THE BOLOGNA OPEN CLUSTER CHEMICAL EVOLUTION PROJECT: MIDTERM RESULTS FROM THE PHOTOMETRIC SAMPLE

ANGELA BRAGAGLIA AND MONICA TOSI
INAF-Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy; angela.bragaglia@bo.astro.it, monica.tosi@bo.astro.it
Received 2005 September 11; accepted 2005 October 27

ABSTRACT

We describe a long-term project aimed at deriving information on the chemical evolution of the Galactic disk from a large sample of open clusters. The main property of this project is that all clusters are analyzed in a homogeneous way to guarantee the robustness of the ranking in age, distance, and metallicity. Special emphasis is devoted to the evolution of the earliest phases of the Galactic disk evolution, for which clusters have superior reliability with respect to other types of evolution indicators. The project is twofold: on one hand we derive the age, distance, and reddening (and indicative metallicity) by interpreting deep and accurate photometric data with stellar evolution models, and on the other hand, we derive the chemical abundances from high-resolution spectroscopy. Here we describe our overall goals and approaches and report on the midterm project status of the photometric part, with 16 clusters already studied, covering an age interval from 0.1 to 6 Gyr and galactocentric distances from 6.6 to 21 kpc. The importance of quantifying the theoretical uncertainties by deriving the cluster parameters with various sets of stellar models is emphasized. Stellar evolution models assuming overshooting from convective regions appear to better reproduce the photometric properties of the cluster stars. The examined clusters show a clear metallicity dependence on the galactocentric distance and no dependence on age. The tight relation between cluster age and magnitude difference between the main-sequence turnoff and the red clump is confirmed.

Key words: Galaxy: disk — Galaxy: evolution — Hertzsprung-Russell diagram — open clusters and associations: general

Online material: color figures

1. INTRODUCTION

In the last decade, our understanding of the chemical evolution of the Galaxy has significantly improved, thanks to the efforts and achievements on both the observational and theoretical sides. Numerical chemical evolution models nowadays can satisfactorily reproduce the major observed features of the Milky Way (e.g., Lacey & Fall 1985; Tosi 1988; Matteucci & François 1989; Ferrini et al. 1994; Giovagnoli & Tosi 1995; Timmes et al. 1995; Chiappini et al. 1997; Boissier & Prantzos 1999). They are considered successful only when they reproduce the current distribution with galactocentric distance of the star formation (SF) rate (e.g., as compiled by Lacey & Fall 1985); the current distribution with galactocentric distance of the gas and star densities (see, e.g., Tosi 1996; Boissier & Prantzos 1999; and references therein); the current distribution with galactocentric distance of element abundances as derived from H II regions and B stars (e.g., Shaver et al. 1983; Smartt & Rolleston 1997); the distribution with galactocentric distance of element abundances at slightly older epochs, as derived from type II planetary nebulae (PNe II; e.g., Pasquali & Perinotto 1993; Maciel & Chiappini 1994; Maciel & Köppen 1994; Maciel et al. 2003); the age-metallicity relation not only in the solar neighborhood (Twarog 1980) but also at other distances from the Galactic center (e.g., Edvardssön et al. 1993); the metallicity distribution of G dwarfs in the solar neighborhood (e.g., Rocha-Pinto & Maciel 1996); the local present-day mass function (e.g., Scalo 1986; Kroupa et al. 1993); and the relative abundance ratios (e.g., [O/Fe] vs. [Fe/H]) in disk and halo stars (e.g., Barbuy 1988; Edvardsson et al. 1993).

There are, however, several open questions that still need to be answered. One of the important long-standing questions concerns the evolution of the chemical abundance gradients in the Galactic disk. The distribution of heavy elements with galactocentric distance, as derived from young objects such as H II regions or B stars, shows a trend in the disk of the Galaxy and of other well-studied spirals, which is usually interpreted as a linear negative gradient. It is not clear yet whether the gradient slope changes with space and time and, if it does, whether it flattens or steepens.

Galactic chemical evolution models do not provide a consistent answer: even those that are able to reproduce equally well the largest set of observational constraints predict different scenarios for early epochs. By comparing with each other the most representative models of the time, Tosi (1996) showed that the predictions on the gradient evolution range from an initially positive slope that then becomes negative and steepens with time, to an initially negative slope that remains roughly constant, to an initially negative, steep slope that gradually flattens with time (see also Tosi [2000] and Chiappini et al. [2001] for updated discussions and references).

From the observational point of view, the situation is not much clearer. Data on field stars are inconclusive due to the large uncertainties affecting the older, more metal-poor ones. PNe are better indicators, thanks to their brightness. Type II PNe, whose progenitors are on average 2–3 Gyr old, provide information on the Galactic gradient at that epoch and show gradients similar to those derived from H II regions. However, the precise slope of the radial abundance distribution, and therefore its possible variation with time, is still subject to debate. The PNe data of Pasquali & Perinotto (1993), Maciel & Chiappini (1994), and Maciel & Köppen (1994) showed gradient slopes slightly flatter than those derived from H II regions, but Maciel et al. (2003, 2005) have recently inferred, from a larger and updated PN data set, a flattening of the oxygen gradient slope during the last 5–9 Gyr.

We believe that open clusters (OCs) represent the best tool to understand whether and how the metallicity spatial distribution...
changes with time, since they have formed at all epochs and since their ages, distances, and metallicities are more safely derivable than for field stars. OCs have generally been suggested to show a metallicity gradient (e.g., Janes 1979; Panagia & Tosi 1981; Friel 1995; Carraro et al. 1998; Friel et al. 2002), and Maciel et al. (2005) have recently suggested that OC literature data are consistent with those on PNe in the indication of a flattening of the gradient over time. However, the spatial and temporal evolution of the metallicity distribution of OCs are still uncertain.

Bragaglia et al. (2000), using the compilation of ages, distances, and metallicities listed by Friel (1995) and dividing their clusters into four age bins, found no significant variation in time of the gradient slope. However, rather than reflecting the Galaxy evolution, this may be an effect of inhomogeneity in the treatment of cluster data taken from different literature sources. Carraro et al. (1998), using the metallicities of 37 OCs derived by Friel’s group from low-resolution spectra and ages and distances based on their own synthetic color-magnitude diagrams (CMDs), tried to measure the time dependence of the radial metallicity gradient. They found hints that the gradient may be slightly shallower at the present time than in the past, but again, the results may be affected by uncertainties related to the uneven quality of the literature data to which they applied the synthetic CMD method. Similarly, Friel et al. (2002) presented new, improved data on the metallicity of 39 OCs and derived a smooth radial gradient, with the indication that its slope may be steeper for old clusters, but they did not consider this a firm result due to the different space distributions of young and old OCs.

Against the view of an OC radial abundance gradient, Twarog et al. (1997), and more recently Corder & Twarog (2001), have argued that what is observed is a step distribution in OC metallicity rather than a smooth gradient: clusters with $R_{GC} \leq 10$ kpc have solar metallicity (with some dispersion), while clusters farther away have $[\text{Fe/H}] \sim -0.3$ dex (again with some dispersion). Yong et al. (2005) also find a discontinuity at 10 kpc in the radial distribution of the OC metallicity and a base of $[\text{Fe/H}] \sim -0.5$ beyond that radius, but they agree on the existence of a smooth gradient in the inner regions.

Open clusters are also good tracers of the Galaxy formation mechanism (Freeman & Bland-Hawthorn 2002), in particular of the thin disk. The old OCs may date the Galactic disk as an alternative to white dwarfs, which still give a wide range of values depending on the adopted cooling models (Hansen & Liebert 2003). OCs do not offer only a value integrated over the whole disk but give information on its different parts. If the discontinuity at 10–12 kpc described above is real, it may represent the limit of the original thick disk or the connection of OCs to the presence of accreted satellites (Frinchaboy et al. 2004, 2006; Bellazzini et al. 2004) or to the occurrence of major merger events (Yong et al. 2005). These possibilities are not mutually excluding, since the accretion-related clusters would be those in the outer part of the Galaxy, where the concept of the “true” disk is fuzzy. As already noted by Friel (1995), old OCs may be the few survivors of the original ones that formed in the early Galaxy, or they may be the product of later accretion or interaction with merging satellites.

Finally, OCs are excellent tests for stellar evolution theory, since they contain simple stellar populations (i.e., coeval stars with equal metallicity). Viable stellar evolution models must therefore reproduce the various features (morphology, number counts, color, and luminosity functions [LFs]) of their CMDs. Comparing theoretical and observational CMDs, one can discriminate among different models and select the most realistic ones. The method of using synthetic CMDs to compare with observational data has proven to be much more informative and rewarding (Aparicio et al. 1990; Tosi et al. 1991; Skillman & Gallart 2002) than classical isochrone fitting. These Monte Carlo simulations allow modeling of several additional parameters that dictate the distribution of points in the CMD, such as stochastic SF processes, binary fraction, photometric spread, main-sequence (MS) thickness, data incompleteness, and small-number statistics. Consequently, the results not only provide a measure of the properties of the cluster but can also constrain the SF history and the initial mass function (IMF).

To try to improve our understanding in all these subjects, it is crucial to build up a large sample of open clusters for which the age, distance, and metallicity are all derived in the most precise and homogeneous way, to avoid spurious effects due to inhomogeneous treatments. For this reason we are undertaking a long-term project of accurate photometry and high-resolution spectroscopy to homogeneously derive ages, distances, reddening, and element abundances in open clusters of various ages and Galactic locations, and eventually to infer from them the evolution of the metallicity radial distribution. To this aim we need to collect at least 30 clusters evenly distributed in age, metallicity, and galactocentric distance bins to allow for reliable derivation of possible trends (or lack thereof). Age, distance, and reddening are obtained by deriving the CMDs from deep, accurate photometry and applying to them the synthetic CMD method described by Tosi et al. (1991). Accurate chemical abundances are obtained from high-resolution spectroscopy, applying to all clusters the same method of analysis and the same metallicity scale.

Here we describe the results obtained for the first half of the photometric sample. Spectroscopic abundances have been presented so far only for NGC 6819 (Bragaglia et al. 2001), NGC 2506, NGC 6134, IC 4651 (Carretta et al. 2004), and Cr 261 (Carretta et al. 2005) and will be the subject of forthcoming papers. This paper is organized as follows: the Bologna Open Cluster Chemical Evolution (BOCCE) photometric sample is described in § 2 and the application of the synthetic CMD method in § 3. The results obtained so far by BOCCE on age, distance, and reddening are summarized in § 4 and discussed in § 5 in terms of testing for the stellar evolution models. Contaminating effects are examined in § 6. A discussion of the midterm evolution picture obtained from the currently assembled sample is provided in § 7, and a summary is in § 8.

2. THE PHOTOMETRIC SAMPLE

Homogeneity is a fundamental requirement when using different data sets to make detailed comparisons between observational data and models. To truly understand the variations in the different model parameters, one must minimize systematic errors. What is needed for the purposes described above is a large data set of open clusters, all observed with the same technique, analyzed with the same method, accurately and consistently calibrated in the same photometric system, and with well-determined incompleteness factors and photometric errors. Our photometric sample is being built following these requirements.

Up to now we have acquired the photometry for more than 30 clusters, in some cases only in the $B$ and $V$ bands, in others also in the $I$ band, and in a few cases also in the $U$ and additional bands. About half have been analyzed. All magnitudes have been calibrated to the Johnson–Cousins system via observations of primary and secondary standard stars (Landolt 1992; Stetson 2000) properly selected to cover the color range of the cluster stars. All the data have been reduced with point-spread-function-fitting packages particularly suitable for crowded field photometry; we
have used DAOPHOT in most cases (Stetson 1987; Davis 1994), and ROMAFOT (Buonanno et al. 1983) and PSFex (E. Bertin 2000, private communication) in a few others. In all cases incompleteness factors and photometric errors have been determined with the help of extensive artificial star tests. All the details can be found in the original papers quoted in Table 1.

We have already published the results for 16 of these clusters,1 which are listed in Table 1 together with the derived age, distance modulus, reddening, indicative metallicity, and references. For the sake of homogeneity, all the listed quantities refer to the best cases obtained with synthetic CMDs (see the following sections) based on the Padova stellar models (hereafter the BBC models; Bressan et al. 1993; Fagotto et al. 1994), because these are the tracks that more often turned out to provide the best fit to the data. There are (a few) cases, however, in which other stellar models were found to better reproduce the data (see the following sections and the papers quoted in Table 1 for details). The metallicities indicated in Table 1 are those of the stellar models in better agreement with the data and cannot be taken as accurate determinations of the cluster elemental abundances, for which detailed spectroscopic analysis is necessary.

The cluster positions in the Milky Way are shown in Figure 1, in which the four main spiral arms, as delineated by Georgelin (1976) and Taylor & Cordes (1993), are also displayed. The Sun is assumed to be located at 8 kpc from the Galactic center. The clusters already analyzed and published within the BOCCE photometric project are shown as filled circles, while those with ongoing analysis (listed in the first rows of Table 2) are represented by open circles; open triangles indicate the remaining clusters (also listed in Table 2) for which photometric observations have already been performed.

Figure 2 shows the empirical CMDs in $B - V$ color of the 16 clusters analyzed so far. They are plotted in order of decreasing age (see Table 1, § 4) rightward from the top left panel. The corresponding CMDs in $V - I$ for those clusters for which observations were also performed with the $I$ filter are shown in Figure 3.

The appearance of the CMDs clearly reflects both the Galactic locations of the clusters and the telescope performances. Most clusters were observed with CCDs mounted at 1 m class telescopes (the 1.5 m Danish and the 0.9 m Dutch telescopes in La Silla, Chile, the 1.5 m Bologna Observatory telescope in

![Figure 1](attachment:image1.png)

Fig. 1.—Positions on the Galactic plane of the OCs in our sample. Filled circles represent published OCs, open circles work in progress, and open triangles the remaining clusters. We show the positions of the Sun and the Galactic center and a sketch of the spiral arms (Norma [1], Scutum-Crux [2], Sagittarius-Carina [3], and Perseus [4]). [See the electronic edition of the Journal for a color version of this figure.]

![Figure 3](attachment:image3.png)

Fig. 3.—Empirical CMDs in the $V - I$ filter of the 16 clusters analyzed so far. The corresponding CMDs in $B - V$ are shown in Figure 2.

### Table 1

| Cluster       | $l$ (deg) | $b$ (deg) | Age (Gyr) | $(m - M)_B$ | $E(B - V)$ | $m_0$ (M$_\odot$) | $Z$ | $d$ (kpc) | $R$ (kpc) | $\Delta V$ | References |
|---------------|-----------|-----------|-----------|-------------|------------|-------------------|----|-----------|-----------|------------|------------|
| Cy 261        | 301.68    | -5.63     | 6.00      | 12.20       | 0.30       | 1.10              | 0.020 | 2.74      | 6.96      | 2.60       | 1          |
| NGC 2243      | 293.50    | -17.97    | 4.00      | 12.80       | 0.06       | 1.20              | 0.006 | 3.45      | 10.20     | 2.20       | 2          |
| Be 29         | 197.98    | +8.03     | 3.70      | 15.60       | 0.12       | 2.70              | 0.004 | 13.05     | 20.81     | 2.00       | 3          |
| NGC 6253      | 335.46    | -6.25     | 3.00      | 11.00       | 0.23       | 1.40              | 0.050 | 1.58      | 6.60      | 2.00       | 4          |
| Be 22         | 199.88    | -8.08     | 2.40      | 13.80       | 0.64       | 1.50              | 0.020 | 5.75      | 14.02     | 1.50       | 5          |
| Be 21         | 186.84    | -2.51     | 2.20      | 13.50       | 0.78       | 1.40              | 0.004 | 5.01      | 12.99     | 1.80       | 6          |
| NGC 6819      | 73.98     | +8.48     | 2.00      | 12.20       | 0.12       | 1.60              | 0.020 | 2.72      | 7.71      | 2.00       | 7          |
| NGC 2506      | 230.56    | +9.94     | 1.70      | 12.60       | 0.05       | 1.70              | 0.020 | 3.26      | 10.38     | 1.60       | 8          |
| Cr 110        | 209.65    | -1.98     | 1.70      | 11.45       | 0.57       | 1.60              | 0.004 | 1.95      | 9.74      | 1.65       | 9          |
| NGC 6939      | 95.90     | +12.30    | 1.30      | 11.30       | 0.34       | 1.85              | 0.020 | 1.78      | 8.37      | 1.55       | 10         |
| Pismis 2      | 258.85    | -3.34     | 1.10      | 12.70       | 1.29       | 1.95              | 0.020 | 3.46      | 9.31      | 0.85       | 11         |
| NGC 2660      | 265.93    | -3.01     | 0.95      | 12.30       | 0.40       | 2.10              | 0.020 | 2.88      | 8.69      | 0.50       | 12         |
| NGC 2099      | 177.64    | +3.09     | 0.43      | 10.50       | 0.36       | 2.70              | 0.008 | 1.26      | 9.26      | 0.40       | 7          |
| NGC 2168      | 186.59    | +2.22     | 0.18      | 9.80        | 0.20       | 4.00              | 0.008 | 0.91      | 8.91      | 0.30       | 7          |
| NGC 2533      | 221.67    | -1.33     | 0.12      | 10.20       | 0.22       | 4.50              | 0.020 | 1.10      | 8.85      | 0.50       | 7          |
| NGC 7790      | 116.59    | -1.01     | 0.10      | 10.20       | 0.54       | 5.00              | 0.020 | 3.39      | 9.99      | 0.30       | 13         |

Note.—We assume $R_{GMC} = 8$ kpc.

1 All the published data are available in electronic form from the Base Des Amas maintained by J. C. Mermilliod at http://obswww.unige.ch/webda/webda.html.

References — (1) Gozzi et al. 1996; (2) Bonifazi et al. 1990; (3) Tosi et al. 2004; (4) Bragaglia et al. 1997; (5) Di Fabrizio et al. 2005; (6) Tosi et al. 1998; (7) Kalirai & Tosi 2004; (8) Marconi et al. 1997; (9) Bragaglia & Tosi 2003; (10) Andreuzzi et al. 2004; (11) Di Fabrizio et al. 2001; (12) Sandrelli et al. 1999; (13) Romeo et al. 1989.
more, the contamination is lower in the third quadrant (180° to 270°) than in the others, with nearby systems such as NGC 2099, NGC 2168, NGC 2323, NGC 6819, and NGC 6939, with Galactic longitude between ~74° and ~221°, as heavily contaminated as NGC 6253 and Cr 261. This depends partly on the proximity of populous spiral arms and partly on the presence of overdensities such as the disk warp and/or accreted satellite streams (see § 5).

3. THE APPLICATION OF THE SYNTHETIC CMD METHOD

Ages, reddening, and distances of all clusters have been derived applying the synthetic CMD method (Tosi et al. 1991) to the empirical CMDs. The best values of the parameters are found by selecting those synthetic CMDs with morphology, number of stars in the various evolutionary phases, and LFs in better agreement with the empirical ones.

The synthetic CMDs are constructed via Monte Carlo extractions of mass-age pairs according to an assumed IMF, SF law, and time interval of the SF activity. Each extracted synthetic star is placed in the CMD by suitable interpolations from the adopted stellar evolution tracks and adopting the Bessell et al. (1998) tables for photometric conversion to the Johnson-Cousins photometric system. The absolute magnitude is converted to a provisional apparent magnitude by applying (arbitrary) reddening and distance modulus. The synthetic stars extracted for any provisional magnitude and photometric band are assigned the photometric error derived for the actual stars of the same apparent magnitude. Then, they are randomly retained or rejected on the basis of the incompleteness factors of the actual data, derived from extensive artificial star tests.

Once the number of objects populating the whole synthetic CMD (or portions of it) equals that of the observed one, the procedure is stopped, yielding the quantitative level of the SF rate consistent with the observational data for the prescribed IMF and SF law. To evaluate the goodness of the model predictions, we compare them with the observational LFs, the overall morphology of the CMD, the stellar magnitude and color distributions, and the number of objects in particular phases (e.g., at the main-sequence turnoff [MSTO], on the red giant branch [RGB], and in the clump). A model can be considered satisfactory only if it reproduces all the features of the empirical CMDs and LFs. Given the uncertainties affecting both the photometry and the theoretical parameters (stellar evolution tracks included), the method cannot provide strictly unique results; however, it allows us to significantly reduce the range of acceptable parameters.

In this way we derive the age, reddening, and distance of the cluster and indicate the metallicity of the stellar evolution models in better agreement with the data. In principle, the latter should be indicative of the cluster metallicity, but this depends significantly on some of the stellar model assumptions, such as opacities.

To estimate if, and how many, unresolved binary systems could be present in the cluster, the synthetic CMDs are computed assuming either that all the cluster stars are single objects or that an (arbitrary) fraction of them are members of binary systems with random mass ratios. The effect of unresolved binarism on the V’ magnitude and B’ – V’ color was first addressed by Maeder (1974) and more recently discussed by Hurley & Tout (1998). Here we have also recalculated the effect on the $V' - I'$ color using the Padova isochrones (Bertelli et al. 1994) and have included it in the construction of the synthetic CMDs. Figure 4 shows the adopted magnitude and color variations of MS objects of solar metallicity as a function of the mass ratio between the secondary and the primary component of the unresolved system. Again, the comparison of the resulting morphology and thickness of the synthetic MSs of each cluster with the observed ones allows us to derive information on its most likely fraction of binaries.

The advantage of the synthetic CMD method over classical isochrone fitting to derive the cluster parameters is manifest: with the synthetic CMDs we take into account both the number of stars predicted by the adopted stellar tracks in each evolutionary phase (directly related to the stellar lifetimes in that phase) and the effects of the photometry (errors, incompleteness, and image blend) on the morphology and spread of the various CMD sequences. This clearly provides a larger number of constraints and leads to a better selection of the solution, if not to its uniqueness. For instance, an isochrone may appear to well fit the data, but then the corresponding distribution of the number of stars on the MS or at its TO may be completely at odds with the empirical ones, and the case must be rejected or be given a lower ranking with respect to other models (see, e.g., Kalirai & Tosi 2004). Moreover, the blue and red edges of the

| Cluster         | $I$ (deg) | $b$ (deg) | Age (Gyr) |
|-----------------|-----------|-----------|-----------|
| NGC 3960        | 294.37    | +6.18     | 1.3       |
| Be 17           | 175.65    | -3.65     | 12.0      |
| Be 32           | 207.95    | +4.40     | 3.4       |
| To 2            | 232.83    | -6.88     | 1.0       |
| Mel 71          | 228.95    | +4.50     | 0.2       |
| NGC 4815        | 303.62    | -2.09     | 0.2       |
| King 11         | 117.16    | +6.48     | 1.1       |
| NGC 1193        | 146.81    | -12.16    | 7.9       |
| NGC 2204        | 226.01    | -16.11    | 0.8       |
| NGC 2477        | 253.56    | -5.84     | 0.7       |
| NGC 2849        | 265.27    | +6.36     | 0.6       |
| NGC 6134        | 334.92    | -0.20     | 0.9       |
| NGC 6603        | 12.86     | -1.31     | 0.2       |
| Be 19           | 176.90    | -3.59     | 3.1       |
| Be 20           | 203.48    | -17.37    | 6.0       |
| Be 60           | 139.43    | +0.22     | 5.0       |
| IC 361          | 147.48    | +5.70     | 0.1       |
| IC 1311         | 77.69     | +4.28     | 0.4       |
| IC 4651         | 340.09    | -7.91     | 1.1       |
| IC 4756         | 36.38     | +5.24     | 0.5       |
| Trumpler 5      | 202.86    | +1.05     | 5.0       |

Notes: — Data are taken from Dias et al. (2002). On the first six, work is in progress, while for the others we have only acquired the data.
MS distribution are important tools to quantify both the reddening (its mean value in the cluster direction and the existence of differential variations) and the presence of binary stars.

To test the effect of different input physics on the derived parameters, we have run the simulations of each cluster CMD with several different types of stellar evolutionary tracks. The adopted sets were chosen because they assume different prescriptions for the treatment of convection and range from no overshooting to rather high overshooting from convective regions. They are thus suitable to evaluate the intrinsic uncertainties still related to stellar evolution models. The three types of stellar models applied to all clusters are the tracks of Ventura et al. (1998; P. Ventura 2000, private communication; hereafter the FST models) with high ($\eta = 0.03$), moderate ($\eta = 0.02$), and no overshooting ($\eta = 0.0$); the tracks of the Padova group (Bressan et al. 1993; Fagotto et al. 1994) with overshooting; and the tracks of the Frascati group (hereafter the FRA models; Dominguez et al. 1999) with no overshooting. The parameters of some of the clusters were also inferred, in the original papers, adopting the models computed by the Geneva group (Maeder & Meynet 1989; Schaller et al. 1992; Charbonnel et al. 1993) and by Vandenberg (1985).

Some of the clusters of our sample were analyzed and published before the advent of the stellar models currently available, and their parameters were then derived with the same method but with different stellar tracks than clusters more recently studied. For such systems we have rederived the age, distance, and reddening with the version of the BBC, FRA, and FST models quoted above, so that all the results presented here

![Figure 2](image-url)
have been obtained consistently. For the sake of homogeneity, the forthcoming analyses of the remaining clusters of the BOCCE project will also be performed with the same sets of evolution tracks.

For those cases in which the metallicities are not well constrained, we allow different values in our comparisons. We consider as solar-metallicity tracks those with \( Z = 0.02 \), because they are the ones calibrated by their authors on the Sun, independently of the circumstance that nowadays the actual solar metallicity is suggested to be lower (see Asplund et al. 2004).

All models assume that the SF activity has lasted 5 Myr (i.e., approximately an instantaneous burst relative to the age of most of our studied clusters) and that the stars were formed following a single slope (\( x = 1.35 \) Salpeter IMF over the whole mass range covered by the adopted tracks (0.6–100 \( M_\odot \)); however, these simplistic assumptions do not affect our results, as demonstrated by several checks made assuming both different burst durations and different IMFs.

4. AGES, REDDENINGS, AND DISTANCES FROM THE CMDs

Table 3 lists the age (in gigayears), intrinsic distance modulus, and reddening derived for each cluster with the synthetic CMD method using the three different sets of stellar models described above. Each triplet of parameters refers to the best cases obtained with the BBC, FRA, and FST models for all the tested metallicities. The differences in the derived quantities provide a quantitative estimate of the intrinsic error attributable to the stellar evolution tracks.

Age is the parameter most affected by the theoretical uncertainties. Table 3 shows that there can be a factor of up to 1.8 between ages derived with stellar models with or without overshooting from convective regions. It is well known that, for a given mass, stellar models taking overshooting into account have larger cores and are therefore brighter than models without it. This makes them appear as stars of slightly larger mass.

Correspondingly, an object of given luminosity in the framework of overshooting models has a lower mass (and therefore an older age) than with no overshooting. Indeed, this is what we find for the majority of our studied clusters: the BBC and FST models provide ages older than the FRA models. The few exceptions to this rule are due to uncertainties on the best-fitting model metallicity. If we do not consider the two oldest clusters, Cr 261 and NGC 2243, for which the BBC models appear to have problems (see § 5), the ages derived with the two types of overshooting models, BBC and FST, are in fairly good agreement with each other, since they differ at most by 20%.

Distance modulus and reddening appear to be much less affected by differences in the adopted stellar models, especially if we take into account that the available BBC, FRA, and FST evolutionary tracks do not have the same nominal metallicities. In the range of interest for open clusters, the BBC models are available for metallicity \( Z = 0.004, 0.008, 0.02, \) and \( 0.05 \), the FRA models for \( Z = 0.001, 0.006, 0.01, \) and \( 0.02 \), and the FST models for \( Z = 0.006, 0.01, 0.02, \) and \( 0.03 \). Hence, only the CMDs of solar-metallicity clusters could be compared with synthetic CMDs with the same metallicity for all types of tracks. This leads to an uncertainty in the derived reddening, which inevitably implies an uncertainty also in the distance modulus. On the other hand, all theoretical CMDs were transformed to the observational plane with the same photometric conversion tables (Bessel et al. 1998) instead of directly taking values given by each group, thus avoiding a further source of uncertainty.

Since the BBC models have turned out to better reproduce the overall features of the empirical CMDs of most of the clusters, we adopt their resulting parameters as reference values of age, intrinsic distance \( m - M \), and reddening \( E(B-V) \) attributed to each cluster by the BBC stellar models from the application of the synthetic CMD method. The corresponding TO mass, model metallicity, and distance \( d \) from the Sun and \( R \) from the Galactic center are also given. In a few cases (see § 5) the BBC evolution tracks were found to reproduce the clusters’
observed properties less satisfactorily than the FST or the FRA models. We have flagged with a colon the values in Table 1 corresponding to these cases, which are to be considered more uncertain. In the case of Cr 261, in which the BBC models are likely to have failed, Table 1 shows the values inferred with the FST models. These values happen to be in agreement with those derived for Cr 261 by Carraro et al. (1999) via isochrone fitting with the new Padova stellar models (Girardi et al. 2000).

Detailed comparison with other analyses of each cluster has been performed in the individual papers shown, and we do not repeat it here; we only mention the recent work on NGC 2243 by Anthony-Twarog et al. (2005) since our original paper is old, and this study constitutes an important improvement on this cluster. As part of a larger project involving a series of key open and globular clusters, they used Strömgren photometry to derive the cluster parameters, arguing that intermediate-band photometry is able to reach more precise results than broadband photometry, in particular for the metallicity. NGC 2243 was targeted because it is old, metal-poor, and just outside their proposed discontinuity near $R_{GC} = 10$ kpc. They compare their results with those of Bonifazi et al. (1990), finding good agreement. This is still true with our present analysis, since they find as best values $E(B-V) = 0.055$, $[\text{Fe/H}] = -0.57$, age $= 3.8$ Gyr, and apparent distance modulus 13.15 (see our updated parameters in Tables 1 and 3). They also rightly caution that since the resulting estimates are tied to the adopted set of evolutionary tracks, it is safer to work on a relative scale to derive the properties of a sample of clusters. They also compare Be 29 to NGC 2243, again finding very good agreement with our determinations.

5. THE CLUSTER CMDs AS STELLAR EVOLUTION TESTS

When the BOCCE project started many years ago (Romeo et al. 1989), the stellar evolution models available in the literature were still significantly affected by uncertainties in the treatment of the convective regions, in the adopted opacity tables, and in the normalization to observed systems. The photometric conversions from the theoretical effective temperature–luminosity plane to the empirical color-magnitude plane were also very uncertain and were often created ad hoc for each grid of stellar tracks, to let it reproduce the colors of observed objects. Moreover, most stellar models were computed for relatively small mass ranges,
and it was therefore quite difficult to set up a homogeneous set of models covering the whole mass range of interest for open clusters (i.e., low- and intermediate-mass stars from 0.6 to 8–10 $M_\odot$). As a consequence, several of the adopted models were unable to properly reproduce all the CMD features of our observed clusters; first of all, the color of the RGB and the morphology of the MSTO.

The three types of stellar models (BBC, FRA, and FST) adopted now are those that have proven most successful so far in reproducing the observational properties of the clusters. Nonetheless, none of them reproduces perfectly all the CMD features. The differences between predicted and observed features sometimes may be attributed to uncertainties in the data, but in most cases they are the systematic consequence of the stellar model assumptions.

The FST models are very instructive in this respect, because for any given mass and metallicity they provide three sets of tracks computed with the same assumptions except for the amount of overshooting. By comparing the synthetic CMDs based on these three different amounts of overshooting ($\eta = 0.0$, 0.02, and 0.03) with the empirical CMDs of our clusters, we have found (P. Ventura et al. 2006, in preparation) that the models with overshooting are in much better agreement with the data than the models without it. Even for Cr 261, for which core overshooting is in practice not effective because at that old age (6 Gyr with the FST models) MS stars have low mass and hence radiative cores, the $\eta = 0.02$ models are slightly better than the $\eta = 0.0$ ones. The only exception to this rule is NGC 2243 (which is also rather old, with an age of 4 Gyr with the BBC models and 2.9 with the FST ones), for which all the FST models fail to provide a good fit to the empirical CMD, but the ones with $\eta = 0.0$ are less inconsistent than the others. In all the other cases with TO mass large enough to let the stellar core be convective (and overshooting be effective), the $\eta = 0.0$ models either do not correctly populate the clump and/or the TO region or do not show the correct MS curvature.

It is interesting that while the need of overshooting in the FST models is evident, it is almost impossible to systematically choose between $\eta = 0.02$ or 0.03 from our data. For some clusters we do not find significant differences in the agreement between empirical and synthetic CMDs switching from 0.02 to 0.03; for other clusters (Be 29, Cr 110, NGC 6939, and Pismis 2) we find that the $\eta = 0.02$ models better reproduce the data; but for yet other clusters (NGC 6819, NGC 2660, NGC 2168, and possibly NGC 2323) we find instead a better fit with the $\eta = 0.03$ models. Looking at the values listed in Table 1, one might be tempted to find hints for an anticorrelation between the age of the cluster and the amount of overshooting, but we think that the sample is still too small, the uncertainties too large, and the relation too loose to support this suggestion.

One intriguing aspect of stellar evolution models concerns the slope of the lower MS. Sometimes the photometry is not accurate enough to allow for a safe definition of the MS shape and curvature at faint magnitudes, but there are cases in which the photometry is reliable and the synthetic CMDs (and isochrones) do not reproduce them perfectly. This problem has been recently addressed by Grocholski & Sarajedini (2003), who presented a comparative study of isochrone fits to CMDs in the visual and infrared bands. They took five sets of theoretical models and compared them in the luminosity-temperature plane. They fitted the observed CMDs of six open clusters of various ages and metallicities with the five sets of isochrones and found a variety of inconsistencies on the lower MS slope. Their results are somewhat affected by the fact that they use the isochrones as transformed from the theoretical plane (luminosity and temperature) to the observational one (magnitudes and colors) by each group of stellar modelers, i.e., following different prescriptions and introducing differential variations on the slope itself. In our case this differential (and unknown) effect is absent, because we transform all the theoretical models with the same conversion tables. Still, we find the same kind of problems as described by Grocholski & Sarajedini: when the observed CMDs are deep enough, the fit to the lower MS is often (but intriguingly not always) bad. This happens in general around $M_V \approx 8$ for the visual colors and is attributed by Grocholski & Sarajedini to some ingredient still missing in the model atmospheres for low-mass stars. Indeed, this is likely to be at least one of the causes. For instance, the circumstance that most photometric conversions are applied under gray atmosphere assumptions, which are not likely to be applicable to stars with $M_V \geq 8$, is a probable source of inconsistency. Whatever the reason, there is no single set of tracks able to match all CMDs in all colors, at all ages, and for all metallicities. All of them behave quite well in some cases, but not in others.

With our sample of OCs we have found that the FST models in some cases predict MS slopes that are too steep at the lower masses, in spite of usually being able to reproduce the observed features of the upper MS and TO better than other models. In fact, we have found that while reproducing the colors and magnitudes of the upper MS, the faint end of the FST synthetic MS is too blue (and bluer than that of the BBC and FRA models) for NGC 2243, NGC 6819, and NGC 6939. In a few cases (e.g., NGC 2660) the FST models overpredict the number of faint MS objects more than other stellar tracks (i.e., more than attributable to evaporation effects).

The FRA models are the only ones able to reproduce well the MS curvature of NGC 6819 and Pismis 2 and fit perfectly the older cluster Cr 261. On the other hand, they often overpopulate the post-MS phases and present a TO morphology that is too hooked at young and intermediate ages (see, e.g., NGC 2099, NGC 2168, NGC 2323, and NGC 6819 in Kalirai & Tosi [2004]), which makes them less viable than other tracks for clusters younger than ~2 Gyr.

The BBC tracks turn out to be in overall better agreement with the observed CMDs. In other words, they steadily provide a good fit to the data of (almost) any age and metallicity, even if they may appear to reproduce detailed features, such as MS gaps and bumps, TO shape, and clump numbers, in a less strikingly good manner than other models. The only case in which the BBC tracks have not led to a convincing result is Cr 261. For that cluster we (Gozzoli et al. 1996) found an age of 11 Gyr with the BBC models, much older than with tracks without overshooting, as if overshooting were strongly active in the cluster stars despite their low mass (the TO mass is about 1.1 $M_\odot$), which implies a radiative and not a convective core. We have reexamined its case with the FRA and FST models, not available at the time of that study, and have found a very good fit to the observational CMD for an age of 5 Gyr with the FRA models or 6 Gyr with the FST models (independently of the adopted amount of overshooting, as expected, since overshooting should not be active in low-mass stars). The problem with the BBC tracks

---

2 For instance, Twarog et al. (2003) have suggested the existence of a color term in the calibration of our photometry of NGC 6253, comparing it to other analyses of the same cluster; for this cluster there also appear to be quite large zero point shifts among the available photometries. Anyway, the values they derive for this cluster are in reasonable agreement with our findings: a metallicity definitely higher than solar, age between 2.5 and 3.5 Gyr, reddening of 0.26, and an apparent distance modulus between 11.6 and 12.2.
(and isochrones; Bertelli et al. 1994) is that at ages of 6–9 Gyr they show a hooked TO, which is usually appropriate for younger systems and does not reproduce the smooth tighter morphology of the TO of Cr 261. At older ages, the BBC TOs recover the proper shape, but then the clump luminosity becomes excessively bright for Cr 261. It is interesting to note that the new Padova isochrones (Girardi et al. 2000) present TO shapes much more similar to those of the FST and FRA models (and of Cr 261; see also Carraro et al. 1999 and their Fig. 1) at these ages. We thus feel that the BBC stellar models might have had some problems in the TO evolutionary phases of low-mass stars, subsequently overcome in more recent computations.

6. FIELD CONTAMINATION, REDDENING, AND BINARY SYSTEMS

A safe derivation of cluster age, reddening, and distance from CMDs requires not only reliable photometry with accurate calibration, but also a careful analysis of the background/foreground contamination and as much as possible information on the actual cluster membership of the measured stars. In fact, the shape and luminosity of the cornerstones for the parameter derivation (upper MS, TO, and clump) may be significantly altered by the presence of line-of-sight intruders. Unfortunately, studies of radial velocities or proper motions of the individual stars are available for only a few open clusters, and often the only means to estimate cluster membership is by comparison with nearby blank fields. De-contamination is even more crucial if one also aims at deriving the cluster IMF or the SF rate. We thus emphasize the importance of acquiring the photometry of appropriate blank fields, even if this requires additional observing time and a careful choice of the cluster IMF or the SF rate. We thus consider these clusters as having suffered significant contamination and as much as possible information on the actual MS, TO, and clump) may be significantly altered by the presence of line-of-sight intruders. Unfortunately, studies of radial velocities or proper motions of the individual stars are available for only a few open clusters, and often the only means to estimate cluster membership is by comparison with nearby blank fields. De-contamination is even more crucial if one also aims at deriving the cluster IMF or the SF rate. We thus emphasize the importance of acquiring the photometry of appropriate blank fields, even if this requires additional observing time and a careful choice of the field position. The case of the beautiful CMDs from the CFHT open cluster survey (Kalirai et al. 2001a, 2001b, 2001c, 2003) is illustrative. Despite the large field of view of the CFH12K mosaic camera (42’ × 28’), Kalirai & Tosi (2004) have found that in the case of NGC 2168 and NGC 2323, many cluster members are still present, even at the edges of the observed field; the lack of observations of an external field prevents any reliable estimate of the background/foreground contamination.

Open clusters are affected by dynamical friction with the Galactic disk and by stellar evaporation so that stars that were initially members can be found at rather large distances from the cluster center. An example is given, e.g., by Be 22 (Di Fabrizio et al. 2005, see Figs. 4 and 5), for which we acquired a comparison field at a distance of 30’ from the cluster center that still shows a MS similar to that of the cluster. Since this MS is not present in the Galactic synthetic models of the field disk population by Robin et al. (2003), its most likely interpretation is that cluster members are present even at such a large distance. This makes it additionally uncertain to infer membership by statistically subtracting the objects found in adjacent fields. For this reason we have generally restricted our derivation of the cluster parameters to the CMDs of their most central regions, where field contamination is smaller. The synthetic CMD method, by providing the theoretical number of stars in all evolutionary phases, allows us to easily distinguish the clusters for which evaporation is more likely to have occurred. Clusters whose fainter MSs are systematically underpopulated with respect to those of the corresponding synthetic CMDs are robust candidates for evaporation, once the reliability of the incompleteness factors is guaranteed by extensive and appropriate artificial star tests. In our sample we have found that NGC 6253, NGC 6819, Be 29, and Cr 261 have faint MSs systematically less populated than the corresponding ones predicted by all the stellar models. We thus consider these clusters as having suffered significant evaporation of low-mass stars during their life. These four systems are among the oldest ones of the provisional BOCCE sample and have had more time than the others to lose an appreciable fraction of their stars. It is interesting to note, however, that Be 21 and NGC 2243, which are also older than 2 Gyr, do not show evidence of evaporation. NGC 2243 is by far the most distant OC from the Galactic plane in our entire sample, and this may explain it; no simple explanation is available for Be 21.

We have not generally tried to determine the extension of our OCs, partly because it was outside the main goal of our project and partly because our field of view is often so small as to make it impossible. Only for the farthest clusters (Be 29, Be 22—already discussed in Di Fabrizio et al. [2005], and Be 21) or for the few observed with a larger field of view (NGC 6939 and Cr 261) is the exercise worthwhile. The radial extent of the four OCs observed with the CFHT has already been determined (Kalirai et al. 2001a, 2001c, 2003): NGC 6819 has a radius of 9.5 and NGC 2099 of 13.9, while the determinations for NGC 2323 (about 15’) and NGC 2168 (more than 20’) are more uncertain, since the clusters seem to fill the entire field of view. We computed the radial star density distribution for Be 29, Be 21, NGC 6939, and Cr 261. We show in Figure 5 the projected density distribution (in annuli 10’ or 20’ wide) for the four OCs, giving the distance from the centers both in arcseconds and in parsecs. The only one for which a flattening of the distribution is indisputable, so that we can determine where the cluster disappears, is Be 29 (with a radius less than about 3’, in good agreement with the value in the Dias et al. [2002] catalog). The distribution for Be 21 is still decreasing at our field’s edge, and the same seems to be the case for NGC 6939, where we chose only stars brighter than $V = 22$ to avoid problems with an excessive field star fraction and incompleteness of our photometry. Finally, Cr 261 (for which we considered only stars brighter than $V = 20$) seems to constitute a small fraction of the observed field, as already found by Gozzi et al. (1996).

As for many disk objects, our clusters are generally affected by significant reddening. However, only a few of them clearly also suffer from differential reddening. The synthetic CMD method, by distributing the stars in the CMD according not only to the evolutionary phase but also to photometric errors and fractions of unresolved binary systems, allows one to quantify differential reddening more safely than with simple isochrone fitting. A varying reddening widens the whole MS by a given amount $\Delta E(B-V)$, while unresolved binaries produce a secondary sequence redder/brighter than the single-stars MS, intersecting it above the TO region. In practice, differential reddening and binarism are distinguishable from each other because the former implies a smooth spread of the MS from the TO down to its faintest portions, while unresolved binaries, even if distributed with random mass ratios, imply a split of the MS and the appearance of a bright “appendix” (up to 0.75 mag brighter, corresponding to equal-mass binaries) on top of the TO. Based on these arguments, we have found that Be 21 and Pismis 2 are the only systems of our current sample clearly affected by differential reddening [0.04 $\leq \Delta E(B-V) \leq 0.1$]. Work (Bragaglia et al. 2006) on the photometric data and the spectra of three stars in NGC 3960 also indicate for this cluster some differential reddening, confirming the finding by Prisinzano et al. (2004). Instead, all the clusters seem to contain unresolved binary systems, with estimated percentages varying between 15% and 60%.

NGC 2099, NGC 2168, NGC 2323, and NGC 6819, in addition to the binary sequence, show MS widths larger than attributable to the measured photometric errors (Kalirai & Tosi 2004). This
could be due to a differential reddening of the order of 0.01 mag and/or to internal metallicity spread. However, in these cases we rather tend to ascribe the MS width to the difficulty in calibrating the different CFH12K CCD chips (H. McCracken 2005, private communication).

7. DISCUSSION AND PRELIMINARY RESULTS

With the derived reddening and distance modulus, the observational CMDs can be plotted as absolute magnitude versus intrinsic color (Fig. 6). In this reference frame the TO brightness obviously anticorrelates with the cluster age, while the clump luminosity at first sight is roughly constant, although actually inversely proportional to the chemical abundance. At first-order approximation, the magnitude difference $\Delta V$ between TO and clump is thus an age indicator. A safe use of this indicator requires a careful and homogeneous definition of the reference TO and clump points, which are affected by photometric uncertainties, including blending of unresolved stars, small-number statistics, and background/foreground contamination. In practice the identification of the reference points differ from one author to the other. For instance, Twarog & Anthony-Twarog (1989) define the morphological age ratio, reddening-independent and almost metallicity-independent, as the magnitude difference between the brightest TO point and the clump, divided by the color difference between the RGB color at the clump luminosity and the bluest TO point. Janes & Phelps (1994) adopt as the morphological age index the magnitude distance from the red clump of the inflection point between the TO and the base of the RGB, as did more recently Salaris et al. (2004). Carraro & Chiosi (1994) assume that the reference TO luminosity is 0.25 mag fainter than observed in the CMD because of the possible presence of unresolved binaries that brighten the apparent TO.

The oldest cluster of our provisional sample is Cr 261, whose age has been conservatively estimated with the FST models due to the problems with the BBC tracks discussed in § 6. Its $\Delta V$ is 2.6. The next older systems are in the interval 3–4 Gyr (Be 29, NGC 2243, and NGC 6253), with $2 \leq \Delta V \leq 2.5$. The clusters younger than 1 Gyr (NGC 7790, NGC 2323, NGC 2168, NGC 2099, and NGC 2660) all have $\Delta V$ between 0.2 and 0.5, and both the TO and the clump are much more difficult to distinguish because of the small number of cluster members in these evolutionary phases.

Figure 7a shows that $\Delta V$ seems well correlated with the cluster age derived with our method, and the line represents a preliminary
calibration of this relation. Although it appears as a very reasonable approximation, we do not make use of it in its present form: these 16 clusters are still too few to give a reliable calibration between $\Delta V$ and age because they were not chosen for this purpose and do not sample the entire relevant age range (see, e.g., Salaris et al. [2004] for a discussion on their choice of calibrating clusters). In particular we miss the oldest OCs, and a definitive calibration will have to wait until at least Be 32 (age $\sim$ 6 Gyr), Be 17, and NGC 6791 (both with age $\sim$ 10 Gyr) are properly analyzed (for the first two clusters, work is already in progress). Furthermore, precise metallicities are, or will soon be, available for (most of) the clusters in our sample, either from our work (e.g., Cr 261 [Carretta et al. 2005], NGC 6791 [Gratton et al. 2006], Be 17, and Be 32, for which we have acquired high-resolution spectra) or from the literature (e.g., Be 29 [Carraro et al. 2004] and Be 17 [Friel et al. 2005]). This is important to test the metallicity dependence of the $\Delta V$-age relation. As explained in, e.g., Salaris et al. (2004), isochrones of different metallicity have different values of $\Delta V$ for the same age, since the luminosities of the TO and the red clump depend in different ways on age and metal abundance. In particular, lower metallicities should show a larger $\Delta V$ for the same age. In our case the situation is confused; we have three clusters with the same $\Delta V$, but the age difference does not seem to correlate univocally with the metallicity. Larger samples, and better defined metal abundances, have to be employed to decide whether and how this influences the calibration of this useful relation.

Fig. 6.—CMDs for the 16 OCs in absolute magnitude and intrinsic color.
From the derived distance moduli and reddenings we calculated the Galactic position of the clusters, used to draw Figure 1. NGC 6253 is the system closest to the Galactic center, and Be 29 the farthest one. To better visualize the relations (or lack thereof) between age, galactocentric distance, and metallicity we have plotted these quantities in Figures 7b–7d. We recall, however, that the metallicity derived here is that of the BBC models in better agreement with the cluster CMDs and should not be taken as a precise measure of the actual cluster metallicity. To safely determine the cluster chemical abundances, accurate spectroscopic studies are necessary. Bearing this caveat in mind, Figure 7 shows that the only relation clearly existing between the derived quantities is the metallicity dependence on galactocentric distance (Fig. 7d), while there is no apparent relation between age and metallicity. If we do not take the outermost point into account, we cannot exclude a dependence of the cluster age on galactocentric distance; however, the spread in Figure 7b is quite large, and we need a much larger sample to better pinpoint this relation (or lack thereof). Similar results were already found and discussed by Janes & Phelps (1994) and Phelps et al. (1994) with a much larger sample of clusters but more uncertain parameter derivation. Carraro et al. (1998) argued that after correcting the cluster metallicities for the radial gradient effect, their clusters do show an age-metallicity relation similar to that inferred from field stars in the solar neighborhood. However, their corrected age-metallicity distribution (their Fig. 8) looks as scattered as ours (Fig. 7c), with no apparent trend. Yong et al. (2005) find no correlation between age and metallicity in their compiled sample of OCs.

Do we really see a radial abundance gradient in the Galactic disk? Figure 8 shows our data3 compared to the homogeneous samples by Friel et al. (2002) and Twarog et al. (1997). As already mentioned in § 1, the latter, on the basis of their homogenization of OC metallicities, presented the hypothesis that the true original metallicity distribution in the Galactic disk is not described by a simple linear gradient but is a step distribution, with the two metallicity levels indicated by the dashed lines: [Fe/H] = 0 for R < 10 kpc and −0.30 for R > 10 kpc. [See the electronic edition of the Journal for a color version of this figure.]

3 We have translated our photometrically determined Z-values to the corresponding [Fe/H] values for more immediate comparison with the two other samples. We also plot here the available [Fe/H] values based on high-resolution spectroscopy that are not (yet) on a thoroughly homogeneous scale, since three of them come from the literature (see Table 4).
(and a dispersion of ±0.1 dex) and those outside with a metallicity 0.3 dex lower, with a similar dispersion (see Fig. 8 [bottom], which uses data from Twarog et al. [1997]). They discussed at length the different metallicity distributions of clusters and field stars and suggested that the differences are mostly due to the much larger orbital diffusions of individual stars. Corder & Twarog (2001) modeled the evolution of both a linear and a step distribution in metallicity for field stars and open clusters, and found that a step distribution does appear as a linear gradient if orbital diffusion is the dominant factor, such as for field stars. For open clusters, evaporation dominates instead, allowing the original discontinuity to be preserved. The large sample in Twarog et al. (1997) was dominated by youngish clusters (age <2 Gyr), and the original step distribution (which still survives) could be recognized. Corder & Twarog (2001) attribute the linear gradient found, e.g., by Friel (1995), to the too-small radial baseline, with most of clusters near the discontinuity (in the range 8–12 kpc). They suggest concentrating efforts on objects much closer to, and farther from, the Galactic center to avoid this effect.

Our clusters cannot prove or disprove this description yet; we still have too few objects at any given $R_{GC}$, we are biased toward large ages, and our homogeneous metallicities come from the evolutionary tracks. Our inner clusters have predominantly solar metallicity, and of the three OCs definitely outside the 10 kpc limit (remember that we are using $R_{GC,0} = 8$ kpc), two have [Fe/H] $\approx -0.4$ (from spectroscopic analyses), and one has $Z = 1Z_\odot$ (Be 22, from the synthetic CMD method; see, however, Villanova et al. 2005). More clusters at these galactocentric distances should be studied in detail, and a more precise abundance determination has to be performed. We list in Table 4 the currently available metallicities based on high-resolution studies; five were determined by our group, and three come from literature, so they are not yet on a homogeneous scale.

In any case, a simple single-slope gradient cannot be the best answer; our present sample contains the very distant cluster Be 29, which has abundances higher than what is given by a linear extrapolation of the gradient found for OCs closer to the Galactic center (see Fig. 8, top, middle). The same is true for Saurer A with $R_{GC} \approx 19$ kpc and [Fe/H] $= -0.38$ (Frinchaboy & Phelps 2002; Carraro et al. 2004). The fact that inner and outer disk clusters do not seem to follow the same radial abundance distribution was already noticed by Carraro et al. (2004), who proposed two alternatives: a different chemical evolution history for the outer disk (e.g., Chiappini et al. 2001) or an extragalactic origin for Be 29 and Saurer A.4 Yong et al. (2005), combining literature data with high-resolution spectral analysis of M67 and five outer disk OC’s (Be 20, Be 21, Be 29, Be 31, and NGC 2141), also argue that open clusters show a linear metallicity gradient in the regions within 10–12 kpc from the Galactic center but have a roughly constant metal content from there outward. Their favored interpretation is that the outer clusters are the result of SF triggered by a major merger event. Direct capture of alien clusters from accreted dwarf galaxies seems unlikely, since the relatively high [$\alpha$/Fe] ratios measured in their five clusters are not consistent with those measured in nearby dwarf galaxies (Venn et al. 2004 and references therein).

Cranzo et al. (2003) and Frinchaboy et al. (2004) connected several open and globular clusters to the Galactic anticenter stellar structure (GASS [e.g., Newberg et al. 2002], also called the Ring or the Monoceros Ring). Bellazzini et al. (2004) proposed a few open clusters to be linked to the Canis Major dwarf that may (Martin et al. 2004) or may not (Momany et al. 2004) be a real accreted satellite, and that may (Martin et al. 2005) or may not be (Peñaarrubia et al. 2005) the cause of the GASS. The two groups have different approaches. Crane et al. (2003) and Frinchaboy et al. (2004, 2006) use the position and radial velocity of Galactic clusters to see if they lie along the GASS, while Bellazzini et al. (2004) look at the CMDs of clusters at about the same position and distance of the CMa system and compare the cluster and surrounding field population with that of the CMa.

A few clusters in our sample have been considered to be associated with CMa or the GASS on the basis of their CMD and/or radial velocity. For To 2 (Frinchaboy et al. 2004, 2006; Bellazzini et al. 2004) and Be 29 (Frinchaboy et al. 2004, 2006) there is a strong positive indication. Be 22, on the contrary, has been discarded both by our work (Di Fabrizio et al. 2005) on the basis of a comparison between the CMDs of the central and control fields and that of the CMa overdensity, and by Frinchaboy et al. (2006) because its radial velocity does not fit the GASS longitude-velocity trend (this also remains true considering the slightly lower radial velocity determined by Villanova et al. [2005]). In the case of Be 29 we have tried to apply both methods to our data (Tosi et al. 2004): the Galactic coordinates and radial velocity (measured by Braggaglia et al. [2005] and by Carraro et al. [2004]) put it right in the GASS (see also Fig. 1 in Frinchaboy et al. 2006), but our field of view is too small to give a definite answer about similarities between Be 29 and CMa or dissimilarities with the expected Galactic disk population based on the model of Robin et al. (2003).

All the other clusters of our present sample are too close to the Galactic center and/or have radial velocities that exclude the association with the Ring (see Table 4). We have checked that no unpredicted component was evident in our CMDs by

---

4 They associated Be 29 with the Monoceros Ring but not Saurer A, at variance with Frinchaboy et al. (2004, 2006).

---

| Cluster     | RV (km s\(^{-1}\)) | [Fe/H] | Z   | References |
|-------------|-------------------|--------|-----|------------|
| Cr 261      | -25.9             | -0.03  | 0.020 | 1          |
| NGC 2243    | +61.0             | -0.48  | 0.006 | 2          |
| Be 29       | +24.6             | -0.44  | 0.004 | 3          |
| NGC 6253    | -26.2             | +0.36  | 0.050 | 4          |
| Be 22       | +95.3             | -0.32  | 0.020 | 5          |
| Be 21       | +12.4             | -0.54  | 0.004 | 6          |
| NGC 6819    | +4.2              | +0.09  | 0.020 | 7          |
| NGC 2506    | +83.7             | -0.20  | 0.080 | 8          |
| Cr 110      | +40.0             | -0.10  | 0.010 | 9          |
| NGC 6939    | -19.0             | 0.010  | 0.001 | 10         |
| Pismis 2    | +49.8             | 0.010  | 0.001 | 11         |
| NGC 2660    | +21.2             | 0.010  | 0.001 | 12         |
| NGC 2099    | +7.7              | 0.010  | 0.001 | 13         |
| NGC 2168    | -8.0              | 0.010  | 0.001 | 14         |
| NGC 2323    | +9.0              | 0.010  | 0.001 | 15         |
| NGC 7790    | -78.0             | 0.010  | 0.001 | 16         |

Notes.—References are for both the radial velocity (RV) and [Fe/H] when the latter is available. We also give for comparison Z, the photometric metallicity, taken from Table 1; $Z = 0.004$, 0.006, 0.02, and 0.05 correspond to [Fe/H] $\approx -0.7$, -0.5, 0.0, and +0.4, respectively.

* These [Fe/H] values are measured by our group.
comparison with the ones produced by the Robin et al. (2003)
Galactic model, in each direction, for the appropriate field of view,
and taking into account the magnitude limit and completeness
factor of our photometry. This test is of course truly significant
only for the cases in which the field of view was large enough to
sample even a marginally contaminating population.

The importance of understanding the true origin of outer disk
open clusters is clear. For instance, Be 29, the farthest known OC,
is fundamental to studying the metallicity gradient if its
origin is fully Galactic. On the other hand, if Be 29 is demonstra-
ted to come from another galaxy with a different chemical
history, the interest would be shifted toward understanding which
signatures (if any) characterize the accreted populations in order
to identify and separate them in the Galactic disk. The Sagittarius
dwarf appears to display chemical peculiarities (Bonifacio et al.
2004; McWilliam & Smecker-Hane 2005), and recently Sbordone
et al. (2005) claimed that at least one star, a possible member
of the CMa, shows chemical signatures (abundance ratios of
$\alpha$-elements, Cu, and heavy neutron capture elements such as
La, Ce and Nd) more appropriate for Local Group dwarf gal-
axies than for the Milky Way.

Both To 2 and Be 29 have been studied with high-resolution
spectroscopy; do they show similar signatures? In To 2 Brown
et al. (1996) measured $\alpha$-elements and La. For the latter they
found [La/Fe] = 0.5, and for the former, [$\alpha$/Fe] = +0.07 dex,
a value in perfect agreement with those for many other old OCs
(see, e.g., Friel et al. 2003) but unlikely for dwarf galaxies, for
which it tends to be less than solar (Venn et al. 2004). Carraro
et al. (2004) did not measure heavy elements in their two Be 29
targets but found $\alpha$-elements said to be enhanced with respect
to solar values, at variance, e.g., with NGC 2243, which has similar
overall metallicity ([Fe/H] around $-0.4$ dex). However, from the
values published in their Table 5, [$\alpha$/Fe] is about 0.08 dex, exactly
the average found for NGC 2243 by Gratton & Contarini (1994)
and again a common value for old open clusters.

8. SUMMARY

To summarize the midterm results of the photometric BOCCE
project:

1. We confirm the tight relation between the cluster age and
the magnitude difference between MSTO and clump luminosity
levels but caution against its application to young objects, for
which small-number statistics and field contamination may make
the determination of the two luminosity levels too uncertain.

2. We confirm the anticorrelation between metallicity and
distance from the Galactic center. We do not find evidence of
discontinuities around 10–15 kpc from the center, but our sample
is still too small to distinguish between a smooth gradient and
alternative distributions.

3. We definitely find no correlation between cluster age and
metallicity.

4. We cannot completely exclude an age–galactocentric dis-
tance relation in the inner 10–15 kpc.

Most of the oldest clusters of the sample (NGC 6253, NGC
6819, Be 29, and Cr 261) show clear evidence of evaporation of
their lowest mass stars. Almost all our clusters appear to have
stars (still bound members?) with the same CMD morphology
at quite large cluster radii. This circumstance makes it crucial to
always observe control fields at appropriate distances from the
cluster center.

We emphasize the importance of deriving the cluster param-
ters with more than one set of stellar evolution models and
with the same photometric conversion tables to allow for a direct
comparison of the different model predictions and for a correct
evaluation of the theoretical uncertainties of the results. We have
not found a set of evolutionary tracks able to reproduce in detail
all the observed features of old and young, metal-rich and metal-
poor clusters. However, all three evolution sets adopted in this
project perform quite well in comparison with the observational
CMDs and LFs of the examined clusters, with the BBC models
often being found in better agreement with the data. Overtaking
from convective regions appears to provide a better fit to the
observed properties of stars in the various evolutionary phases, with
some hints that it might be more conspicuous in younger systems.
As also found by Grocholski & Sarajedini (2003), the CMD re-

dition of the apparent metallicity distributions. Nonetheless,
we consider it useful to illustrate the importance of a homo-

These results are by no means conclusive, since we need to at
least double our cluster sample to get enough statistics in each age
and distance bin. Moreover, we need to derive accurate chemical
abundances from high-resolution spectra for a thorough inter-
pretation of the apparent metallicity distributions. Nonetheless,
we consider it useful to illustrate the importance of a homo-
geneous approach in the derivation of the global cluster prop-
erties and emphasize the need for further accurate studies of
these Galactic objects, which can tell us so much more than
others about the Milky Way evolution.

We thank all the colleagues who have collaborated so far on
the photometric part of the BOCCE project: Gloria Andreuzzi,
Lino Bonifazi, Antonio Carusillo, Luca Di Fabrizio, Flavio Fusi
Pecchi, Enrico Gozzoli, Don Hamilton, Gianni Marconi, Ulisse
Munari, Luigi Pulone, Giuseppina Romeo, Stefano Sandrelli, and
Gianni Tessicini. Jason Kalirai has also participated, providing
information in advance of publication. We also wish to thank the
anonymous referee for the very encouraging report. We have
made extensive use of the Base Des Amas, a very useful tool for
these Galactic objects, which can tell us so much more than
others about the Milky Way evolution.

REFERENCES

Andreuzzi, G., Bragaglia, A., Tosi, M., & Marconi, G. 2004, MNRAS, 348, 297
Anthony-Twarog, B. J., Atwell, J., & Twarog, B. A. 2004, AJ, 129, 872
Aparicio, A., Bertelli, G., Chiosi, C., & Garcia-Pelayo, J. M. 1990, A&A, 240,
262
Ashplund, M., Grevesse, N., Sauval, A. J., Allende Prieto, C., & Kiselman, D.
2004, A&A, 417, 751
Barbuy, B. 1988, A&A, 191, 121
Barrado y Navascues, D., Deliyannis, C. P., & Stauffer, J. R. 2001, ApJ, 549, 452
Bellazzini, M., Ibata, R., Monaco, L., Martin, N., Irwin, M. J., & Lewis, G. F.
2004, MNRAS, 354, 1263
Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, A&AS, 106,
275
Bessell, M. S., Castelli, F., & Plez, B. 1998, A&A, 333, 231
Boissier, S., & Prantzos, N. 1999, MNRAS, 307, 857
Bonifacio, P., Sbordone, L., Marconi, G., Pasquini, L., & Hill, V. 2004, A&A,
414, 503
