Properties of Hot, Massive Stars: The Impact of \textit{FUSE}

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\textbf{Abstract.} The impact of \textit{FUSE} upon the fundamental parameters of OB stars and Wolf-Rayet stars is reviewed. The stellar wind signatures available in the far-UV provide us with important additional diagnostics of effective temperature. Together with improved non-LTE stellar atmosphere models allowing for line blanketing and stellar winds, this has led to a downward revision in the spectral type-temperature calibration for O stars versus Vacca et al. (1996) In addition, the Lyman continuum ionizing fluxes from O dwarfs are compared with previous calibrations of Panagia (1973) and Vacca et al. We also discuss mass-loss rates in OB stars, such that agreement between recent theoretical predictions (Vink et al. 2000, 2001) and observations of O supergiants is possible, solely if winds are clumped in the far-UV and Hα line forming regions, as favoured by line profile comparisons for P V 1118-28 (early to mid O) or S IV 1062-1073 (late O to early B) in \textit{FUSE} datasets. In contrast, B supergiant wind strengths are predicted to be much higher than observations indicates, especially if their winds are also clumped. Finally, significant upward revisions in wind velocities of very late WN stars are indicated by N II 1085 resonance line observations, plus elemental abundances in OB and WR stars are briefly discussed.

1. Introduction

Massive stars ($\geq 10M_\odot$) play an important role in the ecology of their host galaxies, which belies their rarity. O stars are generally the dominant source of Lyman continuum photons in galaxies, whilst their fast, dense winds are the principal source of kinetic energy in young bursts of star formation. Wolf-Rayet stars, the chemically evolved descendants of OB stars, also contribute to chemical and kinetic enrichment of galaxies via their very dense stellar winds, plus Lyman continuum photons and ultimately as core-collapse Supernova, which further dynamically and chemically modify their environment.

Although the majority of our understanding about luminous, hot stars originates from ground-based optical spectroscopy, their energy distributions peak in the far- or extreme-UV. The first rocket UV observations revealed the characteristic P Cygni signatures of mass-loss from massive stars (e.g. Morton 1967). Longward of Lyα, primarily \textit{IUE} has provided observations of a very large database of OB stars, within the Milky Way, plus Magellanic Cloud supergiants (Walborn et al. 1985), supplemented by \textit{HST} datasets of fainter Magellanic Cloud stars (Walborn et al. 1995a; Walborn et al. 2000; Evans et al. 2004b) whilst only a few early-type stars have been observed in the far-UV prior to \textit{FUSE}, with \textit{Copernicus} (Snow \& Morton 1976) and more recently HUT (Walborn et al. 1995b; Schulte-Ladbeck et al. 1995). Far-UV \textit{FUSE} atlases have
been presented by Walborn et al. (2002) for Magellanic Cloud OB stars, by Pellerin et al. (2002) for Milky Way OB stars and by Willis et al. (2004) for Wolf-Rayet stars.

2. Stellar temperatures of early-type stars

Reliable stellar temperatures \( T_\ast \) for early-type stars are of fundamental importance since bolometric luminosities and ionizing fluxes are extremely sensitive to temperature. Here we first discuss the difficulties involved with deriving stellar temperatures for OB stars, together with the role played by \textit{FUSE} in identifying the inconsistencies from spectroscopic results obtained until recently.

2.1. Non-LTE models

Since the UV-optical continuum spectral energy distribution of early-type stars differ only subtly between O2 and B0 stars, the determination of \( T_\ast \) requires the comparison of line profiles of adjacent ionization stages of the same element (He for O stars, Si for B stars) with model atmosphere codes. LTE model atmospheres (e.g. Kurucz 1979) are widely used in stellar astrophysics. However, this treatment assumes that the ionization state of the gas and the populations of the atomic levels can be obtained from the local \( T_e \) and \( n_e \) via the Saha-Boltzmann distribution, such that collisional processes occur faster than radiative processes. Unfortunately, the opposite is true in hot star winds, so it is necessary to solve the equation of statistical equilibrium everywhere, i.e. non-LTE.

The major complication of non-LTE is that a determination of populations uses rates which are functions of the radiation field, itself is a function of the populations. Consequently, it is necessary to solve for the radiation field and populations simultaneously, which is computationally demanding, and requires an numerical iterative scheme to obtain consistency. Unfortunately, the problem is too complex for analytical solutions. Considerable effort has gone into developing realistic non-LTE model atmospheres for early-type stars in recent years by a number of independent groups. Up until very recently, the non-LTE model atmosphere code TLUSTY (Hubeny 1988) or SURFACE/DETAIL (Butler & Giddings 1985) represented the standard approach for O stars, based upon H-He plane-parallel geometry. A compilation of properties of O stars based largely upon such an approach was presented by Vacca et al. (1996).

However, two potentially significant effects were lacking in this approach; (i) the atmospheres of early-type stars are not composed of solely H and He, such that the collective effect of metals within the atmosphere may significantly affect the ionization structure via so-called line blanketing. Unfortunately, consistently treating metal ‘line blanketing’ in non-LTE atmospheres is computationally demanding, although great progress has now been achieved by various groups including TLUSTY (Hubeny & Lanz 1995; Lanz & Hubeny 2003); (ii) the presence of stellar winds complicates the geometry, such that a proper treatment requires spherical geometry. Winds may contaminate (‘fill-in’) photospheric absorption lines in OB stars, causing temperatures to be overestimated still further in the standard plane-parallel assumption (Schaefer & Schmutz 1994; Bohannan et al. 1990).
At present, there are two line blanketed non-LTE spherical model atmospheres widely in use that permit (consistent) detailed studies of far-UV, UV and optical spectroscopy of O stars, namely CMFGEN (Hillier & Miller 1998) and Fastwind (Santaloya-Rey et al. 1997; Herrero et al. 2002). In addition, WM-basic (Pauldrach et al. 2001) permits UV spectral synthesis, although presently this lacks an appropriate treatment of line broadening for optical spectral features.

2.2. Temperature scale of early-type stars

A number of quantitative studies of OB stars were carried out in the last decade in which non-LTE plane-parallel model atmospheres for photospheric optical lines of H and He (to derive $T_\ast$) were successfully combined with spectral synthesis codes for UV ($IUE/HST$) metal lines (to derive wind properties), such as Pauldrach et al. (2001) and Haser et al. (1998). However, Early Release Observations from $FUSE$ included two mid-O supergiants for which previously optically derived temperatures proved very poor matches to the UV spectral region (Fullerton et al. 2000). In contrast with the familiar N\textsc{v}, Si\textsc{iv} and C\textsc{iv} saturated P Cygni line profiles from $IUE/HST$, unsaturated lines from trace ions were covered by $FUSE$, e.g. C\textsc{iii}, N\textsc{iii}, S\textsc{iv}, P\textsc{iv} permitting a greater diagnostic role with regard to the ionization balance of metal species. For the case of Sk 80 (AzV 232, O7Iaf\textsuperscript{+}) in the SMC, the metal lines in the $FUSE$ spectral window indicated a substantially lower $T_\ast$ (by 15%) than previous helium lines from optical studies (Puls et al. 1996).

This major inconsistency was ultimately resolved via the use of line blanketed, spherical, non-LTE models, introduced above, together with $FUSE$, $IUE/HST$ and optical datasets in which the wind and line blanketing had a substantial effect on the helium ionization balance (see e.g. Repolust et al. 2004), and confirmed the earlier $FUSE$ far-UV result for Sk 80 (Crowther et al. 2002a). Subsequently there have been a number of studies of Galactic and Magellanic Cloud O stars based on Fastwind and CMFGEN analyses of optical datasets, plus UV/far-UV spectroscopy in some instances. Overall, recent results indicate a lower $T_\ast$ scale for dwarfs, giants and supergiants, as indicated in Figs. 1, 2 and 3, respectively. The trend towards 2–3kK lower $T_\ast$ is also true for B supergiants (Crowther et al. 2005).

Agreement between results from the different model atmosphere codes is good in all cases for which optical diagnostics are included, across each host galaxy. The principal outliers are results from Bianchi & Garcia (2002) and Garcia & Bianchi (2004) in which solely far-UV $FUSE$ and UV $IUE$ spectroscopy of Galactic O stars were analysed using WM-basic. Since it is not possible to compare their predicted optical photospheric lines with observations, caution is presently advised regarding their validity.

In contrast with O and early B stars, recent spectroscopic results for Wolf-Rayet stars have, in general, led to an increase in stellar temperatures\textsuperscript{1} relative to earlier calculations. Current line blanketed models for WR stars (e.g. CMFGEN) are effectively identical to those used for O stars with winds, whilst previ-

\textsuperscript{1}Since WR winds are optically thick, stellar temperatures generally refer to deep layers (Roseland optical depth $\tau_{\text{Ross}} \sim 10$ or 20) rather than the conventional $\tau_{\text{Ross}}=2/3$
Figure 1. Effective temperatures of O dwarfs versus the Vacca et al. (1996) calibration, based on Galactic results from Martins et al. (2004), Bianchi & Garcia (2002), Garcia & Bianchi (2004) and Repolust et al. (2004), LMC/SMC results from Massey et al. (2004) and Bouret et al. (2003). For this and subsequent figures, CMFGEN (black filled), FASTWIND (grey filled) and WM-basic (open).

Figure 2. Effective temperatures of O giants and bright giants versus the Vacca et al. (1996) calibration, based on Galactic results from Herrero et al. (2002), Bianchi & Garcia (2002) and Repolust et al. (2004), LMC/SMC results from Bouret et al. (2003), Walborn et al. (2004), Hillier et al. (2003), Massey et al. (2004) and Evans et al. (2004)
Figure 3. Effective temperatures of O supergiants versus the Vacca et al. (1996) calibration, based on Galactic results from Herrero et al. (2002), Bianchi & Garcia (2002), Repolust et al. (2004) and Garcia & Bianchi (2004), LMC/SMC results from Crowther et al. (2002), Hillier et al. (2003), Evans et al. (2004), Massey et al. (2004)

Several studies employed non-LTE H-He or H-He-CNO spherical non-LTE models. Why has the temperature scale for WR stars moved in the opposite sense? Blanketing has the effect of re-distributing extreme-UV flux to longer wavelengths such that higher temperatures are required to maintain a specific wind ionization balance of, say, helium for WN stars or carbon for WC stars.

2.3. Ionizing fluxes

Naturally, lower $T_*$ for OB stars impacts upon bolometric luminosities (since bolometric corrections are very sensitive to temperature for O stars) and Lyman continuum fluxes, due to lower, softer extreme-UV fluxes. By way of example, in Fig. 4 we compare recent results for O dwarfs discussed above with calibrations from Panagia (1973) and Vacca et al. (1996). We find that the Vacca et al. calibration overestimates contemporary determinations of ionizing fluxes from O stars at all spectral types, whilst the Panagia calibration is more reliable at later subtypes, but also overestimates fluxes amongst early O stars. Such revisions naturally have great influence on the stellar content of H II regions, although the widely adopted N(LyC)$=10^{49}$ ph s$^{-1}$ for O7V stars remains a reasonable assumption (Vacca 1994). Conversely, higher stellar temperatures of WR stars leads to a greater contribution from such stars in the Lyman continuum ionization budget of H II regions.
3. Wind properties of early-type stars

Global wind properties of hot stars may be characterized by mass-loss and wind velocity. The former depends on application of varying complexity of theoretical interpretation, whilst the latter can be directly measured with minimal interpretation.

3.1. Wind velocities

UV and far-UV P Cygni profiles from metal resonance transitions provide a direct indication of stellar wind velocities of early-type stars. Two approaches are possible – either the maximum blueward extent of saturated ‘black’ absorption troughs can be directly measured from observations (e.g. Prinja & Crowther 1998), or fit using techniques such as the Sobolev with exact integration (SEI) method (e.g. Haser et al. 1998). Since many far-UV P Cygni lines are unsaturated, ‘black’ wind velocity measurements from \textit{FUSE} spectroscopy are generally restricted to a few strong wind lines, such as Ni\textsc{iii} λ989-991. Willis et al. (2004) compare wind velocities of Wolf-Rayet stars from \textit{FUSE} datasets with literature UV/optical measurements, and find overall good agreement, with the exception of very late subtype WN stars, for which Ni\textsc{ii} λ1085 P Cygni profiles indicated wind velocities up to a factor of two times higher than previously estimated.
3.2. Mass-loss rates – evidence for clumping?

Several techniques are available for the determination of empirical mass-loss rates in early-type stars, involving radio, optical and UV/far-UV observations. Theoretical mass-loss rates have been published by Vink et al. (2000, 2001).

**Radio** For nearby Galactic OB stars with strong winds, probably the most robust method of determining mass-loss rates is via the thermal free-free excess at IR/mm/radio wavelengths following e.g. Wright & Barlow (1975). Unfortunately, stars with relatively weak winds possess very modest radio excesses, multiple frequency observations are necessary to ensure against non-thermal radio emission from colliding winds, plus no progress with extragalactic early-type stars is presently possible due to sensitivity limits with current facilities. The radio photosphere of O stars (hundreds of \( R_\odot \)) greatly exceeds that from UV/optical emission lines (typically 1–2 \( R_\odot \)).

**Optical** Optical (e.g. H\(\alpha\)) or near-IR (e.g. Br\(\alpha\)) spectroscopy offers a readily available indicator of mass-loss in early-type stars within the Local Group, subject to difficulties with nebular contamination from H\(\text{II}\) regions (Massey et al. 2004). The main limitation with such diagnostics are that complex non-LTE models introduced above need to be employed for reliable mass-loss rates (e.g. Repolust et al. 2004). Alternatively, analytical techniques can be used (e.g. Puls et al. 1996), provided they are suitably calibrated against non-LTE model results (Markova et al. 2004).

To date, the most extensive multi-wavelength studies of mass-loss, specifically, Crowther et al. (2002), Hillier et al. (2003) and Evans et al. (2004) have derived mass-loss rates of Magellanic Cloud OB stars from H\(\alpha\) observations, and compared predicted UV and far-UV line profiles with observations. With one exception (AzV 235), agreement was very good except that the predicted P Cygni absorption components of P\(\text{V} \lambda 1118-28\) (in mid O stars) and S\(\text{IV} \lambda 1062-1068\) (in late O/early B stars) were too strong. One was able to resolve the discrepancy either by (a) reducing the Phosphorus abundance below that expected (although the Sulphur abundance is well known from nebular studies) or, (b) introducing clumped winds in which lower mass-loss rates were able to reproduce the H\(\alpha\) profile. In general, clumped versus homogeneous models showed otherwise very subtle differences, such that the availability of unsaturated P Cygni profiles in FUSE datasets offers the best opportunity to investigate clumping in OB stars.

**UV and far-UV** Finally, the SEI method can be used to derive optical depths (or alternatively \( \dot{M}_q \), where \( q \) represents the ionization fraction of the specific ion relative to the total for that element) versus velocity for unsaturated UV and far-UV P Cygni line profiles. Massa et al. (2003) have analysed a sample of LMC O stars using the SEI method. Rather than derive mass-loss rates, they instead adopt theoretical mass-loss rates from Vink et al. (2000) to investigate the ionization balance in O stars. From P\(\text{V} \lambda 1118-28\) they find \( q(\text{P}^{5+}) \) never exceeds \( \sim 0.2 \), such that either (i) the calculated mass-loss rates are too high; (ii) the adopted P abundance is too large, or (iii) the winds are strongly clumped. The latter possibility obviously ties in naturally with the above arguments from more complex techniques. Massa (these proceedings) discusses recent extensions to this study involving Galactic OB stars.
3.3. An empirical metallicity dependence of wind strength?

Current radiatively driven wind theory predicts a modest dependence of mass-loss rate versus metallicity \((Z, \text{Vink et al. 2001})\). Consequently, considerable effort is presently underway to establishing an empirical dependence by comparing Solar neighbourhood OB stars to counterparts in the LMC and SMC, where the metallicity is a factor of \(\sim 2\) to \(\sim 4\)–5 times lower, respectively.

Wind velocities of LMC O stars differ little from Galactic counterparts, although a more prominent effect is observed in the SMC amongst early O stars (Walborn et al. 1995a; Prinja Crowther 1998). More critically, in Fig. 5 we present derived wind momenta of O supergiants in the Milky Way/LMC/SMC, assuming homogeneous winds, with the Vink et al. (2000) Galactic calibration (for \(T_\ast \geq 27.5 \text{kK}\)), together with predictions for LMC and SMC metallicities \((\dot{M} \propto Z^{0.69}; \text{Vink et al. 2001})\). The comparison appears poor, although modest clumping would resolve the Galactic O supergiant mismatch, via a decrease in empirical mass-loss rates by \(\sim 0.3\)–0.5 dex. For the SMC supergiants there is a greater observational scatter, such that some supergiants would agree with the prediction for clumped winds, whilst others would fall far below. A similar comparison for B supergiants is presented in Fig. 6 now relative to the Vink et al. calibrations for stars with \(T_\text{eff} \leq 22.5 \text{kK} \) ( \(\dot{M} \propto Z^{0.64}; \text{Vink et al. 2001}\)). In contrast, the measured wind densities of Galactic and SMC B supergiants fall below the predictions, such that clumping would only worsen
the comparison. Consequently, significant problems clearly remain, although observationally SMC supergiants do show weaker wind densities than LMC and Galactic counterparts, although a larger sample size for all galaxies is urgently required for firmer conclusions. Such a study is ongoing via several groups, including our own. Our approach is to combine high quality optical (VLT/UVES) spectroscopy with far-UV (FUSE) spectroscopy of Magellanic Cloud OB stars drawn from the Guaranteed Time program P117 (P.I.: J. Hutchings) plus the ongoing Legacy program P511 (P.I.: W. Blair).

3.4. Wolf-Rayet stars

Finally, let us briefly discuss WR stars. Since their winds are denser than OB stars, they offer a great many more wind diagnostics, although as their photospheres are not directly observable, it is necessary to derive their wind and physical properties simultaneously. Crowther et al. (2000) illustrates the quality of synthetic fits to far-UV/UV/optical/near-IR spectroscopy that is possible, for the case of a WO star in the LMC. WR winds have long been established to be clumped, specifically via the strength of electron scattering wings on line profiles (Hillier 1991), rather than far-UV P Cygni profiles.

In contrast with OB stars, historically no (heavy) metallicity dependence of WR winds has been adopted, although Crowther et al. (2002b) argue in favour of a metallicity dependence, on the basis of iron-peak lines providing the principal
line driving in WR stars (even within the carbon-rich atmosphere of a WC star). C III λ5696 was identified as particularly sensitive to wind strength, such that early WC subtypes (with weak/absent λ5696) are anticipated in metal poor environments such as the LMC, as observed (Breysacher et al. 1999), and late WC subtypes (with strong λ5696) are anticipated in metal rich environments, such as M83, also as observed (Crowther et al. 2004).

4. Elemental Abundances

To date, the bulk of stellar abundance studies of OB-type stars have focussed upon H/He contents (e.g. Herrero et al. 1992) rather than light (CNO) or heavy (iron peak) elements. Despite numerous metal lines in the FUSE spectral window, these are primarily wind influenced, such that the prime abundance lines are observed in the blue and yellow visible. Recent studies of OB supergiants by Crowther et al. (2002a), Hillier et al. (2003) and Evans et al. (2004a) reveal partially CNO-cycle processed material at their surfaces. Indeed, Walborn et al. (2004) find similar levels of nitrogen enhancement and oxygen depletion in a subset of early O giants. Iron abundances of Magellanic Cloud O stars have been estimated by Haser et al. (1998) from UV HST/FOS spectroscopy, and by Hillier et al. (2003) from HST/STIS spectroscopy. Since the bulk of the iron lines (Fe IV–VI observed in O stars fall in the HST/IUE domain, no further progress has been possible with FUSE.

Metal abundance studies of Wolf-Rayet stars are also optically derived, in general, although iron lines are again exclusive to the HST/IUE region, and suitable oxygen lines in WC stars are located around λ3000Å (Hillier & Miller 1999). Overall, WC and especially WO stars are very rich in carbon and oxygen (Crowther et al. 2000, 2002b) with hydrogen and nitrogen absent, whilst fully processed CNO cycle products are observed in WN stars, with hydrogen present in most late WN subtypes (Crowther et al. 1995). The most comprehensive abundance studies of WR stars to date have been carried out for two late WN stars by Herald et al. (2001), including HUT spectroscopy. Detailed studies using FUSE datasets are presently ongoing.

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