LETTER TO THE EDITOR

How universal are the two young cluster sequences?

The cases of the LMC, SMC, M 83, and the Antennae[*]

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ABSTRACT

Aims. Recently a new analysis of cluster observations in the Milky Way found evidence that clustered star formation may work under tight constraints with respect to cluster size and density, implying that only two sequences exist. Our aim is to investigate whether similar sequences can be found in other nearby galaxies.
Methods. This is done using data of cluster properties from the literature.
Results. For the extragalactic young stellar clusters we detect an overall trend in the cluster-density scaling that is comparable to the relation obtained for Galactic clusters, although differences may exist. For the LMC and SMC clusters, the densities are below the Galactic data points and/or the core radii are smaller than those of data points with comparable density. For M 83 and the Antenna clusters, the core radii are possibly comparable to the Galactic clusters but it is unclear whether they have similar expansion speeds. These findings should serve as an incentive to performing more systematic observations and analysis to answer the question of why there may be a similarity between young Galactic and extragalactic star cluster sequences.

Key words. Local Group – open clusters and associations: general – Magellanic Clouds – Galaxy: structure

1. Introduction

Lada & Lada (2003) showed that in our Galaxy most stars do not form in isolation but in cluster environments. These young clusters typically consist of thousands of stars or more with densities ranging from <0.01 to several 10^5 $M_\odot$ pc^{-3}. This wide variety of observed cluster densities leads to the assumption that clusters are formed over this entire density range. Albeit Maiz-Apellaniz (2001) noticed that two types of clusters in the Galaxy exist, only recently did Pfalzner (2009) find that massive clusters develop in a bimodal way as illustrated in Fig. 1, where the red, green, and blue symbols represent clusters with ages $t_c < 4$ Myr, 4 Myr $< t_c < 10$ Myr, 10 Myr $< t_c < 20$ Myr, respectively. Two well-defined sequences in the density-radius plane emerge showing the *bi-modal nature of the cluster evolution.*

Pfalzner (2009) classified the two modes as starburst and leaky cluster sequences. The starburst cluster sequence implies a population of compact clusters (0.1 pc) with high initial densities (10^5–10^6 $M_\odot$ pc^{-3}), which then expand with the mass-density decreasing as $\sim R^{-3}$ (a true 2σ-fit gives a R^α-dependence with $\alpha = -2.71 \pm 0.32$) and evolve to have sizes of a few pc over a period of 10 Myr or longer. Prominent members of this type of cluster are, for example, Arches, NGC 3603, and Westerlund 1. The leaky cluster sequence implies the creation of a second population of diffuse clusters (~ 5 pc) which expand loosing mass during the process, until they have sizes of a few tens of pc. The expansion also follows a predefined track, but here the density decreases as $\sim R^{-4}$ (true fit value $\alpha = -4.07 \pm 0.33$). Here
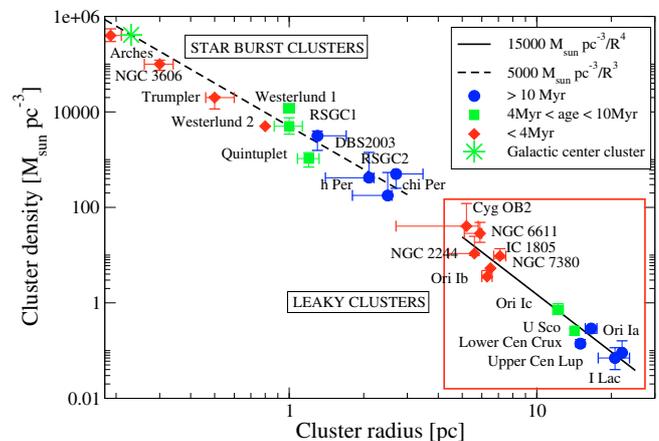
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[*] Tables 2–5 are only avilable in electronic form at http://www.aanda.org

Fig. 1. Cluster density as a function of cluster size for clusters more massive than 10^3 $M_\odot$ as published by Pfalzner (2009, references therein).

NGC 6611, Ori 1a-c, or U Sco are typical examples. We note that the cluster radii were not determined in exactly the same way for all clusters shown in Fig. 1. However, the starburst cluster values all represent the core radii apart from χ Per and h Per (for a discussion of the determination of these two radii, see Pfalzner 2009).

It follows that star formation occurs only under an extremely limited set of conditions, and may require a fundamental revision of star-formation hypotheses for our Galaxy. This immediately raises the questions of the origin of these two distinct cluster sequences and whether similar density-radius correlations could

Table 1. Determination methods of radius, mass and age and background consideration.

Galaxy	Radius determination	Mass determination	Background	Age determination
LMC[1]	King profile fit half-surface brightness	from mass/light ratio from evolutionary code[5]	mean surface brightness in annulus at $r \gg R_c$	combination of IMF [8] and evolutionary code[5]
SMC[2]	King profile fit half-surface brightness	from mass/light ratio from evolutionary code[5]	mean surface brightness in annulus at $r \gg R_c$	Based on color−magnitude diagram[12]
Antennae[3]	Fit with ISHAPE code[6]	*UBVI*-colors and mass/light ratio[7] with extinction-corrected SSP	Fit with ISHAPE code	LICK line strength indices and [11]
M 83[4]	Fit with ISHAPE code[6]	Isochromes[9]	Fit with ISHAPE code	*UVBI*-colors, 2-color and S-sequence diagram [10]

[1] Mackey & Gilmore (2003a); [2] Mackey & Gilmore (2003b); [3] Mengel et al. (2008); [4] Larsen & Richter (2004); [5] Fioc & Rocca-Volmerangen (1997); [6] Larsen (1999); [7] Anders & Fritz-von-Alvensleben (2003); [8] Kroupa et al. (1993); [9] Girardi (2000); [10] Girardi (1995); [11] Schweizer (2005); [12] Chiosi (1995).

be found in other galaxies. This Letter addresses the latter question.

Most of the extragalactic clusters that one observes are likely to belong to the starburst cluster sequence because although their extension is on average smaller, the luminosity of their high number of O-stars is much easier to detect than the smaller number of O stars spreading over a larger area in leaky clusters. In all subsequent figures to Fig. 1, only the starburst clusters of the Galaxy are therefore shown for comparison and the radial extent is the core radius.

The Milky Way is currently not in a intense star formation phase which accounts for the scarcity of starburst clusters in the Galaxy. Another reason is that extinction at low latitudes hampers the detection of distant Galactic clusters. In contrast, there are starburst and interacting galaxies such as the "Antennae", where many clusters with masses $>10^4\ M_\odot$ are observed with ages < 1 Gyr (Zhang & Fall 1999). In between, there exist the dwarf starburst galaxies such as NGC 4214, where several massive clusters with ages < 100 Myr are visible in the central regions.

This letter presents a first investigation of whether similar development tracks can be found for clusters in these different galaxies. Observationally, one is restricted to nearby galaxies, and even there radii are only resolved for a very limited sample. Here we scanned the literature for data of clusters younger than 30 Myr in the Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC), Messier 83 (M 83), and the Antennae.

2. Limitations

Comparing clusters in the Milky Way with extragalactic clusters intrinsically has its limitations. In particular, the age-dating in both cases is different: whereas for Milky Way clusters ages can be based on individual stars, in distant clusters they are determined from integrated colors. The comparison of radii is even more complex since different definitions exist resulting in various measurement methods. In addition, the effects of the different spatial resolutions, background, and photometric bandpasses adapted can strongly influence the results. In general, we compare the core radii of the different clusters (note that Fig. 1 contains partly different definitions of radii, for a discussion see Pfalzner 2009). Ideally, one should use the same age, mass, and radii determination techniques for all investigated clusters. However, unfortunately for most of the clusters no public data are yet available, so literature data were used. Table 1 lists for each of the investigated galaxies the methods used for age, mass, radius, and background determination.

3. Magellanic clouds

Since the LMC and SMC are at distances of 50 kpc and 60 kpc (Schaefer 2008), respectively, their system of star clusters can be studied in far more detail than those of more distant hosts. Compared to the Galaxy, the Magellanic clouds are gas-rich and metal-poor, thus providing a different environment for stars to form and evolve.

3.1. LMC

Rich clusters in the LMC span a wide range in ages, $6 \leq \log(\text{yrs}) \leq 10$. Most clusters that are younger than $\simeq 3$ Gyr have metallicities of between 1/2 and 1/3 of solar values (Santiago 2008). Although thousands of clusters are known in the LMC, only a few fulfill the specific conditions of our study, i.e. cluster age < 20 Myr with known mass and radial extent. Figure 2a shows the density as a function of cluster radius for LMC clusters. The data are taken from Maykey & Gilmore (2003) and compared to the starburst cluster sequence of the Galaxy. Most of the LMC cluster data points lie below those of the Galaxy. The same applies when comparing the cluster age to the cluster radius (see Fig. 2b).

3.2. SMC

The Small Magellanic cloud (SMC) is the closest star-forming dwarf galaxy (∼60 kpc). Its present-day metallicity ($Z = 0.004$) and low dust content (30 times lower than in the Milky Way) make the SMC a prototype late-type dwarf. At these low metallicities one expects that the resulting reduced stellar wind can modify the early evolution of clusters since the powerful winds characteristic of systems of solar metallicities do not exist and therefore might not be able to remove the gas left from star formation. Unfortunately we found only one cluster younger than 30 Myr of known density and radius, whose data point is slightly above the Galactic star cluster track in Fig. 2a.

3.3. Discussion

The very limited data available for the LMC and SMC provide a first indication of a similar sequential track for the LMC and SMC as in the Galaxy possibly at lower density values for the LMC. One possible reason for this lower track could be the lower metallicities of the LMC system (Cepheid metallicities of $Z = 0.0091+/-0.0007$ and $0.0050+/-0.0005$ for the LMC and SMC, respectively, compared to $Z = Z_\odot \sim 0.02$; Keller & Wood 2006).
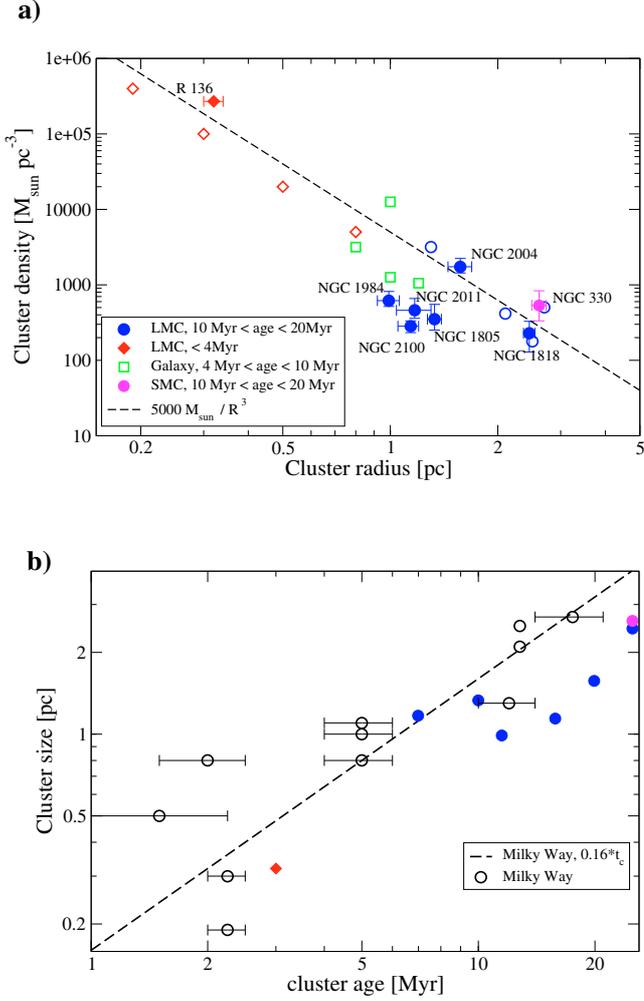
a)

b)

Fig. 2. a) Cluster density as a function of cluster radius and **b)** cluster size as a function of cluster age. Here the LMC and SMC (purple circle) clusters are shown as filled symbols and the Milky Way as open symbols (same clusters as in Fig. 1). The values for the clusters in the LMC are taken from Mackey & Gilmore (2003a) and McLaughlin & van der Marel (2005), the SMC value from Mackey & Gilmore (2003b).

The lower metallicities may lead to a higher Jeans mass and therefore higher initial mass limit in general (Clark & Bromm 2002). At the same mass, lower metallicity stars are more luminous (e.g., Bertelli et al. 2008). Hence, including the effect of mass segregation, the centers of low metallicity star clusters may be overluminous compared to higher metallicity clusters, resulting in the underestimate of their sizes. However, it is unclear whether this effect is strong enough to produce the observed difference in the size measurements.

The uncertainties in the distance modulus of the LMC (LMC: 18.54+/−0.018; SMC: 18.93+/−0.024; Keller & Wood 2006) is small and cannot be responsible for the entire size discrepancy. The clusters are seen against the stellar background of the LMC/SMC. This may result in an underestimation of the contribution of the more extended off-center stellar cluster brightness distribution that is not dominated by luminous stars. This effect will lead to an underestimation of the cluster size.

4. The Antennae

The Antennae are the nearest and most well studied pair of merging galaxies, consisting of two large spirals that began to collide
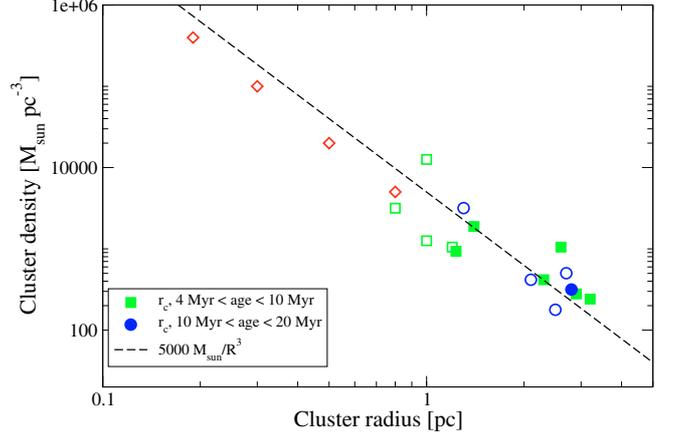

Fig. 3. Cluster size as a function of cluster age. The Antennae clusters (data from Bastian et al. 2009) are shown as filled symbols. The Milky Way clusters are also indicated (open symbols).

a few 10^8 yr ago. The ongoing merger is almost certainly responsible for the large population of clusters. Understanding the formation and disruption of clusters in this setting is important because it represents a latter-day example of the hierarchical formation of galaxies, a process that operated even more effectively in the early universe. Fall et al. (2005) find a steep decline in the number of clusters as a function of age, which they interpret as a sign of intensive disruption of these clusters. They conclude that the short timescale on which the clusters are disrupted indicates that most of them are not gravitationally bound. So the Antennae seem to show a high rate of "infant mortality" similar to the Milky Way. Since the clusters are initially disrupted mainly by internal processes, they expect the age distribution to be largely independent of the properties of the host galaxy.

Since only values of the effective radii r_{eff} (half-light radii) are given for the Antennae clusters in Fig. 3, core radii r_c were derived by assuming a factor of 3 difference between r_{eff} and r_c as deduced for globular clusters (Schweizer 2005). Whether this relation holds as well for young clusters is uncertain. The core radii inferred in this way fit quite well onto the Galactic starburst cluster sequence, but in general the ages of the clusters are younger than those of equivalent Galactic starburst clusters.

5. M 83

The nearby spiral galaxy M 83 is known to have a rich population of relatively young clusters, most likely due to its high star formation rate. Using the cluster data by Larsen & Richtler (2004), Fig. 4 shows the cluster density as a function of effective radius. As for the Antennae galaxy, we inferred the core radii by assuming a factor of 3 difference between r_{eff} and r_c, as performed for globular clusters (Schweizer 2005). The data obtained in this way lie on the Galactic starburst cluster sequence.

6. Conclusion

For the extragalactic young stellar clusters, that we have studied, the overall trend in the cluster radius versus cluster density relation seems to follow the relation obtained for Galactic starburst clusters by Pfalzner (2009). For the LMC clusters differences possibly exist, the densities being mostly below the comparable Galactic data of equal radius, or the radii being smaller than those of data points of comparable density. This might indicate
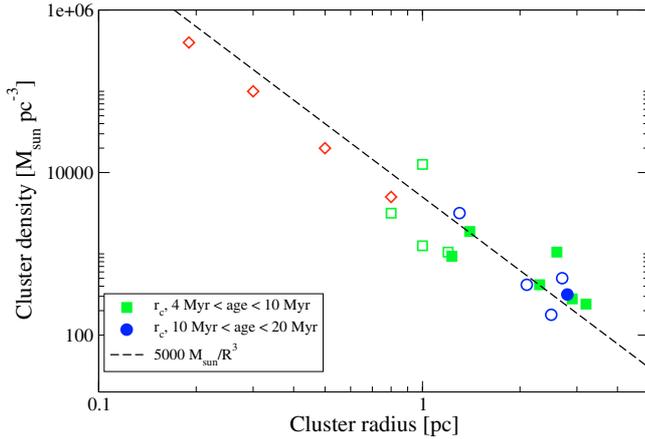
Fig. 4. Cluster size as a function of cluster age. The M 83 clusters (Larsen & Richtler 2004) are shown as filled symbols. The Milky Way clusters are indicated in addition (open symbols).

that the sizes of the LMC clusters are systematically smaller than the Galactic cluster sizes. This may be caused by intrinsic observational effects.

However, the sample size of extragalactic young clusters (<20 Myr) with known radii and masses is so small that this investigation can only be regarded as a first hint that the young starburst cluster sequence might also exist in galaxies other than the Milky Way. In this study, only literature values of age, mass, and radius have been used mostly, which were obtained by different methods. Further studies with a larger sample size and more homogenous data acquisition will be required to confirm this result.

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Table 2. Properties of clusters younger than $\log(t_c) = 8.00$ in the LMC.

Identifier	log(age) [Myr]	Δ age	Radius [pc]	Δ radius	M_{total} [$M_\odot$]	ΔM_{total}	$\log(\rho)$ [$M_\odot$/pc^{-3}]	$\Delta\rho$
NGC 1805[1]	7.0	0.3	1.33	0.06	3.52	0.13	2.54	0.2
NGC 1818[1]	7.4	0.3	2.45	0.09	4.13	0.15	2.35	0.2
NGC 1984[1]	7.06	0.3	0.99	0.07	3.38	0.24	2.79	0.2
NGC 2004 [1]	7.30	0.2	1.57	0.13	4.43	0.38	2.32	0.2
NGC 2011[1]	6.99	0.3	1.17	0.12	3.47	0.14	3.24	0.12
NGC 2100[2]	7.20	0.3	1.14	0.14	4.43	0.13	3.05	0.2
R 136[1]	6.48	0.18	0.32	0.02	4.55	0.21	4.47	0.08

[1] Mackey & Gilmore (2003a); and [2] McLaughlin & van der Marel (2006).

Table 3. Properties of clusters younger than $\log(t_c) = 8.00$ in the SMC from (Mackey & Gilmore 2003b).

Identifier	log(age) [Myr]	Δ age	Radius [pc]	Δ radius	M_{total} [$M_\odot$]	ΔM_{total}	$\log(\rho)$ [$M_\odot$/pc^{-3}]	$\Delta\rho$
NGC 330	7.4	0.4	2.61	0.12	4.58	0.2	2.72	0.2

Table 4. Properties of clusters younger than $\log(t_c) = 7.50$ in the Antennae from Bastian et al. (2009).

Identifier	log(age) [Myr]	Radius [pc]	log(mass) [$M_\odot$]	$\log(\rho)$ [$M_\odot$/pc^{-3}]
T54	6.9 ± 0.1	3.7	4.8 ± 0.3	2.49
T 270	<6.8	9.3	5.4 ± 0.3	1.89
T 324	6.5–6.8	7.7	5.2 ± 0.3	2.54
T 343	6.5–6.8	8.8	5.4 ± 0.3	1.96
T 365	6.5–6.8	4.3	5.3 ± 0.3	2.80
T 367	6.5–6.8	6.6	5.2 ± 0.3	2.14

Table 5. Properties of clusters younger than $\log(t_c) = 7.50$ in M 83 from Larsen (2004).

Identifier	log(age) [Myr]	r_{eff} [pc]	log(mass) [$M_\odot$]	$\log(\rho)$ [$M_\odot$/pc^{-3}]
N5236-502	8.0 ± 0.1	7.6 ± 1.1	5.15 ± 0.83	$2.8 \pm 1.0 \times 10^3$
N5236-805	7.1 ± 0.2	2.8 ± 0.4	4.16 ± 0.67	$1.6 \pm 1.1 \times 10^4$