Stellar Lunch

Blue Supergiants as distance and stellar metallicity measures in the Local Volume

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Abstract

Rolf Kudritzki and co-workers at the IfA, University of Hawaii (and elsewhere) have, over the past 14 years, been developing techniques to use low resolution spectroscopy of distant B-A supergiants to measure stellar metallicity, surface gravities, reddening and extinction, absolute bolometric magnitudes and distances. With the current 8-10 metre class telescopes the technique permits these measurements out to distances approaching 10Mpc. This talk will be about their latest methods and their basis.
TABLE 1
ADOPTED TEMPERATURE SCALE

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>$T_{\text{eff}}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B8</td>
<td>12000</td>
</tr>
<tr>
<td>B9</td>
<td>10500</td>
</tr>
<tr>
<td>A0</td>
<td>9500</td>
</tr>
<tr>
<td>A1</td>
<td>9250</td>
</tr>
<tr>
<td>A2</td>
<td>9000</td>
</tr>
<tr>
<td>A3</td>
<td>8500</td>
</tr>
<tr>
<td>A4</td>
<td>8350</td>
</tr>
</tbody>
</table>

Figure 1: from Kudritzki et al. (2003)

Massive stars during their evolution toward the red supergiant stage pass through the phase of late B and early A supergiants quickly and with roughly constant mass and luminosity (Meynet & Maeder 2000; Meynet et al. 1994; Heger & Langer 2000). This means that in this phase the stellar gravity $g$ and effective temperature $T_{\text{eff}}$ are coupled through the condition $g/T_{\text{eff}}^4 = \text{const}$. We call $g/T_{\text{eff}}^4$ the “flux-weighted gravity.” Assuming that mass and luminosity follow the usual relation $L \propto M^\alpha$ ($\alpha \sim 3$), we derive a relationship between absolute bolometric magnitude $M_{\text{bol}}$ and the flux-weighted gravity of the form

$$-M_{\text{bol}} = a \log (g/T_{\text{eff}}^4) + b,$$

with $a$ of the order of $-3.75$. This means that for these spectral types the fundamental stellar parameters of effective temperature and gravity are tightly coupled to the absolute magnitude rendering the possibility of purely spectroscopic distance determination. In the following, we refer to equation (1) as the “flux-weighted gravity–luminosity relationship” (FGLR).

Figure 2: from Kudritzki et al. (2003)
The adopted temperature scale

TABLE 1

Adopted Temperature

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>T$_{\text{eff}}$ (K)</th>
<th>M$_{\text{bol}}$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>54600</td>
<td>-4.39</td>
</tr>
<tr>
<td>A1</td>
<td>53000</td>
<td>-4.28</td>
</tr>
<tr>
<td>A2</td>
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<td>-4.18</td>
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<tr>
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<td>-4.08</td>
</tr>
<tr>
<td>A4</td>
<td>48600</td>
<td>-3.98</td>
</tr>
</tbody>
</table>

The small standard deviation obtained in Figure 2 might be an artifact resulting from the relatively low number of objects. This is a very encouraging estimate. Note that at this relative uncertainty of 0.05 for $M_{\text{bol}}$, we estimate the uncertainty in $M_{\text{bol}}$ from equation (1) to be about 0.3 mag for a single object. This is used in units of 10$^4$ K.

Figure 3: from Kudritzki et al. (2003)

Figure 2.—Absolute bolometric magnitude vs. logarithm of flux-weighted gravity of B8 to A4 supergiants in NGC 300 and NGC 3621. Note that $T_{\text{eff}}$ is used in units of 10$^4$ K.

Figure 4: from Kudritzki et al. (2003)
the gravities are larger than for luminosity class Ia) and may lead to inaccurate stellar parameters. As shown by Evans & Howarth (2003), the uncertainties introduced in this way could be significant and would make it impossible to use the FGLR for distance determinations. In addition, the metallicities derived might be unreliable. This posed a serious problem for the low resolution study of A supergiants in distant galaxies.

This problem was overcome only very recently by Kudritzki et al. (2008) (herafter KUBGP), who provided the first self-consistent determination of stellar parameters and metallicities for A supergiants in galaxies beyond the Local Group based on the detailed quantitative model atmosphere analysis of low resolution spectra. They applied their new method on 24 supergiants of spectral type B8 to A5 in the Scultor Group spiral galaxy NGC 300 (at 1.9 Mpc distance) and obtained temperatures, gravities, metallicities, radii, luminosities and masses. The spectroscopic observations were obtained with FORS1 at the ESO VLT in multi object spectroscopy mode. In addition, ESO/MPI 2.2m WFI and HST/ACS photometry was used. The observations were carried out within the framework of the Araucaria Project (Gieren et al. (2005b)). In the following we discuss the analysis method and the results of this pilot study.

4. A Pilot Study in NGC300 - Analysis Method

For the quantitative analysis of the spectra KUBGP use the same combination of line blanketed model atmospheres and very detailed NLTE line formation calculations as Przybilla et al. (2006) in their high signal-to-noise and high spectral resolution study of galactic A-supergiants, which reproduce the observed normalized spectra and the spectral energy distribution, including the Balmer jump, extremely well. They calculate an extensive, comprehensive and dense grid of model atmospheres and NLTE line formation covering the potential full parameter range of all the objects in gravity ($\log g = 0.8$ to 2.5), effective temperature ($T_{\text{eff}} = 8300$ to 15000K) and metallicity ($[Z] = \log Z/Z_\odot = -1.30$ to 0.3). The total grid comprises more than 6000 model stars.

The analysis of the each of the 24 targets in NGC 300 proceeds in three steps. First, the stellar parameters ($T_{\text{eff}}$ and $\log g$) are determined together with interstellar reddening and extinction, then the metallicity is determined and finally, assuming a distance to NGC 300, stellar radii, luminosities and masses are obtained. For the first step, a well established method to obtain the stellar parameters of supergiants of late B to early A spectral type is to use ionization equilibria of weak metal lines (OI/II; MgI/II; NI/II etc.) for the determination of effective temperature $T_{\text{eff}}$.

Figure 1. Left: Isocontours of H$\delta$ equivalent widths (solid) and Balmer jump $D_B$ (dashed) in the ($\log g$, $\log T_{\text{eff}}$) plane. The isocountours start with 1 $\AA$ equivalent width and increase in steps of 0.5 $\AA$. Right: Same as left but for the flux weighted gravity $\log g_F$ instead of gravity $\log g$. Note that the flux weighted gravity isoscontours start with 0.1 dex and increase by 0.1 dex. Figure 5: from Kudritzki et al. (2008a)
and the Balmer lines for the gravities \( \log g \). However, at the low resolution of 5 \( \AA \) the weak spectral lines of the neutral species disappear in the noise of the spectra and an alternative technique is required to obtain temperature information. KUBGP confirm the result by Evans & Howarth (2003) that a simple application of a spectral type–effective temperature relationship does not work because of the degeneracy of such a relationship with metallicity. Fortunately, a way out of this dilemma is the use of the spectral energy distributions (SEDs) and here, in particular of the Balmer jump \( D_B \). While the observed photometry from B-band to I-band is used to constrain the interstellar reddening, \( D_B \) turns out to be a reliable temperature diagnostic, as is indicated by Fig. 1. A simultaneous fit of the Balmer lines and the Balmer jump allows to constrain effective temperature and gravity independent of assumptions on metallicity. Fig. 2 demonstrates the sensitivity of the Balmer lines and the Balmer jump to gravity and effective temperature, respectively. At a fixed temperature the Balmer lines allow for a determination of \( \log g \) within 0.05 dex uncertainty, whereas the Balmer jump at a fixed gravity yields a temperature uncertainty of 2 percent. However, since the isocontours in Fig. 1 are not orthogonal, the maximum errors of \( T_{\text{eff}} \) and \( \log g \) are 5 percent and 0.2 dex, respectively. These errors are significantly larger than for the analysis of high resolution spectra, but they still allow for an accurate determination of metallicity and distances.

The accurate determination of \( T_{\text{eff}} \) and \( \log g \) is crucial for the use of A supergiants as distance indicators using the relationship between absolute bolometric magnitude \( M_{\text{bol}} \) and flux weighted gravity \( \log g_F \) defined as
\[
\log g_F = \log g - 4 \frac{\log T_{\text{eff}}}{4}
\] (4.1)
where \( T_{\text{eff,4}} = T_{\text{eff}}/10000 \text{K} \) (see Kudritzki, Bresolin & Przybilla 2003). The relatively large uncertainties obtained with this fit method may cast doubts whether \( \log g_F \) can be obtained accurately enough. Fortunately, the non-orthogonal behaviour of the fit curves in the left part of Fig. 1 leads to errors in \( T_{\text{eff}} \) and \( \log g \), which are correlated in a way that reduces the uncertainties of \( \log g_F \). This is demonstrated in right part of Fig. 1, which shows the corresponding fit curves of the Balmer lines and \( D_B \) in the \((\log g_F, \log T_{\text{eff}})\) plane. As a consequence, much smaller uncertainties are obtained for \( \log g_F \), namely \( \pm 0.10 \) dex. KUBGP give a detailed discussion of physical reason behind this.

Figure 6: from Kudritzki et al. (2008a)
Knowing the stellar atmospheric parameters \( T_{\text{eff}} \) and \( \log g \), KUBGP are able to determine stellar metallicities by fitting the metal lines with their comprehensive grid of line formation calculations. The fit procedure proceeds in several steps. First, spectral windows are defined, for which a good definition of the continuum is possible and which are relatively undisturbed by flaws in the spectrum (for instance caused by cosmic events) or interstellar emission and absorption. A typical spectral window used for all targets is the wavelength interval \( 4497 \ \text{Å} \leq \lambda \leq 4607 \ \text{Å} \).

Fig. 3 shows the synthetic spectrum calculated for the atmospheric parameters of target No. 21 (the previous example) and for all the metallicities of the grid ranging from \([Z] = -1.30\) to \([Z] = 0.30\).

It is very obvious that the strengths of the metal line features are a strong function of metallicity. In Fig. 4 the observed spectrum of target No. 21 in this spectral region is shown overplotted by the synthetic spectrum for each metallicity. Separate plots are used for each metallicity, because the optimal relative normalization of the observed and calculated spectra is obviously metallicity dependent. This problem is addressed by renormalizing the observed spectrum for each metallicity so that the synthetic spectrum always intersects the observations at the same value at the two edges of the spectral window (indicated by the dashed vertical lines). The next step is a pixel-by-pixel comparison of calculated and normalized observed fluxes for each metallicity and a calculation of \( \chi^2 \)-value. The minimum \( \chi^2([Z]) \) as a function of \([Z]\) is then used to determine the metallicity. This is also shown in Fig. 4. Application of the same method on different spectral windows provides additional independent information on metallicity and allows to determine the average metallicity obtained from all windows. A value of \([Z]\) = -0.39 with a very small dispersion of only 0.02 dex. However, one also need to consider the effects of the stellar parameter uncertainties on the metallicity determination. This is done by applying the same correlation method for \([Z]\) for models at the extremes of the error box for \( T_{\text{eff}} \) and \( \log g \). This increases the uncertainty of \([Z]\) to \( \pm 0.15 \) dex, still a very reasonable accuracy of the abundance determination.

The fit of the observed photometric fluxes with the model atmosphere fluxes was used to determine interstellar reddening \( E(B-V) \) and extinction \( A_V = 3.1 \ E(B-V) \). Simultaneously, the fit also yields the stellar angular diameter, which provides the stellar radius, if a distance is adopted. Alternatively, for the stellar parameters (\( T_{\text{eff}}, \log g, [Z] \)) determined through the spectral analysis the model atmospheres also yield bolometric corrections \( BC \), which we use to determine bolometric magnitudes. These bolometric magnitudes then also allow us to compute radii. The radii determined with these two different methods agree within a few percent. Gieren et al. (2005a)
in their multi-wavelength study of a large sample of Cepheids in NGC 300 including the near-IR have determined a new distance modulus $m-M = 26.37$ mag, which corresponds to a distance of $1.88$ Mpc. KUBGP have adopted these values to obtain the radii and absolute magnitudes.

5. A Pilot Study in NGC300 - Results

As a first result, the quantitative spectroscopic method yields interstellar reddening and extinction as a by-product of the analysis process. For objects embedded in the dusty disk of a star forming spiral galaxy one expects a wide range of interstellar reddening $E(B-V)$ and, indeed, a range from $E(B-V) = 0.07$ mag up to $0.24$ mag was found. The individual reddening values are significantly larger than the value of $0.03$ mag adopted in the HST distance scale key project study of Cepheids by Freedman et al. (2001) and demonstrate the need for a reliable reddening determination for stellar distance indicators, at least as long the study is restricted to optical wavelengths. The average over the observed sample is $\langle E(B-V) \rangle = 0.12$ mag in close agreement with the value of $0.1$ mag found by Gieren et al. (2005a) in their optical to near-IR study of Cepheids in NGC 300. While Cepheids have somewhat lower masses than the A supergiants of our study and are consequently somewhat older, they nonetheless belong to the same population and are found at similar sites. Thus, one expects them to be affected by interstellar reddening in the same way as A supergiants.

Fig. 5 shows the location of all the observed targets in the $(\log g, \log T_{\text{eff}})$ plane and in the HRD compared to the early B-supergiants studied by Urbaneja et al. (2005). The comparison with evolutionary tracks gives a first indication of the stellar masses in a range from $10 M_\odot$ to $40 M_\odot$. Three targets have obviously higher masses than the rest of the sample and seem to be on a similar evolutionary track as the objects studied by Urbaneja et al. (2005). The evolutionary information obtained from the two diagrams appears to be consistent. The B-supergiants seem to be more massive than most of the A supergiants. The same three A supergiants apparently more massive than the rest because of their lower gravities are also the most luminous objects. This confirms that quantitative spectroscopy is -at least qualitatively - capable to retrieve the information about absolute luminosities. Note that the fact that all the B supergiants studied by Urbaneja et al. (2005) are more massive is simply a selection effect of the V magnitude limited spectroscopic survey by Bresolin et al. (2002). At similar V magnitude as the A supergiants those objects have higher bolometric corrections because of their higher effective temperatures and are, therefore, more luminous and massive.

Figure 4: Left: Observed spectra of target No. 21 for the same spectral window as Fig. 3 overlaid by the same synthetic spectra for each metallicity separately. Right: $\chi(Z)$ as obtained from the comparison of observed and calculated spectra. The solid curve is a third order polynomial fit.
Model atmospheres

Two kinds of classical (plane-parallel, hydrostatic and stationary) model atmospheres are typically applied in the contemporary literature for analyses of BA-SGs: line-blanketed LTE atmospheres and non-LTE H+He models (without line-blanking) in radiative equilibrium. First, we discuss what effects these different physical assumptions have on the model stratification and on synthetic profiles of important diagnostic lines. We therefore include also an LTE H+He model without line-blanking and additionally a grey stratification in the comparison for two limiting cases: the least and the most luminous supergiants of our sample, η Leo and HD 92207, of luminosity class (LC) Ib and Iae. The focus is on the photospheric line-formation depths, where the classical approximations are rather appropriate – the velocities in the plasma remain sub-sonic, the spatial extension of this region is small (only a few percent) compared to the stellar radius in most cases, and the BA-SGs photospheres retain their stability over long time scales, in contrast to their cooler progeny, the yellow supergiants, which are to be found in the instability strip of the Hertzsprung-Russell diagram, or the Luminous Blue Variables.

The non-LTE models are computed using the code TLUSTY (Hubeny & Lanz 1995), the LTE models are calculated with ATLAS9 (Kurucz 1993), in the version of M. Lemke, as obtained from the CCP7 software library, and with further modifications (Przybilla et al. 2001b) where necessary. Line blanketing is accounted for by using solar metallicity opacity distributions (ODFs) from Kurucz (1992). For the grey temperature structure, $T^4 = \frac{1}{\tau} T^4_{\text{eff}} \left(1 + q(r)\right)$, exact Hopf parameters $q(r)$ (Mihalas 1978, p. 72) are used.

Figure 9: Details of model atmospheres used, from Przybilla et al. (2006)

References


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