Are the shapes of coronal emission measure distributions controlled by rotation and convection zone parameters?

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Abstract. We present new studies of HD 35850, an F8 V star with $v_{\text{sin}}i = 50$ km/s, and HD 20630 (κ¹ Ceti), a G5 V star with $v_{\text{sin}}i$ about 8 km/s. From ASCA data and EUVE spectra we derive emission measure (EM) distributions that can be compared with published results for other F-K stars, many of which are members of open clusters or moving groups. Typically the EM peaks near log(T) = 6.2, 6.8, and 7.4. We find that these peaks differ for two stars with very different rotation rates, convective-zone depths, and ages. The Güdel (1997) stochastic microflare theoretical model matches the empirical EM distribution of HD 35850.

Analyses of ASCA and EUVE spectra are providing coronal emission measure (EM) distributions for main-sequence and pre-main sequence stars in the F-K spectral type range. A general trend of increasing X-ray luminosity and hotter X-ray energy distribution with increasing rotation rate and smaller age has been known for some time based on observations with the Einstein and ROSAT satellites. The higher energy resolution of ASCA and EUVE now permits studies of the shape of the coronal EM distribution as a function of these same parameters. We have obtained and analyzed ASCA and EUVE spectra of an F8 V and a G5 V star to study how the coronal temperature structures differ with convective zone depth, rotation rate, and age.

1. Observations of HD 35850

HD 35850 = HR 1817 is a rapidly rotating ($v_{\text{sin}}i \approx 50$ km/s), Pleiades age ($t \approx 100$ Myr) F8 V star in an extreme state of magnetic activity for an F star with X-ray luminosity ($L_x \approx 1.5 \times 10^{30}$ erg/s). A full description of this work is now published (Gagné et al. 1999). Our observations consist of:

- EUVE SW (75–180 Å), MW (180–370 Å), and LW spectra (1995 October 23–30).
• McMath-Pierce Ca II HK spectra (1995 October 2–12).

• ASCA SIS0 data (1995 March 12) analyzed by Tagliaferri et al. (1997).

2. Results for HD 35850

• No large flares are evident in the EUVE DS light curve, but the data scatter is real, indicating many small to moderate flares. The EUVE DS light curve indicates a rotation period of 1.40 days.

• The rich EUV spectrum contains lines of Fe XI to Fe XXIV formed between \( \log T = 6.1 \) and \( \log T = 7.2 \) (see Gagné et al. 1999). An IDL EM analysis of the EUVE spectra yields \( N_{\text{HI}} = 1.7 \times 10^{18} \text{ cm}^{-2} \) and the coronal abundance of Fe relative to the solar photosphere \( Z_{\text{Fe}} = 1.15^{+0.75}_{-0.35} \).

• The SPEX differential emission measure code (Kaastra et al. 1996) analysis of the EUVE spectrum yields best fit values \( N_{\text{HI}} = 1.4 \times 10^{18} \text{ cm}^{-2} \) and \( Z = 1.0 \), but an analysis of the ASCA data with the same code assuming \( N_{\text{HI}} = 1.4 \times 10^{18} \text{ cm}^{-2} \) yields \( Z = 0.50^{+0.31}_{-0.16} \).

• Mathioudakis and Mullan (1998) have also analyzed EUVE spectra of HD 35850 and conclude that the coronal Fe abundance is subsolar. We believe that their conclusion overpredicts the EUV continuum flux.

• The Fe XXI 102 Å/129 Å line ratio yields \( \log n_e < 11.6 \text{ cm}^{-3} \).

• The derived and published parameters for HD 35850 are listed in Table 3 of Gagné et al. (1999). We note that the line-to-continuum ratio seen in the EUVE spectrum requires roughly solar Fe abundances, whereas the low resolution ASCA data for HD 35850 and RS CVn systems indicate subsolar abundances. X-ray spectra from Chandra and XMM are needed to resolve this discrepancy.

• The X-ray surface flux on HD 35850 (\( F_X = 1.8 \times 10^7 \text{ ergs cm}^{-2} \text{ s}^{-1} \)) is comparable to cooler dwarfs of comparable age and rotation like EK Dra (G0 V) and AB Dor (K1 V), which also have saturated X-ray activity.

• HD 35850 shows a double-peaked EM distribution with peaks at \( 6.3^{+1.6}_{-2.3} \) MK and \( 25.1^{+6.5}_{-5.2} \) MK and a broad minimum at intermediate temperatures (see Figure 1). Other active stars show similar shape EM distributions.

• We have compared our empirical EM distributions with the stochastic microflare theoretical model of Güdel (1997) in which magnetic loops receive a series of energy pulses of finite duration characterized by \( dN/dE \propto E^{-\alpha} \), where \( N(E) \) is the number density of flares in the energy interval \([E, E + dE]\). Solar and stellar optical flare monitoring gives \( 1.6 < \alpha < 2.5 \). Energy is lost by conduction to the chromosphere and radiation into space. Models with \( \alpha \approx 1.8 \) yield an equilibrium temperature of 6 MK, the dominant flare peak near 26 MK, and a broad EM minimum between these two temperatures (see Figure 2) similar to the empirical EM distributions.
Figure 1. Best-fit emission-measure distribution based on the IDL (dash-dotted line) and SPEX (solid line and error bars) analyses of the EUVE SW and MW lines and continuum.

Figure 2. EM distribution produced by the microflaring model if we assume $\alpha = 1.8$, compact loops with a semi-length of $2.6 \times 10^9$ cm, and full surface coverage. In this case, the equilibrium temperature is $T \approx 6 \times 10^6$ K and a dominant peak occurs near $T \approx 26 \times 10^6$ K.

- We conclude that microflare heating is a likely explanation for the saturated X-ray emission of the most active, Pleiades-age F, G, and K stars.

3. Observations of $\kappa^1$ CETI

We have also begun the analysis of two EUVE observations of the less active star $\kappa^1$ Ceti (G5 V) = HD 20630. The first observation of 158 ks began on 1994 October 13, and the second observation of 168 ks began on 1995 October 6. The 1994 and 1995 Deep Survey data sets each show one flare. The high temperature lines like Fe XXIII 132.85 Å are much weaker in the $\kappa^1$ Ceti EUVE spectrum compared to the HD 35850 spectrum. Figure 3 shows the EM distribution for $\kappa^1$ Ceti constructed using the same techniques as for HD 35850. We find that $\log N_{\text{HII}} = 17.7$ and the Fe abundance is 0.75 times solar.
4. Comparison of $\kappa^1$ Ceti and HD 35850

The EM distribution for $\kappa^1$ Ceti lacks the high temperature component that is dominant in HD 35850 (F8 V), EK Dra (G0 V) and AB Dor (K1 V). Also the EM peaks are at 2 and $5 \times 10^{50}$ cm$^{-3}$ compared to 120 and $160 \times 10^{50}$ cm$^{-3}$ for HD 35850. We believe that the much lower level of activity in $\kappa^1$ Ceti shown by the low EM and absence of a high temperature ($\log T = 7.4$) peak in the EM distribution result from the slow rotation ($v_{\text{sin}i} \approx 8$ km/s) and larger age of $\kappa^1$ Ceti rather than its deeper convective zone because young, rapidly-rotating cool stars like EK Dra and AB Dor do show the high temperature peak. Models for F8 V stars show a convective zone thickness 0.14$R_\star$, compared to 0.34$R_\star$ for G5 V stars. Application of the Gudel (1997) stochastic microflare theoretical model to the $\kappa^1$ Ceti data should tell us how the loop structure and microflare heating differ in less active stars compared to very active stars.

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References