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THE ERUPTING WOLF-RAYET BINARY HD 5980 IN THE SMALL MAGELLANIC CLOUD: SPECTRAL TRANSITION FROM B1.5Ia$^+$ TO WN6 AND THE ACCOMPANYING LIGHT CURVE.

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RESUMEN

En este artículo analizamos espectros de alta resolución obtenidos con el *IUE* del sistema HD 5980 cerca del máximo de la erupción y un año posterior a este máximo. Mostramos que el primer espectro de esta secuencia contiene líneas que son típicas de los espectros de estrellas B1.5Ia$^+$. Los siguientes espectros muestran un incremento sistemático en T_{eff} y contienen líneas en absorción de Fe IV y Fe V. Después de un año, el espectro tiene las características de una estrella WN6. Presentamos también las curvas de luz correspondientes a dos bandas del contínuo en el UV (1300 Å y 1850 Å) abarcando un período de un año a partir del máximo de la erupción en el visual. Estas curvas muestran la presencia de ambos eclipses del sistema binario.

ABSTRACT

In this paper we analyze the high dispersion *IUE* spectra of the erupting Wolf-Rayet system HD 5980 obtained shortly after the maximum in the optical light curve and one year later. We show that the earliest spectrum has features which are characteristic of B1.5Ia$^+$ spectra. Subsequent spectra indicate a photosphere which is gradually increasing its T_{eff}, containing Fe IV and Fe V absorption features, and becoming finally a WN6. We also present a UV light curve at two wavelength bands (1300 Å and 1850 Å) covering a year after maximum in the eruption, where both eclipses of the 19.3 day orbit are evident.

Key words: **BINARIES: ECLIPSING — STARS: INDIVIDUAL: (HD 5980) — STARS: VARIABLES: OTHER (LUMINOUS BLUE VARIABLES) — STARS: WOLF-RAYET — ULTRAVIOLET: SPECTROSCOPY**

1. INTRODUCTION

HD 5980 is one of the most fascinating systems one can encounter among massive stars. With a bolometric magnitude of 12.8 (Massey et al. 1989), it is the most luminous object in the SMC cluster NGC 346, and it contains at least two massive stars in a highly eccentric, eclipsing 19.3-day orbit. As a Wolf-Rayet star, it has made its way through the spectral types of the WN sequence ranging from WN3 to WN8, or perhaps even later, and, as we shall show in this paper, has even presented an early B-type spectrum. It has undergone an eruption in which its visual luminosity brightened by more than 3 magnitudes (Barbá et al. 1995; Cellone et al. 1996) with characteristics in its optical spectrum indicative of an LBV-type event. All these changes have occurred during the past 18 years and are the result of physical processes which have seriously disturbed the outer layers in at least one of the two eclipsing stars, driving it into a highly unstable state. HD 5980 may well challange the status of η Carinae as the most luminous and peculiar of the LBV's, and at the same time, may provide clues to understanding this object that has been called one of the most "disconcerting astrophysical objects" (Viotti 1995).

The preliminary events prior to the large eruption of HD 5980 in 1994 have been described by Koenigsberger et al. (1994; Paper I). General descriptions and characteristics of the eruption in the optical and in the UV regions have been reported, respectively, by Barbá et al. (1995) and Koenigsberger et al. (1995; Paper II). Because it is a multiple system, there is some uncertainty as to which of the stars is the unstable one. According to the arguments presented in Paper II, there is no question that the changes in the wind structure leading up to the eruption occurred within the 19.3-day eclipsing pair. There is, however, apparently contradictory evidence as to which of these two stars is undergoing the changes. In Paper II we argued in favor of the more luminous of the two stars (the one "in front" at orbital phase 0.36) and originally classified as WN4 by Breysacher, Moffat, & Niemela (1982) as being responsible for the changing wind structure. However, Barbá et al. (1995) conclude that the other star, the one in front of the system at phase 0.00, is responsible for the eruption because of the presence of emission lines in the optical spectrum which follow its orbital motion.

HD 5980 is a complicated system in which a variable (because of the eccentricity of the system) interaction of two stellar winds is present. Regardless of which of the two stars is the unstable one, the changes it is undergoing will produce changes in the interaction between the two stars. Thus, models involving the interaction between the two stars must be evaluated as possible scenarios that could reconcile the apparently contradictory evidence mentioned above. In this paper we will concentrate on identifying photospheric like absorption features in the high dispersion *IUE* spectra in order to associate a spectral type to the pseudophotosphere of the erupting star. A discussion of which star contains these features, however, will be deferred to a later time.

2. THE LIGHT CURVE

The Fine Error Sensor (FES) on board the *IUE* satellite provides count rates which can be converted to visual magnitudes through the calibrations of Imhoff & Wasatonic (1986) and Perez (1992). In addition, flux levels at selected continuum wavelength regions can be measured very reliably, particularly from the low-dispersion spectra, thus providing simultaneous visual and UV brightness values. In Figure 1a we present the visual (mostly FES) and UV (1850 Å) light curves of HD 5980 between 1978 and 1995, showing that there was a simultaneous brightening in both the visual and the UV spectral regions beginning in 1986, approximately. Prior to this, there are indications that the visual brightness was increasing while the UV brightness was decreasing. No *IUE* data exist between late 1991 and late 1994, when the maximum in the eruption occurred. The UV light curves at two wavelength regions (1300 Å and 1850 Å) following the eruption covering the time period between late 1994 and late 1995 are illustrated in Figure 1b (see Barbá et al., these proceedings, for the corresponding visual light curve). The data prior to 1992 (prior to HJD 2446800) and the 1994 data (HJD 2449674 to 2449720) are taken, respectively, from Paper I and Paper II. The post-eruption UV light curves can be divided into two portions: a) Between HJD 2449670 and 2449720 during which time interval there is a rapid decline followed by a less pronounced brightness increase. Here, the eclipses ("+" and "x") are evident only during the ascending branch of the 1300 Å light curve. b) Between HJD 2449830 and 2449990 there is gradual decrease in brightness in both wavelength bands, with the eclipses clearly present. It is unfortunate that due to satellite constraints, *IUE* was not able to observe HD 5980 between HJD 2449720 and 2449830, resulting in the gap in the data.

Although there is not sufficient data to cover properly the orbital cycle, if we combine all the 1995 data by normalizing flux values to unity for orbital phases $0.5 - 0.6$, we can estimate the average depth of the eclipses. We find that for the 1850 Å band which has less scatter, the primary minimum (orbital phase 0.0 according to the Breysacher & Perrier 1980 ephemeris) has a depth of ~ 0.18 mag while the secondary minimum has an average depth of 0.11 mag.

3. ANALYSIS OF THE UV LINE SPECTRUM

High dispersion *IUE* spectra were obtained in 1994 starting on HJD 2449680 until HJD 2449718 (7 spectra), and in 1995 from HJD 2449784 until HJD 2449987 (10 spectra). The 1994 *IUE* spectra differ markedly from

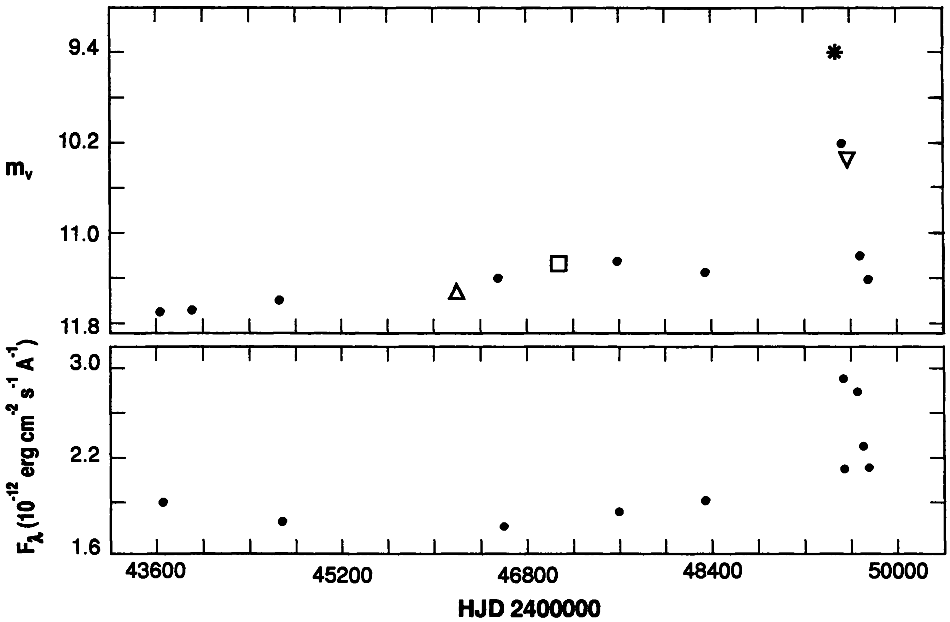

Fig. 1a. Visual (top) and UV (1850 Å) light curves of HD 5980 for 1978-1995. Filled-in circles correspond to *IUE* FES and UV data; asterisk represents data from Barbá et al. (1995), inverted triangle from M. Peña. Remaining symbols as is Paper I.

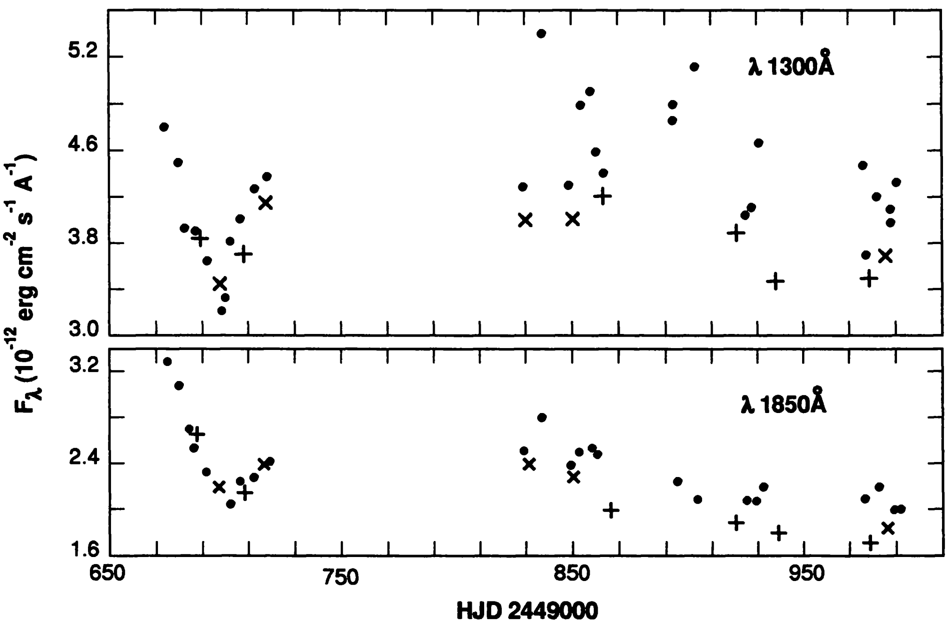

Fig. 1b. UV 1300 A (top) and 1850 light curves for data of 1995 from low dispersion *IUE* spectra. Different symbols represent orbital phases as follows: "x" → $0.28 < \phi < 0.39$; "+" → $0.98 < \phi < 0.05$; filled in circles: other phases.

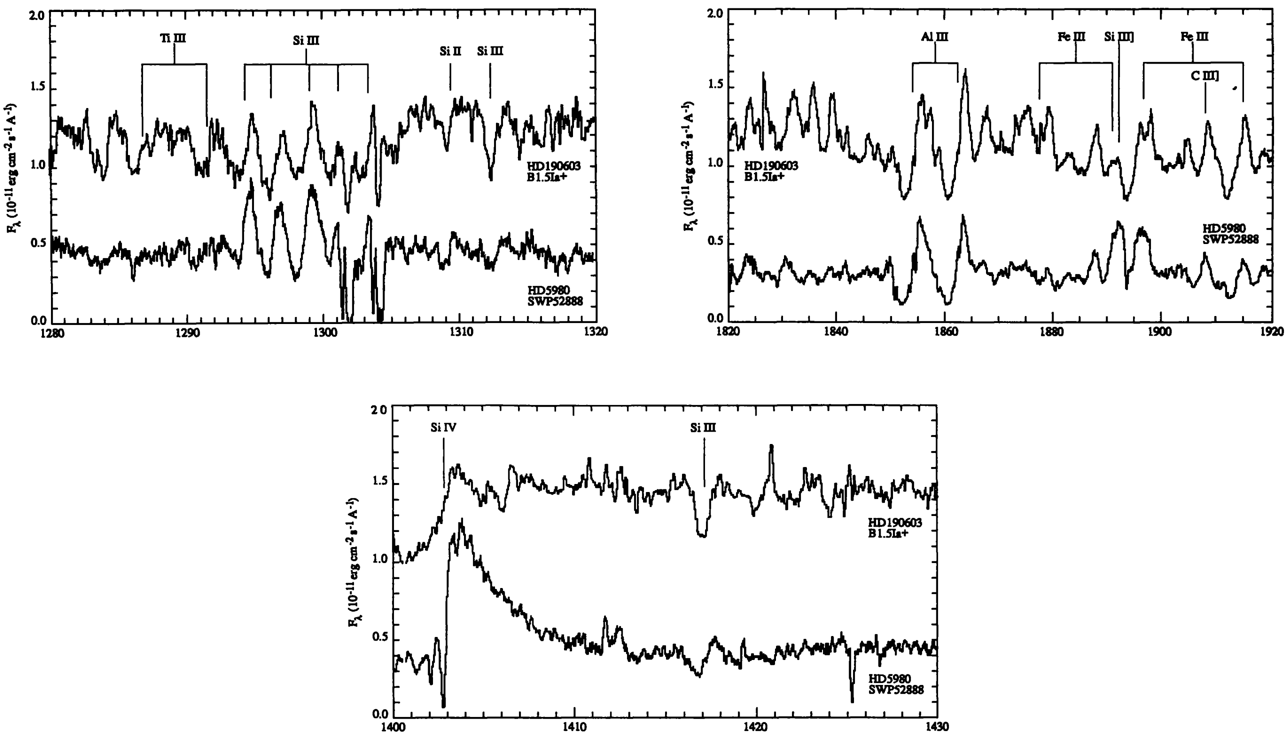

Fig. 2a,b,c. Selected spectral regions of the high dispersion spectra of HD 5980 (SWP 52888) and the B1.5Ia$^+$ star HD 190603. The wavelength scale of HD 5980 is shifted so as to account for the relative velocity of the SMC (+150 km s) with respect to the Sun. The spectrum of HD 190603 is shifted vertically by 8×10^{-12} erg cm^{-2} s^{-1} A^{-1} for display purposes. Tick marks indicate laboratory wavelength of line transitions, identified by the corresponding ionic species.

those obtained in 1991 and 1995, where the spectra show clear WR features corresponding to the WN sequence. In the next sections we describe the spectral characteristics in late 1994 and in late 1995.

3.1. The First 1994 Spectrum

In Figure 2 we present a selection of wavelength regions of the first of the high dispersion spectra obtained during the eruption, SWP 52888, plotted along with the spectrum of HD 190603 (SWP 1822), a B1.5Ia$^+$ star selected from the Atlas of *IUE* B-star spectra (Walborn et al. 1995). In this figure, as in all subsequent figures, the wavelength scale of HD 5980 has been shifted towards shorter wavelengths by an amount corresponding to -150 km s^{-1} to correct for the relative motion of the SMC with respect to the Sun, and the data have been smoothed by averaging 7 (3 for HD 190603) contiguous points. The spectrum of HD 190603 has been shifted vertically for clarity. No correction for interstellar reddening or flux degradation of the *IUE* has been applied.

Figure 2 illustrates similarities between this spectrum of HD 5980 and that of the B1.5 supergiant. The Si II and Si III lines which characterize UV spectra of B stars (Massa 1989) are clearly present in both spectra. In Table 1 we present equivalent widths of a few of the Si II, Si III, Si IV and Al III lines in HD 5980 and three comparison stars: HD 152236 (B1.5Ia$^+$; SWP 8914), HD 190603 (B1.5Ia$^+$; SWP 1822) and HD 151804 (O8Iaf; SWP 5140). Negative values correspond to emission lines while positive ones to absorption lines. The differences in the absorption line equivalent widths between the "standard" B1.5Ia$^+$ spectrum and SWP 52888 can be explained in terms of: a) the dilution of the lines by the continuum of HD 5980's binary companion; b) the lower metallicity in the SMC with respect to the Galaxy. However, similar values for the line ratios in the two B1.5 supergiants and HD 5980 are obtained.

HD 5980 has stronger P Cygni features than HD 190603, a fact that is most evident in the Si III multiplet at 1300 Å (Fig. 2a) and in Si III 1417 Å (Fig. 2b) where emission components are seen to be more intense

TABLE 1

EQUIVALENT WIDTHS (MÅ)

Line[a]	SWP 8914 B1.5Ia$^+$	SWP 1822 B1.5Ia$^+$	SWP 5140 O8Iaf	SWP 52888 B1.5Ia$^+$ +WN?
Si II 1265	1000	970	100	350
Si III 1299	820	610	80	260
Si II 1309	250	280	70	180
Si III 1417	520	540	np?	390
O IV 1338	np	np	515	60
Al IIIe1854	−2390	−4000:	...	−2360
Al IIIa1854	1570	2160	np	1550
Al IIIe1862	−2200	−3120	np?	−1390
Al IIIa1862	1540	1980	np	1740
Si IVe1402	− 300	− 530	−6000	−5200

[a] np = not present.

in HD 5980. In both stars the AlI III resonance doublet lines at 1854, 1863 Å present fully developed P Cyg profiles as well as do the multiplet 34 lines of Fe III (Fig. 2c). There are, however, a few significant differences, mainly in the strength and width of the resonance Si IV doublet at 1393, 1402 Å (Fig. 1b illustrates Si IV 1402 Å) and the intercombination line of N IV] 1486 Å which are much stronger and broader in HD 5980 than in HD 190603; and in heavy-metal lines which are much weaker in HD 5980, as would be expected from the lower metallicity of the SMC as compared to the Galaxy (see cf., Lennon et al. 1990). The lower metallicity effects are also clearly illustrated by the relative strengths of the Ti III photospheric absorption lines (Fig. 2a) which are prominent in HD 190603 but nearly undetectable in HD 5980. Absorption lines of Fe IV are also present in the spectra and will be discussed in the following section.

Another important difference in the strong P Cygni profiles of HD 5980 as compared to the other B1.5 supergiants analyzed, is that these lines do not saturate to zero flux levels in HD 5980, although the Al III P Cyg absorptions do saturate in the B1.5 supergiants we measured, and the Si IV absorption component saturates in all supergiants (Drew 1990). Despite their saturated (i.e., flat minima) appearance, the minimum flux levels in these HD 5980 P Cygni absorption components are: F(Si IVa 1393 Å) = 1.37×10^{-12} erg cm^{-2} s^{-1} Å^{-1} and F(Al III 1854 Å) = 1.20×10^{-12} erg cm^{-2} s^{-1} Å^{-1}. Clearly, this indicates the contribution from a continuum source in which negligible Al III and Si IV P Cyg absorptions are present (i.e., the companion), a fact which may allow an independent estimate of the relative continuum luminosities in the members of the binary system to be made. That is, assuming that the Al III and Si IV P Cyg absorption components in HD 5980 saturate to zero flux levels in the star where they originate, we derive a luminosity ratio $F1/F2 \sim 1.5$, and 1.9, respectively, for the 1950 and 1300 Å wavelength regions. Hence, under the assumption of saturated P Cyg absorption lines, in SWP 52888 the erupting star is 1.5 − 1.9 times brighter than its companion in the UV if only two stars are contributing to the spectrum.

TABLE 2

MAXIMUM VELOCITIES FOR REGIONS OF LINE FORMATION IN SWP 52888

Line	V_{edge}	Line	V_{edge}
Si II 1264.73	−430	Al III 1854.72	− 670
Si III 1296.73	−260	Si IV 1393.76	−1640
Si III 1417.24	−195	C IV 1548.18	−1700
Si III 1312.58	− 60	...	...

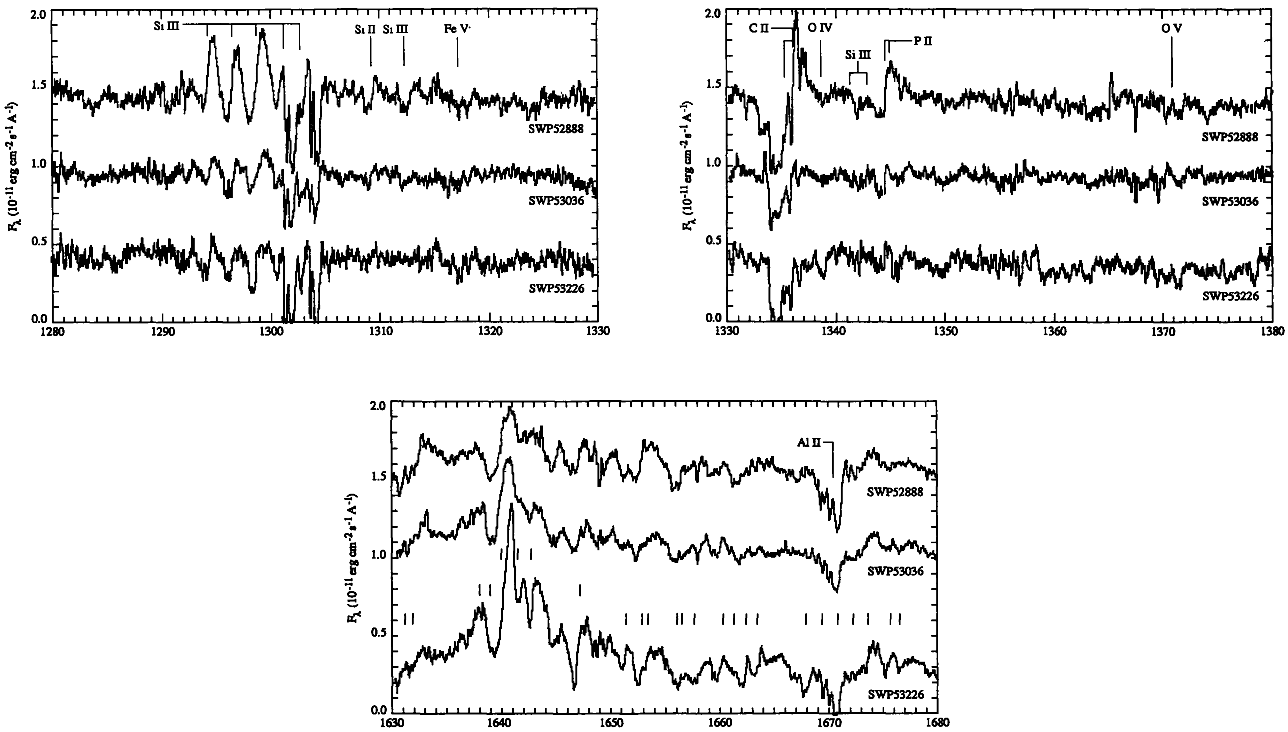

Fig. 3a,b,c. Variations in the spectra of HD 5980 over time for spectra obtained in late 1994. From top to bottom, the dates of observations (−HJD 2449000) are 680.5, 697.5, and 717.5; and the corresponding orbital phases are 0.51,0.39, and 0.43. The wavelength scale is shifted as described in Figure 2. Spectra are displaced vertically for illustration purposes.

The velocities of the regions in which the different lines are being formed can be estimated by the extent of the P Cygni absorption components on the shortward side of the line. The velocity corresponding to the position in the absorption component where the line joins the continuum level for those lines in which blending effects are not too severe is listed in Table 2. A velocity gradient in the Si II and Si III lines is present, similar to that shown to exist in B supergiants by Massa et al. (1992), where more optically thick lines sample the layers of the star which are further out than the less optically thick lines, which lie at lower expansion velocities.

3.2. The Subsequent 1994 Spectra

As described in Paper II, there is a rapid evolution of the emission line spectrum in HD 5980 towards higher degrees of ionization over the following ∼40 days after our initial observation. This trend towards higher degrees of ionization is also present in the absorption features. In Figure 3 we plot SWP 52888, an intermediate spectrum in the sequence (SWP 53036) and the last spectrum of this sequence (SWP 53226). The effect on the Si II and Si III lines is illustrated in Figure 3a, where the P Cygni emission components of the Si III 1300 Å multiplet weaken significantly, and the Si II Å 1309 and Si III 1312 Å absorption features weaken until they become undetectable. In this same figure, a line at 1317 Å, attributable to Fe V is seen to become stronger. In Figure 3b the C II 1335 Å P Cygni emission is seen to decrease (note that the absorption includes SMC+Galactic ISM absorptions), while the photospheric (non-displaced) O IV 1338 Å and O V 1371 Å lines become more prominent. Figure 3c illustrates one of the spectral regions in which a large number of Fe IV lines can be resolved. Each of these lines is, in general, a blend of several Fe IV lines, as listed by Ekberg & Edlen (1978), and their identification was made using a synthetic Fe IV spectrum produced as in Koenigsberger (1990). In this figure the tick marks indicate the rest wavelength position of the strongest line in each of the Fe IV blends. The strength of these Fe IV features increases over the ∼ 40 days covered by the observations with SWP 53226 showing the strongest and sharpest Fe IV features. This spectrum also contains numerous Fe V lines, not evident previously. It is important to note that these changes in degree of ionization of the

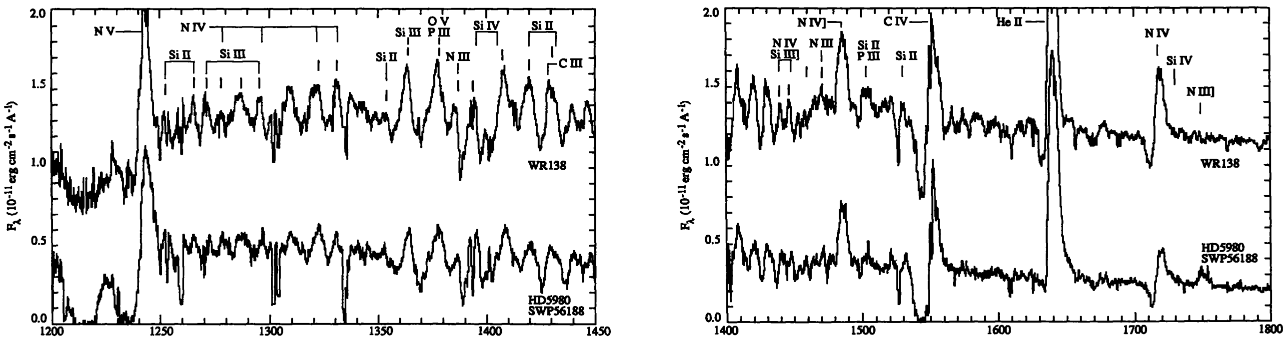

Fig. 4. Comparison between HD 5980 in late 1995 (SWP 56188; bottom) and HD 193077 (WN6+abs), which has been shifted vertically by 8×10^{-12} ergs cm^{-2} s^{-1} A^{-1}. Thick tick marks indicate lines which were identified by Koenigsberger (1990) as having significant contributions from Fe V and/or Fe VI. Other ionic contributions are listed above the lines.

absorption features occur while the UV continuum luminosity is increasing (see Fig. 1b). Also it is important to note that SWP 53036 and SWP 53226 were both obtained at similar orbital phases.

All the Fe IV lines indicate outward motion of the absorption line forming region: the average position of the center of 32 Fe IV blends measured in SWP 53226 yields a velocity of -76 ± 60 km s^{-1}, with respect to the rest wavelength of the SMC. For lines which are not severly blended, edge velocities were measured and they range from -120 to -240 km s^{-1}, with an average of -195 ± 45 km s^{-1}. This velocity is similar to the edge velocity of -200 km s^{-1} from the Si III 1296 Å and Si III 1417 Å lines in this same spectrum. No change in the edge velocity of Si IV (-1640 km s^{-1}) is detected over the 37 days of these observations, although the Al III 1854 Å P Cygni absorption component now extends only to -280 km s^{-1}. Finally, C IV 1550 Å presents a well developed P Cyg profile which, however, does not saturate to zero flux intensity in its absorption component. The maximum extent of the absorption indicates an expansion velocity of ~ -2300 km s^{-1} for this line forming region.

We have not been able as yet to detect variations within this series of spectra that can be associated with the orbital phase of the observation and thus we conclude that the eruptive event overwhelmes the binary interaction effects which usually produce periodic spectral variations.

3.3. The Spectrum in Late 1995

In Figure 4 we present the *IUE* spectrum of HD 5980 (SWP 56188) obtained in November 1995, compared with the Galactic WN6+abs system HD 193077 (=WR 138). The emission-line spectrum of HD 5980 at this time is nearly identical to that of WR138, for which detailed line identifications are given in Koenigsberger (1990), and hence we can assign a spectral type of WN6 to HD 5980 at this time.

It is interesting to note that a large number of the lines in HD 193077 were identified as having strong contributions from Fe V and Fe VI. These are identified with the thick tick marks in Figure 4. Other contributors to each line are listed above the features. There is no evidence for the narrow Si II, Si III, and Fe IV absorption features nor the Al III P Cygni profiles observed in 1994. The most important differences between HD 5980 and HD 193077 are: a) the C IV 1550 Å P Cygni absorption component in the former is stronger (note that it now saturates to zero flux intensity!); b) N III] 1750 Å is present in HD 5980, but absent in HD 193077.

The edge velocity for C IV in HD 5980 is -2550 km s^{-1}, similar to the value it had in late 1991. Strong orbital phase-dependent profile variations in the emission lines are observed, qualitatively similar to those present in 1989–1991.

4. CONCLUSIONS

The *IUE* observations contain a wealth of information regarding HD 5980 and the eruptive phenomenon which has occurred.

The B1.5Ia$^+$ spectrum allows us to assign an effective temperature of $\sim$ 20 000 K (Massey et al. 1989). Presumably, at maximum its effective temperature would have been even lower. Its subsequent effective temperature increase moves it rapidly to the left on the HR diagram. It is interesting to note that with a $M_{bol} = -12.8$, if only two stars constitute HD 5980, each of these is extraordinarily luminous. For example, the visual magnitude of the system in 1979 is 11.7; adopting a distance modulus of 18.8, and the luminosity ratio for the two stars derived by Breysacher & Perrier (1990), very large bolometric corrections (−6 and −5) are required to achieve $M_{bol} = -12.8$ of the system. One possible estimate of bolometric magnitudes is −12.6 and −11.1, for the two stars, corresponding to $\log L_{bol}/L_{\odot}$ of 6.9 and 6.3, respectively. Both of these values, for $T_{eff} \approx 20\,000$ K place the erupting star above the HD limit (Humphreys & Davidson 1994) on the HR Diagram.

There are numerous questions which arise regarding the phenomenon which we are witnessing in HD 5980: What is the evolutionary state of the star which is undergoing the changes? Are these changes associated with a transition from one evolutionary state to another? What are the physical processes involved in the eruptive event? What role does the binary companion play in the eruptive phenomenon? In addition to radiation pressure, what other forces are driving the wind and how does the wind structure depend upon these other factors?

Because this event in HD 5980 occurred during the lifetime of the *IUE* Observatory and because it has been the object of several detailed investigations before its eruptive behavior became evident, HD 5980 may provide answers to some of these fundamental questions. Continued monitoring is of utmost importance as are the construction of theoretical scenarios that may shed light on eruptive phenomena such as we are witnessing in this most interesting binary system.

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