X-ray Flare Light Curves and Dimensions of the Flaring Regions

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Abstract. The decay of flare X-ray light curves provides information on the dimensions of the flaring region. We show that a reliable estimate of such dimensions must take into account the temperature evolution as tracer of the presence of heating during the decay. Many solar flares appear sustained by prolonged heating episodes. We describe a method to estimate their spatial extension based on the analysis of the decay of their X-ray light curve and temperature, and show that the results are in good agreement with their dimensions measured on Yohkoh/SXT images.

1. Introduction

The decay time of flare X-ray light curve has been frequently used to estimate the length of the flaring coronal loops (e.g. Haisch 1983, Reale et al. 1988, van den Oord et al. 1988). However this estimation is affected by several problems. Since the light curve results from the combined effect of plasma cooling, plasma emitted spectrum and its folding through the instrumental spectral response, it is not straightforward to connect the light curve decay time to the conductive cooling time, which is linked to the loop length; furthermore the plasma cooling can be significantly delayed by the presence of sustained heating during the flare decay.

We have devised a more refined technique to derive the dimensions of spatially-unresolved flaring stellar loops. It is based on extensive hydrodynamic loop modeling, tuned to the instrument response, applicable straightforwardly to data, and it includes the effect of the heating (using the temperature decay).

We outline here the method and some testing on *spatially-resolved* solar flares observed with Yohkoh/SXT (see Reale et al. 1997 for more details).

2. The method

It has been shown that the cooling of a flaring loop is characterized by:

1. a *spontaneous* decay time $\tau_{th} = 120 L_9/\sqrt{T_7}$ where L_9 is the loop half-length (10^9 cm) and T_7 is the flare maximum temperature (10^7 K) (Serio et al. 1991), when no heating is released during the decay;

2. a power law trajectory in the density-temperature plane, whose index (slope in a Log/Log plot) depends on the decay time of the heating released in the loop during the decay and ranges between a maximum of ~ 2 for no heating and a minimum of ~ 0.5 for very long heating $\tau_H \gg \tau_{th}$ (Sylwester et al. 1993).

The concept of the method is to link these two pieces of information as follows:

a) We have computed a grid of hydrodynamic models of decaying flaring loops with various lengths and heating decay times (Palermo-Harvard hydrodynamic code, Betta et al. 1997).

b) The loop decay is modelled starting from conditions typical of flare maximum.

c) We synthesize the emission of each loop folded through the spectral response of Yohkoh/SXT, and, treating it as real data, we obtain the light curve, its decay time τ_{LC}, the trajectory in the $\log EM^{1/2}$-$\log T$ diagram and its slope ζ.

d) By fitting the results of the models, we find a relationship $\tau_{LC}/\tau_{th} = F(\zeta)$ between the light curve decay time, normalized to the characteristic decay time, and the slope in the presence of various amounts of heating. This quantifies the effect of the heating on the light curve.

e) We use this relationship to find an expression for the loop length:

$$L_9 = \frac{\tau_{LC}\sqrt{T_7}}{120F(\zeta)} \tag{1}$$

which can be applied directly to real data.

3. Testing on flares observed by Yohkoh/SXT

We have applied the method to estimate the loop length to solar flare decays monitored with Yohkoh/SXT, which both provides temperature diagnostics and spatially resolves flaring loops. Flare data obtained from Yohkoh/SXT consist of sequences of images composed by 64×64 pixels of 2.45 arcsec in the Be 119 μm and Al 11.4 μm filters. We have computed the light curve decay time and the slope of the trajectory of the $\sqrt{EM} - T$ diagram. We use expression (1) to derive the loop size L_9. We then compare the result to the length measured from a direct inspection of the images.

Representative results are shown in Figs. 1, 2, and 3 for three flares starting at the date and time reported above each figure (yymmdd.hhmm, then it is reported the time of the specific image shown). In the first two flares there is evidence of significant heating ($\tau_H \approx 4$ and 1 τ_{th}, respectively) marginal in the third. For each flare we show an image of the flaring structure in the Al 11.4 μm filter band at the time reported after the flare date in the figure title. Inside

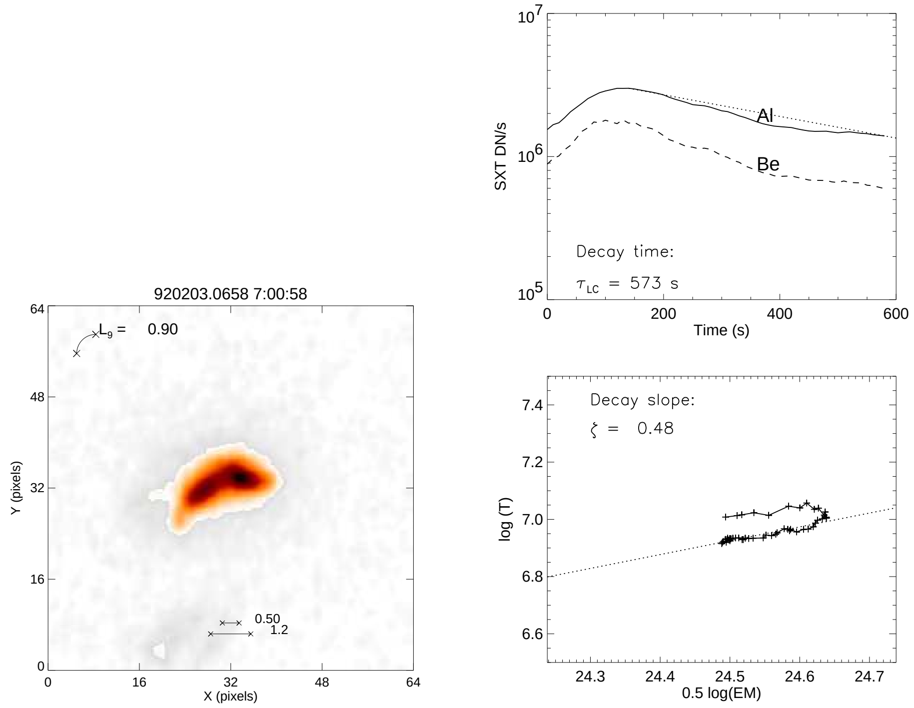

Figure 1. Flaring region as imaged by Yohkoh SXT in the Al 11.4 μm filter (*left*), the flare light curves in the Be and Al 11.4 μm filters (*upper right*), and the flare evolution in the $EM^{1/2} - T$ diagram (*lower right*). The flare occurred at the date reported above the image (yymmdd.hhmm) and the image is taken at the time reported after the flare date. Inside the image we show in scale the loop half-length L_9 (*left upper corner*) predicted by our method and its minimum and maximum linear projections on the solar disk (*below the flaring structure*). The decay time in the Al 11.4 μm filter is reported in the light curve panel and the decay slope in the $EM^{1/2} - T$ diagram.

each image we show in scale the loop half-length predicted by the method and its minimum and maximum linear projections on the solar disk, since it is untrivial to obtain information on the orientation of the loop. Aside each image we show the flare light curves in two filters, with the decay time in the Al 11.4 μm filter, and the flare trajectory in the $\sqrt{EM} - T$ plane with the decay slope.

We applied this test to 20 flares observed with Yohkoh/SXT. We obtained that the scale lengths provided by Eq. (1) are consistent, or at worst, in some cases, marginally consistent, with the size of the structures in the images in 17 of 20 flares. A detailed inspection of the three cases of disagreement has shown that the failure is well motivated (Reale et al. 1997).

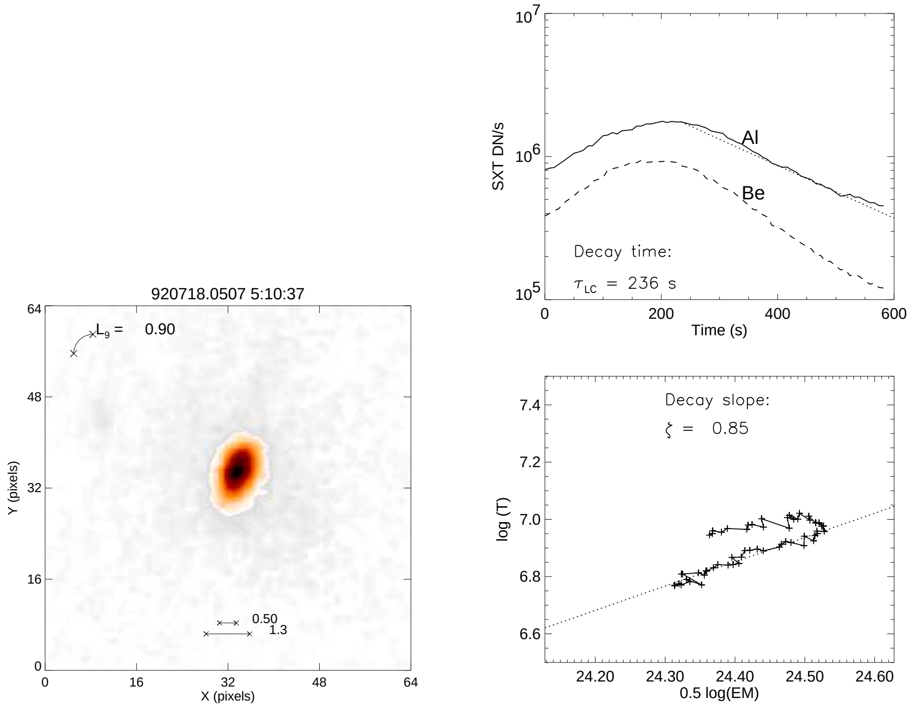

Figure 2. Same as Fig.1 for a second flare

4. Discussion and conclusions

The importance of this approach lies in the fact that, at variance with previous ones, by combining temporal (the light curve) and spectral (the $\sqrt{EM} - T$ diagram) information, it takes into proper quantitative account the effect of a prolonged heating during the decay.

Notice that estimates based only on plasma cooling times would lead to values larger by a factor ~ 2 to ~ 10 than those obtained from expression (1), most of them unrealistically large when compared to the structures in the SXT images.

The consistency of the predictions with the observed morphology supports the validity of our approach and makes us confident for the application of the method to flares observed with instruments with no angular resolution. Its relatively straightforward applicability makes it particularly appropriate for systematic analysis.

The extensive application to stellar flares observed with telescopes such as ROSAT/PSPC and ASCA/SIS promises to constrain the dimensions of flaring regions on stars, and to infer the characteristics of the heating during the decay.

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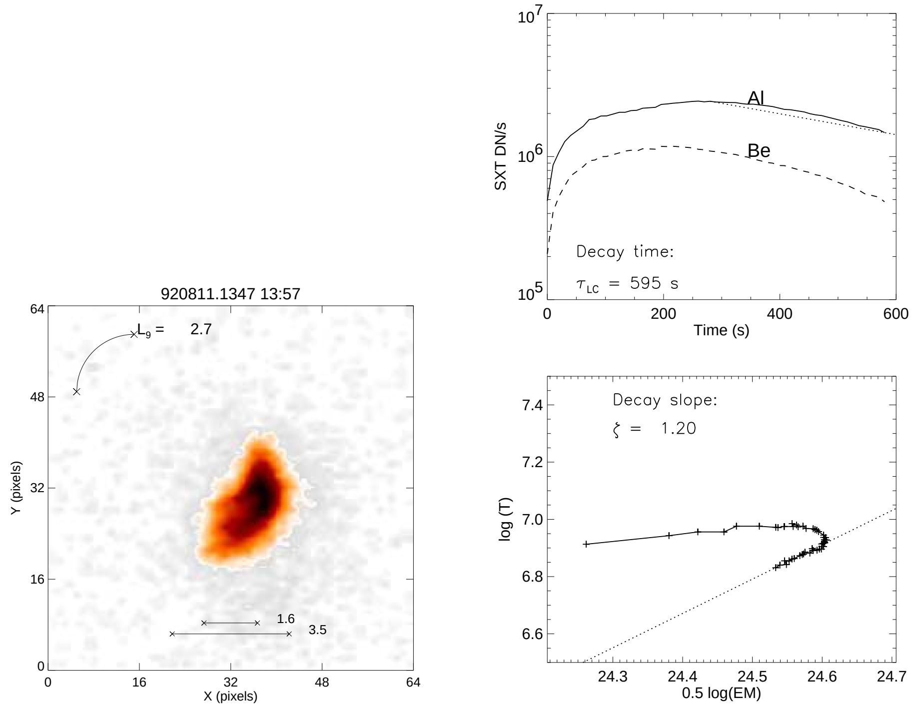

Figure 3. Same as Fig.1 for a third flare

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References

Betta R. M., Peres G., Serio S., Reale F., 1997, A&AS, 122, 585.

Haisch B.M., 1983, in Activity in Red-Dwarf Stars, eds. P.B. Byrne, M. Rodonó, Reidel, Dordrecht, p.255.

Reale F., Peres G., Serio S., Rosner R., Schmitt J.H.M.M., 1988, ApJ 328, 256.

Reale F., Betta R., Peres G., Serio S., McTiernan J., 1997, A&A, in press.

Serio S., Reale F., Jakimiec J., Sylwester B., Sylwester J., 1991, A&A, 241, 197.

Sylwester B., Sylwester J., Serio S., et al., 1993, A&A, 267, 586.

van den Oord G.H.J., Mewe R., Brinkman A.C., 1988, A&A, 205, 181.