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EFFECTS OF SHOCK-PRODUCED X-RAYS ON THE IONIZATION BALANCE IN THE WIND OF ε Ori

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ABSTRACT We report on our initial series of calculations to study the effects of shock-produced X-rays on the ionization state of hot star winds. For the wind of ε Ori (B0 Ia), we investigate the dependence of the ionization distribution on X-ray source characteristics.

INTRODUCTION

Hot stars have high mass loss rates and are known to be X-ray emitters. The X-ray emitting plasmas typically have characteristic temperatures of $10^6 - 10^7$ K and luminosities of $L_{\mathrm{x}} \sim 10^{-7} L_{bol}$. The source of the X-rays is not currently known. The most likely candidates are strong shocks propagating through their winds (Lucy 1982, Owocki et al. 1988) or coronae at the base of their winds (Cassinelli and Olson 1979, Waldron 1984).

Surprisingly little is known about the physical characteristics of hot star winds, such as the temperature structure and ionization distribution. Previous notable studies of wind ionization include Klein and Castor (1981), Pauldrach (1987), and Drew (1989). Drew pointed out the importance of heavy element line cooling in influencing the temperature structure of hot star winds. This effect leads to significantly lower temperatures compared to those found in previous studies. However, comparison of calculated ionization distributions and those deduced from observations of UV P-Cygni profiles (Groenewegen and Lamers 1991) finds significant discrepancies between theory and observation.

In this paper, we describe our initial series of calculations aimed at achieving a better understanding of the physical state of hot star winds. Our calculations are in many ways similar to those reported by Drew (1989), but with one important exception: we include the effects of Auger ionization resulting from the X-rays. The location of the X-ray source in our models is variable; it can be positioned at the base of the wind to simulate a corona, or can be embedded in the cooler wind to simulate a shock. Below we describe results for the particular case of ε Ori (B0 Ia). We shall focus in particular on the sensitivity of the wind ionization distribution to the X-ray source location.

MODELS

Multilevel statistical equilibrium calculations were performed to predict the distribution of atomic level populations throughout the wind. The following effects are included in our model: photoionization from photospheric radiation ($h\nu < 54$ eV), diffuse radiation from the He II Lyman continuum (54 eV

$< h\nu \lesssim 100$ eV), and X-ray radiation ($h\nu \gtrsim 100$ eV); photoexcitation and spontaneous decay; radiative and dielectronic recombination; and collisional excitation, deexcitation, ionization, and recombination. Calculations were performed for multicomponent plasmas (H, He, C, N, O, and Si) consisting of a total of 25 ions and 87 atomic levels. The levels and ions were selected so that a direct comparison with the results of Drew could be made.

The radiation field is modelled as follows. Below the He II photoionization edge (54 eV), the photospheric radiation flux is taken from non-LTE model atmosphere tables of Mihalas (1972), and corrected by the geometric dilution factor. Between the He II Lyman edge and about 100 eV, it is assumed the wind is optically thick. At these frequencies we assume the radiation field is given by the local continuum source function. Above 100 eV, the radiation field is constrained from X-ray satellite observations (see, e.g., Cassinelli et al. 1981). The frequency-dependent X-ray flux is computed using the XSPCT code (Raymond and Smith 1977). In the calculations described below, we assume an X-ray temperature of $T_{\rm x} = 10^{6.5}$ K and emission measure of 10^{55} cm^{-3}. The attenuation of X-rays by inner-shell absorption is included in our calculations.

Photoexcitation rates are computed using the Sobolev approximation (see Castor 1970). Photoionization out of excited states is included. Bound-free cross sections for all levels and subshells were obtained from Hartree-Fock calculations (Wang 1991). Low-temperature dielectronic rate coefficients are based on the work of Nussbaumer and Storey (1983).

RESULTS

Results for calculations for the wind of ε Ori are shown in Fig. 1. Relevant parameters used in the calculations are shown in Table I. Results for ionization distributions for N and O are shown for 3 cases: (i) no X-ray source, (ii) an X-ray source at the base of the wind (coronal model), and (iii) an X-ray source at $r = 3R_*$ (shock model). In each case we use a wind temperature distribution based on the results of Drew.

Figure 1 shows the ionization fractions of N III, N IV, N V, O III, O IV, and O VI as a function of radius for each of the three calculations. In each case N IV and O III are the dominant stage of ionization. It is also seen that the N III, N IV, and O III distributions are almost identical in each case; i.e., their abundance is unaffected by the X-rays. Also note that the N V and O VI fractions in the absence of an X-ray field are predicted to be less than 10^{-6}. For the coronal X-ray case the N V and O VI fractions decrease with radius — gradually in the case of N V and more dramatically for O VI. For the shock X-ray case the N V and O VI fractions peak at the shock location ($r = 3R_*$).

TABLE I ε Ori Parameters

$R_{\rm x} = 34$ R$_\odot$	$v_\infty = 2,010$ km/s
$T_{eff} = 27,500$ K	$T_{\rm x} = 10^{6.5}$ K
$g = 1,000$ cm^2/s	$EM_{\rm x} = 1 \times 10^{55}$ cm^{-3}
$\dot{M} = 1 \times 10^{-6}$ M$_\odot$/yr	

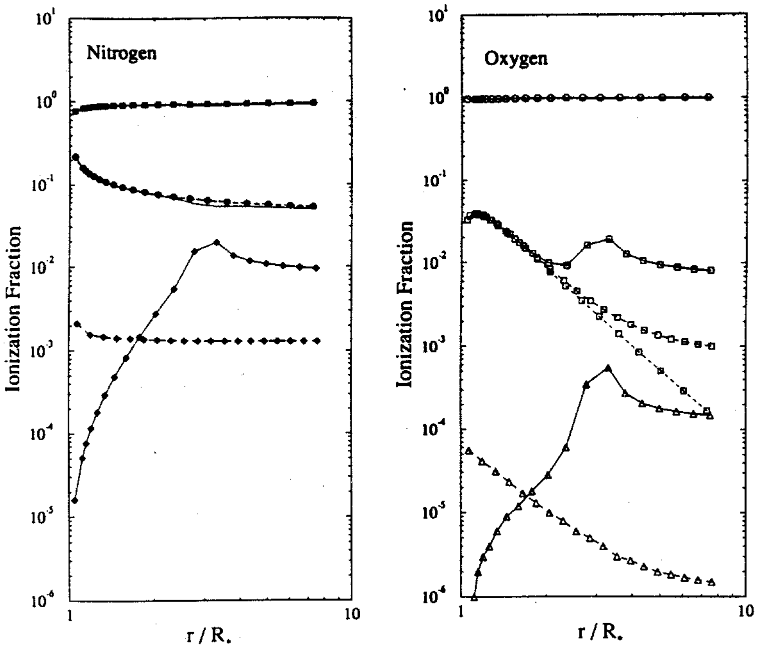

Fig. 1. Ionization distributions for N III (•), N IV (□), N V (◇), O III (○), O IV (□), and O VI (△). Results are given for 3 cases: shock X-ray model (solid curve), coronal X-ray model (dashed curve), and no X-rays (dotted curve). Note the radically different dependence of the N V and O VI fractions on the X-ray source location.

The rapid decrease in abundance in the direction of the star results from inner-shell attenuation by the intervening wind.

A detailed analysis of the influence of X-rays on the ionization state of hot stars winds will be presented in a forthcoming paper.

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