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IUE OBSERVATIONS OF WOLF-RAYET BINARY SYSTEMS IN THE SMALL MAGELLANIC CLOUD

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ABSTRACT

The results of *IUE* observations of three SMC W-R binary systems at various orbital phases are presented. Selective atmospheric eclipse effects are evident in HD 5980 (WN 4 + O7 I:) and Sk 188 (W0 4 + O4 V), and are very weak or absent in Sk 108 (WN 3 + O6.5 I:). The difference in heavy-metal content between the SMC and Galactic objects is especially manifest in the lack of atmospheric eclipse effects due to a clustering of Fe v and Fe vi lines in the wavelength range 1360–1470 Å in HD 5980.

Subject headings: galaxies: Magellanic Clouds — stars: abundances — stars: binaries — stars: Wolf-Rayet — ultraviolet: spectra

I. INTRODUCTION

The Wolf-Rayet (W-R) stars present us with one of the most extreme examples of sustained mass loss through a stellar wind. Although radiation pressure on atomic lines is probably the major mechanism driving these winds, other additional mechanisms may be necessary to initiate such massive outflows. However, only the theory of radiation pressure has been extensively developed (e.g., Lucy and Solomon 1970; Castor, Abbott, and Klein 1975; Abbott 1982; Friend and Castor 1986). Other mechanisms which have been suggested as important in driving the winds include stellar rotation (Limber 1964; Sreenivasan and Wilson 1982), magnetic fields (Cassinelli 1982; Underhill 1984; Maheswaran and Cassinelli 1988; but see Nerney and Seuiss 1987), radial and nonradial pulsations (Maeder 1985; Vreux 1985; Castor 1986; but see Mathews and Beech 1987; Cox and Cahn 1988). Because of the controversy surrounding the effective temperatures of W-R stars, it is not clear what the relative importance of these additional mechanisms might be, when compared to radiation pressure. If W-R stars in general are as hot as suggested by the results of Rublev (1975) and Cherepashchuk, Eaton, and Khaliullin (1981; see also Eaton, Cherepashchuk, and Khaliullin 1985*a*), then radiation pressure alone may suffice (Pauldrach *et al.* 1985).

It is important to note that while stellar rotation, magnetic fields, and pulsational instability are intrinsic factors which are peculiar to each individual star, the magnitude of the effects of radiation pressure can be thought of more in terms of a global property. This property is related to the ambient metallicity; i.e., there is a dependence of mass-loss rate due to radiation pressure on spectral lines, on the abundance of heavy elements (Abbott 1982). Evidence in favor of this effect is found from a comparison of the stellar winds in early-type stars of the Galaxy with those of the Magellanic Clouds (see Hutchings 1980; Garmany and Conti 1985). Thus, if radiation pressure dominates as a mechanism for driving the flow in W-R stars, then one might expect to find a correlation between the metallicity and the magnitude of the mass-loss rate. Furthermore, the structure [i.e., $v(r)$, $N(r)$, $T(r)$] of the stellar winds of metal-rich and metal-poor W-R stars may be significantly different. Recent models by Kudritzki, Pauldrach, and Puls (1987) do indeed show this to be the case for O stars with differing metallicities.

It could be argued that since W-R winds presumably contain nuclear processed material, the difference between heavy-element abundances in Galactic and SMC W-R stars would not be as great as in the case of O stars. However, this is true only for elements such as He and C, the direct products of H- and He-burning, respectively. As illustrated by Abbott (1982), some of the more important elements in driving the wind are those which are not synthesized in the early stages of stellar evolution.

A very useful tool for probing the wind structure in W-R stars is that of selective atmospheric eclipses in binary systems in which the companion (usually a luminous O-type star) traverses behind a significant portion of the W-R star's wind during its orbit. Thus, the intervening wind absorbs the continuum radiation of the companion at selected wavelengths, the strength of the absorption being proportional to the column density of material. This mechanism was first identified by Munch (1950) to be responsible for emission line profile variations in V444 Cyg, and provides a tool for empirically determining wind characteristics (see Khaliullin and Cherpashchuk 1976, and references therein; Koenigsberger 1983; Koenigsberger and Auer 1985; Eaton *et al.* 1985*a*, *b*). The phenomenon of atmospheric eclipses in W-R stars was first discussed by Kopal and Shapley (1946), who derived the opacity distribution of the W-R wind as a function of radius for V 444 Cyg, although these authors treated the effects on the continuum radiation only.

In a previous paper (Koenigsberger and Auer 1985) we reported the phase-dependent variations which occur in the lines of the UV (1200–2000 Å) spectra of Galactic WN + O

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binary systems. The dominant mechanism responsible for the variations was found to be selective atmospheric eclipses of the luminous O star's disk by the W-R star's wind.

In this paper we extend this study to three W-R binary systems in the Small Magellanic Cloud, where the ambient heavy-metal abundances are significantly lower than those in the Galaxy. The objectives of the present observations were to determine whether selective atmospheric eclipses occur and, when they do, search for differences between the variability in SMC and Galactic binary systems. The three systems studied are the brightest W-R stars in the SMC: HD 5980 = AB5, Sk 108 = AB6 = R31, and Sk 188 = AB8.

A preliminary report on the phase-dependent variations of HD 5980 compared with those of a Galactic system of similar type has been presented by Koenigsberger, Moffat, and Auer (1987).

II. OBSERVATIONS AND REDUCTIONS

a) IUE Observations

The *IUE* satellite and its instruments have been described by Boggess *et al.* (1978*a*, *b*). The UV observations were made with the short-wavelength prime (SWP) camera, in low-dispersion mode with the large aperture during the NASA/US2 (high background radiation) shifts. Exposure times were typically 6, 10, and 16 minutes, respectively, for the three stars and were chosen to optimize the count levels in the continua at wavelengths longer than 1350 Å. Thus, the strongest emission-line peaks are often partly saturated, as are the continua shortward of 1350 Å. Each binary system was generally observed at least once in each of eight shifts, spread over the interval 1986 November 9–24. In addition, all previous UV observations of these three systems (both low and high resolution) were drawn from the archives of the National Space Science Data Center.

The standard extraction and reduction procedures available at the GSFC Regional Data Analysis Facility (RDAF) were employed. The equivalent widths were measured only on the low-dispersion spectra, due to the difficulty in establishing a reliable continuum level on high-dispersion *IUE* spectra. The full widths at half-intensity maximum (FWHM) of the lines were obtained by fitting a Gaussian profile.

The fine error sensor (FES) measurements were converted to a visual magnitude scale using the calibration of Imhoff and Wasatonic (1986).

b) Optical Observations

Spectra of Sk 108 on the optical region (4000–5000 Å) were obtained by AFJM with the IDS at the 1.5 m ESO telescope on 1982 December (see Moffat, Seggewiss, and Shara 1985, for details of this equipment). The journal of observations is presented in Table 3.

III. RESULTS

The orbital parameters of the three binary systems are listed in Table 1.

Strong, phase-dependent variations were observed in HD 5980 and Sk 188, similar to those which occur in the Galactic systems, resulting from selective atmospheric eclipse. In Sk 108 the phase-dependent variations show a different behavior. We now discuss each system in detail separately.

a) HD 5980

The oribital elements have been determined from optical investigations (see Breysacher and Perrier 1980, hereafter BP; Breysacher, Moffat, and Niemela 1982). Figure 1 illustrates schematically the geometrical setting of this system.

The description of previous *IUE* observations of this system did not approach the question of variability, probably because these observations did not include spectra obtained near orbital phase 0.36, when the O star is on the far side of the W-R wind. As we shall show below, it is at these phases that the strongest changes occur in the spectra.

The UV data for this system consist of 12 new and five archival low-resolution images, and seven archival high-resolution images. A useful phase coverage was achieved among the new low but not the archival high dispersion spectra. In Table 2A we list the low-dispersion SWP number, the observation date, and the orbital phase computed with the ephemeris of BP. Furthermore, column (4) indicates the portion of the spectrum which was exposed beyond the optimum count levels, often all the spectrum below 1350 Å and the peak of the He II λ1640 line. The overexposed portions of the spectra are automatically calibrated with an extrapolated intensity transfer function. We find the resulting absolute fluxes on the overexposed portions of the spectra to be overestimated by $\sim$10%–15%, as indicated by ratios of two consecutive spectra of the same star, such as SWP 29673 and SWP 29674. Columns (5)–(9) of Table 2A contain, respectively, the equivalent widths of C IV λ1550, N IV λ1718 (absorption and emission components) and He II λ1640 (emission component).

Table 2B contains the measured continuum flux in the wavelength region 1760 Å, the FES visual band counts, and the corresponding magnitudes.

An interesting aspect in the UV spectrum of HD 5980 is the apparent weakness of the Si IV λ1400 P Cygni line, given that the companion is classified as an O7 I. Sekiguchi and Anderson (1987) illustrate the relationship between the equivalent widths of the Si IV absorption and emission components as a function of spectral type and class in Galactic OB stars. If we assume that the Si IV feature in HD 5980 arises only in the O star, its intrinsic equivalent widths may be estimated from $W_2 = W_{tot}(F_{c1}/F_{c2} + 1)$, where F_{c1}/F_{c2} is the ratio of W-R to O

TABLE 1

CHARACTERISTICS OF THE OBSERVED SMC BINARY SYSTEMS

System	Spectral Type	Period (days)	e	Initial Epoch (JD)	Source
HD 5980	WN 4 + O7 I:	19.266	0.49	2,443,159.771	1 (O star in front)
Sk 108	WN 3 + O6.5 I:	6.5380	0	2,443,477.23	2 (W-R star in front)
Sk 188	WO 4 + O4 V	16.644	0	2,444,985.1	3 (W-R star in front)

SOURCES.—(1) Breysacher and Perrier 1980. (2) Hutchings *et al.* 1984. (3) Moffat, Breysacher, and Seggewiss 1985.

TABLE 2A

LINE MEASUREMENTS FOR HD 5980

SWP	JULIAN DATE (−2,440,000)	t (minutes)	PHASE[a]	OVEREXPOSURE[b]	W (C IV)[c] Absorption (Å)	W (C IV)[c] Emission (Å)	W (N IV)[c] Absorption (Å)	W (N IV)[c] Emission (Å)	W (He II)[c] EMISSION (Å)
1598	3650.488	5	0.538	...	7.7	−5.7	1.1	−2.8	−12.7
11189[d].........	4634.557	13	0.601	...	8.7	−9.0	1.8	−4.1	−20.4
14112	4754.374	5	0.819	<1280, He II	6.2	−8.7	1.8	−5.1	−24.0
14135	4756.227	3	0.916	...	5.8	−7.5	1.5	−2.4	−24.3
14166	4758.822	3	0.051	...	7.7	−6.1	2.1	−2.4	−19.5
29633	6743.674	6	0.074	<1340, He II	7.8	−6.6	1.6	−4.7	−21.8
29673	6748.884	5	0.344	He II	7.0	−8.8	2.2	−2.1	−28.6
29674	6748.911	8	0.346	<1380, He II	6.7	−7.7	2.3	−2.6	−26.0
29681	6749.716	6	0.388	<1380, He II	8.6	−4.9	2.4	−0.3	−21.8
29690	6750.835	6	0.446	<1350, He II	8.7	−4.3	2.7	−0.6	−21.7
29693	6750.935	6	0.451	<1350, He II	8.3	−4.2	2.5	−0.2	−21.5
29699	6751.849	6	0.498	<1380, He II	8.0	−5.9	2.2	−3.5	−23.5
29702	6751.948	6	0.504	<1380, He II	7.6	−8.9	1.1:	−2.9	−23.0
29705	6752.667	5	0.541	<1320, He II	7.8	−7.0	2.1	−3.7	−25.0
29708	6752.770	5	0.546	<1330, He II	7.5	−7.4	2.3	−4.3	−25.6
29736	6757.882	5	0.812	<1320, He II	6.1	−10.0	2.1	−4.6	−29.0
29743	6758.693	5	0.854	<1320, He II	6.9	−7.5	2.1	−5.1	−30.8

[a] Orbital phase computed with the ephemeris of Breysacher and Perrier 1980.
[b] Portion of the spectrum which is overexposed; for He II this refers to top half of profile.
[c] Equivalent widths: positive is absorption, negative is emission.
[d] Small aperture (rest with large).

TABLE 2B

CONTINUUM MEASUREMENTS FOR HD 5980

SWP	Phase[a]	F_c(1760 Å)[b]	FES[c]	m(1760)[d]	m(FES)[e]
29633.........	0.074	1.9	341	+0.00	11.42
29673.........	0.344	1.6	294	+0.19	11.59
29674.........	0.346	1.5	299	+0.26	11.57
29681.........	0.388	1.7	321	+0.12	11.49
29690.........	0.446	1.8	337	+0.06	11.44
29693.........	0.451	2.0	334	−0.06	11.45
29699.........	0.498	1.8	345	+0.06	11.41
29702.........	0.504	2.0	351	−0.06	11.39
29705.........	0.541	1.9	346	0.00	11.41
29708.........	0.546	1.9	351	0.00	11.39
29736.........	0.812	1.8	358	+0.06	11.37
29743.........	0.854	1.9	349	0.00	11.40

[a] Orbital phase based on the ephemeris of Breysacher and Perrier 1980.
[b] Flux in units of 10^{-12} ergs cm^{-2} s^{-1} $Å^{-1}$.
[c] Fine error sensor counts out.
[d] Differential magnitude derived from values in col. (3).
[e] FES magnitudes based on the Imhoff and Wasatonic 1986 calibration.

TABLE 2C

WIDTHS OF LINES FOR HD 5980

SWP	C IV Absorption	C IV Emission	He II EMISSION	N IV Absorption	N IV Emission
1598.........	3.4	5.7	4.2	1.9	4.1:
11189.........	3.6	5.1	4.8	2.6	4.3
14112.........	2.9	3.7	4.6	2.4	4.5
14135.........	2.9	3.9	5.6	2.4	2.9
14166.........	3.4	4.0	4.5	2.8	2.1
29633.........	3.3	3.1	4.4	2.2	3.6
29673.........	3.1	4.0	4.5	2.6	2.7
29674.........	3.0	3.3	4.5	2.9	3.2
29681.........	3.6	3.0	4.1	2.8	0.9
29690.........	3.7	2.6	4.2	3.0	2.0
29693.........	3.5	3.5	4.1	2.2	1.3
29699.........	3.5	2.9	4.4	2.7	2.8
29702.........	3.3	5.4	4.6	1.7	3.0
29705.........	3.3	3.0	4.4	2.2	4.5
29708.........	3.2	4.8	4.5	2.1	5.5
29736.........	2.7	4.2	4.3	2.6	3.0
29743.........	3.1	3.1	4.5	2.1	3.8

NOTES.—Widths are values derived using the RDAF routine "WIDNET," given in Å. If the profile is Gaussian, FWHM = 2.354 × width.

TABLE 2D

HIGH-DISPERSION ARCHIVAL OBSERVATIONS

SWP	JULIAN DATE (−2,440,000)	PHASE	RELATIVE VELOCITY SHIFTS (km s^{-1}) N V λ1244	C IV λ1550	He II λ1640
4277.........	3921.134	0.57	0 = ref	0 = ref	0 = ref
4345.........	3927.617	0.91	−149	−124	−83
4958.........	3980.976	0.68	−158	−195	−82
11175.........	4632.338	0.49	+149:	0	−58 N V weak
11190.........	4634.593	0.60	+10	+67	+53 He II strong
15072.........	4869.518	0.80	−129	−103	−102 He II strong
15080.........	4870.519	0.85	−226	−118	−165 He II strong

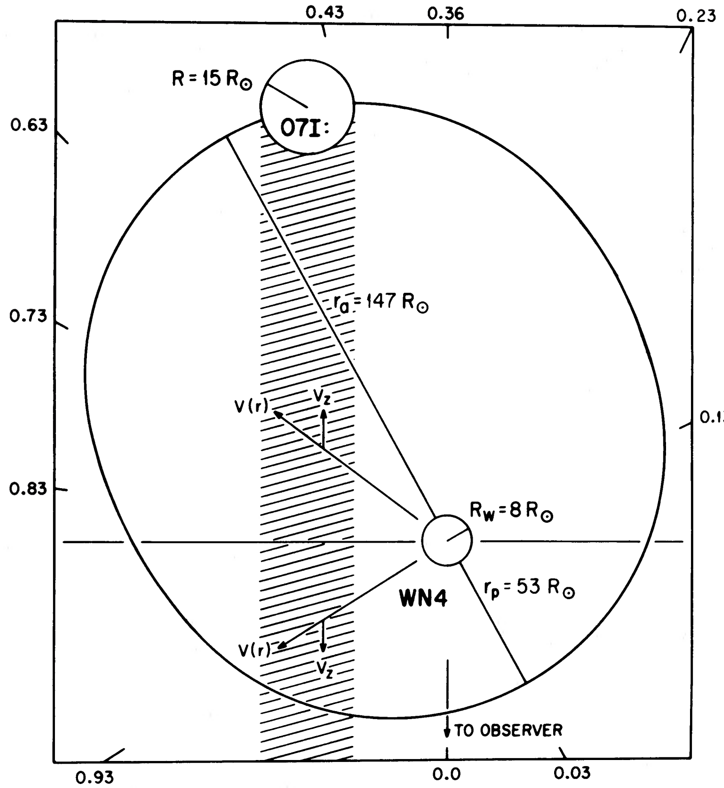

FIG. 1.—Geometry of the orbit of HD 5980. The marked orbital phases are marked at the corresponding position of the O star. Orbital phase zero in this system is set at primary eclipse, which occurs when the O star is in front of the W-R. We have assumed $R_w \approx 8\ R_\odot$ and $R_{\rm O7\,I} \approx 15\ R_\odot$ and have adopted $a = 100\ R_\odot$. The figure is scaled accordingly. The shaded column represents the portions of the W-R wind which are projected upon the O star's disk and are responsible for the atmosphere eclipse effects.

star continuum emission and $W_{\rm tot}$ is the measured equivalent width. In HD 5980, $W_{E_{\rm tot}} \approx 1.1$ Å and $W_{A_{\rm tot}} \leq 1.4$ Å, as measured from the mean low-dispersion spectrum (the average of the 12 1986 spectra). Using these values and the Sekiguchi and Anderson calibration, we find that the O star may indeed be an O7–O8 supergiant if $F_{c_1}/F_{c_2} \approx 4$. However, the uncertainties are significant: (1) as with most W-R star spectra, the proper continuum level is very difficult to determine for the W_A, W_E measurements; (2) the absorption component equivalent width is an upper limit since there is an important contribution to this feature from unresolved interstellar lines (see Savage and de Boer 1981; Hutchings 1982); (3) the Sekiguchi and Anderson calibration is based on a sample of Galactic stars.

i) *Continuum Light Curve*

One of the peculiarities of HD 5980 is its highly eccentric orbit ($e = 0.49$), with primary continuum eclipse (O-star in front) taken to coincide with phase 0.0, as illustrated in Figure 2*a*, where the BP light curve is reproduced. The width of the secondary eclipse at $\phi = 0.36$ is noteworthy. (The broad wings of the light curve provide a measure of the extent of electron scattering in the wind.) The depth of the optical secondary eclipse is ~ 0.22 mag.

The FES light curve (Fig. 2*b*) shows a clear minimum close to $\phi = 0.34$, with an estimated depth of eclipse of 0.19 mag. In Figure 2*c* we plot the monochromatic continuum flux representative of the wavelength region 1760 Å as a function of orbital phase. The continuum level was interpolated by eye, and flux values were converted to a relative magnitude scale using the value for SWP 29633 as a reference. This plot shows a minimum near $\phi = 0.35$, with an estimated amplitude of 0.22 mag. Although the number of data points is not sufficient to correct the BP orbital period, Figures 2*b* and 2*c* suggest that there is a shift in the minima of 0.01 in phase with respect to the BP light curve. This would imply an orbital period of 19.2645 ± 0.0005 days, which overlaps with the BP value of 19.266 ± 0.003 days to better than 1 σ. In this paper we will continue to use the phases derived from the BP period.

ii) *Variations of the UV Emission Lines*

The effects of selective atmospheric eclipse in this system are strong, as is evident from Figures 3*a* and 3*b*. As with the Galactic WN + O systems, the N IV λ1718 P Cygni structure changes drastically as the O star proceeds along the far side of the W-R wind, to the extent that it appears totally in absorption at $\phi = 0.45$ (Fig. 3*a*). Enhanced absorption is also present at the He II λ1640 and C IV λ1550 lines. However, the absorption that accompanies these changes in the Galactic systems at 1350–1470 Å (dominated by unresolved absorption lines of Fe V) is absent in HD 5980. This is a result of the lower heavy-metal abundances (the light "metals" such as C, N, O are probably less underabundant than Fe in HD 5980) in the SMC with respect to the Galaxy, and has been discussed in more detail by Koenigsberger, Moffat, and Auer (1987). We refer also to similar results for SMC cool supergiants by Spite and Spite (1987).

We also note the absence of a strong C IV spike in Figure 3*b*. According to Koenigsberger and Auer (1985), this spike in

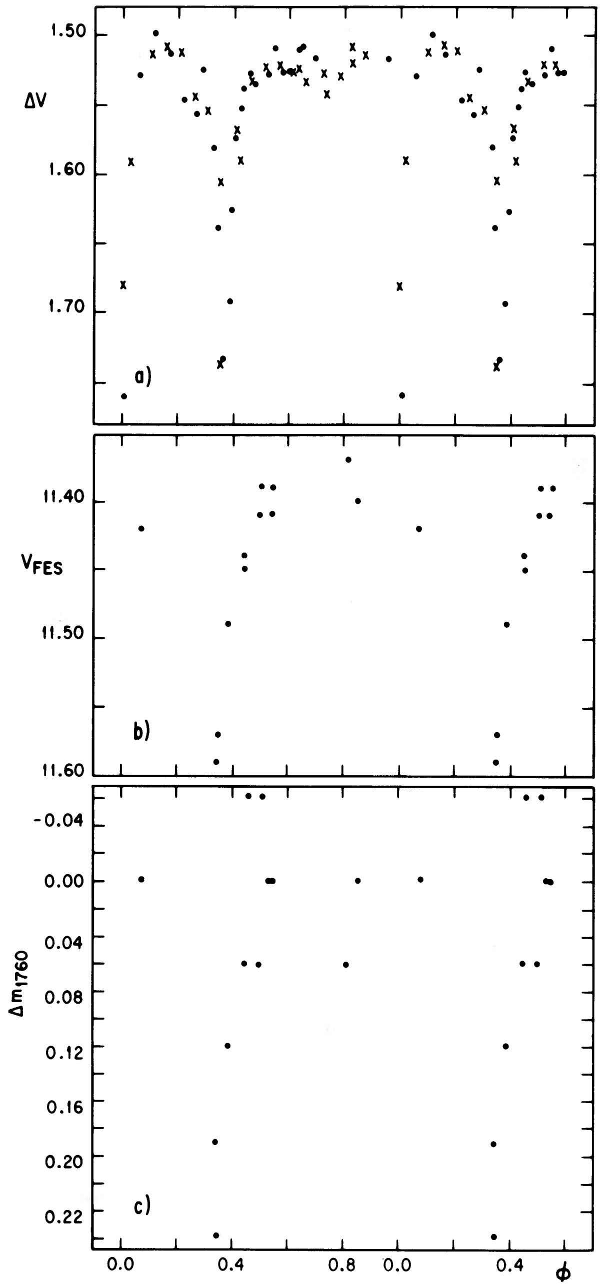

FIG. 2.—Continuum light curves of HD 5980: (*a*) visual magnitudes (taken from Breysacher and Perrier 1980); (*b*) FES counts converted to visual magnitudes using the Imhoff and Wassatonic (1981) calibration; (*c*) interpolated fluxes at $\lambda \approx 1760$ Å converted to a magnitude scale.

the ratio at phases when the O star is "in back" in the Galactic systems results from the wind-wind collision.

The selective atmospheric eclipse at 1718 Å is also viable on the high-resolution spectrum SWP 11175, which corresponds to orbital phase 0.49, when it is put into ratio with SWP 15080 (orbital phase 0.85), for example. The absorption which emerges in this ratio extends from 1715.9 to 1724.7 Å, corresponding to a velocity spread of 1700 km s^{-1}, centered at 1718.8 Å.

The equivalent widths listed in Table 2A are plotted as a function of the BP orbital phase in Figure 4. The large decrease in the emission components around phase 0.45 mostly reflects the superposition of absorption of the O star's continuum by the W-R wind. There is a significant decrease in He II and C IV emission line intensities also at phases near 0.0 (O star in front). The fact that the C IV absorption component is slightly enhanced at this phase might suggest that what is being observed is the atmospheric eclipse of the W-R disk by the O star's wind. However, this is in contradiction with the very weak Si IV feature, which indicates that the wind of the O7 I: star is not significant. Thus, the more likely interpretation is that the O7 I: star partially eclipses the W-R star's emitting wind (see Kuhi 1968 for an application of this type of eclipse).

It is noteworthy that the strongest absorption effects in the lines of HD 5980 are observed slightly after secondary eclipse ($\Delta\phi \approx 0.07$). In the Galactic system V444 Cyg, maximum line absorption also occurs after continuum eclipse of the O star by the WN 5 component, although $\Delta\phi \approx 0.03$ only (Eaton, Cherepashchuk, and Khaliullin 1985*a*). It is unfortunate that we do not have as broad a phase coverage of HD 5980 (spectra immediately prior to continuum eclipse are lacking) as available for V444 Cyg, and thus we can only speculate on an explanation for this phase shift. Given the geometry of the elliptical orbit, it is at these phases ($\phi \approx 0.4$) that the line of sight to the O star traverses the largest range in velocity components of the wind (see Fig. 1). This means that for each spectral line which presents absorption, the wavelength interval over which this absorption occurs is greatest at these phases. This explanation, however, is not applicable to V444 Cyg, since its orbit is circular. Thus, if phase shifts in both stars are to be attributed to similar phenomena, an alternative scenario is required; perhaps the most likely explanation lies in a change in the velocity/ionization structure of the W-R wind, such that the line opacity (for the lines visible in the *IUE* wavelength range) first increases due to ionization effects, and then decreases, due to density effects, as a function of distance from the star. This would lead to a line optical depth distribution which is similar to that arrived at by Castor (1970), through profile modeling techniques. In addition, an asymmetry is required at least in the case of V444 Cyg, since the strongest absorption occurs only after primary eclipse, and not before. This may be related to the wind-wind interaction effects which might be expected in such a system (Prilutskii and Usov 1976; see also Shore and Brown 1988). Such an interaction, however does not seem very likely to be a dominant effect in HD 5980, given the relatively large orbital separation.

Figure 5*a*–5*c* show a plot as a function of orbital phase of the UV emission-line half-widths obtained by fitting a Gaussian profile with the RDAF software routine WIDNET, and Figure 5*d* shows the half-width of He II λ4686, using the data of Breysacher, Moffat, and Niemela (1982). The UV lines show the same trend as He II λ4686, i.e., the width of the lines decreases at conjunctions, with respect to elongations. A similar but less pronounced phenomenon is known to occur in CQ Cep (Hiltner 1950; Stickland *et al.* 1984). In the case of eclipsing, or nearly eclipsing binary systems, it is easy to understand why this effect is present: the width of a line depends upon the maximum line-of-sight velocity components of the wind. When the O star is between the observer and the W-R star, it is physically blocking the line of sight to those portions of the wind which have the highest velocity components along the line of sight. Thus, the line appears to be narrower. When the W-R star is between the observer and the O star, selective atmospheric eclipses will also tend to make the line narrower.

b) *Sk 108*

i) *Optical Observations*

This system has been studied at optical wavelengths by Moffat (1982) and by Hutchings *et al.* (1984). The journal of observations of the new IDS optical spectroscopy is given in Table 3. The mean fluxed IDS optical spectrum is presented in Figure 6, where the spectral types of both components are confirmed: N v is stronger than N iv and N iii (=WN 3; Smith 1968), while the ratio of He ii λ4541 to He i λ4471 absorption lines indicates that the companion is close to O6.

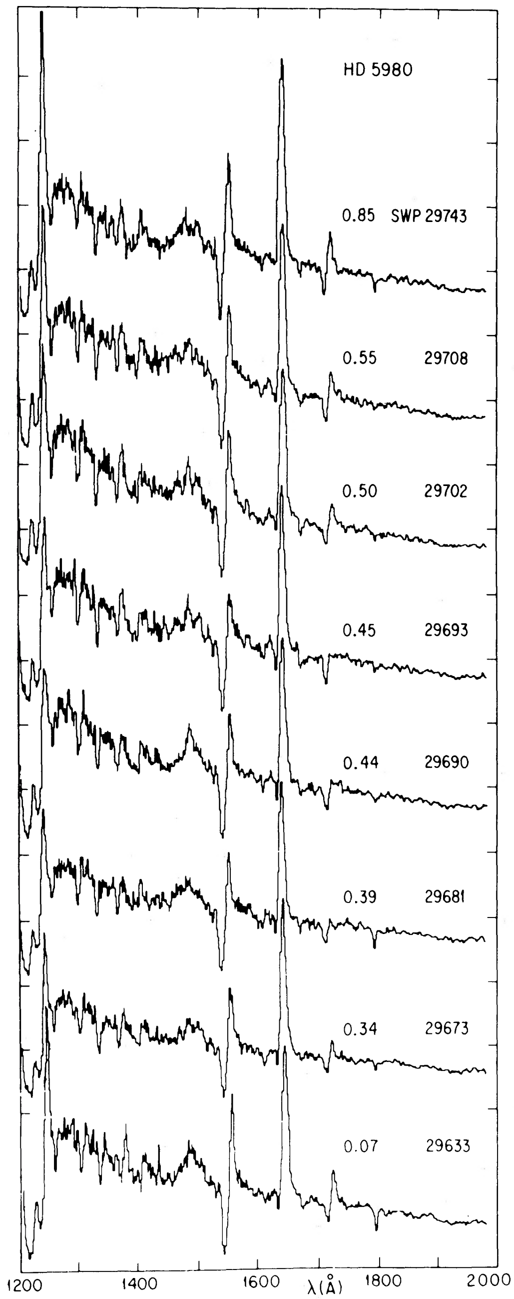

FIG. 3*a*

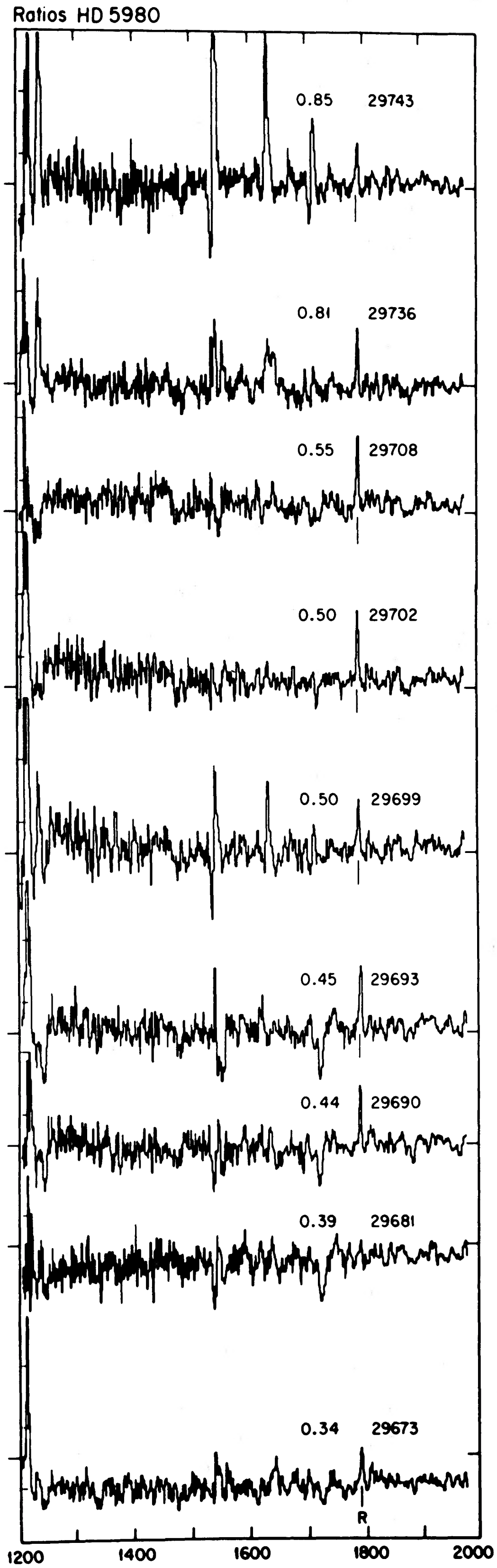

FIG. 3*b*

FIG. 3.—(*a*) Individual low-dispersion spectra of HD 5980 placed in order of increasing orbital phase. Note the strong change in N iv λ1718, with the strongest effect occurring at $\phi \approx 0.43$. The feature at 1800 Å is a reseau mark. (*b*) Ratios of the spectra taken with SWP 29633 in the denominator.

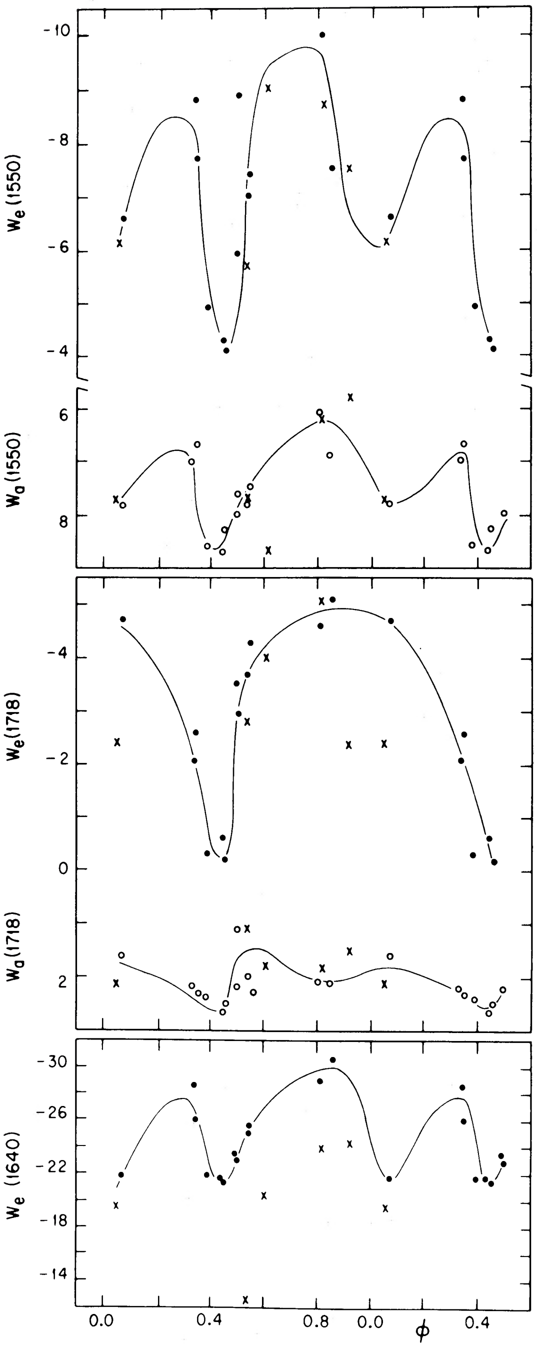

FIG. 4.—Equivalent widths of lines in the low-dispersion spectra of HD 5980 plotted as a function of orbital phase: (a) C IV λ1550 and N IV λ1718 (emission and absorption components); (c) He II λ1640 (emission only). Negative W_e corresponds to emission, and positive W_e to absorption. Circles represent observations obtained in the 1986 sessions, while crosses represent archival data. Curves are a hand-drawn estimate of the trend in the data.

One apparent peculiarity in the absorption spectrum is that the equivalent width of Hβ [W(Hβ) = 1.23 Å] is smaller than that of Hγ [W(Hγ) = 1.85 Å] and Hδ[W(Hδ) = 1.48 Å]. This could be due to contamination of Hβ by nebular emission. Assuming that the observed Hγ equivalent width is the intrinsic equivalent width of the O star, then, M_v(Hγ) = $-$6.2. Taking Hβ directly would make this brighter. The absolute magnitude of WN 3 stars is -3.9 ± 0.6 (σ), based on 26 LMC

TABLE 3

IDS SPECTROSCOPY OF SK 108

Julian Date (−2,440,000)	Phase[a]	RV (km s^{-1})	W_e (Å)[b]	FWHM (Å)
5310.556.........	0.411	+327	−9.0	26
5311.547.........	0.562	−37	−7.7	31
5313.539.........	0.867	+39	+8.3	32
5314.536.........	0.020	+488	−7.0	26
5315.538.........	0.173	+654	−9.8	30

[a] From Hutchings *et al.* 1984.

[b] Mean absorption line equivalent widths: W_a(Hβ) = 1.23 Å; W_a(Hγ) = 1.85 Å; W_a(Hδ) = 1.48 Å.

stars (Breysacher 1986). Thus, the optical observations alone indicate that the O star is probably a supergiant, as already noted by Moffat (1982), who, however, noted that the prime luminosity indicator Si IV λ4089/He II λ4143 appears to contradict high luminosity (Ia). (See also below.)

In Figure 7 we plot the radial velocity (RV), equivalent width (W_e), and full width at half-maximum (FWHM) of the He II λ4686 emission line as a function of orbital phase. The RV curve is very similar to that of Hutchings *et al.* (1984), except for a 0.05 phase shift which may be due to an insufficiently precise ephemeris. There is no evidence for large phase-dependent variations on the FWHM or W_e in He II λ4686 as in HD 5980. Figure 7 does, however, show a possible low-amplitude dip at $\phi = 0$ (W-R star infront). Thus, strong perturbation effects are not evident. However, the orbital inclination is apparently large enough to yield a 0.03 mag dip in the light curve (Seggewiss 1988) at orbital phase $\phi = 0$. This is typical of W-R + O systems (Lamontagne and Moffat 1987) and can be attributed to varying electron scattering opacity in the W-R wind as the O star orbits within the wind. The FES light curve, shown in Figure 8, reveals a similar trend.

ii) *IUE Observations*

The existing *IUE* data are listed in Table 4. Sk 108 was observed with *IUE* by Hutchings (1980), 1982) within his program of spectroscopy of Magellanic Cloud Stars.

1. *Spectrum.*—As for lines in the optical spectrum, the UV line spectrum is very diluted. The only emission lines which are clearly present in the low-dispersion spectra are N V λ1240, C IV λ1550, and He II λ1640. At high dispersion (SWP 15908, $\phi = 0.31$), there is a very weak emission line at 1722 Å, with a shortward shifted absorption having an estimated total width of 900 km s^{-1}. A similar shortward-shifted absorption is present at 1640 Å, with an estimated total width of 500 km s^{-1}. Taking the interstellar C IV λ1548 absorption as a reference point, the estimated total width of the corresponding P Cyg absorption is 1600–2000 km s^{-1}, depending on how the coninuum level is chosen. This large difference in implied wind speeds could be associated with optical depth effects if the N IV ion density is much smaller than the C IV ion density in the WN star (note that the ionization potential of N IV is larger than that of C IV, and we are dealing with a WN 3 star, where N V dominates). However, a more plausible interpretation is that the C IV P Cyg absorption originates primarily in the O star's wind, while the N IV and He II P Cyg absorptions are intrinsic to the W-R star (see also below). Note that the implied terminal speed for the O-star wind is consistent with values obtained by Garmany and Conti (1985) for SMC O stars. The largest values for the equivalent widths of the Si IV emission and absorption components are, respectively, $W_E = 0.7$ Å and

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TABLE 4

IUE OBSERVATIONS OF Sk 108

SWP	JULIAN DATE (−2,440,000)	t^a	m(FES)	PHASE[b]	He II W_e (Å)	He II Width (Å)	C IV W_e ON RATIO OF SWP/SWP 29675
2954	3794.975	15	...	0.600	−4.3	5.6	−2.3
4925	3976.023	10	...	0.291	−2.6	4.8	−3.6
6965	4170.472	11	...	0.033	−4.4	7.7	−3.7
20635	6743.765	10	12.25	0.623	−5.8	6.5	−1.8
29636	6743.787	7	12.25	0.626	−3.5	5.1	−2.8
29675	6748.946	10	12.27	0.415	−4.2	4.8	[0.0][c]
29692	6750.904	10	12.28	0.715	−3.8	6.1	−1.5
29701	6751.920	10	12.28	0.870	−4.3	6.4	−2.7
29707	6752.737	10	12.31	0.995	−3.7	6.0	−3.6:
29738	6757.951	5	12.27	0.793	−3.5	5.3	−1.3
29745	6758.774	10	12.25	0.919	−4.7	5.2	−3.6
4926[d]	3976.083	300	...	0.301			
15908[d]	4969.950	354	...	0.314			

[a] Exposure time in minutes: overexposed below 1350 Å on all 1986 spectra of 10 minutes.
[b] Orbital phase computed with ephemeris of Hutchings *et al.* 1984.
[c] Reference spectrum.
[d] High dispersion.

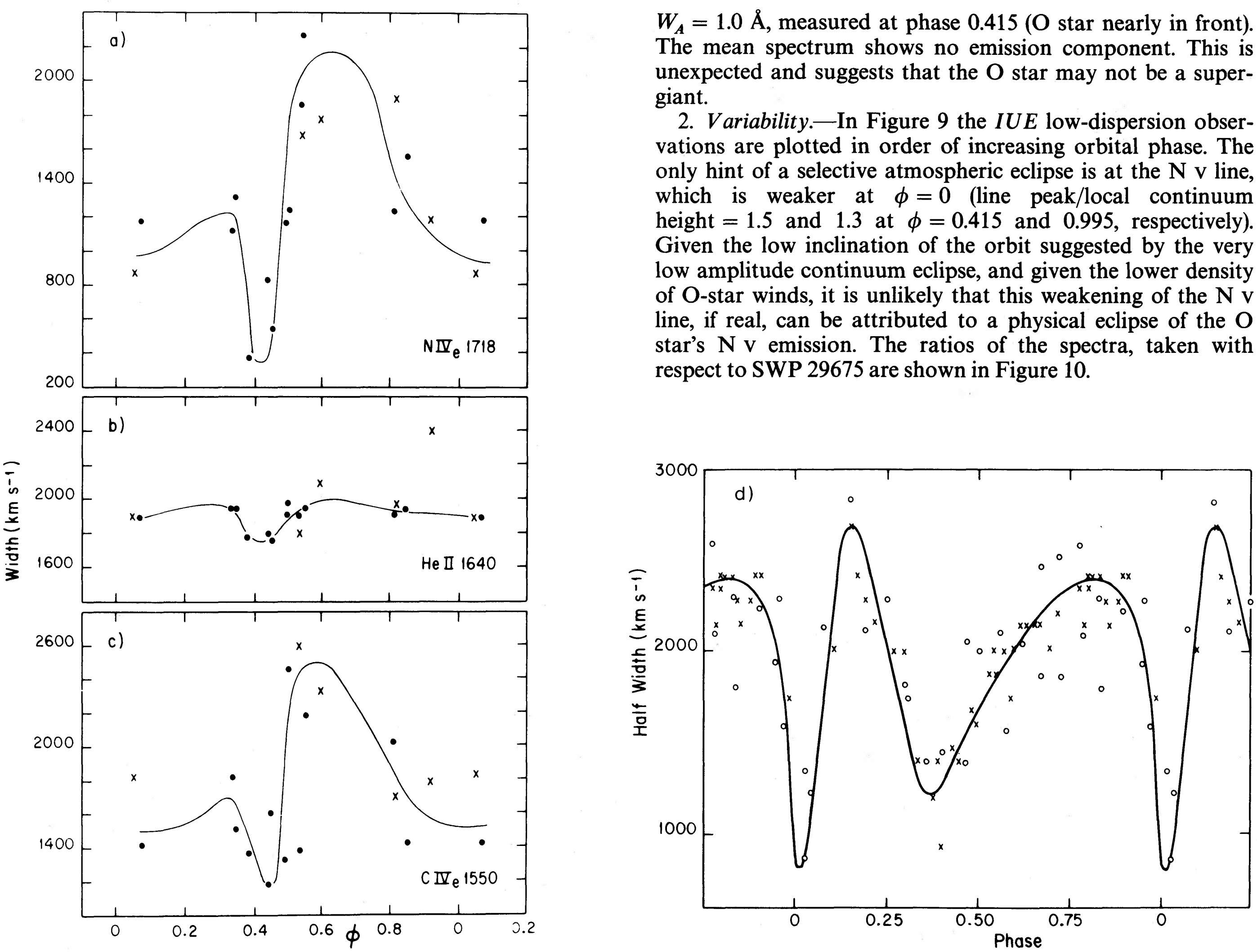

FIG. 5.—(*a*)–(*c*) Plot as a function of orbital phase of UV emission half-widths (FWHM = 2.354 × width if profile is Gaussian), and (*d*) the half-width of He II λ4686, from Breysacher, Moffat, and Niemela (1982). Hand-drawn curves represent a conjecture as to the behavior of the lines.

W_A = 1.0 Å, measured at phase 0.415 (O star nearly in front). The mean spectrum shows no emission component. This is unexpected and suggests that the O star may not be a supergiant.

2. *Variability*.—In Figure 9 the *IUE* low-dispersion observations are plotted in order of increasing orbital phase. The only hint of a selective atmospheric eclipse is at the N V line, which is weaker at $\phi = 0$ (line peak/local continuum height = 1.5 and 1.3 at $\phi = 0.415$ and 0.995, respectively). Given the low inclination of the orbit suggested by the very low amplitude continuum eclipse, and given the lower density of O-star winds, it is unlikely that this weakening of the N V line, if real, can be attributed to a physical eclipse of the O star's N V emission. The ratios of the spectra, taken with respect to SWP 29675 are shown in Figure 10.

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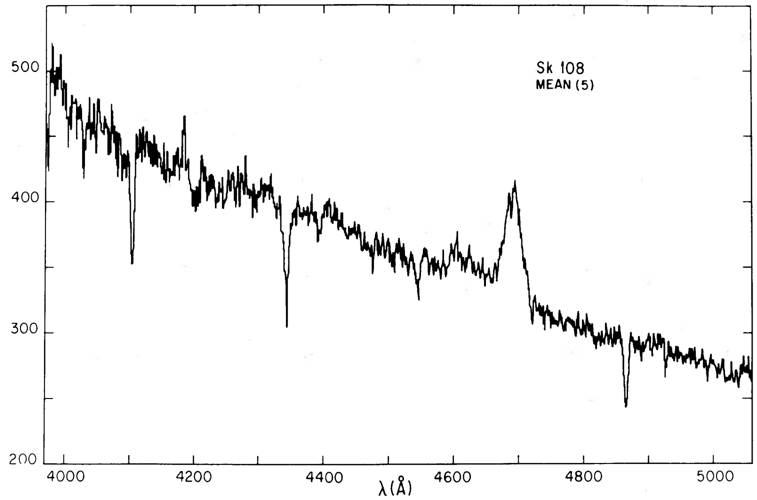

FIG. 6.—Mean IDS optical spectrum of Sk 108. The ordinate is in units of 2×10^{16} ergs cm^{-2} s^{-1} Å^{-1}.

Similar "nonvariability" has been noted by Auer, Colomé, and Koenigsberger (1988) in low-dispersion *IUE* spectra of the Galactic WC + O system HD 97152. This system has a small orbital inclinations ($i \sim 45°$; St-Louis *et al.* 1987), but very strong emission lines, leading to very weak atmospheric eclipse effects. Thus, pending a more detailed analysis of the orbital parameters of Sk 108, the main conclusion we draw is that the orbital inclination is also relatively small. However, if the 3% dip in the optical LC is indeed due to *e*-scattering of the O star's continuum by the W-R wind, then selective atmospheric eclipses are to be expected, since the opacity in lines is greater than that due to free electrons; however, these effects might be below the detection limit of the *IUE* data for lines other than N v λ1240.

Other variations seen in the present set of Sk 108 data are (1) the possible presence of a stronger C IV P Cyg absorption component at $\phi = 0.42$, relative to the other phases covered by our data (Fig. 9); and (2) a rapid change in the profile and equivalent width of He II λ1640 between the only two consecutive spectra of our set (SWP 29635 and 29636) (Figs. 11 and 12). With respect to the first point, Koenigsberger and Auer (1985) also found the C IV absorption component in Galactic WN + O systems to be stronger (and more extended) when the O star is in front rather than on the far side of the W-R wind. The implication of higher velocity (but lower density) winds in the O star member of the system is consistent with a similar conclusion derived by Garmany *et al.* (1981) and Bruhweiler, Parsons, and Wray (1982). With respect to the second point, we can only speculate at this time that this may be similar to

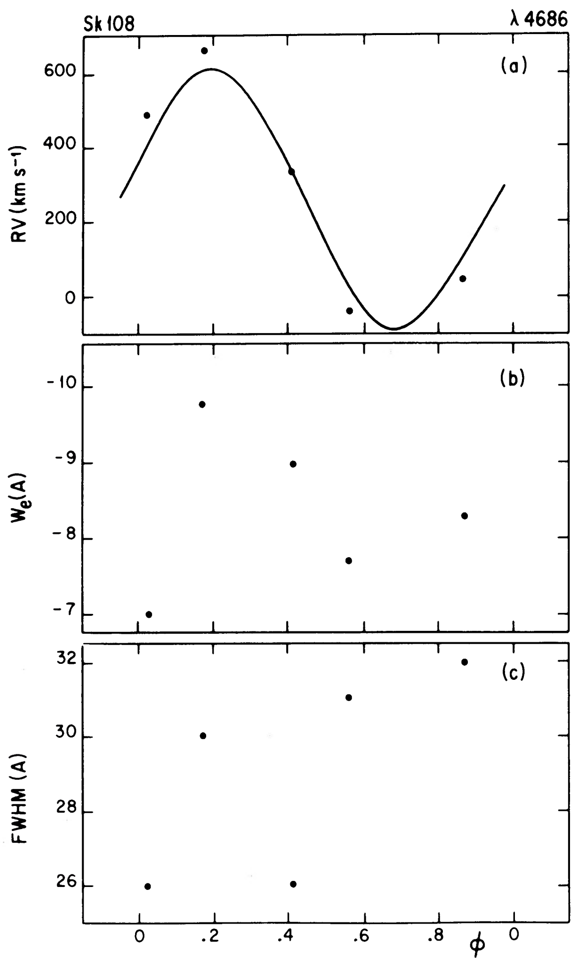

FIG. 7.—(*a*) Radial velocity (km s^{-1}) with the Hutchings *et al.* (1984) RV curve superposed, (*b*) equivalent width (Å), and (*c*) full width at half-maximum (Å) of the He II λ4686 emission line as a function of orbital phase for Sk 108.

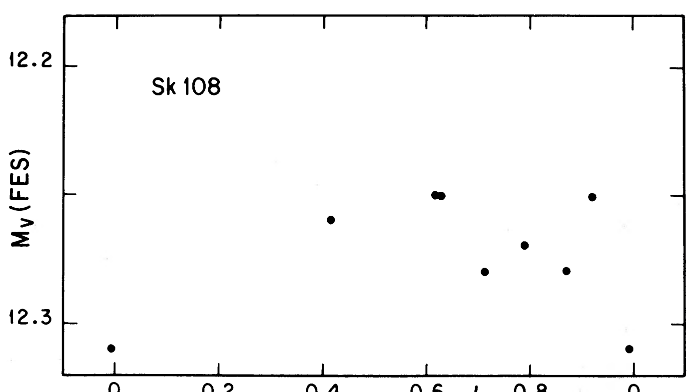

FIG. 8.—FES light curve of Sk 108 as in Fig. 2*b* for HD 5980

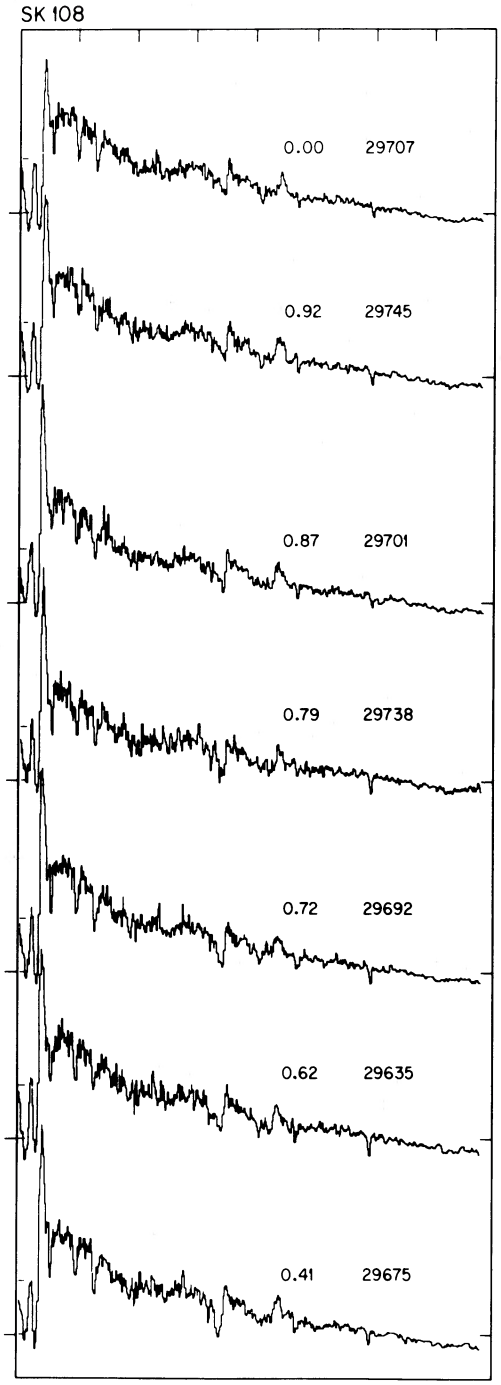

FIG. 9.—Individual low-dispersion spectra of Sk 108 placed in order of increasing orbital phase.

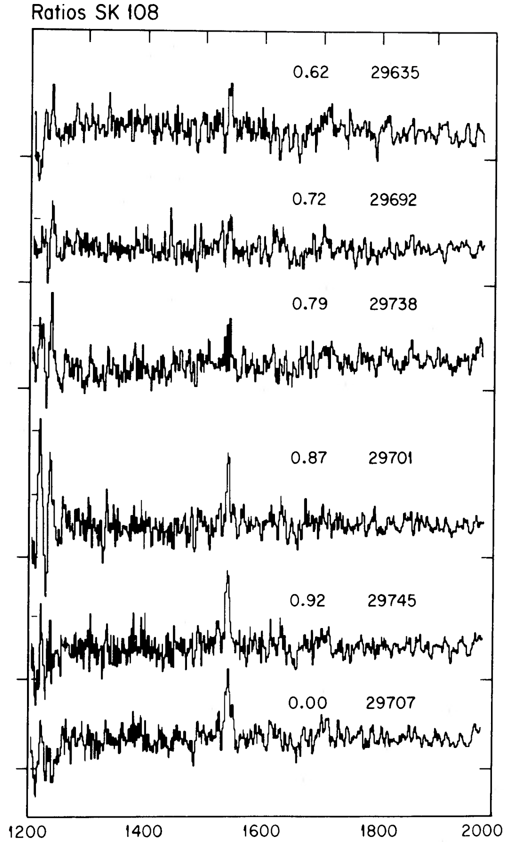

FIG. 10.—Ratio of low-dispersion spectra of Sk 108, taken with respect to SWP 29675, which corresponds to phase 0.41 (i.e., O star "in front").

the rapid variability that was seen on one occasion in the Galactic WN 4 + O system HD 90657 (Koenigsberger and Auer 1985), although one cannot exclude random errors at this level.

c) Sk 188

This is one of the four Population I WO stars known (Barlow and Hummer 1982), and the only spectroscopic binary among them (Moffat, Breysacher, and Seggewiss 1985). Table 5 contains the information from the *IUE* observations of this system.

i) *Spectrum*

The optical spectrum has been described by Breysacher and Westerlund (1978) and Moffat, Breysacher, and Seggewiss (1985). The latter classify the components of this system as WO4 + O4 V. *IUE* and optical spectra of this system are also discussed by Barlow and Hummer (1982) and Hutchings (1982).

The UV spectrum of Sk 188 is indeed spectacular: strong and broad emission lines are observed at 1170 Å (C III), 1243 Å (O V + C III), 1341–1345 Å (O IV), 1366–1371 (O V + ?), with weaker emission at 1640 Å (He II).

TABLE 5

IUE OBSERVATIONS OF Sk 188

SWP	Julian Date (−2,440,000)	*t* (min)	Phase	*m* (FES)
29634............	6743.722	20	0.661	12.89
29672............	6748.840	16	0.969	12.84
29680............	6749.681	16	0.019	12.87
29691............	6750.869	16	0.090	12.84
29700............	6751.883	16	0.151	12.82
29706............	6752.703	16	0.201	12.91
29737............	6757.917	16	0.514	12.87
29744............	6758.731	16	0.563	12.85
7623[a]...........	4248.880	400	0.767	...

[a] High dispersion.

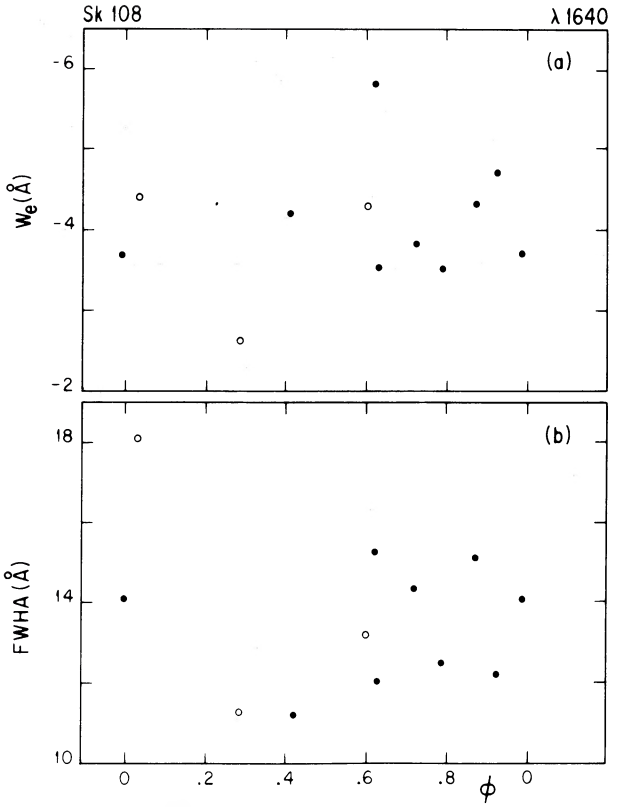

FIG. 11.—Plot of (*a*) the equivalent width and (*b*) the FWHM of He II λ1640 as a function of orbital phase for Sk 108. Open circles correspond to archival data.

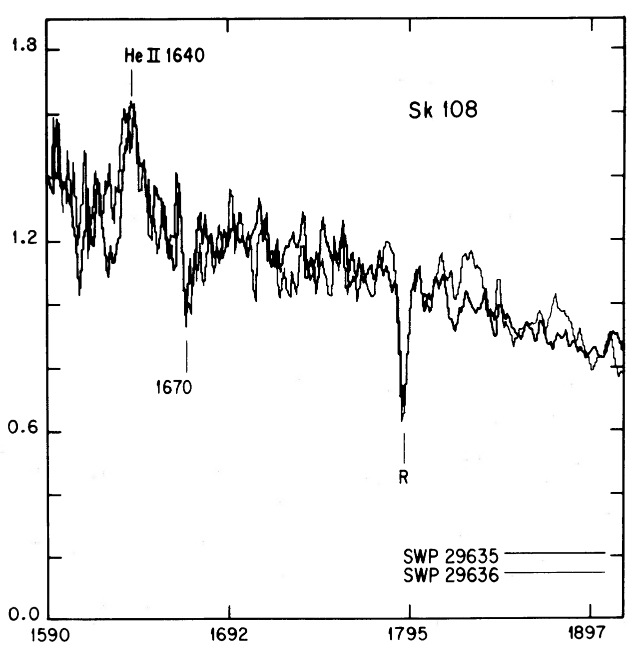

FIG. 12.—Comparison of two consecutive spectra of Sk 108 in the wavelength region longward of 1640 Å showing possible short–time scale variability.

The presence of photospheric absorptions at 1226–28 Å (Si II), 1640 Å (He II), and 1718 Å (N IV) arising in the O-star companion is inferred by their apparent disappearance at orbital phase 0.97, when the O star is eclipsed by the W-R star's wind. We might be seeing the effects of W-R wind electron scattering on the profiles of photospheric absorption of the O star, as detected by Munch (1950) during eclipses of the O star in V444 Cyg. That is, the absorption lines become shallower and broader near phase zero, thus making them effectively "disappear" (i.e., washed out) in our low-dispersion data.

ii) *Variability*

The FES magnitudes listed in Table 5 have the same trend with orbital phase as the light curve obtained by Moffat, Breysacher, and Seggewiss (1985), where maximum light occurs at $\phi = 0.0$ (W-R star in front).

The spectra, which cover orbital phases 0.97 through 0.00–0.66, are plotted in Figure 13. The gap in the data in SWP 29680 is due to a malfunction during data transmission which resulted in the loss of the data in this wavelength range.

Variations were detected in the lines at 1230, 1343, 1368, and 1550 Å. These variations are more evident in Figure 14, where the ratios of each spectrum divided by the spectrum corresponding to $\phi = 0.66$ (SWP 29634) are plotted. This latter image was the most strongly overexposed (see Table 5). The hatched regions indicate the location of the overexposed portions of SWP 29634 (at which extrapolated intensity transfer functions were applied during the data extraction procedure), and at which the absolute fluxes are not fully reliable. There is, however, no question of the reality of the variations observed at the emission-line wavelengths, since these correspond to variations of 30%–50%, much greater than the error introduced by the extrapolated ITF. Furthermore, there does not appear to be a discontinuity between the ratio values within and outside of the hatched regions in Figure 14.

The emission lines which are most strongly affected by the atmospheric eclipse are the lines of O IV λλ1338–43, O V λ1371, and C IV λ1550, i.e., those with the greatest intensity. It is interesting to note that He II λ1640 is not affected at all. This may result from a combination of an unfavorable orbital inclination and a very small representative radius for the He II emission, which is due to a reduced He abundance in this very evolved WC–type star.

IV. DISCUSSION AND CONCLUSION

We have presented the results of *IUE* observations of three W-R binary systems in the SMC. This is an extension of previous observations of Galactic W-R systems, the main objective of which is the search for, and interpretation of, phase-dependent spectral variability, leading to a better understanding of W-R stars and their strong winds. A pending paper in this series will deal with W-R systems in the LMC and will contain the final conclusions. Here we will just highlight the results of the current investigation.

As in the Galactic WR + O systems with large enough orbital inclinations, selective atmospheric eclipses are evident in HD 5980 and Sk 188. The apparent absence of this phenomenon in Sk 108 can be atrributed to (1) a combination of a weaker wind and small orbital inclination and (2) a very high degree of ionization, such that lines which are prone to selective atmospheric eclipse (such as N IV λ1718) are not present in the spectrum. We note that no known Galactic binary systems has a W-R component as hot as WN 3 (Massey 1981).

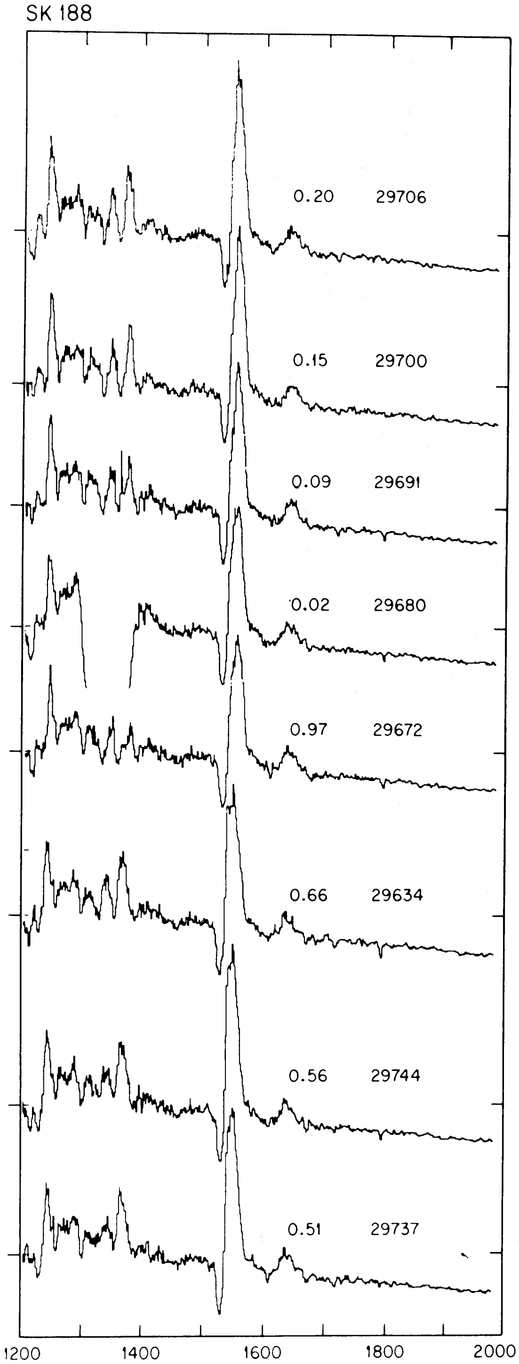

FIG. 13.—Individual spectra of Sk 188 placed in order of increasing orbital phase.

In HD 5980, the strongest selective atmospheric eclipse occurs after continuum eclipse of the O star, a phenomenon which also is seen in the galactic system V444 Cyg. This is a potentially important effect since it suggests a difference in the ionization structure of the inner portions of the W-R wind, as compared with regions further out, as well as a possibly non-spherically symmetric wind, at least in the case of V444 Cyg.

The major difference between the present SMC and the previous Galactic observations is the absence of atmospheric eclipse effects in the wavelength range 1350–1500 Å in HD 5980, as compared with its analogous Galactic counterparts. Given that this wavelength region contains a pseudo-continuum due to Fe v lines (Koenigsberger 1988), an estimate of the difference in Fe abundance in the SMC and Galactic W-R's can be derived (Koenigsberger, Moffat, and Auer 1987). There is also no evidence for the presence of a Fe pseudo-continuum opacity source in Sk 188, the other SMC system in which we observe atmospheric eclipses.

The importance of heavy-metal abundances in driving the winds through line radiation pressure and the much lower abundance of these elements in the SMC as compared to the Galaxy suggest that in HD 5980 radiation pressure may not be

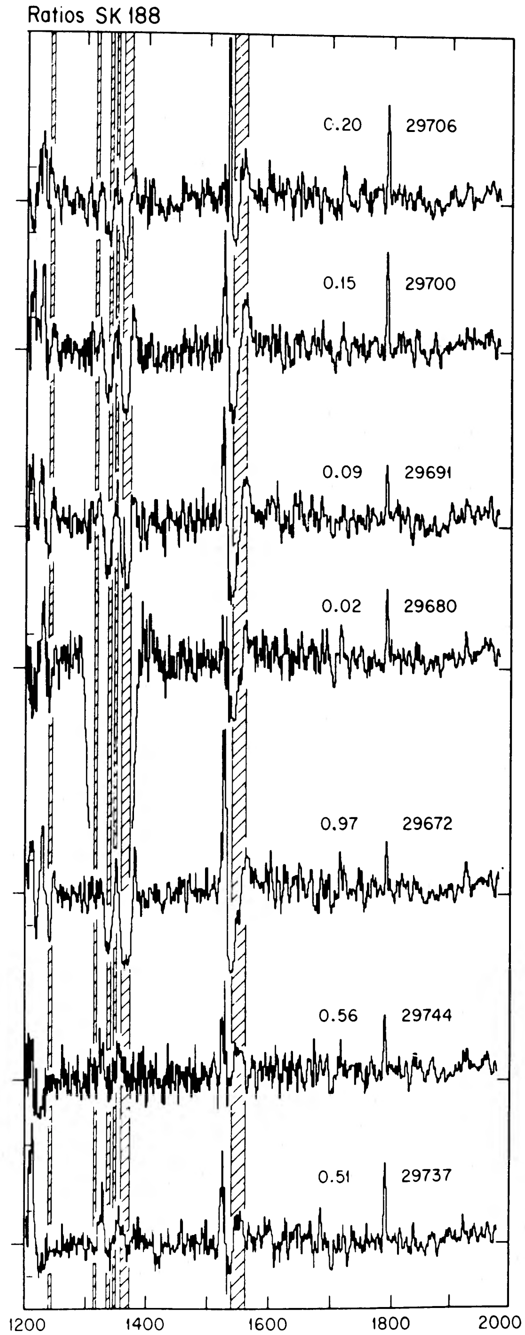

FIG. 14.—Ratios of the low-dispersion spectra of Sk 188 taken with respect to SWP 29634 (i.e., with respect to spectrum corresponding to orbital phase 0.66, when the O star is close to the near side of the W-R star). The gap in the data at phase 0.02 is due to a malfunction during the satellite data transmission.

the only mechanism responsible for the wind (assuming that the WN star is similar to its Galactic counterparts). On the other hand, the weak wind implied by the relatively weak emission lines in Sk 108 is consistent with the lower metal abundances.

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