Extra-galactic Distances with Massive Stars: The Role of Stellar Variability in the Case of M33

Chien-Hsiu Lee (李見修)
Subaru Telescope, NAOJ, 650 N Aohoku Pl, Hilo, HI 96720, USA; leech@naoj.org

Received 2017 April 17; revised 2017 July 10; accepted 2017 July 11; published 2017 July 28

Abstract

In modern cosmology, determining the Hubble constant \( (H_0) \) using a distance ladder to percent level and comparing with the results from the Planck satellite can shed light on the nature of dark energy, physics of the neutrino, and curvature of the universe. Thanks to the endeavor of the SH0ES team, the uncertainty of the \( H_0 \) has been dramatically reduced, from 10% to 2.4%, and with the promise of even reaching 1% in the near future. In this regard, it is fundamentally important to investigate the systematics. This is best done using other good independent distance indicators. One promising method is the flux-weighted gravity luminosity relation (FGLR) of the blue supergiants (BSGs). As BSGs are the brightest objects in galaxies, they can probe distances up to 10 Mpc with negligible blending effects. While the FGLR method delivered distance is in good agreement with other distance indicators, it has been shown that this method delivers greater distances in the cases of M33 and NGC 55. Here, we investigate whether the M33 distance estimate of FGLR suffers systematics from stellar variability. Using CFHT M33 monitoring data, we found that 9 out of 22 BSGs showed variability during the course of 500 days, although with amplitudes as small as 0.05 mag. This suggests that stellar variability plays a negligible role in the FGLR distance determination.

Key words: galaxies: distances and redshifts – galaxies: individual (M33, NGC 55) – stars: early-type – supergiants

1. Introduction

Determining extra-galactic distances with exquisite precision and narrowing down the Hubble constant (\( H_0 \)) to 1%–2% have long been quests for modern observational astronomy. Accurate and precise \( H_0 \) measurements from the distance ladder method, when compared with the cosmic microwave background (CMB) results from the Planck satellite, can provide constraints on the equation of state of dark energy, the mass of the neutrino, and the spatial curvature of the universe (Hu 2005; Planck Collaboration et al. 2016). We note that extracting \( H_0 \) from the CMB measurements requires an assumption about the cosmology of our universe, for instance, that the universe is flat. A discrepancy between \( H_0 \) obtained from the CMB measurements and other direct local \( H_0 \) measurements indicates that the applied standard cosmological model is not correct.

Thanks to the endeavor of the SH0ES team (Riess et al. 2016), the \( H_0 \) uncertainty has been dramatically improved from 10% to 2.4%, with the promise of 1% in the near future. In this regard, understanding the systematic errors associated with the present established methods is vital. If we want to reach a 1% precision of \( H_0 \), then overcoming and investigating the systematics is fundamentally important, which is best done by using other good independent distance indicators.

Under this context, independent distance estimates other than the Cepheid method are pivotal. One promising method is using the blue supergiants (BSGs), as proposed by Kudritzki et al. (2003, 2008). While the flux-weighted gravity luminosity relation (FGLR) method delivers distances in basic agreement with other distance indicators in several extra-galactic systems, there are some marginal discrepancies in M33 and NGC 55, both toward a greater distance from FGLR. In this work, we investigate whether such discrepancies could originate from stellar variability.

Our paper is organized as follows. We provide an overview of the FGLR method and its tension with Cepheids distance estimates in the cases of M33 and NGC 55 in Section 2. In Section 3, we investigate the stellar variability of M33 BSGs using CFHT observations, followed by a discussion and summary in Section 4.

2. FGLR Distance Estimate and Its Tension with Cepheids Distance in the Cases of M33 and NGC 55

The BSG is a short phase when massive stars (12–40 \( M_\odot \)) evolve off main-sequence and toward the red supergiant phase. At this stage, the mass and luminosity are roughly constant (Meynet & Maeder 2000), meaning the surface gravity (\( g \)) and effective temperature (\( T_{\mathrm{eff}} \)) are coupled as \( g/T_{\mathrm{eff}}^4 = \) constant. Kudritzki et al. (2003, 2008) then defined flux-weighted gravity as \( g_f = g/T_{\mathrm{eff}}^4 \). Assuming the usual mass–luminosity, \( L \propto M^4 \), where \( \alpha \approx 3 \), Kudritzki et al. (2003, 2008) thus derived a relation with the absolute bolometric magnitude \( M_{\mathrm{bol}} \) and the flux-weighted gravity as

\[
M_{\mathrm{bol}} = a(\log g_f - 1.5) + b, \quad (1)
\]

where \( a = 3.41 \) and \( b = -8.02 \) according to Kudritzki et al. (2008).

The advantage of the BSG method is multi-fold. As the brightest stars in the optical wavelength, they can be used to determine distances up to 10 Mpc. Their bright nature also implies that they are hardly affected by blending effects (which is often a concern for Cepheids). In addition, from broadband photometry, their line-of-sight extinction can be well constrained (which is an issue for Cepheids PL with optical photometry). The BSG method has been applied to WLM (Urbaneja et al. 2008), M33 (U et al. 2009), M81 (Kudritzki et al. 2012), M106 (Kudritzki et al. 2013), NGC 3621 (Kudritzki et al. 2014), NGC 3109 (Hosek et al. 2014), and NGC 55 (Kudritzki et al. 2016).
We then compare the FGLR derived distances with other methods, as shown in Table 1. For illustrative purpose, we use the mean and standard deviation of all distance estimates in the literature, extracted from the NASA Extra-galactic Database.¹ While most of the distance estimates from FGLR are in good agreement with other distance indicators, there are two systems, i.e., M33 and NGC 55, that show farther distances from FGLR than other distance indicators. This suggests that either other distance indicators all deliver shorter distances, or the BSGs used in FGLR are fainter than expected. We recall that the FGLR methods take into account the line-of-sight dust extinction and the BSGs are so bright that they are hardly affected by blending; thus, we can rule out the contamination from dust extinction or blending. To have a fair comparison, we now consider other distance indicators with high precision. Here, we focus on the near-infrared Cepheid PL relation, a very reliable technique that is also cited by the FGLR working group (Kudritzki et al. 2016). Though Cepheid PL, in optical, may suffer from effects such as dust extinction and metallicity, these effects are negligible in the infrared. Furthermore, with exquisite angular resolution from HST or ground-based AO, we can correct for the blending effects.

The Araucaria project has applied the NIR Cepheid PL and obtained an M33 distance modulus of 24.62 ± 0.07 mag (Gieren et al. 2013), in line with the vast majority of the distance anchor methods with better precision, but differs significantly (0.31 mag shorter) with the FGLR method. As for the case of NGC 55, the Araucaria project obtained an NIR Cepheid distance modulus of 26.43 ± 0.09 mag (Gieren et al. 2008), which is 0.42 mag smaller than the FGLR distance estimate. While Kudritzki et al. (2016) speculated the differences between NIR Cepheids and FGLR distances of NGC 55 to stem from the blending effects, especially because NGC 55 is an edge-on galaxy, this is not the case for M33, which is a face-on galaxy. As the NIR Cepheid PL is a very reliable method, this calls for further investigations of the FGLR method, especially the variability of the BSGs employed by the FGLR method.

3. Variability Survey of M33

We noticed that there were works on variability influences on FGLR with NGC 300 and NGC 55. For NGC 300, Bresolin et al. (2004) have shown that BSG variability, while present with an amplitude of 0.05 mag or smaller, has a negligible effect on FGLR distances. Additionally, Kudritzki et al. (2008) used this galaxy as one of their FGLR calibrators, leading to $a = 3.41$ and $b = −8.02$ based on the Araucaria Cepheid distance. For NGC 55, Kudritzki et al. (2016) used only targets with variability amplitudes smaller than 0.05 mag—based on the comprehensive study by Castro et al. (2012)—and include this amount of variability in their distance error estimate. In addition to NGC 55 and NGC 300, M33 is another galaxy under scrutiny in this paper. Because of the discrepancy, it is an important case to investigate and determine the effects of variability again.

Luckily, there was a deep M33 variability survey conducted by the CFHT telescope (Hartman et al. 2006). Hartman et al. (2006) made use of the MegaCAM on-board CFHT; with MegaCAM’s wide field-of-view (1 × 1 deg²), the entire M33 galaxy can be observed with one single shot. This survey was carried out in three seasons between 2003 and 2005, with three Sloan g-, r-, and i-filters, and obtained a total of 33 epochs. As M33 is a very crowded stellar field, the data were analyzed using the image subtraction process proposed by Alard & Lupton (1998). This allows one to extract high-precision photometry down to the limiting magnitude even in very crowded stellar fields like M33. Hartman et al. (2006) then went through the resolved stars in the M33 images and detected 36709 varying sources that show variability at $>5\sigma$ level, compared to a constant flux light curve.

We then searched the variable catalog from Hartman et al. (2006) for the 22 BSGs that were used in the U et al. (2009) FGLR work, and found that 9 show variability from the 33 epochs of the CFHT data, up to 0.1 mag level variation, or 0.05 mag in semi-amplitude, as shown in Figure 1.

4. Discussion and Summary

As has been shown by the CFHT multi-epoch data, the M33 BSGs used in U et al. (2009) exhibit the level of variability in the same order of magnitudes as seen in BSGs in NGC 300 (Bresolin et al. 2004). As has been discussed in (Bresolin et al. 2004), this has a negligible effect on the FGLR distance estimates. Even more so, such variability has been taken into account in the uncertainties of the FGLR distance determination (see e.g., Kudritzki et al. 2016), which is an empirically calibrated relation using a large sample of stars (see, e.g., Kudritzki et al. 2003, 2008, Urbanaje et al. 2017).

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¹ https://ned.ipac.caltech.edu

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Table 1: Distance Modulus from FGLR and Other Methods

| Name | FGLR (mag) | Cepheids IR PL (mag) | NED (mag) |
|------|------------|----------------------|-----------|
| WLM  | 24.99 ± 0.10 | 24.924 ± 0.042(statistic) ± 0.065(systematic) (1) | 25.00 ± 0.47 |
| M33  | 24.93 ± 0.11 | 24.62 ± 0.07 (2) | 24.68 ± 0.34 |
| M81  | 27.70 ± 0.10 | ... | 27.82 ± 0.32 |
| NGC 3621 | 29.07 ± 0.09 | 29.16 ± 0.27 |
| NGC 3109 | 25.55 ± 0.09 | 25.71 ± 0.024(statistic) ± 0.065(systematic) (3) | 25.60 ± 0.29 |
| NGC 55 | 26.85 ± 0.10 | 26.434 ± 0.037(statistic) ± 0.087(systematic) (4) | 26.41 ± 0.32 |

Notes.

a The values are taken from the Araucaria project, which delivers both FGLR and Cepheid IR PL distance estimates. As both the FGLR and Cepheid IR PL distances are from the same working group, this provides a high accuracy consistency check of the FGLR method. (1) from Gieren et al. (2008), (2) from Gieren et al. (2013), (3) from Soszynski et al. (2006), (4) from Gieren et al. (2008).

b The values are taken from the NASA Extra-galactic Database, using the mean and standard variation from all of the distance estimates in the literature.

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While there is a marginal discrepancy between the FGLR and Cepheid distance estimates of M33, our investigation indicates that we can rule out stellar variability as the cause of such tension. We note that the distance estimates using eclipsing binaries (Bonanos et al. 2006) also showed comparatively greater distances in the case of M33, which is in agreement with the FGLR method. As we have eliminated stellar variability as a possible cause of tension between FGLR and Cepheid distances, the cause of these discrepancies remains an open question, and awaits different perspectives and further investigation.

We are grateful to the referee for the insightful comments, which greatly improved this manuscript. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to make use of observations from this mountain.

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Figure 1. Light curves of nine M33 variable BSGs used in the FGLR distance estimate (U et al. 2009). Data gathered from CFHT M33 variability (Hartman et al. 2006) in Sloan g-, r-, and i-band.
