Quantitative spectral analysis of early B-type supergiants in the Sculptor galaxy NGC 300

Miguel Alejandro Urbaneja, Artemio Herrero, Fabio Bresolin, Rolf-Peter Kudritzki, Wolfgang Gieren and Joachim Puls

ABSTRACT

The spectra of two early B-type supergiant stars in the Sculptor spiral galaxy NGC 300 are analysed by means of non-LTE line blanketed unified model atmospheres, aimed at determining their chemical composition and the fundamental stellar and wind parameters. For the first time a detailed chemical abundance pattern (He, C, N, O, Mg and Si) is obtained for a B-type supergiant beyond the Local Group. The derived stellar properties are consistent with those of other Local Group B-type supergiants of similar types and metallicities. One of the stars shows a near solar metallicity while the other one resembles more a SMC B supergiant. The effects of the lower metallicity can be detected in the derived wind momentum.

Subject headings: galaxies: individual (NGC 300) — stars: abundances, early-type, supergiants, fundamental parameters, winds, outflows

1. Introduction

The 8-10 meter class telescopes and their new generation instruments make it possible to extend the quantitative stellar spectroscopy beyond the Local Group. Early B-type su-
pergiant stars are ideal targets for detailed spectroscopy even at low resolution (R~1000). Their blue spectra are rich in metal features which allows us the analysis of chemical species like C, N, O, Si and Mg. Although our knowledge of the evolution of massive stars still has open questions, most of the recent works indicate that the blue luminous supergiants do not show any contamination of their oxygen surface abundances during the early stages of their evolution, neither the O-types (??)\text{villamariz2002}, nor the B-types (??)\text{smartt1997, montereverde2000, smartt2002}, nor the A-types (??)\text{venn1995, takeda1998, przybilla2002}, which enables a direct comparison between the stellar oxygen abundances and the ones derived from H II regions. This has become extremely important, especially in the extragalactic field where oxygen is used as the primary metallicity indicator, due to the fact that at high metallicity (larger than approx. 0.5 solar) strong line methods must be used, for which the choice of the calibration strongly influences the derived abundances (??)\text{kewley2002, pilyugin2002}. In addition to chemical abundance studies, blue luminous stars have strong radiatively driven mass outflows which can provide us with information on extragalatic distances by means of the Wind Momentum - Luminosity Relationship, WLR (?\text{and references therein\text{kudritzki2000}}).

Recently, and within a wide program aimed at the spectroscopy study of luminous blue stars beyond the Local Group, first steps have been done for A-type supergiants in NGC 3621 (??, 6.7 Mpc away,)\text{bresolin2001}. Quantitative spectroscopy has been shown to be possible for A-type supergiants (??)\text{bresolin2002a} and Wolf-Rayet stars (??)\text{bresolin2002b} in NGC 300, 2.02 Mpc away in the Sculptor group. Here we report the first quantitative analysis of B-type supergiants (hereafter B-Sg) out of the Local Group, presenting the detailed chemical pattern along with the stellar parameters and the wind properties. The technique will be applied in a forthcoming paper to a large set of early B-Sg located at several galactocentric distances in order to derive radial abundance gradients of the \( \alpha \)-elements. Combined with the results of a similar study of A-type supergiants it will provide a wealth of information on the chemical evolution of the host galaxy NGC 300.

2. Observations

The stars are part of a spectroscopic survey of photometrically selected blue luminous supergiants in the Sculptor galaxy NGC 300, obtained at the VLT with the FORS multiobject spectrograph, and described in detail by \text{bresolin2002a}, which presents a spectral catalog of 70 luminous blue supergiants in the blue region (\( \sim \) 4000 - 5000 Å). The selected stars are identified as B-12 and A-9 in that spectral catalog (see their Table 2 and finding charts). In September 2001 the spectra of the H\( \alpha \) region were obtained in order to measure the mass-loss
rates, which provide us with a complete coverage of the 3800 - 7200 Å wavelength range at R~1000 resolution. The reader is referred to [bresolin2002a](#) for a detailed description of the observations and reduction process, as well as for the photometry and the spectral classification of the stars.

3. Spectral analysis

The spectra of early B-Sg are dominated by the O II lines, followed by N II/N III, Si III/Si IV, C II/C III and Mg II, in addition to H and He I lines. At high resolution it is possible to detect some other metal lines of Al III, S II/S III and Fe III but, due to their intrinsic weakness, these lines do not have any influence in the analysis at low resolution and could hardly be used to fix the abundance of such elements. Fig. 1 shows the high resolution - high S/N ratio (R~15000, SNR~350) blue spectrum of the Galactic supergiant HD14956 (B1.5Ia), and the same spectrum degraded to the resolution of the NGC 300 data, R~1000 (labeled as #d in the figure). We have also included the identification of the more important lines. As can be seen, only a few strong lines remain isolated at that low resolution, therefore the analysis must be based on the comparison of the observed spectra to a set of model atmospheres that include a vast number of lines in the calculation of the emergent fluxes. We have taken into account more than two hundreds metal lines in the 3800 - 6000 Å wavelength range. It is important to include extensive metal line lists because of the fact that some spectral features are formed by the contribution of several chemical species (e.g. the strong blend of O, N and C at ~ 4650 Å). We have excluded some strong isolated lines because our atomic models do not consider the levels involved in these transitions. Nevertheless, these lines are isolated and have no influence on the results.

Even considering the noise effects in the lower resolution FORS spectra (displayed also in Fig. 1), strong metal features can still be detected and used for a detailed chemical abundance analysis. In particular a wealth of information can be extracted from the selected regions at 4070, 4320, 4420 (O II), 4550 - 4570 (Si III), 4600 - 4660 (O II, N II, N III and C III) and 5010 (N II and He I).

3.1. Atmosphere models

We use the newest version of the FASTWIND code ([santolayarey1997](#)) which solves the radiation transfer in a moving media by means of suitable approximations which simplify the numerical treatment of the problem but without affecting the physical
The atmospheric structure is treated in a consistent way, assuming a $\beta$-velocity law in the wind, ensuring a smooth transition between the "photosphere" and the "wind"; the temperature structure is approximated by means of non-LTE Hopf functions carefully chosen to ensure the flux conservation better than 2% at any depth point; rate equations are solved in the co-moving frame scheme, with the coupling between the radiation field and the rate equations solved using local ALOs (?; following)\textsuperscript{puls1991}. This new version includes the effects of the line blanketing. The reader is referred to Puls et al. (2003, in preparation) for a detailed description. We have analysed two Galactic stars, 10 Lac (O9V) and HD209975 (O9.5Ib) in order to compare our results with the ones obtained with other codes. In the case of 10 Lac, our results agree with the recent ones by ?)?[see their comparison to the results by Hubeny et al. 1998]\textsuperscript{herrero2002}. The derived parameters for HD209975 are consistent with the results by ?)?[villamariz2002 which used plane-parallel model with line blocking.

A model is prescribed by the effective temperature $T_{\text{eff}}$, the surface gravity $\log g$, the stellar radius $R_*$ (all these three quantities are defined at $\tau_{\text{Ross.}} = 2/3$), the mass-loss rate $\dot{M}$, the wind terminal velocity $v_\infty$, the $\beta$ exponent of the wind velocity law, the He abundance $Y_{\text{He}}$, the microturbulent velocity $v_{\text{turb}}$ and, in the case of B-type stars, the Si abundance. The $T_{\text{eff}}$ is well determined from the Si III triplet and the blends of Si IV (with O II at 4090 Å and with O II/He I at 4120 Å), and the surface gravity from the Balmer hydrogen lines, provided that the mass-loss rate information is extracted from the H\textalpha profile. An important issue concerns the wind terminal velocity, that must be adopted from a spectral type - $v_\infty$ empirical calibration (?)?\textsuperscript{haser1995, kudritzki2000}. The assumed terminal velocity affects the derived $\dot{M}$ and the $\log g$. But, with the joined information from H\textalpha and H\beta, the mass-loss rate and $v_\infty$ can be constrained to yield reasonable uncertainties in $\log g$. The stellar radius is derived interactively from the absolute magnitude, deduced from the apparent magnitude after adopting a distance modulus (?; $\mu = 26.53$, )\textsuperscript{freedman2001}, and the model emergent flux (?)?\textsuperscript{kudritzki1999}, which also provides the reddening by the comparison of the synthetic colors with the observed ones.

### 3.2. Results

Best-fitting models are displayed in Fig. 1 and the results summarized in Tab. 1. The derived $\beta$ values are consistent with those obtained by ?)?[kudritzki1999 for Galactic B-Sg, with lower values excluded by the arise of emission wings in the synthetic H\textalpha profiles. We estimated an uncertainty of ±0.25 in $\beta$. In the case of B-12 only the higher Balmer lines have been considered in the surface gravity determination, as the cores of H\gamma and
Hβ are particularly affected by the sky substraction. As it has been quoted, the O and N abundances are very well constrained because of the large number of features from these species. The presence of a lot of weak metal lines in the 4600 - 4700 Å wavelength range makes the selection of the continuum level in this area difficult, good S/N ratio is also needed to disentangle between a real feature and the noise effects. Final abundance uncertainties are estimated to be ± 0.2 dex from model comparisons (see Fig. 2).

We define the mean metallicity as the sum of the α-elements abundances, \( X_{Si} + X_{Mg} + X_{O} \) and refer it to the Sun abundances by Grevesse et al. (1998; at the early stages of massive star evolution, the O surface abundance is not affected by the CNO cycle, which means that the abundance of the α-elements is a direct measurement of the ZAMS metallicity of the star. The results for B-12, located close to the galactic center, resembles the abundance patterns of the early B-Sg in the solar neighborhood, having a solar metallicity within the uncertainties of the analysis. On the other hand A-9, in the outskirts of the galaxy, has clearly a lower metallicity, around 0.3 \( Z_{\odot} \). This is in agreement with the results for A-8, a B9-A0 supergiant close to A-9, by Bresolin et al. (2002a). These authors find a mean metallicity of 0.2 \( Z_{\odot} \) for A-8. We must emphasize that both the model atmospheres and the metallicity indicators are different, but the results agree extremely well. The metallicity and the spatial location of both stars in NGC 300 points to a M33-like radial metallicity gradient. The CNO abundances indicate a different degree of chemical evolution, while B-12 displays a normal CNO spectrum, A-9 shows indications of strong N enrichment.

Synthetic magnitudes and colors (see Tab. 2) are consistent with almost no reddening for both stars, except the observed \((V-I)\) for B-12 that seems to be anomalous, probably reflecting the presence of the H II region. Fig. 3 shows the location of the stars on the Hertzprung-Russel diagram, along with theoretical stellar tracks without rotation at solar metallicity from Schaller et al. (1992). We have also added the location of the Galactic stars 10 Lac, HD209975 and HD14956 as a reference.

Comparing the wind momentum of both NGC 300 stars with the results for Galactic supergiants (Fig. 3.2), B-12 agrees well with the results by Herrero et al. (2002) for O-type supergiants in the Galactic association Cyg OB2, as does HD14956. Note, however that the Herrero et al. (2002) stars are considerably hotter than the ones considered here. The wind momentum of A-9 is also compatible with the WLR of Galactic early B-Sg as derived by Kudritzki et al. (1999). With respect to this relationship, however, B-12 (being an early B-type supergiant as well) shows an enhanced wind momentum rate, which might be related to clumping effects in the wind that would produce an overestimation of the mass-loss rate. The failure of our models to reproduce the blue absorption of Hα for B-12, in parallel with an Hγ core which is too strongly refilled might then be explained by this effect, at least in part,
and not only by the rather problematic sky substraction outlined above. The location of A-9, compared to HD14956, reflects the lower metal content of the NGC 300 supergiant. It must be considered here that we have adopted the same $v_\infty$ for both stars, HD14956 and A-9, while a lower value for A-9 could be expected due to its lower metallicity (\cite{kudritzki2000}). In any case the effect of the lower wind terminal velocity would reduce even more the wind momentum of A-9, reinforcing the difference with respect to the Galactic B1.5Ia.

Recently \cite{kudritzki2003} have proposed a new extragalactic distance indicator, the "Flux-weighted - Luminosity Relationship (FGLR)". The results for both NGC 300 B-type supergiants, B-12 and A-9, follow this relationship, within the observed scatter (see the Fig. 2 of the latter reference).

We are grateful to L. J. Corral for making us available the spectrum of HD14956. MAU thanks F. Najarro for providing the routines for the computation of the synthetic magnitudes. AH and MAU thank the Spanish MCyT for a support under project PNAYA2001-0436, partially funded with FEDER funds from the EU. WG gratefully acknowledges financial support for this work from the Chilean Center for Astrophysics FONDAP 15010003.

REFERENCES

Table 1. Best-fit model parameters

<table>
<thead>
<tr>
<th>ID</th>
<th>Teff</th>
<th>log g</th>
<th>R</th>
<th>Y(_{He})</th>
<th>(v\text{_{turb}})</th>
<th>(v\text{_{\infty}})</th>
<th>(\dot{M})</th>
<th>(\beta)</th>
<th>(\epsilon\text{_{Si}})</th>
<th>(\epsilon\text{_{O}})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kK</td>
<td>dex</td>
<td>R(_{\odot})</td>
<td>km s(^{-1})</td>
<td>km s(^{-1})</td>
<td>10(^{-6}) M(_{\odot}) yr(^{-1})</td>
<td></td>
<td></td>
<td>dex</td>
<td>dex</td>
</tr>
<tr>
<td>B-12</td>
<td>24.0±1.0</td>
<td>2.60±0.15</td>
<td>43.5±1.5</td>
<td>0.10</td>
<td>20.</td>
<td>1500.</td>
<td>3.00±0.50</td>
<td>1.50</td>
<td>7.45</td>
<td>8.65</td>
</tr>
<tr>
<td>A-9</td>
<td>21.0±1.0</td>
<td>2.50±0.15</td>
<td>32.0±1.0</td>
<td>0.10</td>
<td>15.</td>
<td>800.</td>
<td>0.25±0.07</td>
<td>2.00</td>
<td>7.10</td>
<td>8.30</td>
</tr>
</tbody>
</table>

Note. — The metal abundances are expressed as \(\epsilon_A = 12 + \log(A/H)\), while \([M/H] = (M/H)_* - (M/H)\).
Table 2. Observed and synthetic magnitudes and colors.

<table>
<thead>
<tr>
<th>ID</th>
<th>$V$</th>
<th>$B - V$</th>
<th>$V - I$</th>
<th>$M_V$</th>
<th>$M_B - M_V$</th>
<th>$M_V - M_I$</th>
<th>$BC$</th>
<th>$E(B-V)$</th>
<th>$E(V-I)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-12</td>
<td>19.30</td>
<td>-0.18</td>
<td>0.00</td>
<td>-7.29</td>
<td>-0.17</td>
<td>-0.23</td>
<td>-2.33</td>
<td>0.00</td>
<td>0.23</td>
</tr>
<tr>
<td>A-9</td>
<td>20.23</td>
<td>-0.17</td>
<td>...</td>
<td>-6.36</td>
<td>-0.16</td>
<td>-0.20</td>
<td>-1.97</td>
<td>0.00</td>
<td>...</td>
</tr>
</tbody>
</table>

Note. — We have adopted a distance modulus $\mu = 26.53 \pm 0.07$ [?] [freedman2001].
Fig. 1.— Observed spectra of B-12 and A-9, the Galactic B-type supergiant HD14956, the same spectrum degraded to the NGC 300 data resolution and the final fits. The spectra have been shifted for the sake of clarity. An identification of most prominent features are given: O (dotted, without labels), Si (dashed-dotted-dotted), N (dashed), C (dashed-dotted-dashed), Mg (solid), H and He.
Fig. 2.— Selected regions of the observed spectrum of A-9, the final fit and two models at $\pm 0.2$ dex to illustrate the uncertainties of the analysis. Line identification as in the previous figure.
Fig. 3.— Location of the NGC 300 B-type supergiants in the HR diagram. We have also added the Galactic stars HD14956, HD209975 and 10 Lac. The theoretical stellar tracks without rotation at solar metallicity are taken from [Schaller1992]. Note that A-9 has a metallicity of only 0.3$Z_\odot$. 
Wind momentum - Luminosity Relationship. Filled circles stand for the NGC 300 stars and the square denotes HD14956, while the triangles represent the Cyg OB2 OB supergiants from Herrero et al. (2002). Solid line is the theoretical prediction by \( \textit{vink2000} \) for \( T_{\text{eff}} \geq 27500 \) K, and the dashed-dotted line is the fit to the Galactic early B-type supergiant data from \( \textit{kudritzki1999} \). The modified wind momentum is defined as
\[
D_{\text{mod}} = M v_{\infty} (R_*/R_\odot)^{1/2}.
\]