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IMPLICATIONS FROM EXTREME-ULTRAVIOLET OBSERVATIONS FOR CORONAL HEATING OF ACTIVE STARS

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ABSTRACT

Extreme Ultraviolet Explorer (*EUVE*) data of two active solar analogs, 47 Cas and EK Dra, were used to investigate flare statistics and the distribution of the flare occurrence rate in energy. The *EUVE* satellite observed each star for almost 7 days. Simultaneous spectral data from its spectrometers were used to derive temperature and abundance characteristics of their coronae. The emission models were derived from differential emission measure distributions by fitting optically thin thermal models to the spectra. The Deep Survey instrument photon lists were analyzed by applying different time binnings. A total of 28 flares were identified for further analysis. The timing study provided estimates for the total radiative energy loss of each flare. The differential distribution of flares in total X-ray energy is found to be a power law ($dN/dE \propto E^{-\alpha}$, with $\alpha \approx 2.2 \pm 0.2$) valid in the energy range between 3×10^{33} and 6×10^{34} ergs. The power-law index is larger than that for typical solar flares but is similar to indices found recently for small-scale solar events. If the power law continues to energies of moderate solar flares, then the total energy emitted by the ensemble of all flares may suffice to explain all of the observed flaring and "quiescent" X-ray emissions of the two stars. A considerable portion, if not all, of the energy required to heat their coronae could thus be provided by flares.

Subject headings: stars: activity — stars: coronae — stars: flare — stars: individual (47 Cassiopeiae, EK Draconis) — X-rays: stars

1. INTRODUCTION

A lively debate on heating mechanisms of solar and stellar coronae to temperatures exceeding 10^6 K has identified numerous possible processes (e.g., Ionson 1985; Narain & Ulmschneider 1990; Zirker 1993; Haisch & Schmitt 1996). Recent observations and theoretical work have given impetus to one particular class of coronal heating mechanisms, those that involve flares that heat the outer atmospheric layers of the stars.

There is ample support for the hypothesis that flares can heat coronae, although no evidence is unequivocal. Doyle & Butler (1985) and Skumanich (1985) noted that the apparently nonflaring ("quiescent") coronal X-ray luminosity of active stars L_X is correlated with their time-averaged *U*-band flare luminosity, suggesting that flares could release sufficient energy that ultimately is observed as quiescent coronal emission. This L_X is itself correlated (at least for active stars) with the quiescent radio luminosity (Güdel & Benz 1993). The latter is synchrotron radiation from relativistic electrons. On the Sun (and on flaring stars), these electrons are accelerated during flare episodes. Benz & Güdel (1994) found that the stellar correlation is approximately followed by solar flares, thus providing a strong link between quiescent emission and flares.

Active stellar coronae show quiescent temperatures of 10–30 MK (e.g., Haisch & Schmitt 1996), values that the solar corona attains exclusively during flares (Watanabe et al. 1995). Characteristic emission measure distributions of active solar analogs were successfully reproduced by simple statistical hydrodynamic simulations of a rapid sequence of flares (Güdel 1997). Robinson et al. (1995) found evidence for numerous transition region (TR) flares in late-type active stars. Also, broadened TR emission line profiles have been interpreted (Linsky & Wood 1994; Wood et al. 1996) in terms of a large number of explosive events similar to flare events previously identified in the solar TR (Dere, Bartoe, & Brueckner 1989).

Solar flares have been found to be distributed in energy according to a power law, i.e., for the flare rate *dN* within an energy interval $[E, E + dE]$, one finds that

$$\frac{dN}{dE} = k_1 E^{-\alpha} \tag{1}$$

with a typical power-law index of $\alpha \approx 1.5$–1.8 [Crosby, Aschwanden, & Dennis 1993; the cumulative distribution for $\alpha > 1$ is given by $\int_E^\infty (dN/dE')\, dE' = k_2 E^{-\alpha+1}$, where $k_2 = k_1/(\alpha - 1)$ and k_1 are constants]. A similar power-law index was found for soft X-ray flares on M dwarfs (Collura, Pasquini, & Schmitt 1988). However, if $\alpha > 2$, then an extrapolation to flare energies below the detection limit would be sufficient to produce the luminosity of the quiescent corona, because the integrated power,

$$P = \int_{E_0}^{E_{\max}} \frac{dN}{dE} E dE = k_2 \frac{\alpha - 1}{\alpha - 2} (E_0^{2-\alpha} - E_{\max}^{2-\alpha}), \tag{2}$$

can be arbitrarily large for small values of E_0. Thus, it is crucial to investigate whether the solar flare energy distribution steepens at lower energies (Hudson 1991), perhaps allowing for quiescent coronal heating by "microflares" (see, e.g., Lin et al. 1984; Parker 1988). Recent solar observations are now supporting this flare-heating hypothesis. Although Shimizu (1995) reported $\alpha \approx 1.6$ for small active-region transient brightenings ($\geq 10^{27}$ ergs), Porter, Fontenla, & Simnett (1995) found $\alpha \approx 2.3$ for still smaller events, and Krucker & Benz (1998) mea-

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sured $\alpha = 2.3–2.6$ for numerous microflares in the quiet solar corona.

We investigated the question of coronal flare heating mechanisms for two young stars whose coronae could be scaled-up versions of the solar corona. We took advantage of long, uninterrupted (except for occultations by the Earth) observations in the 40–190 Å range, using the *Extreme Ultraviolet Explorer* (*EUVE*; $P_{orb} = 96$ min: Malina & Bowyer 1991). This range contains a number of emission features that are formed in typical coronal flare plasmas but are also present in the quiescent coronal emission seen on active stars.

2. OBSERVATIONS AND DATA REDUCTION

Our first target, 47 Cas (HD 12230; F0 V), is a nearby star (distance ≈ 33.6 pc). Judged from its space motions, it is a probable member of the Pleiades Moving Group with an age of ≈100 Myr. Güdel et al. (1998) found it to be an astrometric binary with the secondary star most likely being an active G dwarf that is responsible for most of the observed coronal X-ray emissions. We observed 47 Cas in the Guest Observer Program of *EUVE* during almost 7 contiguous days. A short (5^h40^m) cut in the last part of the observation was due to a target-of-opportunity event (TOO). We also reanalyzed the *EUVE* data of EK Dra (HD 129333; G0 V). EK Dra is also a probable member of the Pleiades Moving Group and reveals rapid rotation ($P_{rot} = 2.7$ days), indicating youth. The *EUVE* spectral analysis with a description of the observation and the star is given by Güdel et al. (1997).

For the spectral analysis of 47 Cas, we used the short- (SW) and medium-wavelength (MW) spectrometer data only, since no obvious emission lines were visible in the long-wavelength spectrometer data. Standard reduction in IRAF was performed. We extracted each spectrum along the dispersion direction using rectangular boxes for the sources and two parallel boxes for the backgrounds. We extracted the light curves from the Deep Survey (DS) data, using circles around the sources and concentric annuli to define the backgrounds. The influence of the detector "dead spot" on the light-curve variability of both stars was also investigated, and no significant effect was found. Figure 1 shows the light curves with one good time interval (bin size of 1 orbit, about 2000 s on source) in each bin.

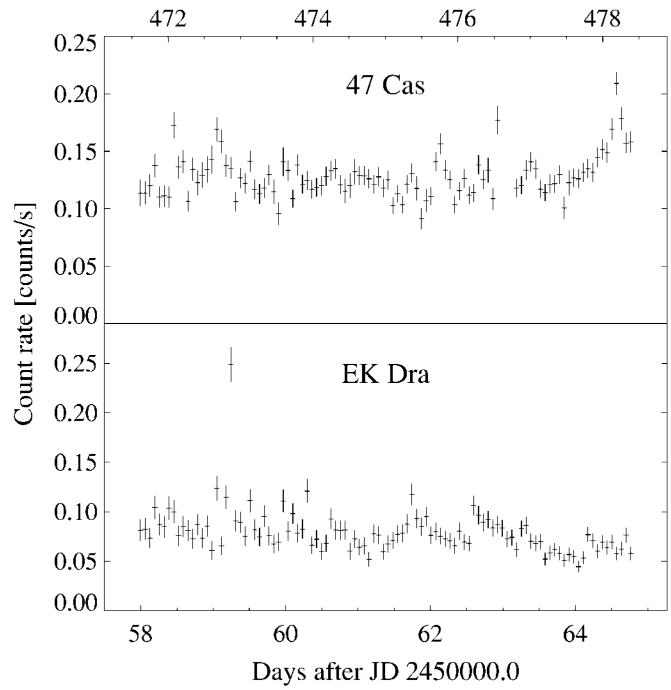

FIG. 1.—DS light curves of 47 Cas and EK Dra. The bin size corresponds to one *EUVE* orbit (96 minutes).

3. ANALYSIS METHODS AND RESULTS

The *EUVE* spectrum of the complete observation of 47 Cas was analyzed with the Utrecht software SPEX (Kaastra, Mewe, & Nieuwenhuijzen 1996) in the same way as we previously analyzed the spectrum of EK Dra (Güdel et al. 1997). This spectrum represents the average state of the corona, including flares. The observations are not sensitive enough to derive the run of the temperature across the flares. The coronal temperatures measured by *ASCA* during a purely quiescent state of EK Dra were, however, very similar to the present results (Güdel et al. 1997). We rebinned the observed spectrum to resolutions commensurate with those of the *EUVE* spectrometers (0.5 and 1 Å for the SW and MW, respectively), leading to 385 useful data channels (excluding the He II λ303.78 line). Several iron lines with ionization stages from Fe XV to Fe XXIII were detected, implying line formation temperatures ranging from $10^{6.3}$ to $10^{7.0}$ K. The collisional ionization equilibrium (CIE) model in SPEX was used with a hydrogen absorption component to determine the iron abundance and the interstellar hydrogen column density N_H. From a three-temperature CIE model, we found an Fe abundance of about 0.3 times the solar photospheric value and $N_H \approx 10^{18}$ cm^{-2}. We then carried out a differential emission measure distribution (DEM) fit to the spectrum using Chebychev polynomials (see Audard, Güdel, & Guinan 1998).[2]

For the flare statistics, we adapted a procedure from Robinson et al. (1995). In short, this method characterizes the statistical distribution of the number of counts per bin for any given regular time binning of the quiescent time intervals. Sufficiently long stretches of quiescent emission were available from the 47 Cas light curve. For EK Dra, we simulated a stochastic photon list with an average count rate identical to the relatively short quiescent intervals toward the end of the observation. We started the procedure with small bins (1/50 of 96 min) which were first randomized in time and then rebinned with binning factors between 10 and 100 (resulting in bin sizes of 1/5 to 2 times 96 min). The rebinning was applied for 100 different relative time shifts (phases) by a fraction of a bin, but for each bin we retained only the highest number of counts that it could thus comprise. The complete procedure was repeated for many different realizations of the initial randomization to obtain a robust quiescent count distribution (for each rebinning factor; see Robinson et al. 1995 for further details, also their Fig. 5*b*). These distributions define the probability for a bin to be in a quiescent state, given its number of counts. We next binned the full data set (including the flares) with any binning factor and phase shift and could therefore, by comparing with the quiescent distributions, find the probability for each bin to be quiescent.

We plot the probability for the presence of quiescent bins as a function of time (*x*-axis) and bin size (*y*-axis; see Fig. 2 for 47 Cas). The flare significance increases from light gray (probability for quiescence to occur by chance between 10^{-3} and 10^{-4}) to black (probability smaller than 10^{-6}). A flare on

[2] Available at http://astro.estec.esa.nl/XMM/news/ws1/ws1_papers.html.

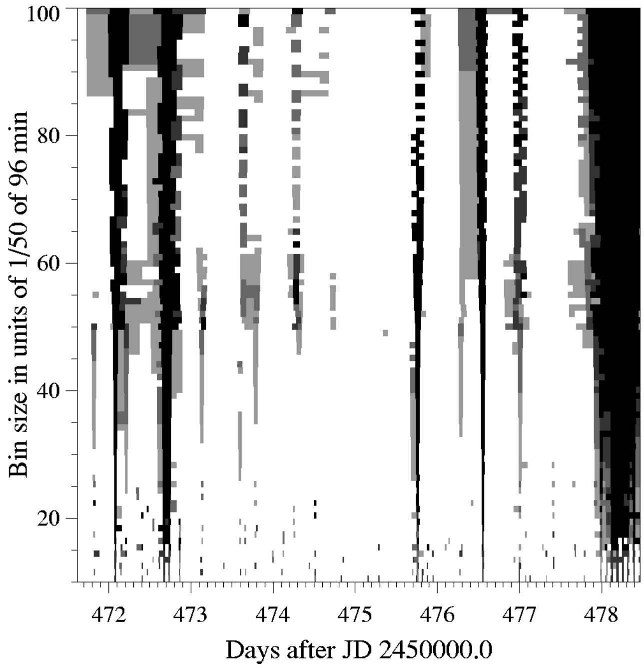

FIG. 2.—Probability of flaring emission as a function of time and bin size for 47 Cas. The flare significance increases from light gray to black. We excluded the detection at day 476.6 that is affected by the short interruption during the TOO.

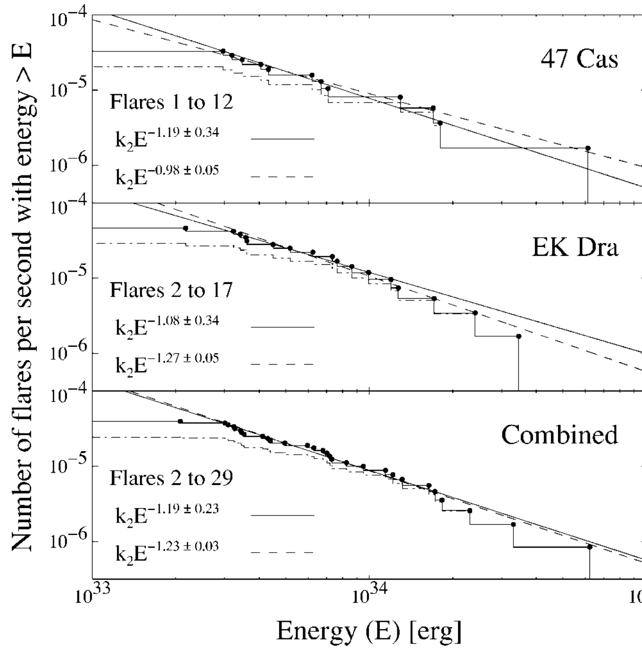

FIG. 3.—Cumulative flare rate distributions in energy for 47 Cas, EK Dra, and the combined distribution. Corrected distributions are plotted as solid lines, while uncorrected distributions are plotted as dash-dotted lines. Also shown are power-law fits to the *corrected* distributions using the method of Crawford et al. (*solid line*) and, for comparison, a least-squares fit (*dashed line*). Note that the power-law indices of these *cumulative* distributions are $\alpha - 1$ (see text following eq. [1]).

47 Cas just before the TOO interruption was excluded because its end time could not be determined. Finally, 12 flares were extracted for 47 Cas and 17 for EK Dra. Next, we defined a lower envelope to each star's light curve with smoothed splines, above which we fitted Gaussians to the identified flares. The duration of a flare was defined as the FWHM; its beginning and end were defined as the times separated from the maximum by 2 σ. The parameters of the last flare of 47 Cas had to be estimated because of its peculiar shape. The total EUV+X-radiated energy of each flare and the cumulative flare rate distributions were determined as follows. We derived the total number of counts between the beginning and the end of each flare (quiescent+flare contribution). The mean background level was estimated just before and after the flare to derive the "flare-only" counts. The DEM fits were used to compute the conversion factor (C) that relates the DS count rate (μ) to the total radiative energy loss from the corona. From the computed average EUV+X-ray luminosity L_X between 0.01 and 10 keV, we obtained $C \approx 1.97 \times 10^{31}$ ergs per count for 47 Cas ($L_X = 2.5 \times 10^{30}$ ergs s^{-1}, $\mu = 0.127$ counts s^{-1}) and $C \approx 2.1 \times 10^{31}$ ergs per count for EK Dra ($L_X = 1.54 \times 10^{30}$ ergs s^{-1}, $\mu = 0.074$ counts s^{-1}).

Approximately 60% of the duration of the EUV light curve of each star is occupied by identified flares. Overlapping flares are therefore likely. Because our flare identification procedure naturally detects the stronger flare in any overlapping pair, the flare rates had to be corrected iteratively. The flare rate at the energy of the second-largest flare was corrected by a factor $T_{total}/(T_{total} - T_{largest})$, where T_{total} is the total observing time span (≈7 days for each observation) and $T_{largest}$ is the interval of time between the beginning and the end of the largest flare. Analogously, the correction for the third-largest flare took into account the time intervals of the largest and second-largest flares, and so on. Finally, the combined distribution was constructed for a total time span equal to the sum of both observation time spans. A conversion factor equal to the mean of the conversion factors, weighted with the inverse square of the DS count rates, was applied.

Figure 3 shows the resulting corrected (*solid*) and uncorrected (*dash-dotted*) cumulative energy distributions for 47 Cas (*top*), EK Dra (*middle*), and both combined (*bottom*). For all panels, we fitted the *corrected* distributions. The solid line shows the best fit using the method of Crawford, Jauncey, & Murdoch (1970) adapted to our distributions. For comparison, a least-squares fit is shown (*dashed line*). The lowest-energy flare of EK Dra was too close to the detection threshold and was not considered. The indices derived from the method of Crawford et al. ($\alpha = 2.19 \pm 0.34$, 2.08 ± 0.34, 2.19 ± 0.23 for 47 Cas, EK Dra, and the combined distribution, respectively) are very similar and larger than 2. Fits to the *uncorrected* distributions yield $\alpha \approx 1.8$, but these distributions obviously deviate largely from power laws. We estimated the minimum energy E_0 in equation (2) using the best-fit power law (with $\alpha = 2.19 \pm 0.23$) and an upper limit $E_{max} \approx 6.2 \times 10^{34}$ ergs (corresponding to the largest flare of the combined distribution). We obtained $\log E_0 = 30.2^{+1.4}_{-14.6}$ and $31.2^{+0.8}_{-4.8}$ using the average luminosities of 47 Cas and EK Dra, respectively. These energies are far below the detection threshold but include, within the confidence limits, flare energies typical for the Sun, possibly even microflares.

EUVE has a low (≈30%) duty cycle, meaning that good time intervals are no longer than ≈2000 s, and some 3000 s per orbit are lost in "bad time intervals." Many flares with durations ≲3000 s could therefore remain undetected. From a linear regression on the log-log plane, we found that the relation between the FWHM durations (D) and the total X-radiated energies of the flares followed approximately a power law

$D \propto E^{0.4}$, similar to solar results (Crosby et al. 1993). For $D \approx 3000$ s, the flare energy should be about 10^{32} ergs, an order of magnitude below the lowest-energy flare detected. This effect should therefore be irrelevant. If it were, the distribution would steepen. However, smaller flares are especially prone to poor coverage; the peak region of the flare curve may be missed. The possible underestimation of the energies of the smallest flares could lead to a further slight steepening of the distribution. Another steepening effect is possible if the energy of larger flares were reduced by simultaneous, undetected smaller-scale flares. We neglect these effects, but note that they could slightly increase the value of α.

4. DISCUSSIONS AND CONCLUSIONS

We have analyzed two week-long *EUVE* observations of two active, young solar analogs, 47 Cas and EK Dra. These are considered to represent our Sun at younger stages of its evolution. They show enhanced levels of activity, with frequent flares superposed on a quiescent emission level 2–3 orders of magnitude larger than the Sun's. The temperatures of the average coronal plasmas are high, with peaks of the emission measure up to 20–30 MK.

We consider the observed flares to originate from various active regions, since flaring occurs during various phases of the stellar rotation and both stars are extremely active. Therefore, the flare rate distribution required a correction for effects due to superposition. For 47 Cas and EK Dra, respectively, 12 and 16 flares in the range 3×10^{33}–6×10^{34} ergs were used in the analysis. Despite the somewhat small statistics, the flare rate distribution in energy over the complete 1.5 orders of magnitude is a power law, with a best-fit index $\alpha \approx 2.2 \pm 0.2$ derived from the method of Crawford et al. (1970). Our value of α is larger than that derived by Collura et al. (1988) for M dwarfs and also larger than that for solar flares (Crosby et al. 1993). However, our index α agrees with new statistics for small-scale solar flares (Krucker & Benz 1998; Porter et al. 1995, but see Shimizu 1995). We note that the available *EUVE* data do not allow the determination of coronal plasma temperatures. While such information would improve the estimates of the energy losses, we expect that corrections due to variable temperatures during each flare would only slightly shift the energy scale by a constant factor. Our determination of α slightly exceeds the critical limit of 2, suggesting for both observations that flares could heat a considerable part, if not all, of the observable X-ray/EUV corona. Inclusion of flares down to radiative-energy ranges of $\log E_0 \approx 30.2^{+1.4}_{-14.6}$ and $31.2^{+0.8}_{-4.8}$, respectively, would provide sufficient heating for the whole corona of each star. Such energies comprise radiative energies of solar flares and microflares. Our observations support this flare-heating hypothesis for these two young solar-like stars and during the given observing times *if* the power law continues down to energies of moderate flares. A considerable portion, if not all, of the energy required to heat their coronae could be provided by flares.

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