Far-UV FUSE spectroscopy of the O\textsc{vi} resonance doublet in Sand 2 (WO)

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ABSTRACT

We present Far-Ultraviolet Spectroscopic Explorer (FUSE) spectroscopy of Sand 2, a LMC WO-type Wolf-Rayet star, revealing the O\textsc{vi} resonance P Cygni doublet at 1032–38 Å. These data are combined with HST/FOS ultraviolet and Mt Stromlo 2.3m optical spectroscopy, and analysed using a spherical, non-LTE, line-blanketed code. Our study reveals exceptional stellar parameters: $T_\ast \sim 150,000$K, $v_\infty = 4100$ km s$^{-1}$, log $(L/L_\odot) = 5.3$, and $\dot{M} = 1 \times 10^{-5} M_\odot$ yr$^{-1}$, if we adopt a volume filling factor of 10%. Elemental abundances of C/He$\sim 0.7 \pm 0.2$ and O/He$\sim 0.15^{+0.10}_{-0.05}$ by number qualitatively support previous recombination line studies. We confirm that Sand 2 is more chemically enriched in carbon than LMC WC stars, and is expected to undergo a supernova explosion within the next $5 \times 10^4$ yr.

Subject headings: stars: Wolf-Rayet – stars: evolution – stars: individual
(Sand 2)

1. Introduction

Wolf-Rayet (WR) stars provide keys to our understanding of massive stellar evolution, nucleosynthesis processes and chemical enrichment of the ISM. Of these, the oxygen-sequence (WO) introduced by Barlow & Hummer (1982) is by far the rarest. Their high excitation oxygen emission lines are widely interpreted as revealing the late core helium-burning or possibly carbon-burning stage (Smith & Maeder 1991), of importance for constraining the controversial $^{12}$C(\textit{$\alpha$, $\gamma$})$^{16}$O reaction rate.

In spite of searches in all Local Group galaxies, only six massive WO stars are known to date, namely Sand 1 (Sk188) in the SMC, Sand 2 (BAT99–123) in the LMC, Sand 4
(WR 102), Sand 5 (WR 142) and MS4 (WR 30a) in our Galaxy, and DR1 in IC1613. Since \( \text{O vi} 3811–34\AA \) is a primary WO classification diagnostic, with an equivalent width of up to 1700\AA~(Kingsburgh, Barlow & Storey (1995, hereafter KBS), observations of \( \text{O vi} 1032–38\AA \) are keenly sought. However, its location in the far-UV has ruled out such observations to date. This situation has changed following the successful launch of the Far-Ultraviolet Spectroscopic Explorer (\( \text{FUSE} \), Moos et al. 2000), which permits routine high dispersion far-UV spectroscopy of massive stars in the Magellanic Clouds.

In this Letter, we analyse \( \text{FUSE} \) spectroscopy of Sand 2 (Sanduleak 1971), alias Sk−68° 145 = Brey 93 = BAT99-123 (Breysacher, Azzopardi & Testor 1999), together with \textit{Hubble Space Telescope (HST)} and ground-based datasets.

2. Observations

Previously unpublished far-UV, UV and optical/near-IR spectroscopy of Sand 2 have been obtained with \( \text{FUSE} \), \textit{HST} and the Mt Stromlo and Siding Spring Observatory (MSSSO) 2.3m, respectively.

2.1. Far-UV spectroscopy

Sand 2 was observed by \( \text{FUSE} \) as part of the Early Release Observation programme X018 on 1999 Oct 31. A 8134 sec exposure of Sand 2 with the 30” × 30” (LWRS) aperture provided data at \( R \sim 12,000 \) with the two Lithium Fluoride (LiF) channels, covering \( \lambda \lambda 979–1187\AA \), obtained in time-tag (TTAG) mode. At this epoch, the two Silicon Carbide (SiC) channels, covering \( \lambda \lambda 905–1104\AA \), were badly aligned so that SiC data were of poor quality.
Sand 2 data were processed through the pipeline data reduction, CALFUSE (version 1.6.8), and are shown in Fig. 1. The pipeline extracted the 1D spectrum, removed the background, and corrected for grating wobble and detector drifts. No corrections for astigmatism or flat fielding have been applied. From Fig. 1, the far-UV continuum flux of Sand 2 is low ($\approx 5 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$), with two principal stellar features, O\textsc{vi} $\lambda$1032-38 and C\textsc{iv} $\lambda$1168. The latter is blended with C\textsc{iii} $\lambda$1175, while C\textsc{iv} $\lambda$1108 and O\textsc{vi} $\lambda$1125 are present, though weak. The FUSE spectrum is affected by a multitude of interstellar absorption features, principally H\textsc{i} and H\textsc{2}, plus airglow emission features due to Ly$\beta$, [O\textsc{i}] and [N\textsc{i}].

2.2. Near-UV spectroscopy

Sand 2 was observed with the HST Faint Object Spectrograph (FOS) instrument during 1996 March (PI: D.J. Hillier, Program ID 5460). Exposures totalling 5980, 3780 and 1090 sec were obtained with the G130H, G190H and G270H gratings, respectively. Many important spectral features are identified in the HST/FOS dataset (see also KBS), principally C\textsc{iv} $\lambda$1550, C\textsc{iii} $\lambda$2297, He\textsc{ii} $\lambda$1640, O\textsc{iv} $\lambda$1340, O\textsc{v} $\lambda$1371, $\lambda$2781–87. Following Prinja, Barlow & Howarth (1990) we find $v_\infty=4100$ km s$^{-1}$ from C\textsc{iv} $\lambda$1548–51 (KBS derived 4500 km s$^{-1}$ from IUE spectroscopy).

2.3. Optical spectroscopy

We have used the Double Beam Spectrograph (DBS) at the 2.3m MSSSO telescope to observe Sand 2 on 1997 Dec 24–27. Use of a dichroic and the 300B, 600B and 316R gratings permitted simultaneous spectroscopy covering 3620–6085Å and 6410–8770Å for 1200 sec, plus 3240–4480Å and 8640–11010Å for 2500 sec. A 2$''$ slit and 1752×532 pixel SiTE CCD’s
provided a 2 pixel spectral resolution of $\sim 5\text{Å}$. A standard data reduction was carried out, including absolute flux calibration, using wide slit spectrophotometry of HD 60753 (B3 IV) and $\mu$ Col (O9 V), plus atmospheric correction using HR 2221 (B8 V). Convolving our dataset with Johnson broad-band filter profiles reveals $V=15.1$ and $B-V=+0.54$ mag. Since these are contaminated by emission lines, we have convolved our data with Smith $ubvr$ narrow-band filters to reveal $v=16.1$, $u-b=-0.19$, $b-v=-0.07$ and $v-r=-0.14$ mag.

Our optical dataset confirms the spectral morphology previously presented and discussed by KBS, with exceptionally strong O\textsc{iv} $\lambda3400$, O\textsc{iv} $\lambda3818$, C\textsc{iv}+He\textsc{ii} $\lambda4660$ and C\textsc{iv} $\lambda5801$. Depending on the WO selection criteria, its spectral type is WO3 (Crowther, De Marco & Barlow 1998) or WO4 (KBS).

3. Quantitative analysis of Sand 2

Wolf-Rayet winds are so dense that non-LTE effects, spherical geometry and an expanding atmosphere are minimum assumptions.

3.1. Analysis technique

We employ the code of Hillier & Miller (1998), cmfgen, which iteratively solves the transfer equation in the co-moving frame subject to statistical and radiative equilibrium in an expanding, spherically symmetric and steady-state atmosphere. These models account for clumping, via a volume filling factor, $f$, and line blanketing, both of which have a significant effect on the physical properties of WC stars (e.g. Hillier & Miller 1999). Through the use of ‘super-levels’, extremely complex atoms can be included. For the present application, a total of 3,552 levels (combined into 796 super-levels), 60 depth points and 63,622 spectral lines of He\textsc{i-ii}, C\textsc{ii-iv}, O\textsc{ii-vi}, Ne\textsc{ii-iv}, Si\textsc{iv}, S\textsc{iv-vi}, Ar\textsc{iii-v}, and
Fe\textsc{iv–viii} are considered simultaneously (see Dessart et al. 2000 for the source of atomic data used).

We adopt a form for the velocity law (Eqn 8 from Hillier & Miller 1999) such that two exponents are considered ($\beta_1=1$, $\beta_2=50$, $v_{\text{ext}}=2900$ km s$^{-1}$, $v_{\text{turb}}=100$ km s$^{-1}$), with the result that acceleration is modest at small radii, but continues to large distance ($0.9v_\infty$ is reached at $100R_\star$).

Our spectroscopic analysis derives $\dot{M}/\sqrt{f}$, rather than $\dot{M}$ and $f$ individually, since line blending is severe in Sand 2. A series of models were calculated in which stellar parameters, $T_\star$, log ($L/L_\odot$), $\dot{M}/\sqrt{f}$, C/He and O/He, were adjusted until the observed line strengths and spectroscopic fluxes were reproduced. We adopt $0.4Z_\odot$ abundances for Ne, Si, S, Ar and Fe. The distance to the LMC was assumed to be 51.2 kpc (Panagia et al. 1991).

The wind ionization balance is ideally deduced using isolated spectral lines from adjacent ionization stages of carbon (C\textsc{iii} $\lambda2297$, C\textsc{iv} $\lambda5801-12$) or oxygen (O\textsc{iv} $\lambda3404-14$, O\textsc{v} $\lambda3144$, O\textsc{vi} $\lambda5290$). In practice this was difficult to achieve for Sand 2 because of the severe line blending.

### 3.2. Stellar parameters

Our initial parameter study of Sand 2 revealed a fairly similar spectral appearance spanning $120\text{kK} \leq T_\star \leq 170\text{kK}$, with log ($L/L_\odot$)=5.28 and log ($\dot{M}/M_\odot\text{yr}^{-1}$) = $-4.94$ fixed. The principal differences between these models are that (i) the observed strength of the O\textsc{vi} $3811–38\text{Å}$ doublet, plus lines in the red such as C\textsc{iv} 7700Å favour a high $T_\star$; (ii) the weakness of the O\textsc{vi} 1032–38Å doublet, as revealed by FUSE, favours a lower $T_\star$. Since other parameters, in particular abundances, are largely unaffected by these discrepancies, we shall adopt $T_\star=150\text{kK}$ (i.e. $R_\star=0.65R_\odot$). Note that higher luminosity models do
produce significant effects, such as a dramatic weakening of C\textsc{iv} 5801–12Å emission.

Fig. 2 compares our synthetic spectrum with the observed far-UV, UV and optical spectroscopy of Sand 2. Our model is reddened by $E(B-V)=0.08$ mag due to our Galaxy, obtained from the reddening map of Burstein & Heiles (1982). An additional LMC component of 0.11 mag was required, such that $M_v = -3.0$ mag. In the absence of a far-UV extinction law, standard UV laws (Seaton 1979; Howarth 1983) are extrapolated for $\lambda \leq 1200$Å with (variable) influence on the fit quality to \textit{FUSE} data.

Overall the observed spectrum of Sand 2 is very well reproduced by the model, with most He\textsc{ii}, C\textsc{iii}-iv and O\textsc{iv}-vi lines matched in strength and shape, except for O\textsc{vi} $\lambda\lambda 3811–34$ (model too weak) and O\textsc{vi} $\lambda\lambda 1032–1038$ (model too strong) as discussed above. In particular, the flat-topped nature of C\textsc{iii} $\lambda 2297$ is well matched. It is clear that although WO stars have little or no C\textsc{iii} $\lambda 5696$ (a classification diagnostic), other C\textsc{iii} lines are indeed present (Hillier 1989). Many spectral features in Sand 2 are due to blends because of the very broad spectral lines and the fact that recombination lines of O\textsc{vi} and C\textsc{iv} overlap with He\textsc{ii} lines. For example, the spectral feature at $\lambda\lambda 4650–4686$ has principal contributors He\textsc{ii} $\lambda 4686$, C\textsc{iii} $\lambda\lambda 4647-50$, C\textsc{iv} $\lambda 4658$ and C\textsc{iv} $\lambda 4685$, while minor contributors include C\textsc{iv} $\lambda 4646$, $\lambda 4689$ and O\textsc{vi} $\lambda 4678$.

He\textsc{ii} $\lambda 5412$/C\textsc{iv} $\lambda 5471$ provides an excellent diagnostic of C/He (e.g. Hillier & Miller 1998) for spectroscopic studies of WC stars. However, the large line widths of WO stars, and the fact that C\textsc{iv} $\lambda 5412$ (14–8) contributes to He\textsc{ii} $\lambda 5412$ (7–4) hinders the use of these lines (see inset box in Fig. 2). Instead, we are able to derive C/He$\sim 0.7\pm0.2$ by number from He\textsc{ii} (6–4) $\lambda 6560$/C\textsc{iv} $\lambda 7700$, although C\textsc{iv} (12–8) contributes to the former. Other C\textsc{iv} and He\textsc{ii} recombination lines show excellent agreement, except that C\textsc{iv} $\lambda 1107$ is predicted to be stronger than \textit{FUSE} observations reveal.

In contrast to WC stars, numerous oxygen recombination lines are present in the
UV and optical spectra of WO stars (e.g. Ovi λ5290, λ2070). From their strength relative to He and C recombination lines, we estimate O/He~ 0.15^{+0.10}_{-0.05} by number. The weakness of lower ionization oxygen features, such as Oiv λ1400 and Ov λ3150 also argue against higher O/He ratios, although Ov λ5590 favours O/He~0.25. Poor fits to Ovi λλ1032–38 and λλ3811–34 are discussed above, while Ov λλ2781–87 and Oiv λλ3063–71 are systematically too weak for all models.

We present the predicted temperature structure of our Sand 2 model in Fig. 3. Although Sand 2 is an extremely hot star, its very high content of efficient C and O coolants (see Hillier 1989) directly results in a very cool (<10kK) outer wind (r/R_* > 100). Consequently, the ionization structure of metal species is predicted to be very stratified, such that O^{6+} is the dominant ionization stage for r/R_* <5, yet O^{3+} is dominant for r/R_* >25.

The high stellar temperature of Sand 2 implies a high bolometric correction (~5.7 mag) and consequently hard ionizing spectrum, such that 50% of the emergent photons have energies greater than 13.6eV (912Å Lyman edge), and 30% greater than 24.6eV (504Å HeI edge). The ionizing fluxes in the HI, HeI, and HeII continua are 10^{49.1} s^{-1}, 10^{48.8} s^{-1} and 10^{40.3} s^{-1}, respectively. WO stars are known to produce strong nebular HeII λ4686 emission in associated HII regions (e.g. Kingsburgh & Barlow 1995), although the predicted number of HeII continuum ionizing photons in our Sand 2 model is much lower than those inferred from other WO stars.

4. Discussion

Abundances derived here qualitatively support the results from KBS, who used recombination line theory to derive C/He=0.5 and O/He=0.1 for Sand 2. WO stars are well
suited to recombination studies for carbon, although oxygen is somewhat more problematic for recombination line studies, since the ionization structure is more complex (see Fig. 3), and few lines have available coefficients.

Gräfener, Hamann & Koesterke (1999) have carried out a detailed non-LTE spectroscopic analysis of Sand 2 (see Gräfener et al. 1998). Overall, we confirm their $\dot{M}/\sqrt{T}$ determination, but derive a higher luminosity (by 0.2 dex) and temperature (they derived $T_*=101$ kK), attributable to the incorporation of line blanketing. More significantly, we obtain systematically lower metal abundances (they estimated C/He=1.3 and O/He=1.2), such that the oxygen mass fraction for Sand 2 is only 16%, versus 50% according to Gräfener et al. (1999). We attribute this major revision to improved spectroscopic and atomic datasets (Gräfener et al. used simple C and O model atoms plus low S/N optical data). Our higher luminosity and clumpy wind conspire to revise the wind performance ratio, $\dot{M}v_\infty/(L/c)$, from 56 to 12.

Fig. 4 compares the luminosities and (C+O)/He ratios for Sand 2 with six LMC WC4 stars, updated from Dessart (1999). He improved upon similar work by Gräfener et al. (1998) using line blanketed, clumped models, revealing a greater range of carbon abundances, $0.1 \leq C/He \leq 0.3$ (due to improved spectroscopy), systematically higher luminosities (because of blanketing and improved redenings), and lower mass-loss rates (due to clumping). The carbon enrichment of Sand 2 is substantially higher than the WC4 stars, although O/He does not differ so greatly from the WC4 sample, for which O/He $\leq 0.08$. This supports the suggestion by Crowther (1999) that unusually high oxygen enrichment may not be a pre-requisite for a WO classification.

We have superimposed (non-rotating) evolutionary tracks from Meynet et al. (1994) at $0.4 Z_\odot$ for $M_{\text{initial}}=60, 85$ and $120 M_\odot$ on Fig. 4. These evolutionary models predict C/O$\sim 2$ when C/He$\sim 0.7$, in conflict with our determination of C/O$\sim 4$. Better agreement
is expected for evolutionary models in which rotation is accounted for, since these predict higher C/O ratios during the WC/WO phase (Maeder & Meynet 2000). From interior models, $M_{\text{initial}} \geq 60M_\odot$ for Sand 2, with a corresponding age of $\sim 3$–$4.3$ Myr, such that a supernova is expected within the next $0.1$–$5 \times 10^4$ years. The stellar luminosity implies a current mass of $10M_\odot$ (Schaerer & Maeder 1992), such that the mean post-main sequence mass-loss rate is $2.5$–$5 \times 10^{-5} M_\odot \text{yr}^{-1}$.

Quantitative analysis of other WO stars suffer from either (i) high interstellar reddening (WR 102, WR 142), (ii) complications because of binarity (Sand 1), or (iii) large distances (DR1). Nevertheless, we expect similar C and O enrichment to that derived here for Sand 2 (KBS).

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Fig. 1.— Observed FUSE (CALFUSE 1.6.8) spectroscopy of Sand 2, rebinned to 15 km s\(^{-1}\), revealing the P Cygni O\textsc{vi} resonance doublet at 1032–38 Å. The far-UV spectrum is affected by interstellar atomic and molecular hydrogen lines, plus airglow from [O\textsc{i}], [N\textsc{i}] and Ly\(\beta\).

Fig. 2.— Comparison between far-UV (FUSE), UV (HST/FOS), optical and near-IR (MSSSO 2.3m) spectroscopy of Sand 2, shown as a solid line, together with our synthetic spectrum (dotted line), reddened by \(E(B - V) = 0.08\) (Gal) and 0.11 (LMC). Correction for interstellar H\textsc{i} and H\textsc{2} in the far-UV has been applied following J.E. Herald, D.J. Hillier & R.E. Schulte-Ladbeck (in preparation), for which we adopt \(T_{\text{ISM}} = 100\) K, \(v_{\text{turb}} = 10\) km s\(^{-1}\). We use log(\(n(\text{H}\textsc{i})/\text{cm}^2\)) = 20.6 (Gal) plus 21.3 (LMC) (Shull & van Steenberg 1985; Koornneef 1982), plus log(\(n(\text{H}\textsc{2})/\text{cm}^2\)) = 20.

Fig. 3.— Theoretical temperature distribution for our Sand 2 model versus Rosseland optical depth, indicating selected stellar radii, \(R_*\), plus the ionization balance of C, O and Fe.

Fig. 4.— Comparison between the luminosity \((L_\odot)\) and surface abundances ((C+O)/He, by number) of Sand 2 (triangle) with six LMC WC4 stars (circles, Dessart 1999), plus evolutionary predictions of Meynet et al. (1994) for \(M_{\text{initial}} = 60\) (dotted), 85 (dot-dashed) and 120 \(M_\odot\) (dashed), including locations of SN explosions (stars).
