Isolating the pre-main sequence in Collinder 34, NGC 3293, NGC 3766 and NGC 6231

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ABSTRACT
We employed field star decontaminated 2MASS photometry to study four nearby optical embedded clusters – Collinder 34, NGC 3293, NGC 3766 and NGC 6231 – obtaining deep colour-magnitude diagrams and stellar density profiles. We found what seems to be pre-main sequences detached in different amounts from main sequences in these diagrams. The structural analysis of each cluster revealed different radial distributions for these two sequences. We argued that the detached evolutionary sequences in our sample may be evidence of sequential star formation. Finally, we compared the sample cluster parameters with those of other young clusters in the literature and point out evidence that NGC 3766 and NGC 6231 might be evolving to OB associations.

Key words: open clusters and associations: individual: Collinder 34 – open clusters and associations: individual: NGC 3293 – open clusters and associations: individual: NGC 3766 – open clusters and associations: individual: NGC 6231

1 INTRODUCTION
Young star clusters remain embedded in molecular clouds during the first $\sim 10$ Myr of their existence, so that their stellar content should be observed in infrared wavelengths (Lada & Lada 2003). During this stage, they have a lot of stars that do not fuse hydrogen yet, the pre-main sequence (PMS) stars distinguished from the main-sequence (MS) stars.

As plotted in a colour-magnitude diagram (CMD), these two classes of stars are distributed along different tracks that can be modeled by means of theoretical isochrones (e.g. Siess, Dufour & Forestini 2000; Marigo et al. 2008). Stars with colour and magnitudes occurring along the same curve are expected to be coeval. Factors such as binarity, variability, differential reddening, photometric uncertainties and continuous star formation cause spread around these isochrones (Bonatto, Bica & Lima 2012b, Bonatto, Bica & Lima 2012a). Photometry of PMS stars is specially affected by these factors. Among them stand out the T Tauri, young variables with circumstellar disks and infrared excess emission (Furlan et al. 2009).

Snapshots of the dynamical stages of a star cluster may be obtained from radial density profiles (RDPs). Embedded clusters are not expected to have profiles following an isothermal sphere model (e.g. King 1962). Nevertheless, some of these density profiles are fitted by a King-like model providing reliable structural parameters. RDP analyses can also reveal clues on cluster dissolution when extended profiles are observed (e.g. Saurin, Bica & Bonatto 2012) and gradients in the ratios of high-to-low-mass and old-to-young stars that may be interpreted as mass and age segregation (e.g. Hillenbrand 1997).

Using Two Micron All Sky Survey (2MASS) photometry we analyze the evolutionary sequences and radial profiles of a sample of young clusters in order to investigate triggered/sequential star formation (e.g. Saurin, Bica & Bonatto 2010). The sample consists of objects catalogued by Collinder (1931) who has established some of the bases of the modern cluster analysis. We selected four clusters, the little studied Collinder 34, plus NGC 3293 (Collinder 224), NGC 3766 (Collinder 248) and NGC 6231 (Collinder 315) that are bright nearby young clusters previously studied in various wavelengths (e.g. Dias et al. 2002, Kharchenko et al. 2013). In the present work we perform a field star decontamination procedure in order to isolate and go deeper than previous studies into the PMS of these clusters.

This paper is organized as follows. In Sect. 2 we explain the field star decontamination method. In Sect. 3 we build CMDs and estimate astrophysical parameters. In Sect. 4 we analyze the radial density profiles and derive structural pa-
Table 1. Adopted central coordinates for the clusters. By columns: (1) star cluster identification; (2) Galactic longitude; (3) Galactic latitude; (4) right ascension (J2000); (5) declination (J2000).

| cluster     | l   | b   | α   | δ    |
|-------------|-----|-----|-----|-----|
| Collinder 34| 138°03 | +1°50 | 02h59m23s17 | +60°33’59”5 |
| NGC 3293   | 285°86 | +0°07 | 10h35m53s10 | −58°13’55”5 |
| NGC 3766   | 294°12 | −0°03 | 11h36m14s00 | −61°36’30”0 |
| NGC 6231   | 343°46 | +1°18 | 16h54m10s06 | −41°49’30”1 |

2MASS photometry of the clusters in the J, V, and K bands within large circular areas (r = 100 arcmin). We restricted our analyses to stars with photometric errors ≤ 0.1 mag in each band.

The results show that the clean CMDs are essential guides for the optimal setting of theoretical isochrone curves and estimating reliable parameters (Sect. 3). Circular areas of different radii were tested, but we found that larger radii resulted in lower subtraction efficiencies, while smaller radii removed too many points from the CMDs—including stars catalogued as members.

The resulting subtraction efficiencies were 90.4 ± 1.8 per cent for Collinder 34, 83.4 ± 1.0 per cent for NGC 3293, 92.5 ± 0.5 per cent for NGC 3766, and 82.8 ± 0.9 per cent for NGC 6231.

Decontamination procedure enhances the PMS and enables to detect the low mass limit of the MS, as expected from PMS to MS evolution. This cutoff is detected for all sample clusters (Figs. 11). An important feature in the CMDs of the sample is the MS and probable PMS. This feature has also been observed in Trumpler 37 (Saurin et al. 2012).

2MASS photometric uncertainties and degeneracies do not allow to detect metallicity differences for young populations. Thus, we adopted Solar-metallicity isochrones, suitable for the Galactic disc in general. For the MS of all clusters we used 10 Myr or 20 Myr Padova isochrones (Marigo et al. 2008) plus 0.2, 1, and 5 Myr PMS isochrones of Siess et al. (2000) converted to 2MASS photometry (Kenyon & Hartmann 1995).

For each cluster, reddening and distance have been obtained from a mean of a spectral type calibration using a catalogued blue star, avoiding spectroscopic binaries and variables (Table 2). The following stars listed in the SIMBAD astronomical database (Wenger et al. 2000) have been used in spectral type classifications: TYC 4048-1432-1 for Collinder 34, CPD-57 3520 for NGC 3293, CPD-60 3120 for NGC 3766, and SBL 164 for NGC 6231. Table 3 shows the parameters (m−M)J, E(J−H) and E(J−Ks), obtained from the MS isochrone solutions, and E(H−Ks), A_J,
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$E(B-V)$ and $A_V$, estimated using the relations given by 
Dutra, Santiago & Bica (2002).

Heliocentric and Galactocentric distances for each cluster have been estimated using the photometric parameters and assuming that the distance from the Sun to the Galactic centre is $R_0 = 8.4\pm0.6$ kpc (Reid et al. 2009). The resulting values are in Table 5.

A mass estimate of the MS stellar content was made by summing the individual masses of each star according to the mass-luminosity relation for dereddened colours and magnitudes. Collinder 34 has MS stellar masses in the range $1.4M_\odot$ to $17.8M_\odot$, and its MS mass amounts to $359^{+37}_{-22}M_\odot$. For NGC 3293, the range is $1.7M_\odot$ to $17.8M_\odot$, yielding a MS mass of $899^{+11}_{-11}M_\odot$. For NGC 3766, the range is $1.2M_\odot$ to $11.2M_\odot$, yielding a MS mass of $1682^{+31}_{-31}M_\odot$. For NGC 6231, the range is $2.5M_\odot$ to $17.8M_\odot$, yielding a MS mass of $1939^{+13}_{-13}M_\odot$. A similar procedure is not possible for the PMS, so we simply counted the number of stars and multiplied it by a mean PMS stellar mass. This is $0.6M_\odot$ by assuming an initial mass function of Kroupa (2001) in the range $0.08M_\odot$ to $7M_\odot$. All these masses were derived within circular areas of radius 10 or 20 arcmin (Sect. 2) and are summarized in Table 4. Note that these values must be lower limits, owing to the presence of dust and gas, unresolved binaries, and the fact that we have considered only the more probable cluster members (decontaminated CMDs).

Additional comparisons with sequences of dwarfs and giants Schmidt-Kaler (1982), and the classical T Tauri stars (CTTs) locus (Meyer et al. 1996) – transposed into the 2MASS photometric system using the relations derived by Carpentier (2001) – in extinction corrected colour-magnitude diagrams (2CDs) show a significant population in the PMS locus (Figs. 4-5).

Using concentric annuli and the corresponding radial distance of the most populated position within each annulus, we built stellar RDPs for the four clusters. Since the PMS profiles are not matched by isothermal sphere models, we have chosen to fit only the MS profiles, except for Collinder 34 that has very low density of MS stars. Thus, structural parameters (Table 6) for NGC 3293, NGC 3766 and NGC 6231 were estimated by fitting their MS RDPs with a non-linear least-squares routine to a King-like (2-parameter) model given by

$$\Omega(r) = \Omega_0 + \frac{\Omega_0}{1 + (r/r_c)^2}$$

where $\Omega_0$ is the central surface density, $r_c$ is the core radius and $\Omega_0$ is the background density measured in a surrounding annulus ($80 \leq r \leq 100$ arcmin) and kept constant. The best fittings have a relatively small amount of scatter around the profile, so that the root-mean-square errors are about 2 (Table 5).

5 DISCUSSION

A comparison of the MS structural parameters obtained in this work (Table 6) with those available in the literature (Table 5) reveals similarity within uncertainties for NGC 3293 and NGC 3766. The core radius of NGC 6231 is smaller than that reported in the literature, but its MS profile represents well the core and the extension structures (Fig. 12).

Notably, each cluster in this work features a detached reddened ensemble of stars in its CMDs (Sect. 3) with colour gaps $\Delta(J-K_S)$ in the range 0.25-1.5 mag (Table 7). In addition, the density profiles of MS and PMS do not match each other in shape nor in extension (Figs. 10-12). We analyse whether these particularities are connected to a second generation of PMS stars distributed like a halo. We emphasize that the present field star decontamination allows to access the PMS population.

Sequential star formation may be triggered by stellar winds of massive stars or supernovae explosions. Two mechanisms were proposed to explain this process: collect-and-collapse Elmegreen & Lada (1977) and radiation-driven implosions Sandford, Whitaker & Klein (1982). Both may operate simultaneously in a star forming region, but the former is an important mechanism of massive star formation because the expanding H II region sweeps out the cloud collecting material as a snowball Zavagno et al. (2004).

Signposts of collect-and-collapse and radiation-driven implosions remain for a while. Cometary globules such as CG7S Lefloch & Lazareff (1995), and bright-rimmed clouds such as BRC 14 Loren & Wootten (1978), both in the complex of the Heart and Soul nebulae (that embeds Collinder 34), may be characteristic of radiation-driven implosions and collect-and-collapse, respectively.

Such substructures, further neighbouring and projected objects in the area of the sample clusters are shown in Figs. 13-16 with Digitized Sky Survey 2 (DSS2) $R$ band images generated by SkyView McGlynn et al. (1996).

In the following, we carry out individual analyses of each cluster.
Figure 1. Collinder 34: 2MASS colour-magnitude diagrams extracted inside $r \leq 10$ arcmin. Mean uncertainties are represented by error bars. Top panels: observed photometry with $J_s(J-H)$ (left) and $J_s(J-K_S)$ (right). Middle: field equal-area extraction. Bottom: decontaminated CMDs with 10 Myr Solar-metallicity Padova isochrone and 0.2, 1 and 5 Myr PMS isochrones. Light-shaded polygon: MS colour-magnitude filter. Heavy-shaded polygon: the same for the PMS stars. The arrows indicate the reddening vectors for $A_J = 0.42$ mag.
Figure 2. NGC 3293: similar to Fig. The arrows indicate the reddening vectors for $A_J = 0.26$ mag.
Figure 3. NGC3766: similar to Fig. 1 but with a 20 Myr Padova isochrone. The arrows indicate the reddening vectors for $A_J = 0.35$ mag.
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Figure 4. NGC 6231: similar to Fig. The arrows indicate the reddening vectors for $A_J = 0.40$ mag.
Table 2. Reference stars used for the spectral type calibration of the theoretical isochrones. By columns: (1) star identification; (2) associated cluster; (3) right ascension (J2000); (4) declination (J2000); (5) \( J - H \) apparent magnitude; (6) \( J - K_S \) colour; (7) spectral type.

| star cluster | \( \alpha \) | \( \delta \) | \( m_J \) | \( J - H \) | \( J - K_S \) | ST |
|--------------|----------|----------|--------|-----------|-----------------|-----|
| TYC 4048-1432-1 | Collinder 34 | \( 02^h 50^m 21^s 19^s \) | +60°25′22″ | 9.464±0.022 | 0.034±0.036 | 0.029±0.030 | B8 |
| CPD-57.3520 | NGC 3293 | \( 10^h 35^m 56^s 61^s \) | −58°12′40″ | 10.197±0.027 | −0.022±0.037 | −0.061±0.035 | B2 |
| CPD-60.3120 | NGC 3766 | \( 11^h 36^m 08^s 25^s \) | −61°34′19″ | 10.661±0.026 | 0.005±0.037 | 0.031±0.033 | B4 |
| SBL 164 | NGC 6231 | \( 16^h 53^m 46^s 99^s \) | −41°48′55″ | 11.683±0.023 | 0.058±0.038 | 0.036±0.045 | B7 |

Table 3. Photometric parameters of each cluster. By columns: (1) star cluster identification; (2) distance modulus; (3),(4),(5) 2MASS colour excesses; (6) \( J \) band absorption; (7) \( E(B-V) \) colour excess; (8) \( V \) band absorption.

| cluster | \( m-M \) | \( E(J-H) \) | \( E(J-K_S) \) | \( E(H-K_S) \) | \( A_J \) | \( E(B-V) \) | \( A_V \) |
|---------|----------|-----------------|-----------------|-----------------|--------|-----------------|--------|
| Collinder 34 | 12.03±0.19 | 0.15±0.03 | 0.24±0.05 | 0.09±0.02 | 0.42±0.08 | 0.49±0.10 | 1.51±0.30 |
| NGC 3293 | 12.44±0.03 | 0.10±0.04 | 0.15±0.06 | 0.06±0.02 | 0.26±0.10 | 0.31±0.12 | 0.96±0.37 |
| NGC 3766 | 11.85±0.03 | 0.13±0.05 | 0.20±0.08 | 0.07±0.03 | 0.35±0.14 | 0.41±0.16 | 1.28±0.50 |
| NGC 6231 | 11.71±0.02 | 0.14±0.04 | 0.23±0.06 | 0.08±0.02 | 0.40±0.11 | 0.46±0.13 | 1.44±0.40 |

5.1 Collinder 34

Collinder 34 (Fig. [13]) is part of the complex of the Heart (Sh2-190) and Soul (Sh2-199) nebulae, a star forming region ionized by the Cas OB6 association.

Originally catalogued by Collinder [1931] at the B1900 coordinates \( \alpha = 02^h 43^m 30^s \) and \( \delta = +60^\circ 01'00'' \), it was recently identified as SA124 [Glushkova et al. 2010]. Actually, Collinder 34, together with Collinder 32 (also known as the IC 1848 cluster), is inserted in a hierarchical structure of the Collinder 33 association.

Collinder 34 is located inside a bubble in the “baby’s head” of the Sh2-199 nebula, centred in the O-type star HD18326. It is surrounded by several infrared clusters – embedded in Sh2-201, BRC 13 and BRC 14 [Chauhan et al. 2011] – together with the small optically visible cluster BDS 58 [Bica et al. 2003].

Among the clusters in the present study, Collinder 34 has the narrowest colour gap between MS and PMS (Fig. [1]), \( \Delta(J-K_S) \sim 0.25 \) mag. Its PMS population shows some dispersion in the 2CD (Fig. [1]) and a small near-IR excess, typically associated with optically thin dust circumstellar disks featured by Weak-lined T Tauri stars (WTTs). This is consistent with the location of the bulk of the PMS in a region limited by \( (J-H) \lesssim 0.5 \) and \( (H-K_S) \lesssim 0.5 \) [Meyer et al. 1997]. In addition, a few points are located in \( (H-K_S) > 0.5 \), a region usually occupied by Herbig Ae/Be stars [Hernández et al. 2005].

Stellar RDPs of Collinder 34 (Fig. [9]) show a structure dominated by the PMS with its MS stars concentrated in the core. The MS profile presents an excess near the centre that cannot be interpreted as core collapse in such a young cluster. This may be characteristic of primordial mass segregation caused by competitive accretion that preferentially forms massive stars in the deepest part of the cluster potential well [Bonnell et al. 2001].

5.2 NGC 3293

Projected close to the \( \eta \) Carinae nebula, the star cluster NGC 3293 (Fig. [13]) forms an interacting pair with NGC 3324 [de la Fuente Marcos & de la Fuente Marcos 2004; de la Fuente Marcos & de la Fuente Marcos 2010].

The sequences of NGC 3293 are separated in the decontaminated CDMs (Fig. [2]) by a gap of \( \Delta(J-K_S) \sim 1.5 \) mag, with a heavily reddened ensemble of stars. While, its RDPs (Fig. [10]) show a centrally concentrated structure of MS stars well fitted by Eq. [1] (Table [5]) with the reddened envelope surrounding the core, like a halo.

An inspection of the 2CD (Fig. [6]) suggests that a fraction of these reddened stars might be background dwarfs and giants that were not removed by the decontamination procedure (Sect. [2]). Apparently, any nearby area was not adequate to model the field in detail. Anyway, the bulk of the reddened ensemble is outside the strip of dwarfs and giants, and might be formed by T Tauri stars with an absorption of \( A_V \sim 3.5 \) mag.

5.3 NGC 3766

The cluster NGC 3766 (Fig. [15]) in the Carina complex includes the supernova remnant G294.1-00.0 [Green 2003] and at least 16 classical Be stars [McSwain, Huang & Gies 2001].

Decontaminated CDMs of NGC 3766 (Fig. [3]) show a colour gap of \( \Delta(J-K_S) \sim 0.5 \) mag separating a broad MS and an elongated PMS. The shock wave of the supernova G294.1-00.0 might have removed the circumstellar disc of part of the PMS stars causing that elongation. In fact, an examination of the 2CD (Fig. [7]) reveals a PMS with little or no near-IR excess, consistent with discless T Tauri stars.

Regarding the cluster structure, the stellar RDPs of NGC 3766 (Fig. [11]) have a well fitted King-like profile of MS.
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stars (Table 5) in a centrally concentrated structure with excess near the centre, similar to Collinder 34. In addition, its PMS stars surround the MS core, suggesting a halo.

5.4 NGC 6231

The cluster NGC 6231 (Fig. 16), at the core of the Sco OB1 association [Perry et al. 1990], is rich in early-type stars (at least 150) and more than half of its OB stars are members of binary systems [Raboud 1996; Sana et al. 2008].

NGC 6231 is inside a large bubble in the Gum 55 H II region. Stellar winds of massive stars, like WR 79
Figure 9. Collinder 34: stellar RDPs built with stars filtered by colour and magnitude (Fig. 1). Top panel: total profile (MS + PMS). Middle panel: MS profile. Bottom panel: PMS profile.
Figure 10. NGC 3293: same as Fig.1. The fitted King-like model (Eq.1) is shown as a solid line in the middle panel. The core radii ($r_c$) are indicated and the $3\sigma$ background stellar levels (Table5) are represented by the narrow horizontal stripes and $1\sigma$ fit uncertainty, by the shaded regions along the fits. The positions of nearby projected objects are indicated.
Figure 11. NGC 3766: same as Fig. [10].
Figure 12. NGC 6231: same as Fig. 10.
Galactocentric distance considering R stellar mass; (8) total stellar mass; (9) age of the MS isochrone.

Table 4. Derived scale parameters and mass of the clusters. By columns: (1) star cluster identification; (2) Heliocentric distance; (3) Galactocentric distance considering \( R \); (4) angular radial limit; (5) linear radial limit; (6) MS stellar mass; (7) PMS stellar mass; (8) total stellar mass; (9) age of the MS isochrone.

| cluster     | \( d_\odot \) (kpc) | \( d_{GC} \) (kpc) | \( r_{RDP} \) (arcmin) | \( R_{RDP} \) (pc) | \( M_{MS} \) (\( M_\odot \)) | \( M_{PMS} \) (\( M_\odot \)) | \( M \) (\( M_\odot \)) | \( t_{MS} \) (Myr) |
|-------------|----------------------|---------------------|------------------------|-------------------|--------------------------|--------------------------|------------------|------------------|
| Collinder 34 | 2.1±0.2              | 10.1±0.2            | 15.12±0.70             | 9.2±1.0           | 359±37                   | 131                      | 490±37           | 10               |
| NGC 3293    | 2.7±0.1              | 8.1±0.1             | 11.77±0.49             | 9.3±0.6           | 899±11                   | -                        | -                | 10               |
| NGC 3766    | 2.0±0.1              | 7.8±0.1             | 46.27±1.56             | 26.7±1.9          | 1682±31                  | 317                      | 1998±31          | 20               |
| NGC 6231    | 1.8±0.1              | 6.7±0.1             | 68.26±2.41             | 36.2±2.3          | 1939±17                  | -                        | -                | 10               |

Table 5. Structural parameters obtained by fitting Eq. (1) to the MS stellar RDPs. By columns: (1) star cluster identification; (2) background stellar density; (3) central stellar density; (4) angular core radius; (5) linear core radius; (6) root-mean-square error.

| cluster     | \( \Omega_{bg} \) (stars/arcmin\(^2\)) | \( \Omega_c \) (stars/arcmin\(^2\)) | \( r_c \) (arcmin) | \( R_c \) (pc) | \( E_{rms} \) |
|-------------|----------------------------------------|--------------------------------------|--------------------|---------------|---------------|
| NGC 3293    | 0.27±0.01                              | 11.18±0.06                          | 1.09±0.30          | 0.9±0.3       | 2.14          |
| NGC 3766    | 1.76±0.01                              | 5.26±1.21                           | 4.24±0.72          | 2.5±0.4       | 1.88          |
| NGC 6231    | 0.08±0.01                              | 3.29±1.39                           | 2.63±0.68          | 1.4±0.4       | 2.20          |

\( \text{(van der Hucht 2001), or past supernovae explosions might have depleted the central area of the cloud resulting in a low differential reddening and a deficit of H\alpha emission in the PMS stars (Sung, Bessell & Lee 1998).} \)

Decontaminated CMDs of NGC 6231 (Fig. 8) show a narrow MS separated from a heavily reddened ensemble of stars by a wide colour gap of \( \Delta(J-K_S) \sim 1.0 \text{mag} \), like that of NGC 3293 (Sect. 5.4).

The 2CD of NGC 6231 (Fig. 8) shows that the reddened ensemble is placed along a broad band with a high absorp-

\( \text{tion of NGC 3293 (Sect. 5.2), background dwarfs and giants seem to have survived to decontamination.} \)

Finally, the stellar MS RDP of NGC 6231 (Fig. 12) is well fitted by Eq. (1) (Table 5). Such profile matches that by Sung, Sana & Bessel (2013) which extents to 20 arcmin for high mass stars and shows an extension in 20 < \( r < 60 \text{arcmin}. \)

5.5 Diagnostic diagrams

In order to compare the derived cluster parameters – radial limit, age, Galactocentric distance and mass – of the present sample with those of other clusters, we built diagnostic diagrams (Fig. 17) for a selected sample of young objects within the age range 1 Myr to 14 Myr. They are: NGC 4755 (Bonatto et al. 2008); NGC 6611 (Bonatto, Santos & Bica 2006); Bochum I and NGC 6823 (Bica, Bonatto & Dutra 2008); NGC 2244 and NGC 2239 (Bonatto & Bica 2009); Collinder 197 and vdB 92 (Bonatto & Bica 2010); and Trumpler 37 (Saurin et al. 2012).

The radius time evolution of the clusters seems to be constrained by the Galactocentric distance and mass, as seen in Fig. 17 panels (a), (b) and (c). The more massive clusters NGC 3766 and NGC 6231 appear to keep most of their stars despite the relatively smaller Galactocentric distance. They have comparable radii to those of Bochum 1 and Trumpler 37, systems that seem to be evolving to OB associations. On the other hand, Collinder 34 and NGC 3293 occupy intermediate positions in the diagrams, mixed to the ordinary embedded clusters. Our sample is inserted into a scale of early evolving star clusters tending to dissolution, as expected for most of the embedded clusters (Lada & Lada 2003).

6 CONCLUDING REMARKS

We have studied four young star clusters and found CMDs with detached PMS from the MS at least for two objects. Colour gaps between these evolutionary sequences were revealed by field star decontamination – 0.25 mag for Collinder 34, and 0.5 mag for NGC 3766. This might be evidence of sequential star formation.

On the other hand, the clusters NGC 3293 and NGC 6231 have wider colour gaps, 1.5 and 1.0 mag, respectively. An inspection of their 2CDs suggests that those heavily reddened ensembles appear to be contaminated by residual background dwarfs and giants of the field. Anyway, the bulk of these ensembles might consist of very reddened PMS stars.

Spatial structures of the sequences of each cluster were examined by means of stellar RDPs revealing that the detached sequences are distributed in different ways for each cluster. The MS profiles of NGC 3293, NGC 3766 and NGC 6231 have been fitted by a King-like model yielding similar structural parameters as compared to the litera-
Table 6. Cluster parameters from the literature: Dias et al. 2002 (D2002); Piskunov et al. 2007 (P2007); Bukowiecki et al. 2011 (B2011); and Kharchenko et al. 2013 (K2013). By columns: (1) star cluster identification; (2) Heliocentric distance; (3) Galactocentric distance; (4) core radius; (5) tidal radius; (6) total stellar mass; (7) age; (8) reference.

| cluster  | $d_\odot$ (pc) | $d_{GC}$ (pc) | $R_c$ (pc) | $R_t$ (pc) | $M$ ($M_\odot$) | Age (log(Age)) | ref. |
|----------|----------------|---------------|------------|------------|----------------|----------------|------|
| NGC 3293 | 2327 -         | -             | -          | -          | -              | 7.014          | D2002 |
|          | 2441 -         | 1.30±0.16     | 8.69±1.04  | -          | -              | 6.75           | K2013 |
| NGC 3766 | 2218 -         | -             | -          | -          | -              | 7.32           | D2002 |
|          | 1745 -         | 1.3±0.7       | 6.9±1.4    | 2149±259   | 7.52           | P2007          |
|          | 1685 -         | 0.91±0.13     | 11.19±1.76 | -          | 7.95           | K2013          |
| NGC 6231 | 1243 -         | -             | -          | -          | 6.843          |                | D2002 |
|          | 1393 -         | 6.84±0.66     | 13.43±0.70 | -          | 7.05           | K2013          |
Figure 14. NGC 3293: same as Fig. 13. $R_c$ from the MS profile fitting (Table 5).

Table 7. Star cluster RDPs diagnostic. By columns: (1) star cluster identification; (2) MS RDP morphology; (3) PMS RDP morphology; (4) extended RDP; (5) RDP with central excess; (6) $(J-K_S)$ gap between MS and PMS.

| cluster     | $RDP_{MS}$ | $RDP_{PMS}$ | $RDP_{ext}$ | $RDP_{exc}$ | $\Delta(J-K_S)$ |
|-------------|------------|-------------|-------------|-------------|-----------------|
| Collinder 34| non-King   | King-like   | no          | yes         | 0.25            |
| NGC 3293    | King-like  | non-King    | yes         | no          | 1.5             |
| NGC 3766    | King-like  | non-King    | yes         | yes         | 0.5             |
| NGC 6231    | King-like  | non-King    | yes         | no          | 1.0             |

Furthermore, the RDPs of Collinder 34 and NGC 3766 present central excesses that may represent primordial mass segregation.

Finally, this study suggests that reddened halos of PMS stars as formed from the parental cloud may still be present after 5-20 Myr.

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Figure 15. NGC 3766: same as Fig. 13. \( R_e \) from the total profile fitting (Table 5).

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Figure 16. NGC 6231: same as Fig. 13. $R_c$ from the MS profile fitting (Table 5).

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Young clusters with a detached pre-main sequence

Figure 17. Diagnostic diagrams comparing cluster parameters. Some error bars are smaller than the symbols.