THE WO WOLF-RAYET STARS

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Sanduleak (1971) has listed five stars, not apparently associated with planetary nebulae, which show very strong O VI 3811,34 Å emission. He pointed out that two of them are in the Magellanic Clouds and have absolute magnitudes comparable to those of classical (Population I) Wolf-Rayet stars. O VI emission is know to occur in some classical Wolf-Rayet stars, but not with the extreme strength shown by the Sanduleak stars. We have obtained absolute optical spectrophotometry (3100 - 7400Å) of all five of these stars, using the UCL Image Photon Counting System and RGO Spectrograph on the Anglo-Australian Telescope. Figure 1 shows their relative flux distributions. Inspection shows that Sand 1 is very lightly reddened, Sand 2 and 3 have intermediate reddening, and Sand 4 and 5 are heavily reddened. IUE ultraviolet spectrophotometry has been obtained of the first three stars; Sand 4 and 5 are too heavily reddened for IUE spectra to be feasible.

The optical spectrum of Sand 3 has been described by Barlow, Blades and Hummer (1980) and shown to be of extremely high excitation, with emission lines of C V, O VII and O VIII present, along with lines of He II, C IV, O V and O VI. We will argue below that Sand 3 is not in fact a Population I object.

In Figure 1, the strongest emission features in the five spectra are those of O VI λ3811,34; the complex of C IV λ4658 and He II λ4686; and C IV λ5801,12. Emission lines of C III are completely absent in all five stars and C IV is the only ion of carbon present in Sand 1,2,4 and 5. The strong emission feature peaking at 3400Å in Sand 1 and 2 is due to multiplets 2 and 3 of O IV (3d-3p and 3p'-3s', between 3381Å and 3426Å). This O IV feature does not appear to be present in the remaining stars, their spectra in this region showing only O VI 7 → 6 at 3434Å. A feature at 6068Å, due to O VIII 10 → 9, 13 → 11, is present in the spectrum of Sand 4. It is possible to argue that the Sanduleak stars are an extension of the WC sequence to earlier spectral types, since classical WC5 stars have strong O IV 3400Å emission, but with C III also present. However, Sand 1,2,4 and 5 would not fit easily into the classification scheme for planetary nebula nuclei proposed by Mendez and Niemela (1982); all being WC4 in that

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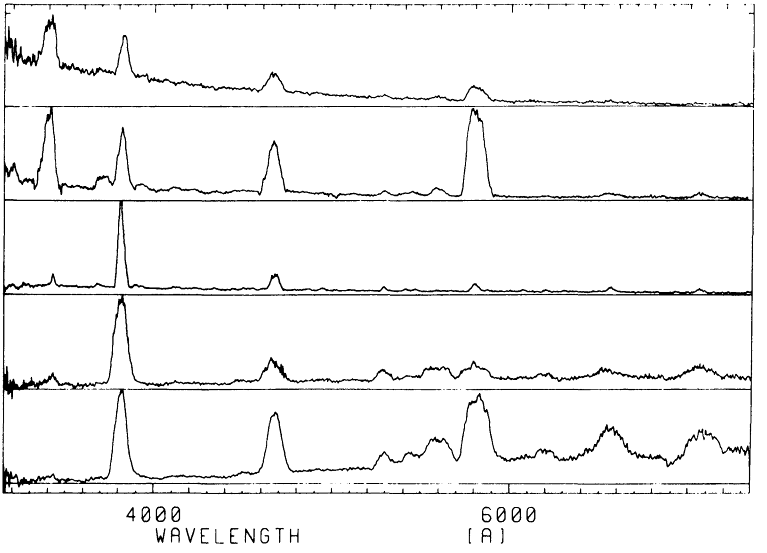

Figure 1. Absolute spectrophotometry from 3150-7400 Å for the stars Sand 1 (top) to Sand 5 (bottom), in the form of F_λ versus λ.

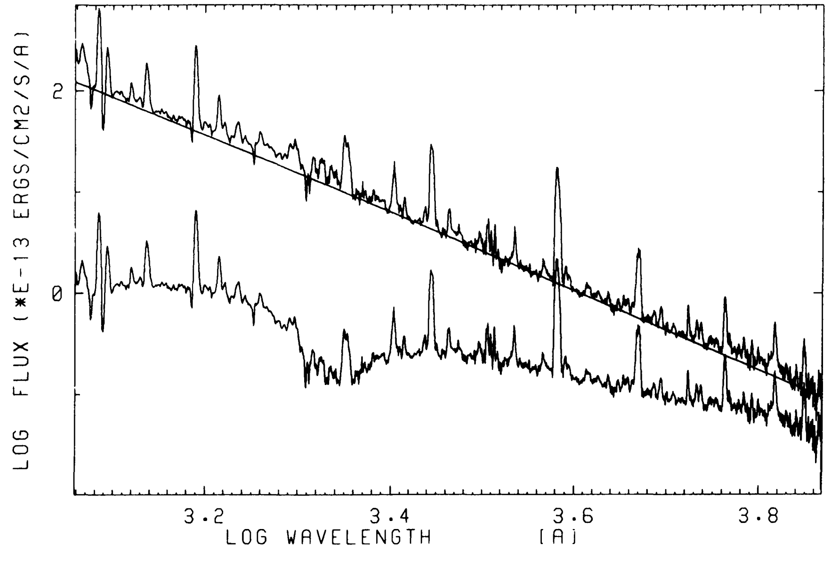

Figure 2. Combined ultraviolet and optical spectrophotometry for Sanduleak 3, in the form of $\log(F_\lambda)$ versus $\log\lambda$. Bottom: the observed flux distribution. Top: after dereddening by E(B-V) = 0.50. Also shown is a $T_* = 2\times10^5$ K blackbody, normalised to the dereddened spectrum at 1400 Å.

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system. We argue instead that the Sanduleak stars 1,2,4 and 5 should be considered as a separate WO sequence, defined mainly by the relative strengths of O IV, O V and O VI. This is for both the practical reason that the only ion of carbon present is C IV and for the heuristic reason that we believe that their spectra reflect an actual enhancement of the abundance of oxygen, relative to the WC stars. Such an enhancement of oxygen can be interpreted as due to α-particle capture by carbon nuclei during the late stages of core helium burning in an initially massive star, the enriched material eventually being exposed at the surface by mass loss stripping. In this scenario WO stars represent the next evolutionary stage after the WC phase, being either at the end of core helium burning or already in the core carbon burning stage. The small number of WO stars found, relative to WC stars, is consistent with this hypothesis.

In order of increasing excitation, the WO sequence runs: Sand 2,1,5,4. The Wolf-Rayet catalogue of van der Hucht et al. (1981) defines the WC4 subtype as having strong C IV λ5801,12 and weak or absent C III λ5696. By analogy, we define the latest WO subtype (WO4) to have C IV strong and C III absent, plus very strong O IV λ3400 and O VI λ3811,34; with O IV ∿ O VI. Subtype WO3 has O VI > O IV whilst WO2 has O IV absent and OV λ5590 < C IV λ5801,12. Subtype WO 1 has O V ⩾ C IV. With so few stars per subtype at present, the numbering system must be considered tentative.

Table 1 presents some derived parameters for the Sanduleak stars. Columns 1 and 2 give the name and assigned spectral type for each star, whilst column 3 gives the wind terminal velocity, v_∞. For Sand 1, v_∞ was determined from the edge velocity of the C IV resonance line in a 400 minute IUE high-resolution SWP exposure. For the remainder, v_∞ was assumed to be given by half the full width of the O VI λ3811,34 feature. Columns 4,5 and 6 give the values of V,(B-V) and A_V for each star. The magnitudes were determined from the spectrophotometry by estimating the continuum flux level at 5460Å(V) and 4400Å(B) and will thus be fainter than magnitudes determined by filter photometry, since emission lines will be included in the latter. To obtain A_V, an intrinsic $(B-V)_0 = -0.32$ and R = 3.1 were assumed, except for the case of Sand 3, where A_V was determined by nulling the 2200Å extinction feature. Columns 7 and 8 give the distances (where known) and the derived absolute magnitudes M_V.

STAR	Sp. Type	v_∞(km s^{-1})	V	(B-V)	A_V	D(kpc)	M_V
SAND 1 (SK188)	WO4+O7 III	4200	13.40	-0.33	0.0	66.1(SMC)	-5.7
SAND 2 (FD 73)	WO4	4000	16.44	0.08	1.24	52.5(LMC)	-3.4
SAND 3		2700	14.24	0.21	1.55		
SAND 4	WO1	5500	14.64	1.33	5.12		
SAND 5 (ST 3)	WO2	5800	13.56	1.72	6.32	1.0*(Be87)	-2.8

* Turner and Forbes (in van der Hucht et al., 1981).

Quite similar absolute magnitudes are derived for Sand 2 and 5, whilst the continuum of Sand 1 is dominated by the O7 III companion. If it is assumed that Sand 4 also has M_V -3, a distance of 3.2 kpc is derived, which seems quite reasonable. Although the (continuum) absolute magnitudes of the WO stars are fainter than those of Pop.I WN and WC stars, it should be borne in mind that their energy distributions are probably significantly hotter and that a much larger fraction of their luminosity appears in emission lines. Thus their bolometric luminosity may not differ significantly from those of other WR stars.

We have excluded Sand 3 from the above classification scheme since we now believe that it is the remnant central star of a planetary nebula (PN) which is no longer visible. Our reasons are as follows: (1) Its spectrum is of much higher excitation and its wind velocity much lower than those of the other Sanduleak stars; (2) If M_V were equal to -3 for Sand 3, it would be 14 kpc distant and 3 kpc above the Galactic plane. A Galactic latitude of $+12^0$ would, on the other hand, be quite consistent with PN nucleus status; (3) The optical and UV spectrum of Sand 3 is virtually identical to those of the PN central stars of NGC 5189 and NGC 6905; (4) The λ1238,40 resonance line of N V is definitely absent in the spectrum of Sand 2, consistent with its being a massive star in a late or post-helium burning phase, as nitrogen should be completely destroyed in the early stages of helium burning (Paczynski 1973). However, N V resonance line emission is present in the UV spectrum of Sand 3 (as it is also in the spectrum of the nucleus of NGC 5189), inconsistent with a massive star origin. The nuclei of planetary nebulae, on the other hand, are helium shell burning objects. The 'dredge-up' mechanism of Iben (1975) can therefore operate to bring to the surface (stripped of hydrogen by mass loss in this case) the products of shell helium burning, which are then diluted by surface material (He, N) from the previous hydrogen shell burning phase.

Figure 2 shows both the observed and dereddened UV + optical spectrum of Sand 3. From constraints placed by the depth of the 2200Å extinction feature and by the overall continuum slope, it was found that $E(B-V) = 0.50 \pm 0.05$. Also shown is a 2×10^5 K blackbody fitted to the dereddened continuum. Dereddening with larger or smaller values of E(B-V) was found to lead to an incomplete cancellation of the 2200Å feature plus an inability to fit the continuum with a blackbody of any temperature. It is estimated from continuum fitting that a lower limit to the stellar blackbody temperature is 1.5×10^5 K, whilst no upper limit can be set.

The intensities of all the recombination lines in the dereddened spectrum of Sand 3 have been measured and compared with theoretical Case B recombination line predictions for the relevant ions. These were calculated by Hummer and Storey (1982) in exactly the same manner as described by Hummer et al (1982). The results for the case of $T_e = 2 \times 10^5$ K and $n = 10^{11}$ cm^{-3} were found to give an excellent fit to the observed relative line intensities of transitions within He II, C IV, C V, O VI, O VII and O VIII; covering upper levels as low as 3 and as high as 15 over the wavelength range 1170 - 7100Å. A full description of our results will be given elsewhere, but we present below the derived relative abundances (by number), normalised to He^{2+} = 100.

Ion	He^{2+}	C^{4+}	C^{5+}	O^{6+}	O^{7+}	O^{8+}
Relative Abundance	100 ± 15	45 ± 10	2.7 ± 0.2	3.4 ± 0.8	1.2 ± 0.2	0.83 ± 0.26

The surface chemical composition of Sand 3 (by mass) is thus H : He : C : O = 0 : 38 : 54 : 8. Since the mass fraction of oxygen in a ZAMS star is only 1%, these results indicate enhancement of oxygen through α-particle capture by carbon, in addition to the expected enhancement of carbon by the triple-α process. The ultraviolet spectrum of Sand 3 (and also those of NGC 5189 and NGC 6905) shows strong lines of Ne V at λ1719, 1980 and 2250Å, whilst lines of Ne VII and Ne VI probably also contribute to the latter two features. This provides further evidence for the operation of the α-particle capture mechanism, since neon is the next element in the capture chain after oxygen.

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DISCUSSION FOLLOWING BARLOW

Massey: Certainly the most infamous of He WR stars which show O VI λ3811, 3834 is the WN3 "pec" star HD 104994. Its optical spectrum looks much like that of the other WN3 stars. Why do you see O VI here? The overall envelope excitation must be similar to the other WN3's.

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Barlow: For the very highest stellar temperatures one would expect almost all oxygen to be in the O^{6+} ionization stage. Due to the dependence of recombination rate on nuclear charge squared this will give rise very efficiently to O VI lines. However, if this WN3 star has an absolutely identical spectrum to other WN3 stars, apart from the presence of the O VI lines, then one would presumably have to invoke a higher abundance of oxygen.

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