A NEW EXTRAGALACTIC DISTANCE DETERMINATION METHOD USING THE FLUX-WEIGHTED GRAVITY OF LATE B AND EARLY A SUPERGIANTS

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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 multobject 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: distances and redshifts — galaxies: stellar content — 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) has 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 indicator. While hot O stars provide so far the best calibration of the WLR (Puls et al. 1996, 2002), it is the visually brightest late B and early A supergiants \((M_V = -9)\) that offer the largest potential as extragalactic standard candles (Kudritzki 1998; Kudritzki et al. 1999). This can now be investigated for the nearby galaxies \((D < 10 \text{ Mpc})\) 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 relation between the equivalent width of H\(_\alpha\) and the absolute bolometric magnitude \(M_b\) has always been a major drawback for these techniques (Humphreys 1988; Tully & Wolff 1984).

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).

Assuming constant luminosity and, in particular, a simple 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
TABLE 1
Adopted Temperature Scale

| Spectral Type | $T_{\text{eff}}$ (K) |
|---------------|---------------------|
| B8            | 12000               |
| B9            | 10500               |
| A0            | 9500                |
| A1            | 9250                |
| A2            | 9000                |
| A3            | 8500                |
| A4            | 8350                |

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 Very Large Telescope (VLT), medium-resolution (~5 Å) spectra of 70 blue supergiant candidates were obtained and spectral types, magnitudes, and colors (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 H $\alpha$ region emission; i.e., we avoid objects with a clear indication of nebular H$\alpha$ emission or with a hint of nebular emission at H$\gamma$ above or below the two-dimensional 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 Figure 1. We then calculate intrinsic colors 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 Figure 2, which shows a surprisingly tight correlation, as predicted by equation (1). The linear regression coefficients are $a = -3.85$ and $b = 13.73$, the standard deviation of 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 the Hubble Space Telescope before we follow up on the relative distance of these two galaxies.

4. OBJECTS FROM LOCAL GROUP GALAXIES

The small standard deviation obtained in Figure 2 might be an artifact resulting from the relatively low number of objects.
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 multicolor photometry of galaxies containing a young stellar population to identify possible blue supergiants and subsequent medium-resolution (∼5 Å) multiobject 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 color so that an accurate correction for reddening and extinction is possible. Applicability of the FGLR will then provide the absolute bolometric magnitude, which by comparison with the dereddened visual magnitude will give the distance modulus. Assuming a residual scatter of σ = 0.3 mag for the FGLR (see Figs. 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 multiobject spectrographs attached to 8 m 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 α 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 ∼2 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. Multiobject spectrographs with rather high spectral resolution attached to 8–10 m 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 not only will 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 Mbol = −8 mentioned above.

Another very important issue is the fraction among the sample of observed blue supergiants evolving backward 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 us 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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