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

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ABSTRACT

We report on $V$ CCD photometry of two fields centered in the region of the open clusters NGC 6404 and NGC 6583 down to $V = 22.0$. These clusters have never been studied insofar, and we provide for the first time estimates of their fundamental parameters, namely, radial extent, age, distance and reddening. We find that NGC 6404 radius is 2.0 arcmin, as previously proposed, while NGC 6583 radius 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 disk toward the Galactic Center direction. This baseline is currently rather narrow especially for clusters of this age.

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

1 INTRODUCTION

Intermediate age and old open clusters (older than half a Gyr) are widely used to probe the chemical evolution of the Galactic disk (Friel & Janes 1993, Carraro & Chiosi 1994, Carraro et al. 1998, Friel et al. 2002, Carraro et al. 2004), since they cover the entire life of the disk and are evenly distributed across the disk itself.

With these objects it is possible to derive the age-metallicity relationship and the present and past radial abundance gradients in the Galactic disk; these relations are routinely used to constrain Galactic chemical evolution models (Tosi 1996). One of the major limitation 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 center, and none is currently known to lie closer than 7.5 kpc from the Galactic center (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 anticenter direction we expect quite a few clusters due to the low efficiency of clusters 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 et al. (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-old open clusters. This search is complementary to our survey of the open cluster remnants (Villanova et al. 2004) designed to seek for old open clusters in an advanced stage of dynamical evolution, close to their final dissolution and merging with the general Galactic disk field.

In this paper we report on NGC 6404 and NGC 6583, two clusters located low in the Galactic plane, not very far from the Galactic Center direction (see Table 1) and which fulfill our searching criteria.

The layout of the paper is as follows. Sect. 2 illustrates the observation and reduction strategies. An analysis of the geometrical structure and star counts in the field of the two clusters are presented in Sect. 3, whereas a discussion of the Color-Magnitude Diagrams (CMD) is performed in Sect. 4. Sect. 5 deals with the determination of clusters reddening,
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Figure 1. A finding chart with the observed area in the region of the open cluster NGC 6404. The sizes of the dot are proportional to the magnitudes of the stars. North is up, east on the left, and the field is centered at the cluster nominal center (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 dot are proportional to the magnitudes of the stars. North is up, east on the left, and the field is centered at the cluster nominal center (see Table 1).

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

| Name   | RA   | DEC   | L    | B    |
|--------|------|-------|------|------|
|        | hh:mm:ss | ° : ′ : ″ | [deg] | [deg] |
| NGC 6404 | 17:39:37 | -33:14:48 | 355.66 | -1.18 |
| NGC 6853 | 18:15:49 | -22:08:12 | 9.28  | -2.53 |

distance and age and, finally, Sect. 6 summarizes our findings.

2 OBSERVATIONS AND DATA REDUCTION

CCD V I observations were carried out with the eight CCDs mosaic camera on-board the 1.3m Warsaw telescope at Las Campanas Observatory (Chile), in the nights of July 2 to 4, 2004. The two clusters were centered in chip #3. With a pixel size of 0′′.26, and a CCD size of 4096 × 2048 pixels, this samples a 17′.7 × 8′.9 field in the sky. However, we trimmed the CCD and at the end used in this study an actual area of 13′.8 × 8′.9.

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 air-masses during the observations. Fig. 1 shows the finding chart in the area of NGC 6404, and Fig. 2 in the area of NGC 6583. In both figures North is up, and East on the left.

Both the field were centered in the clusters nominal centers (Dias et al. 2002 †). However, the coordinates of NGC 6583 turned out to be slightly off-set (about -20′) in declination, and the new coordinates are: α = 18h 15m 49s, δ = −22° 08′ 30″. We shall use these new coordinates throughout this paper.

The data have been reduced with the IRAF‡ 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:

\[ v = V + v_1 + v_2 \times X + v_3 (V - I) \]
\[ i = I + i_1 + i_2 \times X + i_3 (V - I) \]

where \( V \) and \( I \) are standard magnitudes, \( vi \) are the 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 color coverage. The final r.m.s. of the calibration are 0.034 and 0.033 for the V and I filter, respectively.

† http://www.astro.iag.usp.br/wilton/clusters.txt
‡ IRAF is distributed by NOAO, which are operated by AURA under cooperative agreement with the NSF.
Table 2. Journal of observations of NGC 6404, NGC 6583 and standard star fields (July 2-4, 2004).

| Field    | Filter | Exposure time [sec.] | Seeing ["] | 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|

Table 3. Coefficients of the calibration equations

\[
\begin{align*}
  v_1 &= 2.029 \pm 0.005 \\
  v_2 &= 0.15 \pm 0.02 \\
  v_3 &= -0.022 \pm 0.005 \\
  i_1 &= 2.002 \pm 0.005 \\
  i_2 &= 0.07 \pm 0.02 \\
  i_3 &= 0.072 \pm 0.005
\end{align*}
\]

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 \( V \) mag., while in the insert 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§ site maintained by J.-C. Mermilliod.

3 STAR COUNTS AND CLUSTERS SIZE

Dias et al. (2002) report preliminary estimates of NGC 6404 and NGC 6583 diameters amounting to 5 arcmin. By inspecting Fig 1 and 2 we can recognize that Dias et al. estimate is surely 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 clusters area and part of the surroundings, we performed star counts to obtain an improved estimate of the clusters size.

We derived the surface stellar density by performing star counts in concentric rings around the clusters nominal centers (see Table 1) and then dividing by their respective surfaces. Poisson errors have also been derived and normalized.

§ http://obswww.unige.ch/webda/navigation.html
to the corresponding surface. Poisson errors in the field star counts turned out to be very small, and therefore we are not going to 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 Galactic disk field has been estimated by considering all the stars in the corresponding magnitude bin, located outside 4.0 arcmin from the cluster center, and by normalizing counts over the adopted area.

The cluster seems to be populated by stars of magnitude in the range $12 \leq V \leq 18$, 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 under-density of stars (at the level of the field) at about half an arcmin from the nominal center. This is compatible with the loose nature of NGC 6404 (see also Fig. 1).

In conclusion, we are going to adopt the value of 2 arcmin as NGC 6404 radius 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 Galactic disk field has been estimated by considering all the stars outside 4.0 arcmin from the cluster center, and by normalizing counts over the adopted area.

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 over-density of stars. Outside, the counts level off to the field star counts value.

We thus adopt the value of 1 arcmin as NGC 6503 radius throughout this paper. This estimate is a factor of two smaller than that reported by Dias et al. (2002).

4 THE COLOUR-MAGNITUDE DIAGRAMS

In Figs. 6 and 7 we present CMDs of NGC 6404 and NGC 6583, respectively. They are plotted as a function of radius, in order to facilitate their interpretation. In fact the clusters are located quite low onto the Galactic plane toward the Galactic Center direction, and hence we expect quite a significant contamination from the Galactic disk 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 Sect. 3.

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 $V=21.0$, and the Galactic disk 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 this is the major cause), photometric errors which 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 $V=13.5-14.5$, $(V-I)=2.0-2.5$, which resemble a 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 Sect. 3), whereas the right panel contains the stars located outside 4 arcmin from the cluster center, where we estimated the contribution of the field population to be dominant.

The following remarks can be done closely inspecting these two panels:

- 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;
- Almost all the probable RGB stars are inside the inner region, which implies by the way that the cluster underwent some dynamical relaxation;
- Most of the stars above the TO are probably field stars, since they lie almost all out of the cluster radius (see right panel); nevertheless some of them still remain, and they might be blue straggler stars, quite common in clusters like this.

The shape of the TO and a 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. 1999).

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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 the Main Sequence (MS) extends from $V=14.5$ to $V=21.0$, and the Galactic disk 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 Sect. 3), whereas the right panel contains the stars located outside 4 arcmin from the cluster center, where we estimate the contribution of the field population to be dominant.

The following considerations can be done:

- 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 $V \approx 19.0$;
- 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).
- Most of the stars above the TO are probably field stars, since they lie all out 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 that one 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 clusters basic parameters. To achieve this, we make use of the comparison between the stars distribution 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 et al. (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 details, in Fig. 8 we present the CMD for the stars within 2.0 arcmin from the cluster center (see Sect. 3), and overimposed 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 in the bottom of the MS, where, by the way, it is not easy to distinguish the cluster MS from the field. We are keen to believe that the bulk of stars above the TO are most probably field stars.

We achieved this results by shifting the isochrone with $E(V-I) = 0.63 \pm 0.05$ (for NGC 6583) and $(m - M) = 13.50 \pm 0.20$ (errors by eye).

Like NGC 6404, we also tried to over-impose a lower metal abundance, but the fit turned out to be quite poor. The same occured 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 toward the center direction. This implies a distance from the Galactic center 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, also NGC 6583 might play an important role in defining the precise shape of the radial abundance gradient in the inner regions of the Galactic disk.

5.2 NGC 6583

In Fig. 9 we present the CMD for NGC 6583 stars located within 1.0 arcmin from the cluster center (see Sect. 3), and super-imposed 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 this 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 over-impose a lower metal abundance, but the fit turned out to be quite poor. The same occured with higher metallicity isochrones.

Therefore, we suggest that this cluster also possesses a solar metal abundance.

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Therefore, also NGC 6583 might play an important role in defining the precise shape of the radial abundance gradient in the inner regions of the Galactic disk.

6 CONCLUSIONS

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

In detail, we find that:

- Both clusters are of intermediate age; NGC 6404 is 0.5 Gyr old, NGC 6583 1.0 Gyrs old;
- The reddening $E_{B-V}$ turns out to be $0.92 \pm 0.05$ for NGC 6404 and $0.51 \pm 0.05$ for NGC 6583; for both clusters solar metallicity isochrones provide a reasonable fit across the whole CMDs; by the way this metal abundance is not
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       |

unexpected at the clusters position; in fact for this age range the radial abundance gradient is almost flat around the solar metallicity:

• We place NGC 6404 and NGC 6583 at about 1.7 and 2.1 kpc from the Sun toward the Galactic Center direction;
• This way they both turn out to be intermediate-age open clusters located inside the solar ring, in a region from the Galactic Center where clusters of this age were never found insofar.

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

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