Probing the age and structure of the nearby very young open clusters NGC 2244 and NGC 2239

C. Bonatto\textsuperscript{1*} and E. Bica\textsuperscript{1†}
\textsuperscript{1} Departamento de Astronomia, Universidade Federal do Rio Grande do Sul
Av. Bento Gonçalves 9500, Porto Alegre 91501-970, RS, Brazil

ABSTRACT
The very young open cluster (OC) NGC 2244 in the Rosette Nebula was studied with field-star-decontaminated 2MASS photometry, which shows the main-sequence (MS) stars and an abundant pre-MS (PMS) population. Fundamental and structural parameters were derived with colour-magnitude diagrams (CMDs), stellar radial density profiles (RDPs) and mass functions (MFs). Most previous studies centred NGC 2244 close to the bright K0V star 12 Monocerotis, which is not a cluster member. Instead, the near-IR RDP indicates a pronounced core near the O5 star HD 46150. We derive an age within 1—6 Myr, an absorption $A_V = 1.7 \pm 0.2$, a distance from the Sun $d_\odot = 1.6 \pm 0.2$ kpc ($1.5$ kpc outside the Solar circle), an MF slope $\chi = 0.91 \pm 0.13$ and a total (MS+PMS) stellar mass of $\sim 625 M_\odot$. Its RDP is characterised by the core and cluster radii $R_c \approx 5.6'$ ($2.6$ pc) and $R_{RDP} \approx 10'$ ($4.7$ pc), respectively. Departure from dynamical equilibrium is suggested by the abnormally large core radius and the marked central stellar excess. We also investigate the elusive neighbouring OC NGC 2239, which is low-mass ($m_{MS+PMS} \approx 301 M_\odot$), young (5 ± 4 Myr) rather absorbed ($A_V = 3.4 \pm 0.2$), and located in the background of NGC 2244 at $d_\odot = 3.9 \pm 0.4$ kpc. Its RDP follows a King-like function of $R_c \approx 0.5' \approx 0.5$ pc and $R_{RDP} \approx 5.0' \approx 5.6$ pc. The MF slope, $\chi = 1.24 \pm 0.06$, is essentially Salpeter’s IMF. NGC 2244 is probably doomed to dissolution in a few 10$^7$ yr. Wide-field extractions and field-star decontamination increase the stellar statistics and enhance both CMDs and RDPs, which is essential for faint and bright star clusters.

Key words: (Galaxy:) open clusters and associations: general; (Galaxy:) open clusters and associations: individual: NGC 2244 and NGC 2239.

1 INTRODUCTION
Still in the process of emerging from the parent molecular cloud, star clusters younger than about 5 Myr usually present a developing main sequence (MS) and a significant population of pre-MS (PMS) stars. However, depending on the initial cluster mass, star-formation efficiency and mass of the more massive stars, the rapid early gas removal (from supernovae and massive star winds) may impart important changes to the original gravitational potential. One consequence of the reduced potential is that stars, especially the low mass ones, moving faster than the scaled-down escape velocity may be driven into the field. Over a time-scale of 10 – 40 Myr, this effect can dissolve most of the very young star clusters (e.g. Goodwin & Bastian 2000). Indeed, estimates (e.g. Lada & Lada 2003) predict that only about 5% of the embedded clusters are able to dynamically evolve into bound open clusters (OCs).

On observational grounds, the dramatic changes in the potential affecting the early cluster spatial structure should be reflected on the stellar radial density profile (RDP). Bochum 1 (Bica, Bonatto & Dutra 2008, for instance, can be an example of this scenario, in which the irregular RDP does not follow a cluster-like profile. This suggests significant profile erosion or dispersion of stars from a primordial cluster.

In the present paper we address the case of NGC 2244 in the Rosette Nebula, which is also related to the Monocerotis OB2 association (e.g. Román-Zúñiga & Lada 2008). Historically, in colour-magnitude diagram (CMD) studies some authors centred the large-scale structure on 12 Mon, which is a bright foreground star of spectral type K0V. When only wide-field CMDs are considered, the adoption of this centre does not affect the results. However, as will be explored in
this work in the context of investigating the cluster structure, that region is definitely at the cluster periphery.

Based on Shanghai Observatory plates with baselines of 34 and 87 yr, Chen, de Grijs & Zha (2007) derived proper motions (PMs) and membership probabilities for NGC 2244. They found mass segregation, but no velocity-mass dependence, indicating a primordial mass segregation related to the star-formation process. With arguments based on published initial mass functions (IMFs) and the measured internal velocity dispersion of $\approx 35$ km s$^{-1}$, they concluded that NGC 2244 will be dissolved on a short time-scale.

Additionally, in the area of the Rosette Nebula, the cluster candidate NGC 2239 has been frequently included in catalogues, but hardly studied. Both NGC 2244 and NGC 2239 are optical clusters, while the area includes numerous infrared embedded clusters in the Rosette Molecular Cloud (e.g. Phelps & Lada 1997).

This work employs 2MASS near-IR J, H, and K$_s$ photometry. The 2MASS spatial and photometric uniformity allow extractions of wide surrounding fields that provide high star-count statistics. This property makes 2MASS an excellent resource to extract photometry of a broad variety of star clusters, the wide field ones in particular. For this purpose we have been developing quantitative tools to statistically disentangle cluster evolutionary sequences from field stars in CMDs. Decontaminated CMDs have been used to investigate the nature of cluster candidates and derive their astrophysical parameters (e.g. Bica, Bonatto & Camargo 2008).

Basically, we apply (i) field-star decontamination to measure the statistical significance of the CMD morphology, which is fundamental to derive reddening, age, and distance from the Sun, and (ii) colour-magnitude filters, which are essential for intrinsic stellar RDPs, as well as luminosity and mass functions (MFs). In particular, the use of field-star decontamination in the construction of CMDs has proved to constrain age and distance more than working with raw (observed) photometry, especially for low-latitude OCs (Bonatto et al. 2006a).

2MASS can be deep for nearby young or old OCs. For instance, our group has studied the young OCs NGC 6611 (Bonatto, Santos Jr. & Bica 2006) and NGC 4755 (Bonatto et al. 2006b). Abundant pre-MS (PMS) stars were seen in the $\approx 1$ Myr old NGC 6611, which is essentially embedded, and a few remaining ones in the $\approx 14$ Myr old NGC 4755. As nearby older OCs we cite NGC 2477 (Bonatto & Bica 2003) and M67 (Bonatto & Bica 2003).

In this paper we apply our set of analytical tools to the 2MASS photometry of the stars in the area of NGC 2244 to derive its fundamental parameters, structure and fraction of MS and PMS stars. We also investigate the neighbouring cluster NGC 2239.

This paper is organised as follows. In Sect. 2 we recall literature data on NGC 2244. In Sect. 3 we describe the 2MASS photometry and compare it with the available optical data; we also describe the field-star decontamination algorithm and build CMDs. In Sect. 4 we derive cluster fundamental parameters. In Sect. 5 we derive structural parameters by means of stellar RDPs. In Sect. 6 we provide estimates of cluster mass. In Sect. 7 we compare the structural parameters and dynamical state of the present clusters with those of a sample of nearby OCs. Concluding remarks are given in Sect. 8.

2 PREVIOUS WORK ON NGC 2244

Several studies on NGC 2244, especially photometric and spectroscopic ones, are available in the literature.

The WEBDA$^1$ database locates the cluster centre at $\alpha(2000) = 06^h 31^m 55^s$ and $\delta(2000) = +04^\circ 56' 30'', and provides a distance from the Sun $d_0 = 1.45$ kpc, reddening $E(B-V) = 0.46$, and an age of 7.9 Myr.

With UBV photometry, Ogura & Ishida (1981) obtained $E(B-V) = 0.47$, a total to selective extinction ratio $R_V = 3.2$, $d_0 = 1.42$ kpc, 4 Myr of age, and a total mass of 5000 $M_\odot$. With similar data, Hensberge, Pavlovski & Verschueren (2000) derived an age of 2 Myr. $R_V = 3.2 \pm 0.07$, $E(B-V) = 0.44$, and $d_0 = 1.4 \pm 0.1$ kpc.

In a comprehensive study of the Northern Monoceros region, Pérez (1991) found an apparent diameter of 24', an age within 1.45–3.63 Myr, $d_0 = 1.67$ kpc, $E(B-V) = 0.48$, and a total mass of 770 $M_\odot$ for NGC 2244.

Park & Sung (2002) found an average $E(B-V) = 0.47 \pm 0.04$, $R_V = 3.1 \pm 0.2$, and $d_0 = 1.66$ kpc. By comparing their photometric results with theoretical evolution models, they derived a main-sequence turnoff (MSTO) age of 1.9 Myr and a PMS age spread of about 6 Myr. The IMF slope calculated for the mass range $3.2 \lesssim m(M_\odot) \lesssim 100$ is flat ($y = -0.3 \pm 0.1$).

Berghofer & Christian (2002) used optical photometry of X-ray selected stars to estimate an isochrone age of 3 Myr, but significantly younger stars are detected.

L$^2$ (2005) provided updates on the nature of this young OC, including its central position, physical scale, and stellar population. They found substructures in NGC 2244 with 2MASS, in particular a companion 6.6 pc west (in fact $\approx 2.3$ pc) from the cluster center.

In a Chandra study of NGC 2244, Wang et al. (2008) detected over 900 X-ray sources, 77% of which having optical or FLAMINGOS NIR counterparts. Their X-ray-selected population is estimated to be nearly complete between 0.5 and 3 $M_\odot$. The K-band LFs indicate a normal Salpeter IMF for NGC 2244, which differs from the top-heavy one reported in earlier optical studies that lacked a good census of $\lesssim 4$ $M_\odot$ stars. The X-ray LF indicates a population of $\approx 2000$ stars with a spatial distribution strongly concentrated around the central 05 star, HD 46150. The other early O star, HD 46223, has few companions. The cluster’s stellar RDP shows two structures: a power-law cusp around HD 46150 extending for $\sim 0.7$ pc, surrounded by an isothermal sphere reaching out to 4 pc with core radius $R_c = 1.2$ pc. This double structure, combined with the absence of mass

---

1 The Two Micron All Sky Survey, All Sky data release Skrutskie et al. (1997), available at http://www.ipac.caltech.edu/2mass/releases/allsky/

2 obswww.univie.ac.at/webda
The very young OCs NGC 2244 and NGC 2239

Figure 1. Top-left panel: $1^\circ \times 1^\circ$ DSS B image of NGC 2244 and the Rosette Nebula, centred on the coordinates of Table 1. Right: $30^\prime \times 30^\prime$ image of the same region; circles indicate the cluster radii (Sect. 5) of NGC 2244 (East) and NGC 2239 (West). Several centres adopted for these clusters are identified in the right panel. The K0V star 12 Mon is indicated by position 'B'. Other positions as indicated by the keys in Table 1. Bottom: $K_s$ image of NGC 2244 taken from the 2MASS Image Service focusing on the compact core within $3^\prime \times 3^\prime$. Same centre as in the B image. Orientation: North to the top and East to the left.

Though the X-ray spectra of OB stars are soft and consistent with the standard model of small-scale shocks in the inner wind of a single massive star, the fraction of X-ray-selected members with $K$-band excesses caused by inner protoplanetary discs is 6%, slightly lower than the 10% disc fraction estimated from FLAMINGOS. The Rosette X-ray spectra of OB stars are soft and consistent with the standard model of small-scale shocks in the inner wind of a single massive star.

Recently, Román-Zúñiga & Lada (2008) reviewed the Rosette Complex, in particular they refer to the position of two OCs, NGC 2244 at position 'C' in the top-right panel of Fig. 1 and the other at position 'A', designated as NGC 2237. We call attention that their NGC 2244 actually is in the region of the original NGC 2239, while NGC 2237 refers to NGC 2244, near the position of HD 46150.

Román-Zúñiga & Lada (2008) build a scenario where an expanding H II region generated by a large OB association interacts with a giant molecular cloud, which harbours a number of embedded and open clusters.

The wealth of papers on NGC 2244 reflects the complex - and, at the same time beautiful - nature of the interplay between bright massive stars, faint pre-MS stars and a thinning dust shroud, all embodied in a single and relatively nearby object. Fig. 1 illustrates this scenario. In the
Table 1. Previously adopted centres of NGC 2244 and NGC 2239

| Cluster         | α (2000) (hms) | δ (2000) (°′″) | ℓ (°) | b (°) | Key | R | Reference               |
|-----------------|----------------|----------------|--------|-------|-----|---|-------------------------|
| (1)             | (2)            | (3)            | (4)    | (5)   | (6) | (7) | (8)                     |
| NGC 2237        | 06:31:58.5     | +04:54:35.7    | 206.34 | −2.07 | A   | —  | Román-Zúñiga & Lada (2008) |
| NGC 2244        | 06:32:18.0     | +04:52:00.0    | 206.42 | −2.02 | B   | —  | Sulentic & Tifft (1973)   |
| NGC 2244        | 06:30:36.1     | +04:58:50.6    | 206.12 | −2.34 | C   | —  | Román-Zúñiga & Lada (2008) |
| NGC 2244        | 06:31:55.0     | +04:58:30.0    | 206.28 | −2.06 | D   | —  | WEBDA                   |
| NGC 2244/12 Mon | 06:32:19.2     | +04:51:21.6    | 206.43 | −2.02 | E   | ~ 24| SIMBAD                  |
| NGC 2244        | 06:31:55.4     | +04:56:35.3    | 206.30 | −2.07 | F   | ~ 10| This work               |
| NGC 2239        | 06:30:54.0     | +04:57:00.0    | 206.18 | −2.29 | G   | ~ 18| Sulentic & Tifft (1973)   |
| NGC 2239        | 06:30:57.3     | +04:58:09.0    | 206.17 | −2.27 | H   | ~ 5 | This work               |

Table Notes. (†): 12 Mon as the centre of NGC 2244. Col. 7: cluster radius.

3 Extracted from the Canadian Astronomy Data Centre (CADC), at [http://cadcwww.dnd.nrc.ca/](http://cadcwww.dnd.nrc.ca/)
4 http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=II/246
5 According to the 2MASS Level 1 Requirement, at [http://www.ipac.caltech.edu/2mass/releases/allsky/doc/](http://www.ipac.caltech.edu/2mass/releases/allsky/doc/)
6 http://simbad.u-strasbg.fr/simbad

DSS[4] B image (top-left panel) NGC 2244 emerges from the thin dust of the Rosette central part, which is also surrounded by strong gas emission. Indeed, gas emission and dust absorption are nearly absent in the XDSS image (top-right), and especially in the 2MASS image (bottom). Different centres adopted for NGC 2244 in previous (mostly optical) studies are indicated in the top-right panel. However, when seen in Ka, the cluster is highly concentrated on HD 46150 (bottom panel), suggesting a compact core. A similar centre for NGC 2244 had already been suggested by, e.g. Pérez, Thé & Westerlund [1987].

The different centres are summarised in Table 1 which shows some confusion in the identification of the actual centre of NGC 2244. As will be discussed in Sect. 5, we take as centre the coordinates that present the maximum stellar density (Fig. 11) computed within circles of 0.25′ in radius, for MS and PMS stars taken isolatedly (Sect. 3.3). The resulting coordinates (Table 1) are similar to those given by WEBDA. The same procedure was applied to find the centre of NGC 2239 (Sect. 5).

3 NEAR-IR AND OPTICAL PHOTOMETRIES COMPARED

Since the Rosette Nebula reaches about 1°, it is interesting to compare large-scale properties of the optical data with those in the near-IR.

2MASS J, H, and Ka photometry was extracted in a wide circular field with Vizier[4]. The basic condition is that the extraction radius Rext should be large enough to allow determination of the background level (Sect. 5). We used Rext = 50′ (NGC 2244) and Rext = 30′ (NGC 2239), which are considerably larger than the respective cluster radii (Sect. 5) and Table 1. In the absence of significant differential absorption [Bonatto & Bica 2002], wide extraction areas provide statistics for a consistent colour and magnitude characterisation of field stars. For decontamination purposes, comparison fields were extracted within wide rings located beyond the cluster radii. As photometric quality constraint, the 2MASS extractions were restricted to stars (i) brighter than the 99.9% Point Source Catalogue completeness limit in the cluster direction, and (ii) with errors in J, H, and Ka lower than 0.1 mag. The 99.9% completeness limits refer to field stars, and depend on Galactic coordinates. Figure 2 (panel a) shows the distribution of uncertainties as a function of magnitude for the stars in the direction of NGC 2244. The fraction of stars with J, H, and Ka uncertainties lower than 0.05 mag is ≈ 80%, ≈ 70% and ≈ 60%, respectively. We employ the relations Aλ/Av = 0.276, Aλ/Av = 0.176, Aλ/Av = 0.118, and Aj = 0.76 × E(J−H) [Dutra, Santiago & Bica 2002], with RV = 3.1. They stem from the extinction curve of Cardelli, Clayton & Mathis [1989].

The available B and V photometry for NGC 2244 was taken from SIMBAD[4] within the same extraction radius as that used for 2MASS. As expected, the number of detected stars at a given radius in the optical is significantly lower than in the near-IR (Fig. 2 panel b). Indeed, the ratio of the number of stars detected in the near-IR to the optical Nnear/Nopt increases with distance to the cluster centre, being Nnear/Nopt ≈ 2 for R ≤ 10′ (approximately the cluster region) and Nnear/Nopt ≈ 24 for R ≤ 80′. Except for the innermost region, the stellar spatial distribution detected with 2MASS follows a cluster-like profile (Sect. 5), while the optical distribution deviates by a large amount (panel b). One conclusion is that analysis based on star-counts in a dust-rich region is more realistic in the near-IR than in the optical. Also, panel (b) shows that dust is thicker at large radii. This may have introduced biases in some of the previous optical studies.

The spatial dependence of the colours towards NGC 2244 is examined in Fig. 2 for the 2MASS (panel c) and optical (e) bands. The fiducial lines have been built as running averages of the raw (observed) data, with 10 points for R < 2′, 100 for 2′ < R < 20′, and 1000 for R > 20′. Colours in both domains present a similar pattern, characterised by a blue core (R ≤ 2′) containing essentially the MS
stars. For larger radii, foreground stars dominate the optical photometry, while the near-IR probes deeper regions. A similar effect occurs in the average magnitudes (panels d and f).

As suggested by the $\Delta R = 6'$ linear extractions along the N-S and E-W directions (Fig. 3), a reasonable spatial uniformity level occurs with the 2MASS near-IR photometry. Besides NGC 2244 itself, the next conspicuous bump is caused by NGC 2239 at $\approx 15'$ to the West. These profiles guided the comparison field selection.

Finally, in Fig. 4 (top panels) we show the spatial distribution of the stellar surface-density ($\sigma$, in units of stars arcmin$^{-2}$) around NGC 2244, measured by 2MASS photometry. The surface density is computed in a rectangular mesh with cells of dimensions 2.5' $\times$ 2.5', with meshes reaching total offsets of $|\Delta \alpha| = |\Delta \delta| \approx 20'$ with respect to the centre (Table 1), in right ascension and declination. The respective isopheth surfaces are shown in the bottom panels, in which NGC 2239 shows up as a lower concentration at $\approx 15'$ to the West of NGC 2244. Two cases are considered in Fig. 4 the observed (raw) photometry (left panels) and the MS + PMS stars taken separately (right) by means of a colour-magnitude filter (Sect. 3.3). Since an important fraction of the contaminant stars are excluded by the colour-magnitude filter, the surface density distribution of NGC 2244 (and NGC 2239) is better defined with respect to the surroundings.
3.1 Colour-magnitude diagrams with 2MASS photometry

CMDs displaying the $J \times (J-K_s)$ and $K_s \times (J-K_s)$ colours built with the raw photometry of NGC 2244 are shown in Fig. 5 (panels a and b). The sampled region ($R < 5'$) corresponds to about half the cluster radius (Sect. 5). When qualitatively compared with the CMDs extracted from the equal-area comparison field (panels c and d), features typical of a very young OC emerge. A relatively vertical and populous MS (at $0.0 \lesssim (J-H), (J-K_s) \lesssim 0.3$) truncated for stars fainter than $\approx 12.5$ (or mass $\lesssim 2.8 \, M_\odot$ - Sect. 4) in both $J$ and $K_s$, stand out over the field contamination.

3.2 Field decontamination

As expected of low-Galactic latitude clusters (Table 1), the stellar surface-density in the direction of NGC 2244 (Fig. 4) confirms that the field-star contamination, including Mon OB2 and disc stars, should be taken into account. Further confirmation is provided by the qualitative comparison between the CMDs extracted within the cluster and field (Fig. 5). Obviously, the field contribution should be quantified for a better definition of the intrinsic CMD morphology.

Although difficult, decontamination is a very important step in the identification and characterisation of star clusters. Most of the different approaches (e.g. Mercer et al. 2004) are based essentially on two different premises. The first relies on spatial variations of the star-count density, but does not take into account CMD evolutionary sequences. Alternatively, stars of an assumed cluster CMD are subtracted according to similarity of colour and magnitude with the stars of an equal-area comparison field CMD. Together with the present one, these methods are based on photometric properties only. Ideally, more robust results on membership determination would be obtained if another independent parameter, such as the PM of member and comparison field stars, is taken into account. However, for PM to be useful the cluster should be relatively nearby (e.g. Alessi, Moitinho & Dias 2003) and/or to have been observed in widely-apart epochs preferentially with high resolution, as for the globular cluster (GC) NGC 6397 (Richer et al. 2008). Neither condition is fully satisfied for NGC 2244, which is relatively distant (Sect. 1) and was observed by 2MASS in a single epoch. As a consequence, only about 50% of the stars within $R = 10'$ of NGC 2244 have optical PM measured (Sect. 3.3).

Our decontamination algorithm is fully described in Bonatto & Bica (2007a, b) and Bica & Bonatto (2008). For clarity, we provide here only a brief description. The algorithm measures the relative number densities of probable field and cluster stars in cubic CMD cells with axes along the $J$ magnitude and the $(J-H)$ and $(J-K_s)$ colours. It (i) divides the full range of CMD magnitude and colours into a 3D grid, (ii) estimates the number density of field stars in each cell based on the number of comparison field stars with similar mag-
Figure 7. Similar to Fig. 6 for the region $R < 4'$ (panel a) of NGC 2239, and the equal-area comparison field (b). Panels (c)-(f): decontaminated CMD with different age/distance from the Sun solutions. Bright stars with SIMBAD optical data are indicated as open circles. Arrows show the reddening vector computed for $A_V = 2$.

3.2.1 Decontaminated surface densities and CMDs

We take the decontaminated surface-density distributions (Fig. 6) as an efficiency indicator. For the present clusters, the central excesses have been significantly enhanced with respect to the raw photometry (Fig. 1), while the residual surface-density around the centre has been reduced to a minimum level. By design, the decontamination depends essentially on the colour-magnitude distribution of stars located in different spatial regions. The fact that the decontaminated surface-density presents a conspicuous excess only at the assumed cluster position implies significant differences among this region and the comparison field, both in terms of colour-magnitude and number of stars within the corresponding colour-magnitude bins. This means cluster expectations, which can be characterised by a single-stellar population, projected against a Galactic stellar field.

The decontaminated CMDs are shown in the bottom panels of Figs. 6 and 7. As expected, essentially all contamination is removed, leaving stellar sequences typical of mildly reddened young OCs, with a well-developed MS and a significant population of PMS stars, especially in NGC 2244.

Although in both cases the MS width is rather tight and appears to be dominated by photometric errors, we cannot exclude the possibility of differential reddening to account for part of the observed spread, especially towards faint stars. To examine this issue we show, in Figs. 6 and 7 (panels e and f), reddening vectors computed with the 2MASS (Sect. 5.1) for a visual absorption $A_V = 2$, approximately the absorption derived for NGC 2244 and NGC 2239 (Sect. 3.1). Together with the decontaminated CMDs, this experiment shows that differential reddening in both clusters is not significant.

We conclude that the qualitative and quantitative expectations of the decontamination algorithm have been satisfied by the output. In both cases, the decontaminated photometry presents a relevant excess, with respect to the surroundings, in the surface-density distribution (Fig. 5). In addition, field-decontaminated CMDs extracted from the spatial regions where the excesses occur (Figs. 6 and 7), present statistically significant cluster CMDs.

3.3 Colour-magnitude filters

To minimise CMD noise, we apply colour-magnitude filters to the raw photometry to exclude stars with colours unlike those of the cluster sequence. The filters are wide enough to include cluster MS stars and the 1σ photometric uncertainties. For very young OCs such as NGC 2244 and NGC 2239, we also include filters to account for the PMS population. The colour-magnitude filters for the present OCs are shown in Figs. 6 and 7.

3.4 Proper motions

Another indication of the star cluster nature of NGC 2239 is provided by NOMAD PM data taken for the stars extracted within the same spatial region as the 2MASS data. However, the correspondence between NOMAD and 2MASS detections is not complete, with $\approx 50\%$ of the stars detected with 2MASS included in NOMAD, for the colour-magnitude filtered photometry of both NGC 2244 and NGC 2239.

In Fig. 8 we show histograms of the right ascension.
NGC 2244 (Fig. 6) and NGC 2239 (Fig. 7) present MS and PMS stellar distributions as constraints. We adopt solar metallicity isochrones because the clusters are young and not far from the Solar circle (see below), a region essentially occupied by \([Fe/H] \approx 0.0\) OCs \(^9\) (Franciosini et al. 2003).

To deal with the MS we use Padova isochrones \(^{10}\) (Girardi et al. 2002) computed with the 2MASS \(J, H,\) and \(K_s\) filters. The tracks of Siess, Dufour & Forestini \((2000)\) are used to characterise the PMS distributions.

We take \(R_\odot = 7.2 \pm 0.3\) kpc \(^9\) (Bica et al. 2004) as the Sun’s distance to the Galactic centre to compute Galactocentric distances, a value derived by means of the GC spatial distribution. \(^{10}\)

Historically, different approaches have been used to extract astrophysical parameters from isochrone fits. The simplest ones are based on a direct comparison of a set of isochrones with the CMD morphology, while the more sophisticated ones include photometric uncertainties, binarism, and metallicity variations. Most of these methods are summarised in Naylor & Jeffries \((2006)\), in which a maximum-likelihood CMD fit method is described. We caution that, because of the 2MASS photometric uncertainties for the lower sequences, a more sophisticated approach for isochrone fitting might lead to an overinterpretation.

For the above reasons, fits are made by eye, with the MS and PMS stellar distributions as constraint. We also require that, because of the probable presence of binaries, the adopted (single-star) MS isochrone should be shifted somewhat to the left of the MS fiducial line, i.e. a median line that takes into account the MS spread, including the photometric uncertainties as well \((e.g.\) Bonatto, Bica & Santos Jr. \((2003)\) and references therein). In the following we discuss the present clusters individually.

### 4.1 NGC 2244

The decontaminated CMD morphology of NGC 2244 (Fig. 8) shows a nearly-vertical MS at \(J \lesssim 13\) and \(0.0 \lesssim (J - K_s) \lesssim 0.4\), and a population of low-mass PMS stars at \(J \gtrsim 13.5\) and \(0.9 \lesssim (J - K_s) \lesssim 1.5\). Taken together, these stellar sequences unambiguously characterise a very young OC.

Allowing for photometric uncertainties, acceptable fits to the decontaminated MS morphology are obtained with any isochrone with age in the range 1—6 Myr. The PMS stars in Fig. 8 are basically contained within the 0.2 Myr and 0.6 Myr PMS isochrones \((\text{Siess, Dufour & Forestini} \ 2000)\), thus implying a similar age range as the MS. Accordingly, we take the 3 Myr isochrone as representative solution.

With the adopted solution, the fundamental parameters of NGC 2244 are a near-IR reddening \(E(J - H) = 0.17 \pm 0.02\) (or \(E(B - V) = 0.54 \pm 0.06\) and \(A_V = 1.7 \pm 0.2\), an observed and absolute distance moduli \((m - M)_J = 11.5 \pm 0.2\) and \((m - M)_D = 11.03 \pm 0.21\), respectively, and a distance

---

\(^{9}\) \text{http://stev.oapd.inaf.it/cgi-bin/cmd} \quad \text{These isochrones are very similar to the Johnson-Kron-Cousins ones (e.g. Bessell & Brett (1988), with differences of at most 0.01 in colour (Bonatto, Bica & Girardi (2003).}\n
\(^{10}\) Other recent studies gave similar results, e.g. \(R_\odot = 7.2 \pm 0.9\) kpc \((\text{Eisenhauer et al.} \ 2003)\), \(R_\odot = 7.62 \pm 0.32\) kpc \((\text{Eisenhauer et al.} \ 2009)\) and \(R_\odot = 7.52 \pm 0.10\) kpc \((\text{Nishiyama et al.} \ 2006)\), with different approaches.
Together with young MS and PMS isochrones, both distances are used as starting point to search for fundamental parameters. The possible solutions are summarised in Fig. 9 for both the far (left panels) and near (right) distances. We consider the MS ages of 1 Myr (middle panels) and 5 Myr (bottom). The best fit for these ages was for $d_\odot \approx 3.9 \pm 0.4$ kpc and $d_\odot \approx 1.7 \pm 0.3$ kpc. Within uncertainties, they are consistent with those derived for the bright stars. The MS+PMS solutions for $d_\odot \approx 3.9$ kpc (Fig. 9 panels c and f) appear to account for essentially all of the decontaminated CMD sequences. Irrespective of age, the near solutions, on the other hand, fail to explain several faint stars below the MS.

Considering all available morphological and photometric properties, the best overall CMD fit (Fig. 9 panel e) corresponds to an age 5 ± 4 Myr, $E(J − H) = 0.34 \pm 0.02$, $E(B − V) = 1.10 \pm 0.06$, $A_V = 3.4 \pm 0.2$, $(m − M)_J = 13.9 \pm 0.2$, $(m − M)_O = 12.95 \pm 0.21$, $d_\odot = 3.9 \pm 0.4$ kpc, and $R_{GC} = 10.8 \pm 0.3$ kpc, thus $\approx 3.6$ kpc outside the Solar circle. Thus, the B5 star GSC00154-01659 is probably a cluster member, while the A2 star GSC00154-01659 is probably in the foreground. We conclude that NGC 2239 lies $\approx 2.3$ kpc in the background of NGC 2244.

### 4.3 Colour-colour diagrams

When transposed to the near-IR colour-colour diagrams $(J − K_s) \times (H − K_s)$, the age and reddening solutions of NGC 2244 and NGC 2239 derived above consistently match the field-star decontaminated photometry of these OCs (Fig. 9 left panels). Since they include PMS stars, we use tracks of Siess, Dufour & Forestini (2000) to characterise the age of NGC 2244 (≈ 3 Myr) and NGC 2239 (≈ 5 Myr). MS stars lie on the blue side of the diagram. Interestingly, only a low fraction of the stars of these OCs appears to be very reddened. In both cases, the distribution suggests a low fraction of disc stars, consistent with the estimates in the range 6-10% (Wang et al. 2008).

### 4.4 The fraction of PMS and MS stars

Right after formation, most of a cluster’s mass is stored in the PMS stars that, eventually, shed the dust layers and emerge into the MS (Sect. 1). Thus, the number of MS and PMS stars evolve in opposite directions with cluster age, till all stars are in the MS. Indeed, NGC 2244 and NGC 2239 present different fractions of MS and PMS stars (Figs. 9 and 10), which is consistent with the different ages.

To further explore this issue we compute the ratio of the number of PMS to MS stars $f_{PMS/MS} = n_{PMS}/n_{MS}$. Then we examine the age dependence of $f_{PMS/MS}$ for the very young OCs, located at a similar distance as NGC 2244, studied by our group with the same methods as those employed in NGC 2244 and NGC 2239. These conditions are satisfied by NGC 6611 (1.3 ± 0.3 Myr, $d_\odot \approx 0.6$, $V = 3$ kpc in the background of NGC 2244.

Together with young MS and PMS isochrones, both distances are used as starting point to search for fundamental parameters. The possible solutions are summarised in Fig. 9 for both the far (left panels) and near (right) distances. We consider the MS ages of 1 Myr (middle panels) and 5 Myr (bottom). The best fit for these ages was for $d_\odot \approx 3.9 \pm 0.4$ kpc and $d_\odot \approx 1.7 \pm 0.3$ kpc. Within uncertainties, they are consistent with those derived for the bright stars. The MS+PMS solutions for $d_\odot \approx 3.9$ kpc (Fig. 9 panels c and f) appear to account for essentially all of the decontaminated CMD sequences. Irrespective of age, the near solutions, on the other hand, fail to explain several faint stars below the MS.

Considering all available morphological and photometric properties, the best overall CMD fit (Fig. 9 panel e) corresponds to an age 5 ± 4 Myr, $E(J − H) = 0.34 \pm 0.02$, $E(B − V) = 1.10 \pm 0.06$, $A_V = 3.4 \pm 0.2$, $(m − M)_J = 13.9 \pm 0.2$, $(m − M)_O = 12.95 \pm 0.21$, $d_\odot = 3.9 \pm 0.4$ kpc, and $R_{GC} = 10.8 \pm 0.3$ kpc, thus $\approx 3.6$ kpc outside the Solar circle. Thus, the B5 star GSC00154-01659 is probably a cluster member, while the A2 star GSC00154-01659 is probably in the foreground. We conclude that NGC 2239 lies $\approx 2.3$ kpc in the background of NGC 2244.

### 4.3 Colour-colour diagrams

When transposed to the near-IR colour-colour diagrams $(J−K_s) \times (H−K_s)$, the age and reddening solutions of NGC 2244 and NGC 2239 derived above consistently match the field-star decontaminated photometry of these OCs (Fig. 9 left panels). Since they include PMS stars, we use tracks of Siess, Dufour & Forestini (2000) to characterise the age of NGC 2244 (≈ 3 Myr) and NGC 2239 (≈ 5 Myr). MS stars lie on the blue side of the diagram. Interestingly, only a low fraction of the stars of these OCs appears to be very reddened. In both cases, the distribution suggests a low fraction of disc stars, consistent with the estimates in the range 6-10% (Wang et al. 2008).

### 4.4 The fraction of PMS and MS stars

Right after formation, most of a cluster’s mass is stored in the PMS stars that, eventually, shed the dust layers and emerge into the MS (Sect. 1). Thus, the number of MS and PMS stars evolve in opposite directions with cluster age, till all stars are in the MS. Indeed, NGC 2244 and NGC 2239 present different fractions of MS and PMS stars (Figs. 9 and 10), which is consistent with the different ages.

To further explore this issue we compute the ratio of the number of PMS to MS stars $f_{PMS/MS} = n_{PMS}/n_{MS}$. Then we examine the age dependence of $f_{PMS/MS}$ for the very young OCs, located at a similar distance as NGC 2244, studied by our group with the same methods as those employed in NGC 2244 and NGC 2239. These conditions are satisfied by NGC 6611 (1.3 ± 0.3 Myr, $d_\odot \approx 0.6$, $V = 3$ kpc in the background of NGC 2244.

Together with young MS and PMS isochrones, both distances are used as starting point to search for fundamental parameters. The possible solutions are summarised in Fig. 9 for both the far (left panels) and near (right) distances. We consider the MS ages of 1 Myr (middle panels) and 5 Myr (bottom). The best fit for these ages was for $d_\odot \approx 3.9 \pm 0.4$ kpc and $d_\odot \approx 1.7 \pm 0.3$ kpc. Within uncertainties, they are consistent with those derived for the bright stars. The MS+PMS solutions for $d_\odot \approx 3.9$ kpc (Fig. 9 panels c and f) appear to account for essentially all of the decontaminated CMD sequences. Irrespective of age, the near solutions, on the other hand, fail to explain several faint stars below the MS.

Considering all available morphological and photometric properties, the best overall CMD fit (Fig. 9 panel e) corresponds to an age 5 ± 4 Myr, $E(J − H) = 0.34 \pm 0.02$, $E(B − V) = 1.10 \pm 0.06$, $A_V = 3.4 \pm 0.2$, $(m − M)_J = 13.9 \pm 0.2$, $(m − M)_O = 12.95 \pm 0.21$, $d_\odot = 3.9 \pm 0.4$ kpc, and $R_{GC} = 10.8 \pm 0.3$ kpc, thus $\approx 3.6$ kpc outside the Solar circle. Thus, the B5 star GSC00154-01659 is probably a cluster member, while the A2 star GSC00154-01659 is probably in the foreground. We conclude that NGC 2239 lies $\approx 2.3$ kpc in the background of NGC 2244.

### 4.3 Colour-colour diagrams

When transposed to the near-IR colour-colour diagrams $(J−K_s) \times (H−K_s)$, the age and reddening solutions of NGC 2244 and NGC 2239 derived above consistently match the field-star decontaminated photometry of these OCs (Fig. 9 left panels). Since they include PMS stars, we use tracks of Siess, Dufour & Forestini (2000) to characterise the age of NGC 2244 (≈ 3 Myr) and NGC 2239 (≈ 5 Myr). MS stars lie on the blue side of the diagram. Interestingly, only a low fraction of the stars of these OCs appears to be very reddened. In both cases, the distribution suggests a low fraction of disc stars, consistent with the estimates in the range 6-10% (Wang et al. 2008).

### 4.4 The fraction of PMS and MS stars

Right after formation, most of a cluster’s mass is stored in the PMS stars that, eventually, shed the dust layers and emerge into the MS (Sect. 1). Thus, the number of MS and PMS stars evolve in opposite directions with cluster age, till all stars are in the MS. Indeed, NGC 2244 and NGC 2239 present different fractions of MS and PMS stars (Figs. 9 and 10), which is consistent with the different ages.

To further explore this issue we compute the ratio of the number of PMS to MS stars $f_{PMS/MS} = n_{PMS}/n_{MS}$. Then we examine the age dependence of $f_{PMS/MS}$ for the very young OCs, located at a similar distance as NGC 2244, studied by our group with the same methods as those employed in NGC 2244 and NGC 2239. These conditions are satisfied by NGC 6611 (1.3 ± 0.3 Myr, $d_\odot \approx 0.6$, $V = 3$ kpc in the background of NGC 2244.
Figure 10. The ratio of the number of PMS to MS stars follows an exponential-decay function (dashed line) with cluster age: \( n_{PMS}/n_{MS} \propto \exp(-\text{age}/\tau) \), with \( \tau = 5.6 \pm 1.6 \text{Myr} \). Fit uncertainties (1\( \sigma \)) are within the shaded region.

Despite the considerable uncertainties in age and the relatively small number of clusters, the \( f_{PMS/MS} \) ratios shown in Fig. 10 appear to be consistent with the expected trend with cluster age. Indeed, we found that the ratios follow the exponential-decay function \( f_{PMS/MS} \propto e^{-(\text{age}/\tau)} \), with the time-scale \( \tau = 5.6 \pm 1.6 \text{Myr} \). Thus, it would take less than about 30 \text{Myr} for a cluster to retain only \( \approx 5\% \) (a typical Poisson fluctuation) of the original PMS stars. It would be interesting to check this trend - and the above time-scale - for a statistically significant sample of young clusters, so that other parameters, such as cluster mass, and environmental effects can be considered as well.

5 CLUSTER STRUCTURE

We use the projected stellar RDPs, defined as the stellar number density around the cluster centre, to derive structural parameters. To minimise noise, we work with colour-magnitude filtered photometry to isolate the MS and PMS stars, which enhances the RDP contrast relative to the background, especially in crowded fields (e.g. Bonatto & Bica 2007b). However, field stars with colours similar to those of the cluster are expected to remain inside the colour-magnitude filter, affecting the intrinsic RDP in a way that depends on the relative densities of field and cluster stars. The contribution of the residual contamination to the observed RDP is statistically evaluated by means of its extension into the field.

Rings of increasing width with distance from the cluster centre are built to avoid oversampling near the centre and undersampling at large radii. The set of ring widths used is \( \Delta R = 0.25, 0.5, 1.0, 2.0, \) and \( 5' \), respectively for \( 0' \leq R < 0.5', 0.5' \leq R < 2', 2' \leq R < 5', 5' \leq R < 20', \) and \( R \geq 20' \). The residual background level of each RDP corresponds to the average number-density of filtered field stars. The \( R \) coordinate (and uncertainty) of each ring corresponds to the average position and standard deviation of the stars inside the ring.

The colour-magnitude filtered RDPs of the clusters are shown in Fig. 11. As expected, minimisation of the number of non-cluster stars by the colour-magnitude filter resulted in RDPs with a high contrast relative to the background. For NGC 2244 we also show the RDPs built with the MS and PMS stars separately (left panels). Interestingly, while the MS RDP (panel b) has a conspicuous density excess for \( R \approx 0.15' \), the PMS stars (panel c) are found only for \( R \geq 0.4' \). The presence of NGC 2244 causes a bump in the MS RDP of NGC 2244 (panel b). Similarly, NGC 2244 shows up in the RDP of NGC 2239 (d). Fig. 11 also shows the RDP produced with the star 12 Mon as centre (panel d). It is clear that 12 Mon cannot be the centre of NGC 2244.

Most star clusters have RDPs that follow a well-defined analytical profile e.g., the empirical, single mass, modified isothermal spheres of [King 1966] and [Wilson 1973], and the power law with a core of [Elson, Fall & Freeman 1987]. Each function is characterised by a different set of parameters that are related to cluster structure. For simplicity and considering the error bars of the RDPs in Fig. 11, we adopt the function \( \sigma(R) = \sigma_0 + \sigma_0/(1 + (R/R_c)^2) \), where \( \sigma_0 \) is the residual background density, \( \sigma_0 \) is the central density of stars, and \( R_c \) is the core radius. It is similar to the function introduced by [King 1962] to describe the surface brightness profiles in the central parts of GCs. To minimise degrees of freedom, \( \sigma_0 \) and \( R_c \) are obtained from the fit, while \( \sigma_0 \) is measured in the field. The RDP bins corresponding to the neighbouring clusters were ignored in the fit. The best-fit solutions are shown in Fig. 11 and the parameters are given in Table 2. For absolute comparison with other clusters, Table 2 gives parameters in absolute units.

Within uncertainties, the adopted King-like function describes well the colour-magnitude filtered RDP of NGC 2239 (panel d) along the full radius range. The same applies only for \( R \gtrsim 1' \) for the RDP of NGC 2244. The innermost bin in the MS (and to a lesser degree to the MS+PMS) RDP (panel b) presents a several \( \sigma \) excess over the fit. This RDP cusp basically corresponds to the detached grouping of stars (with a diameter of \( \approx 0.25' \)) around HD 46150, seen in Fig. 11 (bottom-right panel). Our inner RDP shape agrees with that derived by [Wang et al. 2008] with FLAMINGOS. In old star clusters, such a central RDP excess can be attributed to a post-core collapse, like...
Table 2. Derived cluster structural parameters

| Cluster      | $\sigma_{bg}$ | $\sigma_0$ | $R_c$ | $R_{RDP}$ | $\delta_c$ | $I'$ | $\sigma_{bg}$ | $\sigma_0$ | $R_c$ | $R_{RDP}$ |
|--------------|---------------|------------|-------|-----------|------------|-----|---------------|------------|-------|-----------|
| NGC2244$^\dagger$ | 1.53 ± 0.02  | 3.87 ± 0.65 | 5.6 ± 0.8 | 10.0 ± 2.0 | 3.5 ± 0.6 | 0.466 | 7.0 ± 0.4 | 17.8 ± 3.0 | 2.6 ± 0.4 | 4.7 ± 0.9 |
| NGC2244$^\ddagger$ | 0.12 ± 0.01  | 0.95 ± 0.43 | 1.2 ± 0.9 | 8.0 ± 1.0  | 9.2 ± 4.1 | 0.466 | 0.5 ± 0.1 | 4.4 ± 1.9  | 0.6 ± 0.4 | 3.7 ± 0.5 |
| NGC2244$^*$  | 1.41 ± 0.09  | 3.61 ± 0.61 | 5.7 ± 0.8 | 12.0 ± 2.0 | 3.6 ± 0.6 | 0.466 | 6.5 ± 0.4 | 16.6 ± 2.8 | 2.7 ± 0.4 | 5.6 ± 0.9 |
| NGC2239$^\circ$ | 1.90 ± 0.05  | 12.77 ± 4.77 | 0.5 ± 0.1 | 5.0 ± 1.0  | 7.7 ± 2.9 | 1.127 | 1.5 ± 0.1 | 10.0 ± 3.7 | 0.5 ± 0.1 | 5.6 ± 1.1 |

Table Notes. RDPs built considering separately the MS+PMS (†), MS ($\ddagger$) and PMS ($*$). Core ($R_c$) and cluster ($R_{RDP}$) radii are given in angular and absolute units. Col. 6: cluster/background density contrast parameter ($\delta_c = 1 + \sigma_0/\sigma_{bg}$), measured in the colour-magnitude filtered RDPs. Col. 7: arcmin to parsec scale.

Figure 11. Stellar RDPs built with colour-magnitude filtered photometry. Solid line: best-fit King-like profile. Horizontal shaded polygon: background. Shaded regions: 1σ King fit uncertainty. Note the central density excess in the RDP of NGC 2244 in panels (a) and (b). The RDP with 12 Mon as centre in shown in (d).

those detected in some GCs (e.g. Trager, King & Djorgovski 1995). It has been detected as well in Gyr-class OCs, such as, e.g. NGC3960 (Bonatto & Bica 2006) and LK 10 (Bonatto & Bica 2009). Another very young cluster harbouring such a detached core producing an RDP central cusp is NGC6823 (Bica, Bonatto & Dutra 2008). Clusters are not expected to dynamically evolve into a post-core collapse on short time-scales, and the cusp must have been caused by star-forming effects. The compact core within the eroded profile of Bochum1 (Bica, Bonatto & Dutra 2008) can be a long-lived structure in young clusters. Consequently, this central cusp in such a young cluster as NGC2244 suggests a significant deviation from dynamical equilibrium (Sect. 7).

The density contrast parameter $\delta_c = 1 + \sigma_0/\sigma_{bg}$, which is relatively high ($3.5 < \delta_c < 9.2$) for the present RDPs, is also given in Table 2. Since $\delta_c$ is measured in colour-magnitude filtered (lower noise) RDPs, it is usually higher than the visual contrast produced by images (e.g. Fig. 1). Taken at face value, the core radius of NGC2244 (for the MS+PMS stars) $R_c \sim 2.6$ pc would put it beyond the median value of the distribution derived for a sample of relatively nearby OCs by Piskunov et al. (2007), NGC2239, on the other hand, falls on the low-$R_c$ tail. Besides, assuming the relation tidal radius $\sim 2 \times R_{RDP}$ (Bonatto & Bica 2003), both clusters fall around the median value of the tidal radius distribution.

6 CLUSTER MASS

Both clusters clearly present distinct populations of MS and PMS stars (Figs. 6 and 7). As the first step to estimate the cluster masses we build the luminosity functions (LFs) in the $K_s$ band for the MS and PMS stars separately, by means of the respective colour-magnitude filters (Sect. 3.2). We show them in Fig. 12, where the similar age, different distances and number of members are reflected, especially on the different MS and PMS cutoffs. In both cases the PMS LFs present the expected steep increase towards faint magnitudes, as expected from MS LFs. The very young OCs NGC 2244 and NGC 2239, the tidal radii are a factor $\sim 6$ pc would put it beyond the...
magnitudes (low-mass stars), which confirms that PMS stars are an important fraction of the members.

For a more objective investigation on the stellar mass distribution we build the MFs \( \phi(m) = \frac{dn}{dm} \) for the current MS stars that, in turn, can be used to compute the mass stored in stars. Similarly to the RDPs (Sect. 3), we work with colour-magnitude filtered photometry to minimise noise. First we build the LF independently for each 2MASS band, both for the cluster region \((R < R_{\text{RDS}})\) and comparison field. The intrinsic LFs are obtained by subtracting the respective (equal-area) comparison field LF from that of the cluster. The intrinsic LFs are transformed into MFs with the mass-luminosity relations obtained from the corresponding age and distance from the Sun solutions (Sect. 4). The final MF is produced by combining the \( J, H \) and \( K_s \) MFs into a single MF. Further details on MF construction are given in Bica, Bonatto & Blumberg (2006). The effective MS stellar mass ranges are \((4.6 \pm 2.2) \leq m(M_\odot) \leq 60 \) (NGC 2244) and \((3.2 \pm 0.5) \leq m(M_\odot) \leq 14 \) (NGC 2239). As Fig. 12 (bottom panels) shows, the MS MFs are rather smooth and present different lower and upper masses, which reflects the lower distance and younger age of NGC 2244 with respect to NGC 2239.

Since PMS stars are abundant in both clusters, it is important to build their MF as well. In Fig. 7 (right panels) we show the evolutionary tracks (Siess, Dufour & Forestini 2000) of PMS stars of different masses superimposed on the decontaminated CMDs of NGC 2244 and NGC 2239. It is clear, especially for NGC 2244, that PMS stars less massive than \( 1 M_\odot \) are the most abundant component. Similarly to the MS, the PMS MFs are built with the number of PMS stars among any two tracks in the cluster region and comparison field. Finally, we add the MS and PMS MFs to produce the total MF of each cluster (Fig. 12).

The number of MS \( (n_{\text{MS}}) \) and PMS \( (n_{\text{PMS}}) \) members in NGC 2244 (for \( R < R_{\text{RDS}} \)) are derived by counting the stars in the background-subtracted colour-magnitude filtered photometry. We apply the same approach as above to compute the PMS mass. There are \( n_{\text{MS}} = 26 \pm 3 \) and \( n_{\text{PMS}} = 301 \pm 60 \) stars; the corresponding mass values are \( m_{\text{MS}} = 389 \pm 44 \) \( M_\odot \) and \( m_{\text{PMS}} = 236 \pm 46 \) \( M_\odot \) (computed assuming the average mass between any two evolutionary tracks in Fig. 7). Thus, the total stellar mass of NGC 2244 is \( m_{\text{MS+PMS}} \approx 625 M_\odot \), which agrees with the \( 770 M_\odot \) mass estimated by Pérez (1994). We note that this value is about 10\% of the mass estimated by Ojha & Ishida (1981) for NGC 2244. However, this difference may arise from the present detailed analysis - especially the decontamination and the separation of MS and PMS stars in the construction of the cluster MF. The same analysis applied to NGC 2239 yields \( n_{\text{MS}} = 26 \pm 3, n_{\text{PMS}} = 70 \pm 11, m_{\text{MS}} = 141 \pm 16 M_\odot, m_{\text{PMS}} = 160 \pm 32 M_\odot \), and the total stellar mass \( m_{\text{MS+PMS}} \approx 301 M_\odot \), about half the mass of NGC 2244.

Considering the MS stars isolated, the MFs can be well represented by the function \( \phi(m) \propto m^{-(1+\chi)} \), with the slopes \( \chi = 0.24 \pm 0.09 \) and \( \chi = 0.76 \pm 0.08 \), respectively for NGC 2244 and NGC 2239. Both values are flatter than the \( \chi = 1.35 \) of Salpeter (1955) initial mass function (IMF). A flat MF slope was also found for NGC 2244 by Park & Sung (2002). However, when the MS and PMS stars are taken together, the slopes become steeper, \( \chi = 0.91 \pm 0.13 \) and \( \chi = 1.24 \pm 0.06 \). While within uncertainties the total MF of NGC 2239 is comparable to the Salpeter (1955) IMF, the MF of NGC 2244 remains somewhat flatter, but still consistent with the conclusions of Wang et al. (2008).

### 7 DISCUSSION

Constrained by isochrone fits (Sect. 4), we could derive fundamental and structural parameters of the young OCs NGC 2244 and NGC 2239, part of them for the first time. We use them to compare some of their properties with those of well-studied OCs.

#### 7.1 Diagnostic diagrams

We further investigate the nature of NGC 2244 and NGC 2239 with diagrams that examine relations among astrophysical parameters of OCs in different environments. They were introduced by Bonatto & Bica (2003). As reference sample we use some bright nearby OCs (Bonatto & Bica 2003; Bonatto et al. 2006a), and a group of OCs projected towards the central parts of the Galaxy (Bonatto & Bica 2007a). Also included are the young OCs NGC 6611 with the age \( \sim 1.3 \) Myr (Bonatto, Santos Jr. & Bica 2006), NGC 6823 with \( \sim 4 \) Myr and Bochum I with \( \sim 9 \) Myr (Bica, Bonatto & Dutra 2008).
NGC 6611 and NGC 6823 serve as comparison with gravitationally bound objects of similar age, while Bochum 1 is a star cluster fossil remain that might be dynamically evolving into an OB association. The full sample of comparison OCs is characterised by ages in the range \( \sim 1.3 \text{ Myr} \) to \( \sim 7 \text{ Gyr} \), and Galactocentric distances within \( 5.8 \lesssim R_{\text{GC}} \text{(kpc)} \lesssim 8.1 \).

Their parameters have been obtained following the same prescriptions as those for NGC 2244 and NGC 2239.

The diagrams are shown in Fig. 13, where panels (a) and (b) examine the dependence of cluster \( (R_{\text{RDP}}) \) and core \( (R_c) \) radii on cluster age, respectively. Most of the small-radius OCs (especially in \( R_{\text{RDP}} \)) occur at an age \( \sim 0.5 - 1 \text{ Gyr} \), the typical time-scale of OC disruption processes near the Solar circle (e.g. Bergond, Leon & Guilbert 2001; Lamers et al. 2003). Both NGC 2244 and NGC 2239 present a cluster radius comparable to that of NGC 6611 (and in general equivalent to other young OCs). The same applies to the core radius of NGC 2239. NGC 2244, on the other hand, has an \( R_c \) too large when compared to the reference OCs.

Core and cluster radii of the reference OCs follow the relation \( R_{\text{RDP}} = (8.9 \pm 0.3) \times R_c^{1.0+0.1} \) (panel c) suggesting a similar scaling for both kinds of radii. While NGC 2239 fits tightly in that relation, NGC 2244 deviates again probably because of the exceeding cluster radius. A dependence of OC size on Galactocentric distance is suggested by panel (d), as discussed by Lynga (1982) and Tadross et al. (2002). While NGC 2244 follows the trend, NGC 2239 deviates somewhat. This relation may be partly primordial, in the sense that the high molecular gas density in central Galactic regions may have produced small clusters (e.g. van den Bergh, Morby & Pazder 1991). After formation, mass loss due to stellar and dynamical evolution (e.g. mass segregation and evaporation), together with tidal interactions with the Galactic potential and giant molecular clouds, also contribute to the depletion of star clusters, especially the low-mass and centrally located ones.

When the mass-density radial distribution follows a King-like profile (e.g. Bonatto & Bica 2007), the cluster mass inside \( R_{\text{RDP}} \) can be computed as a function of the core radius \( (R_c) \) and the central mass-surface density \( (\sigma_{\text{core}}) \), \( M_{\text{clus}} = \pi R_c^2 \sigma_{\text{core}} \ln [1 + (R_{\text{RDP}}/R_c)^2] \). With the above relation (panel c) between \( R_c \) and \( R_{\text{RDP}} \), this equation becomes \( M_{\text{clus}} \approx 13.8 \sigma_{\text{core}} R_c^3 \). The observed relation of core radius and cluster mass is examined in panel (e). The reference OCs, together with NGC 2239 and especially NGC 2244, are contained within King-like distributions with central mass densities within \( 30 \lesssim \sigma_{\text{core}} \text{(M}_\odot \text{ pc}^{-2}) \lesssim 600 \). NGC 2244 appears to have too big a core radius for its total mass.

Finally, when the total (MS+PMS) MF slope is considered (panel f), NGC 2239 and especially NGC 2244, appear to have MFs flatter than those of similarly young OCs. On the other hand, their slopes are equivalent to those derived for some old OCs in the reference sample. In general, flat MFs reflect advanced dynamical evolution (e.g. Bonatto & Bica 2003).

What follows from the above analysis is that while NGC 2239 appears to be characterised by parameters of a typical young OC, NGC 2244, on the other hand, exhibits evidence of a system far from dynamical equilibrium, which agrees with Chen, de Grijs & Zhao (2007) and Wang et al. (2008).

### 8 SUMMARY AND CONCLUSIONS

In the present paper we employ the wide-field and near-IR depth provided by 2MASS to focus on the Rosette Nebula cluster NGC 2244 and the nearby projected OC NGC 2239. Our approach relies essentially on field-star decontaminated 2MASS photometry, which enhances cluster CMD evolutionary sequences and stellar radial density profiles, producing more constrained fundamental and structural parameters.

Previous studies were mostly based on optical photometry and/or near-IR with small angular fields. However, 2MASS can still provide additional insight (Sect. 3). The set of tools developed by our group allowed to unambiguously isolate MS and PMS stars that, in turn, resulted in well-defined CMDs, RDPs and mass functions. In addition, we explore proper motion properties to investigate the other cluster in the area, NGC 2239.

Taken together, the (decontaminated) MS and PMS sequences of NGC 2244 provided an age range 1—6 Myr, an
absorption $A_V = 1.7 \pm 0.2$, and a distance from the Sun $d_\odot = 1.6 \pm 0.2$ kpc ($\approx 1.5$ kpc outside the Solar circle). These parameters are consistent with most of the previous estimates. The (MS+PMS) MF slope $\chi = 0.91 \pm 0.13$ is somewhat flatter than the Salpeter (1955) IMF. With a total (MS+PMS) stellar mass of $m_{\text{MS+PMS}} \approx 625 M_\odot$ derived in the present work, NGC 2244 is not as massive as previously estimated (Sect. 2). The King-like profile fit to the (MS+PMS) stellar RDP was obtained with a core radius $R_c \approx 5.6 \pm 2.6$ pc; the corresponding cluster radius is $R_{\text{RDP}} \approx 10 \pm 4.7$ pc. Compared to a set of well-known OCs, the core radius of NGC 2244 appears to be abnormally big, which puts it at unusual loci in the structural/dynamical diagnostic-diagrams (Sect. 7.1). NGC 2244 has a central cusp that cannot be fitted by e.g., a King’s law. This cusp is probably due to a star-formation effect, and not the product of dynamical evolution. We conclude that NGC 2244 is not in dynamical equilibrium, consistent with Chen, de Grijs & Zhao (2007) and Wang et al. (2008).

NGC 2239 is a low-mass ($m_{\text{MS+PMS}} \approx 301 M_\odot$), young (5 ± 4 Myr) and somewhat more absorbed ($A_V = 3.4 \pm 0.2$) OC, at $d_\odot = 3.9 \pm 0.4$ kpc, thus in the background of NGC 2244. Structurally, its RDP can be represented by a King-like profile with $R_c \approx 0.5' \pm 0.5$ pc and $R_{\text{RDP}} \approx 5.0' \approx 5.6$ pc. With $\chi = 1.24 \pm 0.06$, its composite MS+PMS MF slope is essentially Salpeter’s IMF. These parameters characterise an average young OC, as compared to the reference nearby OCs (Sect. 7.1). While NGC 2239 is a normal young OC with MS and PMS stars distributed according to a cluster RDP, NGC 2244 appears to be another example, like Bochum 1 (Bica, Bonatto & Dutra 2008), of an open cluster doomed to dissolution in a few 10^7 yr. The present work shows the importance of field-star decontamination and wide-field extractions to get the best stellar statistics and to produce high-quality CMDs and RDPs.

ACKNOWLEDGEMENTS

We thank the referee, Dr. M. Pérez, for comments. We acknowledge support from the Brazilian Institution CNPq. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Centre/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This research has made use of the WEBDA database, operated at the Institute for Astronomy of the University of Vienna.

REFERENCES

Alessi B.S., Moitinho A. & Dias W.S. 2003, A&A, 410, 565
van den Bergh S., Morby C. & Pazder J. 1991, ApJ, 375, 594
Bergöhöfer T.W. & Christian D.J. 2002, A&A, 384, 890
Bergond G., Leon S. & Guilbert J. 2001, A&A, 377, 462
Bessel M.S. & Brett J.M. 1988, PASP, 100, 1134
Bica E., Bonatto C. & Dutra C. 2008, A&A, 489, 1129
Bica E., Bonatto C., Barbuy B. & Ortolani S. 2006, A&A, 450, 105
Bica E., Bonatto C. & Blumberg R. 2006, A&A, 460, 83
Bica E. & Bonatto C. 2008, MNRAS, 384, 1733
Bica E., Bonatto C. & Camargo D. 2008, MNRAS, 385, 349
Binney J. & Merrifield M. 1998, in Galactic Astronomy. Princeton, NJ: Princeton University Press. (Princeton series in astrophysics)
Bonatto C. & Bica E. 2003, A&A, 405, 525
Bonatto C., Bica E. & Girardi L. 2004, A&A, 415, 571
Bonatto C., Bica E. & Santos Jr. J.F.C. 2005, A&A, 433, 917.
Bonatto C. & Bica E. 2005, A&A, 437, 483
Bonatto C., Santos Jr. J.F.C. & Bica E. 2006, A&A, 445, 567
Bonatto C., Kerber L.O., Bica E. & Santiago B.X. 2006a, A&A, 446, 121
Bonatto C., Bica E., Ortolani S. & Barbuy B. 2006b, A&A, 453, 121
Bonatto C. & Bica E. 2006, A&A, 455, 931
Bonatto C. & Bica E. 2007a, MNRAS, 377, 1301
Bonatto C. & Bica E. 2007b, A&A, 473, 445
Bonatto C. & Bica E. 2008, A&A, 477, 829
Bonatto C., Bica E. & Santos Jr. J.F.C. 2008, MNRAS, 386, 324
Bonatto C. & Bica E. 2009, MNRAS, 392, 483
Cardelli J.A., Clayton G.C. & Mathis, J.S. 1989, ApJ, 345, 245
Chen L., de Grijs R. & Zhao J.L. 2007, AJ, 134, 1368
Dutra C.M., Santiago B.X. & Bica E. 2002, A&A, 383, 219
Eisenhauer F., Schödel R, Genzel R., Ott T., Tecza M., Abuter R., Eckart A. & Alexander T. 2003, ApJ, 597, L121
Eisenhauer F., Genzel R., Alexander T. et al. 2005, ApJ, 628, 246
Elson R.A.W., Fall S.M. & Freeman K.C. 1987, ApJ, 323, 54
Friel E.D. 1995, ARA&A 1995, 33, 381
Girardi L., Bertelli G., Bressan A., Chiosi C., Groenewegen M.A.T., Marigo P., Salasnich B. & Weiss A. 2002, A&A, 391, 195
Goodwin S.P. & Bastian N. 2006, MNRAS, 373, 752
Hensberge H., Pavlovski K. & Verschueren W. 2000, in Star formation from the small to the large scale, ESLAB symposium 33, Noordwijk, The Netherlands. Edited by F. Favata, A. Kaas, and A. Wilson.
Hurley J. & Tout A.A. 1998, MNRAS, 300, 977
Kerber L.O., Santiago B.X., Castro R. & Valls-Gabaud D. 2002, A&A, 390, 121
King I. 1962, AJ, 67, 471
King I. 1966, AJ, 71, 64
Lada C.J. & Lada E.A. 1995 in Star formation from the small to the large scale, ESLAB symposium 33, Noordwijk, The Netherlands. Edited by F. Favata, A. Kaas, and A. Wilson.
Li J.Z. 2005, ApJ, 625, 242
Lynga G. 1982, A&A, 109, 213
Macciéjewski G. & Niedzielski A. 2007, A&A, 467, 1065
Mercer E.P., Clemens D.P., Meade M.R., Babler B.L., Indebetouw R., Whitney B.A., Watson C., Wolfire M.G. et al. 2005, ApJ, 635, 560
The very young OCs NGC 2244 and NGC 2239

Naylor T. & Jeffries R.D. 2006, MNRAS, 373, 1251
Nilakshi S.R., Pandey A.K. & Mohan V. 2002, A&A, 383, 153
Nishiyama S., Nagata T., Sato S., Kato D., Nagayama T., Kusakabe N., Matsunaga N., Naoi T. et al. 2006, ApJ, 647, 1093
Ogura K. & Ishida K. 1981, PASJ, 33 149
Park B.-G. & Sung H. 2002, AJ, 123, 892
Pérez M.R. 1991, RMxAA, 22, 99
Pérez M.R., Thé P.S. & Westerlund B.E. 1987, PASP, 99, 1050
Phelps R.L. & Lada E.A. 1997, ApJ, 477, 176
Piskunov A.E., Schilbach E., Kharchenko N.V., Röser S. & Scholz R.-D. 2007, A&A, 468, 151
Richer H.B., Dotter A., Hurley J., Anderson J., King I., Davis S., Fahlman G.G., Hansen B.M.S. et al. 2008, AJ, 135, 2141
Román-Zúñiga C.G. & Lada E.A. 2008, chapter in Handbook of Star Forming Regions, Vol. I: The Northern Hemisphere, Ed. Bo Reipurth, ASP
Salpeter E. 1955, ApJ, 121, 161
Sharma S., Pandey A.K., Ogura K., Mito H., Tarusawa K. & Sagar R. 2006, AJ, 132, 1669
Siess L., Dufour E. & Forestini M. 2000, A&A, 358, 593
Skrutskie M., Schneider S.E., Stiening R., Strom S.E., Weinberg M.D., Beichman C., Chester T., Cutri R. et al. 1997, in The Impact of Large Scale Near-IR Sky Surveys, ed. F. Garzon et al., Kluwer (Netherlands), 210, 187
Sulentic J.W. & Tifft W.G. 1973, in The revised new catalogue of nonstellar astronomical objects, Tucson: University of Arizona Press
Tadross A.L., Werner P., Osman A. & Marie M. 2002, NewAst, 7, 553
Trager S.C., King I.R. & Djorgovski S. 1995, AJ, 109, 218
Wang J., Townsley L.K., Feigelson E.D., Broos P.S., Getman K.V., Román-Zúñiga C.G. & Lada E. 2008, ApJ, 675, 464
Wilson C.P. 1975, AJ, 80, 175