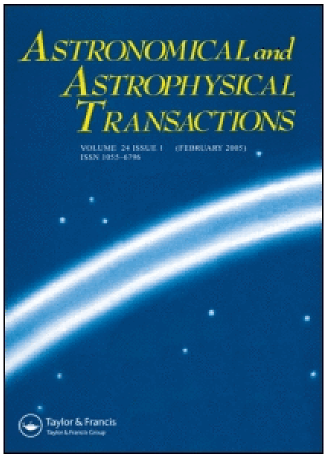

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THE ROLE OF CENTRAL DENSITY IN THE EVOLUTION AND FORMATION OF LMC CLUSTERS. OBSERVATIONAL EVIDENCE

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The central density ϱ_0 in $M_{\odot}$ pc^{-3} of a stellar system is known to be one of the principal parameters determining its dynamical history and disruption time. The central density of young populous clusters seems also to be a predominant parameter for mass segregation effects. The theoretical definition of bound or unbound stellar systems, based on their central density and the corresponding observational constraints regarding their classification (in stellar associations and open or globular clusters) are discussed. We also present our results on the spatial distribution of the star clusters in the LMC and SMC according to their central density, and the possible explanations for cluster formation in galaxies, which can be derived from these distributions.

KEY WORDS Magellanic Clouds – Galaxy – Globular clusters, open clusters and associations: general

1 INTRODUCTION

It is known that stars are formed in groups, which vary from binaries to very large stellar aggregates. The variety of these systems, their formation, evolution and their final survival are very important astrophysical topics from both the stellar and the galactic point of view. Any stellar group, which exceeds in number density the local density, is called a stellar system (star cluster or stellar association). The definition and the classification of the various systems has for many years and still is, been a subject for debate among astronomers as the observational evidence increases dramatically with technology. The role of (*i*) self gravity due to the total mass of the stars in the system and the local environment and (*ii*) the mechanisms dominating each stage during its lifetime, are the major subjects of investigation.

The structural parameters and their evolution, the spatial distribution of stars of various masses in each system during its lifetime, the important time scales and the distribution of the various systems in the parent galaxy, are among the many questions towards our understanding of the astrophysics of stellar systems. Structural parameters such as (*i*) the core radius r_c, showing the scale of the central density peak, (*ii*) the tidal radius, r_t, a limiting radius showing the influence of the environment and (*iii*) their fraction r_t/r_c, a measure of the central concentration (King, 1966, 1980) well describe the stellar systems after they are formed.

From the time a system is formed until its dissolution these structural parameters suffer significant changes, because of the continuous energy redistribution. These changes are due to (1) the primordial gas behaviour, (2) the encounters of the star members between themselves (two body encounters), (3) each individual star being acted upon by the time changing potential of the system as a whole (violent relaxation; Lynden-Bell, 1967), (4) the existence of binaries, (5) rotation, etc (Chandrasekhar, 1943; von Hoerner, 1957; Spitzer, 1969, 1975; Ligthman and Shapiro, 1977; Spurzem, 1996, 1997).

The time scales during which major changes occur in stellar systems are determined by the mechanisms dominating each specific era of the system's lifetime, and the most significant parameters are the total number of stars and the central density (Lightman and Shapiro, 1978; Meylan and Heggie, 1997 and references therein).

The central density and its role as one of the dominant parameters for several aspects of stellar systems studies is reviewed . All available observational evidence (concerning the central density of LMC stellar systems) showing its importance to all stages of stellar systems' lifetimes are given and discussed in connection with the theoretical models.

2 DENSITY AND THE CLASSIFICATION OF STELLAR SYSTEMS

The stellar systems can be classified according to various parameters, such as their stellar content (young, old), their morphology (globular, open), their formation stage (embedded or protoclusters, exposed) and their dynamical status (bound, unbound). The latter is a basic definition that was used very early to distinguish two major classes of systems. The systems in the first class are very strongly gravitationally bound, so they would survive as long as the parent galaxy exists, whereas the systems in the second class have a very limited lifetime of dissolution and they are a continuous source of enrichment of field stellar populations in the parent galaxy.

However the term 'globular cluster' (GC) has several times been misinterpreted, when the definition implies that the prototypes are the GCs of our Galaxy (Richtler

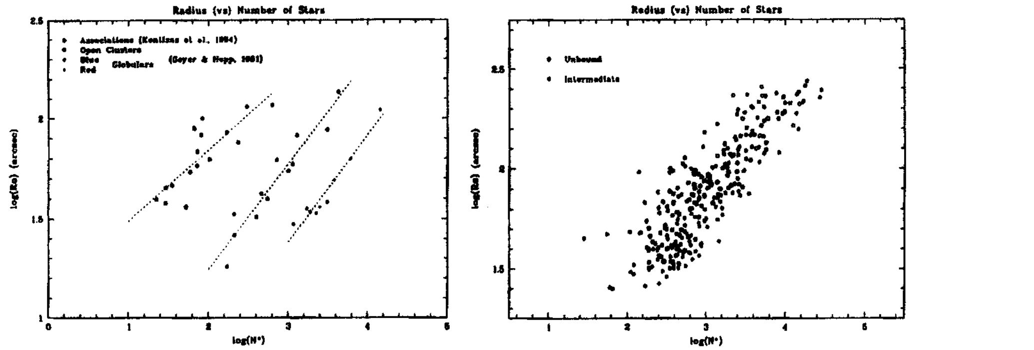

Figure 1 The relation between the total number of stars and the central density for the various stellar systems. *Left:* Systems detected by eye (Kontizas *et al.*, 1994; Geyer and Hopp, 1981). *Right:* Results of an objective detection based on the value of ϱ_0 (Gouliermis *et al.*, 2000a, b).

et al., 1998). Therefore the young globular-like young LMC clusters are not proper GCs. But in terms of bound–unbound we could say that morphologically and dynamically they are true bound GCs.

The 'bound' systems are characterised by their high central mass volume density. If this density is high enough to render the group stable against tidal disruption (a) by the galaxy and (b) by passing interstellar clouds, then we can set critical values which are $\varrho_0 \gtrsim 0.1 M_\odot$ pc^{-3} (Bok, 1934) in the first case and $\varrho_0 \gtrsim 1.0 M_\odot$ pc^{-3} (Spitzer, 1975) in the second case, assuming conditions known for our Galaxy. A system is '*bound*' when its total energy (potential and kinetic) is negative, whereas it is '*unbound*' when the total energy is positive. According to these definitions a system with high internal velocities will be soon 'unbound', even if initially ϱ_0 exceeds the value of $1.0 M_\odot$ pc^{-3}. Under these assumptions one could use the central stellar density as the criterion for detecting loose stellar systems such as the associations and open clusters in galaxies (Figure 1).

In a systematic survey of a large part (6.°5 × 6.°5) around the Bar of the LMC we have performed star counts and detected all stellar systems that were found to have a density above 3σ relative to the local field (Gouliermis *et al.*, 2000b). This criterion allows us to develop an objective method of detecting stellar systems, including those already found by eye a long ago. The central density (within the region where half of the total number of stars were found in each system) was used as the first criterion to classify the detected systems according to the limits of 0.1 and 1.0 $M_\odot$ pc^{-3}, mentioned above (Gouliermis *et al.*, 2000a).

All the systems with $\varrho_0 \leq 0.1 M_\odot$ pc^{-3} are most probably stellar associations (*unbound* systems in Figure 1 (right)). The systems with $0.1 M_\odot < \varrho_0 < 1.0 M_\odot$ pc^{-3} are classified as *intermediate* stellar systems with characteristics resembling those of open clusters (Figure 1 (right)). The conventional globular clusters were found with central densities exceeding the critical values confirming that they are dynamically 'bound'

3 THE ROLE OF DENSITY IN THE FORMATION AND DYNAMICAL EVOLUTION OF CLUSTERS

Although the mechanisms and the nature of formation of clusters are different to its dynamical evolution, observational evidence and theoretical assumptions do not allow us a completely separate study of the two clusters' lifetimes. The formation of clusters occurs in dense cores of molecular clouds. To understand this process we need to solve two problems: (a) how dense cores form in giant molecular clouds and (b) how this core is fragmented into stars.

If we accept that at the beginning of its life a GC has a very small potential energy, the collapsing protocluster should have a small final radius and a small mass loss rate, in order to be able to survive and continue its life as a bound system. The ionised mass around a hot star depends on the density, meaning that the higher the density, the less ionised mass there is (small Strömgren sphere). Therefore dense protoclusters suffer less mass loss and the star formation efficiency is higher, allowing us to assume a primordial role of density. To achieve a dense protocluster core, Murray and Lin (1996) argued that fragmentation must be delayed, by a longer cooling time, during which thermal instabilities grow. The cooling time t_c depends on the cooling function Λ, the density of hydrogen nuclei n, the ionization fraction X and the temperature T. The low metallicity of the Magellanic Clouds (MCs) favours a long cooling time and therefore the occurrence of young GCs, with originally dense cores.

The next main question is where stars of different masses form. There are several theoretical scenarios favouring central or peripheral mass segregation of massive stars or no mass segregation at all (Lynden-Bell, 1967; Shu, Adams and Lizano, 1987; Murray and Lin, 1996). Does the central density play a critical role in this effect? There are several models which favour primordial massive star central segregation in GCs but no definite answer has yet been found. However, there is observational evidence allowing us to approach this problem.

3.1 The Case of 'Young GCs' in the LMC, SMC

We will present results from HST observations of populous young MC clusters, since these observations enable us to check the distribution at the innermost cluster regions. Fischer *et al.* (1998) published an extensive work on NGC 2157 where they found that mass segregation is observed and it is most likely an initial condition of the cluster stars. In a recent investigation of four clusters from our HST data, two of them (NGC 1818 and NGC 2100) were found with clear indications of mass segregation, whereas NGC 2004 and NGC 330 show no such evidence (Kontizas *et al.*, 2000). Among the diagnostics for central mass segregation, the cumulative luminosity functions (LFs) show that their slopes at the inner regions of the clusters are different from those in the outer regions if the clusters demonstrate the phenomenon, otherwise the slopes are the same (Figure 2). Mass segregation is also observed with AAT in the young LMC GCs NGC 2098 and SL 666 (Kontizas

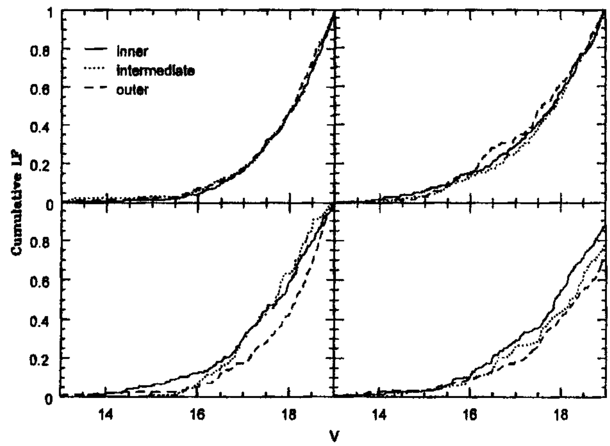

Figure 2 The cumulative luminosity function for stars on the main sequence in the clusters NGC 330 (top left), NGC 1818 (bottom left), NGC 2004 (top right) and NGC 2100 (bottom right) in three radial zones.

et al, 1998). In all cases the clusters are young and whenever mass segregation is observed, it is most likely primordial. Thus, one may ask *why sometimes mass stratification is observed and in other cases not.* We considered metallicities, the location in the parent galaxy and ages for all the clusters of our sample observed with HST and AAT. None of these parameters seem to be relevant to the occurrence of mass segregation. The only parameter which seems to be partially relevant is the central surface density. Specifically, direct counts at the clusters centres on the PC frames of the WFPC2 HST observations give values of 7.96, 0.42, 17.33 and 26.42 stars pc^{-2} for NGC 1818, NGC 2100, NGC 2004 and NGC330 respectively. So it appears that mass segregation is not present in clusters with very high central densities.

Still, in all four cases the clusters are too young to have relaxed by a slow two-body encounter mechanism through dynamical evolution. Therefore the observed mass segregation is most likely primordial. The models of cluster formation by Murray and Lin (1996) show that, under some specific circumstances, the high density in the centre of massive protoclusters may prevent mass segregation within the cluster core. In a more recent investigation by Raboud and Mermilliot (1998) it was found that very young open clusters exhibit initial mass segregation of the massive stars in their centre. Indeed open clusters in our galaxy are all less dense systems than GCs and therefore, if they are not dynamically relaxed, they are expected to present primordial mass segregation.

3.2 Dynamical Evolution and Development of Mass Stratification

Contrary to the previous problem, it is well established that dynamical evolution leads to mass stratification with the most massive stars centrally concentrated. If

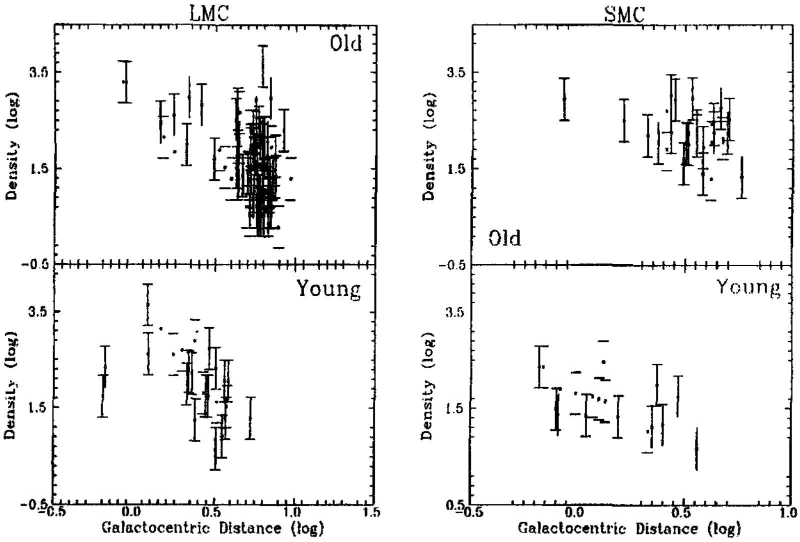

Figure 3 Spatial distribution of central densities ϱ_0, (vs) galactocentric distance R_{gc}, for the young and old LMC (left) and SMC (right) clusters.

two mass groups of stars with mass m_1, m_2 respectively and number densities n_1, n_2 are present in a cluster, there are encounters between the two groups, which change the mean energy of each group and the corresponding equipartition times $t_{eq}(1,2)$, $t_{eq}(2,1)$. However conservation of energy requires that:

$$\frac{t_{eq}(1,2)}{n_1} = \frac{t_{eq}(2,1)}{n_2} \quad \text{(Spitzer, 1975).}$$

It is therefore evident that the density of each group of stars plays an important role. In specific cases of ratios of n_2/n_1 the equipartition time becomes shorter than the mean relaxation time t_r and mass stratification occurs somewhat earlier than t_r. In our Galaxy it is demonstrated that normal dynamical segregation of mass is common since the GCs of the Galaxy are old enough to have ages several times the t_r. Among the most recent relevant studies with HST, in cluster NGC 6397 it is found that the bright stars are centrally concentrated with a striking deficiency of faint stars (Sosin and King, 1995), not observed before. The authors conclude that it is not surprising that the dynamical segregation of masses should be very large in a cluster of high central concentration.

4 WHERE DENSE CORE CLUSTERS FORM AND SURVIVE IN A GALAXY

An important issue of the role of central density is also shown in the radial distribution of clusters according to their central density as defined before. A large

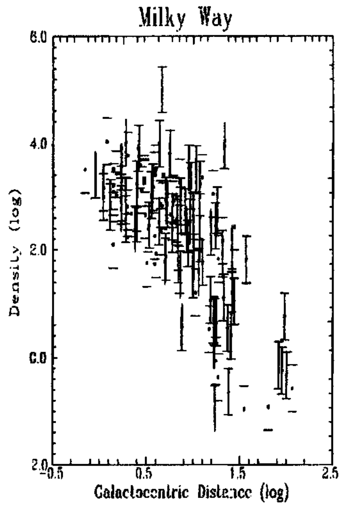

Figure 4 Spatial distribution of central densities ϱ_0, (vs) galactocentric distance R_{gc}, for the galactic globular clusters.

sample of LMC and SMC clusters, which was measured in a homogeneous data set (Kontizas *et al.*, 1990), has shown that the LMC young stellar systems with dense cores are found in the inner parts of the parent galaxy (Figure 3), whereas this is marginally the case for the older systems too (Kontizas *et al.*, 1997). However the clusters in the SMC do not exhibit such a distribution.

A similar diagram for our own Galaxy's GCs indicates a change in the slope at a distance of about 10 kpc (Figure 4). This is in agreement with the hypothesis of two GC sub-systems in our galaxy. The clusters of the system outside 9 kpc are the metal-poor ones and probably show that the outermost clusters survive even with very low central densities. This observation would mean that tidal truncation is a major mechanism of cluster disruption and it is more effective in the inner regions. On the other hand Figure 3 illustrating the behaviour of the initial distribution of the young LMC systems can be interpreted as a result of the parent galaxy's rotation (Firmani *et al.*, 1996). LMC is known to have a high rotational velocity, therefore mass and energy redistribution leads to the formation of more massive and compact clusters in the innermost regions. On the contrary this is not the case for the SMC where the rotational velocity is negligible.

Milky Way GCs represent the distribution of the oldest stellar system component. The observed slope is steeper for clusters at $R_{gc} \gtrsim 9$ Kpc, due to the initial conditions, whereas the tidal influence, for clusters of the inner system, makes the slope less steep. Therefore the observed change of slope in the spatial distribution of the GCs according to their central densities can be explained as a combination of both, an explanation reported by Surdin (1997). So the Galaxy and the LMC, two galaxies with high rotation, show a trend in the spatial distribution of the central densities of their cluster systems, with the most dense found closer to the centre of the galaxy, whereas there is no such trend in the SMC, a galaxy with negligible rotation.

5 CONCLUSION

Concluding we have to emphasise the influence of central density to all aspects of cluster formation and evolution. Although the role of this parameter is not new, the available observational capabilities only now allow us to stress its importance.

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