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The early expansion of cluster cores

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ABSTRACT

The observed properties of young star clusters, such as the core radius and luminosity profile, change rapidly during the early evolution of the clusters. Here we present observations of six young clusters in M51 where we derive their sizes using *Hubble Space Telescope* (*HST*) imaging and ages using deep Gemini-North spectroscopy. We find evidence for a rapid expansion of the cluster cores during the first 20 Myr of their evolution. We confirm this trend by including data from the literature of both Galactic and extragalactic embedded and young clusters, and possible mechanisms (rapid gas removal, stellar evolutionary mass loss and internal dynamical heating) are discussed. We explore the implications of this result, focussing on the fact that clusters were more concentrated in the past, implying that their stellar densities were much higher and relaxation times ($t_{\rm relax}$) correspondingly shorter. Thus, when estimating if a particular cluster is dynamically relaxed (i.e. when determining if a cluster's mass segregation is due to primordial or dynamical processes), the current relaxation time is only an upper limit, with $t_{\rm relax}$ likely being significantly shorter in the past.

Key words: open clusters and associations: general – galaxies: individual: M51 – galaxies: star clusters.

1 INTRODUCTION

The early evolution of stellar clusters and aggregates has a rich variety of physical processes at work including stellar formation and evolution, gas inflow and outflow, stellar feedback and turbulence, the merging of stellar clumps and possibly, stellar interactions. The combination and effective efficiencies of these processes determine if the cluster, or part thereof, becomes/remains bound or if it forms an unbound loose aggregate of stars which will slowly blend into the background field population. These processes leave their mark on the cluster, in the size (core or effective radius), mass, profile shape and possibly on the stellar mass function.

This work is a continuation of our previous investigations on the implications of rapid residual gas expulsion (RGE) on the survivability and properties of young clusters (Bastian & Goodwin 2006; Goodwin & Bastian 2006). In previous papers we have explored the evolution of the luminosity profile of the clusters as well as their dynamical state. Both were found to be highly variable which led us to conclude that the observed properties of young clusters were merely snapshots in their evolution and should not be regarded as their final properties. One general prediction from our models, as well as other models of RGE (e.g. Goodwin 1997; Kroupa & Boily 2002), is that the cluster will expand in response to the loss of the residual gas, the exact amount of which will depend on the (effective) star formation efficiency.[1]

In the current work, we investigate the evolution of core radii for a sample of young clusters. The sample is partly composed of a small survey of young (age <30 Myr) clusters in M51 for which we use high signal-to-noise ratio (S/N > 100) optical spectra in order to derive their ages, and *Hubble Space Telescope*-Advanced Camera for Surveys (*HST*-ACS) imaging to derive their core radii.

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[1] Goodwin (2008) reiterates that it is not the star formation efficiency *per se* that is the critical factor in determining the effect of RGE, rather the dynamical state of the cluster at the onset of RGE which can be parametrized as an effective star formation efficiency.

We supplement this sample with clusters taken from the literature, composed of both embedded and open clusters in the Galaxy, as well as massive extragalactic clusters. These data sets are designed to complement the study of Mackey & Gilmore (2003) who derived the core radius for 63 clusters in the Large Magellanic Cloud (LMC)/Small Magellanic Cloud (SMC) and found a strong relation between the core radius of a cluster and its age (as first found by Elson 1991), in the sense that older clusters have a wider spread of core radii than young clusters.

The core radius of a cluster is a particularly interesting parameter as it is largely responsible for setting the time-scale over which the cluster evolves dynamically. For a given mass, it is the core radius which will set the core relaxation time-scale and determine how quickly dynamical mass segregation proceeds and whether or not stellar mergers are likely to take place (Freitag, Gürkan & Rasio 2006), assuming that the underlying stellar initial mass function (IMF) is sufficiently broad (Gürkan, Freitag & Rasio 2004). The core radius of the cluster is expected to increase during the first few 10s of Myr due to three main effects. First, from stellar evolution in which the most massive stars lose mass (this effect is heavily amplified if the core is mass segregated[2] – e.g. Mackey et al. 2007). Secondly, due to the expulsion of gas left over from the non-100 per cent efficiency star formation process (RGE; see Goodwin & Bastian 2006; Goodwin 2008 and references therein). Thirdly, dynamical heating of the core through 'dark objects' (i.e. black holes and neutron stars) interactions with lower mass stars (e.g. Merritt et al. 2004; Mackey et al. 2007, 2008). All three effects are understood relatively well theoretically (see the recent review by Baumgardt & Kroupa 2007) and all are likely to play a large role. The goal of the present paper is to test this theoretical framework with observations. In addition to the above effects, external perturbations such as interactions with giant molecular clouds (GMCs) and other clusters, disc shocking and spiral arm passages are expected to also heat the cluster, causing them to expand (e.g. Gieles et al. 2006; Gieles, Athanassoula & Portegies Zwart 2007).

This paper is organized in the following way. In Section 2 we present the observations and numerical techniques. In Section 3 we describe in detail the methods employed to derive the age and core radius of each of the clusters in the M51 sample. In Section 4 the age–core radius relation is discussed using the M51, Galactic and other extragalactic cluster samples and in Section 5 possible mechanisms are summarized. We discuss the results and implications in Section 6 and summarize the results in Section 7.

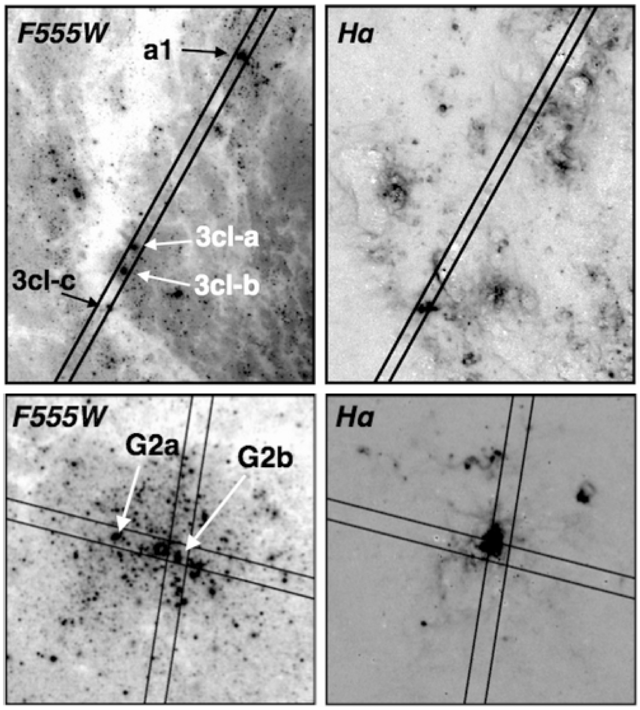

Figure 1. Top: slit positions superimposed on *HST* F555W and Hα (continuum subtracted) images of four of the clusters in the sample. Each image is 27.5×33.75 arcsec^2, corresponding to 1.12×1.375 kpc^2. North is up and east is to the left. Bottom: slit positions superimposed on *HST* F555W and Hα (continuum subtracted) images of the two clusters within the complex G2. Each image is $\sim$610 pc on a side. All images are shown in negative scaling, where dark shading refers to greater intensity and light regions are places of low intensity or high extinction.

2 OBSERVATIONS

The spectroscopic observations were taken the nights of 2006 May 25–26, using the Gemini Multi-Object Spectrograph (GMOS) on the Gemini-North telescope in long slit mode (PI: Bastian, GN-2006A-C-9). We used a slit width and length of 1.0 arcsec and 5.5 arcmin, respectively, and the B600 grating to achieve a resolution of $\sim$150 km s^{-1}. We chose three slit positions which were based on the catalogue of young cluster complexes in M51 by Bastian et al. (2005), and we use their naming convention throughout this paper (the cluster positions in the galaxy can be found using fig. 1 in Bastian et al. 2005). For each slit position, we obtained two 1800-s exposures, which were centred on 508 and 512 nm. For all observations the seeing was in the 70th percentile (i.e. better than 0.8 arcsec). The data were flat-fielded, bias subtracted, wavelength calibrated, extracted and combined using standard GEMINI/IRAF software.

Since the slit positions were chosen to cover multiple complexes in the same pointing, the positions were independent of paralactic angle. As such, we have not corrected for wavelength-dependent slit losses, which accounts for some of the observed differences in the spectral shapes of the clusters. The slit and cluster positions are shown in Fig. 1, their coordinates are given in Table 1 and the spectra are shown in Fig. 2.

Each slit contained one to four clusters with individual clusters a1 and G2b observed during two different pointings (i.e. for a total of four exposures for these clusters). The spectra show features common to young stellar populations, namely a combination of emission lines and strong Balmer absorption lines.

The structural parameters of the clusters were derived using *HST*-ACS-WFC (Wide Field Channel) observations (F435W, F555W and F814W). These observations were taken as part of the Hubble Heritage Project in 2005 January (proposal ID 10452, PI: S. V. W. Beckwith) and the data reduction and processing are described in detail in Mutchler et al. (2005). Throughout this paper we will use the standard B, V, I notation to discuss the colours of the clusters; however, we note that no transformation has been applied.

We adopt a distance to M51 of 8.4 Mpc (Feldmeier, Ciardullo & Jacoby 1997).

[2] I.e. the most massive stars are found preferentially in the centre of the cluster, more than would be expected from randomly sampling from the stellar IMF in a centrally concentrated profile.

Table 1. The properties of observed clusters in M51.

Cluster ID	Age[a] (Myr)	$\chi^2_{\nu,\mathrm{best}}$ [b]	Age[c] (Myr)	R_{core} (pc)	Coordinates (J2000)
a1	$5_{4}^{8.9}$	4.1	7.3_{4}^{10}	0.63 ± 0.10	13:29:54.64 47:12:08.1
3cl-a	$16.5_{12.6}^{25.1}$	1.5	20_{14}^{28}	1.65 ± 0.05	13:29:55.59 47:11:50.9
3cl-b	5_{4}^{6}	4.7	6_{10}^{4}	1.02 ± 0.33	13:29:55.67 47:11:48.8
3cl-c	3_{2}^{5}[d]	–	–	0.38[e]	13:29:55.81 47:11:45.6
G2a	6_{4}^{14}	1.9	10_{5}^{12}	1.08 ± 0.35	13:29:43.31 47:11:38.8
G2b	5_{3}^{7}	–	–	0.42[e]	13:29:43.02 47:11:37.8

[a]The best-fitting age is given (solar metallicity), along with the lower and upper limits as defined in the text.
[b]χ^2 of the best-fitting template age for Hβ.
[c]Same as for [a], but for $Z = 0.008$.
[d]Age based on the presence of Wolf–Rayet emission features in the spectrum.
[e]Only an upper limit, as discussed in the text.

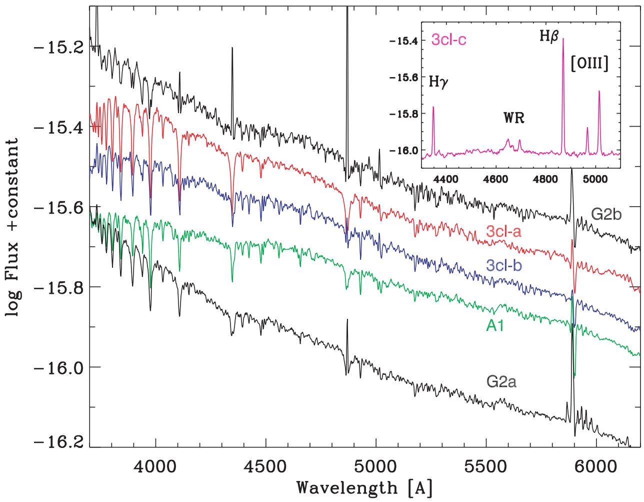

Figure 2. Spectra of the six clusters observed in M51. Differences in the continua of the spectra are due to different amounts of extinction and also due to the time and angle of the different slits, as no atmospheric dispersion correction was applied. Strong emission lines in cluster 3cl-c are labelled in the inset.

3 MEASURING PARAMETERS

3.1 Ages

Optical spectra are a powerful way to derive accurate ages for young clusters (e.g. Trancho et al. 2007a,b). For the present study we adopt the technique presented in Konstantopoulos et al. (2008), and we refer the reader there for the details of the method. In short, the method compares the detailed line profile shapes of the Hγ and Hβ lines with the González Delgado et al. (2005) simple stellar population (SSP) models which have been degraded in resolution to match the observations (we have used a Salpeter stellar IMF, and solar metallicity tracks). The comparison between the model and observed spectra is done on rectified spectra in two bands which straddle the line. The centre of the line is avoided in order to minimize contamination from any underlying emission component. This comparison is done for model ages between 4 and 10 Gyr and the model with the lowest reduced χ^2, χ^2_ν, is selected. The range of acceptable model ages was determined by comparison of the models and observations by eye. In particular, we compared the linewidth and overall profile fit, including small features in the profile which were seen in the observed spectrum as well as the best-fitting model. An example of the procedure (3cl-a) is shown in Fig. 3.

We have also fitted clusters a1, g2a, 3cl-a and 3cl-b with SSP model tracks with $Z = 0.008$, for which find good agreement with the solar metallicity fits. The results are given in Table 1; however, due to the good agreement, we will adopt the ages derived assuming solar metallicity throughout the paper. We note that cluster a1 is found in the centre of an Hα bubble which is approximately 80 pc in radius. This may argue for a higher age, namely that found using the $Z = 0.008$ models, but for consistency we adopt the younger $Z = 0.02$ results for cluster a1.

For cluster 3cl-c, the lack of any absorption lines in the observed spectrum makes this technique unfeasible. However, this cluster appears to be deeply embedded in a dust lane and has strong emission associated with it (see top panel of Fig. 1), which points to a very young age ($\ll$10 Myr). Additionally, the 'blue bump' is clearly observable in the spectrum at ~4650 Å which is a feature normally attributed to the presence of Wolf–Rayet stars. Such stars have very short lifetimes and their presence in the cluster indicates an age between 2 and 5 Myr (see Crowther 2007, and references therein).

Cluster G2b appears similar to 3cl-c in the lack of strong absorption lines. It does not, however, show any strong Wolf–Rayet features in the spectrum. Because of the proximity of this cluster to the H II region seen in the right-hand panel of Fig. 1, we associate this cluster with a young age, namely 5 ± 2 Myr.

3.2 Structural parameters

In order to determine the structural parameters of the clusters we used the ISHAPE algorithm (Larsen 1999). We empirically derived the point spread function (PSF) from bright isolated stars in the field of view.

(i) 3cl-a, 3cl-b, a1: these three clusters are extremely bright in all three bands (*BVI*) and hence we were able to have the index of the Elson, Fall & Freeman (1987, hereafter EFF) profile as a free parameter. A fitting radius of 15 pixel (~30 pc) was used. The errors were estimated from the standard deviation between the *B*-, *V*- and *I*-band fits. We have also estimated the errors in the fits using version 0.93.9beta of ISHAPE, which calculates the errors, including

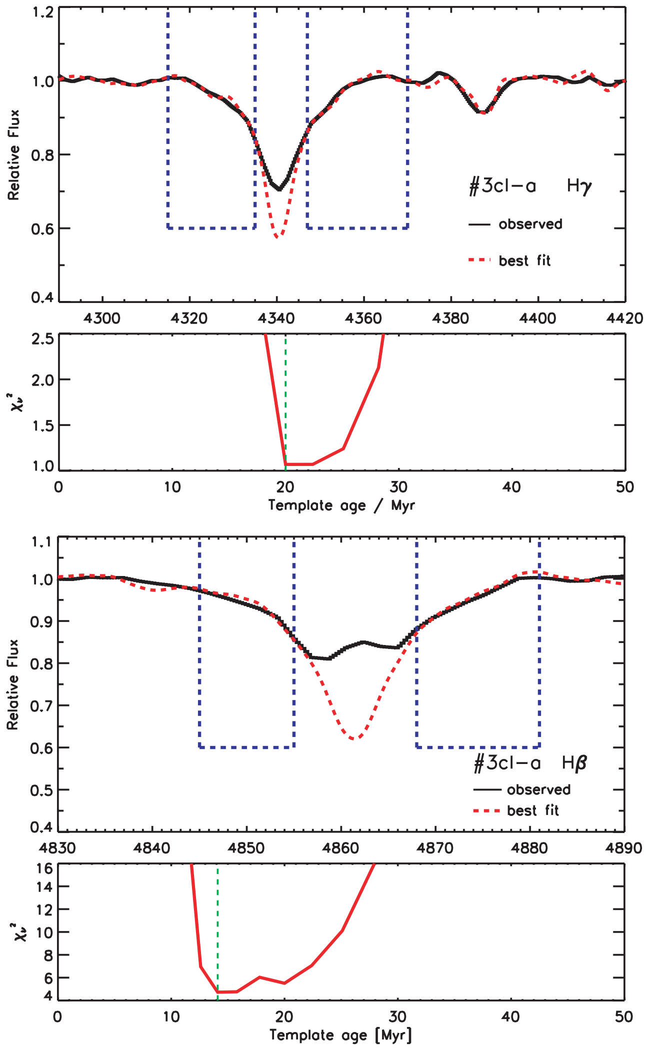

Figure 3. The observed spectra and best-fitting template spectra for cluster 3cl-a around the Hγ (top) and Hβ (bottom) absorption lines. The (blue) dashed boxes represent the spectral wavelength region used in the fits, where the centre of each line was not used due to a clear emission component. The lower plot in each panel shows the χ^2_ν result for each model fit, along with the best-fitting model (marked as a vertical dashed line).

correlations between the parameters, and find errors slightly smaller than the standard deviation between the filters.

(ii) G2a: no best fitting profile could be found, so we assumed an EFF profile and varied the index between 1 and 2.5 ($2 \le \gamma \le 5$), which are typical values for clusters in the LMC (e.g. Mackey & Gilmore 2003). We carried out the fits on all three bands (*BVI*) and took the average. The error was estimated in the same way as the above clusters.

(iii) 3cl-c, G2b: we used a fitting radius of 10 pixel due to contamination from nearby objects. No clear best-fitting profile could be found. We put an upper limit on the size by fitting EFF profiles with indices between 1 and 2.5 ($2 \le \gamma \le 5$) and found cluster radii between 0 (unresolved) and 0.42 pc.

One potential caveat in this method is that it implicitly assumes that the distribution of light within the cluster represents the underlying distribution of mass. If these clusters are, however, severely mass segregated then the profile derived from the light will underestimate the actual core radius (since the light will be dominated by

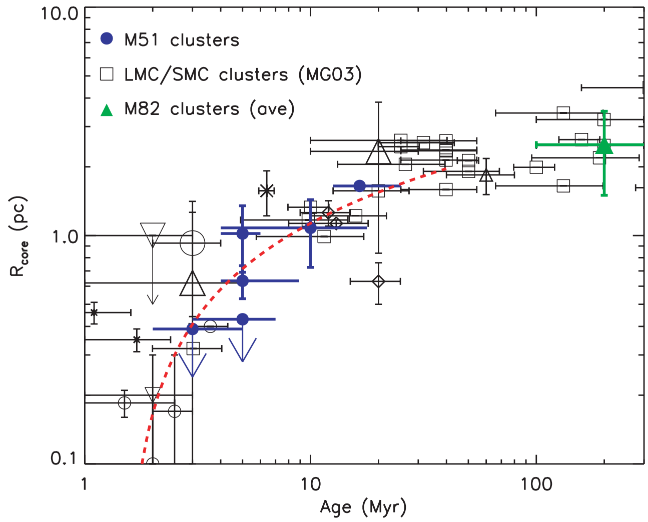

Figure 4. The relation between core radius and age of M51 clusters (filled blue circles) and other clusters taken from the literature. The large symbols represent median values of cluster surveys, see text for details. The dashed (red) line is a logarithmic fit to the data, done by eye ($R_{\rm core}$ [pc] = 0.6 ln (age [Myr]) − 0.25).

the most massive stars which are more concentrated than the lower mass stars – e.g. Gaburov & Gieles 2008).

4 THE CORE RADIUS/AGE RELATION

Fig. 4 shows the relation (filled blue circles) between the derived core radius and age for the six clusters in M51. There is a clear relation, with older clusters being larger than younger ones.

Young clusters are generally not found in isolation, but rather as parts of larger complexes due to the hierarchy of star formation (e.g. Zhang, Fall & Whitmore 2001; Bastian et al. 2005). As such, we expect, and observe, many sources around the young clusters (e.g. in the complex G2). These additional sources may cause blending with the clusters of interest, making them appear larger than they actually are. This bias, however, works in the opposite way to the observed trend (that the younger clusters are smaller), hence the actual trend may be stronger than we have observed.

In order to check if the observed relation between age and core radius is simply a reflection of an underlying mass–radius relation, we have estimated the mass of each of the clusters. For this we have compared the observed *BVI* colours of each cluster to the Galaxy Evolution (GALEV) SSP models, assuming solar metallicity and a Salpeter IMF (Anders & Fritze-v. Alvensleben 2003). We use the best-fitting spectroscopic age of each cluster and determine the cluster reddening based on the deviation between the observed colours and those expected at that age. We then use the age-dependent *M*/*L* (mass–luminosity) ratios to estimate the mass using the extinction corrected *V*-band flux.

We find that clusters a1, 3cl-a, 3cl-b and 3cl-c have similar masses within a factor of 2 ($\sim$0.7−1.3 $\times$ 10^5 M$_\odot$). G2a and G2b have similar masses (a few $\times 10^4$ M$_\odot$), although G2a is at least twice as large (core radius) as G2b. Hence we conclude that there is not any strong mass–radius relation present within this small data set.

In order to understand the $R_{\rm core}$–age relation we searched the literature and found young clusters which have had their ages and core radii measured. We take only clusters which have had their ages derived by either colour–magnitude diagram (CMD) fitting or spectroscopic age dating in order to have as clean a sample as possible. Mackey & Gilmore (2003) presented a large data base of LMC/SMC clusters with accurate core radii and ages, these are shown as open squares in Fig. 4. In the Galaxy there have been a number of massive young clusters discussed, including NGC 3603, Westerlund 1, Westerlund 2, the Arches and the Orion Nebula cluster (ONC; compilation taken from Brandner et al. 2008; however, using an age of 1.5 Myr for the ONC – Jeffries 2007), NGC 2316 (Teixeira et al. 2004), Trumpler 14 and DBSB48 (Ortolani et al. 2008). Some massive extragalactic clusters have also been included, namely NGC 1569B (Larsen et al. 2008), NGC 5236−805 (Larsen & Richtler 2004), NGC 6946−1447 (Larsen et al. 2001), M82F (Bastian et al. 2007, and references therein) and M82-A1 (Smith et al. 2006).

In addition, we also include surveys of cluster systems. The surveys are included in Fig. 4 as large open symbols, where the error bars on $R_{\rm core}$ represent the standard deviation of all members and the symbols represent the median. The Rosette nebula (Román-Zúñiga et al. 2008) was included, which is a group of nine clusters still in the embedded phase (age ∼3–5 Myr). We include the survey of embedded clusters by Lada & Lada (2003) (assigning an average age of 3 ± 2 Myr). From the Kharchenko et al. (2005) catalogue of open clusters we take the mean core radius of all clusters with ages between 10 and 30 Myr (three clusters with estimated core radii larger than 20 pc were excluded). We have taken the mean values of Johnson, Indebetouw & Pisano (2003) for young embedded radio detected clusters in IC 4662 whose core radii were estimated to be less than 1 pc, with adopted ages of 1–3 Myr. Finally, we include all clusters in M82 with ages between 100 and 200 Myr, from the recent study by Konstantopoulos et al. (in preparation).

Fig. 4 clearly shows that the all of the clusters follow the trend observed in the M51 clusters – core radii increasing with age. The possible causes of this, and the implications are discussed in the next section.

Such a relation between cluster size and age has been seen before, albeit with smaller samples. Román-Zúñiga et al. (2008) have recently shown a similar relation among seven embedded clusters in the Rosette nebula, which they attribute to the effects of RGE. In this case, the clusters are expected to have ages less than ∼5 Myr, and hence should not have had a significant amount of mass loss due to stellar evolution. Additionally, in a sample of young extragalactic clusters, Maíz-Apellániz (2001) found a relation between the size of a cluster and its age, which he attributed mainly to stellar evolutionary mass loss. Comparison of detailed *N*-body models with observations of the ONC also led Scally, Clarke & McCaughrean (2005) to suggest that, despite its young age (∼1.5 Myr), this cluster was substantially more dense in the past. Figer (2008) has estimated the density of young massive clusters in the Galaxy, and using his data (excluding the Galactic Centre cluster) it is clear that there is a strong trend of decreasing density with increasing age, consistent with the findings of the current study. Brandner (2008) also has noted that young clusters in the Galaxy have larger sizes at higher ages. Finally, we note that Scheepmaker et al. (2007) found larger sizes for red (presumably older) clusters in the disc of M51 than blue clusters; however, precise age dating of the clusters was not available.

5 POSSIBLE CAUSES

As mentioned in Section 1, there are a number of possible causes for the expansion of cluster cores with age. We limit our discussion here to causes that operate on the early evolution of clusters ($\lesssim$100 Myr).

5.1 Expansion by dynamical heating due to stellar mass black holes

Merritt et al. (2004) and Mackey et al. (2007, 2008) have suggested that the presence of stellar mass black holes in star clusters can lead to the expansion of the core radius. The stellar mass black holes form a dynamically distinct (invisible) 'core' and transfer energy into a stellar 'halo' causing the halo to expand, thus increasing the observed (i.e. stellar) core radius. Merritt et al. (2004) explain the spread in the observed core radii with age in the LMC/SMC data of Mackey & Gilmore (2003) by effectively changing the initial size scale of the cluster (through changing the scaling to *N*-body units). Mackey et al. (2007, 2008) can explain the same spread by introducing different degrees of initial mass segregation into their clusters and by changing the fraction of black holes that are retained by the cluster (i.e. not lost due to large natal kick velocities).

5.2 Stellar evolution

When a star cluster loses mass, it will expand in an attempt to regain virial equilibrium. The mass loss due to stellar evolution will therefore result in an expansion of the core during the first $\lesssim$100 Myr when a large fraction (∼20 per cent) of the initial mass is lost. However, detailed *N*-body simulations including this effect find that the maximum growth factor of the core radius is only about a factor of 2 (e.g. Portegies Zwart et al. 1999).

However, Mackey et al. (2007, 2008) show that the effect of stellar evolution on the expansion of a cluster is far more significant if primordial mass segregation is included (Mackey et al. allow their cluster to relax for 450 Myr before turning-on stellar evolution). Their mass segregated clusters are initially compact, with $R_{\rm core} \simeq 0.25$ pc at $t \simeq 2$–3 Myr, which lies nicely on our empirical fit in Fig. 4. Because of the high fractional mass loss by stellar evolution in the core, the value of $R_{\rm core}$, in the simulations of Mackey et al. (2007, 2008), increases with log(age) roughly as $R_{\rm core} = 2\log(\mathrm{age}) - 1$, which resembles our empirical curve $R_{\rm core} = 1.4\log(\mathrm{age}) - 0.25$. If we attribute the core expansion as observed in Fig. 4 entirely to stellar evolution, it implies that all of the clusters we observe started with a strong degree of mass segregation. Gaburov & Gieles (2008) note that $R_{\rm core}$ of mass segregated star clusters *appear* to increase with age by roughly a factor of 2, due to the massive stars that populate that core at young ages (this effect is also included by Mackey et al. 2007, 2008).

5.3 Residual gas expulsion

Clusters initially contain a significant gas fraction which is expelled by feedback from the most massive stars after a few Myr. The rapid change in the potential of the cluster causes the cluster to expand, and possibly be destroyed (see Goodwin 2008, and references therein). Simulations show that $R_{\rm core}$ will expand by a factor of 5–10 over ∼10 Myr as the cluster attempts to regain virial equilibrium (see Kroupa, Aarseth & Hurley 2001; Goodwin & Bastian 2006; Baumgardt & Kroupa 2007). The $R_{\rm core}$ evolution of unbound clusters is very similar to the empirical fit of Fig. 4, i.e. $R_{\rm core}$ increases linearly with log(age). Baumgardt & Kroupa (2007) find clusters that remain bound after an expansion of a factor of ∼5, making RGE a plausible explanation for the observed increase in $R_{\rm core}$. However, Baumgardt & Kroupa (2007) defined their core radii in terms of the Lagrangian radii, which contains a fixed fraction of the total mass, as compared to our method which defines the core radius in terms of a profile fit. Therefore, a direct comparison between the works should be taken with caution.

For the clusters that remain bound after RGE, $R_{\rm core}$ reaches a maximum and then decline after RGE. The reasons for this are twofold. First, clusters tend to 'overshoot' in their attempt to revirialize and oscillate around virial equilibrium. Thus the $R_{\rm core}$ are sometimes larger than for a virialized cluster. Secondly, $R_{\rm core}$ as measured from observations will tend to overestimate the final ('true') $R_{\rm core}$. After RGE a cluster will lose a (significant) fraction of its stars even if a bound cluster remains at the end ('infant weight loss'; see e.g. Goodwin & Bastian 2006). However, stars escape at a finite speed and so will be physically associated with the cluster for several Myr (as appears to be observed in a number of clusters as an excess of light at large radii; see Bastian & Goodwin 2006). Thus an observer may fit a profile that overestimates $R_{\rm core}$ for the final luminosity profile of the equilibrium cluster (Goodwin & Bastian 2006).

5.4 A combination of effects

Stellar evolution and an associated expansion in the core radius *must* occur in young clusters. However, how effective this is clearly highly dependent on the degree of mass segregation present in the cluster at the onset of massive star death.

Similarly, RGE *must* occur as after a few Myr clusters change from being embedded to naked. However, the effectiveness of gas expulsion depends significantly on the dynamical state of the cluster at the onset of gas expulsion, a factor for which we have very few observational or theoretical constraints (Goodwin 2008).

The presence of a significant 'dark' component in clusters as required for later dynamical expansion is difficult to determine observationally. It seems plausible that at least some of the massive stellar remnants from early stellar evolution should remain in the cluster, but the numbers and their dynamical importance are unclear. It should be noted that this is the only mechanism so far proposed that can explain the later (>100 Myr) expansion in core radii seen in the LMC/SMC.

Thus at least two of these proposed causes must be at work in causing the increase in $R_{\rm core}$ with time, and probably all three (and possibly other, as yet unknown mechanisms). In a future paper we will theoretically investigate the causes of core expansion in detail.

6 DISCUSSION AND IMPLICATIONS

6.1 Effect on dynamical age estimates

The results presented in Fig. 4 show that estimates of the dynamical age of a cluster, which can be defined as the number of *core* relaxation times ($t_{\rm rel}$) that have passed, will be wrong when using the current $R_{\rm core}$. Because $R_{\rm core}$ was smaller in the past, the cluster has dynamically evolved more than one would infer from the current properties (e.g. Portegies Zwart & Chen 2008). Using the empirical fit displayed in Fig. 4 we can estimate a correction factor F, that is, the ratio of the true dynamical age over the dynamical age assuming that $R_{\rm core}$ has been constant. Here we define the dynamical age as the number of core relaxation times that have passed, so that $F \equiv N_{\rm trel,real}/N_{\rm trel,current}$.

The core relaxation time-scales as $R_{\rm core}^{3/2}$ so we can calculate F as

$$F(t) = \frac{\int_0^t \left[R_{\rm core}(t')\right]^{3/2} \mathrm{d}t'}{t\, R_{\rm core}^{3/2}(t)}, \tag{1}$$

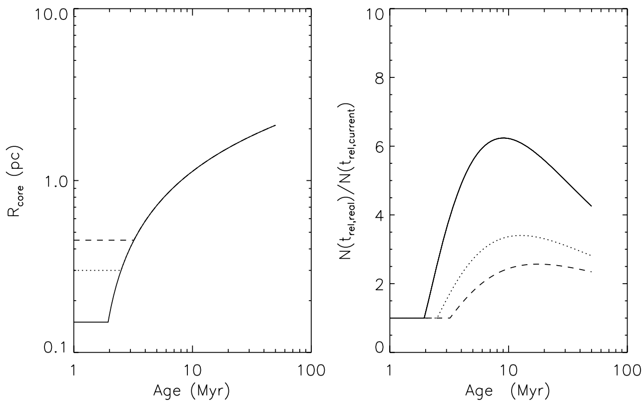

Figure 5. Left: the evolution of $R_{\rm core}$ for three different initial radii, using the functional fit to the data in Fig. 4. Right: the ratio of $N(t_{\rm rel,real})$ (the real number of relaxation times that have actually passed) to $N(t_{\rm rel,current})$ (the number of relaxation times that have passed assuming that the current relaxation time has been constant throughout the life of the cluster). Depending on the initial radius and age of the cluster, using $t_{\rm rel,current}$ significantly underestimates the number of relaxation times that have elapsed within the cluster.

where we use $R_{\rm core}(t') = 1.4 \log\,(\mathrm{age}) - 0.25$ (Fig. 4). Since the empirical fit goes to $-\infty$ at $t = 0$, we have to assume an initial $R_{\rm core}$ at $t = 0$. In Fig. 5 we show in the left-hand panel the functional form of the empirical fit, for three initial $R_{\rm core}$. In the right-hand panel we show the resulting $F(t)$ that follows from a numerical integration of equation (1). F depends strongly on the initial $R_{\rm core}$, but we can safely say that for the observed value of very young clusters, F is somewhere between 3 and 5 at its peak value at an age of $\sim$10 Myr. For ages $\lesssim$2 Myr, $F = 1$ because we have assumed a constant $R_{\rm core}$ equal to the initial $R_{\rm core}$ there. F decreases again for ages $\gtrsim$10 Myr because the increase of $R_{\rm core}$ has slowed down.

The results above and those shown in Fig. 5 are also valid for the *core* crossing time of a cluster in the limit that no stellar mass is lost during the expansion. However, if mass loss is included the effect would be stronger on the crossing time (since $t_{\rm cross} \propto M^{-0.5}$) and weaker on the relaxation time (since $t_{\rm relax} \propto M^{0.5}$). If the core would lose 50 per cent of its mass during the expansion phase, then $t_{\rm cross}$ would increase by a factor of $\sqrt{2}$ and $t_{\rm relax}$ would decrease by the same amount.

This effect must be taken into account when estimating the dynamical age of a cluster, for example to see whether the degree of mass segregation is of primordial or dynamical origin. We discuss this more in Section 6.1.1.

6.1.1 *Mass segregation*

Whether a cluster is mass segregated due to dynamical effects (energy equipartition), or if it is primordial (set by the star/cluster formation process) in nature has potentially large ramifications for the star/cluster formation process. In order to test if a cluster's observed mass segregation is dynamical or primordial in nature, a comparison is often made to the observed (current) relaxation time, $t_{\rm rel,current}$, to that of the cluster age. If $t_{\rm rel,current}$ is greater than the cluster age, then the mass segregation is thought to be primordial (e.g. Hillenbrand & Hartmann 1998; de Grijs et al. 2002; Gouliermis et al. 2004; Chen, de Grijs & Zhao 2007).

However, the results shown here indicate that the cluster cores expand rapidly during the first 20 Myr or so, and hence clusters were more compact in the past. Thus, $t_{\rm rel,current}$ may overestimate the initial (and at earlier times) relaxation time by a large factor. Fig. 5 shows an example of this effect, although we note that these calculations are meant as an illustrative example only, as we have not included mass loss. Indeed, Portegies Zwart & Chen (2008) find that the (half-mass) relaxation time can change by a factor of several due to stellar evolution over the first ∼100 Myr.

Depending on the initial radius and cluster age, estimating the number of relaxation times that a cluster has gone through based on the current relaxation time can result in errors of a factor of 1.5 to 6. Since this factor depends strongly on the initial cluster radius, and since this is generally not known nor well constrained, it is highly uncertain how many relaxation times a cluster has actually undergone. Thus, claims of primordial mass segregation based on $t_{\rm rel,current}$ should be taken with caution.

6.1.2 *Stellar mergers*

The observed core expansion will significantly affect the internal dynamics of the cluster, causing the relaxation time to increase rapidly. Freitag (2007) estimates that the relaxation time could be up to 20 times longer after the core expansion phase. This implies that dynamical mass segregation, core-collapse and/or stellar merging only have a brief window in which to operate, namely the embedded phase which lasts for 1–3 Myr. The implications regarding stellar mergers, and the subsequent formation of very massive stars, have been considered in detail by Freitag et al. (2006). They conclude that while the very dense state of the cluster may only last for a short time, this may be compensated by the initially very high densities.

6.2 Older compact clusters

While not found in our literature search (with the exception of NGC 1569B), it is possible that some clusters remain compact ($R_{\rm core} < 1$ pc) during their first 10–100 Myr of evolution. This could happen if the effective star formation efficiency is extremely high, if the gas dispersal time-scale is extremely long, or if the cluster stars were born with subvirial velocities. However, even in these extreme cases, some expansion is expected due to stellar evolution. It is also clear that clusters can be formed initially with large core radii; however, these clusters would be more likely to disrupt completely (due to RGE and stellar evolution) than their more compact counterparts, assuming that the star formation efficiency (or, more correctly, the initial dynamical state of the cluster) does not relate to cluster size.

7 CONCLUSIONS

We have presented high S/N spectra and high-resolution imaging of six clusters in M51. By comparing the Hγ and Hβ lines to template spectra, we have derived their ages. Additionally, we have measured their structural properties using the ISHAPE code of Larsen (1999). We find that the clusters are ∼3 to 25 Myr old and have core radii ranging from <0.4 to 1.6 pc.

We note a strong trend between the core radius and age of the clusters, in the sense that older clusters are larger. Including clusters with measured ages and structural parameters from the literature, we find this to be a common feature in cluster evolution. The most promising explanation of this phenomenon is that clusters expand as they leave their embedded phase, due to the change of gravitational potential within the cluster. The growth in cluster size appears to begin at 2–3 Myr, in good agreement with the expected/observed duration of the embedded phase of cluster evolution and the onset of gas expulsion. As a cluster expands (in particular its core) the relaxation time increases dramatically (Freitag 2007), which limits dynamical mass segregation and significantly lowers the chances of stellar mergers (Freitag et al. 2006).

The rather small range in mass spanned by our M51 cluster sample argues that the observed relation between age and core radius is not simply a reflection of an underlying mass–radius relation. We caution, however, that the observed trend of increasing core radius with age could be an observational artefact if all clusters begin their lives severely mass segregated. This would cause an underestimate of the core radius for younger clusters whose light is dominated by a few very massive stars.

These results show that the early phases of cluster evolution are highly dynamic with many of a cluster's fundamental parameters changing by large factors in a short time. This leads us to caution (as did Goodwin & Bastian 2006) that the determination of the parameters of young clusters must only be taken as instantaneous values, they are not the same as a few Myr previously, nor as they will be a few Myr hence.

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REFERENCES

Anders P., Fritze-v. Alvensleben U., 2003, A&A, 401, 1063
Bastian N., Goodwin S. P., 2006, MNRAS, 369, L9
Bastian N., Gieles M., Efremov Y. N., Lamers H. J. G. L. M., 2005, A&A, 443, 79
Bastian N., Konstantopoulos I., Smith L. J., Trancho G., Westmoquette M. S., Gallagher J. S., 2007, MNRAS, 379, 1333
Baumgardt H., Kroupa P., 2007, MNRAS, 380, 1589
Brandner W., 2008, in Beuther H., Linz H., Henning T., eds, Massive Star Formation: Observations Confront Theory. Preprint (arXiv:0803.1974)
Brandner W., Clark J. S., Stolte A., Waters R., Negueruela I., Goodwin S. P., 2008, A&A, 478, 137
Chen L., de Grijs R., Zhao J. L., 2007, AJ, 134, 1368
Crowther P. A., 2007, ARA&A, 45, 177
de Grijs R., Gilmore G. F., Johnson R. A., Mackey A. D., 2002, MNRAS, 331, 245
Elson R. A. W., 1991, ApJS, 76, 185
Elson R. A. W., Fall S. M., Freeman K. C., 1987, ApJ, 323, 54 (EFF)
Feldmeier J. J., Ciardullo R., Jacoby G. H., 1997, ApJ, 479, 231
Figer D. F., 2008, in Bresolin F., Crowther P. A., Puls J., eds, Proc. IAU Symp. 250, Massive Stars as Cosmic Engines. Combridge Univ. Press, Cambridge, p. 247

Freitag M., 2007, in Beuther H., Linz H., Henning T., eds, Massive Star Formation: Observations Confront Theory. Preprint (arXiv:0711.4057)
Freitag M., Gürkan M. A., Rasio F. A., 2006, MNRAS, 368, 141
Gaburov E., Gieles M., 2008, MNRAS, submitted (arXiv:0801.0596)
Gieles M., Portegies Zwart S. F., Baumgardt H., Athanassoula E., Lamers H. J. G. L. M., Sipior M., Leenaarts J., 2006, MNRAS, 371, 793
Gieles M., Athanassoula E., Portegies Zwart S. F., 2007, MNRAS, 376, 809
González Delgado R. M., Cerviño M., Martins L. P., Leitherer C., Hauschildt P. H., 2005, MNRAS, 357, 945
Goodwin S. P., 1997, MNRAS, 284, 785
Goodwin S. P., 2008, in Perez E., de Grijs R., Gonzalez Delgado R. M., eds, Young Massive Star Clusters – Initial Conditions and Environments. In press (arXiv:0802.2207)
Goodwin S. P., Bastian N., 2006, MNRAS, 373, 752
Gouliermis D., Keller S. C., Kontizas M., Kontizas E., Bellas-Velidis I., 2004, A&A, 416, 137
Gürkan M. A., Freitag M., Rasio F. A., 2004, ApJ, 604, 632
Hillenbrand L. A., Hartmann L. W., 1998, ApJ, 492, 540
Jeffries R. D., 2007, MNRAS, 376, 1109
Johnson K. E., Indebetouw R., Pisano D. J., 2003, AJ, 126, 101
Kharchenko N. V., Piskunov A. E., Röser S., Schilbach E., Scholz R.-D., 2005, A&A, 438, 1163
Konstantopoulos I. S., Bastian N., Smith L. J., Trancho G., Westmoquette M. S., Gallagher J. S., III, 2008, ApJ, 674, 846
Kroupa P., Boily C. M., 2002, MNRAS, 336, 1188
Kroupa P., Aarseth S., Hurley J., 2001, MNRAS, 321, 699
Lada C. J., Lada E. A., 2003, ARA&A, 41, 57
Larsen S. S., 1999, A&AS, 139, 393
Larsen S. S., Richtler T., 2004, A&A, 427, 495
Larsen S. S., Brodie J. P., Elmegreen B. G., Efremov Y. N., Hodge P. W., Richtler T., 2001, ApJ, 556, 801
Larsen S. S., Origlia L., Brodie J., Gallagher J. S., 2008, MNRAS, 383, 263
Mackey A. D., Gilmore G. F., 2003, MNRAS, 338, 85
Mackey A. D., Wilkinson M. I., Davies M. B., Gilmore G. F., 2007, MNRAS, 379, L40
Mackey A. D., Wilkinson M. I., Davies M. B., Gilmore G. F., 2008, MNRAS, 386, 65
Maíz-Apellániz J., 2001, ApJ, 563, 151
Merritt D., Piatek S., Portegies Zwart S., Hemsendorf M., 2004, ApJ, 608, L25
Mutchler M. et al., 2005, BAAS, 37, 452
Ortolani S., Bonatto C., Bica E., Momany Y., Barbuy B., 2008, New Astron., 13, 508
Portegies Zwart S. F., Chen H.-C., 2008, in de Koter A., Smith L., Waters R., eds, ASP Conf. Ser. Vol. 388, Mass Loss from Stars and the Evolution of Stellar Clusters. Astron. Soc. Pac., San Francisco, p. 329
Portegies Zwart S. F., Makino J., McMillan S. L. W., Hut P., 1999, A&A, 348, 117
Román-Zúñiga C. G., Elston R., Ferreira B., Lada E. A., 2008, ApJ, 672, 861
Scally A., Clarke C., McCaughrean M. J., 2005, MNRAS, 358, 742
Scheepmaker R. A., Haas M. R., Gieles M., Bastian N., Larsen S. S., Lamers H. J. G. L. M., 2007, A&A, 469, 925
Smith L. J., Westmoquette M. S., Gallagher J. S., O'Connell R. W., Rosario D. J., de Grijs R., 2006, MNRAS, 370, 513
Teixeira P. S., Fernandes S. R., Alves J. F., Correia J. C., Santos F. D., Lada E. A., Lada C. J., 2004, A&A, 413, L1
Trancho G., Bastian N., Schweizer F., Miller B. W., 2007a, ApJ, 658, 993
Trancho G., Bastian N., Miller B. W., Schweizer F., 2007b, ApJ, 664, 284
Zhang Q., Fall S. M., Whitmore B. C., 2001, ApJ, 561, 727

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