A&A 395, 481–497 (2002)
DOI: 10.1051/0004-6361:20020790


Astronomy & Astrophysics

# The ages of the globular clusters M 71 and 47 Tuc from Strömgren *uvby* photometry⋆,⋆⋆

## Evidence for high ages

F. Grundahl[1], P. B. Stetson[2], and M. I. Andersen[3]

[1] Institute of Physics and Astronomy, Aarhus University, Ny Munkegade, 8000 Aarhus C, Denmark
[2] National Research Council, Herzberg Institute of Astrophysics, Dominion Astrophysical Observatory, 5071 W. Saanich Road, B.C., V9E 2E7, Canada
[3] Division of Astronomy, University of Oulu, PO Box 3000, 90014 Oulun Yliopisto, Finland

Received 19 February 2002 / Accepted 21 May 2002

**Abstract.** New *uvby* CCD photometry for the fairly metal–rich globular clusters M 71 (NGC 6838) and 47 Tuc (NGC 104) is presented. We derive the cluster distances using a sample of field subdwarfs with metallicities determined from *uvby* photometry and accurate parallaxes from the *Hipparcos* mission. The biases associated with the main-sequence fitting technique are discussed and only that due to metallicity is found to be significant, corresponding to a −0.05 mag change in distance modulus. Our main results are that: 1) The distance moduli of 47 Tuc and M 71 are somewhat shorter than that derived by Reid (1998, AJ 115, 204). For M 71 and 47 Tuc we find (metallicity corrected) $(m - M)_V = 13.71 \pm 0.04 \pm 0.1$ and $(m - M)_V = 13.33 \pm 0.04 \pm 0.1$, for adopted reddenings of $E(B - V) = 0.28$ and $E(B - V) = 0.04$ respectively (first errorbar denotes random errors and the second systematic errors). The main source of difference with Reid is the selection of subdwarfs with this study having more intrinsically faint field subdwarfs; 2) These values lead to ages of nearly 12 Gyr when using the isochrones of VandenBerg et al. (2000, ApJ, 532, 430); this estimate does not include the effects of He diffusion. 3) A differential comparison of the cluster colour-magnitude diagrams show that the age difference between the two is very small – less than one billion years. 4) The observed scatter in the $c_1$ index (due to star–to–star nitrogen variations) among main–sequence stars does not allow us to use the $[(v - y)_0, c_0]$ diagram for a distance-independent age determination.

**Key words.** globular clusters: individual: NGC 104, NGC 6838

## 1. Introduction

The metal–rich globular clusters (GCs) play an important role as age tracers of the oldest disk, thick disk and bulge populations since these systems offer the best posibilities for accurate age determinations. Among the approximately 33 clusters listed in the Harris (1996) compilation with [Fe/H] ≥ −0.8 M 71 (NGC 6838) and 47 Tuc (NGC 104) are among the most easily studied due to their closeness (although the reddening of M 71 is substantial, with some differential reddening evident, its low concentration makes it an easy target for precise photometry) and both have been subjects of several studies. Most notably both clusters have a large spread in the carbon and nitrogen abundances among their members, main–sequence (MS) and red giant stars (RGB) alike (Briley et al. 1994; Briley 1997; Cannon et al. 1998; Cohen 1999; Grundahl 1999; Grundahl et al. 1999a).

After the availability of the *Hipparcos* parallax database quite a bit of discussion over the distances (and hence ages) of the globular clusters has emerged in the literature. Several of the first *Hipparcos*-based studies (e.g. Reid 1997 (R97), 1998 (R98); Gratton et al. 1997) concluded that the distances to the metal–poor clusters were significantly larger than previously thought – leading to cluster ages lower by 2–3 Gyr. However some studies, most notably that of Pont et al. (1998) for M 92, concluded that the new parallaxes do not lead to a significantly younger age for this cluster, a result supported by Grundahl et al. (2000). Furthermore, if the longer distance scale is correct, then an apparent dichotomy between the luminosities of the metal–poor field and cluster RR-Lyrae stars appears, in the sense that the luminosities of the cluster RR-Lyraes are brighter than the field RR-Lyraes. See Carretta et al. (2000a) and Catelan (1998) for further discussion of this.

*Send offprint requests to*: F. Grundahl, e-mail: fgj@phys.au.dk

⋆ Based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

⋆⋆ Based on observations obtained with the Danish 1.5 m telescope at the European Southern Observatory, La Silla, Chile.

Several possibilities exist for explaining the "long/short" dichotomy for the cluster distances as there are a number of known problems associated with the main–sequence fitting technique, such as Lutz-Kelker corrections, metallicity bias, binarity among the field subdwarfs, and selection effects (discussed in e.g. R97; R98; Gratton et al. 1997; Carretta et al. 2000b). Perhaps the most important problem lies in the fact that the number of low-metallicity field stars with very accurate parallaxes is quite small – a problem which is currently impossible to circumvent. However, in the case of more metal–rich clusters, such as 47 Tuc and M 71, the steeply rising frequency of subdwarfs with increasing metal abundance ensures that there is a larger sample of field stars with good parallaxes to choose from, compared to the metal–poor case, for the determination of main-sequence distances.

Although M 71 is observationally as easy a target as 47 Tuc there have not yet been any studies as detailed as the Hesser et al. (1987) study for 47 Tuc. The most thorough study so far is that of Hodder et al. (1992). These authors derived an age between 14 and 16 Gyr for the cluster and found an offset of $\Delta V = 0.379$ and $\Delta(B - V) = 0.235$ (sense M 71–47 Tuc) from a differential comparison to the Hesser et al. colour-magnitude diagram for 47 Tuc. Other studies, e.g. Salaris & Weiss (1998), also find the two clusters to have very similar properties within the measuring errors. Chaboyer et al. (1996) found the two to differ in age by 2 Gyr (47 Tuc older) from the $\Delta V_{\rm TO}^{\rm HB}$ method; given the difficulty of locating the turnoff and the lack of precise photometry for M 71 this result is probably still consistent with no age difference. Conversely, Heasley & Christian (1991) found M 71 to be approximately 3 Gyr older than 47 Tuc. Finally, in a homogeneous *VI* photometric study of 34 nearby globular clusters, Rosenberg et al. (1999) concluded that the two clusters differ in age by 6% ± 11%, or 0.9 ± 1.6 Gyr (47 Tuc older), if the "typical" globular cluster age is assumed to be 13 Gyr. In this paper we shall carry out a detailed comparison of the distances and ages for these two clusters, both relative and absolute, based on new Strömgren *uvby* photometry. This allows for the inclusion of a larger number of subdwarfs as a large data base of homogeneous *uvby* photometry already exists unlike the situation for *BVI* photometry.

The outline of the paper is as follows: Sects. 2 and 3 describe the observational material, photometric reductions and calibrations; in Sect. 4 the colour–magnitude diagrams (CMDs) are presented and in Sect. 5 we discuss reddening and metallicity estimates for the clusters. Section 6 presents a brief discussion of the differential ages. In Sect. 7 we deal with the selection of a subdwarf sample and the determination of main–sequence distances. Section 8 discusses the determination of absolute ages for the clusters given the new distance determinations and in Sect. 9 a discussion of our results is given. Finally Sect. 10 concludes and summarises our results.

## 2. Observations and data reductions

The data for M 71 and 47 Tuc were collected at the 2.56 m Nordic Optical Telescope (NOT) on La Palma and the Danish 1.54 m telescope at the European Southern Observatory (ESO) on La Silla, respectively. The data for M 71 were collected between June 26 and July 02, 1995. For 47 Tuc the data were gathered over 10 nights in October 1997. The CCD characteristics for both instruments are listed in Table 1.

**Table 1.** Characteristics for CCDs used.

| | NOT | DFOSC |
|---|---|---|
| CCD type | SITe | Loral |
| Size | $1024^2$ | $2048^2$ |
| RON ($e^-$) | 13.0 | 7.7 |
| Gain $e^-$/ADU | 8.7 | 1.8 |
| Pixel size ″/pix | 0.175 | 0.39 |
| Field size | 3′×3′ | $R = 5\farcm5$ |
| Typical FWHM (″) | 0.75 | 1.6 |

For both clusters and standard stars the observations during the two observing runs followed the same strategy. At both observatories the instruments are mounted on field rotators, allowing the CCD to be oriented differently (relative to the telescope) from one exposure to the next. After each *uvby* exposure sequence we thus rotated the CCD camera by 90 degrees to reduce the effects of inaccurate flatfielding due to scattered light in the optical system (Grundahl & Sørensen 1996). Flat fields were obtained during evening and morning twilight on every clear observing night. As for the cluster frames the CCD camera was also rotated 90 degrees between flat fields. In order to estimate the errors in the flat fielding we derived the quotients between the flux weighted mean flat field and each individual flat field image. For the NOT observations we found only very small differences in the quotient images – always less than 1% In the case of the DFOSC these were slightly larger, typically 1–2%, with the *u* flat fields having the largest variations.

In M 71 we observed a field 2′ north of the center. For 47 Tuc we observed a field covering F1 and some of F2 from Hesser et al. (1987) and one more overlapping field towards the cluster center in order to increase the sample of HB and RGB stars. The F1, F2 field has more observations than the inner one resulting in longer total exposure times.

The filters at the 1.54 m telescope were of inadequate size, which caused some vignetting of the CCD corners; these regions were therefore excluded from further analysis. In Table 2 below we summarize the number of *uvby* observations for each cluster, given as the maximum number of observations and the number of observations on photometric nights for each filter. There is a higher number of *y* and *b* observations than *v* and *u* for 47 Tuc; this is because the *y* and *b* filters were used for aquiring the field resulting in a higher number of short exposure frames. The exposure times for both clusters were typically 300, 600, 900 and 2000 seconds, respectively for the *y*, *b*, *v*, and *u* filters.

Finally, of relevance for this investigation we also observed the southern open cluster IC 4651 in order to check the photometric calibrations, as it has previously been observed in *uvby* by Nissen (1988). This comparison will be carried out below.

**Table 2.** Number of observations.

| | M 71 | 47 Tuc |
|---|---|---|
| $N_y$(max.) | 15 | 20 |
| $N_b$(max.) | 15 | 17 |
| $N_v$(max.) | 16 | 17 |
| $N_u$(max.) | 14 | 14 |
| $N_y$(photom.) | 4 | 7–13 |
| $N_b$(photom.) | 4 | 7–11 |
| $N_v$(photom.) | 4 | 7 |
| $N_u$(photom.) | 4 | 7 |

### 2.1. Standard star observations and photometry

During both observing runs we adopted stars from the lists of Schuster & Nissen (1988, SN88) and Olsen (1983, 1984) as our standard stars because the observations by these authors were very carefully transformed to the standard *uvby* system. (The true fundamental *uvby* standards are too bright ($V \lesssim 6$) to observe easily with a CCD and 2m class telescopes. Furthermore, they are isolated field stars, so that only one can be placed on the CCD at a time.) Since many of the Schuster & Nissen and Olsen stars are brighter than $V \simeq 9.5$ – and some are significantly brighter – we chose to defocus the telescopes such that we would not need exposure times shorter than 5 s in the $y$ filter. To shorten readout time, only frames of 300×300 pixels (NOT) and 500×500 pixels (DK1.54 m) were read out. We shall in the following refer to these stars as *standard stars*, although in a strict sense they are only secondary or even tertiary standards. The stardards were observed over a range of 1–2.5 airmasses, for deriving the extinction coefficients.

The photometry for these frames was done using simple aperture photometry and the magnitude at which the growth curves converged was adopted as the total magnitude. Due to the brightness of the stars the photon noise was negligible in most exposures (0.002 mag or less). Several experiments to determine the sky level were done, and it was found that a 3–sigma clipped mean produced the best results.

In order to derive the transformation from the instrumental system to the standard system we adopted the following equations (after experimenting with different terms and cross terms):

$$\begin{aligned} y_{\rm obs} &= V_{\rm std} + \alpha_y(v-y) + \beta_y(X-1) + \gamma_y T + \delta_y \\ b_{\rm obs} &= b_{\rm std} + \alpha_b(v-y) + \beta_b(X-1) + \gamma_b T + \delta_b \\ v_{\rm obs} &= v_{\rm std} + \alpha_v(v-y) + \beta_v(X-1) + \gamma_v T + \delta_v \\ u_{\rm obs} &= u_{\rm std} + \alpha_u(v-y) + \beta_u(X-1) + \gamma_u T + \delta_u \end{aligned}$$

where $X$ and $T$ denote the the airmass and time of that CCD exposure, and $(v-y)$ is the colour on the *standard* system. On several of the nights the time terms were found to be insignificant. The values for $\alpha$ and $\beta$ were averaged over each observing run, and good consistency was found from night to night. At NOT the transformations are based on observations of 52 different standard stars on two photometric nights. Several of the stars have multiple measurements in order to serve as extinction checks. At the 1.54 m telescope 130 different standard stars were observed in 7 photometric nights. We chose to adopt transformation equations of this form as this has several advantages over transforming the indices: Firstly, the above formulation does not require that stars be observed in all four filters each night, so that it is possible to observe, say, only the $u$ filter for an entire night. Secondly, these equations are more appropriate to the aquisition method of CCD photometry, since the data for the different filters are not obtained simultaneously, unlike the case for the photoelectric photometry of Olsen (1983, 1984) and SN88. Thirdly, the equations are easily modified to accomodate data from non-photometric nights, by eliminating the airmass and time terms and introducing a new zeropoint for each frame obtained under non-photometric conditions. See also Stetson (2000) for a relevant discussion.

The scatter in the residuals ($m_{\rm std.} - m_{\rm transf.}$) is given in Table 3. For the chosen stardards, the highest emphasis was put on stars near the old metal–poor turnoff, but also red stars, including both MS and RGB stars as well as very blue (mainly O and B type) stars were included. We note, however, that there could be enhanced scatter as well as systematic errors in the $v$ and $u$ filters since they contain bands of CN and NH molecules. The 4215 Å CN feature, in particular, is close to the red edge of the $v$ filter, making the transformation of both $u$ and $v$ "risky" for cluster giants.

In Fig. 1 we have plotted the offsets between the standard magnitudes and our transformed values vs. $(v-y)$ for the Olsen and Schuster & Nissen stars. It is evident from the figure that there are no trends of the residuals with colour, except that for stars redder than $(v-y) = 1.1$ the scatter appears higher than for the bluer stars. We speculate that this is due to the enhanced importance of CN bands in the cooler stars. Certainly, in the case of the $u$ band there seems to be rather large scatter for the reddest stars, indicating that the transformed values are subject to an extra parameter which is not included in our transformation equations. We note that for the purposes of this paper this enhanced scatter is not a problem. For the NOT observations the scatter in a similar figure does not show trends with colour either, the main difference being a slightly smaller scatter for the $u$ filter. This is mainly due to the fact that only two standard stars with $(v-y) > 1.5$ were observed at the NOT.

### 2.2. Cluster photometry

For the cluster photometry we used the *DAOPHOT, ALLSTAR* and *ALLFRAME* programs (Stetson 1987, 1994). In order to derive the point spread function (PSF) for each image we made several passes through DAOPHOT/ALLSTAR, and before the final ALLSTAR run each image was examined visually for neighbours close to the PSF candidate stars. Depending on the exact field either the neighbours were added to the star list or the PSF candidate was eliminated from the PSF construction.

The total number of PSF stars for each image varied between 30 and 80. We used a spatially constant PSF for all images, as we found that there was no strong spatial variation of the PSF. This may seem surprising in the case of the observations of 47 Tuc obtained with DFOSC, which is a focal-reducer

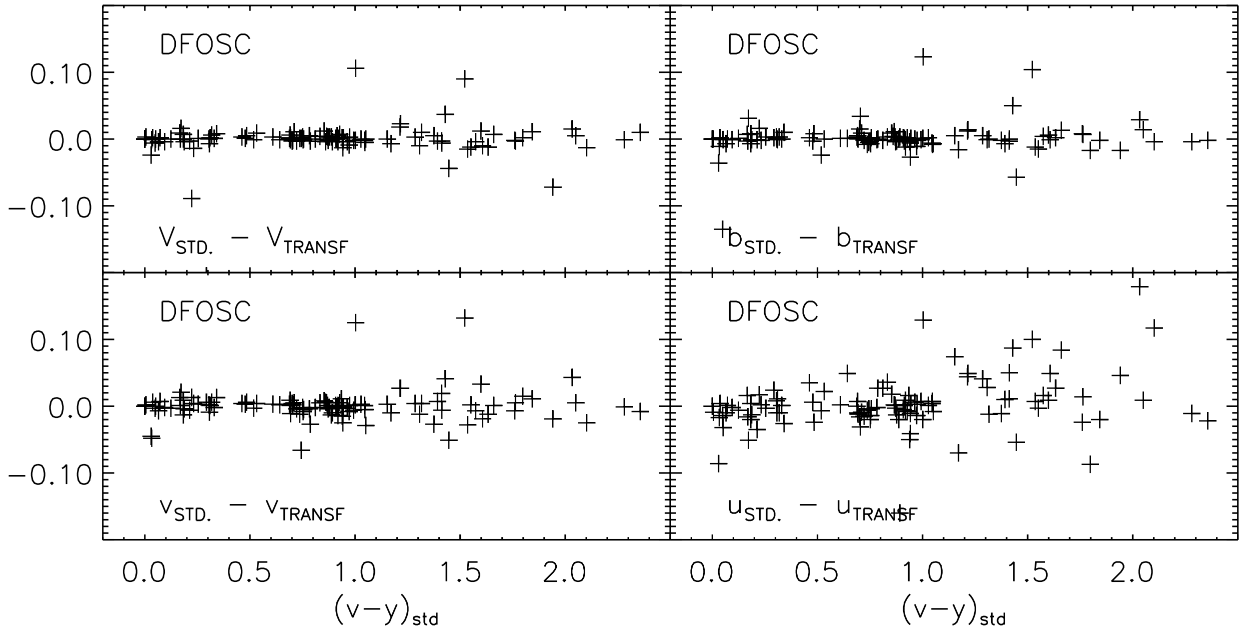


**Fig. 1.** The residuals in the transformation to the standard values for the *uvby* filters as a function of $(v - y)$. Note that there are no trends with colour for the *vby* filters. The *u* filter has somewhat enhanced scatter, especially at the reddest colours.

**Table 3.** Scatter in residuals for std. star transformation.

| Filter | NOT | DFOSC |
|---|---|---|
| *y* | 0.006 | 0.007 |
| *b* | 0.006 | 0.008 |
| *v* | 0.008 | 0.010 |
| *u* | 0.011 | 0.013 |

type instrument. However, as previously mentioned, the vignetting of the field by the undersize filters caused the regions of worst PSF variation (CCD corners) to be excluded from our analysis.

After generating the PSFs we derived positional transformations between a master image and all other images of a given field (DAOMATCH), and subsequently a master list of stellar objects was derived using DAOMASTER. This was then fed to ALLFRAME (Stetson 1994) for the derivation of the final profile fitting photometry.

Due to variations in seeing and focus it is necessary to correct the profile fitting photometry to an "absolute" system (Stetson 1990) such that the photometry for the cluster and standard stars have the same photometric zeropoint. To achieve this, we selected the 40 brightest unsaturated stars in each frame and subtracted all other measured stars from that frame. Following this we derived concentric aperture photometry to large radii and used DAOGROW (Stetson 1990) to derive aperture growth curves and arrive at "total" magnitudes for the 40 stars. The difference between the profile fitting photometry and the DAOGROW "total" magnitude for these was then adopted as the "aperture correction." Typical errors (standard error of mean) for an image are 0.001–0.003 mag.

In Figs. 2 and 3 we show the estimated photometric standard errors for the two clusters as a function of $V$ magnitude for each of the *uvby* bands. It is obvious from these plots that the M 71 data have a higher internal precision and reach fainter apparent magnitudes than the 47 Tuc data. This is because of the larger telescope used and the significantly (factor ~2) better seeing for this cluster.

## 3. Accuracy of transformation to the std. *uvby* system

Since there have been no large scale CCD or photoelectric observations of these clusters in *uvby* we cannot do a rigorous check on our photometry for them; below we shall attempt to carry out indirect comparisons to other *uvby* photometric investigations.

### 3.1. IC 4651

As part of our observing program for 47 Tuc we also observed the open cluster IC 4651, which has previously been observed photoelectrically in *uvby* by Nissen (1988). This allows a check of our transformation to the standard system. We have 10 stars in common with Nissen's objects, and a comparison is shown in Fig. 4. As can be seen from this figure there are small systematic differences no larger than 0.01 mag for $V$, $(b-y)$ and $m_1$ whereas it is of order 0.02 mag in $c_1$. We note that our observations on photometric nights for this cluster consists of 1, 2, 2 and 3 exposures in the $y$, $b$, $v$ and $u$ filters respectively, and are thus subject to uncertainties in the determination of the photometric zeropoints for each frame (aperture corrections). As noted above, 47 Tuc has many more observations on photometric nights. The observations by Nissen (1988) only included stars very near the turnoff of IC 4651, so the span in colour is not large enough to reveal whether the offsets show any trends with the colour of the stars. Given the limited number

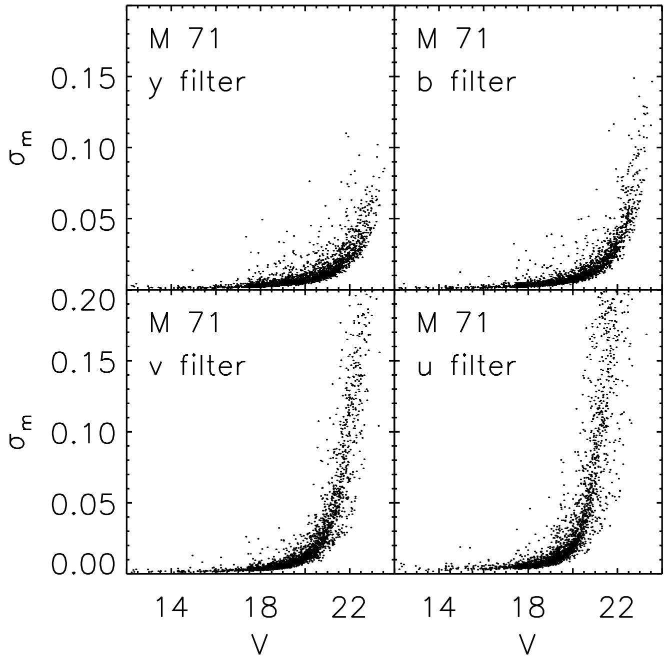


**Fig. 2.** The photometric precision for ≈2700 stars in M 71 with absolute values of *Sharp* $\leq 0.05$. *Sharp* is a DAOPHOT parameter which measures how well the shape of the model PSF matches the star it is being fit to. A good fit has a low absolute value of *Sharp*.

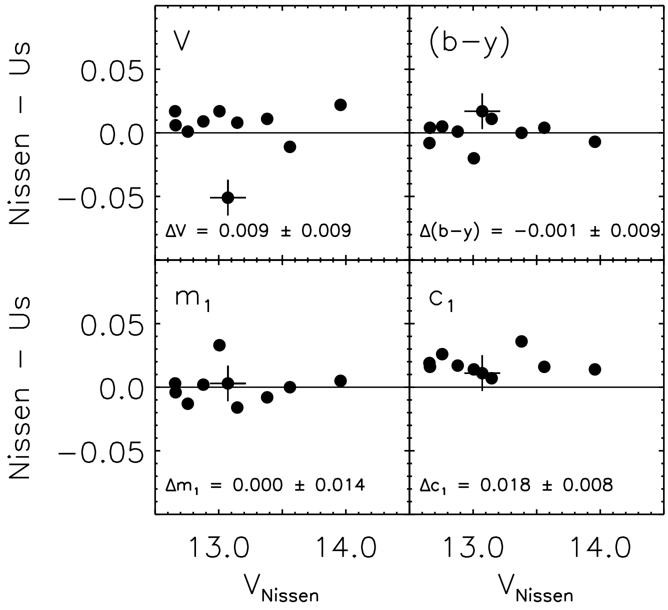


**Fig. 4.** The difference in our *uvby* photometry and that of Nissen (1988) for IC 4651. One star which was found to have a close neighbour in our images has been flagged with a separate symbol (+) and is not included in the calculation of the mean offsets and standard deviations indicated in the plots.

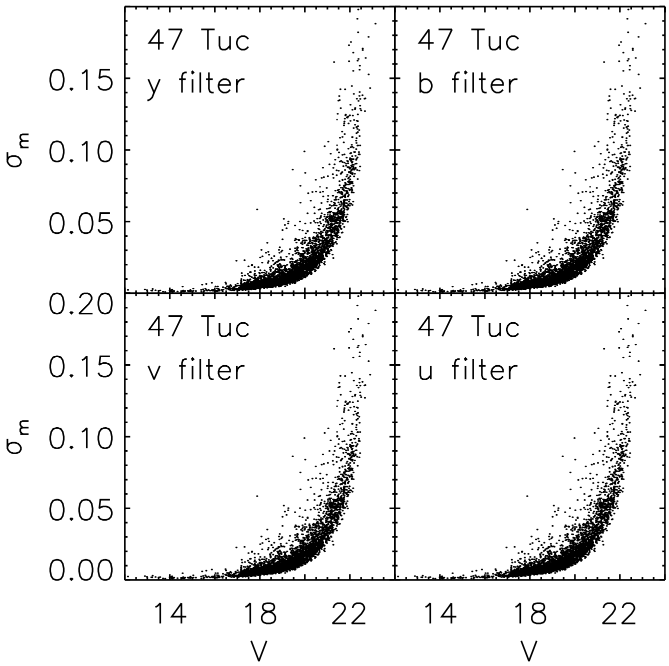


**Fig. 3.** Same as previous figure, except for ≈3700 stars in 47 Tuc.

of observations of this cluster it is not possible to conclude whether the offsets in the various filters are due to systematic errors in the derived photometric transformations or to errors in the aperture corrections. We emphasize that our IC 4651 data have *not* been included in the derivation of our photometric calibration equations; thus this comparison is completely independent of Nissen's (1988) photometry.

### *3.2. 47 Tuc*

While we are not aware of any previously published *uvby* photometry for this cluster, one of us (PBS, unpublished) has re-reduced a large body of *BVI* CCD data for 47 Tuc, including extensive standard star data (Stetson 2000), allowing us to compare our $V$ photometry from transformed $y$ to true broadband $V$. This comparison is shown in Fig. 5 and includes 1078 stars in common. The mean offset between the two $V$ scales is $V_{\rm US} - V_{\rm PBS} = -0.0079$, which we regard as very satisfactory since the filters, CCDs and standard stars employed are completely different. The magnitude differences show no trends with colour or magnitude.

In an attempt to further check our 47 Tuc calibration we compiled from the literature $(B-V)$ photometry and reddenings for the subdwarf stars in R98 and those selected for this study. This allows us to compare the $(B-V)_0$ vs. Strömgren colour relation for field and cluster stars. The $(B-V)$ photometry for 47 Tuc is from the unpublished photometry mentioned above. We show the results in Fig. 6. Here the cluster photometry is plotted as small grey points, and the subdwarfs as black + (R99) and • signs (this study). We see that the $(B-V)_0$ vs. $(b-y)_0$ and $(B-V)_0$ vs. $(v-y)_0$ relations for the field and cluster agree very well. For $(u-y)$ there seems to be some systematic deviation for the reddest stars; however, this is of no importance for the results obtained in this paper. Note that the subdwarfs selected for this plot span the range from −1.0 to −0.5 in [Fe/H] in order to be compatible with the cluster photometry.

In summary, our *vby* photometry for 47 Tuc seems accurately calibrated with likely errors of order 0.01 mag or less. The error in our $u$ photometry is probably of order 0.02 mag.

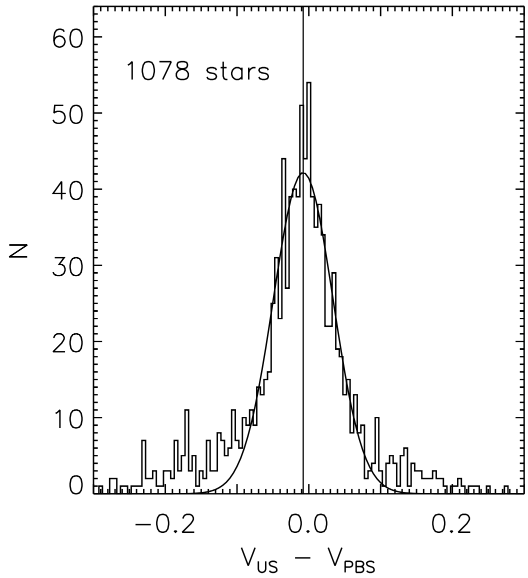


**Fig. 5.** Histogram of the difference in $V$ between this study and independently reduced broadband photometry (PBS). The centroid of the fitted Gausian is at −0.0079.

We cannot perform a similar test of our M 71 photometry since we did not observe clusters with independent *uvby* data during the run where this cluster was observed. However the indication from our standard stars is that our data should be well calibrated.

## 4. Presentation of the CMDs

In Fig. 7 we show the calibrated $(v-y, V)$ and $(u-y, u)$ colour–magnitude diagrams obtained from our data. In particular, we note that the lover main–sequence for M 71 appears very tight and well defined in the CMDs whereas the turnoff region seems slightly broadened in comparison. This is because the slope of the lower main–sequence in the $(v-y, V)$ and $(u-y, u)$ diagrams is very close to that of the reddening vectors: differential reddening tends to scatter stars *across* the turnoff and *along* the lower main squence.

There is a clear presence of stars from the Small Magellanic Cloud in the CMD of 47 Tuc. Fortunately the large difference in distance modulus renders this contamination unimportant for the present study. The level of the SMC red horizontal branch seems to be located at approximately $V = 19.55$ in these data.

The field star contamination for M 71 is more severe and despite the higher precision of the data the CMD seems less well defined near the turnoff than for 47 Tuc. The differential reddening across the face of the cluster is to blame for this. For both clusters the lower panels show that the brightest stars in the $u$ filter are those belonging to the red horizontal branch (RHB) even though the brightest RGB stars have much higher bolometric luminosities. We also note that in each cluster the width of the lower RGB seems rather large. This width is real and not caused by observational scatter, but is more likely due to star-to-star differences in CN strength and differential reddening for M 71.

## 5. Cluster parameters

Before we can derive absolute ages for the clusters it is necessary to estimate their reddenings and metallicities. As both are among the easiest observable metal–rich GCs, a number of studies have been published on this topic.

### 5.1. Reddening

The most commonly (Harris 1996) used value for the reddening of 47 Tuc is $E(B-V) = 0.04$. Crawford & Snowden (1975) determined a slightly lower value of $E(b-y) = 0.021 \pm 0.003$, (based on *uvbyβ* photometry of field stars near 47 Tuc) corresponding to $E(B-V) = 0.03$ but with a possible zero-point error of up to $E(b-y) = 0.013$. Recently Gratton et al. (1997) determined a value (also using *uvbyβ* photometry) of $E(B-V) = 0.055$ mag. It is also possible to estimate the reddening of the clusters using the recent Galactic reddening maps derived from the IRAS and COBE infrared sky surveys (Schlegel et al. 1998). From these maps one finds $\mathrm{E}(B-V) = 0.032$ for 47 Tuc.

The Schlegel et al. (1998) maps indicate a mean reddening of $\mathrm{E}(B-V) = 0.305$ for M 71, in good agreement with the value of 0.28 tabulated by Harris. Sneden et al. (1994) discuss various values for the reddening of M 71 and conclude that it is likely closer to $\mathrm{E}(B-V) = 0.3$ than 0.25 in good agreement with the value of 0.28 found by Hodder et al. (1992), also by a differential comparison to 47 Tuc. The case of M 71 is more complicated than this, however, as the Schlegel et al. maps reveal that the reddening is differential across the cluster. As mentioned earlier, this is the most likely explanation for the fact that our high-precision photometry is incapable of obtaining tight sequences for this cluster in any photometric band. During the same observing run where these data were acquired we also observed M 13 (Grundahl et al. 1998), which has a very low reddening, and for which we were able to obtain very tight photometric sequences (except in $c_1$ on the giant branch). From our multiple observations of both clusters we find that, if anything, the photometry for M 71 should be at least as precise as for M 13, but the scatter in the CMD suggests otherwise. In Fig. 7, showing the cluster CMDs, the reddening vector has also been overplotted, and clearly it is very close to being parallel to the unevolved main sequence of M 71 in both the $(v-y, V)$ and $(u-y, u)$ planes.

With independent and accurately calibrated photometry in hand for both clusters we can check whether our photometry is consistent with the above assessments of the mean reddenings. We proceeded by overplotting the CMD of M 71 on that of 47 Tuc, adding arbitrary shifts in colour and luminosity until we found the best match of the two sequences (which turned out to be very good, see below). We did this experiment for the $(b-y, V)$, $(v-y, V)$ and $(u-y, V)$ CMDs, and subsequently calculated what the measured offsets in each colour corresponded to in reddening difference. For the three colour combinations we found $\Delta E(B-V) = 0.236$ mag, 0.239 mag

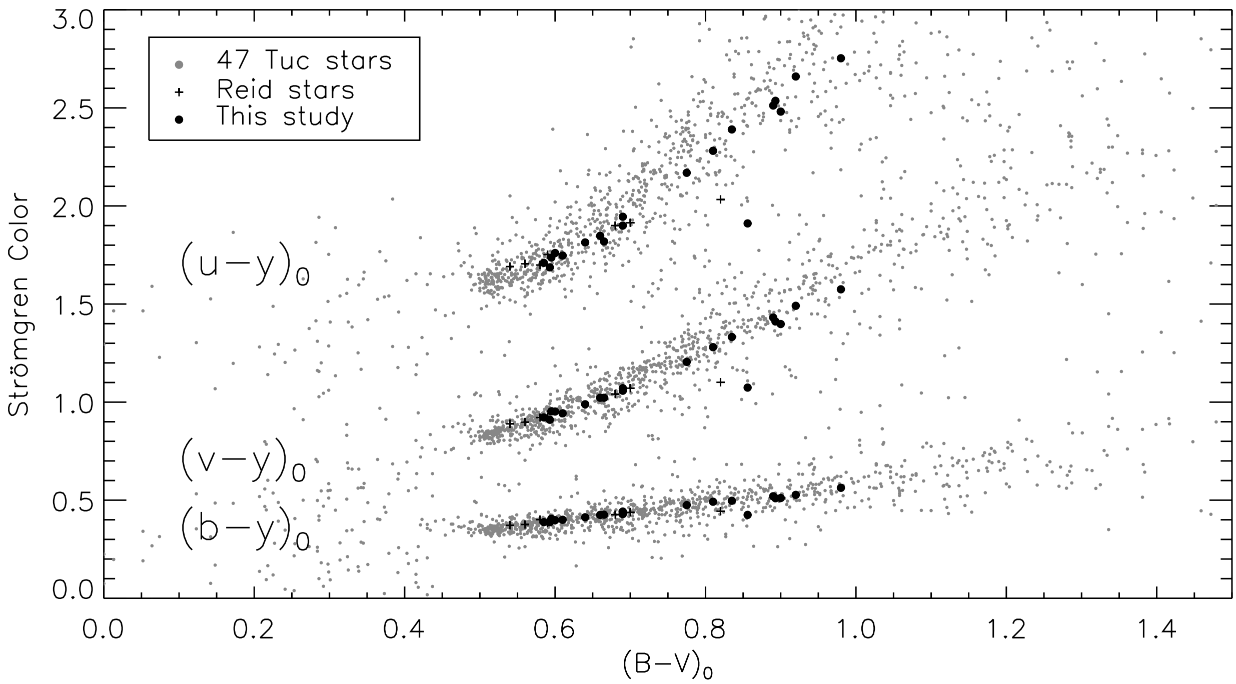


**Fig. 6.** Plot of the $(B-V)_0$ vs. Strömgren colour for field and cluster stars. The 47 Tuc photometry is from this study and the independently reduced *BV* photometry of PBS. $E(B-V) = 0.04$ has been assumed for 47 Tuc.

and 0.226 mag[1]. Henceforth we shall adopt a reddening difference of $\Delta E(B-V) = 0.235 \pm 0.01$ (giving slightly lower weight to the $u-y$ result in light of our IC 4651 comparison) for the difference in reddening between the two clusters. We note that in deriving these mean offsets we found that the differential reddening in M 71 made the registration of the clusters turnoffs slightly ambiguous depending on which region of the M 71 field was used for the comparison. In $(v-y)$ we found an approximate shift of 0.024 mag accros the field. Note that the excellent agreement with the Hodder et al. result for the shift in colour also suggests that our photometry for both clusters is at least as accurate as previously published data.

In conclusion, we shall adopt the "canonical" estimate of $E(B-V) = 0.04$ for 47 Tuc and $E(B-V) = 0.275$ for M 71 in the following. Note that our photometry does not provide essential new information on the absolute value for the cluster reddenings. The value adopted for M 71 depends directly on that used for 47 Tuc.

### 5.2. Metallicity

Several spectroscopic studies of both clusters have been published over the years. Roughly speaking the [Fe/H] values found range between −0.6 and −1.0, with most being close to −0.7. Recently, Rutledge et al. (1997a, 1997b) examined the metallicities for 71 GCs and derived new values on the Zinn & West (1984) and the Carretta & Gratton (1997) scales. They compiled a list of high-dispersion spectroscopic values (their Table 3) which includes 47 Tuc and M 71. From the discussion presented in that work a value of [Fe/H] = −0.70 for both clusters is reasonable for both the Carretta & Gratton and Zinn & West scales and other high-resolution studies. While the absolute metallicity scale for globular clusters may be uncertain by ~0.1 dex, our main purpose here is to stress that the available spectroscopic evidence for these two clusters argues for at most a small metallicity difference between them.

For the evolution of stars the abundance of iron is not the most important heavy element; rather, oxygen, nitrogen and carbon play the most significant role. M 71 was studied by Sneden et al. (1994); these authors found an average oxygen over abundance of [O/Fe] = 0.3. Similarly, Brown & Wallerstein (1992) reported fairly normal Population II abundances of the $\alpha$ elements of 47 Tuc and give [O/Fe] = 0.33. Thus, assuming the two clusters to have very similar heavy-element abundances seems reasonable.

### 5.3. [Me/H] from $m_1$

Schuster & Nissen (1989, SN89) derived metallicity calibrations based on *uvby* photometry of 711 high–velocity and metal–poor stars. As we have employed stars from their (and the Olsen 1983, 1984) study as standard stars their calibrations of [Fe/H] from the Strömgren indices can be applied. There are however several complicating factors when employing these to M 71 and 47 Tuc. Both these clusters are known to exhibit large star–to–star variations in the abundances of (at least) C and N among RGB and upper main-sequence stars (see Cohen 1999; Cannon et al. 1998). These abundance variations could affect both the $u$ and $v$ filter, and thereby the photometric metallicity estimate. This will cause an increased scatter when determining [Me/H] from photometric indicators

[1] Using $A_V = A_y = 3.1E(B-V)$ ; $E(b-y) = 0.7E(B-V)$, $m_0 = m_1 + 0.2\,E(b-y)$ and $c_0 = c_1 - 0.2\,E(b-y)$, we find that: $E(v-y) = 1.19\,E(B-V)$ and $E(u-y) = 1.82\,E(B-V)$.

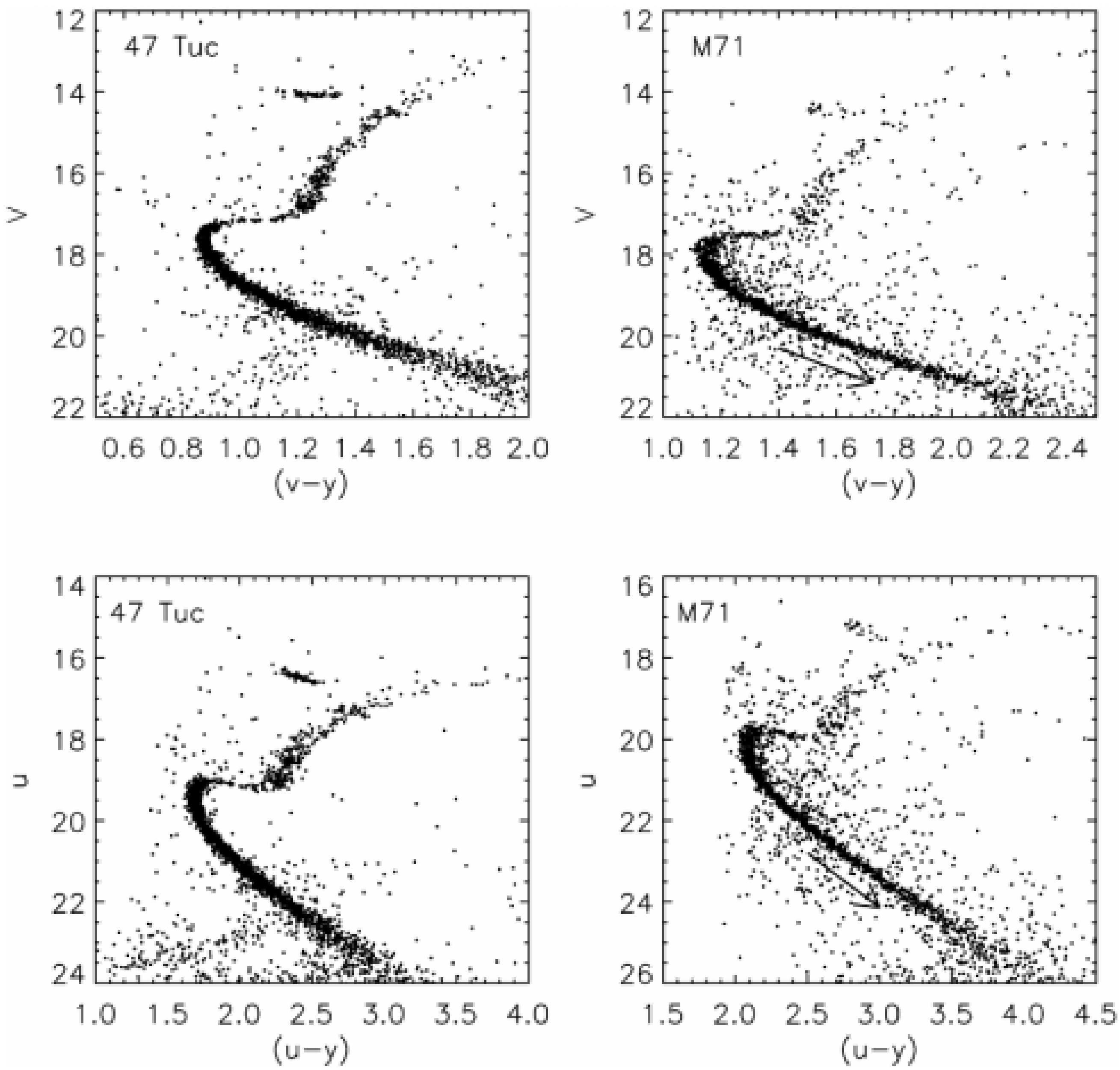


**Fig. 7.** The calibrated $v - y, V$ and $u - y, u$ colour–magnitude diagrams for 47 Tuc (left hand panels) and M 71 (right hand panels). We note that for both clusters the CMDs are very well defined 3–3.5 magnitudes below the turnoff allowing good main–sequence fits to be obtained using *Hipparcos* stars. One unusual point to note from the lower panels is that in the $u$ band the red horizontal–branch stars are as bright as the brightest RGB stars. In the righthand panels the reddening vectors have been overplotted. Stars with more than ten measurements in the $y$ filter and a ratio of observed to expected scatter less than 1.5 are included in the plots. Furthermore, it was required that for 47 Tuc those brighter than $V = 16.9$ should have absolute values of the DAOPHOT parameter *SHARP* less than 0.2. For M 71 the corresponding numbers are 17.25 and 0.1, respectively.

which – if the enhancements of these elements are different from field stars – will cause errors in the determination of cluster metallicities. Note that one does not really determine [Fe/H] from *uvby* photometry, but rather the integrated effect of various metals (many weak lines and molecular bands) primarily in the $v$ filter.

A raw application of the SN89 calibrations leads to histograms of the metallicity distribution peaked at −0.9 and −0.62 for M 71 and 47 Tuc, respectively. We suspect that this difference (if the cluster abundances are indeed identical) is at least partly due to effects of differential reddening in M 71: a change of the reddening from $E(B - V) = 0.275$ to 0.29 changes the derived mean [Fe/H] value from −0.9 to −0.75. If our photometric errors are negligible then this would argue for a reddening closer to $E(B - V) = 0.3$ for this cluster.

Based on high–resolution spectroscopy for a sample of 99 stars Clementini et al. (1999, CGCS) derive a relation between their spectroscopic [Fe/H] values and the photometrically derived values from SN89:

$$[\mathrm{Fe/H}]_{\mathrm{CGCS}} = [\mathrm{Fe/H}]_{\mathrm{SN89}} + 0.102(\pm 0.012),\ \sigma = 0.15$$

where $\sigma$ denotes the dispersion, not the standard error of the mean. From the CGCS study and that of Carretta & Gratton we expect that the metallicity of 47 Tuc based on the SN89 calibration should be –0.8 dex. Given that we determine approximately –0.62 for stars in the TO region the agreement with CGCS is acceptable. Again we caution that the known CN scatter in 47 Tuc (which is also found on the MS) – which is consistent with the $c_1$ scatter that we observe on the subgiant branch – will probably distort the derived Strömgren metallicities.

In summary we will assume that the clusters have identical [Fe/H] of −0.70, on the CGCS scale, as well as identical enhancements of the $\alpha$ elements, [$\alpha$/Fe] = 0.3, as indicated by the high-resolution spectroscopic studies of individual cluster giants. When selecting subdwarfs for determining MS distances we shall however take into account the possible offset of 0.1 dex between the photometrically and spectroscopically derived abundances.

## 6. Relative ages

In order to compare the CMDs of the two clusters we derive the fiducial for 47 Tuc and compare it to the observed CMD for M 71. We derived the fiducial by first plotting a $(v-y, V)$ colour magnitude diagram using only the best measured stars. Then a fiducial was drawn by hand. For each star in our photometry list we then calculated the distance in $(v-y)$ colour from the fiducial curve. For stars brighter than $V = 16$ only those with a distance less than 0.1 mag in $(v-y)$ from the hand-drawn fiducial were selected. For the fainter stars this limit was set at 0.25 mag; we further required for the fainter stars that the ratio of the observed frame-to-frame photometric scatter to the expected average scatter at the stars' magnitude was less than 3. Using these stars, we then calculated robust average points in 0.125 mag $u$, $v$, $b$ and $y$ bins, in such a way that the same stars were used for each of the 4 filters to define fiducial points.

Having photometry in four bands allows a wide variety of comparative plots, but we shall not go through all of these here. Instead we shall focus on a comparison of the cluster loci in the $(v-y, V)$ and $(u-y, u)$ planes. Traditionally, $(b-y)$ has been used as the temperature indicator for Strömgren photometry. After some experimenting (including with clusters of very different metallicities) we find that the $(v-y, V)$ plane offers by far the best means for comparing cluster CMDs, primarily due to the higher sensitivity to temperature of the $v-y$ index compared to $b-y$; ostensibly $u-y$ offers a still longer wavelength baseline, but it turns out that due to the increasing strength of the Balmer convergence and jump in the $u$ filter (Grundahl et al. 1999b), $u-y$ is not a good $T_{\rm eff}$ indicator near the TO. Using $v-y$ as the principal temperature index also reduces the slope of the main sequence in colour magnitude diagrams. For instance, in the $(B-V, V)$ diagram both the main-sequence slope and the reddening vector slope are between 4 and 5 for stars fainter than $\sim 2$ magnitudes below the turnoff, whereas they are closer to 2.5 for $(v-y, V)$. For comparison, the slope is 2.65 in $(u-y, u)$.

Figure 8 shows the comparisons in the two colour–magnitude planes. There is clearly a very good agreement between the CMDs of the two clusters. In the left-hand panel the 47 Tuc fiducial follows the observations of M 71 almost perfectly, from the brightest RGB stars to our faint limit on the main-sequence. The location of their red HB populations also agrees remarkably well. Thus if the cluster abundances are indeed identical then their age difference is very small – less than 10%. From the righthand panel we reach the same conclusion. It is evident that the 47 Tuc $u$ fiducial does not extend as deep as our M 71 photometry, resulting in the bend in the 47 Tuc fiducial at $u > 24$. This bend is the usual consequence of an unavoidable tendency to measure the faintest stars too bright (Stetson & Harris 1988; Stetson 1991); since the magnitude limit is more severe in $u$ than in $y$, the faintest detected stars are measured too blue.

## 7. Main sequence distances

In order to derive an absolute age using isochrone fitting we first need to estimate the cluster distances. With the emergence of the *Hipparcos* database we now have a much larger sample of stars with good parallaxes available for the application of the main–sequence fitting technique. Before proceeding to derive the distances we first address the selection of the subdwarf sample to be used.

### 7.1. Subdwarf selection and biases

Olsen (1983, 1984 and private communication; hereafter referred to as EHO) has produced a large catalog of accurate and homogeneous $uvby\beta$ photometry of more than 30 000 stars in the northern and southern hemispheres (these were also the stars used as our "standard" stars). We derived the reddening and metallicity of every star in this catalog using the calibrations of SN89. Further, we then matched the $uvby\beta$ catalog with the *Hipparcos* database to calculate the absolute magnitude of each star. This sample was then supplemented with stars from the lists of Schuster & Nissen (1988) and Lebreton et al. (1999). For the Lebreton et al. stars we adopted the photometry from Olsen.

Since we have adopted [Fe/H] = −0.70 on the CG spectroscopic scale for the metallicity of the clusters, we have $[{\rm Fe/H}]_{uvby} = -0.8$, given the offset determined by CGCS. The approximate 1-$\sigma$ error in the photometric metallicity determination is 0.15 dex, and we shall adopt a working interval in metallicity ($uvby$ scale) between −0.95 and −0.65 dex, corresponding to $[{\rm Fe/H}]_{\rm Cluster} \pm 1\sigma$. Furthermore we require the relative parallax error, $\sigma(\pi)/\pi$, to be smaller than 0.08 and $M_V$ greater than 5.2 to minimize Lutz-Kelker corrections and avoid problems with evolved stars. This leads to a total sample of 18 stars as listed in Table 4. Stars with "—" as an entry in column 7 do not have H$\beta$ photometry. The stars from the EHO and SN88 samples were required not to have the flags for variability or multiplicity set in the *Hipparcos* main catalog. Due to the strict limits on $\sigma(\pi)/\pi$ the median distance for the stars in the sample is only 40 pc, with a median reddening (from the $uvby\beta$ photometry) of $E(b-y) = 0.006$ for the 11 stars with H$\beta$ measurements. Given a scatter of ~0.015 mag in the SN89 calibration of $E(b-y)$ we will not correct our sample for reddening.

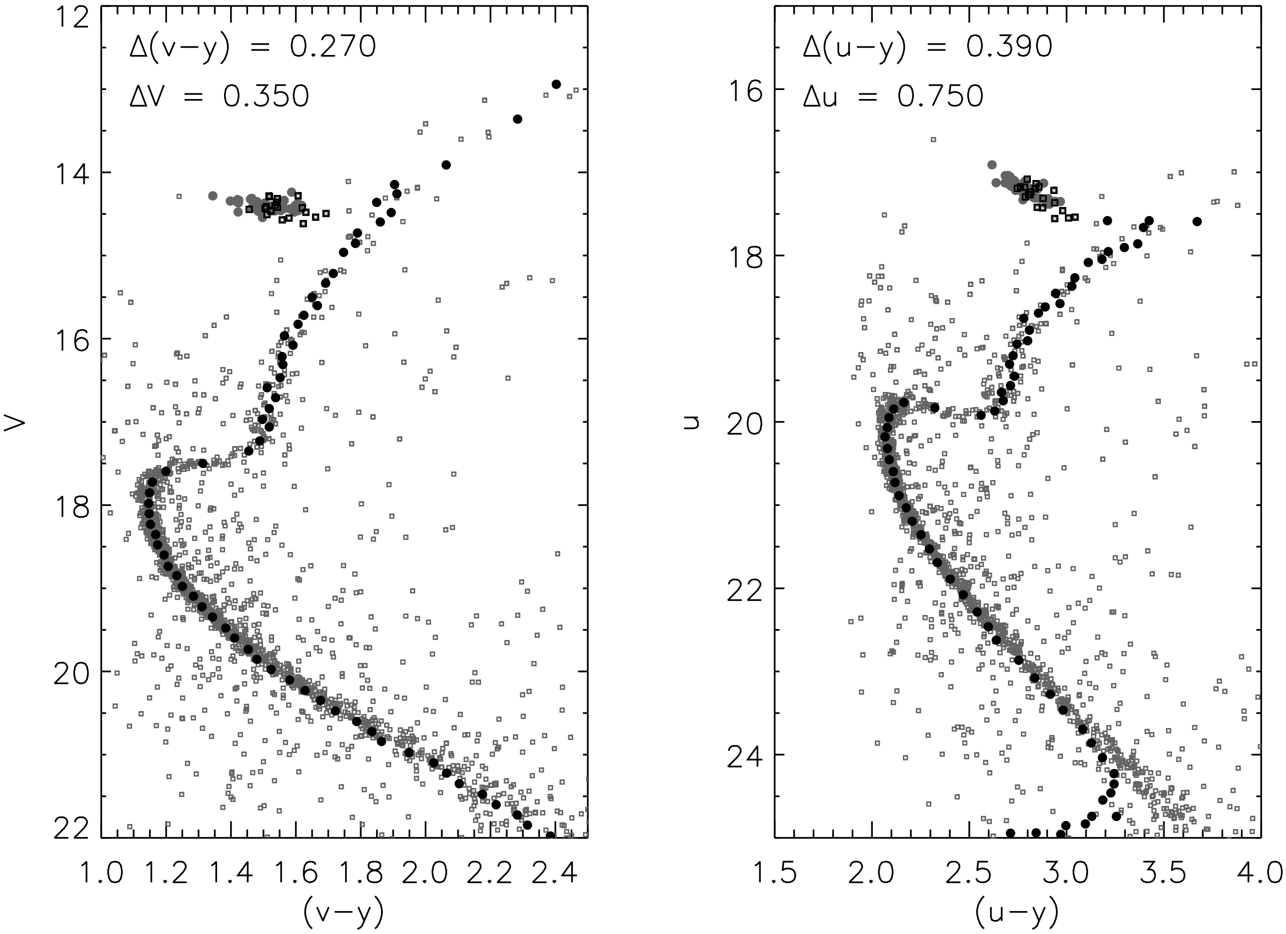


**Fig. 8.** Comparison of the derived 47 Tuc fiducial (*filled black circles*) with the observations of M 71 (*grey squares*) in the $(v-y, V)$ and $(u-y, u)$ diagrams. The offsets applied to the 47 Tuc fiducial are indicated on the plots. Note that for the RHB stars we have plotted the M 71 stars as black squares and the 47 Tuc stars as filled grey circles in order to make the agreement more visible. Note that for both clusters we have plotted the individual RHB stars and not the fiducial.

As has been discussed in previous papers (e.g. Gratton et al. 1997; Reid 1997) on the determination of MS distances there are several possible sources of bias which may affect the determination of cluster distance moduli:

• Metallicity bias — ZAMS location

Since the frequency of field stars in the Solar neighbourhood rises steeply toward higher metallicities, it is conceivable that our sample of subdwarfs will be biased towards higher true effective metallicities due to the measurement errors in [Fe/H]. In order to estimate this effect we have carried out a simulation based on the following: a true metallicity distribution of 300 000 stars as observed in the EHO. From this we pulled 1000 random samples of 18 stars, with Gaussian noise corresponding to a measurement error of 0.15 dex in [Fe/H] added. The difference between the mean metallicity of this sample and the nominal interval midpoint was calculated. We found that for our target interval of −0.65 to −0.95 in [Fe/H] the mean difference between the sample average and the midpoint of the interval (viz. −0.80) was 0.044 dex, in the sense that the sample was more metal rich than the midpoint of the selection range. Note that the average metallicity of our 18 star sample is −0.768, slightly higher than our interval midpoint, as expected from the simulation.

In order to estimate the effect of this offset on our derived distance modulus we have measured the displacement of the Zero Age Main-Sequence (ZAMS) as a function of [Fe/H] at constant colour using the VandenBerg et al. (2000) isochrones. We assumed a colour of $(B-V) = 0.7$, which corresponds roughly to $M_V = 6.0$ on the 47 Tuc main sequence. We found a slope of −1.114 in this relation; thus our metallicity offset of 0.044 dex corresponds to a bias of 0.05 mag in the sense that our derived distance moduli are too large by this amount. At $(B-V) = 0.6$ the slope is −1.21 giving an offset of 0.053 mag. We will use a value for the offset of 0.05 mag in the following.

As an example of the metallicity bias discussed above, we show in Fig. 9 the MS of 47 Tuc shifted by $(m-M)_V = 13.35$. Each of the four panels contain stars in the metallicity interval and with relative parallax errors as indicated on the plot. It is obvious that increasing the mean sample metallicity would lead to differences in the derived distance moduli.

• Lutz-Kelker corrections

As we have imposed a limit of $\sigma(\pi)/\pi \leq 0.08$ in this investigation, the luminosity corrections due to "Malmquist bias" are very small. Adopting the relation given in R97 (Lutz & Kelker 1973 and Hanson 1979) we find the largest corrections to be

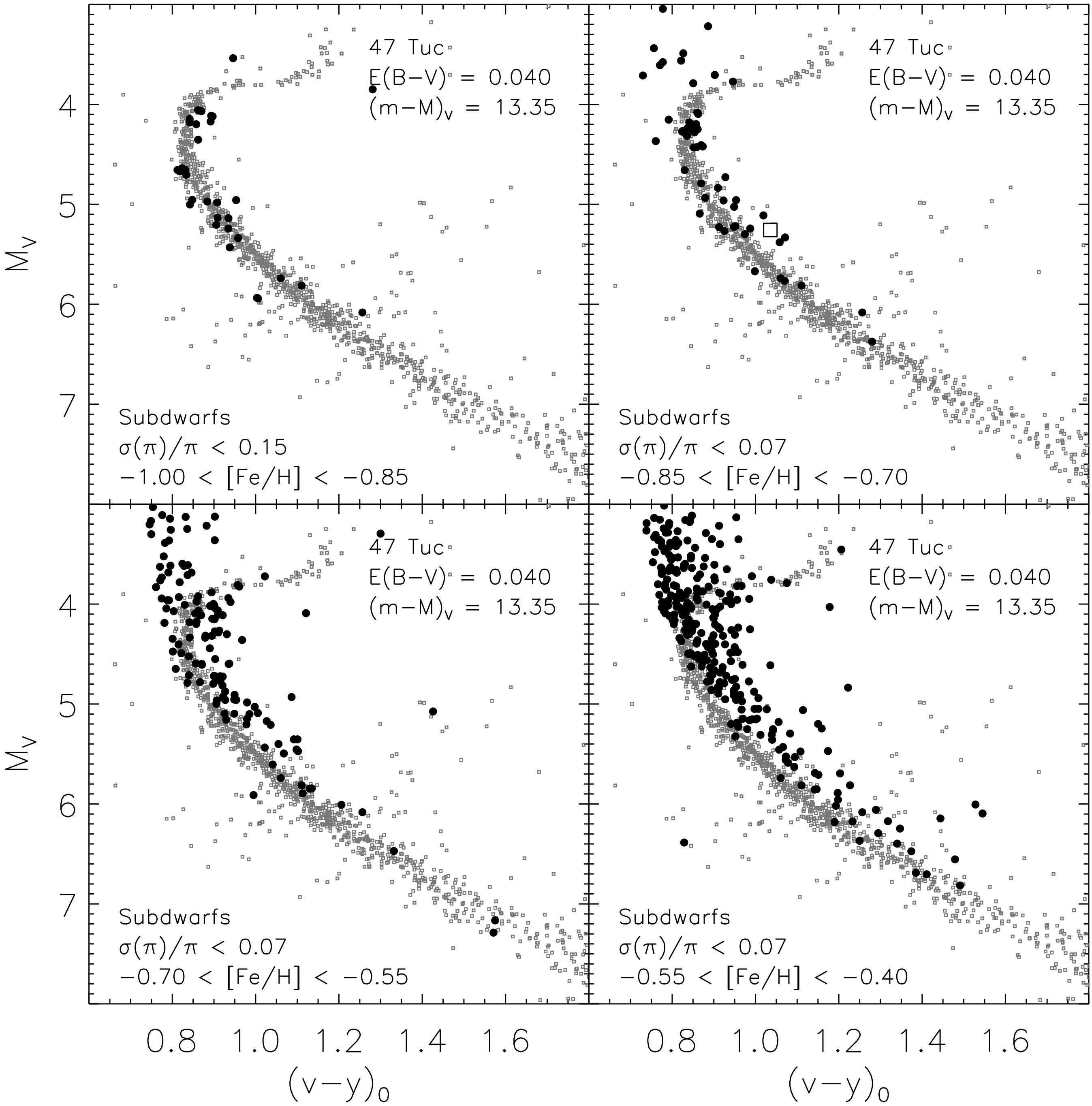


**Fig. 9.** A comparison of the main–sequence of 47 Tuc to the main–sequence defined by local subdwarfs with accurate *Hipparcos* parallaxes. The selection criteria for each panel are indicated in the plot. In each panel subdwarfs with metallicities based on *uvby* photometry has been plotted. The effect of changing the mean metalllicity for the sample is clearly seen. The odd location of HD224930AB (open square, upper righthand panel) is due to its binarity, as both components were included in the aperture for the photoelectric photometry.

−0.05 mag. The median correction is −0.018 mag, but we have added the corrections appropriate to the invididual stars.

• Binarity among the subdwarf sample

It is necessary to check the stars in our selected subdwarf sample for binarity. The presence of faint companions to the stars will tend to "drag" them redward and brightward from the true ZAMS, leading to an overestimate of the cluster distance modulus. Therefore, any information on the binarity of the stars must be used to minimize this bias. We have not checked any of the stars from Lebreton et al. for binarity as this has already been done by these authors. We note however, that HD 224930 is an astrometric binary and we omit it from our sample as the value for the $M_V$ magnitude listed by Lebreton et al. (1999) does not agree (0.4 mag difference) with that given by, e.g., Stetson (1991) and other *uvby* determinations. We note in passing that had we employed this star it would have been located well above the main-sequence (Fig. 9, upper righthand panel) for the two clusters, given the distance we derive. HD 6582 is a

**Table 4.** Field subdwarfs used in MS fitting.

| HD | HIP | $V$ | $(b-y)$ | $m_1$ | $c_1$ | $\beta$ | $M_V$ | $\sigma(M_V)$ | $\pi$(mas) | $\sigma(\pi)$ | $\sigma(\pi)/\pi$ | [Fe/H] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 967 | 1128 | 8.375 | 0.413 | 0.163 | 0.249 | 2.561 | 5.247 | 0.109 | 23.68 | 1.19 | 0.050 | −0.75 |
| 5817 | 4966 | 8.452 | 0.398 | 0.156 | 0.254 | — | 5.219 | 0.070 | 22.56 | 0.73 | 0.032 | −0.71 |
| 6582A | 5336 | 5.159 | 0.438 | 0.195 | 0.210 | 2.554 | 5.768 | 0.010 | 132.40 | 0.60 | 0.005 | −0.81 |
| 11397 | 8674 | 8.950 | 0.425 | 0.224 | 0.188 | 2.568 | 5.262 | 0.165 | 18.30 | 1.39 | 0.076 | −0.77 |
| 68089 | 39911 | 9.590 | 0.405 | 0.143 | 0.236 | 2.571 | 5.469 | 0.143 | 14.99 | 0.99 | 0.066 | −0.86 |
| 104006 | 58401 | 8.894 | 0.492 | 0.296 | 0.213 | — | 6.375 | 0.073 | 31.35 | 1.05 | 0.033 | −0.75 |
| 104800B | 58843 | 9.223 | 0.388 | 0.134 | 0.255 | 2.580 | 5.240 | 0.171 | 15.97 | 1.26 | 0.079 | −0.83 |
| 108564 | 60853 | 9.426 | 0.563 | 0.449 | 0.166 | — | 7.165 | 0.074 | 35.30 | 1.20 | 0.034 | −0.66 |
| 111777 | 62809 | 8.492 | 0.400 | 0.143 | 0.261 | 2.562 | 5.213 | 0.105 | 22.09 | 1.07 | 0.048 | −0.84 |
| 120559 | 67655 | 7.972 | 0.426 | 0.170 | 0.201 | 2.567 | 5.983 | 0.054 | 40.02 | 1.00 | 0.025 | −0.90 |
| 123505 | 69201 | 9.666 | 0.475 | 0.255 | 0.234 | — | 6.272 | 0.171 | 20.95 | 1.65 | 0.079 | −0.66 |
| 126803 | 70829 | 8.934 | 0.429 | 0.200 | 0.213 | — | 5.381 | 0.145 | 19.47 | 1.30 | 0.067 | −0.75 |
| 134088 | 74067 | 8.000 | 0.388 | 0.146 | 0.254 | 2.576 | 5.258 | 0.080 | 28.29 | 1.04 | 0.037 | −0.75 |
| 145598 | 79576 | 8.652 | 0.425 | 0.172 | 0.229 | 2.569 | 5.730 | 0.112 | 26.04 | 1.34 | 0.051 | −0.73 |
| 147127 | 80221 | 8.294 | 0.442 | 0.187 | 0.245 | — | 5.332 | 0.093 | 25.56 | 1.09 | 0.043 | −0.76 |
| 155284AB | 84255 | 8.900 | 0.445 | 0.223 | 0.226 | — | 5.894 | 0.110 | 25.05 | 1.27 | 0.051 | −0.66 |
| 204521 | 105766 | 7.286 | 0.396 | 0.139 | 0.253 | 2.565 | 5.234 | 0.032 | 38.86 | 0.58 | 0.015 | −0.88 |
| 224930AB | 171 | 5.748 | 0.428 | 0.189 | 0.215 | 2.563 | 5.280 | 0.082 | 80.63 | 3.03 | 0.038 | −0.76 |

spectroscopic binary consisting of a G5V and a M6V star (Hale 1994), which probably only has a minor effect on its observed properties in *uvby* so we shall keep it in our sample.

In summary, we find that the strict selection criteria, lead to only a very small bias due to the errors in the determination of metallicities. Our derived distance moduli should also be very little affected by other biases.

### 7.2. Main sequence fits

In Figs. 10 and 11 we show our fits to the main sequences for 47 Tuc and M 71 using the same subdwarf selection criteria for both clusters. Note that only subdwarfs with $M_V \geq 5.2$ have been included (filled black circles) in the derivation of distances. We required the parallax errors to be less than 8% and $[\mathrm{Fe/H}]_{uvby}$ to be in the −0.65 to −0.95 interval. As a further "sanity check" we have also plotted as small black circles stars with $M_V < 5.2$, but we stress again that these are not used in the distance determination. For each subdwarf we calculated the difference between the apparent magnitude of the cluster main sequence (represented by a polynomial) and the absolute magnitude of the subdwarf, at the colour of the subdwarf. This results in an estimate of the cluster distance modulus from each subdwarf. In order to construct the histograms shown in the inserts, each derived value of the distance modulus is represented by a Gaussian of unit height and sigma equal to the error in $M_V$ based on the relative parallax error of the subdwarf. All Gaussians are then added, resulting in the smoothed histograms shown. In the plots we have also indicated, as + signs, the sample of stars from Table 1 in R98, in the metallicity interval (R98 values) between –0.9 and –0.45 and with $M_V$, as given by R98, larger than 4.75. The offset in metallicity between the two samples is $\Delta[\mathrm{Fe/H}] = -0.08 \pm 0.12$ (29 stars), in the sense (R98-*uvby*). (Note that the sample of R98 stars plotted here will not look completely identical to that in Fig. 8 of R98, since their $(B-V)_0$ colours were corrected to a mono–metallicity sequence. Such corrections have not been applied to any of the stars employed in this study.) The stars brighter than $M_V = 5.2$ do not provide any strong constraint on the cluster distances since they are so close to the TO region where the locus is nearly vertical. The distance moduli indicated in the plots were determined by fitting a Gaussian profile (shown as a dashed line) to the main peak in the inset histogram. We find $(m-M)_V = 13.38$ for the distance modulus of 47 Tuc (this includes Lutz-Kelker corrections) and 13.76 for M 71. Correcting for the metallicity bias gives $(m-M)_V = 13.33$ and 13.71, respectively.

### 7.3. Errors

We shall now assess the magnitude of the uncertainties in the main sequence fitting performed here. It is important to distinguish between random and systematic errors. Random errors arise from uncertainties in the photometry of the field subdwarfs and the effect of these is seen directly in the width of the generalized histograms for 47 Tuc and M 71 in Figs. 10 and 11. Here we find widths (from the Gaussian fits) of $\sigma = 0.14$ mag for both clusters. Since we excluded the stars at high distance moduli in the fits the effective number of stars used was 14, hence the uncertainty in the location of the centroid is 0.039. The uncertainties due to the photometric precision for the cluster stars are negligible due to the large number of stars. The value of $\sigma = 0.14$ mag is consistent with the dominant "broadening factors" being parallax uncertainty (the median $\sigma(\pi)/\pi$

is 0.048 giving $\sigma(M_V) \approx 0.10$ mag) and random errors in the metallicity of order 0.10 dex[2], which multiplied with the metallicity sensitivity of the ZAMS location translates into ~0.11 mag. Added in quadrature this gives ~0.15 mag, consistent with the fitting result. Note that the contribution from reddening errors will be small compared to these numbers. Furthermore, the fact that we can reproduce the width indicates that the contribution from unrecognized double stars must be quite small, as both the estimate of the parallax and metallicity errors are very reasonable.

The systematic errors arise from the Lutz-Kelker and metallicity bias and were found to be +0.018 mag and −0.05 mag in the value of $(m - M)_V$ as mentioned above. The error in these estimates is less than 0.01 mag. Further sources of systematic errors are the estimate of cluster reddenings, photometric zeropoints and the zeropoint error of the globular cluster metallicity scale, relative to the subdwarf scale. The error due to an incorrect reddening was simply estimated by repeating our distance determination for different values of the reddening, with $E(B - V) = 0.025$ mag and 0.055 mag as the extremes. This leads to: $\Delta(m - M)_V = 4\,\Delta E(B - V)$ and $\Delta(m - M)_0 = 1.5\,\Delta E(B - V)$. A realistic uncertainty in the reddening for 47 Tuc is 0.015 mag giving an uncertainty of 0.06 mag in the apparent distance modulus. Similarly we find, that for a photometric *accuracy* of 0.01 mag in $V$ and $(v - y)$ the error in the apparent modulus is 0.04 mag (an error in $(v - y)$ mimics an error in the reddening). There is a further possible source of error, in that there may be a metallicity offset between the field-star and GC scales which could arise because most cluster metallicity determinations for GC are done for the brightest RGB stars, so that we are in effect comparing RGB abundances to MS abundances. It is not entirely clear whether the state of current model atmospheres is such that systematic errors are smaller than 0.1 dex so, lacking any more specific information on this point, here we will simply *assume* that possible non-equivalence of RGB and MS metallicity scales contributes 0.1 dex to the overall error budget[3]. We note, that the differences in CN strength between the cluster and field stars could also add a small error that mimics a metallicity error. In Table 5 we have summarized these numbers. Adding them in quadrature leads to a total systematic error of 0.13 mag. Thus, we see that the error in [Fe/H] is by far the most important one through its effect on the location of the ZAMS. We note that this estimate is based on the VandenBerg et al. (2000) models, and may thus be subject to revision if improved models become substantially different. Furthermore we estimated the ZAMS location at a fixed $(B - V)$ as isochrones transformed to *uvby* for a wide metallicity interval are not yet available to us; this may also cause some additional uncertainty.

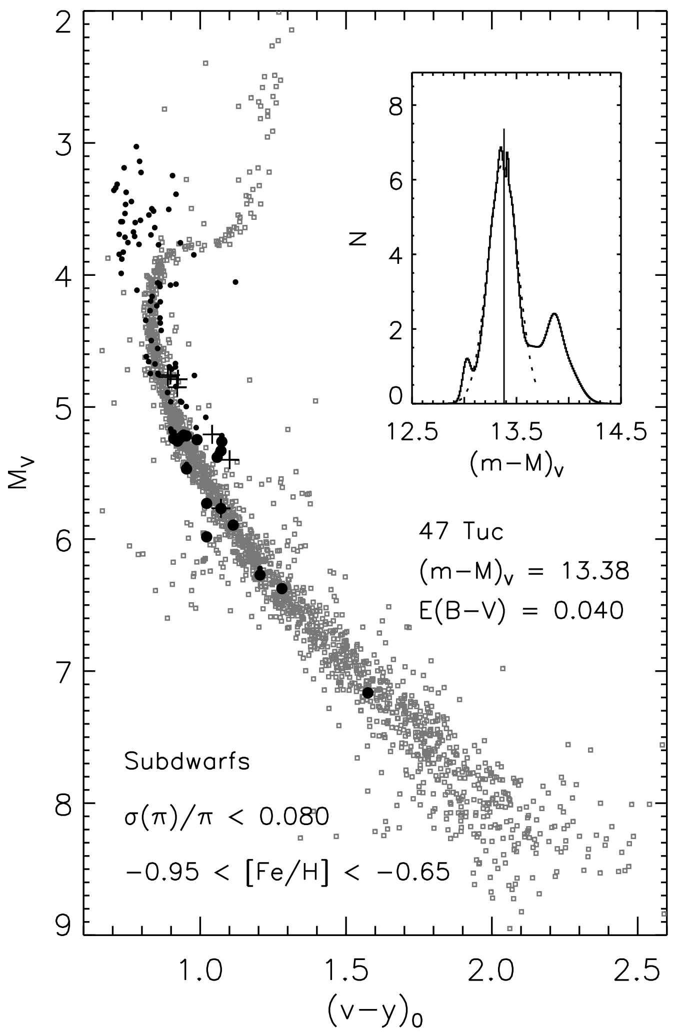


**Fig. 10.** Fit of the 47 Tuc main sequence to the main sequence defined by local subdwarfs with *Hipparcos* parallaxes and relative parallax errors less than 8%. The large filled circles are the stars used in deriving the MS distance, whereas the small circles are included as a "sanity check". Plusses are the stars from R98, which were were selected to have [Fe/H] values between −0.90 and −0.45 (R98 values). The median parallax error for the R98 stars is 4%. The [Fe/H] values indicated on the plot refer to to values from *uvby* photometry.

## 7.4. ZAHB distance

We can also estimate the distance to 47 Tuc from the luminosity of its zero-age horizontal-branch (ZAHB). In Fig. 12 we have overplotted two ZAHB models (VandenBerg et al. 2000, kindly transformed to *uvby* by D. VandenBerg using the same Kurucz models as in Grundahl et al. (1998) on our 47 Tuc data for an assumed distance modulus of $(m - M)_V = 13.33$. We see that the agreement is better for the more metal-poor of the two models. In addition, we note that the agreement between our

[2] The scatter of 0.15 and 0.16 dex reported by CGCS and Schuster & Nissen (1989) is based on an "external" comparison between spectroscopically and photometrically determined abundances, while we are here concerned with the uncertainty due to photometric errors and errors in reddening. If we assume realistic uncertainties in the $(b - y)$, $m_1$ and $c_1$ indices for the field subdwarfs to be 0.005, 0.007 and 0.007 mag, and the uncertainty in the determination of $E(b - y)$ to be 0.01mag, then we find that the $1\sigma$ error in [Fe/H] is 0.10 dex for the SN89 calibrations.

[3] This estimate is probably an upper limit, since Gratton et al. (2001) have found excellent agreement between their abundances for turnoff stars in NGC 6397 and NGC 6752 and the values derived for giants by Carretta & Gratton (1997).

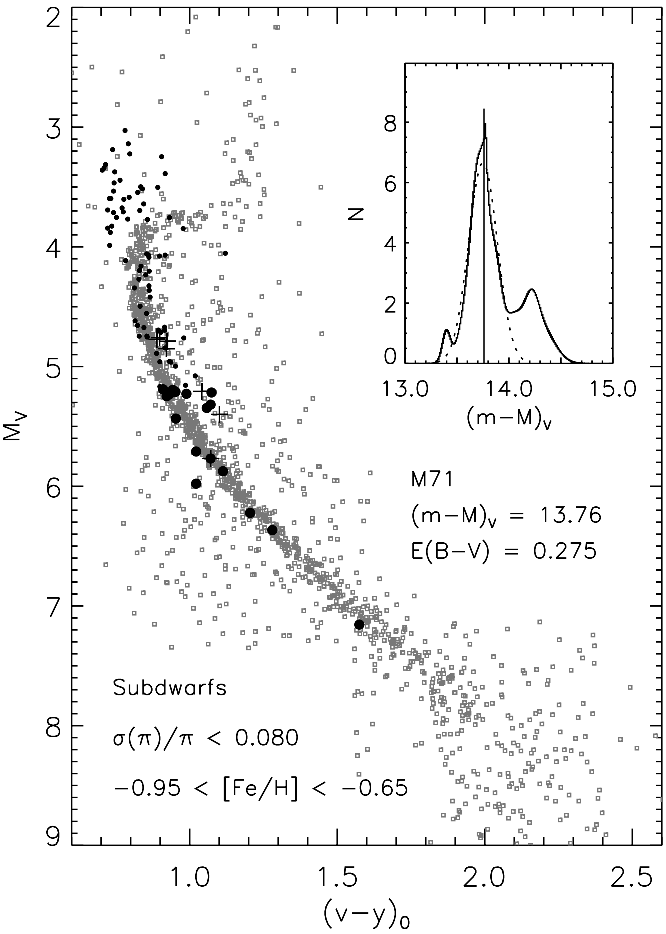


**Fig. 11.** Same as previous figure, only for M 71. Note the significant field stars contamination.

derived distance and the models is excellent, indicating that such ZAHB models are consistent distance indicators.

### 7.5. The $(B-V)_{M_V=6}$–[Fe/H] relation

Gratton et al. (1997) and Carretta et al. (2000) introduced a method for determining cluster distances using a relation between the $(B-V)$ colour at $M_V = 6$ and [Fe/H]. Their updated plot is shown in Fig. 3 of Carretta et al. (2000). Assuming a metallicity of –0.70 for 47 Tuc we estimate the corresponding value of $(B-V)_0$ to be 0.71±0.02. From Fig. 6 we find that $(v-y)_0 = 1.12 \pm 0.02$ at $(B-V)_0 = 0.71$. Using E$(B-V) = 0.04$ we then find $(v-y) = 1.168$. Reading off the 47 Tuc fiducial used in deriving the subdwarf distances we find $V = 19.35$ at $M_V = 6$. This then leads to a value for the apparent distance modulus for 47 Tuc of 13.35 in excellent agreement with the subdwarf value. The uncertainty in this estimate is ~0.15 mag. We note that the fairly large scatter in the $(B-V, v-y)$ relation of Fig. 6 adds significant uncertainty to our estimate. Repeating the same excercise for M 71 we find an apparent distance modulus of 13.82, assuming a reddening of $E(B-V) = 0.275$ – in reasonable agreement with the subdwarf based distance.

**Table 5.** Systematic errors.

| Error source | Size | Effect |
|---|---|---|
| [Fe/H] zpt. | 0.1 dex | 0.11 mag |
| E$(B-V)$ | 0.015 mag | 0.06 mag |
| $(v-y)$ | 0.01 mag | 0.04 mag |
| $V$ | 0.01 mag | 0.01 mag |
| Lutz-Kelker | 0.01 mag | 0.01 mag |
| [Fe/H] Bias | 0.01 mag | 0.01 mag |

Concluding this section, we find that our best estimate for the cluster distances and their errors are $(m-M)_V = 13.33 \pm 0.04 \pm 0.07$ for 47 Tuc and $(m-M)_V = 13.71 \pm 0.04 \pm 0.07$ for M 71, where the first errorbar corresponds to the random and the last to the systematic error (with the possible metallicity scale error neglected).

## 8. Ages

In order to estimate the cluster ages we employ the isochrones of VandenBerg et al. (2000). The transformation to *uvby* colours was carried out by J. Clem, University of Victoria (private comm.). We overplot isochrones for ages 12, 13, and 14 Gyr on the $(v-y,\ M_V)$ plane and the distance moduli and reddenings derived above. Results for 47 Tuc and M 71 are shown in Figs. 13 and 14. As can be seen, the required ages for the two clusters are slightly below 12 Gyr. Taken at face value, the derived distance moduli and reddenings seem to imply that M 71 is slightly younger than 47 Tuc, by 0.5 Gyr, but we emphasize that this is completely within the uncertainties of the distance moduli and the reddenings (and metallicities), such that the differential comparison from Sect. 6 carries a higher weight on the matter of cluster age differences. We note that our estimate for the cluster ages does not include the effects of microscopic diffusion.

### 8.1. Using $c_1$ for a distance independent age

As illustrated by, e.g., Nissen & Schuster (1991) one can use the colour, $c_1$ diagram to determine distance–independent ages for F and G type stars near the turnoff. This method was employed by Grundahl et al. (2000) to estimate the age of M92, resulting in a fairly high age. In principle this method is also applicable to 47 Tuc and M 71, but as shown by Grundahl (1999) and Grundahl et al. (1999a) all globular clusters appear to possess large star-to-star variations in nitrogen abundance, even among stars near the turnoff. In 47 Tuc and M 71 such variations also occur in MS stars, and as shown in Grundahl et al. (2002) they result in significant variations in the $c_1$ index at any evolutionary phase (except on the HB).

Figure 15 shows the $(V, c_1)$ diagram for 47 Tuc. As is clearly seen there is a large scatter near the TO region (which is *not* due to photometric errors). M 71 shows a very similar level of $c_1$ scatter. In fact, from the isochrones provided by J. Clem we estimate that the change in $c_1$ at the TO is about 0.025 mag per Gyr. The MSTO variation in $c_1$ for M 71 and 47 Tuc is of order 0.1 mag effectively making it impossible to

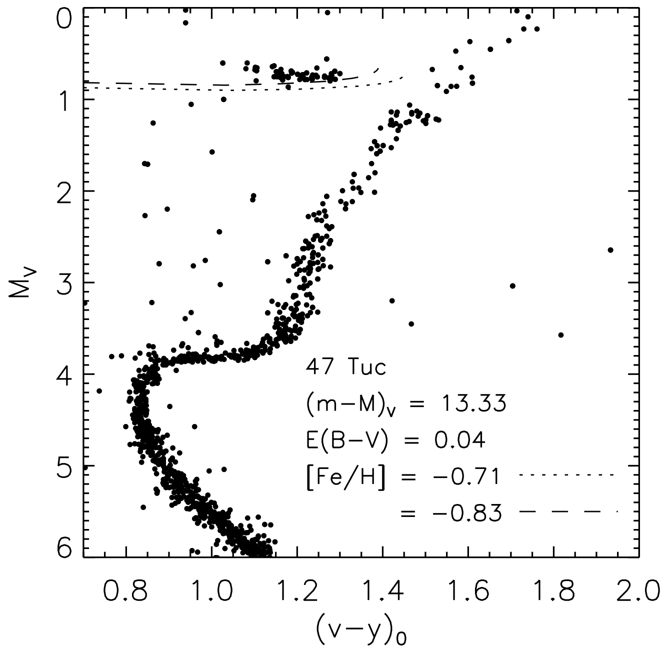


**Fig. 12.** Comparison of the 47 Tuc HB to two ZAHB models from VandenBerg et al. (2000) for [Fe/H] = −0.83 (upper) and [Fe/H] = −0.71 (lower) and [$\alpha$/Fe] = 0.3. The assumed distance modulus is $(m - M)_V = 13.33$.

determine their ages using this approach without detailed spectroscopic information on the C, N abundances.

## 9. Discussion

The distance moduli found in the previous section differ substantially from those found in other recent studies of the distance for these two clusters, e.g., R98 and Carretta et al. (2000b). These studies found an apparent distance modulus for 47 Tuc of 13.68 and 13.57, larger than the 13.4 derived by Hesser et al. (1987) using the level of the red HB (RHB). Our best estimate is in excellent agreement with the Hesser et al. value and, if correct, implies an age of nearly 12 billion years for this cluster and M 71, using the VandenBerg et al. (2000) isochrones.

It is interesting to try to understand the sources which give rise to the difference between the result presented in this work and those of R98 and Carretta et al. (2000b). Carretta et al. derive $(m - M)_V = 13.57$ for an assumed reddening of $E(B - V) = 0.055$. If we correct this value corresponding to a reddening value of $E(B{-}V) = 0.04$ we find instead an apparent distance modulus of 13.49, in better agreement with (although still significantly different from) our value[4].

In the case of the R98 study the fit to the unevolved main sequence involves field stars covering only a fairly small luminosity range of ~1 mag and they do not form a very well defined main sequence. The subdwarf sample used in the present paper is larger and covers a greater range in luminosity.

[4] Reid (1999) remarks that for main sequence fitting an increase in the adopted cluster reddening of $\Delta E(B - V)$ leads to a decrease of $2 \times \Delta E(B - V)$ in $(m - M)_0$.

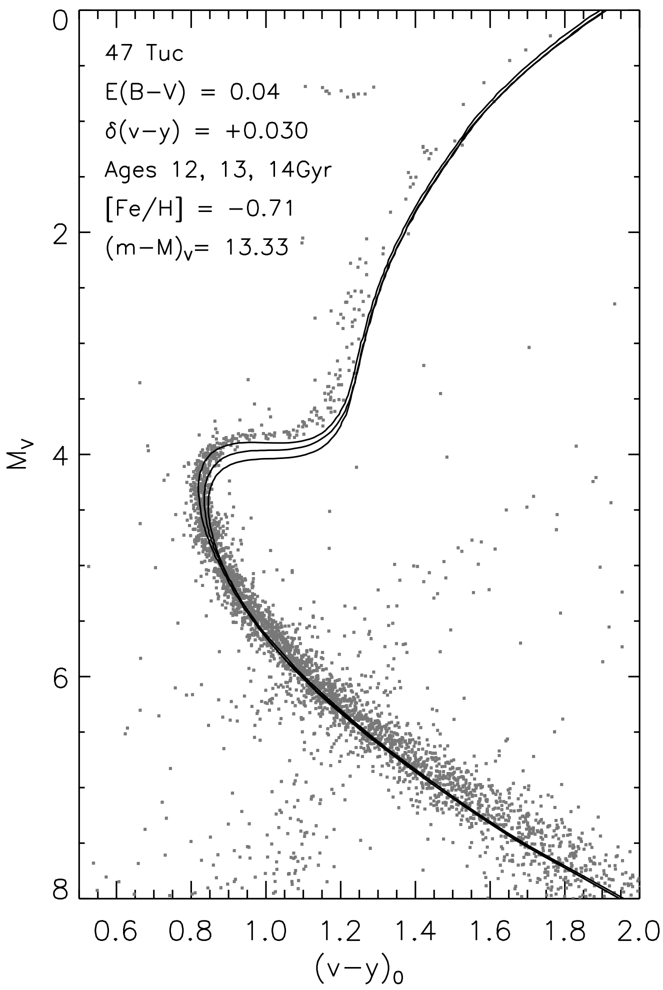


**Fig. 13.** Isochrone fit to the CMD of 47 Tuc, based on the distance determined here.

From Figs. 10 and 11 we see, that adopting distance moduli similar to that found by R98 would result in clearly poorer fits to the lower main sequences of the clusters. However, as the R98 stars have been overplotted in the figures (+ signs) it can be seen that using these stars to define the location of the field star main sequence would force somewhat higher distance moduli to be determined. The reason for this is that the R98 stars appear to lie slightly redward of the main sequence defined by the stars used in this paper. Had we adopted distance moduli for the clusters of 13.68 and 14.06 the lower main sequence stars would have fallen significantly below the main sequence, whereas the R98 stars would match the cluster sequences very well.

We therefore conclude that the high value for the 47 Tuc distance found by R98 is due to the use of field subdwarfs which appear to lie preferentially on the bright (or red) edge of the main sequence. This conclusion is valid even if our globular cluster photometry should turn out not to be correct, simply because the addition of the fainter subdwarfs provides a more secure estimate of the field main-sequence locus. Therefore these differences arise mainly from the different subdwarf samples employed in the two studies.

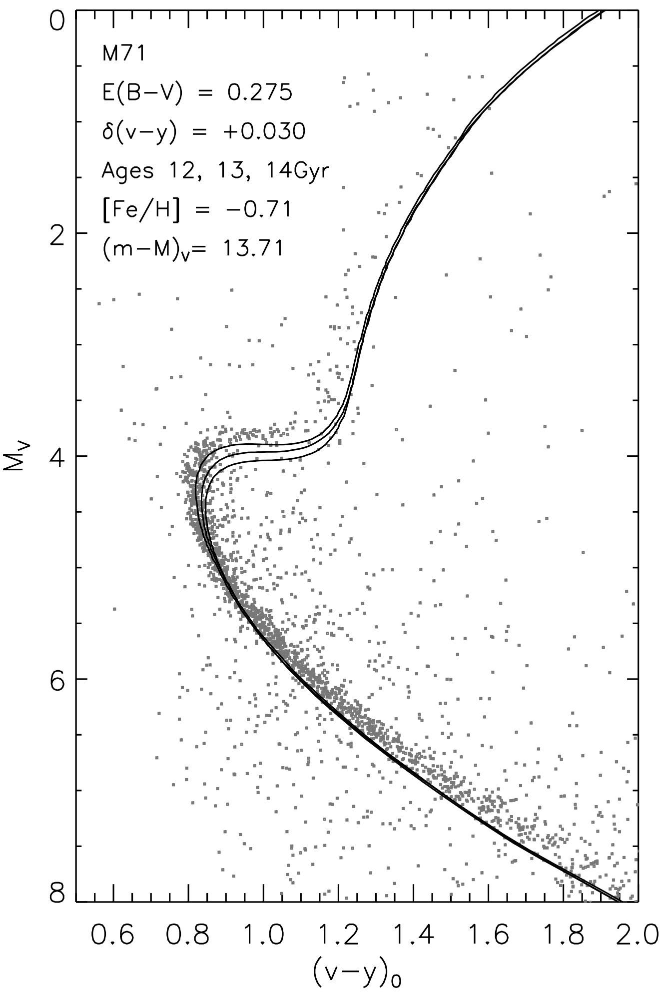


**Fig. 14.** Isochrone fit to the CMD of M 71, based on the distance determined here.

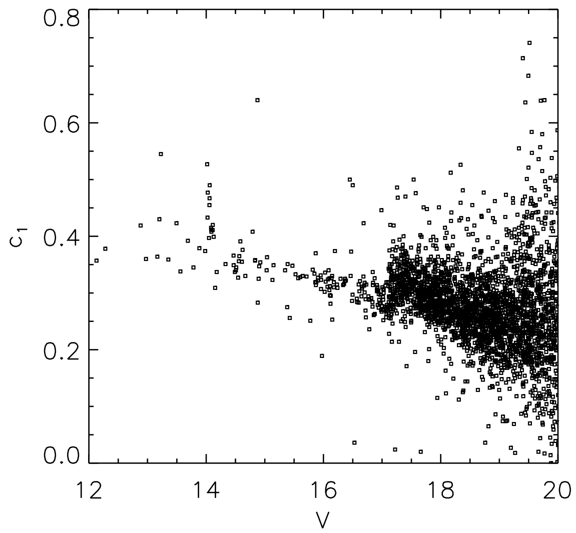


**Fig. 15.** Illustration of the $c_1$ scatter observed among MS stars in 47 Tuc.

Given the report by Grundahl et al. (2000) and VandenBerg (2000) of a fairly short distance modulus for the very metal-poor GC M92 (based on *uvby* photometry and a comparison to the metal–poor field subgiant HD 140283), which in essence corresponds to the pre-*Hipparcos* accepted value, it seems tempting to suspect that the high values for $(m - M)_V^{\rm M92}$ and other clusters (found by several of the first *Hipparcos* based GC distance determinations) could possibly also be due to the very limited number of very metal–poor subdwarfs available in the *Hipparcos* catalog.

Carretta et al. (2000b) suggested that the fact that the *Hipparcos* parallaxes for the metal–poor subdwarfs are systematically smaller than the pre-*Hipparcos* values by itself argues that the GC absolute ages should be lowered by 2.8 Gyr. However, if one shifts through the pre-*Hipparcos* literature on the GC distance scale one finds that due to the lack of sufficient numbers of subdwarfs with good parallaxes those distances were not based entirely on field subdwarfs. Rather, a combination of various methods was used, such as the luminosity of the RR Lyrae stars, the RGB tip, and ZAHB models. We therefore feel that it may not be entirely appropriate to expect a large reduction in the GC ages solely based on the comparison of pre- and post-*Hipparcos* parallax values, and that considerable uncertainty is still associated with the distance estimates for the very most metal-poor clusters based on the main-sequence fitting technique.

Zoccali et al. (2001) have derived $(m-M)_0 = 13.09 \pm 0.13$ for 47 Tuc from an analysis of the cluster white dwarf cooling sequence. Thus, in our view, the current best evidence appears to favor a relatively short distance, and hence high age, for 47 Tuc and M 71 in agreement with the pre-*Hipparcos* values.

## 10. Summary and conclusions

In this paper we have presented new and well calibrated Strömgren CCD photometry for the two fairly metal–rich globular clusters M 71 and 47 Tuc. Our main results are that: based on main-sequence fitting to a sample of 18 stars with $\sigma(\pi)/\pi < 0.08$ from Hipparcos we find the apparent distance modulus to 47 Tuc to be $13.33 \pm 0.04$. The possible systematic errors due to errors in reddening, [Fe/H] scale, photometry and metallicity bias could amount to 0.13 mag (although we are inclined to believe that it could well be smaller), with the error in the [Fe/H] scale as the dominant error. For M 71 we similarly found the apparent distance modulus to be 13.71. These values are in excellent agreement with the pre-Hipparcos values for these clusters. We show that the differences with Reid (1998) and Carretta et al. (2000) are due to the different selection of subdwarfs. The distances lead to ages of nearly 12 Gyr when the data are compared to the isochrones of VandenBerg et al. (2000). Our differential comparison of the cluster CMDs shows that if their heavy element abundances are similar then their ages are indistinguishable. Other distance indicators, ZAHB models and the $(B-V)_{M_V=6}$–[Fe/H] relation yield very similar results for the cluster distances. Due to a large scatter in the $c_1$ index for turnoff and main–sequence stars we could not determine a distance–independent age. The $c_1$ scatter is most likely caused by large star–to–star variations in the nitrogen abundance.

*Acknowledgements.* We thank Neill Reid for providing a machine readable copy of Table 1 in Reid (1998). FG thanks Erik Heyn Olsen for making his large database of *uvby* photometry available. The referee, Michael Hilker, is thanked for a thorough reading and many comments which helped the presentation of the results. FG also acknowledges the generous financial from the Carlsberg foundation. Don A. VandenBerg is thanked for providing financial support during part of this work, as well as models and encouragement. James Clem is thanked for transforming the VandenBerg et al. isochrones into Strömgren colours. The Herzberg Institute of Astrophysics and the Danish Natural Sciences Research Council are also thanked for financial support during part of this work.

## References

Briley, M. M., Hesser, J. E., Bell, R. A., Bolte, M., & Smith, G. H. 1994, AJ, 108, 2183
Briley, M. M. 1997, AJ, 114, 1051
Brown, J. A., & Wallerstein, G. 1992, 104, 1818
Cannon, R. D., Croke, B. F. W, Bell, R. A., Hesser, J. E., & Stathakis, R. A. 1998, MNRAS, 298, 601
Carretta, E., & Gratton, R. G. 1997, A&AS, 121, 95
Carretta, E., Gratton, R. G., & Clementini, G. 2000a, MNRAS, 316, 721
Carretta, E., Gratton, R. G., Clementini, G., & Fusi Pecci, F. 2000b, ApJ, 533, 215
Clementini, G., Gratton, R. G., Carretta, E., & Sneden, C. 1999, MNRAS, 302, 22 (CGCS)
Chaboyer, B., Demarque, P., & Sarajedini, A. 1996, ApJ, 462, 57
Catelan, M. 1998, ApJ, 495, L81
Cohen, J. G. 1999, AJ, 117, 2434
Crawford, D. L., & Snowden, M. S. 1975, PASP, 87, 561
Gratton, R. G., Fusi Pecci, F., Carretta, E., et al. 1997, ApJ, 491, 749
Gratton, R. G., Bonifacio, P., Bragaglia, A., et al. 2001, A&A, 369, 87
Grundahl, F., & Sørensen, A. N. 1996, A&AS, 116, 367
Grundahl, F., VandenBerg, D. A., & Andersen, M. I. 1998, ApJ, 500, L179
Grundahl, F., Briley, M. B., Stetson, P. B., Andersen, M. I., & Moreno, C. 2002, A&A, in preparation
Grundahl, F., VandenBerg, D. A., Bell, R. A., Stetson, P. B., & Andersen, M. I. 2000, AJ, 120, 1884
Grundahl, F. 1999, in Spectrophotometric Dating Stars and Galaxies, ed. I. Hubeny, S. Heap, & R. Cornett, ASP Conf. Proc., 192, 223
Grundahl, F., VandenBerg, D. A., Stetson, P. B., Andersen, M. I., & Briley, M. B. 1999a, in The Galactic Halo: from Globular Clusters to Field Stars; 35th Liege Int. Astroph. Coll.
Grundahl, F., Catelan, M., Landsman, W. B., Stetson, P. B., & Andersen, M. I. 1999b, ApJ, 524, 242
Hale, A. 1994, AJ, 107, 306
Hanson, R. B. 1979, MNRAS, 186, 875
Harris, W. E. 1996, AJ, 112, 1487
Heasley, J. N., & Christian, C. A., in The Formation and Evolution of Star Clusters, ed. K. Janes, ASP Conf. Ser., 13, 266
Hesser, J. E., Harris, W. E., VandenBerg, D. A., et al. 1987, PASP, 99, 739
Hodder, P. J. C, Nemec, J. M., Richer, H. B., & Fahlman, G. G. 1992, AJ, 103, 460
Lebreton, Y., Perrin, M.-N., Cayrel, R., Baglin, A., & Fernandes, J. 1999, A&A, 350, 587
Lutz, T. E., & Kelker, D. H. 1973, PASP, 85, 573
Nissen, P. E. 1988, A&A, 199, 146
Nissen, P. E., & Schuster, W. J. 1991, A&A, 251, 457
Olsen, E. H. 1983, A&AS, 54, 55
Olsen, E. H. 1984, A&AS, 57, 443
Pont, F., Mayor, M., Turon, C., & VandenBerg, D. A. 1998, A&A, 329, 87
Reid, I. N. 1997, AJ, 114, 161 (R97)
Reid, I. N. 1998, AJ, 115, 204 (R98)
Reid, I. N. 1999, ARA&A, 37, 191
Rosenberg, A., Saviane, I., Piotto, G., & Aparicio, A. 1999, AJ, 118, 2306
Rutledge, G. A., Hesser, J. E., Stetson, P. B., et al. 1997a, PASP, 109, 883
Rutledge, G. A., Hesser, J. E., & Stetson, P. B. 1997b, PASP, 109, 907
Salaris, M., & Weiss, A. 1998, A&A, 335, 943
Schlegel, J. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schuster, W. J., & Nissen, P. E. 1988, A&A, 73, 225 (SN88)
Schuster, W. J., & Nissen, P. E. 1989, A&A, 221, 65 (SN89)
Sneden, C., Kraft, R. P, Langer, G. E., Prosser, C. F., & Shetrone, M. D. 1994, AJ, 107, 1773
Stetson, P. B. 1987, PASP, 99, 191
Stetson, P. B., & Harris, W. E. 1988, AJ, 96, 909
Stetson, P. B. 1990, PASP, 102, 932
Stetson, P. B. 1991, AJ, 102, 589
Stetson, P. B. 1991, in The Formation and Evolution of Star Clusters, ed. K. Janes, ASP Conf. Ser., 13, 88
Stetson, P. B. 1994, PASP, 106, 250
Stetson, P. B. 2000, PASP, 112, 925
VandenBerg, D. A., Swenson, F. J., Rogers, F. J., Iglesias, C. A., & Alexander, D. R. 2000, ApJ, 532, 430
VandenBerg, D. A. 2000, ApJS, 129, 315
Zinn, R., & West, M. J. 1984, ApJS, 55, 45
Zoccali, M., Renzini, A., Ortolani, S., et al. 2001, ApJ, 553, 733