Revista Mexicana de Astronomía y Astrofísica, **39**, 213–223 (2003)

ULTRAVIOLET SPECTROSCOPY OF THE MASSIVE LMC MULTIPLE SYSTEMS SK-67°18 (BR 5) AND HD 36402 (BR 31)

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Received 2003 February 20; accepted 2003 May 26

RESUMEN

Reportamos los resultados de observaciones en el UV de dos sistemas binarios cercanos, ubicados en la Nube Mayor de Magallanes, Br 5 y Br 31. Detectamos variabilidad espectral en Br 31 producida por eclipses atmosféricos, así como variaciones en la velocidad radial de algunas de sus líneas, con el periodo de 3.033 días. El espectro UV de este sistema es consistente con la presencia de 3 estrellas calientes en el sistema. En contraste, no podemos confirmar la presencia de más de 2 estrellas calientes en el sistema Br 5, y la debilidad de Si IV 1400 contradice la presencia de una supergigante O-tardía o B-temprana. Detectamos variaciones de velocidad radial consistentes con el movimiento orbital de la componente O3 If*.

ABSTRACT

Following previous *IUE*-based spectroscopic studies of WR+O binaries in the Galaxy and in the SMC, we present a similar study of the two systems, Br 5 [O3 If*(+O) + O8–B0 I(+OB?)] and Br 31 [WC4(+O?) + O8 I:] in the Large Magellanic Cloud. We detect wind eclipse effects in the WC4+O (P = 3.033 d) pair in Br 31 similar to, but weaker than those observed in the Small Magellanic Cloud system Sk 188 (WO4+O4 V). A low-amplitude ($\sim$ 40 km s^{-1}) variation in the radial velocity of UV photospheric absorption lines and the O V 1371 emission with the 3 day period is detected. The radial velocity variations of the photospheric lines may be due to the superposition of the stationary set of absorption lines belonging to the O8 I: star and a broader set of lines belonging to the O-type companion in the close binary pair. The UV continuum energy distribution of Br 31 also supports the optical results that the system contains at least 3 bright stars, one of which is a late O-type supergiant. Contrasting with Br 31, the absence of significant Si IV 1400 Å emission in the UV spectrum of Br 5 contradicts the results from optical spectroscopy that imply that it is triple, with the presence of a late O-type supergiant in the system. Orbital phase-coverage of the *IUE* observations does not allow the detection of possible atmospheric eclipse effects in Br 5, with P = 2.001 d, but radial velocity variations attributable to orbital motion of the O3 If* star are detected.

Key Words: **GALAXIES: LARGE MAGELLANIC CLOUD — STARS: BINARIES — STARS: INDIVIDUAL (SK-67°18, HD 36402) — STARS: WOLF-RAYET — ULTRAVIOLET: SPECTRA**

1. INTRODUCTION

Binary systems containing Wolf-Rayet (WR) stars are of great interest because of the potential for deriving the masses of stars that have left the Main Sequence and are nearing the supernova stage. However, due to the very intense winds that WR stars and their binary companions normally possess, interaction effects between the two stars can act to distort the line profiles in their spectra, and hence distort the radial velocity curves that are used for deriving the stellar masses. Therefore, it is of interest to study and understand the line-profile variability present in WR binary systems and its causes. The physical mechanisms, apart from global radial velocity (RV) shifts, involved in producing line-profile variations in WR binary systems fall into three gen-

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eral categories: (1) atmospheric eclipses, known also as "wind eclipses" or "occultations"; (2) wind-wind collisions; and (3) departures from spherically symmetric, isotropic, time-independent stellar winds.

This is the last of our series of papers devoted to the detection and analysis of orbital-phase dependent spectral line-profile variability in WR+O binary systems based on observations obtained with the *International Ultraviolet Explorer (IUE)* observatory. In Paper I (Koenigsberger & Auer 1985) the results of *IUE* observations of 6 Galactic WN binary systems were presented. Five of the six systems were found to exhibit strong emission-line profile variability on orbital timescales. The sixth system, WR138, is a very long period binary system which displayed no variability over the timescale of the observations.

The dominant source of line-profile variability in the $\lambda\lambda$1200–2000 Å range is wind eclipses and Münch (1950) was the first to attribute optical line profile variability observed in the eclipsing WN5+O6 binary system V444 Cyg to this mechanism. The observable effect can be described as follows: At orbital phases when the companion O-type star is eclipsed by the WR wind, the emission components of the P Cygni line profiles become weaker and the absorption components become stronger. This is due to the absorption of the O-star's continuum at line frequencies by ions in the WR wind. In Paper I we also showed that strong variability in the "continuum" region shortward of 1500 Å was due to a *pseudocontinuum* produced by the large number of Fe V and Fe VI lines, closely packed within the wavelength range $\lambda\lambda$1270–1470 Å (see also Eaton, Cherepashchuk, & Khaliullin 1985), and varying due to the same wind eclipses that affect strong and more isolated lines such as N V 1240, He II 1640, and N IV 1718 Å. The wind eclipses in WR binaries have been used in order to estimate WR wind parameters, such as density (Khaliullin & Cherepashchuk 1976; Willis 1979), the extent of the line emitting region and a trend in the velocity law (Auer & Koenigsberger 1994; Schweickhardt et al. 1999) and the ionization structure (Koenigsberger 1990). Further progress in this direction using wind eclipses has been hampered by our inability to adequately incorporate the effects produced by the second form of interaction effects: wind-wind collisions.

The first spectroscopic observational evidence for wind-wind collisions (WWCs), presented in Paper I, consists of variations in the P Cyg absorption component of lines such as C IV 1550 Å, that are formed in the companion's stellar wind. These variations were interpreted to indicate that the wind of the O-star is prevented from reaching its maximum speed in the direction of the WR star, due to the braking effect of the oppositely-moving WR wind. At least in the case of V444 Cyg, the wind-wind collision occurs very close to the O-star's surface, due to the dominance of the WR wind, and hence, the O-star's wind is not allowed to reach its terminal speed. However, effects such as "radiative braking" (Owocki & Gayley 1995) can cause the WR wind to decelerate as it approaches the O-star, in which case the WWC region is lifted away from the stellar surface. This uncertainty in the parameters that go into calculating the effects of WWC's on the wind structure is just one of the various problems associated with this type of interaction effect.

In subsequent studies, evidence was presented suggesting that not only is the WWC presence observable in absorption lines, but also in the form of a contribution to the emission lines (Shore & Brown, 1988; Moffat 1998). This added emission is also variable with orbital phase and contaminates the effects that are produced by the wind eclipses. It has been very difficult to establish the magnitude of this contribution at optical and UV line wavelengths, with estimates ranging from $\sim$ 10–100% of the emission-lines arising in the WWC region, depending on the specific line involved (e.g., Moffat et al. 1998; Flores et al. 2001). This is unfortunate since the tools exist for deriving the wind velocity and density laws using the wind eclipses (Auer & Koenigsberger 1994), but cannot be effectively applied until we can assess the extent to which the WWC region contaminates the spectrum. A mainly analytical analysis of the effects due to the WWC's in various WR+O systems is summarized in Moffat (1999).

In Paper II (Moffat, Koenigsberger, & Auer 1987), we reported on observations of three WR binaries in the SMC, two of which (HD 5980 and Sk 188) displayed strong variability, while no significant variability was detected for the third system, Sk 108 (WN4:+O6.5 I:, Foellmi, Moffat, & Guerrero 2003). A comparison between the variations produced by wind eclipses in HD 5980 (WN5+O7 I: at that time) and its presumed Galactic counterpart HD 90659 (WN5+O4-6), showed significantly weaker variability in the former's Fe V+VI *pseudocontinuum*, as expected from the much smaller Fe abundance in the SMC, with respect to the Galaxy (Koenigsberger, Moffat, & Auer 1987). Following these observations, HD 5980 underwent a luminous-blue-variable like eruption, leading to spectacular variations in its spectrum on timescales of weeks-months (Barbá et al. 1995; Barbá, Niemela, & Morrell 1997; Koenigsberger et al. 1994, 1995, 1998a;

Moffat et al. 1998; Niemela et al. 1997). Further analyses of the wind eclipse effects have been pending until a better understanding of the eruptive phenomenon can be attained.

In this paper, we present results from the *IUE* observations of two binary systems in the LMC (Br 5 and Br 31), originally selected because of their brightness and known multiplicity, and because they are in an environment with intermediate metallicity between that of the Galaxy and that of the SMC.

2. OBSERVATIONS AND DATA ANALYSIS

The data for Br 5 (Breysacher 1981; = Sk-67°18 in Sanduleak 1970 = BAT99-6 in Breysacher, Azzopardi, & Testor 1999) and Br 31 (= HD 36402 = Sk-67°104 = BAT99-38) were acquired in 1988 with the *International Ultraviolet Explorer* observatory using the short-wavelength prime (SWP) camera in low-dispersion mode. These data and additional data for these targets and other relevant objects were extracted from the *IUE* archive through the Multimission Archive at Space Telescope (MAST). The *NEWSIPS* files were processed with the *iuetools* package and analyzed with IRAF.[4]

No corrections have been applied to the data for interstellar reddening, which is relatively small in the direction of the LMC. Measurements of radial velocities and equivalent widths were generally performed by fitting a Gaussian function to the line profiles, after smoothing with a boxcar function, using 3 points for low resolution and 11 to 55 points for high resolution data. Unless stated otherwise, the velocities are heliocentric and are not corrected for the motion of the LMC (+280 km s^{-1}, Moffat 1989). The journals of the observations for Br 5 and Br 31 are listed in Tables 1 and 3 to 4, respectively.

3. Br 5

Br 5 is a bright object ($M_V = -6.9$) located in the LMC within the stellar association NGC 1747. This association is embedded in the ring-shaped H II region DEM 31 (Davies, Elliott, & Meaburn 1976). Oey (1996) determines this object to be a dense clump with at least three components within the central $\sim 1''$. First classified as O6–7+WN5–6 (Walborn 1977), Br 5 was considered a good LMC binary system to compare with Galactic and SMC counterparts. However, Niemela, Seggewiss, & Moffat (2001) have recently presented the results of optical photometric and spectroscopic observations which show that Br 5 consists of an eclipsing Of+O binary system rather than a WN+O binary. Furthermore, they suggest that the spectrum of the system contains the contribution from 4 stars (2 close pairs). The first pair, believed to consist of Of+O type stars, has a very close orbit ($P = 2.001185$ d; $T_0 =$ JD2446506.338, when the emission-line star is eclipsed) and is responsible for emission line profile variability in He II 4686 Å, and large amplitude RV variations in N IV 4058 Å, He II 4686 Å, and N V 4603 Å. The presence of a second binary is inferred from the strong He I absorption lines which undergo small-amplitude RV variations with $P = 19.265$ d. Because of the strength of these He I lines, the star in which they originate is believed to be very luminous, probably an O8–B0 supergiant. Oey (1996) also concludes that the composite spectrum of Br 5 includes a an early B-type spectrum, but with a lower luminosity; i.e., B II–III.

The photometric light curve displays two eclipses ~ 0.2 mag deep, at phases 0.0 and 0.5 in the 2-day binary, although their exact shapes are somewhat compromised by the difficulties in obtaining good phase coverage with a period so close to 2 days. From the N IV/N III emission line ratio, the N V 4603/19 absorptions and from the fact that the Balmer absorption lines have a mean velocity that is the same as the emission lines (i.e., there is no blue-shift suggestive of these lines having P Cygni absorption components), Niemela et al. (2001) conclude that the brighter of the two stars in the eclipsing system is an O3 If* star (they actually gave O3f*, based on Walborn's 1982 criteria, which should be revised to O3 If* according to Walborn & Fitzpatrick 1990). The mass function of the O3 If* system, $f(m) = 6.5 \pm 0.5\, M_\odot$, implies combined masses of the components in the 2-day binary system larger than $80\, M_\odot$, assuming the O3 If* star to be the more massive one.

3.1. *IUE Spectrum*

Table 1 lists the *IUE* observations (SWP number), date of observation, and orbital phase computed with the ephemeris given above. Seven spectra in the wavelength range 1100–2000 Å were obtained within 7 days, and one high dispersion spectrum was retrieved from the archive. Because of the nearly exact 2-day period and the daily sampling, the phase coverage is very poor, with only 2 different short phase intervals included: 0.16–0.27 and 0.71–0.77. Given that these phases coincide with the elongations, rather than eclipses, no wind eclipse effects are expected, nor were observed. On the other

[4]IRAF is distributed by NOAO which is operated by AURA Inc, under contract with the NSF.

TABLE 1

CENTRAL VELOCITY OF P CYGNI EMISSIONS AND ABSORPTIONS IN Br 5

SWP	$T_{\rm exp}$ (min.)	Year	HJD −2440000	Phase	RV (km s^{-1}) 1549a	1549e	1640e	1718a	1718e
04293hi	300	1978	3923.119	0.155	−900	1300:	1095:	−870	920
33214	5	1988	7257.200	0.209	−1150	1470	730	−1110	1130
33218	8	1988	7258.280	0.748	−1080	1470	1080	−520	1115
33234	8	1988	7260.300	0.758	−950	1780	1320	−350	1300
33235	9	1988	7260.330	0.773	−1090	1770	1380	−520	1600
33244	8	1988	7262.320	0.767	−1020	1630	1000	−620	1600
33256	6	1988	7263.320	0.267	−1080	1490	780	−880	1600::
33268	6	1988	7264.200	0.707	−1000	1670	1400	−500	1350
average	···	···	···	0.75	−1030	1660	1240	−500	1390
average	···	···	···	0.21	−1120	1480	750	−1000	1360

hand, these phases are favorable for obtaining RV variations.

Figure 1 illustrates the average spectrum of Br 5, with the principal line features identified, and compared with the WN4:+O6.5 I: binary system Sk 108 in the SMC, (dotted line; scaled by a factor of 1.33 to correct for the different distances to the LMC and SMC) and HDE268968, an O4 If star in the LMC. The continuum energy distribution of Br 5 is very similar to that of Sk 108, except for the wavelength region shortward of 1600 Å, where Sk 108 is $\sim$ 15% brighter than Br 5. The spectrum of Br 5 shows P Cygni lines of N V 1240, C IV 1550, and N IV 1718, and a relatively weak He II 1640 ($W_\lambda = 10.2$ Å) emission line is present. The deep absorption features in Fig. 1 at $\lambda\lambda$1256, 1300, 1335 Å are Galactic plus LMC interstellar lines which, due to the low resolution of the data are blended together. The Si IV absorption feature at 1400 Å , however, is too broad to be due only to the ISM lines, suggesting the presence of a P Cygni absorption component of Si IV arising in the stellar wind of one or more of the stars in the system. This is confirmed upon inspection of the high dispersion spectrum. It is noteworthy, however, that the Si IV 1400 Å emission line is so weak, making the presence of a late O-type supergiant in the system unlikely. All supergiants later than O6 have strong Si IV P Cygni lines (Atlas of Walborn, Nichols-Bohlin, & Panek 1980; and see below), even at the low metallicities of the SMC, as evidenced by the O7 If supergiant Sk 80. Furthermore, the intensity of this emission is not strongly diluted by the presence of a luminous companion, as

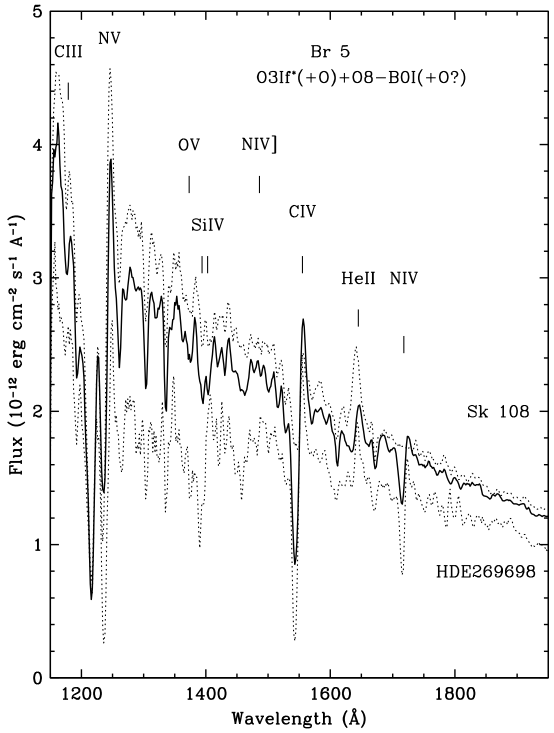

Fig. 1. Average UV spectrum of Br 5 (Sk-67°18) with the principal line features identified (continuous tracing) compared with the spectra of Sk 108 (WN4:+O6.5 I:), which has been rescaled to the flux it would have if it were in the LMC and with HDE269698, an O4 If star in the LMC.

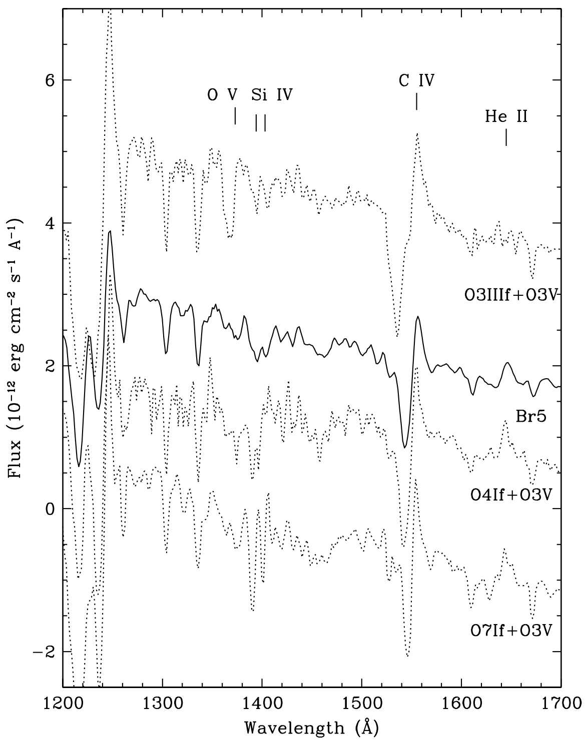

Fig. 2. Comparison of the Br 5 spectrum with the spectra of hypothetical binary systems constructed by adding together combinations of the UV spectra of the following (assumed single) stars: NGC 346–355 (O3 Vf), HDE269810 (O3 IIIf), HDE268968 (O4 If), and Sk 80 (O7 Iaf+). The flux of the SMC stars has been scaled to correct for the different distances between the SMC and LMC. The hypothetical binary spectra are shifted vertically by +1.5, −1.5, and −3 units, while the Br 5 spectrum is unshifted.

we illustrate in Figure 2, where hypothetical spectra of binary systems containing pairs of stars with different spectral types are presented. These pairs are O3 Vf+O3 IIIf, O3 Vf+O4 If, and O3 Vf+O7 If. For clarity in the figure, these hypothetical binary spectra are shifted in the vertical scale by +1.5, −1.5, and −3 units, respectively, while the spectrum of Br 5 is undisplaced. Note the very strong O V 1371 Å absorption feature in the O3 Vf+O3 IIIf system, not evident in Br 5; and the Si IV 1400 Å P Cygni absorption present in the O3 Vf+O7 If system is significantly stronger than observed in Br 5. Clearly, Br 5 is more similar to a combined O3 Vf+O4 If spectral type than to an O3 V+O7 If.

The UV spectral energy distribution of Br 5 does not accomodate more than one other luminous star, in addition to the O3 If* star. Table 2 lists the continuum levels at $\lambda\lambda$1300 and 1700 Å for a selection of SMC (scaled to the LMC distance) and LMC early-type stars. If we assume that the presumed single O3 IIIf, O3 Vf, O4 If, and O7 If stars listed in Table 2 are truly single stars, then we find that Br 5 is less than a factor of two brighter than all of them, except the O3 Vf star, in both wavelength bands. With respect to the apparently single LMC star HDE269698 (O4 If), Br 5 is only $\sim$ 16% brighter at λ1800 Å. Thus, it is difficult to reconcile the optical observational result implying the presence of at least 3 luminous stars, (two of which are O3 If* and an O8–B0 I) in the system with the UV spectrum which does not allow for more than two such stars, and does not support the presence of an O7–B0 supergiant.

3.2. *Radial Velocities*

Columns 6–10 of Table 1 contain the measurements of the centroid of P Cygni absorption and emission features, uncorrected for the motion of the LMC. The bottom two rows contain the average velocity value at orbital phase $\sim$ 0.75 and $\sim$ 0.21, respectively. The RV variations imply that the star with the dominant He II 1640, N IV 1718, and C IV 1550 emission lines is receding from the observer at $\phi = 0.75$, and approaching at $\phi = 0.25$, as shown in the lower panel of Figure 3. This is consistent with the optical RVs of Niemela et al. (2001) for the O3 If* star. The upper panel of Fig. 3 illustrates a portion of the average spectrum at phases 0.21 and 0.75 where the wavelength shift in the N IV 1718, He II 1640, and C IV 1550 lines is evident even on these low dispersion spectra. Note also the relative stability of the Fe II 1608 Å ISM line, showing that the shift in the stellar lines is not due to a zero-point shift in the wavelength calibration. The total amplitude from the RVs of the He II 1640 emission and the N IV 1718 P Cygni absorption is $\sim$ 500 km s^{-1}. Niemela et al. (2001) find 2K = 640 km s^{-1} from the best optical emission line, N IV 4058 Å , which is probably more reliable than the UV value here, given our very limited phase coverage and the low resolution spectra.

3.3. *Wind Velocities*

An estimate of the terminal wind velocities in the system is possible using the high resolution spectrum. The Si IV 1393 P Cygni absorption line provides a “blue” edge velocity of -2000 ± 200 km s^{-1}, after correcting for the LMC motion (adopting +260 km s^{-1} from the Si IV ISM lines in this same

TABLE 2

COMPARISON OF BR 5 WITH OTHER STARS IN LMC AND SMC

Star	Spectrum	Flux (10^{-12} ergs cm^{-2} s^{-1}) 1300	1700	N V	He II	N IV	W_λ (Å) N V	He II	N IV
Br 5	O3 If*+...	2.9	1.7	6.9	3.3	1.7	−2.3	−1.9	−1.0
HDE268968	O4 I	1.9	1.4	3.1	3.7	2.0	−1.6	−2.5	−1.5
HDE269810	O3 IIIf	2.1	1.4	8.9	0.8:	1.4	−3.8	−0.5:	−1.1
Sk 108[a]	WN3+O7 I:	3.3	1.8	11.0	8.5	...	−3.3	−4.5	...
NGC 346–n355[a]	O3 Vf	1.2	0.7	5.2	−0.4	...	−4.2	+0.5	...
Sk 80[a]	O7 Iaf+	2.2	1.2	4.8	4.6	0.4	−1.8	−3.8	−0.3

[a]Fluxes measured on SMC spectra are a factor of 1.33 larger than the actual values since they have been rescaled to place them in the LMC.

spectrum). The large uncertainty is due to the difficulty in defining the position where the absorption component reaches the continuum level and the noise in this region of the spectrum, particularly because the P Cygni absorption is very weak. Other lines that are easier to measure are C IV 1548.19 Å, where the "blue" edge velocity of the P Cygni absorption component is $-2260 \pm 30\,\mathrm{km\,s^{-1}}$, and its "black" portion extends out to $-1830\,\mathrm{km\,s^{-1}}$, and N IV 1718, where we measure the "blue" edge to lie at $-2000\,\mathrm{km\,s^{-1}}$. Thus, the three P Cygni absorption components imply wind velocities of $2000 \pm 200\,\mathrm{km\,s^{-1}}$. Prinja, Barlow, & Howarth (1990) find terminal wind speeds in the range 1820–2420 km s^{-1} for O4–O7 supergiants, while the O3 supergiant studied by these authors has $v_\infty = 3150\,\mathrm{km\,s^{-1}}$, significantly larger than what we find for Br 5.

4. Br 31 = HD 36402

HD 36402 is a WC4(+O?)+O8 I: system with a binary orbit of 3.0328 ± 0.0001 days and initial epoch (inferior conjunction of the WC4 star) HJD2446043.874 (Bartzakos, Moffat, & Niemela 2001). It is unusual compared with Galactic WC binary systems in that its orbital period is very short (although another WC system also in the LMC, Br 32, has an even shorter period; see discussion in Moffat, Niemela, & Marraco 1990). Br 31 displays photospheric absorption lines of He I, He II, and the H-Balmer series in its optical spectrum. The strong emission line of C IV 5812 exhibits RV variations with a range of ~ -100 to $+300\,\mathrm{km\,s^{-1}}$, but the photospheric absorptions appear to be stationary (at $+280\,\mathrm{km\,s^{-1}}$) close to the ISM line RV of the LMC. The RV amplitude with forced $P = 3.03$ d gives $K = 8 \pm 9\,\mathrm{km\,s^{-1}}$, which is compatible with zero; hence, unless the OB supergiant in Br 31 is exceedingly massive (unlikely), Br 31 is at least a triple system. It is assumed that the orbiting companion of the WC4 star is likely a main-sequence O-star (as indicated in brackets), that is fainter than the O8 I: component.

TABLE 3

IUE LOW RESOLUTION OBSERVATIONS OF Br 31 = HD 36402

SWP	Year	HJD −2440000	Phase	O V 1371.3 (km s^{-1})
4910	1979	3974.029	0.513	−22
17083	1982	5121.392	0.832	88
17103	1982	5123.308	0.463	131
33217	1988	7258.237	0.411	131
33226	1988	7259.275	0.752	175
33233	1988	7260.258	0.076	481
33236	1988	7260.367	0.112	328
33257	1988	7263.362	0.100	284
33264	1988	7264.233	0.387	328
33265	1988	7264.258	0.395	437
33266	1988	7264.283	0.403	66

4.1. *IUE Spectrum*

The journal of the observations is listed in Tables 3 and 4. In addition to the observations obtained by us, we include 4 archival low dispersion and 5 high dispersion spectra obtained between 1979 and 1982.

Figure 4 (top panel) illustrates the average (1988 data only) spectrum of Br 31 with the principal line features identified and compared with Sk 188, the WO4+O4 V binary system in the Small Magellanic Cloud studied in Paper II. This is a valid comparison assuming that WO stars may really be classified as

TABLE 4

IUE HIGH RESOLUTION OBSERVATIONS OF Br 31 = HD 36402

SWP	Year	HJD −2440000	Phase	O V 1338 ($\mathrm{km\,s^{-1}}$)	Si III 1297 ($\mathrm{km\,s^{-1}}$)	Si III 1300 ($\mathrm{km\,s^{-1}}$)
4911	1979	3974.092	0.534	30	0	20
5768	1979	4065.733	0.751	40	30	25
13991	1981	4742.858	0.018	0	−30	−10
13997	1981	4743.883	0.356	−20	−20	−30
15049	1981	4867.508	0.119	−40	−20	−110

WC3 (see Polcaro et al. 1999, for a discussion on WO stars as a class). The flux of Sk 188 has been scaled to correct for the difference between the distances to the LMC and the SMC, as in the comparisons shown in Fig. 1 for Br 5. The significant difference between the continuum levels and in the strength of the Si IV 1400 Å P Cygni feature from one binary system to the other is due to the presence of the O-supergiant in Br 31, as opposed to the main-sequence star in Sk 188.

The spectrum of Br 31 contains P Cygni features from C III 1175, C IV 1550, Si IV 1400, N V 1240, O IV 1338, and O V 1371, as well as a broad emission line due to He II 1640 and possible contributions by an Fe IV blend. Also present is a broad absorption due to N IV 1718 Å which is most likely a combination of a P Cygni absorption component and a photospheric absorption line from the non-WC stars in the system.

The bottom panel of Fig. 4 illustrates a comparison between the average Br 31 spectrum and a hypothetical triple star spectrum constructed by adding the spectrum of Sk 188 to that of Sk 80 (O7 Iaf+). The continuum level longward of 1700 Å as well as the He II 1640 Å emission line in Br 31 and the hypothetical triple system are very similar; the Si IV 1400 Å line, however, is stronger in Br 31 than in the synthetic spectrum, as expected since Br 31 contains an O8 I supergiant as opposed to the O7-supergiant in the hypothetical triple-star system.

4.2. *Wind Eclipse Effects*

The phase coverage of the Br 31 *IUE* observations is appropriate to look for WR atmospheric eclipse effects around phase 0.1. At phase 0.08 there is a clear reduction in the apparent continuum level by $\sim$ 7% near 1270 Å and the emission lines of O IV 1338+1343 and O V 1371 become noticeably weaker, compared with other phases. The continuum level longward of 1600 Å is unaffected, however, similar to what has been observed in other systems (Koenigsberger & Auer 1985). These effects are illustrated in Figure 5, where we compare the mean spectra at orbital phases 0.08 (solid line) and 0.74 (dashed line). Although there is no perceivable difference in the continuum level longward of 1700 Å, significant changes are evident in the O IV 1338 Å and O V 1371 Å emission lines. This indicates that at phase 0.08 there is no continuum eclipse, but there is a significant wind eclipse. In Figure 6 we compare the wind eclipse effects in Br 31 (solid line) with those observed in Sk 188 (Paper II), showing that both systems exhibit similar phase-dependent effects, although the eclipses are stronger in Sk 188 than in Br 31. Thus, we can confirm that the WC star is “in front” at phase 0.0, at which time its extended wind absorbs/scatters the continuum emission from the companion at emission line frequencies that are dominant in the WC star.

4.3. *Radial Velocities*

The radial velocities of the P Cygni line profiles in the spectra of HD 36402 were measured by fitting a Gaussian to the top (lower) $\sim$ 50% of the emission (absorption). A trend for systematic phase-dependent variations was found only for the O V 1371 emission line (listed in Table 3), which is illustrated in the bottom panel of Figure 7. Maximum receding velocity occurs near phase 0.25. Assuming that the maximum approaching velocity occurs at phase 0.75, we estimate the semi-amplitude of this radial velocity curve to be $K(\mathrm{O\,V}) \sim 160\,\mathrm{km\,s^{-1}}$. This is smaller than the value of $K(\mathrm{emis.}) = 275 \pm 17\,\mathrm{km\,s^{-1}}$ given by Moffat et al. (1990). The O V 1371 line is formed closer to the WR-star surface than lines from the lower ionization species, and hence, should reflect more closely the true orbital motion. Even so, at phases near 0.5, the RV is smaller than expected from motion in a circular orbit. At this phase the WC star is “behind” its (unseen) companion. In Paper I we showed that the

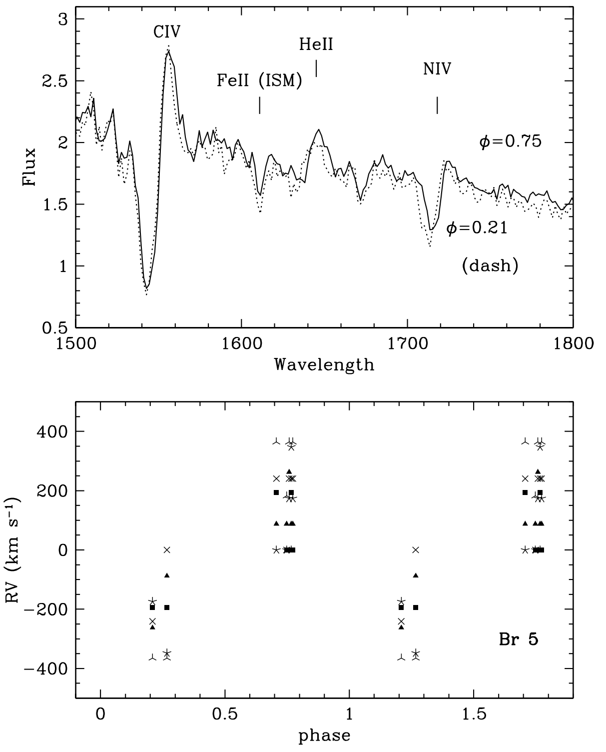

Fig. 3. Radial velocity variations in the *IUE* spectra of Br 5. Top panel: average spectra at phase 0.25 (solid) and 0.75 (dash) displaying shifts in the lines of C IV 1550, He II 1640, and N IV 1718. Bottom panel: RV measurements of absorptions C IVa 1550 (square), N IVa 1718 (triangle) and emissions N V 1240 (cross), N IVe 1718 (star), He IIe 1640 (hat).

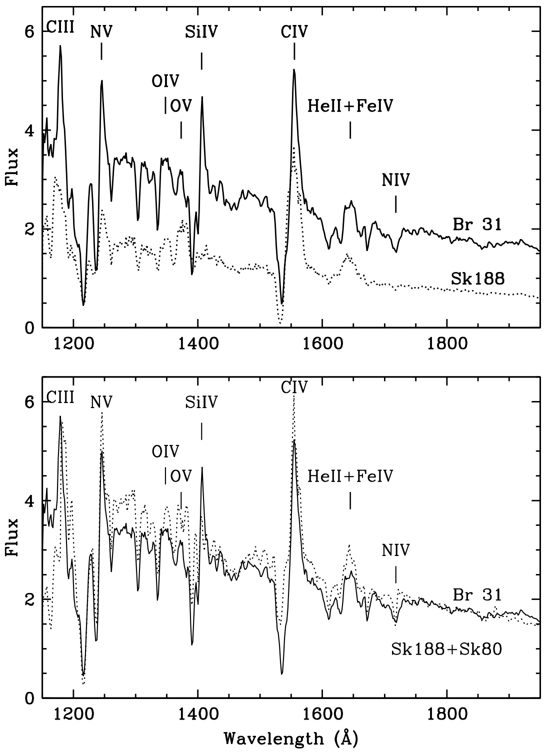

Fig. 4. Top panel: Average (1988 data) *IUE* spectrum of Br 31 with the principal line features identified, compared with the average UV spectrum of the WO4+O4 V binary Sk 188 in the SMC, rescaled to the flux it would have if it were in the LMC. The significant differences between the continuum levels and the intensity of Si IV 1400 Å are consistent with the presence of a supergiant star in the Br 31 system, and the triple star hypothesis. Bottom panel: the same Br 31 spectrum as above (dark line), compared with a synthetic spectrum constructed by adding the spectra of Sk 188 and Sk 80 (O7 If), corrected for the different distances to LMC and SMC.

P Cygni absorption component of lines associated with the WR star in V444 Cyg nearly vanishes when the WR component is eclipsed by its companion. This is because the companion occults the region of the WR wind where the P Cygni absorption component is produced. When the P Cygni absorption is removed, the short-wavelength side of the emission component becomes more extended. This shifts the centroid of the line towards shorter wavelengths, leading to a false RV value.

Also plotted in Figure 7 are the radial velocities of a selection of photospheric absorption lines present in the high-dispersion spectra, and listed in Table 4. The velocity of these lines was measured with respect to nearby interstellar absorption line features, which eliminates any zero-point error in the wavelength calibration of the high dispersion spectra. The O IV 1338 line was measured with respect to the ISM feature located at 1336.8 Å, and the two Si III lines were measured with respect to the ISM line at λ1303.4 Å. The average of the relative velocities (with respect to the ISM lines) for each line was then subtracted to obtain a velocity with respect to the average velocity. This value is plotted in Fig. 7. The three lines display a sinusoidal variation, with an amplitude of $K = 35\,\mathrm{km\,s^{-1}}$ and maximum at phase 0.75, that is, in anti-phase with the UV emission line of O V in the 3-day cycle, suggesting that they arise in the 3-day O companion. The optical lines that give $K(\mathrm{abs.}) = 8 \pm 9\,\mathrm{km\,s^{-1}}$ on the 3-day cycle, apparently arise in the third (O8 I:) star.

Taking $K(\mathrm{O}) = 35\,\mathrm{km\,s^{-1}}$ and $K(\mathrm{WR}) = 300\,\mathrm{km\,s^{-1}}$ (from the optical observations), we find masses $M \sin^3 i = 1.2\,M_\odot$ for the WR star and $10.6\,M_\odot$ for its O-star companion. The mass ra-

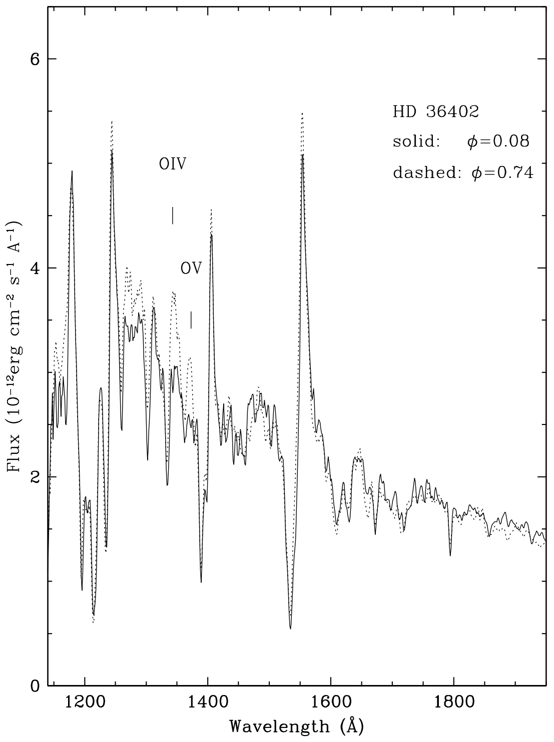

Fig. 5. Comparison of the $\phi = 0.08$ and $\phi = 0.74$ spectra of HD 36402 illustrating the wind eclipse effects at the O IV and O V lines.

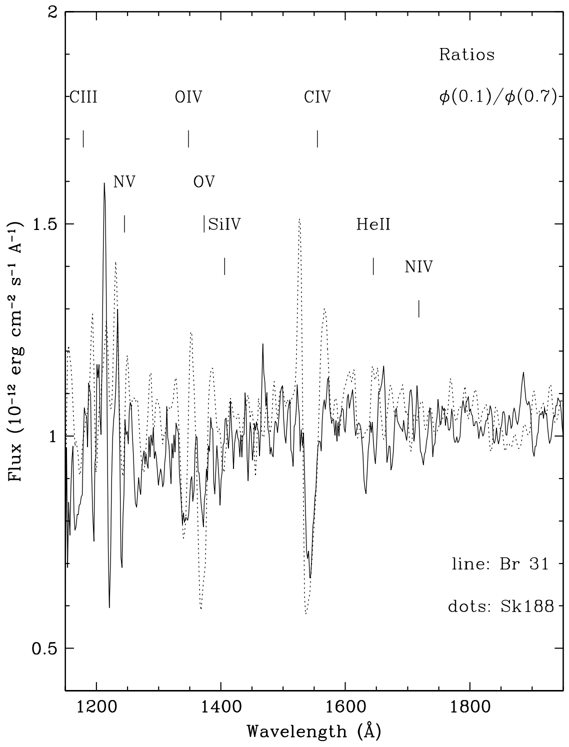

Fig. 6. Ratios for Br 31 (continuous line) and Sk 188 (dashed) of spectra at orbital phase near 0.10 (when the companion star is occulted by the WR star's wind) divided by spectra at phase near 0.75. Both binary systems display wind eclipse effects at the O IV, O V, and C IV lines.

tio is 0.12, which is relatively low for WR+O binaries, although WCE and WNE systems do tend to have lower ratios than WCL and especially WNL systems (e.g., Moffat 1981, 1982). However, given the fact that Br 31 is a triple system and that the photospheric lines observed in the optical spectral region are stationary, the possibility arises that the $35\,\mathrm{km\,s^{-1}}$ variation observed in the UV photospheric lines is produced by the superposition of a set of stationary absorption lines (associated with the O-supergiant) and a set of rotationally broadened absorption lines associated with the close companion of the WC star. Such an effect has been proposed to explain the very low amplitude RV variations in the photospheric absorption lines of the SMC triple system HD 5980 (Koenigsberger, Kurucz, & Georgiev 2002; Georgiev & Koenigsberger 2003). In the case of HD 5980, as could be the case of Br 31, the rotationally broadened lines in one of the close binary members are superposed upon strong and variable emission lines, and thus they are not observable. However, the RV variations ($K \sim 130\,\mathrm{km\,s^{-1}}$ in the case of HD 5980) of these lines, when superposed on the narrower and stationary set of lines arising in the supergiant companion, lead to the observed low amplitude RV variations.

Hence, we conclude that the close companion of the WC star is likely to be an early O-type main sequence star which might be rotating close to the synchronous rotational velocity, but whose lines are not visible due to the low signal-to-noise of the data and due to the fact that they are superposed on the broad and variable emission lines of the WC star.

5. CONCLUSIONS

The binary systems Br 5 and Br 31 were observed with the *IUE* observatory in order to probe the effects due to wind eclipses and analyze the characteristics of their UV spectra. Wind eclipses were detected only in Br 31, where adequate orbital phase coverage was obtained. The effects due to wind eclipses in this system are smaller than those that were observed in the SMC binary system Sk 188. Because the orbital separation in the latter is larger

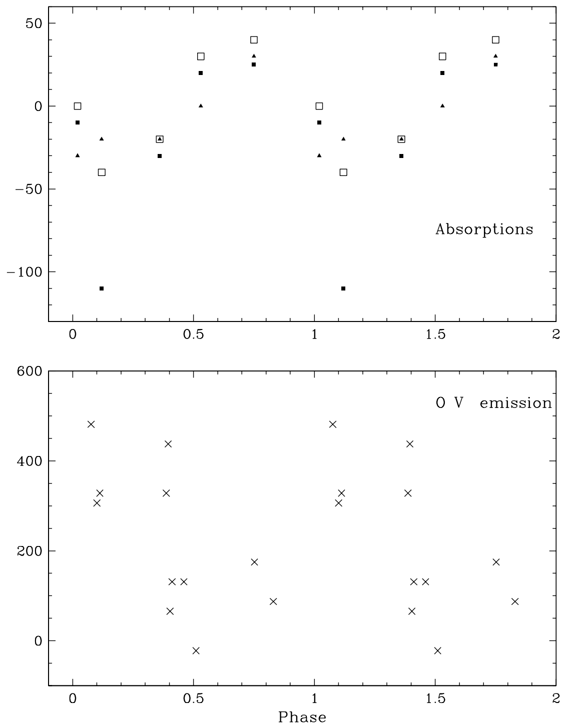

Fig. 7. Radial velocities from *IUE* spectra of HD 36402. Top panel: photospheric absorptions measured in high dispersion spectra from O IV 1338 (open squares), Si III 1297 (triangles), and Si III 1300 (filled squares). Bottom panel: O V 1371 emission line measured on low dispersion data.

than in Br 31, the amount of WR wind material projected upon the O-star's luminous disk during the wind eclipses is larger than in Br 31, most likely accounting for the difference. The UV continuum in Br 31 is a factor of ~ 2 stronger than that of Sk 188 (scaled to the flux it would have if it were in the LMC instead of the SMC), consistent with the result obtained from optical observations that Br 31 is triple. The strength of the Si IV 1400 Å P Cygni feature is also consistent with the optically-derived late O-type supergiant spectral classification for this third object.

Contrary to what we find for Br 31, the UV spectrum of Br 5 is not consistent with the optical results that suggest the presence of a third object or second close binary in the system. We find its UV continuum energy distribution to be very similar to that of the SMC binary system Sk 108 (scaled to the flux it would have if it were in the LMC) which contains WN3+O7 I: stars, and it is only $\sim 16\%$ brighter at 1800 Å than the presumably single LMC O4 If star. Thus, we do not support the conclusion that the system consists of two very hot O-type stars plus a late-type O-supergiant companion. In particular, the strength of the Si IV 1400 Å lines differs considerably from what would be expected from the presence of a late O-type or early B-type supergiant, where strong P Cygni profiles are evident. This presents a puzzle regarding the origin of the He I absorption lines. We cannot exclude, however, the presence of a lower luminosity B-type star, perhaps B II or B III, as proposed by Oey (1995).

This paper is based on data originally obtained by the authors, but later retrieved from the *Multimission Archive at Space Telescope, MAST*. We wish to express our gratitude to Randy Thompson for his support. AFJM thanks NSERC (Canada) and FCAR (Québec) for financial aid, and GK thanks CONACyT for grant 36569 and UNAM/DGAPA grant IN 118202.

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