A new extragalactic distance determination method using the flux-weighted gravity of late B and early A supergiants

Rolf P. Kudritzki, Fabio Bresolin and Norbert Przybilla

Institute for Astronomy, 2680 Woodlawn Drive, Honolulu HI 96822

ABSTRACT

Stellar evolution calculations predict the flux-weighted gravity $g/T_{\text{eff}}^4$ and absolute bolometric magnitude of blue supergiants to be strongly correlated. We use medium resolution multi-object spectroscopy of late B and early A supergiants in two spiral galaxies, NGC 300 and NGC 3621, to demonstrate the existence of such a relationship, which proves to be surprisingly tight. An analysis of high resolution spectra of blue supergiants in Local Group galaxies confirms this detection. We discuss the application of the relationship for extragalactic distance determinations and conservatively conclude that once properly calibrated it has the potential to allow for measurements of distance moduli out to 30.5 mag with an accuracy of 0.1 mag or better.

Subject headings: galaxies: stellar content — galaxies: distances and redshift — stars: early-type

1. Introduction

Bright supergiants in external galaxies have been recognized as valuable extragalactic distance indicators for a long time, since the pioneering work of Hubble (1936). A number of works have attempted to calibrate photometric and/or spectroscopic signatures of blue supergiants (those of spectral type OBA) for this purpose, but the uncertainty in the derived distances (typically 0.4 mag or larger in distance modulus) have always been a major drawback for these techniques (Humphreys 1988, Tully & Wolff 1984).

The discovery of a wind momentum-luminosity relationship (WLR) for blue supergiants (Kudritzki & Puls 2000) exploits the dependency of the strength of the radiation driven winds of massive stars on stellar luminosity, offering a potentially more accurate distance

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1Based on observations obtained at the ESO Very Large Telescope.
indicator. While hot O stars provide so far the best calibration of the WLR (Puls et al. 1996, Puls et al. 2002), it is the visually brightest late B and early A supergiants \( M_V \simeq -9 \) which offer the largest potential as extragalactic standard candles (Kudritzki 1998, Kudritzki et al. 1999). This can now be investigated for the nearby galaxies \( D < 10 \) Mpc) with multiobject spectroscopy at 8-m class telescopes, as the exploratory work of Bresolin et al. (2001, 2002) has shown. Quantitative spectroscopy of individual BA supergiants leads to the determination of gravities, temperatures, metallicities and stellar wind parameters (based on the wind emission in H\( \alpha \)), which are then combined to provide distances.

In this Letter we suggest a novel method, based on the absorption strengths of the higher Balmer lines formed in the photosphere. The concept is not entirely new, since a relationship between the equivalent width of H\( \gamma \) and \( M_V \) for Galactic and Magellanic Clouds BA supergiants, together with a temperature dependence, has already been discussed by several authors (Petrie 1965, Crampton 1979, Tully & Wolff 1984, Hill et al. 1986). The recent improvements in the modelling of A supergiant atmospheres in NLTE and the development of new diagnostic tools (Venn 1995a,b, 1999; Venn et al. 2001, Przybilla et al. 2001; Przybilla & Butler 2001; Przybilla 2002) allows us to determine stellar parameters with unprecedented accuracy and reliability. Based on these achievements, we discuss here a promising application on a set of high-to-intermediate resolution spectra obtained for a sample of A supergiants in the Milky Way, the Magellanic Clouds, NGC 300 and NGC 3621, and few additional objects in a handful of nearby galaxies. The theoretical concept is explained in §2, and we present the observational tests in §3 and §4. Future work on supergiants in nearby galaxies is briefly summarized in §5.

2. Basic concept

Massive stars during their evolution towards 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

\[
-M_{\text{bol}} = a \log(g/T_{\text{eff}}^4) + b \tag{1}
\]

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 Eq. 1 as the “Flux-weighted Gravity - Luminosity Relationship (FGLR)”.

Assuming constant luminosity and, in particular, a simple (one-exponent) power law for the mass-luminosity relationship is, of course, a simplification. One might argue that the mass-loss history of supergiants and its dependence on stellar angular momentum and metallicity will complicate the situation. However, we are encouraged by detailed evolutionary calculations (Meynet & Maeder 2000; Meynet et al. 1994), which indicate for the luminosity and mass range of late B and early A supergiants that the amount of mass lost on the way from the main sequence is still relatively small and that differences in mass-loss caused by stellar rotation and metallicity have no substantial effects on the theoretical FGLRs derived.

Table 1 lists the effective temperature scale for late B and early A supergiants based on the recent quantitative spectroscopic work cited above. We conclude that spectral classification allows for a temperature determination with a relative accuracy of about 4 percent. Then, for a given spectral type (and effective temperature) the higher Balmer lines as typical photospheric absorption lines allow for a rather precise determination of the gravity even for only medium resolution spectra of faint and distant objects (see Fig. 1). Assuming a typical relative uncertainty of 0.05 for \( \log g \) we estimate the uncertainty in \( M_{\text{bol}} \) from Eq. (1) to be about 0.3 mag for a single object. This is a very encouraging estimate. Note that at this point we do not have to worry about absolute errors in the determination of \( g \) and \( T_{\text{eff}} \), as long as we calibrate the method with a stellar sample at a known distance and apply the method strictly differentially.

3. Supergiants in NGC 300 and NGC 3621

Recently Bresolin et al. (2002) studied the population of blue supergiants in the Sculptor Group spiral galaxy NGC 300 at a distance of \( \sim 2.0 \) Mpc (\( m - M = 26.53 \), Freedman et al. 2001). Using FORS1 at the VLT medium resolution (\( \sim 5 \) Å) spectra of 70 blue supergiant candidates were obtained and spectral types, magnitudes and colours (the latter based on the work by Pietrzyński et al. 2001) for 62 objects were presented. These observations provide the ideal data for a careful test of the new method.

In our analysis we restrict ourselves to objects where we can be sure that the higher Balmer lines (H\( \gamma \), H\( \delta \), etc.) are not contaminated by HII region emission, i.e. we avoid objects with clear indication of nebular H\( \alpha \) emission or with a hint of nebular emission at H\( \gamma \) above or below the 2-D stellar spectrum. In addition, we select only spectral types within
a narrow range between B8 and A4, where we know from our recent work (Przybilla et al. 2001; Przybilla & Butler 2001; Przybilla 2002) that our model atmosphere analysis tools are very reliable, in particular with regard to the relative accuracy of a strictly differential study. For the given spectral types we adopt effective temperatures according to Table 1 and determine gravities from the higher Balmer lines as displayed in Fig. 1. We then calculate intrinsic colours with our model atmosphere code to determine reddening and extinction and use the calculated bolometric correction and the distance modulus to obtain bolometric magnitudes.

The data set for NGC 300 is not the only one available to us. In a similar way, Bresolin et al. 2001 have used FORS1 at the VLT to study 17 objects in the spiral galaxy NGC 3621 at a distance of 6.7 Mpc ($m - M = 29.08$, Freedman et al. 2001). Applying the same selection criteria as above we can add four more objects to the sample and apply the same spectral analysis.

The result of the test is displayed in Fig. 2, which shows a surprisingly tight correlation, as predicted by Eq.(1). The linear regression coefficients are $a = -3.85$ and $b = 13.73$, the standard deviation of the the residual bolometric magnitude from this regression being $\sigma = 0.26$ mag. The objects in NGC 3621 seem to indicate a somewhat smaller distance modulus (by 0.2 mag) than adopted. However, we prefer to wait for forthcoming stellar photometry of both NGC 300 and NGC 3621 with the Advanced Camera on board of HST, before we follow up on the relative distance of these two galaxies.

4. Objects from Local Group galaxies

The small standard deviation obtained in Fig. 2 might be an artifact resulting from the relatively low number of objects studied. We, therefore, analyze additional high resolution spectra presently available to us of a larger sample of objects in the Milky Way, the Magellanic Clouds, M31, M33 and NGC 6822. We apply the same technique as before, except for the three objects in the SMC, NGC 6822 and M33, which are extremely metal poor. For those (following Venn 1999) we do not rely on the spectral type, but determine $T_{\text{eff}}$ from the non-LTE ionization equilibrium of Mg I/II and N I/II. We note that the inclusion of the galactic objects is somewhat problematic, as their distances are more uncertain (Kudritzki et al. 1999; Przybilla 2002). We also note that the strictly differential character of our analysis using the same model atmosphere and non-LTE line formation codes and the same technique in fitting Balmer line profiles is essential for the internal accuracy of our method. This is why we do not include the results of other published quantitative studies of additional objects, for which we do not have spectra at our disposal.
Fig. 3 shows the FGLR with all objects included. The regression coefficients are very similar \((a = -3.71, b = 13.49)\) and the standard deviation of the residual bolometric magnitude has only slightly increased to \(\sigma = 0.28\) mag. We note that the scatter increases at absolute magnitudes brighter than \(-8\) mag (see discussion below).

Fig. 3 also includes the relationship obtained from the evolutionary calculations including stellar rotation and mass-loss (Meynet & Maeder 2000). While the slopes practically agree (note that the stellar evolution relationship shows a slight curvature reflecting the mild change in the mass-luminosity exponent \(\alpha\)), there is a small off-set in \(\log(g/T_{\text{eff}}^4)\) by 0.07 dex. This can be the result of a systematic effect in the determination of gravity or in the temperature scale, but it can also indicate a small deficiency of the evolutionary models. In any case, as long as an empirical calibration of the relationship with stars at known distances is used, the accuracy of the distance determination will not be affected.

5. Discussion and future work

The results presented in the previous sections are very encouraging. The flux-weighted gravities of late B and early A supergiants are obviously very tightly correlated with absolute bolometric magnitude. The application of this relationship, once properly calibrated, for extragalactic distance determinations is straightforward. It requires multi-colour photometry of galaxies containing a young stellar population to identify possible blue supergiants and subsequent medium resolution (\(~5\) Å) multi-object spectroscopy (see Bresolin et al. 2001, 2002) to determine effective temperature and gravity directly from the spectra. The spectral analysis will also yield bolometric correction (which is small for these spectral types) and intrinsic colour so that an accurate correction for reddening and extinction is possible. Application of the FGLR will then provide the absolute bolometric magnitude, which by comparison with the de-reddened visual magnitude will give the distance modulus. Assuming a residual scatter of \(\sigma = 0.3\) mag for the FGLR (see Fig. 2 and 3) we estimate that with 10 supergiant stars per galaxy we can achieve an accuracy of 0.1 mag in distance modulus. We are confident that in one night of observing time we can reach down to \(V = 22.5\) with the existing very efficient medium resolution multi-object spectrographs attached to 8m-class telescopes. With objects in an absolute magnitude range between \(-8\) and \(-10\) mag the FGLR method appears to be applicable out to distance moduli of \(m - M = 30.5\) or even beyond.

The restriction to medium resolution spectroscopy in the blue spectral range provides significant advantages. Most importantly, contamination from sky and H II region emission is by far less critical than in the red, which is needed as an additional spectral range, for
instance, for the WLR method, which requires the measurements of Hα profiles with at least \( \sim 2 \text{ Å} \) resolution. Moreover, the amount of observing time for an accurate distance determination is significantly reduced, if only spectra in the blue are required.

The accurate calibration of the FGLR (and the WLR) will become the crucial element of future work, before the method can be applied seriously for extragalactic distance determinations. Local Group galaxies with well determined distances provide the ideal laboratory for this purpose. Multi-object spectrographs with rather high spectral resolution attached to 8 to 10m-class telescopes such as FLAMES (VLT) or DEIMOS (Keck 2) will allow high quality spectra of large candidate samples in each galaxy with a rather modest amount of observing time.

Such a systematic study of hundreds of blue supergiants in Local Group galaxies will not only provide an accurate calibration of the FGLR. It will also enable us to investigate important aspects of stellar evolution, which are related. The most crucial ones concern the role of metallicity and stellar rotation. Investigating stellar evolutionary tracks at different metallicity and with different initial rotation at the main sequence (Meynet & Maeder 2000; Meynet et al. 1994) we find small, but noticeable effects on the theoretical FGLR. Mass-loss in evolutionary stages prior to the blue supergiant phase depends on metallicity (Kudritzki & Puls 2000) and has a small influence on the FGLR. Rotation affects the strength of mass-loss and the internal mixing processes and introduces a modification of the mass-luminosity relationship in the blue supergiant stage. The effect of rotation becomes larger at higher luminosities. This might be the reason for the increase of the residual scatter at luminosities above \( M_{bol} = -8 \) mentioned above.

Another very important issue is the fraction among the sample of observed blue supergiants evolving backwards to the blue after a previous phase as red supergiants. Those objects are expected to have lost a significant fraction of their mass as red supergiants and might form an additional sequence below the observed relationship. Evolutionary calculations indicate that the relative number of those objects might depend crucially on metallicity and rotation. Systematic studies of Local Group galaxies at different metallicity, as proposed above, will allow to investigate this problem.

In general, the observational detection of the tight relationship between flux-weighted gravity and absolute bolometric luminosity is a triumph of two classical areas of astrophysics, stellar evolution and stellar atmospheres. It confirms the general scenario of stellar evolution with mass-loss and rotation away from the main sequence and the predicted mass-luminosity relation. It also confirms the power and accuracy of present day spectroscopic stellar diagnostics. It is very satisfying to see the potential of these disciplines for a significant contribution to quantitative extragalactic studies.
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Table 1. Adopted temperature scale

<table>
<thead>
<tr>
<th>Spectral type</th>
<th>$T_{\text{eff}}$</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>
Fig. 1.— Fit of the Balmer lines H$_\gamma$, H$_\delta$ and H$_\delta$ to H$_{11}$ of the NGC 300 A0Ia supergiant C6 (see Bresolin et al. 2002) using atmospheric models with $T_{\text{eff}} = 9500$K and log $g = 1.60$ (thick line) and 1.65 (thin line) (gravities given in cgs units). Note that the use of information from many Balmer lines enhances the accuracy of the log $g$ determination significantly. The FWHM of the instrumental profile is $\sim 5$ Å, which is larger than the intrinsic width of the Balmer lines and the line broadening through rotation (typically $\leq 50$ km/s for A supergiants). Therefore, the calculations are convolved with the instrumental profile. This explains why gravity effects cannot be seen in the line wings, but only in the cores. These effects in the line cores reflect the changes of the integrated absorption line strength (equivalent width) as a function of gravity.
Fig. 2.— Absolute bolometric magnitude versus 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.
Fig. 3.— Same as Fig. 2 but including objects from Local Group galaxies. The relationship obtained from stellar evolution models at solar metallicity including the effects of rotation (Meynet & Maeder 2000) is also shown and labeled with the initial ZAMS-masses of the corresponding stellar models.