Catching Galactic open clusters in advanced stages of dynamical evolution

M. S. Angelo, A. E. Piatti, W. S. Dias and F. F. S. Maia

1 Laboratório Nacional de Astrofísica, R. Estados Unidos 154, 37530-000 Itajubá, MG, Brazil
2 Consejo Nacional de Investigaciones Científicas y Técnicas, Av. Rivadavia 1917, C1033AAJ, Buenos Aires, Argentina
3 Observatorio Astronómico, Universidad Nacional de Córdoba, Laprida 854, 5000, Córdoba, Argentina
4 UNIFEI, Instituto de Ciências Exatas, Universidade Federal de Itajubá, Av. BPS 1303 Pinheirinho, 37500-903 Itajubá, MG, Brazil
5 Departamento de Física, ICEX, Universidade Federal de Minas Gerais, Av. Antônio Carlos 6627, 31270-901 Belo Horizonte, MG, Brazil

ABSTRACT

During their dynamical evolution, Galactic open clusters (OCs) gradually lose their stellar content mainly because of internal relaxation and tidal forces. In this context, the study of dynamically evolved OCs is necessary to properly understand such processes. We present a comprehensive Washington $CT_1$ photometric analysis of six sparse OCs, namely: ESO 518-3, Ruprecht 121, ESO 134-12, NGC 6573, ESO 260-7 and ESO 065-7. We employed Markov chain Monte-Carlo simulations to robustly determine the central coordinates and the structural parameters and $CT_1 \times (C - T_1)$ colour-magnitude diagrams (CMDs) cleaned from field contamination were used to derive the fundamental parameters. ESO 518-03, Ruprecht 121, ESO 134-12 and NGC 6573 resulted to be of nearly the same young age ($8.2 \leq \log(\text{t yr}^{-1}) \leq 8.3$); ESO 260-7 and ESO 065-7 are of intermediate age ($9.2 \leq \log(\text{t yr}^{-1}) \leq 9.4$). All studied OCs are located at similar Galactocentric distances ($R_G \sim 6-6.9$ kpc), considering uncertainties, except for ESO 260-7 ($R_G = 8.9$ kpc). These OCs are in a tidally filled regime and are dynamically evolved, since they are much older than their half-mass relaxation times ($t/t_{rh} \geq 30$) and present signals of low-mass star depletion. We distinguished two groups: those dynamically evolving towards final disruptions and those in an advanced dynamical evolutionary stage. Although we do not rule out that the Milky Way potential could have made differentially faster their dynamical evolutions, we speculate here with the possibility that they have been mainly driven by initial formation conditions.

Key words: Open cluster remnants – Galactic open clusters – technique: photometric.

1 INTRODUCTION

Open clusters (OCs) in our Galaxy are subject to disruption effects as they dynamically evolve. Those that survive the early gas-expulsion stage ($t \lesssim 3$ Myr; Portegies Zwart et al. 2010) enter in a subsequent phase, during which the stellar population is essentially gas-free. During this phase, different effects take place on the cluster overall dynamics: mass loss due to stellar evolution, preferential evaporation of low-mass stars caused by the internal two-body relaxation, ruled by the Galaxy tidal field, and segregation of higher mass stars and binaries in the cluster centre. As a consequence, the OCs experience structural changes and relations between parameters like core, half-mass and tidal radii together with their present day mass functions can be used as probes of their dynamical states (e.g., Glatt et al. 2011). Due to their physical nature, highly dynamically evolved OCs often contain relatively few members and therefore present low contrast with the Galactic field population (Angelo et al. 2017; Pavani et al. 2011).

Despite these difficulties, it is desirable a uniform characterization of these challenging and usually overlooked objects. Determining the parameters of a large sample of OCs, covering different evolutionary stages and positions within the Galaxy, helps to constrain model parameters (e.g., initial number of stars, initial mass function and fraction of primordial binaries) aimed at investigating the cluster evolution (e.g., de La Fuente Marcos 1997; Portegies Zwart et al. 2001). According to the most updated version of the OCs catalogue compiled by Dias et al. 2002 version 3.5 as of

* E-mail: mangelo@lna.br
function (PSF)-fitting algorithm. We used the software STARFINDER (Diolaiti et al. 2000) which was designed for the analysis of crowded stellar fields, adapted to be executed automatically. The code supposes isoplanatism, which is a reasonable assumption since the fields of view are relatively small ($\sim 13 \times 13$ arcmin$^2$). In order to discriminate and reject unlikely detections, without losing faint stars contaminated by the background noise, only those objects with correlation coefficients between the measured profile and the modeled PSF greater than 0.7 were kept in each image. The astrometric solutions for our frames were computed from the set of positions of the stars in the detector reference system and their equatorial coordinates as catalogued in the UCAC4 (Zacharias et al. 2004). The transformation between the CCD reference system and equatorial system was made through linear equations. The solutions resulted in precisions typically better than $\sim 0.1$ arcsec. The $c$ and $r$ magnitude data sets were then cross-matched by means of the equatorial coordinates for each detected star and a single master table was constructed by compiling the objects detected in the shorter exposure frames, in order to prevent the inclusion of saturated objects, and adding successively to the list the non-coincident ones found in the larger exposure frames.

To transform instrumental magnitudes to the standard system, we measured nearly 100 magnitudes per filter of stars in the standard fields SA 101, SA 107 and SA 110 (Lata et al. 2002). As proposed by Geisler (1996), the $T_1$ magnitudes were sent the effective airmass. The transformation coefficients $c_i$ and $t_{1i}$ ($i = 1,2$ and 3), representing the zero-point, extinction and colour-terms for each filter, respectively, were adjusted with the FITPARAMS task in IRAF. These selected areas were observed in a wide range of airmass ($\sim 1.1 - 2.5$). The adopted analytical forms of the transformation equations are as follows:

\begin{align}
  c &= c_1 + c_2 \times X_C + c_3 \times (C - T_1), \\
  r &= t_{11} + T_1 + t_{12} \times X_T + t_{13} \times (C - T_1),
\end{align}

where lowercase and capital letters represent instrumental and standard magnitudes, respectively. $X_C$ and $X_T$ represent the effective airmass. The transformation coefficients $c_i$ and $t_{1i}$ ($i = 1,2$ and 3), representing the zero-point, extinction and colour-terms for each filter, respectively, were adjusted with the FITPARAMS task in IRAF. The mean values and residuals for all the nights are listed in Table 2. As proposed by Geisler (1996), the $R$ filter is well-known to be an excellent substitute of the $T_1$ filter, with the advantages of increased transmission at all wavelengths and the absence of any red-leak problems. Therefore, we used here instrumental $r$ magnitudes to obtain standard $T_1$ ones.

We finally transformed the instrumental magnitudes to the $CT_1$ Washington system according to the equations (1) and (2), using the INVERTFIT task within IRAF. The final table for each OC consists of an internal identifier (ID) per star, its RA and DEC coordinates, the $C$ and $T_1$ magnitudes followed by their respective uncertainties. A fragment of this information for ESO 065-7 is presented in Table 3. Figure 4 illustrates the typical photometric uncertainties in our photometry, which were derived from the STARFINDER algorithm and then properly propagated into the final magnitudes via the IRAF INVERTFIT task.

We performed artificial star tests to derive the completeness level at different magnitudes. We used the stand-alone ADDSTAR program in the DAOPHOT package (Stetson et al. 1990) to add synthetic stars. We added a number of stars equivalent to $\sim 5$ per cent of the measured stars in order

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1 http://www.noao.edu/sdm/archives.php
2 IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
Table 1. Observations log of the studied OCs.

| Cluster       | RA\(_{2000}\) (h:m:s) | DEC\(_{2000}\) (\(^\circ\):\′:\″) | \(\ell\) (\(^\circ\)) | \(b\) (\(^\circ\)) | Filter | Exposure (s) | Airmass |
|---------------|------------------------|----------------------------------|-----------------|---------------|--------|--------------|---------|
| ESO 518-3     | 16:47:06               | -25:48:18                        | 355.0710        | 12.4265       | C      | 30,300,300   | 1.0,1,1,0 |
|               |                        |                                  |                 |               | R      | 5,30,30      | 1.0,1,1,0 |
| Ruprecht 121  | 16:41:47               | -46:09:00                        | 338.7241        | 0.0944        | C      | 30,30,30     | 1.1,1,1   |
|               |                        |                                  |                 |               | R      | 5,5          | 1.1,1     |
| ESO 134-12    | 14:44:47               | -59:08:31                        | 317.0326        | 0.5929        | C      | 30,300,300   | 1.2,1,2,1 |
|               |                        |                                  |                 |               | R      | 5,30,30      | 1.2,1,2,1 |
| NGC 6573      | 18:13:39               | -22:07:48                        | 9.0490          | -2.0889       | C      | 30,30,300    | 1.0,1,1,1 |
|               |                        |                                  |                 |               | R      | 5,30,30      | 1.0,1,1,1 |
| ESO 260-7     | 08:48:00               | -47:01:48                        | 266.3638        | -2.1920       | C      | 45,450,450   | 1.3,1,3,1 |
|               |                        |                                  |                 |               | R      | 5,10,10,60,60| 1.3,1,3,1,3,1 |

Table 2. Mean values of the fitted coefficients and residuals for the presently calibrated CT\(_1\) photometric data set.

| Filter | Zero point coefficient (mag) | Extinction term (mag) | Residual (mag) |
|--------|------------------------------|-----------------------|----------------|
| C      | 3.873±0.008                 | 0.282±0.002           | -0.165±0.001   |
| T\(_1\) | 3.290±0.030              | 0.089±0.002           | -0.026±0.015   |

Table 3. Identifiers, coordinates and calibrated magnitudes for stars in the field of ESO 065-7.

| Star ID | RA (\(^\circ\)) | DEC (\(^\circ\)) | C (mag) | T\(_1\) (mag) |
|---------|----------------|----------------|--------|--------------|
| 1       | 202.3413696    | -71.2930832    | 13.612 ± 0.001 | 10.748 ± 0.001 |
| 2       | 202.6452332    | -71.2930832    | 13.612 ± 0.001 | 12.526 ± 0.001 |
| 3       | 202.2594004    | -71.2930832    | 13.612 ± 0.001 | 12.526 ± 0.001 |
| 4       | 202.0158546    | -71.2930832    | 13.612 ± 0.001 | 12.526 ± 0.001 |
| 5       | 202.1492004    | -71.2930832    | 13.612 ± 0.001 | 12.526 ± 0.001 |

Figure 1. Photometric uncertainties in C and T\(_1\) filters for stars in the field of ESO 065-7.

Figure 2. Completeness as a function of C and T\(_1\) magnitudes.

3 STRUCTURAL PARAMETERS

Figures 3 and 4 show the finding charts for the OCs studied in this paper. Colours indicate membership likelihoods (Section 4.1); their sizes being proportional to the stars’ brightnesses. Those considered photometric members are highlighted with red open circles. For each OC, stars in the selected control field are represented by open circles.

Deriving structural parameters of stellar clusters usually involves finding the central coordinates of the popula-
tion followed by the fitting of an analytical profile to the stars radial density profile, which is usually built by binning the data into annulus around the derived centre and computing their mean stellar density. There are, however, several drawbacks to this approach. For instance, it is not easy to quantify and often overlooked, how a small change on the central coordinates impact the final structural parameters. Moreover, the choice of the bin size and uniformity are also an issue when creating the radial density profile. Finally, sampling near the centre of the cluster is always a problem when using these methods. They require small radial bins which in turn will produce very small projected areas and poor statistics, leading to artificially high density values in the central bins.

To circumvent these problems, we devised a bayesian method to derive the structural parameters of the clusters by employing a Metropolis-Hastings algorithm (Hastings 1970) to conduct Markov chain Monte-Carlo (MCMC) simulations on the data set. Sampling of the parameter space was done using the method described in Goodman & Weare (2010).

Figure 3. Schematic finding charts of ESO 518-3 (top-left panel), Ruprecht 121 (top-right panel), ESO 134-12 (bottom-left panel) and NGC 6573 (bottom-right panel). Colours indicate membership likelihoods (Section 4.1) and the symbols’ sizes are proportional to the stars’ brightnesses. Photometric members are highlighted with open red circles. The solid lines indicate the core (inner circle) and tidal radii (outer circle). The dashed circle indicates the limiting radius for the decontamination procedure, beyond which stars are selected for the control field (open circles). North is up and East to the left.
which has been largely used in astronomy, having implementations in \textit{R} and \textit{Python} \citep{Foreman-Mackey2013} programming languages.

Input data included the stellar coordinates and the local stellar density ($\rho$), calculated at each star position using a large circular kernel with a fixed size of 6 times the average nearest-neighbour distance of the sample. (see Figure 3). Once an analytical model has been chosen and one set of parameter values is proposed, a model stellar density ($m$) is computed at each datum coordinate and a likelihood value ($L$) is calculated for this particular set of parameters through the equation:

\[
\ln L = \sum_i \ln \left\{ \frac{1}{2\pi\sigma} \exp \left[ -\frac{(\rho_i - m_i)^2}{2\sigma^2} \right] \right\},
\]

where $\sigma$ is the standard deviation of ($\rho - m$). In this paper, we employed the King's \citep{1962ApJ...136..591K} model, expressed by

\[
f(r) = f_0 \left[ \frac{1}{\sqrt{1 + (r/r_c)^2}} - \frac{1}{\sqrt{1 + (r_t/r_c)^2}} \right]^2,
\]

where $r_c$ and $r_t$ are the core and tidal radii, respectively.

The initial guess and prior distribution of the parameters were defined based on the input data. Centre coordinates and central density were estimated as the median values of the 5% highest density points, while background density was estimated as the median of the 20% lowest density points. Core radius and tidal radius were estimated from the marginalised density profile as the full width at half-maximum and the full width at background level, respectively. The priors were defined as wide normal distributions around these values.

The cluster central coordinates and the K62 model structural parameters constitute a 6D parameter space that was randomly sampled by twelve parallel threads (usually called 'walkers') in a 10000 steps simulation. We have found out that this number of threads provided a sufficient sampling of the parameter space as different realisations of the simulation showed no noticeable variations in the parameters posterior distributions. The chain length was defined after the verification that a stationary distribution is typically achieved after 1000 steps, ensuring that the rejection (or 'burning') of the first 20% of the steps is sufficient to remove the transient states (see Figure 6).

As required by the Markov process, a newly proposed parameter set is aways accepted if its likelihood is larger than the likelihood of the current parameter set and is accepted with a probability equal to the ratio of the likeli-
The twelve threads are represented by different coloured lines. The vertical dashed line marks the adopted transition from the transient states to the stationary distribution.

To test the method, a 200 star synthetic cluster was generated following the probability density function of the K62 profile function, immersed in background twice as dense as the cluster mean density, covering an area twice as large as that of the cluster. Figure 5 shows the chart of the simulated cluster and its marginal density profile across the x-axis, from which the initial guess and prior distribution of the parameters were calculated.

Figure 6 shows the time series of all parameters. It can be seen that after a transient period of about 1000 steps, all threads converge to a stationary posterior distribution from which the final parameters are drawn by calculating their marginalised mean and standard deviation. Table 4 compares the simulated cluster true parameters with the ones recovered from the MCMC simulation. Given the large size of the adopted density estimator kernel (similar to the cluster core radius) resulted in an artificial flattening of the density points near the centre of the cluster. To prevent this from affecting our simulations, we removed the central points with radius inferior to half the kernel size from the simulations, and therefore we could not relate the recovered central stellar density with the true (arbitrary) value used in the simulation. Despite that, all other recovered parameters have shown excellent agreement with their true values and also 'fits' very well with the data as it can be seem from Figure 7.

Another tool that is commonly used to infer the quality of a MCMC simulation is the corner plot, shown in Figure 8. It shows, for each parameter, the marginalised distribution of the posterior states (after discarding the initial burnt states) against all other parameters. It is useful for checking, at a glance the uniqueness of the solution found (single peak) and the possible existence of correlation between any two parameters (deviation from the round form). It can be seen, for example, that in this simulation the parameter 2 ($\rho_0$ - third column) shows a strong negative correlation with the parameter 4 ($r_t$) and a weaker one with parameter 5 ($\rho_{bg}$) while also showing a positive correlation with parameter 3 ($r_c$). Being correlated with all other structural parameters would mean that $\rho_0$ is not really a free parameter in the simulation, but a quantity that could be derived through a functional form from the other structural parameters.

After applying the procedure outlined in this section to the studied OCs, we obtained the central coordinates and the best-fitting parameters listed in Table 5. The maximum distance between the new centres (columns 2 and 3 of Table 5) and the literature ones (columns 2 and 3 of Table 1) resulted 1.4′ (for ESO 065-7); the minimum difference resulted 0.14′ (for ESO 518-SC03). The analogous of Figures 6 and 7 for other clusters are shown in the Appendix.

### Table 4. Simulated cluster parameters

| parameter | real     | recovered   |
|-----------|----------|-------------|
| $x_c$ (pix) | 500     | 501.9±0.2   |
| $y_c$ (pix) | 300     | 299.2±0.2   |
| $r_c$ (pix) | 25      | 25.8±0.7    |
| $r_t$ (pix) | 90      | 87±3        |
| $\rho_{bg}$ (pix)$^{-2}$ | 0.0128  | 0.0128±0.0002 |

4 CMD ANALYSIS

4.1 Membership and fundamental parameters determination

We extracted $C$ and $T_1$ magnitudes of stars located in concentric annular regions (widths proportional to $r_c$ and cen-
Dynamically evolved Galactic OCs

Figure 8. Corner plot showing the density of the posterior states around the most likely parameters (dashed lines). Parameters 0 – 5 represented are, respectively, the central coordinates \((x_c, y_c)\), the core stellar density \((\rho_0)\), core radius \((r_c)\), tidal radius \((r_t)\) and background density \((\rho_{bg})\).

Table 5. Redetermined central coordinates, Galactocentric distances and structural parameters of the studied OCs.

| Cluster     | RA \(2000\) (h:m:s) | DEC \(2000\) (°′″) | R\(_{GC}\) (kpc) | \(r_c\) (pc) | \(r_t\) (pc) | \(h\) (pc) | \(R_{J}^{\dag}\) (pc) |
|------------|----------------------|---------------------|-----------------|-------------|-------------|-----------|------------------|
| ESO 518-3  | 16:47:06             | -25:48:23           | \(6.0 \pm 0.6\) | \(0.72 \pm 0.03\) | \(0.61 \pm 0.06\) | \(5.84 \pm 0.64\) | \(2.52 \pm 0.27\) |
| Ruprecht 121 | 16:41:46             | -46:09:19           | \(6.5 \pm 0.5\) | \(1.31 \pm 0.04\) | \(0.87 \pm 0.04\) | \(3.39 \pm 0.19\) | \(4.23 \pm 0.37\) |
| ESO 134-12 | 14:44:18             | -59:08:51           | \(6.7 \pm 0.5\) | \(2.64 \pm 0.11\) | \(1.27 \pm 0.06\) | \(6.01 \pm 0.20\) | \(4.63 \pm 0.38\) |
| NGC 6573   | 18:13:41             | -22:07:15           | \(6.4 \pm 0.5\) | \(0.19 \pm 0.02\) | \(0.12 \pm 0.03\) | \(0.60 \pm 0.04\) | \(1.84 \pm 0.22\) |
| ESO 260-7  | 08:47:58             | -47:02:41           | \(6.9 \pm 0.5\) | \(0.06 \pm 0.19\) | \(1.32 \pm 0.07\) | \(7.17 \pm 0.32\) | \(4.14 \pm 0.27\) |
| ESO 065-7  | 13:29:22             | -71:16:55           | \(6.9 \pm 0.5\) | \(0.37 \pm 0.04\) | \(0.96 \pm 0.04\) | \(5.24 \pm 0.31\) | \(2.65 \pm 0.23\) |

Note: The angular separations (in arcmin) where converted to physical distances (in pc) using the expression:
\[
\left(\frac{\pi \theta}{10800}\right) \times 10^{\left[\frac{(m - M)_0 + 5}{5}\right]} \text{pc}
\]
where \((m - M)_0\) is the cluster distance modulus (see Table 7).

\(*\) Half-mass radius (Section 4.2).

\(\dag\) Jacobi radius (Section 5).

tered on the studied OCs; Figure 9, as well as of those distributed in a control field. Control field stars are represented with open circles in Figures 3 and 4. Firstly, we used this information to build \(T_1 \times (C - T_1)\) CMDs for stars inside each selected annular region. Then we executed a routine that evaluates the overdensity of stars in the cluster CMD relative to the control field CMD in order to establish photometric membership likelihoods. The algorithm is fully described in Maia et al. (2010). Briefly, the cluster and field CMDs are divided into small cells with sizes that are proportional to the mean uncertainties in magnitude and colour index. Here we used cell sizes \(\Delta T_1\) and \(\Delta (C - T_1)\) that are, respectively, equal to 20 and 10 times the sample mean uncertainties in \(T_1\) and \((C - T_1)\). Taking into account our whole sample, both \(\Delta T_1\) and \(\Delta (C - T_1)\) translate into \(~0.5\) mag. These cells are small enough to detect local variations of field-star contamination along the sequences in the cluster CMD, and large enough to accommodate a significant number of stars.

Membership likelihoods \((L)\) are assigned to stars in each cell according to the weight function

\[
L = e^{- \left( \frac{N_{clu} \times A_{clu}}{N_{fld} \times A_{fld}} \right)^2} \times e^{- \left( \frac{r_t}{h} \right)^2},
\]

where \(r_t\) is the tidal radius, \(N_{clu}\) is the number of stars counted within a cell in the cluster CMD and \(N_{fld}\) is the number of stars counted in the corresponding cell within the control field CMD. The multiplicative factors \(A_{clu}\) and \(A_{fld}\) properly take into account differences in the areas corre-
sponding to the cluster and field stars, respectively, in each decontamination procedure run. This formulation has the advantage of considering both the photometric and structural informations.

The cell positions are changed by shifting the entire grid by one-third of the cell size in each direction. Also, the cell sizes are increased and decreased by one-third of the average sizes in each of the CMD axes. Considering all possible configurations, 81 different grid sets are used. For each pair cluster-control field, the star membership likelihood is derived from the average of the memberships obtained over the whole grid configurations. This procedure is illustrated in Figure 3 which shows the results of the decontamination algorithm applied to Ruprecht 121. Four annular regions with width ≈ 0.5 \( r_e \) were employed in this case. The colour-bars indicate membership likelihoods. Analogous figures for the other studied OCs are showed in the Appendix.

Groups of stars with high \( L \) values are significantly contrasting with the field and provide useful constraints for isochrone fitting, although some interlopers remain. The presence of residuals in the CMDs, specially red stars (Figures 10 and 11), is an expected issue, since these clusters are located at relatively low Galactic latitudes (\(|b| < 13^\circ\), Table 1) and thus the statistical analysis is subject to a certain degree of variability of the stellar density, reddening, luminosity function and colour distribution of the disc field stars.

A new generation of PARSEC-COLIBRI isochrones (Marigo et al. 2017) was used to estimate the OC astro-physical properties by matching them to the distribution of stars with \( L > 0.5 \) (Figures 10 and 11). We made use of a set of solar metallicity isochrones ranging from 7.50 up to 8.60 in steps of 0.05 in log(\( t \)), for the younger OCs, and ranging from 9.00 up to 9.60 for the older OCs. Each isochrone was reddened and vertically shifted by using the following relations: \( E(C-T_{\text{J}})/E(B-V) = 1.97 \), \( A_T V/E(B-V) = 2.62 \) (Geisler 1996) until matching the observed OC CMD features. Reddening values from dust maps \( E(B-V)_{\text{dust}} \) (Schlafly & Finkbeiner 2011), Green et al. 2015, whenever available, were used as initial guesses and then we tested values in the range \( \sim 0.5 - 2 \times E(B-V)_{\text{dust}} \).

We also considered for each isochrone matching the effect of unresolved binaries. To do this we shifted the isochrone in steps of 0.01 mag in direction of decreasing \( T_{\text{J}} \) down to 0.75 mag, which is the limit corresponding to unresolved binaries of equal mass. Finally, we chose the isochrone which best resembles the sequences traced by the stars with \( L > 0.5 \) (see Table 2). Stars with available Gaia DR1 parallaxes \( (\pi) \), see Table 3) were labelled in the CMDs of ESO 134-12, ESO 260-7 and ESO 065-7. As these stars were not fitted by the chosen isochrones (Figures 10 and 11), they were dismissed as possible clusters members.

Fundamental parameters for these objects were also derived by K13. In what follows, we summarize the main discrepancies with our results. (i) Regarding \( E(B-V) \), the greatest difference is found for ESO 518-03; relatively to our value, K13 found a value 50% smaller; for the other clusters, differences vary from 4% to 30% ; (ii) for log(\( t \)), we found good agreement with the literature values within 0.2 dex in the cases of Ruprecht 121, ESO 260-7 and ESO 065-7; for the other clusters, the differences in log(\( t \)) are 0.87 (ESO 518-3), 0.65 (ESO 134-12) and 0.45 (NGC 6573), with K13 presenting:

### Table 6. Gaia DR1 parallaxes and proper motions for stars in the OC observed fields.

| Cluster | ID | \( \pi \) (mas) | \( \mu RA \) (mas yr\(^{-1}\)) | \( \mu DEC \) (mas yr\(^{-1}\)) |
|---------|----|----------------|----------------------|----------------------|
| ESO 134-12 | 327 | 0.82 ± 0.36 | -7.43 ± 1.15 | -8.05 ± 0.49 |
| 346 | 2.44 ± 0.33 | 9.41 ± 1.37 | 4.64 ± 0.44 |
| ESO 260-7 | 2 | 1.81 ± 0.34 | -12.32 ± 1.52 | -1.40 ± 0.86 |
| 4 | 0.83 ± 0.31 | -4.71 ± 1.41 | 10.35 ± 1.02 |
| 662 | 1.42 ± 0.35 | -11.28 ± 1.00 | 12.03 ± 0.86 |
| 663 | 0.26 ± 0.52 | -5.52 ± 2.30 | 5.54 ± 1.57 |
| ESO 065-7 | 275 | 0.39 ± 0.34 | -10.12 ± 0.57 | -3.62 ± 0.82 |
| 786 | 0.60 ± 0.41 | -20.07 ± 0.70 | -14.20 ± 0.92 |

We derived individual masses of photometric cluster members by interpolation in the theoretical isochrone, properly corrected by reddening and distance modulus (Figures 10 and 11), from the star \( T_{\text{J}} \) magnitude. The half-mass radius of each OC \( (r_h) \), Table 5 was derived directly from the list of members, by taking their individual masses and distances to the cluster centre. Then, the clusters’ mass functions (MF, Figure 12) were constructed by counting the number of stars in linear mass bins (i.e., \( \xi (m) = dN/dm \)), which were then converted to the logarithmic scale and plotted in Figure 12. Poisson statistics was assumed for uncertainties determination. The dotted vertical lines correspond to the 50% completeness limit of our photometry, for reference (see also Figure 2). Star counts inside each bin were weighted by the photometric membership likelihoods (Figures 10 and 11) and corrected for completeness (Figure 2). Finally, the total observed cluster masses \( (M_{\text{obs}}) \) were determined by discrete sum of the mass bins in Figure 12. They are listed in Table 7 where the uncertainties come from error propagation.

For comparison purposes, the initial mass function (IMF) of Kroupa (2001) was scaled according to each photometric cluster mass and superimposed to the observed mass functions (solid lines in Figure 12). Except for ESO 260-
7, all studied OCs present signals of low-mass stars deple-
tion, which is a signature of dynamically evolved OCs (de
La Fuente Marcos 1997; Portegies Zwart et al. 2001; Baum-
gardt & Makino 2003). In all cases, the more massive bins
are consistent with the IMF steepness, although with some
scatter. We also checked for possible variations in the steep-
ness of the derived MF across the studied OCs. For each
object, we built two additional MFs: one for stars located in
the range $0 < r < 0.5 r_{\text{max}}$ and another one for the region
$0.5 r_{\text{max}} < r < r_{\text{max}}$, where $r_{\text{max}}$ is the maximum distance
of photometric members to the cluster centre. The results
are show in Figure 13 for ESO 065-7 and in Figure A9 for

**Table 7.** Fundamental parameters, relaxation times and photometric masses ($M_{\text{phot}}$) for the studied clusters. $M_{\text{Kroupa}}$ and $N_{\text{Kroupa}}$ are upper limits for cluster mass and number of stars, respectively.

| Cluster       | $(m-M)_0$ (mag) | $d$ (kpc) | $E(B-V)$ (mag) | log($t$/yr) | $t_{\text{rh}}$ (Myr) | $M_{\text{phot}}$ ($M_\odot$) | $M_{\text{Kroupa}}$ ($M_\odot$) | $N_{\text{Kroupa}}$ |
|---------------|----------------|-----------|----------------|-------------|------------------------|------------------------------|---------------------------|----------------|
| ESO 518-3     | 11.60 ± 0.30   | 2.09 ± 0.29 | 0.80 ± 0.10   | 8.30 ± 0.10 | 1.43 ± 0.25            | 111 ± 17                     | 376                        | 835            |
| Ruprecht 121  | 11.00 ± 0.30   | 1.58 ± 0.22 | 1.00 ± 0.05   | 8.35 ± 0.10 | 3.18 ± 0.24            | 405 ± 32                     | 1592                       | 3565           |
| ESO 134-12    | 11.50 ± 0.30   | 2.00 ± 0.28 | 1.05 ± 0.10   | 8.25 ± 0.10 | 6.82 ± 0.53            | 500 ± 33                     | 1520                       | 3360           |
| NGC 6573      | 11.00 ± 0.30   | 1.58 ± 0.22 | 0.80 ± 0.10   | 8.35 ± 0.10 | 0.12 ± 0.04            | 35 ± 9                      | 124                        | 279            |
| ESO 260-7     | 12.65 ± 0.30   | 3.39 ± 0.47 | 0.40 ± 0.05   | 9.15 ± 0.10 | 6.77 ± 0.61            | 152 ± 14                     | 531                        | 1380           |
| ESO 065-7     | 11.90 ± 0.30   | 2.40 ± 0.33 | 0.40 ± 0.05   | 9.45 ± 0.05 | 4.02 ± 0.34            | 86 ± 10                      | 380                        | 1077           |

Figure 9. Decontamination procedure applied to stars in four annular regions centered on Ruprecht 121. In each case, cluster (left) and control field (middle) $T_1 \times (C - T_1)$ CMDs were represented. The rightmost CMD shows the derived membership likelihoods, as indicated in the colour bars.
the other 5 OCs. In all cases the derived MFs do not deviate significantly from the Kroupa IMF, except in the lower mass bins, which are affected by preferential evaporation of low-mass stars.

Since there may be member stars below the detection limits, we performed rough estimates of upper mass limits \(M_{\text{Kroupa}}\) and number of stars \(N_{\text{Kroupa}}\) by integrating the scaled Kroupa’s law down to a stellar mass of 0.1\(M_\odot\). The resulting \(M_{\text{Kroupa}}\) and \(N_{\text{Kroupa}}\) values are shown in Table 7. As can be seen, the \(M_{\text{phot}}\) values resulted to be \(\sim 30\) per cent of \(M_{\text{Kroupa}}\) for all studied OCs.

5 DISCUSSION

In order to study the evolutionary stages of the OC sample, we considered parameters closely associated with their dynamical evolution, i.e., age, stellar mass, core, half-mass...
and tidal radii. We in addition computed the half-mass relaxation times according to the equation (Spitzer 1987)

$$t_{rh} = 0.138 \frac{M^{1/2}}{G^{1/2} \langle m \rangle \ln(0.4 N)},$$

(6)

where $G$ is the gravitational constant, $M$ is the cluster mass ($M_{\text{phot}}$, Table 7), $r_h$ is the half-mass radius (Table 5), and $\langle m \rangle = M/N$ is the global mean stellar mass, where $N$ is the number of photometric members (Figures 10 and 11).

The $t_{rh}$ tells us about the typical timescale in which a system reaches thermal equilibrium (Portegies Zwart et al. 2010). From a theoretical point of view, it is the timescale on which stars tend to establish a Maxwellian velocity distribu-
tion, continuously repopulating its high-velocity tail and thus losing stars by evaporation. The $t_{\text{ch}}$ values derived for the studied OCs are listed in Table 7. The derived ages resulted at least one order of magnitude larger than $t_{\text{ch}}$ (Figure 14 panel (b)), which suggests that these OCs have had enough time to evolve dynamically. This is also true even if we considered $M_{\text{Kroupa}}$ and $N_{\text{Kroupa}}$ from Table 7 to compute $t_{\text{ch}}$, still supporting that the OCs have lived many times their $t_{\text{ch}}$.

The Jacobi radii (Table 3) were also determined from the equation (von Hoerner 1957):

$$R_J = \left(\frac{M_{\text{clu}}}{3M_G}\right)^{1/3} \times R_G,$$

where $M_{\text{clu}}$ is the cluster mass and $M_G$ is the Milky Way (MW) mass inside the cluster Galactocentric distance ($R_G$). This formulation assumes a circular orbit around a point mass galaxy. The value of $M_G = 5 \times 10^{11} M_{\odot}$ was obtained from the MW mass profile of Taylor et al. (2016). The $R_G$ were obtained from the distances in Table 3 assuming that the Sun is located at $8.0 \pm 0.5 \text{kpc}$ from the Galactic centre (Reid 1993).

The analysis of the derived structural parameters can give some indications of the OCs’ dynamical stage. In this context, it is important to highlight that quantities such as mass, $r_1/r_J$, the concentration parameter $c = \log(r_1/r_c)$ (Figure 15) and $r_c/r_J$ depend on the unknown initial formation conditions. What follows are considerations made on the basis of the observed trend between various structural parameters in a large sample of OCs and can give an indication of the dynamical stage of these systems in the simplified assumption that all OCs were born with the same mass, density profile and stellar population.

Figure 14 panel (a), shows the ratio $r_c/R_J$ for the studied OCs. As can be seen, ESO 518-3, ESO 134-12, ESO 260-7 and ESO 065-7 present tidal radius larger than their respective Jacobi radii, which suggests that these OCs might be experiencing relatively important mass loss processes, just towards final disruption. On the other hand, Ruprecht 121 and NGC 6573 have most of their stellar contents within their Jacobi volume, and therefore they are under relatively less notable mass loss. Ruprecht 121 may be a transition object entering in its final disruption stage, with its $r_1$ comparable to $R_J$. It is noticeable that NGC 6573 presents the poorest CMD and, at the same time, it is the most compact OC within our sample. Although underpopulated, its compact structure apparently allowed this OC to keep its remnant stellar content gravitationally bounded throughout its dynamical evolution.

Since the studied OCs have lived many times their typical relaxation times, it is expected some trend of the present-day cluster mass with the $age/t_{ch}$ ratio. Figure 14 panel (b), depicts such a relationship for them (black symbols) and for 236 OCs located in the solar neighbourhood analysed by Piskunov et al. (2007). Filled grey symbols represent Piskunov’s OCs within the age range ($\sim$ 0.14 – 0.28 Gyr) of 4 of our studied OCs, namely: ESO 518-3 ($t = 0.20 \pm 0.05$ Gyr), Ruprecht 121 ($t = 0.22 \pm 0.05$ Gyr), ESO 134-12 ($t = 0.18 \pm 0.04$ Gyr) and NGC 6573 ($t = 0.22 \pm 0.05$ Gyr); blue symbols represent clusters within the age range $\sim 1.0 - 1.7$ Gyr, which corresponds to ESO 260-7 ($t = 1.4 \pm 0.3$ Gyr); the green symbol corresponds to the age range $\sim 2.5 - 3.1$ Gyr, which complies with ESO 065-7 ($t = 2.8 \pm 0.3$ Gyr).

Piskunov et al. (2007) derived $r_c$ and $r_J$ by fitting K62 profiles to the cluster stellar density distributions and masses from their $r_I$ values. We computed here $r_I$ values assuming that the cluster stellar density profiles are indistinguishably reproduced by K62 and Plummer (1911) models. Hence, $t_{ch}$ values were derived from equation 3. The six studied OCs span the most evolved half part of the $age/t_{ch}$ ratio range and tend to present higher masses compared to their solar neighborhood counterparts with compatible $age/t_{ch}$ values. This is an expected result, since all studied OCs (except for ESO 260-7) are located inside the solar ring ($R_G < 8 \text{kpc}$) and thus subject to a stronger Galactic tidal field compared to clusters in the solar neighborhood. Their more massive nature may have allowed them to live for many times their $age/t_{ch}$ ratios.

Figure 14 (c) shows the $r_h/R_J$ versus $R_G$ plot. The distribution of clusters in this plot gives some indication of the strength of the Galaxy tidal field and it was employed by Baumgardt et al. (2010) to identify two distinct groups of globular clusters in the Milky Way. We can notice the absence of clusters with $r_h/R_J > 0.5$. Such clusters should be quickly destroyed, since they would be subject to strong tidal forces. Following Baumgardt et al. (2010), the dashed line was plotted here as a reference and it depicts the position that a cluster with $M = 10^5 M_{\odot}$ and $r_h = 3 \text{pc}$ would have at different Galactocentric distances. Except for NGC 6573, all studied clusters present $r_h/R_J$ in the range $\sim 0.20 < r_h/R_J < 0.35$ and therefore they are more tidally influenced, which is consistent with the overall disruption scenario. On the other hand, the dynamical evolution of the compact cluster NGC 6573 ($r_h/R_J \sim 0.07$) seem to be mainly driven by its internal relaxation.

In the panel (d) of Figure 14, we plotted the positions of the studied OCs in the $r_c/r_h$ versus $r_h/R_J$ plane. We included the evolutionary path (solid arrow, Heggie & Hut 2003) of
Dynamically evolved Galactic OCs

Figure 14. Plots (a) $r_t/R_J$ versus $R_t$, (b) logarithm of mass versus age/$t_{rh}$ ratio, (c) $r_h/R_J$ versus $R_G$ and (d) $r_c/r_h$ versus $r_h/t_t$ ratio for the studied clusters. In panel (b), open symbols and filled coloured ones represent 230 OCs from the sample of Piskunov et al. (2007, see text for details). Black filled symbols are: ▶ (ESO 518-3), ♦ (Ruprecht 121), ■ (ESO 134-12), ▲ (NGC 6573), ▼ (ESO 260-7) and • (ESO 065-7).

cluster would follow if it were tidally filled at the beginning of its evolution. In such a case, $r_h/r_t$ remains constant during the cluster evolution and $r_c$ and $r_h$ decrease due to violent relaxation in the cluster core region followed by two-body relaxation, mass segregation and finally core-collapse. This is consistent with the results of direct $N$–body simulations of [Gieles & Baumgardt (2008)], for which clusters that begin their evolution in their tidal regime dissolve completely in this regime. The derived $r_h/r_t$ ratio for the present cluster sample is $0.19 \pm 0.05$, which is consistent with the expected value for a tidally filled cluster.

Figure 15 shows the concentration parameter $c$ (=$\log(r_t/r_c)$) as function of $\log$($age/t_{rh}$) for the studied OCs and for Piskunov et al.’s sample. The $c$ parameter of the studied OCs vary from moderate ($\sim 0.3$) to relatively high ($\sim 0.9$) values. The ensemble of points show a general trend, although with considerable scatter, in which the dynamical evolution conducts to greater $c$ values and that star clusters tend to initially start their dynamical evolution with relatively small-concentration parameters [Piatti (2016) and references therein). In this context, highly dynamically evolved star clusters, which suffered from severe mass loss, can have relatively low $c$ values.

It is enlightening to note that part of our sample is composed by clusters (namely, ESO 518-3, Ruprecht 121, ESO 134-12 and NGC 6573) with compatible $R_G$ and similar young ages (Tables 5 and 7, respectively), considering uncertainties. Despite this, we distinguish two groups: one near to disruption (ESO 518-3 and ESO 134-12) and those in advanced dynamical stage (Ruprecht 121 and NGC 6573). We speculate with the possibility that these differences might...
be traced back to their progenitor OCs, although we should not rule out that the Galactic gravitational field could play a differential role. The older studied OCs (ESO 260-7 and ESO 065-7) are also near to disruption at different $R_G$. Differences in the Galaxy tidal field could, at least partially, explain the difference in the $r_h$ values of these both clusters. Nevertheless, considering their ages and $R_G$, differences in the potential lead to a small variation ($\lesssim 10\%$) in $r_h$ (figure 1 of [Miholics et al. 2014]). This suggests that the internal interactions have relaxed the mass distribution internally in such a way that these clusters strongly feel the tidal field of the Galaxy (in fact, ESO 260-7 and ESO 065-7 present the highest $r_h/R_J$ ratios among our sample).

6 SUMMARY AND CONCLUDING REMARKS

In this paper we analysed the evolutionary stages of six sparse OCs, namely: ESO 518-3, Ruprecht 121, ESO 134-12, NGC 6573, ESO 260-7 and ESO 065-7. We employed photometric data in the Washington $C$ and $T_1$ bands from publicly available CTIO images. Markov chain Monte-Carlo simulations were performed in order to determine the central coordinates and the structural parameters by fitting K62 model to the stellar profiles. In order to check the method efficiency, it was previously employed on data of a synthetic star cluster.

We employed a decontamination technique that performs statistical comparisons between OC and control field CMDs ($T_1 \times (C - T_1)$, in our case), attributing membership likelihoods ($L$) to each star. The more probable members provide useful constraints for isochrone fitting, from which we derived the OCs’ fundamental parameters age, distance modulus and reddening. Solar metallicity isochrones provided adequate fits for our OCs. We found that four of our OCs are relatively young and within a relatively narrow age range ($8.2 \leq \log(t \text{ yr}^{-1}) \leq 8.3$); the older OCs present reasonably compatible ages ($\log(t \text{ yr}^{-1})$ in the range $9.2 - 9.4$). Except for ESO 260-7 ($R_G = 8.9\text{kpc}$), all the studied OCs are located at compatible Galactocentric distances ($R_G$ in the range $6.0 - 6.9\text{kpc}$), considering uncertainties.

Individual masses for the member stars were estimated from their positions relatively to the fitted isochrone, from which the OC mass functions and present-day observed masses ($M_{\text{phot}}$) were obtained. The $M_{\text{phot}}$ of the six OCs span a wide range ($\log M = 1.5 - 2.7$) and we also estimated upper mass limits assuming a Universal IMF described by a [Kroupa (2001)] law, which resulted in the mass range $\log(M_{\text{Kroupa}}) = 2.1 - 3.2$. We found evidence of low-mass stellar depletion, which is expected for dynamically evolved stellar systems.

From the analysis of the derived parameters we found that:

- Two groups of OCs can be identified: a group of OCs towards final disruption ($r_h/R_J > 1$) and another in an advanced dynamical stage ($r_h/R_J < 1$).
- The positions of the studied OCs in the mass versus log (age/$t_{rh}$) and $c$ versus log (age/$t_{rh}$) planes are compatible with the hypothesis of dynamically evolved stellar systems; the derived $r_h/r_J$ ratios are consistent with the expected value for tidally filled clusters.
- The dynamical evolution of the compact cluster NGC 6573 seems to mainly driven by internal interactions, while the other OCs are more strongly tidally influenced, as can be seen in the $r_h/R_J$ versus $R_G$ plane.
- Their distinct dynamical stages could be due to different initial formation conditions, although the Milky Way tidal field could have played also a role.

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APPENDIX A: SUPPLEMENTARY MATERIAL

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.
Figure A1. Same of Figure 6 but for the OCs ESO 518-3 (top left panel), Ruprecht 121 (top right panel), ESO 134-12 (middle left panel), NGC 6573 (middle right panel), ESO 260-7 (bottom left panel) and ESO 065-7 (bottom right panel).
Figure A2. Normalised background subtracted radial density profiles of ESO 518-3 (top left panel), Ruprecht 121 (top right panel), ESO 134-12 (bottom left panel) and NGC 6573 (bottom right panel), showing a K62 profile model function (solid line) fitted to the data.
Figure A3. Same of Figure A2 but for the OCs ESO 260-7 (left panel) and ESO 065-7 (right panel).
Figure A4. Same as Figure 9 but for ESO 518-3.
Figure A5. Same of Figure 9 but for ESO 134-12.
Figure A6. Same of Figure 9 but for NGC6573.
Figure A7. Same of Figure 9 but for ESO 260-7.
Figure A8. Same of Figure 9, but for ESO 065-7.
Figure A9. Same of Figure 13 but for the OCs ESO 518-3 (top left panel), Ruprecht 121 (top right panel), ESO 134-12 (middle left panel), NGC 6573 (middle right panel) and ESO 260-7 (bottom panel).