ON THE RELATIVE DISTANCES OF \( \omega \) CENTAURI AND 47 TUCANAE

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ABSTRACT

We present precise optical and near-infrared ground-based photometry of two globular clusters (GCs): \( \omega \) Cen and 47 Tuc. These photometric catalogs are unbiased in the red giant branch (RGB) region close to the tip. We provide new estimates of the RGB tip (TRGB) magnitudes—\( m_\mathrm{TRGB} \) = 9.84 \pm 0.05, \( \omega \) Cen; \( m_\mathrm{TRGB} \) = 9.46 \pm 0.06, 47 Tuc—and use these to determine the relative distances of the two GCs. We find that distance ratios based on different calibrations of the TRGB, the RR Lyrae stars, and kinematic distances agree with each other within 1 \( \sigma \). Absolute TRGB and RR Lyrae distance moduli agree within 0.10–0.15 mag, while absolute kinematic distance moduli are 0.2–0.3 mag smaller. Absolute distances to 47 Tuc based on the zero-age horizontal branch and on the white dwarf fitting agree within 0.1 mag, but they are 0.1–0.3 mag smaller than TRGB and RR Lyrae distances.

Subject headings: globular clusters: general — globular clusters: individual (\( \omega \) Centauri, 47 Tucanae)

1 INTRODUCTION

The road to quantitative astrophysics is paved with improvements in the absolute cosmic distance scale. Accurate primary distances based on trigonometric parallaxes are limited to measurements with the Hipparcos satellite (van Leeuwen et al. 2007), with the Fine Guidance Sensor on board the Hubble Space Telescope (Benedict et al. 2007; Evans et al. 2008) and with near-infrared interferometers on the ground (Kervella et al. 2006). Secondary distance estimates have relied either on period-luminosity relations for classical Cepheids (Sandage & Tammann 2006; Fouqué, et al. 2007; Caputo 2008), RR Lyrae stars (Szewczyk et al. 2008), type II Cepheids (Feast et al. 2008; Groenewegen et al. 2008); or on fits to the main sequence (Gratton et al. 2003), the white dwarf (WD) cooling sequence (Zoccali et al. 2001; Layden et al. 2005), the zero-age horizontal branch (ZAHB; Caloi & D’Antona 2005; Salaris et al. 2007), or the TRGB (Madore & Freedman 1995; Salaris & Cassisi 1998; Bellazzini 2008). Kinematic distances to GCs offer promise as a new and independent primary distance indicator. This method is based on the ratio between the dispersions in proper motion and radial velocity of cluster members. The accuracy of this method is limited only by the precision of the measurements and the size of the sample and, barring unrecognized systematic errors, absolute distances with an accuracy of 1% might be provided (King & Anderson 2002).

All the above methods have practical limitations, and a definitive consensus on low- and intermediate-mass indicators has not yet been reached. The typical problems affecting current distance estimates might be split into two groups: (1) precision, i.e., the ongoing effort to reduce random observational errors; and (2) accuracy, i.e., the never-ending struggle to identify and eliminate systematic errors. Problems associated with the former group can be alleviated by increases in sample size and in signal-to-noise ratio. Usually, problems connected with the latter group can be recognized and addressed only by comparing results obtained by completely different methodologies. The number of GCs for which we have distance estimates based on different methods is quite limited. However, a few GCs do have distances based on multiple methods including the TRGB (Bellazzini et al. 2004), RR Lyraes (Del Pino et al. 2006, hereafter DP06; Sollima et al. 2008), and kinematics (van de Ven et al. 2006; McLaughlin et al. 2006). Even with this extremely limited sample, we have evidence that the kinematic distances are significantly and systematically smaller than distances based on the other methods. The difference ranges from 5% for M15 (McNamara et al. 2004), to 10%–15% for both \( \omega \) Cen (van de Ven et al. 2006; DP06) and 47 Tuc (McLaughlin et al. 2006). On the other hand, distances to 47 Tuc based on the ZAHB and on the WD fitting are on average 10% smaller than distances based on other methods (Salaris et al. 2007).

2 OBSERVATIONS AND DATA REDUCTION

The \( B, V \), and \( I \) data considered for this investigation come from the database of original and archival observations which have been collected, reduced, and calibrated by one of the authors in an ongoing effort to provide homogeneous photometry on the Landolt (1992) photometric system for a significant corpus of astronomically interesting targets—including, most particularly, globular clusters (Stetson 2000). For \( \omega \) Cen, we currently have a catalog consisting of 518,905 stars with at least two measurements in each of the three optical bands; these span an area with extreme dimensions on the sky of 37.2’ (E-W) by 40.6’ (N-S). These data were obtained in the course of 14 observing runs with various telescopes and cameras. The corresponding numbers for 47 Tuc are 193,679 stars in an area of 35.3 by 41.3’ from 16 observing runs. As we have said above, systematic errors cannot be found by consideration of one data set or one methodology alone. However, in the absence of truly independent confirmation we nevertheless feel confident, on the basis of the observed consistency of the results within and between the
different observing runs available to us, that these optical catalogs of the two clusters are on a common photometric system to well under 0.01 mag.

To provide photometric indices with greater temperature sensitivity we matched the optical catalog for ω Cen with a multiband NIR catalog derived from observations obtained with ISAAC at the VLT (ESO, Paranal) and SOFI at the NTT (ESO, La Silla). A significant fraction of the SOFI data have already been presented by DP06, while the ISAAC data will be presented by A. Calamida et al. (2008, in preparation). These data cover an area of 12′ × 12′ centered on the cluster; we have supplemented them with 2MASS data for the more external regions. We ended up with a final catalog including ~200,000 stars with at least one measurement in at least two NIR bands, and we ended up with a catalog including ~198,000 stars with at least one measurement in both optical and NIR bands.

3. RESULTS AND DISCUSSION

To identify of the TRGB, we need to distinguish the asymptotic giant branch (AGB) stars. To do this, we adopted optical–NIR CMDs. Data for ω Cen (see top panel of Fig. 1) show that in the J, B − K CMD the AGB stars separate well from RGB stars for 11 ≤ J ≤ 12, while at the bright end they are, at fixed color, slightly brighter than RGB stars.

The other panels show the distribution of bright stars in three different optical/NIR CMDs for ω Cen, where the red circles represent the candidate AGB stars selected in the top panel. Overall, this figure suggests that the sample of bright RG stars is minimally contaminated by AGB stars. Given that, we were able to estimate the RGB luminosity function. Note that the our sample includes ~220 stars within one I-band magnitude of the tip. This is roughly a factor of 2 larger than the number considered necessary for a robust TRGB detection (Madore & Freedman 1995) and ≈20% larger than the sample adopted by Bellazzini et al. (2001).

Data plotted in the top panel of Figure 2 show a well-defined jump in the star counts for m_I ~ 9.85, which we take to mark the position of the TRGB. The identification is supported by the smoothed luminosity function obtained using a Gaussian kernel with standard deviation equal to the photometric error (Sakai et al. 1996; middle panel). The bottom panel shows the response of the edge detector, a four-point Sobel filter convolved with the smoothed luminosity function; the dashed vertical lines mark the detection of the TRGB at m_I(TRGB) ~ 9.84 ± 0.05. It is worth noting that the current TRGB estimate is in excellent agreement with the value provided by Bellazzini et al. (2001), i.e., m_I(AGB) = 9.84 ± 0.05. To estimate the dereddened magnitude, we adopted a reddening of E(B − V) = 0.11 ± 0.02 (Kaluzny et al. 2002; Calamida et al. 2005). This value, combined with the analytical relation for stellar extinction by Cardelli et al. (1989), gives for the Cousins I passband A_I = 0.59 × A_V = 0.59 × 3.1 × 0.11 ± 0.02 = 0.20 ± 0.06 mag. Therefore, we end up with m_I(AGB) = 9.64 ± 0.08. The error budget includes the uncertainties in the absolute zero-point calibration (<0.01), the cluster reddening, and the reddening law (Fitzpatrick 1999).

We adopted the same approach to estimate the TRGB in 47 Tuc. In the absence of other NIR observations, we have cross-correlated our optical catalog with the 2MASS NIR catalog, resulting in a catalog including ~15,000 stars with measurements in optical and NIR bands. As illustrated by the error bars in Figure 3, the photometric accuracy is very good from

![Figure 1](image1.png)  
Fig. 1.—(a) Optical–NIR J, B − K CMD of the bright region J ≤ 14 of ω Cen. Red circles display candidate AGB stars. The number of stars selected and the adopted selection criteria (intrinsic photometric error, separation) are also labeled. The error bars on the right display standard errors in magnitude and color. (b) Same as (a), but for the I, B − K CMD. (c) Same as (a), but for the I, V − K CMD. (d) Same as (a), but for the I, B − I CMD. The red circles plotted in the last three panels are the candidate AGB stars selected from the I, B − K CMD.

![Figure 2](image2.png)  
Fig. 2.—Top: I-band luminosity function for the bright end of the RGB in ω Cen. The vertical dashed lines indicate the position of the TRGB. Middle: Smoothed luminosity function of the same RGB region obtained using a Gaussian kernel with standard deviation equal to the photometric error (Sakai et al. 1996). Bottom: Response of the Sobel filter to the smoothed luminosity function.
the TRGB down to the red HB (H ≈ 12, B − K ≈ 3). As was the case for ω Cen, we find that star counts close to the TRGB should be minimally contaminated by AGB stars.

We estimate that the TRGB in 47 Tuc is located at $m_i(\text{TRGB}) = 9.46 ± 0.06$ (Fig. 4, vertical lines). This estimate agrees quite well with the estimate of Bellazzini et al. (2004), i.e., $m_i(\text{TRGB}) = 9.40 ± 0.13$. Note that the latter estimate includes a small correction to allow for the limited number of RGs in the last magnitude ($N_{\text{RG}} = 80$). Our sample includes 97 RGs in the same magnitude range—an increase of ~25%—bringing us closer to the number 100 stars which was proposed as the reference density for the method. We have therefore chosen not to apply this correction. To estimate the unreddened magnitude, we adopt $E(B − V) = 0.04 ± 0.02$ (Salaris et al. 2007) which, with the Cardelli et al. relation $A_V = 0.59 \times A_I, A_I = 0.59 \times 3.1 \times 0.04 ± 0.02 = 0.07 ± 0.06$ mag, gives $m_{i,0}(\text{TRGB}) = 9.39 ± 0.08$. The error budget includes the same sources of uncertainty as before.

To use the TRGB method to estimate the relative distance independently, we must correct for the difference in the clusters’ metal content. The TRGB calibration provided by Salaris & Cassisi (1998) relies on theoretical models, while that provided by Bellazzini et al. (2004) relies on the absolute distance of ω Cen based on the eclipsing binary [13.65 ± 0.11, $E(B − V) = 0.13 ± 0.02$; Thompson et al. 2001] and on an average distance for 47 Tuc [13.31 ± 0.11, $E(B − V) = 0.04$]. For our purposes we require only the slope of the metallicity-TRGB relation, and in this the two calibrations are in substantial agreement: using the quoted relations and iron abundances of [Fe/H] = −1.7 (ω Cen, metal-poor peak; Johnson et al. 2008) and [Fe/H] = −0.7 (47 Tuc), the differential corrections are +0.09 and +0.06 with an uncertainty of 0.03 if we assume a generous error allowance of 0.2 dex on the metallicity difference between the two clusters. Therefore, splitting the difference between the two corrections, the relative distance becomes $\delta d = 9.64 ± 0.08$ (ω Cen) − 9.39 ± 0.08 (47 Tuc) + 0.08 = 0.33 ± 0.11 mag. For comparison, absolute kinematic distances to ω Cen and 47 Tuc have been recently provided by van den Ven et al. (2006) and by McLaughlin et al. (2006). The implied relative distance between the two clusters is $\delta d = 13.41 ± 0.13$ (ω Cen) − 13.02 ± 0.19 (47 Tuc) = 0.39 ± 0.23 mag.

A similar value results if we use RR Lyrae stars to estimate the relative distances: the variable V9 (log $P = −0.1326$) is the only RR Lyrae currently known in 47 Tuc and it is suspected to be slightly evolved (Storm et al. 1994). K-band magnitudes have been shown to be minimally affected by evolutionary corrections (Bono et al. 2003; Catelan et al. 2004) and by assuming $E(B − V) = 0.04$ and the Cardelli law, we found $(k_{K}(V9)) = 12.66 ± 0.02$ mag. Fortunately, there are five RR Lyrae stars: V90, V127, V136, V87 (Kaluzny et al. 2004), and V141 (Clement et al. 2001) in ω Cen with periods ranging from log $P = −0.155$ to −0.119 and with accurate K-band mean magnitudes $(K_{K}) = 12.92 ± 0.03$. In order to account for the difference in metal abundances we adopted the metallicity estimates for individual RR Lyraes provided by Rey et al. (2000) and found that the mean metallicity for these five is $[\{Fe/H\}] = −1.53 ± 0.17$. The difference in mean magnitude as a function of the iron content was estimated using the theoretical calibration of DP06. The independent theoretical calibration provided by Catelan et al. (2004) provides very similar distances (DP06). For a difference in metal abundance of 0.8 dex$^{13}$ the difference in the K band is 0.07$^{14}$ mag. Therefore, the relative distance based on RR Lyraes is $\delta d = 12.92 ± 0.30$ (ω Cen) − 12.66 ± 0.02 (47 Tuc) + 0.07 = 0.33 ± 0.07 mag. We thus find that relative distances based on three completely independent methods

$^{13}$ Note that the mean metallicity of the five RR Lyrae stars in ω Cen is not exactly the same as the RG metallicity that we employed for the TRGB.

$^{14}$ Estimates based on the K-band P-L relations for $Z = 0.0001$–0.001–0.004 listed in Table 1 of DP06.
agree within 1 σ, or ~3% in distance, although admittedly the current analysis is based on only two GCs.

We now want to take a closer look at the consistency of our relative cluster distances with inferences from various proposed absolute distance scales that have been established on the basis of much larger samples of GCs. The zero point of the TRGB calibration provided by Lee et al. (1993) relies on cluster distances obtained with the $M_p$ vs. [Fe/H] relation for RR Lyrae stars. On this distance scale $\omega$ Cen $\mu = (9.64 \pm 0.08) + (4.01 \pm 0.05) = 13.65 \pm 0.09$, and for 47 Tuc $\mu = (9.39 \pm 0.08) + (3.93 \pm 0.05) = 13.32 \pm 0.09$ mag, for a modulus difference of $\Delta \mu = 0.33 \pm 0.13$ mag. We did not consider the TRGB calibration provided by Rizzi et al. (2007), since 47 Tuc is outside the metallicity range covered by this calibration. The use of the empirical color-metallicity relation for TRGB stars by Bellazzini et al. (2001) and of the Rizzi’s TRGB calibration would provide distances very similar to the above ones. The TRGB calibration provided by Salaris & Cassisi (1998) is brighter in absolute terms, but new findings (Cassisi et al. 2007) indicate that the discrepancy is significantly reduced.

From absolute distances based on the empirical $K$-band P-L relation for RR Lyrae stars provided by Sollima et al. (2008) we found $\mu = 13.75 \pm 0.11$ for $\omega$ Cen while for 47 Tuc we found, using the same unreddened magnitude as before for V9, $\mu = 13.47 \pm 0.11$, and therefore $\Delta \mu = 0.28 \pm 0.14$ mag. We note that the quoted absolute distances to $\omega$ Cen agree quite well with the distances based on the eclipsing binary $[3.71 \pm 0.11, 13.75 \pm 0.04, E(B-V) = 0.11 \pm 0.02]$ (Thompson et al. 2001; Kaluzny et al. 2002). The distances to 47 Tuc agree quite well with the distance based on main-sequence fitting $[13.40 \pm 0.03, E(B-V) = 0.04]$ (Gratton et al. 2003), but are systematically larger than distances based on fitting the WD cooling sequence $[13.15 \pm 0.14, E(B-V) = 0.04]$ (Zoccali et al. 2001) and the ZAHB $[13.18 \pm 0.03]$ (Salaris et al. 2007). Unfortunately, robust distance estimates to $\omega$ Cen based on these two methods are either not available or hampered by its spread in metal content. However, the use of these moduli and of the average TRGB and RR Lyrae relative distances would provide distances to $\omega$ Cen similar to the kinematic distances, but systematically smaller than the other standard candles.

Thus, we are left with the following evidence: (1) differential distance moduli or—equivalently—distance ratios based on (a) the absolute $I$-band relation for the TRGB, (b) the $K$-band P-L relations for RR Lyrae stars, and (c) the kinematic method agree with each other to within the precision of each method, or roughly 0.06 mag (see Table 1). This finding suggests that the estimated metallicity dependences of the different methods are consistent among themselves, since these two clusters differ in metallicity by ~1 dex. However, we obviously cannot completely exclude the possibility that the agreement is either fortuitous or a result of error cancellation. (2) Absolute distances based on current calibrations of the TRGB and RR Lyrae methods agree with each other to 0.10–0.15 mag, but the kinematic distance scale is 0.2–0.3 mag shorter (see Table 1). The same outcome applies to 47 Tuc distances based on ZAHB and WD fitting, they agree with each other within 0.10 mag, but they are 0.1–0.3 mag smaller than TRGB and RR Lyrae distances (Salaris et al. 2007). Taken together, points 1 and 2 suggest that our Population II distance scale is not at present limited by random errors due to data precision or sample size, but rather by systematics: either a systematic error shared by the TRGB method and the RR Lyrae method, due perhaps to a common rung in the calibration ladder that leads to their respective zero points, or a systematic bias inherent to the kinematic method that is common to the independent studies of $\omega$ Cen and 47 Tuc.

While we wait for accurate trigonometric parallaxes for GCs from SIM and Gaia, similar analyses of new GCs should help to clarify the relative impact of random and systematic errors among the various distance indicators.

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