The initial mass distribution of the M82 star cluster system

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Received date; accepted date

ABSTRACT

We explore whether we can constrain the shape of the initial mass distribution of the star cluster population in M82's ∼ 1 Gyr-old post-starburst region "B", in which the present-day cluster mass function (CMF) is closely approximated by a log-normal distribution. We conclude that the M82 B initial CMF must have had a mean mass very close to that of the "equilibrium" CMF of Vesperini (1998). Consequently, if the presently observed M82 B CMF has remained approximately constant since its formation, as predicted, then the initial CMF must have been characterized by a mean mass that was only slightly larger than the present mean mass. From our detailed analysis of the expected evolution of CMFs, we conclude that our observations of the M82 B CMF are inconsistent with a scenario in which the 1 Gyr-old cluster population originated from an initial power-law mass distribution. Our conclusion is supported by arguments related to the initial density in M82 B, which would have been unphysically high if the present cluster population were the remains of an initial power-law distribution.

Key words: galaxies: individual: M82 – galaxies: starburst – galaxies: star clusters

1 INTRODUCTION

The derivation of galaxy formation and evolution scenarios using their star cluster systems as tracers is limited to the study of integrated cluster properties for galaxies beyond the Magellanic Clouds, even at Hubble Space Telescope spatial resolution. In this context, one of the most important and most widely used diagnostics is the distribution of cluster luminosities, or – alternatively – their associated masses, commonly referred to as the cluster luminosity and mass functions (CLF, CMF), respectively.

In de Grijs et al. (2003b; see also de Grijs 2002; de Grijs et al. 2003a) we reported the discovery of an approximately Gaussian (or log-normal) CLF (and CMF) for the roughly coeval star clusters at the intermediate age of ∼ 1 Gyr in M82's fossil starburst region B. This provided the first deep CLF (CMF) for a star cluster population at intermediate age, which thus serves as an important benchmark for theories of the evolution of star cluster systems. Recently, Goudfrooij et al. (2004) added a second important data point to constrain such theories, based on the roughly 3 Gyr-old cluster population in NGC 1316, for which they also detected a clear turn-over in their CLF1.

Starting with the seminal work by Elson & Fall (1985) on the young Large Magellanic Cloud (LMC) cluster system (with ages ≲ 2 × 10⁹ yr) seems to imply that the CLF of young star clusters (YSCs) is well described by a power law of the form \( N_{\text{YSC}}(L) dL \propto L^{\alpha} dL \), where \( N_{\text{YSC}}(L) dL \) is the number of YSCs with luminosities between \( L \) and \( L + dL \), with \(-2 \leq \alpha \leq -1.5\) (e.g., Elmegreen & Efremov 1997; Whitmore et al. 2002; Bik et al. 2003; de Grijs et al. 2003c; Hunter et al. 2003; see also Elmegreen 2002). On the other hand, for old globular cluster (GC) systems with ages ≥ 10⁹ yr, the CLF shape is well established to be roughly Gaussian (or log-normal), characterized by a peak (turn-over) magnitude at \( M_V \approx -7.4 \text{ mag} \) and a Gaussian FWHM of ∼ 3 mag (Harris 1991; Whitmore et al. 1995; Harris et al. 1998). This shape is almost universal, showing only a weak discussion in Goudfrooij et al. (2004), the turn-over in the 3 Gyr-old metal-rich (\( Z \sim Z_{\odot} \)) "inner" cluster population (\( R \leq 9.4 \text{ kpc} \)) in NGC 1316 occurs at \( M_V \approx -6.2 \), with a half width at half maximum (based on their Fig. 3f) of ∼ 1.2 mag (FWHM ∼ 2.4 mag). Assuming a Salpeter-like IMF with masses \( m_* \geq 0.1 \text{ M}_\odot \), the GALAX simple stellar population models (Schulz et al. 2002; Anders & Fritze-v. Alvensleben 2003) indicate a mean cluster mass of \( \log(M_\odot/M_\odot) \approx 4.0 \), with a FWHM of ∼ 0.9 dex. These are significantly smaller masses (and a smaller width) than expected for globular cluster progenitors.

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1 However, note that based on the published CLFs and the dis-
dependence on the metallicity and mass of the host galaxy, and on the position within the galaxy (e.g., Harris 1996; Gnedin 1997; Kavelaars & Hanes 1997; Baumgardt 1998; Whitmore et al. 2002; Dirsch, Schuberth & Richtler 2005).

This type of observational evidence has led to the popular, but thus far mostly speculative theoretical prediction that not only a power-law, but any initial CLF (CMF) will be rapidly transformed into a Gaussian (or log-normal) distribution because of (i) stellar evolutionary fading of the lowest-luminosity (and therefore lowest-mass) objects to below the detection limit; and (ii) disruption of the low-mass clusters due both to interactions with the gravitational field of the host galaxy, and to internal two-body relaxation effects leading to enhanced cluster evaporation (e.g., Elmegreen & Efremov 1997; Gnedin & Ostriker 1997; Ostriker & Gnedin 1997; Fall & Zhang 2001).

The shape of the CLF (CMF) of YSC systems has recently attracted renewed theoretical and observational attention. It has been pointed out that for YSCs exhibiting an age range, one must first correct their CLF to a common age before a realistic assessment of both their present-day and initial CLF (CMF) can be achieved (e.g., Meurer & CMF for YSC systems are intrinsic to the cluster population or artefacts caused by the presence of an age spread in the cluster population – which might mask a differently shaped underlying distribution – is therefore a matter of ongoing debate (see, e.g., Fritze-v. Alvensleben 1998, 1999; Carlson et al. 1998; Whitmore et al. 1999; Zhang & Fall 1999; Vesperini 2000, 2001).

The models built on either of these two assumptions for the initial mass distributions, i.e., power law or log-normal, give rise to temporal dependences of the CLF and CMF that are already well established by the time a cluster population reaches the age of \( \lesssim 1 \) Gyr (see, e.g., Vesperini 1998, 2000, 2001; Fall & Zhang 2001), i.e., the age of the M82 B cluster population. The M82 B cluster population represents an ideal sample to test these evolutionary scenarios for, since it is a roughly coeval intermediate-age population in a spatially confined region, where the characteristic cluster disruption time-scale is among the shortest known in any galactic disc region (e.g., de Grijs et al. 2003a, but see Section 4).

In this paper (Section 3) we will compare the observationally determined parameters for the M82 CLF and CMF (introduced and discussed in Section 2) to the model predictions based on both the log-normal (Vesperini 1998, 2000, 2001) and the initial power-law distributions (e.g., Fall & Zhang 2001). We will then (Section 4) discuss the best constraints we can set on the disruption time-scale for M82, assuming both an initial log-normal distribution and an initial power law (following de Grijs et al. 2003a). This will then be used (Section 5) to arrive at our best estimate for the shape of the initial CMF in M82 B. Finally, we summarise our results and conclusions in Section 6.

2 THE M82 B CLUSTER MASS FUNCTION

We detected some 110 young and intermediate-age star clusters in the post-starburst region “B” near the centre of the nearby, prototype starburst galaxy M82 (de Grijs et al. 2001). Their age distribution showed a clear peak around the time of the onset of the gravitational interaction with M82’s large neighbour spiral, M81.

Our recent re-analyses of these data using an improved approach (de Grijs et al. 2003a,b, Parmentier, de Grijs & Gilmore 2003) confirmed that the M82 B cluster system is characterized by a significant, well-defined peak of cluster formation, roughly defined within the age limits of \( 8.7 \lesssim \log(\text{Age/yr}) \lesssim 9.2 \). Since this peak may have been broadened by uncertainties in the age determinations (see de Grijs et al. 2003a), this age range should be considered an upper limit to the duration of enhanced cluster formation in M82 B. This implies that the clusters contained in this peak likely represent a roughly coeval population. For such a coeval population, the observational selection effects are very well understood (de Grijs et al. 2003a,b), while the dynamical cluster disruption effects are very similar for this entire population.

2.1 Robust detection of a log-normal CMF at intermediate age

We restricted our analysis to the CLF, and its associated CMF, of the clusters formed in the peak of cluster formation to avoid unnecessary and ill-understood complications. We corrected our “peak cluster sample” to a common age of 1 Gyr (i.e., coinciding with the peak of cluster formation), using the Starburst99 SSP models (Leitherer et al. 1998; Whitmore et al. 2002; Dirsch, Schuberth & Richtler 2005), although the effects of this correction are small because of the relatively narrow age range. The resulting CLF at a common age of 1 Gyr, and the corresponding CMF, are shown in Fig. 1, where we distinguish between clusters with well-determined ages [i.e., \( \Delta \log(\text{Age/yr}) \lesssim 1.0 \); shaded histograms] and the full cluster sample (open histograms) covering the age range of the burst.

Within the – mostly Poissonian – uncertainties, both the age-normalised CLF and the CMF can be adequately described by a log-normal (or Gaussian) distribution. The CLF in Fig. 1a is characterised by a peak luminosity of \( M_V^p = -7.3 \pm 0.1 \) mag, and a Gaussian FWHM of \( \sim 3.1 \)
mag. The CMF exhibits a peak at $\log(M_d/M_\odot) = 5.1 \pm 0.1$ and a Gaussian FWHM of $\sim 1.2$ dex ($\sigma_{\text{Gauss}} \approx 0.5$ dex).

The fact that we considered an approximately coeval subset of the M82 B cluster population, combined with our use of the 100 per cent completeness limit as our base line ensures the robustness of the CMF peak detection. The original sample selection was essentially based on a cross correlation of the source detections in the $V$ (F555W) and $I$ (F814) Hubble Space Telescope filters, visually complemented by extended objects that were missed by the automated source detection. None of the latter objects, however, were brighter than the 100 per cent completeness limit of the data in M82 B. While in de Grijs et al. (2001) we quoted the completeness limits for point sources, we found that the equivalent limits for “realistic” cluster sizes of $R_{\text{eff}} = 5$ pc vary by $\leq 0.5$ mag. This is sufficiently small so as to not affect our results on the turn-over (considering that the vast majority of clusters are only slightly more extended than point sources – see fig. 10 in de Grijs et al. 2001), which occurs some 2 mag brighter than the 100 per cent completeness limit.

One have to be aware that variable extinction across the field of view (as present in M82 B; de Grijs et al. 2001, 2003a; Parmentier et al. 2003) could in principle cause an artificial turn-over even if the intrinsic luminosity distribution were a power law. However, we note that most clusters are affected by $A_V \ll 1$ mag, with only a very small fraction having $A_V > 1$ mag. Nevertheless, in order to account for the variable extinction and other potential selection effects, we did not use the 50 per cent completeness limit to base our conclusions on regarding the turn-over (as is customarily done), but the full, 100 per cent limit. The difference between these 2 limits is $\sim 1$ mag (see fig. 7a in de Grijs et al. 2001), while the turn-over was found another $\sim 2$ mag brighter than this limit. Unless the extinction for most clusters is well above $A_V = 1$ mag, (which is not supported by our analysis), this essentially rules out extinction effects as cause for an artificial turn-over.

On a related note, since all of the clusters considered for the turn-over analysis have approximately the same age, it follows from stellar population synthesis that they are also characterised by similar colours, so that any extinction will have a blanket effect on all clusters; variable extinction will dim different clusters differently, but will not in any way be colour related for this particular coeval sample.

Finally, the most important assumption we made to validate the turn-over as based on a statistically complete sample is that the star clusters we detected, i.e., the ones relatively close to the surface area of M82 B, are fully representative of the M82 B population as a whole. We believe this to be justified, for the following reason. The population of M82 B clusters peaks at an age of $\sim 1$ Gyr. Over such a period of time since their formation, differential rotation of the region in which they were found, between about 0.5 and 1 kpc from the galaxy’s centre, would have been expected to have smeared out the clusters’ locations, yet this has not happened. This is most likely owing to the fact that M82 B is spatially coincident with the end of the M82 bar (see de Grijs 2001 for a discussion). M82 B has therefore retained its intrinsic properties over at least the last Gyr – this applies to both the surface and the interior of the region. As such, we believe that the clusters we discuss here are representative of the area as a whole.

### 2.2 Luminosity to mass conversion: choice of IMF

Our M82 B cluster mass estimates are based on a Salpeter-like stellar IMF (with masses $m_\star \geq 0.1 M_\odot$). However, we realise that recent determinations of the stellar IMF deviate significantly from that representation at low masses. The low-mass stellar IMF is significantly flatter than the Salpeter slope. The implication of this is, therefore, that we have overestimated the individual cluster masses. If we use a more modern IMF, such as that of Kroupa, Tout & Gilmore (1993), we have likely overestimated our individual cluster masses by a factor of 1.7 to 3.5 for an IMF containing stellar masses in the range $0.1 < m_\star/M_\odot < 100$ (de Grijs et al. 2003a). The exact factor depends on which slope we adopt for the lowest stellar mass range, $0.08 < m_\star/M_\odot < 0.5$. This corresponds to a correction of $-0.23$ to $-0.54$ in the peak of the CMF, so that a more realistic estimate for the peak of the M82 B CMF would be $\langle \log(M_d/M_\odot) \rangle = 4.7 \pm 0.2$. The width of the corrected CMF remains the same, since every individual cluster mass is simply corrected for by the same additive amount in logarithmic mass space.

### 3 CONSTRAINTING THE EVOLUTIONARY SCENARIOS

In de Grijs et al. (2003a,b) we also found that the characteristic disruption time-scale for the clusters in M82 B, $t_{\text{dis}} \sim 3 \times 10^6$ yr for $10^4 M_\odot$ clusters, is considerably shorter than that in the solar neighbourhood (i.e., $t_{\text{dis}} \sim 1.6 \times 10^9$ yr; Lamers et al. 2005b).2

In the following subsections, we will discuss the implications of the observed CLF and CMF shapes (i.e., the peaks and widths of the distributions) at the associated intermediate age in the evolutionary framework of both the initial power-law and the initial log-normal mass distributions.

### 3.1 Predictions for a power-law initial cluster mass distribution

The most popular star cluster evolution models assume that the initial distribution of cluster masses is well-represented by a power law, which then rapidly transforms into a log-normal distribution due to dynamical evolution effects (e.g., Harris & Pudritz 1994; Okazaki & Tosa 1995; McLaughlin & Pudritz 1996; Elmegreen & Efremov 1997; Gnedin & Ostrikov 1997; Murali & Weinberg 1997; Vesperini 1997, 1998; Baumgardt 1998; Fall & Zhang 2001, and references therein; Parmentier & Gilmore 2005; see also Elmegreen 2002). We note that while there is general consensus that an initial power-law distribution is rapidly transformed into a log-normal CMF, the detailed predictions of these models differ significantly from each other.

Whitmore et al. (2002) calculated the expected evolution of the $\sim 1.5$ Gyr-old log-normal-like CLF in NGC 3610, and showed that an initial Schechter-type CMF (based on initial conditions and subsequent evolution of the CMF

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2 Note that this short disruption time-scale is based on the assumption of an initial power-law CLF (CMF). We will return to this issue in Section 4.
given by Fall & Zhang (2001)], in combination with evolu-
tionary fading of the stellar population, lead to the peak
luminosity and width of the cluster luminosity function to
remain virtually unchanged for a Hubble time. Model calcu-
lations based on a power-law or Schechter-type initial cluster
mass distribution (e.g., Fall & Zhang 2001) suggest that, in
a Milky Way-type gravitational potential with a strongly
radially dependent radial anisotropy of the cluster veloc-
ity distribution, the turn-over of the cluster mass distri-
bution will move towards higher masses by approximately
\[ \Delta \log (M_{\odot}/M_{\odot}) \approx +0.9 \]
by the time the cluster population reaches an age of 12 Gyr, i.e., similar to the median age of
the Galactic GC system. This implies that the star cluster
system in M82 B, where the characteristic disruption time-
scaling is significantly shorter than in the Galactic halo, will be
dominated by higher masses than the Galactic GC system
when it reaches a similar age, and most of the present-day
clusters will be depleted.

Furthermore, Vesperini (2001) calculated the evolution
of fiducial star cluster systems with physically realistic pa-
rameters spanning the entire observational parameter space,
using \( N \)-body models, and concluded that it is not straight-
forward, indeed very difficult, to produce (nearly) universal
CLFs and CMFs in very different types of galaxies if starting
from initial power-law distributions.

A first-order comparison between the observed CMF in
M82 B (see Fig. 1b) and the predictions of the Fall & Zhang
(2001) models also attests to these problems: while we ob-
serve a peak in the M82 B CMF at \( \log (M_{\odot}/M_{\odot}) = 5.1 \pm 0.1 \)
and a Gaussian width consistent with the universal CMFs of
old GC systems, the Fall & Zhang (2001) models at an age
of 1.5 Gyr predict, for either a power-law, a truncated power
law (see also Parmentier & Gilmore 2005), or a Schechter-
type initial CMF, a peak at \( \log (M_{\odot}/M_{\odot}) \approx 4.5 \) and a sig-
nificantly broader mass distribution than observed for the
Milky Way GC system (their Fig. 3). Because of the sys-
tematic uncertainties inherent (i) to the different methods
of mass determination, (ii) to the sample selection\(^3\), (iii) to
the photometric uncertainties for our M82 B cluster sample,
and (iv) to the differences in the radial extent sampled [Fall
& Zhang (2001) sample a large radial extent, at large galac-
tocentric distances, where the effects of dynamical friction
are significantly smaller than at the relatively small radii of
our M82 B clusters], these differences between the M82 B
CMF and the model-predicted CMF of Fall & Zhang (2001)
at a similar age may not be significant. We will investigate
the effects of different characteristic disruption time-scales
on the resulting CMF in Section 5.

3.2 A log-normal initial mass distribution?

Vesperini’s (1998, 2000, 2001) suggested that the temporal evolu-
tion of a log-normal initial CMF describes the currently
observed old GC luminosity and mass functions very well.
Recently, Parmentier & Gilmore (2005) showed that in or-
der to obtain the radial mass and number distributions of
the Milky Way’s Old Halo GCs, the GC system must have
been depleted in low-mass objects \( ab \ initio \). They argue that
the current CMF of Milky Way Old Halo GCs is most easily
obtained from an initial log-normal CMF, although a trun-
cated power-law CMF (truncated at \( M_{\odot} \sim 10^3 M_{\odot} \)) cannot
be ruled out.

The rationale for adopting a log-normal initial CMF was
provided by the shape of the CMFs in the outer regions of
massive elliptical galaxies, where the initial conditions are
likely retained because of the low efficiency of cluster dis-
ruption processes expected at large galactocentric distances
(Vesperini 2000; see also McLaughlin, Harris & Hanes 1994;
Gnedin 1997).

Vesperini’s (1998, 2000) \( N \)-body models follow the evolu-
tion of GC systems for a Hubble time in time-independent
gravitational potentials of Milky Way-type and “elliptical”
host galaxies modeled as isothermal spheres with constant
round, circular velocity. His models include the full treatment
of stellar evolution (and hence mass loss from individual stars,
which contributes to up to \( \sim 18 \) per cent of the initial total
cluster mass after 15 Gyr), two-body relaxation, interactions
with the underlying, galactic tidal field, and dynamical fric-
tion. The main results from these model runs, and of Ves-
perini’s (2000) comparison with a large sample of elliptical
galaxies, are that for a large number of host galaxy para-
eters, the mean mass and dispersion do not differ significantly
from their initial values, although the fraction of surviving
clusters, and therefore the cluster disruption efficiency, does
in fact vary significantly (see also Vesperini 1998).

3.3 Relevance to the M82 B cluster system

We will now consider the observational parameters of the
M82 B cluster system in the context of these evolutionary
scenarios. We first need to establish the relevance of these
models for the interpretation of the M82 B cluster system,
however.

First, clusters on elliptical orbits are expected to dis-
rupt more quickly than those on circular orbits with the
same apogalactic distance (Baumgardt 1998; Baumgardt &
Makino 2003, Wilkinson et al. 2003). However, Vesperini’s
(1998, 2000) assumption that all clusters are orbiting the
galactic centre on circular orbits does not introduce severe
complications. M82 B is located between \( \sim 500 \) pc and 1
kpc from its galactic centre, where the rotation curve of the
\( \text{Hz} \) gas has reached a constant velocity of \( \sim 140 \) km s\(^{-1}\)
(Wills et al. 2000). Although at an age of \( \sim 1 \) Gyr the cluster
system is \( \sim 25 – 50 \) rotation periods old, the region is
still spatially closely confined. Thus, any deviation from cir-
cular velocities – and therefore any time dependence of the
gravitational potential of the host galaxy – will have been
experienced in a self-similar fashion by the cluster system
as a whole, and will not have propagated differentially into
the system.

Secondly, M82 is clearly not elliptical (nor a large spi-
ral), but an irregular galaxy. However, the main effect of
constraining the shape of the host galaxy to resemble an
isothermal “elliptical” is that the cluster system is evolving
in a smooth gravitational potential. Despite their appear-
ance, the conditions governing the M82 B cluster system
(i.e., gravitational pull, cluster velocity distribution) are re-

\(^3\) We have shown (de Grijs et al. 2003a,b) that by selecting a
magnitude-limited cluster sample, our cluster sample is almost
100 per cent complete (see Fig. 7 in de Grijs et al. 2001), so that
our results are very robust against statistical uncertainties.
3.4 Constraints and implications from the M82 clusters

Having established that Vesperini’s (1998, 2000) models that start from a log-normal CMF are indeed relevant in the context of the M82 B intermediate-age cluster system, we will now discuss the implications of the observational CLF and CMF parameters for this scenario.

After an initial rapid decrease in the mean cluster mass — caused by mass loss due to normal stellar evolution in the first ∼ 1 Gyr (Vesperini 2000; Baumgardt & Makino 2003) — the mean cluster mass is expected to remain constant to within ∼ 0.025 dex in \( \log (M_{cl}/M_\odot) \), for an underlying galaxy mass on the order of the mass of M82 (inside the radius of M82 B). This implies that the peak in the CMF (Fig. 1b) will likely remain constant for a Hubble time, within the observational uncertainties [see Vesperini’s (2000) Fig. 11; see also Vesperini’s (1998) discussion on the equilibrium CMF], irrespective of the cluster disruption time-scale in this galaxy. The short disruption time-scale in M82 B, if correct (see Section 4), will simply deplete the star cluster system at an accelerated rate compared to galaxies with longer characteristic cluster disruption time-scales.

One of the main pieces of observational evidence in support of a scenario in which the initial CMF in M82 B may have been log-normal is therefore the fact that the turnover in the M82 B CMF is observed for an intermediate-age cluster system as young as ∼ 1 Gyr, with characteristic parameters (both the mean mass and the dispersion in mass) very similar, if not identical, to those of M81 and M82 and of selected regions in M33 and M51. They compared their time-scales with those derived from a number of \( N \)-body simulations in the Milky Way, M31, M87 and old elliptical galaxies (e.g., Harris 2001). This would be very difficult to achieve if the initial CMF had been closely approximated by a power-law (see Vesperini 1998, 2001). In the latter case, the mean mass will increase significantly by the time the M82 B cluster system reaches an age similar to the Galactic GCs, while the dispersion in mass decreases, so that one must conclude that the M82 B CLF and CMF may not evolve into universal distributions.

In addition, Vesperini (1998) showed that any reasonable log-normal initial CMF will evolve towards the shape and parameters of the equilibrium CMF, i.e., \( \log (M_{cl}/M_\odot) \) ≃ 5.02 (including the effects of disc shocking) and \( \sigma \approx 0.67 \). The speed at which this will occur depends on the initial deviation of the system from the equilibrium CMF. Therefore, the fact that for M82 B we observe \( \log (M_{cl}/M_\odot) = 5.1 \pm 0.1 \) and \( \sigma \approx 0.5 \), at an age of ∼ 1 Gyr, implies that the M82 B initial CMF must have had a mean mass very close to that of the equilibrium CMF [see Vesperini’s (1998) Fig. 12].

Finally, Vesperini’s (2000) Fig. 13 allows us to take the opposite approach: if we are currently probing the final CMF, then the initial CMF must have been characterized by a mean mass that was only slightly larger than the present mean mass, and in fact still within the observational uncertainties. This is a robust result, and holds for gravitational potentials associated with host galaxies spanning the entire observational range of masses and effective radii.

4 A REVISED DISRUPTION TIME-SCALE FOR M82 B?

In de Grijs et al. (2003a), we used the distributions of the M82 B cluster masses and ages to derive a cluster disruption time-scale for this region of \( t_{\text{dis}} = 30 \times (M_{cl}/10^4 M_\odot)^{0.62} \) Myr, using the method developed by Boutloukos & Lamers (2003). Lamers et al. (2005a) used a similar approach to derive the equivalent cluster disruption time-scales of the solar neighbourhood, the Small Magellanic Cloud, and of selected regions in M33 and M51. They compared their time-scales with those derived from a number of \( N \)-body simulations in the parameter space defined by the ambient density and the disruption time-scale. They found that

4 We note that under the assumption of a log-normal initial CMF, the NGC 1316 initial CMF must have been characterized by a very low mean mass if it were to evolve to its current mean mass of \( \log (M_{cl}/M_\odot) \) = 4.0 at an age of ∼ 3 Gyr, and it is unlikely that this system will attain a Milky Way-type mean GC mass over a Hubble time. In addition, none of the Vesperini models allow for mean masses as low as those implied by the Goudfrooij et al. (2004) results for NGC 1316.
\[ t_{\text{dis}} = C_{\text{env}} \left( \frac{M_{\text{cl}}}{10^4 M_{\odot}} \right)^{0.62} \left( \frac{\rho_{\text{amb}}}{M_{\odot} \text{pc}^{-3}} \right)^{-0.5}, \] 

where \( \rho_{\text{amb}} \) is the ambient density of the environment in which the clusters move, and \( C_{\text{env}} \approx 300 \) to 800 Myr. This predicted relation agrees with the empirically derived cluster disruption time-scales in the SMC, M33, and the solar neighbourhood, but not for M51 which has a significantly shorter disruption time-scale.

We derived a rough estimate for the ambient density of M82 B in de Grijs et al. (2003a), \( \langle \rho \rangle \sim 2.5 M_{\odot} \text{pc}^{-3} \), or \( \log(\rho)(M_{\odot} \text{pc}^{-3}) \sim 0.4 \), although with large uncertainties (see Section 3.3). If we nevertheless add these values for M82 B to Fig. 4 in Lamers et al. (2005a), we see immediately that our new data point for M82 B also lies well below the disruption lines predicted by the two independently developed N-body simulations by Baumgardt & Makino (2003) on the one hand, and Portegies Zwart and colleagues on the other (see Lamers et al. 2005b). This large discrepancy, of a factor of \( \sim 16-17 \) in disruption time between the Baumgardt & Makino (2003) prediction and our result from de Grijs et al. (2003a), prompted us to reconsider the assumptions on which we had based our estimate. It is unlikely that we have underestimated the already significant ambient density in M82 B by several orders of magnitude. In fact, we believe this high ambient density estimate to be an upper limit, as we will discuss below. Is it therefore possible that we may have underestimated the disruption time-scale in M82 B?

Although we quote an uncertainty of about a factor of 2 in the characteristic disruption time-scale, Fig. 7 of de Grijs et al. (2003a) implies that our estimate of \( t_{\text{dis}} \) is a firm lower limit, and seems to rule out a much shorter characteristic disruption time-scale.

However, our density estimate is a back-of-the-envelope guess with uncertainties of about an order of magnitude. In fact, we used a V-band mass-to-light (M/L) ratio of about 0.5–1 to obtain this density estimate, but in de Grijs et al. (2001) we provided evidence that the disk of M82 B shows active star formation until about 20–30 Myr ago. At an age of 25 Myr, the V-band M/L ratio \( \sim 0.1 \), i.e., a factor of 5–10 lower than what we used for our density estimate. This reassessment, combined with the realisation that M82’s velocity curve (Wills et al. 2000) at the radius of region B indicates a \( \sim 3 \) times smaller ambient density, \( \rho_{\text{amb}} \), confirms our suspicion that the value used for \( \rho_{\text{amb}} \) is an upper limit. Moreover, if we employ the 5–10 times lower V-band M/L ratio instead, the M82B data point shifts to a location very close to that of M51 in Fig. 4 of Lamers et al. (2005a).

We note that the most crucial assumption underpinning our disruption time-scale estimate is that of the initial cluster mass distribution. For both the M82 B time-scale, and in Lamers et al. (2005a), we used an initial power-law CMF. This is a good assumption for young cluster systems (de Grijs et al. 2003c). In de Grijs et al. (2003a) we showed that in order to produce a log-normal present-day CMF in M82 B as observed from an initial power-law distribution, an extremely short disruption time-scale is required. However, we noted in Section 3.4 that the observed CMF in M82 B resembles Vesperini’s (1998) (quasi-)equilibrium CMF relatively closely. Let us therefore consider the implications of this close coincidence in shape, combined with the mass dependence of the disruption time-scale, for the time-scale on which a typical \( \sim 10^4 M_{\odot} \) cluster is expected to disrupt.

Our 100 per cent completeness limit, shown in Fig. 1 as the vertical dashed lines, occurs at a cluster mass of \( \log(M_{\text{cl}}/M_{\odot}) \geq 4.4 \) (Fig. 1b). The implication of our assumption of “instantaneous disruption” is that \( t_{\text{dis}} \lesssim 10^9 \) yr, i.e., less than the present age of the clusters formed simultaneously in the burst of cluster formation. Therefore, we conclude that if the initial CMF in M82 B were log-normal, we cannot constrain the characteristic disruption time-scale to better than \( t_{\text{dis}} \lesssim 10^9 \) yr.

5 DISCUSSION

We randomly distributed 120,000 clusters, following two distinct mass distributions: a power-law mass spectrum \( dN \propto M_{\odot}^2 dM_{\odot} \) and a log-normal mass function \( dN/d\log M_{\odot} \). Lamers et al. (2005b) have shown that the decreasing mass of a cluster can be described to a very high accuracy as

\[ \frac{M_{\text{cl}}(t)}{M_i} = \left\{ \frac{\mu_{\text{ev}}(t)}{\gamma t_{\text{dis}}} \right\}^{1/\gamma}, \]

where \( M_{\text{cl}}(t)/M_i \) is the mass of a cluster with initial mass \( M_i \) that is still bound at an age \( t \). In this equation, \( \mu_{\text{ev}}(t) \) is the fractional mass decrease of the cluster because of stellar evolution only. The temporal evolution of \( \mu_{\text{ev}}(t) \) is given by Eqs (2) and (3) of Lamers et al. (2005b), which match the predictions of the GALEV SSP models very accurately. We adopt \( \gamma = 0.62 \) (Boutleukos & Lamers 2003; Baumgardt & Makino 2003; Lamers et al. 2005b). The cluster disruption time-scale \( t_{\text{dis}} \) depends on the initial mass \( M_i \) of the cluster and on the ambient density \( \rho_{\text{amb}} \) as given by Eq. (1). We will consider the disruption time-scale derived by Baumgardt & Makino (2003; their Eq. 10) based on a large set of N-body simulations, taking into account the combined effects of stellar evolution, two-body relaxation and the external tidal field. In addition, we also investigate the disruption time-scale obtained by de Grijs et al. (2003a), which is \( \sim \) at the average ambient density of M82 B, \( \rho_{\text{amb}} = 2.5 M_{\odot} \text{pc}^{-3} \) (see Section 4) \( \sim 16 \times \) shorter than the N-body simulation estimate. In order to take into account dynamical friction, clusters with orbital decay time-scales (e.g., Binney & Tremaine 1994) shorter than a given time \( t \) are removed from the cluster system at that time. Owing to the intermediate age of the M82 B cluster system, the impact of dynamical friction proves negligible, however. Finally, we normalised the mass distributions evolved to an age of 1 Gyr to the observed number of clusters, i.e., the subsample of the 42 clusters with the most accurately determined ages (see Fig. 1).

To assess the robustness of the evolved CMFs with respect to the age and spatial distributions of the clusters, we considered the following cases. First (cases 1,3 in Figs. 2 and 3), all clusters were assumed to be 1 Gyr old and located at the same galactocentric distance of \( D = 0.7 \) kpc. Consequently, they are all characterized by the same ambient density \( \rho_{\text{amb}} \approx 2.5 M_{\odot} \text{pc}^{-3} \), and thus by the same disruption time-scale. Secondly (case 2 in Figs. 2 and 3), we considered the case of a cluster system characterized by uniform distributions in age and galactocentric distance. Following our definition of the burst of cluster formation (see Fig. 1), the lower and upper limits of the age distribution are \( \log(t/\text{yr}) = 8.7 \) and 9.2, respectively. As for
the spatial distribution, clusters were assumed to be distributed uniformly in galactocentric distance across the region \((0.4 \leq (D/{\text{kpc}}) \leq 1.0)\), the radial extent of M82 B. In this case, the cluster system probes a range of ambient densities and, therefore, of characteristic disruption time-scales. We assume that the radial profile of the ambient density is that of a singular isothermal sphere, \(\rho_{\text{amb}} \propto D^{-2}\), and that \(\rho_{\text{amb}}(D = 0.7 \text{kpc}) = 2.5 \, \text{M}_\odot \, \text{pc}^{-3}\).

The initial power-law CMF is characterised by a slope of \(-2\) (see de Grijs et al. 2003c for a review). Fig. 2 shows the corresponding evolved mass distributions, using both the disruption time-scale determined by de Grijs et al. (2003a; case [3]), and the \(16 \times\) longer time-scale suggested by Baumgardt & Makino’s (2003) \(N\)-body simulations (case [1]). We also show the small differences between a coeval (exactly) 1 Gyr-old cluster population, located at a galactocentric distance of \((0.7 \leq \text{age/yr} \leq 9.2)\) and are distributed uniformly across the region \((0.4 \leq (D/{\text{kpc}}) \leq 1.0)\). This uniform distribution in galactocentric distance corresponds to a number density profile scaling as \(D^{-2}\). We checked that the differences caused by assuming radial density profiles following a fairly arbitrary (and shallow) profile \(\rho \propto D^{-0.5}\), as well as a much steeper number density distribution such as that of GCs in the Galactic halo, \(\rho \propto D^{-3.5}\) (e.g., Zinn, 1985), result in identical evolved mass distributions, within the uncertainties. The assumed spatial distribution of the clusters affects our results negligibly, which is a natural consequence of the small radial extent of M82 B. In view of the region’s disturbed appearance and unique star (cluster) formation history, neither a uniform nor a strongly radially dependent initial density distribution can be ruled out a priori.

As expected, if we employ \(t_{\text{dis}} = 30\) Myr (case [3]), the resulting mass distribution is log-normal, and matches the observed mass distribution (Fig. 2) very closely. This is not surprising, since the determination of this short disruption time-scale was based on the assumption of an initial power-law CMF with a slope of \(-2\). [This shows that the assumption of instantaneous disruption, adopted in de Grijs et al. (2003a,b) hardly affects the determination of the disruption time-scales.]

If, instead, we use an initial power-law CMF as before, but now assume that the longer disruption time-scale predicted by Baumgardt & Makino’s (2003) \(N\)-body simulations is correct (cases [1,2]), the evolved cluster mass distribution shows a (broader) peak, shifted to lower masses by more than one order of magnitude. Moreover, we argued in the previous section that our estimate of the ambient density is likely to have been overestimated by at least a factor of 3. Since, in an undisturbed tidal field of a galaxy with a logarithmic potential, the disruption time-scale depends on the ambient density as \(t_{\text{dis}} \propto \rho_{\text{amb}}^{-0.5}\), we have also evolved a power-law with a \(1.7 \times\) larger disruption time-scale (case [4] in Fig. 2); this factor of 1.7 allows for the uncertainty in \(\rho_{\text{amb}}\) between 0.8 and 2.5 \(\text{M}_\odot \, \text{pc}^{-3}\). As expected, this longer, probably more realistic disruption time-scale gives rise to a turnover located at a cluster mass smaller than that derived in cases [1] and [2], thus strengthening the discrepancy between the evolved model and observed CMFs. Therefore, if we assume that Baumgardt & Makino’s (2003) \(N\)-body simulations predict approximately the appropriate cluster disruption time-scale for M82 B, Fig. 2 shows that the observed cluster mass distribution cannot be retrieved from an initial power-law CMF.

We will now approach this issue starting from an initial log-normal CMF. We have assumed that the initial log-normal CMF matches that of the almost universal mass distribution of old GC systems in the local Universe (and thus that of the theoretical (quasi-)equilibrium CMF of Vesperini 1998). If the Baumgardt & Makino (2003) results apply (i.e., \(t_{\text{dis}}^\text{a} \sim 0.5 - 0.8\) Gyr at an ambient density typical of M82 B (i.e., \(\rho_{\text{amb}} \approx 0.8 - 2.5 \, \text{M}_\odot \, \text{pc}^{-3}\)), most of the clusters in the...
log-normal initial CMF of Fig. 3 will not yet have been significantly affected by disruption. Thus, when we evolve this initial CMF to an age of 1 Gyr, the CMF approximately retains its initial shape, as shown in Fig. 3. This result holds irrespective of the underlying cluster age and distance distributions and irrespective of the average ambient density assumed (i.e., the evolved CMFs derived in cases [1,2,4] are identical well within the observational uncertainties). The main difference between the initial and evolved CMFs is therefore caused by the effects of stellar evolution: the shift of the peak of the distribution by ∆ log(M/⊙) ∼ −0.15 is the result of up to 25 per cent of stellar evolutionary mass loss. With the short disruption time-scale of de Grijs et al. (2003a), the final distribution is somewhat more depleted in high-mass clusters (case [3]) in Fig. 3. We also show the evolved 1 Gyr-old CMF assuming a slightly longer disruption time-scale t_{dis} ≈ 50 Myr (case [3]). At an ambient density of 2.5 M_⊙ pc^{-3}, this is 10× shorter than that derived from Baumgardt & Makino’s (2003) N-body simulations. The predicted CMF still matches the observed distribution satisfactorily. Therefore, we note that when starting from an initial log-normal CMF, the evolved mass distributions match the observed distribution in M82 B (Fig. 1b) fairly closely, and that this result holds for a wide range of disruption time-scales.

To assess the robustness of the results presented in Figs. 2 and 3, we have also evolved the log-normal and power-law initial CMFs using Eq. (12) of Baumgardt & Makino (2003). A detailed comparison shows that the results derived based on Eq. (2) above appear robust: the shape of the Gaussian CMF is unaffected by the 1 Gyr-long evolution in either case, and the turnover of the evolved power-law CMF is discrepant with the observed peak by more than one order of magnitude.

5.1 Unphysically high initial densities?

We note, however, that Baumgardt & Makino’s (2003) N-body simulations were performed assuming a smooth underlying tidal field; they do not include the effects of external perturbations such as those caused by encounters with giant molecular clouds. As a result, their cluster disruption time-scale is therefore an upper limit. In view of the uncertainties inherent to the precise disruption time-scale governing M82 B we cannot use this analysis by itself to distinguish conclusively between the log-normal vs. power-law initial CMF. The key question is then whether the combination of (i) an initial power-law CMF, (ii) the present number (and mass) of 1 Gyr-old clusters, and (iii) the very short disruption time-scale of ∼ 30 Myr for a 10^4 M_⊙ cluster can be accommodated in a physically realistic scenario.

Starting from a power-law initial CMF with masses between 10^3 and 3 × 10^6 M_⊙, the ratio of the final (i.e., at an age of 1 Gyr) to initial number of clusters is F_N ≈ 5 × 10^{-4} if t_{dis} ≈ 30 Myr. In this case, the 1 Gyr-old clusters considered here are the survivors of an initial population of ≈ 8 × 10^4 clusters. However, this is a lower limit since these 42 clusters constitute a subsample of the M82 B cluster population, i.e., those located at the “surface” of the region and for which reliable age estimates could be obtained. For an initial cluster mass range with a lower limit of 10^4 M_⊙, the initial number of clusters is significantly lower, i.e., some 8,000, but still very large for the spatially confined M82 B region. The ratio F_M of the final to the initial mass in clusters is ≲ 1 per cent. The present mass of the observed cluster system is at least ∼ 10^7 M_⊙ (and likely much more considering that we have only sampled the outer surface of the region). This implies, therefore, that the initial mass in (bound, long-lived) clusters alone must have been on the order of 10^9 M_⊙, confined to a three-dimensional volume of ∼ 5 × 10^3 pc^{-3} (de Grijs et al. 2003a,b). The initial mean density in bound clusters alone must therefore have been ≥ 20 M_⊙ pc^{-3}, if the initial CMF were a power-law distribution. This is at least an order of magnitude higher than the current total stellar density in M82 B, as well as in the actively cluster-forming centre of M51 (Lamers et al. 2005a). Since the mass in clusters generally only comprises a few per cent of the total mass in disc galaxies, up to about 30 per cent in dense starburst regions like M82 B, it follows that the initial total stellar density required may be as high as ∼ 60 M_⊙ pc^{-3}. Such densities are physically unrealistic in disc regions of “normal” galaxies, even in dense starburst regions. We note in passing that these calculations refer to the (initially) bound clusters only; if unbound clusters were included, the expected initial mean density would be even higher.

Therefore, we conclude that our observations of the present M82 B CMF are inconsistent with a scenario in which the initial cluster population evolved from an initial power-law mass distribution. Note that this applies both to the very short disruption time-scale of ∼ 30 Myr, as well as to the longer time-scale based on the Baumgardt & Makino (2003) results, for which we concluded above that the resulting present-day CMF would peak at much lower masses than observed.

For a log-normal initial CMF combined with the Baumgardt & Makino (2003) disruption time-scale (t_{dis} ≈ 0.5–0.8 Gyr), most of the clusters survive the 1 Gyr-long evolution, i.e. F_N ≈ 0.9. The initial and final numbers of clusters are thus very similar. In order to explore whether the good match between the evolved Gaussian model CMF and the observed distribution actually depends on the small initial number of clusters implied by this survival rate (i.e., whether the mass distribution of the actual data points may be affected significantly by small-number statistics rather than physical effects), we have run simulations starting from 60 clusters (i.e., the approximate number of clusters expected to have been formed initially in this scenario), randomly drawn from the Gaussian initial CMF. The results are shown in Fig. 4 for case [4], where we assume the disruption time-scale predicted by N-body simulations (t_{dis} ≈ 0.8 Gyr). For various random seeds, the predicted cluster mass distributions match the observed CMF satisfactorily, showing that the effects owing to small-number statistics are minimal, and unimportant with respect to our overall conclusions.

It appears, therefore, that on the grounds of both our observational data and the theoretical arguments presented in the previous sections, the initial mass distribution of the

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5 If a cluster is in equilibrium with its environment, as we argued for M82 B in de Grijs et al. (2003a), one can estimate that ρ_{cl}/ρ_{amb} ≈ 3 for a standard Roche solution by assuming that the clusters are characterized by a King (1966) profile, and that its tidal radius equals the Jacobi radius of the host galaxy’s tidal field (see Binney & Tremaine 1994; Lamers et al. 2005a).
M82 B clusters surviving past the “infant mortality” epoch (i.e., the first few Myr in which unbound low-mass clusters are dispersed; e.g., Boily & Kroupa 2003; Vesperini & Zepf 2003; Whitmore 2004; Bastian et al. 2005; Mengel et al. 2005; see also Tremonti et al. 2001) must have been closely matched by a log-normal distribution.

In fact, the presence of a large excess (up to 70–90 per cent; Whitmore 2004; Mengel et al. 2005) of presumably unbound clusters at ages below ~10 Myr in the Antennae system (Whitmore 2004, his fig. 2; Mengel et al. 2005, their fig. 10) and M51 (Bastian et al. 2005, their fig. 10) could, in principle, provide further limits on the initial CMF of both the bound and unbound clusters. A seven to nine-fold increase of unbound clusters at very early times, as implied by these observational studies, although of low mass in general, would boost initial stellar density levels to truly unphysical numbers if the bound, longer-lived clusters were formed following a power-law mass-number scaling. For the initial log-normal CMF scenario, the resulting initial densities could be used to place limits on the total mass (and possibly the number, if the mass distribution were known) in unbound star clusters. However, at this point the observational data are statistically insufficiently robust in terms of excess cluster numbers (similar data are needed for larger numbers of cluster populations), while the masses of these young unbound cluster populations are as yet poorly determined, so that any (statistical) extrapolations to other galaxies are as yet unwarranted.

6 SUMMARY AND CONCLUSIONS

In this paper, we start from the robust detection of de Grijs et al. (2003a,b) of an approximately log-normal CMF for the 1 Gyr-old, intermediate-age star cluster system in M82 B, and explore whether we can constrain the shape of the initial distribution of cluster masses.

In particular, we investigate whether the most likely initial CMF was more similar to either a log-normal or a power-law distribution, by taking into account the dominant evolutionary processes (including stellar evolution, and internal and external gravitational effects) affecting the mass distributions of star cluster systems over time-scales of up to ~1 Gyr in the presence of a realistic underlying gravitational potential. The M82 B cluster population represents an ideal sample to test these evolutionary scenarios for, since it is a roughly coeval intermediate-age population in a spatially confined region. For such a coeval population, the observational selection effects are very well understood (de Grijs et al. 2003a,b), while the dynamical cluster disruption effects are very similar for this entire population.

After considering the gravitational effects and geometry of M82 itself, its starburst region B, and its position in the M81/M82/NGC 3077 group of interacting galaxies, we conclude that we can approximate the gravitational potential felt by M82 B in a time-independent fashion, dominated by the mass of M82 inside the radius of M82 B. In such a static gravitational potential, Vesperini (1998) shows conclusively that there exists a particular CMF of which the initial mean mass, width and radial dependence remain unaltered during the entire evolution over a Hubble time. In fact, the mean mass and width of any initial log-normal CMF tends to evolve towards the values for this equilibrium CMF.

Thus, the fact that for M82 B we observe (log(M/M⊙)) = 5.1 ± 0.1 and σ ≃ 0.5, at an age of ~1 Gyr, implies that the M82 B initial CMF must have had a mean mass very close to that of the equilibrium CMF. If the presently observed M82 B CMF is to remain unchanged for a Hubble time, so that we are currently probing the final CMF, then the initial CMF must have been characterized by a mean mass that was only slightly larger than the present mean mass. This is a robust result, and holds for gravitational potentials associated with host galaxies spanning the entire observational range of masses and effective radii.

From our detailed analysis of the expected evolution of CMFs starting from initial log-normal and initial power-law distributions, we conclude that our observations of the M82 B CMF are inconsistent with a scenario in which the 1 Gyr-old cluster population originated from an initial power-law mass distribution. This applies to a range of characteristic disruption time-scales, from tdis ~ 30 Myr to the ~16 – 30 × longer time-scale resulting from Baumgardt & Makino’s (2003) N-body simulations. Our conclusion is supported by arguments related to the initial density in M82 B, which would be unphysically high if the present cluster population were the remains of an initial power-law distribution (particularly in view of the effects of cluster “infant mortality”, which require large excesses of low-mass unbound clusters to be present at the earliest times).

De Grijs et al. (2003c) showed that the CMFs of YSCs in many different environments are well approximated by power laws with slopes α ≃ −2. However, except for the intermediate-age cluster systems in M82 B (de Grijs et al. 2003a,b) and NGC 1316 (Goudfrooij et al. 2004), the expected turn-over mass (based on comparisons with present-day GC systems and taking evolutionary fading into account) in most YSC systems observed to date occurs close to or below the observational detection limit, simply because of their greater distances and shallower observations. As such, the results presented here and those summarised in de Grijs et al. (2003c) are not necessarily at odds with each other, but merely hindered by observational selection effects.
ACKNOWLEDGMENTS

RdG acknowledges support from The British Council under the UK–Netherlands Partnership Programme in Science, and from the Nuffield Foundation through a New Lecturers in Science, Engineering and Technology Award, and hospitality at the Astronomical Institute of Utrecht University on several visits. GP acknowledges research support from a Marie Curie Intra-European Fellowship within the sixth European Community Framework Programme. We are grateful for research support and hospitality at the International Space Science Institute in Bern (Switzerland), as part of an International Team programme. This research has made use of NASA’s Astrophysics Data System Abstract Service.

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