Characterizing star cluster formation with WISE: 652 newly found star clusters and candidates

D. Camargo, E. Bica and C. Bonatto

1 Colégio Militar de Porto Alegre, Ministério da Defesa - Exército Brasileiro, Av. José Bonifácio 363 Porto Alegre 90040-130, RS, Brazil
2 Departamento de Astronomia, Universidade Federal do Rio Grande do Sul, Av. Bento Gonçalves 9500 Porto Alegre 91501-970, RS, Brazil

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ABSTRACT

We report the discovery of 652 star clusters, stellar groups and candidates in the Milky Way with Wide-field Infrared Survey Explorer (WISE). Most of the objects are projected close to Galactic plane and are embedded clusters. The present sample complements a similar study (Paper I) which provided 437 star clusters and alike. We find evidence that star formation processes span a wide range of sizes, from populous dense clusters to small compact embedded ones, sparse stellar groups or in relative isolation. The present list indicates multiple stellar generations during the embedded phase, with giant molecular clouds collapsing into several clumps composing an embedded cluster aggregate. We investigate the field star decontaminated colour–magnitude diagrams and radial density profiles of nine cluster candidates in the list, and derive their parameters, confirming them as embedded clusters.

Key words: catalogues – Galaxy: disc – open clusters and associations: general – Galaxy: structure.

1 INTRODUCTION

Star cluster formation is a complex process, which is not yet completely understood. These systems are formed within giant molecular clouds (GMCs) that populate the Galactic disc, mainly the spiral arms in an early evolutionary stage. They are known as embedded clusters (ECs) and/or embedded stellar groups (EGRs). The molecular clouds, in which ECs are formed often present filamentary structures (Gutermuth et al. 2009; Myers 2009; Camargo, Bonatto & Bica 2012) that may also be the site of small EGr formation (Bastian 2011; Camargo et al. 2012; Krujissen et al. 2012).

Thus, ECs are fundamental tools to improve our understanding of star formation and evolution as well as the Galactic structures that trace the spiral pattern (Camargo, Bica & Bonatto 2013; Camargo, Bonatto & Bica 2015c). These objects also play important roles in both local and large-scale star formation clarifying the physical processes involved in the individual and Galactic scale of GMCs.

Given the importance of ECs as tools to study the Galactic structure, several surveys have been recently carried out (Bica, Dutra & Barbuy 2003a; Bica et al. 2003b; Lada & Lada 2003; Bica & Bonatto 2005; Borrissova et al. 2011; Majaess 2013; Borrissova et al. 2014; Camargo, Bica & Bonatto 2015a), together with a detailed analysis of their properties (e.g. Camargo, Bonatto & Bica 2009, 2010, 2011; Camargo et al. 2012, 2013).

These surveys suggest that most stars form in clumped environments, with scales ranging from small stellar groups to massive clusters or large associations (Cotera et al. 1999; Motte & André 2001; Mauzerah et al. 2010; Kirk & Myers 2012; Oskinova et al. 2013; Habibi, Stolte & Harfst 2014). Infrared surveys, such as the Two Micron All Sky Survey (2MASS), Spitzer and Wide-field Infrared Survey Explorer (WISE) are uncovering deep ECs and embedded stellar groups in the Galaxy.

Despite advances in our understanding of star cluster formation and their early evolution, there is no consensus on the definition of an EC. There is evidence that in the early evolutionary stages some ECs may contain less than ~10 stars and radii of about 0.2 pc (Testi et al. 1997; Massi, Testi & Vanzi 2006; Rodríguez-González et al. 2008; Alexander & Kobulnicky 2012). In this sense, Hodapp (1994) define clusters as groups of five or more stars. Adams & Myers (2001) classify as stellar groups systems with 10–100 stars, and the most populous ones as clusters. Lada & Lada (2003) suggest that at least 35 stars and stellar mass density of about 1 M⊙ pc−3 (Bok 1934; Spitzer 1958) are required for an EC to survive the tidal disruption by the Galaxy, GMC collisions, and the gas expulsion as a bound system. However, as they suggest that most ECs do not survive the infant mortality, this criterion is only a lower limit for ECs to survive the gas expulsion to become an open cluster (OC). This is not a criterion for EC classifications, on the contrary, it shows that most ECs are below this limit since they argue that more than 95 percent of them are dissolved before 100 Myr.

The present work deals with new discoveries of star clusters, mostly ECs with WISE and analyses of their properties, following the series of recent papers Camargo et al. (2015a,b,c), hereafter Papers I, II and III, respectively.

The paper is organized as follows. In Section 2, we present the search procedure and the newly found clusters. In Section 3, we analyse a subsample of the discovered clusters using 2MASS...
photometry. We also describe the methods employed in the cluster analyses. They employ colour–magnitude diagrams (CMDs) and radial density profiles (RDP). Section 4 is dedicated to the discussion of the results. Finally, in Section 5 we provide the concluding remarks.

2 PRESENT WORK DISCOVERIES

We recently reported the discovery of 446 star clusters, stellar clusters and candidates, mostly projected on the Galactic disc. They were designated Camargo 1 (C 1)–C 446, in a series of analyses. (i) In Paper I, we presented the first large list: C 1–C 437. (ii) In Paper II, we analysed C 438 and C 439, two rare high Galactic latitude clusters and candidates, mostly projected on the Galactic disc. They are not sensitive to the stellar and PMS content, while in W3 (12 µm) and W4 (22 µm) extended structures arise mostly from dust emission. We started out by looking for dust emission nebulae on WISE, followed by a search for stellar overdensities within them. We cross-correlated our objects with previous catalogues or lists (Acker et al. 1992; Bica et al. 2003a,b; Dutra et al. 2003; Bica & Bonatto 2005; Kharchenko et al. 2005a,b; Mercer et al. 2005; Kronberger et al. 2006; Froebrich, Scholz & Raftery 2007; Koposov, Glushkova & Zolotukhin 2008; Glushkova et al. 2010; Borissova et al. 2011; Majaess 2013, and Paper I). Searches for new star discoveries of star clusters and alike are designated C 447–C 1098, thus amounting to 652 new entries (Table 1).

Our initial sample in this study consisted of 862 objects that we detected on the WISE multi-band Atlas, along the four Galactic quadrants, in general for $|b| < 30^\circ$. The subsequent analyses indicated that 212 had already been reported in the literature, or were discarded owing to miscellaneous reasons for a few of them, like probable planetary nebulae or spurious objects when inspected in detail. Thus, 75% of the initial sample were considered to be new star clusters, EGrs or candidates, and were included in the present catalogue. We list in Table 1 38 entries that are shown as examples or discussed in more detail throughout this paper. The complete Table 1 will be available in the online version.

In Figs 1–5 are shown examples of the discovered clusters and alike. All objects were found by means of visual inspections on WISE (Wright et al. 2010), utilizing image services at NASA/IPAC or Aladin. The W1 (3.4 µm) and W2 (4.6 µm) bands are more sensitive to the stellar and PMS content, while in W3 (12 µm) and W4 (22 µm) extended structures arise mostly from dust emission. The subsequent analyses indicated that 212 had already been reported in the literature, or were discarded owing to miscellaneous reasons for a few of them, like probable planetary nebulae or spurious objects when inspected in detail. Thus, 75% of the initial sample were considered to be new star clusters, EGrs or candidates, and were included in the present catalogue. We list in Table 1 38 entries that are shown as examples or discussed in more detail throughout this paper. The complete Table 1 will be available in the online version.

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Figure 1. WISE (10 arcmin × 10 arcmin) RGB images centred on the ECs C 791, C 788, C 860, C 514, C 530 and C 941.

Figure 2. Same as Fig. 1 for the probably more evolved (less embedded) ECs C 1086, C 838, C 769, C 646, C 915 and C 911.
clusters often employ automatic softwares that identify stellar overdensities (e.g. Froebrich et al. 2007). However, heavily dust-obscured ECs may be missed by an automatic algorithm, especially with 2MASS, since a significant fraction of the stellar content may not be accessible. As a consequence, stellar detections in such deeply ECs may be underestimated with respect to the surrounding field. Following Paper I, we tentatively classified the discovered objects in OCs, open cluster candidates (OCCs), ECs, embedded cluster candidates (ECCs), and EGrs. This classification is based on the stellar/dust density estimates on the WISE bands (W1 to W4) and RGB (red green and blue) images (see Paper I). Similar criteria were used in previous works (Hodapp 1994; Bica et al. 2003a; Dutra et al. 2003).

In Figs 1 and 2, we show a representative sample of newly found objects to exemplify the EC classification. In Fig. 1 the stellar content is more embedded than in Fig. 2, which suggests evolutionary effects. Fig. 1 shows six compact relatively isolated ECs. These objects are small dusty and the stellar core is deeply embedded in their natal nebulae. In Fig. 2, C 941, is a very small and poor EC. The structures of ECs in Fig. 2 are dominated by compact cores of stars. In Fig. 3, we show additional objects (Table 1) to clarify the classification, an OC and an OCC without dust emission, an EC with a prominent core, a poor ECC within a dust nebula and two EGrs that are less dense than the EC. Figs 4 and 5 are dedicated to illustrate EC aggregates (Camargo et al. 2011, 2012, Paper III). In the large panel of Fig. 5, we show C 914, C 915, C 916, C 919, C 921 and C 925, together with Sh2-233 SE Cluster, G173 + 2.45 Cluster, SUH 124 and SUH 162 (Solin, Ukkonen & Haikala 2012). These ECs are located in the eastern half of a large star forming complex, where yet more ECs exist. Likewise, in Fig. 4, we appear to be witnessing the birth of a cluster aggregate, however with less members. The emission dust shell suggests that these ECs are coeval. In Fig. 6, we show three interesting closely projected star-forming clumps, which may be an example of multiple cluster formation or just a snapshot view of massive cluster evolution. Such environments differ from cluster aggregates in the sense that their compact nature would favour more frequent cluster interactions, such as mergers.

Fig. 7 shows the angular distribution of the present sample, as compared to the other large WISE cluster surveys (Majaess 2013, Paper I). A few high Galactic objects are beyond $|b| = 30^\circ$ (Table 1), and will be discussed elsewhere.

### 3 Analysis of a Representative Sample

We use 2MASS\(^1\) photometry (Skrutskie et al. 2006) in the $J$, $H$ and $K_s$ bands to analyse the nature of a representative cluster sample. Stars are extracted in circular regions centred in the coordinates of each cluster candidate.

In view of building the intrinsic CMD the observed photometry is submitted to a field-star decontamination procedure, which

\(^1\) The Two Micron All Sky Survey.
**Figure 4.** Shell with C 935, C 936, C 937 and C 938: formation of a cluster aggregate. Top-right: blowup of C 935. Bottom-right: blowup of C 938. Circles indicate OB stars from SIMBAD.

**Figure 5.** Left-hand panel ($2^\circ \times 2^\circ$): dust cloud forming cluster aggregate: C 914, C 915, C 916, C 919, C 921, C 925, Sh2-233 SE Cluster, G173 + 2.45 Cluster, SUH 124 and SUH 162. Top-right: blowup of C 916 (10 arcmin $\times$ 10 arcmin), Bottom-right: blowup of C 925 (10 arcmin $\times$ 10 arcmin).
is described in detail in Bonatto & Bica (2007a,b) and Bica, Bonatto & Camargo (2008). The fundamental parameters are derived by fitting PARSEC isochrones (Bressan et al. 2012) to the J × (J − Ks) decontaminated CMDs. The cluster structures are analysed via RDP. Fig. 8 shows WISE images of their decontaminated CMDs and RDPs. In Table 2, we show the derived cluster parameters from the CMD. The clusters are younger than 5 Myr, and some are as young as 1–2 Myr. Distances are in the range d⊙ = 2.8–6.0 kpc. The RDPs are typical of well-studied ECs (e.g. Bonatto & Bica 2009, 2011), showing a central peak and at times radial dips possibly caused by dust absorption or crowding.

4 DISCUSSION

4.1 Relatively isolated ECs

The ISM consists of a hierarchical structure of gas and dust, from GMC complexes to small cores. Since star clusters emerge from these structures we can expect some similarity mainly in the embedded phase. These objects may span a wide range of sizes, from small and compact ECs with sizes of ∼1 pc to centrally concentrated massive clusters with sizes of ∼10 pc – from relatively isolated ECs to large aggregates.

Subsequent early stages of isolated EC formation are seen in Figs 1 and 2, respectively. Isolated small ECs appear to be relatively common in the Galaxy (Camargo et al. 2011, Papers I and III). Some of the new findings (e.g. C 514 and C 530 in Fig. 1) show clear evidence of ongoing star formation.

4.2 Composite ECs

Figs 4 and 5 show dust complexes where new ECs are born together, forming EC aggregates. EC aggregates are groups of clusters close to each other, formed together after the gravitational collapse and fragmentation of a GMC or a complex of them. Recently, we reported in Paper III an EC aggregate formed by seven ECs with similar age in the Perseus arm. We suggested that an entire GMC or a cloud complex may fragment almost simultaneously generating EC aggregates. Spiral arms may play an important role in the large-scale structure triggering sequential EC formation by shock
Figure 8. WISE (10 arcmin × 10 arcmin) RGB images centred on the EC C 943, C 1043, C 716, C 978, C 741 and C 793, used in CMD and RDP analyses (Section 3).

Table 2. Derived fundamental parameters for confirmed star clusters in this study. Column 2: evolutionary phase – EC means embedded cluster; Columns 3 and 4: central coordinates; Column 5: $E(J - H)$ in the cluster central region. Column 6: age, from 2MASS photometry. Column 7: distance from the Sun. Column 8: $R_{GC}$ calculated using $R_{⊙} = 7.2$ kpc for the distance of the Sun to the Galactic Centre (Bica et al. 2006). Columns 9–11: Galactocentric components. (RDPs for ECs can be seen in Fig. 11.)

| Cluster | Phase | $\alpha$(2000) | $\delta$(2000) | $E(J - H)$ | Age (Myr) | $d_{⊙}$ (kpc) | $R_{GC}$ (kpc) | $x_{GC}$ (kpc) | $y_{GC}$ (kpc) | $z_{GC}$ (pc) | rowsep="1"
|---------|-------|----------------|----------------|-------------|-----------|---------------|----------------|---------------|---------------|---------------|----------------|
| C 716   | EC    | 2:01:31        | 60:32:42       | 0.50 ± 0.03  | 2 ± 1     | 3.1 ± 0.4    | 9.5 ± 0.3     | −9.26 ± 0.29  | 2.31 ± 0.33   | −62.39 ± 8.92 |           |
| C 741   | EC    | 2:25:39        | 61:13:33       | 0.44 ± 0.03  | 2 ± 1     | 2.8 ± 0.4    | 9.4 ± 0.3     | −9.14 ± 0.27  | 1.99 ± 0.28   | 19.29 ± 2.76  |           |
| C 758   | EC    | 2:37:33        | 61:13:21       | 0.32 ± 0.01  | 1 ± 0.5   | 5.1 ± 0.7    | 8.7 ± 0.4     | −7.04 ± 0.02  | 0.97 ± 0.13   | −4.99 ± 0.69  |           |
| C 789   | EC    | 3:15:11        | 59:54:44       | 0.27 ± 0.02  | 3 ± 1     | 3.1 ± 0.3    | 9.8 ± 0.2     | −9.61 ± 0.23  | 2.00 ± 0.19   | 103.84 ± 9.90 |           |
| C 793   | EC    | 3:17:23        | 60:02:07       | 0.26 ± 0.03  | 4 ± 1.5   | 3.0 ± 0.4    | 9.7 ± 0.3     | −9.53 ± 0.33  | 1.93 ± 0.28   | 113.55 ± 16.24 |        |
| C 853   | EC    | 4:07:32        | 50:30:48       | 0.39 ± 0.03  | 2 ± 1     | 3.2 ± 0.5    | 10.2 ± 0.4    | −10.06 ± 0.41 | 1.53 ± 0.22   | −61.90 ± 8.85 |           |
| C 943   | EC    | 6:15:25        | 19:01:40       | 0.22 ± 0.03  | 3 ± 2     | 2.9 ± 0.4    | 10.1 ± 0.4    | −10.05 ± 0.40 | −0.60 ± 0.09  | 48.90 ± 6.99  |           |
| C 978   | EC    | 6:10:50        | 12:32:45       | 0.20 ± 0.03  | 3 ± 1     | 3.7 ± 0.5    | 10.8 ± 0.5    | −10.78 ± 0.5  | −1.10 ± 0.16  | −201.62 ± 28.83 |       |
| C 1043  | EC    | 7:26:04        | −31:39:24      | 0.15 ± 0.02  | 4 ± 2     | 6.0 ± 0.8    | 11.2 ± 0.5    | −9.75 ± 0.4   | −5.40 ± 0.76  | −752.84 ± 105.58 |      |

Compression of large molecular cloud complexes (de la Fuente Marcos & de la Fuente Marcos 2008; Camargo et al. 2011, 2012). EC aggregates are also reported in Camargo et al. (2011, 2013).

The shell configuration of dust and the stellar content in Fig. 4 point to a sequential EC formation via a collect and collapse event (Camargo et al. 2011). In the classical collect and collapse scenario (Elmegreen & Lada 1977; Whitworth et al. 1994) an H II region expands, excited by winds from OB stars, collecting the surrounding material that becomes unstable, and the collapse triggers a sequential star formation. A non-symmetric expanding shell generated by multiple excitation sources or interactions with the surrounding environment may favour the agglutination of neutral material forming dense clumps that are cluster progenitors. The distribution of B stars in Fig. 4 possibly created winds that accumulated material in multiple clumps of dust in the surroundings. On the contrary, other B stars may have have ejected primordial gas from an early cluster, stopping the process of star formation. In addition to runaway massive stars, part of the Galactic isolated OB field stars may be related to such failed clusters. If, on one hand, OB-type stars may disrupt completely an EC during the primordial gas expulsion, on the other hand, they may result in the formation of large molecular cloud complexes (de la Fuente Marcos & de la Fuente Marcos 2008; Camargo et al. 2011, 2012).
WISE-embedded cluster survey

Figure 9. 2MASS CMDs extracted from the \( R = 2 \) arcmin of C 943. Top panels: observed CMDs \( J \times (J - H) \) and \( J \times (J - K_s) \). Middle panels: equal area comparison field. Bottom panels: field star decontaminated CMDs fitted with MS and PMS PARSEC isochrones. We show the reddening vector for \( A_V = 0–5 \).

hand, they may form a second-generation of ECs via sequential cluster formation.

Fig. 6 shows multiple closely packed stellar clumps with ongoing star formation. These structures appear to be common in the Galaxy (Camargo et al. 2011, 2012, 2015a, Paper I). Often these types of cluster-forming regions are considered as a single cluster with fractal structure or subclusters. On the other hand, in the early evolutionary stages several Galactic isolated ECs present structure with sizes of \( \sim 1 \) pc (Testi et al. 1997; Bica et al. 2003a; Lada & Lada 2003; Motte, Schilke & Lis 2003; Adams et al. 2006; Rodríguez-González et al. 2008; Gutermuth et al. 2009; Higuchi et al. 2009; Piatti, Clariá & Ahumada 2010; Camargo et al. 2011; Myers 2011; Alexander & Kobulnicky 2012, and Paper I), similar to those shown in Figs 1 and 2. Compact ECs like C 941 (Fig. 1) also appear to be relatively common in the Galaxy. Therefore, the possibility that massive clusters form by merger of several close ECs cannot be ruled out. The fact of considering such systems as isolated clusters with fractal structure or compact EC aggregates probably not will change their final fate, since both scenarios possibly will lead to a single cluster. However, since in the merging process the ECs do not dissolve, the infant mortality may not be as significant as proposed in previous works. As Lada & Lada (2003) argue that the number of ECs exceeds the number of OCs observed by over an order of magnitude, a high infant-mortality rate is assumed for ECs.

Nevertheless, since the merging possibility in the early formation is not considered, the EC dissolution rate may be overestimated. Fellhauer & Kroupa (2005b) pointed out that within dense aggregates some clusters may merge before the gas expulsion greatly increasing their survival probability. Thus, EC aggregates may be sites of massive cluster formation by merger (Bastian et al. 2005; Fellhauer & Kroupa 2005a, and references therein). Walker et al. (2015) argue that young massive cluster formation may proceed hierarchically rather than through monolithic collapse, with mass becoming more centrally concentrated as the cluster evolves. In this hierarchical merging scenario, small and dense ECs merge to form larger systems leading to a single centrally concentrated cluster (Camargo et al. 2011, 2012; Fujii, Saitoh & Portegies Zwart 2012). In addition, the massive cluster formation by merge explain the excessive age spread for ECs. To conclude, we call attention to the possible environmental conditions where such cluster dynamical evolutionary scenarios may occur more or less frequently, from closely packed ECs (Fig. 6), poorly populated coeval aggregates (Fig. 4) to rich aggregates of ECs in large dust complexes (Fig. 5).
CONCLUDING REMARKS

We communicate the discovery of 652 star clusters and stellar groups using WISE. They were found by one of us (DC) and are designated Camargo 447 (C 447) to C 1068. The present list is a followup of the 446 previous discoveries in Papers I, II and III. In general, the newly found clusters are ECs or EGrs. These objects have probably been neglected in the past, because of the difficulty in detecting them, especially with 2MASS. WISE has finally revealed them, in particular in Majaess (2013), Paper I, and this study. Heavily dust-obscured embedded objects may be more easily detected by visual inspections on the WISE Atlas than by automatic searches of stellar overdensities. The notion that most stars form in massive clusters may also have contributed to that bias. The initial search resulted in 864 objects, but 212 were discarded because they were already reported in the literature, or for reasons like probable planar nebulae, or spurious objects. Thus, 75 per cent of our initial sample was considered to be new star clusters, stellar groups or candidates.

The discovered ECs provide new insights on star cluster formation and their early evolution. We point out that several isolated ECs are compact when compared to classical OCs, with sizes comparable to subclusters or fractals in objects often considered as substructured clusters. On the other hand, some molecular clouds or dust complexes present multiple cluster formation, mainly in filamentary structures. At large scales these structures probably form EC aggregates (e.g. Figs 4 and 5). In small scales, they may merge forming a populous (massive) single cluster. The newly found ECs C 1008, C 1009, together with DBSB 11 (Fig. 6) may have this fate. In this particular viewpoint, some substructured clusters may be only a snapshot view of a merging event. This scenario suggests that there is a continuum of star-forming environments from populous dense clusters to small ECs in relative isolation, such as C 941. Turbulent GMCs typically develop filamentary structures, which appear to be naturally hierarchical.

We analysed the nature of a representative subsample of nine clusters (Section 3), using 2MASS field-decontaminated CMDs and RDPs. The inspection of the WISE images (Fig. 8) and 2MASS decontaminated CMDs (Figs 9 and 10) confirms them as ECs. Since they are younger than 5 Myr (Table 2), their RDPs behave like those of many other ECs so far studied with the same method (e.g. Bonatto & Bica 2009). They are centrally concentrated, and have dips owing to dust absorption or crowding. From their ages they are not expected to follow a King profile, and they do not.

The distribution in Galactic coordinates of the present sample (Fig. 7) shows how loci throughout the disc are becoming explored with WISE, as a consequence of Majaess (2013), Paper I, and this study. However, the plot also points out guiding lines for future searches.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. List of newly found star clusters and candidates.

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