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Star cluster 'infant mortality' in the Small Magellanic Cloud (Redivivus)

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ABSTRACT

The early evolution of star clusters in the Small Magellanic Cloud (SMC) has been the subject of significant recent controversy, particularly regarding the importance and length of the earliest, largely mass-independent disruption phase (referred to as 'infant mortality'). Here, we take a fresh approach to the problem, using an independent, homogeneous data set of *UBVR* imaging observations, from which we obtain the SMC's cluster age and mass distributions in a self-consistent manner. We conclude that the (optically selected) SMC star cluster population has undergone at most ∼30 per cent (1σ) infant mortality between the age range from about (3–10) Myr, to that of approximately (40–160) Myr. We rule out a 90 per cent cluster mortality rate per decade of age (for the full age range up to 10^9 yr) at a $>6\sigma$ level. We independently affirm this scenario based on the age distribution of the SMC cluster sample.

Key words: stellar dynamics – globular clusters: general – open clusters and associations: general – Magellanic Clouds – galaxies: star clusters.

1 INTRODUCTION

The early evolution of the star cluster population in the Small Magellanic Cloud (SMC) has been the subject of considerable recent attention and vigorous debate (e.g. Rafelski & Zaritsky 2005; Chandar, Fall & Whitmore 2006; Chiosi et al. 2006; Gieles, Lamers & Portegies Zwart 2007). The key issue of contention is whether the SMC's star cluster system has been subject to the significant early cluster disruption processes observed in 'normal', interacting and starburst galaxies commonly referred to as 'infant mortality' and 'infant weight loss'. Chandar et al. (2006) argue that the SMC has been losing up to 90 per cent of its star clusters per decade of age, at least for ages from $\sim 10^7$ up to $\sim 10^9$ yr, whereas Gieles et al. (2007) conclude that there is no such evidence for a rapid decline in the cluster population, and that the decreasing number of clusters with increasing age is simply caused by fading of their stellar populations. They contend that the difference between their results was due to Chandar et al. (2006) assuming that they were dealing with a mass-limited sample, whereas it is actually magnitude-limited. In fact, this is not entirely correct; Chandar et al. (2006) analyse the full magnitude-limited sample and conclude that it is approximately surface-brightness limited. They then compare the cluster age distribution of the full sample (expressed in units of dN_{cl}/dt, i.e. the number of clusters per unit time period) to that of a subsample for masses $\geqslant 10^3$ M$_\odot$ (which they do not analyse in the same manner), and suggest both to be similar, although the latter is much flatter,[1] hence giving rise to the discrepancy between their results and those of Gieles et al. (2007). Both studies are based on the same data set, the Magellanic Clouds Photometric Survey (MCPS; Zaritsky, Harris & Thompson 1997).

The main contribution of this paper to the ongoing debate is two-fold: (i) We revisit the SMC's early star cluster evolution using an alternative approach; and (ii) we use independently obtained ages and masses based on an independent data set, i.e. the *UBVR* photometric survey of the Magellanic Clouds by Massey (2002), originally analysed by Hunter et al. (2003). We conclude that there is indeed only marginal evidence for infant mortality in the SMC star cluster sample, supporting the careful analysis of Gieles et al. (2007). In Section 2 we first briefly introduce the concept of cluster infant mortality. We discuss our observational data and the basic analysis leading to the age and mass estimates in Section 3. In Section 4 we justify our choice of age ranges to construct cluster mass functions (CMFs). Finally, in Section 5, we present our case for the absence of significant cluster infant mortality.

2 CLUSTER INFANT MORTALITY

Observations of increasing numbers of interacting and starburst galaxies, including the Antennae system, M51 and NGC 3310, show a significantly larger number of young ($\lesssim$10–30 Myr) star clusters

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[1] Although Chandar et al. (2006) suggest that their sample is roughly mass limited, they also note that the mass-limited subsample, constrained to clusters with masses $\log(M_{cl}/M_\odot) \geqslant 3.5$, shows a flatter age distribution.

than expected from a simple extrapolation of the cluster numbers at older ages, taking into account the observational completeness limits and the effects of sample binning, and under the additional, simplifying assumption that the star cluster formation rate (CFR) has been roughly constant over the host galaxy's history (e.g. de Grijs et al. 2003b; Whitmore 2004; Bastian et al. 2005; Fall, Chandar & Whitmore 2005; Mengel et al. 2005; Chandar, Fall & Whitmore 2006; see also Whitmore, Chandar & Fall 2007 for a presentation of earlier results, and de Grijs & Parmentier 2007 for a review). This significant overdensity remains, even in view of the presence of a recent burst of star cluster formation in many of these galaxies.

These observations have prompted a flurry of activity in the area of star cluster disruption processes. This has led to suggestions that cluster systems appear to be affected by a disruption mechanism that acts on very short time-scales ($\lesssim$10–30 Myr) and which may be mass-independent – at least for masses in excess of $\sim 10^4$ $M_{\odot}$ (e.g. Fall et al. 2005; Bastian et al. 2005; Fall 2006). This fast disruption mechanism, which is thought to effectively remove around 50 (Goodwin & Bastian 2006; although their sample is very probably biased), 70 (Bastian et al. 2005; Mengel et al. 2005) or even 90 per cent (Lada & Lada 1991; Whitmore 2004; Whitmore et al. 2007) of the youngest clusters from a given cluster population, is thought to be the rapid removal of the intracluster gas on a time-scale of $\sim$5 Myr, the signatures of which have been seen in several clusters (Bastian & Goodwin 2006). The observational effect resulting from this rapid gas removal has been coined cluster 'infant mortality' (Lada & Lada 2003); it was originally reported in the context of the number of very young embedded clusters, compared to their older, largely gas-free counterparts in the Milky Way.

The general consensus emerging from recent studies is that rapid gas removal from young star clusters is likely to leave the clusters super-virial and hence lead to the rapid disruption of many clusters (see e.g. Goodwin 1997a,b; Boily & Kroupa 2003a,b; Goodwin & Bastian 2006; see also de Grijs & Parmentier 2007 for a review). This leaves surviving clusters more susceptible to destruction (Vesperini & Zepf 2003; Bastian et al. 2005; Fall et al. 2005).

As described by Goodwin & Bastian (2006, and references therein) the effect of gas removal is to rapidly decrease the potential well in which the stars reside. The cluster will expand in an attempt to return to virial equilibrium. If the virial ratio of the stars *after* gas expulsion is $\gtrsim$3 the cluster will be unable to return to an equilibirum and will be destroyed.[2] Clusters with a higher effective star-formation efficiency than around 30 per cent will survive, but may undergo significant 'infant weight loss' (losing in excess of 50 per cent of their initial mass in some cases). The signature of infant weightloss has been observed in several young clusters (Bastian & Goodwin 2006). The time-scale over which a cluster will be destroyed, or attain a new (lower-mass) equilibrium configuration is 10–40 Myr (depending on the effective star-formation efficiency and the cluster mass).

The 10–40 Myr time-scale of gas removal-induced infant mortality and infant weightloss has important consequences for the analysis and interpretation of the data in this paper. Clusters undergoing expansion will have decreasing surface brightnesses, thus reducing their chances of being detected as they grow older. However, some clusters will recollapse after 10–40 Myr, which may bring them back into the sample. In addition, the speed at which clusters are lost from the sample would be expected to depend on their (initial) mass. Lower-mass clusters which are initially only just above the detection limit will drop out of the sample very quickly, whilst larger clusters may remain in the sample (albeit with a lower surface brightness) for longer. It is also almost impossible (without extensive observations of the surface brightness profiles and/or dynamical state of the cluster) to determine which clusters that are present in this age range will survive gas expulsion, and which are headed for destruction. Thus, the interpretation of the numbers and mass function of clusters in the age range 10–40 Myr is fraught with problems (in addition to these 'physical' problems, age determinations for clusters in this age range also cause problems; see below).

3 A HOMOGENEOUS PHOTOMETRIC DATA BASE

The basis for our detailed re-analysis of the SMC star cluster system is provided by the *UBVR* broad-band spectral energy distributions (SEDs) of Hunter et al. (2003), based on Massey (2002) CCD survey of the Magellanic Clouds.

In a series of recent papers, we developed a sophisticated tool for star cluster analysis based on broad-band SEDs, ANALYSED, which we tested extensively both internally (de Grijs et al. 2003a,b; Anders et al. 2004) and externally (de Grijs et al. 2005), using both theoretical and observed young to intermediate-age ($\lesssim 3 \times 10^9$ yr) star cluster SEDs, and the GALEV 'simple' stellar population (SSP) models (Kurth, Fritze-v. Alvensleben & Fricke 1999; Schulz et al. 2002). The accuracy has been further increased for younger ages by the inclusion of an extensive set of nebular emission lines, as well as gaseous continuum emission (Anders & Fritze–v. Alvensleben 2003). We concluded that the *relative* ages and masses within a given cluster system can be determined to a very high accuracy, depending on the specific combination of passbands used (Anders et al. 2004). Even when comparing the results of different groups using the same data set, we can retrieve any prominent features in the cluster age and mass distributions to within $\Delta\langle\log(\mathrm{Age/yr})\rangle \leqslant 0.35$ and $\Delta\langle\log(M_{\mathrm{cl}}/\mathrm{M}_{\odot})\rangle \leqslant 0.14$, respectively (de Grijs et al. 2005), which confirms that we understand the uncertainties associated with the use of our ANALYSED tool to a very high degree.

In de Grijs & Anders (2006) we presented newly and homogeneously redetermined age and mass estimates for the entire Large Magellanic Cloud (LMC) star cluster sample covered by the Massey (2002) data. Based on the comparison of our results in de Grijs & Anders (2006) with those published previously in a range of independent studies (mostly based on spectroscopic or isochrone analyses), and additionally on a detailed assessment of the age-metallicity and age-extinction degeneracies, we concluded that our broad-band SED fits yield reliable ages, with statistical *absolute* uncertainties within $\Delta \log(\mathrm{Age/yr}) \simeq 0.4$ overall. Here, we extend this to the SMC cluster sample, using the same age-dating technique as described above.

Our cluster age and mass determinations assume an average metallicity of $Z = 0.008$ (where $Z_{\odot} = 0.020$), and a mean foreground extinction $E(B - V) = 0.08$ mag. We will justify both of these choices below. In Fig. 1 we show the distribution of our SMC cluster sample in the log(age) versus log(mass) plane; the adopted 50 per cent completeness limit is overplotted. We have also indicated the regions in this plane from which we have drawn

[2] This is usually given in terms of a star-formation efficiency of $\sim$30 per cent. However, as noted by Goodwin & Bastian (2006), it is the virial ratio of the stars after gas expulsion that is the crucial parameter, and this can only be related to the star-formation efficiency in a simple way if the stars and gas were initially in virial equilibrium with one another. For this reason, Goodwin & Bastian (2006) use the term 'effective star formation efficiency'.

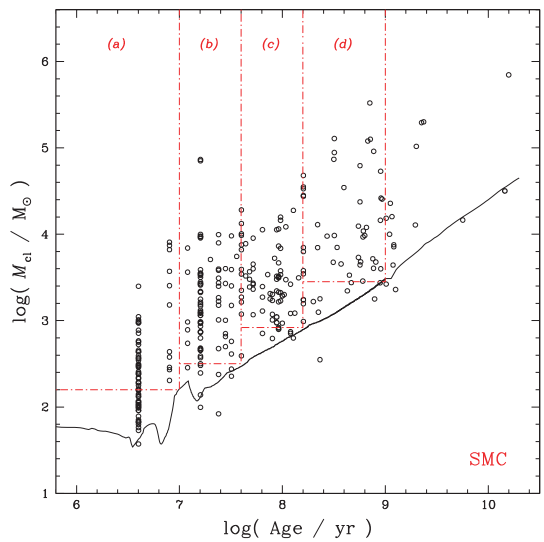

Figure 1. Distribution of the SMC clusters in the log(age) versus log(mass) plane. Overplotted is the expected detection limit based on stellar population synthesis for a 50 per cent completeness limit of $M_V = -4.5$ mag, assuming no extinction. For a nominal extinction of $A_V = 0.08$ mag (assuming the Calzetti attenuation law), the detection limit will shift to higher masses by $\Delta \log(M_{\rm cl}/{\rm M}_\odot) = 0.03$, which is well within the uncertainties associated with our mass determinations (see de Grijs & Anders 2006). The features around 10 Myr are caused by the appearance of red supergiants in the models. The age limits used to generate the different panels in Fig. 2 are shown as the vertical dash-dotted lines; the various subsets are also cross-linked between the figures using the panel indications from Fig. 2. The horizontal dash-dotted lines indicate the 50 per cent completeness limits in mass for each of the age-selected subsamples.

statistically complete subsamples, which we will discuss in detail in Section 4.

The determination of the 50 per cent completeness limit of the SMC cluster data is in essence based on a close inspection of the cluster photometry contained in Hunter et al. (2003) fig. 11. These authors selected their sample from the catalogue of Pietrzyński et al. (1998), matched to the observational field of view of the Massey (2002) data. Therefore, our completeness is that of this catalogue; Hunter and her team did not quantify the completeness levels themselves (D. Hunter, private communication), although they discuss an observed fading limit. However, for our analysis it is important to understand the sample incompleteness affecting our observations. As such, we adopted the conservative approach that the present-day SMC cluster luminosity function (CLF; see Hunter et al.'s fig. 11) is best represented by a power-law function in luminosity. Based on this assumption, we used the same observational data as used by Hunter et al. (2003) to determine the 50 per cent completeness limit at $M_V \sim -4.5 \pm 0.2$ mag (based on a power-law fit to the clusters brighter than $M_V = -5$ mag; varying this lower limit by a few tenths of a magnitude does not result in a significant change), i.e. at the same level as Hunter et al.'s (2003) observed fading limit. We note that if the underlying CLF is *not* a single power law over the entire observed luminosity range, the limit we adopt following this approach is in fact a lower limit. In the latter case the observations will likely be more complete than estimated here. Since the adopted 50 per cent completeness limit describes the lower envelope of the distribution of our SMC cluster sample very well, we are confident that our approach is reasonable. In addition, we point out that a variation in the magnitude limit of 0.2–0.4 mag will shift the mass limit by at most 0.1–0.2 dex, which clearly is still within our range of uncertainties. The magnitude of the shift expected when going from the 50 to the 90 per cent completeness limit in the SMC disc is of the same order, ∼0.5 mag. Finally, we point out that it is most likely that the completeness of our SMC cluster sample is in fact determined by the *U*-band observations. From a direct comparison of the *U*-band and the *V*-band data, we derive a 50 per cent completeness in the *U* band at $M_U = -5.0 \pm 0.3$ mag.

Chiosi et al. (2006) recently analysed the star-formation history in the SMC in detail using an independently selected star cluster sample. Where possible, they derive the extinction towards individual clusters based on colour-magnitude diagram analysis, and otherwise assume a mean extinction $E(B - V) = 0.08$ mag, following Tumlinson et al. (2002) and Hunter et al. (2003; see also Rafelski & Zaritsky 2005). We have adopted the same average extinction value to our SMC cluster sample, using the Calzetti attenuation law (Calzetti 1997, 2001; Calzetti et al. 2000; Leitherer et al. 2002) with $R_V = 4.05$.

Rafelski & Zaritsky (2005) obtained SMC cluster ages of a small cluster sample on the basis of three sets of models, for metallicities of $Z = 0.001$, 0.004 and 0.008. They concluded that some of the lowest-metallicity models could be rejected and adopted $Z = 0.008$ as an appropriate mean metallicity for their SMC cluster sample. Chiosi et al. (2006) also adopted this metallicity, but for their younger sample clusters. For the older ($\gtrsim 1 - 2$ Gyr) clusters, they assumed $Z = 0.004$, as was also done by Hunter et al. (2003). However, as shown in Fig. 1, the large majority of our sample clusters (and in particular the subpopulations we will analyse in more detail below) are younger than ∼1 Gyr, so that we adopt $Z = 0.008$ as the mean metallicity for our SMC cluster sample.

4 THE CLUSTER MASS FUNCTION

In de Grijs & Anders (2006) we presented the cumulative CMFs of the LMC star clusters younger than certain age limits. We concluded that while the older cluster (sub)samples are characterised by CMF slopes consistent with the $\alpha \simeq 2$ slopes generally observed in young star cluster systems – where α is defined as $N(M_{\rm cl}) \propto M_{\rm cl}^{-\alpha}$ – the youngest mass and luminosity-limited LMC cluster subsets show shallower slopes (at least below masses of a few $\times 10^3$ M$_\odot$). We noted that we could not disentangle the unbound from the bound clusters at the youngest ages. This is what we set out to do here for the SMC cluster system.

In order to achieve this goal, we present the CMFs for subsets of our SMC cluster sample in Fig. 2, where the cluster subsamples were selected based on their age distributions. The age limits used to generate the different panels in Fig. 2 are shown as the vertical dash-dotted lines in Fig. 1; the various subsets are also cross-linked between the figures.

A closer look at Fig. 1 reveals that, because of the variation in the observational detection limit as a function of age, the lower-mass limits of our cluster subsamples differ. Thus, the CMFs presented in Fig. 2 are statistically complete above different mass limits, as indicated by the horizontal dash-dotted lines in Fig. 1 and the vertical dotted lines in Fig. 2.

In all panels of Fig. 2, we have overplotted CMFs with the canonical slope of $\alpha = 2$ (corresponding to a slope of -1 in units of d $\log(M_{\rm cl}/{\rm M}_\odot)$/d $\log(N_{\rm cl})$, used in these panels). We have only shifted and scaled these lines vertically, as justified below.

We emphasise that for the star cluster infant mortality study performed here, we need to choose the age ranges of our cluster subsamples carefully, for both physical reasons and also because of

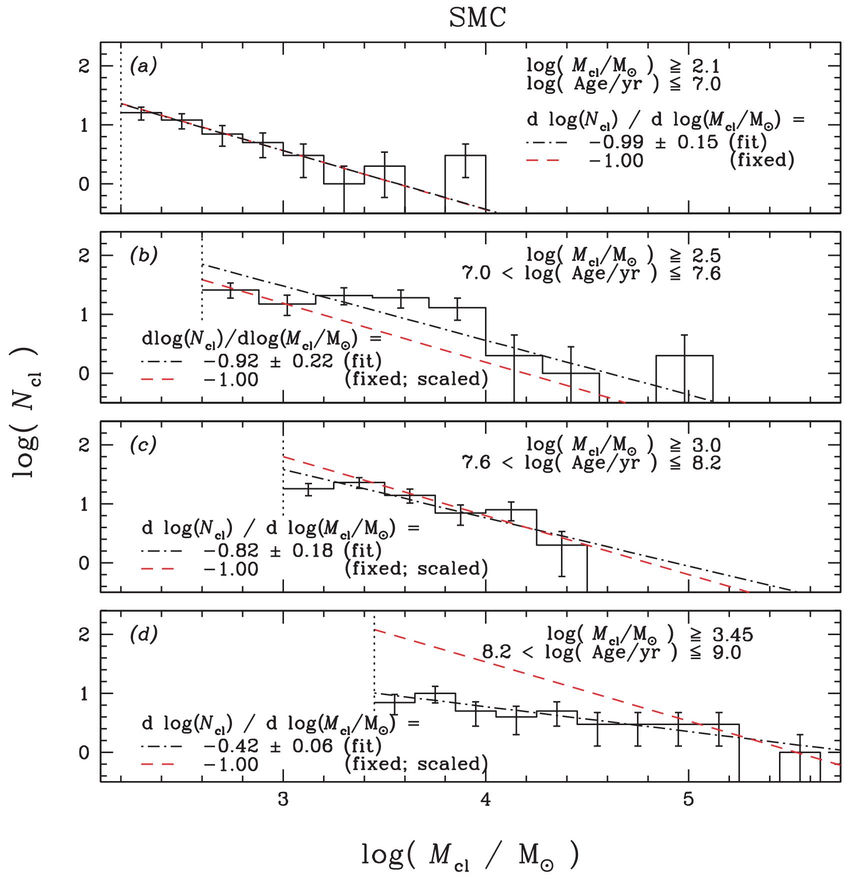

Figure 2. CMFs for statistically complete SMC cluster subsamples. Age and mass ranges are indicated in the panel legends; the vertical dotted lines indicate the lower mass (50 per cent completeness) limits adopted. Error bars represent simple Poissonian errors, while the dashed lines represent CMFs of slope $\alpha = 2$, shifted vertically as described in the text. The dash-dotted lines represent the best-fit CMFs over the relevant mass range. The panel indicators refer to Fig. 1.

the discrete nature of the model isochrones. Regarding the latter, it is well known that broad-band SED fitting results in artefacts in the cluster age distribution. This is predominantly caused by specific features in the SSP models, such as the onset and presence of red giant branch or asymptotic giant branch (AGB) stars at, respectively, ∼10 and ∼100 Myr (e.g. Bastian et al. 2005). Alternatively, both the age-metallicity and the age-extinction degeneracies will affect the resulting cluster age distributions, thus also leading to artefacts in the data (e.g. de Grijs et al. 2003b; Anders et al. 2004). We have attempted to avoid placing our age range boundaries around ages (and, where possible, have taken account of the uncertainties in age in doing so) where the effects of such artefacts might seriously impede the interpretation of the results. For instance, one can see a clear artefact in the cluster age distribution (which we will refer to as a 'chimney') at $\log(\mathrm{Age/yr}) \simeq 7.2$ ($\simeq 16$ Myr); the average uncertainties for these ages are of order a few Myr, so that we decided to limit our youngest cluster subsample to clusters younger than 10 Myr. If, instead, we had adopted an age limit at $\log(\mathrm{Age/yr}) = 7.17$ (15 Myr), we would have had marginally better statistics, but our analysis would be affected by the unknown effects of the age uncertainties associated with this chimney (see Goodwin et al., in preparation, for a detailed discussion of the issues involved).

The rationale for adopting as our youngest subsample all clusters with ages $\leqslant 10$ Myr is that at these young ages, the vast majority of the star clusters present will still be detectable, even in the presence of early gas expulsion (e.g. Goodwin & Bastian 2006) – as long as they are optically conspicuous. The CMF of this subsample is shown in Fig. 2(a).

Fig. 2(c) includes our sample clusters with ages in excess of 40 Myr, up to 160 Myr. While the upper age limit ensures the full inclusion of the clusters affected by the onset of the AGB stage, its exact value is rather unimportant for our analysis, and it was mainly determined by the need to have reasonable statistics in this (and the upper) age range in Fig. 2(d). The lower age limit of this subsample is crucial, however. As shown by Goodwin & Bastian (2006), most dissolving clusters will have dispersed by an age of ∼30 Myr, while the surviving clusters will have returned to an equilibrium state by ∼40 Myr, when some of the early expansion will have been reversed, depending on the effective star-formation efficiency. This latter age is therefore a good lower boundary to assess the surviving star cluster population.

We explicitly exclude any star clusters aged between 10 and 40 Myr from our analysis. In this age range, which is shown in Fig. 2(b) for completeness, it is likely that dissolving star clusters that will not survive beyond about 30–40 Myr might still be detectable and therefore possibly contaminate our sample. In addition, this is the age range in which early gas expulsion causes rapid cluster expansion, before settling back into equilibrium at smaller radii; because of the expanded nature of at least part of the cluster sample, we might not be able to detect some of the lower-luminosity (and hence lower-mass) clusters that would again show up beyond an age of ∼40 Myr. At the same time, the effects of 'infant weight loss' (Weidner et al. 2007) will further confuse the analysis in this age range (see Section 2 for details).

5 IS THERE EVIDENCE FOR CLUSTER INFANT MORTALITY IN THE SMC?

5.1 Young and intermediate-age clusters

In Fig. 2(a), we have included the best-fitting CMF slope (dash-dotted line), in addition to the canonical $\alpha = 2$ CMF slope (dashed line). Both slopes are the same, within the uncertainties. This also shows that the SMC's CMF at the youngest ages is consistent with an $\alpha = 2$ power law down to cluster masses of $\sim 125\,\mathrm{M}_\odot$, within the (Poissonian) uncertainties.

In the simplest case, in which the cluster formation rate has remained roughly constant throughout the SMC's evolution (see, e.g. Boutloukos & Lamers 2003, their fig. 10; see also Gieles et al. 2007), the number of clusters would simply scale with the age range covered. In Figs 2(b), (c) and (d), we show the canonical $\alpha = 2$ CMF scaled from the best-fitting locus in Fig. 2(a) by the difference in (linear) age range between the panels. The main uncertainties introduced by this method are (i) fluctuations caused by small-number statistics in the youngest age range (the effects of which will be enhanced when scaling the young-age CMF to a greater age range), and (ii) the exact length of the youngest age range (especially considering the necessarily short extent of our youngest age bin). While our GALEV SSP models start at an age of 4 Myr, the actual ages of a small subset of our sample clusters might be somewhat younger. This introduces an artificial concentration of clusters at our youngest model age, as can be seen in Fig. 1. It is, unfortunately, not straightforward to remedy this situation based on broad-band imaging observations alone. However, we note that it may take up to 3–5 Myr for an embedded cluster to clear a cavity in its natal gas cloud for its stars to become visible at optical wavelengths (see, e.g. Plante & Sauvage 2002 for a review of embedded young massive star cluster observations). Therefore, we adopt the conservative working assumption that our youngest age range runs from 3–10 Myr. The scaling from the youngest age bin to that covering [40,160] Myr (Fig. 2c, i.e. the most important age range for our CMF comparison in the context of our infant mortality analysis) is therefore a factor of ~ 17, or $\Delta\ \log(N_{\rm cl}) = 1.234$.

Despite the caveat regarding the absence of embedded star clusters in our youngest subsample, we argue that this has a negligible effect on the CMF presented in Fig. 2(a), because of their very small number. Recent, homogeneous observations of the SMC using the *Spitzer Space Telescope* in a number of mid-infrared passbands (Bolatto et al. 2007) have shown that the vast majority of the embedded sources are low-mass ($\ll 100\,\mathrm{M}_\odot$) young stellar objects rather than more massive clusters and associations (we point out that for the comparison done here, we are mostly interested in clusters with masses greater than $10^3\,\mathrm{M}_\odot$). The possible exceptions to this rule are few, and include the four youngest ~ 3 Myr-old SMC clusters, NGC 299, NGC 346, NGC 376, and NGC 602 (e.g. Sabbi et al. 2007).

The scaled canonical CMF in Fig. 2(c) is an almost perfect fit to the observational CMF. Although the best-fitting CMF slope is $\mathrm{d}\ \log(M_{\rm cl}/\mathrm{M}_\odot)/\mathrm{d}\ \log(N_{\rm cl}) = -0.82 \pm 0.18$, this compares to $\mathrm{d}\log(M_{\rm cl}/\mathrm{M}_\odot)/\mathrm{d}\log(N_{\rm cl}) = -1.01 \pm 0.20$ if we ignore the lowest-mass clusters at $\log(M_{\rm cl}/\mathrm{M}_\odot) \leqslant 3.2$, where there may be residual incompleteness effects (see the selection area in Fig. 1 compared to the age-dependent detection limit).

This very good match between the observed CMF for the age range from 40–160 Myr (Fig. 2c) and the scaled CMF from Fig. 2(a) implies that *the SMC cluster system has not been affected by any significant amount of cluster infant mortality for cluster masses greater than a few* $\times 10^3\,\mathrm{M}_\odot$. Based on a detailed assessment of the uncertainties in both the CMFs and the age range covered by our youngest subsample, we can limit the extent of infant mortality between the youngest and the intermediate age range to a maximum of $\lesssim 30$ per cent (1σ). We rule out a ~ 90 per cent (infant) mortality rate per decade of age at a $>6\sigma$ level. This result is in excellent agreement with that of Gieles et al. (2007); it is, however, in direct contradiction to the claim of Chandar et al. (2006) that the SMC cluster system has undergone sustained destruction at very high rates (up to 90 per cent per decade in logarithmic age) for the full age range up to ~ 1 Gyr, although we note that Chandar et al. (2006) do not include the youngest SMC clusters in their analysis.

As an important caveat, we remind the reader that the main underlying assumption leading to this result is the notion that the SMC's CFR has been approximately constant over the time-scale of ~ 1 Gyr. If this were seriously in error, in order for this to give rise to the result reported here, the SMC's average CFR must have been significantly enhanced in the 40–160 Myr-old age range, by up to an order of magnitude, compared to that at present. There is no clear evidence, in either the current data set or the earlier work by Boutloukos & Lamers (2003; see also Gieles et al. 2007), nor in the age distribution of the field stars (Chandar et al. 2006; Chiosi & Vallenari 2007), to suggest that this is the case. In fact, if anything, we might expect an enhanced CFR around the time of the last close encounter between the SMC and the LMC, some 200–500 Myr ago (see, e.g. Heller & Rohlfs 1994; Gardiner & Noguchi 1996; see also Chiosi et al. 2006, but see Chiosi & Vallenari 2007 for an alternative interpretation), i.e. significantly longer ago than the age range probed by our intermediate-age clusters in Fig. 2(b).

For completeness, we also show the best-fit power-law CMF, as well as the scaled canonical CMF, in Fig. 2(b) for the age range between 10 and 40 Myr. Although *we strongly caution against placing too much significance on the analysis of the CMF in this age range*, for the reasons outlined in Section 4, it is interesting to note that the scaled canonical CMF does in fact seem to describe the extremities of this CMF reasonably well. However, at intermediate masses (a few $\times 10^3 - 10^4\,\mathrm{M}_\odot$) the observed CMF exceeds the theoretical prediction for a constant cluster formation rate. Although the effects of cluster expansion and infant weight loss most likely contribute to confusing the emerging picture, the main cause of this discrepancy is owing to the artificial chimney at $\log(\mathrm{Age/yr}) \simeq 7.2$. The cluster numbers in this age range are dominated by this artefact, so it is important that we understand in which sense this affects our results. Because of the discreteness of the isochrones in our SSP models around this age, and the tendency for the broad-band fitting routine to iterate to a local minimum χ^2 solution, most (but not all) of the clusters in this chimney should have been assigned somewhat greater ages. Because their ages have been underestimated (by up to 0.1–0.2 dex in logarithmic age), the associated masses have also been underestimated, by a similar amount. Unfortunately, until more detailed SSP models become available, there is no easy way out. However, a qualitative assessment suggests that if we were able to correct for this chimney, the derived masses of at least a fraction of the clusters affected would be greater, and thus that the apparent excess in Fig. 2(b) would be redistributed towards greater masses. The result would be a smoother CMF, more akin to the scaled canonical $\alpha = 2$ CMF of Fig. 2(a).

The alternative interpretation, i.e. that the star cluster formation rate in the SMC has undergone a significant increase in the age range between 10 and 40 Myr appears to be effectively ruled out by the complementary analysis of Chiosi et al. (2006). In fact, these authors find evidence suggesting the contrary, i.e. that the SMC cluster population has seen periods of enhancement during the first ∼15 Myr, and at around 90 Myr – this implies that in the age range of interest here, the cluster formation rate found by Chiosi et al. (2006) was in fact *reduced* with respect to the most recent cluster forming episode (roughly equivalent to the cluster sample shown in Fig. 2a). Equivalently, neither Rafelski & Zaritsky (2005), nor either Chandar et al. (2006) or Gieles et al. (2007) find an episode of increased cluster formation at a few $\times 10^7$ yr, despite the fundamentally different conclusions drawn by the authors of the latter two studies.

5.2 The oldest sample clusters

Finally, in Fig. 2(d) we show the combined SMC CMF for clusters from 160 Myr up to 1.0 Gyr, as well as the scaled canonical CMF. The latter matches the highest-mass ($\log(M_{\rm cl}/{\rm M}_\odot) \gtrsim 4.8$) part of the observed CMF, but significantly overpredicts the number of lower-mass ($\log(M_{\rm cl}/{\rm M}_\odot) \lesssim 4.8$) clusters. This flattening of the CMF with respect to our intermediate age range (Fig. 2c) evidences the increased importance of mass-dependent cluster disruption, as described in detail by, e.g. Lamers et al. (2005; see specifically their fig. 4). However, we note that the calculations of Lamers et al. (2005) are based on coeval stellar populations, while our oldest age bin contains a mixture of differently aged clusters. Nevertheless, it is apparent from fig. 4 of Lamers et al. (2005) that the flattening of the CMF increases as a function of age, starting at early ages. In a mixed intermediate-age population, the individual roughly coeval subpopulations giving rise to the overall CMF therefore lead to a flattened CMF with respect to the initial cluster mass distribution (which we have shown in the SMC to be equivalent to the canonical $\alpha = 2$ power-law CMF; see Fig. 2a). A comparison of our observations with the Lamers et al. (2005) calculations is therefore relevant to first order. A similar flattening of the CMF with increasing age is also predicted as owing to the effects of the underlying galactic tidal field (e.g. Vesperini & Heggie 1997; Baumgardt & Makino 2003). We will discuss these older clusters in more detail in a follow-up paper (Goodwin et al., in preparation), in which we will discuss the entire evolutionary sequence of the star cluster systems of both Magellanic Clouds, and where we aim to understand the *physics* driving the early evolution of these star clusters systems.

5.3 Additional supporting evidence for little early disruption

In Fig. 3 we show the SMC cluster age distribution expressed in units of $dN_{\rm cl}/dt$, i.e. the number of cluster per unit time-scale (for which we adopt 10^6 yr). To first order, our age distribution is similar to that based on the Rafelski & Zaritsky (2005) data used by both Chandar et al. (2006) and Gieles et al. (2007). It is also roughly similar to the age distribution derived independently by Chiosi et al. (2006).

Gieles et al. (2007) analysed their cluster age distribution very carefully, and found little evidence for infant mortality in the SMC cluster system. They showed that the decline in $dN_{\rm cl}/dt$ in their sample could be attributed entirely to evolutionary fading of the cluster population, irrespective of which SSP models are used. They derived that for a magnitude-limited sample, as also discussed in this paper, the decline in $dN_{\rm cl}/dt$ as a function of age is graphically described by a slope of -0.72, if the cluster ages are based on the GALEV SSP models. In Fig. 3, we show the expected effects of evolutionary fading of the cluster population as the dashed arrow. It is immediately clear that the decline in the age distribution up to $\log({\rm Age\ yr}^{-1}) \simeq 7.8$ can indeed be entirely attributed to evolutionary fading. This is supported by the mass-limited subsamples shown in Fig. 3: for all mass ranges, they show an essentially flat age distribution up to $\sim 10^8$ yr. This is in support of the results of both Gieles et al. (2007), and Chandar et al. (2006, their fig. 1), although the latter authors favoured a different interpretation.

The age distribution at $\log({\rm Age\ yr}^{-1}) \simeq 8.2 \pm 0.3$ (covering the age range from about 80 to 320 Myr) falls below the fading line, however. For a constant cluster formation rate over this entire period, and if we normalise the age distribution at our youngest data point, we would need the SMC cluster sample to have suffered from ∼20 − 50 per cent disruption in order to match the observations. We can firmly rule out a constant ∼90 per cent disruption rate per decade in age, up to an age of 1 Gyr. The expected effects of evolutionary fading combined with a 90 per cent disruption rate are shown as the dash-dotted arrow in Fig. 3. The arrow clearly does not fit the observed age distribution, if we require it to pass through our youngest data point. We note, however, that the slope of this latter arrow is very similar to that of the age distribution of the full SMC sample for ages in excess of a few $\times 10^8$ yr, when secular disruption is likely to take over. We will discuss these older age ranges in detail in Goodwin et al. (in preparation).

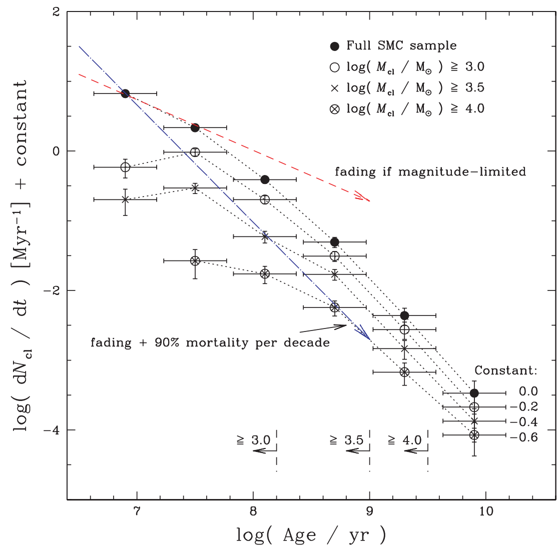

Figure 3. Age distribution of the SMC cluster sample in units of cluster number per Myr. We show four different (sub)samples, including the full magnitude-limited SMC sample, and three mass-limited subsamples, as indicated in the figure legend. The mass-limited subsamples have been shifted vertically by the constant offsets indicated on the right-hand side for reasons of clarity (without these offsets, the data points would all overlap at the oldest ages). For that same reason, we have also connected the data points for each of the (sub)samples. The mass-limited subsamples are ⩾50 per cent complete to the left of the vertical dashed lines at the bottom of the figure, where the numbers refer to the 50 per cent completeness limits for a given range, expressed in $\log(M_{\rm cl}/{\rm M}_\odot)$. The vertical error bars are simple Poissonian errors; the horizontal error bars indicated the age range used for the generation of these data points. Finally, the dashed arrow shows the expected effects due to fading of a cluster sample made up of SSPs, based on the GALEV SSP models (see also Gieles et al. 2007); the dash-dotted arrow represents the combined effects of a fading cluster population and 90 per cent cluster disruption per decade in $\log({\rm Age\ yr}^{-1})$, up to ages of 1 Gyr.

In summary, we set out to shed light on the controversy surrounding the early evolution and disruption of star clusters in the SMC. We embarked on a fresh approach to the problem, using an independent, homogeneous data set of *UBVR* imaging observations, from which we obtained the cluster age distribution in a self-consistent manner. We conclude that the optically selected SMC star cluster population has undergone at most ∼30 per cent (1σ) 'infant mortality'. Using the age distribution of the SMC cluster sample in units of the number of clusters observed per unit time-scale, we independently confirm this scenario. Gieles et al. (2007) reached a similar conclusion.

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