Is the Galactic Disk older than the Halo?

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ABSTRACT

Aim of this study is to infer the age of the Galactic Disk by means of the ages of old open clusters, and comment on some recent claims that the Galactic Disk can be older than the Halo. To this purpose, we analyze the Color–Magnitude Diagrams (CMDs) of six very old open clusters, namely NGC 188, NGC 6791, Collinder 261, Melotte 66, Berkeley39 and Berkeley 17, and determine their ages. For each cluster we use the most recent photometric and spectroscopic data and metallicity estimates. The ages are derived from the isochrone fitting method using the stellar models of the Padua library (Bertelli et al. 1994, Girardi et al. 1998). We find that the ages of these clusters fall in the range 4 to 9-10 Gyr: Melotte 66 is the youngest whereas NGC 6791 and Berkeley 17 have ages of about 9-10 Gyr. Previous estimates for Berkeley 17 indicated an age as old as 12\(^{\pm}2\) Gyr, almost falling within the range of classical globular clusters. In our analysis, this cluster is always very old but perhaps somewhat younger than in previous studies. However, we call attention on the fact that the above ages are to be taken as provisional estimates, because of the many uncertainties still affecting stellar models in the mass range 1.0 to 1.5 \(M_\odot\). Despite this drawback of extant theory of stellar structure, if NGC 6791 and Berkeley 17 set the limit to the age of the Galactic Disk, this component of the Milky Way can be as old as about 9-10 Gyr, but surely younger than the Galactic Halo, at least as inferred from recent determinations of the age of globular clusters. Finally, it is worth recalling that open clusters can only provide a lower limit to the age of the Galactic Disk, while other indicators - like White Dwarfs - are perhaps more suited to this task.

Key words: Star Clusters: open — Galaxy: structure and evolution — Galactic disk: age — Stars: theoretical models

1 INTRODUCTION

In the last decade considerable efforts have been made to collect good quality photometric and spectroscopic data for the oldest open clusters in the Galactic Disk (see Friel 1995 for an exhaustive review on the subject), with the aim of establishing constraints on the age of this component of the Milky Way and to assess whether the age distribution of the open clusters overlaps that of globular clusters (cf. Janes & Phelps 1994).

Since Cannon (1970), the taxonomy of the population of old open clusters is generally based on the morphology of their CMD. Intermediate age open clusters show the so-called Hertzsprung gap between the main sequence band and the red giant region, and a populous clump of He–burning red giant stars, the analog of the Horizontal Branch in globular clusters. Prototypes of this class are NGC 752, NGC 7789 and NGC 2158. At increasing age, the separation between the main sequence and the red giant region gets smaller, and the red clump gets scarcely populated. M 67 and NGC 188 are two well studied examples of this class.

For the purposes of this study, we extend the above classification to three groups: (i) the intermediate-age clusters, i.e. those whose age falls in the interval defined by the Hyades (625 Myr, cf. Perryman et al. 1998) and IC 4651 (1.7 Gyr, cf. Bertelli et al. 1992); (ii) the old clusters whose age is younger than that of M 67 (4.0 Gyr, cf. Carraro et al. 1996); (iii) the very old clusters, i.e. older than M 67 and younger than the bulk of globular clusters (12-13 Gyr, Gratton et al. 1997).

According to Phelps & Janes (1994), there are about 20 clusters older than M 67, even though the published photometry is not yet sufficiently accurate to prove that all of them really belong to the third group in our classification.
Despite their small number, these clusters are very interesting for several reasons. Firstly, they can be used to study the formation and early evolution – both chemical and dynamical – of the Galactic Disk (Carraro et al. 1998a). Secondly, they can map the outer structure of the Galactic Disk, as they are preferentially located high on the galactic plane and towards the galactic anticenter. Finally, once these clusters are accurately ranked in age, they can be used to set a lower limit to the age of the Galactic Disk (Sandage 1989, Carraro & Chiosi 1994), to constrain the evolution of the Milky Way, and to highlight the parental relationship between Galactic Disk and Halo.

NGC 6791 has long been considered as the oldest open cluster, to which Janes (1989) assigned an age of about 12 Gyr. However more recent determinations of the age by Carraro & Chiosi (1994), Carraro et al. (1994a), and Garnavich et al. (1994) have decreased this value down to about 9 Gyr.

In the meantime another very old cluster has been discovered, namely Berkeley 17, whose age is estimated 12.3 ± 2 Gyr (Phelps 1997).

As far as Lynga 7 is concerned, that was long considered as another very old candidate (Janes & Phelps 1994), it has been proven by Tavarez & Friel (1995) to belong to the family of Thick Disk globular clusters.

Since the bulk of globular clusters seem to be 12-13 Gyr old (Gratton et al. 1997), the possibility arises that the Disk might be as old as the Halo, or even older than this (see the discussion in Phelps 1997). This fact bears very much on the time scale of the halo collapse, the initial stages of the formation of the Galactic Disk, and the star formation history of the Galaxy.

To cast light on this topic of paramount importance, we have selected 6 very old open clusters (NGC 188, NGC 6791, Collinder 261, Melotte 66, Berkeley 39 and Berkeley 17) for which good photometric and spectroscopic data were available, and have derived their age in a homogeneous fashion.

With respect to a similar study by Janes & Phelps (1994), the situation is now much improved firstly because better data are at our disposal, and secondly the metal content of these clusters is known from spectroscopic determinations. Therefore another attempt to rank these clusters as a function of the age can be undertaken.

There is one point to be kept in mind from the very beginning, i.e. that old and very old open clusters have their turn-off mass in the risky mass interval, in which a number of important physical facts occur in the interiors of their stars.

| Cluster       | α(2000.0) | δ(2000.0) | l   | b   | [Fe/H] | σ([Fe/H]) | Sourcea | Sourceb |
|---------------|-----------|-----------|-----|-----|--------|-----------|---------|---------|
| NGC 188       | 00:39.4   | +08:04    | 122.78 | +22.46 | −0.05 | 0.11 | (1) | (1,2) |
| NGC 6791      | 19:19:0   | +37:45    | 70.01  | +10.96 | +0.19 | 0.19 | (2) | (3) |
| Collinder 261 | 12:34.9   | −68:12    | 301.69 | −05.64 | −0.14 | 0.14 | (1) | (4,5) |
| Melotte 66    | 07:24:9   | −47:38    | 259.61 | −14.29 | −0.51 | 0.11 | (2) | (6,7) |
| Berkeley 39   | 07:44:2   | −04:29    | 223.47 | +10.09 | −0.31 | 0.08 | (2) | (7) |
| Berkeley 17   | 05:17:4   | +30:33    | 175.65 | −03.65 | −0.29 | 0.13 | (1) | (8,9) |

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The plan of the paper is as follows. In Section 2 we describe the stellar models in usage here, the comparison between two sources of isochrones, i.e. Bertelli et al. (1994) and Girardi et al. (1998), and finally the method we have adopted to derive cluster ages, basically isochrone fit. Section 3, devoted to the analysis of each cluster of our sample, presents the CMDs and our isochrone fits. Finally, Section 4 deals with the age of the Galactic Disk, and draws some concluding remarks.

2 STELLAR MODELS AND ISOCHRONES

The Bertelli et al. (1994) library of isochrones and companion stellar models has long been used in a large variety of astrophysical problems going from studies of CMD of single clusters or complex stellar populations to spectrophotometric synthesis (Bressan et al. 1994).

Recently, Girardi et al. (1998) have revised the input physics of the stellar models and generated a new library of isochrones. In the following we will shortly summarize the key assumptions of the Girardi et al. (1998) models and highlight the points of major difference with respect to Bertelli et al. (1994).

2.1 Stellar models

The stellar models are from Girardi et al. (1998). They consist of a large set of evolutionary tracks for metallicities ranging from $Z = 0.001$ to 0.03, and masses from 0.15 to 7 $M_{\odot}$. Models of low-mass stars are computed at typical mass intervals of 0.1 $M_{\odot}$. Work is progress to extend the library to other metallicities and/or to the range of massive stars.

Details of the input physics. All details about the input physics of the tracks can be found in e.g. Girardi et al. (1996, 1998). Suffice it to mention that they include updated OPAL (Iglesias & Rogers 1996) and low-temperature opacities (Alexander & Ferguson 1994), and a revised equation of state. In comparison with the previous set of the Padua stellar tracks (Bertelli et al. 1994 and references therein), the present ones have slightly different lifetimes (see Girardi et al. 1996), and giant branches which are typically hotter by about 50 to 100 K. These differences result mainly from the inclusion of Coulomb interactions in the equation of state, and from the new low-temperature opacities.

The mass and metallicity resolutions of the grids of evolutionary tracks are suitable for the derivation of accurate isochrones in the CMD. The method in usage here is that of interpolating between equivalent points along the tracks (see e.g. Bertelli et al. 1994). In this way, we generate isochrones for any intermediate value of age and metallicity. Mass loss in the RGB is according to the Reimers (1975) formula with an efficiency factor of $\eta = 0.4$. The bolometric corrections and $T_{\text{eff}}$–colour transformations are derived from the Kurucz (1992) library of model atmospheres (see Bertelli et al. 1994 for details).

Calibrating against the Sun. Bertelli et al. (1994) and Girardi et al. (1998) calibrate the stellar models, i.e. choose the mixing length parameter $\alpha \times H_P$, where $H_P$ is the local pressure scale height, for the outer superadiabatic convection, following different methods. Bertelli et al. (1994) started assuming the metallicity and helium content of the Sun, i.e. $Z_{\odot} = 0.020$ and $Y_{\odot} = 0.28$, and looked for the value of $\alpha$ that would fit the effective temperature of the Sun at the canonical age of 4.5 Gyr. They got $\alpha = 1.63$ but with a small offset in the Sun luminosity ($\log L/L_{\odot} = -0.017$). Girardi et al. (1998) prefer to start from the Sun metallicity ($Z=0.019$), luminosity and effective temperature and look for the values of $\alpha$ and $Y_{\odot}$ that would fit the Sun at the same age. They get $\alpha = 1.68$ and $Y_{\odot} = 0.273$. The small difference in $\alpha$ implies that the isochrones of the Girardi et al. (1998) library will be somewhat hotter during the RGB phase than those of Bertelli et al. (1994).

Enrichment law $\Delta Y/\Delta Z$. All the models calculated for the Bertelli et al. (1994) library made use of the enrichment law $\Delta Y/\Delta Z = 3.0$ or equivalently $Y = Y_P + 3.0 Z$, with $Y_P = 0.23$ the primordial helium content (Torres-Peimbert et al. 1989, Olive & Steigman 1995). Girardi et al. (1998) adopted a slightly different relationship, i.e. $Y = 0.23 + 2.25 Z$ with $\Delta Y/\Delta Z = 2.25$, such as to reproduce the initial helium content of the Sun $Y_{\odot} = 0.273$ as derived from the calibration of the solar model.

Convective overshooting. In all the tracks with $M \geq 1.0 M_{\odot}$, some amount of convective overshooting is adopted. This is expressed by means of the parameter $\Lambda \times H_P$ (see Alongi et al. 1993 for more details on the subject). The way in which convective overshooting is let develop in the range of low mass stars (say 1.0 to 1.5 $M_{\odot}$) bears very much not only on the properties of stellar models, but also on the associated isochrones and related problem of ranking ages.

In Bertelli et al. (1994) the following recipe was adopted: $\Lambda = 0.0$ for $M \leq 1.0 M_{\odot}$, $\Lambda = 0.25$ for $1 M_{\odot} < M \leq 1.5 M_{\odot}$, and $\Lambda = 0.50$ for $M > 1.5 M_{\odot}$.

Girardi et al. (1998) modified this recipe assuming that $\Lambda$ increases linearly with the star mass in the interval $1.0 < (M/M_{\odot}) \leq 1.5$, getting to its maximum value of $\Lambda = 0.50$ only for $M > 1.5 M_{\odot}$.

2.2 Comparing isochrones from different sources

In this section we compare the isochrones by Girardi et al. (1998) with those by Bertelli et al. (1994) in order to estimate possible systematic differences in the final age assignment caused by using different sources of stellar models and/or isochrones.

In Fig. 1 we plot three groups of isochrones taken from Bertelli et al. (1994), dotted lines, and Girardi et al. (1998), solid lines, for the ages of 5, 10, 13 Gyr as indicated. For all cases the chemical composition is solar, i.e. $Y=0.280, Z=0.020$ in Bertelli et al. (1994) and $Y=0.273$, $Z=0.019$ in Girardi et al. (1998). While at the turn-off the two types of isochrones are almost indistinguishable, their RGBs differ in color by a sizable factor. Looking at the case of 10 Gyr, the red clump phase (stationary core He-burning) of the Girardi et al. (1998) isochrone is fainter by about 0.15 mag with respect to that of Bertelli et al. (1994) isochrone.

To better understand the effect of the different assumptions for the calibration against the Sun, the enrichment law, and convective overshooting in particular, we plot in Fig. 2 the turn-off mass $M_{TO}$ as a function of the age

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Figure 1. Isochrones of 5, 10 and 13 Gyr from Bertelli et al. (1994), dotted lines, and Girardi et al. (1998), solid lines. The chemical composition is $Y=0.28, Z=0.020$ in Bertelli et al. (1994) and $Y=0.273, Z=0.019$ in Girardi et al. (1998).

Figure 2. The turn-off mass (in solar units) as a function of the age (in Gyr) for the metallicities $Z=0.004, Z=0.008$, and $Z=0.02$. See the text for the meaning of the horizontal and vertical dotted lines for both sets of isochrones. The left panel is for Girardi et al. (1998), whereas the right panel is for Bertelli et al. (1994). In both panels we draw the lines of constant mass $M_{TO} = 1.0M_\odot$, $M_{TO} = 1.25M_\odot$, and $M_{TO} = 1.5M_\odot$. No convective core can develop for ages older than set by the intersection with the $M_{TO} = 1.0M_\odot$ line (the ages depend, however, on the chemical composition). Girardi et al. (1998) isochrones are less affected by overshooting with respect to the case of Bertelli et al. (1994) for all ages older than set by the intersection with the $M_{TO} = 1.25M_\odot$ line. Once again they depend on the metallicity. The opposite for all the younger ages corresponding to turn-off masses in the range $1.25M_\odot < M_{TO} < 1.5M_\odot$.

Particular useful for age ranking, is the so-called
### Table 2. Basic calibrations

| log(age/yr) | $V_{\text{TO}}$ | $\Delta V_{\text{RGC}}^{\text{TO}}$ | $V_{\text{TO}}$ | $\Delta V_{\text{RGC}}^{\text{TO}}$ |
|------------|-----------------|-----------------|-----------------|-----------------|
| 9.0        | 2.02            | 0.77            | 2.08            | 1.16            |
| 9.2        | 2.68            | 1.70            | 2.68            | 1.79            |
| 9.4        | 3.28            | 2.32            | 3.37            | 2.49            |
| 9.6        | 3.89            | 2.85            | 3.86            | 2.90            |
| 9.8        | 3.83            | 2.72            | 4.20            | 3.16            |
| 10.0       | 4.24            | 3.06            | 4.40            | 3.28            |
| 10.2       | 4.66            | 3.41            | 4.75            | 3.58            |

The method, which correlates the magnitude difference between the red giant clump (RGC) and turn-off (TO) stars to the age. This relation owes its existence to the fact that the RGC luminosity is almost age independent for ages older than about 2 Gyr. This combined with the dependence of the turn-off luminosity on the cluster age, makes the above difference a reasonably good age indicator. The relation is, however, sensitive to the chemical composition and other physical details of model construction. This basic calibration is presented in Table 2 limited to the case of solar composition both for the Girardi et al. (1998) and Bertelli et al. (1994) isochrones. The magnitude of the RGC stars is taken at the lowest luminosity end of the clump.

At given age, the Girardi et al. (1998) isochrones yield values of $\Delta V_{\text{RGC}}^{\text{TO}}$, that are at least 0.15 mag smaller than those from the Bertelli et al. (1994) isochrones. In general the following relation holds

$$ \frac{\Delta(V_{\text{RGC}}^{\text{TO}})}{\Delta \log t} \approx 1.9 \text{ mag/dex} \quad (1) $$

The 0.15 mag difference in $\Delta V_{\text{RGC}}^{\text{TO}}$ between Girardi et al. (1998) and Bertelli et al. (1994) together with the above relationship imply that the ages derived from using the Girardi et al. (1998) isochrones are about 20% older than those one would obtain from using the Bertelli et al. (1994) isochrones (see also the vertical line in Fig. 2).

Finally, we like to remark that the observational $(V - I)$ colors of red giant stars are typically 0.1 mag redder than predicted by the theory. This small discrepancy is less of a problem in the $(B - V)$ colour. The obvious explanation is that the transformations from $T_{\text{eff}}$ to $(V - I)$ colors still suffer from some uncertainty. In recent years, several authors have called attention on this problem (see Worthey 1994; Gratton et al. 1996; Weiss & Salaris 1998), which likely resides in the Kurucz (1992) library of stellar spectra and associated transformations.

#### 2.3 Isochrone fitting method

Isochrone fitting is to be preferred to other more sophisticated methods (e.g. the synthetic CMD technique) for two reasons:

- It gives a straightforward idea of the best fit age.
- It can be used also when no membership for all the cluster stars is available.

Membership is a very delicate issue, because luminosity functions and synthetic CMDs can be successfully used only when the membership is known. Indeed they are based on a quantitative comparison (number of stars in different evolutionary stages) between theory and observations. To assess the membership of all cluster stars is a hard task not always accomplished or feasible (Chen et al. 1998, Von Hippe & Sarajedini 1998).

The cluster metallicities $[Fe/H]$ are translated into theoretical metal abundances $Z$ by means of the relation:

$$ [Fe/H] = \log Z - \log Z_{\odot} - 1.721 $$

To derive the age, distance modulus and reddening of a cluster we proceed as follows.

If RGC stars are present and easy to identify, the $\Delta V_{\text{RGC}}^{\text{TO}}$ method already allows us to select the appropriate age range for the cluster under examination.

The main drawback of the $\Delta V_{\text{RGC}}^{\text{TO}}$ method is the identification of the RGC stars in the CMD of old clusters when the clump gets scarcely populated. The task is even more difficult if one considers that open clusters are usually close to the Galactic Plane and therefore are highly contaminated by field stars.

Once the age range is selected, with the aid of three isochrones of slightly different ages, the appropriate values of reddening and distance modulus are independently derived from the superposition of the theoretical isochrones onto the observed CMDs. Distance moduli were selected to provide a good fit of the turn-off and subgiant branch magnitude at the same time, and reddening was estimated by matching with the isochrone the blue edge of the main sequence band. Finally, only solutions were retained that were able to match the turn-off and subgiant features but also the position of the RGC stars.

In several cases, it was impossible to reproduce the CMD both in the $BV$ and $VI$ pass-bands with a single value of reddening as governed by the relation $E_{(V-I)} = 1.25 E_{(B-V)}$ (cf. Munari & Carraro 1996).

### 3 Cluster by cluster analysis

For each cluster listed in Table 1, we derive the age comparing the observational CMD with isochrones of given metallicity. The analysis is simultaneously made both in the $V$ vs. $B - V$ and $V$ vs. $V - I$ diagrams.

The results are summarized in Table 3, which for each cluster lists the metallicity $Z$, the color excess $E_{(B-V)}$ and $E_{(V-I)}$, the distance modulus $(m - M)_0$, the age $\tau$ (in Gyr), together with their uncertainties.

#### 3.1 NGC 188

The source of photometric data for NGC 188 is the $BV$ photographic survey of McClure & Twarog (1977) and the $VI$ CCD survey of Von Hippel & Sarajedini (1998), whereas the metal abundance $[Fe/H]$ is from Friel et al. (1995).
Figure 3. Isochrones superposed to the CMD of NGC 188. At the right side we indicate the adopted reddening \(E_{(B-V)}\), distance modulus \((m-M)_0\), and age of the isochrone plotted in each sub-panel.

is missing in the \(V\) vs. \((V-I)\) CMD because of the poor statistics. We get an age of 6–7 Gyr, a distance modulus \((m-M)_0 = 11.20 \pm 0.05\), and a color excess \(E_{(B-V)} = 0.12-0.13\). The solution with age of 5 Gyr, \((m-M)_0 = 11.32\), \(E_{(B-V)} = 0.17\) can be discarded because of the poor fit of the red clump stars. Within the observational uncertainties, age, distance modulus, and reddening we have obtained are consistent with published values (see Carraro & Chiosi 1994; Carraro et al. 1994; Von Hippel & Sarajedini 1998).

3.2 NGC 6791

NGC 6791 has received much attention over the past years because of its unique combination of age and metallicity. In addition to being one of the most populous open clusters, it is the most metal-rich and among the oldest clusters at the same time. It contains also seven blue horizontal branch stars.

We adopt the photometric data by Kaluzny & Rucinski (1995), and the spectroscopic metallicity by Friel & Janes (1993). Our best fit is shown in Fig. 4. We get an age of 8–9
Figure 4. Isochrones superposed to the CMD of NGC 6791. At the right side we indicate the adopted reddening $E_{(B-V)}$, distance modulus $(m-M)_0$, and age of the isochrone plotted in each sub-panel.

3.3 Collinder 261

This is a populous cluster studied by Mazur et al. (1995) and Gozzoli et al. (1996), who present photometric data of similar quality. We adopt here the CMDs of Mazur et al. (1995). The metallicity $[Fe/H]$ is derived from the spectroscopic study of Friel et al. (1995). The superposition of theoretical isochrones onto the observational CMDs is shown in Fig. 5. The age cannot be estimated better than 6 – 8 Gyr, even though there is a marginal preference for the narrower range 6 – 7 Gyr, which is reported in Table 3. The
distance modulus is \((m - M)_0 = 12.15 \pm 0.05\), and the color excess is \(E_{(B-V)} = 0.30\). In this case, our age determination is fully consistent with that by Mazur et al. (1995), but only marginally with the one by Gozzoli et al. (1996). Reddening and distance modulus are however in agreement with both previous studies. The cause for the age disagreement can be attributed to differences in the adopted stellar models and technique to generate isochrones and synthetic CMDs.

### 3.4 Melotte 66

\(B\) and \(V\) photometry for Melotte 66 is available only from the photographic study of Anthony-Twarog et al. (1979) which is deep enough to reach the turn-off. In contrast the \(V\) and \(I\) photometric data by Kassis et al. (1997) go much deeper. The cluster is the most metal poor of the sample (Friel & Janes 1993). The comparison with the isochrones is shown in Fig. 6. We get an age of 4 \(- 5\) Gyr, a distance modulus \((m - M)_0 = 13.20 \pm 0.10\), and a color excess \(E_{(B-V)} = 0.20\). The solution with age of 3 Gyr,
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3.5 Berkeley 39

The photometric data for this cluster is from Kassis et al. (1997), whereas the metal abundance is from Friel & Janes (1993). The CMD of Berkeley 39 and the comparison with theoretical isochrones is shown in Fig. 7. The best fit case is for age 5–6 Gyr, distance modulus $(m - M)_0 = 12.975 \pm 0.025$, and color excess $E_{(B-V)} = 0.18 - 0.20$. The solution with age of 7 Gyr, $(m - M)_0 = 12.85$, and $E_{(B-V)} = 0.16$ is rejected because of the poor fit of the turn-off and clump of red stars. The new parameters are significantly different from what found by Carraro & Chiosi (1994), who gave $E_{(B-V)} = 0.10$, $(m - M)_0 = 13.20$, and age of 6.5 Gyr, whereas within the uncertainties reddening and distance modulus are consistent with the determinations by Kassis et al. (1997).
3.6 Berkeley 17

The analysis carried in so far clearly shows that ages based on the new set of isochrones (Girardi et al. 1998) are comfortably consistent with previous estimates. This is an important remark to be made in view of the results we would obtain for the most controversial cluster in the sample, namely Berkeley 17.

This cluster has been studied several times in the optical (Kaluzny 1994; Phelps et al. 1994, 1995; Phelps 1997) and more recently also in the near IR (Carraro et al. 1998b).

Kaluzny (1994) compared Berkeley 17 with NGC 6791 and, assuming that the former is more metal-poor than the latter, concluded that the two clusters are likely coeval (about 9 Gyr old). Moreover, he suggested a distance modulus \( (m-M)_0 \geq 13.26 \) and a reddening \( E_{(B-V)} \geq 0.56 \) or \( E_{(V-I)} \geq 0.70 \).

In contrast, Phelps (1997) using photometric data much similar to that by Kaluzny (1994) reached considerably different conclusions. Specifically, he found a metallicity in the range \(-0.30 \leq [Fe/H] \leq 0.00\), an age of \( 12^{+2}_{-1} \) Gyr, a dist-
Figure 8. Isochrones superposed to the CMD of Berkeley 17 by Kaluzny (1994). At the right side we indicate the adopted reddening $E_{(B-V)}$, distance modulus $(m-M)_0$, and age of the isochrone plotted in each sub-panel.

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In this study we adopt the metallicity by Friel et al. (1995), i.e. $[Fe/H] = -0.29 \pm 0.13$, to which corresponds the metallicity in the range $Z = 0.007 - 0.013$. We explored this metallicity range performing fits for $Z=0.007$, 0.010 and 0.013 (see Figs. 9,10 and 11, respectively). Good fits of the CMDs from both sources of data, shown in Figs. 8 (Kaluzny 1994) and 11 (Phelps 1997), are possible for the following combinations of parameters: $E_{(B-V)} = 0.55 - 0.67$, $E_{(V-I)} = 0.64 - 0.78$, $(m-M)_0 = 12.13 \pm 0.07$, and age $9 \pm 1$ Gyr. The effect of changing the metallicity does not affect the age determination, but only the value of the reddening.

An age of 12 Gyr is clearly ruled out for any metallicity, since fitting the turn-off the theoretical clump turns out to be too bright.

Our analysis stands on the identification of the RGC stars as the handful of objects located at $V \simeq 15.2$ and $B-V \simeq 1.65$ or $(V-I) \simeq 1.72$ (Phelps 1997) and the simultaneous fit of the turn-off, subgiant and RGC stars. The results we get for the cluster parameters are also consistent.
with companion analysis of the CMD in the near IR (J and K pass-bands) by Carraro et al. (1998b).

**Why the new age is younger than what found by Phelps (1997) using the same data, reddening, and distance modulus?**

Phelps’s (1997) result is even more surprising if one considers that passing from Bertelli’s et al. (1994) to Girardi’s et al. (1998) isochrones a systematic increase in the age of about 19% for old clusters like Berkeley 17 is expected.

Owing to the many implications deriving from an age for Berkeley 17 as old as that of the bulk of globular clusters, a close scrutiny of the Phelps (1997) study is required.

His analysis proceeds in two steps. Firstly the CMDs are compared with the VandenBerg (1985) isochrones (they do not extend beyond the subgiant branch) and no assumptions are made for the metallicity, reddening, and distance. Out of this first comparison the conclusion is drawn that \([Fe/H] = -0.23\) and age of 12.5 Gyr best match the BV and VI data. The analysis is then repeated using the Bertelli et al. (1994) isochrones for ages of 10.0, 12.0 and 13.2 Gyr and metallicities \(Z = 0.05, Z = 0.02\) and \(Z = 0.008\). In

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**Figure 9.** Isochrones superposed to the CMD of Berkeley 17 by Phelps (1997), assuming the metallicity value \(Z = 0.007\). At the right side we indicate the adopted reddening \(E_{B-V}\), distance modulus \((m - M)_0\), and age of the isochrone plotted in each sub-panel.
this second approach, the ability of the various isochrones in matching the location of RGC stars is also taken into account. Looking at the series of Figs.7, 8, and 9 in Phelps (1997), we would surely exclude all cases with age 13.2 Gyr and also all cases with $Z=0.05$ and marginally $Z=0.020$ as well, because the RGC stars are not matched. In contrast, the cases with $Z=0.008$ and ages of 10.0 and 12.0 Gyr (to a less extent) provide a satisfactory fit of all the constraints. This is actually what find in our analysis: $Z \approx 0.010$ and age $9 \pm 1$ Gyr. Somehow rejecting his own results and perhaps influenced by the fit with the VandenBerg (1985) isochrones, Phelps (1997) preferred to conclude that the age of Berkeley 17 is $12^{+1}_{-2}$ Gyr. In contrast, the age that we would derive from Phelps’ (1997) study is $11^{+1}_{-1}$ Gyr. The younger age comes from the fainter RGC stars in the Girardi et al. (1994) isochrones.

4 CONCLUSIONS

In this paper we have derived the ages of a sample of very old open clusters. The results are summarized in Table 3.
The ages of the clusters under examination range from 4−5 Gyr (Melotte 66) to 8−9 Gyr (NGC 6791) and 9 ± 1 Gyr (Berkeley 17).

Particularly intriguing is the age we have found for Berkeley 17 (9 ± 1 Gyr). While the new age fairly agrees with the estimate of 9 Gyr suggested by Kaluzny (1994), it is probably younger than the 12±1 Gyr claimed by Phelps (1997) and also the revised value of 11±1 Gyr we have suggested. The reason for the difference is found in the use of different sets of isochrones that differ in some important details.

According to the present analysis the age of Berkeley 17 is no longer embarrassingly close to that of bulk globular clusters: 13 Gyr with a tail down to 11 Gyr (Gratton et al. 1997), but most likely falls back into the classical range for this type of clusters. However an old age such as that found by Phelps (1997) – we prefer to consider here the value of 11±1 Gyr – cannot be firmly excluded because of the many uncertainties still affecting the stellar models in the mass range 1.0 to 1.5 $M_\odot$.

Perhaps, the most important conclusion to be learned from the present study is that we are facing the embarrass-
ing situation in which our poor knowledge of important details of the physical structure of low mass stars in the range 1.0 to 1.5 $M_{\odot}$, for instance central mixing and associated overshooting, does not allow us to derive ages of old open clusters with the required precision. Therefore, to answer the basic question posed by the maximum age of old open clusters with respect to that of globular clusters, one has to wait until this point is clarified. A thorough investigation of the behaviour of convective cores in the mass range 1.0 - 1.5 $M_{\odot}$ is a prerequisite to age studies of any kind.

Despite this serious drawback of extant theory of stellar structure and evolution let us speculate further on the provisional assumption that the ages we have found are not too grossly in error.

If Berkeley 17 and NGC 6791 trace the upper limit to the age of open clusters, how this apply to the age of the Galactic Disk? Are there other not yet discovered open clusters of older age? If open clusters set the a sort of limit to the age of the Galactic Disk, is this value consistent with other independent age estimates of this component of the Milky Way?

A variety of different methods can be used to derive the age of the Galactic Disk. In summary, the situation is as follows:

- The luminosity function of White Dwarfs suggests an age between 6 and 10 Gyr (Bergeron et al. 1997).
- The oldest evolved G and F stars in the Edvardsson et al. (1993) sample have ages around 10 Gyr according to the analysis made by Ng & Bertelli (1997).
- Radio-active dating (from isotope ratios) gives estimates around 9 Gyr (Morell et al. 1992).
- The faintest sequence of subgiant stars suggests an age of about 11 ± 1 Gyr (Jimenez et al. 1998).

Adding together all these different estimates, we can argue that the Galactic Disk has an age of about 9-10 Gyr, 2-3 Gyrs younger than the bulk of globular clusters (13 Gyrs, Gratton et al. 1997). The hint arises that the Milky Way underwent a minimum activity or hiatus in its Star Formation History in the provisional age range 10 to 11 Gyrs ago.

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\[ \tau = 8 \text{ Gyr} \]
\[ (m - M)_0 = 12.20 \]
\[ E_{B-V} = 0.65 \]

\[ \tau = 9 \text{ Gyr} \]
\[ (m - M)_0 = 12.15 \]
\[ E_{B-V} = 0.65 \]

\[ \tau = 10 \text{ Gyr} \]
\[ (m - M)_0 = 12.10 \]
\[ E_{B-V} = 0.65 \]