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B, *V* and *I* photometry of the intermediate metallicity bulge globular clusters NGC 6325 and NGC 6355⋆

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Abstract. Colour-Magnitude Diagrams are presented for the globular clusters NGC 6325 and NGC 6355. These clusters are embedded in crowded bulge fields. Both clusters are concentrated and have blue Horizontal Branches, and NGC 6325 shows a blue tail. We derive a reddening $E(B-V) \approx 0.95$ and a distance from the Sun $d_\odot \approx 6.9$ kpc for NGC 6325, and $E(B-V) \approx 0.78$ and $d_\odot \approx 8.8$ kpc for NGC 6355. They are both at ∼1 kpc from the Galactic center, above the plane. The metallicity has been estimated based on red giant branch morphology, being consistent with an intermediate metallicity of [Fe/H] ≈ −1.3 for both clusters, at the lower end of the metallicity distribution of bulge field stars. They add to the list of blue Horizontal Branch clusters with intermediate metallicities within the bulge volume.

Key words. galaxy: clusters: individual: NGC 6325, NGC 6355 – stars: Hertzsprung-Russell (HR) and C-M diagrams

1. Introduction

As part of an effort to improve the knowledge of the globular clusters projected on the central parts of the Galaxy (Barbuy et al. 1998, 1999), we study two globular clusters for which no CCD photometry is available. NGC 6325 and NGC 6355 are located in reddened zones of Ophiuchus, and are embedded in rich bulge fields. In particular NGC 6325 has conflicting estimations of metallicity in the literature. We suspect that differences in literature parameters possibly arise from contamination by bulge stars and the variable reddening across the clusters and their fields.

We are dealing with compact clusters. NGC 6325 and NGC 6355 have a post-core collapse structure (Trager et al. 1995). NGC 6325 has tidal radius $r_t = 9.6'$, core radius $r_c = 0.03'$ and half light radius $r_h = 0.63'$, whereas NGC 6355 has $r_t = 15.2'$, $r_c = 0.05'$ and $r_h = 0.87'$.

NGC 6325, also named ESO519-SC11 and GCL-58, has equatorial coordinates $\alpha_{2000} = 17^h17^m59.2^s$, $\delta_{2000} = -23^o45'57''$ ($l = 0.97^o$, $b = 8.00^o$). Integrated Q39 photometry provided $E(B-V) = 0.89$ and [Fe/H] = −1.61 (Zinn 1980). Zinn & West (1984) obtained [Fe/H] = −1.44. Integrated DDO photometry (Bica & Pastoriza 1983) reported a reddening value $E(B-V) = 0.92$ and estimated it to be a metal-rich cluster, as also indicated by Hesser & Shawl's (1985) integrated spectral type of G0. Harris (1975) provided a photographic BV CMD of the cluster Red Giant Branch (RGB). Harris' (1996, hereafter H96) compilation (as updated in http://physun.physics.mcmaster.ca/Globular.html) reported parameters from an unpublished CMD: a distance from the Sun $d_\odot = 9.6$ kpc, [Fe/H] = −1.17, $E(B-V) = 0.89$, and a Horizontal Branch (HB) level $V_{HB} = 18.3$. Webbink's (1985) compilation indicated a very low metallicity of [Fe/H] = −2.02, $V_{HB} = 17.3$:, $E(B-V) = 0.86$, $d_\odot = 6.2$ kpc. Minniti et al. (1995) provided an infrared CMD of this cluster and Minniti (1995) measured line indices for individual giants, having obtained an intermediate metallicity of [Fe/H] = −0.90 and $E(B-V) = 0.83$.

NGC 6355, also named GCl-63 and ESO 519-SC15, has coordinates $\alpha_{2000} = 17^h23^m58.6^s$, $\delta_{2000} = -26^o21'13''$ ($l = 359.58^o$, $b = 5.43^o$). Note that in early catalogues NGC 6355 was described as an open cluster, with designations Cr330 and OCl-1036 (Alter et al. 1970).

Zinn (1980) obtained $E(B-V) = 0.78$ and [Fe/H] = −1.51. Zinn & West (1984) obtained [Fe/H] = −1.50. Bica & Pastoriza (1983) derived [Fe/H] = −1.30 and $E(B-V) = 0.62$. The integrated spectral type (Hesser & Shawl 1985) is G0, again suggesting a metal-rich cluster. Harris (1996) reports a distance from the Sun $d_\odot = 7.2$ kpc, [Fe/H] = −1.50,

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$E(B-V) = 0.75$, and $V_{\rm HB} = 17.20$. Webbink (1985) gives [Fe/H] = −1.34, $V_{\rm HB} = 17.2$:, $E(B-V) = 0.73$, $d_\odot = 7.1$ kpc.

Dutra & Bica (2000) compared dust emission reddening values $E(B-V)_{\rm FIR}$ in cluster directions using maps by Schlegel et al. (1998) with reddening values $E(B-V)$ derived from the study of stellar contents of the clusters. For NGC 6325 there is a good agreement between both methods ($E(B-V)_{\rm FIR} = 0.95$ and $E(B-V) = 0.89$), while NGC 6355 is one of the clusters for which a considerable difference is found ($E(B-V)_{\rm FIR} = 1.21$ and $E(B-V) = 0.75$), suggesting the presence of dust in the cluster background.

The absolute magnitudes of NGC 6325 and NGC 6355 given by van den Bergh (1996) are $M_V = -7.20$ and −7.36, respectively, indicating average luminosities among globular clusters in the Galaxy.

In the present study we provide *B*, *V* and *I* CCD photometry for the clusters, to establish their parameters, in particular to check their metallicities, and possible association with the bulge.

In Sect. 2 the observations and reductions are described. In Sects. 3 and 4 we analyse the Colour-Magnitude Diagrams of NGC 6325 and NGC 6355, and their parameters are derived. Concluding remarks are given in Sect. 5.

2. Observations

NGC 6325 was observed on the night of 2000 March 6, with the 1.54 m Danish telescope at ESO, La Silla. The telescope was equipped with the DFOSC camera and a Loral/Lesser CCD detector C1W7 with 2052 × 2052 pixels. The pixel size is 15 μm, corresponding to 0.39′′on the sky, providing a full field of 13′ × 13′. NGC 6355 was observed on the night of 2000 March 7, using the same equipment. Both nights were photometric. The log of observations is presented in Table 1. In Fig. 1 is shown a full field V 180 s. image of NGC 6325. Figure 2 shows a full field V 120 s. exposure of NGC 6355. Figures 1 and 2 both show reddening variations across the fields. The clusters are populous and compact. DAOPHOT II and Allstar have been used to extract the instrumental magnitudes. The calibrations have been carried out using Landolt (1983, 1992) standard stars observed during the same nights. The derived calibration equations for the nights of March 6 and 7 are given in Ortolani et al. (2001) in the study of NGC 6569 and Palomar 11.

The zero point and slope errors of the equations are about ±0.015. The calibration error is largely dominated by crowding effects in the determination of the aperture corrections of the cluster stars. This error is estimated to be about ±0.03 mag. The CCD shutter time uncertainty (around 0.1–0.3 s), related to the short exposures used for the standard stars, leads to an additional 2–3 percent error, which is propagated to the calibration of the longer exposure cluster frames. Thus the final zero point uncertainty of our photometry is estimated to be ±0.05. The atmospheric extinction was corrected using the standard La Silla coefficients ($C_V = 0.13$ and $C_I = 0.1$ mag/airmass).

The present *B* and *V* photometry of NGC 6325 was compared with the photoelectric and photographic photometries by Harris (1975). Only his two faintest photoelectric standard stars are not saturated in our CCD photometry. The difference Harris vs. present CCD photometry for these stars is $\Delta V = 0.05 \pm 0.03$ mag and $\Delta(B-V) = 0.02 \pm 0.02$ mag. The comparison with 6 stars, fainter than $V = 14.8$, with photographic measurements, gives $\Delta V = -0.02 \pm 0.05$ mag and $\Delta(B-V) = -0.06 \pm 0.03$ mag. From this comparison, no evident systematic difference between ours and the Harris photometry is detected. Given the slightly different reddening derived from the $V/V-I$ and $V/B-V$ diagrams (see Sect. 3.2), we checked the consistency of our zero points in *B*, *V*, and *I*, concerning linearity effects or timing errors, by comparing the independently calibrated photometry derived from different frames taken on the same night, with the same filters, but with different exposure times. We find that the night was very stable, with average deviations within 0.02 mag in all colours. This number is consistent with the difference between the present and Harris' photometries. No timing uncertainties or linearity deviations were found in our photometry.

For NGC 6355, the present *B* and *V* photometry was compared with the photoelectric *B* and *V* sequence by Hazen-Liller (1984) in the same field. The difference Hazen-Liller vs. present CCD data for 4 photoelectric standards is $\Delta V = -0.02 \pm 0.02$ mag and $\Delta(B-V) = -0.04 \pm 0.01$ mag. There is excellent agreement, considering the possible sources of systematic errors discussed above.

3. NGC 6325

3.1. Colour-magnitude diagrams

In Fig. 3 we show the V vs. $V-I$ CMD of the field surrounding NGC 6325, corresponding to the full field. It is a typical bulge field, with a very extended giant branch ($\Delta(V-I) \approx 4$ mag) and differential reddening is evident. The blue sequence corresponds to a disk Main Sequence (MS). The bulge red HB and lower giant branch are prominent.

Figure 4 shows the V vs. $V-I$ CMD corresponding to a cluster extraction of $r < 1.6'$ ($r < 250$ pixels). A blue HB is clearly present and a rather steep RGB indicates that it is not a metal-rich bulge cluster.

Figure 5 shows the V vs. $B-V$ CMD for the same extraction as Fig. 4. The blue HB shows some evidence of a blue tail, which is not unexpected for a post-core collapse globular cluster (Fusi Pecci et al. 1993). The V vs. $B-V$ CMD morphology, in particular the RGB inclination, is very sensitive to intermediate and metal-poor metallicities and is used here to estimate the cluster metallicity. The CMD of NGC 6325 is compared to those of NGC 6171 of [Fe/H] = −1.04 and M 5 (NGC 5904) of [Fe/H] = −1.29 (Harris 1996), where the metallicities are according to H96. The mean loci of NGC 6171 and M 5 are adopted from Ferraro et al. (1991) and Sandquist (2000) respectively.

It is better fitted by M 5, from where we deduce [Fe/H] ≈ −1.3 for NGC 6325.

The CMD of NGC 6325 (as well as that of NGC 6355, Sect. 4) are affected by an important differential reddening and field contamination. For these reasons, it is not suitable

Table 1. Log of observations.

Target	Filter	Date	Exp. (s)	Seeing (″)
NGC 6325	V	06.03.00	15	1.7
	V	”	180	1.5
	B	”	120	1.8
	B	”	1200	1.6
	I	”	60	1.2
	I	”	20	1.2
	I	”	240	1.2
NGC 6355	V	07.03.00	30	1.3
	V	”	120	1.3
	V	”	360	1.3
	B	”	600	1.3
	I	”	30	1.2
	I	”	180	1.2

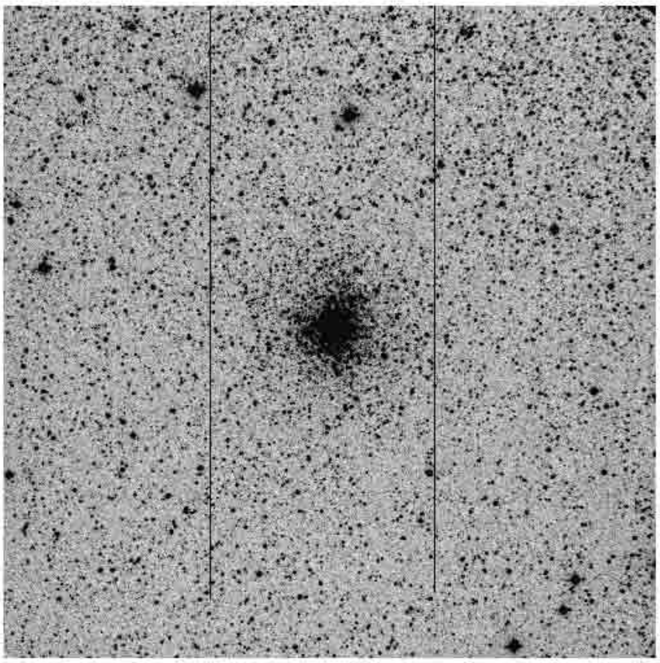

Fig. 1. NGC 6325: V image (180 s) for an extraction of $10' \times 10'$ (1500×1500 pixels). North is at the top and east to the left.

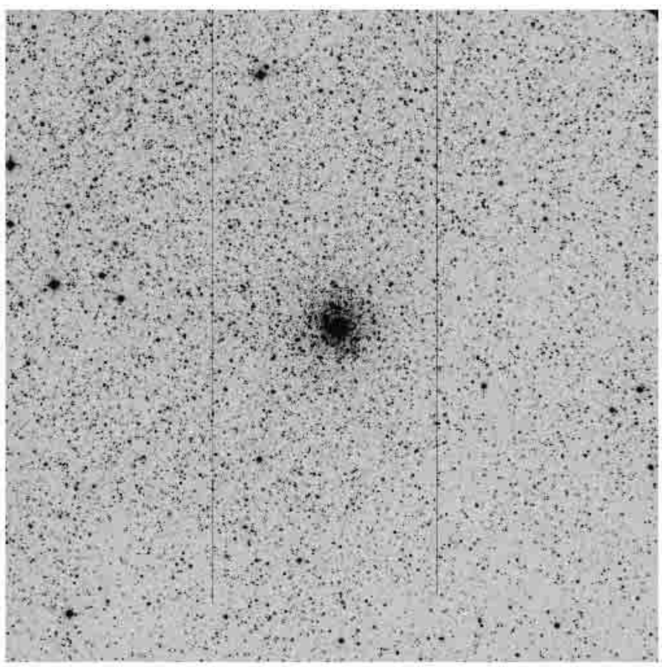

Fig. 2. NGC 6355: V image (120 s) for an extraction of $10' \times 10'$ (1500×1500 pixels). North is at the top and east to the left.

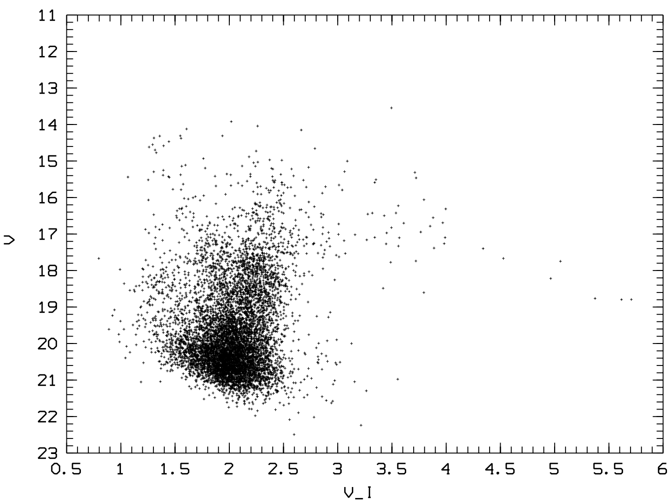

Fig. 3. NGC 6325: V vs. $V-I$ CMD for the full field ($13' \times 13'$).

to apply a more precise method involving the simultaneous estimation of reddening and metallicity, such as that proposed by Sarajedini (1994), given the scatter in the giant branches. Therefore we derive reddening and metallicity independently.

3.2. Cluster reddening and distance

The brightest part of the blue HB level at the RR Lyrae position of NGC 6325 is located at $V_{\rm HB} = 17.80 \pm 0.15$ and the colour of the RGB at the HB level is $B-V = 1.85 \pm 0.05$. The difference with respect to a fit with M 5 is $\Delta(B-V)_{\rm (NGC\ 6325-M\,5)} = 1.00$, and since $E(B-V) = 0.03$ for M 5 (H96), this implies a reddening of $E(B-V) = 1.03$. Adopting the same procedure for the V vs. $V-I$ diagram (Fig. 4), we derive $E(V-I) = 1.15$, which converts to $E(B-V) = 0.86$, using $E(B-V)/E(V-I) = 1.33$. We adopt a mean value of $E(B-V) = 0.95$. With $R = 3.1$ we get $A_V = 2.95$.

In order to estimate the distance we adopted the absolute visual magnitude of HB calibrations of $M_V^{\rm HB} = 0.65$ by Buonanno et al. (1989). Other possible values are for example $M_V^{\rm HB} = 0.72$ using the Chaboyer et al. (1996) formula, and the slightly modified formula by Barbuy et al. (1998) which gives $M_V^{\rm HB} = 0.77$. With the Buonanno et al. value, there results $(m-M)_0 = 14.20$, and a distance from the Sun $d_\odot = 6.9 \pm 1.0$ kpc for NGC 6325. If $M_V^{\rm HB} = 0.77$ is used, we get a distance of $d_\odot = 6.5 \pm 1.0$ kpc or 400 pc closer, a difference below the expected total uncertainties.

Assuming the distance of the Sun to the Galactic center to be $R_\odot = 8.0$ kpc (Reid 1993), the Galactocentric coordinates are $X = -1.2$ kpc ($X > 0$ is on the other side of the Galaxy),

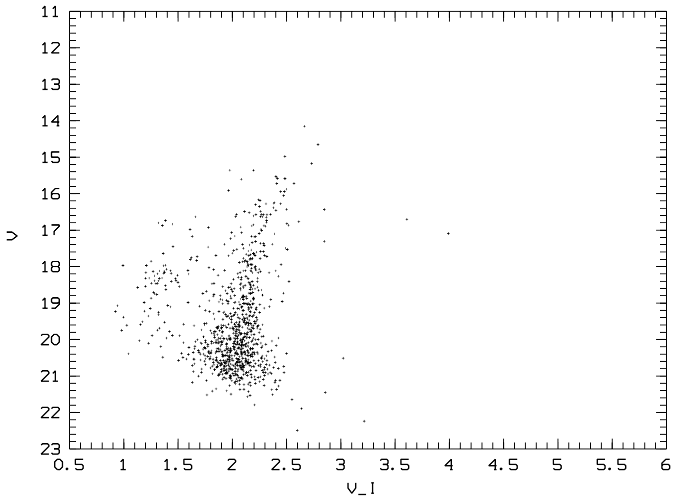

Fig. 4. NGC 6325: V vs. $V - I$ CMD for $r < 1.6'$ ($r < 250$ pixels).

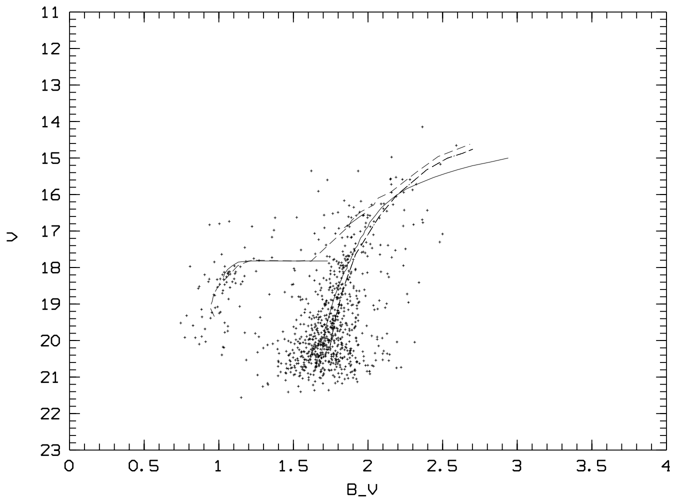

Fig. 5. NGC 6325: V vs. $B - V$ CMD extraction for $r < 1.6'$ ($r < 250$ pixels) with respect to the cluster center. The mean loci of NGC 6171 (solid line) and M 5 (dashed line) are superimposed.

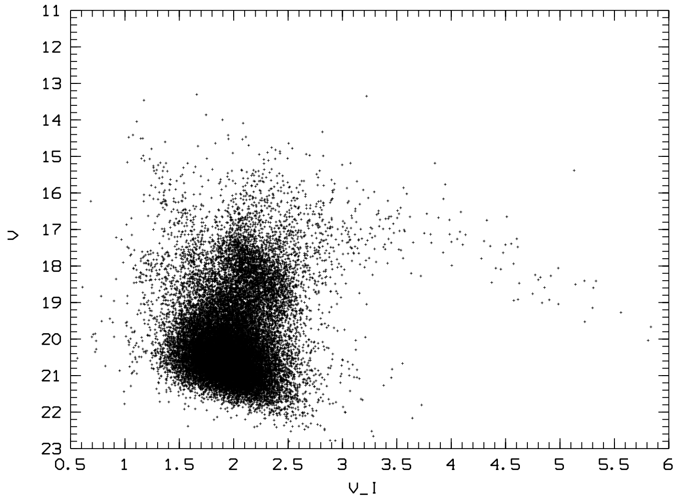

Fig. 6. NGC 6355: V vs. $V - I$ CMD for the full field ($13' \times 13'$).

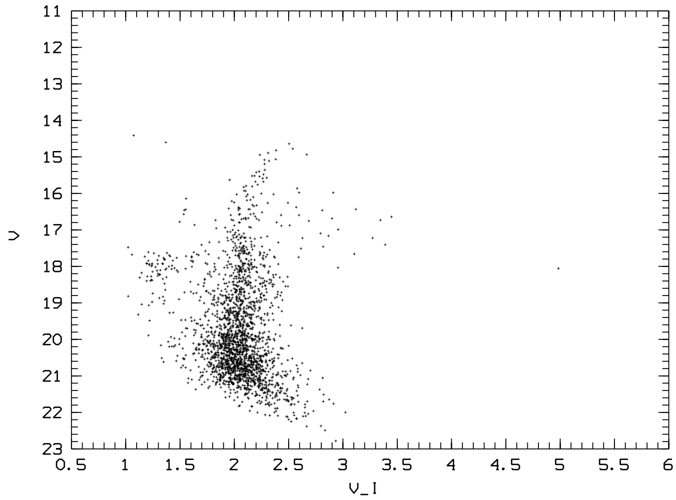

Fig. 7. NGC 6355: V vs. $V - I$ CMD for $r < 1.6'$ ($r < 250$ pixels).

$Y = 0.1$ kpc and $Z = 1.0$ kpc. The distance from the Galactic center is $R_{\rm GC} = 1.6$ kpc, placing the cluster in the central bulge volume.

4. NGC 6355

4.1. Colour-magnitude diagrams

In Fig. 6 we show the V vs. $V - I$ CMD of the full field. Likewise, the field of NGC 6325, it is a typical bulge field, with a RGB extended by $\Delta(V - I) \approx 4.5$ mag. This field, including the bulge sequences as well as the disk MS, is more populated than that of NGC 6325, as expected for its somewhat lower galactic latitude. The field of NGC 6355 has redder colours than that of NGC 6325 by $\Delta(V - I) \sim 0.5$ due to both reddening and blanketing effects.

Figure 7 shows the V vs. $V{-}I$ CMD corresponding to an extraction of $r < 1.6'$ ($r < 250$ pixels). A blue HB is present and RR Lyrae candidates might be present, although contamination may be important. Figure 8 shows the V vs. $B - V$ CMD for an extraction of $r < 29'$ ($r < 75$ pixels), where the blue HB is better defined. Again we tested mean loci for a range of metallicities, and intermediate metallicities are better suited. The mean loci of NGC 6171 and M 5 are overplotted, and $[{\rm Fe/H}] \approx -1.3$ is deduced.

4.2. Cluster reddening and distance

The upper part of the blue HB is located at $V_{\rm HB} = 17.80 - \pm0.2$. The colour of the RGB at the HB level is $V - I = 2.05 \pm 0.1$. The difference with respect to a fit with M 5 is $\Delta(V - I)_{(\rm NGC\ 6355-M\,5)} = 1.07$, and since $E(V - I) = 0.04$ for M 5, this implies a reddening of $E(V - I) = 1.11$, and $E(B - V) = 0.83$. Using Fig. 8, the difference with respect to M 5 is $\Delta(B - V)_{(\rm NGC\ 6355-M\,5)} = 0.7$, and $E(B - V) = 0.03$ for M 5, therefore $E(B - V) = 0.73$. We adopt the mean value of $E(B - V) = 0.78$, and we get $A_V = 2.42$, and using $M_V^{\rm HB} = 0.65$ (Buonanno et al. 1989), $(m{-}M)_0 = 14.73$, and the distance from the Sun $d_\odot \approx 8.8$ kpc for NGC 6355. The reddening value is confirmed to be lower than that derived from the

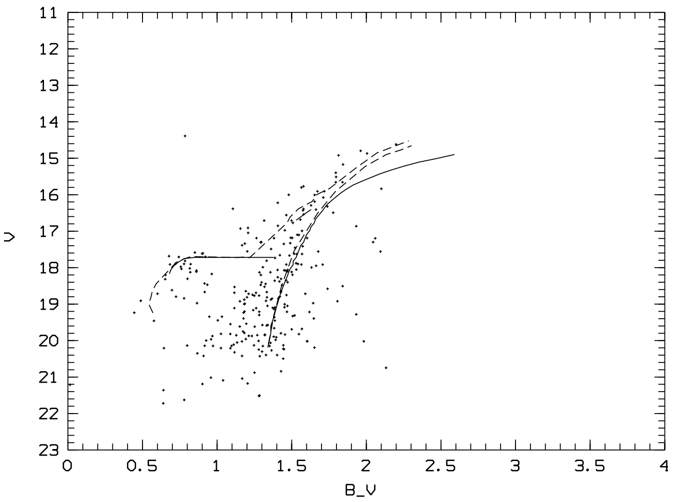

Fig. 8. NGC 6355: V vs. $B - V$ CMD extraction for $r < 29''$ ($r < 75$ pixels) with respect to the cluster center. The mean loci of NGC 6171 (solid line) and M 5 (dashed line) are superimposed.

Schlegel et al. (1998) maps, therefore suggesting that there is some background dust (Dutra & Bica 2000).

The Galactocentric coordinates are $X = 0.1$ kpc, $Y = -0.1$ kpc and $Z = 0.9$ kpc. The distance from the Galactic center is $R_{GC} = 0.9$ kpc. We conclude that NGC 6355 is an intermediate-metallicity cluster near the Galactic center.

5. Concluding remarks

B, V and I CCD Colour-Magnitude Diagrams are provided for the globular clusters NGC 6325 and NGC 6355, from which we analyse their properties.

The reddening value is $E(B - V) = 0.95$ for NGC 6325 and 0.78 for NGC 6355. These relatively high reddening values are consistent with the fact that the clusters are projected behind dark nebulae in the eastern extension of the Ophiuchus complex, at a distance of 120 pc (Cambrésy 1999). NGC 6325 is in the background of the Lynds (1962) dark nebula LDN28, while NGC 6355 is behind LDN1793 – see also Dutra & Bica (2002).

Distances from the Sun $d_\odot = 6.9$ kpc and 8.8 kpc, and Galactocentric distances of $R_{GC} = 1.6$ kpc and 0.9 kpc are found, placing them in the bulge volume.

Recently, Piotto et al. (2002) have published Hubble Space Telescope CMDs of 74 globular clusters, including NGC 6325 and NGC 6355, using the filters F439W and F555W. It is interesting to note that the dispersions are comparable in Piotto et al. and in the present CMDs: for example, the RGB is 0.35 mag wide at F555W $\approx$ 20 in the HST diagrams as well as in the present ones at $V \approx 20$. We conclude that differential reddening is the dominant source of dispersion, due to the foreground dark nebulae cited above.

The clusters have blue Horizontal Branch morphologies, and NGC 6325 shows some evidence of an extended blue tail, also seen in Piotto et al. (2002). By fitting mean loci of reference clusters, we derived [Fe/H] ≈ -1.3. These intermediate metallicities for blue Horizontal Branch clusters characterize a family of bulge clusters. Other examples are NGC 6522, NGC 6540, HP 1, NGC 6558, NGC 6256, NGC 6717 – see discussion in Ortolani et al. (1999a) and references therein. A comparison of this domain of metallicities with those of the bulge field stars analysed by McWilliam & Rich (1994) shows that they could be the lower end of the metallicity distribution of the bulge. However the bulge volume also contains clusters as metal-poor as [Fe/H] ≈ -2.0 such as NGC 6287 (Stetson & West 1995), Terzan 4 (Ortolani et al. 1997), Terzan 9, NGC 6139 and NGC 6453 (Ortolani et al. 1999b). An observational effort to determine spatial velocities (radial velocities and proper motions) of these clusters would be important to understand the bulge and halo histories and membership of these populations.

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References

Alter, G., Balazs, B., & Ruprecht, J. 1970, in Catalogue of Star Clusters and Associations, 2nd edition, Budapest
Barbuy, B., Bica, E., & Ortolani, S. 1998, A&A, 333, 117
Barbuy, B., Ortolani, S., Bica, E., & Desidera, S. 1999, A&A, 348, 783
Bica, E., & Pastoriza, M. G. 1983, ASSci, 91, 99
Buonanno, R., Corsi, C. E., & Fusi Pecci, F. 1989, A&A, 216, 80
Cambrésy, L. 1999, A&A, 345, 965
Chaboyer, B., Demarque, P., Kernan, P. J., Krauss, L. M., & Sarajedini, A. 1996, MNRAS, 283, 683
Dutra, C. M., & Bica, E. 2000, A&A, 359, 347
Dutra, C. M., & Bica, E. 2002, A&A, 383, 631
Ferraro, F. R., Clementini, G., Fusi Pecci, F., & Buonanno, R. 1991, MNRAS, 252, 357
Fusi Pecci, F., Ferraro, F. R., Bellazzini, M., et al. 1993, AJ, 105, 1145
Harris, W. E. 1975, ApJS, 29, 397
Harris, W. E. 1996, AJ, 112, 1487 (H96)
Hazen-Liller, M. L. 1984, AJ, 89, 1551
Hesser, J. E., & Shawl, S. J. 1985, PASP, 97, 465
Landolt, A. U. 1983, AJ, 88, 439
Landolt, A. U. 1992, AJ, 104, 340
Lynds, B. T. 1962, ApJS, 7, 1
McWilliam, A., & Rich, R. M. 1994, ApJS, 91, 749
Minniti, D. 1995, A&A, 303, 468
Minniti, D., Olszewski, E. W., & Rieke, M. 1995, AJ, 110 1699
Ortolani, S., Barbuy, B., & Bica, E. 1990, A&A, 236, 362
Ortolani, S., Barbuy, B., & Bica, E. 1997, A&A, 319, 850
Ortolani, S., Barbuy, B., & Bica, E. 1999a, A&AS, 136, 237
Ortolani, S., Barbuy, B., & Bica, E. 1999b, A&AS, 138, 267
Ortolani, S., Bica, E., & Barbuy, B. 2001, A&A, 374, 564
Piotto, G., King, I. R., Djorgovski, S. G., Sosin, C., et al. 2002, A&A, 391, 945
Reid, M. 1993, ARA&A, 31, 345
Sarajedini, A. 1994, AJ, 107, 618
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Sandquist, E. L. 2000, MNRAS, 313, 571
Stetson, P. B., & West, M. J. 1995, PASP, 1106, 726
Trager, S. C., King, I. R., & Djorgovski, S. 1995, AJ, 109, 218
van den Bergh, S. 1996, AJ, 112, 2634
Webbink, R. F. 1985, in Dynamics of Star Clusters, ed. J. Goodman, & P. Hut, IAU Symp., 113 (Dordrecht: Reidel), 541
Zinn, R. 1980, ApJS, 42, 19
Zinn, R., & West, M. J. 1984, ApJS, 55, 45