Flares as Heating Agents of Active Late-Type Stellar Coronae?

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Abstract.

We present results from a study of statistical flares on active late-type stars (spectral type F to M) using *Extreme Ultraviolet Explorer* (*EUVE*) archival data. We used several methods to investigate the flare rate distributions as a function of observed EUV and X-ray emitted thermal energy (found to be $dN/dE \propto E^{-\alpha}$); we include stars with different spectral types, and different intrinsic parameters such as the projected rotational velocity, the rotation period, the X-ray luminosity and the ratio $L_X/L_{\rm bol}$.

We used a flare identification method based on count distributions of "quiescent" emission as a function of temporal bin size. Different types of fits to the cumulative and differential distributions were performed. The derived power-law indices α suggest a weak dependence on spectral type. F and G stars are characterized by $\alpha \gtrsim 2$, while K and M stars have best-fit values below 2, although $\alpha > 2$ cannot be excluded. We test several correlations between the above intrinsic parameters and the power-law indices α or the occurrence rates of flares with energies larger than 10^{32} ergs.

1. Introduction

Flares play an important role in the chromospheric and coronal activity. While their presence in stellar light curves provides hints for magnetic activity in stellar outer atmospheres, their role in coronal heating is still unclear. It has been proposed that flares might provide the energy required to heat coronal plasma to the several MK temperatures typically observed (e.g., Parker 1988). Consistent with the Sun, stellar flares have been found to be distributed in energy in a power law ($dN/dE \propto E^{-\alpha}$), with the index α around 2. Hudson (1991) pointed out for the solar case that, if $\alpha > 2$ and the power law can be extrapolated to sufficiently small flare energies, then very large amounts of energy are potentially available for coronal heating. Recently, Audard et al. (1999) have found a value of $\alpha \approx 2.2 \pm 0.2$ for two young active solar analogs. They suggested that the coronae of these stars could be heated by flares. We have performed a follow-up

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study for several other sources with different spectral types and activity levels, making a total of 12 coronal sources (including the two solar analogs of the previous study).

In addition to coronal heating, flares are signatures of the overall magnetic activity of stars (see, e.g., Simon 2000). We have tested some correlations between the parameters of their energy distributions (such as the index α and the flare occurrence rate) and physical activity indicators (the projected rotational velocity, the X-ray luminosity, and its ratio with the bolometric luminosity). Further tests will be found in Audard et al. (2000).

2. Data Reduction and Selection

Archival Deep Survey (DS) data from the *EUVE* satellite (Malina & Bowyer 1991) were used to study the contribution of flares to the observable EUV+X-ray emission of stellar coronae. We chose active coronal sources, as they often show flares. Note that observations from a star that had been observed more than once have been counted as separate coronal sources. Indeed, the typical time interval between two observations was about a year. Therefore identical stellar activity levels cannot be assumed. Standard data reduction was performed using the IRAF software and the euv 1.8 package. Careful checks were performed to exclude sources with significant incursions into the DS "dead spot". Our selection list contains 12 stellar sources (1 F-type, 4 G-type, 2 K-type, and 5 M-type coronal sources). We do not claim our sample to be complete in any sense. However, we believe that this sample correctly represents the content of the main-sequence cool stars in the *EUVE* archive. Table 1 gives the name of the stellar source (Col. 2), its spectral type (Col. 3), its distance d (Col. 4), the rotation period P (Col. 5), the projected rotational velocity (Col. 6), the color index $B-V$ and the visual magnitude V (Cols. 7 & 8), and the *EUVE* observing window (Col. 9).

Table 1. Target Selection List.

	Source Name	Spectral Type	d (pc)	P (d)	$v \sin i$ (km/s)	$B-V$ (mag)	V (mag)	*EUVE* Observing Date
1	HD 2726	F2 V	45.07	$\cdots$	13.2	0.367	5.67	09/08/95 → 16/08/95
2	47 Cas	G0–2 V	33.56	1.0	95.0	0.620	$\cdots$	23/01/97 → 29/01/97
3	EK Dra	G1.5 V	33.94	2.605	17.3	0.626	7.60	06/12/95 → 13/12/95
4	κ Cet	G5 V	9.16	9.4	3.9	0.681	4.84	13/10/94 → 18/10/94
5								06/10/95 → 13/10/95
6	AB Dor	K1 V	14.94	0.515	93.0	0.830	6.88	12/11/94 → 17/11/94
7	ϵ Eri	K2 V	3.22	11.3	2.0	0.881	3.72	05/09/95 → 13/09/95
8	GJ 411	M2 V	2.55	$\cdots$	< 2.9	1.502	7.49	22/03/95 → 04/04/95
9	AD Leo	M3 V	4.90	2.7	6.2	1.540	9.43	03/05/96 → 06/05/96
10	EV Lac	M4.5 V	5.05	4.376	6.9	1.540	10.29	09/09/93 → 13/09/93
11	CN Leo	M8 V	2.39	$\cdots$	< 2.9	2.000	13.54	16/12/94 → 19/12/94
12								24/01/95 → 30/01/95

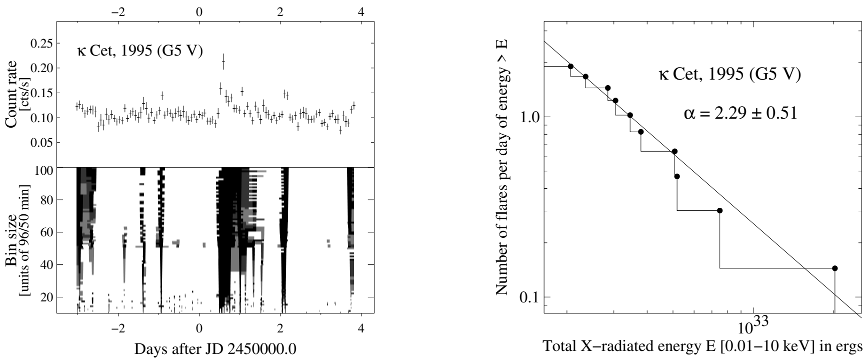

Figure 1. An example of our flare analysis (for κ Cet in 1995).

3. Data Analysis

To identify flares, we used the method developed by Audard et al. (1999), which itself is adapted from Robinson et al. (1995). Photon lists and Good Time Intervals (GTI) are processed within the code. We refer to Audard et al. (1999,2000) for a detailed description. In brief, the method statistically identifies individual flares. It is based on the count distributions of "quiescent" emission and the probability of Poisson occurrence. Figure 1 (left) shows an example for κ Cet. The upper panel gives the light curve (binned with a time interval of 96 min, the orbital period of *EUVE*), while the lower panel gives the corresponding "significance" plot. The latter represents the probability for the presence of quiescent bins as a function of time (x-axis) and bin size (y-axis). The flare significance increases from light gray to black. Then, Gaussian fits were performed above a smooth envelope (the quiescent contribution) in order to obtain the approximate start and end times, and therefore the duration of each flare. Finally, the mean number of counts from a flare was derived and a constant count-to-energy conversion factor of $f = 1.06 \times 10^{27}$ ergs/ct/pc^2 was used together with the source's distance d to derive the total EUV+X-radiated energy E (0.01 – 10 keV).

Differential ($dN/dE = k_1 E^{-\alpha}$) and cumulative ($N(>E) = k_2 E^{-\alpha+1} = \int_E^\infty (dN/dE')dE'$) flare occurrence distributions in energy were then constructed. Figure 1 (right) provides an example for κ Cet. We used a maximum-likelihood procedure, adapted from Crawford, Jauncey, & Murdoch (1970), to fit the cumulative distributions. On the other hand, differential distributions were fitted by power laws within the XSPEC software. From the mean X-ray luminosity ($L_X = \mu \times f \times [4\pi d^2]$, where μ is the mean DS count rate) and the maximum detected flare energy $E_{\rm max}$, the minimum flare energy E_0 required for the power law to explain the mean observed radiative energy loss (L_X) was calculated, assuming that the cumulative flare occurence rate distributions in radiated energy follow the same power law below the flare energy detection limit,

$$E_0 = \left\{ \frac{L_X}{k_2} \left(\frac{\alpha - 2}{\alpha - 1} \right) + E_{\rm max}^{2-\alpha} \right\}^{\frac{1}{2-\alpha}} . \quad (1)$$

Table 2. Fits to the Energy Distributions.

	Cumulative		Differential	Simultaneous	
Name	α^a	$\log(E_0)^b$ [ergs]	α^c	Type	α^c
HD 2726	2.61 ± 0.38	31.7 (29.7, 32.3)	2.43 (1.80, 3.93)	F+G	2.28 (2.03, 2.57)
47 Cas	2.19 ± 0.34	29.7 ($\cdots$, 31.6)	2.62 (1.72, 5.41)		
EK Dra	2.08 ± 0.34	30.2 ($\cdots$, 32.0)	1.78 (1.26, 2.49)		
κ Cet 1994	2.18 ± 0.89	27.2 ($\cdots$, 31.0)	2.55 (0.31, $\cdots$)		
κ Cet 1995	2.29 ± 0.51	29.5 ($\cdots$, 31.1)	2.45 (1.65, 3.80)		
AB Dor	1.88 ± 0.26	$\cdots$ ($\cdots$, 28.8)	1.76 (1.24, 2.72)	K	1.87 (1.50, 2.39)
ϵ Eri	2.40 ± 0.81	29.1 ($\cdots$, 30.7)	2.38 (1.06, 4.05)		
GJ 411	1.63 ± 0.29	$\cdots$ ($\cdots$, $\cdots$)	1.57 (1.08, 2.22)	M	1.84 (1.63, 2.06)
AD Leo	2.02 ± 0.28	26.2 ($\cdots$, 29.8)	1.65 (1.18, 2.35)		
EV Lac	1.76 ± 0.33	$\cdots$ ($\cdots$, 29.1)	1.75 (0.98, 3.33)		
CN Leo 1994	2.21 ± 0.30	29.3 (27.0, 29.8)	2.24 (1.78, 3.04)		
CN Leo 1995	1.46 ± 0.39	$\cdots$ ($\cdots$, $\cdots$)	1.59 (0.84, 2.56)		

[a] Adapted version of Crawford et al. 1970

[b] Minimum energy E_0 required for the power law to explain the total observed radiative energy loss; limits are given in parentheses

[c] χ^2 fit within XSPEC with 68 % confidence ranges for a single parameter

4. Discussion

Table 2 provides the results from the different fitting methods. Power-law indices α are found to range from about 1.5 to 2.6. A trend for a flattening of the energy distributions with later spectral types is suggested. F and G-type stars appear to have indices above 2, while this is not the case for K and M dwarfs. This suggests that in the former, flares play a more dominant role in the heating of coronae, while flares in the latter cannot provide sufficient energy to explain the radiated losses. Assuming that the heating mechanism is identical for each spectral type, we have also performed simultaneous fits to the differential distributions.

With the parameters of the distributions (power-law index and flare occurrence rate), we performed correlation tests with some activity indicators (P, $v \sin i$, L_X, $L_X/L_{\rm bol}$). We did not find any correlation between α and these indicators. However, the occurrence rate of flares with energies larger than 10^{32} ergs was found to be correlated with some of them. Figure 2 shows the correlation between the flare occurrence rate and the X-ray luminosity. Nonparametric correlation tests confirm the presence of a correlation of the form $N(> E) \propto L_X$. Therefore, large, energetic flares are more probable in bright stellar systems.

In Figure 3, we have normalized the X-ray luminosity to its bolometric luminosity. This allows us to compare the different spectral types and provides a measure for the activity level. $L_X/L_{\rm bol} = 10^{-3}$ generally refers to the activity saturation (e.g., Vilhu 1984). We have also normalized each flare occurrence rate to its value that a star adopts when it reaches its saturation level; the analytical power-law relation between the rate and L_X (Fig. 2) was used to get the flare rate at saturation for each stellar spectral type (and therefore each bolometric luminosity). We refer to Audard et al. (2000) for details. Figure 3 clearly shows that the normalized flare rates accumulate at saturation, indicating that the flare rate for a given spectral type does not increase indefinitely after the star reaches the saturation level. On the other hand, the rate increases linearly with the ratio $L_X/L_{\rm bol}$ at unsaturated levels.

5. Conclusion

We have shown that flares are capable of playing a significant role as potential coronal heating agents in active stars. They appear to play a more important role for F and G-type than for later-type dwarfs. Part of this trend might be due to the bias introduced by our identification method and the length of the GTIs. Indeed later-type stars (here K and M stars) show flares that are typically shorter than those of G dwarfs, partly because of the smaller distances of the stars, and give access to less energetic (often shorter) flares. Then, the flare duration competes with the typical GTI duration (about 2000 sec), therefore leading to more probable detections of large, long, flares, while the smaller ones remain partially undetected. This effect may considerably flatten the flare rate distributions. Much more sensitive and uninterrupted observations (such as possible with *XMM*, *Chandra*, and *ASTRO-E*) are required to better constrain the distributions and hence the power-law indices.

In this paper, a correlation between the flare rates and the X-ray luminosity has been reported, suggesting that large, energetic flares occur more frequently on X-ray bright stars. Also, a saturation effect of the normalized flare occurrence rates was indicated, compatible with the saturation effect seen in the X-ray luminosity.

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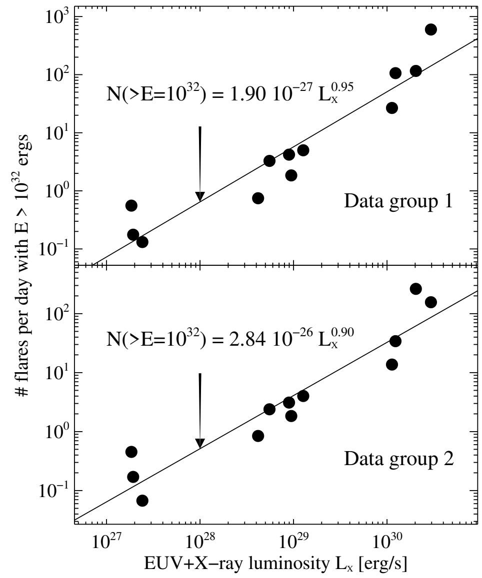

Figure 2. The flare rates with energies larger than 10^{32} ergs vs. the derived luminosity. Data group 1 corresponds to the rates derived from the fits to cumulative distributions, while data group 2 corresponds to the rates derived from the fits to differential distributions. The χ^2 linear best-fits in the log − log plane are shown as straight lines.

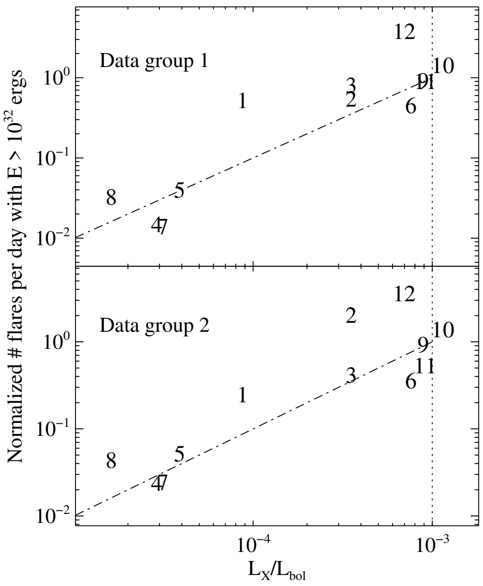

Figure 3. The normalized flare rates with energies larger than 10^{32} ergs vs. the ratio $L_X/L_{\rm bol}$. Data groups 1 and 2 are identical to Fig. 2. The source identification numbers refer to Table 1. The dash-dotted lines are slope 1 lines. The dotted lines represent the saturation level ($L_X = 10^{-3}L_{\rm bol}$).