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SPECTRAL VARIATIONS IN WNE WOLF–RAYET BINARIES: THE Fe V + Fe VI PSEUDO-CONTINUUM

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RESUMEN

Se hace el intento de sintetizar el espectro proveniente de líneas de Fe V y Fe VI, utilizando los datos de Ekberg. Se muestra que las líneas de estos iones, al ser ensanchadas a las velocidades que son típicas de los vientos de estrellas WR, producen un seudocontínuo en los rangos λλ1350 – 1470 (Fe V) y λλ1240 – 1350 (Fe VI). Una combinación lineal de las líneas de Fe V y Fe VI produce un seudocontínuo en el rango espectral λλ1250 – 1470 A. Este coincide con la región del espectro ultravioleta que se ve fuertemente afectada por eclipses atmosféricos en las estrellas Wolf-Rayet de tipo WNE (i.e., WN4 – WN6) que se encuentran en sistemas binarios observados con el *IUE*. El espectro sintético reproduce las variaciones que se han observado en los espectros de baja dispersión de cinco sistemas binarios WN+O en la Galaxia.

ABSTRACT

An attempt is made to synthesize the Fe V and Fe VI line spectra, using the data of Ekberg for these ions. It is shown that the lines of these ions, when broadened to typical velocities in WR winds, produce pseudo-continua in the wavelength regions λλ1350 – 1470 A and λλ1240 – 1350 A, respectively. A linear combination of Fe V and Fe VI lines results in a pseudo-continuum in the λλ1250 – 1470 A region. This coincides with the wavelength region affected by atmospheric eclipses in Wolf-Rayet WNE (i.e., WN4 – WN6) binary systems observed with the *IUE*. The synthesized spectrum reproduces the variations observed in low dispersion *IUE* spectra of five galactic WN+O binary systems remarkably well.

Key words: STARS-WOLF-RAYET – STARS-VARIABLES

I. INTRODUCTION

The Wolf-Rayet stars are one of the most interesting class of stellar objects, not only because of their intrinsic characteristics, but also because they are apparently a link between the Post-Main Sequence stages in the evolution of massive stars and the final stages (i.e., supernova). In addition, their great luminosity permits their detection in neighboring galaxies with relative ease. Since they are associated with a young stellar population, they serve as tracers of regions of star formation. For a more detailed description of the WR stars, the reader is referred to the recent review by Abbott and Conti (1987), and the references therein.

The most important intrinsic characteristic of WR stars is their extraordinary stellar winds. The mass- loss rates estimated for these objects range from $0.8–8. \times 10^{-5}$ $M_{\odot}$ per year (Abbott *et al.* 1986), and, up to now, these winds cannot be explained through conventional mass-loss mechanisms. One of the basic problems is thus the determination of the mechanisms driving the stellar winds of WR stars. Associated with this problem is the question of the stability of the outflow; i.e., to what degree is the mass-loss rate constant with time, and to what degree can the winds be considered to be homogeneous and isotropic.

The general properties of the stellar winds in WR stars can be inferred from the prominent emission lines which are present in their spectra (see for example, Castor 1970). For many years it has been known that the shapes or profiles of these lines are subject to variability. At optical wavelengths, changes in the emission line profiles, primarily of He II 4686, have frequently been reported. The classical example where this occurs is the system V444 Cyg (Münch 1950; Sahade 1958).

Since the profiles of the emission lines represent the properties of the emitting material, the variability implies variations in the state of the wind. However, most of the reported emission-line profile changes have resulted from observations of binary systems. (This is natural since these are the objects which are observed systematically in order to derive orbital parameters!). Thus, it has not always been clear to what extent the presence of a binary companion induces the profile variations, as opposed to intrinsic variability which could be attributed to instabilities of the stellar wind.

Variations which occur periodically, on the orbital timescales, can generally be attributed to the presence of a companion. If information is to be gained from these variations, the mechanisms involved must be understood.

The one mechanism which has been clearly identified with a particular type of profile variability is that of selective atmospheric eclipse. This phenomenon will manifest itself only in binary systems in which the companion has a luminous continuum, and in which the orbital inclination is sufficiently large to permit part of the WR wind to be projected upon the companion's luminous disk. The dominant observational effect is that of an increase in the strength of P Cyg absorption components at orbital phases when the O-star is on the far side of the WR-star's wind. The importance of this phenomenon was first noted by Kopal and Shapley (1946) and Münch (1950) in the context of observations at optical wavelengths. In the far *UV* spectral range ($\lambda\lambda$1200 – 2000 A) the effect is much more striking (Willis *et al.* 1979; Howarth, Willis and Stickland 1982; Hutchings and Massey 1981; Koenigsberger 1983; Koenigsberger and Auer 1985; Eaton, Cherepashchuk and Khaliullin 1985*a*, 1985*b*).

In the WN systems, the dominant profile changes occur in the lines of N IV 1718, He II 1640 and C IV 1550 as well as at $\lambda < 1470$ A, as illustrated in Figure 1, with spectra of V444 Cyg. Here we present spectra obtained at orbital phases near 0.5 (WR "in back") and 0.0 (WR "in front"). These are the low dispersion *IUE* spectra previously discussed by Koenigsberger and Auer (1985), and the reader is referred to this paper for further details. The ratio of these two spectra is shown in Figure 1c, where the variations in the "continuum" shortward of λ1470 A are more evident.

Following a detailed search through line lists for elements ranging from H to Zn, it was proposed (Auer and Koenigsberger 1981; Koenigsberger 1983; Koenigsberger and Auer 1985) that the observed variations in the region $\lambda < 1470$ A were due to a large concentration of Fe V and Fe VI lines. This conclusion was reached because: 1) these ions have transitions between low-lying energy levels which lead to approximately 250 Fe V and 70 Fe VI lines within the wavelength interval of interest; 2) the concentration of Fe V lines decreases sharply at $\lambda \cong 1470$ A; 3) the ionization potentials of Fe V and Fe VI are nearly identical to those of N IV and N V, respectively, which are the dominant ionization stages in WNE stars; and 4) no other ionic species has these properties. Eaton *et al.* (1985) also proposed that Fe V was responsible for absorption in the $\lambda\lambda$1350 – 1470 A region, following the suggestion by Cassinelli (1981, private communication to Eaton *et al.* 1985*a*).

Supporting evidence for Fe V as the opacity source at $\lambda < 1470$ came from *IUE* observations of the SMC binary system HD 5980 (Koenigsberger, Moffat and Auer 1987), where selective atmospheric eclipses were detected at the N IV 1718 and He II 1640 A lines, but not at $\lambda <$ 1470 A consistent with the lower heavy-metal abundances in the SMC.

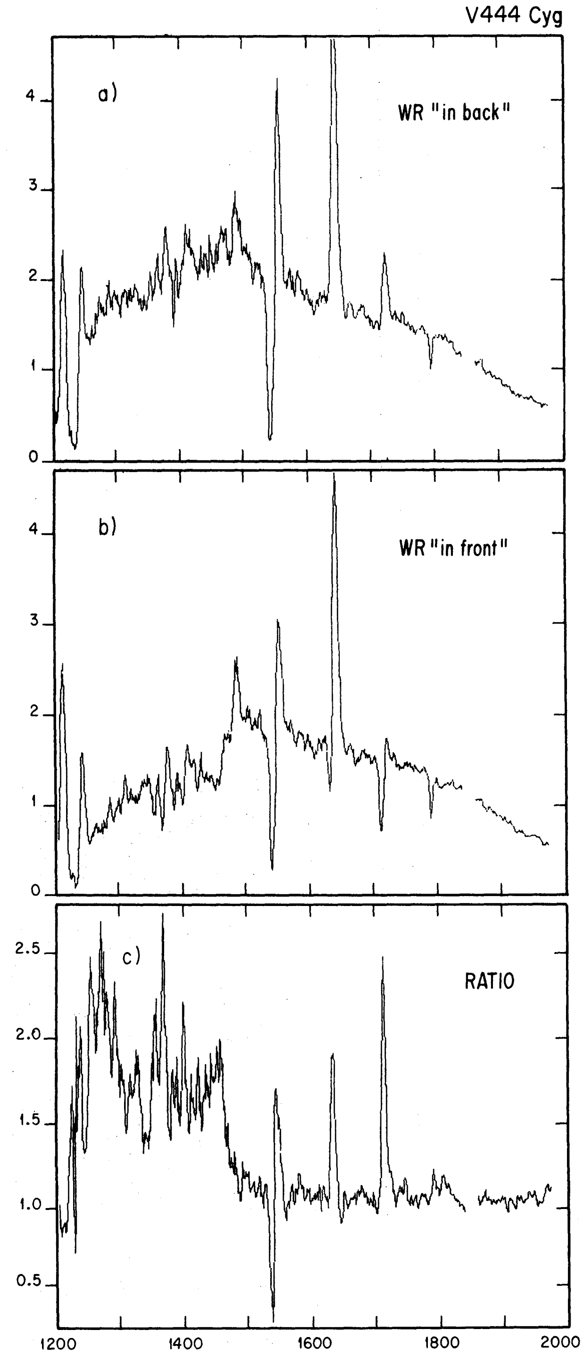


Fig. 1. Spectral variations observed in V444 Cyg with the *IUE*. a) Spectrum at orbital phase 0.5. The intensity scale is in units of 10×10^{-12} erg cm^{-2} s^{-1} A^{-1}; b) Spectrum at orbital phase 0.0 (WR star in front); c) Ratio of a) and b). Data are taken from Koenigsberger and Auer (1985).

From a qualitative standpoint, the conclusion is that the large number of Fe V and Fe VI lines, broadened by the large expansion velocities of the WR winds blend together, thus forming a pseudo-continuum. Given the po-

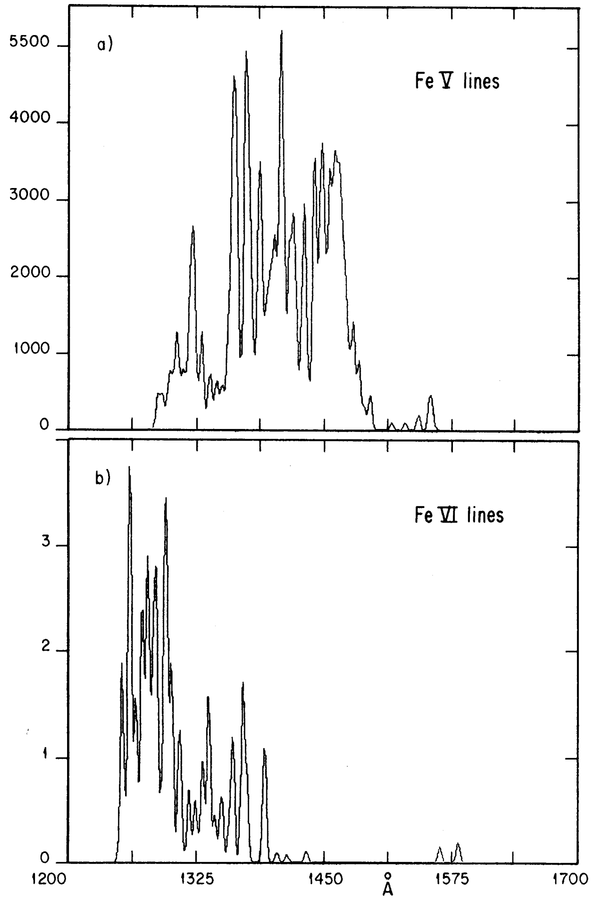


Fig. 2. Plot of Fe V (a) and Fe VI (b) lines taken from Ekberg (1975*a, b*), and broadened with a Gaussian profile to 500 km s^{-1}.

tential importance of this pseudo-continuum for gaining an insight into the structure of the WR winds, a more quantitative analysis is desirable. In this paper, a very primitive attempt is made to synthesize the Fe V and Fe VI line spectra. It is shown that the lines of these ions, when broadened to typical velocities in WR winds, do indeed produce pseudo-continua in the wavelength regions λλ1350 – 1470 A, and λλ1240 – 1350 A, respectively. A linear combination of Fe V and Fe VI lines results in a pseudo-continuum in the λλ1250 – 1470 A region. Furthermore, the synthesized spectrum reproduces the variations observed on low dispersion *IUE* spectra of five galactic WN+O binary systems remarkably well.

II. SPECTRUM SYNTHESIS

The appropriate way to synthesize a spectrum is to solve the stellar atmospheres problem. This is a non-trivial problem even for the simpler atoms. For atoms such as iron, the enormous number of possible transitions precludes such a calculation, even if LTE is assumed. Thus, the simplest approach possible has been adopted here: i.e., the experimental line intensities have been used.

Ekberg (1975*a*, 1975*b*) has provided a comprehensive list of wavelengths and laboratory intensities for Fe V and Fe VI lines in the λλ200 – 1700 A region (see also Fawcett and Henrichs 1974). The lines within the *IUE* short wavelength range, and which are to be discussed here correspond to the $3s^3$ 4s – $3d^3$ 4p transitions of Fe V and the $3d^2$ 4s – $2d^2$ 4p transitions of Fe VI. These are not resonance transitions. The lines in the wavelength range λλ1200 – 1470 of Fe V and Fe VI, with their corresponding laboratory intensities, as listed by Ekberg, were used to generate "synthesized" Fe V and Fe VI spectra, with the intention of simulating the expected spectrum from an optically thin wind, with a mean expansion velocity V_{exp}. The simplest approach possible was adopted. That is, each line was broadened to a Gaussian profile, and the contribution of each line added to each wavelength grid-point. No radiation transfer effects were taken into account.

Synthesized spectra of Fe V and Fe VI were computed independently, and then added, thus permitting different weights to be given to each ion. The distribution of Fe V and Fe VI lines with wavelength is illustrated in Figure 2, where V_{exp} = 500 km s^{-1} has been used. Analogous spectra, but with V_{exp} = 1000 km s^{-1}, are plotted in Figures 3a and 3b. In Figure 3c, a linear combination of Fe V and Fe VI lines is presented. Here, the intensities of Fe V lines have been added to twice the intensities of Fe VI lines. The wavelength resolution of these plots is 1.2 A.

Several important features emerge from Figures 2 and 3:

1). The wavelength regions in which each Fe V and Fe VI contribute are sharply defined.

2) There is no significant Fe V or Fe VI emission longward of λ1470 A.

3) When broadened to 500 km s^{-1}, the blending of lines leads to pseudo-continua in the regions λλ1280 – 1480 A for Fe V and λλ1250 – 1380 A for Fe VI. In the combined Fe V + Fe VI spectrum, this pseudo-continuum extends from λ1280 A to λ1480 A.

An additional point of interest is the presence of the two strong "lines" at λ1364 A and λ1377 A. These are usually present in emission in the WNE stars' spectra From Figures 2 and 3 one can see that each of these "lines" *cannot* be associated with any one Fe V or Fe VI line, but rather is a blend of numerous lines.

III. COMPARISON WITH THE OBSERVATIONS

The ratio of two spectra obtained at different orbital phases of the same binary system permits an objective assessment of the variations, and has the additional benefit of allowing a comparison between the variations in different binary systems. When the variability can be ascribed to atmospheric eclipses, the ratio, as shown in

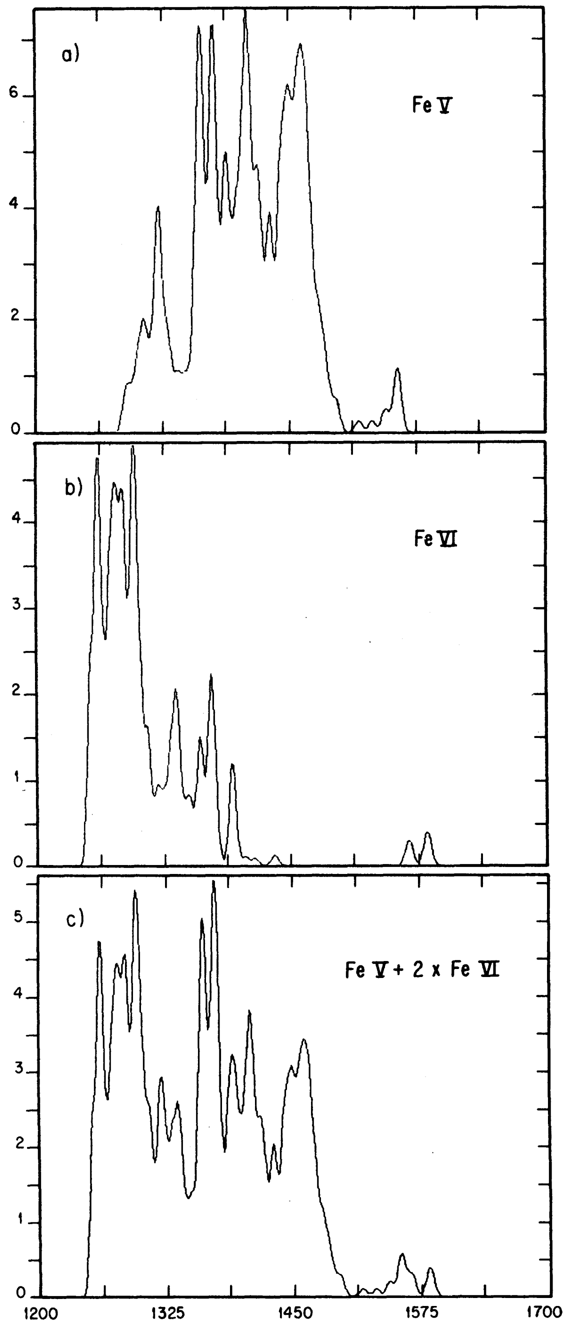


Fig. 3. a) and b) same as Figure 2, but with V_{exp} = 1000 km s^{-1}. c) Linear combination of a) and b).

Figure 1c, can be thought of as representing the wavelength regions at which the opacity sources due to bound-bound transitions of ions in the WR wind are at work.

The ratios for five WNE binary systems are shown in Figure 4, where scaled "synthesized" Fe V + Fe VI spectra have been superposed on the data. Each synthesized spectrum has been normalized to the data at λ1460 A, and shifted slightly on the wavelength scale to achieve a best fit. This wavelength shift (for all cases but HD 211853) is necessary, since the absorption in the WR wind is always displaced to shorter wavelengths due to the wind velocity gradient, which is unperturbed on the side which is *not* facing the O-star.

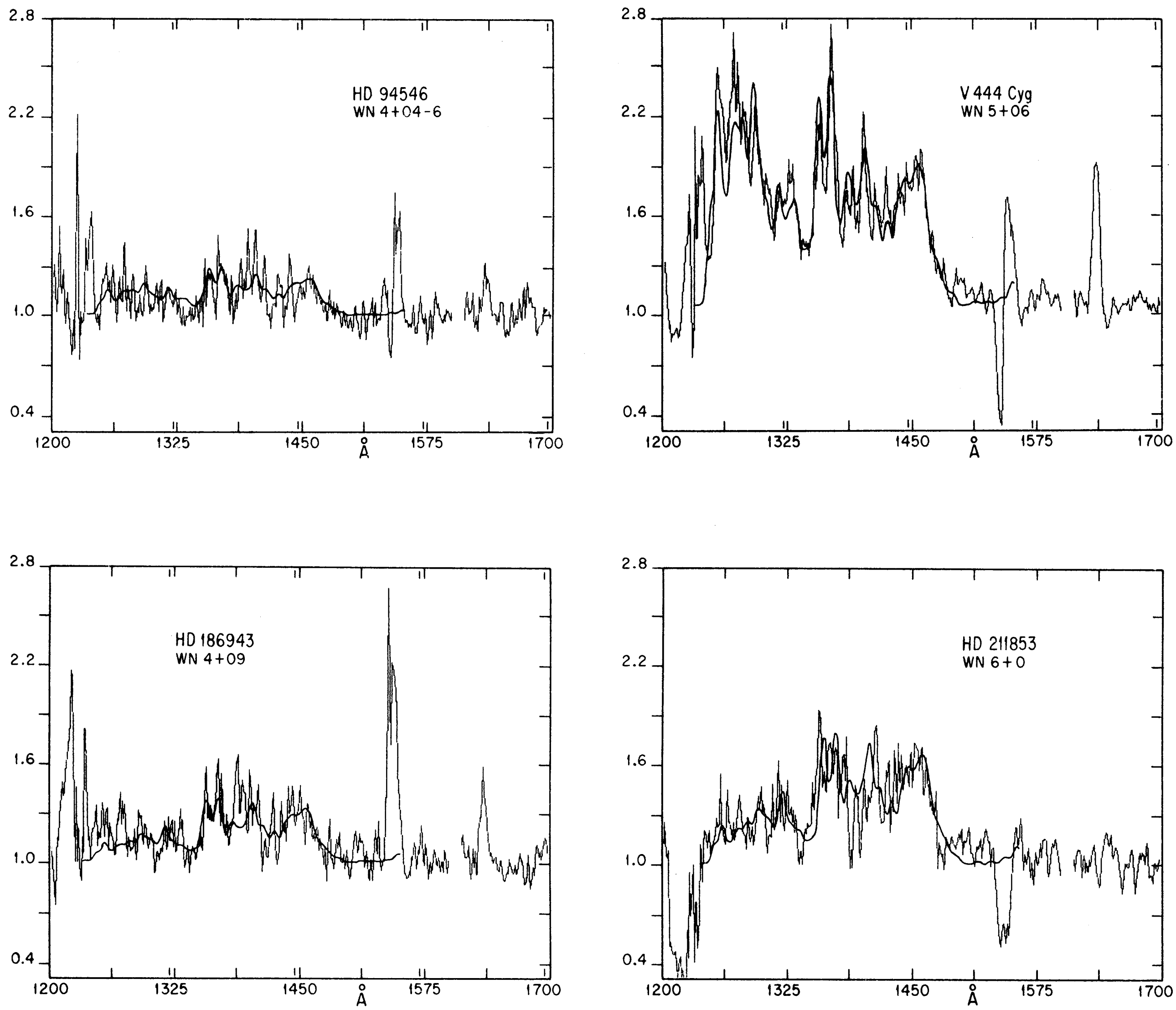
From Figure 4 it is evident that there is very good agreement between the Fe V + Fe VI pseudo-continuum and the portion of the *IUE* spectrum affected by absorption during the atmospheric eclipse. Hence, we are now able to conclude that Fe V and Fe VI ions are indeed responsible for the observed spectral variations at $\lambda <$ 1470 A.

IV. DISCUSSION

We have shown that the variations observed during atmospheric eclipse in WNE + O binary systems in the wavelength range λλ1280 – 1470 A are due to absorption by a pseudo-continuum of Fe V and Fe VI lines. At first glance this might seem unexpected, since the magnitude of the effect at $\lambda <$ 1470 A is as large as in N IV 1718 A, while the (solar) abundance of Fe is an order of magnitude smaller than that of N. However, the very large number of Fe V and Fe VI lines concentrated within a relatively small wavelength interval makes up for the difference in abundances.

The most important conclusion that is derived from this result is that bound-bound transitions between low-lying levels of Fe V and Fe VI ions represent a major source of opacity in the winds of WNE stars, and hence, in the atmospheres of similarly hot stars with similar heavy-element abundances. This might have a bearing on problems such as the *UV* continuum energy distribution of O-stars in clusters. Massa and Savage (1985) found the *UV* continuum of O-stars to be flatter (i.e., to represent cooler temperatures) than the corresponding continuum of B stars in the same cluster. They offer line blanketing by Fe V as a possible explanation, a hypothesis which is strengthened by the present results. It is worth noting that, although we have only considered the lines within the interval λλ1200 – 1470 A, there are similarly densely spaced Fe V and Fe VI lines in the λλ200 – 500 A wavelength region. Furthermore, these lines are the strongest. This implies considerable line blanketing effects which, to my knowledge, have not been taken into account by model atmosphere calculations.

Given that a strongly line-blanketed model atmosphere requires larger temperature gradients for the flux to emerge (Mihalas 1978), two stars with the same mass and in the same evolutionary phase, but with differing heavy-metal abundances, have different surface temperatures; that is, the star with the lower heavy-metal abundance requires a smaller temperature gradient, and thus has a larger surface temperature than its counterpart which has larger heavy-metal abundance. Thus, we may speculate that this might explain why in the LMC there are mostly WN3 and WN4 stars (i.e., the hotter subclasses of WN stars), while these subclasses are scarcer in the Galaxy.



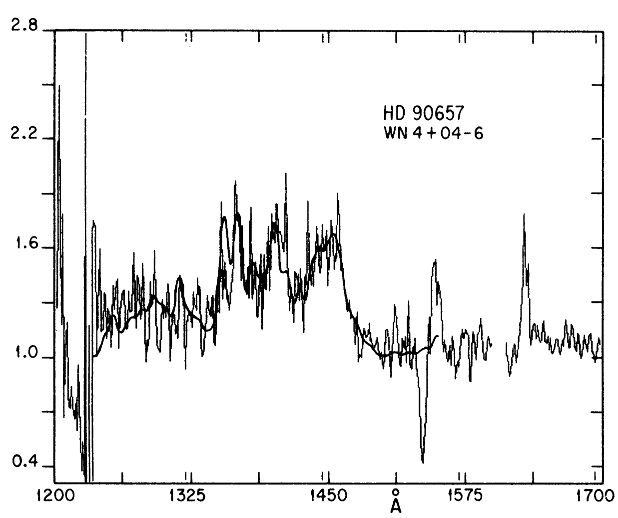


Fig. 4. Comparison of normalized Fe V and Fe VI synthesized spectra (broadened to 1000 km s^{-1}) with the ratios of observed spectra of five WN binary systems. These ratios are the inverse of those plotted by Koenigsberger and Auer (1985). The shorter tick mark on the wavelength scale indicates the necessary shift to the synthesized spectrum in order to achieve the fit. This is typically on the order of -800 km s^{-1}. The linear combination of Fe V and Fe VI lines used in the figures is given below: a) HD 94546, Fe V + Fe VI; b) HD 186943, Fe V + 0.5 × Fe VI; c) HD 90657, Fe V + 0.5 × Fe VI; d) V444 Cyg, Fe V + 2 × Fe VI; e) HD 211853, Fe V + 0.5 × Fe VI.

A comment may be made with respect to further applications of the present study. From Figure 4, it appears that the strongest contribution by Fe VI occurs in V444 Cyg. This is probably a result of the large orbital inclination of this binary system, which allows the O-star to be occulted by the innermost layers of the WR star's wind. Thus, it would be very interesting to obtain spectral ratios, as in Figure 4, as a function of orbital phase, and compare the relative contributions of Fe V and Fe VI.

This ratio should help to determine whether there is a variation in the dominant degree of ionization in the WR wind as a function of distance from the WN core or not.

In this paper we have dealt with the pseudo-continua of the Fe V and Fe VI. It must be kept in mind that Fe IV, too, has a pseudo-continuum, its effects being clearly visible in the λλ1500 – 1800 A wavelength region of the spectra of WC + O binaries (c.f. CV Ser; Howarth, Willis and Stickland 1982). Thus, an analysis of the complete sample of WN and WC binary systems which have been observed with *IUE* might yield fruitful results for understanding differences in the winds of the various WR subtypes.

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