Resolving the 47 Tucanae Distance Problem

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ABSTRACT

We present new B, V and I-band photometry for a sample of 43 local subdwarfs with HIPPARCOS parallax errors < 13%, in the metallicity range $-1.0 < [\text{Fe/H}] < -0.3$, which we use to perform main sequence (MS) fitting to the Galactic globular cluster 47 Tuc. This sample is many times larger than those used in previous MS-fitting studies and also enables us to fit in two colour planes, $V/(B-V)$ and $V/(V-I)$. With this enlarged subdwarf sample we investigate whether the current discrepancy in empirical distance estimates for 47 Tuc, arising from recent MS-fitting and white dwarf fitting results, is due to inaccuracies in the MS-fitting method. Comparison of published photometries for 47 Tuc has revealed systematic offsets which mean that the $(B-V)$ main-line used in previous studies may be too blue by $\sim 0.02$ mag, which would have the effect of making any derived distance modulus too large by around 0.1 mag. Preliminary work has also highlighted discrepancies between results obtained in the 2 colour planes, $V/(B-V)$ and $V/(V-I)$. We have derived main-lines in $V/(B-V)$ and $V/(V-I)$ from the data of Kaluzny et al. (1998), which we have recalibrated from the ‘secondary’ standards in 47 Tuc of Stetson (2000). Using an assumed cluster reddening of $E(B-V) = 0.04$, our best-fit apparent distance modulus is $(m-M)_V = 13.37^{+0.10}_{-0.11}$ in both colour planes, which implies a cluster age of 11.0 ± 1.4 Gyr and leads to a dereddened distance modulus of $(m-M)_0 = 13.25^{+0.06}_{-0.07}$. Comparison with previous work shows that our apparent distance modulus is $\sim 0.2$ mag smaller than those derived in previous MS-fitting studies. The difference is accounted for by our preferred cluster reddening and the recalibration of the cluster photometry, which has made the main-line redder by an average of 0.02 mag in $(B-V)$. Our derived distance modulus is also now plausibly consistent with the short distance recently derived from white dwarf fitting. Independent support for our MS-fitting distance comes from consideration of the Red Clump in the cluster, from which we derive a dereddened distance modulus of $(m-M)_0 = 13.31 \pm 0.05$, which is in agreement with the MS-fitting result.

Subject headings: globular clusters: general – 47 Tuc – stars: evolution – distances
1. Introduction

The age of the globular cluster (GC) 47 Tucanae (NGC 104) plays a fundamental role in the study of the formation mechanism of the Galaxy. 47 Tuc belongs to the ‘thick disk’ population of Galactic GCs and the comparison of its age with that of the more metal poor ‘halo’ GCs and the oldest ‘thin disk’ open clusters provides vital clues about the timescale for the formation of the various Galactic stellar populations (e.g. Salaris & Weiss 1998, Liu & Chaboyer 2000, VandenBerg 2000). In addition, 47 Tuc provides the zero point for the age determination of ‘bulge’ GCs, since their ages are most reliably determined from the differential comparison of their Colour-Magnitude Diagrams (CMDs) with that of 47 Tuc (Ortolani et al. 1995). Since the age of a stellar cluster is best determined from the comparison of the absolute magnitude of the main sequence turn off stars with their theoretical counterpart, the cluster distance modulus must be accurately known.

The two most recent empirical determinations of the 47 Tuc distance provide very different results. By applying the main sequence fitting technique in the \( V/(B-V) \) CMD, using a sample of 7 unevolved subdwarfs with accurate HIPPARCOS parallaxes, and adopting \([Fe/H] = -0.7\) and \(E(B-V) = 0.055\) for the cluster, Carretta et al. (2000) have obtained a distance modulus \((m - M)_V = 13.57 \pm 0.09\) (see also Gratton et al. 1997 and Reid 1998, who obtain similar results using small numbers of HIPPARCOS subdwarfs). Zoccali et al. (2001) have applied the white dwarf fitting technique in the \( m_{336}/(m_{336} - m_{555}) \), \( m_{555}/(m_{555} - m_{814}) \) CMDs, where \( m_{336}, m_{555} \) and \( m_{336} \) correspond roughly to the UVI Johnson-Cousins filters; they used a sample of 6 local DA white dwarfs with accurate parallaxes, together with 21 WDs identified in 47 Tuc, and determined a distance modulus \((m - M)_V = 13.27 \pm 0.14\), adopting \(E(B-V) = 0.055 \pm 0.02\). The discrepancy between these two results is significant, and causes an uncertainty of about 3 Gyr on the cluster age.

In this work we want to investigate whether this disagreement is due to inaccuracies in the MS-fitting distance determination, and provide a new, more solid estimate of 47 Tuc distance modulus. In particular, we aim to greatly improve the reliability of the MS-fitting distance by vastly increasing the number of subdwarfs included in the fitting procedure, having an homogeneous photometric dataset for all of them, and, for the first time, considering the fitting in both the \( V/(B-V) \) and \( V/(V-I) \) Johnson-Cousins planes. Because of the different sensitivities of the \((B-V)\) and \((V-I)\) colours to the stellar metallicities, consistency of the results derived in these two colour planes is a strong test for the reliability of the distances we obtain.

In §2 we present the photometry of our new large subdwarf sample, and discuss the adopted subdwarf metallicities, reddenings and Lutz-Kelker corrections; §3 deals with the 47 Tuc photometry, metallicity and reddening, while the MS-fitting results and related systematic errors are discussed in §4 and §5, respectively. An analysis of the results and comparison with other distance determinations appears in §6, followed by a summary in §7.
2. The Subdwarf Sample

2.1. Selection Criteria

Suitable subdwarfs were selected using 3 basic criteria - metallicity, parallax error and absolute magnitude - as described below.

Metallicities were determined from Strömgren indices, available in the literature, via the calibration of Schuster & Nissen (1989). Likely subdwarf candidates were initially identified from the catalogues of Schuster & Nissen (1988), Schuster, Parrao & Contreras Martinez (1993) and Olsen (1993), however, for the sake of consistency, the averaged indices from Hauck & Mermilliod (1998) were used in the analysis. Metallicities for the subdwarfs were placed on the scale of Carretta & Gratton (1997) (hereafter CG97) using the transformations of Clementini et al. (1999) - note that these transformations have a dispersion of $\sim 0.16$ dex in the derived metallicity, which comes largely from the Schuster & Nissen calibration. Metallicities were restricted to a range within $\pm 0.4$ dex of the cluster metallicity ($[Fe/H] = -0.7$ is assumed for 47 Tuc - see §3.2), hence the sample stars all lie in the range $-1.0 \leq [Fe/H] \leq -0.3$. This ensures that any uncertainties on the metallicity dependence of the main sequence location are kept to a minimum. 2 of the stars in our sample fall just outside the specified metallicity range when the Hauck & Mermilliod indices are used (HIP 27080 and HIP 43393 at $[Fe/H] = -0.255$ and -0.252, respectively), therefore these stars were omitted from the following analysis.

All stars were required to have HIPPARCOS parallaxes with errors $\leq 13\%$, enabling both an accurate determination of their absolute magnitudes and an assessment of Lutz-Kelker bias in the sample (see §2.3).

The final requirement that $M_V > 5.5$ ensures that stars are unevolved, on the lower main sequence, hence their location in the CMD does not depend on their (unknown) age.

HIPPARCOS entries for all suitable candidates were carefully checked to avoid the inclusion of any suspected binaries or variable stars. We have identified a sample of 50 local subdwarfs which meet all the above criteria and we have acquired new B, V and I-band photometric data for 43 of them.\(^1\)

2.2. Observations and Data Reduction

26 stars in the southern sky sample were observed between January and May 2001 at the Sutherland site of the South African Astronomical Observatory (SAAO) using the modular photometer on the 0.5m telescope. The photometer employs a Hamamatsu R943-02 (GaAs) photomul-

\(^1\)Stars for which we did not manage to acquire new photometry are; HIP nos. 1897, 8102, 10798, 56452, 78241, 111209 and 112870
tiplier and a Johnson-Cousins UBV(RI)C filter set. Magnitudes were calibrated using ‘E-region’
standard stars (see e.g. Menzies et al. 1989) and data reduced using standard SAAO procedures,
as described fully in Kilkenny et al. (1998) and references therein.

29 stars in the northern sample were imaged with the CCD on the 1m Jacobus Kapteyn
Telescope (JKT) on La Palma, on February 9th and June 2nd 2001. The JKT employs a SITe2K
chip and a Kitt Peak BVI filter set was used for all observations of programme and standard stars.
Magnitudes were calibrated from 29 observations of 14 Landolt (1992) standard fields taken over
the 2 nights. Basic data reduction was done using standard routines in the FIGARO data reduction
package and aperture photometry was performed in GAIA.

A comparison of the 12 stars in common between the 2 samples shows excellent agreement in
the V and I filters, the mean differences being 0.006 and -0.002 respectively (SAAO-JKT), with the
B-band magnitudes displaying a slightly larger mean offset of 0.012 (the JKT magnitudes being
brighter). All 3 filters have a dispersion of ~ 0.02 around the mean, and are therefore consistent
with the true offsets being zero. Since several stars in the JKT data have only one observation,
the dispersion in the mean offset was added in quadrature to the photometry errors for these stars.
Table 1 presents the new subdwarf data and lists: HIPPARCOS number, observed V magnitudes,
(B – V) and (V – I) colours, photometry errors (in mags), parallax, parallax error, metallicity
on the CG97 scale, number of observations in each filter and source of photometry (s for SAAO
and j for JKT). Figure 1 shows CMDs in V/(B – V) and V/(V – I) for the absolute magnitudes
calculated from the parallax, and including LK corrections, dividing the subdwarfs into 2 metallicity
bins (–1.0 ≤ [Fe/H] < –0.6 and –0.6 < [Fe/H] < –0.25). The error bars on the colours are
photometry errors only.

2.3. Lutz-Kelker corrections

As a consequence of selecting the subdwarfs on parallax error, their absolute magnitudes are
subject to Lutz-Kelker bias, which leads to a systematic underestimate of their distances (Lutz &
Kelker 1973). Lutz-Kelker corrections for the individual subdwarfs were derived from the distribu-
tion of proper motions for the whole sample, following the procedures of Hanson (1979). The proper
motion distribution, identified from the HIPPARCOS catalogue, was found to be well represented
by a power law of the form \( N(\mu) \propto \mu^{-x} \), where \( x = 2.65 \pm 0.15 \). The appropriate LK correction for
each individual star, \( \Delta M_{LK} \), is then given by:

\[
\Delta M_{LK} = -2.17 \left[ \left( n + \frac{1}{2} \right) \left( \frac{\sigma_\pi}{\pi} \right)^2 + \left( \frac{6n^2 + 10n + 3}{4} \right) \left( \frac{\sigma_\pi}{\pi} \right)^4 \right]
\]

where \( n = x + 1 \) and \( \left( \frac{\sigma_\pi}{\pi} \right) \) is the fractional parallax error.

Since the parallax errors for our sample are restricted to ≤ 13%, LK corrections are small, the
mean value being \( \Delta M_{LK} = -0.05 \) mag.
2.4. Reddening

The Strömgren $H\beta$ index offers the best method for assessing the reddening of individual subdwarfs. 17 stars in our full selected sample have $H\beta$ measurements (Hauck & Mermilliod 1998) from which $E(b - y)$ was derived using the calibration of Schuster & Nissen (1989). $E(B - V)$ can then be calculated assuming $E(B - V) = 1.35E(b - y)$, and standard extinction laws used to determine $E(V - I)$ and $A_V$ (e.g. from Cardelli, Clayton & Mathis 1989). We expect redenings to be very low since the average distance of our sample is only 41pc, the furthest lying at 72pc, and in fact, the reddening distribution of these 17 stars peaks at around $E(b - y) = 0.006$ (corresponding to $E(B - V) = 0.008$), with tails at higher and lower values (some being negative). Since the standard error on the Schuster & Nissen reddening calibration is on the order 0.01 in $E(b - y)$, this distribution is consistent with the ‘true’ reddening being zero for the sample as a whole. We note here that these 17 stars include the full distance range of the sample, from the nearest to the furthest and the derived redenings show no correlation with distance or Galactic latitude or longitude.

Several other authors also conclude that reddening effects are negligible in a region within 75pc of the sun (see, for example, discussions in Perry, Johnston & Crawford 1982, Blackwell et al. 1990 and references therein). Therefore we chose to adopt zero reddening for the full subdwarf sample used in our main fits and note that this choice may produce a small systematic effect on the order of 0.03 mag on the derived distance moduli (see §5.1).

3. 47 Tucanae

3.1. Photometry

All previous MS-fitting studies of 47 Tuc have used the $V/(B - V)$ fiducial sequence from Hesser et al. (1987). Since one of the aims of this work is to extend the wavelength range used for MS-fitting to 47 Tuc we searched for published data which would provide a well populated lower MS, in both $(B - V)$ and $(V - I)$, extending to $\sim 3$ magnitudes below the turn-off, from which fiducial lines could be derived. The data of Kaluzny et al. (1998) seemed ideal for this purpose, as they present $B$, $V$ and $I$ photometry for more than 22,000 stars covering the whole CMD and extending well down onto the lower MS. We derived main-lines by making 0.1 magnitude cuts in $V$ across the main sequence and calculating the mean colour, and the dispersion around this mean. The data of Kaluzny et al. (1998) seemed ideal for this purpose, stars lying more than 1-$\sigma$ from the mean were discarded, and the process repeated until the solution converged. A similar procedure utilizing the mode of the colour distribution across the MS, rather than the mean, produced essentially the same results. Comparison of the $V/(B - V)$ main-line derived in this way from the Kaluzny et al. data showed it to be in good agreement with that of Hesser et al. (see Figure 2).

Preliminary fits using only the SAAO subdwarf data (26 stars) yielded a $(B - V)$ distance
modulus in agreement with previous studies (see section §6). However, there appeared to be a discrepancy of almost 0.3 mag in the derived distance moduli between the \((B - V)\) and \((V - I)\) indices (Percival et al. 2001), which prompted us to investigate further the consistency of the cluster photometry. It should be noted at this point that Hesser et al. (1987) refer specifically to a possible zero-point offset in their \((B - V)\) data - ‘... we believe there is a reasonable possibility that our CCD-calibrated scale for 47 Tuc is correct in V but may be too blue in \((B - V)\) by 0.01 – 0.02 mag’. Since in the MS fitting procedure any error on the colour index is multiplied by the slope on the MS \((\sim 5.5 \text{ in } V/(B - V))\), this immediately suggests that any derived distance modulus may be too large by around 0.1 mag. Comparison of the Kaluzny et al. data with the photoelectrically calibrated MS data of Alcaino & Liller (1987) suggested not only that the \((B - V)\) main-line may be too blue by 0.02 – 0.03 mag, but that the \((V - I)\) main-line may be too red by a similar amount. If real, these zero-point offsets combined together would potentially explain the discrepancy in distance moduli found above.

In order to quantify the suspected zero-point offsets in the Kaluzny data we made a comparison of Stetson’s ‘secondary’ \(BVI_C\) standards in 47 Tuc, available through the Canadian Astronomy Data Centre web site (http://cadcwww.hia.nrc.ca/standards - see Stetson 2000 for details). A coordinate search reliably identified 31 stars in common with the Kaluzny et al. data, which spanned the colour range of the main sequence. Comparison of the photometries showed a constant offset in the \(V\) filter (and similar constant offset in the \((V - I)\) colour index) and a colour dependent offset in \((B - V)\), in exactly the sense suggested above. Specifically these derived offsets are:

\[
\begin{align*}
V_{\text{Stetson}} &= V_{\text{Kaluzny}} - 0.025 \\
(V - I)_{\text{Stetson}} &= (V - I)_{\text{Kaluzny}} - 0.026 \\
(B - V)_{\text{Stetson}} &= 1.091(B - V)_{\text{Kaluzny}} - 0.048
\end{align*}
\]

(see Figure 3).

Applying these offsets, we recalibrated the Kaluzny data from the Stetson standards and rederived main-lines in \((B - V)\) and \((V - I)\), as previously described. The 2 sub-fields for which shorter integration times were used (F19 and F10, see Kaluzny et al. 1998 for details) were neglected as these were clearly not consistent with the remainder of the data. Fits to our preliminary subdwarf data yielded distance moduli that were consistent between the 2 colour indices and so we adopted the recalibrated main-lines for the remainder of the analysis.

Figure 2 compares the original Kaluzny main-lines with the recalibrated ones. The \(V/(B - V)\) plot also shows the main line of Hesser et al. (1987) used in all previous 47 Tuc MS-fitting studies, which is coincident with the original Kaluzny photometry. Figure 3 illustrates the derived photometry offsets between the Kaluzny and Stetson data sets.

We note here that the \((B - V)\) plot in Figure 3 (middle panel) has one point at \((B - V) = 0.57\) which appears slightly discrepant and may be forcing the slope of the best-fit line to be too steep. If this point is neglected (or given lower weighting) the slope reduces slightly and the best-fit line becomes: \((B - V)_{\text{Stetson}} = 1.071(B - V)_{\text{Kaluzny}} - 0.029\). Adopting this relationship for our
recalibration alters the mean offset by no more than 0.003 mag in \((B - V)\), and the effect on our overall results is negligible.

### 3.2. Metallicity and Reddening

To enable accurate distance estimates to be made from any method which compares cluster and field stars (as is the case using MS-fitting techniques) care must be taken to tie the abundance scale used for the calibrating local stars to that of the cluster. Carretta & Gratton (1997) determined metallicities for 24 globular clusters, from cluster giant stars, and find \([Fe/H] = -0.70 \pm 0.07\) for 47 Tuc, which we note is in complete agreement with the Zinn & West value of \([Fe/H] = -0.71 \pm 0.08\) and other spectroscopic studies (as discussed in Rutledge, Hesser & Stetson 1997). Hence, we adopt \([Fe/H] = -0.7 \pm 0.1\) for the cluster metallicity.

For the subdwarfs we are using the CG97 scale, as calibrated by Clementini et al. (1999) from the Schuster & Nissen metallicities and, for our fits to be valid, this scale must be consistent with the metallicity used for 47 Tuc. Metallicities for the calibrating subdwarfs used by Clementini et al. are measured according to procedures which are totally consistent with those used by Carretta & Gratton (1997) to derive the cluster metallicities (see discussion in Clementini et al. 1999), and so the 2 scales should be comparable. Reid (1998) also discusses this point and makes a comparison of the CG97 abundances for a sample of 22 local stars which also have spectroscopically derived abundances from Axer, Fuhrmann & Gehren (1994). Reid finds a mean difference of 0.008 dex in \([Fe/H]\), but with most of the offset coming from stars at the lowest metallicities. However, for \([Fe/H] > -1.3\) (which applies to all of our sample, and 47 Tuc) the abundances are found to be in agreement.

From the above considerations, we make the assumption that the abundance scales we are using for the subdwarfs and the cluster are self-consistent, and therefore any systematic effects should be negligible. However, we note that any systematic change in the metallicity scales of either the subdwarfs or the cluster would affect the derived distances.

Reddening estimates for 47 Tuc from various studies, and using a variety of methods, lie in the range \(E(B - V) = 0.029 - 0.064\) (see e.g. Crawford & Snowden 1975, Dutra & Bica 2000, Gratton et al. 1997 and references therein). We chose to adopt an \(E(B - V)\) value of 0.04 for our main fits, but explored the range \(0.02 \leq E(B - V) \leq 0.06\). The potential systematic errors associated with our choice of cluster metallicity and reddening are assessed in §5.2.
4. Main Sequence Fitting

4.1. Method

The basic method employed in this work consists of using the subdwarfs to create a template main sequence for comparison with the cluster main-line. This is done by deriving the appropriate metallicity-dependent colour shifts which must be applied to the individual subdwarfs in order to ‘adjust’ their metallicity to that of the cluster, \([Fe/H] = -0.7\) (noting that decreasing the metallicity of a main sequence star shifts it to bluer colours in a CMD).

Employing the \(\alpha\)-enhanced isochrones of Salaris & Weiss (1998) for \([Fe/H] = -1.3, -1.0, -0.7, -0.6\) and solar-scaled for \([Fe/H] = -0.3\) the procedure is as follows. For each subdwarf, at its absolute magnitude, interpolate amongst the isochrones to determine the theoretical colour of a star (either \((B-V)\) or \((V-I)\)), at (i) the metallicity of the subdwarf and (ii) the metallicity of the cluster. The difference between these quantities, \(\Delta(B-V)\) or \(\Delta(V-I)\), represents the colour shift required to place the subdwarf at the metallicity of the cluster. This shift is then applied to the observed colour of the subdwarf, at its absolute magnitude, to build up the template MS. Because the metallicity range of our subdwarf sample was restricted to \(\pm 0.4\) dex of the cluster metallicity, the derived colour shifts are small. In \((B-V)\), the mean shift is 0.035 mag (note that some stars shift to bluer and some to redder colours, depending on the metallicity), and the maximum shift is 0.050, whilst in \((V-I)\) the mean and maximum shifts are 0.027 and 0.041 respectively.

In order to check whether the colour shifts are dependent on our choice of isochrones, we carried out tests using different sets of isochrones (e.g. Girardi et al. 2000, the diffusive isochrones of Salaris, Groenewegen & Weiss 2000) and colour transformations (Green, Demarque & King 1987, Castelli 1999). Since we are utilizing relative colours for these shifts, rather than absolute colours (which can vary significantly from model to model) and because we are only adjusting across a narrow metallicity range, the colour shifts produced in the different cases were virtually indistinguishable. Hence we are confident that the resulting template MS is not model dependent.

The template MS is then shifted in magnitude, \(V\), and the best fit to the cluster main-line is found using a least-squares fitting routine (see §4.2 for details). The required magnitude shift is equal to the apparent distance modulus, \((m-M)_V\).

Reid (1997) notes that, to be physically correct, the procedure of shifting subdwarfs to the cluster metallicity should preserve mass. This implies that both the colour and magnitude of each subdwarf should be adjusted to be appropriate to a star of equivalent mass, at the metallicity of the cluster. The main problem here is that mass also evolves along the MS so that, at a given colour, luminosity and metallicity, the mass of a star also depends on its age. Since in general we do not have reliable ages for local subdwarfs it is not possible to apply these magnitude shifts in a physically correct way. However, we did test the effect of applying colour and magnitude corrections assuming an arbitrary fixed age for the subdwarfs of 10 Gyr. The resulting template MS covers a different range of magnitudes than the one which includes colour shifts only, as shifting a star of
fixed mass to a lower metallicity increases its luminosity, and vice-versa. However, since the shape
of the isochrones is very similar across the metallicity range we are using, the shape of the resulting
template is not changed significantly and we found that fits to these revised templates yield the
same distance moduli, to within 0.01 mag, as the templates constructed using colour shifts only, in
both \((B - V)\) and \((V - I)\).

4.2. Distances from MS-fitting

Using the whole sample of 41 subdwarfs, ‘shifted’ to \([Fe/H] = -0.7\) (excluding the 2 stars with
\([Fe/H] > -0.3\)), with magnitudes corrected for LK bias and assuming zero subdwarf reddening,
our best-fit apparent distance modulus is \((m - M)_V = 13.37 \pm 0.03\) from both the \(V/(B - V)\) and
\(V/(V - I)\) fits. The quoted error includes:
i) photometry errors for the subdwarfs
ii) errors on the subdwarf magnitudes as a result of parallax errors, where \(\Delta M_V = 2.17(\Delta \pi/\pi)\)
iii) errors on the subdwarf colours induced by errors on the metallicity calibration, where \(\Delta [Fe/H]_{\text{subdwarfs}} =
\pm 0.16\) dex (the dominant error here is the dispersion in the Schuster & Nissen calibration from the
Strömgren indices)
iv) error on the colour of the cluster main-line resulting from the error on the cluster metallicity
determination, where \(\Delta [Fe/H]_{\text{cluster}} = \pm 0.1\) dex.

The best-fit to the cluster main-line is found by using weighted errors for the subdwarfs, and
minimising \(\chi^2\). The fitting routine takes into account errors in both the \(x\) and \(y\) axes i.e. errors
in both magnitude and colour are accounted for, as detailed above. Figure 4 shows the best fits to
the recalibrated 47 Tuc main line, with error bars representing the errors quoted above.

5. Testing Our Assumptions

5.1. The Subdwarfs; Metallicity, LK Corrections and Reddening

In order to test the consistency of the metallicity-dependent colour shifts applied to the sub-
dwarfs, we defined a subset of the sample with metallicities in the range \(-0.9 < [Fe/H] < -0.5\)
(13 stars). The mean metallicity of this subset is \([Fe/H] = -0.64\) and, since the dispersion on the
metallicity calibration is of the order 0.16 dex, we performed fits to these stars without applying
any metallicity corrections. The derived distance moduli are in agreement with those derived from
the whole (shifted) sample, in both \((B - V)\) and \((V - I)\).

To check that we are making a correct assessment of the LK bias in the full sample, a subset
was defined for which \(\Delta \pi/\pi < 4\%\) (implying \(|\Delta M_{LK}| < 0.015\)) to which LK corrections were not
applied (14 stars). Fits to these stars yield distance moduli in complete agreement with the full,
LK corrected, sample, hence we are confident that the LK corrections are appropriate to the sample
as a whole.

As a further consistency check, fits were made to a subset of the sample for which metallicities are in the range $-0.9 < [Fe/H] < -0.5$ (with a mean of -0.65) and parallax errors are $< 8\%$ (5 stars). The resultant distance moduli are again in agreement with those from the whole sample. As a result of these checks, there do not appear to be any systematic effects arising from the metallicity and LK corrections and so we assume an apparent distance modulus of $(m - M)_V = 13.37$ for the remainder of the analysis.

Table 2 lists the best fit distance moduli in $V/(B - V)$ and $V/(V - I)$ for the full sample and subsets described above, as follows:

1 - Full sample, LK corrected magnitudes, ‘shifted’ to $[Fe/H] = -0.7$
2 - Subset with metallicities in the range $-0.9 < [Fe/H] < -0.5$ (mean $[Fe/H] = -0.64$), fitted without applying metallicity corrections
3 - Subset with parallax errors $< 4\%$, no LK corrections applied
4 - Subset with metallicities in the range $-0.9 < [Fe/H] < -0.5$ and parallax errors $< 8\%$

All the above tests were made assuming zero reddening for the subdwarfs. However, if we apply reddenings derived from the $H\beta$ index to the stars for which this is available and use an average reddening of $E(B - V) = 0.008$ for the rest of the sample (see §2.4), distance moduli are reduced by $\sim 0.03$ mag in all the fits.

The referee expressed concern about the possibility of a metallicity bias in our subdwarf sample which may arise due to the underlying metallicity distribution of the parent population. Since the metallicity distribution of local subdwarfs is strongly skewed towards higher metallicities, this would cause the metallicity of individual subdwarfs to be underestimated and make MS-fitting distances appear too long. We took the underlying ‘true’ metallicity distribution to be represented by the combined samples of Schuster & Nissen (1988) and Schuster, Parrao & Contreras Martinez (1993), since most of our sample was drawn from these catalogues. There is a large peak in this distribution at $[Fe/H]_{SN} \sim -0.2$ due to disk stars, and another smaller peak at $[Fe/H]_{SN} \sim -1.3$ due to the halo population (see Schuster, Parrao & Contreras Martinez 1993, their Figure 1). To quantify the effect on our sample, we made Monte Carlo simulations of the metallicity distribution of the parent population, as described above, combined with random errors, generated assuming a Gaussian error distribution of width 0.16 dex (Schuster & Nissen 1989). Then, at the observed metallicity of each individual subdwarf in our sample, we considered all the stars within 0.16 dex of this value, and calculated the difference between the means of the ‘observed’ metallicities (after the Gaussian errors have been added) and the ‘true’ metallicities (from the initial distribution). The difference between these quantities provides an estimate of the likely bias in our sample. Offsets vary between 0.021 and 0.043 dex with a mean of 0.035 dex, in the sense that the ‘true’ metallicities are higher. Applying individual metallicity corrections to our subdwarfs and refitting the sample to the 47 Tuc main-line results in a distance modulus which is smaller by only 0.02 mag.
5.2. The Cluster; Reddening and Metallicity

Reddening for the cluster was taken to be $E(B-V) = 0.04$ in all our fits. Increasing or decreasing $E(B-V)$ by 0.02 mag changes the apparent distance modulus, $(m-M)_V$, by ±0.1 in the sense that larger assumed reddening produces a longer distance. Since reddening values for 47 Tuc available in the literature are not necessarily in agreement within their quoted errors and come from very disparate methods, we have no way of truly assessing the appropriate reddening to apply or of calculating the associated errors, in a statistical sense. Conservatively, we have chosen to adopt ±0.1 as the reddening-induced error on the apparent distance modulus, although this undoubtedly represents more than a 1σ error. Note, however, that this uncertainty of ±0.1 on the apparent distance modulus, $(m-M)_V$, only induces an uncertainty on the true distance modulus, $(m-M)_0$, of ±0.05.

Our final derived apparent distance modulus for 47 Tuc, including the uncertainties on cluster and subdwarf reddening in the total error budget, is: $(m-M)_V = 13.37^{+0.10}_{-0.11}$, leading to a dereddened distance modulus of $(m-M)_0 = 13.25^{+0.06}_{-0.07}$.

As already discussed, the metallicities we are using for both the cluster and the subdwarfs are consistent with the CG97 scale and therefore we expect there to be no associated systematic errors. However, it should be borne in mind that there is an inherent uncertainty in any study of this kind, since there is always the implicit assumption that the cluster metallicity, generally obtained from giant stars, is the same as that which would be obtained from the cluster main sequence. Coupled with the still controversial zero-point for the absolute temperature scale of giant stars, it is possible that a systematic shift in the metallicity scale may become necessary in the future. Changing the metallicity scale of either the subdwarfs or the cluster, with respect to one another, would modify the distance moduli derived from our subdwarf sample by ~ 0.1 mag for each 0.1 dex change in metallicity, in the sense that decreasing the metallicity of the cluster would decrease the distance, whilst decreasing the metallicity of the subdwarfs would increase it. We note here that if we change the relative metallicities by more than ~ 0.2 dex, the distance moduli we derive from the 2 colour indices are no longer consistent within their errors.

Another cause for concern may be the variation in C and N abundances which are known to exist in 47 Tuc. However, the study of Cannon et al. (1998), which measures abundance variations down onto the main sequence of 47 Tuc, indicates that these are unlikely to affect the broad-band colours used in MS-fitting studies (see their Figure 6).

6. Discussion

Employing our distance determination discussed in the previous section we then determined the age of the cluster. The luminosity of the turn-off was estimated by fitting a parabola to stars in the magnitude range 17.3 < $V$ < 18.0. This yielded a turn-off magnitude of $V_{TO} = 17.66 \pm 0.1$ which,
coupled to our distance modulus and assuming $[Fe/H]=-0.7$, provides an age of $11.0 \pm 1.4$ Gyr when using the Salaris & Weiss (1998) isochrones (for $[Fe/H]=-0.7$, $Y=0.254$, $[\alpha/Fe]=0.4$). The error bar on the age takes into account the error on the cluster distance and the error on the apparent magnitude of the turn off.

For direct comparison with previous MS-fitting work we followed Carretta et al. (2000) by fitting our whole subdwarf sample (LK, reddening and extinction corrected) to the $V/(B-V)$ main-line of Hesser et al. (1987), using a cluster reddening of $E(B-V)=0.055$. The best fit yielded an apparent distance modulus of $(m - M)_V = 13.59 \pm 0.03$ (errors as in §4.2 only), which is in excellent agreement with the Carretta et al. (2000) result of $13.57 \pm 0.09$. The reason for the lower distance modulus we have obtained in the previous section is due to both our preferred cluster reddening, and the recalibration of the 47 Tuc photometry. A reduction of $\sim 0.1$ mag comes from the different cluster reddening, while the rest of the difference is due to the photometry recalibration, which makes the main-line redder, on average, by $\sim 0.02$ in $(B - V)$ (see Figure 2 with the comparison of the main-lines).

To investigate whether our MS-fitting distance is still significantly different from that derived from white dwarf fitting, we determined the 47 Tuc distance modulus with our recalibrated cluster photometry and a reddening $E(B-V)=0.055 \pm 0.02$, as used in Zoccali et al. (2001). We obtain $(m - M)_V = 13.45 \pm 0.10$ which has to be compared with $(m - M)_V = 13.27 \pm 0.14$ obtained from the white dwarf-fitting method. The two results are less discrepant than in the case of the Carretta et al. (2000) main sequence distance, especially if one takes into account the possibility of an additional systematic error of the order of 0.1 mag on the white dwarf distance, due to the uncertainty on the value of the mass and on the thickness of the hydrogen envelopes for the cluster white dwarfs (see the detailed discussion in Salaris et al. 2001).

Independent support for our main sequence distance determination comes from the use of the Red Clump (RC) as a distance indicator. The red horizontal branch of 47 Tuc is the counterpart of the RC in the solar neighbourhood discussed by Paczyński & Stanek (1998), whose I-band absolute magnitude is very precisely determined by HIPPARCOS parallaxes as $M_{I,RC} = -0.23 \pm 0.03$ (Stanek & Garnavich 1998). Girardi & Salaris (2001) have discussed in great depth the use of the RC as standard candle and provide evolutionary corrections to the absolute brightness of the local RC, which take into account the effect of the star formation history and age-metallicity relationship of the stellar population under scrutiny. In the case of a GC like 47 Tuc, the Girardi & Salaris (2001) method predicts a correction of only $+0.03$ to the absolute $I$-band brightness of the local RC. From the recalibrated photometry of Kaluzny et al. (1998) we obtain $I_{RC}=13.18\pm0.02$ which, together with $M_{I,RC} = -0.20 \pm 0.03$ appropriate for the 47 Tuc RC, provides a distance modulus of $(m - M)_{I,RC} = 13.38 \pm 0.04$. Considering a reddening $E(B-V) = 0.04 \pm 0.02$ and the extinction law by Cardelli et al. (1989), one gets a dereddened distance modulus from this method of $(m - M)_{0,RC} = 13.31 \pm 0.05$, which agrees well with that obtained from the main sequence fits, $(m - M)_0 = 13.25^{+0.06}_{-0.07}$. 
7. Summary

We have defined a sample of 50 local subdwarfs in the metallicity range $-1.0 < [Fe/H]_{CG97} < -0.3$, which are suitable for main sequence fitting to the GC 47 Tuc. We have obtained new photometric data in B, V and I for 43 subdwarfs in the sample and use these to derive the 47 Tuc distance modulus in the $V/(B - V)$ and $V/(V - I)$ planes.

From a careful comparison with the 47 Tuc standards of Stetson (2000), we have found that the commonly used Hesser et al. (1987) main-line in $V/(B - V)$ appears to be too blue by an average of 0.02 mag. This implies that any distance modulus derived via MS-fitting from the Hesser main-line would be too large by $\sim 0.1$. In order to perform MS-fitting in 2 colour indices ($(B - V)$ and $(V - I)$), we have derived main-lines from the photometry of Kaluzny et al. (1998), which we have recalibrated using the Stetson (2000) standards.

Theoretical isochrones are used to calculate the metallicity-dependent colour shifts required to move the subdwarfs in the CMD to match the metallicity of the cluster, and hence build up a template MS. However, we find that the particular choice of isochrones does not influence the magnitude of the derived colour shifts and so the method does not appear to be model dependent.

We have investigated the effects of metallicity scales, LK bias and reddening, for both the subdwarfs and the cluster, on the derived distance moduli. We find no appreciable errors arising from either the assumption of zero reddening for the subdwarfs or from our assessment of the LK bias in the sample. The largest single source of error is the uncertainty on the cluster reddening which propagates through to an error on the order of 0.1 mag on the distance modulus. Metallicities used for both the cluster and the subdwarfs are consistent with the CG97 scale and therefore there should be no associated systematic errors. However, any change in zero-point of the metallicity scale which altered the cluster or subdwarfs with respect to each other, would potentially alter the distance moduli by $\sim 0.1$ mag for every 0.1 dex change in the metallicity.

Our best-fit apparent distance modulus for 47 Tuc is $(m - M)_V = 13.37^{+0.10}_{-0.11}$, with an assumed cluster reddening of $E(B - V) = 0.04$. Coupled with our assessment of the apparent magnitude of the turn-off $(V_{TO} = 17.66 \pm 0.1)$, the implied age of the cluster is $11 \pm 1.4$ Gyr. The dereddened distance modulus is $(m - M)_0 = 13.25^{+0.06}_{-0.07}$.

The apparent distance modulus we find for 47 Tuc is $\sim 0.2$ mag smaller than those derived in previous MS-fitting studies. This is due partly to our preferred cluster reddening and partly to the recalibration of the 47 Tuc photometry, which has made the main-line redder than that used by all previous studies, by an average of 0.02 mag in $(B - V)$. Our MS-fitting distance is now plausibly consistent with that derived from white dwarf fitting.

Independent support for our MS-fitting distance is given by consideration of the Red Clump in the cluster, from which we derive a dereddened distance modulus of $(m - M)_{0,RC} = 13.31 \pm 0.05$, which is in good agreement with that derived from MS-fitting.
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REFERENCES


Table 1. New Photometry for Subdwarf Sample

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<td>32</td>
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<td>1.18</td>
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Table 2. Derived Distance Moduli for 47 Tuc

<table>
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<tr>
<th>Sample</th>
<th>N</th>
<th>( V/(B - V) )</th>
<th>( V/(V - I) )</th>
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<tr>
<td>1</td>
<td>41</td>
<td>13.37 ±0.03</td>
<td>13.37 ±0.03</td>
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<tr>
<td>2</td>
<td>13</td>
<td>13.36 ±0.07</td>
<td>13.40 ±0.07</td>
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<td>14</td>
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<td>4</td>
<td>5</td>
<td>13.40 ±0.09</td>
<td>13.35 ±0.08</td>
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Fig. 1.— New photometry for 43 subdwarfs (see Table 1), divided into 2 metallicity bins: $[Fe/H] > -0.6$ (stars) and $[Fe/H] < -0.6$ (squares). Error bars are photometry errors only.
Fig. 2.— Comparison of 47 Tuc main-lines in $V/(B - V)$ (left panel) and $V/(V - I)$ (right panel). Both plots show: original Kaluzny et al. (1998) main-line (dotted line), Kaluzny data recalibrated via Stetson (2000) standards (solid line) and photoelectric data from Alcaino & Liller (1987) (dots). The $V/(B - V)$ plot also shows the Hesser et al. (1987) fiducial sequence (dashed line).
Fig. 3.— Comparison of Kaluzny and Stetson photometries for 47 Tuc from stars in common between the samples. Dotted lines show the derived offsets used to recalibrate the Kaluzny data.
Fig. 4.— Whole LK-corrected subdwarf sample ‘shifted’ to $[Fe/H] = -0.7$ and the recalibrated 47 Tuc main line, using our best-fit distance modulus of $(m - M)_V = 13.37$ in both the $V/(B - V)$ and $V/(V - I)$ plots.