Ionization in the Winds of Early-B Stars: Constraints Imposed by *EUVE*

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Extreme Ultraviolet Explorer (*EUVE*) spectral observations of ε CMa (B2 II) provide significant new information about the ionization dynamics of its wind, its mass loss rate, and the interaction of its wind with the soft X-ray/EUV radiation field. We present results from wind ionization calculations which show how EUV radiation, emitted predominantly in the form of Fe IX-XVI lines from plasma with $T \sim 1 - 3 \times 10^6$ K, significantly alters the ionization state of its wind. EUV photons from the hot plasma photoionize He II in the cool portion of ε CMa's wind, producing anomalously high abundances of He III. The subsequent recombination from He III results in He II Lα (304 Å) and Lβ (256 Å) lines which are observed by EUVE. Also observed is O III $\lambda\lambda$ 374, which results from the O III $\lambda\lambda$ 304 multiplet being pumped by He II Lα — the Bowen mechanism (Cassinelli et al. 1995). We report on initial results from numerical simulations which show the effect of the Bowen mechanism on the O III 374 Å line emission.

1. Introduction

Ultraviolet observations of hot stars (Snow & Morton 1976; Lamers & Morton 1976) have shown that they suffer significant mass loss through high velocity winds. For early-O stars, radio (Bieging, Abbott, & Churchwell 1989) and Hα (Lamers & Leitherer 1993) observations provide evidence for mass loss rates $\sim 10^{-6} - 10^{-5}$ $M_\odot$/yr, while wind velocities can be 3,000 km/s or more. Observational determination of mass loss rates for late-O and early-B stars becomes more difficult, however, because their winds are much weaker; i.e., they tend to exhibit lower densities and lower velocities. Fortunately, *EUVE* observations of the B2 II star ε CMa (Cassinelli et al. 1995) have provided valuable new data for studying the winds of early-B stars. Emission lines between 150 Å and 400 Å have been observed from both the hot X-ray emitting region (Fe IX–XVI) and the cool wind (He II and O III). Below, we present results from wind ionization calculations which show the influence of the soft X-ray/EUV radiation on the ionization state of the wind, and the effect of the Bowen mechanism on the O III 374 Å line intensity.

ROSAT observations of ε CMa (Drew, Denby, & Hoare 1993) showed that ε CMa, like most other hot stars, has a significant X-ray luminosity ($L_X \sim 1 \times 10^{-7} L_{bol}$). Two-temperatures fits to the *ROSAT* data suggest a relatively strong low-temperature component ($T \sim 1 - 2 \times 10^6$ K), and a weaker high-temperature component ($T \sim 8 \times 10^6$ K). Plasmas at these temperatures also exhibit strong Fe line emission between 150 Å and 400 Å, which was observed by *EUVE* for ε CMa. Recent studies (MacFarlane, Cohen, & Wang 1994) have predicted that the soft X-ray/EUV radiation of early-B stars can significantly alter the bulk ionization state of their winds. This is unlike the case of early-O star winds, where X-rays tend to produce only a small (but detectable) perturbation on their ionization distribution (Cassinelli & Olson 1979).

Because *EUVE* has detected both the hot plasma Fe line emission and cool wind He II

S. Bowyer and R. F. Malina (eds.), Astrophysics in the Extreme Ultraviolet, 375–379.

and O III line emission, it presents a rare opportunity to study the interplay of the hot plasma radiation field and the cool wind.

In this paper, we present several results from numerical simulations describing these effects. More detailed descriptions of this work will be presented elsewhere (Cohen et al. 1995, MacFarlane et al. 1995).

2. Models

Detailed descriptions of our wind ionization code have been presented elsewhere (MacFarlane et al. 1993, 1994); only a brief summary is presented here. The wind is assumed to be spherically symmetric with a velocity which increases monotonically with radius. The density is specified by its mass loss rate and assuming, the mass flux is constant with radius. The radiation field includes contributions from: (1) the photosphere, based on Mihalas' (1972) non-LTE models longward of 912 Å and a fit to the *EUVE* data for 350 Å $< \lambda <$ 730 Å; (2) diffuse radiation in the wind; and (3) EUV/X-ray radiation from a high-temperature plasma, which had a frequency-dependence given by XSPEC models (Raymond & Smith 1977) and a power-law temperature distribution determined from the combined analysis of *ROSAT* and *EUVE* data (Cohen et al. 1995). Emission from the hot plasma was assumed to be distributed throughout the wind (shock model), with a peak in the differential emission measure at $r = 1.5\,R_*$ ($\alpha = -3$ in Eqn. (10) of MacFarlane et al. 1993). Radiative transfer effects for all radiation sources were computed using a multi-ray impact parameter model.

Non-LTE atomic level populations were computed by solving multilevel statistical equilibrium equations self-consistently with the radiation field. A total of 81 levels for H, He, and O were considered in our atomic model. It was necessary to consider fine-structure splitting of the O III levels so that the Bowen photoexcitation mechanism (Bowen 1935) could be accounted for. This mechanism arises due to overlap of the He II Lα line at 303.78 Å and the O III $1s^2 2s^2 2p^2\ {}^3P$ - $1s^2 2s^2 2p3d\ {}^3P^0$ multiplet (see Figure 1). When He III recombines to the $n = 2$ state of He II, the Lα photons emitted can be absorbed, producing an anomalously high population of the O III 3d ${}^3P^0$ level. This level subsequently decays to the 3s ${}^3P^0$ level, resulting in the spontaneous emission of the $\lambda\lambda$ 374 multiplet, which is observed as a single emission feature by *EUVE* (Cassinelli et al. 1995). The interaction of overlapping lines is modeled using a generalized Sobolev method with multiple velocity surfaces (Rybicki & Hummer 1978; Puls, Owocki, & Fullerton 1993; see also MacFarlane et al. 1995).

3. Results

We first examine the effect of soft X-ray/EUV radiation on the He ionization balance in the wind of ε CMa. Figure 2 shows computed ionization distributions for He I–III from two calculations: one using a distributed X-ray emission source (solid curves) and the other with no X-ray source (dotted curves). In each case the mass loss rate was $0.8 \times 10^{-8}\ M_\odot$/yr. Clearly, the population of doubly ionized He (circles) is dominated by photoionization due to the hot plasma radiation, which dominates the radiation field at $h\nu > 54$ eV. At relatively low velocities ($v \lesssim 0.4\,v_\infty$ and $r < 1.5\,R_*$) the He III population is lower because of the higher wind densities and the fact that the X-ray differential emission measure peaks at $r = 1.5\,R_*$ in this model. Note that in the absence of X-ray-induced photoionization, the He III fraction is $\lesssim 10^{-4}$ throughout the wind. The distribution of He III in the wind is important because its recombination is the source of photons which are ultimately observed by *EUVE* at 304 Å and 374 Å.

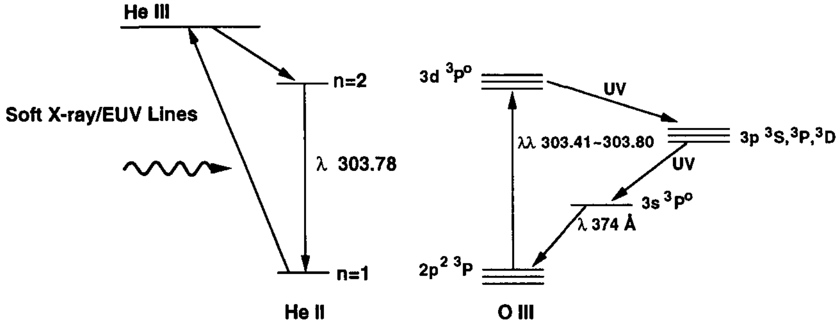

FIGURE 1. Schematic energy level diagram illustrating radiative processes in the wind of ϵ CMa.

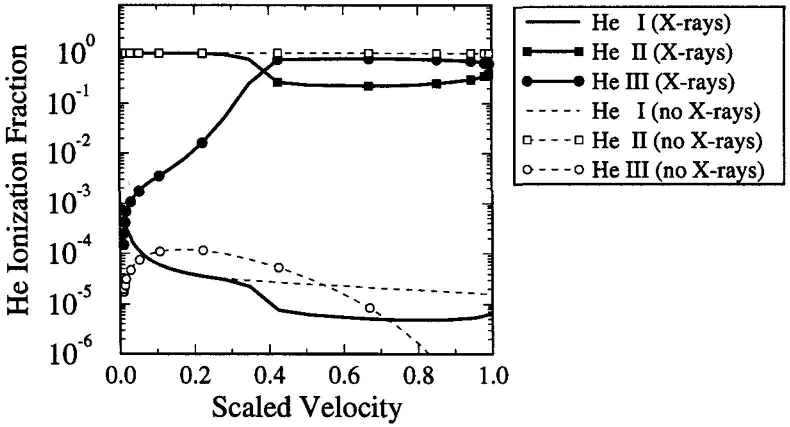

FIGURE 2. Helium ionization distributions calculated with a distributed hot plasma radiation source (solid curves) and with no X-ray radiation source (dashed curves).

The effect of the Bowen mechanism (photopumping of the O III λ 304 multiplet by He II Lα) on the O III $\lambda\lambda$ 374 flux can be seen in Figure 3, where the 374 Å profile is shown from two calculations. The solid curve shows the profile from a calculation in which line overlap effects on the atomic populations were included, while the dashed curve is from a calculation in which photoexcitation due to overlapping lines was neglected. (Note, however, that the emergent spectra, which are computed after the level

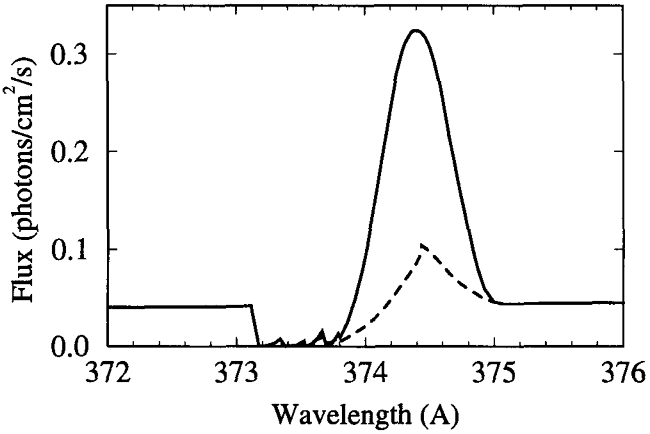

FIGURE 3. Calculated O III λλ 374 line profiles for ε CMa wind ionization models with $\dot{M} = 0.8 \times 10^{-8}$ M$_\odot$/yr. Dashed curve: atomic populations computed without line overlap effects; solid curve: with line overlap effects.

populations are determined, *do* include overlap effects. This gives rise to the structure seen in the absorption component of the profile.) By including the Bowen effect in the calculation, the emission from the 374 Å multiplet is seen to increase substantially. Without the Bowen effect, the λλ 374 profile has the characteristic P-Cygni shape, with blue-shifted absorption and red-shifted emission; that is, scattered photospheric radiation with no additional source of photons. Preliminary results suggest that the best agreement with the *EUVE* data for the 304 Å and 374 Å lines is obtained for mass loss rates of $\sim 1 - 2 \times 10^{-8}$ M$_\odot$/yr. Final results and a complete description of this analysis will be presented in a forthcoming paper.

This work was supported in part by NASA grants NAGW-2210 and NAGW 5-2282.

REFERENCES

BIEGING, J. H., ABBOTT, D. C. & CHURCHWELL, E. 1989, ApJ, 340, 518

BOWEN, I. S. 1935, ApJ, 81, 1

CASSINELLI, J. P. & OLSON, R. E. 1979, ApJ, 229, 304

CASSINELLI, J. P., COHEN, D. H., MACFARLANE, J. J., DREW, J. E., LYNAS-GRAY, A. E., HOARE, M. G., VALLERGA, J. V., WELSH, B. Y., VEDDER, P. W., HUBENY, I., & LANZ, T. 1995, ApJ, 438,932

COHEN, D. H. ET AL. 1995, ApJ, to be submitted

DREW, J. E., DENBY, M. & HOARE, M. G. 1994, MNRAS, 266, 917

LAMERS, H. J. G. L. M. & MORTON, D. C. 1976, ApJS, 32, 715

LAMERS, H. J. G. L. M. & LEITHERER, C. 1993, ApJ, 412, 771

MACFARLANE, J. J., COHEN, D. H., & WANG, P. 1994, ApJ, 437, 351

MACFARLANE, J. J., WALDRON, W. L., CORCORAN, M. F., WOLFF, M. J., WANG, P., & CASSINELLI, J. P. 1993, ApJ, 419, 813

MACFARLANE, J. J., COHEN, D. H., CASSINELLI, J. P. & WANG, P. 1995, ApJ, to be submitted

MIHALAS, D. 1972, NCAR Tech. Note, STR-76

PULS, J., OWOCKI, S. P., & FULLERTON, A. W. 1993, A&A, 279, 457
RAYMOND, J. C. & SMITH, B. W. 1977, ApJS, 35, 419
RYBICKI, G. B. & HUMMER, D. G. 1978, ApJ, 219, 654
SNOW, T. P. & MORTON, D. C. 1976, ApJS, 32, 429