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Stellar Flare Modeling

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Abstract. Based on the solar analogy, models of flare decay have been extensively applied to infer the size of stellar flaring regions. The basic concepts and the most widely used models are reviewed here, describing their advantages and limitations. Most of them assume the decay of single coronal loops but a two-ribbon flare model is also described. Applications are listed, remarking that current models tend to overestimate the size of 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. Other diagnostics from modeling and future developments are mentioned.

1. Introduction and basic concepts

Stellar coronae are spatially unresolved with present-day X-ray telescopes. Many stars show highly transient phenomena with light curves and time scales very similar to solar coronal flares. Here I will discuss models of the decay phase of stellar flares, customarily used to infer the spatial size of the unresolved flaring structures. Several approaches have been applied to analyze observed stellar flares and I will review some widely-used ones and make comparisons among them, remarking their advantages and limitations.

The analysis of stellar X-ray flares is useful for us mainly on two aspects: it allows us to investigate flare mechanisms by observing events in environments and on scales different from solar ones and, since they are highly transient events, their evolution and characteristic time scales can be used to infer the size of the structures where the events occur. However, in order to interpret correctly and reliably the observed evolution and to extract realistic quantitative information, sound physical models are required.

As basic starting point for modeling stellar coronal flares, it is customary to assume that stellar flares share many features with solar flares, which can then be taken as templates. Solar flares are well known to occur in localized regions in the corona, often in single magnetic loop structures, and the involved structures can remain mostly unchanged during the flare evolution (e.g. Pallavicini et al. 1977). Then let's suppose to have a loop and a flare with a light curve like the ones shown in Fig.1. We can divide the flare evolution into three basic phases, the rise phase, the peak phase and the decay phase. The rise phase is generally faster than the decay phase. If the rise phase is not too rapid, we

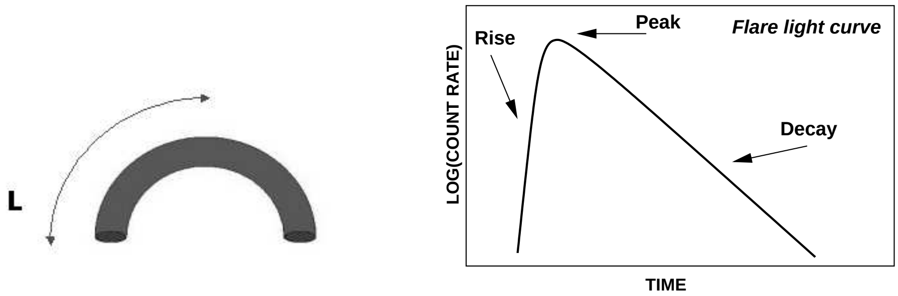

Figure 1. Sketch (*left*) of flaring loop with a given half-length L. Typical flare light curve (*right*) with a fast rise phase, a maximum and slower decay.

can make the hypothesis that, at the flare peak, the flaring plasma approaches an equilibrium condition, with an energy balance between heating source and cooling losses. Let's consider the flaring loop with half-length L, and pressure p at the peak. The pressure can generally be assumed to be practically uniform along the loop, since the pressure scale height $s_p \approx 5\ T_7/g_*$ (10^{10} cm), where T_7 is the flare temperature (10^7 K) and g_* is the gravitational acceleration in solar units, is typically larger than the height of the flaring structures. The conditions of steady-state energy balance then is:

$$E_H - E_{rad} - E_{cond} = 0 \tag{1}$$

where

$$E_{rad} = n^2 P(T) \qquad E_{cond} = \nabla \cdot \mathbf{F}_C \tag{2}$$

E_H being the heating rate per unit volume triggering the flare, E_{rad} the plasma radiative losses, n the plasma density, $P(T)$ the radiative losses per unit emission measure, E_{cond} the thermal conduction losses toward the cooler chromosphere, $\mathbf{F}_C$ the conductive flux.

It has been shown (e.g. Rosner et al. 1978, Kuin & Martens 1981) that in equilibrium condition loop scaling laws hold, linking maximum temperature, pressure, length and heating rate per unit volume of a coronal loop (cgs units):

$$T_{max} = 1.4 \times 10^3 (pL)^{1/3} \tag{3}$$

$$E_H = 10^{-5} p^{7/6} L^{-5/6} \tag{4}$$

We now turn our attention to the decay phase, and see how it depends on the loop size. The decay generally begins as soon as the heating term is switched off, or at least when it begins to decrease significantly. The plasma then cools down by thermal conduction downwards to the chromosphere and by radiation with characteristic times:

$$\tau_{cond} = \frac{3nkT}{\kappa T^{7/2}/L^2} \qquad \tau_{rad} = \frac{3nkT}{n^2 P(T)} \tag{5}$$

respectively, where n is the flaring plasma density, κ is the plasma thermal conductivity, k is the Boltzmann constant, $P(T)$ is the plasma emissivity per

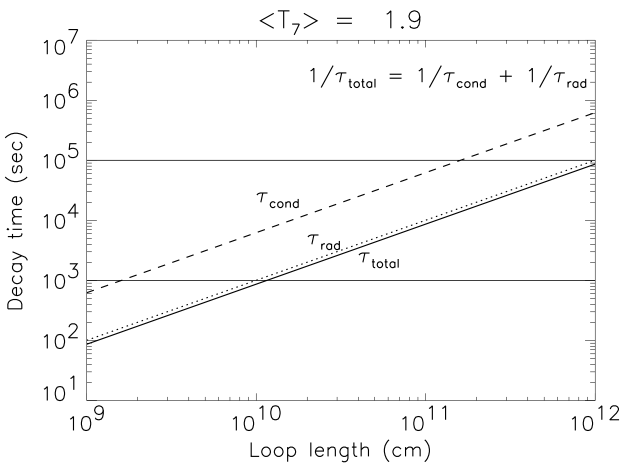

Figure 2. Plasma conduction (dotted line) and radiation (thin solid line) cooling times, and the combination of the two (thick solid line) as a function of the loop half-length, for the labelled maximum temperature (10^7 K). The horizontal lines bound the range of typically observed flare decay times.

unit emission measure. Notice that τ_{cond} depends explicitly on the loop length. Indeed, also τ_{rad} depends on length but implicitly through the density, which is constrained by the scaling law Eq. (3) (and by the equation of state), which depends on length.

Fig. 2 shows the dependence of cooling times (5) on length when the maximum temperature is $T_{max} = 1.9 \times 10^7$ K. The effective cooling will be the combination of the two processes and the cooling time will be shorter than both. In the case shown the radiation time dominates. For typical stellar flare decay times, typically in a range between 10^3 and 10^5 s the loop length is in the range $10^{10} - 10^{11}$ cm. More in general, it has been shown (Serio et al. 1991) that a flaring loop starting from equilibrium decays freely with a global thermodynamic time scale linearly dependent on loop length:

$$\tau_{th} = \frac{120 L_9}{\sqrt{T_7}} \tag{6}$$

where L_9 and T_7 are in units of 10^9 cm and 10^7 K, respectively. In principle, then, a fast decay implies a short loop, a slow decay, a large loop. However there are some crucial assumptions which may not hold in general and make things less trivial: does decay really start from equilibrium conditions? Is heating totally absent during the decay and the loop cool freely? We will see better below that if any of these conditions is not true, we may significantly overestimate the loop length.

2. Stellar flare models

Going into the detail of flare models, we can outline two basic approaches to modeling. The first one is to model specific events in detail by solving in detail the time-dependent hydrodynamic equations of plasma confined in loops. An example of this approach is the hydrodynamic modeling of a flare well observed by the Einstein satellite in 1980 on Prox Cen which lead to the successful fitting of the flare light curve and to constrain the length of the loop presumably involved in the flare (Reale et al. 1988). This approach has the disadvantage to be resource-consuming and practically unfeasible for systematic analysis of large flare samples. The alternative approach is to dismiss accurate description and complete physics in favour of approximate analytic approaches, more adequate to be applied extensively to large number of flares.

In the latter category we can list five among the most widely used methods in analysing stellar flares, which will be named as follows: i) the Quasi-Static cooling method (hereafter QSS, van den Oord & Mewe 1989); ii) the Pure radiation cooling method (Pallavicini et al. 1990); iii) the Rise+Decay method (Hawley et al. 1995); iv) the Hydrodynamic method (Reale et al. 1997); v) the Two-ribbon flare method (Kopp & Poletto 1984). The first four assume that flares occur in single loop structures, the last one in expanding arcades, like those involved in solar two-ribbon flares.

2.1. The Quasi-static approach

The basic assumption of the QSS method is that, starting from an equilibrium condition, "if the heating rate varies only slowly, scaling laws for the quiescent coronal loop can be applied to the decay phase" (van den Oord & Mewe 1989). Then the energy balance in the decay is solved analytically, using loop scaling laws. The loop length is then derived from the light curve decay time:

$$\tau = \alpha \mu^{1/2} L T^{-7/8} \tag{7}$$

where α and μ are constants, under the condition that heating is negligible during the decay. This condition is verified, according to the original formulation of the method, if the ratio of the radiative cooling time to the conductive cooling time is constant throughout the decay:

$$\mu = \frac{\tau_{rad}}{\tau_{cond}} \approx 0.18 \approx \frac{T^{13/4}}{EM} = \text{const.} \tag{8}$$

In fact, this condition is satisfied by equilibrium loops described by the scaling laws. The approach is formally and substantially similar to the one in Serio et al. (1991). However some drawbacks are to be noted. First of all, the quantity μ (Eq.8) is derived indirectly from observations and therefore typically affected by large uncertainties (more than factors two). More important, condition (8) holds for steady-state loops. In particular, it holds if the decay is described by a gradual transition to cooler and cooler equilibrium loops, which can only occur if the heating decays very gradually. In other words, for condition (8) to hold, *heating must be significant in the decay*, in contrast to the original recipe of the method. Hydrodynamic simulations confirm this finding (Reale 2001, in preparation). Therefore heating is treated inconsistently when this method is applied. The advantage of the QSS method is that it is of easy, and, in principle, general applicability. Limitations include the above mentioned inconsistent condition on the presence of heating during the decay and the difficult diagnostics of the heating. Notice that the former problem implies that the flare loop lengths derived with this method (see Table 1) should be treated as upper limits.

2.2. Pure radiative cooling

A simpler approach is based on the simplified assumption that the radiative cooling dominates the decay of the flaring loop, i.e. the radiative cooling time is shorter than the conductive time (Pallavicini et al. 1990). This condition holds for QSS loops (Eq. 8). Then from the flare decay time we can derive directly the density of the cooling plasma. If from spectral analysis the emission measure is known, then the volume can be derived and from it the loop length after making an assumption on the loop aspect. Of course the application of this approach is very straightfoward but results have to be taken as order of magnitude estimates. Furthermore, it includes no effect of heating in the decay and therefore provides essentially upper limits to the loop length.

2.3. Rise+Decay model

Flares are highly dynamic phenomena and the assumption that a flaring loop reaches equilibrium conditions before it decays may not be appropriate. In particular, if the rise phase is not long enough, flaring plasma remains less dense than at equilibrium as the decay starts. The decay will then be slower than expected if starting from equilibrium and, if this is not taken into account in the analysis, the loop length will be overestimated.

The approach described in Hawley et al. (1995) includes the description of the rise phase, and therefore the possibility that the loop is out of equilibrium when the decay starts. It has been derived by solving the time-dependent energy equation in the rise and decay phase separately in different limits: strong evaporation, driven by heating, in the rise phase, and strong condensation, driven by radiation, in the decay phase. This allows to make strong simplifications in the equation. The eventual result is an expression for the loop length basically dependent only on the rise and decay times (τ_{ris}, τ_{dec}) of the light curve:

$$L \approx 0.006\ \tau_{ris}^{3/7}\ \tau_{dec}^{4/7}\ T^{1/2} \tag{9}$$

It is possible to show that, in the limit of long rise time, Eq. (9) is practically equivalent to the QSS and Serio et al. (1991) approaches. This approach has the advantage to include partial filling of the loop, but still it does not include the effect of heating during the decay. Moreover the rise phase is not always visible in stellar flare observations and therefore τ_{ris} may not be well constrained. It has been shown that this method somewhat systematically overestimates the length of solar flaring loops (Metcalf & Fisher 1996). Probably the problem is just that heating in the decay is neglected.

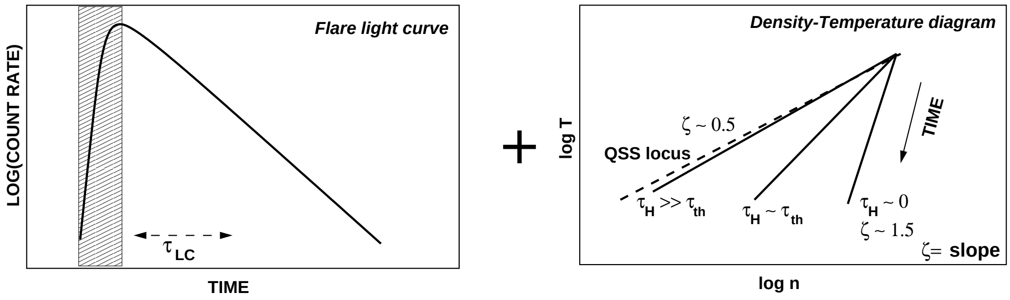

Figure 3. The hydrodynamic method combines the information of the light curve to the information of the density–temperature diagram to derive univocal estimate of the loop length. It requires the decay time and the slope in the n–T diagram, which indicates progressively more significant heating for smaller and smaller slopes.

2.4. Hydrodynamic approach

Just from comparing two light curves with different decay times we cannot say whether the slower decaying one is associated to a longer loop or to a loop of equal length but with a slowly decaying heating. The question now is: how can we diagnose and take into account the possible presence of heating? Light curve alone is insufficient to solve the ambiguity.

The approach by Reale et al. (1997) addresses just this problem. It has been shown that the path followed by the flare decay in the density–temperature (hereafter $n - T$) diagram can provide diagnostics of heating in the decay (Sylwester et al. 1993). In particular, the slope in the n–T diagram is maximum (~ 1.5) in the absence of heating, and decreases toward the locus of the steady-state loops (~ 0.5) as the heating decay time increases. The idea is then to combine the information about the loop cooling times provided by the light curve with the information about the heating time scale provided by the n–T diagram (Fig. 3).

The method has been tuned with a set of time-dependent hydrodynamic simulations of decaying flaring loops with various length, temperature and heating decay time, starting from steady-state conditions at flare maximum. From each simulation the light curve and n–T path are derived for a given selected X-ray telescope. If we plot the light curve decay time normalized to the loop thermodynamic decay time (τ_{LC}/τ_{th}) of all simulations versus their slope ζ in the n–T diagram, we can derive an empirical relationship:

$$\frac{\tau_{LC}}{\tau_{th}} = f(\zeta) \tag{10}$$

which describes the effect of heating on the light curve and yields a correction factor for the loop length formula (see Eq. 6):

$$L_9 = \frac{\tau_{LC}\sqrt{T_7}}{120 f(\zeta)} \qquad f(\zeta) \geq 1 \tag{11}$$

Notice that the correction factor reduces the loop length. The final formula depends only on observable quantities and the coefficients of $f(\zeta)$ have been tuned for several instruments: Einstein/IPC (Favata et al. 2000c), RoSat/PSPC (Reale & Micela 1998, Favata et al. 2000a), EXOSAT/ME (Favata et al. 2000a), ASCA/GIS (Favata et al. 2000b), ASCA/SIS (Favata et al. 2000c), GINGA (Favata et al. 2000a), BeppoSAX/MECS (Maggio et al. 2000), XMM/EPIC (Güdel et al. 2001), Chandra/ACIS. The method has been tested with good success on solar flares (Reale et al. 1997).

The main advantage of this approach is that it includes the effect of sustained heating in the decay. It is tuned on the spectral response of the instruments, and it takes more constraints from data in addition to the light curve, and, although it is derived from detailed hydrodynamic simulations, its application is straightforward. The hydrodynamic methos is more general than the QSS method, in the sense that it includes heating consistently, and with a robust diagnostics, and it provides results comparable to QSS when heating is neglected. Limitations of this method include that it is still a single loop model (as the others described so far), which may be a crude approximation for intense stellar flares (but it has been shown to provide correct scaling sizes when applied to moderately complex loop geometries, Reale et al. 1997), and that the decay is assumed to start from equilibrium (this will be improved soon, Reale 2001, in preparation).

Notice that the hydrodynamic approach has received an important check in a case of a proper stellar flare in which the size of the flaring region could be determined independently: an eclipsed Algol flare observed by BeppoSAX (Favata & Schmitt 1999). The size estimated from the analysis of the eclipse is largely overestimated by the QSS method while a much closer estimate is obtained with the hydrodynamic approach (Fig. 4).

2.5. Two-ribbon flare model

The two-ribbon flare model (Kopp & Poletto 1984, Poletto et al. 1988) assumes that the light curve is dominated by the heating and that the decay is entirely driven by energy released from reconnection of higher and higher loops. Without entering the details, from an exponential fitting of the light curve the method yields the speed and maximum height of the neutral point, i.e. the final height of the largest loop. However, degenerate solutions are found for applications on stellar flares which are much more loosely constrained than solar flares (e.g. Poletto et al. 1988). The advantages of this method are that it accounts for possible change of loop geometry observed in several solar flares and that it includes heating by definition. However, the model is quite empirical, the energy released is prescribed, plasma cooling times are neglected and the size of stellar flaring regions is not well constrained in the end. Given its assumptions, this method should be applied whereas, for instance, the hydrodynamic approach shows that heating dominates the decay and is not able to constrain the loop length, providing only an upper limit.

2.6. Conclusions on models

In summary, each method has its own advantages and limitations. All single loop models tend to overestimate the loop sizes, and the results should then be taken

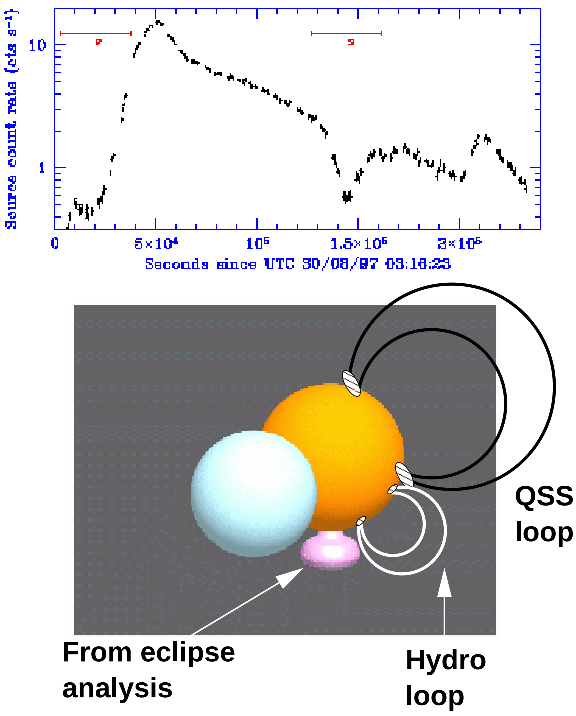

Figure 4. The eclipsed Algol flare observed by BeppoSAX (light curve from Favata & Schmitt 1999) has allowed an independent estimate of the size of the flaring region. The hydrodynamic method yields an estimate of the loop length much closer to the one inferred from the eclipse than the QSS method.

as upper limits on the loop length. The rise+decay model is the only one which includes the description of a decay starting from non-equilibrium conditions. The hydrodynamic model is the only single loop model which takes heating in the decay into account. The two-ribbon flare model is complementary to single loop flare models but yields few constraints for non-solar flares.

3. Flare model applications

Table 1 shows a list of applications of the methods outlined so far. They have been applied mostly to flares observed on active binaries like RSCVn's, on pre-main sequence (PMS) stars and Young Stellar Objects (YSO), on dMe stars and on a few active main sequence stars. As shown in Table 1, the two-ribbon flare model has been applied to many flares on binaries but failed to reproduce the light curve in several cases. The QSS method has also been largely applied, and more recently Algol flares have been analyzed with the hydrodynamic method. The QSS and hydrodynamic models have been mostly applied to flares on PMS.

Table 1. Model applications to stellar flares

Reference	**Star**	**Telesc.**	**KP**[a]	**Pal**	**QSS**	**Haw**	**Hyd**
RSCVn/Algol							
van den Oord et al. 1988	σCrB	exosat	No[b]	X	-	-	-
Osten et al. 2000	σCrB	asca	No	-	X	-	-
Graffagnino et al. 1995	HR5110	rosat	No	-	X	-	-
Kuerster & Schmitt 1996	CFTuc	rosat	No	-	X	-	-
Endl et al. 1997	HUVir	rosat	X	-	X	-	-
Mewe et al. 1997	IIPeg	asca[c]	-	-	X	-	-
Güdel et al. 1999	UXAri	asca[c]	X	-	-	-	-
Favata et al. 2000a	Algol	ginga	-	-	X	-	X
+v. d. Oord & Mewe 1989[d]	Algol	exosat	-	-	X	-	X
+Ottmann & Schmitt 1996	Algol	rosat	-	-	X	-	X
+Favata & Schmitt 1999	Algol	sax	-	-	X	-	X
PMS/YSO							
Preibisch et al. 1995	P1724	rosat	-	X	-	-	-
Hamaguchi et al. 2000	MWC297	asca	-	X	-	-	-
Favata et al. 2001	HD283572	rosat	-	-	-	-	X
+Tsuboi et al. 2000	YLW15	asca	-	-	X	-	X
+Preibisch et al. 1993	LkHa92	rosat	-	-	X	-	X
+Tsuboi et al. 1998	V773Tau	asca	-	-	X	-	X
dM							
Schmitt 1994	EVLac	rosat	X	-	X	-	-
Favata et al. 2000b	EVLac	asca	-	-	X	-	X
Hawley et al. 1995	ADLeo	euve(2)[e]	-	-	-	X	-
Cully et al. 1997	ADLeo	euve(2)	-	-	-	X	-
Favata et al. 2000c	ADLeo	asca(3)	-	-	-	-	X
	ADLeo	rosat(2)	-	-	-	-	X
	ADLeo	einstein	-	-	-	-	X
Reale & Micela 1998	ADLeo	rosat	-	-	X	-	X
	CNLeo	rosat	-	-	X	-	X
Cully et al. 1993	AUMic	euve	-	X	-	-	-
Pan et al. 1997	EQ1839.	ginga	-	-	X	-	X
Pallavicini et al. 1990	14dM	exosat(32)	-	X	-	-	-
Active ZAMS							
Maggio et al. 2000	ABDor	sax(2)	-	-	-	-	X
Güdel et al. 2001	ABDor	xmm	-	-	-	-	X
Covino et al. 2001	Gl355	rosat	-	X	-	-	X

[a] - KP = two-ribbon flare model, Pal = Pure Radiative Cooling, Haw = Rise+Decay, Hyd = Hydrodynamic model (see Sect. 2.).

[b] - The method was applied but failed to reproduce the light curve.

[c] - also observed with EUVE.

[d] - all references preceded by a "+" study the same flare as the just mentioned works by Favata et al.

[e] - more than one flare observed and analyzed

All loop models have been applied to flares on M dwarfs, the hydrodynamic method to flares on two ZAMS stars.

These applications generally involve long-lasting observed flares and tend to find long loops. Flares on active binaries and PMS are generally longer-lasting than on dMe stars and imply longer structures. The decay heating seems to be quite a common feature of the observed flares and implies reductions of the loop length by factors 2-4 with respect to the lengths of freely decaying loops.

4. Other information from modeling

Flare models allow to derive information on the size of flaring structures basically from the analysis of the X-ray evolution (the light curves). Other physical properties of the flaring plasma can be inferred from the analysis of flare data. The analysis of the X-ray spectra, whenever available, typically provides values of temperature and emission measure. By assuming a loop aspect, from the emission measure and the loop length one can obtain an estimate of the plasma density:

$$n \approx \sqrt{\frac{EM}{V}} \tag{12}$$

where $V \approx 2\pi\beta^2 L^3$ is the loop volume and β is the loop aspect defined as the ratio of the loop cross-section radius to the loop half-length.

From the equation of state then the pressure can be inferred:

$$p = 2nkT \tag{13}$$

This pressure can be, for instance, compared to the equilibrium pressure predicted by the loop scaling law Eq. (3) in order to check for loop equilibrium conditions. From the flare temperature and loop length, the loop scaling law (4) allows to estimate the heating rate per unit volume and therefore the total energy involved in the flare. From the estimated pressure one can also infer the magnetic field required for plasma confinement:

$$B \approx \sqrt{8\pi p} \tag{14}$$

5. The importance of other physical effects

The estimation of loop length may be affected by several effects, which are not generally taken into account by simplified flare modeling. In particular, one should check for the possible influence of:

Interstellar absorption, which can be corrected for before modeling (Reale & Micela 1998),

Gravity, which becomes important if the loop length is comparable to pressure scale height. If this is the case, this brings to a flatter decay in the n–T diagram (Reale et al. 1993) but the hydrodynamic method includes this effect consistently (Reale & Micela 1998);

Metal abundance: if the corona is underabundant, this brings to lower radiative losses and therefore to a slower decay. If this is not considered, the loop length will be overestimated.

Plasma confinement: one may wonder whether the assumption of plasma confinement still holds for long-lasting big flares. This question has been addressed by a recent work (Reale et al. 2001): detailed hydrodynamic simulations of flares in a non-confined corona seem to indicate that a flare in open space decays on very short time scales (few minutes) and therefore that plasma has to be confined even in intense long-lasting flares.

6. Future perspectives and conclusions

There are some intriguing questions expected to be addressed by model investigation in the next future. An interesting question concerns the aspect of flaring loops: sometimes in the analysed flares if one assumes 10% as loop aspect as typically done for solar loops (see Section 4.), the flare pressure inferred from the equation of state (13) is larger than the equilibrium pressure obtained from scaling laws (3). This may imply an aspect larger than 10%, which recall configurations more similar to flare arcades. This question may be addressed if good diagnostics of density during flares becomes available. Another issue to be explored is the evidence that several flares show a double exponential decay. Some qualitative models have been proposed (e.g. Cully et al. 1994) but this topics is interesting and deserves further detailed investigations, including solar flares.

In conclusion, flare loop models have been shown to be useful to estimate the size of flaring regions and thereby other physical quantities (e.g. heating evolution, plasma density, magnetic fields). More in general they represent a source of information on stellar coronae. As this review shows, several model approaches are available, which, however, share several common features. It has been shown that due to their assumptions, the models generally tend to overestimate the size of the flaring loops. It is expected that higher quality flare data will bring more constraints on the models and require their further refinement.

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