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FAR ULTRAVIOLET SPECTROSCOPIC EXPLORER SPECTROSCOPY OF THE O VI RESONANCE DOUBLET IN SAND 2 (WO)

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ABSTRACT

We present *Far Ultraviolet Spectroscopic Explorer* spectroscopy of Sand 2, an LMC WO-type Wolf-Rayet star, revealing the O VI resonance P Cygni doublet at 1032–1038 Å. These data are combined with *Hubble Space Telescope* Faint Object Spectrograph ultraviolet and Mount Stromlo 2.3 m optical spectroscopy and analyzed using a spherical, non-LTE, line-blanketed code. Our study reveals exceptional stellar parameters: $T_* \sim 150{,}000$ 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 that it is expected to undergo a supernova explosion within the next 5×10^4 yr.

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

1. INTRODUCTION

Wolf-Rayet (WR) stars provide keys to our understanding of massive stellar evolution, nucleosynthesis processes, and chemical enrichment of the interstellar medium (ISM). Among WR stars, 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), which is important for constraining the controversial ^{12}C(α, γ)^{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 (Sk 188) in the SMC, Sand 2 (BAT 99−123) in the LMC, Sand 4 (WR 102), Sand 5 (WR 142), and MS4 (WR 30a) in our Galaxy and DR1 in IC 1613. Since O VI λλ3811–3834 is a primary WO classification diagnostic, with an equivalent width of up to 1700 Å (Kingsburgh, Barlow, & Storey 1995, hereafter KBS), observations of O VI λλ1032–1038 are keenly sought. However, its location in the far-UV has to date ruled out such observations. This situation has changed following the successful launch of the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*; Moos et al. 2000), which permits routine high-dispersion far-UV spectroscopy of massive stars in the Magellanic Clouds.

In this Letter, we analyze *FUSE* spectroscopy of Sand 2 (Sanduleak 1971), Sk −68°145 = Brey 93 = BAT 99−123 (Breysacher, Azzopardi, & Testor 1999), together with *Hubble Space Telescope* (*HST*) and ground-based data sets.

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2. OBSERVATIONS

Previously unpublished far-UV, UV, and optical/near-IR spectroscopy of Sand 2 has been obtained with *FUSE*, *HST*, and the Mount Stromlo and Siding Spring Observatory (MSSSO) 2.3 m telescope, respectively.

2.1. *Far-UV Spectroscopy*

Sand 2 was observed by *FUSE* as part of the Early Release Observation program X018 on 1999 October 31. A 8134 s exposure of Sand 2 with the 30″ × 30″ large aperture (LWRS) provided data at $R \sim 12{,}000$, with the two lithium fluoride (LiF) channels, covering 979–1187 Å, having been obtained in time-tag (TTAG) mode. At this epoch, the two silicon carbide (SiC) channels, covering 905–1104 Å, 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 Figure 1. The pipeline extracted the one-dimensional spectrum, removed the background, and corrected for grating wobble and detector drifts. No corrections for astigmatism or flat-fielding have been applied. From Figure 1, the far-UV continuum flux of Sand 2 is low ($\approx 5 \times 10^{-14}$ ergs s^{-1} cm^{-2} Å^{-1}), with two principal stellar features, O VI λλ1032–1038 and C IV λ1168. The latter is blended with C III λ1175, while C IV λ1108 and O VI λ1125 are present, though weak. The *FUSE* spectrum is affected by a multitude of interstellar absorption features, principally H I and H_2, plus airglow emission features due to Lyβ, [O I], and [N 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 totaling 5980, 3780, and 1090 s were obtained with the G130H, G190H, and G270H gratings, respectively. Many important spectral features are identified in the *HST*/FOS data set (see also KBS), principally C IV λ1550, C III λ2297, He II λ1640, O IV λ1340, O V λ1371, and λλ2781–2787.

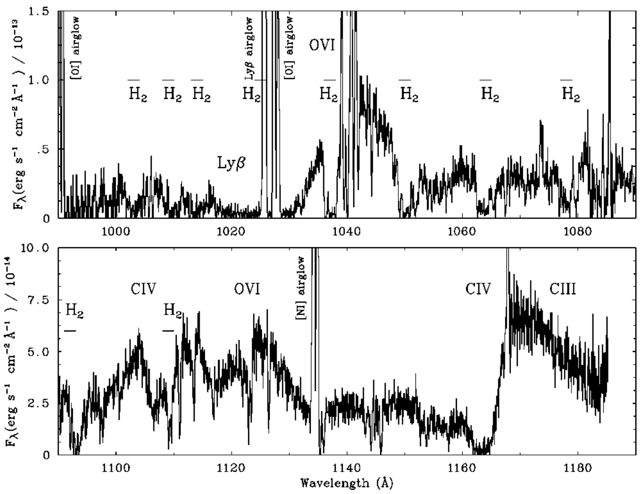

FIG. 1.—Observed *FUSE* (CALFUSE 1.6.8) spectroscopy of Sand 2, rebinned to 15 km s^{-1}, revealing the P Cygni O VI resonance doublet at 1032–1038 Å. The far-UV spectrum is affected by interstellar atomic and molecular hydrogen lines, plus airglow from [O I], [N I], and Lyβ.

Following Prinja, Barlow, & Howarth (1990), we find that $v_\infty = 4100$ km s^{-1} from C IV λλ1548–1551 (KBS derived 4500 km s^{-1} from *IUE* spectroscopy).

2.3. *Optical Spectroscopy*

We have used the double-beam spectrograph (DBS) at the 2.3 m MSSSO telescope to observe Sand 2 on 1997 December 24–27. Use of a dichroic and the 300B, 600B, and 316R gratings permitted simultaneous spectroscopy covering 3620–6085 and 6410–8770 Å for 1200 s, plus 3240–4480 and 8640–11010 Å for 2500 s. A 2″ slit and the 1752 × 532 pixel SITe CCDs provided a 2 pixel spectral resolution of ∼5 Å. A standard data reduction was carried out, including absolute flux calibration, using wide-slit spectrophotometry of HD 60753 (B3 IV) and μ Col (O9 V), plus atmospheric correction using HR 2221 (B8 V). Convolving our data set with Johnson broadband 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* narrowband filters to reveal $v = 16.1$, $u-b = -0.19$, $b-v = -0.07$, and $v-r = -0.14$ mag.

Our optical data set confirms the spectral morphology previously presented and discussed by KBS, with exceptionally strong O IV λ3400, O IV λ3818, C IV + He II λ4660, and C IV λ5801. 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 CMFGEN of Hillier & Miller (1998), which iteratively solves the transfer equation in the comoving frame subject to statistical and radiative equilibrium in an expanding spherically symmetric 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 "superlevels," extremely complex atoms can be included. For the present application, a total of 3552 levels (combined into 796 superlevels), 60 depth points, and 63,622 spectral lines of He I–He II, C II–IV, O II–VI, Ne II–Ne IV, Si IV, S IV–Si VI, Ar III–Ar V, and Fe IV–Fe VIII are considered simultaneously (see Dessart et al. 2000 for the source of atomic data used).

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

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_*, log $(L/L_\odot)$, $\dot{M}/\sqrt{f}$, and C/He and O/He were adjusted until the observed line strengths and spectroscopic fluxes were reproduced. We adopt 0.4 $Z_\odot$ 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 III λ2297 and C IV λλ5801–5812) or oxygen (O IV λ3404–3414, O V λ3144, and O VI λ5290). 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 120,000 K $\leq T_* \leq$ 170,000 K, with log $(L/L_\odot) = 5.28$ and log $(\dot{M}/M_\odot\ {\rm yr}^{-1}) = -4.94$ fixed. The principal differences between these models are that (1) the observed strength of the doublet O VI λλ3811–3834, plus lines in the red such as C IV λ7700, favor a high T_* and (2) the weakness of the doublet O VI λλ1032–1038, as revealed by *FUSE*, favors a lower T_*. Since other parameters, in particular abundances, are largely unaffected by these discrepancies, we shall adopt $T_* = 150{,}000$ K (i.e., $R_* = 0.65\ R_\odot$). Note that higher luminosity models do produce significant effects, such as a dramatic weakening of C IV λλ5801–5812 emission.

Figure 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 because of our Galaxy. This value was 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 λ ≤ 1200 Å with (variable) influence on the fit quality to *FUSE* data.

Overall the observed spectrum of Sand 2 is reproduced very well by the model, with most He II, C III–C IV, and O IV–O VI lines matched in strength and shape, except for O VI λλ3811–3834 (model too weak) and O VI λλ1032–1038 (model too strong) as discussed above. In particular, the flat-topped nature of C III λ2297 is well matched. It is clear that although WO stars have little or no C III λ5696 (a classification diagnostic), other C 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 because recombination lines of O VI and C IV overlap with He II lines. For example, the spectral feature at 4650–4686 Å has principal contributors He II λ4686,

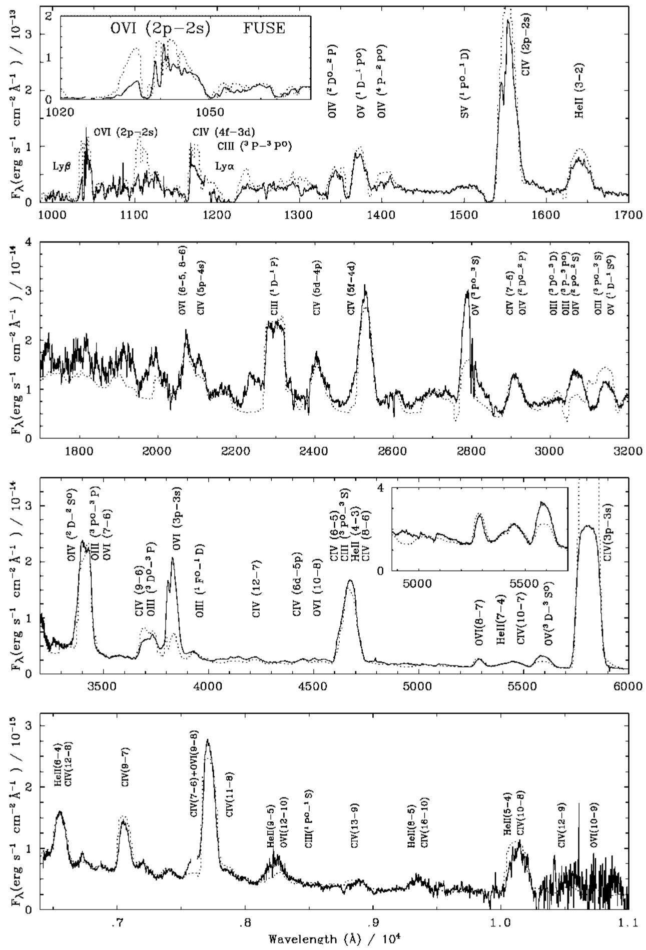

FIG. 2.—Comparison between far-UV (*FUSE*), UV (*HST*/FOS), optical, and near-IR (MSSSO 2.3 m) spectroscopy of Sand 2, shown as a solid line, together with our synthetic spectrum (*dotted line*), reddened by $E(B-V)$ = 0.08 (our Galaxy) and 0.11 (LMC). Correction for interstellar H I and H_2 in the far-UV has been applied following J. E. Herald, D. J. Hillier, & R. E. Schulte-Ladbeck (2000, in preparation), for which we adopt $T_{\rm ISM}$ = 100 K and $v_{\rm turb}$ = 10 km s^{-1}. We use log [n(H I) cm^{-2}] = 20.6 (our Galaxy) plus 21.3 (LMC) (Shull & van Steenberg 1985; Koornneef 1982), plus log [$n(H_2)$ cm^2] = 20.

C III λλ4647–4650, C IV λ4658, and C IV λ4685, while minor contributors include C IV λ4646, λ4689 and O VI λ4678.

He II λ5412/C IV λ5471 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 IV λ5412 (14–8) contributes to He II λ5412 (7–4) hinders the use of these lines (see inset box in Fig. 2). Instead, we are able to derive C/He $\sim 0.7 \pm 0.2$ by number from He II (6–4) λ6560/C IV λ7700, although C IV (12–8) contributes to the former. Other C IV and He II recombination lines show excellent agreement, except that C IV λ1107 is predicted to be stronger than the *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., O VI λ5290, λ2070). From their strength relative to He and C recombination lines, we estimate O/He $\sim 0.15^{+0.10}_{-0.05}$ by number. The weakness of lower ionization oxygen features, such as O IV λ1400 and O V λ3150, also argue against higher O/He ratios, although O V λ5590 favors O/He $\sim$ 0.25. Poor fits to O VI λλ1032–1038 and λλ3811–3834 are discussed above, while O V λλ2781–2787 and O IV λλ3063–3071 are systematically too weak for all models.

We present the predicted temperature structure of our Sand 2 model in Figure 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 (<10,000 K) 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 a hard ionizing spectrum, such that 50% of the emergent photons have energies greater than 13.6 eV (912 Å Lyman edge) and 30% greater than 24.6 eV (504 Å He I edge). The ionizing fluxes in the H I, He I, and He II continua are $10^{49.1}$, $10^{48.8}$, and $10^{40.3}$ s^{-1}, respectively. WO stars are known to produce strong nebular He II λ4686 emission in associated H II regions (e.g., Kingsburgh & Barlow 1995), although the predicted number of He II 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

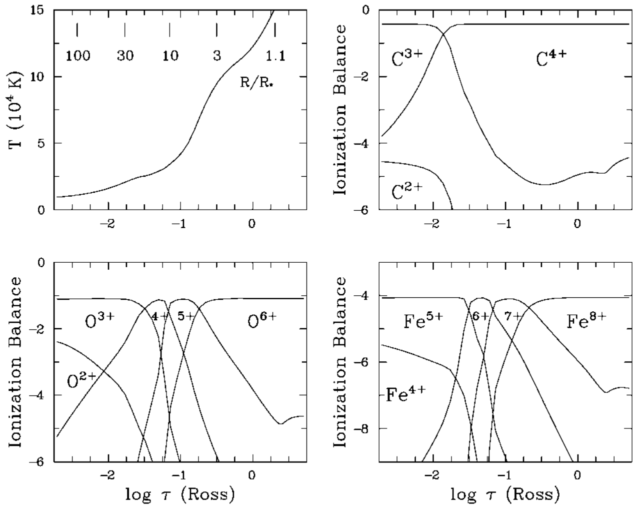

FIG. 3.—Theoretical temperature distribution for our Sand 2 model vs. Rosseland optical depth, indicating selected stellar radii R_* plus the ionization balance of C, O, and Fe.

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 $\dot{M}/\sqrt{f}$ determination but derive a higher luminosity (by 0.2 dex) and temperature (they derived $T_* = 101{,}000$ K) 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 data sets (Gräfener et al. used simple C and O model atoms plus low signal-to-noise ratio 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.

Figure 4 compares the luminosities and (C + O)/He ratios for Sand 2 with six LMC WC4 stars, updated from Dessart (1999). He improved on similar work by Gräfener et al. (1998) using line-blanketed, clumped models, revealing a greater range of carbon abundances, $0.1 \leq$ C/He ≤ 0.3 (due to improved spectroscopy), systematically higher luminosities (because of blanketing and improved reddenings), 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 ≤ 0.08. This supports the suggestion by Crowther (1999) that unusually high oxygen enrichment may not be a prerequisite for a WO classification.

We have superposed (nonrotating) evolutionary tracks from Meynet et al. (1994) at 0.4 $Z_\odot$ for $M_{\rm initial} = 60$, 85, and 120 $M_\odot$ on Figure 4. These evolutionary models predict C/O ~ 2 when C/He ~ 0.7, in conflict with our determination of C/O ~ 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, $M_{\rm initial} \geq 60$ $M_\odot$ for Sand 2, with a corresponding age of ~3–4.3 Myr, such that a supernova is expected within the next (0.1–5) × 10^4 yr. The stellar luminosity implies a current mass of 10 $M_\odot$ (Schaerer & Maeder 1992), such that the *mean* post–main-sequence mass-loss rate is (2.5–5) × 10^{-5} $M_\odot$ yr^{-1}.

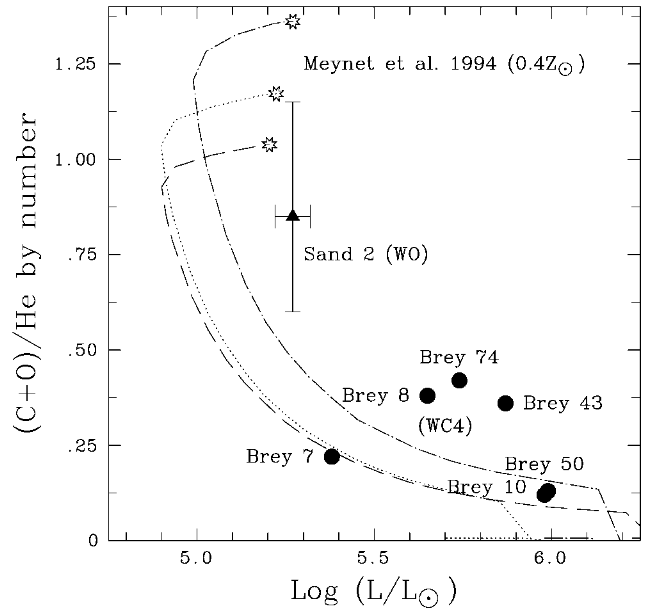

FIG. 4.—Comparison between the luminosity (in units of solar luminosity) and surface abundances [(C + O)/He, by number] of Sand 2 (*triangle*) with six LMC WC4 stars (*circles*; Dessart 1999), plus evolutionary predictions of Meynet et al. (1994) for $M_{\rm initial} = 60$ (*dotted line*), 85 (*dot-dashed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

Quantitative analysis of other WO stars suffers from either (1) high interstellar reddening (WR 102, WR 142), (2) complications because of binarity (Sand 1), or (3) large distances (DR1). Nevertheless, we expect C and O enrichment similar to that derived here for Sand 2 (KBS).

This work is based on data obtained for the Guaranteed Time Team by the NASA-CNES-CSA *FUSE* mission, operated by Johns Hopkins University, from the data archive at the STScI and collected with the NASA/ESA *Hubble Space Telescope*, which is operated by AURA, Inc., under NASA contract NAS5-26555, and with the MSSSO 2.3 m telescope. Financial support is acknowledged from the Royal Society (P. A. C.), NASA contract NAS5-32985 (US *FUSE* participants), STScI grant GO-04550.01-92A, NASA grant NAG5-8211 (both D. J. H.), PPARC (O. D.), and the UCL Perren Fund (L. D.).

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