Distances to the Globular Clusters 47 Tucanae and NGC 362 Using Gaia DR2 Parallaxes

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Abstract

Using parallaxes from Gaia Data Release 2 (Gaia DR2), we estimate the distance to the globular clusters 47 Tuc and NGC 362, taking advantage of the background stars in the Small Magellanic Cloud and quasars to account for various parallax systematics. We found the parallax to be dependent on the Gaia DR2 G-band apparent magnitude for stars with $13 < G < 18$, where brighter stars have a lower parallax zero point than fainter stars. The distance to 47 Tuc was found to be $4.45 \pm 0.01 \pm 0.12$ kpc, and for NGC 362 $8.54 \pm 0.20 \pm 0.44$ kpc, with random and systematic errors listed, respectively. This is the first time a precise distance measurement directly using parallaxes has been determined for either of these two globular clusters.

Key words: globular clusters: individual (47 Tucanae, NGC 362) – parallaxes – stars: distances

1. Introduction

47 Tucanae (47 Tuc) and NGC 362 are two globular clusters seen projected in front of the Small Magellanic Cloud (SMC). Previously, the distance to 47 Tuc has been estimated by methods such as main-sequence fitting (Percival et al. 2002), white dwarf spectral energy distributions (Woodley et al. 2012), RR Lyrae stars (Bono et al. 2008), eclipsing binaries (Thompson et al. 2010), and various other techniques (see Woodley et al. 2012, for a summary of previous methods). For NGC 362, the distance has been estimated using RR Lyrae stars (Szekely et al. 2007). However, a precise distance measurement directly using parallaxes for either of these clusters has never been obtained, due to a required parallax precision of tens of microarcseconds.

Gaia Data Release 2 (Gaia DR2, Gaia Collaboration et al. 2018, 2016) provided the five astrometric parameters (position, parallax, and proper motion) for more than 1.3 billion sources. In particular, the parallaxes, with a median uncertainty 0.04 mas for bright ($G < 14$ mag) sources, can be used to determine distances to an unprecedented number of objects. However, for more distant and fainter stars, the parallaxes become sensitive to systematic errors. These systematics are significant when determining the distance to 47 Tuc and NGC 362.

Globally, the parallax zero point was found by Lindgren et al. (2018) to be $-0.029$ mas, in the sense that Gaia parallaxes are too small. However, adding a global zero point to the data is insufficient as the zero point depends on the position on the sky. It can vary by as much as 0.1 mas globally and 0.04 mas on intermediate ($<20'$) scales and small ($<1'$) scales (Luri et al. 2018). Lindgren et al. (2018) also found a possible dependence on color and magnitude, which can cause variations of 0.02 mas.

Fainter objects tend to have a much larger uncertainty in measured parallax. Since quasars tend to be fainter, this makes using them to account for all of these spatial parallax systematics difficult. As there is only a small number of quasars behind 47 Tuc and NGC 362, quasars are insufficient to account for small-scale parallax zero point variations; thus, we employ the SMC stars behind the clusters to account for these systematics.

The basic premise of this paper is to find the distance to 47 Tucane and NGC 362 by using quasars to account for the intermediate scale parallax systematics, and the SMC stars behind each cluster to account for the small-scale parallax systematics, and to further investigate the color and magnitude dependent parallax systematics to obtain a precise distance estimate to 47 Tuc and NGC 362 using trigonometric parallax.

2. Data

2.1. Selecting SMC and Quasars

For the SMC to quasar comparison, a circular field of 5° in radius was taken around the SMC. Quasars were identified from a cross-match with the ALLWISE catalog (Secrest et al. 2015) found on the Gaia archive (gaiadr2.allwise_best_neighbor; Gaia Collaboration et al. 2018). SMC stars were chosen by a proper motion selection; furthermore, only stars with G-band apparent magnitude ($G$-mag) brighter than 19 were used, as fainter stars have a much larger parallax spread. Finally, a $5\sigma$ parallax error cut was applied to both SMC stars and quasars, where $\sigma$ is the standard deviation of the parallax distribution.

2.2. Selecting 47 Tucane, NGC 362, and SMC Stars

For 47 Tuc, NGC 362, and the SMC stars behind each cluster, the following cuts were applied to obtain the selections used for the analysis. First, for 47 Tuc, stars within one degree of the center of the cluster were selected. For NGC 362, only stars within 0.3 of the center were selected. Second, for both clusters, a proper motion cut was applied to separate cluster stars from SMC stars (see Figure 1). To avoid magnitude dependent systematics, stellar selections were chosen to have the same mean G-band apparent magnitude (see Figure 2). Finally, a $3\sigma$ cut in parallax was applied to remove outliers in each sample.

3. Color and Magnitude Systematics

Lindgren et al. (2018) found that the parallax zero point appeared to vary depending on color and magnitude. We chose our selection of cluster stars and SMC stars to have the same magnitude to avoid this possible systematic. However, as these selections do not have the same average color, we further
In Figure 3, we present a plot of parallax versus $G$-band apparent magnitude for quasars in the ALLWISE catalog (cf. Lindegren et al. 2018), and did the same for the SMC and the Large Magellanic Cloud (LMC). The LMC data were selected in the same manner as the SMC data in Section 2. All three plots show the same trend of brighter stars having a lower parallax zero point.

The linear trend for $G$-mag versus parallax only appears for stars with $G < 18$. The average magnitude of our five-degree SMC selection used to determine the SMC parallax ($\pi_{\text{smc}}$) is 17.9 in $G$-mag, and the quasars are even fainter. Thus we concluded that the magnitude dependent systematic in calculating $\pi_{\text{smc}}$ is insignificant. As we chose our selection of 47 Tuc stars and NGC 362 stars to have the same average $G$-mag as the SMC selection behind each cluster, the magnitude dependence does not affect our results. See Appendix B for

investigate the possible zero point dependence on color and magnitude.

Figure 1. Proper motion selections for the SMC (shown in blue) and foreground cluster stars (in green). The center of each proper motion circle was found by fitting two Lorentzian peaks in proper motion in R.A. and decl., and the radius was taken to be twice the peak’s half maximum width. See Figure 6 in Appendix A for the peak fit.

Figure 2. Color–magnitude diagrams for cluster and SMC stars after the proper motion selection was applied. 47 Tuc and NGC 362 are in green, and the SMC is in blue. The selected stars with the same mean $G$-mag used in the subsequent analysis is shown by the red boxes. The red dots show the mean Gaia DR2 $G_{BP} - G_{RP}$ color and $G$-mag of each selection.
further discussion of the magnitude–parallax systematic for selections that do not have the same $G$-mag. When plotting parallax versus GBP−GRP color, there initially appeared to be a trend for the SMC (see Figure 4). This can partially be explained by the red giant branch of the SMC where stars tend to get redder as they get brighter. When the parallax dependence on magnitude was accounted for, the section between 1 and 1.5 in color no longer has a downward trend. When applying this correction to the LMC and quasar selection, it is unclear as to whether applying the magnitude correction eliminates the possibility of the parallax being dependent on color. However, these effects appear to be minimal between 0.5 and 1.5 in GBP−GRP color, thus we do not account for it in our final result.

![Figure 3](image_url) Parallax as a function of $G$-band apparent magnitude for the five-degree selection of SMC stars, LMC stars, and all quasars over the entire sky matched to the ALLWISE catalog. The running mean is shown in red, and 2σ uncertainty is shown in cyan. For $13 < G < 19$, the running mean was fit to a line, with slopes from left to right, respectively, being 0.00779 ± 0.00027, 0.00399 ± 0.00015, and 0.00545 ± 0.00051 mas/G-mag.

![Figure 4](image_url) Parallax as a function of GBP−GRP color for the five-degree selection of SMC stars, LMC stars, and all quasars matched to the ALLWISE catalog. The running mean is shown in red, and 2σ uncertainty is shown in cyan. Top row is without the magnitude correction. The bottom row is with a magnitude correction intended to set the parallax to zero.

4. Analysis

Let $\pi_{\text{SMC}}$, $\pi_{47}$, and $\pi_{362}$ be, respectively, the true SMC, 47 Tuc, and NGC 362 parallaxes. Since quasars should have a parallax of essentially zero, we subtract the weighted mean quasar parallax from the weighted mean SMC parallax, using $\frac{1}{\sigma_{\pi}}$ as the weight, where $\sigma_{\pi}$ is the error in parallax given by the five parameter astrometric fit. This accounts for a spatially dependent parallax zero point systematic error across the SMC, giving us $\pi_{\text{SMC}}$. The error in averaging the SMC parallax incorporates any systematic errors arising from the depth of the SMC.

Assuming uniform small-scale variations across the one-degree 47 Tuc selection, the weighted mean over our SMC...
selection can be subtracted from the weighted mean over our 47 Tuc selection to get \( \pi_{47} - \pi_{\text{smc}} \).

However, as the distribution of SMC stars behind 47 Tuc is nonuniform (see Figure 5), this could introduce systematic errors. To account for nonuniform small-scale parallax zero point variations, we use a pairwise method. Let \( \hat{\pi}_{47} \) represent the measured parallax for the \( i \)th star in the 47 Tuc selection, then

\[
\hat{\pi}_{47} = \pi_{47} + \delta_{\text{int}} + \delta_{\text{small}},
\]

where \( \delta_{\text{int}} \) is the intermediate scale parallax zero point offset, and \( \delta_{\text{small}} \) is the small-scale spatially dependent parallax offset. Pairing up each 47 Tuc star with the nearest SMC stars, we eliminate the intermediate- and small-scale parallax variations, as stars close in R.A. and decl. should have the same small and intermediate scale parallax zero point offset. The \( n \) nearest SMC stars to each 47 Tuc star have parallaxes of \( \hat{\pi}_{\text{smc}} \), with respective errors \( \sigma_{\text{smc}} \). The weighted mean of those \( n \) stars is \( \bar{\hat{\pi}}_{\text{smc}} \), such that

\[
\bar{\hat{\pi}}_{\text{smc}} = \frac{\sum_{j=1}^{n} w_j \hat{\pi}_{\text{smc}}^j}{\sum_{j=1}^{n} w_j} = \bar{\pi}_{\text{smc}} + \delta_{\text{int}} + \delta_{\text{small}},
\]

where \( w_j = \left( \frac{1}{\sigma_{\text{smc}}^j} \right)^2 \) is the weight, and \( \sigma_{\text{smc}} = \left( \frac{1}{\sqrt{\sum_{j=1}^{n} w_j}} \right) \) is the error in the weighted mean. The \( n \) SMC stars should all have the same \( \delta_{\text{int}} \) and \( \delta_{\text{small}} \). Subtracting the \( i \)th mean SMC parallax from the \( i \)th 47 Tuc parallax, and adding their respective errors in quadrature to get the random error of \( \sigma_i \), we take the weighted mean over \( N \) 47 Tuc stars with \( w_i = \frac{1}{\sigma_i} \) to get

\[
\frac{\sum_{i=1}^{N} w_i (\hat{\pi}_{47} - \bar{\hat{\pi}}_{\text{smc}})}{\sum_{i=1}^{N} w_i} = \pi_{47} - \pi_{\text{smc}}.
\]

Adding the value of \( \pi_{\text{smc}} \) found previously, we find \( \pi_{47} \) and thus the distance to 47 Tuc.

One issue with the pairwise method is that it could double-count SMC stars. Another method to account for a small-scale parallax zero point is to divide the selection into squares and subtract the weighted mean of SMC and 47 Tuc parallaxes in each square, then take a weighted mean over all the squares to get \( \pi_{47} - \pi_{\text{smc}} \).

Applying the above three different methods to NGC 362 stars instead of 47 Tuc stars gives us estimates for \( \pi_{362} \), and the distance to NGC 362.

5. Results

5.1. SMC and Quasars

The weighted average of the SMC parallax was found to be \(-0.0059 \pm 0.0001 \) mas and for the quasars was \(-0.0251 \pm 0.0060 \) mas. The difference gives \( \pi_{\text{smc}} = 0.0192 \pm 0.0060 \) mas, which corresponds to a distance of 52\( \pm^{+23}_{-12} \) kpc.

5.2. 47 Tucane

In the pairwise analysis, we used a search radius of 0\( \degree \)1 around each 47 Tuc star, where the mean parallax of all SMC stars within 0\( \degree \)1 of each 47 Tuc star was subtracted from the parallax of that 47 Tuc star. Using search radii from 0\( \degree \)02 to 0\( \degree \)1 all gave results that agreed within 3\( \sigma \) error (see Appendix A, Figure 7).

For the third method of dividing the selection into squares and subtracting the average SMC and 47 Tuc parallaxes in each square, we used 16 squares of 0\( \degree \).02 to 0\( \degree \)1 on a side. The following results shown in Table 1, and numbers quoted in the remainder of the paper, are listed with random and systematic errors listed respectively (where the systematic errors result from the uncertainties in the parallax of the SMC and the zero points).

5.3. NGC 362

Repeating the processes used for 47 Tuc on NGC 362, we derive the results shown in Table 2. For the pairwise method, we again used a search radius of 0\( \degree \)1 around each NCG 362 star. For squares, we divided the sample into 16 squares of 0\( \degree \)1 on a side since the sample was much smaller.
6. Discussion

6.1. SMC Parallax

An SMC parallax of \( \pi_{\text{smc}} = 0.0192 \pm 0.006 \) mas corresponding to a distance of \( 52 \pm 23 \) kpc agrees within 1\( \sigma \) with the distance estimate of \( 62.1 \pm 1.9 \) kpc given by Graczyk et al. (2014). The large uncertainty in our estimate is primarily due to the parallax spread of the quasars. While our result agrees with the literature values, it is not a particularly insightful result and serves primarily as a way to continue onto the distance determination of 47 Tuc and NGC 362 using parallax measurements. Using the SMC distance from Graczyk et al. (2014) to calculate the distances to 47 Tuc and NGC 362 gives distances of \( 4.51 \pm 0.02 \) kpc and \( 8.76 \pm 0.22 \) kpc, respectively, with random and systematic errors combined. This does shift our values to slightly further distances; however, they are still well within 1\( \sigma \) of our model independent values determined directly with parallax.

6.2. Comparison with Literature Values

Our result for 47 Tuc, \( 4.45 \pm 0.01 \pm 0.12 \) kpc, is close to average for 47 Tuc distance estimates, which range between \( 4.29 \pm 0.47 \) kpc (estimated kinematically by Heyl et al. 2017) and \( 4.94 \pm 0.25 \) kpc found by Bono et al. (2008) using RR Lyrae stars. The most precise literature value comes from horizontal branch fitting from near-IR photometry, where Salaris et al. (2007) found a distance of \( 4.33 \pm 0.06 \pm 0.05 \) kpc (see footnote 1) with random and systematic errors listed respectively. While this distance yields a somewhat smaller error estimate than our result, it is model dependent whereas our distance estimate is not. See Appendix A, Figure 8 for a comparison of our distances with those in the literature from the past 20 years.

For NGC 362, our distance of \( 8.54 \pm 0.20 \pm 0.44 \) kpc agrees within 1\( \sigma \) of the literature values—Harris (1996; 2010 edition) quotes \( 8.6 \) kpc (no error reported) and \( 7.9 \pm 0.6 \) kpc Szekely et al. (2007) using RR Lyrae stars.

Our distance to 47 Tuc is smaller than the RR Lyrae distance, while for NGC 362 it is larger when compared with the RR Lyrae distance from the literature. This could be the result of these authors using different techniques. Bono et al. (2008) used \( K \)-band photometry of a single RR Lyrae star in 47 Tuc, while Szekely et al. (2007) used \( V \)-band photometry for multiple RR Lyrae in NGC 362.

### Table 1

Summary of Results for 47 Tucanae

| Method   | \( \pi_{47} - \pi_{\text{smc}} \) (mas) | \( \pi_{47} \) (mas) | \( d_{47}\) (kpc) |
|----------|----------------------------------------|---------------------|------------------|
| Weighted Mean | 0.2070 ± 0.0013 | 0.2262 ± 0.0013 ± 0.0060 | 4.42 ± 0.02 ± 0.12 |
| Pairwise  | 0.2055 ± 0.0006 | 0.2247 ± 0.0006 ± 0.0060 | 4.45 ± 0.01 ± 0.12 |
| Squares   | 0.2075 ± 0.0022 | 0.2267 ± 0.0022 ± 0.0060 | 4.31 ± 0.04 ± 0.12 |

### Table 2

Summary of Results for NGC 362

| Method   | \( \pi_{362} - \pi_{\text{smc}} \) (mas) | \( \pi_{362} \) (mas) | \( d_{362}\) (kpc) |
|----------|----------------------------------------|---------------------|------------------|
| Weighted Mean | 0.0988 ± 0.0046 | 0.1178 ± 0.0046 ± 0.0060 | 8.49 ± 0.33 ± 0.43 |
| Pairwise  | 0.0981 ± 0.0028 | 0.1171 ± 0.0028 ± 0.0060 | 8.54 ± 0.20 ± 0.44 |
| Squares   | 0.1001 ± 0.0049 | 0.1191 ± 0.0049 ± 0.0060 | 8.39 ± 0.35 ± 0.42 |

6.3. Cluster Properties

From our parallax measurements, the difference in distance moduli between NGC 362 and 47 Tuc is \( 1.415 \pm 0.048 \). From the CMDs, using \emph{Gaia} photometry, we get a mean difference of \( 1.446 \pm 0.004 \) in the magnitude between the red horizontal branch stars of NGC 362 and 47 Tuc. These values agree within 1\( \sigma \) and thus we cannot see significant metallicity effects on the red horizontal branches from this comparison. In any case, our distance uncertainties are too large to probe the modest differences in the magnitudes of RR Lyrae stars expected from theoretical models (Marconi et al. 2015) over the metallicity range spanned by 47 Tuc and NGC 362.

Our distances will have a direct impact on calculating the absolute cluster age. Our somewhat larger distance modulus for NGC 362 compared with the RR Lyrae distance from Szekely et al. (2007), for example, suggests a more luminous turnoff magnitude and hence a slightly younger age for the cluster.

7. Conclusions

In deriving distances to the globular clusters 47 Tuc and NGC 362, we needed to account for the spatial and magnitude dependent parallax systematics in \emph{Gaia} DR2. To accomplish this, we did the following three things:

1. We took a weighted mean of the quasars behind the SMC, which allowed us to find an intermediate scale parallax zero point of \( -0.0251 \pm 0.0060 \) mas, yielding \( \pi_{\text{smc}} = 0.0192 \pm 0.0060 \) mas.
2. We took a selection of foreground cluster stars with the same mean \( M \)-mag as the selection of SMC stars to avoid magnitude dependent parallax systematics.
3. We paired up all SMC stars within 0\( \text{1.4} \) of each cluster star to account for the small-scale parallax zero point variations.

The parallax zero point was not significantly dependent on color for stars between 0.5 and 1.5 in \( G_{\text{BP}} - G_{\text{RP}} \) color, which the majority of stars in our selections lie between. This is not to say that the parallax zero point is entirely independent of color; further investigation into a possible color dependence would be needed for such a statement.

This yields the distance estimate of \( 4.45 \pm 0.01 \pm 0.12 \) kpc for 47 Tuc and \( 8.54 \pm 0.20 \pm 0.44 \) kpc for NGC 362, with random and systematic errors quoted, respectively. This is currently the most precise distance determination to NGC 362 available. While
our estimate for 47 Tuc is not more precise than some previous estimates, it is comparable in precision and not model dependent.

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular, the institutions participating in the Gaia Multilateral Agreement.

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Appendix A

Additional Figures

This section includes supplementary figures.

Figure 6. Lorentzian peak fit of proper motion R.A. for all stars within 1° of 47 Tuc on the left, and in proper motion decl. on the right.

Figure 7. Results for $\pi_{47} - \pi_{\text{smc}}$ and $\pi_{362} - \pi_{\text{smc}}$ using varying search radii in pairwise analysis. Error bars show the 1σ uncertainty.
Appendix B
Method to Account for Magnitude Dependent Parallax Systematics

We originally chose 47 Tuc and SMC stars that did not have the same $G$-mag as shown in Figure 9 and then corrected for the difference in magnitude with the slope of the parallax against $G$-mag.

However, when parallax versus $G$-mag in Figure 3 was fit to a line, the slopes of the three fits did not agree with each other. We then used the slope from the quasar line of best fit of 0.0054 mas/$G$-mag and estimated a larger error in slope of 0.0025 mas/$G$-mag when accounting for the parallax–magnitude systematic. Then by subtracting the average $G$-mag from the foreground cluster and the SMC and multiplying by the slope of 0.0054 mas/$G$-mag, we found the adjusted results for the distances to 47 Tuc and NGC 362 in Tables 3 and 4.

The magnitude–parallax adjusted results then agree with the results previously found when using selections with the same $G$-mag. Due to the uncertainties introduced from correcting for the difference in apparent magnitudes, using selections of the same $G$-mag results in lower systematic errors and thus a more precise result. Additionally, using selections with the same $G$-mag results in the three methods being in better agreement for $\pi_{47} - \pi_{362}$, suggesting that using star selections of different $G$-mag can lead to inconsistencies between methods. However, selecting stars of the same apparent magnitude may not always be a possibility, thus it is important to correct for the magnitude–parallax systematic in such a case.

Figure 8. Literature values for distances to 47 Tuc and NGC 362 from the past 20 years. Distances for 47 Tuc converted from distance modulus, found in Table 1 of Woodley et al. (2012), where values cited from left to right are from Zoccali et al. (2001), Grundahl (2002), McLaughlin et al. (2006), Salaris et al. (2007), Kaluzny et al. (2007), Bono et al. (2008), Thompson et al. (2010), and Woodley et al. (2012).
Figure 9. Color–magnitude diagram for cluster and SMC stars after the proper motion selection was applied. 47 Tuc and NGC 362 are in green, and the SMC is in blue. The original selection of stars with different $G$-mag are shown by the red boxes. The average $G$ mag and $G_{BP} - G_{RP}$ color are shown by the red circles.

**Table 3**

Summary of Results for 47 Tucanae, Where 47 Tuc and SMC Selections Have Different $G$-mag

| Method       | $\pi_{47} - \pi_{smc}$ (mas) | Adjusted $\pi_{47} - \pi_{smc}$ (mas) | $\pi_{47}$ (mas) | $d_{47}$ (kpc) |
|--------------|-------------------------------|----------------------------------------|-----------------|----------------|
| Weighted Mean| 0.1952 ± 0.0031               | 0.2067 ± 0.0031 ± 0.0090               | 0.2257 ± 0.0031 ± 0.0108 | 4.43 ± 0.06 ± 0.21 |
| Pairwise     | 0.1908 ± 0.0200               | 0.2023 ± 0.0020 ± 0.0090               | 0.2213 ± 0.0020 ± 0.0108 | 4.52 ± 0.04 ± 0.22 |
| Squares      | 0.1982 ± 0.0026               | 0.2097 ± 0.0026 ± 0.0090               | 0.2287 ± 0.0026 ± 0.0108 | 4.37 ± 0.05 ± 0.21 |

**Table 4**

Summary of Results for NGC 362, Where NGC 362 and SMC Selections Have Different $G$-mag

| Method       | $\pi_{362} - \pi_{smc}$ (mas) | Adjusted $\pi_{362} - \pi_{smc}$ (mas) | $\pi_{362}$ (mas) | $d_{362}$ (kpc) |
|--------------|-------------------------------|----------------------------------------|-----------------|----------------|
| Weighted Mean| 0.0932 ± 0.0086               | 0.1012 ± 0.0086 ± 0.0082               | 0.1202 ± 0.0086 ± 0.0102 | 8.32 ± 0.59 ± 0.70 |
| Pairwise     | 0.0920 ± 0.0046               | 0.1000 ± 0.0046 ± 0.0082               | 0.1190 ± 0.0046 ± 0.0102 | 8.40 ± 0.32 ± 0.72 |
| Squares      | 0.0943 ± 0.0270               | 0.1023 ± 0.0270 ± 0.0082               | 0.1213 ± 0.0270 ± 0.0102 | 8.2 ± 1.8 ± 0.73 |

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