Dynamical mixing of two stellar populations in globular clusters

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Stars in globular clusters (GCs) exhibit a peculiar chemical pattern with strong abundance variations in light elements along with a constant abundance in heavy elements. These abundance anomalies can be explained by a primordial pollution due to a first generation of fast rotating massive stars which released slow winds into the ISM from which a second generation of chemically anomalous stars can be formed. In particular the observed ratio of anomalous and standard stars in clusters can be used to constrain the dynamical evolution of GCs as around 95% of the standard stars need to be lost by the clusters. We show that both residual gas expulsion during the cluster formation and long term evolution are needed to achieve this ratio.

1 Abundance variations in globular clusters

It has long been known that globular cluster stars present some striking anomalies in their content in light elements whereas their content in heavy elements (i.e., Fe-group, \(\alpha\)-elements) is fairly constant from star to star (with the notable exception of \(\omega\) Cen). While in all the Galactic globular clusters studied so far one finds “normal” stars with detailed chemical composition similar to those of field stars of same metallicity (i.e., same \([\text{Fe}/\text{H}]\)), one also observes numerous “anomalous” main sequence and red giant stars that are simultaneously deficient (to various degrees) in C, O, and Mg, and enriched in N, Na, and Al (for recent reviews see Gratton, Sneden & Carretta 2004 and Charbonnel 2005). In Fig. 1 we present a compilation of data about the observed O-Na anticorrelation in a sample of clusters along with metal-poor halo field stars where such abundance patterns are not detected. Additionally, the abundance of the fragile Li was found to be anticorrelated with that of Na in turnoff stars in a couple of globular clusters (Pasquini et al. 2005, Bonifacio et al. 2007).

These abundance variations are expected to result from H-burning nucleosynthesis at high temperatures up to \(75 \times 10^6\) K (Denisenkov & Denisenkova 1989, 1990, Langer & Hoffman 1995, Prantzos et al. 2007). Since the low-mass stars still on the main sequence or on the RGB display such abundance variations and since these low-mass stars do not produce the required high temperatures to create abundance anomalies, it is expected that they have inherited this chemical pattern at birth.

Here we follow the work of Decressin et al. (2007b) who explore the role of a high initial rotation in such stars, finding that abundance anomalies in globular clusters can lead to an early pollution by fast rotating massive stars. Indeed during main sequence evolution, angular momentum is transported from the centre to the stellar surface, and for stars heavier than 20 \(M_\odot\) with high initial rotation, their surface reaches break-up rotational velocity at the equator (i.e., the centrifugal equatorial force balances gravity). In such a situation, a slow mechanical wind develops at the equator and forms a disc around the stars similar to what happens to Be stars (Townsend et al. 2004, Ekstrom et al. 2008). The second effect of rotation is to transport elements from the convective H-burning core to the stellar surface which enriches the disc with H-burning material. While matter in discs has a slow escape velocity and hence will stay in the potential well of the cluster, matter released during the main part of the He-burning phase and during SN explosions has a very high radial velocity and will be lost by the cluster. Therefore, new stars can only form from the matter available in discs and can become the stars with abundance anomalies we observe today. Thus globular clusters can contain two populations of low-mass stars: a first generation which has the chemical composition of the material out of which the cluster formed (similar to field stars with similar metallicity); and a second generation of stars harbouring the abundance anomalies born from the ejecta of fast rotating massive stars.

2 Number ratio between two populations in globular clusters

Based on the determination of the composition of giant stars in NGC 6752 by Carretta et al. (2007b), Decressin, Charbonnel & Meynet (2007a) determined that around 85% of stars (of the sample of 120 stars) display abundance anomalies. Prantzos & Charbonnel (2006) find similar results for NGC
ONa anticorrelation observed in several clusters and in field stars. Data for NGC 2808 are from Carretta et al. (2006); for NGC 6752 from Carretta et al. (2007b); for NGC 6218 from Carretta et al. (2007a); for NGC 6441 from Gratton et al. (2007); for M 3 and M 13 from Cohen Meléndez (2005) and Sneden et al. (2004); for M 5 from Ivans et al. (2001); for M 4 from Ivans et al. (1999); for NGC 6397 from Carretta et al. (2005); for 47 Tuc from Carretta et al. (2004); for M 10 from Kraft et al. (1995); for M 15 from Sneden et al. (1997); for M 71 from Ramírez & Cohen (2002); for NGC 288 and NGC 362 from Shetrone & Keane (2000); and field from Gratton et al. (2000).

2808 with their analysis of the data of Carretta et al. (2006): 70% of the cluster stars present abundance anomalies.

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 form 10% of the total number of the low-mass stars. To match the observations, one thus requires either (a) a flat IMF with a slope of 0.55 instead of 1.35 (Salpeter value), or (b) that 95% of the first generation unpolluted stars have escaped the cluster Decressin et al. (2007a). In this paper we want to quantify if such high loss of stars is possible and which are the main processes which drive it.

3 Dynamical evolution of globular clusters

First we assume that the globular clusters display primordial mass segregation. Thus the massive stars are located in the center of the clusters. As we expect that the formation of the second generation of low-mass stars happens locally around each massive star (see Decressin et al. 2007a for more details), the second generation of stars will also be more centrally concentrated than the first generation. In such a situation, two competitive processes act in the clusters: the loss of stars in the outer cluster parts will first reduce the number of bound first generation stars; and the dynamical spread of the initially more concentrated second generation stars will stop this differential loss when the two populations are dynamically mixed.

Our analysis based on the N-body models computed by Baumgardt & Makino (2003) with the collisional Aarseth N-body code NBODY4 (Aarseth 1999) is presented in details in Decressin, Baumgardt & Kroupa (2008).

As these models have been computed for a single stellar population, we apply the following process to mimic the formation of a cluster with two dynamically distinct popul-
Radial distribution of the first (dashed lines) and second (full lines) generation of low-mass stars at three different times. Each histogram is normalised to the total number of stars in each population.

In Fig. 2 one can see the radial distribution of the two populations at the same epochs. Initially, the second generation stars with low specific energy are concentrated within 6 pc around the centre of the cluster while stars of the first generation show a more extended distribution up to 40 pc. Progressively the second generation stars spread out due to dynamical encounters so their radial distribution extends. The middle panel in Fig. 2 shows that even after 5 Gyr of evolution the two populations have different distributions. The bottom panel of 2 shows that after nearly 12 Gyr of evolution (slightly more than 2 initial relaxation times) the two populations have similar radial distributions and can no longer be distinguished owing to their dynamical properties.

As previously seen, the effect of the external potential of the Galaxy on the cluster is to strip away stars lying in the outer part of the cluster. Initially, only stars of the first generation populate the outer part of the cluster owing to their high specific energy. Therefore only first generation stars are lost in the beginning. This lasts until the second generation stars migrate into the outer part of the cluster. Depending on the cluster mass, it takes between 1 to 4 Gyr to start a loss of second generation stars. Due to the time-delay to lose second generation stars, their remaining fraction in the cluster is always higher than that of the first generation stars except during the final stage of cluster dissolution. As a direct consequence of our selection procedure, the initial ratio is 0.1; and it then increases gradually with time. It tends to stay nearly constant as soon as the two distributions are similar. Finally, at the time of cluster dissolution (i.e., when the cluster has lost 95% of its initial mass, indicated by the label “dis” in Fig. 2), large variations occur due to the low number of low-mass stars present in the cluster. In Fig 2 we have also indicated the number of passed relaxation times, showing that the increase of the number ratio last only 3 relaxation time.

Over the cluster history, the fraction of second generation stars relative to first generation ones increases by a factor of 2.5. Therefore, when the two populations have the same radial distribution, these stars represent 25% of the low-mass stars present in the clusters. Compared to the observed ratios (70% and 85% in NGC 2808 and NGC 6752 respectively) the internal dynamical evolution and the dissolution due to the tidal forces of the host Galaxy are not efficient enough. An additional mechanism is thus needed to expel the first generation stars more effectively.
4 Gas expulsion

Initial gas expulsion by supernovae is an ideal candidate as it operates early in the cluster history (a few million years after cluster formation). As the gas still present after the star formation is removed, the potential well of the cluster can become unbound. This process has been recently investigated by Baumgardt & Kroupa (2007) who have performed a complete grid of N-body models to study its influences on the cluster evolution by varying the free parameters: star formation efficiency, SFE, ratio between the half-mass and tidal radius, $r_h/r_t$, and the ratio between the timescale for gas expulsion to the crossing time, $\tau_M/\tau_{\text{Cross}}$. In particular they show that gas expulsion can lead to the complete disruption of the cluster in some extreme cases. It should be noted that this process has already been used successfully by Marks, Kroupa, Baumgardt (2008) to explain the challenging correlation between the central concentration and the mass function of globular clusters as found by DeMarchi, Paresce & Pulone (2007).

We have repeated the same method to obtain two populations in globular clusters as we show in § 3 to the models of Baumgardt & Kroupa (2007). Fig. 4 shows that in the case of clusters which lose around 90% of their stars, most first generation stars are lost. At the end of the computation only 5% of first generation stars remain bound to the cluster and around half of second generation stars also escape the cluster. Therefore the number ratio between the second to first generation stars can only increase from 0.1 to 1: half of the low-mass stars are second generation stars. It should be noted that the radial distribution of both populations differs, the second generation stars being more centrally distributed, so that we can expect that this ratio will increase in the long-term evolution of the cluster (see Decressin et al., in preparation).

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