Stellar Coronae in the Chandra and XMM-Newton Era
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Flare Heating of Stellar Coronae

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Abstract. We model the emission from the coronae of active stars FK Aqr, V1054 Oph, AD Leo, and β Per as a superposition of numerous weak flares whose numbers are distributed as a power-law in energy. We find that most of the emission on these stars may be attributed to flaring activity.

1. Introduction

An open question in the field of Solar and stellar astrophysics is the source of heating that causes stellar coronae to reach temperatures of millions of degrees. One possibility is that the coronae are heated by a large number of small flares (see Güdel & Benz 1993; Güdel et al. 1997; Güdel 1997; Audard et al. 1999, 2000).

On the Sun, flares are distributed with energy as a power-law $E^{-\alpha}$ with slope α generally considered to be < 2 (e.g., Hudson 1991; Crosby, Aschwanden, & Dennis 1993; Aschwanden et al. 2000), though recent measurements have indicated that for very low flare energies $\alpha \sim 2.2 - 2.9$ (Krucker & Benz 1998; Parnell & Jupp 2000; Weinbarger et al. 2001). The value of this index is of importance because if it exceeds the critical value of 2, then in principle the entire coronal energy input may be ascribed to flares that are increasingly less energetic, but are more numerous. However, the total energy in these detected flares is yet insufficient to account for the energy deposition in the Solar corona.

For stars, early measurements for large X-ray flares have resulted in $\alpha \approx 1.5 - 1.8$ (Collura et al. 1988; Pallavicini et al. 1990; Osten & Brown 1999), similar to the Solar case. In contrast, analysis of optical data (Robinson et al. 1995, 1999) and inclusion of weaker X-ray flares and correcting for overlapping flares (Audard et al. 2000; Güdel et al. 2001, in preparation) have found that in a large number of cases $\alpha > 2$ for active stars.

2. Data

We present the results of our search for low-intensity flares in *Chandra* data of the active binary Algol and EUVE data of active stars FK Aqr, Wolf 630, and

AD Leo. The stellar parameters are summarized in Table 1. The observed light curves are shown in Figures 1.

3. Analysis and Conclusions

3.1. Method

Because many of the weak flares are "lost" in the confusion of emission from other flares, we model the flare emission rather than attempt to detect individual flares. However, since flare onset is stochastic, light-curves cannot be modeled directly. Instead, we compare distributions of photon *arrival-time differences* obtained from the data $f_{DATA}(\delta\, t)$ and from the model $f_{MODEL}(\delta\, t)$. Fake event lists are generated for specified values of model parameters α, the average flare count rate r_F, and a constant background rate r_B, instrument effects such as Primbsching and good-time interval filtering are applied. The derived f_{MODEL} is compared with the observed f_{DATA} to determine the likelihood of obtaining

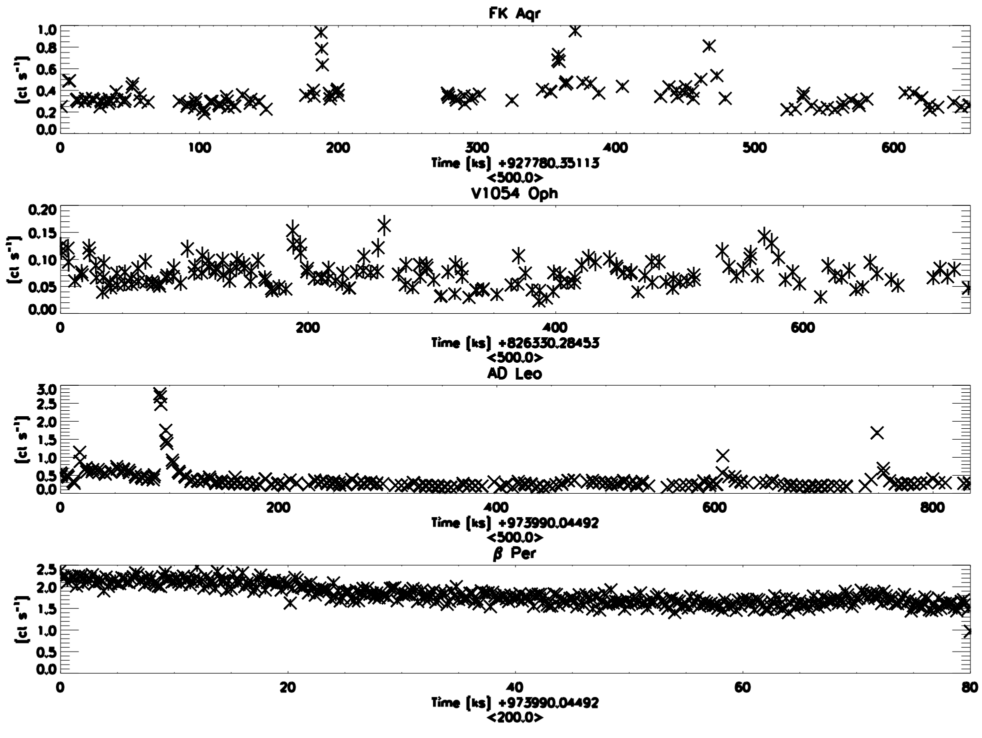

Figure 1. EUVE/DS light curves for FK Aqr (top), V1054 Oph (second), AD Leo (third), and *Chandra* HRC-S/LETG 0^{th} order light curve for β Per (bottom; spanning the eclipse of the B8V star), corrected for instrumental effects. The vertical bars denote the 1σ error on the count rate. The EUVE data are binned at 500 s, while the *Chandra* data are binned at 200 s. Note that there are many obvious flares visible in the light curves, as well as significant variability in the apparently quiescent base emission.

the data for the given parameter values. Because of the stochastic nature of the model, a number of simulations (~ 20) are carried out at each grid point and a median value is chosen to ensure robustness. The parameter space is explored over a grid and assuming flat non-informative priors, the posterior probability distribution of the parameters are determined. The result of testing the method to verify its effectiveness is shown in Figure 2, where the best-fit indices α_{FIT} obtained by fitting to simulated data with specific power-law indices α_{TRUE} are shown.

3.2. Results

We find that $\alpha > 2$ for the active stars studied, and that most of the emission may be attributed to flare emission in the stellar coronae. The detailed results for each star are listed in Table 2. The individual posterior probability distributions of α and r_F are shown in Figures 3 (FK Aqr and V1054 Oph) and 3 (AD Leo and β Per). These results are also consistent with those found by Güdel et al. (2001, in preparation) for AD Leo using an independent method.

3.3. Conclusions

Stellar coronal heating is dominated by impulsive energy releases whose energy output is $\gtrsim 10^{29}$ ergs, i.e., through the milliflare and to the edge of the microflare range. Stellar flare distributions are generally steeper ($\alpha > 2$) than the Solar case over similar energy ranges. There appears to be no truly "quiescent" emission in these low-mass active stars.

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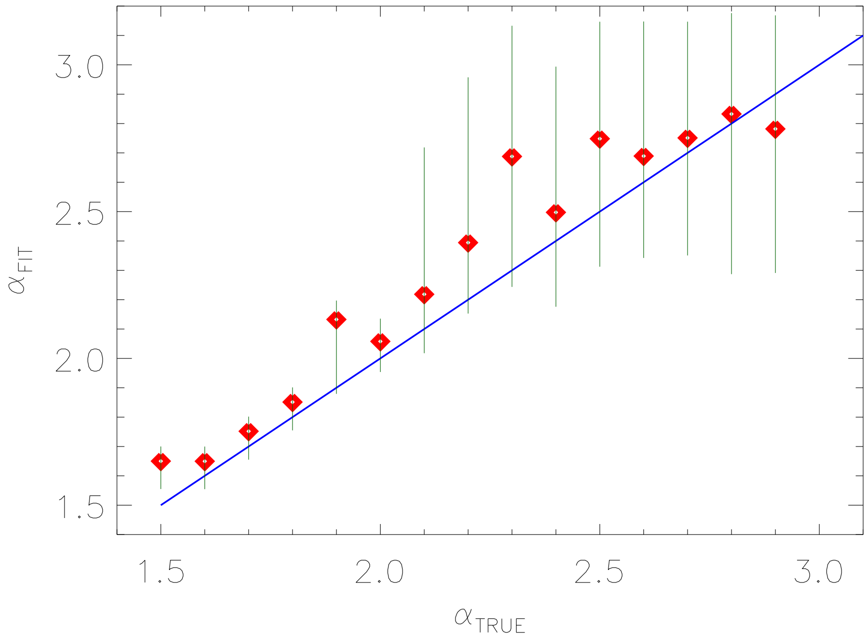

Figure 2. Verification of the algorithm. The best-fit and 90% confidence intervals obtained for a series of simulated datasets are shown as a function of the true α. Note the loss in sensitivity in the method at large α.

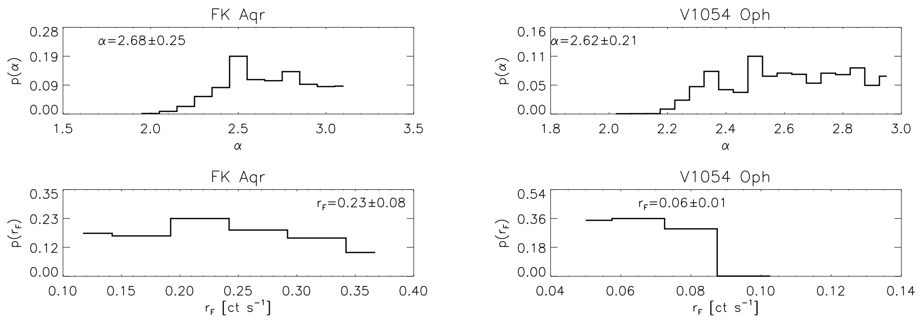

Figure 3. Posterior probability distributions of α (upper panels) and r_F (lower panels) FK Aqr (left) and V1054 Oph (right). The mean values derived from the probability distributions are also shown.

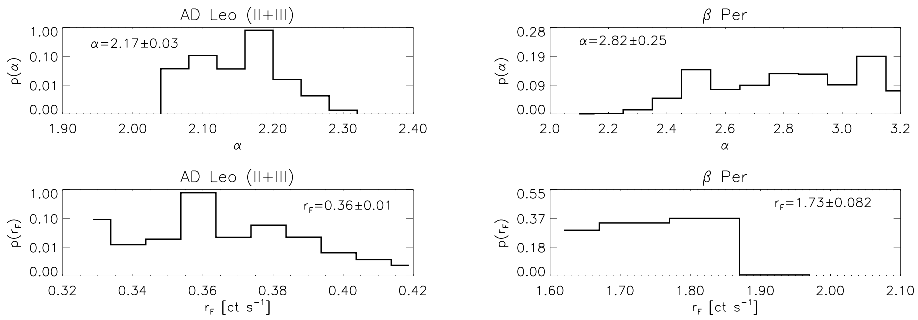

Figure 4. As Figure 3, for AD Leo (left) and β Per (right).

Table 1. Stellar Parameters

	FK Aqr	**v1054 Oph**	**AD Leo**	**β Per**
Other Names	Gl 867A/HD 214479	Wolf 630/Gl 644/HD 152751	Gl 388	Algol/Gl 9110
Description	Low-mass, non-eclipsing spectroscopic binary	Low-mass flare star	Low-mass flare star	short-period eclipsing binary
Spectral Type	dM2e/dM3e	dM3e	dM3e	B8V/K2IV
Period	4.08^d			2.867^d
m_V	$9^m.07$	$9^m.69$	$9^m.43$	$2^m.7$
$B-V$	1.5	1.57	1.54	-0.05
Distance [pc]	8.64	6.5	4.9	28.46
L_X [ergs s^{-1}]	1.3×10^{29}	5.6×10^{28}	8.9×10^{28}	5×10^{30}
Observation	EUVE/139 ks	EUVE/128 ks	EUVE/127-263 ks	Chandra/80 ks

Table 2. Summary of Results

Star	α	Flares %	Normalization[a]	E_{range}[b] log$_{10}$[ergs]	L_{min}[c] [$\times 10^{26}$ erg s^{-1}]
FK Aqr	2.68 ± 0.25	70	3.3×10^4	29.48 - 33.66	0.53
V1054 Oph	2.62 ± 0.21	85	7.4×10^3	29.24 - 32.82	0.30
AD Leo	2.17 ± 0.034	80	2.1×10^4	29.48 - 34.10	0.59
β Per	> 2.4	95	2.0×10^5	30.74 - 35.59	17.44

[a]Normalization factor for power-law distribution

[b]Range of flare energies (50-250 Åpassband) included in calculation

[c]Minimum flare luminosity to which power-law should be extended in order for the flare component to account for the entire emission