EUV Radiation from Hot Star Photospheres: Theory Versus Observations

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The only stars other than white dwarfs whose photospheric extreme ultraviolet radiation has been detected are ϵ and β CMa. It is therefore of considerable theoretical interest to compare the *EUVE* observations of these two giant B stars to predicted spectra. However, both LTE and non-LTE very sophisticated line blanketed model atmospheres fail to match the observed flux. This failure leaves the stellar photosphere theory, even for seemingly "simple" objects as normal B giants were believed to be, in a rather dubious position. This paper briefly summarizes possible reasons for the failure of existing models to describe the *EUVE* observations of hot stars. In particular, we discuss the effects of uncertainties in the line blanketing, and the effects of the photosphere–wind interaction.

1. Introduction

The *EUVE* observations of hot stars present new challenges for the stellar atmospheres theory. It is well known from the theory that the EUV spectra of hot stars may be significantly influenced by departures from the local thermodynamic equilibrium (the so-called non-LTE effects). However, the model implications could not be directly tested by fitting real stellar spectra before we were actually able to observe this spectral region.

It was therefore of considerable theoretical interest to compare the predicted spectra to observations of two giant B stars, ϵ and β CMa, which are the only non-white dwarfs stars for which the Lyman continuum flux can be observed. The fact that LTE models failed to reproduce the observed spectra was not so surprising. However, the real surprise was that even very sophisticated non-LTE line blanketed model atmospheres were similarly unsuccessful. This fact is very disturbing, because the B stars were believed to be relatively simple objects to model. Indeed, they do not possess strong winds; there is no convection in the photosphere; and the continuum opacity is largely dominated by hydrogen and helium. It is fair to say that if we cannot trust computed B star model atmospheres, the models for other stellar types should be trusted even less.

Apart from the alarming consequences for the stellar atmosphere theory *per se*, this failure has profound implications for many branches of astrophysics. For instance, without reliable model atmosphere predictions, we are not able to determine the number of ionizing photons, which consequently leads to significant uncertainties in the interstellar matter modeling.

In this paper we will briefly summarize possible reasons for the failure of existing models to reproduce the *EUVE* observations of hot stars, and outline the way how this situation may be improved.

2. Observations Versus LTE Models for ϵ and β CMa

The detection of ϵ CMa as the brightest EUV source was first presented by Vallerga et al. (1993), and EUV spectrum subsequently analyzed in detail by Cassinelli et al. (1995a; see also Cassinelli, this volume). An analysis of β CMa is in progress (Cassinelli et al. 1995b).

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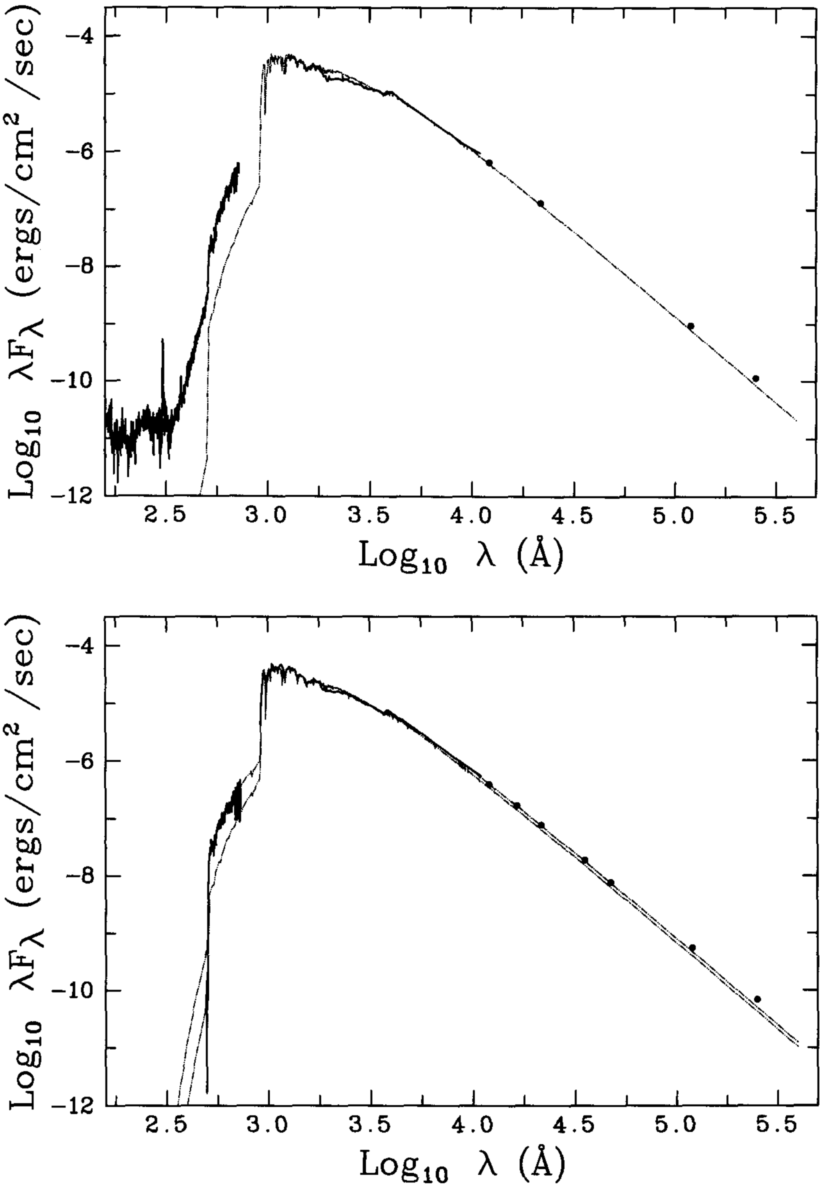

FIGURE 1. Continuous energy distribution from EUV to mid-IR wavelengths, compared with LTE model atmospheres: (*a*) ϵ CMa and model with $T_{\rm eff} = 21,000$ K; $\log g = 3.2$; (*b*) β CMa and models with $T_{\rm eff} = 23,250$ K; $\log g = 3.5$, and $T_{\rm eff} = 24,800$ K; $\log g = 3.7$.

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In Fig. 1, we present the spectra of both stars together with Kurucz LTE model atmospheres, using the effective temperature and surface gravity determined from the total flux and the UV and optical continuum (for details, see Cassinelli et al. 1995a, b). The effective temperature for ϵ CMa, $T_{\rm eff} = 21,000$ K, was determined using the measured total flux and angular diameter (Hanbury Brown et al. 1974).

It is clearly seen that the LTE model atmosphere flux falls significantly short of the observed Lyman continuum flux for ϵ CMa. The observed flux is about 30 times higher than predicted! For the other star, β CMa, the situation is not so clear. When we use the measured angular diameter and the total flux, we obtain $T_{\rm eff} = 24,800$ K. The model flux is then consistent with the UV and even EUV flux, but predicts the V-band flux about 10% higher that observed; such a discrepancy is unacceptably large. If one instead uses the V-band and the total flux but disregards the measured angular diameter, one obtains a lower effective temperature, $T_{\rm eff} = 23,250$ K — for details refer to Cassinelli et al. (1995b). The corresponding model atmosphere yields a good agreement in the optical and the near UV region, but the flux in the Lyman continuum is by factor of 4 lower than the observed one.

Regardless of the magnitude of discrepancy between observations and models for β CMa, the failure of LTE models to describe the observed Lyman continuum for ϵ CMa is undisputable. Therefore, we have to ask: Is LTE a satisfactory approximation? And, if not, are we able to compute sophisticated enough non-LTE models? And, still if so, do non-LTE provide the remedy of the situation? And, if not, what does? The rest of the paper is devoted to discussing these questions.

3. May NLTE Help?

From the general point of view, LTE is an approximation which may, but does not necessarily need to, be applicable. The so-called non-LTE (or NLTE) approach, which allows for departures from LTE, is a fundamentally better approximation to reality and therefore should be preferable. However, the computational effort needed to calculate such models is by orders of magnitude higher than for LTE models. Moreover, since the problem is enormously complicated, one has to sacrifice many features that can be included in LTE but cannot be handled within the framework of NLTE models. A typical example was, till recently, a treatment of the metal line blanketing–see 3.2.

Therefore, from the practical point of view, one has to ask: do we specifically need a NLTE description for predicting an EUV spectrum? And, do we compute NLTE models accurately enough?

3.1. *Why NLTE in EUV?*

There are two basic reasons why one expects that departures from LTE play important rôle in the EUV spectrum region.

First, the EUV spectrum region is the region of very high opacity. Indeed, the opacity in the Lyman continuum, He I resonance continuum, and He II Lyman continuum is the strongest opacity source for all hot stars. Since the opacity is large, the observed spectrum is formed high in the atmosphere where the material density is low. A low density is one of the most important reasons for the breakdown of the LTE approximation, because the collision rates (which tend to maintain the Boltzman-Saha LTE statistical equilibrium) become much smaller than the radiative rates. Since the radiation intensity may strongly deviate from its equilibrium, Planckian distribution, the low density implies that a non-equilibrium radiation will cause a non-equilibrium atomic level population distribution.

The second reason is the extreme sensitivity of the Planck function to small changes

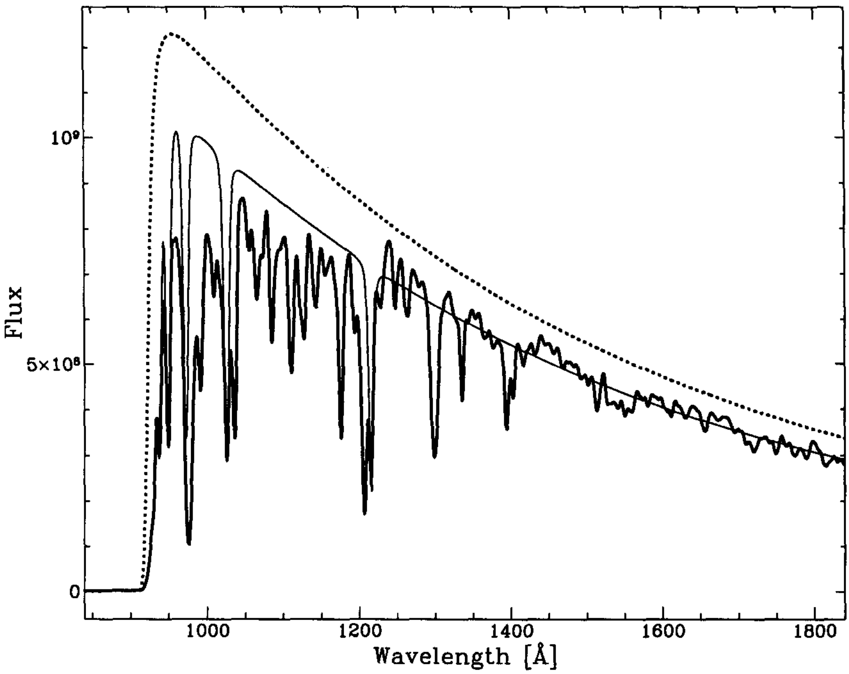

FIGURE 2. Theoretical flux from the unblanketed (thin line) and blanketed (thick lines) NLTE model atmosphere with $T_{\rm eff} = 21,000$ K; $\log g = 3.2$. To demonstrate the importance of line blanketing, the theoretical continuum for the blanketed model is also displayed (dotted line).

in temperature on the short-wavelength side of its maximum. The source function, and therefore the radiation field, are proportional to the Planck function. Consequently, small differences in temperature in the atmosphere, together with departures from LTE, which may produce relatively modest effects in the optical or near-UV spectrum, translate to large differences in the predicted EUV flux.

3.2. *Why Line Blanketing?*

By the term "line blanketing" we understand the effect of thousands to millions of metal lines on the atmospheric structure and predicted emergent spectrum. In the case of early B stars, most lines are located in the traditional UV region ($\lambda 900-2500$ Å). The fact that the line blocking is largest in the UV does not mean that line blanketing is unimportant in the EUV region. As it is well known, line blanketing influences not only the emergent spectrum (the so-called line blocking), but also the atmospheric structure (the back-warming and the surface cooling). The effect of metal lines is illustrated on Fig. 2, where we plot the predicted flux for an atmosphere with $T_{\rm eff} = 21,000$ K; $\log\ g\ =\ 3.2$; both for a simple NLTE hydrogen-helium model, as well as for a H-He-Fe line blanketed model. Therefore, a proper treatment of the UV line blanketing is crucial for understanding the EUV spectrum.

Since departures from LTE and line blanketing are both important, we have to compute fully blanketed NLTE models to resolve the dilemma. Until about a decade ago,

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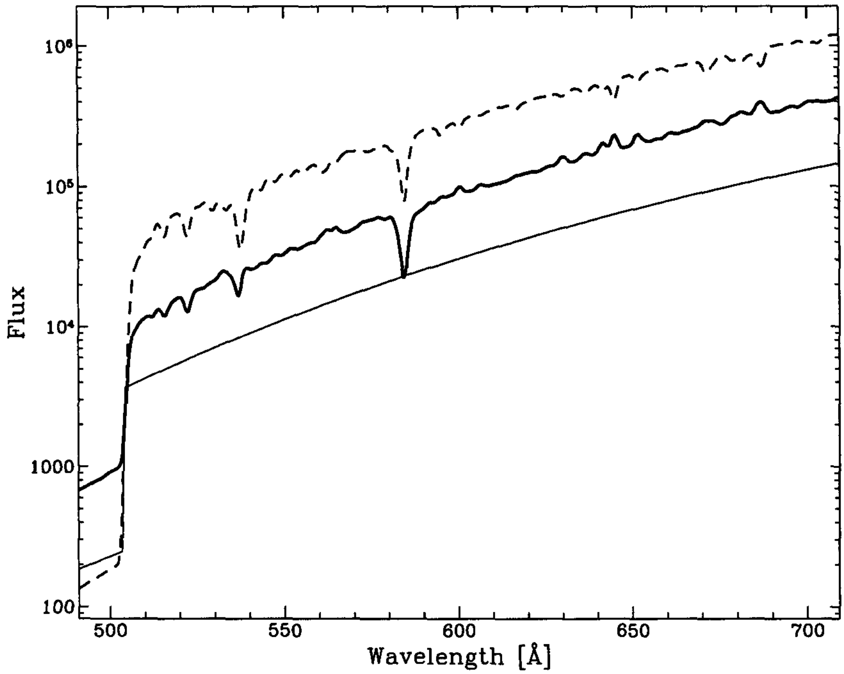

FIGURE 3. Theoretical flux in the Lyman continuum: NLTE unblanketed (thin line) and blanketed (thick line) models, and LTE blanketed model (dashed line), for $T_{\rm eff}$ = 21,000 K; $\log g = 3.2$.

such an endeavor was viewed as hopeless. However, with the advent of fast and ingenious numerical methods for solving the radiative transfer equation, even this barrier is being tackled. Anderson (1985, 1989) was the first who calculated NLTE line-blanketed model atmospheres. Werner and colleagues (Werner 1986; Dreizler & Werner 1993) have developed a very sophisticated code based on the accelerated lambda iteration (ALI) method and computed a number of models for very hot stars. Recently, we have developed an hybrid Complete Linearization/ALI method (Hubeny & Lanz 1995), and incorporated it to our computer code TLUSTY (Hubeny 1988; Hubeny & Lanz 1992).

The first *EUVE* observations of ϵ CMa serendipitously came just when we finished debugging the line-blanketed version of TLUSTY, and applied it by computing several NLTE line blanketed models for hot, metal-rich white dwarfs (Lanz & Hubeny 1995). We have therefore immediately calculated a sophisticated model for ϵ CMA, which took into account all lines of hydrogen and He I, and about 23,000 lines of Fe III and 8000 lines of Fe IV, all in NLTE (some results are presented in Hubeny & Lanz 1995 and Cassinelli et al. 1995). To our surprise and dismay, the NLTE models produced an even lower flux in the Lyman continuum than the LTE models! In Fig. 3, we plot the Lyman continuum flux for the Kurucz LTE model, along with two NLTE models, a simple H-He model, and a line-blanketed H-He-Fe model, for $T_{\rm eff} = 21,000$ K; $\log g = 3.2$ (similarly as in Fig. 2).

In the next Section, we explain the behavior of the emergent flux in the Lyman continuum in more detail. This analysis also allows us to draw conclusions about what has to be done to improve the model atmospheres.

4. Lyman Continuum Flux

According to the Eddington-Barbier relation (see, e.g., Mihalas 1978), the emergent flux in the Lyman continuum is roughly given by

$$F_\nu \approx S_\nu(\tau_\nu = \frac{2}{3}),$$

where S_ν is the source function, and τ_ν the monochromatic optical depth at frequency ν.

Provided that the photoionization from the ground state of hydrogen is the dominant opacity source in the Lyman continuum ($504 < \lambda < 911$ Å), the source function is given by

$$S_\nu \approx B_\nu(T)/b_1,$$

where $B_\nu(T)$ is the Planck function at temperature T, and b_1 is the NLTE departure coefficient for the hydrogen ground state, $b_1 = n_1/n_1^*$, n_1^* being the LTE population.

The predicted flux in the Lyman continuum may be increased either (i) by increasing $B_\nu(T(\tau_\nu = 2/3))$, or, (ii) by decreasing b_1. The former can be achieved either by keeping the temperature structure unchanged, but moving the point where $\tau_\nu = 2/3$ to the physical layers in the atmosphere where the temperature is higher; or by a genuine increase of T in the continuum-forming layers.

Cassinelli et al. (1995a) suggested that the first possibility, a genuine temperature increase in the Lyman continuum forming region, is more likely. This suggestion was based on the observational fact that the far-IR flux at 12μm is of about 17% higher than predicted. This spectrum region is formed at about the same depth in the atmosphere as the Lyman continuum. However, the IR continuum, which is dominated by H I free-free process, cannot deviate very much from LTE. Rising artificially the temperature in the appropriate layers in the atmosphere by about 16% (i.e. by about 2000 K) would fit not only the IR continuum, but also the Lyman continuum without invoking any NLTE effects. But the question of course remains to know what causes such a temperature increase.

The second possibility cannot be realized in the static atmosphere, because the Lyman continuum behaves similarly as a resonance line in a two-level atom, for which the lower level always ends overpopulated with respect to LTE ($b_1 > 1$–see Mihalas 1978). On the other hand, a stellar wind can in principle decrease b_1 below unity by desaturating the Lyman-α line. Such a mechanism was recently suggested by Najarro et al. (1995).

5. Reasons for the Failure of Current Models

5.1. *Uncertainties in the Photospheric Models*

First, the photospheric models may still be not accurate enough. The most significant uncertainty in this respect is the treatment of line blanketing, in the sense that the total blanketing effect was underestimated due to the following reasons:

- We have taken into account only Fe III and Fe IV. Although these ions likely provide most of the line opacity, we have to explore the effects of considering lines of other species, at least in LTE.
- We have considered only about 30,000 iron lines originating between the *observed* energy levels. Although these lines are presumably the strongest ones, they form only a small fraction of the total number of Fe III and Fe IV lines predicted by Kurucz (1991).

This is potentially the most important source of missing opacity in our models. Our experience from white dwarf models (Barstow et al., this volume) shows that the agreement between observations and theory improves considerably when including *all* iron lines.

- We used hydrogenic photoionization cross sections for Fe III. Again, our experience from white dwarf models (Lanz & Hubeny 1995) shows that using the Opacity Project cross-sections for Fe IV, Fe V, and Fe VI (kindly provided to us by Anil Pradhan and Sultana Nahar) has a significant effect on the predicted spectrum.
- We use very rough estimates of collisional rates for excitation and ionization of iron.
- When constructing the Opacity Distribution Functions (ODF) for individual iron superlevels (see Hubeny & Lanz 1995), we have assumed a microturbulent velocity equal to 0 or 2 km s^{-1}. However, the microturbulent velocity may be larger, which would increase the line opacity. This point needs also to be explored in future models.

5.2. *Photosphere-Wind Interaction*

Alternatively, the theory of photospheres itself is more or less correct (in other words, the above listed possibilities will turn out to yield no significant effects), and the solution of the Lyman continuum problem lies in neglecting a photosphere–wind interaction. Indeed, we know that both ϵ and β CMa possess a weak wind ($\dot{M} \approx 1 \times 10^{-8} M_{\odot} \mathrm{yr}^{-1}$– Cassinelli et al. 1995a, b). Thus, the wind may in principle influence the photospheric radiation, via the two following mechanisms:

- Depopulation of the ground state of hydrogen via desaturation of the Lyman-α line due to the velocity field at the base of the wind. This point was discussed in detail by Najarro et al. (1995), who conclude that this effect may partially explain the observed Lyman continuum discrepancy. However, their predictions show that the flux enhancement in the Lyman continuum for the observed value of the mass loss rate is about a factor of 0.5 dex, while the total discrepancy is roughly 1.5 dex.
- Irradiation of the photosphere by X-rays which originate in the wind. X-rays from ϵ CMa were detected by *Rosat* (Drew et al. 1994); Cassinelli et al. (1995a) showed that the *EUVE* observations of the He II Lyman-α line for ϵ CMa may be accounted for by recombination of He^{++} which is produced by these X-rays. However, it is questionable whether the X-rays will also increase the Lyman-continuum radiation. Work on this problem is in progress, but the preliminary results indicate that this is not very likely because the X-rays do not seem to provide enough energy.

5.3. *UV Flux Discrepancy*

It may well happen that the solution of the ϵ CMa puzzle will be provided by a combined effect of all the above mechanisms. However, an important piece of evidence that something on the purely photospheric level is not working well is provided by the flux around λ2200 Å. There is a clear discrepancy here (see Fig. 1), the observed flux being significantly lower than predicted. An analogous flux discrepancy for other stars is routinely attributed to the well-known λ2200 Å interstellar feature. But the *EUVE* observations clearly and undisputably demonstrate that the interstellar column density towards ϵ CMa is very low, $N_H \approx 1 \times 10^{18}$ (Cassinelli et al. 1995a), and therefore the λ2200 feature cannot be of interstellar origin! Moreover, this part of the spectrum is formed very deep in the photosphere (even deeper than the optical flux), so one cannot invoke a photosphere–wind interaction. The most likely reason is, again, a missing photospheric opacity.

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6. Conclusions

We have shown that neither LTE, nor the current most sophisticated non-LTE line blanketed model atmospheres are able to predict the observed flux in the Lyman continuum for ϵ CMa and likely also for β CMa. This finding serves as a sobering reminder that the stellar atmosphere theory has still a long way to go. Importantly, this failure tempers all far-reaching conclusions about the structure of interstellar matter which are based on *theoretical* estimates of the number of ionizing photons (i.e. the Lyman continuum flux) provided by stars.

We have discussed various possible reasons for the discrepancy, and identified several mechanisms which are likely responsible for the model deficiency. We claim that the failure of the present models is not a fundamental failure; it is just an indication that something in the models is still not being done properly.

The story of ϵ CMa nicely illustrates that history repeats itself. Again and again in modern astrophysics, once a new spectral window opens, new observations disagree with predictions based on old models, and consequently an improved theory has to be developed. We were prepared to accept that in the case of hot white dwarfs and coronae of cool stars, but we were caught in surprise in the case of relatively normal B stars. The case of ϵ and β CMa is even more interesting and important, because these are the only two mildly hot and presumably well understood stars which will ever be observed in the Lyman continuum. Their *EUVE* observations are therefore an invaluable piece of information for the development of the stellar atmosphere theory as a whole.

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