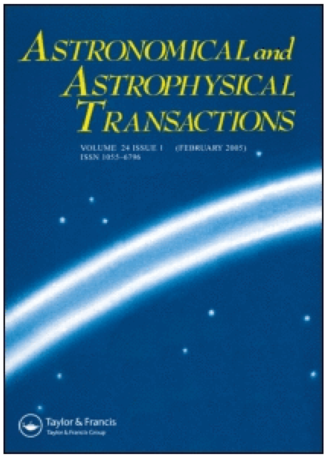

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DIFFERENTIAL EMISSION MEASURE ANALYSIS AND SOURCES OF EUV RADIATION OF CAPELLA'S BINARY

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New EUVE spectra of Capella, containing strong emission lines in the temperature range 10^5–10^7 K, allow us to analyse the structure of the corona and the transition region of active component of this binary. We solve the standard stationary problem of the propagation of the thermal conduction flux from coronal to chromospheric layers. A comparison of the EUVE observational values of the emission measure with those derived from this computation shows that the structure of the lower corona and the upper part of the transition region is caused by a process of propagation of thermal flux from the corona downwards. We hence obtain a temperature distribution with height. Other sources of UV radiation (from the quiet G6 giant, the region of interaction between the stellar wind and the corona) are briefly discussed.

KEY WORDS Active binaries, stellar activity, Capella

1 INTRODUCTION

The outer atmosphere of Capella is a good example for studying the structure of the stellar atmosphere of late-type stars. An analysis of the first UV-spectra of Capella showed the higher activity level of the secondary component of the Capella binary: an F9 giant as compared to the primary star, a G6 III (Katsova and Livshits, 1978; Ayres and Linsky, 1980). The X-ray observations together with the UV data were the basis for the model of the outer atmosphere of the F9 III star of Capella's system (Katsova, 1985); in this model it is argued that the transition region between Capella's chromosphere and corona is much more extended than in the classic case of the Sun and solar-type stars.

Capella has been included in the observational programmes of practically all the space stellar missions from Copernicus up to the Hubble Space Telescope (see, for instance, Linsky *et al.*, 1995). Spectroscopic analysis of the soft X-ray and EUV spectra of Capella was carried out by a number of astrophysical groups (Mewe *et al.*, 1996). These data are the basis for constructing an advanced model of the transition region and the corona of the active component of Capella.

The new spectra of Capella obtained with the Extreme Ultraviolet Explorer (Dupree *et al.*, 1993, Brickhouse, 1996) give the possibility of studying the outer atmosphere of Capella as a whole in the wide temperature range from 2×10^4 to 2×10^7 K. The contribution of the hotter F9 giant dominates the total UV and X-ray radiation at $T \geq 10^6$ K, which permits us to construct a physical model of the lower coronal layers of this star.

Till now one considered that Capella's UV and X-ray radiation originates from the outer atmospheres of both giants, components of this binary system. At present there appears to be some evidence for the existence of an additional source of radiation in the space between these stars. This problem arose for the first time during an analysis of the He I λ 10830Å observational data (Shcherbakov *et al.* 1990), and then the first model of Capella including the interaction of the enhanced stellar wind from the F9 giant with the outer corona of the G6 star was proposed (Katsova, 1992, 1995). The detection of the variability of the EUV line fluxes of Capella during the orbital period (Dupree and Brickhouse, 1995) agreed well with this ideas. Thus, the separation of the contribution into UV and X-ray radiation from the outer atmospheres of the giants and the shock wave located between these stars is extremely important for the further development of this point of view.

We analyse here the differential emission measure distribution versus the temperature presented by Brickhouse (1996) and compare it with the solution of the classical problem of propagation of thermal conduction flux from the corona downwards and conclude that quiscent emission of the corona and upper part of the transition region of the active giant is caused by such a physical process.

2 THE EMISSION MEASURE DISTRIBUTION: THEORETICAL AND OBSERVATIONAL

2.1 *The Theoretical Behaviour of Differential Emission Measure*

To obtain the theoretical behaviour of the emission measure we consider the problem of propagation of the thermal conduction flux from Capella's corona downward to its chromosphere.

The equation of energy balance for layers of the low corona and the transition region is solved for stationary conditions:

$$\frac{d}{dh}(F_{\text{cond}} + F_{\text{rad}}) = \frac{d}{dh}\left(AT^{5/2}dT/dh - n_e^2 L(T)\right) = 0,$$

where F_{cond} is the thermal conduction flux, F_{rad} is the radiative flux, $\kappa = AT^{5/2} = 10^{-6}T^{5/2}$ is the coefficient of thermal conduction; $L(T)$ is the radiative loss function from Raymond and Smith (1977) including an approximation by Tucker *et al.*, 1978. This expression should contain a small additional heating of the atmosphere at the beginning of the propagation of heating. Usually this term is equal to radiative losses in the initial model, i.e. at each level $n_e^2 L_0(T)$ for the time $t = 0$ in the non-stationary problem. We consider below that this small permanent additional heating is included in the radiative losses (with the opposite sign).

The energy balance equation is solved together with the condition that the gas pressure is constant in a layer whose thickness is much less than the height scale in the transition region. The solution of the differential equation can be expressed in the form of integrals; and the differential emission measure DEM = dEM/dT is

$$\mathrm{DEM} = n_0^2 T_{\mathrm{max}}^2 A T^{1/2} \left(F_{\mathrm{cond},0}^2 - 2An_0^2 T_{\mathrm{max}}^2 \int_T^{T_{\mathrm{max}}} L(T) T^{1/2} dT \right)^{-1/2}$$

where n_0, $F_{\mathrm{cond},0}$, T_{max} are the density, the thermal conduction flux and the temperature in the upper boundary of the layer considered (Getman and Livshits, 1996).

As is known, for heating fluxes $F_{\mathrm{cond},0}$ much greater than

$$F_{\mathrm{lim}} = \sqrt{2An_0^2 T_{\mathrm{max}}^2 \int_T^{T_{\mathrm{max}}} L(T) T^{1/2}\, dT},$$

the DEM value is proportional to $T^{1/2}$, which is a solution of the stationary equation of heat propagation without any additional heating and energy losses. If the heating flux which enters the layer considered dissipates there, then the radiative losses are significant, and the solution of the assumed equation for the DEM(T) function corresponds to the case when the limited flux $F_{\mathrm{cond},0}$ is very close to the heating flux at the upper boundary $F_{\mathrm{cond},0}$.

Figure 1 shows the theoretical distributions of differential emission measure DEM versus the temperature for the case of the change-over from large fluxes $F_{\mathrm{cond},0} \gg 1.04 F_{\mathrm{lim}}$ to the corresponding "limiting" value $F_{\mathrm{lim}} = 1.96 \times 10^6$ ergs cm^{-2} s^{-1}. This value and the results of calculations are given for coronal temperature $T_{\mathrm{max}} = 6.9 \times 10^6$ K and the density at the base of Capella's corona $n_0 = 2.8 \times 10^8$ cm^{-3}. As seen in Figure 1, the DEM is proportional to $T^{1/2}$ when the thermal conduction flux exceeds the value of F_{lim}, and DEM(T) rises sharply when the temperature varies from 3×10^5 K to 10^4 K. (For details see Getman and Livshits, 1996, for the solar case.)

2.2 A Comparison of Theoretical and Observational Emission Measure Distributions

As is known, the differential emission measure distribution versus temperature for the quiet Sun and red dwarf stars is similar to those shown in Figure 1 for the case when thermal conduction fluxes are close to their "limiting" value (Gabriel, 1993)

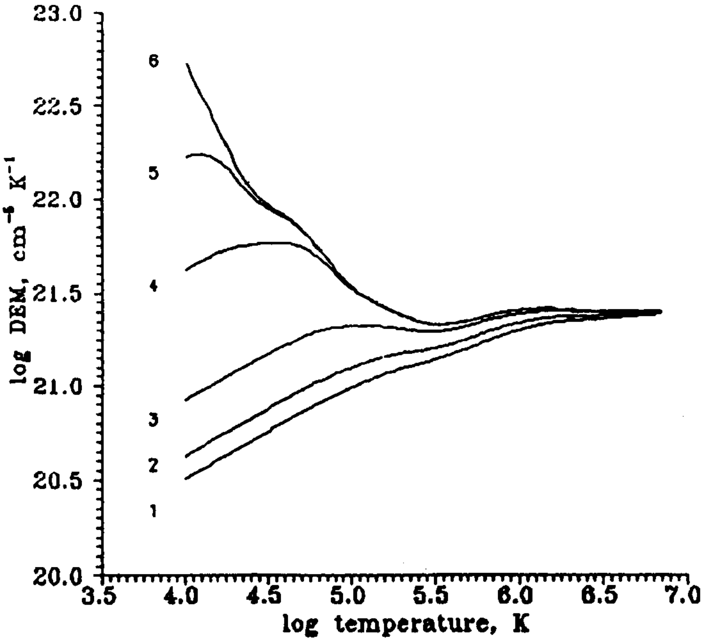

Figure 1 The theoretical distribution of differential emission measure (DEM) versus the temperature for the following $F_{\mathrm{cond},0}/F_{\mathrm{lim}}$ ratios: 1.045 for curve *1*; 1.026 for curve *2*; 1.007 for curve *3*; 1.0003 for curve *4*; 1.00002 for curve *5*; 1.0000015 for curve *6*.

This means that the structure of the transition region is caused by the downward travelling thermal conduction flux. At present, perfect UV-, EUV-, and soft X-ray spectra of Capella give the possibility of analysing this problem for the active F9 giant.

The emission measure distribution versus the temperature given by Brickhouse (1996) includes all the main features of this dependence derived from different recent UV- and X-ray observations. We will consider the temperature range from 2×10^4 to 7×10^6 K excluding the high-temperature maximum EM(T), related to variable radiation by Fe XXI–Fe XXIV ions.

For comparison of our results with the observational EM(T) curve, the theoretical DEM(T) function (Figure 1 for the fluxes close to "limiting" values) is integrated over the interval ΔT associated with the region of the existence of a given ion. The comparison is presented in Figure 2, which shows good agreement between the theoretical and observational results for the low corona and probably the upper part of the transition region, but differences are by a factor of 5–7 in the low-temperature part of the transition region of the active F9 giant. This gives evidence for more active processes in the corona of this star which are highly developed as compared with those in its transition region, whereas the relationship between the emission measure of the high- and low-temperature ranges is opposite in the outer atmospheres of most giants with surface activity.

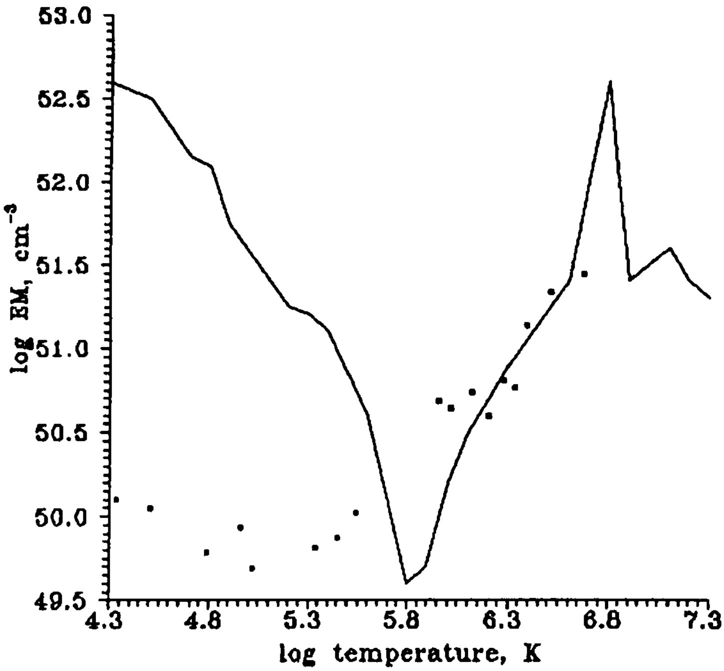

Figure 2 Comparison between the "observational" emission measure (EM) given by Brickhouse (1996), solid line, and EM(T), dots, derived from the theory of propagation of thermal conduction flux from coronal layers downwards.

However, the UV-emission of Capella is too high and cannot be explaned by the downwards travelling thermal conduction flux. This is clear from Figure 3, where the distributions of temperature versus height in the outer atmosphere are given for the solution obtained above (dashed curve for $T = 2 \times 10^4$ K at height $h = 3100$ km) and for the observational EM(T); the pressure in the transition region in both cases is accepted as constant. Physical conditions in the sources of UV- and X-ray radiation turn out to be similar at $T \geq 3 \times 10^5$ K; at lower temperatures there is an excess of emitting gas as compared to that predicted by the theory. Note that the effective thickness of the low-temperature source is around of 3000 km, that is, much more than that predicted by the theory discussed in Section 2.1. It is worth emphasizing that a noticeable part of this low-temperature radiation is due to the quiet rather than the active component of Capella (Linsky *et al.*, 1995).

Thus, the quiet corona of the F9 giant and the upper part of the transition region between its chromosphere and corona are described quite well by this theoretical EM distribution with heating flux close to the "limiting" flux $F_{\mathrm{cond},0} \approx 2 \times 10^6$ erg cm^{-2} s^{-1} and absolute value of density $n_0 = 2 \times 10^8$ cm^{-3}. This value of n_0 is in agreement with that obtained from the EINSTEIN data analysis by Katsova *et al.* (1987) and Badalyan and Livshits (1992).

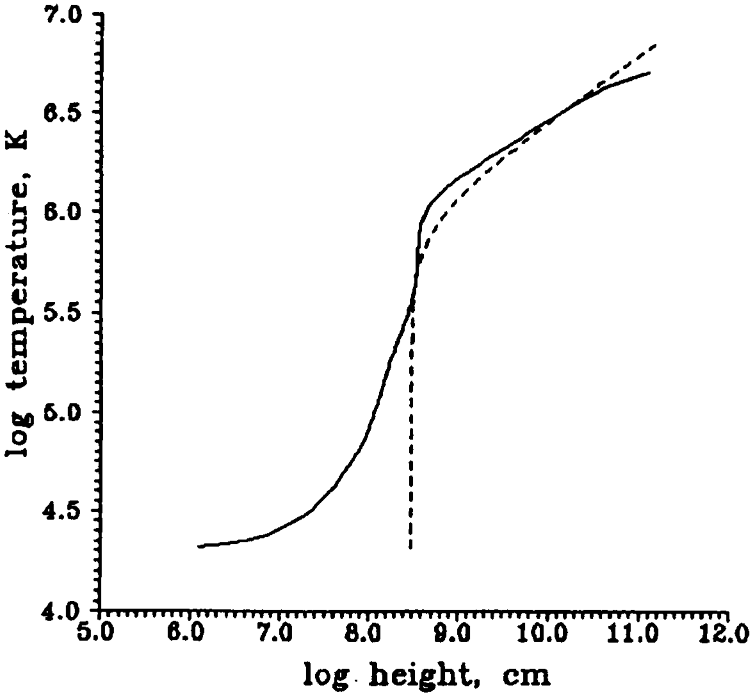

Figure 3 The dependence of the temperature on the height in the outer atmosphere of the secondary component of Capella's binary, F9 giant, (solid line) based on observational values of the emission measure. Theoretical model $T(h)$ derived from theoretical consideration of the propagation of thermal conduction flux from the corona downwards (dashed line).

A discrepancy of two orders of magnitude exists at $2 \times 10^4 < T < 1.6 \times 10^5$ K between the observational EM and the theoretical curve based on the theory of a solar-type thin transition region. To fit both these distributions it is necessary to increase the effective thickness of the emitting region to 3000 km.

The second possibility is to postulate the existense of hot coronal loops with a plasma of temperature 2×10^4–2×10^5 K. Such non-stationary loops are normally observable above sunspots.

3 DISCUSSION

The secondary component, an F9 III star, posseses, apparently, a stationary corona of temperature around 5×10^6 K, and the density at its base is about 2×10^8 cm^{-3}. In this case physical processes, which are typical in the solar corona, are developing in the giant's outer atmosphere, but on a larger scale. This leads us to expect that the interaction between motions in its corona and possible large-scale magnetic fields on this F9 giant lead to the formation of structures similar to solar streamers.

According to Badalyan and Livshits (1992), it should cause an enhanced stellar wind on part of the surface, where a streamer is located.

The structure of the upper part of the transition region is formed due to the propagation of thermal flux from the corona downwards. This is similar to what happens on the quiet Sun.

However, our analysis gives evidence for the existence of additional emission in the temperature range 2×10^4–2×10^5 K. Two things may be responsible for this effect. Firstly, it can be associated with the extent of the transition region due to a stellar wind of moderate temperature, as takes place probably on other active late-type giants and subgiants. It may be that strong developed coronal phenomena on Capella prevent the appearance of radiation relating to "cool" winds in the UV lines of ions existing at temperatures from 10^5 to 10^6 K.

It should be noted however that the contribution of the F9 giant radiation in the temperature range 2×10^4–10^5 K is high (Linsky *et al.*, 1995), and hence this problem requires further investigation, using the technique presented by Wood and Ayres, 1995.

Secondly, in principle, the appearance of additional emission in the lines of ions at temperatures of 2×10^4–2×10^5 K can be associated with the formation of non-stationary loops at this temperature. Such non-stationary loops are observable in the UV above sunspots. But now this assumption seems to be less probable.

Thus, the main part of the EUV emission of Capella arising in a plasma with a temperature of 2×10^6–10^7 K is generated in the corona of the F9 active component of this binary system. But an additional peak of the DEM distribution at $T \sim 6 \times 10^6$ K presented in Figure 2 (Brickhouse, 1996) exists due to radiation of the shock wave in the space between the components of Capella. Hence, we argue that only part of the high-temperature emission arises in the coronae of Capella's giants, but other part originates in the gas flow in the space between the components of Capella's binary (Katsova, 1992, 1995).

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