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ATMOSPHERIC ECLIPSES IN THE SMC WOLF-RAYET ECLIPSING BINARY HD 5980: THE HEAVY VERSUS THE LIGHT METAL ABUNDANCE

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ABSTRACT

Phase-dependent variations in the *IUE* spectra of the SMC 19.6 day eclipsing binary system HD 5980 (WN4 + 07I:) are presented. The effects due to selective atmospheric eclipse at the N V, N IV, He II, and C IV lines are clearly present as in Galactic counterparts. However, the variations in the wavelength band λλ1350–1490 Å, prominent in Galactic WN binary systems, are virtually absent in HD 5980. This is most likely a result from the lower heavy element abundances (specifically iron) in the SMC.

Subject headings: stars: abundances — stars: eclipsing binaries — stars: Wolf-Rayet

I. INTRODUCTION

Selective atmospheric eclipses have been shown to be a tool for probing the wind structure in Wolf-Rayet (W-R) stars (Cherepashchuk, Eaton, and Khaliullin 1984; Eaton, Cherepashchuk, and Khaliullin 1985*a*,*b*; Koenigsberger and Auer 1985, henceforth KA85). Thus far, at least seven W-R binaries within the Galaxy observed with the *IUE* present strong UV emission line variations which can be attributed to selective atmospheric eclipses (see the above references, as well as Hutchings and Massey 1981; Willis *et al.* 1979; Sahade, Kondo, and McCluskey 1984). The most striking orbital phase-dependent changes in the spectra of WN + O binaries are the strengthening of P Cygni absorption components of the N IV 1718, C IV 1550, He II 1640, and N V 1240 lines as the O star companion is seen through successively larger column densities of W-R wind material. These changes at "selective wavelengths" are accompanied by the appearance of a depression in the continuum at λλ < 1490 Å which has been attributed to absorption by Fe V ions in the WN star wind (Koenigsberger 1983; KA85; Eaton, Cherepashchuk and Khaliullin 1985*b*). The larger number of Fe V transitions which lead to lines in this wavelength range as well as the Doppler broadening due to the velocity gradient in the W-R wind result in a pseudocontinuum opacity source. Important contributions to phase-dependent variations due to Fe IV (Sahade *et al.*; Eaton, Cherepashchuk, and Khaliullin 1985*a*) and Fe VI (Koenigsberger 1983; KA85) have also been suggested for other wavelength bands.

In this *Letter* we show that the effects of selective atmospheric eclipses in the N, C, and He lines of the SMC Wolf-Rayet system HD 5980 are very similar to those observed in its Galactic counterparts, while the variations in the λλ1350–1490 Å continuum region are virtually undetectable. This is probably a consequence of the lower initial abundance, particularly of the heavier elements in the SMC with respect to the Galaxy, combined with subsequent nuclear processing in the W-R star interior.

II. OBSERVATIONS AND RESULTS

As part of our program to study phase-dependent variations in W-R binary systems using the IUE satellite (Boggess *et al.* 1978*a*,*b*), we observed HD 5980 on 1986 November 9–24 (UT). All observations were made using the short wavelength prime (SWP) camera, with the large aperture, on low dispersion, and in the NASA US2 shifts. These observations will be discussed in detail elsewhere (Moffat, Koenigsberger, and Auer 1987).

HD 5980, with spectral type WN4+07I:, is an eclipsing binary system in the SMC with relatively well-determined ephemeris (Breysacher and Perrier 1980; Breysacher, Moffat, and Niemela 1982): Primary light minimum corresponding to O star in front occurs at HJD 2,443,158.771 + (19.266 + 0.003)E (phase 0), and secondary minimum occurs 0.36P later (W-R star in front). Particular attention was paid to obtaining UV spectra of HD 5980 at those phases where the O star is occulted by part of the W-R wind. In Figure 1 we present a selection of the spectra. As with its Galactic counterparts, the selective atmospheric eclipse is clearly evident in the N IV 1718 line, which changes from a typical P Cygni profile to a line which appears to be solely in absorption when the O star in on the far side of the W-R. Similar, though relatively less extreme changes occur in the He II 1640, C IV 1550, and N V

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1240 lines (where a contribution to the emission from the O star might be expected). However, there is no evidence for strong changes in the "continuum" at λλ1350–1490 Å, as observed in the Galactic WNs. This difference is illustrated in Figure 2, where we plot the ratio of the spectrum of the system when the W-R star is "in front" of the O star to the spectrum when the W-R is "in back" for both HD 5980 and the Galactic system HD 90657, of similar spectral type, WN4 + O5–8. In the Galactic WNs, as exemplified here by HD 90657, the depths of the N IV and the Fe V absorptions (Fig. 2) are very similar. This is clearly not the case in HD 5980 where the depression in the "continuum" shortward of 1490 Å is conspicuously absent. Since Fe V and N IV have the same ionization potential, and since HD 5980 is an eclipsing system, the only explanation for the difference can be in terms of the lower Fe abundance, relative to N, in SMC objects.

The changes can be quantified by measuring the equivalent widths (W_λ) of the absorptions from the ratios, since these give us a measure of the number of absorbing ions in the W-R wind along the line of sight to the O star. For the N IV absorption W_λ(1700–1730 Å) = 4.2 ± 0.3 Å and 3.5 ± 0.4 Å, for HD 90657 and HD 5980, respectively, while for the Fe V absorption region, the corresponding values are W_λ(1350–1490 Å) = 22.6 ± 2.1 Å and 1.9 ± 2.0 Å, respectively. These values are based on the ratios of three pairs of spectra for each WN system. Thus, while the equivalent widths of the N IV absorption are very similar, W_λ (1350–1490 Å) is about an order of magnitude larger in the Galactic WN.

III. DISCUSSION AND CONCLUSIONS

The variation in the region shortward of 1490 Å in the galactic WN + O systems have been observed in five WN + O systems (see §I for references), and can be attributed to absorption of the O star continuum by Fe V (and in some cases also Fe VI) ions in the W-R wind. The large number of Fe V lines in the λλ1300–1490 Å spectral region, approximately 240 lines (Ekberg 1975), broadened by the expansion velocity of the wind result in a pseudocontinuum opacity source. The importance of Fe IV, Fe V, and Fe VI as sources of line blanketing in O stars has been stressed by Dean and Bruhweiler (1985) and Bruhweiler, Kondo, and McCluskey (1981).

It is important to note that, although the winds of W-R stars are characterized by altered chemical abundances (i.e., they contain nuclear-processed material), the abundances of very heavy elements, such as Fe, must be those with which the progenitor was formed. That is, W-R stars are not believed to be in such advanced stages of evolution so as to have synthesized iron. Thus, the W-R binary systems in which selective atmospheric eclipses are evident present us with a possible technique for readily deriving element abundances in the W-R wind.

Without attempting a detailed analysis at this time, we may roughly estimate the Fe/N abundance in the SMC W-R star with respect to the Galactic W-R as follows: Under the assumption of pure absorption, the observed intensity at orbital phase corresponding to deepest atmospheric eclipse, and the observed intensity at an opposite phase can be written, respectively, as:

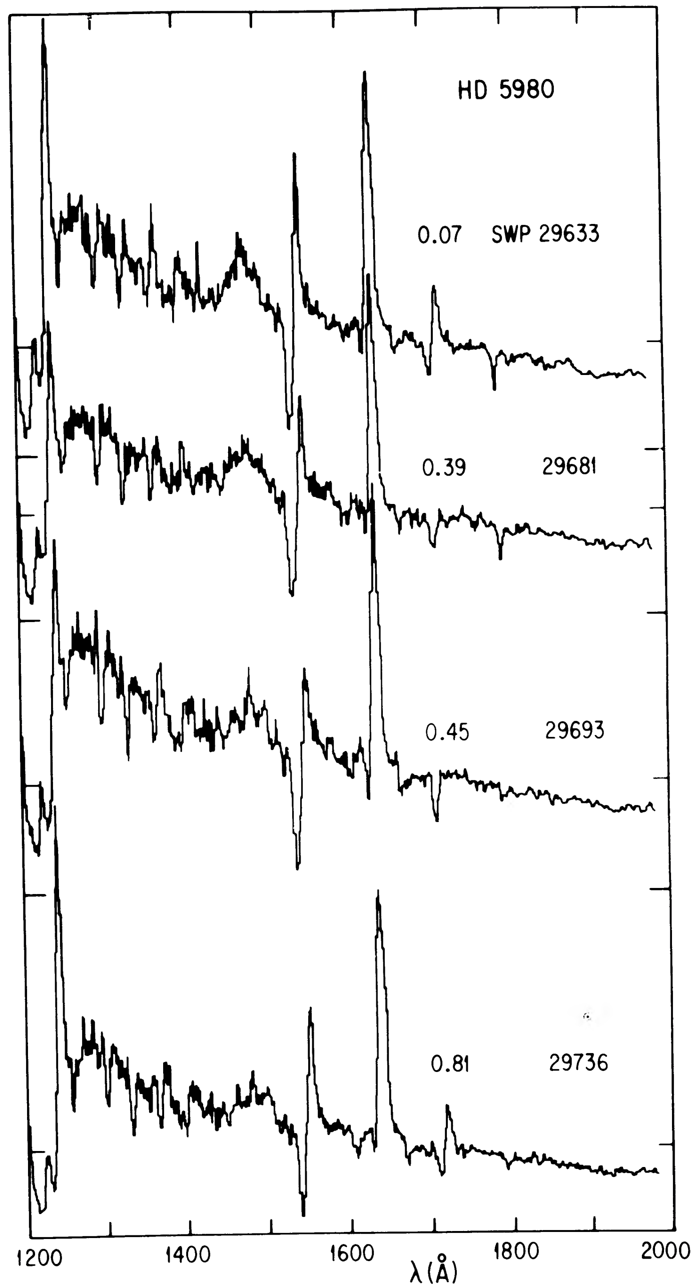

FIG. 1.—*IUE* spectra of HD 5980 sorted in orbital phase, showing the variations in the N IV 1718 Å line. The dip at 1790 Å is produced by a reseau mark on the camera. The plots are displaced vertically with sufficient spacing to allow for clarity. Large tick marks correspond to zero flux level, and small ones to 2×10^{-12} ergs^{-2} cm^{-1} s^{-1} Å^{-1}.

$$I_1 = I_w + I_0 \exp[-\tau_\lambda] \qquad (1)$$

$$I_2 = I_w + I_0, \qquad (2)$$

where I_1, I_2 are the intensities of the W-R and O star, respectively, and τ_λ is the optical depth of the W-R wind

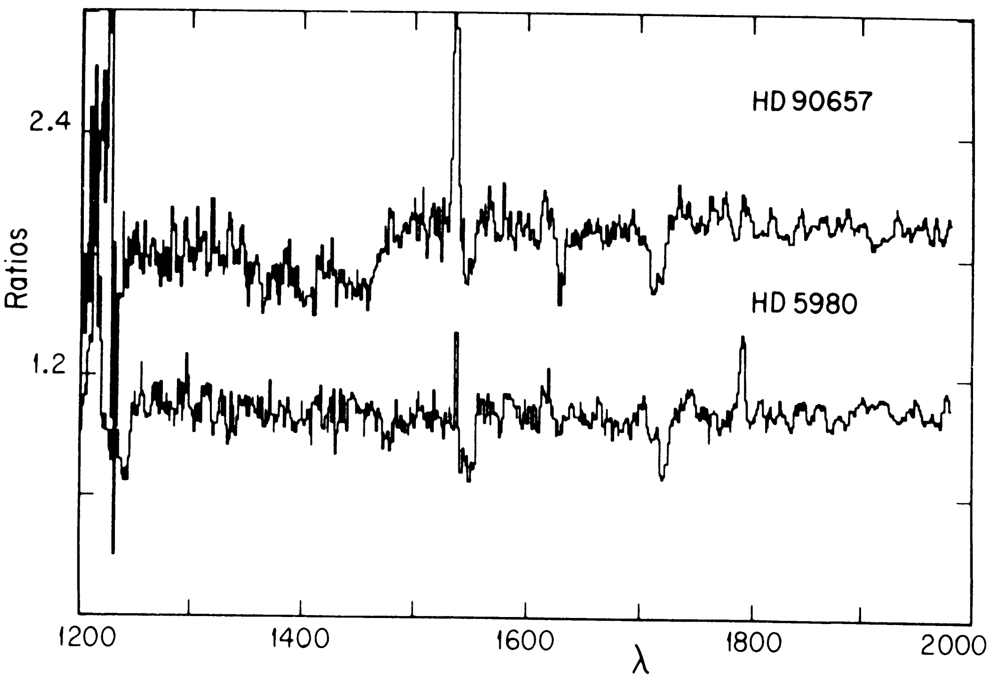

FIG. 2.—Ratios of spectra corresponding to W-R "in front" divided by W-R "in back" for the Galactic system HD 90657 and HD 5980. The absence of the depression in the λλ1350–1490 Å region in HD 5980 is attributed to the lower Fe abundance in the SMC, with respect to the Galaxy.

from front to back along the line of sight to the O star and is given by (Castor, Abbott, and Klein 1975):

$$\tau_\lambda = k_\lambda \rho v_{th} (dv/dr)^{-1}. \qquad (3)$$

Here k_λ is the absorption coefficient for the transition, ρ is the density of absorbers, v_{th} is the thermal speed, and dv/dr is the wind velocity gradient. Equivalent widths, though unconventional, can be obtained from the ratio of the spectra as plotted in Figure 2

$$W = \int_{\lambda - \Delta\lambda/2}^{\lambda + \Delta\lambda/2} (i_R/i_c - 1)\, d\lambda, \qquad (4)$$

where $i_R = I_1/I_2$, and $i_c = 1$. Assuming that the lines are not optically thick ($\tau \ll 1$), then

$$W_\lambda \approx \frac{I_0}{I_0 + I_W} \tau_\lambda \Delta\lambda. \qquad (5)$$

Now, taking the ratio of equivalent widths of two lines (in the same general spectral region), λ_1, λ_2, for the same binary system eliminates the unknown values $I_0/(I_0 + I_w)$, dv/dr, v_{th}, while taking the ratio for the same line in two different binary systems a, b, eliminates k_λ, which is not known for the blend of iron lines. Hence,

$$\frac{W^a_{\lambda_1}/W^a_{\lambda_2}}{W^b_{\lambda_1}/W^b_{\lambda_2}} \approx \frac{\rho^a_{\lambda 1}\rho^b_{\lambda_2}}{\rho^b_{\lambda_1}\rho^a_{\lambda_2}}. \qquad (6)$$

Letting a, b correspond to HD 90657 and HD 5980, respectively, and λ_1, λ_2 correspond to λλ1700–1730 Å (N IV), λλ1350–1490 Å (Fe V), respectively, yields the density ratio of Fe V with respect to N IV for the two W-R stars. Since both W-Rs have the same dominant degree of ionization in their winds (i.e., ionization class WN4), we may assume that the fractional abundances are equal: $N(\text{Fe V})/N(\text{Fe}) \approx N(\text{N IV})/N(\text{N})$. Thus,

$$\frac{\rho^{Gal}_{Fe}}{\rho^{SMC}_{Fe}} \approx \frac{W^{SMC}_{N\,IV}}{W^{Gal}_{N\,IV}} \frac{W^{Gal}_{Fe\,V}}{W^{SMC}_{Fe\,V}} \frac{\rho^{Gal}_{N}}{\rho^{SMC}_{N}} = 9.9 \times \frac{\rho^{Gal}_{N}}{\rho^{SMC}_{N}}. \qquad (7)$$

If we assume that the N abundance in both W-R stars is the same (see Smith and Willis 1983 for N/He abundance determination in LMC W-Rs), we derive an Iron abundance in the SMC which is a factor of ten smaller than in the Galaxy. This result, although in excellent agreement with iron abundances derived from SMC supergiants (Przybylski 1972, 1975), is at best a lower limit, since the N abundances of SMC WN stars are expected to be smaller than that of their Galactic counterparts, due to their initially lower abundance of C, N, O (see, for example, Dufour 1984). An additional source of uncertainty in our result could be the contamination of the 1718 Å feature by Si IV 1722, 1727. However, we estimate the contribution of these lines to be less than 20% for the emission component [since $N(\text{Si})/N(\text{N}) \approx 10^{-1}$ in WNE abundances] and even smaller for the absorption component. Hence, the Si IV contribution to $W_{N\,IV}$ is probably close to the uncertainty of equivalent width measurements.

It is very important to note that although HD 5980 is an eclipsing binary system, HD 90657 is not. Thus, the similar equivalent widths of the N IV absorptions (note also C IV) may be due to the fact that while N (and C) may be lower in HD 5980, there is a larger column density of W-R wind material projected upon the O star's luminous disk than in HD 90657. However, among the five Galactic WN + O systems observed to show the effects of selective atmospheric eclipse, the amplitude of the variations on the low-dispersion spectra are very similar in the N IV and λλ1350–1500 Å regions. The only major difference occurs at $\lambda \leq 1300$ Å, which might correspond to the Fe VI pseudocontinuum, in the sense that the highest orbital inclination system (V444 Cyg) has strong variations here, while the lower inclination systems do not. This might be explained if one assumes that the major contribution to Fe VI lines arises closer to the W-R core than Fe V.

An important consequence of the lower heavy element abundance in HD 5980 is the significant reduction in opacity sources for driving the wind by radiation pressure. Abbott (1982) has discussed the relevance of heavy element abundances in this respect. Thus, given the large difference in heavy element abundances, one would expect the winds of HD 90657 and HD 5980 to differ appreciably, if radiation pressure were the only mechanism driving the winds, and assuming that the luminosities of the WN components are not extraordinarily different. In particular, one might expect smaller wind terminal speeds in HD 5980 than in its Galactic counterparts, as is the case of LMC O and Of stars (Garmany and Conti 1985), and the SMC supergiants (Hutchings 1982). However, upon inspecting high-resolution *IUE* archival data of HD 5980, we find no significant difference between its line widths and those of HD 187282 (in Willis *et al.* 1986), also a Galactic WN4 star (there are no high-dispersion *IUE* spectra of HD 90657). Thus, we are led to conclude that, in addition to radiation pressure on lines, other mechanisms, such as stellar pulsations (see Maeder 1985) may be involved in driving the wind of HD 5980.

Finally, in a more general context, given the strong concentrations of Fe IV–Fe VI ions in diverse regions of the UV spectrum, a difference between the continua of early-type Galactic and SMC stars might be expected due to the different degrees of line blanketing.

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