Mass Segregation in Young LMC Clusters

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Abstract

We present the detailed analysis of Hubble Space Telescope observations of the spatial distributions of different stellar species in two young compact star clusters in the Large Magellanic Cloud (LMC), NGC 1805 and NGC 1818. Based on a comparison of the characteristic relaxation times in their cores and at their half-mass radii with the observed degree of mass segregation, it is most likely that significant primordial mass segregation was present in both clusters, particularly in NGC 1805. Both clusters were likely formed with very similar initial mass functions (IMFs). In fact, we provide strong support for the universality of the IMF in LMC clusters for stellar masses \( m_\star \gtrsim 0.8 M_\odot \).

1 Strong mass segregation on short time-scales

One of the major uncertainties in modern astrophysics is the issue of whether the stellar initial mass function (IMF) is universal or, alternatively, determined by environmental effects. Galactic globular clusters and rich, compact Magellanic Cloud star clusters are ideal laboratories for providing strong constraints on the universality of the IMF, in particular because they are essentially single age, single metallicity systems for which statistically significant samples of individual stars over a range of masses can easily be resolved.

Although the standard picture, in which stars in dense clusters evolve rapidly towards a state of energy equipartition through stellar encounters – with the corresponding mass segregation – is generally accepted, observations of various degrees of mass segregation in very young star clusters (e.g., de Grijs et al.)
2002a,b and references therein) suggest that at least some of this effect is related to the process of star and star cluster formation itself.

The effects of mass segregation in star clusters, with the more massive stars being more centrally concentrated than the lower-mass stars, clearly complicates the interpretation of an observed luminosity function (LF) at a given position within a star cluster in terms of its IMF. Without reliable corrections for the effects of mass segregation, hence for the structure and dynamical evolution of the cluster, it is impossible to obtain a realistic global cluster LF. Quantifying the degree of actual mass segregation is thus crucial for the interpretation of observational luminosity and mass functions (MFs) in terms of the IMF, even for very young star clusters.

The time-scale for the onset of significant dynamical mass segregation is comparable to the cluster’s dynamical relaxation time (Spitzer & Shull 1975, Inagaki & Saslaw 1985, Bonnell & Davies 1998, Elson et al. 1998). A cluster’s characteristic time-scale may be taken to be its half-mass (or median) relaxation time, i.e., the relaxation time at the mean density for the inner half of the cluster mass for cluster stars with stellar velocity dispersions characteristic for the cluster as a whole (Spitzer & Hart 1971, Lightman & Shapiro 1978, Meylan 1987, Malumuth & Heap 1994, Brandl et al. 1996), and can be written as (Meylan 1987):

\[ t_{r,h} = (8.92 \times 10^5) \frac{M_{\text{tot}}^{1/2}}{\langle m \rangle} \frac{R_h^{3/2}}{\log(0.4 \frac{M_{\text{tot}}}{\langle m \rangle})} \text{yr}, \]  

(1)

where \( R_h \) is the half-mass (median) radius (in pc), \( M_{\text{tot}} \) the total cluster mass, and \( \langle m \rangle \) the typical mass of a cluster star (both masses in \( M_\odot \)).

Although the half-mass relaxation time characterises the dynamical evolution of a cluster as a whole, significant differences are expected locally within the cluster. From Eq. (1) it follows immediately that the relaxation time-scale will be shorter for higher-mass stars (greater \( \langle m \rangle \)) than for their lower-mass companions. From this argument it follows that dynamical mass segregation will also be most rapid where the local relaxation time is shortest, i.e., near the cluster centre (cf. Fischer et al. 1998, Hillenbrand & Hartmann 1998). The relaxation time in the core can be written as (Meylan 1987):

\[ t_{r,0} = (1.55 \times 10^7) \frac{v_s R_{\text{core}}^2}{\langle m_0 \rangle \log(0.5 \frac{M_{\text{tot}}}{\langle m \rangle})} \text{yr}, \]  

(2)

where \( R_{\text{core}} \) is the cluster core radius (in pc), \( v_s \) (km s\(^{-1}\)) the velocity scale, and \( \langle m_0 \rangle \) the mean mass (in \( M_\odot \)) of all particles in thermal equilibrium.

It should be kept in mind, however, that even the concept of a “local relaxation time” is only a general approximation, as dynamical evolution is a continuing process. The time-scale for a cluster to lose all traces of its initial conditions also depends on the smoothness of its gravitational potential, i.e. the
number of stars (Bonnell & Davies 1998), the degree of equipartition reached (e.g., Hunter et al. 1995), and the slope of the MF (e.g., Lightman & Shapiro 1978, Inagaki & Saslaw 1985, Pryor et al. 1986, Sosin 1997), among others.

In addition, as the more massive stars move inwards towards the cluster centre, their dynamical evolution will speed up. This process will be accelerated if there is no (full) equipartition (cf. Inagaki & Saslaw 1985), thus producing high-density cores very rapidly, where stellar encounters occur very frequently and binary formation is thought to be very effective (cf. Inagaki & Saslaw 1985, Elson et al. 1987). This may accelerate the mass segregation even more significantly (e.g., Nemec & Harris 1987, De Marchi & Paresce 1996, Bonnell & Davies 1998, Elson et al. 1998). This process will act on similar (or slightly shorter) time-scales as the conventional dynamical mass segregation (cf. Nemec & Harris 1987, Bonnell & Davies 1998, Elson et al. 1998).

2 Mass segregation and implications for the IMF

We obtained F555W and F814W HST/WFPC2 imaging observations of two young compact LMC clusters, NGC 1805 (∼ 10 Myr) and NGC 1818 (∼ 25 Myr), covering a large range of radii (see de Grijs et al. 2002a for observational details). The radial dependence of the LF and MF slopes indicate clear mass segregation in both clusters at radii \( r \lesssim 3 - 6R_{\text{core}} \) (de Grijs et al. 2002a,b).

In Fig. 1a we show the dependence of the cluster core radius on the adopted magnitude (mass) range. For both clusters we clearly detect the effects of mass segregation for stars with masses \( \log(m/M_\odot) \gtrsim 0.2 \) (\( m \gtrsim 1.6M_\odot \)). Stars with masses \( \log(m/M_\odot) \gtrsim 0.4 \) (\( m \gtrsim 2.5M_\odot \)) show a similar concentration, while a trend of increasing core radius with decreasing mass (increasing magnitude) is apparent for lower masses.

Elson et al. (1987) estimated the central velocity dispersion in NGC 1818 to be in the range \( 1.1 \lesssim \sigma_0 \lesssim 6.8 \) km s\(^{-1}\). Combining this central velocity dispersion, the core radius of \( \approx 2.6 \) pc (de Grijs et al. 2002a,b), and the cluster age of \( \approx 25 \) Myr, we estimate that the cluster core is between \( \sim 5 \) and \( \sim 30 \) crossing times old, so that dynamical mass segregation in the core should be well under way. Although we do not have velocity dispersion information for NGC 1805, it is particularly interesting to extend this analysis to this younger (∼ 10 Myr) cluster. We know that its core radius is roughly half that of NGC 1818 (de Grijs et al. 2002a,b), and its mass is a factor of ∼ 10 smaller. Simple scaling of Eq. (1) shows then that the half-mass relaxation time of NGC 1805 is \( \sim 4 - 5 \times \) as short as that of NGC 1818; if we substitute the scaling laws into Eq. (2), we estimate that the central velocity dispersion in NGC 1805 is \( \gtrsim 10 \times \) smaller than that in NGC 1818. From this argument it follows that the cluster core of NGC 1805 is \( \lesssim 3 - 4 \) crossing times old.

However, since strong mass segregation is observed out to \( \sim 6R_{\text{core}} \) and \( \sim 3R_{\text{core}} \) in NGC 1805 and NGC 1818, respectively, for stellar masses in excess
of $\sim 2.5 M_\odot$, it is most likely that significant primordial mass segregation was present in both clusters, particularly in NGC 1805 (cf. Fig. 1b).

Within the uncertainties, we cannot claim that the slopes of the outer MFs in NGC 1805 and NGC 1818 are significantly different, which therefore implies that these clusters must have had very similar IMFs. In fact, in de Grijs et al. (2002c) we extended our study of mass segregation in clusters of various ages to a sample of six rich LMC clusters, selected to include three pairs of clusters of similar age (roughly $10^7$, $10^8$ and $10^9$ yr old), metallicity, and distance from the LMC centre, and exhibiting a large spread in core radii between the clusters in each pair. The large spread in core radii in any given cluster pair was chosen because the core radius distribution of rich LMC clusters systematically increases in both upper limit and spread with increasing cluster age (e.g., Mackey & Gilmore 2002 and references therein).

All clusters show clear evidence of mass segregation: (i) their luminosity function slopes steepen with increasing cluster radius, and (ii) the brighter stars are characterized by smaller core radii. For all sample clusters, both the slope of the luminosity function in the cluster centres and the degree of mass segregation are similar to each other, within observational errors of a few tenths of power-law slope fits to the data. This implies that their initial mass functions must have been very similar, down to $\sim 0.8 - 1.0 M_\odot$ (cf. de Grijs et al. 2002c).

We therefore rule out IMF variations as the main driver of the increasing

Figure 1: (a) – Core radii as a function of magnitude (mass) for both clusters. The error bars are driven by uncertainties in the background subtraction; fitting ranges are indicated at the bottom of the panel. The horizontal dashed lines represent the overall core radii from the clusters’ surface brightness profiles. (b) – Half-mass relaxation time as a function of mass for NGC 1805 and NGC 1818. The best age estimates for both clusters are indicated by horizontal dashed lines.
spread of cluster core radii with age (e.g., Elson et al. 1989).

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