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THE AGES OF THE DISK CLUSTERS NGC 188, M67, AND NGC 752, USING IMPROVED OPACITIES AND CLUSTER MEMBERSHIP DATA

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ABSTRACT

Theoretical isochrones have been constructed using the OPAL opacities to derive the ages of the open clusters NGC 188, M67, and NGC 752 as well as to estimate the amount of convective overshoot at the convective core edge. We find that—under the assumptions made in the models—no overshoot, or a very small amount (up to 0.1 H_p) is allowed for the best fits. Very good agreement is achieved between models and the main sequence, turnoff, subgiant, and giant branch for the clusters NGC 188 and M67. For NGC 188 and M67 we derive the ages: $6.0^{+1.0}_{-0.5}$ Gyr and 4.0 ± 0.5 Gyr, respectively, where the main uncertainty is due to the estimate of the interstellar reddening. The age of NGC 752 is $2.0^{+0.5}_{-0.3}$ Gyr if the adopted metallicity is [Fe/H]$=-0.27$.

1. INTRODUCTION

The relatively old open clusters NGC 188 and M67 have been extensively studied and dated through different techniques. These are the classical comparison of the observed color–magnitude diagram (CMD) to theoretical isochrones, differential comparison of the clusters CMDs (Twarog & Anthony-Twarog 1989, hereafter referred to as TA), the spectroscopic method developed by Hobbs *et al.* (1990) for NGC 188 and Hobbs & Thorburn (1991) for M67 which is based on the determination of the effective temperature of the turnoff stars and is independent of the cluster reddening, and using morphological age indices (Phelps *et al.* 1994). While for M67 most studies agreed to an age between 4–5 Gyr thus making it representative for Population I solar-age stars, NGC 188 presented a more intriguing case. Since, for a long time, it was believed that NGC 188 is the oldest open cluster, characteristic that now is more appropriate to other open clusters (see the recent study of Phelps *et al.* 1994), its age was of a great importance in dating the Galactic disk. Therefore the controversy in the literature concerning the age of NGC 188—an age of 10 Gyr as opposed to 6 Gyr—(see TA; Demarque *et al.* 1992, hereafter referred to as DGG) had major implications in the formation of the galaxy's subsystems: disk and halo. However, this controversy seems to have been resolved since recent studies (TA; DGG; Hobbs *et al.* 1990) agree to an age between 6–7 Gyr.

Knowing relatively accurately and consistently, from various dating techniques, the ages of NGC 188, M67, and the younger NGC 752 is essential for understanding the lithium main sequence depletion mechanism, and, in a larger context, the lithium enrichment in the galaxy (Pinsonneault 1994; Deliyannis *et al.* 1990). Since observations of lithium abundances have been made in all the three clusters (Hobbs & Pilachowski 1986a, b, 1988), reliable ages are particularly desirable.

In this study we test the new physics implemented in the evolutionary code (new OPAL opacities and core convective overshoot) by comparing the theory (isochrones) with observations (CMD) and we determine the ages through isochrone fitting.

Another issue this study will address is the convective overshoot at the edge of the convective core. The CMD of intermediate age clusters (2–3 Gyr) presents a gap in the main sequence close to the turnoff which corresponds to the hydrogen exhaustion phase of the convective core for turnoff stars. The morphology of the gap therefore depends on the size of the convective core as well as on the extent of the possible overshoot at the core edge. Unlike the cases in which the turnoff, the gap, and the blue hook can be well traced and/or described in a quantitative way (NGC 2420, Demarque *et al.* 1994), the CMDs of NGC 188 and M67 are more difficult to interpret, and the situation is very much dependent on the accuracy of the photometry, the cluster membership determinations, and contamination with binaries. As for NGC 752, in addition to the problems mentioned, the small number of cluster stars complicates this issue even more. In order to put some limits on the amount of the possible overshoot, we make use of the latest photometric studies (CCD for NGC 188 and M67 and mostly photoelectric

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for NGC 752) and also the latest most accurate proper motion membership studies. We construct theoretical isochrones for three values of the amount of convective overshoot and compare the CMDs.

In Sec. 2 we describe how the models were constructed: the physics input and the parameter space. In Sec. 3 we present for each cluster, the photometry used and the proper motion membership determinations to finally produce a CLEANed CMD. In Sec. 4 we describe the results obtained and finally we summarize the conclusions of this paper in Sec. 5.

2. THE STELLAR MODELS AND ISOCHRONES

One of the purposes of this study was to investigate the effect of the new OPAL opacities on the stellar evolution models and therefore on the theoretical isochrones and the ages derived, since it was found that the OPAL opacities increase the opacity by factors of 3–4 over the Los Alamos results (Rogers & Iglesias 1992) in some temperature regions. Therefore evolutionary tracks were constructed with the Yale Rotating Evolution Code (YREC) in its nonrotating configuration using the new OPAL opacities and an Anders & Grevesse (1989) solar mixture of metals. Kurucz (1991) opacities were used for temperatures below $\log T=4.0$. It was shown and discussed in DGG and references therein that the stellar models are particularly sensitive to two input physical parameters: the ratio of the mixing length to pressure scale height α and the helium abundance Y, parameters for which we do not have direct information for cluster stars, thus defining one of the main problems in dating star clusters using theoretical isochrones. The solution proposed is the solar calibration of the models: a zero age stellar model of one solar mass is evolved to the age of Sun and—at this age—the model, also called the standard solar model, must have the Sun's luminosity and radius. The luminosity will provide estimates for the helium abundance Y, while the radius will provide estimates for the mixing length parameter α. Recent calculations of the standard solar model (DGG; Guenther *et al.* 1992) with various input physics in the models like opacities, mixtures, model atmospheres provide a helium abundance in the approximate range of 0.27 to 0.29. In our models we adopt a helium abundance $Y=0.28$ which is the closest value to the helium abundances determined in the previous models (Guenther *et al.* 1992) with similar input physics to within few hundredth of the Y value. The mixing length parameter α was determined by solar calibration and using Kurucz model atmospheres tables (Kurucz 1992). The value thus obtained for α is 1.72. We also note that, for the standard solar model, the absolute visual magnitude is $M_v=4.84$ and the color index is $B-V=0.64$. These values were derived using the Revised Yale Isochrones—RYI (Green *et al.* 1987) color calibration, which was also used in deriving the isochrones, and considering the following parameters for the Sun: $[\mathrm{Fe/H}]=0.0$, $T_{\mathrm{eff}}=5780$ K, and $\log g=4.4$.

Another purpose of the study was to estimate the amount of overshoot at the edge of the convective core. The models include the effects of convective overshoot in Zahn's (1991) terminology, that is, in the overshoot region, the composition profile is affected while the local temperature gradient is radiative. The fraction of a pressure scale height (H_p) by which the chemical composition is mixed beyond the core edge will be represented by the parameter D_{mix}. The evolutionary tracks were constructed for $D_{\mathrm{mix}}=0$, 0.1, $0.2H_p$.

We have also considered two chemical compositions: solar ($Z=0.0188$, $Y=0.28$) to represent the clusters NGC 188 and M67 and $Z=0.0100$, $Y=0.26$ for NGC 752 (see Sec. 4 for details on the metallicity of NGC 752). The helium abundance for $Z=0.0100$ was chosen assuming the helium enrichment parameter $R=2$ for solar type stars—where $R=(\Delta Y/\Delta Z)$. Also in the models for $Z=0.0100$, $Y=0.26$ we considered an Eddington grey atmosphere rather than interpolating in the Kurucz atmosphere tables. It was found that, compared to an Eddington atmosphere, the Kurucz model atmospheres affect only the giant branch, displacing it to a slightly redder position (≈ 0.004 in $\log T_{\mathrm{eff}}$). This is because, near the main sequence, and for the mass range relevant for NGC 752 (1.0 to 3.4 $\mathcal{M}_\odot$) the model radii are insensitive to the details of the surface boundary conditions.

The evolutionary tracks were calculated from the zero-age main sequence to the giant branch for 0.6 to 1.7 $\mathcal{M}_\odot$ using steps of 0.05 $\mathcal{M}_\odot$ in mass, and for additional higher masses up to 3.4 $\mathcal{M}_\odot$ depending on the isochrones needed. The isochrones were derived using a modified version (Chaboyer *et al.* 1992) of the code used to construct the RYI and are based on the same color calibration as RYI.

3. THE COLOR–MAGNITUDE DIAGRAMS

3.1 NGC 188

For NGC 188 the observational data consist in the CCD photometry of Caputo *et al.* (1990) combined with membership probabilities (Dinescu *et al.* 1995). We have used membership probabilities based on proper motions and spatial distribution that will clean up the CMD in the turnoff region and giant branch since the membership study goes to a limiting magnitude of $V=16.5$. Due to the conservative way in which the membership probabilities were calculated we use as members all stars with probabilities larger than 50%.

We have also used, for comparison, the CCD study of Kaluzny (1990) since it contains more stars than Caputo *et al.*'s sample, and has a better defined main sequence. Because of the lack of positions, finding chart or cross-identification with any previous study we could not make use of membership probabilities for this sample. Therefore we cleaned up the color–magnitude diagram using the following approach. The data was binned in 0.2 magnitude intervals and for each interval the average $B-V$ color and standard deviation were calculated. Stars lying more than 2 standard deviations from the mean of the bin were rejected. We adopted the $B-V$ standard deviation of the bin rather than using the published observational errors $\sigma(V)$ and $\sigma(B-V)$ for defined magnitude ranges (see Table 8 in Kaluzny 1990) because, in this way, the CMD will retain part of the total scatter. This is important for open clusters because the intrinsic scatter is larger than the observational one, especially for CCD studies when observational errors are small; using the errors in magnitude and color alone to reject points will provide a depleted CMD that allows only for a scatter due to observational errors which is unrealistic for open clusters, since many of highly probable members will be rejected.

3.2 M67

The latest CCD study for M67 was done by Montgomery *et al.* (1993), for the central one-half degree of the cluster, to a limiting magnitude $V=20$. This study contains equatorial coordinates derived from CCD positions transformed to equatorial coordinates using standard reference stars from Girard *et al.* (1989). Therefore a cross-identification with Girard *et al.*'s proper motion membership study was made based on positions and magnitudes. We retained stars that matched position to within 2.0 arcsec and differed by less than 0.5 in V magnitude, and from this sample we retained stars with membership probability (proper motion and spatial) $\geqslant 50\%$. This cleaned up the giant branch, the turnoff, and part of the main sequence down to $V\approx 16$. The gap in the main sequence at $V\approx 16$ is an artifact due to the incompleteness of the proper motion study at faint magnitudes.

3.3 NGC 752

There are several photometric studies for NGC 752 both photographic (Rohlfs & Vanysek 1961; Francic 1989) and photoelectric (Johnson 1953; Eggen 1963). The most recent photometric and radial velocity study of NGC 752 was done by Daniel *et al.* (1994) and it combines different photoelectric data to a common BV system in an attempt to optimally use the present available data. In their combined system they also included stars that lacked photoelectric photometry, thus using the photographic photometry of Rohlfs & Vanysek (1961). We make use of this combined photometric system in defining the CMD and also using proper motion membership probabilities derived by Platais (1991). Stars with probabilities larger than 50% were considered members. As opposed to the previous two clusters discussed, NGC 752 has a small number of cluster members, thus making the CMD rather poorly defined and also prone to distortions due to the presence of binaries. We have eliminated all the possible candidate binaries mentioned in Daniel *et al.* (1994) and identified through different methods: photometric, *uvby* photometry and radial velocity. Thus, from a sample of 124 stars there were left 91 to represent the CMD with probabilities $\geqslant 50\%$. We also include seven stars for which the detection of radial velocity variation is reduced (hotter and/or rotating more rapidly than 30 km s^{-1}) and they may be possible binaries. These stars were classified as rotators by Daniel *et al.* (1994) and we will refer to them similarly. Rapid surface rotation might be expected in stars near the main sequence turnoff in the CMD of NGC 752. These stars are known to have very thin surface convection zones, and are located near the break of the Kraft curve (Kraft 1970; Kawaler 1987). It is known that large rotational velocities can affect luminosities and colors of stars (Roxburgh & Strittmatter 1965). Rotation may thus be responsible for some of the scatter observed near the NGC 752 turnoff. We note, however, that for some cooler G dwarfs, surface rotation is small by the time the cluster has reached the age of 1.7 Gyr (Pinsonneault *et al.* 1990).

4. COMPARISON OF OBSERVATIONS WITH THEORY

In order to compare the observed CMDs with theoretical isochrones, we have fixed two parameters: the metallicity, which was chosen in calculating the evolutionary tracks and the reddening. Then the distance modulus was determined by fitting the observed main sequence for single stars to the theoretical one.

For NGC 188 different studies report different reddening ranging from 0.09 (Eggen & Sandage 1969) to 0.15 (Spinrad *et al.* 1970). We adopt the reddening $E(B-V)=0.12$ given in the study of Twarog & Anthony-Twarog (1989) by a differential comparison of the CMDs of M67 and NGC 188. The metallicity adopted is solar (see Eggen & Sandage 1969; Janes 1979; Hobbs *et al.* 1990). With these values for the reddening and metallicity, the distance modulus obtained for the best fit is $(V-M_v)=11.5$ and the age is 6 Gyr. The main source of errors in the age is the reddening; for a lower limit of $E(B-V)=0.09$ the distance modulus is $(V-M_v)=11.4$ and the age is about 7 Gyr. For a higher limit of the reddening $E(B-V)=0.15$ the distance modulus is $(V-M_v)=11.6$ and the age is 5.5 Gyr. The isochrones for NGC 188 and the CMD from Caputo *et al.* (1990) are presented in Figs. 1(a)–(c), each panel referring to a given value of the core convective overshoot parameter $D_{\rm mix}$. Figure 2 presents the same isochrones as in Fig. 1, but the CMD is from Kaluzny (1990). The isochrones show a very good agreement with the main sequence, turnoff, and subgiant branch. Agreement for the giant branch is difficult to appreciate since the CMD presents a substantial intrinsic scatter already discussed in the literature (McClure & Twarog 1977; Norris & Smith 1985). Also, an inspection of the panels corresponding to $D_{\rm mix}=0.0$, 0.1, $0.2H_p$ shows that the best agreement is obtained for $D_{\rm mix}=0.0H_p$. For $D_{\rm mix}=0.1H_p$, the 6 Gyr isochrone implies the known main sequence gap for the hydrogen exhaustion phase in a convective core, a feature that cannot be distincted in both CMDs. The isochrones for $D_{\rm mix}=0.2H_p$ are the least representative for the CMD of NGC 188. We therefore estimate the age of NGC 188 as $6.0^{+1.0}_{-0.5}$ Gyr, where the errors are estimated from the inspection of the CMD and assuming the error in the reddening of 0.03.

The age thus derived is in good agreement with TA (6.5 ±0.5 Gyr), DGG ($6.5^{+1.5}_{-0.5}$ Gyr, and Hobbs *et al.* (1990) (7.7 ±1.4 Gyr).

For M67 we adopt again a solar metallicity (see Nissen *et al.* 1987; or Hobbs & Thorburn 1991) and a reddening $E(B-V)=0.03$ (Nissen *et al.* 1987). This value of the reddening is a lower limit while an upper limit is about 0.06 (see Janes & Smith 1984; Hobbs & Thorburn 1991). For the reddening adopted the distance modulus derived for the best fit is $(V-M_v)=9.7$ with the corresponding age of 4.0 Gyr. For the upper limit of the reddening $[E(B-V)=0.06]$ the distance modulus is $(V-M_v)=9.8$ with an age of about 3.8 Gyr. Figure 3 shows the fits for M67 for $E(B-V)=0.03$, $(V-M_v)=9.7$ and, as in the previous figures, each panel refers to the three values of the parameter $D_{\rm mix}$. Again very

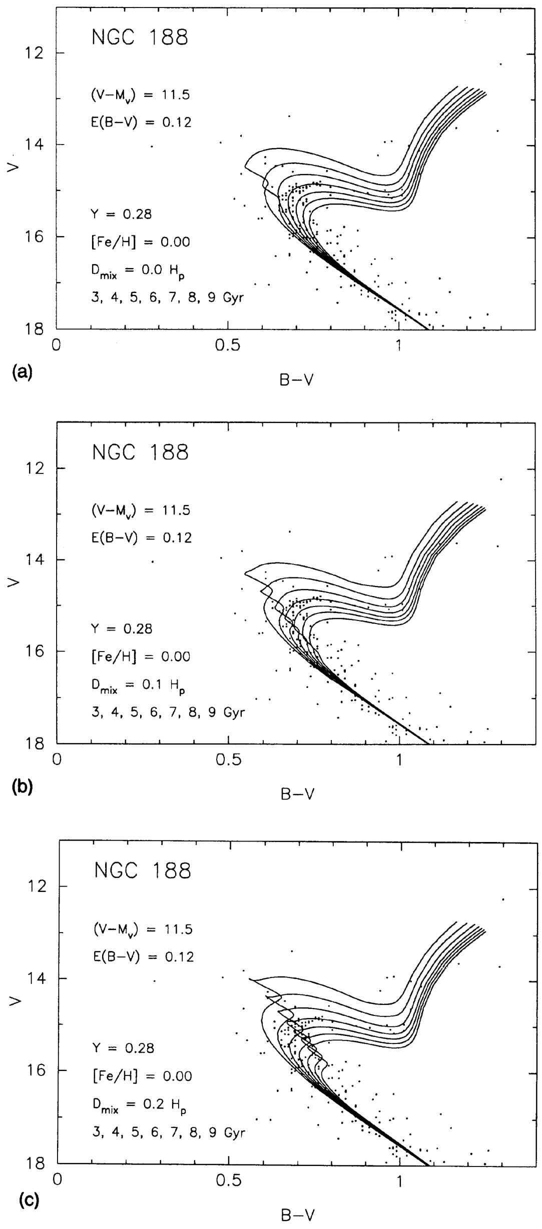

FIG. 1. NGC 188—theoretical isochrones and CMD from Caputo *et al.* (1990). Panels (a), (b), and (c) correspond to core convective overshoot parameter $D_{\rm mix}$=0.0, 0.1, and 0.2H_p, respectively.

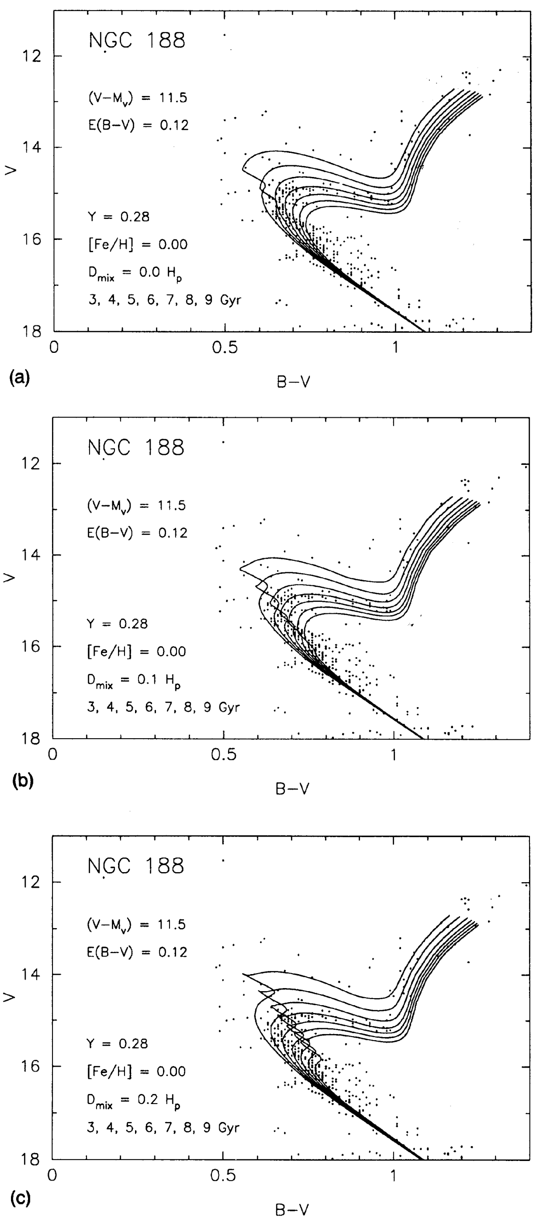

FIG. 2. The same as Fig. 1, but the CMD is from Kaluzny (1990).

good fits are obtained for the main sequence, turnoff, and subgiant region, while the giant branch seems slightly redder than the theoretical models for the given age. As in the previous cases, models with no overshoot, or a very small amount ($D_{\rm mix}$=0.1H_p) seem to best reproduce the observations. The estimate for M67s age is 4.0±0.5 Gyr. For M67, given the smaller range in the reddening estimates than for NGC 188, the error in the age comes from the uncertainty in the reddening, as well as from the ability to fit the isochrones with the CMD.

The latest ages derived for M67 are $4.0^{+1.0}_{-0.5}$ Gyr (DGG), 5.2±1.0 Gyr (Hobbs & Thorburn 1991). For both NGC 188 and M67, the ages are in agreement with the results of Meynet *et al.* (1993), (6.6 Gyr for NGC 188 and 4.0 Gyr for M67), which also constructed isochrones using the recent opacity tables (Rogers & Iglesias 1992).

The last cluster, NGC 752, has a relatively sparse CMD, thus making the main sequence fit more difficult with larger potential errors in the derived distance modulus and age and also difficult to interpret a possible morphology due to core convective overshoot. The metallicity derived for NGC 752 varies approximately from 0.0 to −0.2 based on different studies. We mention here several studies, while for a detailed review we refer to the recent paper of Daniel *et al.* (1994).

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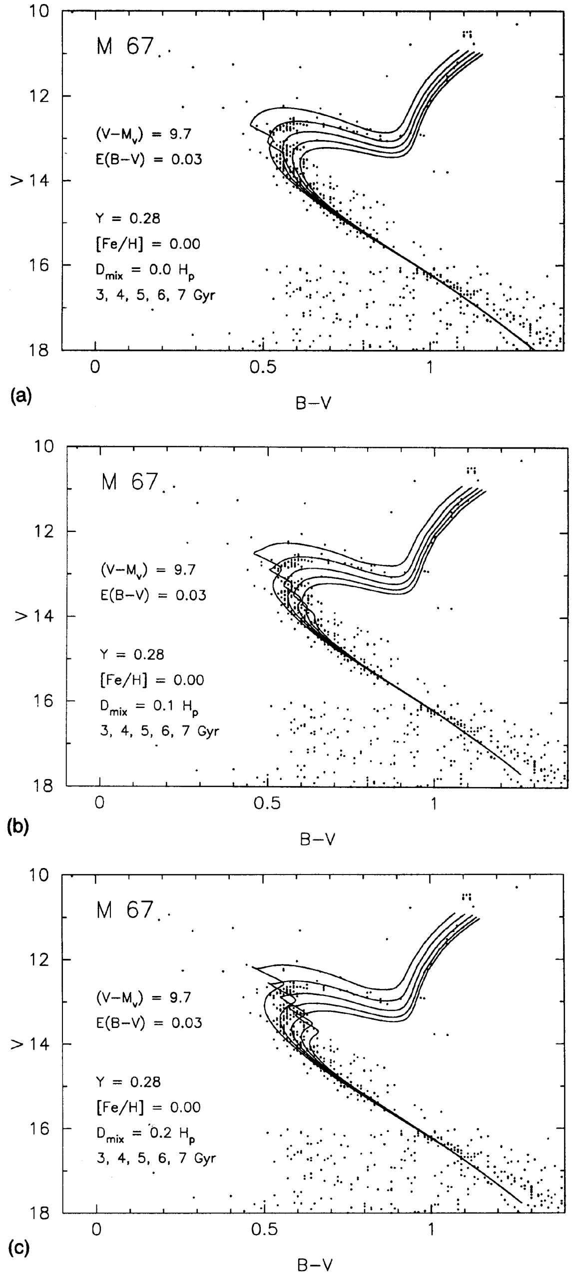

FIG. 3. M67—theoretical isochrones and CMD from Montgomery *et al.* (1993). Panels (a), (b), and (c) correspond to $D_{\rm mix}$=0.0, 0.1, and 0.2H_p, respectively.

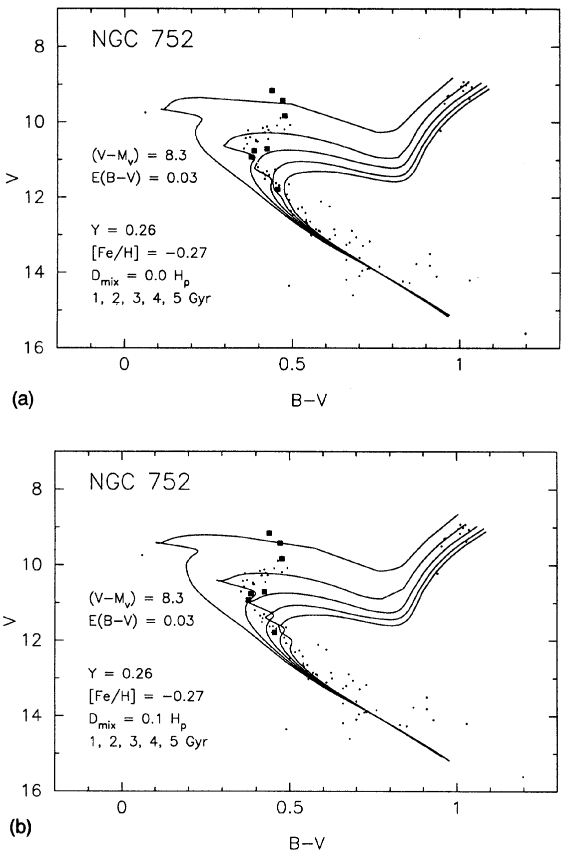

FIG. 4. NGC 752—theoretical isochrones and CMD from Daniel *et al.* (1994); filled squares represent rotators (see Sec. *3.3*). Panel (a) represents $D_{\rm mix}$=0.0H_p and panel (b) represents $D_{\rm mix}$=0.1H_p.

Twarog (1983) derives a [Fe/H]=−0.2±0.1 based on combined photometric data, Nissen (1988) derives a [Fe/H] =−0.05±0.13 from *uvby* photometry, while from recent spectroscopic studies the metallicity is [Fe/H]=−0.09±0.05 (Hobbs & Thorburn 1992—high resolution spectra) and [Fe/H]=−0.16±0.05 (Friel & Janes 1993—medium resolution spectra). We have constructed evolutionary tracks for two extreme values of the chemical composition in order to bracket the metallicity and derive the corresponding upper and lower limits of the age. One set of tracks was computed for Z=0.0188 and Y=0.28 representing solar metallicity and a second set of tracks was computed for Z=0.0100 and Y=0.26, corresponding to the metallicity [Fe/H]=−0.27. The reddening for NGC 752 ranges from 0.03 to 0.04 (see Hobbs & Thorburn 1992; Daniel *et al.* 1994). For this cluster we have adopted both the reddening and the distance modulus from the available cluster parameters in the literature (Friel & Janes 1993; Daniel *et al.* 1994, and references therein) as follows: E($B-V$)=0.03 and ($V-M_v$)=8.3.

The theoretical isochrones corresponding to solar metallicity were slightly above the cluster's main sequence, thus indicating a lower than solar metallicity for the cluster. However, the age of the cluster corresponding to solar metallicity is about 1.7 Gyr.

In what follows, figures and our final estimate of the age, we will consider the isochrones corresponding to Z=0.0100 and Y=0.26. For these parameters the best fit isochrone is for 2 Gyr. An age estimate for the reddening E($B-V$)=0.04 is also 2 Gyr. Provided the reddening values are not largely underestimated or overestimated, for NGC 752, the reddening is not the major source of error in the age. The error in the age introduced by the error in the metallicity is also small compared to the error of the actual fit of the isochrones. In this case, the major source of error in the age is due to the fit of isochrones with a main sequence that has a large intrinsic scatter and few cluster members. The large intrinsic scatter in the main sequence and small number of cluster members (see Sec. *3.3*).

The isochrones and the CMD are presented in Figs. 4(a) and 4(b) for two values of the core convective overshoot parameter $D_{\rm mix}=0.0$, $0.1H_p$, respectively. The 2 Gyr isochrone fits well the main sequence and the giant branch, however, the predicted turnoff is too blue for the observations. Given the observational data, there is no evidence for a large amount of overshoot. From inspecting the CMD and given the uncertainties in the metallicity and helium abundance, we estimate an age of $2.0^{+0.5}_{-0.3}$ Gyr.

Other studies derived the following age for NGC 752: 1.9±0.2 Gyr for no overshoot isochrones and 1.7±0.1 Gyr for isochrones with overshoot (Daniel *et al.* 1994), 1.8 Gyr (Meynet *et al.* 1993).

5. SUMMARY

We have determined the ages of the old disk clusters NGC 188 and M67 for a solar metallicity, based on solar calibration and the OPAL opacities. NGC 188 has an age of $6.0^{+1.0}_{-0.5}$ Gyr and M67 has an age of 4.0±0.5 Gyr. We have also determined, on similar model assumptions, the age of NGC 752: $2.0^{+0.5}_{-0.3}$ Gyr. The ages derived agree with the latest age determinations for these three clusters and, as discussed by DGG, the opacities do not affect significantly the ages as long as the mixing length and helium abundance are calibrated to the Sun. The main source of error is the reddening for the older clusters and, in the case of NGC 752, the rather poor defined CMD. The theoretical models were also constructed for three values (for solar metallicity) and two values (for lower than solar metallicity) of the amount of convective overshoot at the core edge in an attempt to determine upper limits of this effect. Models with no overshoot or a small amount ($0.1H_p$) show a better agreement than models with larger overshoot ($0.2H_p$).

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