Stellar clusters in M83: formation, evolution, disruption and the influence of the environment

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ABSTRACT
We study the stellar cluster population in two adjacent fields in the nearby, face-on spiral galaxy M83 using multiwavelength Wide Field Camera 3/Hubble Space Telescope imaging. After automatic detection procedures, the clusters are selected through visual inspection to be centrally concentrated, symmetric, and resolved on the images, which allows us to differentiate between clusters and likely unbound associations. We compare our sample with previous studies and show that the differences between the catalogues are largely due to the inclusion of a large numbers of diffuse associations within previous catalogues as well as the inclusion of the central starburst region, where the completeness limit is significantly worse than in the surrounding regions. We derive the size distribution of the clusters, which is well described by a lognormal distribution with a peak at ∼2.5 pc, and find evidence for an expansion in the half-light radius of clusters with age. The luminosity function of the clusters is well approximated by a power law with an index of −2 over most of the observed range; however, a steepening is seen at $M_V = -9.3$ and −8.8 in the inner and outer fields, respectively. Additionally, we show that the cluster population is inconsistent with a pure power-law mass distribution, but instead exhibits a truncation at the high-mass end. If described as a Schechter function, the characteristic mass is $1.6 \times 10^5$ and $0.5 \times 10^5$ $M_\odot$ for the inner and outer fields, respectively, in agreement with previous estimates of other cluster populations in spiral galaxies. Comparing the predictions of the mass-independent disruption (MID) and mass-dependent disruption (MDD) scenarios with the observed distributions, we find that both models can accurately fit the data. However, for the MID case, the fraction of clusters destroyed (or mass lost) per decade in age is dependent on the environment; hence, the age and mass distributions of clusters are not universal. In the MDD case, the disruption time-scale scales with galactocentric distance (being longer in the outer regions of the galaxy) in agreement with analytic and numerical predictions. Finally, we discuss the implications of our results on other extragalactic surveys, focusing on the fraction of stars that form in clusters and the need (or lack thereof) for infant mortality.

Key words: galaxies: individual: M83 – galaxies: star clusters: general.

1 INTRODUCTION
A by-product of the star formation process is the formation of stellar groups, some of which are gravitationally bound and likely long-lived, while other groups are unbound and will disperse into the field. In the Galaxy, the former are often referred to as open clusters, while the latter are known as associations. However, for most extragalactic studies, the limited spatial resolution, even when using Hubble Space Telescope (HST) imaging, as well as the lack of dynamical information for individual stars, makes the distinction between these two groups challenging. This is particularly difficult
at young (<10 Myr) ages before significant dynamical evolution has taken place. Such ambiguities can severely affect the interpretation of extragalactic cluster samples, especially when large numbers of young groups are present, as in starburst galaxies. For galaxies that have a dominant older population, such as post-merger remnants, like NGC 7252 (Schweizer & Seitzer 1998) or NGC 1316 (Goudfrooij et al. 2001), clusters can be straightforwardly defined due to their compact nature and the fact that associations have dissolved into the field.

Using a sample of resolved stellar groups of various ages (including groups fully resolved into their constituent stars as well as groups that appear extended on images) compiled from the literature, Portegies Zwart, McMillan & Gieles (2010, hereinafter PZMG10) have shown that there exists a continuous distribution of stellar structures at young ages (from loose groups to dense clusters), while at older ages (>10 Myr) a bimodal distribution develops, with bound and unbound groups that are clearly distinguishable. This observation fits well with the inferred hierarchical distribution of star formation, where no preferred scale exists from tenths to hundreds of parsecs, meaning that clusters are not distinct or unique objects at young ages (e.g. Bastian 2011). Hence, clusters cannot be defined until a stellar group is dynamically evolved.

Along similar lines, PZMG10 also showed that the derived properties of a cluster population depend on how clusters are defined. For example, the age distribution of loose stellar structures (effective radii, $R_{\text{eff}}$, greater than 6 pc) in the Small Magellanic Cloud (SMC) shows a rapid decline, with the number of groups dropping as a function of age as $r^{-1}$. On the other hand, if only compact groups are considered ($R_{\text{eff}} < 6$ pc), the age distribution is mostly flat, negating the need of large amounts of disruption.

In this work, we study the cluster population of the nearby face-on spiral galaxy M83 using new Wide Field Camera 3 (WFC3) imaging with the HST. In order to define our cluster sample, each cluster candidate is assessed by eye, and only resolved and centrally concentrated objects are included in the sample. The sample covers a large range in galactocentric distances, hence sampling a large range of environmental conditions. Using our conservatively defined cluster sample, we have previously found evidence for a strong dependence of cluster lifetimes on the ambient environment (Bastian et al. 2011, hereinafter B11). Here, we use the same sample to study (i) the distribution of cluster sizes, luminosities and masses; (ii) empirical cluster disruption laws; and (iii) relations among the derived parameters (age, mass and radius).

### 1.1 Cluster formation and disruption

The standard paradigm that has developed over recent years is that all or most stars form in clusters, and that a large fraction (~90 percent) of the clusters are destroyed during the process of going from the embedded to the exposed phase (Lada & Lada 2003).\(^1\) This process, known as infant mortality, is thought to be due to the removal of gas left over from the star formation process. This gas expulsion is expected to be largely independent of the ambient environment since gas expulsion is largely an internal process and independent of mass since the mass-loss is driven by violent relaxation (e.g. Goodwin & Bastian 2006). This phase of cluster evolution is expected to last a few crossing times, namely ≲10 Myr for massive dense clusters (PZMG10).

After this initial phase, the surviving clusters are not expected to live indefinitely, but rather to disrupt due to internal (e.g. two-body relaxation, stellar evolution) and external (e.g. tidal fields) processes. Fall, Chandar & Whitmore (2009) have suggested that these processes happen over different time-scales, and hence can be treated independently, in addition to being largely independent of cluster mass. Alternatively, through an analytic approach, Gieles, Heggie & Zhao (2011) find that all processes are acting concurrently and that the lifetime of a cluster depends on the ambient environment and its mass, in agreement with other theoretical investigations (e.g. Hénon 1961; Spitzer 1987).

Observationally, the situation is less clear, and the community has yet to reach a consensus regarding the amount of disruption observed in populations as well as the role of cluster mass and environment in the process. There have been two main empirical disruption laws put forward in the literature, based on different cluster samples in a variety of galaxies (explained in detail below). In only one case, the SMC, have the advocates for the different scenarios used the same data set (Chandar, Fall & Whitmore 2006; Gieles, Lamers & Portegies Zwart 2007), and even there the authors have reached different conclusions.

The first empirical disruption law considered here is mass-dependent disruption (MDD, Lamers et al. 2005). This was first presented in Boutloukos & Lamers (2003), assuming instantaneous disruption, in order to explain the observed cluster population properties in the Galaxy, the SMC, M33 and M51 (however, see Larsen 2008, for a thorough review of empirical MDD laws). In this scenario, the lifetime of a cluster is dependent on the initial mass of the cluster as $M^\gamma$, with $\gamma \sim 0.62$, and on the ambient environment with clusters surviving longer in galaxies with weak tidal forces and low numbers of giant molecular clouds (GMCs). The empirical model was updated in Lamers et al. (2005; this is the form that we adopt here, which includes gradual cluster mass-loss), applied to a distance-limited sample of open clusters in the Milky Way in Lamers & Gieles (2006), and was shown to agree with predictions from numerical N-body experiments in Gieles et al. (2004).

The second empirical disruption law considered here is mass-independent disruption (MID, Whitmore, Chandar & Fall 2007). In this scenario, cluster disruption is independent of cluster mass and the ambient environment. While the classic infant mortality falls in this category and is thought to last for ≲10 Myr (e.g. Lada & Lada 2003), the concept has been expanded up to ages of ~1 Gyr and has been invoked to explain cluster populations in the Antennae (Fall, Chandar & Whitmore 2005), the Large Magellanic Cloud (LMC; Chandar, Fall & Whitmore 2010a), and the inner regions of M83 (Chandar et al. 2010b, hereinafter C10; Fouesneau et al. 2011). The model is described in detail in Whitmore et al. (2007). This disruption scenario results in ‘universal’ age and mass distributions, with the number of clusters $d^2N_{\text{cluster}}/dMdt \propto M^{-2}$, as cluster disruption dominates (over formation) the shape of the distributions.

Elmegreen & Hunter (2010) and Kruijssen et al. (2011a) have shown that MID can be an emergent result of MDD. In this scenario, clusters are destroyed through strong interactions with the hierarchical interstellar medium, a process that may be (largely) mass-independent if the shocks are strong enough but should depend strongly on the ambient density of the gas (i.e. environment).

One of the goals of this study is to distinguish between these two models, and place additional constraints upon them. Additionally,

\(^1\) However, recent studies on the spatial distribution of both high-mass (e.g. Lamb et al. 2010; Bressert et al. 2011) and low-mass (e.g. Bressert et al. 2010) young stars have shown that clusters may be the fundamental unit of star formation. Indeed, clusters are not expected to be if star formation follows a continuous distribution which would result in stars forming in a continuous distribution, from dense clusters to (near) isolation (cf. Bastian 2011).
we would like to understand the differences between the age and mass distributions derived in the different studies. The new M83 WFC3 images provide a rich data set with which we can test each of the possibilities for the differences reported in the literature. In B11, we investigated possible differences between the ages/masses derived for the clusters in the data set used here and the catalogue used in C10 and Whitmore et al. (2011, hereinafter W11). We found a good agreement in the derived ages/masses between the two data sets, when a source appeared in both catalogues. We concluded that the likely differences derived between the respective groups was due to sample selection and/or differing analysis methods.

In B11, we used the data sets presented here to study the dependence of environment on the cluster disruption process. Comparing the distribution of clusters in colour–colour space as well as through quantitative comparison between the age–mass distributions between the two fields, we found clear evidence for the strong influence of environment on cluster disruption. The inner region of the galaxy was found to have a relatively high rate of cluster disruption, in agreement with C10, while in the outer regions, clusters appeared to be much longer lived. This is in agreement with predictions of the MDD scenario, and was attributed to the different GMC densities and tidal fields experienced by the clusters in the two fields.

1.2 Cluster size distribution

In spite of the nearly six orders of magnitude in observed cluster masses, the radii of clusters appear to occupy a relatively narrow range, with effective radii largely contained between 0.5 and 10 pc in effective (half-light) radii (e.g. PZMG10). The large range of mass and narrow range of size means that any cluster mass–radius relation must be inherently shallow, which is unexpected, given the strong mass–radius relation of star-forming molecular clouds and cores (cf. Ashman & Zepf 2001). The observed radius distribution of clusters is in general adequately described by a lognormal distribution with a peak at 3–4 pc. This has been found for young populations in M51 (Scheepmaker et al. 2007) and M101 (Barmby et al. 2006) as well as for populations of old globular clusters (e.g. Jordán et al. 2005). In fact, the peak of the distribution has been suggested to be a distance indicator (Jordán et al. 2005).

Here we investigate whether the size distribution of clusters in M83 is the same as found for other young cluster systems as well as any dependence of the size on the age or mass of the cluster. This will provide constraints on the formation and evolution of clusters. Additionally, along with the mass of a cluster, we will use the size to estimate the dynamical stability of stellar groups (Gieles & Portegies Zwart 2011, hereinafter GPZ11) in order to see how well our cluster selection criteria work.

This paper is organized as follows. In Section 2, we introduce the data used, the sample selection, photometry, and fitting techniques, and compare our sample to previous studies. In Section 3, we present the results of this study. We constrain cluster disruption models in Section 4 and in Section 5 we discuss some of the implications of our results. Finally, we summarize our main findings in Section 6.

2 OBSERVATIONS

The data used in this work were partially presented in C10 (who studied just the inner field) as well as in B11 (who studied both fields), and are briefly summarized here. The imaging consists of Early Release Science data (GO 11360, PI: O’Connell) taken with the UVIS and infrared (IR) detectors of the WFC3 onboard the HST of two adjacent fields in M83. The ‘inner field’ covers the nucleus of the galaxy as well as the inner spiral arms, while the ‘outer field’ extends the contiguous coverage into the outer parts of the galaxy. For each pointing, images in the F336W (U – 2225 s), F438W (B – 1840 s), F657N (Hα – 1484 s) and F814W (I – 1213 s) filters were taken with the WFC3-UVIS detector. The numbers inside the parentheses are the exposure times in each of the filters. Additionally, the data set also contains V-band images; although the specific filters differ between the two pointings, the F555W (1203 s) and F550M (1203 s) filters were used in the inner and outer fields, respectively. Both these filters will be referred to as the ‘V band’, although no transformations between any filters and the corresponding Cousins–Johnson filter system were performed. Additionally, we also use two pointings of the IR-WFC3 detector with the F110W (J – 1797 s) and F160W (H – 2397 s) filters. These images do not cover the full field of view of the optical WFC3 images, as the IR channel has a slightly smaller field of view. All data were taken from the WFC3 Early Release Science website2 fully reduced.

The positions of the WFC3 pointings are shown in Fig. 1 and the F438W (B) band image of the field of view is shown in Fig. 2. As in C10 and B11, we adopt a distance from M83 of 4.5 Mpc (Thim et al. 2003).

2.1 Sample selection

It is often assumed that all stars form in ‘clusters’, although defining a ‘young cluster’, as opposed to an association, is non-trivial. Even within the solar neighbourhood, the estimated fraction of young stellar objects in clusters varies from ~20 to ~90 per cent depending on how clusters are defined (Bressert et al. 2010). This confusion is likely the result of the hierarchical distribution of star formation (e.g. Efremov & Elmegreen 1998; Elmegreen 2002) where no distinct borders exist between clusters (or even subclusters), associations and complexes. In this view, clusters are merely the densest structures in a continuous distribution of star formation, and do not

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2 http://archive.stsci.edu/prepds/wfc3ers/m83datalist.html
represent any unique spatial scale (as no unique spatial scale exists within an hierarchical or fractal distribution). The importance of cluster selection, and the caveats associated with different techniques, is discussed in detail in Silva-Villa & Larsen (2011).

GPZ11 have suggested a dynamical definition of clusters, namely that the age of the stellar group (the stellar age, assuming a single formation epoch) is greater than the instantaneous crossing time (based on the estimated mass and radius) and define a quantity $\Pi = \frac{t_{\text{age}}}{t_{\text{cross}}}$. Unbound associations (on any scale) will expand with time, causing the crossing time to increase in proportion with age, meaning $\Pi$ will stay at or below unity. On the other hand, clusters will remain compact (although there may be some expansion, see Bastian et al. 2008 and Section 3.2) meaning that $\Pi$ will increase with age. By applying this criterion to a sample of young stellar groups in the Galaxy, Local Group and nearby galaxies, GPZ11 found that for groups with ages less than 10 Myr, $\Pi$ was a continuous distribution, with no distinct break at $\Pi = 1$. However, for groups older than 10 Myr, the $\Pi$ distribution became bimodal, with clusters ($\Pi > 1$) and associations ($\Pi < 1$) becoming distinct populations.

For observational studies of extragalactic systems, where resolution effects limit the ability to study the structure of regions in detail, the result is that it is impossible to define a complete cluster sample at young ages (<10 Myr). After this age, compact and centrally concentrated stellar structures are likely to be clusters, and it is possible to compile a well-defined sample. The implications of this for extragalactic surveys are discussed in more detail in Section 5.

With these caveats in mind, below we discuss how our cluster sample was defined. As a first step, we ran SExtractor (Bertin & Arnouts 1996) over the $B$, $V$ and $I$ images with settings chosen to select a large number of candidates, including many false detections. These three catalogues were then cross-correlated, and only candidates detected in all three images were kept. We then used ISHAPE (Larsen 1999) to estimate the size of each group, and only selected resolved objects (full width at half-maximum $> 0.2$ pixels; this is the limit where resolved/unresolved sources can be reliably distinguished). The point spread function (PSF) used for ISHAPE was derived for each filter independently, using bright, isolated, unresolved sources (i.e. stars) on the images. The $V$-band image of each cluster candidate was then examined, and only resolved, centrally concentrated and symmetric sources were retained as clusters. Approximately 40–50 per cent of the initial candidates were removed during this step. A sample of objects that were excluded at this stage are labelled in Fig. 3 and shown in detail in Fig. 4. It is likely that some fraction of the stars in the groups presented in Fig. 4 will end up in clusters after the system has dynamically evolved (e.g. the individual peaks in c13861), but it is not possible to tell what fraction based on imaging alone.

We have adopted relatively strict selection criteria for selecting our sample in order to be able to compare our observations with models of cluster evolution and disruption, which assume that clusters are dense centrally concentrated objects. We emphasize that visual inspection of cluster candidates necessarily introduces a level of subjectivity in the process; hence, the catalogues of cluster candidates may differ between different authors. This point must be borne in mind when interpreting the results and will be discussed in detail in Section 5. We note that this two-step process of visual inspection of the source candidates found by automated methods has been found necessary in other recent works (e.g. Larsen 2004; Silva-Villa & Larsen 2010, 2011; Annibali et al. 2011).

Importantly, we note that age was not used in the cluster selection procedure. As will be discussed below, young stellar groups were preferentially excluded from our sample due to the application of the above criteria. The implications of this will be discussed in more detail in Section 5.

Finally, we note that the selection of clusters using visual inspection is affected by the resolution of the observations. In relatively distant systems, like the Antennae galaxies (e.g. Whitmore et al. 2010) or NGC 3256 (e.g. Goddard, Bastian & Kennicutt 2010), it will be more difficult to distinguish between clusters and associations, so these studies likely contain a larger fraction of associations in their cluster catalogues. This point will be further discussed in Section 5.

### 2.2 Photometry and fitting

Once we produced a cluster catalogue, we carried out aperture photometry for each of the sources. We adopted an aperture size for all bands of 5 pixels, and a background annulus with inner and outer radii of 8 and 10 pixels for the WFC3-UVIS images, respectively. For the IR channel, we used the same physical size apertures and background, that is, accounting for the differing pixel sizes. The zero-points were taken from the STScI web page.

Additionally, we corrected the $F336W$ zero-point for an ~4 per cent additional correction.

3 http://www.stsci.edu/hst/wfc3/phot_zp_lbn
Figure 3. A colour composite image of an $\sim 815 \times \sim 665$ pc$^2$ region in the inner field. The $B$, $V$ and H$\alpha$ images are shown in blue, green and red, respectively. Sources from the C10 sample are shown as the (green) circles, while clusters in this paper are shown as the (magenta) squares. Additionally, six sources from the C10 sample that are not in the current sample, and are shown in detail in Fig. 4, are labelled.

Figure 4. Top and middle rows: examples of sources included in C10 that are not considered ‘clusters’ in this study, with each image centred on the source in the C10 catalogue. The background shows a colour composite image (26 pc on a side) with $B$, $V$ and H$\alpha$ represented in blue, green and red, respectively. The contours denote V-band flux levels in steps of 10 per cent from the maximum level of the source in question. The bar in the lower right-hand corner of each panel represents 5 pc. The ID from C10 is given in the upper right-hand corner of each panel. Bottom row: a sample of sources in the C10 catalogue that are also included in this work.

efficiency (Jason Kalirai, private communication). Additionally, we carried out photometry of our catalogue sources (only for the inner field) adopting the same parameters as Chandar et al. (2010b) and compared the results with their published catalogue. Comparison between our photometry and that of W11 shows good agreement (mean deviations in colour $<0.03$ mag, accounting for the $F336W$ shift, which was not applied in W11). We note that the correction of the 4 per cent additional efficiency does not significantly affect the derived properties of the clusters.

Aperture corrections for each of the filters were derived from a sample of $\sim 15$ resolved clusters on the images. The resulting corrections from 5 to 15 pixels are: 0.43, 0.41, 0.41, 0.43, 0.44 and 0.45 mag for the $F336W$, $F438W$, $F547M$, $F555W$, $F657N$ and $F814W$ filters, respectively. We added an additional 0.05 mag error in quadrature to the measured error for aperture correction uncertainties. Finally, we corrected for Galactic extinction (Schlegel, Finkbeiner & Davis 1998).

Once we have performed aperture photometry on the cluster catalogue, we proceed to estimate the age, mass and extinction of each of the candidates. Only clusters with photometry in $U$, $B$, $V$ and $I$ are included. The properties were estimated by comparing simple stellar population (SSP) models to the observations. We adopted the fitting procedure of Adamo et al. (2010a, b) and the Yggdrasil SSP models (Zackrisson et al. 2011) for a Kroupa (2001) initial mass function (IMF), using STARBURST99 Padova-asymptotic giant branch stellar population spectra (Leitherer et al. 1999; Vázquez & Leitherer 2005) for $\sim 2.5$ times solar metallicity ($z = 0.050$; Bresolin & Kennicutt 2002). The fits were carried out including the $U$, $B$, $V$, $I$ and H$\alpha$ photometry. The Yggdrasil SSP models include nebular and continuum emission, allowing the H$\alpha$ fluxes to be used to differentiate young extincted clusters from older non-extincted clusters that have similar $U - B$ and $V - I$ colours. The impact of including (or not) the J- and H-band photometry will be discussed in detail in a forthcoming paper (Adamo et al., in preparation).

The masses derived in this way are the current masses, not the initial masses, meaning that stellar evolutionary mass-loss has been taken into account (i.e. the initial masses are 10–30 per cent higher, depending on age, if there would have been no disruption).
The catalogue of the measured (magnitudes, positions, sizes) and estimated (age, mass, extinction) properties for the sample is given on the CDS website.

In this work, we limit our analysis, when cluster parameters are fitted, to those clusters that have masses in excess of $5 \times 10^2 M_\odot$ in order to minimize the effects of stochastic sampling of the stellar IMF that can severely affect the derived age and mass distributions (e.g. Maíz Apellániz 2009; Fouesneau & Laçon 2010; Silva-Villa & Larsen 2011). Additionally, we do not include the inner 450 pc (in projection) around the galaxy nucleus as the star formation rate (SFR) may vary there (e.g. Harris et al. 2001) and the detection limit is significantly worse than in the outer regions. After applying these mass and position limits, our final sample contains 381 and 370 clusters in the inner and outer fields, respectively. The age–mass distributions for these clusters are shown in Fig. 5.

2.3 Comparison with previous studies

In B11, we compared the derived ages for a sample of 48 clusters in common between this work and that of C10 (and published in W11). Overall, the agreement is excellent, with only a handful ($<8$ per cent) of clusters showing age differences larger than 0.5 dex.

Our sample selection differs notably from previous studies of extragalactic cluster populations, which impacts some of the conclusions reached in this work relative to what has been reported earlier. The cluster population in the inner field has been studied in detail in C10, and in this section, we compare the samples, and discuss how the different samples influence the results. There are two main differences between the sample in this work and the one presented in C10. The first is the use of visual inspection of the images, and the inclusion of only centrally concentrated compact and symmetric sources. The second difference is that we do not include the inner portions of the galaxy (within ~450 pc of the galactic centre in projection). The effects of these two differences are discussed in turn below. We note that the comparison below is restricted to the inner field only, as it is the only field analysed by C10.

2.3.1 The effect of sample selection

In Fig. 3, we show a colour image of a section of the south-east corner of the inner field, covering a portion of the inner spiral arm. Additionally, we show all of the source candidates from this work (magenta squares) and the C10 catalogue (green circles). While a number of sources appear in both catalogues, it is clear that many do not. In order to highlight the differences, we show a blowup of candidate sources in the C10 catalogue that do not appear in this work, in Fig. 4, along with V-band flux contours (in steps of 10 per cent from the maximum level of the source). Each of these sources fails to meet our selection criteria based on morphology, hence would likely fall into the associations category and not clusters based on the GPZ11 definition, if a characteristic size could be defined, which is not possible due to the complicated morphologies. Physically, some part of each of these associations may become bound and will eventually form a cluster; however, it is impossible to tell the fraction (if any) from imaging alone. Some regions, for example, c14148 or c13861, clearly do not fulfill our symmetry criterion. Part of other regions, for example, c27398 or c26946, may be defined as a cluster, depending on how exactly the selection is done. This shows, in part, the subjectivity that enters the source-selection process.

However, we expect such subjective biases to be mainly applicable to the younger regions, since clusters will become more uniform (smooth) as they dynamically evolve (as the substructure is removed, e.g. Bastian et al. 2009b) and associations will dissolve into the background. In Fig. 6, we show the distribution of ages for each of the catalogues, divided into sources that appear in both catalogues (solid lines) and those that appear only in one of the two (dashed lines). Only sources outside the inner 450 pc are included from each catalogue. In the top panel, we show the age distribution from the C10 catalogue, while the bottom panel shows the age distribution in this work. All sources in the respective catalogues have been used in the figure, that is, no cut on mass has been applied (contrary to the rest of this paper).

Focusing on the top panel, we see that the distribution of ages of the sources in common between the catalogues does not have a strong dependence on age (i.e. being dominated by only the youngest or oldest clusters). However, the sources in the C10 catalogue that do not appear in the present catalogue are strongly peaked at young ages (<10 Myr), confirming that the differing selection criteria between the two studies are largely limited to the youngest ages. This confirms the expectations discussed above.

In the bottom panel, we see that the age distribution of the sample that is in common with C10 and the sample not in common does not show such a difference. From these two panels, we conclude that the two catalogues differ mainly in the youngest ages.

Due to this difference, we will largely limit our analysis to clusters with ages in excess of 10 Myr. However, we will return to this difference when discussing the fraction of star formation that happens in clusters, as well as the role of infant mortality, in Section 5, both of which are heavily affected by the sample selection.

We emphasize the subjective nature of the differences between the two studies. The present sample clearly misses some fraction of clusters that form from the densest parts of associations, while the C10 sample includes a larger number of young objects for which we cannot be sure whether they are (or will remain) bound. This shows the limitation of extragalactic studies of young cluster populations.
The same as Fig. 6, except now all objects in C10 are included (including those within the inner ∼450 pc). As in Fig. 6, we see that the two catalogues differ most at the youngest ages.

In Fig. 7, we show the age distribution of the full C10 sample (i.e. including the inner regions) split into sources found in the current catalogue (solid line) and absent in our catalogue (dashed line). As was seen in the proceeding section, but now amplified even more, the C10 sample contains a large number of young sources that are not included in our sample.

The removal of the inner 450 pc of the galaxy from our sample should not affect our results if the cluster age and mass distributions are universal (i.e. independent of location, e.g. Whitmore et al. 2007). We will, however, still have a large range of environments to sample to search for the environmental dependence of cluster disruption as well as any truncation that may exist in the MF (above our detection limit).

In Section 4, we will show that the age distributions, beyond the first 10 Myr, of the C10 and present catalogues agree quite well in the inner field, giving confidence in the ability to study extragalactic cluster populations. We will then be in a position to compare the inner and outer fields to gain insight into the influence of the environment in the cluster formation and destruction processes.

2.4 Π distribution

As discussed above, it is not trivial to distinguish bound stellar groups (i.e. clusters) from unbound aggregates (i.e. associations) for young stellar systems. At older ages, that is, a few tens of Myr, this distinction is much easier to make due to the dispersal and disappearance of unbound associations into the field. However, at young ages, stellar groups often appear to be hierarchical or filamentary (e.g. Gutermuth et al. 2005, 2009; Allen et al. 2007), making it difficult to distinguish groups that are gravitationally bound versus those that will disperse. Even in fully resolved stellar systems it is non-trivial to define which stars belong to clusters (e.g. Bressert et al. 2010).

In order to address this uncertainty, we have applied the GPZ11 definition of a cluster, namely that the age of the system is greater than the instantaneous crossing time, parametrized by Π. Without kinematic information on each of the stars within a cluster, it is impossible to measure τcross. However, if one assumes that the clusters are in virial equilibrium, then the velocity dispersion can be estimated by combining the estimated mass and radius of each group. This in turn can be compared to the derived age of the cluster (through SSP modelling) to estimate whether the cluster is bound (see GPZ11).
2.5 Completeness limits and the luminosity function

In order to use the $\Pi$ definition of a cluster, accurate sizes are needed. This, in turn, requires high enough signal-to-noise ratio in order to obtain reliable profile fits to the individual clusters. In order to determine the limiting magnitude for reliable fits, we employed a similar technique to that used by Silva-Villa & Larsen (2011). Artificial clusters were created by stochastically sampling the stellar IMF (Kroupa 2001), adopting a total stellar mass of $1 \times 10^5 M_\odot$ and an age of 50 Myr. Luminosities and colours were assigned to each star by applying the Marigo et al. (2008) isochrones. Images of the artificial cluster were then made by convolving them with the empirically derived PSF and the WFC3-UVIS properties. Clusters were created with effective radii of 3 and 5 pc, following a King (1962) profile. 100 realizations were made for each effective radius and added to the images. We focused our attention on the $V$-band images since the selection was based largely on those.

The clusters were then scaled to various luminosities to test for completeness. We found that clusters in the interarm regions of M83, where the background is low, were readily detected fainter than $V = 23$ mag. However, in the crowded and bright regions in spiral arms, the detection limit was notably brighter. We adopted the detection limits of $V = 22$ and 22.5 mag in the inner and outer fields, respectively. These conservative limits were found by requiring that the artificial clusters could be identified and the properties robustly determined even in crowded, high-background regions. We note that some fainter clusters appear in our catalogue due to different aperture sizes during the selection stage and the final photometry.

The resulting luminosity functions (LFs) of clusters for the inner and outer fields are shown in Figs 9 and 10, respectively. The LFs are shown as cumulative functions and have been offset for clarity. In each figure, the $I$, $V$, $B$ and $U$ bands are shown from top to bottom in the upper panels. The dashed lines in the top panels show the maximum-likelihood fit over the range covered by the line, with measured values shown in parentheses, assuming the form $dN/dL \propto L^{-\alpha}$. The lower panels show linear fits (made in the cumulative distribution) to the distribution in 1.0-mag bins. As in previous studies, we find that $\alpha = 2.0$ provides a good fit to the data over most of the observable range (de Grijs et al. 2003). We note that associations with sizes of several tens or even hundreds of pc also show the same LF (Bastian et al. 2007), so a power law with an index of $-2$ appears to be a general result of star formation and not specific to clusters. This index is likely due to the scale-free and hierarchical nature of the interstellar medium from which stars form (Elmegreen 2002).
However, we see a steepening of the LF above the V-band magnitudes of 19 and 19.5 (corresponding to the absolute V-band magnitudes of $-9.3$ and $-8.8$) in the inner and outer fields, respectively. This steepening has been observed in the LF at these magnitudes of cluster populations in a sample of galaxies (Larsen 2002; Gieles et al. 2006a, b; PZMG10) and has been interpreted as being due to a truncation in the underlying MF at high masses. The underlying MF of clusters and the possible truncation at high masses will be further discussed in Section 3.3.

2.6 Star formation history of M83

When using observations of cluster populations in order to understand cluster disruption, it is important to take into account changes in the star formation history (SFH) of the galaxy during the period under study. For example, if the SFH of a galaxy has been increasing, this will have the same observational signature as MID (i.e. more young clusters will be seen in both cases). Hence, cluster disruption will be overpredicted in such a case if the SFH is not taken into account (e.g. Bastian et al. 2009a). This type of degeneracy has also been discussed in Pellerin et al. (2010) and Annibali et al. (2011).

Since we are studying the cluster population within a single galaxy, separated into two radial bins, it is important to check if the SFH between the two fields has been the same. In particular, we need to check if there is a radial dependence in the SFH (outside the inner $\sim 450$ pc). In order to check this, we have used the resolved stellar population analysis carried out by Silva-Villa & Larsen (2011) in M83, based on two pointings of the Advanced Camera for Surveys (ACS) onboard the HST. Their two fields are centred at nearly the same galactocentric radii as the WFC3 observations used in this work (centred at $\sim 2.9$ and $4.8$ kpc from the galactic centre in the ACS study and $2.5$ kpc and $4.75$ kpc in this study). Silva-Villa & Larsen (2011) have derived the SFH within these fields for the past 10–100 Myr.

The ratio of the derived SFHs of the two fields is shown in Fig. 11. The comparison of the SFHs in the two ACS fields centred at about the same galactocentric distances as our WFC3 fields shows that the ratio of the SFRs in the two ACS fields has remained relatively constant (within $\sim 50$ per cent) over the past 100 Myr. However, it is important to note that the outer ACS field is located quite far from our outer WFC3 field, and we do not have strong constraints on any azimuthal variations in the SFHs. We therefore do not have very strong constraints on the relative SFHs of the two WFC3 fields.

3 EMPIRICAL AGE, MASS AND SIZE DISTRIBUTIONS

Using the derived properties of the 751 clusters in our sample, we can now investigate properties of the cluster population as a whole. In particular, we are interested in properties that vary as a function of environment, which will give the best constraints on cluster formation, evolution and destruction.

Here, we focus on (i) the cluster radius (size) distribution in comparison to the results of other cluster populations available in the literature; (ii) the form of the MF, in particular, on any possible truncation at high masses; and (iii) the age distribution, which will be used to study cluster disruption. Due to interdependencies between the age and mass distributions as well as completeness issues, issues (ii) and (iii) will be modelled simultaneously.

3.1 Age distributions

As noted in B11, the distribution of cluster ages appears to be different between the two fields. This was based on the estimated ages/masses, but could also visually be seen by looking at the colour distributions of the populations in the two fields. Both populations had similar mean/median $V-I$ colours, but the outer field had a significantly redder $U-B$ colour. When comparing the distribution to SSP models, it was shown that extinction could not be the cause, as the inner field is expected to have more extinction, and then the $V-I$ colours between the two fields should also be different.

In Fig. 12, we show the age distribution (number of clusters per unit time) for the inner and outer fields. The sample used is mass limited, with a lower limit of $5 \times 10^3$ $M_{\odot}$. At older ages, both samples are affected by the completeness limit (i.e. the drop in $dN/dt$ at older ages). We find that for most mass-cuts, the outer field has a median age that is two to three times higher than the inner field.

![Figure 12](https://example.com/figure12.png)

**Figure 12.** The age distribution (number of clusters per unit time) for the inner (filled circles) and outer (open triangles) fields. Only clusters with masses above $5 \times 10^3$ $M_{\odot}$ are used. The bars in the bottom of the panel show the age bins used for the plot. In order to minimize the effect of spurious features in the age distribution, a series of overlapping bins are used. Ages above $\sim 1$ Gyr are highly uncertain and the sample is affected by completeness issues above this age.
The age versus size relation of clusters in the inner (top panel) and outer (bottom panel) fields. The best linear fit to the data is shown as a dashed (red) line. Note the similar expansion in both fields, implying that cluster expansion is driven by internal mechanisms or by a similar observational bias.

fields (fitted separately) as the dashed (red) lines. The resulting relations are also given in the panels. Both fields show the same trend, which will be discussed in more detail below.

As noted above, the outer field has a significantly older median age than the inner field (approximately a factor of 2 or 3 higher, depending on the mass-cut). Hence, simply due to the observed expansion (discussed below), we would expect clusters in the outer field to be larger, on average, than those in the inner field. Quantitatively, based on the median age difference, we would expect the clusters to be ~0.4 pc larger in the outer field. This is quite similar to the observed difference of ~0.3 pc, suggesting that the observed size difference between the two fields is driven mainly (or completely) by the expansion of clusters and the difference in the average age between the two fields.

Another possibility of the driver behind the age–size relation would be an underlying age–mass relation. Since we are not sensitive to old, low-mass clusters, this could affect our size distributions. In order to test this, we performed a bivariate fit on the data (again, limiting the analysis to clusters more massive than 5 × 10^3 M⊙ and ages less than 1 Gyr). We fit a function of the form

\[ R_{\text{eff}} \propto t^{a_1} M^{a_2}, \]  

where \( t \) and \( M \) are the age and mass of a cluster, respectively. The fitting was carried out independently for each field. For Field 1, we find \( a_1 = 0.22 \pm 0.04 \) and \( a_2 = 0.04 \pm 0.08 \). This shows that the observed increase in size with age is not strongly affected by any mass relation. For Field 2, we find \( a_1 = 0.24 \pm 0.06 \) and \( a_2 = 0.22 \pm 0.15 \). Here the result is more ambiguous; again, we do see an intrinsic relation between age and size, but also a weak relation between mass and size, albeit with large errors.

3.2 Size distribution

Next, we turn to the effective radius (or size) distribution of the clusters in our sample. In Fig. 13, we show the distribution of measured radii in the V band for each of the two fields. For the fits, we have adopted an EFF profile (Elson, Fall & Freeman 1987) with index \( \gamma/2 = 1.5 \) and a fitting radius of 5 pixels. Additionally, we show the best-fitting lognormal functions to each of the data sets, which are shown as the light (red) lines. Both distributions appear to be reasonably fitted with a lognormal function, although we note that we are not sensitive to very small clusters (<0.5 pc) as they will appear as unresolved on the HST images. The size distributions peak at ~2.3 and ~2.6 pc for the inner and outer fields, respectively. The results are unchanged if the B or I bands were used instead.

These results are very similar to those found by Scheepmaker et al. (2007) for the cluster population of M51 (with a median effective radius of 2.1 pc and a similar lognormal form) and for clusters in M31 (Vansevicius et al. 2009, 2.1 pc when binned in the same way as done here). It is also close to the median value of 3.2 pc for ‘blue clusters’ in M101 derived by Barmby et al. (2006). The median size, however, is much smaller than that found by Mayya et al. (2008) for massive (>10^4 M⊙) clusters in M82 (with a median of ~10 pc). However, studies of individual massive clusters in M82 result in much smaller sizes (with a median of ~1.8 pc; e.g. McCrady, Gilbert & Graham 2003; Smith et al. 2006).

Scheepmaker et al. (2007) found an interesting trend between cluster radius and galactocentric distance in that clusters farther from the galactic centre were larger on average. A similar trend is seen in Fig. 13 for the clusters in M83. In order to see whether this reflects different formation mechanisms, we have looked for correlations of \( R_{\text{eff}} \) with other derived properties. In Fig. 14, we show the observed relation between the size and age of clusters in the two fields. Only clusters with masses above 5 × 10^3 M⊙ were used. Additionally, we show the best-fitting linear relation for both

\[ \log R_{\text{eff}} = 0.225 \times (\log \text{age}) - 1.44 \]  

\[ \log R_{\text{eff}} = 0.235 \times (\log \text{age}) - 1.50 \]
Given these results, we conclude that there is evidence for an increasing size as a function of age, qualitatively similar to that observed in other cluster populations (Mackey & Gilmore 2003; Bastian et al. 2008). This could be a physical effect, due to internal heating by stellar mass black holes, hard binaries and stellar evolution (e.g. Merritt et al. 2004; Mackey et al. 2007, 2008; Gieles et al. 2010a), or gas expulsion (Goodwin & Bastian 2006), or a combination of the above effects. Alternatively, it could be a selection effect due to the assumption of a single profile to fit all clusters, that is, ignoring mass segregation or the evolution of the profile shape (e.g. Gaburov & Gieles 2008), or a stochastic effect with the profile of the younger clusters being dominated by a few very bright stars, which tends to result in smaller derived radii than the true value (Silva-Villa & Larsen 2011). A detailed study of the profile shapes and sizes of a sample of clusters in our catalogue will be presented in a forthcoming paper (Konstantopoulos et al., in preparation).

3.3 The cluster mass distribution

One of the basic properties of a cluster population is the distribution of cluster masses. Previous studies of extragalactic cluster populations have generally found a power-law-type distribution with few high-mass and many low-mass clusters, namely $dN/dM \propto M^{-\beta}$. Many studies have derived values of $\beta \sim 2$ (e.g. Zhang & Fall 1999; Bik et al. 2003; de Grijs et al. 2003; McCrady & Graham 2007) for various mass ranges, from a few thousand solar masses to $>10^5 M_\odot$. However, based on the luminosity distributions of cluster populations in a sample of spiral galaxies, Gieles et al. (2006a, Gieles et al. 2b) found evidence for a truncation in the distribution at the high-mass end, which they approximated as a Schechter function (i.e. a power law at the low-mass end with an exponential cut-off at high masses). Further evidence for a Schechter-type distribution was presented by Bastian (2008) based on the observed relation between the SFR of a galaxy and the luminosity of its brightest cluster. Larsen (2009) studied the relation between the age of a cluster and its luminosity in a sample of 16 galaxies and concluded that a Schechter function with a cut-off of a few times $10^3 M_\odot$ provided a good fit to the data. Maschberger & Kroupa (2009) showed that the cluster population in the LMC has a truncation in the MF at $\sim 7 \times 10^3 M_\odot$. Finally, Gieles (2009) developed a series of analytic solutions for the evolution of a Schechter MF due to cluster disruption, and showed that this provided a good fit to the age–mass distributions of clusters in M51.

Whitmore et al. (2010) did not see a truncation in the MF of clusters in the Antennae galaxies based on power-law fits to the data, although we note that their last two data points lie below the predictions of a pure power law. A lack of a truncation was also reported in the cluster populations of M83 (C10) and M51 (Chandar et al. 2011).

Since the truncation in the MF that has been proposed previously is generally near the end of the distribution, low number statistics often can mask such a truncation, especially if the data are binned. To avoid such an artefact from entering into our analysis, we will study the cumulative distribution of stellar clusters in M83. The derived cluster mass distributions for the inner (top panel) and outer (bottom panel) fields of M83 for clusters with ages between 3 and 100 Myr are shown in Fig. 15 as the filled (red) circles. If the distribution is described by a pure power law (i.e. without truncation), then the points should follow a straight line. However, it is clear that both fields show a bend in their distributions.

In order to quantify the apparent bend, we have created a suite of Monte Carlo models. We stochastically sample from a power-law MF with an index of $-2$, sampling the same number of clusters as the observed distributions (i.e. the number of clusters with ages between 3 and 100 Myr and have masses above $5 \times 10^3 M_\odot$). Each field was treated separately. The lines in Fig. 15 show the results of a series of Monte Carlo simulations that adopt the same number of clusters as the observations (only those used in the figure) for a pure power-law mass distribution with an index of $-2$ and no upper mass truncation. The solid line shows the median mass expected, while the dashed and dotted lines enclose 50 and 90 per cent of the simulations, respectively.

Figure 15. The distribution of cluster masses with ages between 3 and 100 Myr. The filled (red) circles represent the observations for each field. The lines denote the results of a series of Monte Carlo simulations that adopt the same number of clusters as the observations (only those used in the figure) for a pure power-law mass distribution with an index of $-2$ and no upper mass truncation. The solid line shows the median mass expected, while the dashed and dotted lines enclose 50 and 90 per cent of the simulations, respectively. Note that both the inner and outer field distributions are inconsistent with the pure power-law case and require a truncation in the MF at high masses.

We conclude that the MF of clusters in M83 is not well fitted by a pure power law, but instead requires a truncation at the high-mass
and using an integrating factor, we have
\[ \dot{M} = \frac{M_{\text{MID}}}{\lambda_0} \exp\left(\frac{-M_{\text{MID}}}{M_{\text{MID}}/\lambda_0}\right). \] (2)

Here, \( \dot{M}/(dM/dt) \) is the probability of forming a cluster with an initial mass between \( M_i \) and \( M_i + dM_i \) in an interval \( dt \). The (exponential) truncation of the MF occurs at \( M_c \). The constant \( \Lambda \) relates to the CFR as
\[ A = \text{CFR} / \text{E}(M_{\text{MID}}/M_c), \]
where \( M_{\text{MID}} \) is the lower limit of the MF and \( \text{E}(x) \) with \( n = 1 \) is a generalized expression of the exponential integral (Gieles 2009).

The age-dependent MF at older ages can be described by so-called evolved Schechter functions (Jordán et al. 2007). For this, we need to find the evolution of the mass of a cluster as a function of the MDD and MID parameters. For this we use the descriptions given in Gieles (2009) and Larsen (2009), respectively. Here we introduce the evolved Schechter function for the combined evolution, including MDD and MID.

The mass-loss rate of the cluster, \( \dot{M} \), constitutes the mass-loss rates due to MDD, \( \dot{M}_{\text{MDD}} \), and the one due to MID, \( \dot{M}_{\text{MID}} \):
\[ \dot{M} = \dot{M}_{\text{MDD}} + \dot{M}_{\text{MID}}. \] (3)

For \( \dot{M}_{\text{MDD}} \), we use the formalism of Lamers et al. (2005) and Gieles (2009), namely, that the disruption time-scale is \( t_{\text{dd}} = t_{\text{dd}}M^\gamma \), where \( \gamma \geq 0.65 \) and \( t_{\text{dd}} \) is a constant that depends on the environment. From this, we find
\[ \dot{M}_{\text{MDD}} = -M/\text{dd} = -M^{1-\gamma}/t_{\text{dd}}. \]
The mass evolution in the MID case is \( M(t) = M_i(t_i/t_s)^\gamma \), where \( t_s \) is the time that MID starts and \( \lambda = \log_{10}(1 - \text{F}_{\text{MID}}) \), where \( \text{F}_{\text{MID}} \) is the fraction of the mass that is lost per age dex. From this, we find \( \dot{M}_{\text{MID}} = \lambda M/t_s \). We note that we have assumed that in the MID case each cluster loses a certain fraction of its mass, rather than a certain fraction of clusters being completely destroyed, while the others are not affected. If the cluster MF is a pure power law of index \( -2 \), there is no distinction between these two interpretations, as they both result in the same distributions. However, if there are features in the cluster MF, such as in a Schechter function, then the results may differ. Particularly, if MID is applied to the \( dM/dt \) distribution (i.e. all clusters lose 90 percent of their mass), then the Schechter mass decreases with time. On the other hand, if it is applied to the \( dV/dt \) distribution (i.e. 90 percent of all clusters are destroyed, irrespective of mass), then the Schechter mass remains constant.

Combining the mass-loss from the MDD and MID models results in the total mass-loss rate of
\[ \dot{M} = \frac{M^{1-\gamma}}{t_{\text{dd}}} + \frac{\lambda M}{t_s}. \] (4)

This non-separable first-order differential equation can be solved after a variable substituting \( y = M^\gamma \) and using an integrating factor, and the result is
\[ M = \left[ M_i \left( \frac{1}{t_{\text{dd}}} \right)^{\lambda y} - \frac{\gamma}{1 - \lambda y} \frac{1}{t_s} \right]^{1/y}. \] (5)

For convenience, we introduce the new variables \( F_{\text{MID}} = (t_i/t_s)^y \) and \( \Delta_{y} = \gamma/(1 - \lambda y) \) such that \( M = [M_{\text{F}_{\text{MID}}} - \Delta_{y} M_{\text{F}_{\text{MID}}}]^{1/y} \). Note that for no MID, that is, \( F_{\text{MID}} = 0 \), we have \( F_{\text{MID}} = 1 \) and \( \Delta_{y} = \gamma t_i/t_s \), and equation (5) reduces to the result of only MDD (equation 24 in Gieles 2009).

---

4.1 Model description

We create artificial age and mass distributions of cluster populations using the two disruption models MID and MDD. First, a value for the (galaxy-wide) SFR needs to be chosen. Then, a cluster formation efficiency \( \Gamma \) (Bastian 2008) needs to be assumed, such that the cluster formation rate \( \text{CFR} = \Gamma \times \text{SFR} \). We use a Schechter-type cluster IMF
\[ \frac{d^2 N}{dM dt} = AM^{-\gamma} \exp\left(\frac{M}{M_c}\right). \] (2)

Figure 16. The same as Fig. 15, but now the lines represent Monte Carlo models sampling from a Schechter MF. The simulations adopt truncation masses, \( M_c \), of \( 5 \times 10^5 \) and \( 1 \times 10^5 \, M_{\odot} \), respectively.

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4 MASS DISTRIBUTION AND CLUSTER DISRUPTION

As discussed in Section 1, two main empirically based scenarios of cluster disruption have been put forward in the literature. These two scenarios differ in the roles that the environment and cluster mass play in the cluster-disruption process. In the MDD scenario, cluster disruption is driven largely by internal processes; hence, the environment or cluster mass play a limited, if existent, role (e.g. Fall et al. 2009). In the MID scenario, the average lifetime of a cluster increases with increasing mass (i.e. more massive clusters live longer), and the lifetime decreases for increasing GMC density or stronger tidal fields (e.g. Lamers et al. 2005).

The data set presented here is ideal for differentiating between these two scenarios due to the sampling of a relatively large range of galactocentric distances (i.e. ambient environments) and a large sample of clusters to limit Poissonian noise. Below we describe the models and then apply them to the observations to provide new constraints.

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The final distribution of masses as a function of age can be found from conservation of number
\[
\frac{d^2 N}{dMdt} = \frac{d^2 N}{dMdt} \frac{\partial M_i}{\partial M} \tag{6}
\]
that is,
\[
\frac{d^2 N}{dMdt} = A F_{\text{MID}} M_i^{\gamma - 1} (M_i^{\gamma} + \Delta t)^{1/\gamma} \exp \left[ - \frac{(M_i^{\gamma} + \Delta t)^{1/\gamma}}{F_{\text{MID}} M_i} \right]. \tag{7}
\]

To create the age distribution of a population, we simply integrate over all masses, that is,
\[
\frac{dN}{dt} = \int_{M_i}^{\infty} \frac{d^2 N}{dMdt} dM, \tag{8}
\]
and equivalently for the mass distribution, we find
\[
\frac{dN}{dM} = \int_{M_{\text{min}}}^{M_{\text{max}}} \frac{d^2 N}{dMdt} dt. \tag{9}
\]

4.2 Fitting the observations

As in B11, we chose to split our catalogue into three age bins (age \(\leq 10\) Myr, 10 < age \(\leq 100\) Myr and 100 < age \(\leq 1000\) Myr) and look at the mass distribution of the clusters in each bin. Note that the oldest bin is somewhat incomplete at low masses. This is the same technique as used to study disruption in the SMC (de Grijs \\& Goodwin 2008), the LMC (Chandar et al. 2010a) and M83 (C10). The benefit of using this technique is that it allows the completeness limit to be seen relatively clearly. Additionally, the number of clusters per bin is divided by the linear age range covered to get a normalized MF. If the CFR of a galaxy has been constant, and disruption has not affected the population, then the three mass distributions should lie near the top of each other, modulo shot noise and stellar evolutionary effects.

We adopt equal-number bins in order to avoid small-N biases (e.g. Maíz Apellániz \\& Ubeda 2005). We use eight clusters per bin, except for the oldest ages in the outer field where we use 11 per bin due to the larger scatter. The observed distributions are shown in Fig. 17. As noted previously, the youngest-age bin (\(\leq 10\) Myr) may be under-represented due to the difficulty in distinguishing clusters from associations.

In the following sections, we compare the observations to a set of models visually in order to derive characteristic values. In all cases, the vertical shift is normalized to the intermediate-age bin (10 < age \(\leq 100\) Myr).

4.2.1 Only allowing MID

First, we investigate models where only MID is included. The best-fitting model is shown in Fig. 17, along with the best-fitting parameters. Our results for the inner field agree well with that found by C10, namely that the observed distributions can be well fitted with purely MID and that a Schechter function is not required to fit the data (although it also fits when a value of \(M_c \sim 10^5\) \(M_\odot\) is used). However, as discussed in B11, the disruption rate in the outer field appears to be much lower. A pure MID model does provide a good fit to the data; however, instead of \(F_{\text{MID}} = 0.8\)–0.9, a value of \(F_{\text{MID}} = 0.5\) is needed. Even in the pure MID case, it is clear that environmentally-dependent disruption is required to fit the data. This is consistent with the Elmegreen \\& Hunter (2010) model of cluster disruption (see also Kruijssen et al. 2011a), which may be mass-independent but is strongly dependent on the environment.
and $\gamma$ and $C$.

130 Myr, while for the outer field, we find $M_c = 4.7 \times 10^5 M_\odot$ and $t_\nu = 6200$ Myr.

Figure 18. The same as Fig. 17, except now the dashed lines show the best-fitting models for MDD.

4.3 Maximum-likelihood fitting

As noted above, however, simply comparing the models to the observations directly results in acceptable fits for both purely MDD and MID. Additionally, one can think of a hybrid model, where cluster disruption is mass-independent for the first $\sim 10$ Myr and afterwards becomes mass-dependent (e.g. Bastian et al. 2009a). Due to the limited dynamic range of the data, it is presently not possible to definitively constrain the disruption law. However, the pure environmentally-independent MID scenario that results in 'universal' age and mass distributions is disfavoured, given the observed differences between the two fields. For the remainder of this section, we focus on pure MDD models.

In order to carry out a binning-independent analysis, we have also compared the pure MDD models to the observations using a maximum-likelihood-fitting technique. Here, we adopted $\gamma = 0.65$ and fit on $t_\nu$ and $M_c$. The results are shown in Fig. 19. The best-fitting model for the inner field has $M_c = 1.6 \times 10^5 M_\odot$ and $t_\nu = 130$ Myr, while for the outer field, we find $M_c = 5 \times 10^5 M_\odot$ and $t_\nu = 600$ Myr. The disruption time-scale in the inner region of M83 is similar to that derived for the inner regions of the spiral galaxy M51 (100–200 Myr; Gieles et al. 2005).

In both fields, a Schechter function is required to fit the data; however, $M_c$ appears to be a factor of $\sim 2$–4 larger in the inner field. This suggests that the truncation mass may be dependent on environment, consistent with the discovery of significantly more massive clusters in starburst galaxies (e.g. Maraston et al. 2004; Whitmore et al. 2010). The characteristic mass derived for each field is consistent with that implied by the bend observed in the LF discussed in Section 2.5.

In order to test how robust our parameter determinations are, we have generated 50 realizations of stochastically generated cluster populations for five different combinations of $t_\nu$ and $M_c$. For each realization, we selected 380 clusters that match our selection criteria (i.e. are more massive than our lower mass limit) and use the same fitting code as was used in the observations. The results are shown in Fig. 20. We see that the fitting method can successfully recover the input values of $t_\nu$ and $M_c$, increasing the level of confidence for a truncation in the MF, as well as for differing values of $t_\nu$ and $M_c$ for the two fields, although some small biases may remain.

5 DISCUSSION: INFANT MORTALITY, CLUSTERED STAR FORMATION, AND IMPLICATIONS FOR EXTRAGALACTIC SURVEYS

As noted throughout this work, obtaining a full census of young clusters ($< 10$ Myr) in extragalactic studies is not possible, due to the difficulty in distinguishing clusters from unbound associations. This echoes the results of Bressert et al. (2010) and GPZ11 who showed that even within the Galaxy, it is not possible to distinguish clusters/associations until they are dynamically evolved. This makes it difficult to directly estimate the fraction of stars that form that will end up as part of a bound cluster ($\Gamma$; Bastian 2008); hence, indirect tracers may be required. For extragalactic surveys, depending on the selection criteria adopted, the fraction of young stars in clusters can vary by a factor of 2 or more. In Fig. 4, a selection of young groups are shown that are not included in the cluster sample in this work. For each of these regions, it is possible (even likely) that some fraction of the young stars will end up in clusters; however, it is not possible to estimate this fraction from the observations. This effect may explain why estimates of $\Gamma$ of distant starburst galaxies are higher than seen in local galaxies (e.g. the Antennae: Fall et al. 2005; NGC 3256: Goddard et al. 2010), although a physical difference between starbursts and quiescent galaxies is not ruled out (Adamo, Ostlin & Zackrisson 2011).

Including unbound associations (which by definition do not appear in older age bins) in the youngest age bins of cluster populations will lead to the interpretation that some fraction of the young 'clusters' must disrupt on short time-scales. This has contributed to the idea of infant mortality, and likely accounts for a significant portion of the observed drop between the youngest ($< 10$ Myr) age bin and the following bins (e.g. Bastian et al. 2005; Fall et al. 2005; Adamo et al. 2011; Bonatto & Bica 2011). If restrictive definitions of samples are used, the degree of infant mortality needed to explain a population is much lower than if loose definitions are used.

Since cluster formation is a highly dynamic process, and it is likely that clusters lose mass due to internal and external effects during their early evolution, the fraction of stars found in clusters may be strongly dependent on the age of the cluster population under study. In the limiting case where clusters do not lose mass after their formation, one simply needs to look at evolved clusters. Alternatively, if clusters lose mass or are destroyed rapidly during their early dynamical evolution, the fraction of stars in clusters may be impossible to define.

One way to distinguish between classical infant mortality and the inclusion of associations in the sample is through measurements of the dynamical stability of young massive clusters (YMCs). If infant mortality is driven by gas expulsion and it significantly affects dense massive clusters, then many/most YMCs should show large velocity dispersions due to their expansion. Extragalactic YMCs indeed appear to be 'supervirial', which has been interpreted as evidence of their impending dissolution (Goodwin & Bastian 2006). However, Gieles, Sana & Portegies Zwart (2010b) have shown that high-mass binaries are likely significantly contributing to the observed high velocity dispersions. For YMCs within the Galaxy or...
the Magellanic Clouds, however, individual stars can be resolved for multi-epoch velocity monitoring (or proper motion studies) in order to remove binaries. The sample is still small, but preliminary works on NGC 3603 (Rochau et al. 2010), the Arches (Clarkson et al. 2011; Clarkson et al., in preparation), Westerlund 1 (Mengel & Tacconi-Garman 2007; Cottaar et al., in preparation) and R136 (Hénault-Brunet et al., in preparation) indicate that they have low velocity dispersions, either in a virial or subvirial state. This suggests that they are already in dynamical equilibrium at a very young age (<3 Myr), consistent with the cluster formation simulations of Kruisjes et al. (2011b), but in contrast with the infant mortality scenario (see the recent review by Bastian 2011, who discuss this in more detail). Larger samples of young clusters will be needed to confirm or refute the infant mortality scenario.

6 CONCLUSIONS

We have presented an analysis of the cluster population in M83 based on HST/WFC3 observations. In particular, we have based our analysis largely on a comparison between the cluster populations in the inner and outer regions of the galaxies. Our main conclusions are summarized below.

(i) Sample selection. We have taken a relatively conservative approach in identifying clusters, only using those that are resolved, centrally concentrated and symmetric. This removes many associations from the sample, but at the expense of missing some clusters that are within larger associations. As shown by GPZ11, it is not possible to differentiate between clusters and associations until they are dynamically evolved. Additionally, when constructing extragalactic samples, it is often impossible to define the limits of clusters, or whether some parts of larger associations will become/remain bound. As such, the definition of clusters is often ambiguous at young ages and it becomes difficult to construct unique samples.
which likely causes much of the disagreement in the literature. However, at ages older than $\sim 10 \text{Myr}$, most clusters appear to be distinct objects, allowing for complete and unambiguous samples to be drawn.

(ii) Comparison with previous results. The cluster population in the inner field of the galaxy has been studied in detail in C10. While the cluster samples used in C10 and in this work differ at the youngest ages (see Section 2.3), we find good agreement between our results and theirs after $\sim 10 \text{Myr}$. Before this age, the samples disagree due to (a) selection criteria; and (b) the inclusion of the nuclear region of the galaxy in C10. After $\sim 10 \text{Myr}$, the age and mass distributions derived for the inner field in this work are consistent with those of C10.

(iii) $\Pi$ distribution. We have compared our cluster sample with the dynamical definition of a cluster given by GPZ11, namely that $\Pi \left( t_{\text{age}}, r_{\text{core}} \right)$ is greater than 1. We find that the vast majority of the objects ($\sim 95\%$) that were selected through visual inspection are clusters according to the $\Pi$ definition. The fraction of clusters that were missed is not possible to estimate at the moment, since it is difficult to define a characteristic size within crowded regions or associations.

(iv) Size distribution. We find that the size distribution of clusters in M83 is adequately fitted by a lognormal distribution with a peak at 2.3 and 2.6 pc in the inner and outer fields, respectively. However, below $\sim 0.5 \text{pc}$, our catalogue may be incomplete due to the inability to resolve clusters from point sources. Additionally, we find a trend between age and cluster size, such that older clusters are larger on average. Whether this is a physical effect or due to the fitting procedure is uncertain.

(v) Luminosity distribution. The luminosity distribution of clusters in the $U, B, V$ and $J$ bands can be approximated by a power-law distribution with index $-\alpha$. Over the full range where we are complete, we find $1.1 \leq \alpha \leq 2.1$, similar to that seen in other studies, with the bluer bands having shallower indices. Additionally, we find evidence of a truncation or bend in the LF at $M_V = -9.3$ and $-8.8$ for the inner and outer fields, respectively. This is similar to that seen in the cluster populations of M51 and NGC 6946.

(vi) Mass distribution. The distribution of cluster masses also appears to follow a power law with an index of $\sim -2$ over most of the observed range. However, the upper end of the MF appears to be truncated. This is shown using cumulative fractions; however, we note that the effect is not seen clearly if binning is used. Monte Carlo simulations are used to show the significance of the results. Including disruption, we find best-fitting values of $1.6 \times 10^5$ and $5 \times 10^3 M_\odot$ for the inner and outer fields, respectively. These values are consistent with that implied by the observed bends in the luminosity distributions. This suggests that the truncation mass is dependent on environment, likely related to the maximum mass of GMCs.

(vii) Cluster disruption. Finally, we have studied the role of cluster disruption in shaping the population. We have tested the observations against predictions from MDD models as well as MID models. We have also presented a formulation of how the two models can be combined. We find that both the MDD and the MID models can provide adequate fits to the data, if a Schechter MF is used. If the pure MID model is used, the fraction of clusters disrupted every decade in age varies as a function of environment, in apparent contradiction to the ‘universal’ age and mass distributions predicted by the preferred form of MID. If the pure MDD model is used, we find that the characteristic disruption time-scale is a factor of $\sim 4$ longer in the outer field, in agreement with analytic and numerical predictions.

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