SF2A 2010
S. Boissier, M. Heydari-Malayeri, R. Samadi and D. Valls-Gabaud (eds)

MULTIPLE POPULATIONS IN GLOBULAR CLUSTERS: A THEORETICAL POINT OF VIEW

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Abstract. Globular clusters exhibit peculiar chemical patterns where Fe and heavy elements are constant inside a given cluster while light elements (Li to Al) show strong star-to-star variations. Besides precise photometric studies reveal that numerous globular clusters display multiple or broad main sequences, subgiant or giant branches. This peculiar chemical pattern can be explained by self-pollution of the intracluster gas occurring in the early evolution of clusters. Here the possible strong impact of fast rotating massive stars is reviewed. First providing they rotate initially fast enough they can reach the break-up velocity during the main sequence and a mechanical mass-loss will eject matter from the equator at low velocity. Rotation-induced mixing will also bring matter from the convective core to the surface. From this ejected matter loaded in H-burning material a second generation of stars will born. The chemical pattern of these second generation stars are similar to the one observed for stars in globular cluster with abundance anomalies in light elements. Then during the explosion as supernovae the massive stars will also clear the cluster of the remaining gas. If this gas expulsion process acts on short timescale it can strongly modify the dynamical properties of clusters by ejecting preferentially first generation stars.

Keywords: stars: abundances, stars: evolution, stars: mass loss, globular clusters: general, stellar dynamics, methods: N-body simulations

1 Introduction

Globular clusters are self-gravitating aggregates of tens of thousands to millions of stars that have survived over a Hubble time. Many observations show that these objects are composed of multiple stellar populations. The first evidence rests on the chemical analysis that reveals large star-to-star abundance variations in light elements in all individual clusters studied so far, while the iron abundance stays constant (for a review see Gratton et al. 2004). These variations include the well-documented anticorrelations between C-N, O-Na, Mg-Al, Li-Na and F-Na (Kraft 1994; Carretta et al. 2007; Gratton et al. 2007; Pasquini et al. 2007; Carretta et al. 2010; Lind et al. 2009). H-burning at high temperature around 75×10^6 K is required to explain this global chemical pattern (Arnould et al. 1999; Prantzos et al. 2007). As the observed chemical pattern is present in low-mass stars both on the red giant branch (RGB) and at the turn-off that do not reach such high internal temperatures, the abundance anomalies must have been inherited at the time of formation of these stars.

Besides, deep photometric studies provide another indications for multiple populations in individual GCs with the discoveries of multiple giant and sub-giant branches or main sequences. In ω Cen a blue main sequence has been discovered (Bedin et al. 2004) that is presumably related to a high content in He (Piotto et al. 2005; Villanova et al. 2007). A triple main sequence has been discovered in NGC 2808 (Piotto et al. 2007). The additional blue sequences are explainable by a higher He content of the corresponding stars which shifts the effective temperatures towards hotter values. He-rich stars have also been proposed to explained the morphology of extended horizontal branch (hereafter HB) seen in many globular clusters (see e.g., Caloi & D'Antona 2005). Whereas no direct observational link between abundance anomalies and He-rich sequences has been found, this link is easily understood theoretically as abundance anomalies are the main result of H burning to He.

These observed properties lead to the conclusion that globular clusters born from giant gas clouds first form a generation of stars with the same abundance pattern as field stars. Then a polluting source enriches

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the intracluster-medium with H-burning material out of which a chemically-different second stellar generation forms. This scheme can explain at the same time the abundance anomalies in light elements and He-enrichment.

Two main candidates that reach the right temperature for H-burning have been proposed to be at the origin of the abundance anomalies (Prantzos & Charbonnel 2006): (a) intermediate mass stars evolving on the thermal pulses along the asymptotic giant branch (hereafter TP-AGB), and (b) main sequence massive stars. After being first proposed by Cottrell & Da Costa (1981) the AGB scenario has been extensively studied (see e.g., Ventura & D'Antona 2008a,b, 2009, see Ventura, this volume) and has been seriously challenged by rotating AGB models that predict unobserved CNO enrichment in low-metallicity globular clusters (Decressin et al. 2009).

On the other hand, as being suggested by Brown & Wallerstein (1993) and Wallerstein et al. (1987), massive stars can also pollute the interstellar medium (ISM) of a forming cluster (see Smith 2006; Prantzos & Charbonnel 2006). In particular Decressin et al. (2007b) show that fast rotating massive stars (with a mass higher than $\sim 25\ M_{\odot}$) are good candidates for the self-enrichment of globular clusters. An alternative suggestion has been proposed by de Mink et al. (2009) to considered non-conservative mass-transfer from binaries stars. In the following we will only considered the consequences of the pollution by rotating massive stars.

In the wind of fast rotating massive stars (WFRMS) scenario, rotationally-induced mixing transports H-burning products (and hence matter with correct abundance signatures) from the convective core to the stellar surface. Providing initial rotation is high enough, the stars reach the break-up on the main sequence evolution. As a result a mechanical wind is launched from the equator that generates a disk around the star similar to that of Be stars (e.g. Townsend et al. 2004). Later, when He-burning products are brought to the surface, the star has already lost a high fraction of its initial mass and angular momentum, so that it no longer rotates at the break-up velocity. Matter is then ejected through a classical fast isotropic radiative wind. From the matter ejected in the disk, a second generation of stars may be created with chemical pattern in agreement with observations. Latter on when the He-burning products reach the surface the star do not rotate any longer at the critical velocity and this matter is ejected in fast radiative winds which will escape the cluster (see Decressin et al. 2007a).

2 Dynamical consequences for globular clusters

Based on the determination of the composition of giant stars in 19 globular clusters by Carretta et al. (2009b) the stars with abundance anomalies populated between 50 to 80% of the cluster stars. How to produce such a high fraction of chemically peculiar stars? The main problem is that assuming a Salpeter (1955) IMF for the polluters, the accumulated mass of the slow winds ejected by the fast rotating massive stars would only provide 10% of the total number of low-mass stars. To match the observations thus requires either (a) a flat IMF with a slope of 0.55 instead of 1.35 (Salpeter's value), or (b) that 95% of the first generation stars have escaped the cluster (Decressin et al. 2007a). Here we first verify whether such a high loss of stars is possible, and which are the main processes that could drive it.

The viability of a self-enrichment scenario by fast-rotating massive stars has been explored by Decressin et al. (2008). They have shown that first-generation low-mass stars are mainly lost from the cluster, which is assumed to initially be in dynamical equilibrium and mass-segregated, before two-body relaxation induces a spread of second generation stars and a full mixing of the cluster.* Afterwards, the evolution is smoother and the variation in the fraction of second-generation stars takes longer. Any radial difference between first and second generation stars is erased after 10-12 Gyr of evolution because the cluster relaxation time (a few Gyr) is much shorter than the age of the clusters. Even if the relaxation-driven evaporation increases the fraction of second generation (which harbour abundance anomalies) to about 25%, this ratio remains too low to fully explain the observations (between 50–80%, Carretta et al. 2009a). The increase in the fraction of second-generation stars mainly occurs in the early times and points towards the high sensitivity of the fraction of second-generation stars on cluster dynamics.

As it operates early in the cluster history (a few million years after cluster formation at the latest), initial gas expulsion by supernovae is an ideal candidate for such a process. As the gas still present after the star formation is quickly removed, it ensues a strong lowering of the potential well of the cluster so that the outer parts of the cluster can become unbound.

Baumgardt & Kroupa (2007) computed a grid of N-body models to study this process and its influence on cluster evolution by varying the free parameters: star formation efficiency, SFE, ratio between the half-mass

*D'Ercole et al. (2008) find similar results with the AGB scenario.

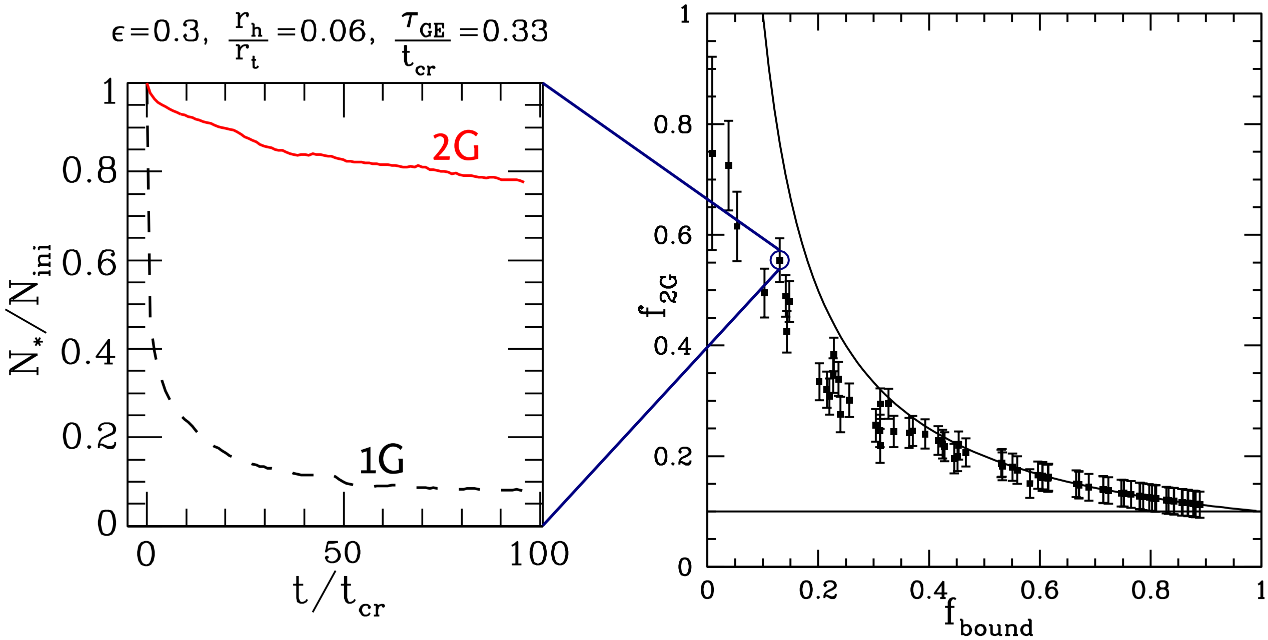

Fig. 1. *Left:* Number of first (dotted line) and second (full line) generation stars relative to their initial number as a function of time for a cluster with the following initial properties: $\epsilon = 0.3$, $r_{\rm h}/r_{\rm t} = 0.06$ and $\tau_{GE}/t_{\rm cr} = 0.33$. *Right:* Fraction of second-generation stars as a function of the final fraction of bound stars at the end of the computations of Baumgardt & Kroupa (2007), i.e., after about 100 initial crossing times. Dashed lines indicate limiting cases where no second-generation stars are lost (upper) and no preferential loss of first-generation stars occurs (lower). Estimates of the statistical errors are also included based on the number of first, N_1, and second, N_2, generation stars bound to the cluster.

and tidal radius, r_h/r_t, and the ratio between the timescale for gas expulsion to the crossing time, $\tau_M/t_{\rm Cross}$. They show in particular that, in some extreme cases, the complete disruption of the cluster can be induced by gas expulsion. This process has also been used successfully by Marks et al. (2008) to explain the challenging correlation between the central concentration and the mass function of globular clusters as found by De Marchi et al. (2007).

To explore the evolution of two distinct generation of stars, the N-body models of Baumgardt & Kroupa (2007) have been artificially divided into two populations: about 10% of the stars with initially low specific energy (i.e., low velocity stars orbiting near the cluster centre) mimic second generation stars while the others stars represent the first generation. Fig. 1 (left panel) shows that in the case of a cluster which loses around 90% of its stars, the ejection of stars from the cluster mostly concerns first generation ones. At the end of the computation only 7% of first generation stars remain bound to the cluster along with most of second generation stars. Therefore the number ratio between the second to first generation stars increases by a factor of 10: half of the population of low-mass stars still populating the cluster are second generation stars. The final fraction of second generation stars is strongly dependent of the initial properties of the cluster as shown in Fig. 1 (right panel) where this number is shown as a function of the fraction of star still bound to the cluster for the whole set of computation done by Baumgardt & Kroupa (2007) (see Decressin et al. 2010 for more details).

Thus if globular clusters are born mass segregated, dynamical processes (gas expulsion, tidal stripping and two-body relaxation) can explain the number fraction of second generation stars with abundance anomalies.

T.D. acknowledges support from the Swiss National Science Foundation (FNS) and from the "Programme National de Physique Stellaire" of CNRS/INSU, France.

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