LONG-DURATION SOLAR AND STELLAR FLARES

GIANNINA POLETTO

Osservatorio Astrofisico di Arcetri, Firenze, Italy

Abstract. According to one of the most popular classifications, solar flares may be assigned either to the category of small short-lived events, or to the category of large, long-duration two-ribbon (2-R) flares. Even if such a broad division oversimplifies the flare phenomenon, our knowledge of the characteristics of stellar flares is so poor, that it is worthwhile to investigate the possibility of adopting this classification scheme for stellar flares as well. In particular we will analyze Einstein observations of a long duration flare on EQ Peg to establish whether it might be considered as a stellar analogy of 2-R solar events. To this end we apply to EQ Peg data a reconnection model, developed originally for solar 2-R flares, and conclude that stellar observations are consistent with model predictions, although additional information is required to identify uniquely the physical parameters of the flare region. Application of the model to integrated observations of a 2-R solar flare, for which high spatial resolution data are also available, shows, however, that future integrated observations may allow us to solve the ambiguities of the model and use it as a diagnostic tool for a better understanding of stellar flares.

1. Introduction

Solar flares may differ widely in a number of properties such as the size of the flaring region, the duration of the event, and the energy released. Small events, for instance, last only a few minutes and release about 10^{29} ergs, i.e., about 10^{-3} less energy than is released in the larger events which span a time interval on the order of a few hours. Nevertheless, several authors tried, in the past, to classify solar flares according to their 'basic' characteristics. As a result, different classifications have been proposed (Pallavicini, 1977; Tanaka, 1983; Švestka, 1986) which oversimplify the flare phenomenon, the more they are concise, but still provide an overall description of the more fundamental aspects of a flare. In the well-known two-group classification which we will adopt in the following, small events are interpreted as involving one or a few loops and are referred to as compact or single-loop flares, while large events, which occur in an arcade of loops and are characterized at the chromospheric level by the appearance of the two bright Hα ribbons from which they take their name, are considered as typical representative of the second class of flares.

The different behavior of flares pertaining to the two classes is usually ascribed to the different physical mechanisms involved in the event. A short-lived energy input and a local magnetic field disruption account for compact flares; a continuous energy release and a global magnetic field disruption are invoked to explain two-ribbon events. In these latter flares the growing system of loops which rises in the corona and the increasing ribbon separation at the chromospheric level are interpreted as different manifestations of a reconnection process which closes back to a lower energy state an arcade of loops which had been torn open beforehand by an unspecified eruptive phenomenon.

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The energy released from stellar flares on M dwarf stars, although much larger than the energy released in solar flares, is delivered, as in the Sun, on time-scales ranging from a few minutes to a few hours. This behavior may be taken as an indication that flares on M stars imply the same mechanisms invoked in the solar case and possibly may be classified either as compact or as two-ribbon flares. If this were the case, it would be possible to apply to stellar flares the methods which proved successfull in modeling solar flares.

Attempts along this line are quite scanty. A hydrodynamic numerical code which describes the behavior of plasma confined in a rigid closed loop and heated by a strong heat pulse has been used by Reale *et al.* (1988) to model an X-ray flare on Prox Cen. This hydrodynamical model has been able to reproduce fairly well the temporal behavior of the X-ray emission from compact solar flares. Fisher and Hawley (1989) applied a flare loop evolution model, valid in the limit of weak evaporation, to reproduce the rise phase and the initial decay of a flare on AD Leo. This work is based on an attempt to extend to the stellar case the 'scaling laws', widely used in modeling solar loops. Poletto, Pallavicini, and Kopp (1988) and Van den Oord and Mewe (1988) interpreted a few stellar flares on the basis of a model (Kopp and Poletto, 1984) which had been originally developed for solar two-ribbon flares.

Clearly any attempt to extrapolate solar models to the stellar case is risky: integrated stellar observations do not provide all the information which would be needed for a safe extension to stellar phenomena of models originally developed to interpret events observed on the Sun with high spatial and temporal resolution. This, however, represents a workable technique for a better use of stellar data, provided one keeps in mind the uncertainties implied in such an extension. With this respect it is important to establish if, and how, a model capable of describing high-resolution data can be successfully applied to spatially-integrated data.

The present paper will focus on long-duration flares, in an attempt to establish whether long-lasting stellar flares can be interpreted as stellar counterparts of solar two-ribbon flares. To this end we apply a reconnection model, successfully applied to 2-R solar flares, to a flare observed on EQ Peg (Section 2), and check whether the profile of the magnetic energy release, as predicted by model, matches the X-ray light curve, as observed by EXOSAT. Extending previous works (Poletto, Pallavicini, and Kopp, 1988; Van den Oord and Mewe, 1988), we show (Section 3) that it is possible to reach an agreement between the data and the analytical predictions throughout the whole flare lifetime (after the impulsive phase). However, even if consistency between model predictions and observations is easily reached, the model is unable to choose, among the different scenarios which allow for consistency, the one which better approximates the real situation. To overcome this severe limitation, we apply (Section 4) the model to integrated observations of a solar 2-R flare, whose characteristics are well known from high-resolution data, and compare the parameters predicted by the model on the basis of integrated observations with results obtained from high-resolution data. This comparison shows that the correct parameters of the flareing region can be uniquely determined whenever its density is known from observations. Future integrated observations of stellar flare spectra may provide this data and we conclude that the 2-R model, complemented by this further information, may be used as a diagnostic tool to infer unidentified flare parameters and define uniquely the flare scenario.

2. The Reconnection Model

As mentioned above, the reconnection model hypothesizes that an open magnetic field, created by an eruptive phenomenon, closes back to a lower energy state. In this process open field lines are driven toward the neutral sheet by an unbalanced Lorentz force, and reconnect at progressively higher levels in the corona. The excess magnetic energy released by reconnection shows up as thermal energy of the bright X-ray loops (Hirayama, 1974; Kopp and Pneuman, 1976).

These basic ideas have been worked out subsequently by a few authors (Pneuman, 1981, 1982; Cargill and Priest, 1982) to provide a comprehensive description of the relationships between the various phenomena observed in two-ribbon flares. When the magnetic field configuration is simple enough, a two-dimensional model may be adequate to describe the flare region topology, provided is understood that such a simplified description has, by necessity, to overlook some characteristics – e.g., magnetic shears – which may be relevant when a more detailed representation of the event is required. Such a simplified model has been developed analytically by Kopp and Poletto (1984), who assumed the initial open configuration to be radial and the reconnected one to be potential between the solar surface ($r = R_0$) and a spherical equipotential source surface at $r = r_1$ (neutral point height), and non-potential and still radial above this height. With these assumptions Kopp and Poletto solved Laplace equation for the scalar potential ψ and expressed its solution in terms of a single Legendre polynomial of degree n. Once the scalar potential is known, its partial derivatives, with respect to spatial coordinates, give the magnetic field components at any position r. The effect of reconnection progressing to higher and higher altitudes is mimicked by allowing r_1 to take increasingly higher values and constructing a sequence of field configurations with successively higher closed field lines. These, if the function $r_1 = r_1(t)$ is known, may be directly compared with the configuration observed at time t. Conversely, when the function $r_1(t)$ is unknown, its profile can be determined *a posteriori*, by matching the calculated magnetic topology to the observed one.

From the analytical expression of the magnetic field it is trivial to derive the total magnetostatic energy $E = \int (B^2/8\pi)\,\mathrm{d}V$ as a function of the height $r_1 = r_1(t)$. Since the field is potential up to r_1 and non-potential above, the stored energy decreases as r_1 rises to higher altitudes, and at any time t the liberated energy is given by

$$\mathrm{d}E/\mathrm{d}t = (1/8\pi)2n(n+1)(2n+1)^2 R_0^3 B_0^2 \{I_{12}(n)/P_n^2(\vartheta_{12})\} \times \\ \times \{(r_1/R_0)^{2n}[(r_1/R_0)^{2n+1} - 1]/[n + (n+1) \times \\ \times (r_1/R_0)^{2n+1}]^3\} \,\mathrm{d}/\mathrm{d}t(r_1/R_0)\,. \tag{1}$$

An exhaustive description of the reconnection model can be found in the above quoted reference. Here it will suffice to clarify the relation between individual parameters in (1) and observations. The degree n of the Legendre polynomial is a free parameter which is adjusted to fit the latitudinal width of the flaring region, smaller n corresponding to larger regions. B_0 is a parameter related to the magnetic field strength in the region: larger B_0's imply a larger magnetic energy content. The function $r_1 = r_1(t)$ can be derived from high spatial resolution observations by measuring, at different times t during the flare lifetime, the height of the most recently formed X-ray loop, generally assumed to lie immediately below the reconnection altitude. Finally, R_0 is the stellar radius, and $I_{12}(n) = \int P_n^2 \, d(\cos\theta)$, with the integration extended over the lobe width.

3. Modeling EQ Peg Flare

When modeling solar flares, the choice of n, B_0, $r_1 = r_1(t)$, is not free: observations of the size of the region, of the magnetic field strength in the flaring area, and of the rise of X-ray loops in the corona provide all the information necessary to determine these parameters and evaluate uniquely the temporal profile of the magnetic energy release. Stellar flare integrated observations provide none of the previous information. Therefore, in order to apply the reconnection model, one has to devise some criteria to establish the behavior of these quantities.

The value n of the degree of the Legendre polynomial can be parametrized to represent different flaring region sizes. There is evidence that stellar active regions may be larger than solar active regions. Therefore, besides $n = 17, 35$ (latitudinal width, respectively, 5, 10 deg) we considered also smaller n values ($n = 5, 9$; latitudinal width, respectively, 33 and 20 deg). The function $r_1 = r_1(t)$ can be determined only by resorting to the solar case. From the observations of a number of two-ribbon solar events, it appears that the upward expansion of the hot loop system can be described by an exponential law of the form

$$r_1(t) = 1 + (H/R_0)\,[1 - \exp(-t/t_0)]\,, \tag{2}$$

where H is the maximum height reached by the X-ray loops (on the order of the width of the flaring region), and t_0 is a constant which depends on the duration of the event. In the following we assume this law to hold also in the stellar case. We notice that if we make the further assumption that the longitudinal extent of the region is about twice its latitudinal width (as in the Sun), (2) allows us to evaluate the volume of the flaring region at any time t. The magnetic field strength in the region can be either chosen *a priori* to be large enough to provide for the flare energy requirement (see, for instance, Poletto, Pallavicini, and Kopp, 1988), or determined by assuming that the loop plasma is magnetically confined. In this case the gas pressure, at any time t, is derived from the temperature and emission measure given by X-ray observations and the volume calculated from the model – as described above – and the magnetic field strength is set to the value required by a balance between gas and magnetic pressures.

These criteria allow us to calculate, through (1), the magnetic energy release rate and to check whether the calculated energy release matches the X-ray light curve. To this end we used EXOSAT observations of the flare which occurred on EQ Peg on 6 August, 1985. Figure 1 shows the four curves which give the rate of magnetic energy release for $n = 5, 9, 17, 35$ superposed to the light curve of the flare as derived from the Medium Energy experiment data (≈ 2–10 keV) (dots). Each curve provides a different scenario for the flaring region. Low n values correspond to large regions, with large volumes (high H values), and, since densities are evaluated from the emission measure, densities lower than in regions characterized by larger n. As a consequence, also the gas pressure and the magnetic field strength are smaller for low n, even if, due to the large volume, the magnetic energy content is higher for lower n. In spite of these differences each curve may be scaled down to match quite closely the observed X-ray light curve. While the reconnection model can represent the data, its inability to make a choice among sets of different parameters appear as a major shortcoming in all practical applications of the model. Next section shows how to overcome this difficulty.

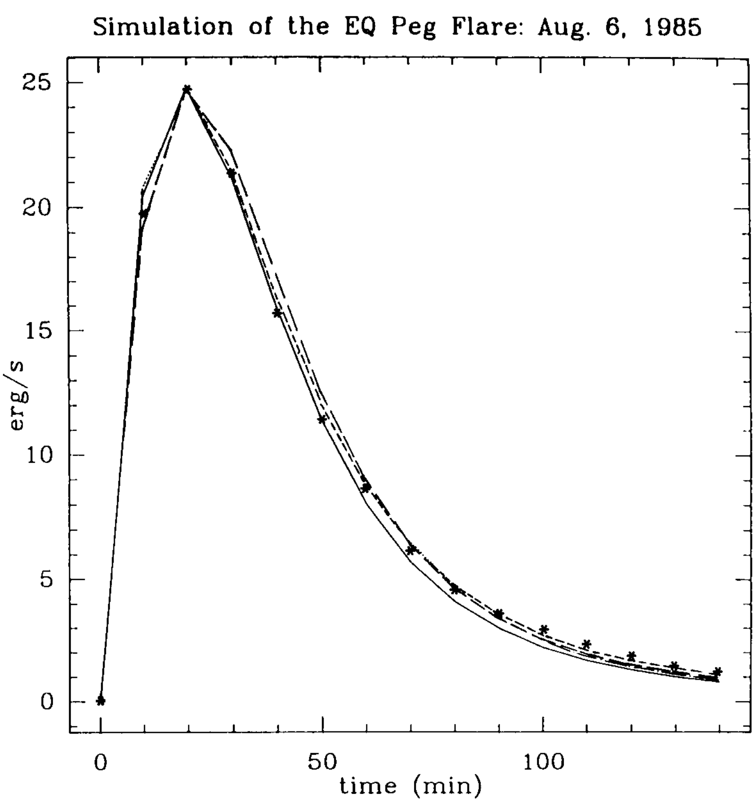

Fig. 1. The rate of energy release during the flare observed on EQ Peg on 6 August, 1985 is shown here as derived from EXOSAT Medium Energy observations in the band 2–10 keV (dots) and as predicted by the reconnection model simulations (solid, dotted, long-dash, short-dash curves). The analytical curves have been calculated through the relationships (1) and (2) (see text): t_0 has been set to 8000 s; the constant H is set equal to the region width and the parameter B_0 is derived from the balance between gas and magnetic pressure.

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4. Modeling Integrated Solar Flare Data

In spite of the pessimistic conclusion of the previous paragraph, we notice that the specification of an additional parameter would be sufficient to identify a realistic scenario. For instance, assuming recent observations of magnetic field in the dM star AD Leo (Saar and Linsky, 1985) to be representative of typical magnetic field strength in M stars, we will be drawn to consider, as the most plausible scenario for the EQ Peg flare region, a width on the order of 10–20 deg, a magnetic field strength on the order of 2000–3000 G, and an electron density which from $3.6–9.7 \times 10^{12}\ \mathrm{cm}^{-3}$ at peak X-ray intensity, decreases to $3–8 \times 10^{11}\ \mathrm{cm}^{-3}$ by the end of the flare.

Observations of stellar magnetic field are, however, much too scanty to rely heavily on them. Also the size of the active region, which determines n, and, therefore, points to a unique model, is obviously not provided by X-ray integrated stellar observations. We apparently lack the means to verify whether the model is realistic. However, applying the model to integrated observations of solar flares, for which high-resolution observations are also available, we have the possibility of checking if and how well the real scenario is approximated, and, possibly, to find out how integrated observations can be supplemented to provide the scenario known, from high-resolution data, to be realistic. Such an opportunity is offered by the SOLRAD satellites, which made integrated solar observations at the same time that Skylab high-resolution data were gathered.

The solar two-ribbon flare which occurred on 29 July, 1973, had been observed both by Skylab and SOLRAD, and showed such a simplified and regular behavior as to be the very prototype of 2-R flares (Martin, 1979; Nolte *et al.*, 1979; Petrasso *et al.*, 1979; Moore *et al.*, 1980; Švestka *et al.*, 1982). The size of the active region where the flare occurred, its magnetic field strength distribution, the growth of the hot X-ray loops with time, have all been observed in great detail. Only SOLRAD-type integrated data would be available, however, if the Sun had been observed as a star. Assuming this is the case, we repeated the procedure used in the EQ Peg flare simulation, and matched the observed light curve with the magnetic energy release curve predicted by the reconnection model. Results of this simulation are shown in Figure 2. Analytical curves calculated with the same parameters and assumptions adopted when modeling the EQ Peg flare (namely, same values for the n parameter; maximum height of the X-ray loops equal to the width of the active region; balance between magnetic and gas pressure) are superposed to integrated data in the 1–8 Å band from SOLRAD 9 observations. Once more, independently of the choice of the parameters, the analytical curves fit the data quite well, even if, as shown in Figure 3, the gas pressure, evaluated from SOLRAD data and volumes predicted by the model, strongly varies as a function of n. Nevertheless, we are unable to select the more realistic scenario.

Skylab high-resolution observations, however, provide a means to evaluate the pressure of the loop plasma. Densities in hot loops have been derived from the time delay an X-ray loop takes to cool down to chromospheric temperatures (Švestka *et al.*, 1982). From these densities and temperatures determined from the ratio between fluxes in two SOLRAD channels, the gas pressure may be calculated (solid line in Figure 3). Clearly

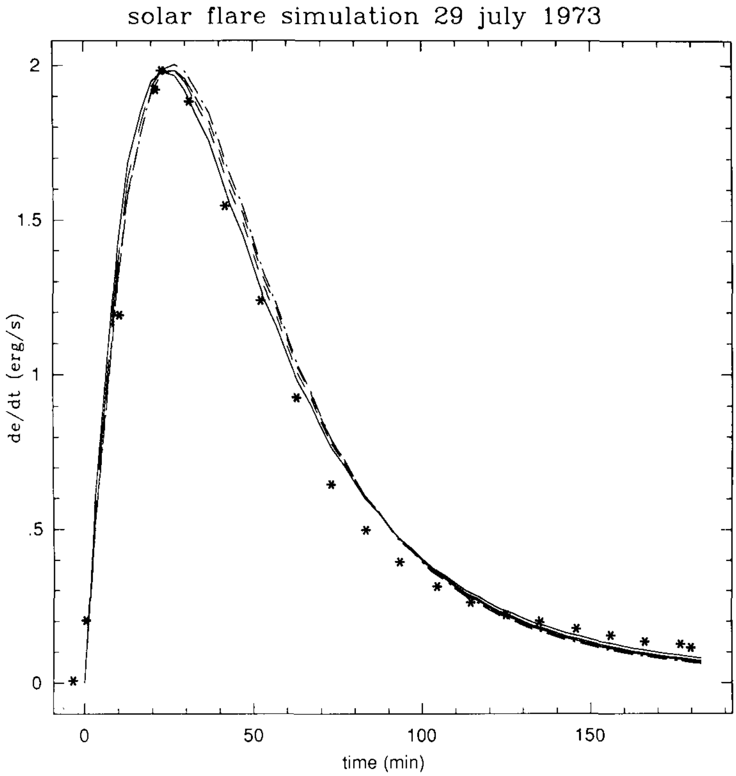

Fig. 2. The rate of energy release during the solar flare observed on 29 July, 1973 is shown here as derived from SOLRAD 9 data in the 1–8 Å band, and as predicted by the reconnection model simulations (solid, dotted, long-dash, short-dash). As in Figure 1, simulations with different n are indistinguishable when scaled down to fit the observed energy release rate.

the model with $n = 17$ approximates the physical conditions of the loop plasma better than the others.

In fact high-resolution observations allow us to establish that the model with $n = 17$ gives a realistic description of the flaring region. Both its volume (Moore *et al.*, 1980) and the value of the average magnetic field at the photospheric level (100 G) (Michalitsanos and Kupferman, 1974), are identified correctly. At higher levels a comparison between the values given by the model for the magnetic pressure at the heights new loops are formed and the values of the gas pressure in these loops, calculated from X-ray observations, shows that, between 7000 and 90 000 km, the magnetic field strength in the potential approximation adopted by the model is within 40% of the value required for a magnetic confinement of the loop plasma. We conclude that the model with $n = 17$ is realistic and may be selected from the set of different simulations whenever densities in the flaring region are known.

Although unavailable at present, this requirement does not appear impossible to meet. Future X-ray missions, like AXAF and XMM, will obtain spectra with high enough resolution to separate a number of density-sensitive lines (Linsky, 1987; Barr *et al.*,

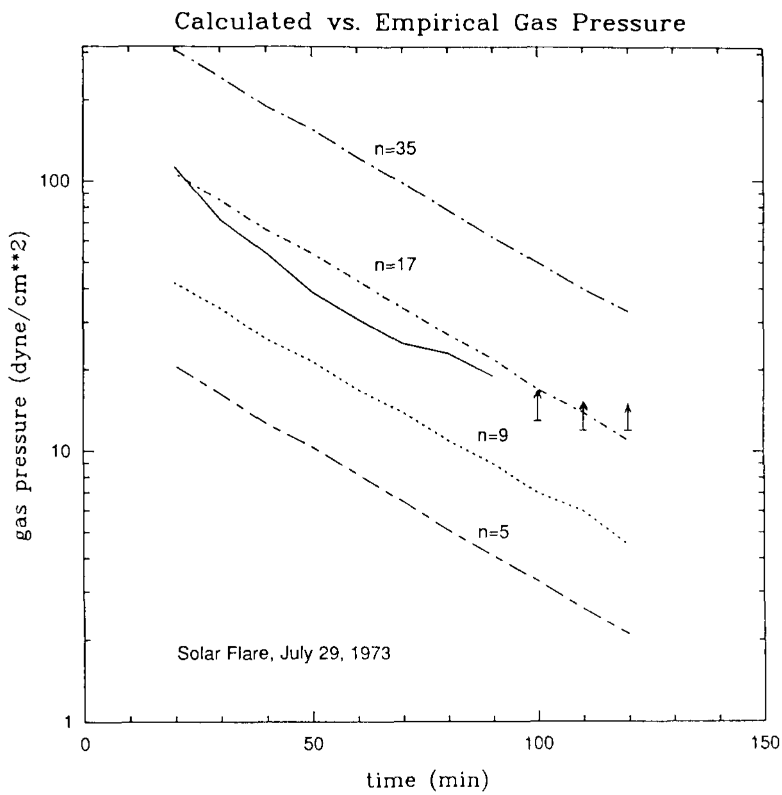

Fig. 3. Gas pressure vs time in the solar flare of 29 July, 1973. The solid curve shows the behavior of the empirical gas pressure at different times as evaluated from temperatures derived from the ratio of SOLRAD 9 fluxes in the bands 1–8 and 8–20 Å, and densities derived from the time a loop takes to cool down from X-ray to chromospheric temperatures. At late times, only lower limits to the density values can be given; the corresponding gas pressures are marked with arrows. The four curves labelled by the value of the parameter n give the profile of the gas pressure vs time as evaluated from temperatures and emission measures derived from SOLRAD 9 data and volumes predicted by the reconnection model. Smaller n imply larger volumes and, as a consequence, smaller densities and gas pressures.

1988). Integrated observations will, therefore, supply the value of density in stellar flares, thus giving the reconnection model the capability of providing crucial information about the stellar flaring regions: their size at the photospheric level (via the value of n), their volume at different times during the flare (via the law describing the rise of hot X-ray loops in the corona), and the average magnetic field strength (via magnetic confinement of the loop plasma) at different heights in the region.

5. Concluding Remarks

Before drawing any conclusion from these results, a number of points need to be discussed. If the energy released by reconnection has to account for the total energy released in the gradual phase of the flare, we have to make sure not only that the profile of the magnetic energy release vs time reproduces the actual temporal profile of the rate of flare energy release, but also that the energy released by reconnection meets quantitatively the total energy output. Therefore, two questions need to be asked: can we safely assume the X-ray light curve to be representative of the temporal profile of the overall flare energy release? And how does the total energy released by the flare compare with the energy released in the X-ray band?

We refer the reader to Poletto, Pallavicini, and Kopp (1988) for a more thorough discussion of these points. Briefly, we recall here, as to the first point, that, resorting to solar observations, we can consider the profile of the energy released in the X-ray band as representative of the overall profile of the radiative flare energy. Flare light curves at different wavelengths, after the precursor and impulsive phase, do not show relevant differences, except for the microwave range, energetically unimportant (e.g., Kane, 1974; Lin, 1975). Whether this is representative of the profile of the overall flare energy output, is a more difficult question to answer: information about the temporal profile of the mechanical energy associated with the flare is scanty, at best.

As to our second question, following Canfield *et al.* (1980) and resorting once more to the solar analogy, we may assume the total energy radiated by the flare to be about ten times larger than the energy released in the X-ray bands we considered. The magnetic energy supply has to be at least as large, and possibly larger, if it has also to provide for other flare energy losses.

A solution to these problems will allow us to define more precisely the constraints the reconnection model has to satisfy. Still, such a model, besides accounting for solar two-ribbon flares, is capable of reproducing the X-ray light curve of stellar long-duration flares, while providing for their energy requirement (the magnetic energy released in the EQ Peg flare simulations is larger than the X-ray energy losses by a factor ranging between 14 and 35, depending on the value of n). Lacking further observational evidence about the characteristics of stellar flares, rather than claim that two-ribbon stellar flares have been identified, it may be safer to claim that the predictions from the reconnection model are consistent with observations of long duration stellar flares. We recall, however, that experimental evidence for a temporary increase in the column absorption density along the line-of-sight at the time EINSTEIN observed a long lasting event on the dM star Prox Cen was fundamental to an earlier suggestion for the presence of two-ribbon flares on stars (Haisch *et al.*, 1988). In fact we have shown that the X-ray light curve of the Prox Cen flare can be simulated by the reconnection model (Poletto, Pallavicini, and Kopp, 1988). This, however, is not the only interpretation supported by the data (Peres, 1989).

Besides establishing, with the limitations mentioned above, that there may be counterparts to two-ribbon solar flares, it has to be stressed that the reconnection model, when supplemented by integrated observations of density-sensitive lines, has the capability of determining a number of parameters which provide a complete description of the flaring region. Its determination of the magnetic field strength and size of stellar flaring regions may be compared with independent determinations of the same quantities from other techniques and provide a cross-check on the derivation of stellar flaring region parameters. In a field where the unavailability of high resolution observations sets severe limits to the amount of information that can be drawn from the data, it is especially relevant to establish alternative means to achieve a reliable description of phenomena which are unobservable in detail. This seems the more promising area of applicability of the model.

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