Zwicky Transient Facility and Globular Clusters: Calibration of the gr-band Absolute Magnitudes for the Yellow Post-asymptotic-giant-branch Stars

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Abstract

We present the first absolute calibration for the yellow post-asymptotic-giant-branch (PAGB) stars in the g and r band based on time-series observations from the Zwicky Transient Facility. These absolute magnitudes were calibrated using four yellow PAGB stars (one nonvarying star and three Type II Cepheids) located in the globular clusters. We provide two calibrations of the gr-band absolute magnitudes for the yellow PAGB stars, by using an arithmetic mean and a linear regression. We demonstrate that the linear regression provides a better fit to the gr-band absolute magnitudes for the yellow PAGB stars. These calibrated gr-band absolute magnitudes have a potential to be used as Population II distance indicators in the era of time-domain synoptic sky surveys.

Unified Astronomy Thesaurus concepts: Globular star clusters (656); Post-asymptotic giant branch stars (2121); Wide-field telescopes (1800); Sky surveys (1464); Distance indicators (394)

1. Introduction

Post-asymptotic-giant-branch (hereafter PAGB) stars are the low- to intermediate-mass stars at their final and short-lived stage of stellar evolution before entering the planetary nebulae phase. PAGB stars evolve with nearly constant luminosity but with increasing effective temperature on the Hertzsprung–Russell (H-R) diagram. During such evolution, these PAGB stars become Type II Cepheids, or more specifically the RV Tauri (RV Tau) stars (for example, see Jura 1986; Alcock et al. 1998), when they cross the instability strip on the H-R diagram.

The idea of using PAGB stars as Population II distance indicators has been proposed in the past (Bond 1997). This is because PAGB stars have the largest luminosity for the low- to intermediate-mass stars throughout their lifetime, with $M_{bol} \sim -3.38$ mag based on ten yellow, or intermediate-temperature, PAGB stars located in seven globular clusters (Ciardullo et al. 2022). Since half of them are Type II Cepheids, Ciardullo et al. (2022) calibrated the Johnson V-band absolute magnitude of yellow PAGB stars using the nonvariable stars with colors in the range of $0.0 \lesssim (B-V) \lesssim 0.5$ mag, i.e., blueward of the instability strip, and obtained $M_V = -3.37 \pm 0.05$ mag. The reasons, or advantages, for choosing the blue colors have been extensively discussed in Ciardullo et al. (2022). Obviously, selecting the nonvarying yellow PAGB stars (blueward of instability strip) has an advantage on reducing the observing time, because in general RV Tau stars have pulsation periods longer than $\sim 20$ days. As pulsating stars, RV Tau stars also obey a period–luminosity color relation, implying a color–magnitude relation (at fixed period) on the color–magnitude diagram (CMD).

Given that the ugriyz filters, or a subset of them, are increasingly popular among various synoptic sky surveys, with a representative example of the Vera C. Rubin Observatory’s Legacy Survey of Space and Time (LSST; Ivezić et al. 2019), it is desirable to calibrate the absolute magnitudes of the yellow PAGB stars in these filters in addition to the V band. Similar to the work of Ciardullo et al. (2022) in the V band, our goal is to calibrate the gr-band absolute magnitudes for the yellow PAGB stars located in the globular clusters by using the photometric data obtained from the Zwicky Transient Facility (ZTF; Bellm et al. 2019; Graham et al. 2019; Masci et al. 2019; Dekany et al. 2020). Out of the ten yellow PAGB stars listed in Ciardullo et al. (2022), four of them are located in the southern globular clusters (ω Centauri and NGC 5986), which are outside the footprint of ZTF. Hence, our calibration was done on the remaining nonvariable yellow PAGB stars and the Type II Cepheids.

2. ZTF Mean Magnitudes

ZTF is a 47 squared-degree wide-field synoptic northern sky survey utilizing the Palomar 48 inch Samuel Oschin Telescope located in southern California, USA. The majority of the ZTF observations were conducted with the customized g and r filters, with additional i-band observations from the partner surveys. All of the ZTF images were processed through a dedicated reduction pipeline (Masci et al. 2019), and the ZTF photometry was calibrated to the Pan-STARRS1 (Chambers et al. 2016; Magnier et al. 2020) AB magnitude system.

As in Ngeow et al. (2022), ZTF gr-band light curves for the two nonvariable yellow PAGB stars, M19 ZNG4 and M79 PAGB, were extracted from the ZTF PSF (point-spread function) catalogs. No ZTF i-band data were available for 5 RV Tau stars, however, could be a mixed of both PAGB stars and post-red-giant-branch stars (for example, see Manick et al. 2018; Giridhar 2020, and reference therein).

6 ZTF observations were divided into public surveys, partner surveys, and Caltech (California Institute of Technology) surveys. For more details, see Bellm et al. (2019).
these two targets in the ZTF Public Data Release 10 and the partner surveys data until 2022 March 31. After excluding data points with non-zero flags and infobits,\(^7\) ZTF light curves for these two targets are presented in Figure 1. As in Bond et al. (2016), we do not detect obvious variability for M79 PAGB at \(\sim 0.03\) mag level (the dispersion of the light curves). In case of M19 ZNG4, Bond et al. (2021) suspected this star does not exhibit variability based on two observations separated by one night (plus earlier low-quality data). The ZTF light curves confirmed this target does not exhibit obvious variability at \(\sim 0.05\) mag level. Hence, we obtained straight weighted mean magnitudes in the \(gr\) band for these two PAGB stars, as reported in Table 1.\(^8\)

Among the four Type II Cepheids listed in Ciardullo et al. (2022) that are observable with ZTF, three of them (V11 in M2, V42, and V84 in M5) have \(gr\)-band mean magnitudes derived in Ngeow et al. (2022), and they are given in Table 1. The Type II Cepheid V17 in M28 was excluded in Ngeow et al. (2022) due to blending.

### 3. Analysis and Results

Apparent mean magnitudes of the five targets listed in Table 1 were converted to absolute magnitudes by adopting the distances to their host globular clusters from Baumgardt & Vasiliev (2021), with extinction corrections based on the the Bayerstar2019 3D reddening map (Green et al. 2019). For more details on the extinction corrections, see Ngeow et al. (2022). Errors on the absolute magnitudes were based on the propagated errors on the apparent mean magnitudes (ranging from \(\sim 0.002\) mag to \(\sim 0.008\) mag), the errors on the distance, and the errors returned from the Bayerstar2019 3D reddening map. The final \(gr\)-band absolute magnitudes are listed in the last two columns of Table 1.

The absolute magnitudes for M19 ZNG4 seem to be brighter than other targets listed in Table 1, which hints at an issue of blending. Indeed, if we transformed the \(gr\)-band apparent magnitudes to the \(V\) band via the transformation provided in Tonry et al. (2012), we obtained \(V = 12.333 \pm 0.014\) mag. This \(V\)-band magnitude is brighter than the value of 12.512 \(\pm 0.006\) mag given in Bond et al. (2021), suggesting additional fluxes were included presumably due to blending. In contrast, the transformed \(V\)-band apparent magnitude for M79 PAGB is 12.197 \(\pm 0.012\) mag, in good agreement with the value found in (Bond et al. 2016, 12.203 \(\pm 0.008\) mag). Hence, we discarded M19 ZNG4 for the calibration of the \(gr\)-band absolute magnitudes for the yellow PAGB stars.

Based on M79 PAGB and the three Type II Cepheids, the weighted means of the \(gr\)-band absolute magnitudes are
\[
M_g = -3.19 \pm 0.14\text{ mag},
M_r = -3.44 \pm 0.04\text{ mag}.
\] (1)

Errors on these absolute magnitudes were calculated based on small number statistics (Dean & Dixon 1951; Keeping 1962, p. 202), as there are only four stars in the sample. These mean absolute magnitudes are marked as solid lines in Figure 2. The \(g\)-band absolute magnitude exhibits a larger error due to its larger color-dependency as shown in the left panel of Figure 2. We have overlaid a PAGB evolutionary track, selected from models constructed in Miller Bertolami (2016) and Moehler et al. (2019), in Figure 2. The theoretical luminosities and effective temperatures along this track have been converted to the \(gr\)-band absolute magnitudes using an online tool PARSEC Bolometric Correction (Chen et al. 2019).\(^9\) The PAGB evolution track shows a larger gradient on the \(g\)-band CMD than the \(r\)-band CMD, explaining the larger error on Equation (1). Therefore, we fit a linear regression to these four stars and yields:\(^10\)
\[
M_g = 1.30(\pm 0.15)(g - r) - 3.53(\pm 0.04),
M_r = 0.30(\pm 0.15)(g - r) - 3.53(\pm 0.04).
\] (2)

Both linear regressions give the same standard deviation of 0.03 mag. As demonstrated in Figure 2, in the \(g\) band these four stars are better described with a linear regression than adopting

\(^7\) For the definitions and meanings of flags and infobits, see “The ZTF Science Data System (ZSDS) Explanatory Supplement” document, available at https://irsa.ipac.caltech.edu/data/ZTF/docs/ztf_explanatory_supplement.pdf.

\(^8\) The \(g\)-band mean magnitude for M79 PAGB remained unchanged whether the “outlier” point at \(g \sim 12.5\) mag was excluded or not.

\(^9\) http://stev.oapd.inaf.it/YBC/

\(^10\) Due to small number of data points, errors on the regression coefficients given in Equation (2) might be underestimated. Using alternative pair bootstrap regression method (note that this method might not valid for small number of data points), we found that errors on these regression coefficients could be \(\sim 2\) to \(\sim 10\) times larger. Therefore, when applying Equation (2) in distance scale applications, extra care has to be taken into account for estimating the errors in the derived distances. For a through discussion on errors propagation for distance scale estimation, see the appendix in Feigelson & Babu (1992).
Figure 2. Extinction-corrected CMD for M79 PAGB (magenta triangles), the three Type II Cepheids (blue squares), and other Type II Cepheids compiled in (Ngeow et al. 2022, cyan circles). The crosses marked the discarded yellow PAGB star, M19 ZNG4. The solid lines represent the mean absolute magnitudes as given in Equation (1), while the dashed lines are the fitted linear regressions given in Equation (2), extrapolated to redder colors. The dotted lines are the theoretical PAGB evolution track adopted from Moehler et al. (2019), with a metallicity of −2.3 dex and a zero-age horizontal-branch mass of 0.55 $M_\odot$, converted to the observed planes using the PARSEC Bolometric Correction online tool. Note that the track is used for illustration purpose and not for fitting the data. Error bars on the majority of the data points are smaller than the size of the symbols.

In this work, we have derived the $gr$-band absolute magnitudes for yellow PAGB stars that can be used as Population II distance indicators. Both the mean absolute magnitudes and color-dependent linear regressions were derived based on four yellow PAGB stars located in the globular clusters, by using the homogeneous ZTF data and adopting the same sources for the distance to the globular clusters and reddening corrections. In this way, we minimize the possible systematic errors arising from inhomogeneous data sets.
Figure 2 demonstrates that the Type II Cepheids can be included together with the nonvarying yellow PAGB star to increase the sample size. Certainly, searching for the nonvarying yellow PAGB stars in distant galaxies only requires single-shot observations, which is advantageous for expensive or competitive observations such as using the Hubble Space Telescope (Ciardullo et al. 2022). On the other hand, long-term synoptic sky surveys such as LSST will naturally provide time-series data to search for the long period Type II Cepheids, as long as these Type II Cepheids or RV Tau stars could be identified as the low-surface-gravity PAGB stars. This would increase the number of suitable yellow PAGB stars to serve as distance indicators, hence reducing the statistical errors when deriving the distances to their host galaxies.

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Facility: PO:1.2 m. Software: astropy (Astropy Collaboration et al. 2013, 2018), dustmaps (Green 2018), Matplotlib (Hunter 2007), NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020).

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11 Recall that not all RV Tau stars are PAGB stars. How to identify PAGB stars using conventional broad-band photometry is beyond the scope of this paper.

12 http://www.astropy.org