STELLAR FLARING LOOPS

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ABSTRACT. We propose and test a procedure tailored to analyse extensively and systematically stellar X-ray flares, such as those observed in open clusters. The method yields a reliable estimate of the dimensions of the coronal flaring loops and of the presence of a significant heating during the flare decay, it is based on the decay of the light curve and of temperature indicators, and it has been developed and tested successfully on spatially-resolved solar flares. We illustrate the application on flares observed with ROSAT/PSPC.

1. Rationale

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). In particular the length has been derived comparing the light curve decay time to the plasma characteristic cooling times by conduction and radiation. However these estimates are affected by problems, which can make then severely unreliable. First of all, the light curve results from the combined effect of plasma cooling, plasma emitted spectrum and its folding through the instrumental spectral response; furthermore, the plasma cooling can be delayed by the presence of sustained heating during the flare decay, and the length derived thereby can be grossly overestimated.

In this perspective, we have devised a more refined technique to derive the dimensions of flaring stellar loops from the analysis of the flare decay observed by ROSAT/PSPC (see Reale & Micela 1997 for further details). The technique is based on extensive hydrodynamic modeling of the decay of flaring loops. Then the results of the modeling are used to synthesize the plasma emission as would be detected by the ROSAT/PSPC. By including the decay of temperature indicators in the flare analysis we succeed in taking into account the effect of a prolonged heating during the decay.

The method has been tested on solar flares observed with Yohkoh/SXT (Reale et al. 1997): the predicted loop dimensions are fairly in accordance to those measured on the SXT images, even in the presence of deviations from some fundamental model assumption, such as the semicircular shape, or the unchanging magnetic field geometry.

Although the method is developed using hydrodynamic modeling, it is applicable straightforwardly to data, by using characteristic quantities such as the light curve decay time.

In the following we outline the characteristics of the method and an application to a flare on the star AD Leo.

2. The method

We have considered a grid of hydrodynamic models of decaying flaring loops and synthesized their emission folded through the spectral response of ROSAT/PSPC. The plasma is confined in a semi-circular loop and the symmetry allows to model half of the loop. In the assumption that plasma bulk motion and energy transport occurs mostly along the magnetic field lines, we solve numerically the one-dimensional hydrodynamic equations of for a compressible fluid, taking into account gravity, viscosity, radiative losses and thermal conduction of coronal plasma. We use the new Palermo-Harvard hydrodynamic code, with adaptive grid and high spatial resolution even in the thin and moving transition region (Betta et al. 1997).

We compute the hydrodynamic evolution of the plasma confined inside the loop, starting from conditions typical of flare maximum and switching off, either abruptly or gradually, the heating which caused the flare, therefore following the flare decay.

The model provides the evolution of plasma temperature and density along the loop during the flare decay. From density and temperature we synthesize the plasma emitted spectra and, by folding them with the instrument energy response, the expected ROSAT/PSPC spectra.

By integrating each spectrum we derive the global light curve and its decay time τ_{LC}. Then the method requires to obtaing information about the temperature decay.

In order to improve upon isothermal temperature fittings and to increase the sensitivity to temperature variations we use a model-independent proxy for temperature. We optimize the choice of this proxy with a Principal Component Analysis (PCA, e.g. Murtagh & Heck 1987).

PCA is a multivariate statistical data analysis technique: if we have M objects in a N-dimensional space, PCA determines the directions of maximum data spread defining a new N-dimensional orthogonal set of vectors, sorted by decreasing the variance along these new directions. The direction determined by the first component (the first vector of the new orthogonal base) is the direction of maximum spread of the original data, the second component determines the direction of maximum of the residual spread and so on.

We have searched the principal components on a set of noiseless spectra of hydrostatic loop model (Serio et al. 1981). Each principal component PC is defined by a linear combination of the normalized and scaled PSPC PI channels (Ch_i) with weights w_i.

The first principal component is our proxy for temperature: we will call it Spectral Shape Index (SSI). It explains $\sim$ 72% of the entire variance.

¿From the synthesized PSPC spectra, we then obtain the trajectory in a plane $(\text{Count rate})^{1/2} = CR2$ vs. SSI and its slope ζ. This plane is equivalent to a density-temperature diagram, which has been shown to provide a diagnostics of flare heating during the decay of solar flares (Sylwester et al. 1993).

We performed an extensive set of simulations of flaring decaying loops, with various assumptions on the length, flare temperature, stellar surface gravity and radius, and heating decay time. By finding an empirical relationship $F(\zeta)$ linking the light curve decay time τ_{LC} and the slope ζ in the CR2 vs. SSI plane of the model decaying loops,we derive a formula for the loop length:

$$L = \frac{\tau_{LC}\sqrt{T_{max}}}{\alpha F(\zeta)} \qquad (cm) \tag{1}$$

where $\alpha = 3.7\ 10^{-4}$ (cgs units) and T_{max} is obtained from the maximum value of SSI reached in each flare. We have found that loops shorter than the pressure scale height behave differently from longer loop.

As a result, using equation (1), the loop length can be derived from the PSPC flare data, without any modeling and temperature fitting. Analogous formulae can easily be obtained for other X-ray instruments such as ASCA/SIS, or forth-coming ones, such as those on board AXAF and XMM.

To assess quantitatively the self-consistency and the uncertainties of our method, we have applied the formula to all our model loops. We find no significant systematic difference between the predicted and the real lengths and an average spread of ~ 20 % originating from the modeling and the interpolation to derive $F(\zeta)$.

3. The application

The loop length formula has been first applied to a flare well-observed on the dM3.5e star AD Leonis (distance 4.9 pc, radius 0.49 $R_{\odot}$, gravity $\log g = 4.7$). We have considered the flare decay phase, starting from 48384.6 MJD, and divided the data into four segments, roughly of the same duration (~ 150 sec). Then we have considered the four spectra integrated in each segment, subtracting from them the spectrum observed in the quiescent phase, averaged in the period before the flare.

We have derived a light curve decay time of $\tau_{LC} \approx 680$ s and a slope the trajectory in the $CR2 - SSI$ diagram $\zeta = 13.7$. The value of the trajectory slope tells us that in this flare the effect of sustained heating on the decay is marginal.

In Fig.1 we imagine the possible scenario of the flaring loop on AD Leo. The inferred loop is shown in scale with respect to a possible coronal disk of AD Leo, and compared to the one obtained from comparing the light curve decay time to radiative and conductive cooling times, as typically done so far to estimate flaring loop lengths. The length is overestimated by the more crude method even in this flare where the heating effect is marginal.

4. Conclusions

The method is very appropriate for extensive and systematic application to flares observed with ROSAT/PSPC. It should allow to study statistically the distribution of the dimensions of stellar flaring loops, important to understand the stellar coronal physics. Furthermore the identification of significant heating during the decay and the estimate of the heating decay time, in connection with the different stellar environment conditions, will certainly allow to investigate the flare heating mechanisms under a new perspective.

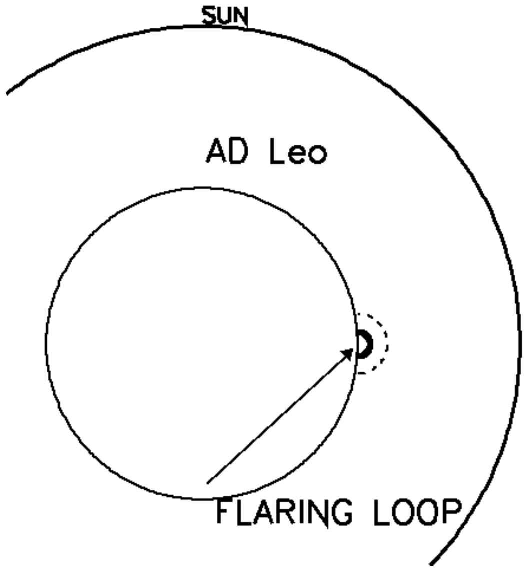

Fig. 1. The flaring loop on the star AD Leo: the flaring loop that we infer from the analysis of the flare decay on the scaled stellar disk. The big outer circle outlines the solar disk in scale. The *dashed curve* is the loop that we would obtain just from a crude application of radiative and conductive cooling times often used in literature to estimate flaring loop lengths.

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