The corona and upper transition region of $\epsilon$ Eri

S. A. Sim and C. Jordan

Department of Physics (Theoretical Physics), University of Oxford, 1 Keble Road, Oxford, OX1 3NP, UK

Abstract. We discuss emission measure models of the upper transition region and corona of the active dwarf $\epsilon$ Eri, developed from HST-STIS and EUVE observations. Theoretical calculations based on an energy balance between thermal conduction and radiation losses in the upper transition region are performed. It is shown how the results of these calculations may be compared with the observations to deduce filling factors for emitting material in the atmosphere. It is found that, as in the Sun, the emitting material occupies only a small fraction of the transition region, but expands to fill the corona.

1. Introduction

$\epsilon$ Eri (HD 22049, K2 V) is a well-observed young dwarf star, with a shorter rotation period (Donahue, Saar, & Baliunas 1996) and higher mean coronal temperature than the Sun, making it an ideal example for studying the coronal properties of stars more active than the Sun. Our objective is to develop semi-empirical models of the outer atmosphere of the star, from the temperature minimum through the chromosphere and transition region to the corona. When complete these models will be used to study the non-thermal energy requirements of the star. Such studies can be used to investigate stellar scaling laws, such as those discussed by Montesinos & Jordan (1993), providing clues to the nature of atmospheric heating in late-type stars.

Here we discuss emission measure modelling of the upper transition region and corona and show how, with the application of simple physical assumptions, we may obtain information about the spatial distribution of emitting material in the stellar atmosphere.

2. Observations

The modelling to be discussed here is based on observations of $\epsilon$ Eri made with the Space Telescope Imaging Spectrograph (STIS) on the HST and the Extreme Ultraviolet Explorer (EUVE) satellite. The STIS observations cover the wavelength ranges 1140–2382 Å and 2574–2846 Å (Jordan et al. 2001a,b). This spectral range contains many emission lines formed under chromospheric and transition region conditions. In addition we have identified the magnetic dipole lines of Fe XII at 1242.00 Å and 1349.38 Å (Jordan et al. 2001a). These lines form at significantly higher temperatures ($\approx 1.4 \times 10^6$ K) than the other
uv lines observed; thus the STIS spectrum can provide simultaneous information about the properties of material at high and low temperatures. Various density sensitive line ratios (including the ration of the Fe XII lines) have been used to measure mean pressures in the transition region which are needed for the construction of atmospheric models (Jordan et al. 2001b).

The EUVE observations show many lines formed in the high transition region and corona, particularly lines of Fe in high ionization states. These observations are discussed by Laming, Drake, & Widing (1996) and Schmitt et al. (1996).

3. Emission measure modelling

Schmitt et al. (1996) and Laming et al. (1996) both used the EUVE observations of ε Eri to construct emission measure distributions for the upper atmosphere of the star. We have used the EUVE fluxes of lines of Fe IX to Fe XVI and Fe XVIII to Fe XXI given by Schmitt et al. (1996) to make a new apparent emission measure distribution, using atomic data from the CHIANTI database (v3.01) (Dere et al. 1997; Landi et al. 1999) and an up-to-date hydrogen column density for the line of sight to ε Eri (Dring et al. 1997).

The quantity obtained directly from the stellar observations is the apparent emission measure which we define in terms of a radial coordinate \( r \) as

\[
EM_a = \int N_e N_H f(r) G(r) \frac{A_t}{A_\star} \, dr
\]

where \( N_e \) and \( N_H \) are the electron and hydrogen number densities respectively, \( f(r) = (r/R_\star)^2 \), \( G(r) \) is a geometric correction factor for a chosen geometry, \( (A_t/A_\star) \) is the ratio of the true emitting area to the total (unresolved) stellar surface area \( A_\star = 4\pi R_\star^2 \), and \( R_\star \) is the stellar radius. The integral runs over the whole region of line formation.

Fig. 1 shows emission measure loci derived from the EUVE Fe line fluxes. These are the values of \( EM_a \) required to produce all the line flux at a given \( T_c \). We adopt an Fe abundance \( N_{Fe}/N_H = 2.57 \times 10^{-5} \) (Drake & Smith 1993) and the ionization balance calculations of Arnaud & Rothenflug (1985). Allowing for reasonable uncertainties in the atomic data and extracted line fluxes, the emission measure distribution shows a peak indicating a coronal temperature around \( \log T_c = 6.4 \) with a peak emission measure around \( \log EM_a = 28.3 \). Unfortunately there are no strong Fe XVII lines observed with EUVE that could constrain the high temperature side of the emission measure peak.

The choice of ionization balance calculations used affects the implied coronal temperature. Fig. 2 shows the emission measure loci derived using the ionization balance of Arnaud & Raymond (1992) and the same line fluxes as in Fig. 1. It can be seen that this ionization balance implies a higher temperature, around \( \log T_c = 6.5 \) or 6.6, again uncertain due to the absence of Fe XVII lines.
Figure 1. Apparent emission measures derived from EUVE observations using the ionization balance of Arnaud & Rothenflug (1985). Each locus is from an Fe line and is labelled with the stage of ionization.

Figure 2. Apparent emission measures derived from EUVE observations using the ionization balance of Arnaud & Raymond (1992). Each locus is from an Fe line and is labelled with the stage of ionization.
4. Energy balance calculations

4.1. Motivation

By initially setting the area factor $A_t/A_*=1$, for a chosen geometry (for brevity we give the formulation for a plane parallel layer but in the calculations that follow a spherical geometry is adopted), the apparent emission measure distribution may be converted to a *spatially averaged true emission measure* which we define as

$$EM_{\text{average}}(0.3) = \int N_e N_h \, dh$$  \hspace{1cm} (2)

where the integral is chosen to run over a depth interval corresponding to a temperature range $\Delta \log T_e = 0.3$ dex. This quantity (which has been deduced from the spatially unresolved observations) is necessarily an average over the stellar surface of the true emission measure ($EM_t(0.3)$) of the emitting material.

The true (spatially resolved) emission measure is related to the average deduced from observations by

$$EM_t(0.3) A_t = EM_{\text{average}}(0.3) A_*$$  \hspace{1cm} (3)

Thus if a theoretical model of $EM_t(0.3)$ can be made, this can be compared with the observed $EM_{\text{average}}(0.3)$ and the area filling factor $A_t/A_*$ can be deduced.

4.2. The energy balance

The conductive energy flux in the stellar atmosphere, $F_c$ may be written as

$$F_c = -\kappa T_e^{5/2} \frac{dT_e}{dh}$$  \hspace{1cm} (4)

where $\kappa T_e^{5/2}$ is the coefficient of thermal conductivity. Using this to eliminate the temperature gradient, the emission measure gradient may be written as

$$\frac{d \log EM_t(0.3)}{d \log T_e} = \frac{3}{2} + 2 \frac{d \log P_e}{d \log T_e} + \frac{d \log A_t}{d \log T_e} - \frac{d(A_t F_c) T_e}{A_t F_c}$$  \hspace{1cm} (5)

where $P_e = N_e T_e$ is the electron pressure (Jordan 2000). Equation (5) is appropriate for plane parallel geometry. A similar result is found for spherical geometry (Philippides 1996), but contains additional geometric terms.

Provided that the coronal heating is not dominated by small hot loops, we may assume that the upper transition region is heated by thermal conduction from the overlying corona. Thus we assume an energy balance between the net conductive flux and radiation losses in the upper transition region which leads to (Jordan 2000)

$$\frac{d(A_t F_c) T_e}{dT_e} \frac{T_e}{A_t F_c} = \frac{2 P_{\text{rad}}(T_e) EM_t^2(0.3)}{0.8 \kappa P_e^2 T_e^{3/2}}$$  \hspace{1cm} (6)

where $P_{\text{rad}}(T_e)$ is the radiative power loss of a plasma of known composition at temperature $T_e$. 

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Figure 3. Calculated and observed apparent emission measures. The thin solid curve is the emission measure locus derived from STIS observations of the Fe XII 1242 Åline. The thick lines are calculated apparent emission measure distributions with different coronal parameters (see text for full details): the solid line has an electron pressure ($P_e = N_e T_e$) in the upper transition region of $\log P_e = 15.8$, the dotted line has $\log P_e = 15.6$ and the dashed line has $\log P_e = 16.0$.

By combining Equations (5) and (6), neglecting the term describing the variation of $A_t$ with $T_e$ in Equation (5) and assuming hydrostatic equilibrium, we can derive the logarithmic emission measure gradient in the upper transition region. Then from a chosen starting point (characterised by a coronal temperature $T_c$, peak emission measure $EM_t(T_c)$ and pressure $P_e$) the true emission measure distribution $EM_t(0.3)$ in the upper transition region can be obtained by integrating the calculated emission measure gradient.

4.3. Results

Fig. 3 shows calculated apparent emission measure distributions for various coronal parameters (in a spherically symmetric geometry to convert from the true emission measure calculated as described above to the apparent emission measure, it is necessary to include the geometric factors $G(r)$ and $f(r)$). In these calculations we have adopted a stellar radius of $0.792 R_\odot$ (using the angular diameter given by Ayres et al. 1983 and the distance from the Hipparcos catalogue) and a surface gravity $\log g = 4.75$ (Drake & Smith 1993). Also shown is the emission measure locus derived from the STIS observations of the Fe XII 1242 Åline using the atomic data from CHIANTI and the ionization balance of Arnaud & Rothenflug (1985). As an observed quantity this locus represents a spatially averaged apparent emission measure.

The best value of the mean electron pressure $P_e = N_e T_e$ in the regions where the Fe XII lines form (based on the observed density sensitive Fe XII line ratio from STIS) is $\log P_e = 15.8$ (Jordan et al. 2001b). Adopting this pressure in the upper transition region (specifically at $\log T_e = 5.3$) and adopting the coronal
temperature indicated by the EUVE results with the Arnaud & Rothenflug (1985) ionization balance ($\log T_c = 6.4$), the true emission measure distribution from the peak in the corona down through the upper transition region can be calculated for a chosen peak emission measure. Initially, this peak emission measure was varied until the emission measure correctly reproduced the observed Fe X\textsc{ii} 1242 Åflux. The solid line in Fig. 3 is that emission measure distribution. Since this computed true emission measure distribution directly produces the observed Fe X\textsc{ii} flux, it corresponds to a model in which the coronal (or more precisely high transition region where the Fe X\textsc{ii} lines form) filling factor is 1.0. This model emission measure distribution can be used to estimate the filling factor lower in the transition region by comparing it with an apparent emission measure distribution deduced from the STIS observations of lower temperature transition region lines (such as the resonance lines of N\textsc{v}). The apparent emission measure deduced from the low temperature lines is shown by Jordan, Sim, & McMurry (2001). This implies a transition region filling factor close to 0.1.

To investigate the possibility that the filling factor in the region of Fe X\textsc{ii} line formation is not unity, one must vary the peak emission measure. Subject to the assumptions in the modelling (and in particular to the adopted Fe abundance), one cannot lower the peak emission measure below the value that directly predicts the observed Fe X\textsc{ii} flux; if the true emission measure were lower then to give the correct average emission measure one would require $A_t/A_c > 1$, which is unphysical. It is possible that the peak emission measure could be lower if the Fe abundance were higher. If one were to raise the peak emission measure then it would be expected that the higher true emission measure would overpredict the observed Fe X\textsc{ii} flux and so an area factor less than unity would be required for such a model to agree with the observations. However, the peak emission measure cannot be increased arbitrarily, for a given pressure and temperature. This can be seen by substituting Equation (6) into Equation (5). If the emission measure is too large, the last term in Equation (5) will change the sign of the emission measure gradient, causing it to turn upwards in the transition region (at higher temperatures than the actual upturn in the observed emission measure distribution). The emission measure at the low temperature end of the upper transition region will then rapidly diverge to unphysically large values. Physically, this corresponds to conduction depositing more energy than the plasma can lose by radiation. This process means that there is a critical solution (which is a maximum peak emission measure) that produces a physically realistic model. For the chosen pressure of $\log P_e = 15.8$ and coronal temperature $\log T_c = 6.4$, the solution described in the previous paragraph is very close to this critical solution. This means that the peak emission measure cannot be raised significantly beyond the value used above.

There is significant uncertainty in the measured pressure, largely due to the atomic data (Jordan et al. 2001b). To investigate the sensitivity to pressure, calculations have been performed at pressures $\log P_e = 15.6$ and 16.0, using the same coronal temperature of $\log T_c = 6.4$. The critical energy balance solutions obtained with these new pressures are shown in Fig. 3 as the dotted and dashed lines respectively. With a pressure of 15.6, the critical solution lies well below the observed Fe X\textsc{ii} locus and so within the modelling assumptions, it is not possible to obtain a model consistent with the observations. With the higher pressure of $\log P_e = 16.0$ the critical solution lies above the observed Fe X\textsc{ii} locus.
and thus places a limit on the Fe XII filling factor of $A_t/A_* > 0.6$ (this is a limit because the peak true emission measure can physically be lower than the critical solution, leading to a greater filling factor).

As discussed in Section 3, there is some uncertainty in the coronal temperature. To allow for this the critical energy balance solutions have been found for the same three pressures as above at coronal temperatures of $\log T_c = 6.5$ and 6.6. It is found that for these higher temperatures the critical solutions for $\log P_e = 15.6$ and $\log P_e = 15.8$ are too low to reproduce the observed Fe XII flux, showing that for models with these temperatures to be consistent with the observations the pressure must be higher. At higher temperatures the constraints on the filling factor produced by the $\log P_e = 16.0$ solutions become tighter.

Table 1 summarises the various parameters used in the energy balance calculations and gives the filling factors deduced. Those entries in the table marked with $\times$ are unphysical because they require filling factors $> 1$. These models (and in particular the model using the best temperature and pressure discussed above) are consistent with a atmospheric structure for $\epsilon$ Eri similar to that of the Sun. They suggest that in the transition region the emission comes predominantly from a small fraction of the stellar surface ($\approx 10$ per cent). Higher in the atmosphere the emission appears to come from more and more of the surface area until it fills most of the corona. This picture of expanding regions of emission is also consistent with the EUVE lines: comparing Figs. 1 and 3 we see that the area factor required to make the solid line model in Fig. 3 consistent with each of the loci in Fig. 1 in turn would be largest for the high $T_e$ ions and smallest for the low $T_e$ ions, implying that the high $T_e$ material fills more of the available area than the low $T_e$ material. However, this type of comparison does not deserve detailed examination since the models in Fig. 3 are based on the STIS observations which are not simultaneous with the EUVE data.

Table 1. Parameters used and filling factors deduced from energy balance calculations. $T_c$ is the coronal temperature (in K); $P_e$ is the electron pressure at $\log T_e = 5.3$, defined as $P_e = N_e T_e$ in units of cm$^{-3}$K; $A_{\text{coronal}}$, $A_{\text{TR}}$ are the areas occupied by emitting material in the region of Fe XII line formation and the transition region (around $\log T_e = 5.3$) respectively; $A_*$ is the total stellar surface area. Entries marked $\times$ are unphysical (see text). All the entries for $P_e = 16.0$ are critical solutions (see text).

<table>
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<th>$\log T_c$</th>
<th>$\log P_e$</th>
<th>$A_{\text{coronal}}/A_*$</th>
<th>$A_{\text{TR}}/A_*$</th>
<th>$A_{\text{TR}}/A_{\text{coronal}}$</th>
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5. Conclusions

The sensitivity and wavelength coverage of the \textit{STIS} instrument have made reliable measurements of fluxes for uv lines in the spectrum of \( \epsilon \) Eri possible, allowing a model of the outer atmosphere of the star to be developed. In particular the identification of the Fe XII lines in the \textit{STIS} spectrum gives simultaneous information on the transition region and inner corona.

Although the observations can provide only spatially averaged information about the conditions in the star, the derived emission measure distribution can be compared with theoretical emission measure distributions based on physical assumptions to deduce some information about the spatial inhomogeneity of emitting material. By assuming an energy balance between thermal conduction and radiation losses in the upper transition region we have been able to estimate filling factors for coronal and transition region emitting material and have found a similar behaviour to that observed in the Sun, namely that the fractional area occupied by emitting material is small in the mid transition region (about 10 per cent) and rises to around unity at coronal temperatures. We will develop this work by including the effect of a height dependent area filling factor in Equation (5). We also intend to complete a new chromospheric model. The full chromosphere-coronal model will be used to establish the non-thermal energy requirements of this active star.

References

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