be derived for the decay of flare temperature T and radiative energy E. These read:

$$T = T_0 \left(1 + \frac{t}{3\tau_0}\right)^{-\frac{8}{7}} \tag{9}$$

$$E = E_0 \left(1 + \frac{t}{3\tau_0}\right)^{-4} \tag{10}$$

where $\tau_0 = 3kT_0/n\Lambda(T)$ is the radiative cooling time at the start of quasi-static cooling. Note that μ can be rewritten in terms of observable quantities as $\mu \sim T^{13/4}/EM$ and hence the constancy of this ratio throughout the flare decay can be tested observationally from time-resolved spectral data.

By fitting the observed light curve, and using the measured T, one gets τ_0 and n. From the known value of the ratio μ one also determine L and finally, from the measured value of EM and the derived values of n and L, one determines $N\alpha^2$, in much the same way as for $\mu = 1$. A generalisation is also possible to the case of continuous heating in the decay, although it is not completely clear in this case whether one can solve for both τ_0 and the heating rate in a unique way. As a matter of fact, in all analyses made up to now of actual flare data (e.g. van den Oord & Mewe 1989, Ottman & Schmitt 1994, Schmitt 1994, Ottmann 1995) the observed light curve was consistent with negligible heating in the decay phase, in spite of the flare long decay time. When no heating is present, there is little difference between the flare parameters derived assuming radiative cooling or quasi-static cooling, except for the parameter $N\alpha^2$ which cannot be determined in the former case. For instance, the density and volume derived by White et al. (1986) for a large flare on Algol assuming radiative cooling were 3×10^{11} cm^{-3} and 1×10^{31} cm^3, respectively, while van den Oord & Mewe (1989) with the quasi-static cooling model derived 2.6×10^{11} cm^{-3} and 1.4×10^{31} cm^3. They also derived a loop height of 5.1×10^{10} cm and $N\alpha^2 = 4.4 \times 10^{-3}$ while White et al. (1986) estimated a height of $(2-5) \times 10^{10}$ cm, within a factor 2 from the value given by the quasi-static cooling model. For a single loop with $\alpha = 0.1$, one would get $N\alpha^2 = 1.0 \times 10^{-2}$, again within a factor of 2 with respect to van den Oord and Mewe (1989). For another flare on Algol which lasted a factor 4 longer, Stern et al. (1992) derived a loop height a factor 4 larger, and a density a factor 5 lower, using again the quasi-static cooling model. The volume was a factor 36 larger and $N\alpha^2 = 3.0 \times 10^{-3}$.

3.3 Reconnection model

All parameters in the previous two sections were derived under the condition (either assumed or inferred) that there is no heating during the flare decay.

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Although this possibility cannot be excluded, it appears rather unlikely for long duration flares which last hours and even days. In the Sun, where we know at least approximately the flare density and geometry, the observed decay times of long-duration flares are usually much longer than the radiative cooling time. This proves that there is additional heating in the decay phase, and even more so if conduction losses are not neglible with respect to radiative losses. A model which predicts continuous energy release during the decay phase is the reconnection model of solar two-ribbon flares of Kopp & Poletto (1984) which has been applied to stellar flares by Poletto et al. (1988).

In the reconnection model, a magnetic configuration, torn open by an unspecified explosive event, relaxes back to a lower energy closed configuration. Energy is released gradually as the field lines reconnect at progressively higher altitudes during the flare decay. This process can be modelled analytically in a simple two-dimensional magnetic configuration (described in terms of a single lobe of a Legendre polynomial of degree m). The rate of energy release is given by:

$$\frac{dE}{dt} = A(m,\theta_0)R_\star^3 B_M^2 \frac{y^{2m}[y^{(2m+1)}-1]}{[m+(m+1)y^{(2m+1)}]^3}\frac{dy}{dt} \tag{11}$$

where $R_\star$ is the radius of the star, $A(m,\theta_0)$ is a known function of the degree m of the Legendre polynomial and of the heliographic latitude of the flare region, B_M is the maximum photospheric field strength in the region, y is the height of the reconnection point expressed in terms of the stellar radius, and dy/dt is its upward velocity. For the latter, one can take:

$$y(t) = \frac{h}{R_\star} = 1 + \left(\frac{H_M}{R_\star}\right)\left[1-\exp(-\frac{t}{\tau_0})\right] \tag{12}$$

where H_M is the maximum height reached by the reconnection point during its upward movement and τ_0 is the time constant of the process.

Analysis of Eq. 11 shows that the shape of the energy release curve depends almost exclusively on the time constant τ_0, while its absolute value depends on both the photospheric magnetic field B_M and the degree m of the Legendre polynomial (and hence on the size of the flaring source, larger values of m corresponding to smaller regions). Clearly, the energy release will be larger for higher photospheric magnetic fields and/or larger regions. Thus, if the energy released in the X-ray band is a constant fraction of the total energy released in the reconnection process, by fitting the observed light curve one can determine the time constant τ_0 but cannot separate the source size from the magnetic field strength. The same flare can be reproduced by either a small loop with strong magnetic field, or by a large loop with weaker magnetic field (Poletto 1989, Pallavicini 1992b, Schmitt 1994).

As shown by Schmitt (1994) for the specific case of a long duration flare on the UV Ceti-type star EV Lac, the situation is even more complex. Not only different reconnection models could reproduce the observed light curve (thus leaving essentially unconstrained the loop size), but also models with no heating in the decay (like the quasi-static cooling model discussed above) could also reproduce the same flare. In the latter case, the inferred loop length is 6×10^{11} cm (much larger than the pressure scale height) and the density is 3×10^{10} cm^{-3}, while densities in excess of 10^{12} cm^{-3} are obtained from the reconnection model if the flare region is sufficiently compact. In this case, the inferred loop length is a factor 100 smaller than for the quasi-static cooling model, although reconnection models with larger volumes and lower densities are also acceptable. In the absence of additional constraints (like a direct measurement of the electron density from density sensitive line ratios), it is difficult to discriminate between these possible solutions, although the enormous loop height predicted by the quasi-static cooling model ($\sim$ 10 stellar radii) appears rather unrealistic, if at all acceptable.

4 Conclusions

It is clear from the discussion above that the derivation of flare parameters from spatially unresolved stellar observations (at least of the quality available at present) is a rather tricky business, and that published values should therefore be considered with great caution.

An alternative way to get information on flare loop sizes is to use full hydrodynamic calculations which predict the time behaviour of density, temperature and flow velocity in a magnetically confined loop structure subject to a prescribed heating perturbation (e.g. Peres 1989). For instance, Reale et al. (1988) used a hydrocode to infer a loop length $L = 1.4 \times 10^{10}$ cm for a small flare on Proxima Cen observed by *Einstein*. On the other hand, Cheng & Pallavicini (1991) argued that the inferred loop length was largely the consequence of the assumed absence of additional heating during the decay phase. Reale et al. (1993) have suggested to use the ratio of the decay times of temperature and density as a diagnostics of the loop length. The predicted dependence, however, becomes much flatter when loop integrated quantities are used instead of the values at the loop top, and the predicted ratio is also a strong function of the amount of heating in the decay phase. In practice, rather than a direct diagnostic tool, this ratio is more useful to restrict the range of hydrodynamic models to be explored to fit the observed light curve.

To conclude, any real progress in this area has probably to wait for a major stepforward on the observational side. The Japanese satellite ASCA is already providing spectral data which are of far better sensitivity and resolution of anything else obtained in the past. However, it will be only with *AXAF* and *XMM* at the turn of the century that it should be possible to obtain time-resolved spectroscopy and density-sensity line ratios of the quality needed to constrain stellar flare parameters in an effective way.

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J. van Paradijs: You noted that an X-ray flare was observed in the *ROSAT* All-Sky-Survey from the B5 star TT Lupi. Would you expect that?

R. Pallavicini: Of course not, since these stars are not expected to have magnetic activity. However, there are a number of B and A stars detected by *ROSAT* and some of them have been found to flare. One possibility is that the X-ray emission and the flare come from a late-type companion. A flare for instance was also detected by *EXOSAT* (and confirmed by *ROSAT*) on the A star Castor A+B.

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