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The WO stars

IV. Sand 5: a variable WO star*

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Abstract. We report the results of 10 years (August 1986-July 1996) of intermediate and low resolution spectroscopic observations of the WR star Sand 5 (WR 142), the nearest and less studied member of the small WO-subgroup which is located in the peculiar open cluster Berkeley 87. The wide spectral coverage (306-716 nm) and high S/N ratio, allowed us to measure in Sand 5 numerous emission features, and to separate most line blends. We have identified emission lines belonging to a very wide ionization range, from He II, C III, C IV, O IV, up to O V, O VI, and, notably, O VIII. The line broadness varies from 1600 km s^{-1} for O VIII to 3000/4600 km s^{-1} (O VI), 4100 km s^{-1} (O V), 4700/6200 km s^{-1} (C IV), and 5600 km s^{-1} (He II), which implies a ionization stratification in the wind and an acceleration of the outflowing matter from $\leq$1600 km s^{-1} up to the wind terminal velocity of $\sim$6000 km s^{-1}. During the extensive period covered by our observations the spectrum of Sand 5 has remained essentially constant. However we have noticed a marked fading of the contribution of He II to the 467 nm emission in 1992-1996, while the O VIII 606 nm doublet was not detected in 1987 and in 1989, suggesting that both events might be associated with irregular long term wind structure variation. ¿From the analysis of the continuum energy distribution we argue for a large interstellar extinction of E_{B-V}=2.1, with a reddening excess of about δE_{B-V}=0.4 local to the star, and a steep power-law $\lambda^{-3.85}$ distribution of the stellar continuum. We finally discuss the possible evolutionary state for Sand 5.

Key words: line: formation, identification – stars: evolution – stars: individual (Sand 5) – stars: mass-loss – stars: Wolf-Rayet

1. Introduction

Despite its small distance from the Sun ($\simeq$ 0.95 kpc; Turner & Forbes, 1982; Polcaro et al. 1989), Sand 5 (α_{1950}=20^h 19^m 52^s.2, δ_{1950}=37° 12′ 53″, finding chart in Turner and Forbes, 1982) is the less studied of the four "Population I WO" stars listed by Barlow & Hummer (1982). This is most probably due to the complexity of the region where this star lies. Actually, Sand 5, also named ST3 (Stephenson, 1966), and WR 142 (van der Hucht et al. 1981), is a member of the peculiar open cluster Berkeley 87. The reddening is largely variable within the cluster (Turner & Forbes, 1982) and its age ($\simeq$ 2-3 My), as evaluated from the H-R diagram, seems to be in disagreement with the age of the cluster member BC Cyg (M3.5 Ia). In addition, many members of the cluster show peculiar spectral characteristics, such as the B2Iabe star 3 (here and in the following the number refers to the catalogue of Turner & Forbes, 1982), and the puzzling variable star 15 (V 439 Cyg, Polcaro et al. 1989).

The cluster is very dense with about 100 member stars listed by Turner and Forbes (1982) within 16 arcmin from the cluster centre, corresponding to a 10 pc diameter circle at a distance of 0.9 kpc. A much larger star density of 5 arcmin^{-2} was derived from deep CCD V and R images of the central part of the cluster (Polcaro et al. 1991b). Berkeley 87 contains many compact H II regions, strong OH masers and CO and Ammonia molecular clouds (e.g. Dent et al. 1988, and references therein). Two intense IRAS sources are present in the cluster, one coincident with BC Cyg and the other close to the cluster centre (Polcaro et al. 1991a). Diffuse far-infrared emission is also observed (e.g. Polcaro et al. 1991a, and references therein).

Our optical observations of the sky region around Sand 5 and other cluster stars indicate the presence of a quite unusual diffuse emission at 581 nm, very strong and broad compared with the other observed emission lines. Polcaro et al. (1991b, 1991c) interpreted this feature as being due to the shock waves which are produced in the interaction of the wind of Sand 5 with that of the other cluster members. We also argued that this shock could be energetic enough to power a strong high energy emission. Actually, Berkeley 87 is located inside the error box of the COS B γ-ray source 2CG075+00 with an observed photon flux of 10^{-6} cm^{-2} s^{-1} in the energy range above 100 MeV (e.g. Pollock et al. 1987). The Cygnus region, in which Berkeley 87 is located,

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* Based on observations collected at the 1.5 m telescope of the Bologna Astronomical Observatory at Loiano

has been observed during the Compton GRO satellite Phase 1 observing period. A recent analysis of the EGRET data (Fichtel et al. 1994) identifies the COS B source 2CG 075+00 with the point source CGRO J2021+37. Manchanda et al. (1996) have argued that the position of this source is perfectly compatible with that of Berkeley 87, supporting our previous interpretation.

During 1986-1996 we obtained several spectra of Sand 5 and of its surrounding nebulosity, in order to get information on its evolutionary status, as we did for the WO star Sand 4 (Polcaro et al. 1992, hereafter Paper I), its surrounding nebulosity G2.4+1.4 (Polcaro et al. 1995, hereafter Paper II), and for the O VI sequence nucleus of the Planetary Nebula NGC 5189 (Polcaro et al. 1996, hereafter Paper III).

The present paper is devoted to the study of the stellar spectrum of Sand 5. The observations and data reduction techniques are discussed in Sect. 2, Sect. 3 is devoted to the analysis of the line variability, line profiles and wind velocity field, and to the stellar energy distribution and reddening. In Sect. 4 we discuss the nature and evolutionary stage of Sand 5 and in Sect. 5 we give some concluding remarks.

2. Observations and data reduction

The spectra of Sand 5 and of the surrounding nebula have been obtained during 1986-1996 at the Cassegrain focus of the 1.52 m Telescope of the Loiano Station of the Bologna Astronomical Observatory, using a variety of focal plane instrumentation. During 1986-1992 the telescope was equipped with a Boller & Chivens spectrograph. In 1986, the photon detector was an EMI 9914 image intensifier tube with Kodak IIaO plates. A total of 14 trailed spectra have been collected covering the ranges 363-440 nm and 430-508 nm in the second order, and 520-667 nm in the first order, with exposure times from 4 to 30 min. In 1987, 1989, and 1992 the detector was a 384×576 pixel Thomson 7882 CCD. A single near-IR spectrogram was obtained in May 1992 covering the range 984-1097 nm with a resolution of 0.45 nm. A Wratten near-IR filter was used in order to filter out the second order. In 1994 and in 1996, we used the Bologna Faint Objects Spectrometer and Camera (BFOSC, Merighi et al. 1994) which has a Thomson 1024×1024 CCD detector. Table 1 gives the detailed log of the observations.

The data were reduced at IAS using standard procedures for flat-field correction and sky subtraction, as described in Paper I. For the flux calibration from 1989 we used the standard stars Feige 15 and Kopf 27. The calibration of the near-IR band spectrum of 1992 was obtained by assuming for the energy distribution of the standard star Kopf 27 a Rayleigh-Jeans distribution, normalized to the star's visual spectrum. The corresponding flux of Kopf 27 at 1 μm turned out to be 2.1×10^{-13} watt m^{-2} nm^{-1}. This procedure might introduce a systematic error, which however can be estimated as soon as the near-IR spectrophotometry of Kopf 27 will be available. No calibration is available for the 1986 and 1987 spectrograms. The comparison of the spectrograms taken in different epochs shows that they overlap with each other within the calibration accuracy. Also the fluxes are in agreement with the photometry of Turner & Forbes (1982), and of Polcaro et al. (1991a) within less than 10%, which is an indication both of the accuracy of the spectrophotometry and of the absence of a significant flux variability (with the exception of a few lines, as discussed below). Being confident on the flux constancy of Sand 5, we have calibrated the 1987 spectrum using the 1989 flux calibrated continuum. For what concerns the spectrograms taken in 1986 with the image intensifier tube, we have used a standard calibration curve for the tube+plate system in order to allow a qualitative analysis of the line profiles.

We have obtained a very wide spectral coverage (from 320 to 716 nm) mid resolution, calibrated spectrogram, with peak S/N ratios larger than 100. This represents the highest resolution and widest range spectrum of Sand 5 so far published. The near-IR spectrogram of May 1992 is noisy, and has been essentially used to derive the mean stellar flux. Fig. 1 shows the optical spectrum of Sand 5 in 1992-1994.

The results of our measurements of the 1992-1994 spectrum of Sand 5 are shown in Table 2, where the data are arranged in a standard way, as in our previous works. The successive table columns give:

(1) heliocentric line barycentre (in nm) of the measured feature;

(2) total width (in nm) of the measured feature;

(3) emission line equivalent widths (in nm);

(4) adopted continuum level (in 10^{-9} W m^{-3}, i.e. 10^{-15} erg cm^{-2} s^{-1} nm^{-1}) local to the feature;

(5) measured line flux in 10^{-16} W m^{-2} (=10^{-13} erg cm^{-2} s^{-1});

(6) line flux in 10^{-15} W m^{-2} (=10^{-12} erg cm^{-2}s^{-1}), corrected for E_{B-V}=2.1;

(7) identification of the ion contributing to the observed line;

(8) laboratory wavelength;

(9) remarks: "main": main contributor to the feature; "contr": contributor to the feature; "?": uncertain identification, or possible contributor.

The measurements were made on the not dereddened spectrograms. For the line identification we used our previous works (Papers I and III), as well as the publications of the National Bureau of Standards (NSRDS-NBS 3), the Spectrophotometric Atlas of Torres & Massey (1987), the Kingsburgh & Barlow (1995) paper on the WO stars, and other references given in Paper III.

As discussed in Paper I for the case of the WO star Sand 4, the main source of error in the line measurements is the uncertainty on the true continuum level. For this reason the application of analytical formulae for the computation of the errors is meaningless. In our case we empirically evaluated the upper limit of the error on the equivalent widths to be of the order of 20%.

2.1. The emission line spectrum of Sand 5

In the following we discuss the results of the measurements of the individual emission features. Each line is identified by its barycentric wavelength.

- *324.3 nm*. This line is at the edge of our near-UV spectrum and thus is very difficult to measure since the continuum level

Table 1. Observation log of Sand 5

date	exp.time (sec)	instrument	spectr. range (nm)	resolution (nm)	slit
1986 Aug 1-2	various	B&C+EMI	363.0-667.0	0.1/0.2	trailed
1986 Sept 21	various	B&C+EMI	363.0-667.0	0.1/0.2	trailed
1987 Aug 7	600	B&C+CCD	432.1-684.1	0.60	4″×80″
1989 Aug 26	800	B&C+CCD	410.7-705.4	0.60	4″×80″
1992 May 25	3600	B&C+CCD	984.0-1097.	0.45	2.″5×3′
1992 June 6	1800	B&C+CCD	606.5-716.4	0.36	2.″5×3′
1992 June 6	2400	B&C+CCD	439.5-496.6	0.18	2.″5×3′
1994 Oct 18	1800	BFOSC	320.0-580.0	0.19	2.″5×9′
1996 July 23	1800	BFOSC	430.0-635.0	0.41	2.″0×3′

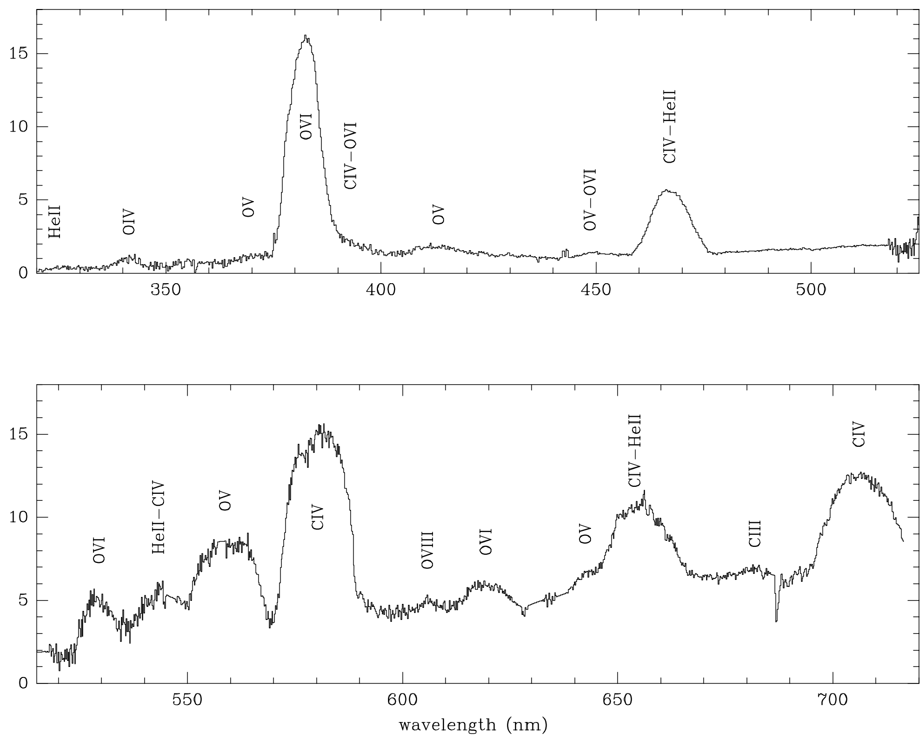

Fig. 1. The optical spectrum of Sand 5 in May-June 1992 and October 1994. The emission features are identified with their main contributing ions. Ordinates are fluxes (in erg $cm^{-2}s^{-1}nm^{-1}$), not corrected for the interstellar extinction.

is badly defined. Because of the low efficiency of the detector at these wavelengths, the line must be quite strong. We suggest that this feature could be identified with the He II 320.31 nm line, belonging to the same sequence of the strong 468.5 nm line. In this case its measured barycentric wavelength is redshifted due to the lack of detector sensitivity at wavelengths shortward of 320 nm.

- *341.5 nm*. Broad line extending from ∼334.6 nm to ∼345.7 nm. The line has been identified by Kingsburgh et al. (1995) with the O VI 343.4, 343.8 (7-6, 11-8) doublet, but, due to the position of the line barycentre, it is most probably a blend of this doublet with O IV λ340.0 (3d ^{2}D-3p ^{2}P^0), which has been observed by the same authors in other WO stars spectra. A partial contribution to the flux can come from the incomplete subtraction of the [Ne V] 342.6 nebular line.

- *369.3 nm*. Weak broad and shallow line extending from ∼364.3 nm to the blue wing of the strong 383 nm feature. Following Torres & Massey (1987), this line has been identified with the O V 3d^{3}D°-3p^{3}D system. Contrary to the case of Sand 4 (Paper I) where this line smoothly merges with the strong O VI emission, in Sand 5 the two features are rather well separated.

- *382.7 nm*. This is by far the strongest feature in the optical spectrum of Sand 5. It is characterized by a broad profile from 373.4 nm to about 391 nm, with a *red tail* extending to about 401 nm. In the higher resolution (but lower S/N) 1986 spectrum, two separate peaks at 381 and 384 nm, with a minimum at about 382.5 nm, are clearly visible (see Fig. 1a of Polcaro et al. 1991b. We apologize for an accidental error in that figure in the label of the O VI line). The line barycentre is slightly redshifted with respect to the mean wavelength of the O VI doublet. The line displays an asymmetric profile with an extended red wing and a sharp blue edge with a flux minimum at ∼374 nm, which can be attributed to a P Cygni absorption of the O VI λ381.1 line, extending to about 373.8 nm (-5700 km s^{-1}). Alternatively, the

Table 2. The optical spectrum of Sand 5 in 1992-1994

BAR WL nm (1)	WID nm (2)	EQW nm (3)	CONT $10^{-9}Wm^{-2}$ (4)	F_l $10^{-16}Wm^{-2}$ (5)	F_l° $10^{-15}Wm^{-2}$ (6)	ION (7)	LAB WL nm (8)	REMARKS (9)
324.2	≥6.7	3.9	2.9	≥0.47	.....	He II	320.310	uncertain
341.5	11.7	10.9	3.5	0.38	8.00	O IV	340.0	main
						O VI	343.4, 343.8	contr
369.3	12.0	2.4	8.5	0.18	3.75	O V	369.2, 372.6	main
382.7	28.4	125.6	11.1	13.8	85.7	O VI	381.135	main
						O VI	383.424	main
393.:	.....	.....	.....	.....	.....	C IV	393.4-3.4	contr; red wing of 382.7
						O VI	393.7	contr
						O VII	388.71	?
413.5	16.3	4.2	12.1	0.69	.....	O V	412.0-421.1	main
448.7	10.7	1.0	11.0	0.20	0.96	O V	449.8	main
						O VI	449.9	main
						O V	452.2	contr
						O V	452.30	contr
						He II	454.159	contr
						C V	452.00	contr
						O V	455.40	contr
						O VII	456.6	?
467.2	20.7	37.4	12.2	4.6	6.89	He II	468.568	main
						C IV	465.830	main
						C IV	464.68, 8.54	?
529.6	12.2	10.1	16.0	2.97	1.69	O VI	529.0	main
543.4	13.1	13.4	21.9	4.28	1.31	He II	541.152	main
						C IV	547.0	main
						C IV	541.1	contr
558.9	19.1	28.9	40.9	6.06	2.00	O V	557.90	main
						O V	560.06	main
580.4	26.5	44.1	37.2	16.8	3.20	C IV	580.133	main
						C IV	581.198	main
605.9	7.2	0.72	42.8	0.34	0.28	O VIII	606.42	main
						O VIII	606.82	main
619.5	16.4	3.9	43.8	1.65	0.36	O VI	620.2	main
						He II	611.8,617.1,623.4	contr
642.6	.....	.....	.....	.....	.....	O V	646.30	contr; blend with 654.1
						O V	650.02	contr
						He II	640.6, 652.7	contr
654.1	29.4	11.8	58.1	7.65	0.79	He II	656.010	main
						C IV	655.96	main
680.:	10.3	0.6	5.5	0.03	0.18	C III	672.7-677.3	main
						C IV	674.7	contr
702.2	≥17	72.9	5.30	40.0	0.53	C IV	706.24	main; cut by spectrum edge

flux minimum could be due to the red wing of the 369.3 nm emission. The extended red wing, which was also observed in Sand 4 (Paper I), might be attributed to asymmetric Thomson scattering wings and/or to the C IV and O IV emission lines discussed below. The marked deviation of the line profile from a Gaussian one (Table 3, column 9) could be at least partly ascribed to the fact that the line is actually a blend. On the other hand the peculiar line shape might possibly reflect the wind characteristics.

- *391-401 nm*. Red wing of the O VI feature extending from ∼390.9 nm to ∼401.0 nm, which can be attributed to a blend of C IV 393.4 (6p-5s), 392.9 (13-7) and O VI 393.7 (13-9), and, possibly, O VII 388.71. Actually, these lines appear clearly separated in the spectra of the extragalactic WO stars (Kingsburgh & Barlow 1995).

- *413.5, 423.4 nm*. This is a shallow emission which extends from ∼405 nm to 420/424 nm, and probably even farther, and should be an unresolved blend of several lines. Kingsburgh et al. (1995) observed in the spectrum of the WO stars Sand 2, Sand 4 and Sand 5 a broad emission feature extending from 405.5 nm to 425.5 nm which they identified with a blend of multiplets 4 and 11 of O V, with a possibile contribution of

Table 3. Main profile parameters of the line spectrum of Sand 5 in 1992-1994

BAR WL nm (1)	ION (2)	LAB WL nm (3)	V_{-} kms^{-1} (4)	V_{+} kms^{-1} (5)	FWHM nm (6)	GAUS kms^{-1} (7)	ASYM (8)	KURT (9)
341.5	O IV	340.0	-4500	+5000	11.3	6000	.....	.....
369.3	O V	369.2	-4000	+3400	.....	.....	.....	.....
382.7	O VI	381.13	-5100		12.0	4600[b]	-0.10	1.17
	O VI	383.42		+5800:[a]				
413.5	O V	412.4	-5400	+6400:[a]	16.2	7040:[a]	-0.12	1.00
448.7	O V[a]	452.2	-5200		10.7	4200	0.06	0.48
467.2	C IV	465.83	-4900		12.7	3900[b]	-0.02	1.34
	He II	468.57		+5600				
529.6	O VI	529.0	-3600	+3300	7.3	2500	-0.19	1.11
543.4	He II[a]	541.15	-3000:	+4200:	11.1:	3700:	0.00	1.14
558.9	O V	557.90	-5000		14.7	4100[b]	0.16	1.27
	O V	560.06		+5200				
580.4	C IV	580.13	-5300		16.2	4700[b]	0.00	1.57
	C IV	581.20		.....				
605.9	O VIII	606.42	-1600:		6.3	1600[b]	-0.09	1.28
	O VIII	606.82		+1400:				
619.5	O VI	620.2	-3900	+3500	12.5	3600	0.00	1.39
654.1[a]	C IV	655.96	a	a	20.0	5500	0.07	1.11
	He II	656.01						
702.2	C IV	706.24	-6200	+6300:	19.1	4900	-0.05	1.40

Notes to the table: [a] See discussion on individual lines (Sect. 2.1). [b] Doppler broadening corrected for the line blend.

the Si IV 408.9-411.6 doublet. The measurement of the feature is difficult because of the uncertainty in determining the local continuum. The line barycentre confirms that the strongest line of O V RMT 4 at 412.39 nm should be the main contributor to the feature.

- *448.7 nm*. Shallow emission on the blue side of the strong 467 nm feature. Its main contributors are, most probably, O V λ449.8 and O VI λ449.9. Our study of the [WC 2]-type nucleus of the PN NGC 5189 (Paper III), where this blend is partially resolved, allows us to identify a contribution to this feature from O V $\lambda\lambda$452.3 (RMT 15, 3d′-3p′), 452.2 (9-7), and 455.4 (RMT 7, 3d′-3p′), He II λ454.1 (9-4), and C V λ452.0 (9-7). O VII λ455.6 (11-9) should also contribute to this weak feature. On the other hand in Sand 5 the line barycentre is at a shorter wavelength with respect to the laboratory wavelengths of all the previously cited lines. In Paper I we suggested for this feature in Sand 4 a possible contribution from the still unidentified emission feature close to the wavelength of the emission lines identified by Morrell et al. (1991) at 448.5 and 450.3 nm in the spectrum of some O-type stars.

- *467.2 nm*. Strong and extended emission (from 458.2 nm to 477.3 nm). As discussed in Paper I for Sand 4, this feature in Sand 5 is a blend of He II 468.6 and C IV 465.8, with a comparable contribution, as also suggested by the line variability discussed below. The blue limit if attributed to the C IV line, corresponds to a velocity of -4900 km s^{-1}, while the red limit provides a velocity limit of +5600 km s^{-1} to the He II line. The line width, corrected for the line blending, suggests a Doppler velocity of 3900 km s^{-1}.

- *529.6 nm*. This line, due to O VI λ529.0 (8-7), shows a highly asymmetric profile, similar to that of the stronger O VI λ382 line. A flux minimum near 520-522 nm can be likely attributed to a P Cygni absorption of O VI. This feature is also present in the low resolution 1987 and 1989 spectra. In the red wing of this feature, a relatively narrow unidentified line, peaking at 534.9 nm, is marginally present.

- *543.4 nm*. The emission extends from $\sim$535.7 nm to $\sim$548.7 nm. It is a blend of He II λ541.1 (7-4), and C IV λ547.0 (10-7), with a contribution of C IV λ541.1 (14-8), but its profile is difficult to measure, being severely blended with the λ529.6 and λ558.9 features.

- *558.9 nm*. This strong, broad (from 548.7 nm to 569.8 nm) line is due to the O V $\lambda\lambda$557.9-560.1 blend. The line is partially contaminated by the sky line at 557.7 nm. The blue wing is merging with the λ543.4 feature. The line has a flat top extending from 553.3 nm to about 563 nm.

- *580.4 nm*. This C IV doublet is extending from 569.8 nm to about 594 nm, with a maximum at $\sim$580.4 nm. A hump in the line profile at about 589.3 nm might be due to the C IV 13-8 transition at 586.5 nm. However this identification is doubtful as the line should be much weaker than the 9-7 C IV transition observed at 706.2 nm. A partial contribution to the flux can come from the incomplete subtraction of the diffuse nebular line described by Polcaro et al. (1991a). A red wing (Thomson scattering?) is marginally present.

- *605.9 nm*. This line is narrower than the other features (FWHM = $\sim$6.3 nm), and peaks at 605.9 nm. We found only O VIII as a possible identification of this line. O VIII lines have been identified in the spectrum of O VI sequence PN nuclei (e.g. Barlow et al. 1980, Paper III), and of the WO star Sand 4 (Paper I, Kingsburg & Barlow 1995). O VIII could possibly be present at 434 nm in the spectrum of Sand 4 (Paper I).

- *619.5 nm*. Broad emission extending from 612.1 nm to 627.5 nm. The main contributor is most probably the O VI (11-9, 13-10) doublet. The corresponding V_-, V_+, and $V_{doppler}$ suggest an expansion velocity of 3500/3900 km s^{-1} (Table 3). The He II transitions to the n=5 term could contribute to the feature.

- *654.1 nm*. Very broad and asymmetric feature extending from about 636.4 nm to about 671.4 nm, with a very complex structure. The maximum is at 655.5, quite close to the Hα nebular emission. A second, partially resolved, maximum is at 642.6 nm. The feature is difficult to measure because of the many sky emissions which cannot be completely eliminated. Possible contributors to the feature are the He II Br-α line at 656.0 nm, the He II Pfund lines at 640.6-652.7 nm, C IV 656.0 nm, and O V 646.0, 646.6 and 650.0 nm. We suggest that He II λ656.0 and C IV λ656.0 are the main contributors to the feature as we argued in the case of Sand 4 (Paper I). The relative contribution of the two lines should be comparable, as discussed in Sect. 3.1 below.

- *680 nm*. A shallow, weak feature peaking at about 680 nm, and extending from about 670 nm to the atmospheric absorption band. Strong emission is present at this wavelength in the early-type WC stars where it is attributed to the C III RMT 3 blend from 672.7 to 677.3 nm (Torres & Massey, 1987), possibly blended with the multiplet 19 of the same ion at 685.7 to 687.2 nm, and with the C IV 674.7 nm 16-9 transition, which however is expected to be weak. If this line is attributed to the C III, this ion should also contribute to the 467.2 nm feature. We recall that the 680 nm feature is marginally visible, although with a smaller intensity, in the spectrum of Sand 4 as well. A completely different interpretation of this feature might be given on the basis of recent studies of the optical spectra of symbiotic stars. In fact, in the high ionization symbiotic stars a broad and intense emission is present near 683 nm (with a weaker companion line at 708 nm), which has been identified by Schmid (1989) as due to Raman scattering of the O VI UV resonance lines at 103.2, 103.8 nm emitted by the hot compact component of the symbiotic system. The lines are scattered by line-of-sight neutral hydrogen which, in the case of the symbiotic systems, is that of the atmosphere of the late-type component. The presence of the 683 nm feature in Sand 5 might be something more than a chance occurrence since in this star O VI is present very strongly in emission already in the optical range, while the 382 nm doublet is not visible in the most studied symbiotic star RR Tel (e.g Thackeray, 1977) which, on the other hand, exhibits the 683 nm feature quite strongly in emission. Furthermore, in order to have an efficient Raman scattering a large column density of neutral hydrogen in the line of sight is required (10^{22}-10^{23} cm^{-2}, depending on the expected strength of the UV O VI lines). Hydrogen might be present in the neighbourhoods of the WO star as the result of massive mass loss from a H-rich wind during the earlier post-MS evolution of the star. Actually, according to current evolutionary models of massive stars, several $M_\odot$ are lost during this phase. Observationally there is some evidence for the presence of diffuse matter around Sand 5, as discussed below. However, the Raman scattering process would imply that the velocity broadening of the UV O VI 103.8 nm line is six times smaller than the 680 nm feature, which seems unrealistic. Therefore we attribute this emission to C III.

- *706.2 nm*. Wide feature with a small but well defined flat top, extending from 703 to 707 nm. It is cut at longer wavelengths by the end of the 1992 spectrogram, but its profile is perfectly defined. The line barycentre is exactly at the laboratory wavelength of the C IV 706.2 nm 9-7 transition. We notice that the Doppler width of this emission, corrected for the line blend, is definitely wider than that of the 580 nm feature.

2.2. The near IR spectrum

As discussed above, a single near-IR spectrum of Sand 5 was obtained in May 1992. Due to the instrumentation set-up, and the weak stellar flux at these wavelengths, the obtained S/N ratio is low ($\simeq$ 5). Furthermore, the spectrum is affected by the crowding of a great number of nebular and sky lines (both in absorption and in emission). Actually, meaningful data were obtained only in the range 984-1045 nm, while at longer wavelengths the signal drops down due to the low quantum efficiency of the detector. The spectrum was binned from the original bin width of 0.45 nm to 1.0 nm in order to increase the S/N ratio. A single stellar feature with a barycentric wavelength of 997 nm was recognizable, while, at about 1000 nm, the spectrum starts to rise, possibly because of the 1012.4 He II feature which dominates the IR spectrum of Sand 5 (Howarth & Schmutz, 1992), up to its longer wavelength edge. However, no firm conclusion can be obtained on this part of the spectrum. The continuum flux near 1 μm is of $\sim 1.2\times10^{-8}$ W m^{-3} (1.2×10^{-14} erg cm^{-2}s^{-1}nm^{-1}).

2.3. The high resolution 1986 spectrum

The observational run of 1986 has made use of an instrumental configuration allowing in principle a higher spectral resolution in the near UV and blue ranges. On the other hand, the instrumental set-up (image intensifier plus plate) makes the conversion from plate densities to intensities unreliable. Some interesting results could nevertheless be extracted from the wavelength calibrated density plots. It is possible to see in the profile of the O VI λ382 feature a clear doubling into two components. Furthermore, in the blue wing a number of humps corresponding to He II, O V, O IV, and C IV lines have been identified by Polcaro et al. (1991b), suggesting that the possible O VI P Cygni absorption can be partially masked by these emissions.

In 1986 we also took a long exposure blue spectrogram of the star, that resulted saturated at the top of the 467.2 nm feature. The unsaturated profile of this line appears asymmetric, with an indication of a red wing. In this spectrum, we have found a number of weak lines, including the He II lines at 434, and 486 nm, and, possibly, O V λ493.5. Many lines are also present, with a considerable flux, in the lower resolution 1987 spectrum, while the same spectral regions appear devoided of lines in 1992 and 1994 (Fig. 1). Most probably, these differences are due to real spectral changes, a point which will be discussed in the next Sect. 3.1.

The lower resolution red spectra do not add much information on Sand 5, except for the presence of the O VIII λ606 line which is important for the long term behaviour of the star, as discussed below.

3. Discussion

3.1. Line variability

Our flux calibrated spectrograms of 1989, 1992, and 1994 show the same flux levels in the common spectral ranges. Therefore the stellar spectrum can be considered essentially stable on a long time scale. In addition most of the lines have, within the instrumental uncertainty, the same intensity and profile in the various spectra, with two important exceptions, the O VIII 606 nm feature, and the He II-C IV blend at 467 nm. The emission peak at 606 nm is in fact not observable in the spectrograms obtained in 1987 and 1989, while it is clearly visible in 1992, in 1996, and in the uncalibrated 1986 spectrogram discussed above. Since the S/N ratio is large ($\simeq$30), we believe that this variation cannot be an instrumental artefact.

Another important change was noted in the intensity and profile of the He II-C IV blends at 467 and 654 nm. In 1992 and 1994 the 467 nm line appears weaker than in the previous years, and slightly blue-shifted (the barycentric wavelengths were 467.52 nm in 1987, 467.43 nm in 1989, 467.36 nm in 1992, and 467.24 nm in 1994). We also notice that this feature is narrower, and blue-shifted in the uncalibrated 1986 spectrogram. In Fig. 2 we compare the two spectral regions in 1989 and 1992. C IV λ465.83 and He II λ468.57 are the main contributors to the 467 nm emission feature. The observed weakening is associated with a shift of the line barycentre towards the laboratory wavelength of the C IV line. This strongly suggests that the variation must be totally attributed to the He II line, as also confirmed by the constancy of the other C IV lines in the spectrum of Sand 5. The He II 468 nm line belongs to a transition between low E.P. levels (it corresponds to the hydrogen Paschen-α transition) and its excitation might be peculiar. Therefore the observed variability might be associated with some kinds of structure modification of the stellar wind.

According with the current evolutionary models, the WO stars, as well the earlier WCs, are in the He-shell, C-core burning phase (e.g. Hamann et al. 1992) and might be subject to some kinds of structure instability leading to surface oscillation. These oscillations should produce waves which, during their propagation through the stellar wind reduce the ionization especially of the innermost parts of the wind, and increase the excitation of He II in the outer layers.

The observations lead us to suggest that Sand 5 is subject to recurrent changes of the wind structure, with epochs (1987 and 1989) during which the wind has a lower ionization level than in 1986, 1992, and 1996. When the wind is less ionized, the He II 468 nm line is stronger, thus suggesting a kind of anticorrelation between O VIII and He II. The He II weakness in October 1994, when the star was not observed in the red, is suggestive that also in that epoch the star was in a "hot phase". The most recent spectrum shows that Sand 5 in July 1996 was still in this state. We also note that the O VIII 606 nm line is present in emission in the lower resolution spectrogram of Sand 5 taken by Torres & Massey (1987) between October 1980 and February 1983, while the line was not reported by Kingsburg et al. (1995) in their identification list of the star, which is based on spectra of Sand 5 taken in August 1978 and August 1992.

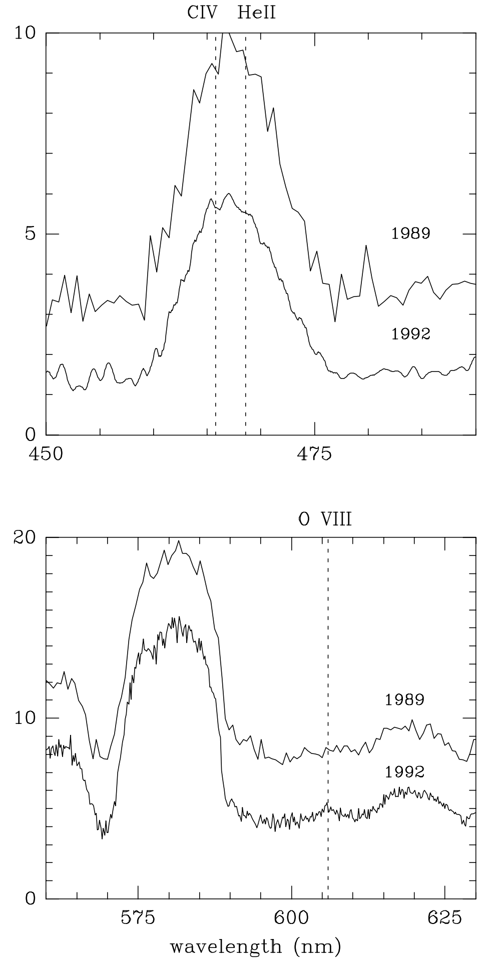

Fig. 2. Spectral variation of Sand 5 during 1989-1992 (Sect. 3.1). *Upper panel*: the 467 nm feature. *Lower panel*: the O VIII 606 doublet. Ordinates are undereddened fluxes in 10^{-14} erg cm^{-2}s^{-1} nm^{-1}, with the 1989 spectrogram vertically shifted.

Finally, as discussed in Sect. 2.3, the spectral region between 480 nm and 520 nm, that appears line-free in the 1992-1994 spectra, displays in 1986 and 1987 some shallow features, which, although close to the noise level, appear to be definitely present. We want to stress also that the equivalent widths of many of the features we have measured significantly differ with those reported by Kingsburg et al. (1995). This fact could be due to a different choice of the continuum (and this is the reason why in our papers we normally give in the identification table the continuum *local to the feature*). But we cannot rule out the possibility that the intensity of some lines has really varied, in agreement with our results.

3.2. Line profiles and velocity field

A discussion of the line profiles cannot be conclusive without considering the broadening mechanisms (wind velocity field, electron scattering, line and continuum opacity, etc.), which are the necessary ingredients to compute the theoretical profiles to be compared with the observations. On the other hand, for the computations some input data on the wind structure are required which can only be derived from an empirical analysis of the observations. Therefore in the following discussion we shall analyze the line profile using simplified assumptions, such as a Gaussian line profile.

The line profile measurements were performed on the reddening corrected spectrogram, assuming a power law continuum with α=-3.85, as discussed in Sect. 3.3. The basic data on the line profiles are summarized in Table 3 where the successive columns give:

(1) line barycentre;

(2) main contributor(s) to the feature;

(3) laboratory wavelength;

(4) the radial velocity V_- of the blue limit of the emission feature; in the case of a blend of two contributors of comparable intensity, the velocity is referred to the bluer component;

(5) the radial velocity V_+ of the red limit of the emission feature; in the case of a blend, the velocity is referred to the redder component;

(6) full width at half maximum (in nm);

(7) velocity broadening (in km s^{-1}) derived by assuming for the line a Gaussian profile, and taking into account the separation of the doublets;

(8) *line asymmetry* and (9) *kurtosis*, as defined by Whittle (1985). A kurtosis larger than one corresponds to a profile more stubby than a Gaussian one.

As discussed above, in the case of a blend of two lines with comparable strength, such as the C IV λ465.83-He II λ468.57 blend at 467.2 nm, the V_- and V_+ velocities are referred to the bluer and redder components of the blend, respectively. The Doppler velocity is derived from the line FWHM reduced of the wavelength difference of the two components (2.74 nm in the above case), and assuming a Gaussian profile. In principle the velocities derived from the blue and red edges of the emissions should be used with some caution, because of the difficulty to determine these edges. However, we have found for most lines a good agreement between V_- and V_+ and the Doppler velocity which make us confident in the use of both data. In some cases, such as for the 654.1 nm feature, the wings appear more extended than expected because of the presence of weaker unresolved lines. The presence of line blends is also underlined by the line profile parameters asymmetry and kurtosis in the last columns of Table 3, as also discussed above in the analysis of the individual lines (Sect. 2.1).

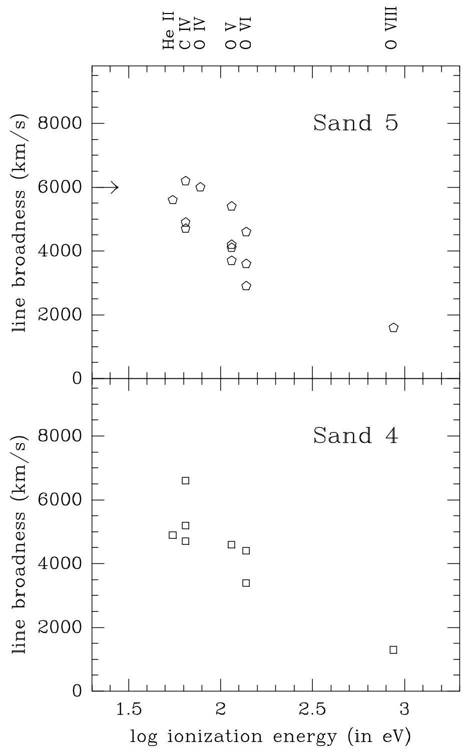

Fig. 3. Line broadness gradient in the WO stars Sand 5 *(upper panel)* and Sand 4 *(lower panel)*. The adopted wind terminal velocity in Sand 5 is indicated with an arrow. Abscissae are the logarithm of the ionization energy to the next ionization stage

In Fig. 3 (upper panel) we have plotted the line broadness (as in col. 7 of Table 3) versus the logarithm of the ionization energy. The various lines do not have the same width, as expected if formed in a constant velocity wind, but the velocity broadening spans from a minimum of 1600 km s^{-1} to about 6200 km s^{-1}. In particular it appears that the very high energy O VIII lines are much narrower (1600 km s^{-1}) than the other lines, which is suggestive of a ionization stratification in an accelerated wind, with the higher temperature lines formed in the inner, lower velocity regions. A velocity gradient is also evident in the other ions,with a velocity broadening of 3100/4600 km s^{-1} for O VI, 3700/4800 km s^{-1} for O V, 5200 km s^{-1} for O IV, 5600 km s^{-1} for He II, and 4700 to 6200 km s^{-1} for C IV. In spite of the presence of some spread in the Doppler velocities of different lines of the same ion, the lines of the higher ionization species (O VI and O V) are systematically narrower than those of O IV, C IV, and He II. A similar pattern is present in the wind of the WO star Sand 4 (Paper II) as shown in the lower panel of Fig.3.

There is a clear evidence that different lines of the same ion do not have the same width, as it is for instance the case of the C IV lines at 465.8, 581.0 and 706.0 nm (see Fig. 3). A similar behaviour was recently found by Schulte-Ladbeck et al. (1995) in two WR stars, and is probably to be attributed to line opacity effects.

The variability of the line profiles, even for lines of the same ion, and the necessity to take into account the contribution of the many unresolved weak lines render a precise abundance determination difficult. While this would be a fundamental step towards understanding the nature of the WO stars, it requires rather a spectral synthesis procedure in order to account properly for effects like line opacity variations, including scattering contributions. An analysis of this kind is postponed to a subsequent paper.

3.3. Stellar energy distribution and reddening

As discussed above, the interstellar reddening inside Berkeley 87 varies across the cluster. Turner & Forbes (1982) have drawn the detailed iso-reddening curves, and their map has been confirmed by our observations (e.g. Polcaro et al. 1991a). The reddening map shows a distribution similar to that of the IR-line emission of the molecular cloud (Dent et al. 1986). We could thus rely on the E_{B-V} value of 1.7 given by Turner & Forbes (1982) for the site of the WO star. On the other hand, if we correct the spectrum of Sand 5 with this value, we find a slope of the blue continuum which is in disagreement with the high ionization level indicated by the emission line spectrum of the star.

The exact evaluation of the star reddening is complicated by the poor knowledge of the intrinsic continuum of WR stars. It has been shown, from a sistematic analysis of the energy distribution of WR stars of different spectral types (Morris et al. 1993), that in most cases their continua can be fitted with a power law with spectral indices grouped around -2.85. We have therefore assumed for Sand 5 a power law continuum energy distribution for the whole wavelength range from 320 nm to 1 μm, and have corrected the observed spectrum with different colour excesses (with the standard galactic extinction law). We have found that with E_{B-V}=2.1, the continuum from the near UV to the near IR can be fitted with a single power law distribution with exponential index of -3.85 (see Fig. 4). This is steeper than the average slope of the WR continuum, but still compatible with the frequency distribution of α in single WR stars found by Morris et al. (1993). A lower index would be compatible with an even larger extinction, and would still provide a good fit of the optical continuum, but it would also imply the presence of a rather unrealistic IR excess.

This suggests that Sand 5 is surrounded by a quite dense material, producing a circumstellar reddening excess of at least 0.4. Such circumstellar reddening indicates that probably Sand 5, like most of the WO stars (see e.g. Kingsburgh et al. 1995; Lozinskaya 1991) is surrounded by a nebula probably formed by the stellar wind. A circumstellar reddening of similar strength has been found around the other galactic WO star Sand 4 (Paper II). In this regard we remind that the low resolution spectrogram of August 1989, which was obtained with excellent sky conditions, clearly shows around Sand 5 a diffuse emission centered at the same wavelength of the very prominent stellar C IV 580.3-581.2 nm doublet. Polcaro et al. (1991b) interpreted this diffuse emission as due to a strong shock in the hypersonic, C-rich wind of the star associated with the COS-B γ-ray source. The confirmed identification of this γ-ray source with the cluster region by the CGRO observations shows that most of our model is still valid although the nebula appears now much more complex than our preliminary analysis of 1991 had foreseen.

Actually, the higher spectral and spatial resolution, and the much longer exposures of the spectrograms taken in 1992, 1994, and 1996 allowed the discovery of many nebular lines (e.g. H and He lines) from the sky area surrounding Sand 5. On the other hand, the detailed spectral analysis of this nebula is made difficult because of the overlap with the diffuse emission from the intercluster material in Berkeley 87 (e.g. Dent et al. 1988; Polcaro et al. 1991b). The strong light pollution of the telescope site, that generates a crowding of local sky lines, makes this task even more cumbersom. A careful data processing is needed in order to correct for the presence of spurious spectral lines and, therefore, the results of this analysis will be presented in a forecoming paper.

4. The nature and evolutionary stage of Sand 5

The spectrum of Sand 5 is typical of the so-called WO-spectral type. It is characterized by quite a wide ionization range, with lines belonging to transitions of different ionization species, such as He II, C IV, and O IV up to O V, O VI, O VIII, and, possibly, C III. The strength of the O VI 382 nm feature is typical of these stars, while it is much weaker or absent in the earlier WC types (e.g. Polcaro et al. 1996). The spectrum of Sand 5 is quite similar to that of the other galactic WO star Sand 4 which we have described in Paper I. In particular, we have identified in both stars the hydrogen-like O VIII species, which is indicative of the presence of ionizing photons above the 871 eV ionization limit of O^{+7}.

Most of the lines are present in both stars, proving that they have rather similar atmospheric envelopes. Also the line velocity parameters are similar. There are nevertheless some significant differences. Probably, the most striking one is the much larger intensity in Sand 5 of the 580 nm C IV emission relatively to the other features. The C IV features show profiles which can be more closely represented by a Gaussian profile than in Sand 4. In addition, in Sand 5 in 1992-1996 the O VIII 606 nm line is more intense than in our June 1990 spectrograms of Sand 4. In Paper I we also noted a marked difference in the intensity of the 467 nm feature with respect to an earlier spectrum of Sand 4 obtained by M.J. Barlow. It is interesting to notice that the presence of a variable O VIII feature in the spectrum of Sand 5 and the possible variability of the C IV-He II blend at 467 nm casts serious doubts on the possibility to establish a firm sequence inside the spectral class based on the relative intensity of different features (see e.g. Kingsburg et al., 1995).

We argued elsewhere (Polcaro et al. 1996) that in many respects the WO stars behave like extreme WCs, with wind velocities systematically faster than in the earlier WC stars, and that several hints point towards identifying the WO stars as those stars that, in the evolutionary models, are coming to the end of the phase of helium burning in a shell. The presence of three such stars in our Galaxy (Sand 4, Sand 5, and WR30a), though, probably implies that the end of this phase is less sharp than

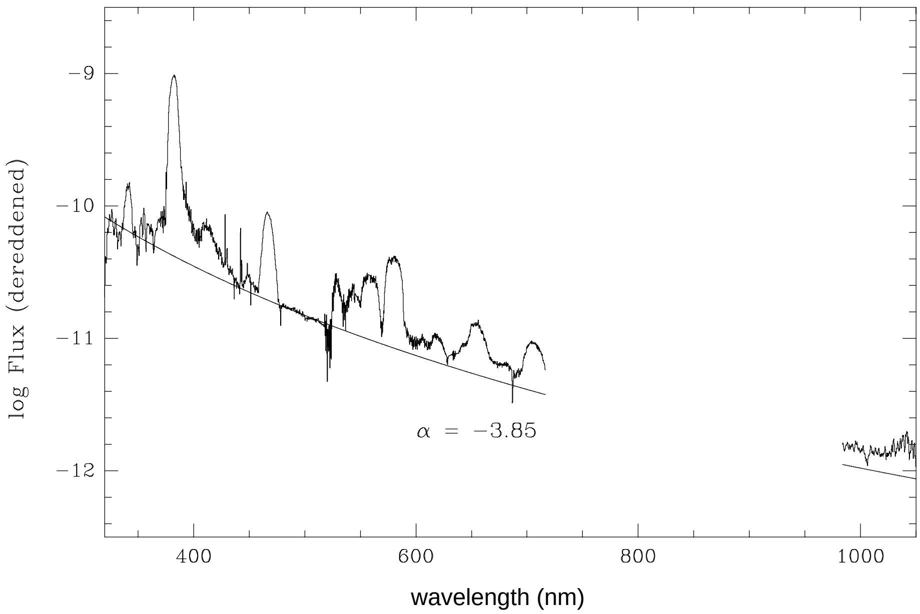

Fig. 4. The energy distribution of Sand 5. Ordinates are logarithm of fluxes (in erg $cm^{-2}s^{-1}nm^{-1}$) corrected for an interstellar extinction of E_{B-V}=2.1. The stellar continuum is fitted by a power law with exponential index of -3.85 (continuous line) as discussed in Sect. 3.3.

foreseen by the current models, and that the transition would occur through instability stages with "hot" and "cold" phases of the kind that are observed in the Luminous Blue Variable stars.

Finally, it is of interest to notice that, while the membership of Sand 5 to the 2 Myr old cluster Berkeley 87 is undisputable, all the evolutionary tracks of high mass stars so far computed are pointing to a WN phase for a 2 Myr old object, even in the extreme case of M_0=120 $M_\odot$ (e.g Hamann et al. 1992 Maeder 1990). In fact, Polcaro et al. (1991a) have remarked the difficulty of modeling the evolutionary status of Barkeley 87. ¿From many points of view the cluster appears similar to the other young clusters located in the Cygnus X sky area, as it has been shown by the study of Turner & Forbes (1982). On the other hand, many of the cluster peculiarities still remain unexplained. We believe that at least some of these can be explained as the result of the interaction of the Sand 5 highly energetic wind with the other cluster members (Polcaro et al. 1991b), and of a nested star forming episode sequence (Polcaro et al. 1991a). But these hypotheses must now be reconsidered as our understanding of the evolution of high mass stars improves.

5. Conclusions

Ten years of spectrophotometric monitoring of Sand 5 have allowed us to confirm previously known results and to draw attention to some new phenomena, which might be of importance for modelling the winds of WO stars.

1. The wind of the WO star Sand 5 displays a very wide ionization range, as indicated by the simultaneous presence in its optical spectrum of five ionization stages of the same element (Oxygen). We confirm that the highest energy level is represented by the O VIII recombination lines (871 eV), while the lowest energy ion is probably C III. However, the equivalent widths of some of the lines differ from those observed by Kingsburgh et al. (1995). This is probably due either to a different choice of the continuum level or to line variability.

2. We have observed for the first time variable velocity widths among different lines. There is an evident anticorrelation between the line width and ionization energy, which suggests a ionization stratification of the wind, and an acceleration of the outflowing matter (if ionization decreases with height in the wind) up to about 6000 km s^{-1}. A similar anticorrelation is also present in the other WO star Sand 4 (Paper I), as well as in the two WR stars studied by Schulte-Ladbeck et al. (1995). We also find that the velocity width is not the same among different lines of the same ion (e.g. C IV $\lambda\lambda$465.8, 581, and 706), which should be the result of line and continuum opacity effects which need to be taken into account for the derivation of the wind velocity law. P Cygni blue-shifted absorption components, and Thomson scattering red wings might be present in some lines.

3. Helium is definitely present in Sand 5 as also observed by Kingsburgh et al. (1995) (as well as in Sand 4, Paper I), which will probably require a change in our current ideas about the evolutionary stage of WO stars.

4. A new result is also that the atmosphere of Sand 5 is slightly unstable, as disclosed by the temporary disappearence of the O VIII emission, which appears to be associated with the strengthening of the He II 468.6 nm radiation dilution sensitive line. We suggest that this results from cyclic oscillations of the star which causes the propagation of density waves through the stellar wind. A systematic spectroscopic monitoring of the optical spectrum, (better if associated with broad and narrow-band photometry,) should give a better insight in this phenomenon, in particular in the repeatibility and the time scale, which are fundamental requirements to understand whether the variation is associated with a structure pulsation.

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