Near-infrared photometry of four metal-rich bulge globular clusters: NGC 6304, 6569, 6637 and 6638

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Accepted 2005 April 26. Received 2005 April 7; in original form 2005 January 11

ABSTRACT
We present high-quality near-infrared (near-IR) photometry of four bulge metal-rich globular clusters, namely NGC 6304, 6569, 6637 and 6638. By using the observed colour–magnitude diagrams we derived photometric estimates of the cluster reddening and distance. We performed a detailed analysis of the red giant branch (RGB), presenting a complete description of its morphologic parameters and evolutionary features (bump and tip). Photometric estimates of the cluster metallicity were obtained using the updated data set (published by our group) linking metal abundance to a variety of near-IR indices measured along the RGB. The detection of the RGB bump and tip is also presented and briefly discussed.

Key words: techniques: photometric – globular clusters: individual: NGC 6304 – globular clusters: individual: NGC 6569 – globular clusters: individual: NGC 6637 – globular clusters: individual: NGC 6638 – infrared: stars.

1 INTRODUCTION
Bulge globular clusters (GCs) are key templates of simple stellar populations for studying the stellar and chemical evolution in the high-metallicity domain.

A few optical and near-infrared (near-IR) ground-based photometric studies of the bulge GCs have been performed over the past decade (see e.g. Frogel, Kuchinski & Tiede 1995; Ortolani, Barbuy & Bica 1996; Ortolani, Bica & Barbuy 1996; Guarnieri et al. 1998; Heitsch & Richtler 1999; Davidge et al. 1992; Momany et al. 2003). However, the relative faintness of these targets in the optical, the lack of complete and homogeneous surveys, the modest performances of the previous generation of IR arrays (i.e. limited size, large fraction of bad pixels, etc.), prevented a detailed and quantitative characterization of the post-main sequence (post-MS) evolution in the high-metallicity domain, as potentially traced by this GC subsystem. In this respect, the Two-Micron All-Sky Survey (2MASS) could represent a step forward but its modest spatial resolution and photometric deepness prevent it sampling the cluster population with sufficient accuracy and statistical significance, particularly in the core region.

In this framework, our group started a long-term project devoted to fully characterizing the stellar populations in the bulge GC system, by using colour–magnitude diagrams (CMDs) and luminosity functions (LFs) in the near-IR (see Ferraro et al. 2000; Valenti et al. 2004a; Valenti, Ferraro & Origlia 2004b,c; Sollima et al. 2004). As is well known, in this spectral domain the reddening andblanketing effects at high metallicity are much less severe than in the optical, moreover, the sensitivity to the physical parameters of cool stars is at a maximum and the contrast between the red giants and the fainter MS population is greater than in any other optical passband, drastically reducing the crowding, even in the innermost core region (see e.g. Ferraro 2002, and references therein). As a first and major step forward in the study of the Bulge stellar population we are performing an homogeneous survey of a statistical significant sample of clusters in the near-IR. Such a photometric screening of the bulge GC system with similar accuracy as that obtained for the halo GCs system (see Ferraro et al. 2000) will provide: (i) a global check of the stellar evolution models in the high-metallicity domain; (ii) direct and quantitative comparison between the stellar population in the halo and bulge GC system; (iii) an accurate calibration of a few major integrated observables, to characterize the unresolved stellar populations in extragalactic bulges.

A set of near-IR photometric indices (i.e. colours, magnitudes and slopes) defined by Ferraro et al. (2000) and widely discussed in Valenti et al. (2004b,c) (hereafter Paper I and Paper II, respectively) have been derived to describe the morphology of the red giant branch (RGB) together with its main evolutionary features, such the RGB bump and tip.

In this paper we present a detailed IR study of the RGB sequence for a sample of four metal-rich bulge GCs (namely, NGC 6304, 6569, 6637 and 6638, see Table 1), affected by a moderate reddening \(E(B - V) < 0.6\) (see Table 2). These clusters have been the subject of several studies, but mainly in the optical range; no
Table 1. The observed sample of clusters parameters from the Harris (1996) catalogue.

| Name  | $a_{2000}$ | $b_{2000}$ | $l^\circ$ | $b^\circ$ | $M_V$ |
|-------|------------|------------|----------|----------|-------|
| NGC 6304 | 17h 14m 32s.5 | -29° 27' 44'' | 355.83 | 5.38 | -7.26 |
| NGC 6569 | 18h 13m 38s.9 | -31° 49' 35'' | 0.48 | -6.68 | -7.83 |
| NGC 6637 | 18h 31m 23s.2 | -32° 20' 53'' | 1.70 | -10.27 | -7.47 |
| NGC 6638 | 18h 30m 56s.2 | -25° 29' 47'' | 7.90 | -7.15 | -6.78 |

near-IR CMDs are available for NGC 6638 and 6569. Piotto et al. (2002) published $B$, $V$ Hubble Space Telescope photometry of all the programme clusters. The derived CMDs clearly show an HB morphology and a curved RGB which are typical signatures of a metal-rich population; however, only in the case of NGC 6637 and 6638 are the subgiant branch (SGB) and the turn-off (TO) regions well defined. V, I ground-based photometry of NGC 6034, 6637 and 6638 has been presented by Rosenberg et al. (2000) within a Galactic GCs survey devoted to deriving the relative ages of the Milky Way GCs. However, the relative high reddening and foreground contamination by MS stars, prevented a sufficiently accurate detection of the TO level. Moreover, the RGB sequence is not properly sampled and defined. Ortolani et al. (2000, 2001) presented V, I photometry of NGC 6304 and 6569, respectively, finding the presence of a red clumpy HB, a curved RGB and high level of field contamination. The advantages of observing these clusters in the near-IR has been well demonstrated by Ferraro et al. (1994) and Davidge et al. (1992) who published $B$, $V$, $J$, $K$ photometry of NGC 6637 and $V$, $K$ photometry of NGC 6304, respectively. The limited performances of the previous generation of IR arrays allowed only a partial sampling (in both space and deepness) of the RGB, which, however, is clearly defined in their observed $K$, $V$ – $K$ CMDs, thanks to the wide ($V$ – $K$) spectral baseline.

In the present study, for the programme clusters we sampled the entire RGB extension in the $J$, $H$ and $K$ bands, and we presented new estimates of the reddening and distance by comparing the IR CMDs with those of two reference clusters (47 Tuc and M 107) with well-known extinction and distance modulus.

The paper is organized as follows: the observations and data reduction are presented in Section 2, while in Section 3 we describe the properties of the CMDs. Section 4 describes the method applied to derive an estimate of the cluster reddening and distance. In Section 5 we present the study of the RGB sequence: by using LFs, CMDs and RGB fiducial ridge lines, we derive the main RGB morphological and evolutionary features, and their dependences on the cluster metallicity. The results of the transformations between the observational and theoretical planes for the RGB bump and tip luminosities are presented in Section 6. Finally, in Section 7 we briefly summarize our results.

2 OBSERVATIONS AND DATA REDUCTION

A set of $J$, $H$ and $K$ images of four bulge clusters, namely NGC 6304, 6569, 6637 and 6638, was obtained at the European Southern Observatory (ESO), La Silla on 2004 June, using the near-IR camera SOFI, mounted at the ESO New Technology Telescope. During the observing runs two data sets were secured as follows.

(i) The standard resolution set. A series of images in the $J$, $H$ and $K$ bands were obtained using SOFI in large mode. In this combination the camera has a pixel size of 0.288 arcsec and a total field of view of 4.9 × 4.9 arcmin$^2$. The images are the combination of 42, 72 and 99 exposures, each one 3-s long, in the three passbands ($J$, $H$ and $K$, respectively).

(ii) The high-resolution set. High-resolution images of the inner region of each cluster were also secured. The high-resolution mode (SOFI coupled with the focal elongator) yields a pixel size of 0.146 arcsec and a total field of view 2.49 × 2.49 arcmin$^2$. High-resolution images are the average of 30 single exposures, each 1.2-s long.

All the secured images were roughly centred on the cluster centre. Note that the region covered by our observations allows us to sample a significant fraction of the total cluster light (typically ~80–95 per cent) in all the programme clusters. During the three nights of observation the average seeing was always quite good (full width at half maximum, FWHM ≈ 0.8 arcsec). Every image has been background subtracted using sky fields located several arcmin away from the cluster centre, and flat-field corrected using dome flat-fields, acquired with the standard SOFI calibration setup.

Standard crowded field photometry, including point spread function (PSF) modelling, was carried out on each frame using DAOPHOT/ALLSTAR (Stetson 1994). For each cluster, two photometric catalogues (derived from high and standard resolution images), listing the instrumental $J$, $H$ and $K$ magnitudes, were obtained by cross-correlating the single-band catalogues. The standard and high resolution catalogues have been combined by means of a proper weighted average, weighting more the high-resolution measurements in the innermost region of the cluster. In principle, this strategy allows us to minimize the blending effects. The internal photometric accuracy has been estimated from the rms frame-to-frame scatter of multiple stars measurements. Over most of the RGB extension, the internal errors are quite low ($\sigma_J \sim \sigma_H \sim \sigma_K < 0.03$ mag), increasing up to ~0.06 mag at $K \geq 16$. By using the Second Incremental Release Point Source Catalogue of 2MASS,

Table 2. Metallicity, reddening and distance modulus of the programme clusters.

| Name  | [Fe/H]$^{Z85}_{C}$ | [Fe/H]$^{CG97}_{C}$ | [M/H] | $E(B - V)^{H96}$ | $E(B - V)^{CG97}$ | $E(B - V)^{H96}_{\text{derived}}$ | $(m - M)^{H96}_{\text{der}}$ | $(m - M)^{CG97}_{\text{der}}$ |
|-------|-----------------|-----------------|-------|----------------|----------------|----------------------------|----------------|----------------|
| NGC 6304 | -0.59 | -0.28 | -0.05 | 0.53 | 0.50 | 0.52 | 13.90 | 13.88 |
| NGC 6569 | -0.26 | -0.79 | -0.64 | 0.55 | 0.44 | 0.49 | 15.15 | 15.40 |
| NGC 6637 | -0.59 | -0.68 | -0.55 | 0.16 | 0.17 | 0.14 | 14.78 | 14.87 |
| NGC 6638 | -1.15 | -0.97 | -0.69 | 0.40 | 0.42 | 0.43 | 14.91 | 15.07 |

Notes. *Metallcity in the Z85 scale. +Metallcity in the CG97 scale, as computed from the Z85 estimates by using equation (7) of CG97 and following the prescription of (Ferraro et al. 1999).
the instrumental magnitudes were then converted into the 2MASS photometric system.$^1$

The photometric catalogues have been also astrometrized on to 2MASS, using a procedure developed at the Bologna Observatory (Montegriffo, private communication) and successfully applied to other clusters (see e.g. Ferraro et al. 2003; Sollima et al. 2004; Papers I and II, and references therein) providing rms residuals of $\approx0.2$ arcsec in both RA and Dec.

3 COLOUR–MAGNITUDE DIAGRAMS

All stars detected over the entire science fields have been plotted in the ($K, J - K$) and ($H, J - H$) CMDs shown in Figs 1 and 2. The main features of the CMDs are as follows.

(i) The giant branch is well populated in all clusters, even in the brightest magnitude bin, allowing a clear definition of the mean ridge line up to the tip.

(ii) The photometry is deep enough to reach the base of the RGB at $K \sim H \sim 15$ mag, i.e. 3–4 mag below the horizontal branch (HB). The SGB region is not well defined, preventing any feasible detection of the TO level.

(iii) The HB appears as a red clump well separated from the RGB. This is the typical morphology of high-metallicity clusters such as 47 Tuc and M 107.

(iv) In the CMDs of NGC 6304, the RGB is scattered, and this is mainly due to contamination by bulge field giants (see Section 4.1). The blue sequence at $(J - K) \approx 0.55$, extending up to $K \sim 14$ mag, corresponds to a disc MS contamination (see Ortolani et al. 2000).

(v) Long-period variables have been identified, to properly locate the RGB tip (see Section 5.2).

4 REDDENING AND DISTANCE MODULUS

As discussed in Section 2, the photometry of the four clusters presented here have been reported in the 2MASS photometric system, hence they are fully consistent with the 24 GCs published in Papers I and II. This allows us to perform a detailed study of the RGB features.
using the photometric indices defined by Ferraro et al. (2000) and calibrated in Papers I and II. In line with the assumptions in those papers, we adopted the distance scale established by Ferraro et al. (1999), who derived the distance modulus for a sample of 61 Galactic GCs based on an empirical estimation of the zero-age HB level. Here the distance modulus for the programme clusters is derived by comparing the CMDs with those of two reference clusters selected from the sample presented by Ferraro et al. (2000), and applying a differential method. As widely discussed in Paper I, this procedure allows us to derive simultaneously distance modulus and reddening estimates. As reference clusters we adopted 47 Tuc (for NGC 6304 and 6637) and M 107 (for NGC 6569 and NGC 6638), because they have very similar metallicity and HB morphology, respectively (see Fig. 3).

The differences in colours and in magnitudes between the reference and the programme clusters have been computed by shifting the CMD of each cluster to match the RGB and the HB of the reference clusters. In particular, the colour shifts \([\delta(J - H)\) and \(\delta(J - K)\)] have been used to derive an estimate of the relative reddening. The extinction coefficients listed by Savage & Mathis (1979) [\(A_J/E(B-V) = 0.87, A_H/E(B-V) = 0.54\) and \(A_K/E(B-V) = 0.38\)] have been adopted. The results are listed in Table 2, as can be seen our reddening estimates nicely agree (within 0.1 mag) with those listed by Harris (1996),2 and Schlegel, Finkbeiner & Davis (1998). The shifts in magnitudes \((\delta J\) and \(\delta K)\) once corrected for relative reddening have been used to obtain an estimate of the distance modulus for each clusters. The derived distances are listed in Table 2, column 9, and compared with those found in the Harris (1996) compilation (column 8). Note that the distance modulus obtained here for NGC 6637 turns out to be ~0.2 mag larger than that found by Ferraro et al. (1994). This is mainly owing to a zero-point difference between the 2MASS photometric system and that adopted by Ferraro et al. (1994).

### 4.1 The origin of the red sequence in NGC 6304

The case of NGC 6304 deserves a brief discussion because a careful examination of its CMDs has revealed the presence of a quite scattered RGB sequence (see Figs 1 and 2). The photometric errors are not large enough to justify such a spread in colour. Moreover the same RGB morphology shown by our IR CMDs is also present.

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2 For the updated version (2003) of that work, see http://physwww.mcmaster.ca/%7Eharris/mwgc.dat
in the 2MASS catalogue of the same region, ruling out the possibility that the observed feature is due to any spurious effect in our photometry.

As can be clearly seen in Fig. 4, in the case of NGC 6569, 6637 and 6638 the \((J-K)\) colour distribution of the RGB stars, computed in a bin of \(\sim 1.5\) mag, can be reproduced by a single Gaussian with a \(\sigma\) value compatible with the internal photometric errors. Conversely, NGC 6304 shows a colour distribution with a pronounced tail toward the red. At least two Gaussian components are needed in order to reproduce the colour distribution shown in Fig. 4. The main and bluer component is representative of the cluster RGB stars, its colour distribution has in fact a \(\sigma = 0.045\) comparable with those of the other clusters. A secondary component at \(\delta(J-K) \sim 0.1\) is needed in order to fit the red tail of the colour distribution (see Fig. 4). In order to check whether the red sequence could be due to field contamination, we investigated the field region around the cluster, by using 2MASS data. In particular, Fig. 5 shows the cluster CMD as obtained from our observations (Fig. 5a), and for comparison the CMDs of four control fields located at \(\sim 13\) arcmin from the cluster centre (towards the north, south, east and west; Fig. 5b). As can be seen, most field giants lie on the red side of the NGC 6304 RGB. In order to make the effect more clear we divided the RGB region of the CMDs into two boxes: blue and red, respectively. As shown in Fig. 5, the vast majority of the field RGB stars lie in the red box, while only a few field giants are on the blue side of the box. To quantify the observed effect the number of field stars, per square arcmin, lying in the blue and red boxes in a bin of 1 mag has been computed. The derived density distribution is compared with the same quantity in the SOFI field. The result shown in Fig. 6, clearly indicates that almost all stars lying in the red box of Fig. 5(a) are due to Bulge field contamination (see i.e. Fig. 6b).

Note that the same procedure has been applied to all the programme clusters. In NGC 6569, 6637 and 6638 the level of bulge field contamination is always less than 15 per cent.

### 5 THE MAIN RGB FEATURES

As already discussed in detail by Ferraro et al. (2000) and Paper I and II, a complete characterization of the RGB sequence, as a function of the cluster metallicity, requires an appropriate definition of its morphological and evolutionary features, by using suitable
CMDs and LFs. Briefly, the morphological characteristics of the RGB sequence can be obtained by computing a set of photometric indices (see Section 5.1) such as: (i) colours at fixed magnitudes; (ii) magnitudes at constant colours; and (iii) the RGB slope. In fact, (1) the absolute colour position and (2) the morphology of the RGB sequence progressively change with increasing cluster metallicity. The bump and tip are the main RGB evolutionary features: the RGB bump traces a significant change in the evolutionary rate of the stars along the RGB, and the RGB tip flags the end of the RGB evolutionary phase (see Section 5.3).

As carried out in our previous studies, both the [Fe/H] in the Carretta & Gratton (1997, hereafter CG97) scale and the [M/H] global metallicity, which takes into account the contribution of the α elements, are considered. The latter has been computed using

\[
[M/H] = [\text{Fe/H}]_{\text{CG97}} + \log(0.638 f_\alpha + 0.362),
\]

where \(f_\alpha\) is the enhancement factor of the α elements (i.e. [\alpha/\text{Fe}] \approx +0.3 \text{ dex}). Following Ferraro et al. (2000) and Paper I and II, an \(\alpha\)-enhancement factor linearly decreasing to zero for metal-rich clusters with [Fe/H]_{CG97} \leq -1 have been adopted. However, it must be noted that, there is a growing number of recent high-resolution spectroscopic observations of both bulge cluster and field giants (Rich & McWilliam 2000; Carretta et al. 2001; Origlia, Rich & Castro 2002; Origlia & Rich 2004; Zoccali et al. 2004; McWilliam & Rich 2004; Origlia, Valenti & Rich 2005) which point towards a constant value of \(\alpha\) enhancement up to solar metallicity. If a constant enhancement of \([\alpha/\text{Fe}] \approx +0.3 \text{ dex}\) over the full range of metallicity is adopted, the global metallicity of the programme clusters listed in Table 3 must be increased, on average, by a few hundredths dex, the exact amount depending on their actual metallicity (the effect of such an assumption will be discussed in a forthcoming paper, Ferraro et al. (in preparation).

![Figure 6. Density distribution of stars detected in SOFI (open histograms) and in 2MASS (shaded histograms) fields calculated within: both boxes (a), only the red box (b) and only the blue box. For each magnitude bin the percentage of field contamination is indicated.](https://academic.oup.com/mnras/article-abstract/361/1/272/1022568)

### Table 3. Adopted parameters for the observed clusters.

| Name       | [Fe/H]_{CG97} | [M/H] | \(E(B - V)\) | \(m - M\) |
|------------|---------------|-------|---------------|-----------|
| NGC 6304  | -0.68         | -0.55 | 0.58          | 13.88     |
| NGC 6569  | -0.79         | -0.64 | 0.49          | 15.40     |
| NGC 6637  | -0.68         | -0.55 | 0.14          | 14.87     |
| NGC 6638  | -0.97         | -0.69 | 0.43          | 15.07     |
| 47 Tuc\d | -0.70         | -0.59 | 0.04          | 13.32     |
| M 107\d  | -0.87         | -0.70 | 0.33          | 13.95     |

Note: ‘\d’ from table 2 of Ferraro et al. (1999).

### 5.1 The RGB morphology

In order to derive the colours at fixed magnitudes and the magnitudes at fixed colours the first step is the definition of the RGB fiducial ridge lines from the CMDs. We followed the prescriptions discussed in detail in Ferraro et al. (2000) and Valenti et al. (2004a). In the case of NGC 6304, where the field contamination causes the observed splitting of the RGB sequence, the fiducial ridge line has been computed using only the main, blue component (see Section 4.1).

By using the values of reddening and distance modulus listed in Table 3, the observed RGB ridge lines of the programme clusters have been also converted in the absolute plane. Once the intrinsic RGB ridge lines are obtained, a complete description of the RGB morphology, as a function of the cluster metallicity, follows directly.

The RGB \((J - K)_{\odot}\) and \((J - H)_{\odot}\) intrinsic colours corresponding to four different magnitude levels, namely \(M_k = M_H = (-5.5, -5, -4, -3)\), as defined in Ferraro et al. (2000), are listed in Table 4, while their trends with the cluster metallicity are shown in Figs 7 and 8, respectively. Our results agree nicely with the calibration relations (solid lines) derived in Paper I (see equations A1–A8 and A17–A24 in appendix A of Paper I), and with previous studies from Cohen & Sleeper (1995; Ferraro et al. 2000; Valenti et al. 2004a, Paper I), the linear scaling of the colours with cluster metallicity is confirmed, up to the highest metallicities. Tables 5 and 6 list the various photometric estimates of metallicity in both the CG97 and the global metallicity scales, as computed using the relations (A1–A8 and A17–A24) of Paper I and the colours listed in Table 4. They are all consistent within \(\pm 0.1\) dex.

The behaviour of the RGB magnitudes at fixed colours as a function of metallicity has been investigated in all the observed clusters. Table 4 lists the derived \(M_k\) and \(M_H\) magnitudes at constant \((J - K)_{\odot}\) and \((J - H)_{\odot}\) colours. Fig. 9 shows how these two indices linearly correlate with the metallicity in both adopted scales. The paper I sample together with the corresponding calibration relations are also plotted. A detailed discussion on the errors associated with the derived colours and magnitudes can be found in Paper I. Here we just point out that, while the accuracy on the derived colours at fixed magnitudes is mainly driven by the uncertainty on the distance modulus, the errors associated on the derived magnitudes at constant colours depend both on the reddening and the distance uncertainty with almost the same weight. Column 4 of Tables 5 and 6 lists the photometric estimate of [Fe/H] and [M/H], respectively, derived by averaging the metallicity computed using relations (A33), (A37), (A35) and (A39) of Paper I and the absolute \(M_k\) and \(M_H\) magnitudes listed in Table 4.

Another photometric estimate of the cluster metallicity is provided by the RGB slope, which turns out to be particularly powerful...
Table 4. Photometric indices describing the RGB location in colour and in magnitude in the $K$, $J - K$ and $H$, $J - H$ planes, for the observed clusters.

| Name | NGC 6304 | NGC 6569 | NGC 6637 | NGC 6638 |
|------|----------|----------|----------|----------|
| $(J - K)_0^{M_K=-5.5}$ | $0.984 \pm 0.052$ | $0.954 \pm 0.052$ | $0.986 \pm 0.051$ | $0.918 \pm 0.050$ |
| $(J - K)_0^{M_K=-5}$ | $0.928 \pm 0.052$ | $0.899 \pm 0.052$ | $0.927 \pm 0.051$ | $0.863 \pm 0.050$ |
| $(J - K)_0^{M_K=-4}$ | $0.827 \pm 0.052$ | $0.800 \pm 0.052$ | $0.820 \pm 0.051$ | $0.767 \pm 0.050$ |
| $(J - K)_0^{M_K=-3}$ | $0.738 \pm 0.052$ | $0.716 \pm 0.052$ | $0.727 \pm 0.051$ | $0.686 \pm 0.050$ |
| $(J - H)_0^{M_H=-5.5}$ | $0.812 \pm 0.035$ | $0.770 \pm 0.035$ | $0.809 \pm 0.034$ | $0.754 \pm 0.034$ |
| $(J - H)_0^{M_H=-5}$ | $0.772 \pm 0.035$ | $0.735 \pm 0.035$ | $0.766 \pm 0.034$ | $0.717 \pm 0.034$ |
| $(J - H)_0^{M_H=-4}$ | $0.699 \pm 0.035$ | $0.668 \pm 0.035$ | $0.686 \pm 0.034$ | $0.647 \pm 0.034$ |
| $(J - H)_0^{M_H=-3}$ | $0.634 \pm 0.035$ | $0.607 \pm 0.035$ | $0.616 \pm 0.034$ | $0.584 \pm 0.034$ |
| $M_K^{(J-K)_0=0.7}$ | $-2.52 \pm 0.04$ | $-2.79 \pm 0.04$ | $-2.68 \pm 0.04$ | $-3.19 \pm 0.04$ |
| $M_H^{(J-H)_0=0.7}$ | $-4.02 \pm 0.04$ | $-4.49 \pm 0.03$ | $-4.19 \pm 0.03$ | $-4.77 \pm 0.03$ |
| RGB slope | $-0.094 \pm 0.005$ | $-0.089 \pm 0.003$ | $-0.092 \pm 0.003$ | $-0.087 \pm 0.004$ |

Figure 7. RGB mean $(J - K)_0$ colour at fixed $M_K = (-5.5, -5, -4, -3)$ magnitudes as a function of the CG97 metallicity scale (left panels) and of the global metallicity (right panels). Filled circles show the bulge clusters observed here, empty circles are the clusters presented in Paper I. The solid lines are the calibration relations published in Paper I.

Figure 8. The same as Fig. 7, but for the $(J - H)_0$ colours.

5.2 The RGB evolutionary features

The RGB bump flags the point when, during the post-MS evolution of low-mass stars, the narrow hydrogen-burning shell reaches the discontinuity in the hydrogen distribution profile, generated by the previous innermost penetration of the convective envelope. The detection of the RGB bump in Galactic and Local Group stellar systems, has been subject of many studies (see i.e. Fusi Pecci et al. 1990; Ferraro et al. 1999; Zoccali et al. 1999; Ferraro et al. 2000; Bellazzini et al. 2001, 2002; Monaco et al. 2002; Riello et al. 2003; Valenti et al. 2004a; Sollima et al. 2004; and Paper II), demonstrating how this feature can be safely identified by using suitable...
CMDs and LFs. In fact, the position of the RGB bump corresponds to a peak in the differential LF and to a slope change in the integrated LF. Following the same procedure adopted by Ferraro et al. (2000), Valenti et al. (2004a) and Paper II, the RGB bump of the programme clusters has been detected in all the passbands. As an example, Figs 10 and 11 show the integrated and differential LFs, in the K band, for RGB stars in all the observed clusters.

The observed J, H and K bump magnitudes are listed in Table 7. Fig. 12 shows the behaviour of the absolute magnitudes of the RGB bump as a function of metallicity in both adopted scales. The location of the bump in NGC 6304 is somewhat uncertain due to the bulge field contamination (see Section 4.1). Indeed, the RGB LF in this cluster shows a few, broad/asymmetric peaks, the most pronounced being about 0.3-mag fainter than the corresponding peak in NGC 6637; by assuming the same age and same helium content for the two clusters, this would imply a difference in metallicity of $\delta$[M/H] $\sim$ 0.15 dex.

Using equations (1)–(6) of Paper II linking the bump magnitude to the cluster metal content we have also derived independent estimates of metallicity in both adopted scales (see Table 7).

For stellar populations older than $\tau \approx$ 1–2 Gyr (i.e. when stars less massive than $M \approx$ 2.0 $M_\odot$ are evolving) the RGB tip reaches its maximum luminosity, and it remains approximately constant on increasing the population age. The calibration of the relation linking the RGB tip magnitude to the cluster metallicity is, therefore, a fundamental step in view of using the RGB tip luminosity as a standard candle (see Bellazzini et al. 2001). In Paper II we recently published an updated calibration of the RGB tip magnitudes with varying metallicity in the near-IR J, H and K bands, based on a sample of 24 Galactic GCs. Here we present the estimates of the RGB tip luminosity for the programme clusters obtained following the same procedure adopted there. Briefly, this method is based on the assumption that the brightest non-variable star along the RGB can be considered as representative of the RGB tip level. The presence in our IR catalogue of variable stars along the RGB has been checked using the catalogue by Clement et al. (2001). The few

| Name   | [Fe/H]$_{[CG97]}$ | [Fe/H]$_{[H]}$ | [Fe/H]$_{[mag]}$ | [Fe/H]$_{[slopa]}$ | [Fe/H]$_{[bump]}$ | ([Fe/H]) |
|--------|------------------|----------------|-----------------|-------------------|------------------|----------|
| NGC 6304 | −0.68            | −0.73          | −0.69           | −0.71             | −0.55            | −0.70    |
| NGC 6569 | −0.79            | −0.90          | −0.84           | −0.82             | −0.97            | −0.88    |
| NGC 6637 | −0.68            | −0.78          | −0.76           | −0.76             | −0.77            | −0.77    |
| NGC 6638 | −0.97            | −1.06          | −0.98           | −0.87             | −1.11            | −1.00    |

**Table 6.** [M/H] photometric estimates for the observed clusters obtained by using the RGB morphological (colours, magnitudes and slope) and evolutionary (bump) features.

| Name   | [M/H]  | [M/H]$_{[col]}$ | [M/H]$_{[mag]}$ | [M/H]$_{[slopa]}$ | [M/H]$_{[bump]}$ | ([M/H]) |
|--------|--------|----------------|----------------|------------------|-----------------|----------|
| NGC 6304 | −0.55  | −0.58          | −0.56          | −0.57            | −0.44            | −0.54    |
| NGC 6569 | −0.64  | −0.74          | −0.70          | −0.68            | −0.80            | −0.73    |
| NGC 6637 | −0.55  | −0.62          | −0.62          | −0.61            | −0.61            | −0.62    |
| NGC 6638 | −0.69  | −0.90          | −0.83          | −0.72            | −0.92            | −0.84    |

**Table 7.** Near-IR and bolometric RGB bump and tip of the observed cluster sample.

| Name   | NGC 6304   | NGC 6569   | NGC 6637   | NGC 6638   |
|--------|------------|------------|------------|------------|
| $J_{\text{bump}}$ | 14.03 ± 0.10 | 14.93 ± 0.05 | 14.28 ± 0.05 | 14.45 ± 0.05 |
| $H_{\text{bump}}$ | 13.33 ± 0.10 | 14.23 ± 0.05 | 13.78 ± 0.05 | 13.73 ± 0.05 |
| $K_{\text{bump}}$ | 13.13 ± 0.10 | 14.08 ± 0.05 | 13.65 ± 0.05 | 13.58 ± 0.05 |
| $J_{\text{tip}}$ | 9.06 ± 0.23  | 10.52 ± 0.21 | 9.91 ± 0.23  | 8.61 ± 0.24  |
| $H_{\text{tip}}$ | 8.02 ± 0.25  | 9.49 ± 0.22  | 9.08 ± 0.22  | 8.89 ± 0.28  |
| $K_{\text{tip}}$ | 7.65 ± 0.33  | 9.21 ± 0.26  | 8.72 ± 0.31  | 8.61 ± 0.35  |
| $M_{\text{bump}}$ | 1.10 ± 0.22  | 0.55 ± 0.22  | 0.67 ± 0.22  | 0.51 ± 0.22  |
| $M_{\text{tip}}$ | −3.59 ± 0.33 | −3.59 ± 0.26 | −3.34 ± 0.31 | −3.88 ± 0.35 |

**Figure 9.** Upper panels: $M_K$ at fixed ($J - K$)$_0$ = 0.7 as a function of the metallicity in the CG97 scale (a) and in the global scale (c). Lower panels: $M_{J0}$ at fixed ($J - H$)$_0$ = 0.7 as a function of the metallicity in the CG97 scale (b) and in the global scale (d). The filled circles refer to the present sample, the empty circles the sample of Paper I. The solid lines are the calibration relations derived in Paper I.
variables are marked as large filled triangles in the CMDs plotted in Figs 1 and 2. The measures of the RGB tip obtained for the programme clusters are listed in Table 7, while Fig. 13 shows the absolute RGB tip magnitudes as a function of the cluster metallicity in both adopted scales. As can be seen, our results nicely agree with the relations derived in Paper II. Note that in the case of NGC 6637, the brightest non-variable RGB star is different from that the one identified by Ferraro et al. (2000) as representative of the tip level. This is due to the fact that the star used by Ferraro et al. (2000) was a blend, which we were able to separate into two stars, thanks to the superior spatial resolution of SOFI.

6 THEORETICAL PLANE

In order to compare the observed RGB evolutionary features with model predictions, it is necessary to transform the observables into...
the theoretical plane, by converting the absolute magnitudes into the bolometric one. In doing this, the bolometric corrections for Population II giants published by Montegriffo et al. (1998) were used. Table 7 lists the bolometric magnitudes of both the RGB bump and the tip for the observed cluster sample, Figs 14 and 15 show their trends with respect to cluster metallicity in both adopted scales. As can be seen, the values obtained for the programme clusters fit well into the relations calibrated in Paper II.

Theoretical predictions of the bump features by Straniero et al. (1997) show excellent agreement with the observations (see Fig. 14). Because of the statistical fluctuations affecting the observed RGB tip, intrinsically poorly populated in GCs (Castellani, Degl’Innocenti & Luridiana 1993), the theoretical predictions of this feature (see e.g. Caloi et al. 1997; Salaris & Cassisi 1997) have to be considered as an upper luminosity boundary to the observed values.

7 SUMMARY AND CONCLUSIONS

High-quality near-IR photometry of NGC 6304, 6569, 6637 and 6638 have been presented. By using CMDs and LFs we performed a detailed analysis of the RGB morphology and evolutionary features. New estimates of the cluster distance and extinction have been obtained. A set of photometric indices has been used to provide photometric estimates of the cluster metallicity in both the [Fe/H] and the [M/H] scales. We find [Fe/H] = −0.70, −0.88, −0.77, −1.00 and [M/H] = −0.54, −0.73, −0.62, −0.84 for NGC 6304, 6569, 6637 and 6638, respectively. The bump and the tip bolometric luminosities are in excellent agreement with the theoretical predictions.

Figure 14. Bolometric magnitudes of the RGB bump as a function of the cluster metallicity in both the CG97 (upper panel) and the global (low panel) scales. Filled circles show the present cluster sample and empty circles are the Paper II data set. The solid lines are the calibration relations from Paper II. Two theoretical predictions have been plotted in the lower panel: Caloi, D’Antona & Mazzitelli (1997) (dotted line) and Salaris & Cassisi (1997) (dashed line).

Figure 15. Bolometric magnitudes of the RGB tip as a function of the cluster metallicity in both the CG97 (upper panel) and the global (low panel) scales. Filled circles show the present cluster sample and empty circles are the Paper II data set. The solid lines are the calibration relations from Paper II. Two theoretical predictions have been plotted in the lower panel: Caloi, D’Antona & Mazzitelli (1997) (dotted line) and Salaris & Cassisi (1997) (dashed line).

ACKNOWLEDGMENTS

The financial support by the Ministero dell’Istruzione, Università e Ricerca (MIUR) is kindly acknowledged. It is a pleasure to thank the anonymous referee for a number of useful comments which significantly improved the presentation of this work. Part of the data analysis has been performed with the software developed by P. Montegriffo at the Osservatorio Astronomico di Bologna (INAF). We thank Sergio Ortolani for making available the optical photometry of NGC 6569. We warmly thank the ESO-La Silla Observatory Staff for assistance during the observations. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and Infrared Processing and Analysis Centre/California Institute of Technology, founded by the National Aeronautics and Space Administration and the National Science Foundation.

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