Revised Stellar Temperatures for Magellanic Cloud O Supergiants from *FUSE* and VLT-UVES Spectroscopy

P. A. Crowther\(^2\), D. J. Hillier\(^3\), C. J. Evans\(^2\), A. W. Fullerton\(^4,5\), O. De Marco\(^2,6\), A. J. Willis\(^2\)

**ABSTRACT**

We have undertaken quantitative analysis of four LMC and SMC O4–9.7 extreme supergiants using far-ultraviolet *FUSE*, ultraviolet *IUE/HST* and optical VLT UVES spectroscopy. Extended, non-LTE model atmospheres that allow for the consistent treatment of line blanketing (Hillier & Miller 1998) are used to analyse wind and photospheric spectral features simultaneously. Using H\(\alpha\) to constrain \(\dot{M}\), He\(i\)-\(ii\) photospheric lines reveal stellar temperatures which are systematically (5–7.5kK) and substantially (15–20%) lower than previously derived from unblanketed, plane-parallel, non-LTE photospheric studies. We have confidence in these revisions, since derived temperatures generally yield consistent fits across the entire \(\lambda\lambda 912–7000\)Å observed spectral range. In particular, we are able to resolve the UV-optical temperature discrepancy identified for AzV 232 (O7 Iaf\(^+\)) in the SMC by Fullerton et al. (2000).

The temperature and abundance sensitivity of far-UV, UV and optical lines is discussed. ‘Of’ classification criteria are directly linked to (strong) nitrogen enrichment (via N\(\text{III} \lambda 4097\)) and (weak) carbon depletion (via C\(\text{III} \lambda\lambda 4647-51\)), providing evidence for mixing of unprocessed and CNO processed material at their stellar surfaces. Oxygen abundances are more difficult to constrain, except via O\(\text{II}\) lines in the O9.7 supergiant for which it is also found to be somewhat depleted. Unfortunately, He/H is very difficult to determine in individual O supergiants, due to uncertainties in microturbulence and the atmospheric scale height. The effect of wind clumping is also investigated, for which P\(\text{V} \lambda\lambda 1118–28\) potentially provides a useful diagnostic in O-star winds, unless phosphorus can be independently demonstrated to be underabundant relative to other heavy elements. Revised stellar properties affect existing calibrations of (i) Lyman continuum

\(^2\)Dept. of Physics & Astronomy, University College London, Gower Street, London WC1E 6BT, England

\(^3\)Department of Physics & Astronomy, University of Pittsburgh, 3941 O’Hara Street, PA 15260

\(^4\)Dept. of Physics & Astronomy, University of Victoria, P.O. Box 3055, Victoria, BC, V8W 3P6, Canada

\(^5\)Center for Astrophysical Sciences, Dept. of Physics & Astronomy, The Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21286

\(^6\)Department of Astrophysics, American Museum of Natural History, Central Park West at 79th St, New York, NY 10024
photons – a factor of two lower for the O4 supergiant; and (ii) kinetic energy released into the ISM by O supergiants. Our results also have importance for the calibration of the wind momentum-luminosity relationship for OB stars, particularly since the stars studied here are amongst the visually brightest OB stars in external galaxies.

Subject headings: stars:early-type, stars: ultraviolet, stars: fundamental parameters, stars:mass-loss

1. Introduction

The existence of winds in O-type stars has been established since the 1960’s, when the first rocket-ultraviolet (UV) observations revealed the characteristic resonance line P Cygni signatures of mass loss (Morton 1967). Far-ultraviolet (FUV) spectroscopy of O-type stars with Copernicus, the Hopkins Ultraviolet Telescope and ORFEUS missions revealed many additional stellar-wind features. The launch of the Far Ultraviolet Spectroscopic Explorer (FUSE) telescope (Moos et al. 2000) has provided a new opportunity to study a wide variety of OB stars spanning a range of metallicities, Z, at high spectral-resolution.

Of primary interest is the dependence of mass-loss rates for luminous OB stars on Z. Theoretically, the strength of radiatively driven O-star winds is predicted to depend on metallicity, Z, as \( \dot{M} \propto Z^{0.5-0.7} \) (Kudritzki, Pauldrach & Puls 1987; Vink, de Koter & Lamers 2001). Observationally, the principal method of deriving mass-loss properties of O stars has been via radio observations for stars within a few kpc, or H\( \alpha \) observations more generally (Puls et al. 1996). FUSE revives the possibility of using UV resonance lines to determine mass-loss rates empirically.

Observational results from H\( \alpha \) have been combined with theoretical predictions to generate the so-called Wind-Momentum-Luminosity Relationship (WLR; Kudritzki & Puls 2000), which can be used to determine extragalactic distances. To date, such studies almost exclusively employed plane-parallel, non-LTE models for determinations of temperature (using photospheric He lines), and separately use wind models to determine mass-loss rates (using H\( \alpha \) or UV wind profiles). Recent examples of the latter approach include Pauldrach et al. (1994) and Pauldrach, Hoffman & Lennon (2001). Clearly, the underlying assumption in such studies is that the effects of winds on photospheric optical lines is negligible – see, however, Gabler et al. (1989) and Schaerer & Schmutz (1994). Generally either line blanketed or spherically extended model atmospheres have

\[ ^1 \text{Based on observations made with the NASA-CNES-CSA Far Ultraviolet Spectroscopic Explorer. FUSE is operated for NASA by The Johns Hopkins University under NASA contract NAS5-32985. Also based in part on observations collected at the European Southern Observatory Very Large Telescopes in programs 65.H-0705 and 67.D-0238, plus archival data obtained with the NASA-ESA Hubble Space Telescope and NASA-ESA-PPARC International Ultraviolet Explorer.} \]
been employed (e.g. Herrero, Puls & Villamariz 2000). Rarely have both effects been considered simultaneously.

Since OB supergiants have an enormous impact on the chemical and dynamical evolution of their environments, their properties are of considerable interest. Recently, Fullerton et al. (2000; hereafter Paper I) presented a study of AzV 232 (O7 Iaf+, SMC) and Sk-67° 111 (O6 Ia(n)fp var7, LMC) based on FUSE spectroscopy. Non-LTE wind models allowing for line blanketing and an expanding atmosphere (Pauldrach et al. 2001) were used to constrain their stellar temperatures to $T_{\text{eff}} \sim 32\text{kK}$ based on FUSE FUV wind profiles. In contrast, recent non-LTE, plane-parallel, hydrostatic studies of AzV 232 (e.g. Puls et al. 1996), derived a substantially higher stellar temperature of $T_{\text{eff}} \sim 38\text{kK}$ from optical photospheric lines. This represents an important discrepancy with respect to derived bolometric luminosities ($\propto T_{\text{eff}}^4$), and so indirectly affects the calibration of the WLR.

In this paper, we investigate the properties of a small sample of extreme OB supergiants in the Magellanic Clouds to verify whether the supergiants studied in Paper I are typical, and if so, how these discrepancies may be resolved. These stars were selected to cover a wide range of spectral types, with the additional criteria that (i) they should have low interstellar H$_2$ column densities to minimize contamination in the FUSE region; and (ii) they should have small projected rotational velocities. We supplement the FUSE spectroscopy with IUE and HST UV spectroscopy, together with ground-based optical observations in order to help resolve previously conflicting determinations of stellar temperature and mass-loss rate. To date, UV studies of OB stars generally adopt temperatures from optical plane-parallel analyses (e.g. Haser et al. 1998). The sole exception was HD 93129A (O2 If*, Walborn et al. 2002b) for which Taresch et al. (1997) consistently analysed its optical, UV, and FUV spectrum.

The paper is structured as follows. Observations of the four program O supergiants are presented in § 2, followed by a determination of stellar parameters using standard plane-parallel methods in § 3. Spherical, line-blanketed models are utilised in § 4, revealing a substantial revision in stellar properties. Abundances, including CNO elements are discussed in § 5, whilst clumping in O supergiants is considered in § 6. Finally, our conclusions are reached in § 7.

2. Observations

Basic observational quantities for our targets are provided in Table 1. All supergiants have ”Ia+” spectral types, although the meaning of the ”+” differs between the sample, namely SiIV λλ 4088–4116 emission for the O4–6 supergiants and HeII λ4686 emission in the O9.7 star. Note that Sk −66°169 is not HDE 269889 (Walborn, priv. comm.), in conflict with the SIMBAD database entry for this star. The observed energy distribution of Sk −66°169 supports $V=11.56$ mag (Fitz-

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7Classification revised recently by Walborn et al. 2002a
patrick 1988), rather than \( V = 12.56 \) mag (Isserstedt 1975).

### 2.1. Far-UV Spectroscopy

Spectra of our program stars were obtained as part of the FUSE Principal Investigator Team programs P117 (P.I.: J. Hutchings) and P103 (P.I.: K. Sembach), plus Cycle 1 Guest Investigator program A133 (P.I.: A.W. Fullerton) between 1999 December and 2000 September. These observations were made in time-tag mode through the \( 30'' \times 30'' \) (LWRS) aperture. Total exposure times were 5 ksec (Sk\( -66^\circ\)169), 12 ksec (AzV 232), 27 ksec (HDE 270952) and 222 ksec (HDE 269698, this is the mean spectrum obtained during a monitoring program). As described by Moos et al. (2000) and Sahnow et al. (2000), FUSE data consist of spectra with a resolving power of \( \sim 15,000 \) from two Lithium Fluoride (LiF) channels, which cover \( \lambda \lambda 990–1187 \) Å, and two Silicon Carbide (SiC) channels, which cover \( \lambda \lambda 905–1105 \) Å.

Spectra from each channel were processed by the current version of the standard calibration pipeline (CALFUSE 2.0.5), which corrects for drifts and distortions in the readout electronics of the detectors, removes the effects of thermally induced grating motions, subtracts a background image, corrects for residual astigmatism in the spectrograph optics, and applies flux and wavelength calibrations to the extracted spectra. Spectra from the individual channels were subsequently aligned, merged, and resampled to a constant wavelength step of 0.13 Å in the manner described in Walborn et al. (2002a).

Our calibrated spectra are shown in Fig. 1, along with identifications for important stellar features. FUSE complements existing UV spectroscopy of OB stars by providing high and low excitation P Cygni resonance profiles, including important lines belonging to C\( \text{III} \), N\( \text{III} \), O\( \text{VI} \), P\( \text{V} \), S\( \text{IV} \), S\( \text{VI} \). In §4 we shall demonstrate the superior sensitivity of these diagnostics to stellar temperature and abundances, relative to the usual UV P Cygni resonance lines of C\( \text{IV} \), N\( \text{V} \) and to a lesser degree Si\( \text{IV} \). Systematic trends in these features have been discussed in detail by Walborn et al. (2002a).

### 2.2. UV Spectroscopy

Complementary high-dispersion UV spectroscopy has been obtained from the IUE and HST data archives. All our program stars have been observed with the IUE satellite, with the large aperture (LAP) in the short-wavelength (SWP) channel at high resolution (HIRES). In the case of AzV 232, multiple exposures were obtained.

In addition, AzV 232 and HDE 269698 were observed by HST–FOS in 1995 January, at a higher S/N than IUE, albeit with reduced spectral resolution (see Walborn et al. 1995a). We present IUE and HST UV spectroscopy of our program stars in Fig. 2. From the presence of strong P Cygni
N\text{v} \lambda\lambda1238-42, Si\text{iv} \lambda\lambda1393-1402, and C\text{iv} \lambda\lambda1548-51 profiles, it is clear that each possesses a very powerful stellar wind.

2.3. Optical Spectroscopy

Ground-based optical spectroscopy of our program stars was obtained with the European Southern Observatory (ESO) 8.1 m Very Large Telescope (VLT) in Paranal, Chile. Supplementary long-slit datasets were also taken with the 2.3 m Australian National University (ANU) telescope, or 3.9 m Anglo-Australian Telescope (AAT), both in Siding Spring, Australia.

The VLT observations were obtained during 2001 September 27–28 with the UV-Visual Echelle Spectrograph (UVES) mounted on Kueyen (UT2). The Dichroic # 2 was used with a standard blue setting for CCD #2 ($\lambda$=437nm) providing continuous coverage between $\lambda\lambda$3731 and 4999, recorded on a single 2x4K EEV CCD (15x15$\mu$m pixels). A non-standard red setting for CCD # 4 ($\lambda$=830nm) with an identical EEV CCD covered $\lambda\lambda$6370–8313, plus a 2x4K MIT/LL CCD (15x15$\mu$m pixels), covered $\lambda\lambda$8290–10252. A 1" wide slit was used in variable seeing conditions (0.8–2"), providing a 2 pixel spectral resolution of 0.09 Å at H\text{\alpha}.

We have used the flux distributions obtained from long-slit, intermediate-dispersion spectra of our targets to help correct for the grating blaze function in our echelle data, particularly in the vicinity of lines with broad emission wings (e.g., H\text{\alpha}).

Observations covering H\text{\alpha} and He\text{\ii} $\lambda5412$ were obtained with the Faint Object Red Spectrometer 2 (FORS2) also mounted on Kueyen (UT2) during poor seeing conditions in 2000 September. FORS2 was used in long-slit mode with a 600R grism, 2048x2048 pixel CCD and 0.7" slit, providing spectral coverage of $\lambda\lambda5330–7540$ and 3 pixel resolution of 3.6 Å. Subsequently, 2.3 m ANU observations were taken with the Double Beam Spectrograph (DBS) on 2000 December 12–15. The 1200 line mm$^{-1}$ blue and red gratings were used with the corresponding arms of DBS plus identical 1752x532 SITE CCDs (15x15$\mu$m pixels), covering a spectral range of 3969–4967 Å (blue) and $\lambda\lambda$5750–6710Å (red). A 1.5" wide slit was used in moderate seeing conditions ($\sim$1.2") to achieve a 2 pixel spectral resolution of 1.2 Å.

Complementary blue high-dispersion spectroscopy of HDE 270952 and Sk $–66^\circ169$ was collected at the AAT with the UCL echelle spectrometer (UCLES) during 1997 January. The 31 line mm$^{-1}$ grating, Tektronix 1024x1024 pix CCD and 2" slit provided complete blue spectral coverage of $\lambda\lambda3874–5093$ at a resolution of 0.15 Å at H\text{\gamma}.

All datasets were cleaned of cosmic rays, bias corrected, flat fielded, and optimally extracted in IRAF (v2.118). Subsequent reductions (wavelength correction and merging of echelle orders) were

*IRAF is written and supported by the National Optical Astronomy Observatory (NOAO) in Tucson, AZ; http://iraf.noao.edu/*
carried out with FIGARO (Shortridge et al. 1999) and related packages.

Since the blue optical spectral morphology for most of our sample has recently been discussed elsewhere (e.g. Fitzpatrick 1991; Walborn 1977; Walborn et al. 1995a), in Fig. 3 we merely show rectified VLT spectroscopy of our targets in the vicinity of Hα, once again indicating powerful stellar winds in all cases.

2.4. Stellar Wind Velocities

For the present targets, we present measurements of $v_{\text{black}}$ (Prinja, Barlow & Howarth 1990) in Table 2 for several UV and FUV lines, in some cases updated from Prinja & Crowther (1998). Note that the shape of the absorption trough of the C III λ977 resonance line is strongly affected by absorption from interstellar Lyγ, so this line should generally not be used as a $v_\infty$ indicator.

In order to derive terminal velocities we require a reliable measurement of the stellar radial velocity, which is obtained from UVES datasets, via optical He photospheric lines. We generally adopt terminal velocities from N III λ990, which provides good consistency with the usual Si IV λ1394-1407 and C IV λλ1548-51 diagnostics. Uniquely for Sk−66°169, we adopt the (higher) terminal velocity from Si IV instead. In general, reasonable consistency is achieved relative to Sobolev with Exact Integration (SEI) line profile modeling (Haser 1995; Haser et al. 1998; Massa et al. 2002) as indicated in Table 2.

3. Stellar Parameters Derived from Plane-Parallel Hydrostatic Models

Before we discuss results for our program stars allowing for the presence of stellar winds, we first follow the usual method of determining stellar temperatures, surface gravities and helium abundances, namely via the standard plane-parallel, hydrostatic methods as employed by Herrero et al. (1992) and Smith & Howarth (1994).

3.1. Technique

A large grid of hydrostatic, plane-parallel model atmospheres calculated with TLUSTY (Hubeny & Lanz 1998) were used, involving $T_{\text{eff}}$, log $g$ and He/H, as follows. Parameters are found by mapping the locus of models that reproduce the measured equivalent widths in the ($T_{\text{eff}}$, log $g$) plane for each optical helium line. The He II lines are strongly sensitive to temperature for O stars and λ4200, 4541 are used as the primary temperature diagnostics (He II λ4686 is not considered due to the wind effects for this line). Following Smith & Howarth (1998), a microturbulence of ξ = 15 km s$^{-1}$ is adopted for this part of the analysis. Values in the range 10–20 km s$^{-1}$ are considered for our subsequent analysis based on extended, line-blanketed model atmospheres (§ 4).
The determination of \( \log g \) from Balmer line wings is challenging for stars with such strong winds, since \( \text{H}\delta \) is strongly blended with \( \text{N}\text{iii} \lambda 4097 \) and \( \text{Si}\text{iv} \lambda\lambda 4088-4116 \), and \( \text{H}\beta - \gamma \) show emission in their red wings. Consequently, the values derived here are from \( \text{He} \) and \( \text{H}8 \). The wings of the lines are compared with the grid of model spectra and a \( \chi^2 \) value is found for each model and then the locus of minima is mapped in the \((T_{\text{eff}}, \log g)\) plane.

Prior to Balmer line fitting, a measure of the macroscopic broadening of the lines is required to convolve with the models before comparison with observations. As in Herrero et al. (1992) the projected rotational velocity \( v \sin i \) is found using the \( \text{He}\text{i} \) lines. A model spectrum that reproduces the observed helium equivalent widths is interpolated from the grid, mapped onto the observations and then the broadening of the convolved model for which \( \chi^2 \) is a minimum is taken as \( v \sin i \).

Stellar parameters are selected from the \((T_{\text{eff}}, \log g)\) fit diagram (e.g. Smith & Howarth 1998). Ideally, the single point where the loci intersect gives the parameters for the model spectrum that best describes the star. A model spectrum is then calculated with those parameters. Comparison of the model with the observations permits a qualitative “by-eye” inspection of the line fits and small changes of order \( \Delta T_{\text{eff}} = 1\text{kK} \) or \( \Delta \log g = 0.1 \) are made if the overall quality of the fits is improved. The strongest weight was given to \( \lambda 4388 \) and \( \lambda 4922 \) for \( \text{He}\text{i} \) lines (not available for HDE 269698).

In principle the helium abundance is determined by choosing the fit diagram with the smallest intersection region in the \((T_{\text{eff}}, \log g)\) plane for differing values of \( \text{He}/\text{H} \). However, no obvious improvement over the fits at solar abundance was revealed. Initial values at solar abundance were taken from the fit diagrams and then if a consistent model fit could not be obtained higher values were investigated. If the new model gave more a consistent fit that value was adopted.

### 3.2. Hydrostatic Model Results

As an example of the fit quality achieved, we present \textsc{tlusty} model fits to UVES optical observations of HDE 269698 in Fig.4. Clearly, \( \text{He}\text{i-ii} \) (photospheric) absorption lines are well reproduced, in contrast with (wind) emission at \( \text{He}\text{ii} \lambda 4686 \). \( \text{H}\alpha \) is totally dominated by wind emission, whilst other members of the Balmer series, up to and including \( \text{He}\text{e} \), also suffer from wind contamination. Consequently, a firm determination of \( \text{He}/\text{H} \) is extremely difficult for such extreme O supergiants. Surface gravities rely principally on the blue wings of Balmer-series members. As discussed elsewhere (e.g. Puls et al. 1996), the neglect of wind contamination systematically underestimates the true surface gravity by \( \sim 0.05-0.1 \text{ dex} \).

Spectroscopic results are presented in Table 3 for our program stars, including previous results by Puls et al. (1996) for HDE 269698 and AzV 232. Overall, previous hydrostatic results are supported by our \textsc{tlusty} studies, except that a somewhat higher \( T_{\text{eff}}=31\text{kK} \) is derived for Sk\( -66^\circ 169 \) than \( T_{\text{eff}}=28\text{kK} \) obtained by Lennon et al. (1997).
4. Stellar Parameters Derived with Extended, Line-Blanketed Models

Fig. 4 illustrates the successes and failures of plane-parallel techniques. Photospheric profiles in OB stars can be readily matched allowing determination of physical parameters, yet in many non-dwarf O stars, wind contamination prevents robust results. Such techniques, including those presented above, generally neglect the effect of metal line blanketing (see, however, Hubeny et al. 1998). This has importance for the ionization structure. Therefore, we have additionally calculated spherically extended models which explicitly allow for line blanketing, in order to better constrain the fundamental properties of OB supergiants.

4.1. Modeling codes

Several model atmosphere codes are now available for modeling the photospheres and stellar winds of early-type stars without making the traditional core-halo approximation (see Crowther 1999 for a summary). We have carried out test calculations using ISA-WIND (de Koter, Schmutz & Lamers 1993; de Koter, Heap & Hubeny 1997), CMFGEN (Hillier & Miller 1998) and WM-BASIC (Pauldrach et al. 2001), for which a reasonable degree of consistency in the emergent FUV and UV spectra and wind ionization structure was obtained. Calculations carried out at our request for ζ Pup with the Potsdam code (Gräfener et al. 2002) also show remarkably good consistency.

For the present application, our requirements include the need to study wind and photospheric features simultaneously, and to consider line blanketing. We have therefore selected CMFGEN, given that: (i) WM-BASIC does not yet properly account for Stark broadening in optical photospheric lines, despite its extremely thorough (albeit approximate) treatment of line blanketing and shocks; (ii) the Sobolev assumption which makes ISA-WIND so computationally quick, also hinders its usefulness for realistic photospheric modeling of OB-type stars. Although the stellar photosphere and the highly supersonic wind are accurately parameterized by this code, the interface between these two regimes is poorly represented by the Sobolev approximation.

CMFGEN solves the equations of statistical equilibrium, radiative transfer and radiative equilibrium, and incorporates line blanketing directly through use of a super-level approach (Hillier & Miller 1998). The ions included in our calculations are presented in Table 4. We construct two different model atoms: one appropriate for early O supergiants, the other for late O supergiants.

The input atmospheric structure, connecting the spherically extended hydrostatic layers to the β-law wind, is achieved via a parameterized scale height, h. This is defined relative to the surface gravity of the star in Hillier et al. (2002), via:

\[
h = 1.2 \times 10^{-3} \frac{(1 + \gamma)}{\mu(1 - \Gamma)} \frac{T_e}{g} R_\odot,
\]

where \(\gamma\) is the mean number of electrons per ion, \(\mu\) is the mean ionic mass, \(\Gamma\) is the ratio of radiation pressure to \(g\), and \(T_e\) is the local electron temperature in Kelvin. We initially adopt
\( h = 0.005 R_\star \), which is subsequently revised based on fits to the wings of He\,i and Balmer lines. At high Rosseland optical depth, the parameterized form of our velocity law may be replaced with the equivalent plane-parallel hydrostatic structure obtained from TLUSTY (Hillier et al. 2002). For the present application this option is not utilized, since the program O supergiants all possess extremely extended atmospheres, such that use of hydrostatic models, even at depth is questionable. Comparisons between TLUSTY and CMFGEN have been undertaken in the case of very low mass-loss rates by Hillier & Lanz (2001) and were found to be fully consistent in the case of negligible spherical extension.

The formal solution of the radiative-transfer equation to obtain the final emergent spectrum is computed separately, and includes standard Stark broadening tables for H\,i, He\,i-ii. Except where noted, these calculations assume a radially dependent ‘microturbulence’ of the form used by Haser et al. (1998), with \( \xi_{\text{min}}=10 \text{ km s}^{-1} \) at the base of the wind and \( \xi_{\text{max}}=100 \text{ km s}^{-1} \) at \( v_\infty \). Haser et al. (1998) and Hillier et al. (2002) discuss the effect of varying \( \xi \) in O-star models.

It has been established that high ionization stage resonance lines, most notably O\,vi \( \lambda\lambda 1032-38 \) and N\,v \( \lambda\lambda 1238-42 \), can only be reproduced in most O stars by considering X-rays (e.g. Pauldrach et al. 1994, 2001; Haser et al. 1998). X-rays are thought to originate in O star winds via the intrinsic instability of radiatively driven winds (e.g. Owocki, Castor & Rybicki 1988; Feldmeier 1995), and affect high ions via Auger-ionization (Cassinelli & Olson 1979). However, MacFarlane et al. (1993) demonstrated for \( \zeta \) Pup that it is solely these ion fractions throughout the wind that are sensitive to the X-ray flux. Consequently, the inclusion or exclusion of X-rays is generally not relevant to the determination of fundamental stellar parameters and abundances.

Further, fitting O\,vi and N\,v requires several parameters to be varied, including shock temperature, emissivity, X-ray luminosity, all of which are \textit{a priori} unknown, and some of which are likely degenerate. Therefore, we have chosen against attempts to \textit{derive} shock parameters for the program stars, but instead \textit{adopt} a uniform set of X-ray properties for all final model calculations. We use a rather soft two component Raymond & Smith (1977) X-ray spectrum, with \( 3 \times 10^6 \text{K} \) and \( 5 \times 10^6 \text{K} \), respectively. We scale their volume filling factors to ensure \( \log L_X/L_{\text{bol}} \sim -5.4 \). This is towards the high end of observed values for O stars (Chlebowski, Harnden & Sciortino 1989), but as we shall demonstrate below, it should be stressed that the bolometric luminosities of O supergiants previously derived may have been overestimated through inadequate temperature determinations. Two further assumptions are that the filling factor of the 5 million Kelvin component is fixed at a factor of two smaller than the 3 million Kelvin component.
4.2. Technique

For individual stars, our approach is as follows. We adjust the stellar temperature\(^9\) and mass-loss rate of an individual model until the ‘photospheric’ He\(\text{II}\) \(\lambda 4542\) and He\(\text{I}\) \(\lambda 4471\) lines are matched, and simultaneously, we vary the total mass-loss rate until the shape of H\(\alpha\) is also reproduced. If necessary, we adjust the exponent of the \(\beta\)-law until H\(\alpha\) is better reproduced (see e.g. Fig. 15 in Prinja et al. 2001). For the present sample \(1 \leq \beta \leq 2\), with a typical accuracy of \(\pm 0.2\). Fig. 5 illustrates this approach for HDE 269698, via a series of identical models except for increasing mass-loss rate. Note that some features are very sensitive to mass-loss rate (H\(\alpha\), He\(\text{II}\)), some are modestly affected (He\(\text{I}\) \(\lambda 4471\), N\(\text{IV}\) \(\lambda 4058\)), whilst others are rather insensitive (N\(\text{III}\) \(\lambda\lambda 4634–41\)).

This figure also illustrates that, increasing the mass-loss rate, with all other parameters held fixed, the ratio of the ‘photospheric’ O-star classification lines, He\(\text{II}\) \(\lambda 4542\) and He\(\text{I}\) \(\lambda 4471\), changes significantly. This implies that an O supergiant with a strong stellar wind may possess a lower stellar temperature than an O dwarf of identical spectral type. The usual assumption that stellar winds do not affect optical photospheric lines is invalidated for such stars, as previously suggested by, e.g., Schaerer & Schmutz (1994). Further, line blanketing affects the ionization balance of helium via backwarming, such that the effect is two-fold relative to H-He plane-parallel, hydrostatic models. Martins, Schaerer & Hillier (2002) demonstrate the considerable effect of including line blanketing for O dwarfs.

Fortunately, the central absorption strength in our primary diagnostic lines is rather insensitive to adopted atmospheric scale height, as discussed in detail by Hillier et al. (2002). The scale height is varied in the final stages of the analysis to ensure good consistency with observed wings of Balmer and He\(\text{I}\) lines.

The helium content is held fixed at He/H=0.2 by number, since this is typical of other extreme O supergiants (e.g. Crowther & Bohannan 1997). The weak dependence of, e.g., He\(\text{I}\) \(\lambda 4471\) and He\(\text{II}\) \(\lambda 4542\) on changes in He/H, and subtle dependence on temperature, atmospheric scale height and microturbulence (Smith & Howarth 1998), means that this ratio is exceptionally difficult to measure in practice. As we shall show, all program O supergiants are at least partially CNO processed, so some level of He enrichment is expected. Fortunately, the exact He content of individual stars is not crucial to the fundamental temperature scale of O supergiants which we are primarily concerned with here. For \(0.1 \leq \text{He/H} \leq 0.4\), the potential uncertainty introduced into mass-loss rate determinations is at most \(\sim 30\%\), unless clumping plays a role (see § 6). Other elemental abundances are initially fixed at \(0.4Z_\odot\) (LMC) or \(0.2Z_\odot\) (SMC) as determined from oxygen abundances in these galaxies (Dufour 1984; Russell & Dopita 1990). Subsequently, CNO abundances are varied in order to better match ultraviolet and optical metal lines. HDE 269698 was one of two LMC O

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\(^9\)Defined, as is usual for an extended atmosphere, as the effective temperature corresponding to the radius at a Rosseland optical depth of 20.
supergiants included in the study of Haser et al. (1998), who obtained 0.5–0.8\( Z_\odot \) from model fits to \textit{HST}-FOS spectroscopy. Abundance changes in non-CNO elements (e.g. S, Fe) would lead to somewhat improved fits, but this was not attempted since it was not central to the primary goal of this work. Our only exception to this is for phosphorus, since this is of relevance to the question of clumping in O stars (see § 6).

At each step in the iterative process we ensure that the predicted flux distribution matches the de-reddened energy distribution. Interstellar reddening laws follow Seaton (1979), Howarth (1983) and Bouchet et al. (1985) for the Galaxy, LMC and SMC, respectively. An average Galactic contribution of E(B-V)=0.04 (SMC) or 0.07 mag (LMC) is assumed following COBE/DIRBE results (Schlegel, Finkbeiner & Davis 1998). Distances of 50 kpc and 60 kpc are adopted for the LMC and SMC, respectively (Westerlund 1997).

In all cases, we have selected targets with minimal molecular-hydrogen column densities (Tumlinson et al. 2002). Therefore the strongest interstellar contribution to the FUV spectrum is the atomic hydrogen series, which has been taken into account following fits to Ly\( \alpha \), following Herald, Hillier & Schulte-Ladbeck (2001).

In order to avoid unnecessary repetition, we first discuss results for HDE 269698 in detail, followed by a concise summary for the remaining stars. The effect of \( \dot{M} \) has already been presented for HDE 269698 in Fig. 5 so we limit our subsequent discussion to the effects of temperature and abundance variations on optical, UV and FUV spectral diagnostics.

4.3. Multi-wavelength study of HDE 269698(O4 Iaf+)

4.3.1. Optical diagnostics

In Fig. 6 we compare optical observations of HDE 269698 with synthetic spectra for a wide range of temperatures, 34kK\( \leq T_{\text{eff}} \leq 46kK \), selected to reproduce the observed H\( \alpha \) emission and absolute visual magnitude, \( M_V \). For each temperature, two models are presented – one in which CNO elements are fixed at 0.4\( Z_\odot \) (dotted), with the other N-rich (\( \epsilon_N = 6.0\epsilon_{N,\odot} \)) and CO-poor (\( \epsilon_C = 0.05\epsilon_{C,\odot} \), \( \epsilon_O = 0.1\epsilon_{O,\odot} \)) (solid). The latter values are those which will be subsequently determined for HDE 269698 in the present section, whilst X-rays are neglected for this part of the analysis, and shall only be considered in the final model comparisons (see § 4.3.2). The parameters from these models, spanning 0.4 dex in luminosity, are listed in Table 5. The optical spectrum of this star has previously been studied by Puls et al. (1996), whilst Haser et al. (1998) analysed its HST-FOS spectrum.

Fig. 6 reveals that for the parameter space investigated, some spectral features (N\( \text{II}-\text{V} \) and He\( i \)) are very sensitive to \( T_{\text{eff}} \), whilst others (He\( ii \)) are not. For lower temperature models of \( T_{\text{eff}} \approx 25kK \), which we shall discuss below for Sk \( -66^\circ 169 \), He\( i-\text{II} \) sensitivities are reversed. From § 3.2, hydrostatic fits to the optical He\( i-\text{II} \) lines of HDE 269698 indicate \( T_{\text{eff}} \approx 46.5kK \). Our unified
code reveals that negligible He I λ4471 (the only prominent blue optical He I diagnostic) is predicted at such a high temperature. This line favours a much lower stellar temperature of $T_{\text{eff}} = 40 \pm 1$ kK.

Variable CNO abundances do not affect the strength of optical He I-II lines, but some optical CNO lines are extremely abundance sensitive ($\mathrm{N}\,\mathrm{II}\,\lambda\lambda\,4634-41$, $\mathrm{C}\,\mathrm{II}\,\lambda\lambda\,4267-51$; $\mathrm{N}\,\mathrm{IV}\,\lambda\,4058$). Weak emission from $\mathrm{S}\,\mathrm{IV}\,\lambda\lambda\,4486-4504$ is predicted at the lowest temperatures, supporting the positive identification of these features by Werner & Rauch (2001).

For HDE 269698 we are unable to match the observed optical spectrum with cosmic CNO abundances – the same is true for all Of supergiants with strong $\mathrm{N}\,\mathrm{III}\,\lambda\lambda\,4634-41$ and weak $\mathrm{C}\,\mathrm{III}\,\lambda\lambda\,4647-51$. For a N-rich, C-poor atmosphere we are able to find a good match to the optical spectrum at $T_{\text{eff}} \sim 39$ kK from fits to $\mathrm{N}\,\mathrm{IV}\,\lambda\,4058$, $\mathrm{N}\,\mathrm{V}\,\lambda\lambda\,4603-20$, $\mathrm{N}\,\mathrm{III}\,\lambda\lambda\,4634-41$ and $\mathrm{N}\,\mathrm{IV}\,\lambda\lambda\,4710-29$ (not shown). Oxygen diagnostics are absent from the optical, with the possible exception of $\mathrm{O}\,\mathrm{III}\,\lambda\lambda\,5592^{10}$, such that we are unable to determine oxygen abundances. Significantly higher temperatures are excluded by the observed weakness of $\mathrm{N}\,\mathrm{V}\,\lambda\lambda\,4603-20$ and strength of $\lambda\lambda\,4634-41$.

Taresch et al. (1997) used the $\lambda\lambda\,4603-20$ lines to constrain the temperature for HD 93129A (O2 If). Since ‘Of’ stars are defined via $\mathrm{N}\,\mathrm{III}\,\lambda\lambda\,4634-41$ and He II $\lambda\,4686$ emission, one might argue that all Of supergiants exhibit partially processed CNO surface abundances (see also the discussion in Voels et al. 1989).

The broad emission feature in the vicinity of $\mathrm{N}\,\mathrm{III}\,\lambda\lambda\,4634-41$ and He II $\lambda\,4686$ is due to incoherent electron scattering of line photons from these multiplets (Hillier et al. 2002). Electron scattering also affects the Stark wings of the Balmer series, of relevance for surface gravity determinations.

Since the stellar wind of HDE 269698 is so powerful, wind and line blanketing dramatically affect the ionization balance of helium and nitrogen, such that a much lower stellar temperature is appropriate than deduced from pure H-He hydrostatic models, resulting in a reduced luminosity, from $1.6 \times 10^6 L_\odot$ for $T_{\text{eff}} = 46.5$ kK in the plane-parallel calculations to $9.5 \times 10^5 L_\odot$ for $T_{\text{eff}} = 40$ kK obtained here. Bohannan et al. (1986, 1990) have previously emphasised the effect of wind blanketing for the temperature of $\zeta$ Pup (O4 I(n)f), morphologically very similar to HDE 269698, implying a reduction from $T_{\text{eff}} = 46.5$ kK to 42 kK. The greater effect obtained here is due to line blanketing and the use of a spherical atmosphere instead of their ‘core-halo’ approach. Additionally, the inclusion of metal species allows us to use alternative temperature diagnostics, which give essentially identical results$^{11}$.

For our N-rich model atmosphere, solely $\mathrm{N}\,\mathrm{III}\,\lambda\lambda\,4379$, not presented in our figures, is badly predicted (too strong in absorption) for $T_{\text{eff}} = 40$ kK. We have investigated this failure, which cannot easily be attributed to incorrect $\mathrm{N}\,\mathrm{III}$ atomic data, nor is it unique to HDE 269698, since other stars in our sample suffer from similar deficiencies (see also Hillier et al. 2002). Further investigations are

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$^{10}$ $\mathrm{O}\,\mathrm{III}\,\lambda\lambda\,5592$ is not covered by our high quality UVES spectroscopy for any of our targets.

$^{11}$ We admit a formal uncertainty of $\pm 1$ kK on our derived stellar temperatures, so that the value obtained from optical He I-II lines (40 kK) is indistinguishable from that using $\mathrm{N}\,\mathrm{III-V}$ ($\sim 39$ kK).
presently underway, but unlike \( \lambda\lambda 4634–41 \) where a well known process (dielectronic recombination) produces emission, no such mechanism is known for \( \lambda 4379 \). \( \text{N} \text{\textsc{iii}} \ \lambda\lambda 4510–4547 \) is not well reproduced either, but this is directly attributable to our model atom, since few quartet levels are considered, and further allowance needs to be made for autoionization processes.

\[ \text{4.3.2. UV diagnostics} \]

In contrast with most previous studies, which tend to concentrate solely on optical or UV modeling, we additionally compare UV and FUV observations with our synthetic spectra, determined from our optical analysis. In this way, one might be able to have confidence in results obtained using only optical temperature diagnostics, for those stars without UV observations.

Fig. 7 displays the rectified \textit{HST} spectroscopy of HDE 269698 covering \( \lambda\lambda 1220–1750 \), together with synthetic spectra from our models discussed above, again omitting X-rays for the moment.

\( \text{C} \text{\textsc{iv}} \ \lambda\lambda 1548–51, \text{N} \text{\textsc{iv}} \ \lambda 1718 \) and \( \text{He} \text{\textsc{ii}} \ \lambda 1640 \) are remarkably insensitive to stellar temperature in this temperature range. In contrast, weaker wind features do respond to temperature. \( \text{Si} \text{\textsc{iv}} \ \lambda\lambda 1393–1402 \) greatly increases in strength at low temperatures, whilst \( \text{O} \text{\textsc{v}} \ \lambda 1371 \) becomes prominent at high temperatures and \( \text{S} \text{\textsc{v}} \ \lambda 1501 \) is present except at the highest temperatures. \( \text{O} \text{\textsc{v}} \ \lambda 1371 \) has previously been used as a temperature indicator for early O supergiants by de Koter, Heap & Hubeny (1997), together with \( \text{O} \text{\textsc{iv}} \ \lambda\lambda 1338-43 \). In addition, the iron forest is particularly sensitive to stellar temperature. At low temperatures \( \text{Fe} \text{\textsc{v}} \) features between \( \lambda\lambda 1350 \) and 1500 are very prominent, with \( \text{Fe} \text{\textsc{iv}} \) lines between \( \lambda\lambda 1550 \) and 1700 present, whilst at high temperatures, \( \text{Fe} \text{\textsc{vi}} \) is strong between \( \lambda\lambda 1250 \) and 1350, with \( \text{Fe} \text{\textsc{v}} \) weaker and \( \text{Fe} \text{\textsc{iv}} \) absent. \( \text{N} \text{\textsc{v}} \ \lambda\lambda 1238–42 \) is rather temperature sensitive, but its strength is generally more indicative of X-rays than temperature.

Turning to abundance diagnostics, in contrast with optical CNO metal lines, UV lines are in general extremely poor indicators of CNO abundance, with few exceptions. \( \text{N} \text{\textsc{iv}} \ \lambda 1486, \lambda 1718 \) and \( \text{O} \text{\textsc{iv}} \ \lambda\lambda 1338-43 \) reveal (generally weak) abundance sensitivity.

Overall, intermediate-temperature models provide the best match to the iron forest, although the accuracy with which one can derive \( T_{\text{eff}} \) in this way is lower than that offered by optical-line diagnostics. optical line diagnostics. A high stellar temperature of \( T_{\text{eff}} \sim 46kK \), as obtained in § 3.2 from plane-parallel optical methods, is firmly excluded by the observed weakness of \( \text{Fe} \text{\textsc{vi}} \) and \( \text{O} \text{\textsc{v}} \ \lambda 1371 \). Haser et al. (1998) encountered problems with the latter in their UV analysis of HDE 269698 since they adopted \( T_{\text{eff}}=47.5kK \) from Puls et al. (1996). A lower temperature of \( T_{\text{eff}} \sim 35kK \) is actually favored by the strength of \( \text{Si} \text{\textsc{iv}} \), although \( \text{Fe} \text{\textsc{iv}} \) becomes too strong at this temperature. \( \text{N} \text{\textsc{iv}} \ \lambda 1486 \) is well matched with our N-rich atmosphere, whilst \( \text{N} \text{\textsc{iv}} \ \lambda 1718 \) is much better reproduced with a normal N abundance. Overall, the UV spectrum of HDE 269698 is broadly consistent with a N-rich, C-poor model with \( T_{\text{eff}}=37.5\pm2.5kK \).

Finally, let us turn to the FUV. \textit{FUSE} spectroscopy of HDE 269698 between \( \lambda\lambda 910 \) and 1175
is presented in Fig. 8, together with synthetic spectra from our set of models presented above. In contrast with the HST spectral region, the low- and high-ionization wind features now provide excellent temperature diagnostics, whilst iron features are weak or absent. The temperature sensitivity of C\textsc{iii} $\lambda\lambda 977, 1175$ and N\textsc{iii} $\lambda\lambda 989-91$ is striking, as is the abundance sensitivity of the latter. No match to $\lambda 989-91$ can be achieved without N enrichment, whilst P Cygni emission at N\textsc{iv} $\lambda 955$ and $\lambda 923$ is a little too strong at $T_{\text{eff}}=40\text{kK}$, although the latter is heavily contaminated by the interstellar HI Lyman series.

The observed strength of $\lambda 1175$ argues in favour of C depletion for $T_{\text{eff}} \sim 40\text{kK}$. As with Si\textsc{iv} in the HST spectrum, S\textsc{iv} $\lambda\lambda 1062-1073$ suggests a lower temperature of $T_{\text{eff}} \sim 37\text{kK}$. Its strength is affected by the adopted CNO abundance since these act as the principal wind coolants. P\textsc{v} $\lambda\lambda 1118-28$ (see below) and N\textsc{iv} $\lambda 955$ prove relatively insensitive. Unusually amongst the present sample, S\textsc{vi} $\lambda\lambda 933-44$ is well reproduced in the (strong) blue P Cygni component, but not in the (weak) red component, suggesting that this component is affected by a feature absent from the models (Walborn et al. 2002a). P\textsc{iv} $\lambda 950$ is not responsible since this is accounted for in our models.

Finally, it is apparent that the O\textsc{vi} $\lambda\lambda 1032-38$ doublet is weakly present in HDE 269698. Solely the $T_{\text{eff}}=46\text{kK}$ synthetic spectrum reveals any prominent O\textsc{vi} wind feature, albeit much weaker than observed. As discussed in § 4.1, X-rays are generally required in order to reproduce the strength of such ‘super-ions’ in O stars (e.g. Pauldrach et al. 1994, 2001), which are omitted for the moment. Our final HDE 269698 fit does include X-rays, producing stellar O\textsc{vi} $\lambda\lambda 1032-38$ with approximately the correct strength.

In contrast with Paper I, allowance for the stellar wind and line blanketing permits broadly consistent results to be obtained for HDE 269698 using optical, UV and FUV diagnostics, as presented in Figs. 9-10, which show our final fits to HDE 269698 for $T_{\text{eff}}=40\text{kK}$, $\log(L/L_\odot)=5.98$, $\log g=3.6$, $\dot{M}=8.5\times 10^{-6} \, M_\odot \text{yr}^{-1}$, $v \sin i=80 \, \text{km s}^{-1}$, $\beta=1$ and $v_\infty=1750 \, \text{km s}^{-1}$, as discussed above except that X-rays are now considered. With this set of parameters, overall consistency is excellent with the exception of N\textsc{iv} $\lambda\lambda 1718, 4058$ (too strong), Si\textsc{iv} $\lambda\lambda 1393-1402$ (too weak), S\textsc{iv} $\lambda\lambda 1062-1072$ (too weak) and P\textsc{v} $\lambda\lambda 1118-28$ (too strong – see § 6).

In contrast with the present results, which employ a single stellar atmospheric code, previous studies of HDE 269698 used a variety of tools. For example, the photospheric optical lines were analysed using a conventional plane-parallel hydrostatic non-LTE model by Puls et al. (1996), whilst fits to H\alpha were carried out using a different procedure. Haser et al. (1998) subsequently used a third technique – selecting a spherical, extended non-LTE model atmosphere to analyse the UV spectrum.
4.4. Other O supergiants

We shall now discuss the other three O supergiants studied in this work, ordered by spectral type. Final stellar parameters for all our program stars are listed in Table 6, and compared with previous results for these stars. In all previous cases temperatures are derived from hydrostatic, plane-parallel models (e.g. Herrero et al. 1992), whilst mass-loss rates are obtained from Hα modeling (e.g. Puls et al. 1996) and wind velocities are obtained from SEI line profile modeling (Haser 1995). For each star, optical and UV/FUV synthetic spectra from these parameters are compared with observations. Bolometric corrections (B.C.) differ from the Vacca, Garmany & Shull (1996) $T_{\text{eff}}$–B.C. calibration by typically $-0.1$ mag. Temperatures are again revised downward, such that B.C.$= -3.2$ mag for AzV 232 ($T_{\text{eff}}=32.5$K) versus B.C.$= -3.6$ mag ($T_{\text{eff}}=37.5$K) obtained previously by Puls et al. (1996).

Spectroscopic analysis of HDE 270952 and AzV 232 proceeds in a similar manner to HDE 269698, with an identical atomic model (Table 4). Optical He i-ii diagnostics provide the best-fit temperature whilst Hα provides the mass-loss rate in each case. As with HDE 269698, the only way in which we are able to reproduce the observed spectrum is via N- enrichment and C- depletion in each case. Oxygen is again much more difficult to constrain. X-rays are included in the final model atmosphere calculations, albeit with generic parameters.

4.4.1. HDE 270952 (O6 Iaf$^+$), LMC

For HDE 270952, $T_{\text{eff}}=33.5$K, $M=1.1 \times 10^{-5} M_\odot$ yr$^{-1}$, log($L/L_\odot$)$=5.86$, $h=0.002 R_*$, and a supersonic velocity law of $\beta=1.3$ provides an overall excellent match to the optical spectrum as illustrated in Fig. 11. The $\beta$ law was principally determined from fits to Hα and He ii $\lambda$4686 (see Hillier et al. 2002 for the sensitivity of other O-star line profiles to $\beta$). He ii $\lambda\lambda4200, 4542$ absorption profiles are reproduced well, as is the absorption of He i $\lambda$4471, although there is a P Cygni emission in this feature which is not reproduced. The same is true for Hβ and perhaps Hγ. We predict an emission component of He i $\lambda$6678 in the observed blend with He ii $\lambda$6683, but the observed emission is stronger and sharper than predicted.

We derive $\epsilon_N = 4.5\epsilon_{N,\odot}$ for HDE 270952 using N iii $\lambda$4097. A higher abundance is suggested by $\lambda\lambda4634-41$, although other N iii features (e.g. $\lambda\lambda4510-47$) argue for a lower N abundance. In contrast, the weak C iii $\lambda\lambda4647–51$ multiplet argues for depleted C abundance of $\epsilon_C = 0.1\epsilon_{C,\odot}$. As with HDE 269698, the absence of any strong optical oxygen diagnostics prevent a reliable determination, so $\epsilon_O = 0.2\epsilon_{O,\odot}$ is adopted for oxygen.

In the UV, the IUE HIRES SWP dataset is of rather low S/N. Nevertheless, the Fe iv-v forest, and Si iv $\lambda\lambda1393-1402$ are well reproduced, except for the strength of the red emission component, for $T_{\text{eff}}=33.5$K as shown in Fig. 12. The superior diagnostics offered by the FUV FUSE region also support the optically derived temperature and abundances. Si iv $\lambda\lambda1062–73$, C iii $\lambda\lambda977, 1175$ and
\(\text{N}\text{ III }\lambda\lambda 989–91\) are all well matched, as is the \(\text{S}\text{ V}\text{ I }\lambda\lambda 933-44\) region, in contrast with \(\text{HDE 269698}\). As for \(\text{HDE 269698}\), an improved fit to \(\text{P}\text{ V}\text{ }\lambda\lambda 1118–28\) can be achieved via clumping (see § 6) or a reduced phosphorus abundance. \(\text{N}\text{ IV }\lambda 955\) is rather too strong, suggesting a reduced N-abundance, although the (theoretically) more abundance-sensitive \(\text{N}\text{ IV}\) \(\lambda 1486\) emission line is matched rather well, as is \(\text{N}\text{ III }\lambda 1750\). The only prominent deficiency in the UV/FUV synthetic spectrum is \(\text{N}\text{ V}\text{ }\lambda\lambda 1238–42\), which is rather weak, despite the inclusion of X-rays, suggesting the need for a harder X-ray spectrum and/or higher filling factors.

4.4.2. \(\text{AzV 232} (\text{O7 Iaf}^+), \text{SMC}\)

The optical spectral morphology of \(\text{AzV 232}\) is rather similar to that of \(\text{HDE 270952}\) except for a somewhat weaker emission-line spectrum. Consequently, the derived stellar parameters are broadly similar. Hillier et al. (2002) describes in detail \textsc{cmfgen} model comparisons for \(\text{AzV 83}\) (also \(\text{O7 Iaf}^+\)), a spectroscopic twin of \(\text{AzV 232}\) (Walborn et al. 2000) using identical techniques, so we defer to their more extensive discussion. For \(\text{AzV 232}\), we determine \(T_{\text{eff}}=32\text{kK}, M=4.5\times10^{-6} M_\odot\text{ yr}^{-1}, \log(L/L_\odot)=5.85, h=0.005 R_\ast\) and a supersonic velocity law with \(\beta=1.65\), as presented in Fig. 13. These parameters are in close agreement with those obtained from our analysis of \textit{FUSE} spectroscopy in Paper I. The revision in parameters for \(\text{AzV 232}\) versus Puls et al. (1996) are as great as for \(\text{HDE 269698}\) (Table 6).

From \(\text{H}_{\alpha}\) modeling we obtain a slightly slower \(\beta\)-law than Puls et al. who obtained \(\beta=1.4\), also from \(\text{H}_{\alpha}\). In general, there is a tendancy for exponents determined from UV SEI line profile modeling to be lower. Haser (1995) obtained \(\beta=1.0\) from \(\text{N}\text{ V}\text{ }\lambda\lambda 1238–42, \text{Si IV }\lambda\lambda 1393–1402, \text{C IV }\lambda\lambda 1548–51\), and \(\text{N IV }\lambda 1718\) \(\text{AzV 232}\), although the quality of fits are of similar quality to that obtained for these profiles in the present study. This difference should be taken into consideration when comparing UV and optically derived velocity laws. Puls et al. (1996) discuss similar discrepancies for \(\zeta\text{ Pup}\).

Optical \(\text{H}\) and \(\text{He}\) line profiles are well matched, with the exception of \(\text{H}\beta\) (the central emission is due to incorrectly subtracted nebular \(\text{H}\beta\) from \(\text{NGC 346}\)). We obtain \(\epsilon_{\text{N}}=2.0\epsilon_{\text{N},\odot}\) from the fit to \(\text{N}\text{ III }\lambda 4097\), whilst \(\epsilon_{\text{C}}=0.07\epsilon_{\text{C},\odot}\) from \(\text{C}\text{ III }\lambda\lambda 4647-51\). Again, oxygen is poorly constrained from the optical, with \(\epsilon_{\text{O}}=0.1\epsilon_{\text{O},\odot}\) adopted. UV (\textit{HST-FOS}) and FUV (\textit{FUSE}) comparisons are again very good, as illustrated in Fig. 14, including \(\text{C}\text{ III, N}\text{ III, Si IV, Si IV, C IV}\) although \(\text{N}\text{ IV }\lambda 1718\) is too strong, and \(\text{He}\text{ II }\lambda 1640\) too weak. This latter feature is reproduced much better when compared to higher resolution, albeit lower S/N \textit{IUE} high-dispersion datasets. The predicted \(\text{P}\text{ V}\text{ }\lambda\lambda 1118-28\) absorption is too strong, which as we shall show in § 6 is either indicative of clumping or a reduced P abundance. The main failure for our \(\text{AzV 232}\) model is \(\text{N}\text{ V}\text{ }\lambda\lambda 1238-42\), again, for the adopted X-ray parameters. To reiterate, the stellar parameters derived from our analysis are insensitive to these X-ray parameters.
4.4.3. Sk$-66^\circ 169 (O9.7Ia^+)$, LMC

For Sk$-66^\circ 169$, the lower observed ionization led to the selection of a slightly different atomic model (Table 4), whilst a higher microturbulence of $\xi=20$ km s$^{-1}$ reproduced observed optical diagnostic line profiles better than the generic $\xi=10$ km s$^{-1}$. Villamariz et al. (2002) recently derived $\xi=20$ km s$^{-1}$ in their analysis of the Galactic O9.5 Ib supergiant HD 209975. An optimum fit to He I ($\lambda \lambda 4121, 4338, 4471, 4713$) and He II ($\lambda \lambda 4200, 4542$) absorption lines reveals $T_{\text{eff}}=26$ kK, whilst H$\alpha$ indicates $\dot{M}=6.5 \times 10^{-6} M_\odot$ yr$^{-1}$, log($L/L_\odot$)=5.86, and $h = 0.002 R_*$, again with a velocity law of $\beta=1.75$ – see Fig. 15. This figure also shows that the Si IV $\lambda \lambda 4088-4116$ and Si III $\lambda \lambda 4552-4576$ lines are also consistently matched for this temperature, although note the poor agreement with H$\delta$, uniquely for this star. Unusually, at least for the present sample, He II $\lambda 4686$ emission is strongly overestimated for our derived stellar temperature. Reproducing the strength of $\lambda 4686$ in O stars is generally problematic, even using spherically extended non-LTE models (e.g. Herrero et al. 2000). In order to reproduce its observed strength in Sk$-66^\circ 169$, we require a slightly lower temperature of $T_{\text{eff}}=24$kK. At this lower temperature, the Pickering He II series, $\lambda 4542, \lambda 4200$ become very weak, although the He I lines are essentially unchanged, with poorer agreement for the Si III-IV diagnostics. Therefore, we adhere to our preferred solution of $T_{\text{eff}}=26$kK despite this obvious failure. Adopting a clumped model for Sk$-66^\circ 169$ would help to resolve this discrepancy, since He II $\lambda 4686$ emission is strongly overestimated for our derived stellar temperature. Reproducing the strength of $\lambda 4686$ in O stars is generally problematic, even using spherically extended non-LTE models (e.g. Herrero et al. 2000). In order to reproduce its observed strength in Sk$-66^\circ 169$, we require a slightly lower temperature of $T_{\text{eff}}=24$kK. At this lower temperature, the Pickering He II series, $\lambda 4542, \lambda 4200$ become very weak, although the He I lines are essentially unchanged, with poorer agreement for the Si III-IV diagnostics. Therefore, we adhere to our preferred solution of $T_{\text{eff}}=26$kK despite this obvious failure. Adopting a clumped model for Sk$-66^\circ 169$ would help to resolve this discrepancy, since He II $\lambda 4686$ emission is reduced, with negligible effect on the photospheric lines.

In addition to Si, CNO optical lines are generally well reproduced at this temperature, requiring $\epsilon_N = 2.0 \epsilon_{N,\odot}$ from N III $\lambda 4097$ and N II $\lambda 4601-43$. Carbon and oxygen abundances of $\epsilon_C = 0.15 \epsilon_{C,\odot}$, $\epsilon_O = 0.3 \epsilon_{O,\odot}$ are obtained from O II $\lambda \lambda 4097-4120$, C III $\lambda \lambda 4647-51$ and O II $\lambda \lambda 4638-76$ (a blend), plus other O II features.

In the UV, comparison between observations and synthetic spectra is hindered by the low S/N in the IUE HIRES dataset. Nevertheless, the very strong Fe IV absorption between $\lambda \lambda 1500$ and 1750 is well matched by the synthetic spectrum (see Fig. 16). Si IV $\lambda \lambda 1393-1402$ is well matched, as is Al III $\lambda \lambda 1852-62$, although blanketing produces a C IV $\lambda 1548-51$ P Cygni emission profile which is clearly too weak in the synthetic spectrum. The only other prominent feature not matched by the model is (presumably) N V $\lambda \lambda 1238-42$, which is not predicted with our assumed X-ray parameters. The only discernable effect of X-rays is a slight strengthening of C IV $\lambda \lambda 1548-51$.

For the FUSE FUV dataset, agreement is excellent for $T_{\text{eff}}=26$kK, namely P IV $\lambda 950$, P IV $\lambda 950$ and $\lambda \lambda 1025-1033$, N II $\lambda \lambda 1084-6$, S IV $\lambda \lambda 1062-1073$, 1099 and Si III $\lambda \lambda 1110-1113$. N II is one of the few abundance-sensitive UV lines, although it is strongly temperature sensitive, which hinders its reliable use. Our assumed X-ray model has no effect on FUV wind diagnostics.

Amongst other UV and FUV lines, only Al III $\lambda 1852$ (fit worsens) and C III $\lambda 977$ (fit improves) are particularly sensitive to a reduced temperature of $T_{\text{eff}}=24$kK, as implied by the He II $\lambda 4686$ emission strength.
5. Abundances

Our results are amongst the first determinations of CNO abundances in O supergiants, although AB supergiants have been studied in detail (Venn 1996, 1999).

Metal abundance studies of Galactic O supergiants remain surprisingly sparse: Pauldrach et al. (1994, 2001) obtained partially CNO-processed material for ζ Pup (O4 I(n)f) and α Cam (O9.5 Ia) with N/C~5 by number, whilst Villamariz et al. (2002) recently obtained N/C=1 for HD 209975 (O9.5 Ib). Taresch et al. (1997) studied the nitrogen spectrum of HD 93129A (O2 If*) revealing $\epsilon_N = 2\epsilon_{N,\odot}$, whilst Pauldrach et al. (2001) determined N/C~4 by number for α Cam (O9.5 Ia).

Amongst Magellanic Cloud O stars, the sole result involving carbon and nitrogen was by Haser et al. (1998) who obtained N/C~5 for the SMC O2 giant NGC 346 #3 (Walborn et al. 2002b). Haser et al. (1998) were unable to determine CNO abundances for HDE 269698 due to problems with reproducing the unsaturated lines of N IV λλ1338-43 and O V λ1371. Such problems were probably due to the use of an erroneous stellar temperature for HDE 269698, and the fact that (more sensitive) optical lines were excluded.

Our results broadly support previous investigations, namely (substantial) nitrogen enrichment, plus (modest) carbon depletion, i.e. reveal N/C~3 (Sk −66°169), 10 (HDE 270952, AzV 232) or 30 (HDE 269698), by number. Unfortunately, Venn (1999) was only able to derive an upper limit to the carbon abundance in her study of SMC A supergiants, such that N/C≥1. Nevertheless, she also supported a general nitrogen enrichment, of between 0.2 and ≥1.2 dex. How do such abundance ratios compare with theoretical expectations for post-main sequence massive stars?

A major deficiency with the previous generation of evolutionary models for massive stars was that He and N enrichments for OB stars were not predicted until much later stages of evolution (Maeder & Meynet 2000). In contrast, recent models accounting for rotational mixing do predict N/C ratios which are much higher than the initial (solar) N/C ratio of ~0.2 by number. For example, Meynet & Maeder (2000) discuss the evolution of an initial 60 $M_\odot$ star at (solar) metallicity, initially rotating at 300 km s$^{-1}$. Rotational mixing permits changes to the surface N/C ratio, i.e. N/C~6 during the O-supergiant phase, when He/H=0.2, and subsequently N/C=12 when He/H=0.25 (Meynet, priv. comm.).

In general, our results indicate moderate carbon and oxygen depletions relative to LMC/SMC H II regions, with nitrogen substantially enriched. If we were to assume that we are solely witnessing CNO-processed material at the surface, one would expect carbon (and oxygen) depletions which are substantially greater to produce the necessary nitrogen enrichment, since the total CNO abundance is maintained within the CNO-cycle. Indeed, the problem is potentially even more acute, since up until now we have adopted nominal LMC (SMC) CNO abundances which are scaled to 0.4 (0.2) $\epsilon_{\odot}$, where $\epsilon_{\odot}$ refers to the solar metallicity of a particular element. In reality, the Magellanic Cloud nitrogen abundance from which these stars recently formed is considered to be much more depleted, with ~0.1$\epsilon_{\odot}$ in the LMC (Garnett 1999; Korn et al. 2002), and 0.03$\epsilon_{\odot}$ in the SMC (Peimbert,
The apparent problem is best illustrated for AzV 232 in the SMC for which carbon is only a factor of two depleted relative to typical SMC values (Garnett et al. 1995), whilst nitrogen is a factor of one hundred times higher than normal SMC values. Oxygen cannot easily remedy this situation, since the CN cycle precedes the ON cycle. Besides, it suffers a similar depletion to carbon (Peimbert et al. 2000). Similarly, taking HDE 270952 as representative of the LMC stars, discrepancies are somewhat similar: carbon and oxygen are again only a factor of two depleted relative to H\textsc{ii} regions or B stars, whilst nitrogen is a factor of 50 times higher than LMC values (Garnett 1999; Korn et al. 2002).

How can we resolve this puzzle? A likely solution is that we are witnessing evidence of mixing. The surface abundances are not solely exhibiting products of CNO processing, but instead a mixture of initial abundances, plus CNO processed material. In this case we would expect strong N enrichment, which is observed, but (assuming, say, 50% initial abundances) a reduction in C by no greater than a factor of two, which we also observe. In principal, one could get an estimate of the amount of mixing that has occurred. Detailed comparisons with evolutionary models accounting for rotation await appropriate calculations for low-metallicity environments. One might question the high nitrogen abundance in AzV 232 as determined by cmfgen, but N\textsc{iii} \(\lambda 4097\) appears to be a very sensitive abundance indicator. Indeed, the optical N\textsc{iii} spectral morphology of AzV 232 is remarkably similar to Galactic counterparts such as HD 163758 (O6.5 Iaf), suggesting similar present-day N abundances, despite very different initial abundances.

6. Clumping in O supergiants?

Observations universally point to the structured nature of OB winds, via UV (e.g. Massa et al. 1995) and optical spectroscopic monitoring campaigns (e.g. Eversberg, Lepine & Moffat 1998), and mm/radio imaging (e.g. Blomme et al. 2002). Hydrodynamic models also indicate that their winds are clumped and time variable (e.g. Owocki et al. 1988). For Wolf-Rayet stars, all stellar lines are formed in the clumped wind whilst the situation for O-type stars is less clear, with clumping originating above the stellar surface – perhaps above the formation region of the usual diagnostic lines. It is apparent that shocked, clumpy, models are required to match the O\textsc{vi} doublet in our program stars, plus N\textsc{v} in some cases. Precise shock parameters cannot yet be derived uniquely from optical and UV spectra. Nevertheless, it is possible that clumping may also affect some of our adopted wind diagnostics of O stars. If so, we may use this fact to investigate the degree of clumping for the inner wind of O stars. We have calculated a model of AzV 232 identical to that discussed above, except that its volume filling factor is reduced from 100% to 10%, and mass-loss rate reduced to \(2\times10^{-6} \, M_\odot \, \text{yr}^{-1}\). Overall, we find very few differences from the smooth model. The O supergiant case is in stark contrast with Wolf-Rayet stars for which electron scattering wings provide very important probes of clumping (Hillier 1991; Schmutz 1997).
One potentially useful diagnostic is the $\text{P~V} \lambda\lambda 1118-28$ doublet for which the non-clumped model overpredicts both absorption and emission for HDE 269698, HDE 270952 and AzV 232 (see also Massa et al. 2002). $\text{P}^{4+}$ is the dominant phosphorus ion throughout most of the wind of AzV 232 (if $T_{\text{eff}} \sim 32\text{ kK}$), so that the clumped model reveals weaker profiles, in better agreement with observation - see Fig. 17. One might argue that $\text{P~V}$ represents a useful probe of the degree of clumping in O stars, except that a similar effect is found by reducing the elemental abundance of phosphorus from $\epsilon_{\text{P}} = 0.2\epsilon_{\text{P,}\odot}$ to $\epsilon_{\text{P}} = 0.05\epsilon_{\text{P,}\odot}$ (Fig. 17). Similar results are obtained for HDE 269698 and HDE 270952. Pauldrach et al. (1994) have previously indicated a reduced abundance of phosphorus by a factor of 1.5–2 relative to solar values for $\zeta$ Pup (O4I(n)f) from $\text{P~V} \lambda\lambda 1118–28$ observations with Copernicus.

7. Discussion and Conclusions

Our analysis of optical H-He wind and photospheric profiles of luminous O supergiants, using line-blanketed, extended model atmospheres, reveal systematically ($\sim 15–20\%$) lower temperatures than plane-parallel results based solely on optical H-He photospheric lines (e.g. Herrero et al. 1992). Our results are supported by UV HST and especially FUV FUSE spectroscopy of metal wind lines and photospheric iron lines in these stars. Initial FUSE datasets of AzV 232 raised questions about the validity of temperatures derived from plane-parallel O supergiant models (Paper I), which unified model atmospheres such as Hillier & Miller (1998) can now resolve.

Fig. 18 compares temperatures for O supergiants derived here with those from previous compilations by Böhm-Vitense (1981), Schmidt-Kaler (1982), Howarth & Prinja (1989) and most recently by Vacca et al. (1996). Of these, one might expect Vacca et al. to be the closest match to the present results, yet the reverse is true, especially at the earliest subtypes. This can be understood from the fact that Vacca et al. included the most recent spectroscopic results, excluding wind or line blanketing. Consequently, $\zeta$ Pup (O4I(n)f) was included in their calibration with $T_{\text{eff}}$(no wind blanketing)$=46.5\text{ kK}$, rather than $T_{\text{eff}}$(wind blanketing)$=42\text{ kK}$ (Bohannan et al. 1986), although the ‘core-halo’ approach was followed in their study. Test calculations carried out for $\zeta$ Pup, which consistently include sphericity and line blanketing, indicate $T_{\text{eff}} \sim 39\text{ kK}$, illustrating the additional effect that line blanketing plays.

More recently, Herrero et al. (2000) compared results of early O supergiants obtained with plane-parallel models that accounted for line blanketing with those obtained using spherical models for which blanketing was omitted. For HD 15570 (O4If$^+$), Herrero et al. obtained $T_{\text{eff}}$(blanketed$)=50\text{ kK}$ versus $T_{\text{eff}}$(spherical)$=42\text{ kK}$. Stellar temperature determinations of O supergiants undertaken during the past decade are summarised in Table 7, sorted by the degree of complexity implemented; i.e., plane-parallel versus spherical, plus unblanketed versus line blanketed. From Table 7, blanketing and sphericity have rarely previously been simultaneously considered (Pauldrach et al. 1994, 2001), with only Taresch et al. (1997) successfully combining optical/UV/FUV diagnostics. A critical revision to the temperature calibration of O supergiants clearly requires analysis of a substantially
larger sample of targets, using the methods outlined here, which is currently underway. Revisions do not necessarily possess a strong metallicity dependence, since AzV 232 (SMC) possesses a similar difference from standard calibrations to the three LMC stars studied here (Fig. 18). Wind strength is more critical – one would expect the greatest deviations from conventional temperature scales for those stars with the highest wind densities, i.e. those with Hα and He II λ4686 emission.

Similar calculations for O dwarfs – also allowing for line blanketing – obtained ∼5% lower temperatures than unblanketed results (Herrero, Puls & Villamariz 2000; Martins et al. 2002). Independent observational evidence in favour of (1–2kK) lower temperatures of O dwarfs may be drawn from studies of O-type binaries (e.g. Harries, Hilditch & Hill 1998). The rarity of O supergiants within short-period eclipsing binary systems prevents direct determinations of radii, and thus temperatures, for O supergiants. The greater effect identified here for extreme O supergiants may reasonably be attributable to the effect of strong winds on the photospheric lines.

Our results argue for a substantial revision in stellar parameters for O supergiants versus those derived from previous spectroscopic techniques. For HDE 269698, the reduction in temperature implies a decrease in luminosity from ∼1.6×10^6 L⊙ to 1.0×10^6 L⊙. Such changes greatly affect the number of Lyman-ionizing photons emitted – in the case of HDE 269698, the standard T_{eff}-calibration would imply that its Lyman-ionizing output is a factor of two higher than the 10^{49.7} ph s^{-1} determined here. The ionizing flux of HDE 269698 below the HeI λ504 edge is reduced by a factor of three to 10^{49.0} ph s^{-1}. Similar changes are obtained for the other program stars. Fortunately, comparisons of nebular strengths in young, massive clusters with their constituent O stars are generally weighted towards main-sequence populations. Nevertheless, cases exist where individual O stars dominate H II regions (e.g. Oey et al. 2000) which would be dramatically affected by such large temperature changes.

Masses are more difficult to constrain, but the decrease in the spectroscopic luminosity and gravity also cause large differences from previous determinations. Consequently, evolutionary model comparisons with O supergiants carried out previously may not have been using the appropriate tracks in many cases. Although initial (and indeed current) rotational velocities for the program stars are not known, adopting v_{init}=300 km s^{-1} suggest an initial mass of 75 M⊙ for HDE 269698 according to evolutionary models (Fig. 8 of Meynet & Maeder 2000). In contrast, an initial mass in excess of 120 M⊙ would be implied by models on the basis of its previously determined higher luminosity. Our results do not solve the long-standing ‘mass discrepancy’ for O stars (Herrero et al. 1992) between evolutionary and spectroscopic mass determinations, since the reduction in spectroscopic luminosity is also accompanied by a reduced mass. Again, using HDE 269698 as an example, the reduction in spectroscopic gravity from log g ∼3.7 to log g ∼3.35 implies a decrease from ∼70 M⊙ to ∼35 M⊙ in its current mass.

The revision in luminosity also implies a different mass-loss rate. Table 5 shows a 35% reduction in M˙ for HDE 269698 (without accounting for the possibility that the wind is clumped). This revision affects the kinetic energy injected by individual stars or a young, massive cluster to the
ISM, since this is more dependent on the O supergiants and WR properties than on the main sequence stars (e.g. Crowther & Dessart 1998).

These effects have major consequences for the Wind-Momentum-Luminosity Relationship (WLR). In Fig. 19, we present the WLR for Galactic (circles), LMC (squares) and SMC (triangles) luminous O stars from Puls et al. (1996, open symbols). Also shown is the form of the Wind-Momentum-Luminosity Relationship (dotted line) for Galactic O supergiants according to Kudritzki & Puls (2000). We have added current results for our sample of LMC and SMC targets (filled symbols), two of which are in common with Puls et al. (1996). Revisions in parameters are illustrated in these cases with arrows. Clearly, when the present results are extended to a larger sample of luminous OB stars, substantial revisions to the empirical relationship of Kudritzki & Puls (2000) are expected.

FUV FUSE spectroscopy has proved to be invaluable for the present analysis. In contrast with HST/IUE, the availability of unsaturated resonance lines from dominant ionization stages of “cosmically rare” elements (e.g. P v λλ1118–28) represents a potentially exciting new diagnostic of wind clumping in O stars. Elements such as S and P are especially useful since they do not change substantially dueing the evolution of a massive star, in sharp contrast to CNO. FUSE provides many additional wind features, such that we no longer have access to only the saturated (model insensitive) C iv λλ1548–51 and X-ray influenced N v λλ1238–42 wind lines. Our ongoing FUSE program will aim to undertake detailed modeling of UV wind lines for a large sample of O stars, covering a greater range of spectral types and luminosity classes.

This work is based, in part, on data obtained by the NASA-CNES-CSA FUSE mission operated by the Johns Hopkins University. Financial support has been provided by NASA contract NAS5-32985 (U. S. participants), the Royal Society (PAC) and PPARC (OD, CJE). We wish to thank John Hutchings and Ken Sembach for the use of data from P.I. Time programs P117 and P103, respectively; Adi Pauldrach, Alex de Koter for the use of their stellar-atmosphere codes; and Goetz Gräfener for undertaking test calculations for ζ Puppis. We are grateful to Nolan Walborn for detailed comments on a draft of this paper.
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This preprint was prepared with the AAS LaTeX macros v5.0.
Table 1: Target Stars. Assumed distance moduli to the Magellanic Clouds are 18.5 (LMC) and 18.9 (SMC), whilst reddenings are derived from the mean of (i) intrinsic colours from FitzGerald (1970) and Schmidt-Kaler (1982); (ii) fitting final stellar models to UV-optical spectrophotometry. Atomic and molecular hydrogen column densities are obtained from fitting Ly$\alpha$ in this work, and fitting H$_2$ lines in $FUSE$ spectra by Tumlinson et al. (2002), respectively.

| Object     | Alias   | Galaxy | Sp. Type | Ref. | $V$  | $B - V$ | Ref. | $E(B - V)$ | $\log N$(H$_1$) | $\log N$(H$_2$) | $M_V$ |
|------------|---------|--------|----------|------|------|---------|------|------------|----------------|----------------|-------|
| HDE 269698 | Sk-67° 166 | LMC    | O4 Iaf+  | 1    | 12.27| −0.22   | 2    | 0.08       | 20.7           | 15.7           | −6.5  |
| HDE 270952 | Sk-65° 22 | LMC    | O6 Iaf+  | 1    | 12.07| −0.19   | 3    | 0.07       | 21.0           | 14.9           | −6.7  |
| AzV 232    | Sk 80   | SMC    | O7 Iaf+  | 1    | 12.36| −0.21   | 5    | 0.09       | 21.0           | 15.3           | −6.8  |
| Sk−66°169  |         | LMC    | O9.7 Ia+ | 4    | 11.56| −0.13   | 4    | 0.10       | 20.5           | <14.0          | −7.3  |

(1) Walborn 1977; (2) Ardeberg et al. 1972; (3) Isserstedt 1979; (4) Fitzpatrick 1988; (5) Azzopardi, Vigneau & Macquet 1975
Table 2: Wind velocities ($v_{\text{black}}$) observed at UV ($IUE$, $HST$) and FUV ($FUSE$) wavelengths for our program stars, including radial velocity measurements, $v_r$. Previous determinations are by Haser (1995, H95) and by Massa et al. (2002, M02). Our adopted value is provided in the final column, taken from $N\text{III}$, with the exception of Sk $-66^\circ 169$ for which $Si\text{IV}$ was used.

| Object   | Sp. Type | Dataset | $v_r$ | $N\text{III}$ | $N\text{V}$ | $Si\text{IV}$ | $C\text{IV}$ | $H95$ | $M02$ | $v_\infty$ |
|----------|----------|---------|-------|---------------|-------------|--------------|-------------|-------|-------|-------------|
| HDE 269698 | O4 Iaf+ | FUSE,HST | 265   | 1750          | 1740        | 1725         | 1900        | 1800  | 1750 |
| HDE 270952 | O6 Iaf+ | FUSE,IUE | -240  | 1520          | 1460        | 1520         | 1350        | 1520  |       |             |
| AzV 232   | O7 Iaf+ | FUSE,HST | -165  | 1330          | 1360        | 1290         | 1225        | 1400  | 1330 |
| Sk $-66^\circ 169$ | O9.7 Ia+ | FUSE,IUE | -295  | 910           | 1000        | 990          | 800         | 1000  |       |             |
Table 3: Stellar parameters of program stars derived here from hydrostatic, plane-parallel models (TLUSTY), together with previous determinations from Puls et al. (1996) or Lennon et al. (1997). Radii (and hence luminosities) are derived following $5\log\left(\frac{R}{R_\odot}\right) = 29.57 - M_V - V(T_{\text{eff}})$ from Herrero et al. (1992) for consistency.

| Object   | Sp Type | $T_{\text{eff}}$(kK) | $R/R_\odot$ | $\log(L/L_\odot)$ | $\log g$ | $y$ | $M(M_\odot)$ | $v\sin i$ | Ref.        |
|----------|---------|---------------------|-------------|-------------------|----------|-----|--------------|----------|-------------|
| HDE 269698 | O4 Iaf+ | 46.5                | 20.6        | 6.25              | 3.7      | 0.09| 70           | 100      | This work   |
|          |         | 47.5                | 19.5        | 6.24              | 3.6      | 0.1 | 80           |          | Puls et al. |
| HDE 270952 | O6 Iaf+ | 41                  | 25.6        | 6.22              | 3.5      | 0.09| 68           | 90       | This work   |
| AzV 232 | O7 Iaf+ | 39                  | 26.3        | 6.16              | 3.4      | 0.12| 57           | 60       | This work   |
|          |         | 37.5                | 29.5        | 6.19              | 3.2      | 0.2 |              |          | Puls et al. |
| Sk $-66^\circ$169 | O9.7 Ia+ | 31                  | 38.5        | 6.09              | 3.1      | 0.09| 27           | 100      | This work   |
|          |         | 28                  | 44.6        | 5.98              |          |     |              |          | Lennon et al. |
Table 4: Atomic models for early and late O supergiants. For each ion F denotes full levels, S super levels, and T the number of bound-bound transitions considered. Most ions are common to all stars, except where noted: C\textsc{ii}, O\textsc{ii}, Al\textsc{iii}, Si\textsc{iii}, S\textsc{iii} and Fe\textsc{iii} are only included in late O supergiant models (indicated in bold); whilst N\textsc{v}, O\textsc{vi}, S\textsc{vi} and Fe\textsc{vii} are only included in early O supergiant models (shown in italics).

| Element | I         | II        | III       | IV        | V         | VI        | VII       |
|---------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|         | F S T     | F S T     | F S T     | F S T     | F S T     | F S T     | F S T     |
| H       | 30 20 435 |           |           |           |           |           |           |
| He      | 49 40 325 | 30 20 435 |           |           |           |           |           |
| C       |           | 30 16 115 | 54 29 268 | 18 13 76  |           |           |           |
| N       |           | 41 21 144 | 90 47 733 | 60 34 331 | 18 13 85  |           |           |
| O       |           | 60 20 405 | 45 25 182 | 29 13 148 | 23 13 65  | 15 9 42   |           |
| Al      |           |           |           |           |           |           |           |
| Si      |           |           |           |           |           |           |           |
| P       |           |           |           |           |           |           |           |
| S       |           |           |           |           |           |           |           |
| Fe      |           |           |           |           |           |           |           |

Note: F denotes full levels, S super levels, and T the number of bound-bound transitions considered.
Table 5: Stellar models for HDE 269698 (O4 Iaf+), selected to match the observed Hα emission and absolute magnitude, $M_V$ ($h=0.005 \, R_\odot$). In all cases, two models are calculated, one with CNO elemental abundances set to $\epsilon = 0.4 \epsilon_\odot$, with helium and nitrogen assumed to be enriched in the other (He/H=0.2 by number, $\epsilon_N = 6 \epsilon_{N,\odot}$) with carbon and oxygen both depleted ($\epsilon_C = 0.05 \epsilon_{C,\odot}$, $\epsilon_O = 0.1 \epsilon_{O,\odot}$). A supersonic velocity law with $\beta=1.0$ is found to provide the best match to the shape of Hα.

| $T_{\text{eff}}$ | $R_*$ | $\log(L/L_\odot)$ | $\log g$ | $\dot{M}$ | $v_\infty$ |
|-----------------|-------|-------------------|----------|----------|-----------|
| kK              | $R_\odot$ | cgs               |          | $M_\odot \text{yr}^{-1}$ | km s$^{-1}$ |
| 46              | 19.1  | 6.17              | 3.55     | $9.75 \times 10^{-6}$ | 1750       |
| 43              | 19.7  | 6.08              | 3.45     | $9.75 \times 10^{-6}$ | 1750       |
| 40              | 20.5  | 5.98              | 3.35     | $8.5 \times 10^{-6}$  | 1750       |
| 37              | 21.0  | 5.88              | 3.25     | $6.75 \times 10^{-6}$ | 1750       |
| 34              | 22.3  | 5.78              | 3.15     | $7.25 \times 10^{-6}$ | 1750       |

Table 6: Stellar parameters of program stars derived from stellar wind models (Hillier & Miller 1998), including bolometric corrections, B.C. Approximate elemental mass fractions, $\epsilon$, relative to solar values are indicated, whilst He/H=0.2 is adopted for all program stars. Previous wind determinations (based in part on hydrostatic models) are also included here for comparison (Puls et al. 1996; Lennon et al. 1997).

| Object | Sp Type | $T_{\text{eff}}$ | $R_*$ | $\log g$ | $\log(L/L_\odot)$ | $\dot{M}$ | $\beta$ | $v_\infty$ | $\epsilon_C$ | $\epsilon_N$ | $\epsilon_O$ | Ref. |
|--------|---------|-----------------|-------|----------|-------------------|----------|--------|----------|--------------|--------------|--------------|------|
| HDE 269698 O4 Iaf+ | 40 | 20.5 | 3.6 | $-3.7$ | 5.98 | $8.5 \times 10^{-6}$ | 1.0 | 1750 | 0.05 | 9.0 | 0.1 | This work |
| HDE 270952 O6 Iaf+ | 33.5 | 25.0 | 3.2 | $-3.2$ | 5.86 | $11.0 \times 10^{-6}$ | 1.3 | 1520 | 0.1 | 4.5 | 0.2 | This work |
| AzV 232 O7 Iaf+ | 32 | 27.5 | 3.1 | $-3.1$ | 5.85 | $4.5 \times 10^{-6}$ | 1.65 | 1330 | 0.07 | 2.0 | 0.1 | This work |
| Sk $-66^\circ$169 O9.7 Ia+ | 26 | 40 | 2.8 | $-2.5$ | 5.82 | $6.0 \times 10^{-6}$ | 1.75 | 1000 | 0.15 | 2.0 | 0.3 | This work |
|          | 28 | 41.5 | 6.00 | $20.0 \times 10^{-6}$ | – | 1000 | | | | | | Lennon et al. |
Table 7: Stellar temperatures (in kK) of O supergiants as derived from plane-parallel (p-p) models including/excluding line blanketing (l.b.) and/or sphericity (sph). Wind blanketed results from the core-halo approach are presented in parenthesis, whilst spherical, l.b. models using optical, UV and FUV diagnostics are indicated in bold.

| Object       | Sp Type | galaxy | \( T_{\text{p-p}}^{\text{eff}} \) | \( T_{\text{p-p+l.b.}}^{\text{eff}} \) | \( T_{\text{sph}}^{\text{eff}} \) | \( T_{\text{sph+l.b.}}^{\text{eff}} \) | Ref |
|--------------|---------|--------|----------------------------------|----------------------------------------|---------------------------------|--------------------------------------|-----|
| HD 93129A    | O2 If*  | Galaxy | 50.5                             | 52                                      | 8                               |                                                     |     |
| Cyg OB2 #7   | O3 If*  | Galaxy | 51                               |                                        | 8                               |                                                     |     |
| HDE 269698   | O4 Iaf+ | LMC    | 49                               | 40                                      | 11                              |                                                     |     |
| Sk –67°167   | O4 Inf+ | LMC    | 47.5                             |                                        | 5                               |                                                     |     |
| HD 15570     | O4 If+  | Galaxy | 50                               | 42                                      | 8                               |                                                     |     |
| ζ Pup        | O4 If   | Galaxy | 46.5                             | (42)                                    | 42                              | 1, 4                                                |     |
| HD 14947     | O5 If+  | Galaxy | 43.5                             | 45                                      | 40                              | 5,8                                                 |     |
| Cyg OB2 #8c  | O5 If   | Galaxy | 48                               |                                        | 7                               |                                                     |     |
| Cyg OB2 #9   | O5 If   | Galaxy | 44.5                             |                                        | 7                               |                                                     |     |
| Cyg OB2 #11  | O5 If+  | Galaxy | 43                               |                                        | 7                               |                                                     |     |
| HDE 270952   | O6 Iaf+ | LMC    | 41                               | 33.5                                    | 11                              |                                                     |     |
| λ Cep        | O6 I(n)fp | Galaxy | 38                               | 41.5                                    | 37                              | 5,8                                                 |     |
| AzV 232      | O7 Iaf+ | SMC    | 39                               | 32                                      | 11                              |                                                     |     |
| HD 192639    | O7 Ib(f) | Galaxy | 38.5                             |                                        | 3                               |                                                     |     |
| HD 193514    | O7 Ib(f) | Galaxy | 38                               |                                        | 3                               |                                                     |     |
| HD 210809    | O9 Ib   | Galaxy | 33                               |                                        | 3                               |                                                     |     |
| AzV 469      | O9 Ib   | SMC    | 34                               |                                        | 9                               |                                                     |     |
| α Cam        | O9.5 Ia | Galaxy | 30                               | (30)                                    | 29                              | 2, 5, 10                                             |     |
| Cyg OB2 #10  | O9.5 I  | Galaxy | 31                               |                                        | 7                               |                                                     |     |
| HD 209975    | O9.5 Ib | Galaxy | 32.5                             |                                        | 3                               |                                                     |     |
| HD 19409     | O9.7 Ib | Galaxy | 31.5                             |                                        | 3                               |                                                     |     |
| Sk –66°169   | O9.7 Ia+ | LMC    | 31                               | 26                                      | 11                              |                                                     |     |

(1) Bohannan et al. (1986); (2) Voels et al. (1989); (3) Herrero et al. (1992); (4) Pauldrach et al. (1994); (5) Puls et al. (1996); (6) Taresch et al. (1997); (7) Herrero et al. (1999); (8) Herrero et al. (2000); (9) Dufton et al. (2000); (10) Pauldrach et al. (2001); (11) this work
Fig. 1.— Calibrated FUSE spectra of HDE 269698, HDE 270952, AzV 232, Sk −66°169 (top to bottom). Important stellar features are identified in the panels. Lines due to the atomic Lyman series are indicated.

Fig. 2.— Ultraviolet spectrograms of our program O supergiants based on IUE or HST observations.

Fig. 3.— UVES Hα profiles for our program O supergiants.

Fig. 4.— Comparison between UVES observations (solid) of HDE 269698 (O4 Iaf+) and synthetic profiles (red, dotted) obtained with TLUSTY (Teff = 46.5kK, log g = 3.7).

Fig. 5.— Theoretical synthetic spectra for HDE 269698 with Tef f = 40kK, log L/L⊙ = 5.98, vsin i = 80 km s⁻¹ differing only in M: 6×10⁻⁶yr⁻¹ (red, dotted), 8.5×10⁻⁶yr⁻¹ (green, dashed), and 11×10⁻⁶yr⁻¹ (blue, dot-dashed). UVES observations are indicated as solid lines. Notice the sensitivity of some features – principally He II λ4686 and Hα – to mass-loss, whilst others (e.g. N III λλ4634–41) are unaffected.

Fig. 6.— Comparison between optical (UVES) observations of HDE 269698 (O4 Iaf+) and synthetic spectroscopy (vsin i = 80 km s⁻¹) for a range of stellar temperatures, with mass-loss rates adjusted to reproduce the observed Hα emission profile. Models with processed (solid) and unprocessed (0.4Z⊙, dotted) CNO abundances are indicated in each panel. The blue optical lines of HeI λ4471, N III λ4634-41, N IV λ4058, N V λλ4603-20 are very sensitive to temperature and abundance. In addition to the usual helium and metal lines, our models include the newly identified S IV λλ4486–4504 lines (Werner & Rauch 2001).
Fig. 7.— Comparison between UV (HST) observations of HDE 269698 (O4Iaf+) and synthetic spectroscopy ($v \sin i = 80$ km s$^{-1}$) for a range of stellar temperatures, with mass-loss rates adjusted to reproduce the observed H$\alpha$ emission profile. Models with processed (solid) and unprocessed (0.4Z$_\odot$, dotted) CNO abundances are indicated for each model. In contrast with the optical, UV P Cygns lines are rather insensitive to temperature and abundance variations. The greatest morphological differences over the temperature range covered are due to the weak iron features – Fe vi $\lambda\lambda$1250–1350, Fe v $\lambda\lambda$1350–1500, and Fe IV $\lambda\lambda$1550-1700. For comparison purposes, the synthetic model is corrected for Ly$\alpha$ at 1215.7Å, with log($H_2$/cm$^{-2}$)=20.7.

Fig. 8.— Comparison between FUV (FUSE) observations of HDE 269698 (O4Iaf+) and synthetic spectroscopy ($v \sin i = 80$ km s$^{-1}$) for a range of stellar temperatures, with mass-loss rates again adjusted to reproduce the observed H$\alpha$ emission profile. Models with processed (solid) and unprocessed (0.4Z$_\odot$, dotted) CNO abundances are indicated for each model. The P Cygni profiles sampled in the FUSE spectral range, in contrast with the HST range, are very sensitive to temperature and abundances variations, notably C iii $\lambda$977, N iii $\lambda\lambda$989-91, O vi $\lambda\lambda$1032-8, S iv $\lambda\lambda$1062-72, P v $\lambda\lambda$1118-28 and C iii $\lambda$1175. For comparison purposes, the synthetic model is corrected for the Lyman HI series (principally Ly$\beta$ at 1025.7Å, and Ly$\gamma$ at 972.5Å) with log($H_2$/cm$^{-2}$)=20.7.

Fig. 9.— Comparison between optical UVES line profiles of HDE 269698 (solid, O4Iaf+) and synthetic cmfgen spectra (red, dotted) for our final parameters, $T_{\text{eff}}=40$K, log($L/L_\odot$)=5.98, log $g=3.6$, $\dot{M}=8.5 \times 10^{-6}$ $M_\odot$yr$^{-1}$, $v \sin i =80$ km s$^{-1}$, $\beta=1$ and $v_\infty=1750$ km s$^{-1}$.

Fig. 10.— Comparison between UV HST and FUV FUSE observations of HDE 269698 (solid, O4Iaf+) and synthetic cmfgen spectra (red, dotted) for our final parameters, $T_{\text{eff}}=40$K, log($L/L_\odot$)=5.98, log $g=3.6$, $\dot{M}=8.5 \times 10^{-6}$ $M_\odot$yr$^{-1}$, $v \sin i =80$ km s$^{-1}$, $\beta=1$ and $v_\infty=1750$ km s$^{-1}$. The synthetic model is corrected for the Lyman HI series (principally Ly$\alpha$ at 1215.7Å, Ly$\beta$ at 1025.7Å, and Ly$\gamma$ at 972.5Å) according to Herald et al. (2001) with log($H_2$/cm$^{-2}$)=20.7.

Fig. 11.— Comparison between optical UVES line profiles of HDE 270952 (solid, O6Iaf+) and synthetic cmfgen spectra (red, dotted) for our final parameters, $T_{\text{eff}}=33.5$K, log($L/L_\odot$)=5.86, log $g=3.2$, $\dot{M}=11 \times 10^{-6}$ $M_\odot$yr$^{-1}$, $\beta=1.3$, $v \sin i =80$ km s$^{-1}$, and $v_\infty=1520$ km s$^{-1}$.

Fig. 12.— Comparison between UV HST and FUV FUSE observations of HDE 270952 (solid, O6Iaf+) and synthetic cmfgen spectra (red, dotted) for our final parameters, $T_{\text{eff}}=33.5$K, log($L/L_\odot$)=5.86, log $g=3.2$, $\dot{M}=11 \times 10^{-6}$ $M_\odot$yr$^{-1}$, $\beta=1.3$, $v \sin i =80$ km s$^{-1}$, and $v_\infty=1520$ km s$^{-1}$. The synthetic model is corrected for the Lyman HI series (principally Ly$\alpha$ at 1215.7Å, Ly$\beta$ at 1025.7Å, and Ly$\gamma$ at 972.5Å) according to Herald et al. (2001) with log($H_2$/cm$^{-2}$)=21.0.
Fig. 13.— Comparison between optical UVES line profiles of AzV 232 (solid, O7 Iaf+) and synthetic cmfgen spectra (red, dotted) for our final parameters, $T_{\text{eff}}=32\text{kK}$, $\log(L/L_{\odot})=5.85$, $\log g=3.1$, $M=4.5 \times 10^{-6} \, M_{\odot} \, \text{yr}^{-1}$, $\beta=1.65$, $v \sin i=80 \, \text{km s}^{-1}$, and $v_{\infty}=1330 \, \text{km s}^{-1}$.

Fig. 14.— Comparison between UV HST and FUV FUSE observations of AzV 232 (solid, O7 Iaf+) and synthetic cmfgen spectra (red, dotted) for our final parameters, $T_{\text{eff}}=32\text{kK}$, $\log(L/L_{\odot})=5.85$, $\log g=3.1$, $M=4.5 \times 10^{-6} \, M_{\odot} \, \text{yr}^{-1}$, $\beta=1.65$, $v \sin i=80 \, \text{km s}^{-1}$, and $v_{\infty}=1330 \, \text{km s}^{-1}$. The synthetic model is corrected for the Lyman HI series (principally Ly$\alpha$ at 1215.7Å, Ly$\beta$ at 1025.7Å, and Ly$\gamma$ at 972.5Å) according to Herald et al. (2001) with $\log(H_2/\text{cm}^{-2})=21.0$.

Fig. 15.— Comparison between optical UVES line profiles of Sk$-66^\circ 169$ (solid, O9.7 Ia+) and synthetic cmfgen spectra (red, dotted) for our final parameters, $T_{\text{eff}}=26\text{kK}$, $\log(L/L_{\odot})=5.82$, $\log g=2.8$, $M=6.0 \times 10^{-6} \, M_{\odot} \, \text{yr}^{-1}$, $\beta=1.75$, $v \sin i=100 \, \text{km s}^{-1}$, and $v_{\infty}=1000 \, \text{km s}^{-1}$.

Fig. 16.— Comparison between UV IUE and FUV FUSE observations of Sk$-66^\circ 169$ (solid, O9.7 Ia+) and synthetic cmfgen spectra (red, dotted) for our final parameters, $T_{\text{eff}}=26\text{kK}$, $\log(L/L_{\odot})=5.82$, $\log g=2.7$, $M=6.0 \times 10^{-6} \, M_{\odot} \, \text{yr}^{-1}$, $\beta=1.75$, $v \sin i=100 \, \text{km s}^{-1}$, and $v_{\infty}=1000 \, \text{km s}^{-1}$. The synthetic model is corrected for the Lyman HI series (principally Ly$\alpha$ at 1215.7Å, Ly$\beta$ at 1025.7Å, and Ly$\gamma$ at 972.5Å) according to Herald et al. (2001) with $\log(H_2/\text{cm}^{-2})=20.5$.

Fig. 17.— Comparison between observed FUSE P\,\nu\,\lambda\lambda 1118–28 profiles in AzV 232 (solid) and our standard model parameters (upper panel, red dotted), and cases for which the wind is clumped with a volume filling factor of $f=0.1$ (central panel, red dotted) or P/H is reduced by a factor of four (lower panel, red dotted).
Fig. 18.— Temperature calibrations for O supergiants from various sources (red: Böhm-Vitense 1981; green: Schmidt-Kaler 1982; blue: Howarth & Prinja 1989; black: Vacca et al. 1996), universally based on plane-parallel hydrostatic results, versus our spectroscopic determinations, allowing for the stellar wind and line blanketing. Minor revisions to these calibrations at the earliest subtypes are needed due to the revisions of Walborn et al. (2002a). For example, HD 93129A, one of two O3 supergiants included in the Vacca et al. calibration, has subsequently been re-classified to O2If*.

Fig. 19.— Reduced wind momentum ($\dot{M}v_\infty R^{0.5}$, cgs units) versus luminosity ($\log L/L_\odot$) for Galactic (circles), LMC (red, squares) and SMC (blue, triangles) O stars. Open symbols refer to data from Puls et al. (1996), whilst filled in symbols are from the present work (two in common – arrows indicate revision in parameters). Also shown is the form of the wind-momentum luminosity relationship (dotted line) for Galactic O supergiants according to Kudritzki & Puls (2000).
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