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ULTRAVIOLET VARIABILITY OF THE MASSIVE W-R BINARY SYSTEM HDE 311884 = WR 47

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ABSTRACT

We present *IUE* observations and their analysis of the massive WN6+O binary system HDE 311884. The phase-dependent variations are like those of WN4–6 binaries studied previously, with atmospheric eclipses evident in the N IV 1718 Å and C IV 1550 Å lines, and in the Fe V + VI pseudocontinuum at $\lambda < 1480$ Å. The considerable variability longward of 1700 Å is due mostly to Fe II and Fe III lines.

Subject headings: stars: binaries — stars: individual (HDE 311884) — stars: Wolf-Rayet — ultraviolet: spectra

1. INTRODUCTION

Wolf-Rayet (W-R) stars are presumed to be the direct descendents of the most massive O stars, and as such, they constitute evolutionary phases prior to the supernova explosion in which massive stars blow nuclear processed material via stellar winds into the interstellar medium (see Abbott & Conti 1987 and Chiosi & Maeder 1986 for general reviews on W-R stars). According to current evolutionary scenarios, after the O star leaves the hydrogen main sequence, it undergoes large scale mass loss (the details of which are not yet understood) until inner layers are exposed, where chemical abundances have been modified by the nuclear processes. It is then that W-R stars appear.

Among the various subclasses of W-R stars, the WN6 and WN7 stars are believed to represent the transition phases between the massive O star and the fully developed W-R star, in which H is practically absent, and He and N or He and C are the most abundant elements, respectively. Thus, it is by studying members of the WN6–7 subclasses that insight might be gained into the processes by which a massive star loses up to 80% of its initial mass and exposes layers in which the products of advanced He burning (i.e., the WO stars) are present.

The binary system HDE 311884 = WR 47 (van der Hucht et al. 1981) contains the most massive W-R star known with any certainty. Hence, this W-R star represents one of the closest evolutionary phases to that of the main-sequence O star progenitor and makes it particularly interesting in the above context.

Because of its relative faintness in the visible and blue and its location in the southern hemisphere, an optical study of WR 47 was initiated only relatively recently. Niemela, Conti, & Massey (1980) presented the first radial velocity curves and determined minimum masses ($M \sin^3 i$) of 40 $M_\odot$ for the WN6 component and 47 $M_\odot$ for the O star. A more recent determination (Niemela & Mandrini 1991) yielded similar values. Moffat et al. (1990) determined the orbital inclination, an improved orbital period, and the mass-loss rate, based on polarimetric and photometric observations over many orbital cycles. With the orbital inclination, the mass of the W-R star is 48 $M_\odot$. Table 1 gives a recompilation of the known parameters of the WR 47 binary system.

The components of the binary system are classified as WN6 and O5:V (Niemela et al. 1980), on the basis of the optical spectrum, although Lamontagne & Moffat (1987) have suggested that WN7 might be more appropriate for the W-R component.

The UV (1200–2000 Å) wavelength range covered by the *IUE* satellite contains a wealth of lines arising from resonance transitions of ions with widely differing ionization potentials (e.g., O I to O V), as well as an enormous number of interesting lines arising from transitions between low-lying excited states and from semiforbidden transitions giving rise to intercombination lines. This wavelength range has thus proved to be very useful for the study of the properties of the winds in hot stars. In the particular case of W-R binary systems, the occurrence of atmospheric eclipses (occultation of the O star continuum by the W-R star's wind) allows for detailed analyses of the W-R star's wind characteristics (see Koenigsberger 1990a, and references therein).

In this paper we present the result of six *IUE* observations of WR 47, where the general phase-dependent variations are found to be similar to those observed in other WN+O binary systems.

2. OBSERVATIONS

We observed WR 47 at NASA/GSFC using the SWP (Short Wavelength Prime) camera with the large aperture in the low-dispersion mode during the US2 (high background radiation) shifts on 1988 April 4–11. Table 2 contains the SWP number, exposure time, date and UT of observation, corresponding JD, orbital phase according to the improved ephemeris of Moffat et al. (1990), orbital impact parameter, and the counts recorded by the FES (Fine Error Sensor), which is a measure of the visual magnitude. The large differences in exposure times are due to constraints imposed by the background radiation levels. With $m_v = 11.1$, and $E(B-V) = 1.16$ [Conti & Morris 1990; however, van der Hucht et al. 1988 give $E(B-V) = 1.23$], WR 47 is the reddest WR binary system observed thus far with the *IUE*. It is interesting to note that during our scheduled shifts

[1] Guest Observer, *International Ultraviolet Explorer*.

TABLE 1

PHYSICAL PARAMETERS OF HDE 311884

Parameter	Value	References
Spectrum	WN6 + O5:V	
Period (days)	6.2399	1
E_0 (JD)	2,443,918.4	2
$Mw \sin i (M_\odot)$	47	3
$a \sin i (R_\odot)$	64	
i	70	1
M(WN6) $(M_\odot)$	48	1
M(O5) $(M_\odot)$	57	1

REFERENCES.—(1) Moffat et al. 1990; (2) Niemela & Mandrini 1989. E_0 refers to O star in back of WR; (3) Niemela, Conti, & Massey 1980.

the background radiation levels for the first 4 hr were extraordinarily low for a US2 shift due to a recent solar flare, thus enabling the relatively long exposures necessary to study this system properly. However, except for one spectrum (SWP 33243) the quality of the data below 1500 Å is very poor. This is true even for SWP 33208 (the spectrum with the longest exposure time) because of the atmospheric (wind) eclipse which coincided with this observation (see below). An estimate of the maximum pixel-to-pixel noise level was obtained by dividing each spectrum by its five-point smoothed spectrum and measuring the mean height of the maximum deviations from unity. These are listed in Table 3 for the wavelength intervals 1200–1450, 1450–1650, and 1650–2000 Å, where the improved response for longer wavelengths is evident. It is only in the $\lambda > 1650$ Å interval that the maximum noise levels lie below 10%.

The data reduction was performed at the GSFC Regional Data Analysis Facility (RDAF) with the standard routines, and the analysis was done both at the Instituto de Astronomía, and at the GSFC RDAF through UNAM's satellite link into the NSF Internet and SPAN.

The four spectra corresponding to orbital phases in which the O star is "on the far side" of the W-R, with respect to the observer (i.e., $0.88 < \phi < 1.08$) were co-added and a three-point smoothing function was applied. This spectrum was dereddened, using $E(B-V) = 1.16$ (Conti & Morris 1990) with the standard Savage & Mathis (1979) interstellar extinction law and is shown in Figure 1*a*. In Figure 1*b* we illustrate the spectrum of the WN6+O binary system HD 211853 obtained at orbital phase 0.03, dereddened with $E(B-V) = 0.74$ and smoothed the same as Figure 1*a*. This corresponds to an orbital impact parameter $p = 25\ R_\odot$, which is only slightly smaller than the mean for the WR 47 spectra of Figure 1*a*. The individual spectra of HDE 311884 were also smoothed and

TABLE 3

NOISE LEVELS

WAVELENGTH INTERVAL (Å)	SWP 33208	SWP 33213	SWP 33219	SWP 33227	SWP 33243	SWP 33255
1200–1450......	20%	24%	21%	35%	18%	30%
1450–1650......	8	15	15	21	9	14
1650–2000......	5	9	7	15	5	6

dereddened in the same manner and are presented in Figure 2, where they are ordered according to the orbital phase. All measurements, however, were performed on the unsmoothed data. Specifically, the intensity F at the maximum of each emission feature on each individual spectrum was recorded, as well as the equivalent width of selected lines. In columns (2) and (3) of Table 4, the mean (over the six spectra) flux and the corresponding standard deviation are listed, respectively. Table 5 contains the measurements of the equivalent widths of the strongest features. Negative values correspond to emission components. These measurements are particularly difficult shortward of 1600 Å, where the definition of a continuum level is very arbitrary, resulting in an estimated uncertainty of 2 Å in the stronger lines.

3. RESULTS

3.1. *The W-R Star Spectrum*

As with other members of the WN class, the dominant emission lines arising in the W-R wind are N V 1240, N IV] 1486, C IV 1550, He II 1640, and N IV 1718 (Figs. 1*a* and 1*b*). The UV spectrum of HDE 311884 is very similar to that of another massive WN6+O binary system, HD 211853 during atmospheric eclipse (Fig. 1*b*), except for the fact that the latter has a stronger contribution of C lines in its spectrum, which has led to its reclassification as WN/WC (Conti & Massey 1989). The strong variations, as a function of orbital phase, in the region $\lambda < 1470$ Å indicate the presence of unresolved lines of Fe V and Fe VI (see below). In addition, there are numerous weaker but still resolved emission lines.

It is very difficult to unambiguously assign identifications for lines in W-R spectra, and particularly in this case where the quality of the data is not optimum, except for the region longward of 1700 Å. However, we are aided by the fact that there is an atmospheric eclipse at line frequencies. The enhancement of a P Cyg absorption component has the effect of "cutting into" neighboring emissions, thus making the line appear sharper and well-defined. This eclipse is expected to be strongest for lines arising in transitions with low-lying lower levels, i.e., the lower levels having relatively long lifetimes. This is obviously

TABLE 2

IUE OBSERVATIONS OF HDE 311884

SWP	T_{exp} (minutes)	Date Observed (1988)	UT (Start time)	JD (−2,440,000)	Phase[a]	$p/R_\odot$ [b]	FES Counts
33208..........	160	Apr 4	18:04	7256.25	0.92	38.6	122
33213..........	105	Apr 5	18:0	7257.25	0.08	38.6	152
33219..........	75	Apr 6	19:32	7258.31	0.25	...	129
33227..........	100	Apr 7	19:33	7259.31	0.41	...	133
33243..........	120	Apr 10	17:48	7262.24	0.88	49.5	125
33255..........	90	Apr 11	17:29	7263.25	0.04	28.2	127

[a] Orbital phases computed using $2{,}443{,}918.4 + 62399E$ (W-R in front) from Moffat et al 1990.
[b] Impact parameter $p = a[\sin^2(2\pi\phi) + \cos^2(2\pi\phi)\cos^2 i]^{1/2}$.

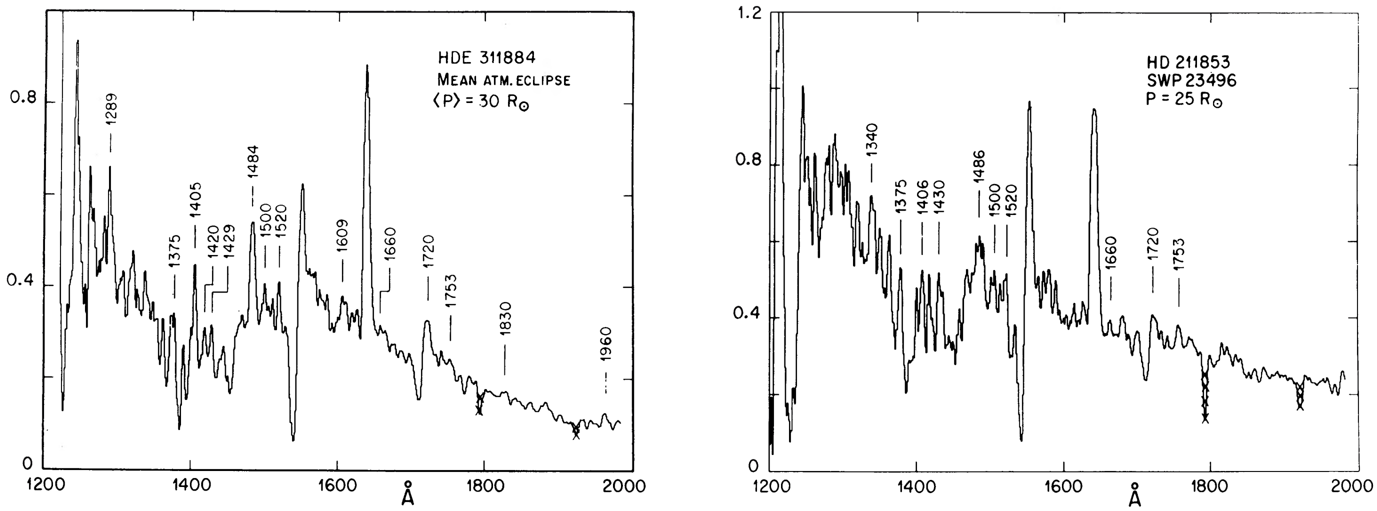

FIG. 1*a*

FIG. 1*b*

FIG. 1.—(*a*) Average of four spectra obtained during atmospheric (wind) eclipse of HDE 311884, dereddened with $E(B-V) = 1.16$. The crosses indicate the position of reseaux. The intensity scale is in units of 10^{-10} ergs cm^{-2} s^{-1} Å^{-1}. (*b*) Same as (*a*) for HD 211853, dereddened with $E(B-V) = 0.74$.

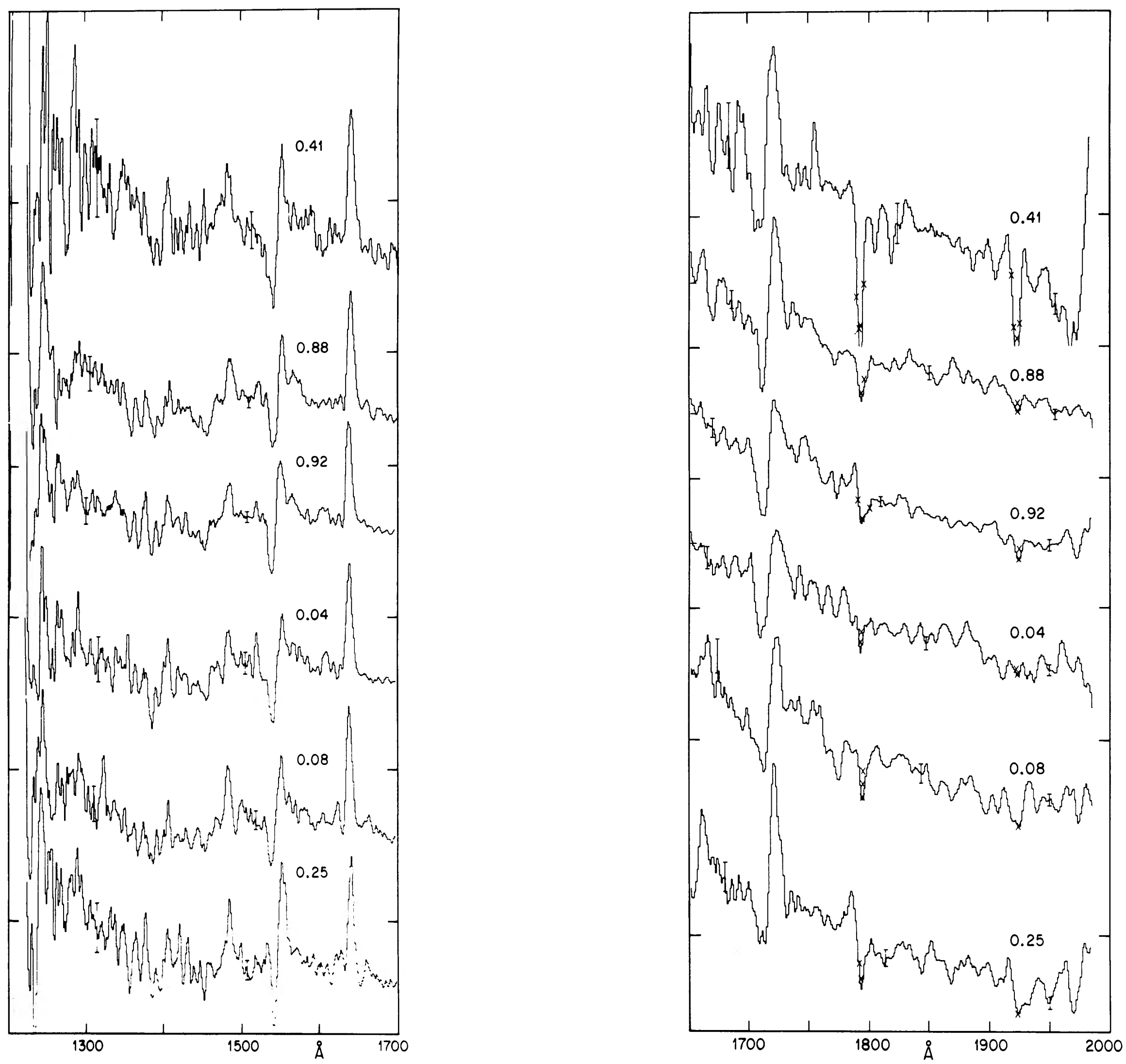

FIG. 2*a*

FIG. 2*b*

FIG. 2.—(*a*) Individual dereddened three-point smoothed spectra in the wavelength range 1200–1700 Å, ordered according to orbital phase. The vertical error bars near 1300 and 1500 Å give an estimate of the noise levels. The tick marks on the vertical scale correspond to 6×10^{-10} ergs cm^{-2} s^{-1} Å^{-1}. (*b*) Same as (*a*) for the 1650–2000 Å region, with error bars near 1675, 1810, and 1950 Å. The tick marks on the vertical scale correspond to 2×10^{-10} ergs cm^{-2} s^{-1} Å^{-1}.

TABLE 4

EMISSION LINES IN THE *IUE* SPECTRUM OF HDE 311884

λ[a] (1)	$\langle F \rangle$[b] (2)	$\sigma/\langle F \rangle$ (3)	Identfication (4)
1245 P	0.35	0.13	N V, C III
1265	0.29	0.06	Si II
1288*	0.39	0.11	Si III
1330	0.36	0.12	C II
1336	0.36	0.06	C II
1362	0.39	0.11	Si III, Fe V+VI
1374	0.44	0.15	P III, Fe V+VI
1401	0.46	0.14	Si IV
1406	0.62	0.15	Si IV, O IV]
1417	0.47	0.14	Si III, Fe V
1420	0.59	0.18	Si III, Fe V
1430	0.52	0.12	C III, Fe V
1447	0.48	0.17	Si III, Fe V
1460	0.52	0.13	Fe V, Fe IV
1484 P	0.99	0.17	N IV]
1499	0.71	0.12	P III, Si III
1520* P	0.70	0.12	Si II, Fe II, Cu II
1530	0.62	0.12	Si II, Cu II
1553 P	1.22	0.21	C IV
1567	0.80	0.11	Fe IV, Fe II
1607	0.68	0.12	Fe II
1625	0.70	0.08	Fe IV, Fe II, C III
1641	1.70	0.09	He II
1659*	0.67	0.06	Fe IV, Fe II, O III
1677	0.64	0.07	Fe II, Fe IV
1697*	0.61	0.10	N III
1720* P	0.87	0.14	N IV, Si IV
1745	0.61	0.04	N III], Ni II
1752*	0.61	0.09	N III, Ni II
1767* P	0.54	0.06	N II, Fe III, Fe II, C II
1782 (P)	0.57	0.07	Ni II, Fe III, Fe II, Si I
1828	0.44	0.04	Ni II, Si I
1840	0.37	0.03	Fe II, Si III, N III, N II, Ni II
1861	0.32	0.04	Al III, Fe II, Fe III, N II
1875*	0.33	0.04	Fe II
1881*	0.32	0.04	N III, Fe II, N II
1899*	0.28	0.05	Fe III
1915*	0.26	0.05	Fe III, Fe II

[a] Asterisks indicate lines reported by Bruegmann & Crenshaw 1989 as SWP artifacts on exposures longer than 3 hr; P indicates P Cygni profile.

[b] Averaged (over the six nondereddened, unsmoothed spectra) flux in units of 10^{-13} ergs cm^{-1} s^{-1} Å^{-1}.

true of the resonance lines, and those lines whose lower levels are connected to the ground state by a forbidden or semi-forbidden transition. Lines which arise from transitions in which the lower level is coupled with an optically thick resonance transition will also display strong atmospheric eclipses. This is the case of N IV 1718 ($2s2p\ ^1P^0$–$2p^2\ ^1D$), whose lower level is coupled to the transition to the ground state which results in a line at 765 Å (i.e., $2s^2\ ^1S$–$2s2p\ ^1P^0$). Thus, we have been able to discard as possible identifications those ionic species arising from transitions between highly excited levels (for example, N IV) for many of the lines.

TABLE 6

POSSIBLE PHOTOSPHERIC ABSORPTIONS

λ	W_a (Å)	Ion	Comments
1274	2.5	...	
1303	0.6	Si III	
1334	2.1	C II+O IV	+IS C II
1371	0.5	O V	
1386	2.4	Si IV	+P Cyg?
1395	2.2	Si IV	+P Cyg?
1502	0.8	...	
1526	...[a]	Si II	+IS Si II
1533	...[a]	Si II	
1608	1.2	Fe II	+IS Fe II
1806	1.3	Si II	+IS?
1819	1.3	Si II	+IS?

[a] Not measurable.

The list of possible identifications is given in the last column of Table 4. This has been taken primarily from the list of identifications of the lines in the spectrum of HD 193077 (WN6) given by Koenigsberger (1990b) and from the line list of Kelly & Palumbo (1975) and Striganov & Svetitskii (1968). As usual, a very large range in ionization potentials (Fe II–Fe VI, for example) is present.

3.2. *The O Star Spectrum*

We have one spectrum (SWP 33227) taken at an orbital phase when the O star is "in front" of the W-R. Although this spectrum is very noisy at the short-wavelength portion, it is possible to identify numerous absorption features which could be attributed to photospheric lines arising in the O star. These are listed in Table 6 together with their equivalent widths. Many of these may have a strong contribution from interstellar absorptions. Also, the wind of the companion may be significant enough to produce P Cygni profiles in lines such as C IV.

The line at 1502 is a strong absorption feature in dwarfs and giants from O3 to O7, while in the supergiants it remains strong up to O9.7. It is evident in O8 V nitrogen-enhanced stars, and it turns into a P Cyg line at WN-A's (Walborn, Nichols-Bohlin, & Panek 1985). Feibelman & Bruhweiler (1989) were unable to identify this line, at 1501.49 Å in the spectrum of the planetary nebula nucleus of PN 75+351. Its presence would be consistent with the O5 optical classification of the companion in HD E311884.

3.3. *Variability*

The spectrum of HDE 311884 undergoes phase-related variations very similar to those observed in other WN + O binary systems such as V444 Cyg, HD 211853, HD 186943, HD 90657, and HD 94546 (Koenigsberger & Auer 1985). Most of the variations can be interpreted in terms of wind eclipses: The strong lines N V 1240, N IV 1486, C IV 1550, He II 1640,

TABLE 5

EQUIVALENT WIDTHS (Å)

SWP	Phase	C IVa	C IVe	N IVa	N IVe	He IIe	N IV]	N Ve
33208	0.92	7.7	−10.3	3.7	−4.4	−20.2	−5.5	−7.1
33213	0.08	5.3	−10.9	(2.7)	−5.5	−21.8	−8.0	−8.3
33219	0.25	4.6	−17.9	1.8	−8.4	−19.8	−10.7	−5.3
33227	0.41	8.3	−9.2	2.5	−8.5	−25.6	−4.3	...
33243	0.88	6.5	−8.4	2.4	−7.5	−21.5	−7.1	−8.6
33255	0.04	6.9	−5.6	2.9	−4.8	−19.6	−4.2	...

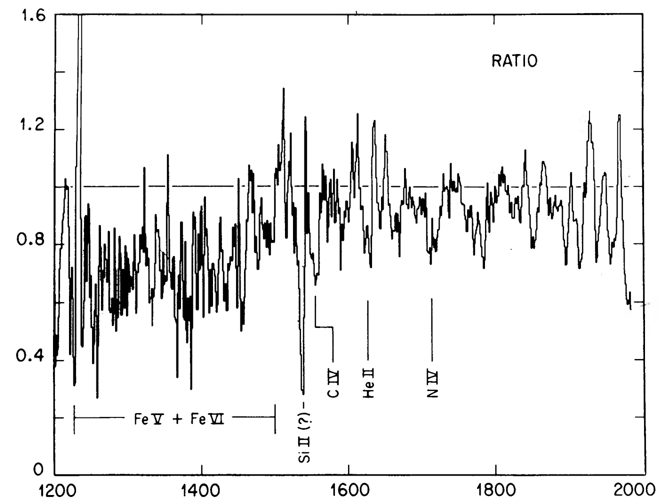

FIG. 3.—Ratio of spectra at atmospheric eclipse (Fig. 1*a*) and the five-point smoothed spectrum corresponding to orbital phase 0.25 (W-R receding from the observer). The effects of eclipse of the O-star continuum by Fe V + VI, C IV, He II, and N IV ions are marked. Other absorptions longward of 1750 Å appear to be due mostly to Fe II and Fe III blends.

and N IV 1718 become weaker at orbital phases 0.92–0.04, with respect to orbital phase 0.25, as expected if the W-R wind is eclipsing the O star's continuum. In Figures 2*a* and 2*b*, the individual, three-point smoothed spectra are displayed for the 1200–1700 and 1650–2000 Å wavelength ranges, respectively. In these figures we have placed vertical error bars, using the data of Table 3, near 1300, 1500, 1670, 1810, and 1950 Å to enable a more meaningful assessment of weak emission-line variations. Thus, for example, we may safely say the line at 1660 Å (Fe IV + Fe II + O III]) is very weak or absent at orbital phases 0.92 and 0.04, as compared with phase 0.25. Another example of weak variability is the line at 1520 (Si II + Fe II) which is absent at phase 0.41 while relatively strong at most other phases. In this case we are probably observing the effects of absorption by Si II ions in the wind of the O star.

The spectral range $\lambda < 1470$ Å is depressed during orbital phases 0.88–0.08 due to absorption/scattering by the Fe V and Fe VI pseudocontinua (see Koenigsberger 1988, 1990a). This is clearly shown in Figure 3, where we plot the following ratio: in the numerator is the sum of the four spectra obtained at orbital phases 0.88, 0.92, 0.04, and 0.08 (i.e., when the O star is "in back"), and in the denominator is the three-point smoothed spectrum taken at orbital phase 0.25 (i.e., when there is negligible W-R wind projected upon the O star). This phenomenon is common to all the Galactic WN + O binary systems with small enough separations, large enough orbital inclinations, and/or extended enough W-R winds observed with the *IUE* thus far. The signal-to-noise ratio is unfortunately too low to be able to analyze the relative Fe V/Fe VI distribution as a function of distance from the WR core, as has been done for the five other Galactic WN systems (Koenigsberger 1990a).

The spectra also undergo notable changes longward of 1750 Å which are probably associated with variations in lines of Fe II and Fe III, mostly. It is very interesting to note that only when there is a large velocity gradient along the line of sight to the O star does the absorption become so broad as to produce a pseudocontinuum. This occurs in Fe V and Fe VI, but not in Fe II–Fe IV, although these latter ions also produce lines which are very densely spaced in well-defined spectral regions. This leads to the conclusion that the W-R wind is no longer accelerating in those regions where Fe II–Fe IV prevail.

Finally, we should note the variations which occur on the shortward edge of the C IV 1550 P Cyg absorption component. The width of this feature becomes very large at phase 0.41, especially when compared with the profile at orbital phase 0.25, where an emission is very evident near 1533 Å. This emission is responsible for the strong apparent absorption at approximately 1533 Å in Figure 3 and is most likely due to Si II 1533. Note the almost P Cygni–looking feature in the spectrum of HD 211853 also at this wavelength. This makes measurements of terminal wind speeds derived from the C IV lines very unreliable.

4. CONCLUSIONS

In this paper we present the results of six *IUE* observations of WR 47, where the general phase-dependent variations are found to be similar to those observed in other WN + O binary systems.

We note that if it is the presence of Si II 1533 in absorption which is responsible for the enhanced width of the C IV 1550 P Cyg absorption component at certain orbital phases, then special attention should be given to the question of measuring terminal velocities in W-R winds in binaries using this line. In the case of HD 211853, this Si II line actually presents a P Cyg profile which seriously deforms the C IV absorption component.

HDE 311884 warrants careful attention, and a better set of UV observations in order to determine the characteristics of the W-R wind as well as of the O star companion. In particular, it would be highly desirable to obtain data with a high enough dispersion and signal-to-noise ratio to enable a study of the photospheric absorption lines arising in the O star companion. In addition, given the strong atmospheric eclipse observed in HDE 311884, it should be very interesting to compare the wind structure as derived from the profile variatons with that of other WN stars in which the same effect is observed.

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