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BINARY STARS**

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Contribution to IAU Colloquium No. 152

and

**DISSECTING THE EUV SPECTRUM OF CAPELLA**

Nancy S. Brickhouse  
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Invited Review at IAU Colloquium No. 152

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P. 3

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# High Temperature Structure in Cool Binary Stars

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Strong high temperature emission lines in the EUVE spectra of binary stars containing cool components [Alpha Aur (*Capella*), 44i Boo, Lambda And, and VY Ari] provide the basis to define reliably the differential emission measure of hot plasma. The emission measure distributions for the short-period ( $P \leq 13$  d) binary systems show a high temperature enhancement over a relatively narrow temperature region similar to that originally found in *Capella* (Dupree *et al.* 1993). The emission measure distributions of rapidly rotating single stars 31 Com and AB Dor also contain a local enhancement of the emission measure although at different temperatures and width from *Capella*, suggesting that the enhancement in these objects may be characteristic of rapid rotation of a stellar corona. This feature might be identified with a (polar) active region, although its density and absolute size are unknown; in the binaries *Capella* and VY Ari, the feature is narrow and it may arise from an interaction region between the components.

## 1. Introduction

The emission measure defined by the well-exposed EUV spectra of the binary system *Capella* (G8 III + G0 III) surprisingly revealed a *narrow* high temperature "bump" (Dupree *et al.* 1993) occurring at  $T = 6.3 \times 10^6$  K. The feature is continuously present irrespective of the orbital phase of the system (Dupree *et al.* 1994; 1995), and may arise from a continuously visible hot region on one component, or from an interacting region between the stars. The distribution of the high temperature emission measure in the *Capella* system differs from the broad emission measure distribution found in a solar active region (see Brickhouse *et al.* 1995). We investigate whether this feature is characteristic of binary systems and whether rotation controls its presence.

## 2. Spectra and the Emission Measure Distribution

EUVE spectra from our Guest Observer program and from the EUVE Science Data Archives were obtained for 4 binary systems (VY Ari, *Capella*, 44i Boo,  $\lambda$  And) and two rapidly rotating single stars (AB Dor and 31 Com). EUV spectra were extracted from the images and calibrated in a uniform manner. The reduced spectra are shown in Fig. 1. In spite of the varying physical characteristics of the stars, there are similarities among the spectra. The resonance line of He II ( $\lambda 304$ ) dominates the MW spectra; strong resonance lines of iron dominate the SW spectra. However, the relative strengths of the lines differ among these objects, and so require detailed evaluation of the emission measure. It is the strength of the Fe XVIII and Fe XIX transitions relative to Fe XX, XXIII that controls the presence of the locally enhanced emission measure (the "bump") in *Capella*.

Signal to noise ratios were evaluated at the EUVE spectral resolution, and only the strongest features ( $S/N \approx 9 - 15$ ) were selected to determine the emission measure. Correction of the observed fluxes for interstellar absorption was made with  $N_H$  from Table 1. The H/He abundance ratio was set to 11.6 (Kimble *et al.* 1993) and helium was assumed to be neutral. Assumption of higher values for  $N_H$  would strengthen the



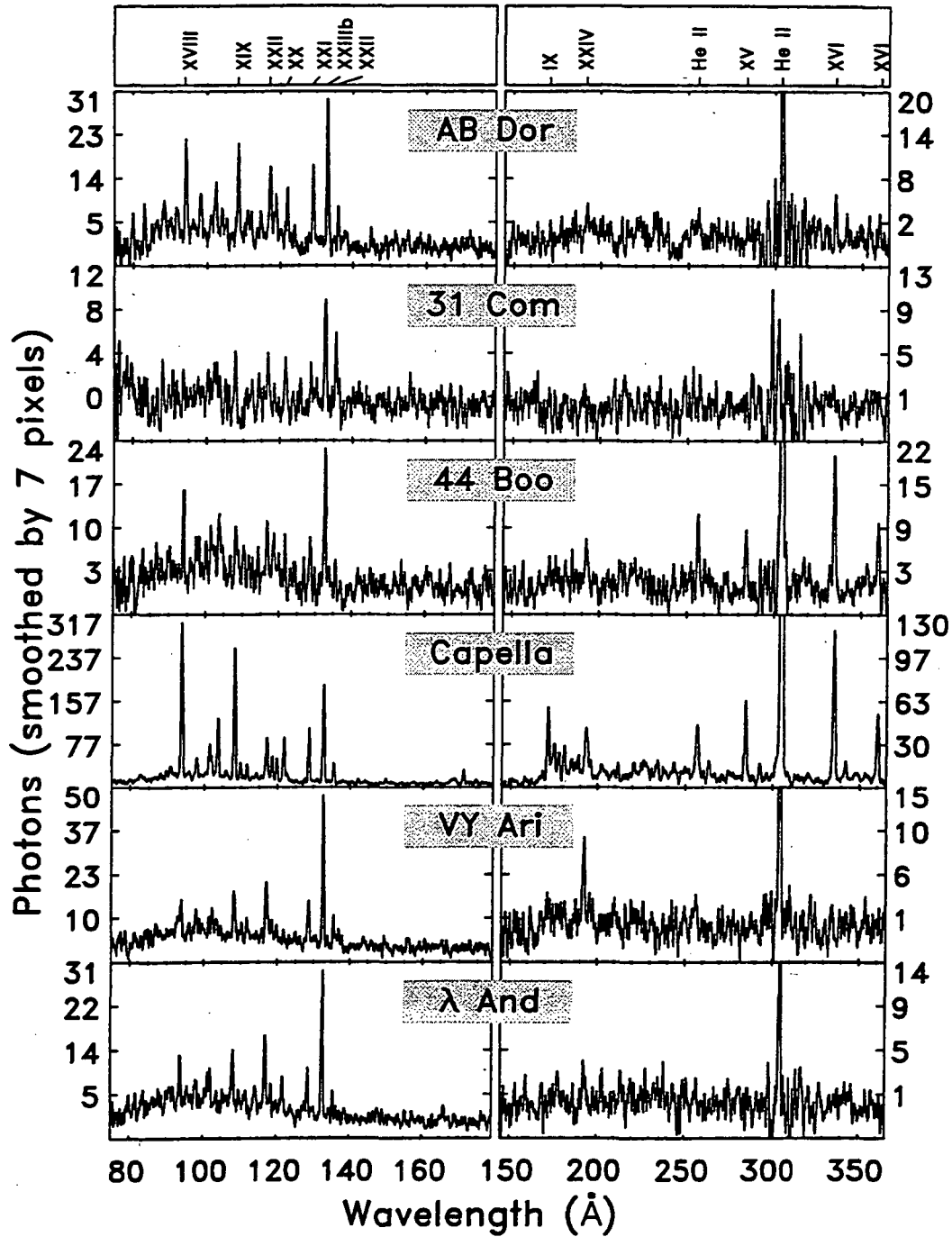


FIGURE 1. EUVE spectra in the SW (*left panel*) and MW (*right panel*) band for the rapidly rotating single stars AB Dor and 31 Com and the binaries 44 Boo, *Capella*, VY Ari, and λ And. Species of Fe are marked by ionization stage. Fe XXIII (λ132.8) is blended with Fe XX.

HD	Star	Sp. Type/Lum.	$P_{\text{orbital}}$ (days)	$P_{\text{phtm.}}$ (days)	$N_H$ ( $\text{cm}^{-2}$ )	SW Exp (s)
17433	VY Ari†	K3-4V-IV	13.208	16.64	$1.0 \times 10^{18}$	168557
34029	$\alpha$ Aur‡	G0 III/G8 III	104.0	8/80	$1.8 \times 10^{18}$	281571
36705	AB Dor¶	K1 IIIp	...	0.514	$1.0 \times 10^{18}$	166460
111812	31 Com	G0 III	< 6	...	$1.0 \times 10^{18}$	84503
133640	44 $\iota$ Boo††	G0 V	0.268	...	$1.0 \times 10^{18}$	104145
222107	$\lambda$ And†	G8IV-III	20.52	53.95	$4.0 \times 10^{18}$	105701

TABLE 1. PARAMETERS OF TARGET STARS

† RS CVn-type binary.

‡ RS CVn-type binary; EUVE spectra of *Capella* taken at several phases were averaged together.

¶ Rapidly rotating single star.

|| 31 Com is a rapidly rotating single star thought to be a Hertzsprung Gap giant. The "orbital" period was evaluated from the  $v \sin i$  value of  $77 \text{ km s}^{-1}$ , assuming a radius of  $9R_{\odot}$ .

†† W UMa-type contact binary.

Fe XVI emission ( $\lambda 336$ ) relative to the Fe XV emission ( $\lambda 284$ ) were observed, but leave the fluxes in the short wavelength region ( $\lambda 85$ – $\lambda 170$ ) essentially unchanged.

The emission measure distribution is determined iteratively, by fully integrating the line emissivities through a trial emission measure distribution, and comparing the predicted and observed line fluxes. There is no restriction on the "smoothness" of the emission measure distribution such as occurs with spectral fitting procedures; moreover the fit is not degraded by bins containing noise or weak signals. Only strong lines are considered in evaluating the emission measure. We require that these fluxes agree within acceptable uncertainties which in this case is better than a factor of two. Detailed current models for all iron ions (Brickhouse *et al.* 1995) were used. Results for  $\lambda$  And are taken from another publication (Hanson *et al.* 1995) where fluxes of ultraviolet lines measured with *IUE* were included so that the emission measure below  $2 \times 10^5 \text{ K}$  is well-defined.

### 3. Conclusions

All of the target stars exhibit a range of high ion stages indicating a generally continuous distribution of temperature. The spectral resolution of EUVE demonstrates that two-temperature fits which rely on energy band measures do not represent these stellar atmospheres. For the weaker spectra, the strongest observable lines arise from high stages of ionization (Fe XVIII ... XXIII), the Fe XV ( $\lambda 284$ ) and Fe XVI ( $\lambda 336$  and  $\lambda 361$ ) emission is not prominent, and the emission measure can only be reliably defined in a restricted temperature range.

Inspection of the emission measure distributions contained in Fig. 2 and 3 shows that the *Capella* "bump" is not unique. The binary systems (VY Ari, 44 $\iota$  Boo) clearly show the enhanced emission measure distribution similar to *Capella*. The appearance of the emission measure enhancement is most pronounced in binary systems with short orbital period ( $\leq 13$  days) and/or high rotational velocity. The orbital period of *Capella* is 104 days, however the hot component of *Capella* is rotating rapidly with a period of  $\approx 8$  days (Fekel *et al.* 1986) so that the system may be classified as a rapid rotator for these purposes. The strong lines of Fe XVIII ( $\lambda 93.9$ ) and Fe XIX ( $\lambda 108.4$ ) demand the presence

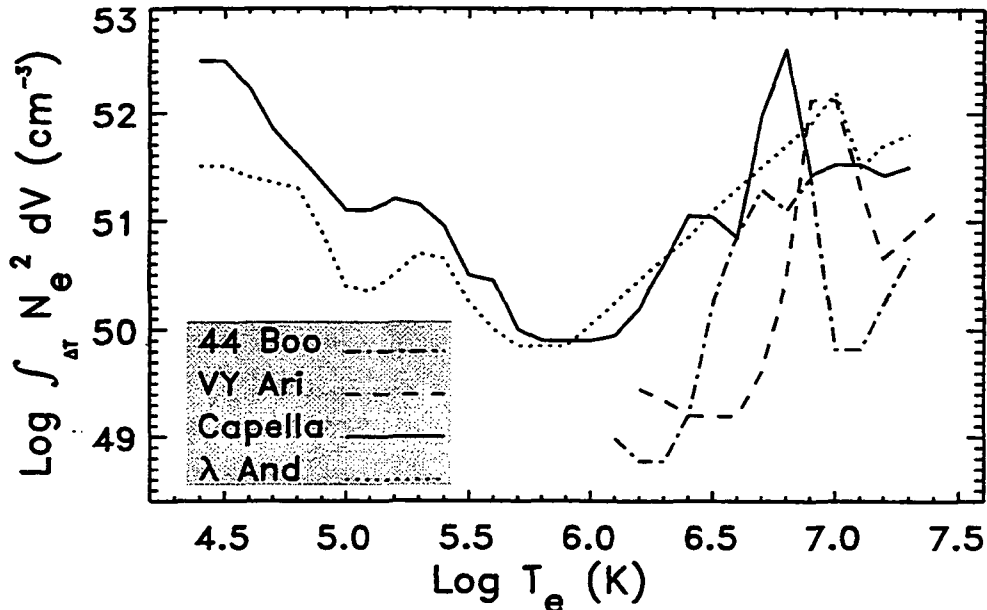


FIGURE 2. Emission measure distribution determined for 4 binary systems.

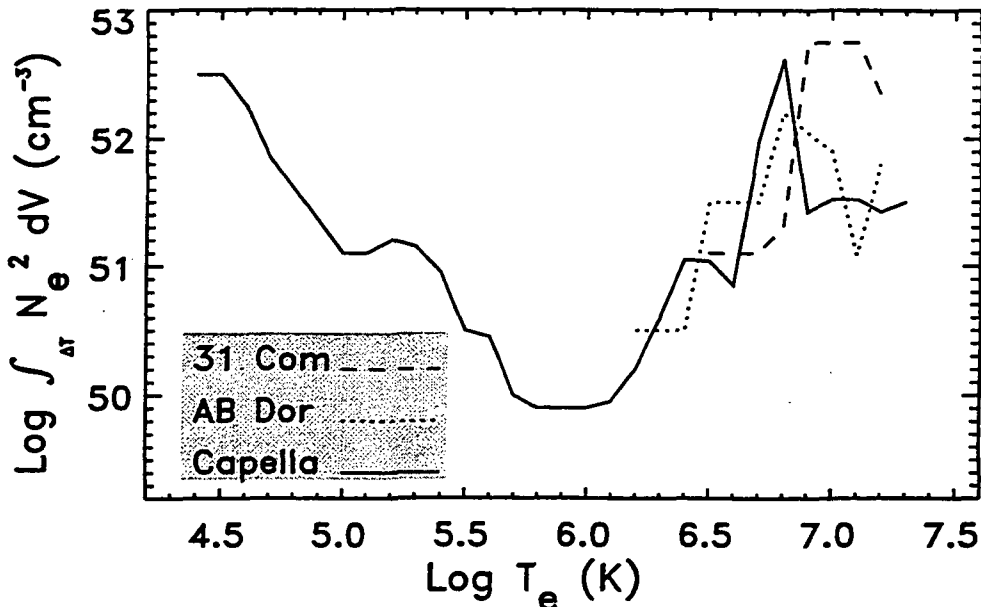


FIGURE 3. Emission measure distribution determined by the strongest lines for 2 rapidly rotating single stars (31 Com and AB Dor) and the binary system *Capella*.

of an increased emission measure in *Capella* for their production. That *44 Boo* would have a similar feature is apparent from inspection of its SW spectrum; the enhancement is broader in temperature than the *Capella* bump. The SW spectrum of *VY Ari* shows an exceptionally strong feature of Fe XX, XXIII ( $\lambda 132.8$ ) relative to the Fe XVIII and XIX transitions; thus the local enhancement of the emission measure occurs at a temperature higher by 0.2 dex, namely  $T(K) = 7.0$  dex. The long period system,  $\lambda$  And has a much

less well defined emission measure enhancement (Hanson *et al.* 1995). The slopes of the emission measures with temperature are consistent with models of magnetic loops or arcades.

Two single stars can address the question of whether the “bump” is unique to binaries. The rapidly rotating single giant 31 Com is of particular interest because it lies in the Hertzsprung gap (Wallerstein *et al.* 1994). Since the hot rapidly rotating secondary in the *Capella* system is believed (Pilachowski & Sowell 1992) to be passing through the Hertzsprung gap too, 31 Com might prove helpful in disentangling the composite EUV spectrum of *Capella*. The star 31 Com has a broad enhancement required by the dominant Fe XXII and Fe XXIII transitions, at a temperature higher (7.0 dex) than the *Capella* feature. Such a broad hot component is not found in the *Capella* emission measure. AB Dor, another rapidly-rotating single giant shows a broad enhancement, also different from *Capella*. Thus, rapidly rotating single stars have “bumps” but they appear different from those in *Capella* and VY Ari.

*Rotation appears to be a significant physical parameter in producing an enhanced emission measure feature in cool star atmospheres.* This feature is generally present in those systems with periods  $\leq 13$  days. However the temperature of the maximum and the width and strength of the enhancement differ from star to star. It is plausible to associate this feature with magnetic structures in a rapidly-rotating corona, in which case it could be dense and of small scale; however, in the binary systems *Capella* and VY Ari, a narrow enhancement (of unknown density) is found. It may be that such a feature results from interaction between the components. Binaries of longer period, represented by  $\lambda$  And and  $\sigma$  Gem (Hanson *et al.* 1995) do not show such well-defined enhancements in the emission measure, although they possess equally hot plasma. However longer EUV exposures are needed on many of these stars to detect weaker species and to define the atmospheric structure over a wider temperature range.

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# Dissecting the EUV spectrum of *Capella*

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Extreme ultraviolet spectra of *Capella*, obtained at various orbital phases over the past two years by the *EUVE* satellite, show strong emission lines from a continuous distribution of temperatures ( $\sim 10^5$ – $10^{7.3}$  K). In addition to the strong He II  $\lambda 303.8$ , the spectra are dominated by emission lines of highly ionized iron. Strong lines of Fe IX, XV, XVI, and XVIII–XXIV are used to construct emission measure distributions for the individual pointings, which show several striking features, including a minimum near  $10^6$  K and a local maximum at  $10^{6.8}$  K. Furthermore, intensities of the highest temperature lines ( $T_e > 10^7$  K) show variations (factors of 2–3) at different orbital phases, while the lower temperature Fe lines show variations of about 30% or less. The low variability of most of the strong low temperature features motivates a detailed analysis of the summed spectrum. With  $\sim 280$  ksec of total exposure time, we have measured over 200 emission features with  $S/N \geq 3.0$  in the summed spectrum. We report here initial results from the analysis of this spectrum. We can now identify lines of Fe VIII and X–XIV, as well as a number of electron density and abundance diagnostic lines.

We also report here the first *direct* measurement of the continuum flux around  $\sim 100$  Å in a cool star atmosphere with *EUVE*. The continuum flux can be predicted from the emission measure model based on Fe line emission, and demonstrates that the Fe/H abundance ratio is close to the solar photospheric value.

## 1. Introduction

*Capella* (Alpha Aurigae; HD 34029) is a bright nearby multiple star system that has been the target of numerous observations over the past two decades in the UV and X-ray regions. Under the Guest Observer Program of the *EUVE* satellite, we have now obtained multiple observations of this source. All of the individual pointings confirm the initial results of the calibration data analysis, reported by Dupree *et al.* (1993): (a) a continuous distribution of temperatures from the transition region to the hot corona; (b) a minimum in the emission measure distribution (EMD) near  $10^6$  K; (c) a local maximum in the EMD at  $10^{6.8}$  K; and, (d) a number of transition region lines that are weak relative to their ultraviolet counterparts. It is the goal of this work to explore the predictive capability of the EMD derived from strong Fe lines. Using the summed spectrum from all the *EUVE* observations, we have now measured over 200 emission features with signal to noise ( $S/N$ )  $\geq 3$  in the three spectrometers. A more detailed analysis can be found in Brickhouse *et al.* (1995b).

The analysis of strong EUV Fe lines reveals complex structure in the *Capella* atmosphere not previously discerned by low resolution X-ray spectroscopy. For example, Swank *et al.* (1981) characterize a number of cool binary coronae as two-temperature distributions using observations taken with the *Einstein* Solid State Spectrometer. Even the moderate resolution *EXOSAT* Transmission Grating Spectrometer was unable to resolve line blends, and thus the multithermal emission models of Lemen *et al.* (1989) are simple parameterizations reliant on global spectral fitting. Among the early results from *EUVE* spectroscopy are clean, strong emission lines of Fe IX, XV, XVI, and XVIII–XXIV in a number of bright active binaries (Dupree *et al.* 1993; Landini & Monsignori Fossi 1993; Stern *et al.* 1995). For example, Dupree *et al.* (1993) report about twenty Fe lines from which an EMD is constructed. While the *Capella* distribution is indeed reminiscent



of two dominant temperatures (unlike certain other sources), a continuous distribution is required to fit the *EUVE* lines.

Given the sharpness of features in *Capella's* atmosphere and the rich diversity of structures found in other sources (Dupree *et al.* 1995), a number of questions arise as to the physical conditions at various temperatures in the transition region and corona. Dupree *et al.* (1993) find evidence for high densities ( $10^{12}$  to  $10^{13}$   $\text{cm}^{-3}$ ) from  $N_e$ -sensitive lines of Fe XXI. Brickhouse *et al.* (1995a) discuss apparent inconsistencies in the densities derived from different line ratios, suggesting that some combination of weak lines, blends, and different source regions for Fe XXI might be responsible. Since these densities at  $T_e \sim 10^7$  K imply small emitting volumes and confining magnetic fields of several hundred gauss, the confirmation of such high densities is a strong motivation for longer observations.

At lower temperatures, the EMD has been much less well constrained, relying solely on Fe IX below  $T_e \sim 2 \times 10^6$  K to connect the transition region to the corona. Since the emission measure minimum is at a significantly higher temperature ( $\sim 10^6$  K) than that of the sun ( $\sim 10^5$  K), the role of various components in the energy balance of *Capella* must be quite different from the sun. The summed spectrum now fills in much of the gap in coverage of Fe ionization stages, adding Fe VIII and X–XIV. Many of these lines are also  $N_e$ -sensitive.

Drake *et al.* (1995) discuss the importance of elemental abundance measurements in stellar coronae for understanding coronal heating, and as Cook *et al.* (1989) point out, significant variations from solar photospheric abundances can also change the shape of the radiative loss function. The summed spectrum of *Capella* includes lines from many of the abundant elements; we report here the analysis of emission formed at high temperature from elements other than Fe. Discussion of EUV lines formed in the transition region and near the emission measure minimum is forthcoming (Brickhouse *et al.* 1995b).

## 2. Observations and data reduction

The individual spectra were acquired over five separate pointings. The extraction techniques, described elsewhere (Dupree *et al.* 1995a), have been applied to the individual observations separately. The spectra are co-added to produce the summed spectra for a total of 2.82, 2.77, and 2.83 ksec for the SW, MW, and LW spectrometers, respectively. Figure 1 shows these spectra, with the S/N curve overplotted. The S/N of individual lines is calculated over the entire line profile, and thus is somewhat better than the peak value shown. Since the individual spectra were accumulated under different conditions, the simple summation leads to a minor degradation of the effective spectral resolution. The strong, isolated spectral lines maintain Gaussian profiles, with fits that are generally improved more by higher S/N than they are degraded by decreased spectral resolution; they are consistent with the performance characteristics described by Boyd *et al.* (1994). For individual lines, the centroid and flux determinations, the continuum flux subtraction and the correction for interstellar absorption are done as in Dupree *et al.* (1993). For blended lines, we require that the line widths, deviations from laboratory wavelengths, and wavelength separations of the individual lines be consistent with the spectrometer characteristics before accepting line identification and fluxes.

Variations during the individual pointings are at the 20% level. Dupree *et al.* (1995b) find that the intensities of the highest temperature lines ( $T_e > 10^7$  K) show modest variations (factors of 2 to 3) with different pointings, while the lower temperature lines ( $T_e < 10^7$  K) show variations of about 30% or less. Ayres (1988) shows that the UV line fluxes are remarkably constant with time as well. While variability in the high

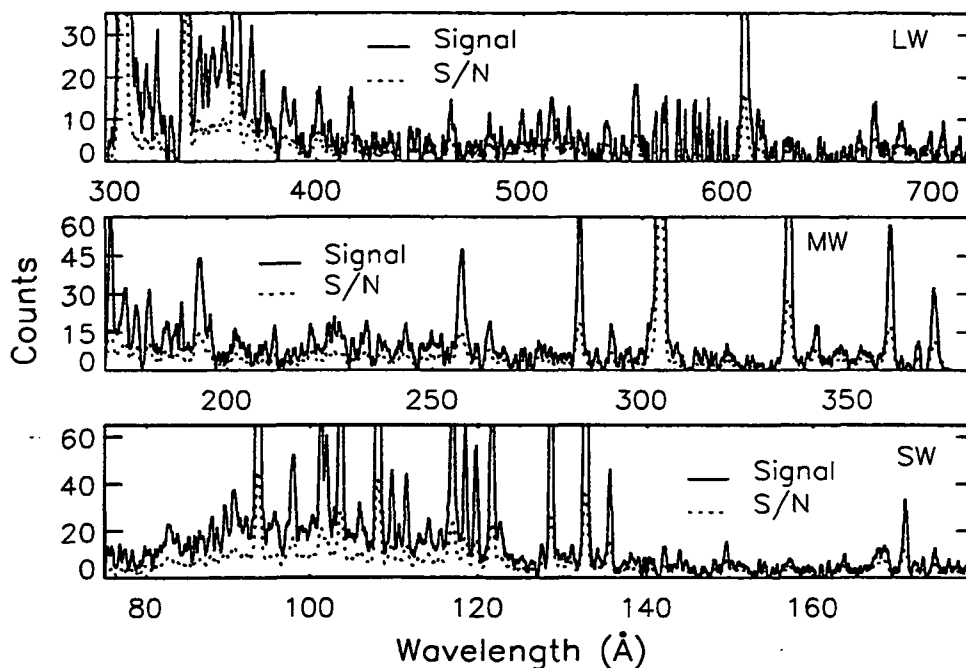


FIGURE 1. *Capella* summed spectrum in the three *EUVE* spectrometers (solid line); signal to noise (dotted line). Curves are smoothed by 5 and 7 pixels, respectively.

temperature lines is useful for line identification and deblending (such as in the blend of Fe XXIV, Ca XVII, Fe XII, and O V around 192Å), the lack of variability over most of the temperature range gives confidence that this analysis is appropriate for typical atmospheric conditions.

### 3. The EMD for the summed spectrum

The analysis of a coronal source through its EMD provides key insights into heating, cooling, and confinement. While these issues are central to much of the EUV work on stellar coronae, the more immediate goal here is to use the predictive capabilities of an EMD, determined by strong lines from a single element, to examine the rich spectrum for other diagnostics. This goal sets the criterion for the “best fit” as the agreement of strong lines with the model. Figure 2 shows our model for the *Capella* spectrum, and the agreement of the lines used in constructing it.

For  $T_e \geq 5 \times 10^5$  K the EMD depends on the the EUV lines of highly ionized Fe. Newly identified lines are discussed by Brickhouse *et al.* (1995b). Although the high temperature extent is not well constrained using EUV lines, this model is now consistent with the *ASCA* continuum above 2 keV (Singh 1994), as well as with the carefully deblended doublet lines of Fe XXIV. We include the X-ray fluxes observed by Vedder & Canizares (1983) in Figure 2, although we do not use these lines in the fitting. It is interesting to note that the two lines formed predominantly at  $T_e = 10^{6.8}$  K (O VIII  $\lambda 18.97$  and Fe XVII  $\lambda 15.01$ ) are in good agreement with the model, while the higher temperature line (Fe XX  $\lambda 12.83$ ) exceeds the prediction of the summed spectrum, but is consistent within the range of variability.

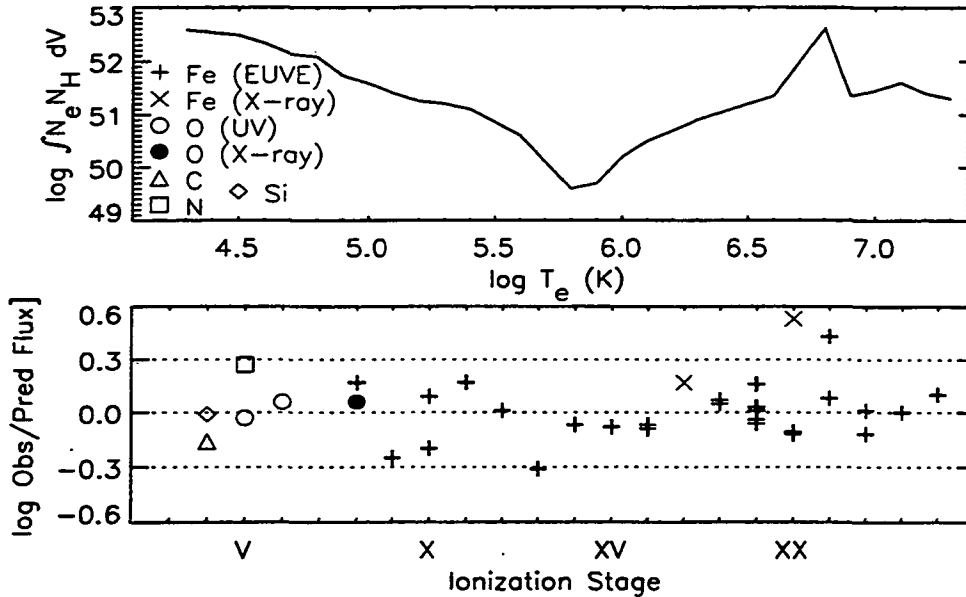


FIGURE 2. *Capella* model. *Upper*: log Emission Measure ( $\text{cm}^{-3}$ ) vs  $\log T_e$  (K). *Lower*: comparison of observed to predicted fluxes for the strong lines. See text for sources of X-ray and UV lines from different elements.

Below this temperature we use the total UV line fluxes measured by Linsky *et al.* (1995) with *HST* and Hurwitz *et al.* (1995) with *ORPHEUS*. As Linsky *et al.* (1995) discuss, the N V resonance line flux may reflect N enrichment in the evolved star, and thus we have forced our fit to the weaker O V line. Many EUV transition region lines are extremely weak relative to the prediction based on the UV emission lines, as initially reported in Dupree *et al.* (1993) and discussed in more detail in Brickhouse *et al.* (1995b).

We cannot emphasize too strongly that the features in the EMD are required by the fluxes of strong lines. For example, *Capella's* local maximum at  $10^{6.8}$  K is determined by eight strong lines of Fe XVIII and XIX, for a total of 7600 counts in the summed spectrum. Continuous distribution models which smooth over this feature will underpredict the emission from other lines formed predominantly at this temperature. On the other hand, a two-temperature model has poor predictive powers for lines formed away from the two dominant temperatures. While the single emission measure at  $10^{6.8}$  K (i.e. the integral over the interval  $\Delta T_e = \pm 0.05$  dex) in our model accounts for about 80% of Fe XVIII and XIX line fluxes (with most of the rest of the flux coming from  $10^{6.7}$  K), it only accounts for 43%, 13%, and 1% of the Fe XVI, XV, and XIV line fluxes, respectively. Thus many temperatures are required to produce the range of Fe ionization stages.

With high S/N spectra and excellent flux calibration, errors in the atomic models begin to dominate the uncertainties. For the more highly ionized Fe species, some collision strengths are as accurate as 10%; for the lower ionization stages (Fe VIII to XIV), collision strengths may be inaccurate at the 30% level or worse. Dielectronic recombination rates are the largest source of uncertainty in the ionization balance, as discussed by Brickhouse *et al.* (1995a). In addition to these uncertainties, many of the lower temperature Fe lines are  $N_e$ -sensitive, and may complicate the emission measure analysis. We find from a synthesis of the Fe XII–XIV spectra that  $N_e \sim 10^9 \text{ cm}^{-3}$  is more consistent with observations than  $10^{10}$  or  $10^{11} \text{ cm}^{-3}$ . While we are not able to measure unblended line ratios from these ions, we are able to isolate several line groups.

At high temperature, line ratio diagnostics give  $\log N_e$  ( $\text{cm}^{-3}$ ) = 11.1 (+0.3, -no constraint) from Fe XXI  $\lambda 128.7/(\lambda 97.9 + \lambda 102.2)$ ; 12.5 (+0.2, -0.1) from Fe XXI  $\lambda 128.7/\lambda 113.3$ ; 12.35 (+0.2, -0.3) from Fe XXI  $\lambda 128.7/\lambda 142.2$ ; 11.73 (+0.2, -0.3) from Fe XXI  $\lambda 128.7/\lambda 145.6$ ; and, 12.05 (+0.3, -no constraint) from Fe XXII  $\lambda 117.1/\lambda 114.4$ . Uncertainties given correspond to 1- $\sigma$  errors in the line ratios. Although the summed spectra provide a great improvement in S/N over the calibration data (Dupree *et al.* 1993), and allow reasonable separation of the blended lines, a large spread remains, which seems to require multiple densities at the source. As noted in Brickhouse *et al.* (1995a), Fe XXI in the model is formed about equally at  $T_e = 10^{6.8}$  K and at  $T_e > 10^7$  K.

#### 4. Measurement of the continuum and the Fe/H abundance ratio

Stern *et al.* (1995) measure the continuum emission for *Algol* by summing the flux in 4 bins to achieve sufficient S/N. We are able to measure *directly* the minimum flux level in the *Capella* summed spectrum, since  $S/N > 3.0$  in every bin throughout the wavelength range 81-123 Å. Figure 3 is a detail of this spectral region. We attribute the minimum flux to real continuum emission (mostly bremsstrahlung), and compare it to model predictions to derive an Fe/H abundance ratio. We find that the Fe/H abundance ratio is  $0.88 \pm 0.13$  solar, assuming the solar values of Anders & Grevesse (1989).

The flux in the pixels which contain the lowest flux values determines the continuum, and the quandary is to select the appropriate number of pixels in the flux averaging. We select the lowest points in the spectrum that agree in value with each other to within their statistical error limits. With smoothing by 3 pixels, this condition produces 14 bins to define the continuum, and the derived error is the standard deviation. The value of the continuum defined in this way is consistent with the measurement determined (from fewer points) with smoothing by 5 or 7 pixels. Furthermore, inspection of line lists gives additional confidence that emission lines are avoided. For all but 3 bins, there are no close wavelength matches with lines listed in the Doschek & Cowan (1984) line list, which includes lines from flaring as well as other solar conditions. We can estimate the contribution from weak, highly ionized Ni by scaling from lines we observe relative to their theoretical Fe counterparts, for which the tokamak line lists of Davé *et al.* (1987) and Stratton *et al.* (1985) are invaluable. The existence of pseudo-continua produced by unknown weak lines is difficult to rule out without models for these weak lines, but their contribution should be well within the errors on the continuum flux measurement.

Figure 3 also shows the temperature-dependence of bremsstrahlung emission. In our model the emission comes predominantly from the  $10^{6.8}$  K local maximum. The model predicts that the continuum emission decreases by about 20% over the range from 85 to 140 Å; we are not able to determine a slope observationally.

#### 5. Elemental abundances at high temperature

The lines used to determine abundances are listed in Table 1. Line emissivities are from Raymond (1988), modified by the atomic data of Zhang *et al.* (1990) for Li-like ions. Figure 4 shows the dependences of model line emissivities and integrated intensities. For the high Z (above Ne) Li-like lines, the emission in our model comes primarily from  $10^{6.8}$  K. The doublet lines are particularly useful, since their line ratio can give additional confidence in the flux measurement. The O and Ni lines in the Table similarly come from this temperature in the model. The errors listed are observational, but there are systematic errors as well, particularly errors in the correction for interstellar absorption. The effect of assuming neutral He is comparable to the errors in  $N_H$  given

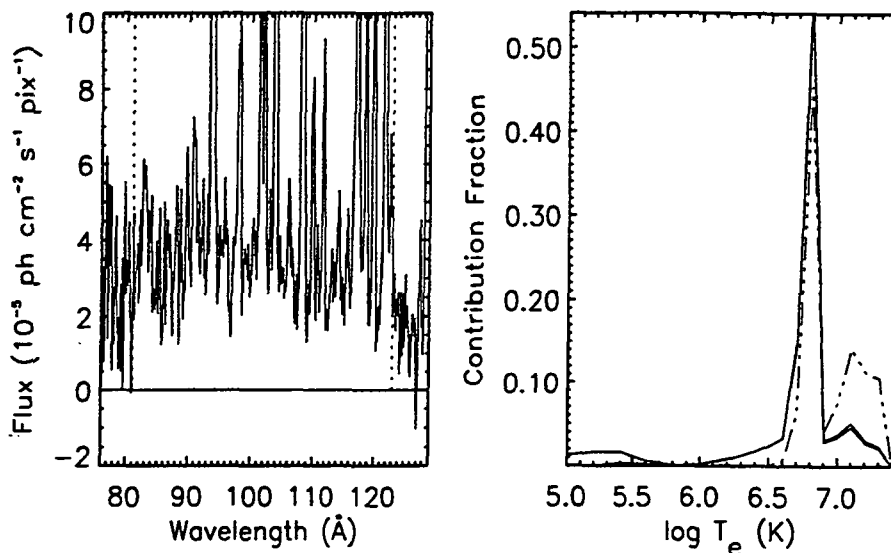


FIGURE 3. *Left*: continuum emission in flux units, where 1 pix = 0.067 Å. Dotted vertical lines indicate the wavelength range for which  $S/N > 3$ . *Right*: model of continuum flux at 100 Å (0.12 keV) (*solid*) and at 6 Å (2.0 keV) (*dash-dotted*) vs temperature. The contribution fraction is the integral of the continuum emissivity over the EMD relative to the total.

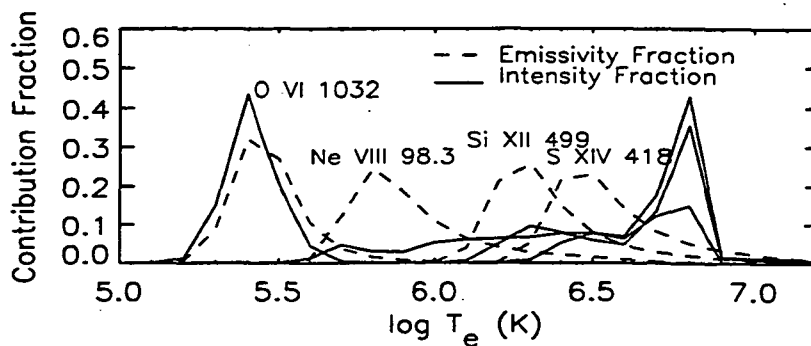


FIGURE 4. The fractional emissivity (*dashed*) and intensity (*solid*) contributions as functions of temperature for selected lines from *Li*-like ions.

by Linsky *et al.* (1993). Vennes *et al.* (1993) show that the fraction of ionized He might be as high as 25%. The abundances in Table 1 derived from lines between 227 and 504 Å would then be somewhat reduced. For Si XII the relative abundance would decrease from 1.99 to 1.65, and would bring the doublet ratio into better agreement with theory.

## 6. Conclusions

High quality *EUVE* spectra of cool stars, such as the summed spectrum of *Capella*, are rich with information on the physical conditions in the atmosphere. Long observations confirm the presence in *Capella* of high densities ( $\geq 10^{12} \text{ cm}^{-3}$ ) at high temperature, but lower densities are present as well at other temperatures. We have now measured the relative abundances of a number of elements which emit radiation at the local maximum

Element	Emission Lines	<i>Capella</i> <sup>†</sup>	<i>Capella</i> <sup>‡</sup>	Solar Corona <sup>¶</sup>
O	O VIII $\lambda$ 102.45 <sup>  </sup>	$0.42 \pm 0.18$	0.13(0.03,0.27)	0.9
	O VIII $\lambda$ 18.97 <sup>††</sup>	$1.02 \pm 0.28$		
Si	Si XII $\lambda$ 499.40	$1.99 \pm 0.38$	0.85(0.67,1.07)	3.6
	Si XII $\lambda$ 520.67			
S	S XIV $\lambda$ 417.61	$1.15 \pm 0.18$	0.73(0.39,1.14)	1.1
	S XIV $\lambda$ 445.77			
Ar	Ar XVI $\lambda$ 353.92	$2.41 \pm 0.31$		1.0
	Ar XVI $\lambda$ 389.14			
Fe	(all)	$0.88 \pm 0.13$	0.46(0.36,0.61)	2.7
Ni	Ni XVII $\lambda$ 249.18	$1.81 \pm 0.20$		3.9
	Ni XVIII $\lambda$ 291.97			
	Ni XVIII $\lambda$ 320.54			

TABLE 1. Elemental Abundances at  $T_e \sim 10^{6.8}$  K<sup>‡‡</sup>

<sup>†</sup> This work. Errors are 1- $\sigma$  estimates of measurement uncertainties, including statistical errors, deblending of weak lines and high order flux subtraction.

<sup>‡</sup> From Drake *et al.* (1994). Allowed ranges reflect 90% confidence levels from X-ray spectral fitting with two temperatures.

<sup>¶</sup> Feldman (1992)

<sup>||</sup> This line was deblended from Fe XXI  $\lambda$ 102.2.

<sup>††</sup> Observed by Vedder & Canizares (1983). Prediction uses the EMD from this work.

<sup>‡‡</sup> Abundances are relative to solar photospheric abundances of Anders & Grevesse (1989).

at  $\sim 10^{6.8}$  K, and find that they are more consistent with solar photospheric than coronal values. Density and abundance measurements may provide keys to understanding the nature of this enhanced emission region. Variability in the  $N_e$ -sensitive lines at the highest temperatures may provide a tool for distinguishing different sources of emission.

The author appreciates the contributions of Andrea Dupree, John Raymond and Greg Hanson. This work has been supported by NAGW-528 and NAG5-2330 to the Smithsonian Institution.

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OMIT

## Coronal Structure in Capella

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### 1. Introduction

Extreme ultraviolet spectra of cool stars are revealing surprising characteristics of the physical conditions present in stellar coronas. Spectra obtained through the Guest Observer Program of NASA's Extreme Ultraviolet Explorer (*EUVE*) satellite probe the temperature range  $\sim 10^4$  to  $10^{7.2}$  K in a collisionally ionized plasma, including stellar chromospheres via strong He II emission, and provide diagnostics of electron density. Binary systems with cool star components are good targets with which to investigate coronal structures.

The binary star *Capella* was used as a calibration target for *EUVE*, and its strong extreme ultraviolet flux produces spectra of superior quality in a relatively short period of time. *Capella* (Alpha Aurigae; HD 34029) is a nearby multiple system in which two bright giant stars (G5 III + G0 III) form a spectroscopic binary. The rich emission line spectrum of *Capella* assisted in calibrating the wavelength scale, and the many emission-line branching ratios verified the relative flux scale of *EUVE*. Its orbital period of 104 days is ideal for spectral observations at different phases.

The first EUV spectrum of *Capella*, (Dupree *et al.* 1993) showed a rich spectrum dominated by iron emission lines: Fe IX, Fe XV–XXIV. The emission measure for the system, determined by ultraviolet and extreme ultraviolet line fluxes, revealed a continuous distribution of plasma temperatures between  $10^5$  and  $10^{7.8}$  K, with a clear minimum near  $10^6$  K. Such a distribution deviates substantially from the canonical solar example with minimum emission measure near  $10^5$  K, a temperature that coincides with the maximum in the radiative loss curve for a collisionally-dominated plasma in ionization equilibrium.

We have an *EUVE* program to observe *Capella* at different phases of its 104-day orbital period. Variations of emission line fluxes, and emission measures with aspect in the system can give clues to the coronal structures. Results of the first five pointings with *EUVE* are

briefly discussed in this poster. Complete results are in preparation for publication (Dupree *et al.* 1995).

### 2. Observations

Extreme ultraviolet spectra ( $\lambda 70 - \lambda 740$ ) of *Capella* were obtained at five different orbital phases (Barlow *et al.* 1993) from December 1992 through February 1994 using the spectrometers on the *Extreme Ultraviolet Explorer* satellite (*EUVE*). All of the spectra show rich emission dominated by iron lines: Fe IX, Fe XV – XXIV. No flaring was present during these observations as determined from the Deep Survey Telescope on *EUVE*.

Inspection of the short wavelength (SW) spectra shown in Figure 1 demonstrates that the three strongest features in the SW spectrum – Fe XVIII ( $\lambda 93.92$ ), Fe XIX ( $\lambda 108.37$ ), and Fe XX, XXIII ( $\lambda 132.85$ ) – show different relative intensities at different phases. The *EUVE* spectra were reduced using software provided by the *EUVE* Guest Observer Center, and fluxes of individual emission lines were extracted from each spectrum. A mean value of the flux of each line was taken and the variation with phase of the line flux to its mean value is shown in Figure 2 for the species of highest excitation. The species of lowest excitation (Fe IX through Fe XVI) show relatively little modulation, the highest temperature species (Fe XX – XXIV) indicate a change with orbital phase. The maximum relative flux appears to occur near phase 0.5 – which in the Barlow *et al.* (1993) ephemeris occurs at maximum velocity separation when the cooler, more massive star (the G5 III star) is approaching.

### 3. Results and Discussion

The *general* form of the emission measure distribution (*cf.* Dupree *et al.* 1993; Brickhouse 1995 for a discussion of its derivation) is reproduced by the *Capella* observations at different phases. Namely, (a.) a continuous distribution of temperatures from the transition region to the hot corona; (b.) a minimum in the emission measure distribution near  $10^6$  K; (c.) a local narrow maximum in the emission measure distribution at  $10^{6.8}$  K. However, the fluxes of high ion species vary significantly when viewed at different orbital phases indicating inhomogeneous structures at temperatures above  $\approx 10^7$  K in the *Capella* system.

Line ratio diagnostics of the Fe XXI ion suggest densities of  $10^{12} \text{ cm}^{-3}$  (Brickhouse 1995). When combined with the emission measure at  $T \approx 10^7$  K, these high densities require a length scale of  $\sim 10^{-2} R_*$ . However,

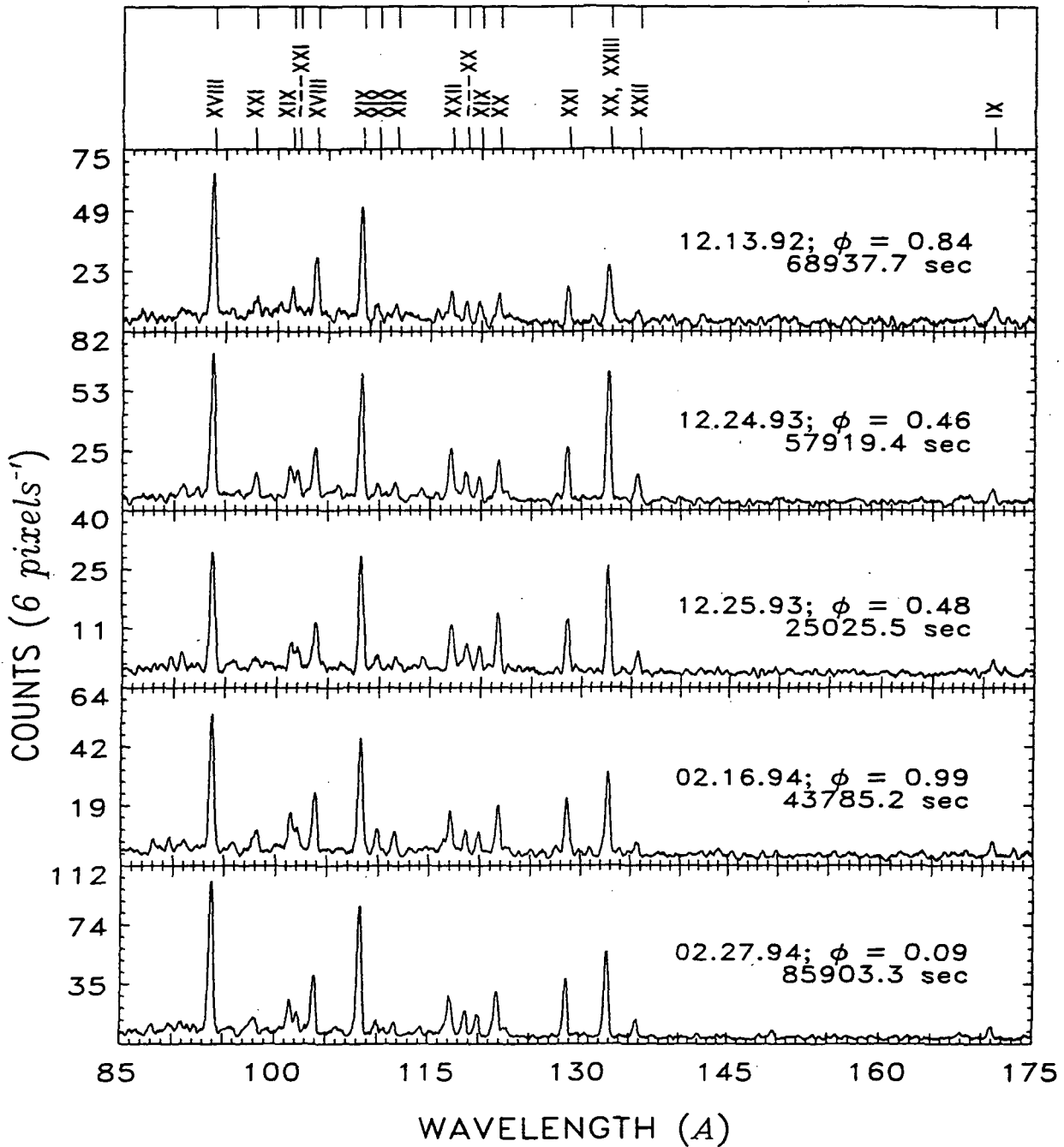


Figure 1: Short wavelength (SW) EUVE spectra of *Capella* taken at 5 phases. Identification of iron emission lines is marked in the top panel. It is obvious that the relative line strengths vary, particularly  $\lambda 132.7$  (Fe XX, XXIII) with respect to  $\lambda 93.9$  (Fe XVIII).

emission from Fe XXI may arise in part from the local emission measure enhancement at  $10^{6.8}K$  which is relatively constant with phase, and in part from material at higher temperatures.

The modulation of the highest temperature species in the *EUVE* spectra resembles that observed in the He I  $\lambda 10830$  line from *Capella*. Shcherbakov *et al.* (1990) extracted the equivalent width of the He I line and its radial velocity from high dispersion near infrared spectra, and found that the radial velocity of the He I absorption corresponded to the orbital variation of the primary star. In addition, the equivalent width of the He I line changed systematically with phase, reaching a maximum near phase 0.5. This led Shcherbakov *et al.* to suggest that an active region producing the absorption was present on one hemisphere – the leading edge of the primary (G5 III) star.

Formation of He I ( $\lambda 10830$ ) in the Sun is affected by the presence of an EUV flux since photoionization by coronal radiation dominates the ionization of He I (Wahlström & Carlsson 1994), and the lower metastable level of this transition is populated by cascades and recombination. A correlation between the  $\lambda 10830$  width and the EUV flux is not unexpected, and provides additional confirmation of the excitation process.

Thus the observed variation of the EUV lines appears to occur on an orbital time scale (104 days), and indicates inhomogeneities in the highest temperature plasma in the *Capella* system.

Identification of the source of the highest temperature emission is puzzling. Ultraviolet emission lines at transition region temperatures ( $T \leq 10^5 K$ ) are thought (Linsky *et al.* 1995) to arise predominantly from the secondary (hotter) star in the system, although only 60–70% of the chromospheric emission originates there. Although the phase coverage for *EUVE* observations is sparse and comprises different epochs, the flux variation is similar to the modulation found in the He I  $\lambda 10830$  line, which originates from the primary star. This similarity suggests the high temperature EUV features could also be associated with the primary star – the G5 III member of the binary. Alternately, the source of the high temperature EUV flux, could be elsewhere in the system, modulated by the orbital motion, and could simply drive the observed variation of the He I  $\lambda 10830$  transition on the primary star.

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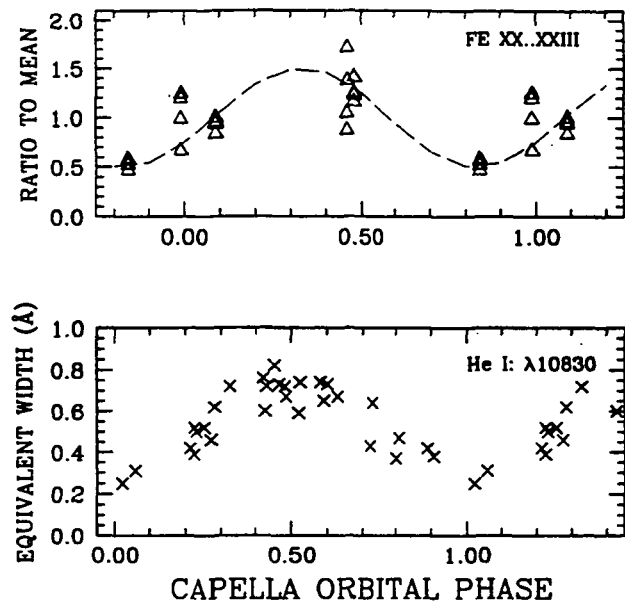


Figure 2: Flux variation of high excitation lines (Fe XX to Fe XXIII) in the *Capella* spectrum as a function of orbital phase of the system. The lower panel displays the change of the equivalent width of the He I  $\lambda 10830$  line with orbital phase (Shcherbakov *et al.* 1990). The correspondence appears better with a phase shift between the EUV and the  $\lambda 10830$  line, which may result from a different coronal structure at the epochs of observation or separation of the emitting regions.

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See Fig  
**EUV SPECTROSCOPY OF COOL STARS**

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**Abstract**

The *Extreme Ultraviolet Explorer* (EUVE) satellite of NASA is acquiring EUV spectra of cool single stars and cool stars in binary systems. These spectra are typically dominated by iron emission lines (Fe IX to Fe XXIV) and many spectra appear similar to the spectra obtained from a Tokamak plasma. Emission measure distributions derived for the emitting plasma in stellar coronas are continuous in temperature, and show enhancements over narrow temperature regions. Electron densities can be high (typically  $\sim 10^{12} \text{ cm}^{-3}$ ) near  $10^7$  K.

**1. Introduction**

EUVE is obtaining extreme ultraviolet spectra in the wavelength region 70 to 700 Å. The in-orbit performance of the spectrometers is described by Boyd *et al.* (1994). The spectral resolution varies from 150 to 400 over each of the three spectrometers: SW: 70-180Å; MW: 170A-365Å; LW: 300A-700Å.

The extreme ultraviolet spectral region is particularly valuable with which to investigate coronal plasmas in cool stars and stellar systems because it contains ion species covering a continuous and broad energy regime, namely from Fe VIII (formed at  $\approx 0.6 \times 10^6$  K) through Fe XXIV (formed at  $\approx 20 \times 10^6$  K). Thus these spectra can be used to define well the temperature structure of the emitting plasma. The EUV spectral region also includes strong emission from He II, formed in stellar chromospheres near  $2 \times 10^4$  K, and weaker emission from elements such as oxygen, neon, magnesium, and silicon. which can define the emission measure distribution at temperatures lower than  $10^6$  K.

Particularly striking was the first EUVE calibration spectrum of the bright binary star *Capella* (Alpha Aur; HD 34029) because of its rich collection of emission lines and its similarity to the spectra of confined plasmas found in a Tokamak (see Fig. 1). The spectrum from the Princeton Large Torus (PLT) when injected with iron, contains emission from ionization stages of Fe XVIII to Fe XXIII as identified in the upper panel of Fig. 1. These transitions are all present in the *Capella* spectrum, although of different

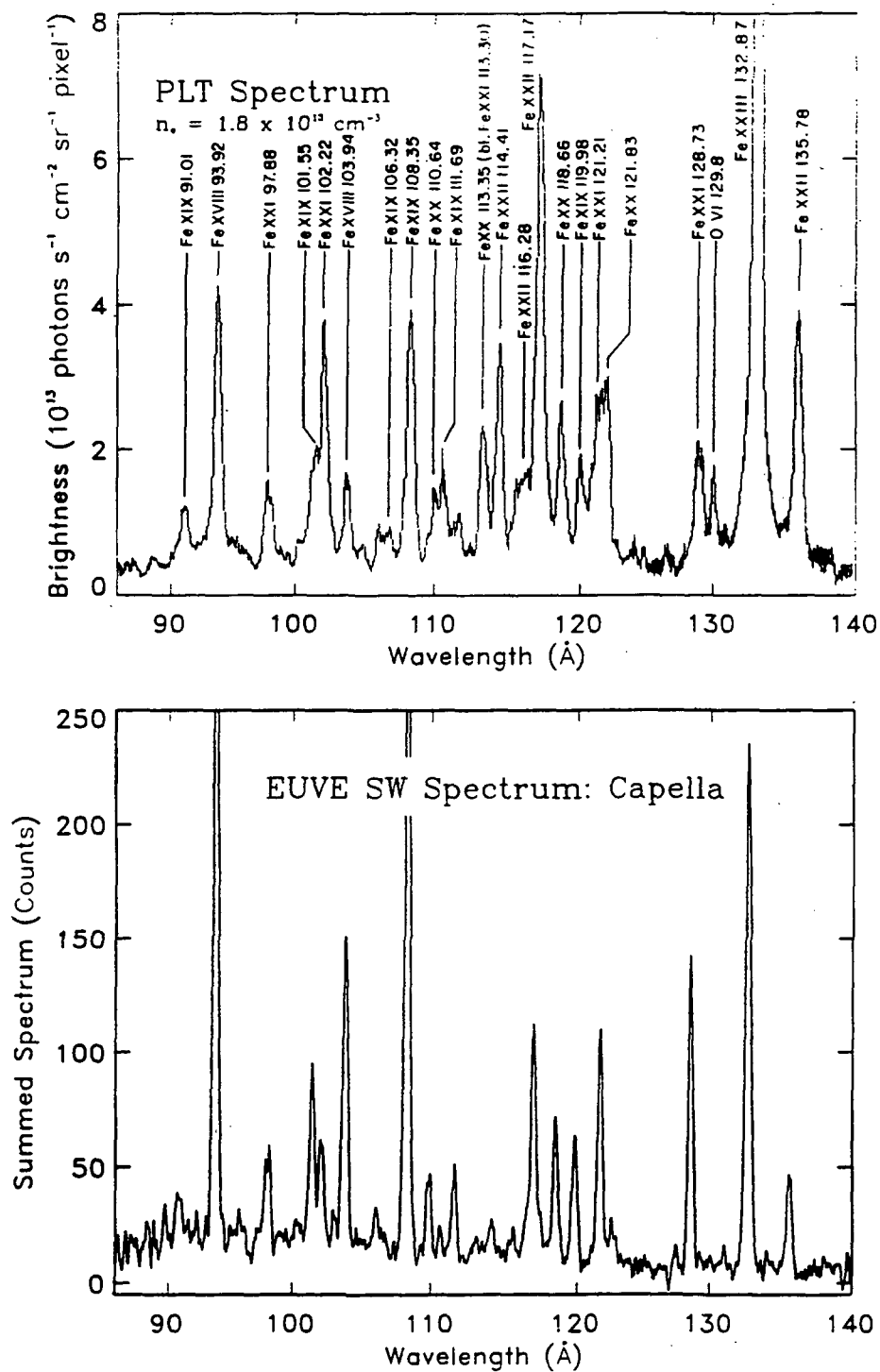


Fig. 1. EUVE Spectrum from the Princeton Large Torus (*top panel* from Stratton *et al.* 1985) and *Capella* (*lower panel*).



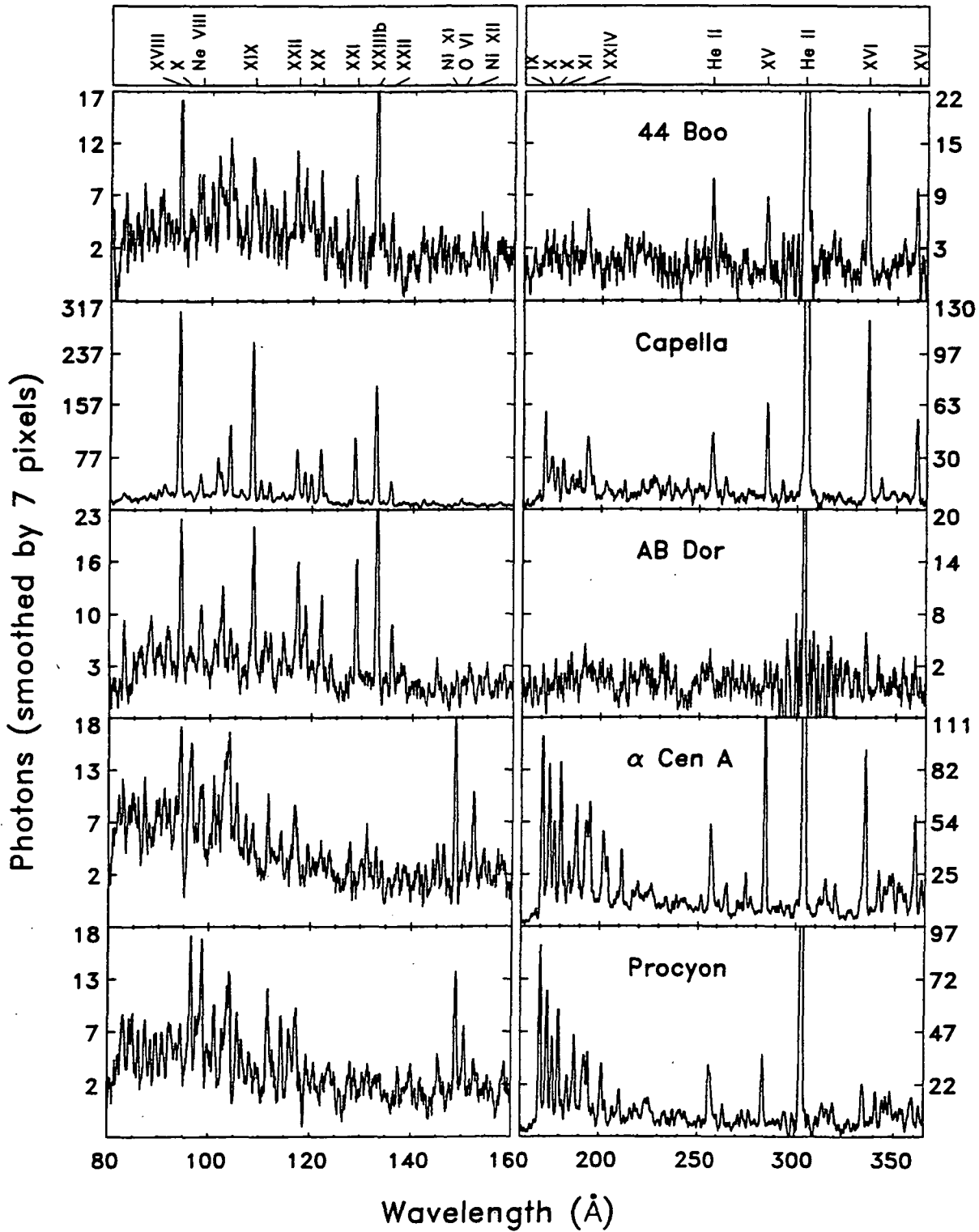


Fig. 2. EUVE spectra of selected cool stars.

relative flux since the temperature distribution of the plasma differs between the two sources. The dominance of Fe XVIII ( $\lambda 93.9$ ) and Fe XIX ( $\lambda 108.4$ ) in the *Capella* spectrum relative to Fe XXIII ( $\lambda 132.7$ ) demonstrates this well. The PLT spectrum contains a transition of O VI ( $\lambda 129.8$ ) which is not observed in *Capella*; we shall show in a later section that the emission measure distribution of the *Capella* plasma is smaller by about a factor of 100 at the temperature where O VI is formed as compared to the highly ionized stages of iron, and thus the O VI line is weak.

Plasma density diagnostics are particularly valuable for astronomical sources since knowledge of the density enables the size of the emitting region to be estimated. The appearance of the Fe XXI ( $\lambda 102.2$ ) transition, a signature of high density, can be noted in the PLT spectrum where the electron density is measured to be  $1.8 \times 10^{13} \text{ cm}^{-3}$ . This is a nice experimental verification of atomic models (Mason *et al.* 1984; Brickhouse *et al.* 1995). The  $\lambda 102.2$  transition is present in the *Capella* spectrum as well, giving support to the high densities ( $\sim 10^{12} \text{ cm}^{-3}$ ) at temperatures  $\sim 10^7 \text{ K}$  indicated by other diagnostic lines.

## 2. Typical EUV Spectra

A selection of spectra from *EUVE* is presented in Figure 2 where two “types” of stellar atmospheres can be easily distinguished. The hottest corona, as found in *Capella* and the PLT spectrum is marked by strong emission at  $\lambda 132.7$  (Fe XX, XXIII), at  $\lambda 93.9$  (Fe XVIII), and  $\lambda 192.1$  (Fe XXIV). These emission lines are apparent in the spectra of 44 Boo (HD 133640; G0 V) and AB Dor (HD 36705; K1 IIIp) in addition to *Capella* (HD 34029; G8 III + G0 III). A “solar” type corona (with coronal temperature about  $10^6 \text{ K}$ ) can be seen in the spectrum of the dwarf stars Procyon ( $\alpha \text{ CMi}$ ; HD 61421; F5 IV) and  $\alpha \text{ Cen A}$  (HD 128620; G2 V). This cooler “solar” type corona is marked by the strong lines of intermediate stages of iron: Fe IX – XI between  $\lambda 170$  and  $\lambda 190$ .

## 3. Analysis of Spectra

To interpret the spectra and derive emission measure distributions characteristic of the material in the stellar atmosphere, we proceed in the following way.

Emission lines from the coronas of cool stars are generally formed under collisional equilibrium conditions. The observed flux in a line is simply proportional to the population of the upper level of the transition,  $N_2$ , evaluated over the line-forming volume:

$$F_{obs} \sim \int N_2 A_{2,1} dV \quad (1)$$

However, in a two-level atom approximation, the population in  $N_2$  is determined by electron collisions from the ground state:

$$N_2 A_{2,1} = N_1 N_e Q_{1,2} \quad (2)$$

where  $Q_{1,2}$  represents the electron collision rate, so that

$$F_{obs} \sim \int \frac{N_1}{N_{total}} \frac{N_{total}}{N_H} N_H N_e Q_{1,2}(T) dV \quad (3)$$

and the ionization equilibrium enters through  $N_{total}/N_H$ . The quantity of interest is the emission measure

$$EM = N_e N_H \Delta V_{(\Delta T)} \quad (4)$$

which is defined over a temperature interval, here 0.1 dex.

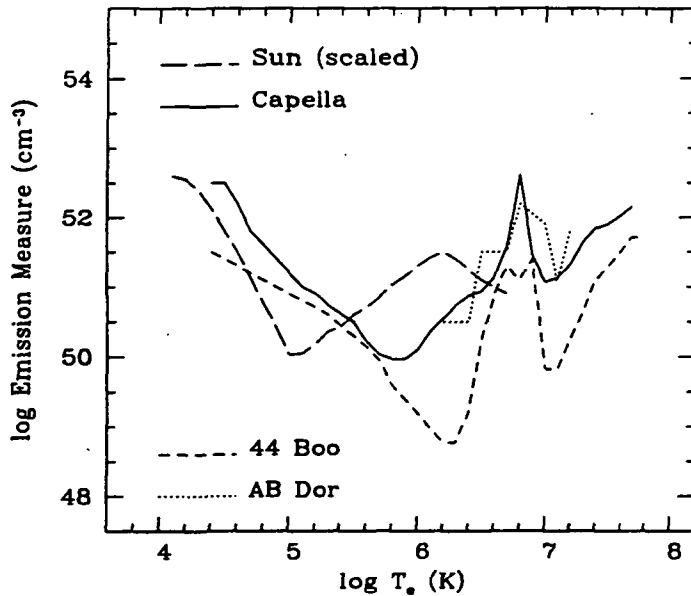


Fig. 3. Emission measure distribution,  $N_e N_H \Delta V_{(\Delta T)}$ , for the Sun and several stars.

To analyze the EUVE spectra, we first select strong unidentified lines, extract their fluxes, and correct for interstellar hydrogen and helium absorption. Next, we rely on current atomic physics and rates such as those in Brickhouse *et al.* (1995). Evaluation of level populations is made with multi-level atoms including metastable levels and many transitions among them including electron and proton collision rates. For calculations of the level populations, an electron density is generally assumed, based on electron density diagnostics or detailed spectral synthesis of selected spectral regions. A grid of electron densities is usually evaluated. The emission rates are integrated through a test atmosphere, and the atmosphere (or emission measure distribution) is modified until the predicted fluxes from the models match the observed fluxes. Strong lines are generally reproduced by the emission measure to better than a factor of two. Typically, for spectra with good signal-to-noise ratios, the deviation between the prediction of the continuous emission measure distribution model and the observed flux is better than 30%. This emission measure defined by the strong lines can then be used to predict the weaker species to facilitate further line identifications and refine the model.

This iterative method has advantages over a global spectral fitting procedure because it relies only on well measured data with reliable fluxes, and because the emission measure curve is not constrained to a simple “smooth” approximation, but allowed to reflect the physics inherent in the observed line emission spectrum. There are sufficient strong lines in the EUV region to define the emission measure well.

#### 4. Conclusions

The emission measure distributions for the Sun and selected stars (Figure 3) illustrate the variety of coronal features present in cool stars, and also contain some puzzling attributes. All of the stars have a *continuous* distribution of temperature, demonstrating that the approximations of one-temperature or two-temperature models are not valid.

The solar emission measure distribution represents the solar network (Raymond and Doyle 1981) and displays a minimum at  $10^5$  K and a broad maximum at  $\sim 10^6$  K which

is characteristic of the coronal temperature. A temperature of  $10^5$  K corresponds to the temperature of maximum radiative loss rate in a collisionally-dominated plasma of solar photospheric abundances in ionization equilibrium. Thus the minimum in the solar emission measure at  $\sim 10^5$  K confirms our understanding of the energetics of the outer solar atmosphere.

However the binary system *Capella* shows a distinctly different emission measure (cf. Dupree *et al.* 1993) in which the minimum is located at  $\sim 10^6$  K, the plasma extends to higher temperatures, and a locally enhanced emission measure distribution occurs at  $10^{6.8}$  K. Similar enhanced features near  $10^{6.8}$  K are found in the emission measure distribution of the rapidly rotating single giant star AB Dor and the contact binary system 44 $\mu$  Boo. Our studies show that the appearance of the *Capella*-like bump is most pronounced in the binary systems with short orbital periods (or rotation period of one component) ( $\leq 13$  days) or in individual stars with high rotational velocity (Hanson *et al.* 1995; Dupree *et al.* 1995). Although the orbital period of *Capella* is 104 days, the secondary star is rapidly rotating with a period of  $\sim 8$  days (Fekel *et al.* 1986). Thus rotation appears to control the appearance of the enhanced emission feature of cool star atmospheres.

The general slope of the high temperature emission measure does not contradict a wide variety of "loop models" in which the high temperature plasma is confined by magnetic fields in the geometry of loops. The electron densities for *Capella* (obtained from the Fe XXI lines at temperatures  $\sim 10^7$  K) suggest, when combined with the required emission measure, that the scale of material at  $10^7$  K is much less than a stellar radius.

Identification of the source of the "bump" – the emission measure enhancement is puzzling. The abundances at this temperature reflect the solar photospheric values (Brickhouse 1995). Such a feature has not been observed in the slowly rotating solar plasma, and appears most pronounced in rapidly rotating systems. It may be a characteristic magnetic structure formed in rapidly rotating stellar coronas. Interaction between components in a binary system might contribute to such a feature.

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