B and V photometry of the metal-rich bulge globular cluster NGC 6304*

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Abstract. We present B and V photometry of the bulge globular cluster NGC 6304. We derive a reddening E(B-V) ≈ 0.5 and a distance from the Sun d⊙ ≈ 6 kpc. From the red giant branch morphology we estimate that the metallicity of NGC 6304 is intermediate between those of 47 Tuc and NGC 6528.

The cluster is foreground to the bulk of the bulge population and the reddenings are comparable.

Evidence of a hot stellar component belonging to the cluster is found. These hot stars could correspond to a blue extended horizontal branch and/or blue stragglers.

Key words: stars: Hertzsprung–Russell (HR) and C-M diagrams – Galaxy: globular clusters: individual: NGC 6304

1. Introduction

We have been systematically observing globular clusters in the central regions of the Galaxy, providing CCD Colour-Magnitude Diagrams (CMD), in view of a better understanding of the globular cluster system properties. In the region within 5° of the Galactic center, we derived improved parameters which permitted to study the structure and other properties of the inner bulge (Barbuy et al. 1998a). Red Horizontal Branch (HB) clusters are dominant in the inner region.

Data on globular clusters in the surrounding region 20°×20° have also been steadily growing in recent years (Barbuy et al. 1999a). Just to mention a few objects: NGC 6256, NGC 6717 = Palomar 9 (Ortolani et al. 1999; Brocato et al. 1996), NGC 6287 (Stetson & West 1995), NGC 6316, NGC 6342, NGC 6496, NGC 6539, Palomar 8 (Armandroff 1988), NGC 6380 and Terzan 12 (Ortolani et al. 1998), NGC 6388 and NGC 6441 (Rich et al. 1997), NGC 6558 (Rich et al. 1998), Terzan 3 and IC 1276 = Palomar 7 (Barbuy et al. 1998b) and Tonantzintla 2 (Bica et al. 1996). For this region a detailed discussion was given in Barbuy et al. (1999a), wherein NGC 6401 was also analysed, and it was shown that the fractions of red and blue horizontal branch clusters are comparable.

NGC 6304, also named ESO454-SC2, is located at α2000 = 17h 14m 32.5s, δ2000 = -29° 27’ 44′′ (l = 355.83°, b = 5.38°). NGC 6304 is a compact cluster with concentration parameter c = 1.80, core radius rc = 0.21′, tidal radius rt = 13.2′ and half light radius rh = 1.4′ (Trager et al. 1995).

In terms of integrated light this cluster has been rather extensively studied. Hess & Shawl (1985) classified the cluster spectroscopically resulting a G3 spectral type which suggests a metallicity higher than that of 47 Tuc. Zinn (1980) gives [Fe/H] = -0.27 derived from integrated photometry, whereas Zinn & West (1984) give [Fe/H] = -0.59 using also integrated spectroscopy. Bica & Pastoriza (1983) obtained [Fe/H] = +0.23 from integrated DDO photometry.

Rutledge et al. (1997) studied the cluster by means of CaII triplet spectroscopy of individual giants where [Fe/H] = -0.38 and [Fe/H] = -0.66 are found in the Zinn & West (1984) and Carretta & Gratton (1997) scales respectively.

An early photographic V vs. B-V Colour-Magnitude Diagram was provided by Hess & Hartwick (1976). They obtained E(B-V) = 0.58 and a distance from the Sun of d⊙ = 5.8 kpc. Davidge et al. (1992) combined V CCD to infrared Hg:Cd:Te array photometry. Their V vs. V-K CMD clearly shows a red HB and they derive E(B-V) ≈ 0.5, and conclude that the metallicity is slightly above that of 47 Tuc.

Webbink’s (1985) compilation gives [M/H] = -0.54, VHB = 16.15, E(B-V) = 0.52 and d⊙ = 6.0 kpc, whereas Harris (1996) reports [Fe/H] = -0.59, VHB = 16.25, E(B-V) = 0.52 and d⊙ = 5.6 kpc.

The available studies show that the cluster is metal-rich, however it is not conclusive whether it is at the level of 47 Tuc or higher. In the present paper we examine several CMD features compared to reference metal-rich clusters trying to better constrain its metallicity, given that the RGB morphology can be used as a metallicity indicator (Ortolani et al. 1991; Barbuy et al. 1997).

In Sect. 2 we present the observations and calibrations. In Sect. 3 we provide the CMD and determine cluster parameters. In Sect. 4 we discuss the CMD of the surrounding field. In Sect. 5 a hot stellar component is discussed. In Sect. 6 concluding remarks are given.

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Log of observations

<table>
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<th>Target</th>
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<td></td>
<td>B</td>
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2. Observations

NGC 6304 was observed in the nights of 1998 July 4–5, with the 1.5m Danish telescope at ESO (La Silla). We employed an EFOSC camera equipped with a Loral/Lesser CCD detector C1W7 with 2052x2052 pixels. The pixel size is 15 μm, corresponding to 0.39" on the sky, which provides a full field of 13'×13'.

The log of observations is provided in Table 1.

In Fig. 1 we show a 180 sec V exposure of NGC 6304, where it is clear that we are dealing with a populous compact cluster in a rich field.

Daophot II was used to extract the instrumental magnitudes. For calibrations we used Landolt (1983, 1992) standard stars in the first night (July 4, 1998) when the template cluster 47 Tuc was also observed, in order to have its bright sequences compared to those of NGC 6304.

Reduction procedures of compact clusters in crowded bulge fields were described in a V and I study of Liller 1 (Ortolani et al. 1996) and in the recent work on NGC 6401 (Barbuy et al. 1999a), observed in the same run. The derived calibration equations are:

\[
\begin{align*}
V &= 24.31 + v \\
B &= 23.93 + 0.07(B - V) + b
\end{align*}
\]

reduced to 1 sec. exposure and 1.0 airmass. The zero point calibration errors arising from crowding effects are estimated to be about ±0.03 mag. The CCD shutter time uncertainties (0.3 sec) related to short exposures done for standard stars, lead to additional 3% error, which is propagated to the calibrations of the long exposure cluster frames. The final magnitude zero point uncertainty is estimated to be of ±0.05. The atmospheric extinction was corrected with the La Silla coefficients (\(C_V = 0.13\), \(C_B = 0.23\) mag/airmass).

We note that the seeing of the second night (July 5) was better, however the night was non photometric. Our final photometry of 47 Tuc comes from the second night set by transferring the first night calibration. NGC 6304 was observed in the second night. It was calibrated using 5 isolated bright stars in common with Hesser and Hartwick (1976). They were used for the zero point calibrations, after correction for the slope coefficients. The final residuals between our calibrated magnitudes and Hesser and Hartwick’s are small (±0.01 mag. in V and \(B - V\)).

A comparison of our final photometric V magnitudes with those by Davidge et al. (1992) is shown in Fig. 2. A bright star sample (V < 17.4) was extracted from their Table 2. We find the median V differences of \(\Delta V = V_{ThisPaper} - V_{Davidge} = 0.04 ± 0.043\). (r < 4.6') containing NGC 6304 and field.
3. NGC 6304

3.1. Colour-magnitude diagrams

In Fig. 2 we show the V vs. B-V diagram of NGC 6304 in an extraction of r < 700 pixels (r < 4.6'), including the cluster and a good sampling of the field. We clearly see a compact red horizontal branch (RHB) at V = 16.25 which is that of the cluster and a diffuse, fainter and redder bulge field RHB at V = 17.2. A clear disk blue main sequence (MS) is also present.

There is evidence of a curved red giant branch (RGB) characteristic of metal-rich populations, like in NGC 6528 and NGC 6553 (Ortolani et al. 1990, 1991, 1992): the RGB brightest part (V ≈ 14.4, B-V ≈ 1.95) is accompanied by a vertical sequence of stars extending 2 magnitudes fainter. Below we investigate whether this sequence is related to the cluster or the bulge field.

In order to better disentangle the features described above, in the following we present different CMD extractions. In Figs. 4a,b we show V vs. B-V CMD extractions corresponding to a central region within 250 pixels (r < 1.6') centered on the cluster, and a ring of 70 < r < 350 pixels (0.5' < r < 2.3') respectively. In both diagrams the cluster sequences are enhanced with respect to Fig. 2, since the field contamination is minimized. It is important to note also that the spread of stars remains comparable in the central part and the surrounding ring, indicating that it is caused by differential reddening rather than photometric errors in the compact core.

The V vs. B−V CMD diagram for 47 Tuc is shown in Fig. 5, to be compared to that of NGC 6304. In this figure we show only the 4000 best fitted stars, corresponding to those less crowded and therefore converging in the PSF fitting with smaller number of iterations.

Fig. 4a shows that the cool giants vertical sequence (Fig. 3) becomes depleted, indicating that it does not belong to the cluster, but to the bulge field. It is also worth noting that the field HB is less dispersed than in Fig. 3, showing that in this smaller extraction, differential reddening is less important.

A blue population of stars could be compatible with a blue extended HB component.

In Fig. 4b, showing the CMD of an adjacent ring, essentially the same features as in Fig. 4a are seen. In this figure we overplot the mean loci of the metal-rich bulge cluster NGC...
Metallicities are often given in terms of [Fe/H], whereas overall metallicities [Z/Z⊙] include all heavy elements taking into account each particular element abundance [X/H]. In old populations where [$\alpha$-elements] are overabundant (McWilliam 1997), [Z/Z⊙] results higher than [Fe/H].

For 47 Tuc we adopt [Fe/H] = -0.7 (Zinn & West 1984) and compute [Z/Z⊙] = -0.3 using abundance ratios from Brown et al. (1990) and Brown & Wallerstein (1992). For NGC 6528 these values are from high resolution detailed analysis of one member star by Barbuy (1999). The values are provided in Table 2. Note that, for the other metal-rich cluster NGC 6553, with CMD similar to that of NGC 6528 (Ortolani et al. 1995a), Cohen et al. (1999) found a higher [Fe/H] and lower abundance ratios than Barbuy et al. (1999b), but the [Z/Z⊙] value remains essentially the same as given in Barbuy et al. (1999b). In fact, the cluster CMD morphology, and more so the RGB morphology, where the stars are dominated by TiO bands (Ti and O are [$\alpha$]-elements), [Z/Z⊙] appears to be the more relevant parameter. By interpolating the measured RGB extent parameters, and applying this to the reference metallicities, we derive [Fe/H] = -0.57 and [Z/Z⊙] = 0.05 (assuming enhancement of [$\alpha$]-elements) for NGC 6304. This metallicity is consistent with the locus of the RGB of NGC 6304 relative to the mean loci of 47 Tuc and NGC 6528 (Fig. 4).

### 3.4. Cluster reddening and distance

The cluster HB is located at $V = 16.25 \pm 0.12$ and the colour of the RGB at the HB level is $B-V = 1.46 \pm 0.03$. The reddening is derived with respect to 47 Tuc. We derive $\Delta(B-V)_{NGC6304-47Tuc} = 0.50$; adopting $E(B-V)_{47Tuc} = 0.04$ (Harris, 1996, updated in http://physun.physics.mcmaster.ca/Globularg.html), we obtain $E(B-V) = 0.54$ or $A_V = 0.54 \times 3.3 = 1.78$. The adopted total-to-selective extinction ratio $R = 3.3$ ratio was assumed considering the metallicity and reddening amount dependences (Barbuy et al. 1998a and references therein). We assumed $M^\text{HB}_\odot = 0.16$ [Fe/H] + 0.98 from Jones et al. (1992), since it is based on metal-rich and intermediate metallicity stars; the zero point is slightly modified to take into account the difference between the magnitude of the red HB and RR Lyrae, as discussed in Guarnieri et al. (1998), and we get $M^\text{HB}_{NGC6304} = 0.9$. The resulting absolute distance modulus of NGC 6304 is $(m-M) = 13.57$, and the distance to the Sun $d_\odot = 5.18 \pm 1.0$ kpc.

Taking NGC 6528 as reference, the reddening would be lower $E(B-V) = 0.34$ (assuming $\Delta(B-V) = 0.20$ as due to blan-keting) or $A_V = 1.12$, which gives $(m-M) = 14.23$ and $d_\odot = 7 \pm 1.0$ kpc.

Since the metallicity and CMD morphology of NGC 6304 are closer to 47 Tuc, we adopt compromise values of $E(B-V) = 0.47$ and $d_\odot = 5.8$ kpc.

We assume the distance of the Sun to the Galaxy center to be $R_\odot = 8.0$ kpc (Reid 1993), consistent with Barbuy et al. (1998), but we point out that in more recent work by Reid (1998) higher values are given. The Galactocentric coordinates are then $X = -2.24$ kpc ($X<0$ refers to our side of the Galaxy), $Y = -0.42$ kpc and $Z = 0.54$ kpc. The distance from the Galactic center is

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**Table 2. CMD metallicity indicators**

<table>
<thead>
<tr>
<th>Cluster</th>
<th>$\Delta V^\text{RGB}_{HB}$</th>
<th>$\Delta (B-V)^\text{RGB}_{HB}$</th>
<th>[Fe/H]</th>
<th>[Z/Z⊙]</th>
</tr>
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<tbody>
<tr>
<td>47 Tuc</td>
<td>2.3</td>
<td>0.81</td>
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<td>-0.32</td>
</tr>
<tr>
<td>NGC 6528</td>
<td>1.4</td>
<td>0.45</td>
<td>-0.5</td>
<td>+0.12</td>
</tr>
<tr>
<td>NGC 6304</td>
<td>1.75</td>
<td>0.56</td>
<td>-0.57</td>
<td>+0.05</td>
</tr>
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</table>

6528 (Ortolani et al. 1992) and of the reference cluster 47 Tuc (Fig. 5). The CMD features seem to be intermediate between those of these clusters. Other morphological indicators are used to better constrain this point (Sect. 3.3).
R_GC = 2.3 kpc. Therefore the cluster is within the bulge volume, which is not unexpected since it is metal-rich, with a populous red HB.

Perryman et al. (1995) showed the Hipparcos CMD for the solar neighbourhood, where the giant clump is located at M_V = 0.9 ± 0.2. It is perhaps not suitable to adopt this intermediate age clump as reference to metal-rich old (low mass) stars. In any case, we assumed this same value for M_{HB}^V of NGC 6304.

4. Surrounding field

Since we employ a large CCD detector with projected area on the sky of 13′ × 13′, we analyse the surrounding field.

In Fig. 5 we show the V vs. B − V CMD of the surrounding field corresponding to an extraction of 400 < r < 1000 pixels (2.6′ < r < 6.5′), avoiding the cluster area. The red sequences are very wide, reflecting a pronounced differential reddening of ∆(B-V) ≈ 1.5 as measured at the red HB level. In fact, by inspection of the J and R ESO/SERC Schmidt plates of field 454, a very patchy dust absorption structure can be seen in the area corresponding to our CCD frame. Southeast in the plate, starting at about 1° from the cluster a heavily absorbed large region occurs.

The field red HB distribution shows evidence of structures: the extent of the HB in Figs. 3 and 4 are similar, but in Fig. 5 we see a double clump. This can be explained by a patchy absorption distribution, as seen in the plates, and possibly some metallicity spread.

The mean level of the field red HB level is at V = 17.2 and B − V = 1.6. This northern galactic hemisphere bulge field at b = 5.3° is approximately symmetrical to Baade’s Window (b = -4.2°) with respect to the Galactic center.

The CMDs of NGC 6528/NGC 6553 (Ortolani et al. 1995a) are essentially the same, and also very similar to Baade’s Window CMD (Ortolani et al. 1995a). Using the study of NGC 6528 by Ortolani et al. (1992) as a V vs. B − V reference for the bulge, the reddening is derived with respect to this cluster.

We obtain ∆(B-V)_{NGC6528−field} = 0.05 and adopting E(B-V)_{NGC6528} = 0.52 we get E(B-V)_{field} = 0.47. This value is the same as that derived for the cluster itself. Assuming R = 3.46 for this metallicity and reddening amount (Barbuy et al. 1998a) we get A_V = 1.63. In addition, the reddening found for this field is remarkably similar to that of Baade’s Window (Terndrup 1988), which could indicate a symmetrical distribution of dust in these two directions. An absolute magnitude of the horizontal branch M_{HB}^V = 0.95 is adopted for the field metallicity. The resulting absolute distance modulus is (m-M)_⊙ = 14.62, and the distance to the Sun d⊙ = 8.4 ± 1.0 kpc.

We conclude that the cluster is located foreground to the bulk of field bulge population in this direction.

5. Hot stars

In Fig. 5 we see evidence of a blue extended horizontal branch at about 16.8 < V < 18.3 and 0.3 < B − V < 0.9. This concentration of hot stars could have some contamination by disk stars but they should not belong to the bulge population, from several evidences: (a) they should be ~ 1 mag fainter, according to the distance of the bulk bulge population seen through the same absorption; (b) Terndrup et al. (1999) estimated a number of 100–200 hot HB bulge stars per square degree, from which number we would expect to have only about 5 to 6 of these stars in our field; (c) Several field diagrams in the bulge taken with comparable field sizes show essentially no hot HB stars at this level of brightness, such as fields close to NGC 6652 (Ortolani et al. 1994), Pal 6 (Ortolani et al. 1995b), Liller 1 (Ortolani et al. 1996), Terzan 10 and ESO 456-SC38 (Ortolani et al. 1997).
These hot stars could be due to a blue horizontal branch tail and/or to blue stragglers. The corresponding stars (69) are spread over all the field, but some of them (11–12) are clearly concentrated in the cluster in the central parts.

In Fig. 7 we show the best fit for this blue sequence with the mean locus of the blue tail cluster NGC 6752 Aurieère & Ortolani 1989), which has an intermediate metallicity ([Fe/H] = -1.55, Harris 1996). It gives an offset of 3.85 mag in V and 0.45 mag in B – V. Adopting (m-M)\(V\) = 13.02 and E(B-V)=0.04 for NGC 6752 we get, from the fit to the blue sequence, (m-M)\(V\) = 15.24, corresponding to 5.4 kpc. This distance is comparable to the 5.8 value obtained for the cluster. The tidal radius (13′) is comparable with the frame dimensions, which suggests that the blue sequence stars belong to the cluster.

In Fig. 8 the spatial distribution of the blue sequence stars marked in Fig. 6 is shown. It basically confirms a concentration in the area of the half light diameter (~ 430 pixels or 2.8′). The blue sequence is compatible with the occurrence of a blue HB tail in this metal-rich cluster. If this is confirmed it would be a similar case to NGC 6388 and NGC 6441 (Rich et al. 1997). Part of these blue sequence stars might be cluster blue stragglers. A bulge cluster with evidence of a blue straggler population is NGC 6652 (Ortolani et al. 1994), which is likewise a compact cluster. It would be desirable to carry out photometry in other wavelengths to further check this interesting hot stellar component, while a CMD field exploration outside the cluster tidal radius could give a more conclusive answer of membership. Proper motion studies and radial velocities would clarify this interesting issue.

6. Conclusions

NGC 6304 is definitely a bulge metal-rich globular cluster located at 6.8° from the Galactic center. A reddening E(B-V) \(\approx 0.5\) and a distance from the Sun d\(\odot\) \(\approx 6\) kpc are derived.

From the CMD morphology, we find that the metallicity of NGC 6304 is intermediate between those of 47 Tuc and NGC 6528, around [Fe/H] \(\approx -0.6\); assuming enhancement of \(\alpha\)-elements likewise 47 Tuc, we obtain [Z/Z\(\odot\)] \(\approx +0.05\) for NGC 6304.

The surrounding bulge field shows a pronounced differential reddening. The bulk of the bulge field population shows a reddening comparable to that of the cluster, but the cluster is slightly foreground.

A hot stellar component is detected that appears to belong to the cluster. These hot stars could be a blue tail horizontal branch and/or blue stragglers. If the former possibility is confirmed NGC 6304 would be another compact bulge cluster with a populous red horizontal branch accompanied by a blue tail, likewise NGC 6388 and NGC 6441 (Rich et al. 1997).

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