

# The initial conditions of young globular clusters in the Large Magellanic Cloud

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## ABSTRACT

$N$ -body simulations are used to model the early evolution of globular clusters. These simulations include residual gas which was not turned into stars, which is expelled from the globular cluster by the actions of massive ( $> 8 M_{\odot}$ ) stars. The results of these simulations are compared with observations of eight LMC globular clusters less than 100 Myr old. These observations are used to constrain the initial conditions that may have produced these clusters. It is found that the observations can be accounted for in a model where the globular clusters form from proto-cluster clouds similar to Plummer models with length-scales in the range  $1 < R_s/\text{pc} < 3$  where the star formation efficiency varies between 25 and 60 per cent. Using these derived initial conditions the survivability of these clusters in both the Galaxy and the LMC is assessed. If the slope of the initial mass function is around  $\alpha = 2.35$  then two or three of these clusters may be able to survive for a Hubble time even in the Galactic halo. In this case these clusters may represent young versions of the Galactic globular cluster population which was severely depleted by the destruction of many of its original members. In the case where  $\alpha = 1.50$ , however, none of these clusters would be expected to survive for more than a few Gyr at most, even within the LMC.

**Key words:** globular clusters: general.

## 1 INTRODUCTION

In this paper the structure of young globular clusters in the Large Magellanic Cloud (LMC) is investigated with respect to theoretical models of globular cluster formation and evolution. Observations are compared with  $N$ -body simulations of globular clusters including stellar evolution and the expulsion of residual gas not consumed in star formation. This allows some limits to be placed on the initial conditions which gave rise to these globular clusters.

An important question in the theory of globular cluster formation and evolution is how similar are these young LMC objects to the precursors of the old globular clusters observed in the Galaxy? Will these young globular clusters also be able to survive for a Hubble time? This paper examines the structure of the young globular clusters found in the LMC and tries to determine their initial conditions and, from the present theoretical understanding of globular clusters, if they will survive for a significant length of time in either the LMC or the halo of the Galaxy.

Globular clusters are usually extremely chemically homogeneous, compact star clusters containing some  $10^4$  to  $10^6 M_{\odot}$  of stars formed, presumably, in one burst of star formation. After this burst of star formation it is assumed that any significant amounts of residual gas remaining in the globular cluster are expelled. This prevents further star formation in a chemically enriched environment and retains the chemical homogeneity of the globular cluster (Lin & Murray 1991).

The LMC provides the nearest example of the present-day formation of globular cluster-type objects. These young LMC objects are variously referred to in the literature as young globular clusters, young populous clusters and blue globular clusters. For the purposes of this paper these objects will be referred to simply as young globular clusters.

If these young globular clusters are, indeed, similar to those that gave rise to the (old) Galactic globular cluster population then their study could provide important clues about the initial conditions and extent of the Galactic globular clusters. The closeness of the LMC allows these objects to be studied in detail and their structural parameters to be determined with some accuracy. Observations reveal a number of general characteristics of young globular clusters in the LMC.

(i) The density profiles in the inner regions of even very young clusters appear to be relaxed and well described by King (1966) models (Chrysovergis, Kontizas & Kontizas 1989, and references therein).

(ii) Spatial density profiles fall off in the outer regions of these clusters as a power law with index  $\gamma + 1 \approx 3.5$ , where  $\gamma$  is a fitting parameter used by Elson, Fall & Freeman (1987, hereafter EFF) defined in Section 2.1.

(iii) Clusters are often found to have large, unbound stellar haloes which may contain up to 50 per cent of the mass of the cluster (EFF; van den Bergh 1991).

It is a young globular cluster with these characteristics that this paper attempts to model with  $N$ -body simulations.

$N$ -body simulations have been recently used to model globular clusters: Fukushige & Heggie (1995) used a  $N$ -body code to model globular clusters and compared these simulations with the Fokker–Planck calculations of Chernoff & Weinberg (1990). In this case the results of both simulations were found to be qualitatively similar. Such results show that the use of  $N$ -body codes for the modelling of systems as large as globular clusters is not without justification. However, as pointed out by Heggie (1995),  $N$ -body simulations are only of use as statistical tests of a system's behaviour. For this reason, the evolution of any one cluster must be tested over a statistically significant number of simulations before any robust conclusions can be drawn about its behaviour.

The effects of the expulsion of residual gas from an  $N$ -body system (an open cluster) were first studied by Lada, Margulis & Dearborn (1984), who found that the expulsion of over 50 per cent of the mass of a cluster may not entirely disrupt that cluster, but can leave a bound core of stars. The inclusion of residual gas and the effects of its expulsion in  $N$ -body simulations of globular clusters have been investigated in a paper by Goodwin (1997, hereafter Paper I) who finds that, while the expulsion of a large fraction of a globular cluster's initial mass is disruptive to the cluster, many clusters may well be able to survive in the Galaxy with star formation efficiencies (SFEs) as low as 20 to 25 per cent with sufficiently strict initial conditions.

This paper assumes that the formation mechanism of globular clusters results in a smooth, relaxed initial stellar distribution similar to the observed distributions of young globular clusters only  $\approx 20$  Myr old (Elson, Fall & Freeman 1989a; Elson 1991). In practice the distribution must be relaxed and smooth before the expulsion of the cluster's residual gas, not necessarily initially. It is assumed that any substructure and clumpiness present in the initial distribution do not significantly affect the dynamics and have been erased by this point.

The survivability of these LMC clusters in the environment of our Galaxy is assessed by comparing their postulated initial conditions with theoretical calculations of the initial conditions required in the Galaxy. The theoretical constraints used are those from Paper I, based upon the King model based simulations of Chernoff & Shapiro (1987). Chernoff & Shapiro presented calculations of the minimum King model required to survive for a Hubble time in the Galaxy for a variety of initial masses, initial mass function slopes and Galactocentric radii. These results are found to be in reasonable agreement with both Fokker–Planck (Chernoff & Weinberg 1990) and  $N$ -body (Fukushige & Heggie 1995) calculations. These constraints were extended in Paper I to include reasonable star formation rates and the expulsion of the residual gas which was not used in star formation. These results provided the maximum scalelength of a Plummer model required for survival for the range of initial conditions in Chernoff & Shapiro, the star formation efficiency and the mechanism for gas expulsion.

## 2 OBSERVATIONS

Eight young LMC globular clusters with well-determined parameters and ages less than 100 Myr have been chosen as indicative of the young clusters in the LMC. These clusters are NGC 1818, 2004, 2156, 2157, 2159, 2164, 2172 and 2214. Their structural parameters and ages are summarized in Table 1. These clusters were all studied by EFF and six of them were studied by Chrysovergis et al. (1989). EFF also included NGC 1831 and 1866 in their original sample.

**Table 1.** Structural parameters of the eight young LMC globular clusters used as comparisons.

Columns: (1) mass, taken from Chrysovergis et al. (1989), except NGC 2159 and 2172 for which is shown the mean of the values given by EFF; (2) central density, from EFF; (3) core radius, from Elson et al. (1989b); (4) age: NGC 1818 average from Will, Bomans & de Boer (1995); NGC 2004, 2164 and 2214 from Girardi et al. (1995); others in EFF from Hodge (1983).

| NGC  | $\log M$<br>( $M_{\odot}$ )<br>(1) | $\log \rho_0$<br>( $M_{\odot} \text{ pc}^{-3}$ )<br>(2) | $r_c$<br>(pc)<br>(3) | $\tau$<br>(Myr)<br>(4) |
|------|------------------------------------|---------------------------------------------------------|----------------------|------------------------|
| 1818 | 4.69                               | 1.6-3.2                                                 | 2.1                  | 30                     |
| 2004 | 4.60                               | 2.0-3.7                                                 | 1.1                  | 20                     |
| 2156 | 4.47                               | 2.0-3.2                                                 | 1.7                  | 65                     |
| 2157 | 4.60                               | 2.0-3.4                                                 | 2.3                  | 32                     |
| 2159 | 5.00                               | 1.7-2.9                                                 | 1.9                  | 65                     |
| 2164 | 4.69                               | 2.1-3.4                                                 | 1.5                  | 98                     |
| 2172 | 4.40                               | 1.5-2.7                                                 | 2.1                  | 65                     |
| 2214 | 4.30                               | 1.4-2.7                                                 | 2.3                  | 83                     |

These clusters have not been included in the main analysis as they are both older than 100 Myr.

It should be noted that the study of Chrysovergis et al. (1989) finds (sometimes substantially) different core radii from Elson, Freeman & Lauer (1989b). These differences are as high as a factor of 2. The values of Elson et al. (1989b) have been used as they are the values used in the profile fittings of EFF.

The quoted masses for these globular clusters should be considered as lower limits on the possible mass. EFF quote the masses over a large range (sometimes over an order of magnitude). Chrysovergis et al. (1989) find masses that are usually at the lower limit of those quoted by EFF, but it should be noted that Lupton et al. (1989) find masses for NGC 2164 and 2214 of  $2 \times 10^5$  and  $4 \times 10^5 M_{\odot}$  respectively.

Of particular interest in this sample are the 'quartet' of globular clusters NGC 2156, 2159, 2164 and 2172. The quartet clusters are located together and three of them (NGC 2156, 2159 and 2172) are coeval. The profiles of these clusters are, however, very different.

A question may be raised over the inclusion of NGC 2214 within this study. There is evidence that NGC 2214 may be the result of a merger, or may even be in the process of merging now (Bhatia & MacGillivray 1988). There is argument over the possible existence of two different age subgiant branches (Sagar, Richtler & de Boer 1991; Lee 1992), and so NGC 2214 has been kept in the sample.

### 2.1 Cluster profiles

EFF constructed density profiles of the eight clusters in this sample. These profiles were of the form [equation (13a) in EFF]

$$\rho(r) = \rho_0 \left( 1 + \frac{r^2}{a^2} \right)^{-(\gamma+1)/2}, \quad (1)$$

where  $a$  is a characteristic radius given by

$$a = r_c (2^{2/\gamma} - 1)^{-1/2}.$$

The density profiles were formed by a deprojection of the luminosity profiles. This deprojection to a density profile assumed a mass-to-light ratio and that it is constant over the whole cluster.

**Table 2.** The values of  $\gamma$  and  $a$  used in the density profiles from equation (1).  $a$  is calculated from the values of  $r_c$  in Table 1.

| NGC  | $\gamma$        | $a$ (pc) |
|------|-----------------|----------|
| 1818 | $2.45 \pm 0.25$ | 2.4      |
| 2004 | $2.20 \pm 0.20$ | 1.2      |
| 2156 | $2.75 \pm 0.45$ | 2.1      |
| 2157 | $2.90 \pm 0.27$ | 2.9      |
| 2159 | $2.15 \pm 0.34$ | 2.0      |
| 2164 | $2.80 \pm 0.30$ | 1.9      |
| 2172 | $3.20 \pm 0.50$ | 2.9      |
| 2214 | $2.40 \pm 0.24$ | 2.6      |

These density profiles are very similar to King (1966) models at low radii (the radii containing approximately 70 per cent of the mass of the cluster and less), while at higher radii they fall off below a King profile.

Values of  $\gamma$  and  $a$  for the eight clusters are shown in Table 2. Using these values and those from Table 1, it is possible to create the density profiles of the clusters. Integrating this in each case then gives the mass distribution. The mass distribution is preferred as it is easier to compare with the  $N$ -body models, because the relatively low number of particles used in the simulations make the construction of a smooth density profile difficult, while the mass distribution is trivially formed from the positions of the particles.

These profiles often show irregularities that are not present in the profiles of older clusters (Elson 1991). EFF suggest that dips and peaks in the outer regions of the luminosity profiles of clusters are probably produced by the presence of ‘clumps’ of stars. The presence of these clumps is smoothed away in the fitting of the best-fitting line to the luminosity profile, and so these clumps are not present in either the density profiles or mass distributions derived from the luminosity profiles. As these dips and peaks are found in the outer regions of the clusters, they do not contain any significant fraction of the mass of the cluster and so may not be very important for the limits of the simulations presented in this paper. However, they do make the form of the profiles at large radii uncertain and, possibly, misleading.

## 2.2 Correlations of cluster properties

A simple statistical analysis of the relationships between various cluster properties has been made to search for clues as to the initial conditions and formation mechanisms of the young globular clusters. Application of the sample correlation coefficient to the data shows that it is consistent with no correlation between  $\gamma$  and any other quantity. Age is also totally uncorrelated with any other parameter of the clusters. Thus the cluster profiles do not appear to represent any sort of evolutionary sequence. This lack of correlations between profile shape and other quantities shows that, in these young globular clusters, the profiles are determined by some other mechanism(s) that is not dependent upon the structural parameters measured now.

## 2.3 Other relevant observations

Observations of LMC globular clusters show that they are more highly elliptical than Galactic globular clusters (van den Bergh & Morbey 1984). The reasons for this high ellipticity are unknown. It

is possible that LMC clusters have high rotational velocities. Elson (1991), however, suggests that the presence of subclumps merging with the main cluster may produce the impression of high ellipticities in these young globular clusters.

It has been noted that the half-mass radii  $r_h$  of globular clusters in the LMC are usually 3 to 4 times larger than for similar Galactic clusters (van den Bergh 1991). This result is only relevant for the older LMC globular clusters, as the Galaxy has no analogues of the LMC’s young clusters. The half-mass radii from simulations of these clusters can, however, be compared with the theoretical constraints on young Galactic globular clusters from simulations.

The mass functions of these clusters have been studied by a number of authors. There is some considerable discrepancy about the value of the mass function slope in the young clusters in the LMC. Mateo (1988) finds, in a study of six young and intermediate-age LMC and SMC clusters, that the mass function slopes are consistent with all being drawn from a single initial mass function of slope  $\alpha = 2.52$ . Sagar & Richtler (1991) find slightly lower, but still Salpeter-type, slopes consistent with  $\alpha = 2.1$ . Elson et al. (1989a), however, in a sample of six of the young LMC clusters from EFF, find that  $0.8 < \alpha < 1.8$ . None of the clusters in these two studies overlaps with any other. A recent determination of the mass function in NGC 2214 by Banks, Dodd & Sullivan (1995) finds  $\alpha \approx 2$ , in contrast to Elson et al.’s (1989a) value of 0.8. Such discrepancies arise due to observational uncertainties and the application of different methods for the determination of mass function slopes. However, they show that little importance should be placed on any individual value.

NGC 2070 is of interest to this study as it is the only LMC globular cluster that has not, as yet, expelled its residual gas. NGC 2070 is the central cluster of the 30 Dor nebula with an age of only a few Myr (Meylan 1993). NGC 2070 is composed of large clumps of stars with little symmetry apparent in the distribution of stars. This clumpiness in the light distribution could, however, be caused by concentrations of high-mass stars and may not trace the mass distribution. King model fits to the luminosity profile of NGC 2070 (including R136) give a core radius of  $\approx 0.4$  pc (Moffat & Sweggewiss 1983). Kennicutt & Chu (1988), however, fit an isothermal profile to the stellar (rather than luminosity) distribution of NGC 2070 with a core radius of 4.5 pc when the contribution of R136 is ignored. Kennicutt & Chu question the significance of the similarity of NGC 2070 to a King model and more evolved globular clusters, doubting that such a young object could have thermalized.

## 3 N-BODY SIMULATIONS

The  $N$ -body code used in this paper is based upon Aarseth’s (1996) NBODY2 code, with the addition of stellar evolution and a variable external potential to model the effects of residual gas loss. This code has been also been described in more detail in Paper I.

A variety of initial conditions were tested to see which combinations produce clusters similar to those observed in the LMC.

In the simulations the stars and gas were originally distributed in a Plummer model. Plummer models were chosen for their simple form which allows the forces due to the gas distribution to be easily calculated. The choice of a Plummer model was not entirely arbitrary, however. Although NGC 2070 is inhomogeneous with little spherical symmetry (see Section 2.3) it does appear that, as a first approximation, it can be considered as a simple (isothermal) distribution, such as a Plummer model. In the absence of a good model to explain globular cluster formation in detail, and

with the limited resolution in such an  $N$ -body code as this, this approximation is used.

The potential of a Plummer model is given by

$$\phi(r) = -\frac{GM}{(r^2 + R_S^2)}, \quad (2)$$

where  $G$  is the gravitational constant,  $M$  is the total mass of the stars or residual gas and  $R_S$  is the length-scale of the potential.

The initial distribution function of the stars in a Plummer model is formed using the procedure detailed by Aarseth, Hénon & Wielen (1974) for random initial conditions. The particles are distributed randomly in phase space in such a way as to produce a Plummer model with an isotropic velocity distribution. The length- and velocity-scales can then be scaled so as to produce the desired scalelength. The velocities of the particles can be scaled to change the kinetic energy,  $T$ , of the system to produce the required virial ratio,  $Q$ , with the potential energy,  $\Omega$ , where  $Q = T/|\Omega| = 0.5$  corresponds to a system in virial equilibrium.

### 3.1 Tidal field

No tidal field was imposed upon the simulations in this paper. The tidal field of the LMC is very weak, and its extent and nature are poorly known (van den Bergh 1991). As the clusters under investigation are all very young, it is unlikely that they will have undergone any significant tidal stripping. A possibly significant number of stars in the cluster may have overflowed the tidal boundary and will be stripped over time; this stripping may unbind the cluster leading to its eventual disruption. In the time-scales considered in this paper, however, this effect is assumed to be negligible in the central  $\approx 200$  pc.

### 3.2 Initial mass function and stellar evolution

The initial mass function (IMF) is taken to be a power law of the form

$$N(M) \propto M^{-\alpha}, \quad (3)$$

where this corresponds to the Salpeter (1955) IMF for the solar neighbourhood when  $\alpha = 2.35$ . In these simulations  $\alpha$  is taken to be 1.50 or 2.35. These values are consistent with observations of the mass function in these clusters (Section 2.3) which are presumably good indicators of the IMF as these clusters have had little time to evolve in any way that may affect the mass function (see Section 4.3). The lower slope of 1.50 was chosen because the effects of mass loss from clusters with IMF slopes lower than this will almost certainly disrupt the cluster on small time-scales (Chernoff & Weinberg 1990).

Simulations were run with equal-mass particles to reduce the effects of relaxation which become apparent in multi-mass simulations (Giersz & Heggie 1996). This is different from the method used in Paper I which used multi-mass models (cf. Fukushima & Heggie 1995). The quantitative results of small- $N$  simulations using the two methods are similar but the exact form of the profiles differs between the methods.

The mass loss from stars due to stellar evolution is included in the code. Each particle represents a group of stars containing the full range of masses. Every Myr the masses of all the particles are changed by an amount representing the mass loss from stellar evolution in that Myr as some stars evolve to their appropriate end-state. High-mass stars ( $M > 8 M_\odot$ ) become type II supernovae and evolve into neutron stars of  $1.4 M_\odot$ . Intermediate-mass stars

( $4 < M < 8 M_\odot$ ) have two possible end-states. They may become type I $\frac{1}{2}$  supernovae which totally destroy themselves, leaving no remnant (Iben & Renzini 1983), or they may evolve into white dwarfs of  $\approx 1.4 M_\odot$ . The final stages of the evolution of these intermediate-mass stars are poorly understood and so either possibility may be used in the code. The difference in remnant mass does not appear to be especially important, although it may affect the evolution of clusters with a low IMF slope which have significant numbers of intermediate-mass stars. Low-mass stars,  $2 < M < 4 M_\odot$ , evolve into white dwarfs of mass  $0.58 + 0.22(m - 1)$ , where  $m$  is the initial mass of the star, all in solar masses (Iben & Renzini 1983). Runs cover, at the very most, a few hundred Myr, normally 100 Myr, and so the evolution of stars of less than  $\approx 5 M_\odot$  is not relevant.

The end-time of stellar evolution is given by fitting a line to the stellar evolutionary calculations of Maeder & Meynet (1988),

$$\log_{10}\left(\frac{M}{M_\odot}\right) = 1.524 - 0.370 \log_{10}\left(\frac{T}{\text{Myr}}\right). \quad (4)$$

These calculations are for solar metallicity stars. The young LMC globular clusters are, at most, 20 times less abundant in metals than solar ( $[\text{Fe}/\text{H}] > -0.7$ ), and hence these models are expected to be reasonably good approximations to the evolution of such stars.

The numbers of stars reaching their end-states at any time are calculated from the slope of the IMF,  $\alpha$ . If  $N_{M_1 \rightarrow M_2}$  is the number of stars in the mass range  $M_1$  to  $M_2$  in a cluster with initial stellar mass  $M_{\text{cl}}$  then

$$N_{M_1 \rightarrow M_2} = M_{\text{cl}} \frac{(\alpha - 2)(M_1^{-(\alpha-1)} - M_2^{-(\alpha-1)})}{(\alpha - 1)(M_{\text{low}}^{-(\alpha-2)} - M_{\text{up}}^{-(\alpha-2)})} \quad (5)$$

[cf. equation (7) in Paper I]. The upper limit of the IMF,  $M_{\text{up}}$ , is taken to be  $15 M_\odot$ . The low-mass end of the IMF,  $M_{\text{low}}$ , is set at  $0.15 M_\odot$ , corresponding to the observed turnover in the mass function in observations of the Galactic globular cluster NGC 6397 (Paresce, De Marchi & Romaniello 1995).

The mass lost by stellar evolution is ignored. Prior to the gas expulsion the mass lost is assumed to be negligible compared with the mass of residual gas (although it is often the driving force behind the residual gas expulsion). After the residual gas has been expelled, any material lost from stellar evolution is assumed to be energetic enough to leave the cluster and not massive enough at any time to affect the dynamics of the stars in the cluster. This assumption in young clusters with low slopes to their mass functions may not be realistic, but is used for simplicity.

### 3.3 Star formation efficiency

The SFE of a globular cluster is one of the most important initial conditions included within this study. The SFE is defined simply as the fraction of the initial mass of gas that is turned into stars. In the Galactic disc, star-forming regions are usually found to have SFEs of order a few per cent (Larson 1986). A simple application of the virial theorem leads to the conclusion that for bound clusters to form and survive the expulsion of residual gas from star formation then an SFE of *at least* 50 per cent is required. Lada et al. (1984) showed that open clusters can retain a bound core of stars with SFEs as low as 30 per cent. Paper I suggested that, if the initial concentration of a globular cluster is high enough, then it could survive the expulsion of residual gas with SFEs possibly as low as 25 per cent. This is possible if the cluster stars are able to settle into a new (larger) dynamical equilibrium which is well inside the tidal limit of the cluster. Clusters were given a variety of SFEs from 10 to

80 per cent. As shown in Paper I, the effect of residual gas expulsion from a cluster is highly dependent upon the SFE.

### 3.4 Residual gas expulsion

The expulsion of the residual gas in the cluster not used in star formation is modelled by a variable external potential acting upon the particles in the cluster (cf. Lada et al. 1984). The residual gas initially has a Plummer distribution, chosen due to the simple analytic form of its potential. The Plummer model is given the same scalelength as that of the stars, but often a different mass (depending upon the SFE of the cluster in question). The effect of stars upon the residual gas is assumed to be restricted to the expulsion of the gas, as the gas is being heated by the massive stars and is present for a relatively short length of time.

In this paper two simplified mechanisms are used to expel residual gas from a globular cluster. The first mechanism is based upon the gradual depletion of the gas in a cluster by the action of the UV fluxes and stellar winds from massive stars [based upon the hydrodynamic simulations of Tenorio-Tagle et al. (1986)]. It may also include some gradual expulsion by supernovae which would be expected if star formation were not virtually instantaneous. This expulsion is simulated by the slow, constant reduction (on a time-scale of a few Myr) of the mass of gas in the cluster to zero, starting a few Myr after the end of star formation. This type of residual gas expulsion was found by Paper I to be the least disruptive to a cluster. This is due to the gradual and global nature of the change in potential, which is slow compared with a crossing time, allowing the stars to adjust gradually.

The second mechanism of residual gas expulsion is by the additive action of large numbers of supernovae near the centre of the cluster to form a ‘supershell’ (of the type observed in OB associations in the Galaxy) which sweeps the cluster clear of gas (Brown, Burkert & Truran 1995). This supershell is modelled by assigning it a radius  $r_{\text{shell}}$  at some time  $t$  depending upon the rate of supernova events  $\dot{N}$ , assumed to be constant during the time over which supernovae occur, the energy of each supernova  $E$ , taken to be  $10^{51}$  erg, and the external gas pressure  $P_{\text{ext}}$  on the shell. This is given by [equation (9) in Brown et al. 1995]

$$r_{\text{shell}} = \left( \frac{3}{10\pi} \frac{E\dot{N}t}{P_{\text{ext}}} \right)^{\frac{1}{3}}. \quad (6)$$

If a star is interior to  $r_{\text{shell}}$  then it feels no force due to the gas, while exterior to  $r_{\text{shell}}$  it feels the same force as if the supershell were not there (from Newton’s first theorem). This mechanism of residual gas expulsion was found by Paper I to be the most disruptive to the cluster, as the shell sweeps out the inner few parsecs (where most of the stars are present) on a time-scale far less than a crossing time. As the gas expulsion from the inner regions is so fast, the assumption that all the supernovae occur at the centre of the shell is probably fair. On such a time-scale the stars are unable to adjust to the change in potential gradually, which results in a more dramatic change. This mechanism is of particular interest, as studies of the dynamics of the gas in the 30 Doradus H II region around the cluster NGC 2070 (which contains the group of massive stars R136) indicate that this region will eventually become a supershell (Chu & Kennicutt 1994). This study also underlines, however, the extremely complex nature of the gas around a large, young star cluster, which a simulation such as this could not attempt to model accurately.

In Paper I it was mentioned that, for low SFEs, not enough high-mass stars might be present to expel the residual gas. This

consideration is not of importance in this paper, owing to the low values of  $\alpha$  for the IMFs. Such values of  $\alpha$  should always produce enough high-mass stars to expel the residual gas for the SFEs of interest.

### 3.5 Core radii

The core radius of a cluster is an important observational quantity. In order to compare simulations and observations, the core radii are calculated in two ways. The first is based on the method described in Casertano & Hut (1985). This method is designed to produce core radii from  $N$ -body simulations which can be compared with observational core radii. The core radius,  $r_c$ , is calculated by

$$r_c = \left( \frac{\sum_{i=1}^n |r_i - r_d|^2 \rho_i^2}{\sum \rho_i^2} \right)^{1/2}, \quad (7)$$

where  $\rho_i = 15/(4\pi r_c^3)$  is the density estimator of particle  $i$  with respect to the sixth nearest particle  $r_6$ , and  $r_d$  is the position of the density centre. In NBODY2 the original procedure has been modified to sum over a central sample of  $n \approx N/2$  particles.

This core radius is compared with the core radius obtained from the fitting of the mass profile derived from equation (1). Fittings may be made with one or two free parameters:  $\gamma$  and  $a$  (related to  $r_c$ ); or, assuming  $r_c$  to be given by equation (7), only  $\gamma$  as a free parameter. These methods usually produce very similar results. Some discrepancy can occur due to the sometimes rapid variations in  $r_c$  from equation (7) caused by the relatively small number of particles (1000) used in most simulations.

### 3.6 Computational parameters

Heggie & Mathieu’s (1986) standard  $N$ -body units were used, where  $M_0 = G = 1$  and  $E_0 = -1/4$ , where  $M_0$  is the initial mass of the particles (i.e. the initial stellar mass of the cluster) and  $E_0$  is the initial energy of the particles. Conversion to units of time (in Myr) for the treatment of stellar evolution was made using the relationship

$$T_c = M_0^{5/2}/(2|E_0|)^{3/2} = 2\sqrt{2}U_t, \quad (8)$$

where  $U_t$  is the unit of time within the code.

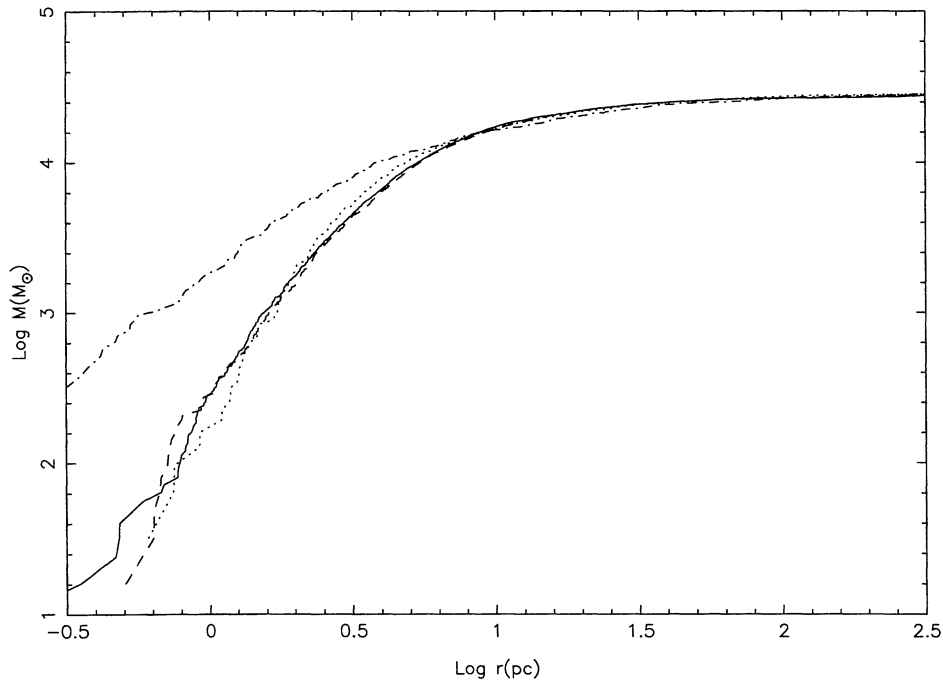
The softening length in all simulations was set to be 1/50. Equal-mass simulations run with softenings between 1/20 and 1/100 show similar results. This level of softening is less than that used in multi-mass simulations where the effects of relaxation are stronger.

The effect of varying the number of particles,  $N$ , used in the simulations is illustrated in Fig. 1. As can be seen, the profiles for  $N \geq 1000$  are very similar: profile fits to all three curves give  $\gamma = 2.9 \pm 0.1$  and  $r_c = 2.6 \pm 0.2$  (errors come from combining the three different fits; they are not the errors inherent in each individual fit). Note also that the mass interior to any radius is virtually the same for the  $N \geq 1000$  runs when  $r \geq 1$  pc.

Most simulations were made with  $N = 1000$  due to the large number of simulations and limits on available CPU time. To test the statistical validity of results (Heggie 1995), most simulations were made three or four times. The initial conditions were kept constant but the random numbers used to generate the distribution function of the stars were given a different ‘seed’. A few simulations were repeated more to reduce statistical noise further.

## 4 RESULTS

The results of the  $N$ -body simulations and their comparisons with



**Figure 1.** Mass profiles after 100 Myr for four identical clusters with  $R_S = 2.4$  pc,  $\alpha = 1.50$  and an SFE of 40 per cent with particle numbers  $N = 500$  (dot-dash line), 1000 (dotted line), 2000 (dashed line) and 4000 (solid line).

observation are presented in this section. In Section 4.1 the general results on the shape and evolution of the profiles of varying different initial conditions are given. A model for the initial conditions of these young globular clusters is suggested. In Section 4.2 the implications of these results for the survivability of these clusters, both in the LMC and in the Galactic environment, are discussed. Finally, in Section 4.3 the effect of the IMF slope upon cluster evolution and survivability is considered.

#### 4.1 The initial conditions of young LMC globular clusters

The aim of the simulations was to find the initial conditions that most affect the shape of the mass distribution profile after gas expulsion, and produce the range of cluster parameters presently observed. The initial conditions that were varied to try to recreate these profiles were the mass, SFE, IMF slope, initial distribution function of the stars and gas expulsion mechanisms. The effects upon the mass distribution profile of altering each of these initial conditions are discussed individually below, followed by a discussion of the set of initial conditions that would result in the variety of young globular clusters in this sample.

When fitting profiles to the mass distributions of the simulations, care was taken to make the fitting similar to that of EFF. The fits were made to a log–log profile of mass–radius and fitted primarily in the inner few parsecs of the simulations. The profile within  $\approx 1$  pc was often not used to fit, as it is highly sensitive to random variations in particle number due to the low numbers of particles used. Fits were made out to  $\approx 200$  pc, a distance similar to that out to which the observational fits were made.

The SFE is found to have the most influence upon the mass profile of the cluster after gas expulsion. The lower the SFE of a cluster, the smoother its profile will be (i.e. the value of  $\gamma$  required to fit the profiles of low-SFE clusters is lower than for high-SFE clusters). The effect of the SFE upon  $\gamma$  during the first 100 Myr is shown in Fig. 2. It

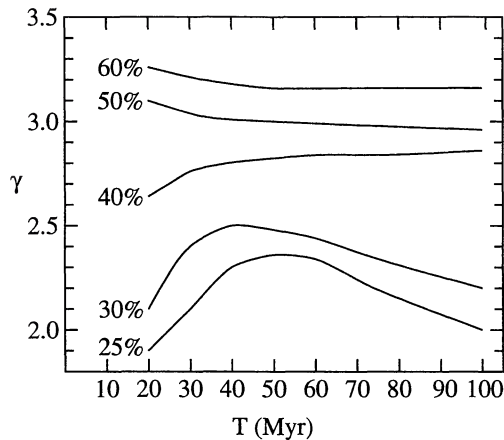
is found not to vary significantly with the chosen IMF or Plummer model scalelength in any simulation. The lines in Fig. 2 are guides only: an average over many simulations. In any particular simulation the fitted value of  $\gamma$  may vary by 0.3 from the plotted values. The general trend is the same, however, in the majority of runs.

Fig. 3 shows that clusters with a low SFE lose a high proportion of their stars rapidly once gas expulsion is complete. Many stars are unbound by the loss of the residual gas and escape from the cluster. This escape is not instantaneous, however, and, during the 10 to 20 Myr required for these stars to escape, the cluster profile appears to have a very low  $\gamma$  (see Fig. 2), a feature which appears to occur in the observations (see Fig. 8, later). In clusters with high SFE, the effect of the residual gas expulsion is not felt so strongly by the cluster and the immediate escape of stars after gas expulsion is not so dramatic. It should be noted that low escape rates in the first 100 Myr do not necessarily produce a bound cluster that will survive. The further effects of stellar evolutionary mass loss and gradual evaporation of stars could well disrupt these clusters (e.g. Chernoff & Weinberg 1990).

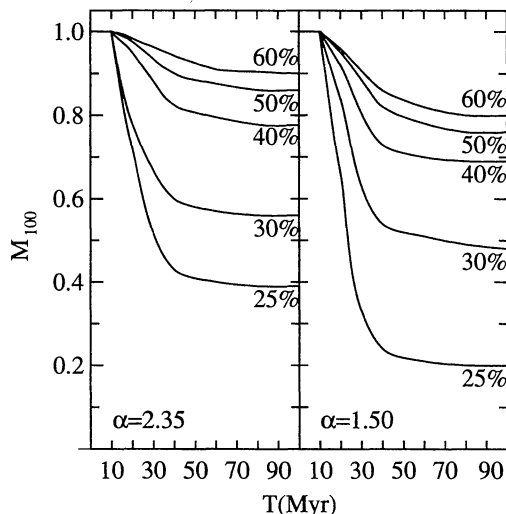
Altering the total initial stellar mass of a cluster is found to have a very small effect upon the resulting shape of the profile. Lower initial mass clusters appear to have a smoother mass distribution than those of a higher mass. However, this effect is very small and is swamped by the effect of changing the SFE. This would explain the lack of any correlation between cluster mass and  $\gamma$  in the sample.

The cluster mass will affect the survivability of a globular cluster, as tidal overflow after residual gas expulsion is more disruptive in low-mass clusters (Paper I). It is this tidal overflow that is assumed to produce the extensive unbound stellar haloes observed in these young LMC globular clusters (EFF).

The mechanism of gas expulsion does also have an effect upon the shapes of the mass profiles. This effect is, again, small compared with the changes caused by different SFEs. The more disruptive supershell expulsion, unsurprisingly perhaps, forms clusters with



**Figure 2.** The evolution of  $\gamma$  over the first 100 Myr for different star formation efficiencies, for clusters that expel their residual gas via a supershell. These clusters had an initial mass of  $5 \times 10^4 M_{\odot}$ .

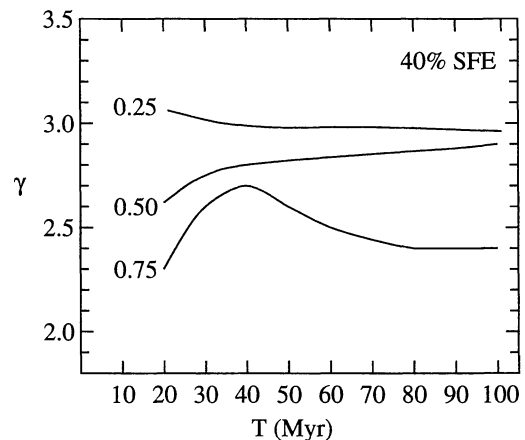


**Figure 3.** The change in the fraction of the initial stellar mass of a cluster remaining within 100 pc of the centre of mass with time for different SFEs from 25 to 60 per cent (as marked). These clusters were initially of mass  $5 \times 10^4 M_{\odot}$  with  $R_S = 2.4$  pc and  $\alpha = 2.35$  or  $\alpha = 1.50$ . In all cases the residual gas was expelled by a supershell mechanism after 9 Myr.

lower  $\gamma$  fits (smoother mass profiles) than the more sedate gradual expulsion mechanism. In addition, supershell expulsion causes the unbinding of a higher proportion of a cluster's stars and the formation of a very large halo of stars.

The observation that these young globular clusters do have large, unbound haloes (EFF; van den Bergh 1991), combined with the evidence that NGC 2070 will eventually form a supershell (Chu & Kennicutt 1994), would appear to suggest that a supershell mechanism for the expulsion of the residual gas may be the better approximation.

The initial virial ratio (initial energy distribution) of the stars in the cluster is found to have a large effect upon the form and evolution of profiles during the first 100 Myr of cluster evolution. The value of  $Q$  can greatly affect the levels of stellar escape after gas expulsion as well as the core radius of the cluster. The virial ratio of the cluster quickly settles down to its equilibrium value of  $Q = 0.5$



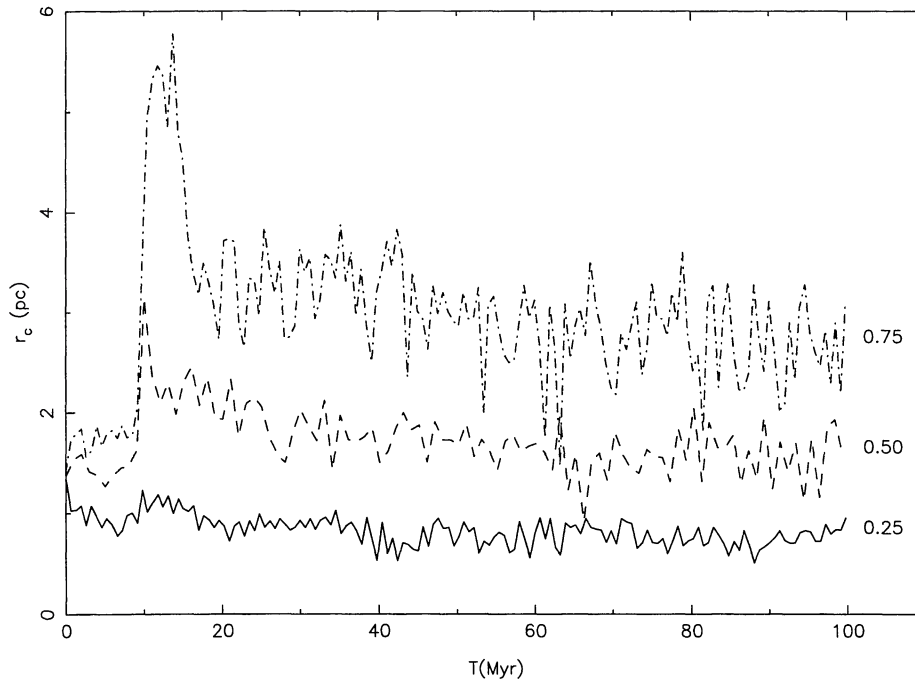
**Figure 4.** The effect of the initial virial ratio  $Q$  upon the evolution of the profile parameter  $\gamma$  for  $Q = 0.25, 0.50$  and  $0.75$ . All three clusters have an SFE of 40 per cent initially with  $R_S = 2.4$ ,  $M_{\text{tot}} = 5 \times 10^4 M_{\odot}$  and  $\alpha = 2.35$ .

for unvirialized clusters (see also Paper I). In attaining this equilibrium, however, the cluster must change its distribution (expanding if  $Q > 0.5$ , and contracting if  $Q < 0.5$ ).

Fig. 4 shows the effect upon the evolution of  $\gamma$  of varying the initial virial ratio. For  $Q < 0.5$  the form and time-scale of the escape are not altered significantly, so that the evolution of  $\gamma$  with SFE remains approximately the same. When  $Q > 0.5$  the cluster's evolution can be significantly changed. The change of  $\gamma$  observed in Fig. 4 when  $Q = 0.75$  corresponds to a far less bound cluster which loses a larger number of its stars immediately after gas expulsion as the velocity dispersion of the cluster is higher (producing a similar evolutionary profile to those of lower SFEs in Fig. 2). After 100 Myr the  $Q = 0.25$  and  $Q = 0.50$  clusters both lose  $\approx 15$  per cent of their particles beyond 100 pc from the cluster core; in the  $Q = 0.75$  case, however, nearly 40 per cent of the particles have passed the 100-pc radius in the same time.

The strong dependence of core radius on the initial virial ratio is shown in Fig. 5. The profiles are unsmoothed and show the variations in  $r_c$  caused by the 'noise' introduced by the low particle number (1000). The expansion to equilibrium and the more disruptive effect of gas expulsion in the  $Q = 0.75$  cluster are shown in the far higher core radius of that cluster compared with the other clusters. In addition this cluster shows a huge expansion of  $r_c$  caused by the act of residual gas expulsion around 9 Myr.

The initial concentration of clusters in the simulations is not an entirely free parameter. The core radii of the simulated clusters have to correspond with the observed range of core radii,  $1 < r_c < 3.5$ , after residual gas expulsion. This limitation is found to place surprisingly strict bounds upon the allowed range of initial stellar distributions (in these cases, the scalelength  $R_S$  of the Plummer models). The core radius of a cluster may increase after gas expulsion by a factor of  $\approx 2$  to 4 for clusters with low SFEs before contracting (see Fig. 5). Residual gas expulsion from clusters with high SFEs ( $> 40$  per cent) does not appear to have a significant effect upon the core radii of the simulations. However, soon after gas expulsion is completed, the central regions of clusters will contract unless the IMF slope is low enough (this is discussed in detail in Section 4.3). In order for the simulation core radii to remain in the observed range over the first few hundred Myr of evolution, the scalelength of the Plummer models (related to core radius by  $r_c = 0.644R_S$ ) is



**Figure 5.** The effect of the initial virial ratio  $Q$  upon the evolution of the core radius  $r_c$  (calculated from equation 7) for  $Q = 0.25, 0.50$  and  $0.75$ . The initial conditions of the clusters were the same as those in Fig. 4.

found to have to lie in the range 1 to 3 pc, depending to some extent upon the IMF slope.

Fig. 6 shows how the evolution of the core radius is strongly dependent upon the SFE of the simulation. Note that the core radii in Figs 6 and 7 are smoothed averages over several simulations. In any one simulation,  $r_c$  fluctuates by  $\approx \pm 0.5$  pc and the average value of  $r_c$  may differ between simulations by about the same amount. These lines should therefore only be taken as guides as to the behaviour of  $r_c$ . The decline in  $r_c$  over the first 100 Myr of the cluster evolution is due to the resettling of the bound cluster core after gas expulsion. Such reductions are also observed in many  $\alpha = 1.50$  simulations which begin to re-expand from the effects of stellar evolutionary mass loss after a few hundred Myr.

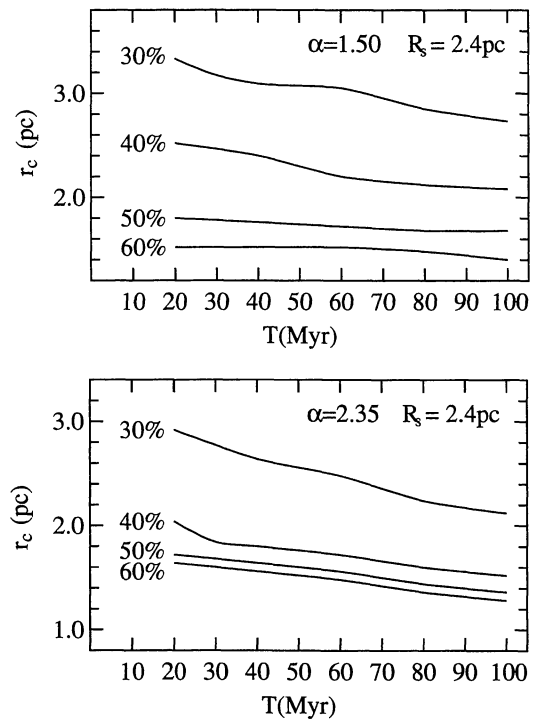
The fraction of particles within  $r_c$  is also found to decline after residual gas expulsion. The level of this decline is also greater for lower SFEs. Initially  $\approx 10$  per cent of particles are within  $r_c$ ; this declines after 100 Myr to  $\approx 7$  per cent with an SFE of 50 per cent, and  $\approx 4$  per cent if the SFE is 30 per cent. The reduction is slightly ( $\approx 1$  per cent) greater for  $\alpha = 1.50$  as opposed to  $\alpha = 2.35$ .

The dependence of  $r_c$  upon the scalelength of the original Plummer model is obvious in Fig. 7. The sample SFE of 50 per cent is chosen to illustrate the general behaviour of  $r_c$  with  $R_s$ . Very low SFEs ( $< 30$  per cent) rise more dramatically with increasing  $R_s$ , limiting the range of allowable Plummer models more.

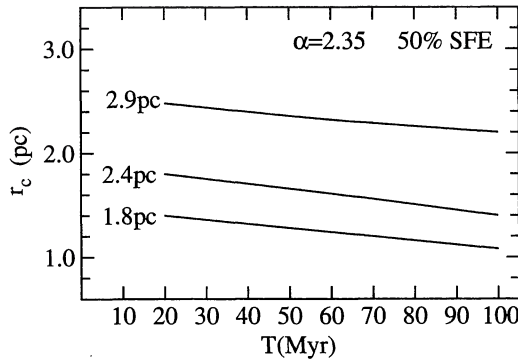
It is found that the profiles of the youngest clusters are often not smooth and easily fitted by the EFF profiles. This appears to be due to the loss of stars immediately following gas expulsion, especially in low-SFE clusters. The bumps, steps and shoulders noted by Elson (1991) in the luminosity profiles are present in the mass profiles of simulated clusters. These departures from the EFF profiles are at their most extreme for a few tens of Myr after the completion of residual gas expulsion. They are gradually smoothed out by dynamical processes and the loss of high-velocity particles from the cluster. Some of the observed structure may be due to the poor

resolution of the  $N$ -body simulation, although such structures are observed in actual clusters.

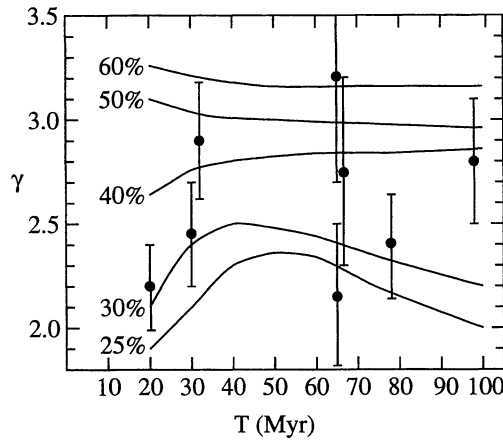
The required length-scales for young clusters ( $< 50$  Myr) are generally independent of the IMF slope. In these young clusters  $\gamma$



**Figure 6.** The evolution of core radius with different SFEs for  $R_s = 2.4$  pc clusters with IMF slopes of  $\alpha = 1.50$  (top) and  $2.35$  (bottom). The core radii are smoothed averages.



**Figure 7.** The change in the evolution of core radius for a 50 per cent SFE,  $\alpha = 2.35$  cluster with different initial Plummer model length-scales. The core radii are smoothed averages.



**Figure 8.** The  $T$ - $\gamma$  evolution for different SFEs with observations (from Tables 1 and 2) overlaid, including the error bars for  $\gamma$ . Note that the  $x$ -position of NGC 2156 has been shifted slightly to the right to allow its error bars and those of NGC 2159 and 2172 to be seen more clearly.

and  $r_c$  are determined more by the results of the residual gas expulsion than by any internal dynamical process such as stellar evolutionary mass loss. In older clusters ( $> 50$  Myr), however, the additional evolutionary effects of a low IMF slope are being felt by the cluster. This results in higher  $r_c$  for a given  $R_s$  and SFE.

Fig. 8 shows the evolution of  $\gamma$  for a variety of SFEs with the observations overlaid. The quoted errors for  $\gamma$  from EFF have been included. Table 3 shows the implied initial conditions for the observed young LMC globular clusters, assuming that they are initially virialized ( $Q = 0.50$ ), combining Fig. 8 and the results for the evolution of  $r_c$  with SFE and  $R_s$ . As can be seen from Fig. 8, the quoted SFEs in Table 3 contain an error of  $\approx \pm 10$  per cent due to the errors in  $\gamma$ . Large error bars also exist for the ages of the clusters; however, these errors would not introduce such a variation into the possible SFEs. Table 3 combines the results from Fig. 8 with values for  $r_c$  for different Plummer model  $R_s$  values to estimate the initial conditions that would result in the observed clusters with IMF slopes of  $\alpha = 2.35$  and 1.50.

The values of  $R_s$  obtained for both IMF slopes are the same for young clusters whose profile is determined by the effect of

**Table 3.** The star formation efficiencies and Plummer model scalelengths for IMF slopes  $\alpha = 2.35$  and 1.50 required to match the observations of the sample clusters that are younger than 100 Myr. All these clusters were initially in virial equilibrium and the residual gas was expelled by a supershell beginning at 9 Myr.

| NGC  | SFE            | $R_s$ (pc)      | $R_s$ (pc)      |
|------|----------------|-----------------|-----------------|
|      |                | $\alpha = 2.35$ | $\alpha = 1.50$ |
| 1818 | 30 per cent    | 1.8             | 1.8             |
| 2004 | 30 per cent    | 1.2             | 1.2             |
| 2156 | 40 per cent    | 2.4             | 2.4             |
| 2157 | 45 per cent    | 2.9             | 1.8             |
| 2159 | $>25$ per cent | 1.8             | 1.2             |
| 2164 | 40 per cent    | 2.4             | 1.8             |
| 2172 | 60 per cent    | 2.9             | 2.6             |
| 2214 | 30 per cent    | 2.4             | 1.8             |

the residual gas expulsion; older clusters tend to have a lower  $R_s$  for  $\alpha = 1.50$ . The quoted  $R_s$  values should be taken as a guide only, and contain an error of at least  $\pm 0.5$  pc. It should be noted that they are for virialized clusters that have had their residual gas expelled by a supershell. Non-virial equilibrium will alter  $R_s$  (decreasing for  $Q > 0.5$  and increasing for  $Q < 0.5$ ), and less disruptive gas expulsion mechanisms will increase  $R_s$ . The relative values will stay approximately the same, however.

Combining the above results as to the effects of various initial conditions upon the mass distributions of young clusters, it is suggested that the population of young LMC globular clusters could have been formed from a fairly uniform population of proto-cluster clouds. The initial star formation forms a fairly relaxed Plummer-like distribution, from which residual gas is expelled by the actions of supernovae. The differences in cluster profiles could be explained as differences in the mass and SFE of the proto-cluster.

This model provides an explanation for the differences observed in the quartet, in particular the coeval clusters NGC 2156, 2159 and 2172. These clusters, despite their striking similarities in age and location, are very different in their profiles. They have the widest range of profile shape observed in the entire sample, with  $\gamma = 2.75$ , 2.15 and 3.20 respectively. If the SFE is the major factor in the determination of profile shape in these clusters, then this discrepancy could be accounted for by varying the SFE between 25 and 60 per cent. The derived scalelength for these clusters is  $\approx 2.4 \pm 0.5$  pc. A constant scalelength of 2.4 pc is possible within the errors quoted for  $\gamma$ . Given this, a common origin for these clusters would appear plausible.

EFF also determined profiles for two other young LMC globular clusters, NGC 1831 and NGC 1866. Neither of these clusters has been included in the main analysis, as they are older than 100 Myr, i.e. 400 and 138 Myr respectively (Girardi et al. 1995). NGC 1866 would not be expected to have had a strong tidal influence from the LMC, but NGC 1831 may have had some significant stripping of its tidal overflow, modifying its profile. NGC 1866 fits well into the model of initial conditions, its profile being explicable with a scalelength of  $\approx 3$  pc and a 40 per cent SFE. NGC 1831 is observed to have  $\gamma = 3.35 \pm 0.56$ , which would seem to imply a high SFE; however, the extent to which its profile would have been modified by the tidal field is difficult to quantify. The core radius of NGC

1831 is also large (3.3 pc) but may have been substantially altered if the cluster had a low slope to its IMF.

#### 4.2 The survivability of the young LMC globular clusters

If the conclusions drawn in the previous section are a fair representation of the initial conditions that have produced the young LMC globular clusters, then it should be possible to say something about the survivability of those clusters. Paper I presented results as to what initial conditions are necessary to produce a globular cluster that will survive for a Hubble time in the Galaxy. These conditions may be applied to the clusters in this sample to assess their survival chances.

Conditions within the LMC, especially with respect to the far weaker tidal field when compared with the Galaxy, will mean that the survival conditions of Paper I are an underestimate of the survivability of the young LMC globular clusters. However, it is of interest to examine whether these clusters would be able to survive within the Galaxy, to test whether they are, indeed, representative of younger versions of the old Galactic globular cluster population.

Interestingly, these clusters lie around the borderline of survival from Paper I. A cluster with an initial mass of  $10^4 M_\odot$ , with a Galactocentric distance of 5 to 8 kpc when  $\alpha = 2.35$ , is estimated to be able to survive if its initial Plummer model length-scale  $R_s \lesssim 1.5$  pc for supershell gas expulsion for an SFE of 50 per cent. For an initial mass of  $10^5 M_\odot$  this rises to  $R_s \lesssim 2.5$  pc. These values are somewhat lower than the scalelengths observed in the simulations that recreate the observed profiles. However, for Galactocentric distances greater than  $\approx 12$  kpc, some of the clusters in this sample should be capable of surviving for a Hubble time if  $\alpha \gtrsim 2$ . Clusters with IMF slopes of  $\alpha = 1.50$  were not considered in Paper I, as Chernoff & Weinberg (1990) showed that clusters with reasonable initial conditions could not survive for a Hubble time in the Galaxy with such IMF slopes.

The range of scalelengths inferred for the initial Plummer models of these globular clusters implies an initial central density within the proto-cluster clouds in the range  $10^3$  to  $10^4 M_\odot \text{ pc}^{-3}$  – similar to that observed in giant molecular clouds in the Galaxy today (Harris & Pudritz 1994). This range is also similar to that found as the borderline survival range for Galactic globular clusters in Paper I. This similarity with Galactic giant molecular clouds is also independent of the IMF slope.

These values for the maximum scalelength required for survival are also dependent upon the SFE of a cluster. The higher the SFE, the less disruptive is the gas expulsion mechanism, and the higher the maximum scalelength required for survival. The clusters in the sample that require low SFEs to produce the observed profiles would not be expected to be able to survive within the Galaxy for a significant length of time. Those clusters with high  $\gamma$  and so, presumably, high SFEs may be able to survive for a Hubble time within the Galaxy.

Considering the less disruptive nature of the environment around the LMC, many of these sample clusters may be expected to survive for a significant length of time ( $\gtrsim 1$  Gyr). NGC 2156 and 2164 in particular would appear to be strong candidates for clusters that could survive for a significant time, even within the Galactic environment, if their IMF slopes are sufficiently high.

At the other extreme, NGC 1818, 2159 and 2214 would almost certainly not be able to survive for any significant length of time in the Galaxy, and maybe not for more than a few hundred Myr even within the LMC. Their low implied SFEs and high core radii are indicative of weakly bound clusters.

#### 4.3 The IMF slope

The slope of the IMF significantly affects the structure and evolution of clusters. The discussion of the effect of the IMF slope is included separately, as it is the least well known of the structural parameters that will affect these clusters. As noted in Section 2.3, values for the IMF slope vary widely between clusters and the methods used to determine them, even within the same cluster. None of these methods is entirely reliable, and selection of the correct value of the IMF slope from the present literature appears impossible. For these reasons the effect of the IMF slope is discussed for all apparently reasonable values.

A note of caution should be added here about the slope of the IMF. The long-term survivability of globular clusters is highly dependent upon this quantity (Chernoff & Shapiro 1987; Chernoff & Weinberg 1990). If the young LMC globular clusters do, indeed, have as low a slope to their IMFs as suggested by some studies (see Section 2.2), then the possibility of their surviving for any significant time, even in the LMC, would appear minimal. Chernoff & Weinberg (1990) find that, for IMF slopes lower than  $\alpha = 1.5$ , a cluster cannot survive for a Hubble time with any reasonable initial conditions (and certainly not for the initial conditions implied for these clusters in this paper).

It seems highly improbable that the slope of the mass function could have been altered greatly by dynamical processes from the slope of the IMF in such young clusters. Multi-mass simulations including a tidal cut-off show a very minor change in the mass function after residual gas expulsion from the preferential escape of low-mass particles ( $\alpha = 2.35$  drops to  $\alpha \approx 2.25$ ). It must be noted, however, that any mass effects would be considerably dampened by the significant softening used in the simulations.

### 5 DISCUSSION

This paper has presented the results of a comparison of observations of young ( $\lesssim 100$  Myr) Large Magellanic Cloud (LMC) globular clusters with  $N$ -body simulations of globular clusters. The  $N$ -body simulations were based on Aarseth's (1996) NBODY2 code. Stellar evolutionary mass loss and a variable external potential used to simulate the expulsion of residual gas (that gas not used to form stars in the initial burst of star formation in the globular cluster) were included in the code.

The aim of the paper was to explore the initial conditions which gave rise to these young globular clusters. The initial conditions of particular interest were the initial spatial and energy distributions of the stars and the star formation efficiency (SFE) of the proto-cluster. The initial mass function (IMF) slope was varied between 2.35 (the Salpeter value) and 1.50, covering the mid- to upper range of the observed values.

The simulations were compared primarily with the observations of eight young LMC globular clusters made by Elson et al. (1987, EFF). EFF found best-fitting luminosity profiles for these clusters and deprojected these to give density profiles. These density profiles were integrated to obtain the mass distribution. The observed and simulated mass distributions were compared to find which initial conditions gave a good representation of the observations.

A simple statistical analysis of the observations from EFF shows that there is apparently no correlation between profile shape and any other measured parameter of the cluster. It is suggested that the prime mechanism for setting the profiles of these young globular clusters comprises the value of the SFE and the residual gas expulsion whose disruptive effect depends upon it.

It is suggested that the variety of young globular clusters observed in the LMC could have been produced from a fairly uniform population of proto-cluster clouds which form stars in a relaxed distribution (similar to a Plummer model with length-scale  $1 < R_s/\text{pc} < 3$ ), with SFEs from 25 to 60 per cent, where the residual gas was expelled by a supershell caused by the supernovae of the most massive stars in the cluster. These scalelengths correspond to central densities similar to those found in giant molecular clouds in the Galaxy (Harris & Pudritz 1994).

The present understanding of star formation, especially in dense environments such as those presumably present in proto-cluster clouds, is not good enough to answer the question of why SFEs should vary so much between different globular clusters (if, indeed, they do). The presence and strength of magnetic fields within the proto-cluster cloud may have a significant effect upon the SFE. The rotation of a proto-cluster cloud could, also, produce an effect upon the SFE.

The most uncertain assumption made is that the initial distribution of the clusters is similar to a Plummer model. This assumption is made partly on the basis of simplicity (and the ability to use a simplification of the complex hydrodynamics of gas expulsion) and partly on the basis of observations of NGC 2070 (Section 2.3). Kennicutt & Chu (1988) question the physical significance of the good fit given by star counts in NGC 2070 to an isothermal profile, as stars still appear to be forming in NGC 2070 and most of the stars to which they fit their profile will, they suggest, disappear over a few tens of Myr. As Kennicutt & Chu's survey only includes stars with  $M > 10 M_\odot$ , this would appear to be so. However, it seems reasonable to assume (in the absence of evidence to the contrary) that these stars would trace the underlying low-mass stellar distribution. In this case the use of a Plummer model would seem not to be too unreasonable a first approximation, especially if the high-mass stars are clumped more than the low-mass stars (i.e. the mass-to-light ratio is not constant).

The stellar population may not be virialized, and the effect that this may have has been discussed in Section 4.1. These simulations also assumed that the velocity distribution is isotropic, which may well not be the case. These clusters are probably rotating and may have other ordered internal motions. What effects these may have is difficult to estimate, but they are assumed to be minimal, especially when compared with the effects of the residual gas expulsion phase.

Whatever the initial stellar distribution function, it is possible to say that in a very short period of time ( $< 20$  Myr) these young globular clusters are well described by King models in their central regions (Chrysovergis et al. 1989), which would suggest that, by this time, they are relaxed. A paper is in preparation in which the effects of a clumpy initial distribution will be investigated. Results appear to show that violent relaxation is able to erase substructure very rapidly; however, the profiles of very clumpy initial distributions are not compatible with observation.

The result that the three coeval clusters (NGC 2156, 2159 and 2172) within the quartet have profiles consistent with very similar initial proto-cluster conditions, but different SFEs, is interesting. These initial conditions are also consistent with those derived for the quartet's fourth member, NGC 2164. Interestingly, the age difference between NGC 2164 ( $\tau = 98$  Myr) and the quartet's other members ( $\tau = 65$  Myr) may suggest that the formation of the other three clusters has been triggered by the residual gas expulsion from NGC 2164. This is a similar scenario to that envisioned for the young LMC double globular cluster NGC 1850 (Gilmozzi et al. 1994).

If, as appears possible, these young LMC clusters are analogues to the young Galactic population in the epoch of globular cluster formation (10 to 15 Gyr ago), they may provide information on that population. As only two or three of the clusters in this sample are good candidates for survival in the Galaxy, this may imply that the initial Galactic population was far larger than that observed today. However, a full analysis of the possible survivability is dependent upon the slopes of the IMFs, which are poorly known, as well as upon full simulations of globular cluster evolution.

## 6 CONCLUSIONS

The conclusions of this paper may be briefly summarized as follows.

- (i) The variety of young globular clusters in the LMC can be explained if they all formed in large proto-cluster clouds with a distribution similar to a Plummer model and with a scalelength of 1 to 3 pc (the majority with a scalelength of around 2 pc). The effects of residual gas expulsion would explain the differences in profiles between clusters if their star formation efficiencies varied between 25 and 60 per cent.
- (ii) The three coeval clusters from the quartet (NGC 2156, 2159 and 2172) have profiles consistent with very similar initial conditions with  $R_s \approx 2.4$  pc if their star formation efficiencies were  $\approx 40$ , 25 and 60 per cent respectively. Their age (65 Myr) is also consistent with their star formation being triggered by the expulsion of residual gas from the quartet's fourth member, NGC 2164 ( $\tau = 98$  Myr).
- (iii) If these clusters have an initial mass function slope similar to the Salpeter value (2.35), then three of the clusters (NGC 1818, 2159 and 2214) would appear to be good candidates for globular clusters that may be able to survive for a Hubble time within the Galaxy. Within the LMC, NGC 2156 and 2172 may also be able to survive for a Hubble time.
- (iv) If the initial mass function slope of these clusters were much lower than 2.35 then none of these clusters would be expected to survive for a significant time in the Galaxy. Even survival for more than a few Gyr within the LMC would seem unlikely due to the large amounts of mass loss from stellar evolution.
- (v) If these clusters do represent a young analogue to the Galactic globular clusters then the initial number of globular clusters in our Galaxy will have been far higher than is observed today. The disruption of clusters from evaporation considered in this paper would be heightened by other processes such as bulge and disc shocking. The present globular cluster population of the Galaxy may represent only a small proportion of the original population.

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## REFERENCES

- Aarseth S. J., 1996, in Benz W., Barnes J., Müller E., Norman M. L., eds, *Computational Astrophysics: Gas Dynamics and Particle Methods*. Springer-Verlag, Berlin, p. 377

- Aarseth S. J., Hénon M., Wielen R., 1974, *A&A*, 37, 183
- Banks T., Dodd R. J., Sullivan D. J., 1995, *MNRAS*, 274, 1225
- Bhatia R. K., MacGillivray H. T., 1988, *A&A*, 203, L5
- Brown J. H., Burkert A., Truran J. W., 1995, *ApJ*, 440, 666
- Casertano S., Hut P., 1985, *ApJ*, 298, 80
- Chernoff D. F., Shapiro S. L., 1987, *ApJ*, 322, 113
- Chernoff D. F., Weinberg M. D., 1990, *ApJ*, 351, 121
- Chrysovergis M., Kontizas M., Kontizas E., 1989, *A&AS*, 77, 357
- Chu Y., Kennicutt R. C., 1994, *ApJ*, 425, 720
- Elson R. A. W., 1991, *ApJS*, 76, 185
- Elson R. A. W., Fall S. M., Freeman K. C., 1987, *ApJ*, 323, 54 (EFF)
- Elson R. A. W., Fall S. M., Freeman K. C., 1989a, *ApJ*, 336, 734
- Elson R. A. W., Freeman K. C., Lauer T. R., 1989b, *ApJ*, 347, L69
- Fukushige T., Heggie D. C., 1995, *MNRAS*, 276, 206
- Giersz M., Heggie D. C., 1996, *MNRAS*, 279, 1037
- Gilmozzi R., Kinney E. K., Ewald S. P., Panagia N., Romaniello M., 1994, *ApJ*, 435, L43
- Girardi L., Chiosi C., Bertelli G., Bressan A., 1995, *A&A*, 298, 87
- Goodwin S. P., 1997, *MNRAS*, 284, 785 (Paper I)
- Harris W. E., Pudritz R. E., 1994, *ApJ*, 429, 177
- Heggie D. C., 1995, preprint, available from astro-ph@xxx.lanl.gov, astro-ph/9511124
- Heggie D. C., Mathieu R. D., 1986, in Hut P., McMillan S., eds, *The Use of Supercomputers in Stellar Dynamics*. Springer, New York, p. 233
- Hodge P. W., 1983, *ApJ*, 264, 470
- Iben I., Renzini A., 1983, *ARA&A*, 21, 271
- Kennicutt R. C., Chu Y., 1988, *AJ*, 95, 720
- King I. R., 1966, *AJ*, 70, 376
- Lada C. J., Margulis M., Dearborn D., 1984, *ApJ*, 285, 141
- Larson R. B., 1986, in Faber S., ed., *Nearly Normal Galaxies*. Springer, New York, p. 26
- Lee M. G., 1992, *ApJ*, 399, L133
- Lin D. N. C., Murray S. D., 1991, in Janes K., ed., *ASP Conf. Ser. Vol. 13, The Formation and Evolution of Star Clusters*. Astron. Soc. Pac., San Francisco, p. 55
- Lupton R. H., Fall S. M., Freeman K. C., Elson R. A. W., 1989, *ApJ*, 347, L201
- Maeder A., Meynet G., 1988, *A&AS*, 76, 411
- Mateo M., 1988, *ApJ*, 331, 261
- Meylan G., 1993, in Smith G. H., Brodie J. P., eds, *ASP Conf. Ser. Vol. 48, The Globular Cluster–Galaxy Connection*. Astron. Soc. Pac., San Francisco, p. 588
- Moffat A. F. J., Sweggewiss W., 1983, *A&A*, 124, 83
- Paresce F., De Marchi G., Romaniello M., 1995, *ApJ*, 440, 216
- Sagar R., Richtler T., 1991, *A&A*, 250, 324
- Sagar R., Richtler T., de Boer K. S., 1991, *A&A*, 249, L5
- Salpeter E. E., 1955, *ApJ*, 121, 161
- Tenorio-Tagle G., Bodenheimer P., Lin D. N. C., Noriega-Crespo A., 1986, *ApJ*, 221, 635
- van den Bergh S., 1991, *ApJ*, 369, 1
- van den Bergh S., Morbey C. L., 1984, *ApJ*, 283, 598
- Will J.-M., Bomans D. J., de Boer K. S., 1995, *A&A*, 295, 54

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