MODELING SOLAR AND STELLAR FLARES

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ABSTRACT

The thermal phase of solar X-ray flares has been described as heating-triggered evolution of plasma confined in coronal loops. This paper describes how the modeling of the thermal phase of spatially resolved solar X-ray flares has been extended to investigate spatially unresolved stellar X-ray flares with different scopes, aims and perspectives. Hydrodynamic models are able to describe the evolution of global flare features, such as the X-ray light curves, and to put constraints on heating location. Based on the solar analogy, either detailed hydrodynamic models or approximate analytical descriptions of the decay of flaring coronal loops or loop systems have been extensively applied to infer the size of stellar flaring regions. Approximate approaches tend to overestimate the size of the flaring regions, in particular in the presence of significant heating during the decay. Such heating is consistently diagnosed and included in a model based on extensive hydrodynamic modeling of decaying loops. Applications to recent data from Chandra and XMM-Newton missions, and present and future perspectives are discussed.

INTRODUCTION

Soft X-ray observations tell us that solar coronal flares are, first of all, extremely localized, involving at most several coronal structures in a small fraction of the solar surface (Figure 1). Most of the brightening occurs inside closed coronal loops where the X-ray emitting plasma is confined by the magnetic field. The plasma mainly behaves like a fluid, and can be described with hydrodynamic models. Although the detailed mechanisms which drive the impulsive energy release triggering a flare are still not completely clear, and have been the object of extensive studies (see Priest & Forbes 2002 for a review on this topic), hydrodynamic models have been shown to provide a good description of the evolution of the flaring plasma and some level of diagnostics of the flare mechanisms.

On the other hand, there is extensive evidence that stellar flares share common features with solar flares (e.g. Gorenstein & Tucker 1976). The light curves are similar, with a steep rising phase and a slower – generally exponential – decay. Despite observational bias toward more frequent detection of more energetic flares, stellar flares have been detected down to energies comparable to those of solar flares (e.g. Haisch et al. 1991). This makes us confident that we can use solar flares as templates and apply flaring loop models to study stellar flares. Of course, the level of diagnostics is different. Stellar flares are spatially unresolved. If we assume that stellar X-ray flares occur inside closed coronal structures as in solar flares, the decay time of the X-ray emission roughly scales as the plasma cooling times. In turn, the cooling times scale with the length of the structure which confines the plasma: the longer the decay, the larger is the structure (e.g. Haisch 1983). Starting from this concept, many analyses of stellar flares have aimed, at first order, at estimating the dimensions of the flaring region, with different approaches, from order-of-magnitude estimates to detailed hydrodynamic modeling. Stellar flares become then unique sources of information about the size of the coronal structures on stars other than the Sun, very difficult to be derived in any other way (e.g. Maggio & Peres 1996). Although the link of the emission decay time to the plasma cooling times holds generally true, a significant residual heating released during the decay may make the decay longer than expected, and therefore lead to overestimate the loop length, if not correctly diagnosed. This makes the scenario of stellar flare modeling complex and the results the subject of debate (see also Reale 2002).

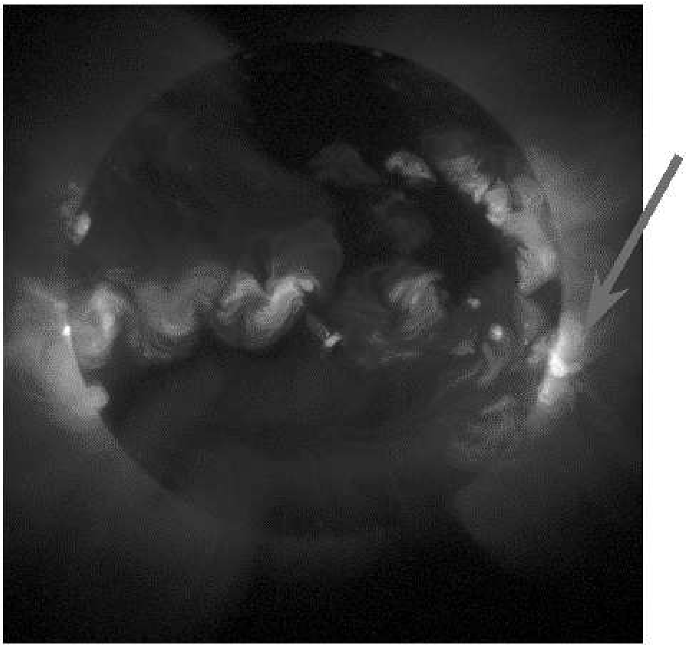

Fig. 1. Solar corona with a flare (pointed by the arrow) observed with Yohkoh/SXT on 13 Jan 1992.

In the following, it is summarized how plasma hydrodynamic models have been applied to study spatially-resolved solar coronal flares and what kind of diagnostics has been derived. Given the validity of such models to describe the general features of solar flares, it is then illustrated their extension to stellar flares, in particular to derive information on the size of the flaring structures. Various approaches are listed and compared, in the light of the comments above, and recent developments driven by high-quality observations from Chandra and XMM-Newton missions are discussed.

MODELING SOLAR CORONAL FLARES

In a soft X-ray flare, most of the emission is due to hot ($\geq$ 10 times the quiescent corona) and dense ($\geq$ 100 times the quiescent corona) plasma confined in magnetic loops. In typical coronal conditions it is customary to assume that plasma moves and transports energy along the magnetic field lines. Then the plasma evolution can be described by means of one-dimensional time-dependent hydrodynamic models (e.g. Priest 1982). Hydrodynamic time-dependent loop models involve the numerical solution of hydrodynamic equations including many physical effects, such as pressure terms, gravity, radiation, thermal conduction, heating (e.g. Nagai 1980, Peres et al. 1982, Doschek et al. 1983, Nagai & Emslie 1984, Fisher et al. 1985, MacNeice 1986, Gan et al. 1991, Reale & Peres 1995, Hori et al. 1997). The equations of conservation of mass, momentum and energy, and the equation of state are then:

$$\frac{\partial n}{\partial t} + v\frac{\partial n}{\partial s} = -n\frac{\partial v}{\partial s} \tag{1}$$

$$nm\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial s} = -\frac{\partial p}{\partial s} - nmg_{||} + \frac{\partial}{\partial s}\left(\mu\frac{\partial v}{\partial s}\right) \tag{2}$$

$$\frac{\partial \mathcal{E}}{\partial t} + v\frac{\partial \mathcal{E}}{\partial s} + w\frac{\partial v}{\partial s} = \mathcal{Q} - n_e n\mathcal{P}(T) + \mu\left(\frac{\partial v}{\partial s}\right)^2 - \frac{\partial F_c}{\partial s} \tag{3}$$

$$\mathcal{E} = \frac{3}{2}p + n_e\chi \tag{4}$$

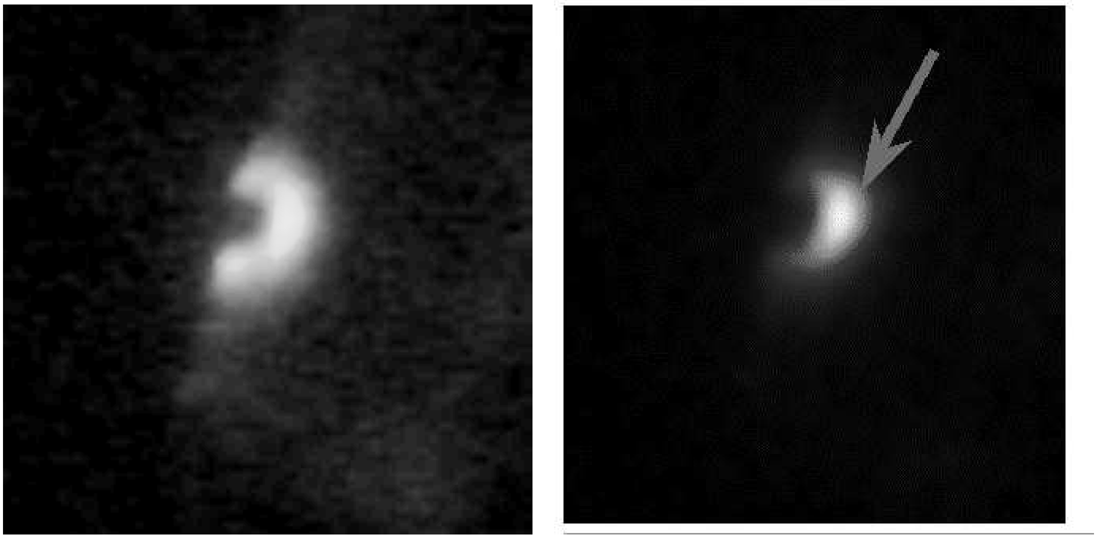

Fig. 2. A solar coronal flare observed with the Yohkoh/SXT: images (160×160 arcsec^2) at two different moments are shown. On the left, early in the rising phase, the entire flaring loop is visible, on the right, at the flare peak, the excess of soft X-ray emission at the loop apex is pointed by the arrow. The grey scales of the images are different.

$$w = \frac{5}{2} p + n_e \chi \tag{5}$$

$$F_c = -\kappa T^{5/2} \frac{\partial T}{\partial s} \tag{6}$$

$$p = (n + n_e) k_B T \tag{7}$$

where s is the field line coordinate; n is the hydrogen number density; $m = 1.257\ m_H$ is the average ion mass with m_H the hydrogen atom mass; n_e is the electron number density; T is the temperature; p is the pressure; $\mathcal{P}(T)$ are the radiative losses per unit emission measure (e.g. Rosner et al. 1978); κ is the thermal conductivity ($\kappa \simeq 0.922 \times 10^{-6}$erg cm^{-1} K$^{-7/2}$); $g_{||}$ is the component of gravity parallel to the field lines; k_B is the Boltzmann constant; $\mathcal{Q}$ is the external energy input which heats the loop plasma and, if impulsive, triggers a flare; t is the time, v is the plasma velocity, μ is the viscosity, χ is the hydrogen ionization potential.

The models are expected to describe the evolution of the flaring plasma so well that they have been applied to simulate specific observed events and to make detailed comparisons with them for diagnostics of flare heating. An example is a compact – single loop – flare well-observed with the *Solar Maximum Mission (SMM)* on 12 November 1980 (Peres et al. 1987). The SMM observation includes, in particular, light curves in several soft X-ray lines collected with the Flat Crystal Spectrometer (FCS) and Bent Crystal Spectrometer (BCS). The flare is triggered by a transient impulsive heating in a loop initially at equilibrium. The hydrodynamic equations are solved numerically as a function of time and of the coordinate along the loop to describe the evolution of the plasma confined in the loop. The output of the numerical code consists of distributions of density, temperature and velocity along the loop sampled regularly during the flare evolution. By convolving the temperature and emission measure (i.e. the square of the density) distributions with the relevant line emissivity functions[1] – filtered through the instrumental filter responses – of the selected X-ray lines, the emission distributions are derived along the loop, and after spatially integrating them, the light curves. The model light curves can be compared directly to the data. Different assumptions on the impulsive

[1]A unit emission measure of optically thin plasma emits radiation in a given spectral line with the same intensity depending only on its temperature. We can then define a line emissivity function per unit emission measure versus temperature which is typically a peaked function with the maximum at the so-called line-formation temperature.

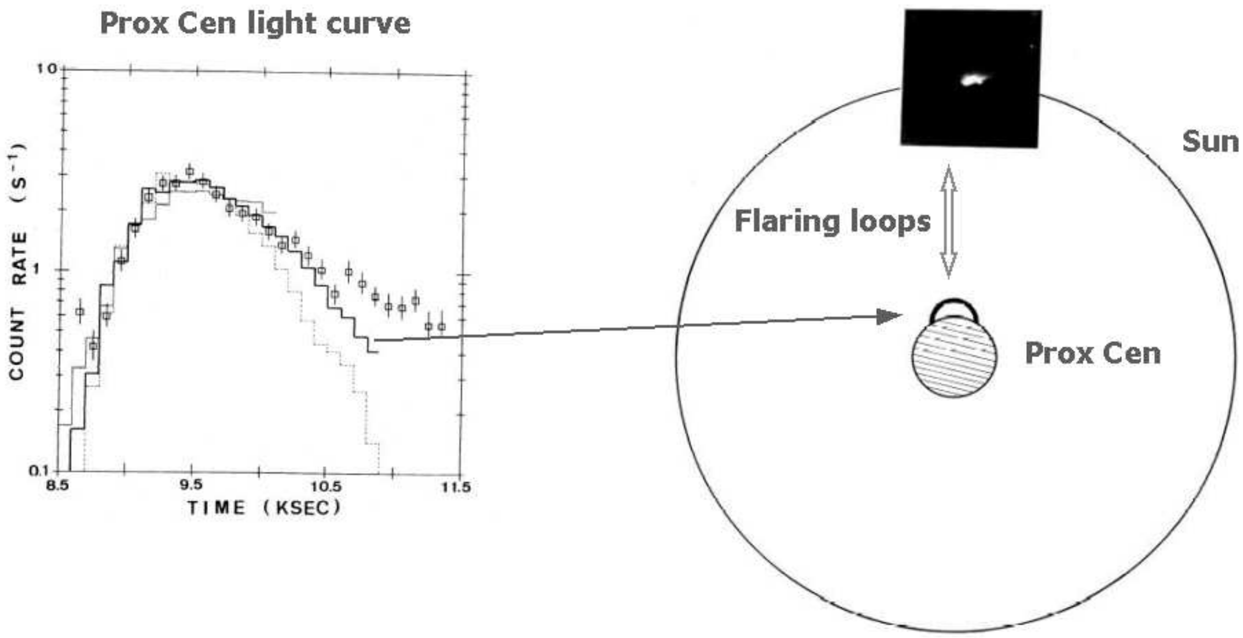

Fig. 3. The fitting with a solar-like hydrodynamic model of the light curve of a flare observed on Proxima Centauri with the *Einstein*/IPC allows to constrain the length of the stellar flaring loop (*adapted from Reale et al. 1988*)
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heating function lead to different shapes of the light curve, and it is therefore possible to put constraints on the location and evolution of the flare heating. The task of the detailed comparison of models with specific observed events is not an easy one and further examples can hardly be found in the literature.

Furthermore, the requirements on the modeling have increased with increasing quality of the data. The Yohkoh mission has brought a quantum leap in the investigation of solar coronal flares, in particular because of the high time/space resolution of the Soft X-ray Telescope (SXT, Tsuneta et al. 1991).

Even in the case of relatively simple single loop events, such as the well-observed flare on 13 January 1992 (Masuda et al. 1994, Figure 2), a more refined approach has been developed and applied. The approach consists of a multiple loop hydrodynamic modeling (Hori et al. 1997). It is assumed that the flare involves several adjacent thin loop strands each heated with out-of-phase thermal pulses. This pseudo-2D modeling is set with configuration and parameters appropriate to describe events such as the one just mentioned. From the computed model results, the emission in the SXT filter bands is then synthesized. This modeling is able to reproduce many observed features, but also detects effects that must be deviations from pure hydrodynamic behavior, in particular the excess of emission at the loop apex, observed in this and many other flares with Yohkoh/SXT (Figure 2). Such bright kernels are in fact currently explained as regions where plasma is governed by a turbulent regime, which is detached from the rest of the loop (Jakimiec et al. 1998). This turbulence may be strictly connected to the presence of non-thermal effects well detected in hard X-rays (Fletcher & Martens 1998). Anyhow, it has been shown that one-dimensional single loop models are able to reproduce well global features of flares, and even of those observed with Yohkoh, such as the light curves in the broad SXT filter bands (Reale et al. 1996, 1997).

STELLAR FLARE MODELING

The applications to solar flares illustrated above suggest that modeling coronal flares as impulsively heated plasma confined in magnetic loops can be taken as a good starting point for extension to study stellar flares.

We can distinguish two basic approaches to the investigation of stellar flares (Reale 2002). One is the

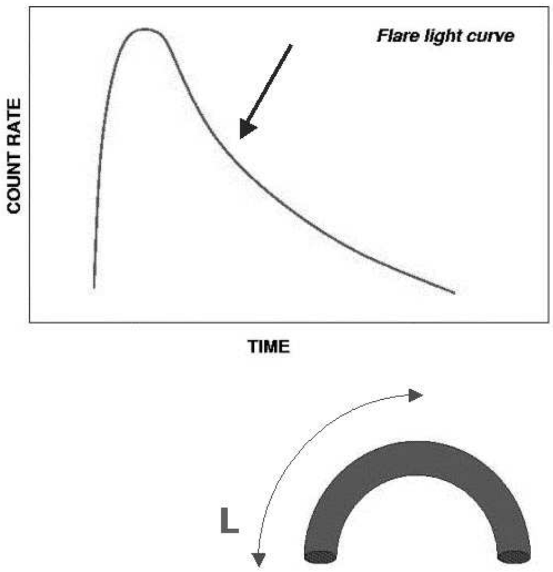

Fig. 4. The decay of stellar flares is used to estimate the length L of the flaring loops.

modeling of specific events with detailed solution of the time-dependent hydrodynamic equations, as described above for solar flares (Eqs.1–7). The other is to dismiss accurate description, complete physics and detailed diagnostics in favor of faster results by means of approximate analytical approaches.

The former approach has been applied to model a well-observed flare on Proxima Centauri with the Imaging Proportional Counter on board the *Einstein* satellite (Reale et al. 1988). Under the assumption of a single loop flare, the hydrodynamic model has been able to describe well the flare light curve and to obtain constraints on the size of the flaring loop (Figure 3) and on the duration and intensity of the flare heating.

Such approach is not always feasible for various reasons. It requires significant effort and computing time and many iterations that cannot practically be applied to extensive flare surveys. Moreover, observational data hardly reach such a high quality and statistics to constrain model parameters and assumptions and to provide really fruitful diagnostics. Therefore, approximate approaches have been largely employed to analyze systematically observed flares. In particular, the size of the flaring regions has been estimated from the analysis of the flare decay phase. The conceptual basis is simply to link the decay time observed from the light curves to the plasma characteristic cooling times (e.g. Reale 2002, Figure 4).

The main mechanisms of plasma cooling in flare conditions are by thermal conduction toward the cooler chromosphere and by radiation, with characteristic cooling times, which can be easily derived from Eqs.1–7:

$$\tau_{cond} = \frac{3nkT}{\kappa T^{7/2}/L^2} \qquad \tau_{rad} = \frac{3nkT}{n^2 \mathcal{P}(T)} \tag{8}$$

respectively, where L is the loop half-length. In the conduction cooling time the dependence on the loop length is explicit. In the radiation time, the dependence on length is implicitly contained in the density through the loop scaling laws (Rosner et al. 1978, Kuin & Martens 1981) which contain loop length as basic parameter. It is possible to define a global thermodynamic loop decay time which is essentially linearly dependent on the loop length (van den Oord & Mewe 1989, Serio et al. 1991):

$$\tau_{th} = \frac{120 L_9}{\sqrt{T_7}} \tag{9}$$

where L_9 and T_7 are in units of 10^9 cm and 10^7 K, respectively.

The obvious implication of this scaling is that a slow flare decay indicates a long loop, and we may even easily find an estimate of L from Eq. 9. Unfortunately, it has been shown that in many flares a residual

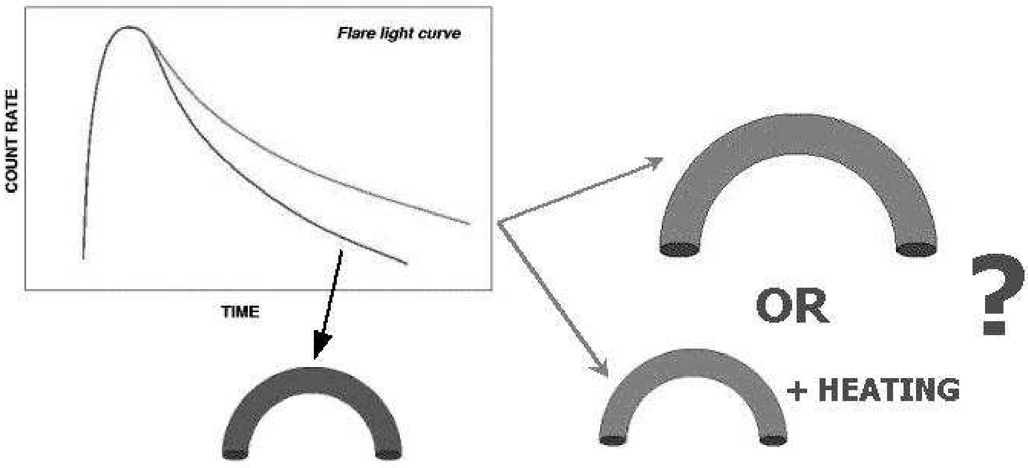

Fig. 5. Two examples of flare light curves are shown in the graph. The flare with the longer lasting decay may occur either in a loop (upper right) larger than the one associated with the faster decay (lower left), due to free plasma cooling, or in a loop with the same length but with a significant heating which drives the decay (sketched as loop + heating): how can we discriminate?

significant heating may be present during the decay. This heating may sustain the decay itself for a time longer than expected and lead to overestimate the loop length, if not properly taken into account (Figure 5).

This aspect has been neglected in some approaches used so far to analyze the stellar flare decay. In the following some of the most widely used approximate methods in analyzing stellar flares are listed, according to a name convention already used in a previous review (Reale 2002): i) the Two-ribbon flare method (Kopp & Poletto 1984); ii) the Quasi-Static cooling method (QSS, van den Oord & Mewe 1989); iii) the Pure radiation cooling method (Pallavicini et al. 1990); iv) the Rise+Decay method (Hawley et al. 1995); v) the Hydrodynamic method (Reale et al. 1997). The Two-ribbon flare method assumes that the flare decay is entirely driven by the heating released by magnetic reconnection of higher and higher loops and neglects completely the effect of plasma cooling. The other four methods are instead based on cooling of plasma confined in a single flaring loop. The hydrodynamic approach is the only one to include consistently both the plasma cooling and the effect of heating during the decay. Notice that heating is instead treated inconsistently in the QSS method (see discussion in Reale 2002).

The hydrodynamic approach (Reale et al. 1997) is based on extensive hydrodynamic simulations of decaying flaring loops used to derive an empirical formula for the loop length, combining the information from the light curve and the density-temperature diagram:

$$L_9 = \frac{\tau_{LC}\sqrt{T_7}}{120 f(\zeta)} \qquad f(\zeta) \geq 1 \tag{10}$$

where τ_{LC} is the decay time of the light curve. This formula is similar to the expression of the loop thermodynamic cooling time (Eq.9), but includes a non-dimensional correction factor $f(\zeta)$, which is larger than one if significant heating is present during the decay, making therefore the loop length shorter than in the absence of heating. ζ is the slope of the decay path in the density-temperature diagram (Sylwester et al. 1993) and is maximum (~ 2) if heating is negligible and minimum (~ 0.5) – the slope of the loci of the hydrostatic loops with decreasing temperature – if heating dominates the decay. The square root of the emission measure has been used as proxy of the density to construct the density-temperature diagram (e.g. Reale et al. 1997).

Heating in the decay has been shown to be important in at least one case of a stellar flare well observed on Algol with the *Beppo*SAX satellite (Favata & Schmitt 1999). In this case the loop size could be estimated independently of cooling times, because the flaring region was eclipsed and the light curve shows a very well defined eclipse pattern. The loop size turned out to be not far from the estimate obtained with the hydrodynamic approach with sustained heating.

These approximate methods have been extensively applied to flares observed on active binaries, young PMS stars (and YSO), late dwarfs and active ZAMS stars, and a detailed list of applications up to 2001, before more recent contributions from Chandra and XMM-Newton observations, can be found in Reale (2002).

From the analysis of the concepts of the methods and of the results of their applications, some general considerations are in order. On the methods:

- All methods have advantages and limitations, e.g. QSS method is easy to apply but does not treat heating consistently, the pure radiation method is of immediate application but oversimplified, the Rise+decay method is the only one to include the effect of a decay not starting from loop equilibrium condition but it does not include the effect of heating, the hydrodynamic method is the only one to include consistently the effect of heating during the decay, but it requires good, time-resolved diagnostics of temperature and density and assumes the decay starting from equilibrium conditions (see Reale 2002 for further discussion).

- The two-ribbon approach is complementary to single loop approaches: it assumes that the flare decay is entirely driven by the heating, whereas in single loop methods the decay is determined mostly by the plasma cooling. However, the two-ribbon approach turns out to be little constraining when applied to spatially unresolved stellar flares.

- The single loop methods tend to overestimate systematically the loop length. The one less affected by such problem is the hydrodynamic method, which is the only one to consistently account for decaying heating and plasma cooling.

On the application of the methods:

- All methods agree on the result that long lasting flares (many hours) systematically correspond to long loops, of the order of the stellar radius or more.

- Flares on binaries and on PMS stars generally last longer and involve longer structures, than on dwarfs, although still of the order of the stellar radius.

- Heating is frequently significant in the decay of observed flares and involves loop lengths smaller by factors, typically from 2 to 4, if taken into account.

A few applications to Chandra and XMM-Newton data have been attempted recently. Some of them do not allow for detailed estimates of the loop length for various reasons, e.g. not enough flare decay is observed (Huenemoerder et al. 2001), the count statistics is too low to allow for time-resolved spectroscopy (Gondoin et al. 2001).

A more complete analysis is applied to the observation of a flare on YY Gem, a dM star (Stelzer et al. 2002). There, the data allow for the derivation of a time resolved density-temperature diagram and lead to an estimate of the loop length, yielding quite a small value ($\approx 2 \times 10^9$ cm), and to diagnose the presence of significant heating in the decay.

The approximate methods may not be strictly applicable to flares showing complex features. For instance, several flares show complex light curves with a decay composed by segments with different time scales (e.g. Osten & Brown 1999). In this case, the analysis needs more care and we may even need to resume to a detailed hydrodynamic modeling.

An example of such a complex flare is one recently observed on Proxima Centauri with XMM-Newton (Güdel et al. 2002, Reale et al. 2003). The flare is very well observed with a highly detailed and time-resolved

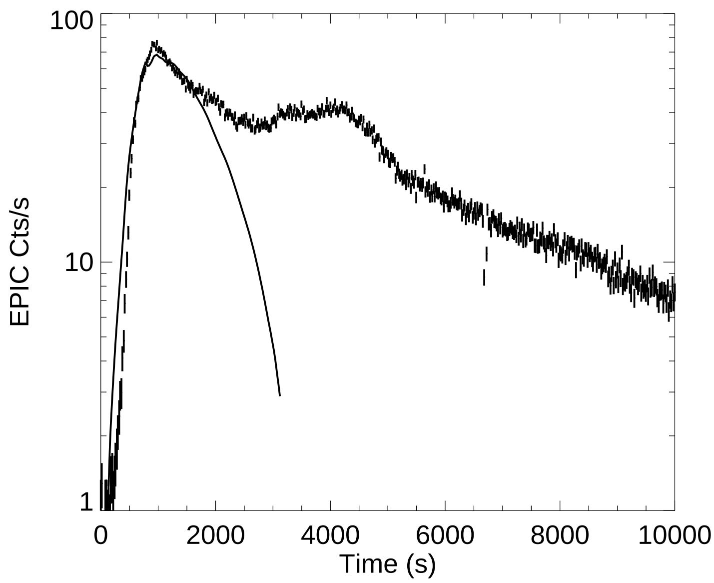

Fig. 6. Light curve of a flare on Proxima Centauri observed with the instrument EPIC-PN on board XMM-Newton. A hydrodynamic model of flaring loop 2×10^{10} cm long, heated at the apex for 600 s (*solid line*) fits well the initial phase of the flare.

light curve (Figure 6). The light curve shows a main initial maximum and a major secondary maximum, broader than the first one. The decay is also complex, it is initially faster and then becomes slower, before and after the second peak. The application of any of the above mentioned approximate methods to this flare is difficult and non-trivial, since we cannot distinguish a single decay trend and extract a single e-folding time. Therefore a detailed hydrodynamic modeling is evidently more appropriate to analyze this flare. An attempt to model this flare is currently in progress (Reale et al. 2003) and some preliminary results are shown next.

The hydrodynamic model is set up with initial guesses on the loop length, the impulsive heating function, the heating intensity and duration, suggested by approximate analysis of the flare scale times and energy budget. Then the full time-dependent hydrodynamic equations (Eqs.1–7) are solved numerically as outlined above (e.g. Reale et al. 1988) to compute the evolution of the plasma along the loop. From the density and temperature distributions along the loop sampled at various times during the computed flaring plasma evolution we synthesize the photons detected at the focal plane of the instrument which really observed the flare – the EPIC PN in this case – and, after the appropriate scaling for the unknown loop cross-section area, and integration on the whole spectral band, we obtain a light curve which can be compared directly to the observed one.

Since from the model we obtain focal plane photon spectra, it is of course also possible to fit them with standard isothermal model spectra and thus to obtain time-resolved density-temperature diagrams, to be compared to those obtained from the data.

Figure 6 shows preliminary results obtained by considering a single loop with half length 10^{10} cm, and injecting in it a heating pulse at the apex, with a time function constant for 600 s and then switched off abruptly. The light curve matches quite well the initial phase of the flare and the initial fast decay, but misses the later decay.

In order to fit the rest of the flare, we may suppose that there is a large contribution from a residual heating during the decay which sustains the slower later decay. However, the presence of a decaying heating may not be sufficient to describe the second peak of the light curve, which may therefore require additional hypothesis, such as the presence of a second connected – maybe larger – flaring loop, within the same global event. These further hypotheses and analyses will be investigated and described in a later work (Reale et al. 2003).

CONCLUSIONS

Time-dependent hydrodynamic loop modeling is able to describe well global features of observed solar coronal flares, such as the light curves and the density-temperature diagrams. Modeling can therefore be safely extended to study spatially unresolved stellar flares, allowing to derive information on the size of the flaring region and on the time-evolution of the heating. Approximate approaches can provide reliable information on stellar flares with simple light curves. More complex stellar events may instead require more detailed modeling, but also provide new interesting clues to understand the general physical mechanisms at work in flares. This may be of help even in the context of solar coronal flares, and therefore marks one important aspect of the solar-stellar connection.

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