Spectroscopic EUVE Observations of the Active Star AB Doradus

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We present observations of the pre-Main Sequence, rapidly-rotating (0.515 day) late-type star, AB Doradus (HD 36705), made by the Extreme Ultraviolet Explorer (EUVE) satellite. A high-quality spectrum was accumulated between November 4–11, 1993, with an effective exposure time of about 40 hours. The data constrain the coronal temperature structure between several 10^4 K up to roughly 2×10^7 K through a differential emission measure analysis using an optically-thin plasma model. The resulting differential emission measure (DEM) distribution shows: a) dominant emission from plasma between about 2×10^6 K and 2×10^7 K, b) very little emission from plasma between 10^5 K and 2×10^6 K, and c) emission from plasma below about 10^5 K. If solar photospheric abundances are assumed, then the *formal* DEM solution also requires the presence of a strong high-temperature component (above about 3×10^7 K) in order to fit the strong continuum emission below about 150 Å; however, we believe that this component of the solution is not physical. The DEM analysis gives a best-fit value for the interstellar hydrogen column density of $N_H = (2.4 \pm 0.5) \times 10^{18}$ cm^{-2}.

1. Introduction

Since its identification as a flaring EINSTEIN X-ray source (Pakull 1981), AB Doradus (HD 36705) has been one of the most frequently observed active late-type stars. Its particular importance is due both to its very short rotation period (0.515 day) for its spectral type of K0-K2 IV-V, and to its proximity to the Sun (distance 20 – 30 pc; Rucinski 1985, Innis, Thompson & Coates 1986). The discoveries of a strong lithium absorption line in its spectrum (Rucinski 1982, 1985) and of kinematic properties characteristic of the Pleiades group (Innis et al. 1986) have established the star as one of the nearest pre-Main Sequence objects in the solar neighborhood, with an inferred age of 10^{6-7} years.

AB Doradus is easily detected in all spectral bands from the X-rays to radio. Following the EINSTEIN observations, Collier Cameron et al. (1988) using the EXOSAT ME detector found a hot thermal corona. The spectral information in this observation was scant but the whole emission in the low (0.05 – 2 keV) and medium (1 – 10 keV) energy ranges of EXOSAT could be explained by a one-component plasma at about 2×10^7 K with an emission measure of about 2.3×10^{53} cm^{-3} (for an assumed distance of 25 pc). X-ray flares were observed with a rate of about one per 0.5-day stellar rotation. The same rate was observed during an extensive multifrequency campaign of coordinated observations extending from X-rays (GINGA satellite) to radio (3 cm, Parkes radio-telescope) conducted by Vilhu et al. (1993). The ROSAT X-ray all–sky survey observations of

AB Dor (Kürster et al. 1992) obtained over a period of more than a month showed erratic variability with very weak rotational modulation.

The corona of AB Dor is also practically always visible in the radio as non-thermal emission at frequencies as low as 843 MHz (Beasley & Cram 1993), and as high as 8.6 GHz (Vilhu et al. 1993). At 6 cm, the star has often shown a clear and regular rotational modulation (Lim et al. 1992, 1994, and references therein). Spectroscopic optical studies of Collier (1982) and Vilhu, Gustafsson & Edvardson (1987) gave $v\,sin\,i = 100 \pm 5$ km/s and a radial velocity constant to ± 2 km/s.

The chromospheric and transition-region emission of AB Doradus was analyzed with the IUE satellite by Rucinski (1985). The overall level of emission was found to be very high and the star seemed to be rather uniformly covered by active regions at that time. This result, together with the hot coronal component derived by Collier Cameron et al. (1988) from the EXOSAT ME spectra suggested an obvious follow-up with the EUVE satellite whose spectral range probes the region of temperatures between 10^5 and 10^7 K.

AB Dor forms a wide binary with the young rapidly-rotating M-type dwarf Rst 137B. Since this secondary is bolometrically about 60 times fainter than AB Dor, and the "saturation" phenomenon (Vilhu & Walter 1987) should apply to Rst 137B as it does to AB Dor, we do not expect Rst 137B to contaminate significantly the EUV spectrum of AB Dor.

2. Observations

The Extreme Ultraviolet Explorer observations of AB Dor started on November 4 and continued for 14 rotations of the star until November 11, 1993. The data were collected in three spectroscopic bands, SW: 80 – 180 Å, MW: 150 – 350 Å, and LW: 300 – 700 Å, as well as with the Deep Sky Survey (DSS) imager (60 – 150 Å). Results of a time variability analysis to study rotational modulation in the EUV spectra, in the DSS channel and from extensive optical and radio ground-based supporting observations will be presented by White et al. (1995a).

An observation of AB Dor with the ASCA X-ray satellite obtained during our EUVE observations (White et al. 1995b) helped to constrain our interpretations. AB Dor did not show any major flares in the EUV, and was in a low-radio-flux state. Optical monitoring (White et al. 1995a) showed no flaring except during a brief period amounting to no more than 5% of the EUVE observation, so that time-averaging of our spectra should result in data representative of the quiescent state of AB Dor with no significant contamination from flare emission.

The effective exposure times for our spectra were about 40 hours. For the final spectral analysis, we rebinned the spectra into wavelength intervals of 0.25 Å, 0.5 Å, and 1.0 Å for the SW, MW, and LW, respectively. This binning corresponds to about 4 original pixels and ensures that the number of counts (source plus background) is large enough in each bin so that the assumption of Gaussian statistics, as implicitly assumed in the χ^2 statistics, is warranted. Typically all bins in the raw data contain 50–100 background counts. Such rebinned spectra over-sample the resolution of the EUVE spectrographs by a factor of 2.

The spectra expressed in total accumulated counts, corrected for the background are shown for the SW and MW bands in Figures 1 and 2. For the stronger lines we indicate the ions from which they originate. In cursory examinations of the spectra, we note that, in addition to the prominent lines in the SW band, we see a relatively strong continuum between about 80 Å and 150 Å. The noise level in the vicinity of the helium lines (e.g. He II at 304 Å line, see Figure 2) is relatively high, even after background subtraction,

FIGURE 1. The EUVE background–corrected spectrum of AB Dor in the SW passband. The best–fit spectrum, of which the differential emission measure distribution **D**(T) is plotted in Figure 3.

FIGURE 2. Same as in Figure 1, for the MW passband. We do not show the LW spectrum which is weak because of the interstellar absorption.

due to strong geocoronal contributions in these lines. This is because AB Dor is situated at a high ecliptic latitude ($-87°$) and therefore on average the angle between the pointing direction of the telescope and the bright Earth is smaller than for most other sources, leading to relatively more scattered geocoronal light entering the detectors.

3. Spectral analysis

To analyze the EUVE spectrum, we calculated isothermal equilibrium spectra utilizing a spectral code which has evolved from the well–known and widely used optically–thin plasma code developed by Mewe and co–workers (e.g. Mewe et al. 1985, 1986), called SPEX (cf. Kaastra and Mewe 1993, Mewe and Kaastra 1994).

Each of the calculated spectra is modified by interstellar absorption using the absorption cross sections of Rumph et al. (1994), and convolved with the instrument response. In the analysis we assume a source distance $d = 25$ pc, and initially we adopt solar photospheric abundances from Anders and Grevesse (1989). When calculating interstellar absorption we use an interstellar hydrogen column density of $N_H = 2.4\ 10^{18}$ cm^{-2} which followed from a best-fit ($N_H = (2.4 \pm 0.5) \times 10^{18}$ cm^{-2}) to the data, with adopted abundance ratios He I/H I = 0.1 and He II/H I = 0.01. However, the final results are not very sensitive to these ratios.

FIGURE 3. Differential emission measure (DEM) curve $\mathbf{D}(\mathrm{T})\Delta\log\mathrm{T}$ for AB Dor corresponding to the best–fit theoretical spectrum shown in Figures 1 and 2, based on standard solar abundances (solid line with error bars) and the DEM derived for the case with the iron abundance reduced by a factor of 3.3 (dashed line). Further reduction of the iron abundance to about 1/7 solar entirely removes the high-temperature component.

In our analysis, we follow the procedure described by Mewe et al. (1995a and these proceedings). The DEM function, defined to be $\mathbf{D}(\mathrm{T}) = n_e n_\mathrm{H} dV/d\log\mathrm{T}$, is the weighting function which measures how strongly any particular temperature contributes to the observed spectrum (T is the electron temperature, n_e the electron density, n_H the hydrogen density, and V the plasma volume). The observed spectrum is interpreted as a statistical realization of a linear combination of isothermal spectra. We implicitly assume that all plasma components are in thermal ionization equilibrium, thus ignoring any transient effects, and we ignore effects associated with the plasma density. The shape of the DEM distribution is derived from the observed emission line *and* continuum fluxes. We stress here that it is important that we include the continuum in our analysis since it is the line-to-continuum ratio that can provide important information on the abundances (in particular the [Fe/H] ratio) and line scattering effects.

For a composite plasma with temperatures ranging from $\mathrm{T_1}$ up to $\mathrm{T_M}$, the net expected spectrum $\mathbf{g}(\lambda_\mathrm{i})$ is given by: $\mathbf{g}(\lambda_\mathrm{i}) = \int \mathbf{f}(\lambda_\mathrm{i},\mathrm{T})\mathrm{n_e n_H(T)dV(T)}$. This can be approximated by $\approx \sum_{\mathrm{j}=1}^{M} \mathbf{f}(\lambda_\mathrm{i},\mathrm{T_j})\mathbf{D}(\mathrm{T_j})\Delta\log(\mathrm{T})$. The inversion problem (equivalent to a Fredholm equation of the first kind) is ill–posed and solutions tend to show large, unphysical oscillations. We therefore apply a second-order regularization ("smoothing"), i.e. of all solutions which are consistent with the data we select the DEM which has the smoothest second derivative. We use a grid of 41 logarithmically spaced temperatures between 0.001–10 keV. In Figure 3, the emission measure is plotted as $\mathbf{D}(\mathrm{T})\Delta\log\mathrm{T}$, with $\Delta\log\mathrm{T} = 0.1$.

The EUVE spectra contain information about plasma emission for the range between about $5-7\times10^4$ K and 2×10^7 K. The maximum in the continuum spectrum moves shortward of the EUVE wavelength range for temperatures exceeding roughly 3×10^6 K, while the associated long-wavelength component in the EUVE range is rather insensitive to changes in the temperature. Therefore, the continuum from plasma with temperatures exceeding roughly 3×10^6 K can only yield evidence that plasma at these temperatures is present, but cannot yield more detailed information on the actual temperature distribution.

The resulting $\mathbf{D}$ is plotted in Figure 3 as a solid line with error bars and the corresponding best-fit spectrum is shown in Figures 1–2 by the thick solid line. We note that, because our method is in principle a linear decomposition method, it does not prevent

D from taking negative values. The DEM inversion procedure produces an essentially perfect fit to the observed spectrum, for the assumed errors as given by Poisson counting statistics. The fit residuals are nowhere larger than 3σ and we found no evidence for systematic tendencies, in the sense of the fit residuals being systematically above or below zero in certain wavelength ranges.

4. Conclusions

The main results of our determination of DEM are as follows:

• At temperatures below about 10^5 K (region "A" in Figure 3) a "chromospheric" component is predominantly determined by the strong He II line at 304 Å and (upper limits of) a few other, weaker lines (e.g. He II 256 Å and O III 507 Å). The strong He II 304 Å line is certainly optically thick, so that the **D**(T) at these temperatures should be regarded only as a formal, certainly not unique solution.

• There is very little emission from plasma between 10^5 K and 2×10^6 K (region "B"). The striking absence of emission in this region is also found for other active cool stars such as α Aur and ξ UMa (Schrijver et al. 1995 and these proceedings).

• Most of the lines in the spectrum of AB Dor (Figures 1–3) are due to various ions of iron, from Fe XV up to Fe XXIV, forming at temperatures from about 2.5×10^6 K up to $\sim 1.6 \times 10^7$ K. This pronounced emission corresponds to region "C" between 2×10^6 K and 2×10^7 K.

• In region "D" the formal **D**(T) solution shows a strong component above about 2.0×10^7 K as a high-temperature "tail", which reflects the presence of a featureless continuum in, foremost, the SW spectrum (cf. Figure 1). This high-temperature component appears to be a common feature in the formal DEM solutions for many other cool stars, while for the quiet Sun itself such a hot component is never detected (Mewe et al. 1995a, Schrijver et al. 1995). Simultaneous ASCA observations of AB Dor do not show any extraordinary hot component (cf. White et al. 1995b, Mewe et al. 1995b). One of possible interpretations of the SW continuum is that its strength relative to the (predominantly Fe) line emission is due to a lower–than–assumed Fe abundance, rather than the presence of very hot plasma (cf. Mewe et al., these proceedings). Through extensive modelling experiments, we found that a reduction of the iron abundance by a factor of seven leads to disappearance of the hot component, and that the EUVE data can be reconciled with the ASCA data. An alternative possibility is that the emitting region is an asymmetric, optically thick but effectively thin plasma in which the photons of the stronger lines are resonantly scattered and destroyed upon impact on the lower chromosphere (cf. Schrijver et al., these proceedings).

The full analysis of the EUVE spectra of AB Dor will appear in *Astrophyscical Journal*, August 20, 1995.

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