Mon. Not. R. Astron. Soc. **356,** 647–653 (2005) doi:10.1111/j.1365-2966.2004.08495.x

NGC 6404 and 6583: two neglected intermediate-age open clusters located in the Galactic Centre direction

Giovanni Carraro,[1,2,3★] René A. Méndez[1★] and Edgardo Costa[1★]
[1] *Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile*
[2] *Astronomy Department, Yale University, PO Box 208101, New Haven, CT 06520-8101, USA*
[3] *Dipartimento di Astronomia, Università di Padova, Vicolo Osservatorio 2, I-35122 Padova, Italy*

Accepted 2004 October 6. Received 2004 September 22; in original form 2004 August 13

ABSTRACT

We report on *VI* charge-coupled device photometry of two fields centred in the region of the open clusters NGC 6404 and 6583 down to $V = 22.0$. So far these clusters have never been studied, and we provide for the first time estimates of their fundamental parameters, namely, radial extent, age, distance and reddening. We find that the radius of NGC 6404 is 2.0 arcmin, as previously proposed, while the radius of NGC 6583 is 1.0 arcmin, significantly lower than previous estimates. Both clusters turn out to be of intermediate age (0.5–1.0 Gyr old), and located inside the solar ring, at a Galactocentric distance of about 6.5 kpc. These results make these objects very interesting targets for spectroscopic follow-up to measure their metallicity. In fact, they might allow us to enlarge by more than 1 kpc the baseline of the radial abundance gradient in the Galactic disc towards the Galactic Centre direction. This baseline is currently rather narrow especially for clusters of this age.

Key words: Hertzsprung–Russell (HR) diagram – open clusters and associations: general – open clusters and associations: individual: NGC 6404 – open clusters and associations: individual: NGC 6583.

1 INTRODUCTION

Intermediate-age and old open clusters (older than half a Gyr) are widely used to probe the chemical evolution of the Galactic disc (Friel & Janes 1993; Carraro & Chiosi 1994; Carraro, Ng & Portinari 1998; Friel et al. 2002; Carraro et al. 2004), since they cover the entire life of the disc and are evenly distributed across the disc itself. With these objects it is possible to derive the age–metallicity relationship and the present and past radial abundance gradients in the Galactic disc: these relations are routinely used to constrain Galactic chemical evolution models (Tosi 1996).

One of the major limitations of the samples commonly in use is the range in Galactocentric distances: a few clusters are known to be located beyond 12 kpc from the Galactic Centre, and none is currently known to lie closer than 7.5 kpc from the Galactic Centre (see Friel et al. 2002, fig. 3). This is basically due to selection effects; star clusters inside the solar ring do not survive for enough time due to encounters with molecular clouds and in general the higher-density environment (Wielen 1971). On the other hand, in the anticentre direction we expect quite a few clusters due to the low efficiency of cluster formation in the Galaxy periphery.

In an effort to enlarge the distance baseline of intermediate-age and old open clusters, we searched for candidates towards the Galactic bulge, by using criteria similar to those adopted by Phelps, Janes & Montgomery (1994), i.e. the presence of a number of similar-brightness red stars. This in fact would imply the existence of a red clump, typical of intermediate-age and old open clusters. This search is complementary to our survey of the open cluster remnants (Villanova et al. 2004) designed to seek old open clusters in an advanced stage of dynamical evolution, close to their final dissolution and merging with the general Galactic disc field.

In this paper we report on NGC 6404 and 6583, two clusters located low in the Galactic plane, not very far from the Galactic Centre direction (see Table 1), which fulfil our searching criteria. The layout of the paper is as follows. Section 2 illustrates the observation and reduction strategies. An analysis of the geometrical structure and star counts in the field of the two clusters is presented in Section 3, whereas a discussion of the colour–magnitude diagrams (CMDs) is performed in Section 4. Section 5 deals with the determination of cluster reddening, distance and age and, finally, Section 6 summarizes our findings.

2 OBSERVATIONS AND DATA REDUCTION

Charge-coupled device (CCD) *VI* observations were carried out with the eight CCDs mosaic camera on the 1.3-m Warsaw Telescope at Las Campanas Observatory (Chile), on the nights of 2004 July 2 to 4. The two clusters were centred in chip 3. With a pixel size of 0.26 arcsec and a CCD size of 4096 × 2048 pixels, this samples

★E-mail: gcarraro@das.uchile.cl (GC); rmendez@das.uchile.cl (RAM); costa@das.uchile.cl (EC)

Table 1. Basic parameters of the observed objects. Coordinates are for J2000.0 equinox.

Name	RA (hh:mm:ss)	Dec. (° : ′ : ″)	L (°)	B (°)
NGC 6404	17:39:37	−33:14:48	355.66	−1.18
NGC 6853	18:15:49	−22:08:12	9.28	−2.53

Table 2. Journal of observations of NGC 6404, NGC 6583 and standard star fields (2004 July 2–4).

Field	Filter	Exposure time (s)	Seeing (arcsec)	Airmass
NGC 6404	V	10, 300, 1200	1.3	1.06–1.15
	I	10, 300, 900	1.3	1.06–1.15
NGC 6583	V	10, 300, 1200	1.2	1.02–1.20
	I	10, 300, 900	1.2	1.02–1.20
SA 104−334	V	3 × 200	1.4	1.24–1.26
	I	3 × 70	1.4	1.24–1.26
PG 1323−085	V	3 × 90	1.3	1.13–1.53
	I	3 × 30	1.3	1.13–1.53
PG 1657+078	V	3 × 300	1.5	1.24–2.04
	I	3 × 100	1.5	1.24–2.04
PG 2213+006	V	3 × 80	1.3	1.14–1.34
	I	3 × 30	1.3	1.14–1.34
PG 1633+099	V	3 × 120	1.2	1.33–1.50
	I	3 × 45	1.2	1.33–1.50
SA 110−362	V	3 × 120	1.2	1.21–1.96
	I	3 × 30	1.2	1.21–1.96
SA 92−355	V	3 × 120	1.6	1.15–1.18
	I	3 × 50	1.6	1.15–1.18

a 17.7 × 8.9 arcmin^2 field in the sky. However, we trimmed the CCD and ultimately used in this study an actual area of 13.7 × 8.9 arcmin^2.

The details of the observations are listed in Table 2, where the observed fields are reported together with the exposure times, the average seeing values and the range of airmasses during the observations. Fig. 1 shows the finding chart in the area of NGC 6404, and Fig. 2 that in the area of NGC 6583. In both figures, north is up, and east is on the left.

Both the fields were centred in the nominal centres of the clusters (Dias et al. 2002).[1] However, the coordinates of NGC 6583 turned out to be slightly offset (about −20′) in declination, and the new coordinates are: $\alpha = 18^{\rm h}15^{\rm m}49^{\rm s}$, $\delta = -22°08'30''$. We shall use these new coordinates throughout this paper.

The data have been reduced with the IRAF[2] packages CCDRED, DAOPHOT, ALLSTAR and PHOTCAL using the point spread function (PSF) method (Stetson 1987). The three nights turned out to be photometric and very stable, and therefore we derived calibration equations for all the 141 standard stars observed during the three nights in the Landolt (1992) fields SA 104−334, PG 1323−085, PG 1657+078, PG 2213+006, PG 1633+099, SA 110−362 and SA 92−355 (see Table 2 for details). The calibration equations turned out of be of the form:

$$v = V + v_1 + v_2 X + v_3(V - I),$$
$$i = I + i_1 + i_2 X + i_3(V - I),$$

where V and I are standard magnitudes, v and i are instrumental ones and X is the airmass; all the coefficient values are reported in Table 3. The standard stars in these fields provide a very good colour coverage. The final rms of the calibration are 0.034 and 0.033 for the V and I filters, respectively. Photometric errors have been estimated following Patat & Carraro (2001).

It turns out that stars brighter than $V \approx 20$ mag have internal (ALLSTAR output) photometric errors lower than 0.10 mag in magnitude and lower than 0.18 mag in colour, as one can readily see by inspecting Fig. 3. There the trend of errors in colour and magnitude are reported against the V magnitude, while in the inset we show the mean errors as a function of the magnitude. The final photometric data (coordinates, V and I magnitudes and errors) consist of 24 295 stars in NGC 6404 and 26 086 stars in NGC 6583, and are made available in electronic form at the WEBDA[3] site maintained by J.-C. Mermilliod.

3 STAR COUNTS AND CLUSTER SIZES

Dias et al. (2002) reported preliminary estimates of the diameters of NGC 6404 and 6583, amounting to 5 arcmin. By inspecting Figs 1 and 2, we can recognize that Dias et al.'s estimate is certainly a reasonable one for NGC 6404, which is a loose open cluster, but it seems to be too large for NGC 6583, which on the contrary appears more concentrated. Since our photometry covers entirely the area of the clusters and part of the surroundings, we performed star counts to obtain an improved estimate of the cluster sizes.

We derived the surface stellar density by performing star counts in concentric rings around the nominal centres of the clusters (see Table 1) and then dividing by their respective surfaces. Poisson errors have also been derived and normalized to the corresponding surface. Poisson errors in the field star counts turned out to be very small, and therefore we shall not show them.

3.1 NGC 6404

The final radial density profile for NGC 6404 is shown in Fig. 4 as a function of V magnitude. The contribution of the Galactic disc field has been estimated by considering all the stars in the corresponding magnitude bin, located outside 4.0 arcmin from the cluster centre, and by normalizing counts over the adopted area.

The cluster seems to be populated by stars of magnitude in the range $12 \leqslant V \leqslant 18$, where it clearly emerges from the background, and then it starts to be well mixed with the field. In this magnitude range the radius is not larger than 2 arcmin, and the cluster exhibits a significant underdensity of stars (at the level of the field) at about half an arcminute from the nominal centre. This is compatible with the loose nature of NGC 6404 (see also Fig. 1). In conclusion, we shall adopt the value of 2 arcmin as the radius of NGC 6404 throughout this paper. This estimate is in good agreement with the value reported by Dias et al. (2002).

3.2 NGC 6583

The final radial density profile for NGC 6583 is shown in Fig. 5 as a function of V magnitude. Also in this case the contribution of the

[1] http://www.astro.iag.usp.br/wilton/clusters.txt

[2] IRAF is distributed by NOAO, which is operated by AURA under cooperative agreement with the NSF.

[3] http://obswww.unige.ch/webda/navigation.html

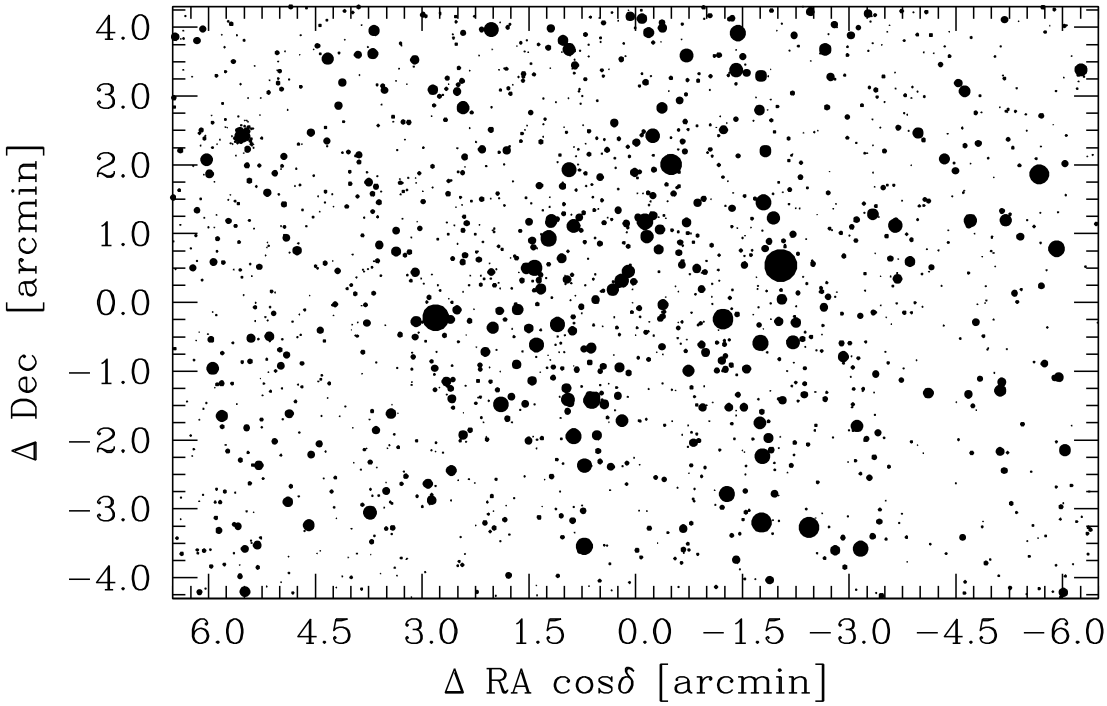

Figure 1. A finding chart with the observed area in the region of the open cluster NGC 6404. The sizes of the dots are proportional to the magnitudes of the stars. North is up, east on the left, and the field is centred at the cluster's nominal centre (see Table 1).

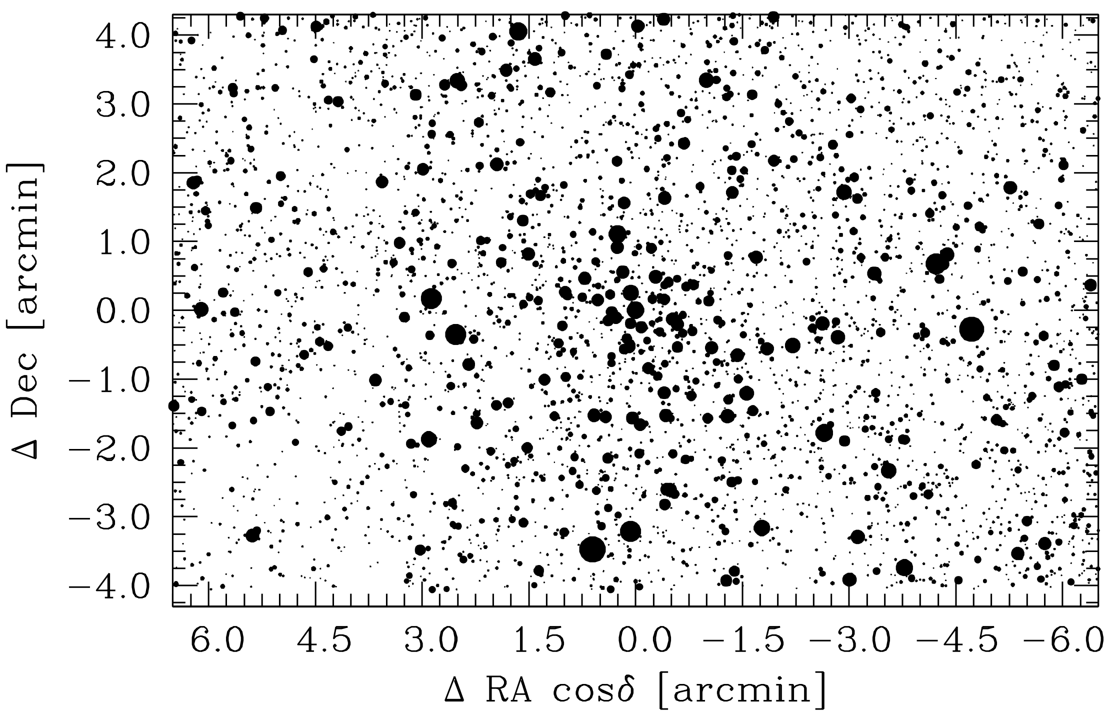

Figure 2. A finding chart with the observed area in the region of the open cluster NGC 6583. The sizes of the dots are proportional to the magnitudes of the stars. North is up, east on the left, and the field is centred at the cluster's nominal centre (see Table 1).

Galactic disc field has been estimated by considering all the stars outside 4.0 arcmin from the cluster centre in the same way as for NGC 6404. Unlike NGC 6404, NGC 6503 is a compact cluster, which clearly emerges above the background down to $V \approx 20$. The cluster radius turns out of be around 1 arcmin. Within this radius, the cluster exhibits a significant overdensity of stars. Outside, the counts level off to the field star counts value. We thus adopt the value of 1 arcmin as the radius of NGC 6503 throughout this paper. This estimate is a factor of 2 smaller than that reported by Dias et al. (2002).

Table 3. Coefficients of the calibration equations.

$v_1 = 2.029 \pm 0.005$	$v_2 = 0.15 \pm 0.02$	$v_3 = -0.022 \pm 0.005$
$i_1 = 2.002 \pm 0.005$	$i_2 = 0.07 \pm 0.02$	$i_3 = 0.072 \pm 0.005$

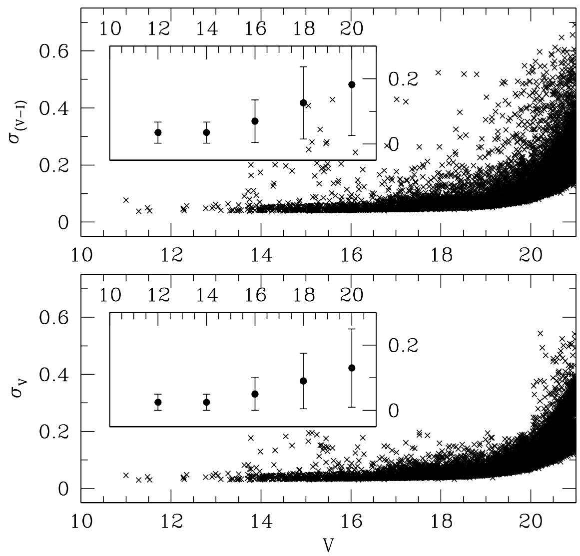

Figure 3. Trends of photometric errors in V and $(V - I)$ as functions of V magnitude.

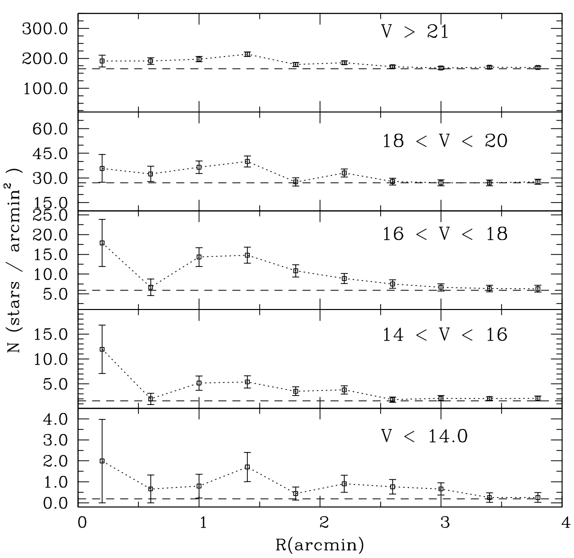

Figure 4. Star counts in the area of NGC 6404 as a function of radius and magnitude. The dashed lines represent the level of the control field counts estimated in the surroundings of the cluster in that magnitude range.

4 THE COLOUR–MAGNITUDE DIAGRAMS

In Figs 6 and 7 we present the colour–magnitude diagrams (CMDs) of NGC 6404 and 6583, respectively. They are plotted as a function of radius, in order to facilitate their interpretation. In fact, the clusters are located quite low on to the Galactic plane toward the Galactic Centre direction, and hence we expect quite a significant contamination from the Galactic disc field stars located in the foreground along the line of sight of the clusters. The cuts according to radius are done on the basis of the results on Section 3.

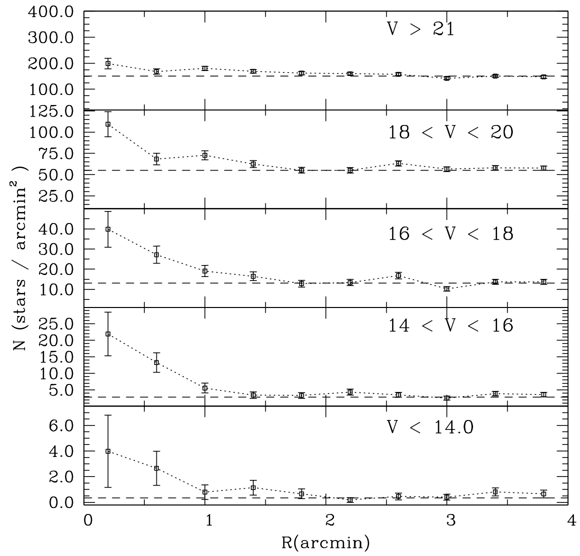

Figure 5. Star counts in the area of NGC 6583 as a function of radius and magnitude. The dashed lines represent the level of the control field counts estimated in the surroundings of the cluster in that magnitude range.

4.1 NGC 6404

The CMDs of NGC 6404 are shown in Fig. 6. In the left panel we plot all the detected stars. Here the main sequence (MS) extends from $V = 14.5$ to 21.0, and the Galactic disc red giant branch (RGB) sequence departs from $V = 20$. The MS is very wide, and this could have different causes, like variable reddening across the observed area (actually we expect that this is the major cause), photometric errors that increase as a function of magnitude (see Fig. 3), and the presence of a number of binary stars. It is very difficult to distinguish from this CMD the presence of a cluster. However, and interestingly, there are a few stars in the red part of the CMD at $V = 13.5$–14.5, $(V - I) = 2.0$–2.5, that resemble an RGB clump.

Much better information can be obtained by looking at the middle and right panels in the same figure. The middle panel contains only the stars located inside the estimated cluster radius (2 arcmin, see Section 3), whereas the right panel contains the stars located outside 4 arcmin from the cluster centre, where we estimated the contribution of the field population to be dominant. The following remarks can be made after close inspection of these two panels:

(i) The MS and the turn-off point (TO) region in the middle panel are much better defined, although the MS is still somewhat wide, mostly due to field star contamination.

(ii) Almost all the probable RGB stars are inside the inner region, which implies that the cluster underwent some dynamical relaxation.

(iii) Most of the stars above the TO are probably field stars, since they almost all lie outside of the cluster radius (see right panel). Nevertheless, some of them still remain, and they might be blue stragglers, quite common in clusters like this.

The shape of the TO and the presence of some clump stars are a clear indication of an age in the range 0.5–1.5 Gyr, depending on the precise metal content of the cluster (Carraro & Chiosi 1994; Carraro et al. 1998).

4.2 NGC 6583

The CMDs of NGC 6583 are shown in Fig. 7, which is similar to Fig. 6. In the left panel we plot all the detected stars. Here

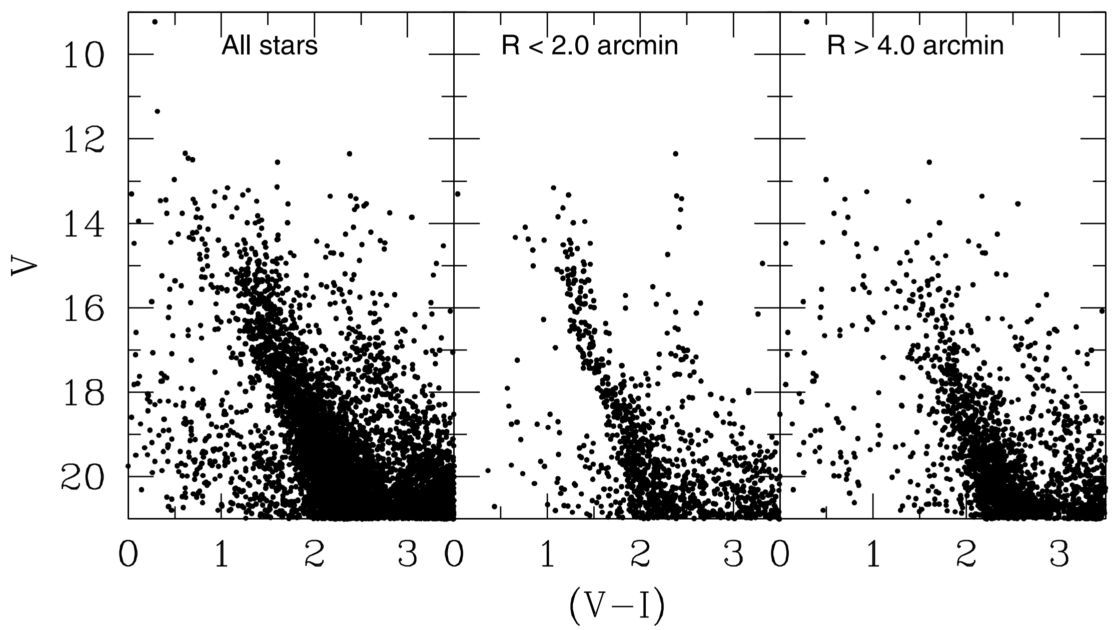

Figure 6. The *V* versus $(V - I)$ CMDs of NGC 6404 as a function of radius from the cluster centre.

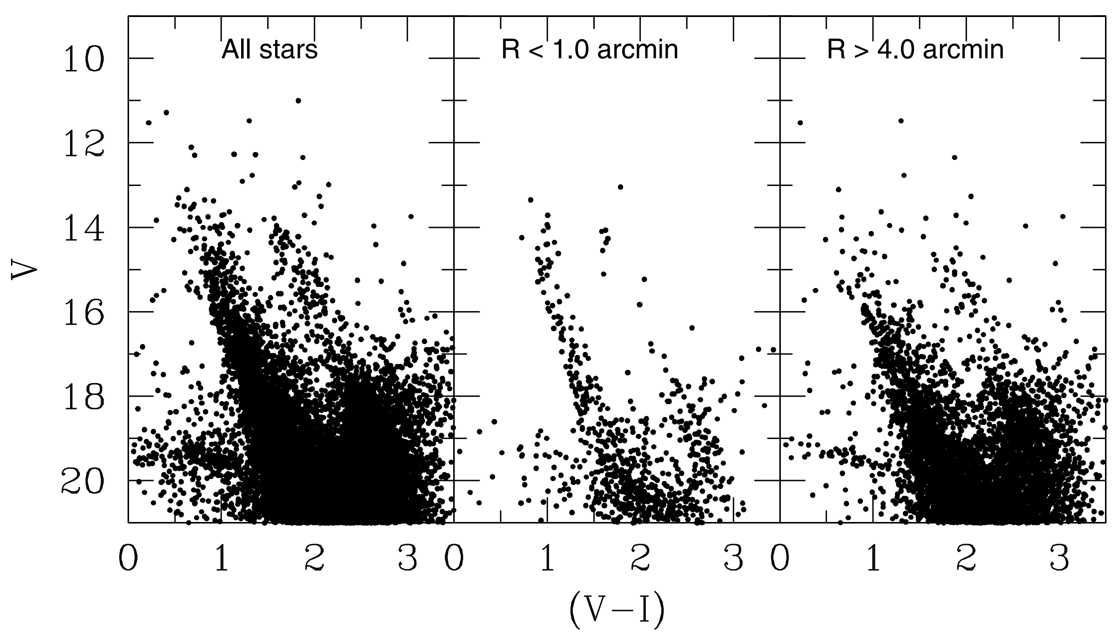

Figure 7. The *V* versus $(V - I)$ CMDs of NGC 6583 as a function of radius from the cluster centre.

the main sequence (MS) extends from $V = 14.5$ to 21.0, and the Galactic disc RGB sequence departs from $V = 190$. Like NGC 6404, it is very difficult to distinguish from this CMD the presence of a cluster, and we do not notice any candidate RGB clump star.

Much better information can be obtained by looking at the middle and right panels in Fig. 7. The middle panel contains only the stars located inside the estimated cluster radius (1 arcmin, see Section 3), whereas the right panel contains the stars located outside 4 arcmin from the cluster centre, where we estimate the contribution of the field population to be dominant. The following considerations result:

(i) The MS and the TO region in the middle panel are much better defined. In particular, the MS is quite narrow and the field star contamination is almost negligible down to $V \approx 19.0$.

(ii) There is a nice almost vertical clump of stars at $V = 14.5$, $(V - I) = 1.5$, similar to the clump observed in open clusters like NGC 2477 (Kassis et al. 1997) or Pismis 2 (Phelps et al. 1994).

(iii) Most of the stars above the TO are probably field stars, since they all lie outside of the cluster radius (see right panel).

In particular, the fine shape of the TO deserves some attention. In fact, the shape of the TO is typical of intermediate-age open clusters, with a blue and red hook clearly visible, notwithstanding some field star contamination. Again, the shape of the TO and the presence of a clump indicate an age in the range 0.5–1.5 Gyr, depending on the metallicity.

5 CLUSTER FUNDAMENTAL PARAMETERS

In this section we provide some estimates of the basic parameters of the clusters. To achieve this, we make use of the comparison between the distribution of stars in the CMD and a set of theoretical isochrones from the Padova group (Girardi et al. 2000). We already have an indication of the cluster age, but we do not know anything about the reddening, the distance and the metallicity. In the following analysis we adopt $R_{\odot} = 8.5$ kpc for the Galactocentric distance of the Sun, $R_V = 3.1$ and the ratio $E(V-I)/E(B-V) = 1.244$ from Dean, Warren & Cousins (1978). The results of the fits are shown in Fig. 8 for NGC 6404 and in Fig. 9 for NGC 6583.

5.1 NGC 6404

In detail, in Fig. 8 we present the CMD for the stars within 2.0 arcmin of the cluster centre (see Section 3), and superimposed an isochrone of 0.5 billion years for solar ($Z = 0.019$) metallicity. The fit is quite good both in the TO and the evolved stars region. The fit is poor at the bottom of the MS, where it is not easy to distinguish the cluster MS from the field. We are keen to believe that the bulk of the stars above the TO are most probably field stars.

We achieved these results by shifting the isochrone with $E(V-I) = 1.15 \pm 0.05$, $E(B-V) = 0.92$, and $(m-M) = 14.75 \pm 0.20$ (errors by eye). We also tried to superimpose a lower metal abundance, but the fit turned out to be quite poor. The same occurred with higher metallicity isochrones. Therefore, we suggest that the cluster possesses a solar metal abundance.

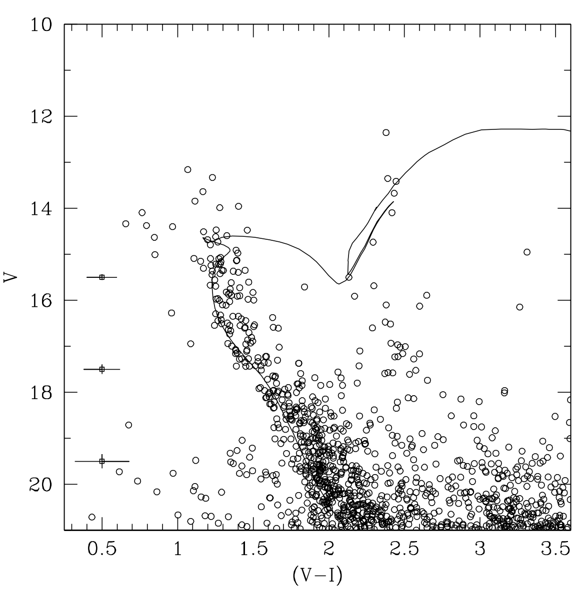

Figure 8. NGC 6404 data in the V versus $(V-I)$ diagram, as compared to the Girardi et al. (2000) isochrone of age 0.5 Gyr (solid line), for a metallicity $Z_{\odot} = 0.019$. A distance modulus of $(m-M)_0 = 11.20 \pm 0.20$ mag, and a colour excess of $E(V-I) = 1.15 \pm 0.05$ mag, are derived. Errors in colour and magnitude at different magnitude levels are also shown.

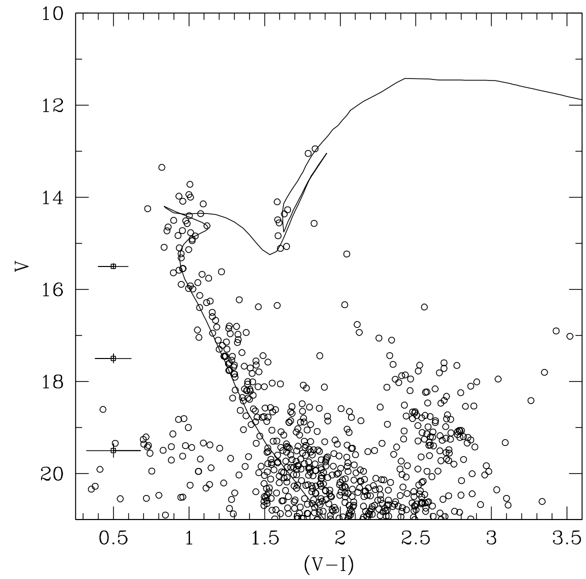

Figure 9. NGC 6583 data in the V versus $(V-I)$ diagram, as compared to the Girardi et al. (2000) isochrone of age 1.0 Gyr (solid line), for a metallicity $Z_{\odot} = 0.019$. A distance modulus of $(m-M)_0 = 11.55 \pm 0.20$ mag, and a colour excess of $E(V-I) = 0.63 \pm 0.05$ mag, are derived. Errors in colour and magnitude at different magnitude levels are also shown.

If this is the case, NGC 6404 turns out to be located 1.7 kpc from the Sun towards the Galactic Centre direction. This implies a distance from the Galactic Centre of 6.8 kpc and a height above the Galactic plane of about −40 pc. According to Friel et al. (2002, fig. 3), NGC 6404 turns out to be an intermediate-age open cluster located 1 kpc away from the lower distance edge of the radial abundance gradient. Therefore, NGC 6404 might play an important role in defining the precise shape of the radial abundance gradient in the inner region of the Galactic disc.

5.2 NGC 6583

In Fig. 9 we present the CMD for NGC 6583 stars located within 1.0 arcmin from the cluster centre (see Section 3), and superimposed an isochrone of 1.0 billion years for a solar ($Z = 0.019$) metallicity. The fit is quite good both along the MS, in the TO region and in the evolved stars one.

We achieved these results by shifting the isochrone with $E(V-I) = 0.63 \pm 0.05$, $E(B-V) = 0.51$, and $(m-M) = 13.50 \pm 0.20$ (errors by eye). Like NGC 6404, we also tried to superimpose a lower metal abundance, but the fit turned out to be quite poor. The same occurred with higher metallicity isochrones. Therefore, we suggest that this cluster also possesses a solar metal abundance.

As a consequence, NGC 6503 turns out to be located 2.1 kpc from the Sun towards the centre direction. This implies a distance from the Galactic Centre of 6.4 kpc and a height above the Galactic plane of about −90 pc. As NGC 6404, NGC 6583 turns out to be an intermediate-age open cluster located more than 1 kpc away from the lower distance edge of the radial abundance gradient. Therefore, NGC 6583 might also play an important role in defining the precise shape of the radial abundance gradient in the inner regions of the Galactic disc.

Table 4. Fundamental parameters of the observed objects.

Name	Radius (arcmin)	$E(V-I)$	$E(B-V)$	$(m-M)_0$	X (kpc)	Y (kpc)	Z (kpc)	Age (Gyr)
NGC 6404	2.0	1.15	0.92	11.30	6.80	−0.14	−0.04	0.5
NGC 6583	1.0	0.63	0.51	11.55	6.40	0.35	−0.09	1.0

6 CONCLUSIONS

We have presented the first CCD *VI* photometric study of the open clusters NGC 6404 and 6583. The CMDs we derive allow us to infer estimates of the cluster basic parameters, which are summarized in Table 4. In detail, our findings are as follows.

(i) Both clusters are of intermediate age; NGC 6404 is 0.5 Gyr old, NGC 6583 is 1.0 Gyr old.

(ii) The reddening $E(B-V)$ turns out to be 0.92 ± 0.05 for NGC 6404 and 0.51 ± 0.05 for NGC 6583. For both clusters, solar metallicity isochrones provide a reasonable fit across the whole CMDs. This metal abundance is not unexpected at the position of the clusters; in fact for this age range the radial abundance gradient is almost flat around the solar metallicity.

(iii) We place NGC 6404 and 6583 at about 1.7 and 2.1 kpc from the Sun towards the Galactic Centre direction.

(iv) In this way they both turn out to be intermediate-age open clusters located inside the solar ring, in a region from the Galactic Centre where clusters of this age have never before been found.

Future work should concentrate on obtaining an estimate of the cluster metal abundance through spectra of the RGB stars. Knowledge of cluster metallicity, which we could not constrain very well, is of paramount importance to better probe the trend of metallicity across the whole Galactic disc (Friel et al. 2002).

ACKNOWLEDGMENTS

The observations presented in this paper have been carried out at Las Campanas Observatory (Chile). The work of GC is supported by Fundación Andes. RAM and EC acknowledge support from the Chilean Centro de Astrofísica FONDAP No. 15010003. This study made use of the Simbad and WEBDA data bases.

REFERENCES

Carraro G., Chiosi C., 1994, A&A, 287, 761
Carraro G., Ng Y. K., Portinari L., 1998, MNRAS, 296, 1045
Carraro G., Bresolin F., Villanova S., Matteucci F., Patat F., Romaniello M., 2004, AJ, 128, 1676
Dean J. F., Warren P. R., Cousins A. W. J., 1978, MNRAS, 183, 569
Dias W. S., Alessi B. S., Moitinho A., Lepine J. R. D., 2002, A&A, 389, 871
Friel E. D., Janes K. A., 1993, A&A, 267, 75
Friel E. D., Janes K. A., Tavarez M., Scott J., Katsanis R., Lotz J., Miller N., 2002, AJ, 124, 2693
Girardi L., Bressan A., Bertelli G., Chiosi C., 2000, A&AS, 141, 371
Kassis M., Janes K. A., Friel E. D., Phelps R. L., 1997, AJ, 113, 1723
Landolt A. U., 1992, AJ, 104, 340
Patat F., Carraro G., 2001, MNRAS, 325, 1591
Phelps R. L., Janes K. A., Montgomery K. A., 1994, AJ, 107, 1079
Stetson P. B., 1987, PASP, 99, 191
Tosi M., 1996, in Leitherer C., Fritze-von-Alvensleben U., Huchra J., eds, ASP Conf. Ser. Vol. 98, The Impact of Stellar Physics on Galaxy Evolution. Astron. Soc. Pac., San Francisco, p. 299
Villanova S., Carraro G., de la Fuente Marcos R., Stagni R., 2004, A& A, in press (astro-ph/0407605)
Wielen R., 1971, A&A, 13, 309