DISTANCES AND ABSOLUTE AGES OF GALACTIC GLOBULAR CLUSTERS FROM HIPPARCOS PARALLAXES OF LOCAL SUBDWARFS*

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ABSTRACT

High precision trigonometric parallaxes from the Hipparcos satellite and accurate metal abundances ([Fe/H], [O/Fe], and [α/Fe]) from high resolution spectroscopy for about 30 local subdwarfs have been used to derive distances and ages for a carefully selected sample of nine globular clusters. We find that Hipparcos parallaxes are smaller than the corresponding ground-based measurements leading, to a longer distance scale ($\sim$ 0.2 mag) and to ages $\sim$ 2.8 Gyr younger. The relation between the zero age horizontal branch (ZAHB) absolute magnitude and metallicity for the nine programme clusters is:

$$M_V(ZAHB) = (0.22\pm0.09)([\mathrm{Fe/H}]+1.5)+(0.48\pm0.04)$$

The corresponding Large Magellanic Cloud distance modulus is $(m-M)_0 = 18.61 \pm 0.07$. The age of the *bona fide* old globular clusters (Oosterhoff II and Blue Horizontal Branch) based on the absolute magnitude of the turn-off is:

$$\mathrm{age} = 11.8^{+2.1}_{-2.5}\mathrm{Gyr}$$

The present age of globular clusters no longer conflicts with standard inflationary models for the Universe.

Key words: Clusters: globulars; Cosmology; Stars: basic parameters; Stars: stellar models.

1. INTRODUCTION

Globular Clusters (GC) are among the oldest objects in our Galaxy, their age thus provides a very stringent lower limit to the age t of the Universe. Recent determinations suggest values of about $14-16$ Gyr for the age of globular clusters ($t = 15.8 \pm 2.1$ Gyr, Bolte & Hogan 1995; $t = 14.6 \pm 2.5$ Gyr Chaboyer et al. 1996; $t = 15^{+5}_{-3}$ Gyr, VandenBerg et al. 1996). These values are in conflict with the age of the Universe derived from the most recent estimates of the Hubble constant and the standard cosmological Eistein-de Sitter model. Since, most recent determinations of H_0 are in the range of $55-75$ km s^{-1}Mpc^{-1} ($H_0 = 73 \pm 10$ km/s/Mpc, Freedman et al. 1997; $H_0 = 63.1 \pm 3.4 \pm 2.9$ km/s/Mpc, Hamuy et al. 1996; $H_0 = 58 \pm 7$ km/s/Mpc, Saha et al. 1997, $H_0 = 56 \pm 7$ km/s/Mpc, Sandage & Tamman 1997), the age of the Universe is constrained to be $t < 11.6$ Gyr in an Einstein-de Sitter model, and $t < 14.9$ Gyr in a flat Universe with $\Omega_m = 0.2$. Current ages for globular clusters result then uncomfortably large in the framework of standard cosmological models.

The most robust indicator of the age of globular clusters is the absolute visual magnitude of the main sequence turn-off, $M_V(TO)$. By comparing $M_V(TO)$ with theoretical isochrones of appropriate metallicity and helium abundance one gets the age of the cluster (see Eq. 3 by Renzini 1991). Since the directly observable quantity is the apparent magnitude of the turn-off, $V(TO)$, it is necessary to know the distance of the cluster. Indeed, the main difficulty in the derivation of the ages of globular clusters is the large uncertainty in the distance scale (Renzini 1991). Independent of the method used, the present 'actual' accuracy in GC distance modulus determinations is of the order of 0.2 mag which, in turn, corresponds to an uncertainty of about 3 Gyr in the age.

The simplest technique to derive distances to clusters is to compare their main sequence (MS) with a suitable template (Sandage 1970): i.e. an adequate sample of metal poor non-evolved subdwarfs with known distances. Unfortunately, the template main sequence for metal-poor globular clusters has been up to now quite uncertain due to the paucity of metal poor subdwarfs for which reliable data are available, i.e. absolute magnitudes and colours accurate to better than a few hundreds of a magnitude (it should be reminded that an error $\Delta V = 0.07$ mag in the magnitude of the turn-off and/or an error $\Delta(B-V) = 0.01$ mag in its colour, both translate into an uncertainty of about 1 Gyr in the derived age), *and* metallicity–[Fe/H] known to $\sim$ 0.1 dex. Table 2 of Renzini (1991) very clearly illustrates the contribu-

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*Based on data from the Hipparcos satellite and from Asiago and McDonald Observatories.

Table 1. Basic data for the field subdwarfs.

HIP. No.	HD/ Gliese	π (mas)	$\delta\pi/\pi$	V_0	M_v	$(B-V)_0$	[Fe/H]	[O/Fe]	[α/Fe]	Note
Stars with Hipparcos parallaxes										
14594	19445	25.85	0.044	8.050 ± 0.010	5.11 ± 0.09	0.454 ± 0.018	-1.91 ± 0.07	0.56	0.38	
15797	G078-33	39.10	0.032	8.971 ± 0.009	6.93 ± 0.07	0.982 ± 0.002	-0.41 ± 0.07		0.16	
66509	118659	18.98	0.064	8.820 ± 0.010	5.20 ± 0.14	0.674 ± 0.002	-0.55 ± 0.07	0.51	0.08	
72998	131653	20.29	0.074	9.512 ± 0.002	6.05 ± 0.16	0.720 ± 0.000	-0.63 ± 0.07	0.36	0.31	
74234	134440	33.68	0.050	9.441 ± 0.001	7.08 ± 0.11	0.853 ± 0.000	-1.28 ± 0.07		0.15	
74235	134439	34.14	0.040	9.073 ± 0.002	6.74 ± 0.08	0.773 ± 0.000	-1.30 ± 0.07		0.29	
78775	144579	69.61	0.008	6.660 ± 0.000	5.87 ± 0.02	0.734 ± 0.004	-0.52 ± 0.13			
95727	231510	24.85	0.062	9.004 ± 0.003	5.98 ± 0.13	0.782 ± 0.002	-0.44 ± 0.07	0.34	0.14	
100568	193901	22.88	0.054	8.652 ± 0.002	5.45 ± 0.11	0.555 ± 0.003	-1.00 ± 0.07	0.35		
112811	216179	16.66	0.086	9.333 ± 0.003	5.44 ± 0.18	0.684 ± 0.002	-0.66 ± 0.07	0.45	0.29	
Stars in Reid's list										
57450	G176-53	13.61	0.113	9.92 ± 0.03	5.47 ± 0.25	0.55 ± 0.01	-1.26 ± 0.07			
103269	G212-07	14.24	0.103	10.18 ± 0.06	5.85 ± 0.22	0.59 ± 0.02	-1.48 ± 0.16			E(B-V)=0.03
106924	G231-52	15.20	0.080	10.19 ± 0.06	6.04 ± 0.17	0.58 ± 0.02	-1.60 ± 0.16			E(B-V)=0.05
Stars with good ground-based parallaxes										
18915	25329	53.7	0.026	8.506 ± 0.001	7.15 ± 0.06	0.863 ± 0.003	-1.69 ± 0.07			
79537	145417	71.1	0.090	7.531 ± 0.001	6.74 ± 0.19	0.815 ± 0.006	-1.15 ± 0.13			

tions to the total error budget in the age estimate due to the various quantities entering the main sequence fitting technique. Uncertainties in distance moduli are by far the most relevant contributors to the total error affecting the age.

2. BASIC DATA FOR THE MAIN SEQUENCE FITTING

2.1. Subdwarf Data

Hipparcos has provided absolute parallaxes for over 118 000 stars, with typical accuracies of ~ 1 mas. We have parallaxes for 99 subdwarfs with metallicities in the range $-2.5 <$ [Fe/H] < 0.2; this sample was complemented with data for about 50 stars (mostly metal-rich) having good ground-based parallaxes and with objects from Reid (1997) list. V magnitudes and colours (Johnson $B-V$ and $V-K$, and Strömgren $b-y$, m_1 and c_1) for the programme stars were obtained from a careful average of the data available in the literature. We also used the V magnitudes and $B-V$ colours provided by Tycho (Grossmann et al. 1995), after correcting them for the systematic difference with ground-based data (0.003 mag in $B-V$).

High dispersion spectra were acquired for about two thirds of the subdwarfs observed by Hipparcos, using the 2.7 m telescope at McDonald and the 1.8 m telescope at Cima Ekar (Asiago), and were used to derive accurate metal abundances. The abundance derivation followed the same precepts of the reanalysis of ~ 300 field and ~ 150 GC stars described in Gratton et al. (1997) and Carretta & Gratton (1997). We found that O and the other $\alpha-$elements are overabundant in all metal-poor stars in our sample. The average overabundances in stars with [Fe/H]< -0.5 are:

$$[\mathrm{O/Fe}] = 0.38 \pm 0.13$$

$$[\alpha/\mathrm{Fe}] = 0.26 \pm 0.08,$$

(see Gratton et al., this volume, for a more detailed description of the abundance analysis results).

Only *bona fide* single stars with $\Delta\pi/\pi < 0.12$ and $M_V > 5.5$ were used in our age derivation, these are listed in Table 1 together with their relevant quantities. Stars brighter than this limit were discarded since they may be evolved off the Zero Age Main Sequence (ZAMS), as well as we eliminated all detected or suspected binaries, except the objects were the separation among the two components is so wide to not disturb the derived absolute magnitudes M_V and the colours. Errors in the derived M_V are ≤ 0.25 mag. An accurate analysis via Monte Carlo simulations, of the Lutz-Kelker corrections most appropriate to our sample, revealed them to be very small ($\Delta M_{LK} = -0.002$) and thus they were neglected. A non-negligible source of systematic errors is, instead, the contamination of the sample of subdwarfs used in the MS fitting technique by unresolved binaries. A very careful procedure was applied to clean up the sample from binaries. Further, a statistical approach was devised to evaluate systematic corrections of our distance moduli for the possible presence of residual undetected binaries.

The field subdwarfs listed in Table 1 were divided into metallicity bins and used to define template main sequences of the proper metallicity to be compared with the globular cluster main loci. To account for the difference between cluster and field star metallicity, the colours of the subdwarfs were corrected for the corresponding shift of the main sequences.

It should be noted that the Hipparcos parallaxes are systematically smaller than those listed in the 1991 version of the Yale Trigonometric Parallax Catalogue (van Altena et al. 1991), so that the derived absolute magnitudes are on average brighter. We anticipate that, everything else being constant, globular cluster ages derived exploiting this new distance scale are about 2.8 Gyr younger than those derived from ground-based parallaxes for the local subdwarfs.

2.2. Cluster Data

Main sequence loci for the programme clusters were taken from literature data. We generally relied upon the quality of the original photometric data, although such a good quality is not always an obvious issue. Column 6 of Table 2 gives references for the adopted colour magnitude diagrams. Cluster metal abundances have recently been obtained by Carretta & Gratton (1997), using high dispersion spectra of cluster giants and an abundance procedure totally consistent with that used for the subdwarf sample. The availability of high quality abundances (standard errors $\sim$ 0.07 dex) for both field subdwarfs and GC giants on a consistent abundance scale is one of the basic ingredients of our study.

Interstellar reddenings for some of the considered clusters may be uncertain by as much as ~ 0.05 mag, implying errors as large as 5 Gyr in the derived ages. Reddening values for the programme clusters have been published by Zinn (1980) and Reed et al. (1988). These values were averaged with new reddening estimates based on Strömgren photometry of nearby field stars, to derive the final adopted reddenings listed in Column 4 of Table 2.

3. GLOBULAR CLUSTERS DISTANCES VIA MAIN SEQUENCE FITTING

Once template main sequences for the appropriate metallicity are determined, and cluster reddenings and metallicities are known, cluster distance moduli are derived by least square fitting of the apparent magnitude of the cluster main sequence at a given colour and the absolute magnitude of the template main sequence at the same colour. Figure 1 displays the fits of the individual GC main sequences with the nearby subdwarfs of the proper metallicity. The derived distance moduli are listed in Column 5 of Table 2.

3.1. Absolute Magnitude of the Horizontal Branch

The absolute magnitude of the Horizontal Branch, $M_V(HB)$, has often been used as a standard candle to derive distances and then ages of globular clusters. The correct dependence of $M_V(HB)$ on [Fe/H] is, however still rather uncertain. We have used our distance moduli, that were determined independently of the Horizontal Branch (HB) luminosity, to derive a new estimate of the $M_V(HB)$ versus [Fe/H] relation. Buonanno et al. (1989) list $M_V(HB)$ values for all the clusters in our sample. A close inspection of their data revealed that these values correspond to a mean magnitude of the HB. They were transformed to $M_V(ZAHB)$'s using the relation given by Sandage (1993), and then combined with the metallicities listed in Table 2 to derive the following relation between absolute magnitude of the HB and metallicity:

$$M_V(ZAHB) = (0.22\pm0.09)([\mathrm{Fe/H}]+1.5)+(0.48\pm0.04)$$

In Figure 2 we compare our new $M_V(HB)$ versus [Fe/H] relation with the predictions of some recent Horizontal Branch models.

The use of the above relationship has a direct impact on several astronomical issues. For instance, since our value of M_V for field RR Lyraes at [Fe/H]= -1.9 ($M_V = +0.33 \pm 0.07$) is 0.11 mag brighter than the value quoted by Walker (1992), we derive a distance modulus for the LMC of $(m - M) = 18.61 \pm 0.07$ (where the error is the statistical one at [Fe/H]= -1.9). If this distance to the LMC is used (rather than the one frequently adopted from Cepheids: $(m-M) = 18.50\pm0.10$), the extragalactic distance scale increases (and estimates of the Hubble constant decrease) by 5 per cent (for instance, the value of H_o derived from SN Ia by Hamuy et al. 1996, would change from $63.1\pm3.4\pm2.9$ to $59.9\pm3.2\pm2.8$).

We only remark that the distance modulus for the LMC based on the Hipparcos calibrations is $(m - M) = 18.70\pm0.10$ from Cepheids (Feast & Catchpole 1997), and $(m - M) = 18.6 \pm 0.2$ from Miras (van Leeuwen et al. 1997) in excellent agreement with our determination. The most recent determination from the expanding ring around the SN 1987a is $(m-M) = 18.58 \pm 0.03$ (Panagia et al. 1997).

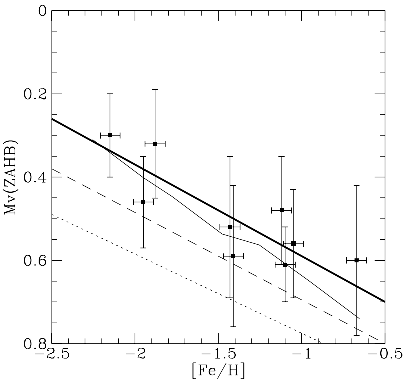

Figure 2. Runs of the $M_V(ZAHB)$ against [Fe/H] for the programme clusters using our distance moduli and $M_V(HB)$ from Buonanno et al. (1989) corrected to the ZAHB using Sandage (1993) relation. The solid thick line is the weighted least square fit line through the points. Also shown are the predictions based on the HB models of Caloi et al. 1997 (solid thin line), VandenBerg 1997 (dotted line), and Salaris et al. 1997 (dashed line).

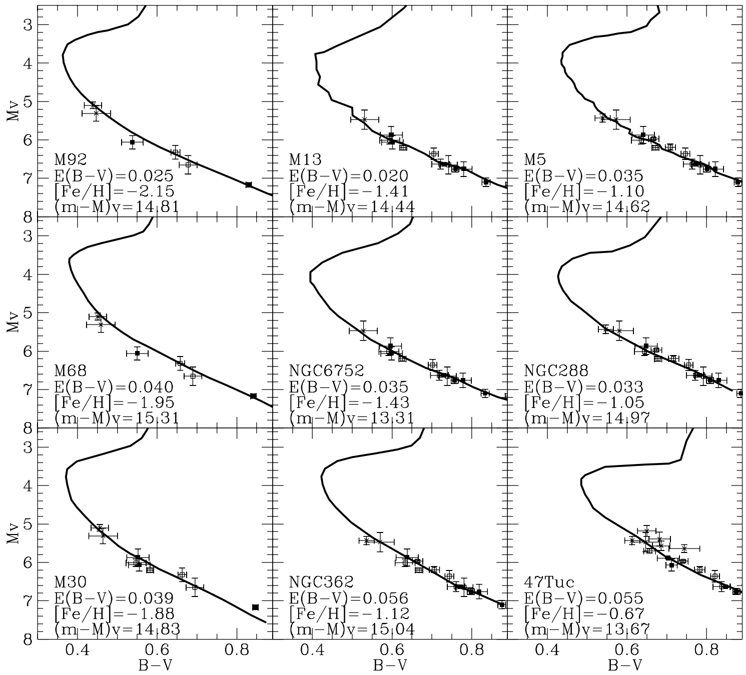

*Figure 1. Fits of the fiducial mean loci of the GCs with the position of the local subdwarfs. Only **bona fide** single stars with $M_V > 5.5$ (solid squares) were used in the fit. Binaries (open squares), and single stars with $5 < M_V < 5.5$ (crosses), are also plotted, but they were not used in the fit. Each star in the plot was shifted by 0.17 × p_i mag, where 0.17 is the average binary correction, and p_i is the probability of star i to be a binary and ranges from 1 for known binaries to 0.08 for supposed single stars.*

4. GLOBULAR CLUSTER AGES

Ages for the programme clusters were derived from the absolute magnitude of the turn-off point, $M_V(TO)$. We used the distance moduli of Table 2 and the TO apparent magnitudes, $V(TO)$ listed by Buonanno et al. (1989). Typical errors quoted for $V(TO)$ are $0.05 - 0.10$ leading to errors of $0.09 - 0.13$ mag, and to a corresponding average random uncertainty of 12 per cent in ages.

Columns 8 to 12 of Table 2 list the ages we derived from different sets of isochrones. Original values from different isochrones have been corrected to a common value $M_{V_\odot} = 4.82 \pm 0.02$ (Hayes 1985) for the solar absolute magnitude. In the isochrones labeled as MLT, convection has been modeled using the Mixing Length Theory, while those labeled as CM use the Canuto & Mazzitelli (1991) theory. On any other respect, these isochrone sets are quite similar to each other: they use updated equation of state (including Debye screening), opacities from the Los Alamos group, and colour transformations according to Kurucz (1993). Our data seem to show that some scatter exists in the ages of Oosterhoff II clusters (M92, M68 and M30), however this scatter is not significantly larger than the expected error bar. Furthermore, the close similarity of the c-m diagrams for the metal-poor clusters strongly supports a common age for these clusters. We have therefore concluded that the Oosterhoff II clusters are indeed coeval, and that the scatter is due to observational errors. A similar conclusion is reached for the Blue Horizontal Branch (BHB) clusters (M13, NGC288, NGC6752). Our age estimates for the Oosterhoff I clusters (M5 and NGC362) are instead $\sim 2.4 \pm 1.3$ Gyr lower than those for the BHB clusters which in turn are similar to those for the Oosterhoff II clusters. A rather low age is found also for 47 Tuc. The reality of this age-difference is argument of hot debate. However we must stress that the absolute luminosity of the turn-off point is not the best procedure for the derivation of *relative* ages, (Stetson et al. 1996). Given the small numbers, the statistical error bars are not very significant. It seems then wiser to exclude the Oosterhoff I clusters and 47 Tuc from our estimate of the age of the oldest globular clusters in our sample. We thus identify the group of *bona fide* old clusters with the Oosterhoff II and the BHB clusters.

Average ages for our *oldest* globular clusters obtained with different isochrone sets are given in Table 3. Although we cannot exclude the possibility that some clusters are older than the average, this is not required by our observations. We will then assume that these average values are the best guess for the age of the oldest globular clusters. If we use isochrones based on the MLT-convection, the mean age for the six *bona fide* old clusters is $11.8 \pm 0.6 \pm 0.4$ Gyr, where the first error bar is the standard deviation of the mean values obtained for different clusters, and the second error bar is the spread of ages derived from different isochrone sets. However, to better quantify the error bars, we used a Monte Carlo procedure to derive the distribution of total errors and to provide the statistical interval of confidence (95 per cent range). The following sources of uncertainty were taken into account: internal errors, uncertainties in the solar M_V, uncertainties due to the statistical

Table 2. Distance moduli and ages for the programme globular clusters.

NGC	Other	[Fe/H]	$< E(B-V) >$	$(m-M)_V$	CMD source	$M_V(HB)$	SC97 MLT (Gyr)	VdB97 MLT (Gyr)	DCM97 MLT (Gyr)	DCM97 CM (Gyr)	B97 MLT (Gyr)
6341	M92	−2.15	0.025 ± 0.005	14.81	1	0.24 ± 0.10	13.6	13.9	13.8	13.0	12.6
4590	M68	−1.95	0.040 ± 0.010	15.32	2	0.39 ± 0.11	11.4	11.6	11.4	11.0	10.3
7099	M30	−1.88	0.039 ± 0.001	14.95	3,4	0.25 ± 0.13	11.1	11.3	11.0	10.7	10.1
6205	M13	−1.41	0.020 ± 0.000	14.45	5	0.50 ± 0.17	12.5	12.3	12.5	11.9	11.7
6752		−1.43	0.035 ± 0.005	13.32	6	0.43 ± 0.17	13.0	12.8	12.7	12.4	12.1
362		−1.12	0.056 ± 0.003	15.06	7	0.37 ± 0.13	9.0	8.8	8.7	8.5	8.0
5904	M5	−1.10	0.035 ± 0.005	14.61	8	0.50 ± 0.09	10.8	10.5	10.4	10.0	9.9
288		−1.05	0.033 ± 0.007	14.95	9	0.45 ± 0.13	11.3	10.9	10.7	10.5	10.4
104	47Tuc	−0.67	0.055 ± 0.007	13.63	10	0.47 ± 0.17	10.8	10.3	9.8	9.7	9.9

CMD source: 1. Stetson & Harris (1988) 2. McClure et al. (1987) 3. Bolte (1987b) 4. Richer et al. (1988) 5. Richer et al. (1986) 6. Penny & Dickens (1986) corrected according to VandenBerg et al. (1990) 7. Bolte (1987a) corrected according to VandenBerg et al. (1990) 8. Sandquist et al. (1996) 9. Buonanno et al. (1989) 10. Hesser et al. (1987)

Table 3. Mean age for bona fide old globular clusters.

Isochrone set	Age
Mixing Length Theory	
D'Antona, Caloi & Mazzitelli, 1997(DCM97)	12.0 ± 0.5
Straniero & Chieffi, 1997(SC97)	12.2 ± 0.4
VandenBerg, 1997(VdB97)	12.0 ± 0.5
Bertelli et al., 1997(B97)	11.3 ± 0.4
Canuto-Mazzitelli Theory	
D'Antona, Caloi & Mazzitelli, 1997(DCM97)	11.6 ± 0.4

correction for binaries, reddening scale, metal abundance scale, stellar model code, convection mechanism, He-sedimentation. In summary we found that the age of the *bona fide* old globular clusters (Oosterhoff II and Blue Horizontal Branch) based on the absolute magnitude of the turn-off is:

$$\text{age} = 11.8^{+2.1}_{-2.5}\text{Gyr}$$

4.1. Preliminary Comparison with other GC Ages Presented at this Symposium

Pont et al. (this volume) have presented results on the age of M92 based on MS fitting and on a slightly different data base, reaching the conclusion that $t_{M92} = 14 \pm 1.2$ Gyr. A few comments on their result is worthwhile here.

The difference in the age derived for M92 cannot be ascribed to differences in the data base. Indeed, if we eliminate from Pont's et al. data stars at $M_V > 5.5$, that may be evolved off the ZAMS, and all the detected or suspected binaries, the two data samples differ by only one object.

Stars brighter than $M_V = 5.5$ may lead to systematic errors in the derived distance moduli, as it is not clear whether GCs and metal-poor field stars are exactly co-eval. For example, a 4 Gyr age difference between a calibrating subdwarf at $M_V = 5$ and a GC would lead to a systematic error of 0.05 mag in the distance modulus.

If binaries are to be included in the sample, they must be corrected to account for the contribution due to the secondary components. However, the correction is uncertain and strongly depends on the luminosity function assumed for the secondary components. We estimate an average binary correction of 0.17 mag (based on the luminosity function of Population I field stars, Kroupa et al. 1993), and multiply it by the probability of each individual star to be a binary. Pont et al. use, instead, an average correction of 0.375 mag, based on the binary mass distribution in Praesepe. This is a dynamically evolved open cluster, where binaries of higher mass ratio are likely to be evaporated and, conversely, equal mass binaries are likely concentrated in the center (Kroupa et al.) thus leading to an overestimate of their number and, in turn, of the derived correction.

There also are differences in the adopted metallicity scale and in the reddenings, but they do not account for the discrepancy in the derived age.

Indeed, the major sources of controversy are the corrections that must be applied to the data. They strongly depend on the selection criteria adopted to build up the sample. Pont's et al. data base is formed by two sub-samples, a first one (about 60 per cent of the stars) selected before the Hipparcos parallaxes were known, and a second one (the remaining 40 per cent) selected *a posteriori* once parallaxes and colours were known. Different corrections should thus be applied to the two different subsets. Pont et al. apply mean bias corrections of +0.064 and −0.115 mag to the subdwarfs and the subgiants, respectively, used to fit the M92 locus. Beside distorting the shape of the template sequence, these large and uncertain corrections have a strong impact on the measure of the distance modulus. Since we do not know in detail how their sample has actually been selected, nor if average or individual star corrections have been computed and applied, we cannot assess the reliability of their derived distance modulus.

Finally, we caution that the use of just one cluster to infer the age of the *oldest* globular clusters may be very dangerous since it strongly relies upon the accuracy of that cluster photometry. For instance, there is a 0.04 mag difference between the colour of the M92 main sequence as presented by Heasley & Christian (1991) and that by Stetson & Harris (1988): this would translate into a 3–4 Gyr difference in the age derived for this important cluster. The use of a not too restricted sample of carefully selected clusters (as we did) reduces the effect of photometric errors and CMD peculiarities.

4.2. Cosmology

Assuming a minimum delay of 0.5 Gyr from the birth of the Universe before the formation of globular clusters our age estimate is compatible with an Einstein-de Sitter model if $H_0 \leq 64$ km s^{-1}Mpc^{-1}, and $H_0 \leq 83$ km s^{-1}Mpc^{-1} in a flat Universe with $\Omega_m = 0.2$. Within the framework of inflationary models (even in the restricted but more elegant solution of the Einstein-de Sitter Universe), the presently determined age for the globular clusters is then consistent with current estimates of the Hubble constant, even without the ~ 5 per cent reduction which is given by the adoption of the present distance scale, or that proposed by Feast & Catchpole (1997). We conclude that, at the present level of accuracy of globular cluster ages, there is no discrepancy with standard inflationary models for the Universe.

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