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The ionization structure of early-B supergiant winds

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Abstract. We present empirically determined ionization conditions for the winds of 106 luminous B0 to B5 stars observed by *IUE*. The UV wind lines are modelled to extract products of mass-loss rates times ionization fractions ($\dot{M}\,q_i(w)$, where $w = v/v_\infty$) for N V, C IV, Si IV, Si III, Al III and C II. We describe the general behaviour of the $\dot{M}\,q_i(w)$ and their ratios, demonstrating that the wind ionization *increases* with distance from the star, contrary to recent findings for O star winds. Using empirical mass-loss rates (from Hα observations) and model prescriptions, we derive mean $q_i(w)$ values integrated over the wind, $\langle q_i \rangle$. These $\langle q_i \rangle$ are quite small, never exceeding 15% for Al III or 2% for Si IV. This is surprising, since the $\langle q_i \rangle$ for these ions clearly peak within the observed spectral range. We conclude that the low $\langle q_i \rangle$ arise because the $\langle \dot{M}\,q_i \rangle$ are underestimated by the wind models, which assume that the outflows are smooth when they are, in fact, highly structured.

Key words. stars: early-type – stars: mass-loss – ultraviolet: stars

1. Introduction

Luminous massive stars are key constituents of galaxies since they provide prolific ionizing radiation and an input of energy and matter to the surrounding environment through strong radiatively driven winds. More specifically, early-type B supergiants ($T_{\rm eff} \sim 12$ to 30 kK) are the most numerous hot luminous stars. They make substantial contributions to the integrated light of starbursts and provide diagnostics of star formation at low and high redshifts (e.g. de Mello et al. 2000). B supergiants are also key markers in the determinations of extra-galactic distances based on the Wind-Momentum-Luminosity (WML) relation (e.g. Kudritzki & Przybilla 2003).

With this in mind, it is clearly important to understand the mass-loss process in B supergiants and derive reliable parameters for mass-loss rates, $\dot{M}$, ionization mixture and wind structure. In this Letter we focus on the empirical ionization structure, as part of a wider comprehensive survey of B supergiants which will be published in a forthcoming paper (Searle et al., in preparation). Line-synthesis modelling has been employed to derive the wind properties of a large sample of B0-B5 stars, for ions with resonance lines available in high-resolution *IUE* data. Our primary aim here is to examine the properties of the ionization state of the winds, determine whether specific ions are near the dominant stage of ionization, and examine how the properties change with spectral type and distance from the star. Our empirical results provide critical constraints for more detailed wind modelling. We highlight the unexpectedly low values that are apparent for the ionization fractions and the potential role of wind clumping.

2. SEI modelling of *IUE* spectroscopic data

Our study of Galactic B supergiant winds is based on high-resolution ($\lambda/\Delta\lambda \sim 10^4$) *IUE* SWP ($1150 \leq \lambda \leq 1900$ Å) spectra of 106 stars. The individual spectra were binned on a wavelength grid with regular sampling of 0.1 Å, and the typical signal-to-noise in the continuum is ~20. The UV spectra of B supergiants contain wind lines from a wide range of ionization states, including C II $\lambda\lambda$1334.53, 1335.71, C IV $\lambda\lambda$1548.20, 1550.77, N V $\lambda\lambda$1238.82, 1242.80, Al III $\lambda\lambda$1854.72, 1862.79, Si III $\lambda\lambda$1206.50 and Si IV $\lambda\lambda$1393.76, 1402.77.

To extract physical parameters from the wind profiles, we used the methods described in detail by Massa et al. (2003). They employ a modified version of the "Sobolev with exact integration" (SEI) code (Lamers et al. 1987). Once the velocity field of the wind is determined, this approach provides reliable radial optical depths for unsaturated wind lines as a function of normalized velocity, $\tau_{\rm rad}(w)$, where $w = v/v_\infty$ and v_∞ is the terminal velocity of the wind. The fits to individual wind lines require parameters for the terminal velocity, "β-type" velocity law, turbulent velocity, and $\tau_{\rm rad}(w)$ (specified as a set of 21 independent velocity bins that are adjusted by a non-linear least squares procedure). Photospheric spectra were supplied using the *IUE* line profiles of the non-supergiant B stars listed by Prinja et al. (2002). The $\tau_{\rm rad}(w)$ were converted into a product of $\dot{M}$ times ionization fraction, $\dot{M}\,q_i(w)$ (see, e.g., Massa et al. 2003). To isolate $q_i(w)$ for each ion requires an estimate of $\dot{M}$. We discuss our approach to this problem in Sect. 3.1.

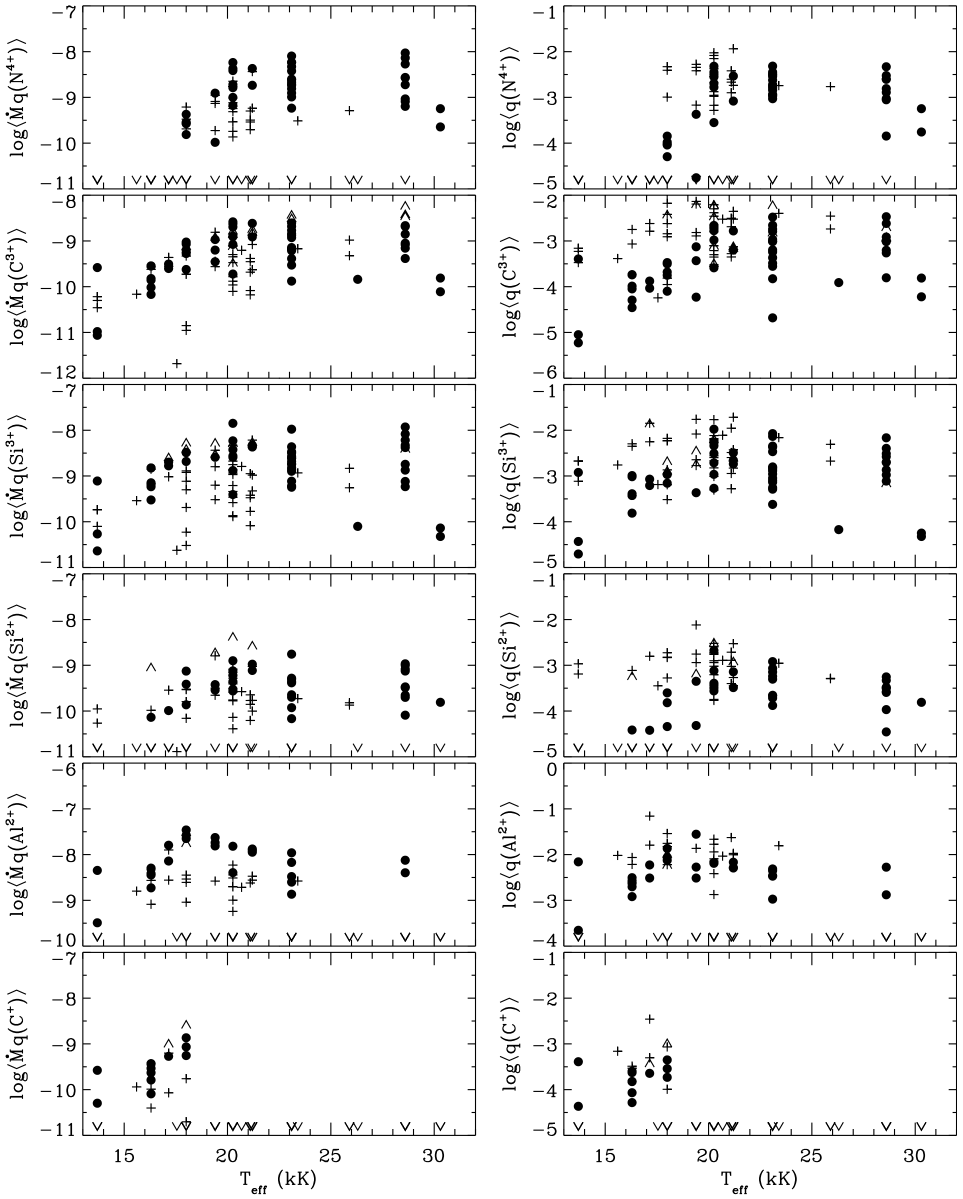

Fig. 1. *Left panels*: $\langle \dot{M}\, q_i \rangle$ values (integrated over $0.2 \leq v/v_\infty \leq 0.8$) versus $T_{\rm eff}$ for the ions studied. *Right panel*: $\langle q_i \rangle$ versus $T_{\rm eff}$ for the same ions. Solid points are measurements from unsaturated lines of stars with $\log(L/L_\odot) \geq 5$, crosses are for similar lines from stars with $\log(L/L_\odot) < 5$. Upward arrowheads indicate lower limits determined from saturated lines ($\langle \tau_{\rm rad} \rangle > 5$ for Si^{2+} and C^{2+}, 6 for C^{3+} and 7 for N^{4+}, Si^{3+} and Al^{2+}), and downward arrowheads indicate upper limits from non-detections ($\tau_{\rm rad}(w) \leq 0.1$ for all w).

3. Ionization conditions

Figure 1 (left panels) shows mean $\langle \dot{M}\, q_i \rangle$ values over $0.2 \leq v/v_\infty \leq 0.8$, for the ions analysed versus $T_{\rm eff}$, and (right panels) the mean $\langle q_i \rangle$ values for the same ions (see Sect. 3.1). We adopted the Humphreys & McElroy (1984) spectral type – $T_{\rm eff}$ calibration. Recent detailed NLTE model atmosphere analyses (e.g. Crowther et al. 2002; Bianchi & Garcia 2002; Herrero et al. 2002) have revised the $T_{\rm eff}$ scale for O-stars downward by ~10–20%. There are also indications that B star temperatures should be reduced as well (e.g. Evans et al. 2004; Searle et al. 2005). However, while the revised $T_{\rm eff}$ of a B0 Ia may be ~2000 K lower than those used in Fig. 1, the differences are expected to be ≲5% at B1 and later (Searle et al. 2005).

We first consider the $\langle \dot{M}\, q_i \rangle$. These behave as expected: at fixed $T_{\rm eff}$, all of the $\langle \dot{M}\, q_i \rangle$ tend to be larger for more luminous stars, with some overlap, and the presence of an ion at a given $T_{\rm eff}$ is related to the energies required to produce and destroy it. Specifically, $\langle \dot{M}\, q(\mathrm{N}^{4+}) \rangle$ and $\langle \dot{M}\, q(\mathrm{C}^{3+}) \rangle$ increase over the entire $T_{\rm eff}$ range. $\langle \dot{M}\, q(\mathrm{Si}^{3+}) \rangle$ appears to peak (or at least plateau) at ~20 kK (with considerable spread at each $T_{\rm eff}$). The peak is more distinct in the less luminous stars, where saturation is not a problem. $\langle \dot{M}\, q(\mathrm{Si}^{2+}) \rangle$ (which can be measured in fewer stars) peaks at ~20 kK. $\langle \dot{M}\, q(\mathrm{Al}^{2+}) \rangle$ peaks at 18 kK with a value $\gtrsim 3 \times 10^{-8}$ $M_\odot$ yr^{-1}, the largest of all ions. Al III is a useful ion for mass-loss studies of cooler B stars, since it rarely saturates (due to its relatively low abundance) and is unaffected by nuclear processing. Note that $\langle \dot{M}\, q(\mathrm{Al}^{2+}) \rangle$ peaks at

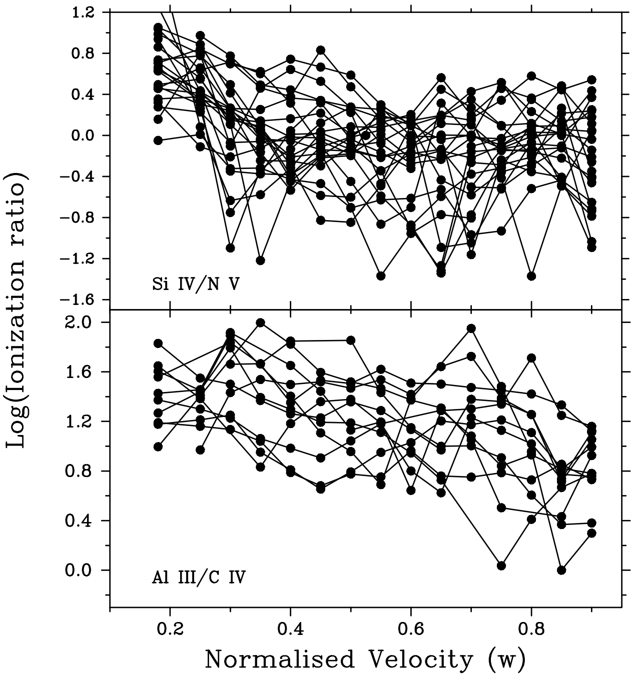

Fig. 2. Ionization fraction ratios of Si^{3+}/N^{4+} (*upper panel*) and Al^{2+}/C^{3+} (*lower panel*) plotted as a function of normalised velocity ($w = v/v_\infty$). Only the cases of unsaturated line profiles are shown.

a lower $T_{\rm eff}$ than $\langle \dot{M}\, q(\mathrm{Si}^{2+})\rangle$, even though a higher energy is required to produce it. This occurs because it is destroyed at a lower energy than Si^{2+}. $\langle \dot{M}\, q(\mathrm{C}^{+})\rangle$ peaks at 18 kK and then abruptly drops to zero – independently of the stellar luminosity. This unique behaviour may be due to the near coincidence of the ionization potentials of C^+ (24.38 eV) and He (24.48 eV). When He ionizes in the stellar photosphere, the stellar radiation field in the He^+ continuum ($228 \leq \lambda \leq 506$ Å) increases dramatically. Indeed, Kurucz (1991) $\log g = 3$ models with $T_{\rm eff} = 17$ and 19 kK show that the integrated flux in this region increases by a factor of 30. This enormous increase could convert all of the C^+ in the wind to C^{2+}. However, these conjectures must be verified by detailed modelling.

We now consider $\dot{M}\, q$ ratios, which are independent of $\dot{M}$. We begin with ratios of the $\langle \dot{M}\, q_i\rangle$, which provide insight into the how the wind ionization responds to $T_{\rm eff}$. The overall trend is that the empirical ionization ratios of N^{4+}/Si^{3+}, C^{3+}/Si^{3+} and Si^{3+}/Al^{2+} increase as a function of $T_{\rm eff}$, indicating that the winds of hotter B supergiants are more highly ionized. Some of the ratios straddle the "bistability jump" at ~21 kK, where there is a ramped increase in the ratio of terminal velocity to escape velocity (e.g. Lamers et al. 1995; Vink et al. 2000). However, the ratios of C^{3+}/Si^{3+}, and Si^{3+}/Si^{2+} do not suggest a dramatic change in the ionization of the winds across the "jump", though the former has a steeper drop below ~20 kK.

Finally, we examine how the ionization of B supergiant winds varies with distance from the star by plotting $\dot{M}\, q_i(w)$ ratios for Si^{3+}/N^{4+} and Al^{2+}/C^{3+} against w ($=v/v_\infty$) in Fig. 2 (for unsaturated cases only). Broadly, the ratios decrease over $0.2 \leq w \leq 0.9$ (typically $1.2 \leq r/R_\star \leq 10$), implying an *increase* in the ionization state with velocity. This is the opposite of the trend found by Massa et al. (2003) in LMC O stars, and is more in agreement with the expectations of the optically thin nebular approximation (e.g., Cassinelli & Olson 1979). It could indicate a fundamental difference between the winds of O and B-type stars. We intend to compare these trends to detailed model predictions in a future publication.

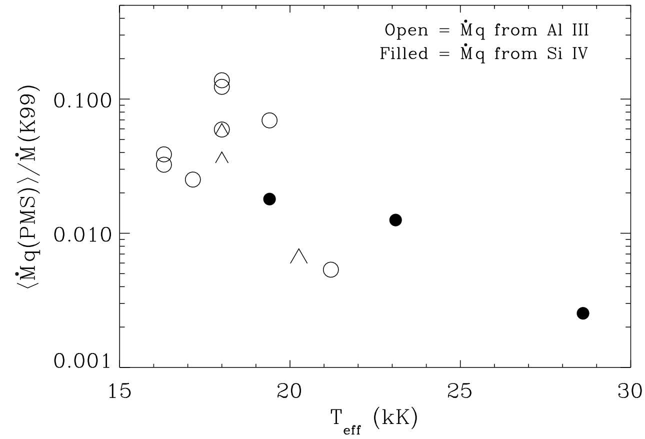

Fig. 3. Mean ionization fraction of Si^{3+} (filled) and Al^{2+} (open), based on the Hα mass-loss rates of Kudritzki et al. (1999; K99).

3.1. Mean ion fractions and $\dot{M}$

Conversion of our $\langle \dot{M}\, q_i\rangle$ measurements into $\langle q_i\rangle$, requires $\dot{M}$ values. We consider two options. First we adopt empirical mass-loss rates determined from a NLTE model atmosphere analysis of Hα profiles by Kudritzki et al. (1999). This accounts for only 14 stars in our sample, but it allows us to compare our results to previous work. The resulting ion fractions for Al III and Si IV are shown in Fig. 3, where we have adjusted the Kudritzki et al. $\dot{M}$s so that the adopted radii and temperatures are consistent with those used in Fig. 1 (the adjustments are typically less than a factor of 2, and not systematic). We see that $\langle q(\mathrm{Al}^{2+})\rangle$ peaks at ~10−15%, which is comparable to the maximum value of $\langle q(\mathrm{P}^{4+})\rangle$ found by Massa et al. (2003, 2004) for O stars mass-loss rates based on the far-UV P V wind lines and either empirical or theoretical $\dot{M}$s. The $\langle q(\mathrm{Si}^{3+})\rangle$ peak is poorly sampled by the data and dominated by low luminosity stars, since the more luminous stars have saturated Si IV wind lines.

Second, since the vast majority of our program stars do not have empirically determined mass-loss rates, we use the Vink et al. (2000, 2001) model prescriptions between stellar parameters and $\dot{M}$. Note that changes of $T_{\rm eff}$ or $L/L_\odot$ resulting from a ±one spectral or luminosity bin error, change these predictions by less than a factor of 2, and that these values are far larger than differences between our adopted parameters and the ones determined by Kudritzki et al. (1999) for stars in common. The right side of Fig. 1 shows the resulting $\langle q_i\rangle$ as a function of $T_{\rm eff}$. Overall, these follow the same trends as the $\langle \dot{M}\, q_i\rangle$. While it *appears* that the *less* luminous stars have larger $\langle q_i\rangle$, this is most likely a result of line saturation in the more luminous stars.

We now consider the four ions which peak in the B star range, to determine if any of them are dominant. We find that $\langle q(\mathrm{Si}^{3+})\rangle$ never exceeds 1.9%, and that the mean of all unsaturated cases near its peak is 0.48%. These quantities for the other ions are: 1.2 and 0.14% (Si^{2+}), 6.9 and 1.7% (Al^{2+}) and 0.34 and 0.08% (C^{+}). The $\langle q(Al^{2+})\rangle$ values are based primarily on high luminosity stars, and these exceeds 2.5% in only one case – somewhat smaller than Massa et al. found for P V in the O stars. The $\langle q(Si^{3+})\rangle$ values are particularly surprising, since models predict it should be $\sim$1 for $18 \leq T_{\rm eff} \leq 20$ kK. However, due to the saturation of the Si IV resonance lines in the more luminous stars, the Si IV result is based exclusively on the less luminous stars in our sample, and Vink et al. (2000) have already pointed out that there is a large discrepancy between their predicted B star mass-loss rates and values based on Hα line profiles for stars with $\log(L/L_\odot) \lesssim 5.8$.

4. Implications for the nature of the mass-loss

The major conclusions of the Letter are:

1. The ionization structure of the winds of B supergiants is different from the O stars (Fig. 2). We caution, however, that most of these results are for low luminosity stars.
2. There is no evidence of an abrupt change of the wind ionization in the temperature region of the bistability jump.
3. The ionization fractions of non-CNO ions never exceed 0.15 (for Al III) in the B supergiants – a result consistent with P V based results in the O stars (Massa et al. 2004).
4. The ionization fractions of Si IV never exceeds 0.02. This result is based exclusively on lower luminosity B supergiants (where the Si IV lines are unsaturated) and holds when using either theoretical or empirical mass loss rates. It suggests that the theory is incomplete for lower luminosity stars and underscores the need for more empirical mass loss rates for these stars.

For Galactic B supergiants, abundance anomalies cannot explain the very low $\langle q_i\rangle$ for Al and Si, since these elements have well known abundances and are unaffected by stellar evolution. Revisions to the B star $T_{\rm eff}$ scale are expected to have little affect on the predicted mass-loss rates at the temperatures where Si^{3+}, Si^{2+} and Al^{2+} peak (see Sect. 3). Note also that for this key temperature range, stellar radii based on the Humphreys & McElroy (1984) calibration differ from the Kudritzki et al. (1999) radii by only $\sim$5−15%. For the range of temperatures and ionizations considered in this Letter, it is highly unlikely that none of the ions are remotely close to dominant. As Massa et al. (2003) discuss concerning a similar result for P V in LMC O-type stars, we suspect that the small ion fractions indicate clumping in B supergiant winds. UV time-series spectroscopy has clearly demonstrated that the winds of early-B supergiants are highly variable and structured, with evidence for rotational modulation in many cases (e.g. Prinja et al. 2002), and optical studies (see, Kaufer 1999) have reached the same conclusions for mid-to-late B supergiants. Furthermore, Blomme et al. (2002) find excess flux at millimetre wavelengths in ϵ Ori (B0 Ia) compared to homogeneous wind model predictions, indicating considerable wind structure at several tens of stellar radii from the photosphere. Note, that if the winds are extremely clumped or structured, we must also re-evaluate the mass loss rates inferred from the radio and Hα observations. As a result, it is difficult at this time to infer how much of the low ionization fractions result from systematics in the measurement processes, and how much results from overestimates of the mass loss rates.

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