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Dynamical evolution of multiple populations in globular clusters

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Abstract. Spectroscopic and photometric studies have shown that many globular clusters host multiple stellar populations. Here we discuss some of the results of our investigations aimed at exploring the dynamical evolution of the structural properties of multiple-population clusters, the evolution of binary stars in multiple-populations clusters and the implications of the formation and dynamical evolution models of multiple-population clusters for the contribution of globular clusters to the assembly of the Galactic halo.

Key words. Galaxy: globular clusters

1. Introduction

The discovery of multiple stellar populations in many globular clusters (see e.g. Gratton et al. 2012 and references therein for a recent review) raises many important questions concerning the formation and dynamical evolution of these stellar systems.

In our recent studies, we have addressed some of these questions and explored the formation and early evolutionary phases of multiple-population clusters, their subsequent long-term dynamical evolution driven by two-body relaxation, the implications of the structural properties of multiple-population clusters for the evolution of a cluster binary star population and the connection between SG stars in clusters and in the Galactic halo.

We summarize here the results of our investigations.

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2. Formation and early evolution

In D'Ercole et al. (2008), we have presented a series of hydrodynamical and N-body simulations modeling the formation and early evolution of multiple-population clusters. We have focussed our attention on models in which second generation (SG) stars form from the ejecta of first generation (FG) AGB stars (Cottrell & Da Costa 1981, Ventura et al. 2001). Our simulations show that the AGB ejecta form a cooling flow and rapidly collect in the innermost regions of the cluster, forming a SG stellar subsystem segregated in the FG cluster inner regions.

In order to form the numbers of SG stars observed today, the FG cluster must have been initially much more massive and dominated by the FG population. The N-body simulations presented in D'Ercole et al. (2008) show that the early cluster expansion triggered by the loss of SN II ejecta leads to the strong preferential loss of FG stars while, the inner SG stars, are unscathed by this early evolution.

During this early evolutionary phase the cluster evolves from a configuration in which FG stars dominate to one with a similar number of FG and SG stars (or even one in which the SG stars are now the dominant population), as observed in several Galactic globular clusters (see e.g. Carretta et al. 2009a,b).

Additional models aimed at exploring the chemical evolution of multiple populations and the origin of the observed chemical patterns have been presented in D'Ercole et al. (2010, 2011, 2012).

3. Long-term dynamical evolution

At the end of the early evolutionary stages after the early loss of FG stars, a cluster will start its long-term dynamical evolution driven by two-body relaxation with a similar number of SG and FG stars and a structure still characterized by a SG subsystem concentrated in the cluster inner regions.

In Vesperini et al. (2013), by means of a survey of N-body simulations we have studied the long-term evolution and spatial mixing of multiple populations starting from a range of initial conditions characterized by different relative concentrations of the spatial distribution of the SG and the FG populations.

Our simulations follow the cluster evolution until the two populations are completely mixed. Until mixing is complete, the radial profile of the SG/FG number ratio, N_{SG}/N_{FG}, is characterized by three regions: 1) a flat inner part; 2) a declining part in which FG stars are increasingly dominant; and 3) an outer region where the N_{SG}/N_{FG} profile flattens again (the profile may rise slightly again in the outermost cluster regions).

The radial variation of N_{SG}/N_{FG} implies that the fraction of SG stars determined by observations covering a limited range of radial distances is not, in general, equal to the SG global fraction, $(N_{SG}/N_{FG})_{glob}$. $(N_{SG}/N_{FG})_{glob}$ provides a fundamental constraint for studies aimed at modeling the formation and dynamical history of multiple-population clusters and it is important to be able to understand the relationship between the observational estimates of the SG-to-FG number ratio and its actual global value. Our simulations show that the distance from the cluster center at which N_{SG}/N_{FG} equals $(N_{SG}/N_{FG})_{glob}$ is approximately between 1 and 2 cluster half-mass radii.

In Vesperini et al. (2013) the time scale for complete mixing is discussed in detail: the results of our simulations suggest that in many Galactic globular clusters SG stars should still be more spatially concentrated than FG stars. A few observational studies have explored the radial variation of the SG/FG number ratio and find that in agreement with the results of the formation and dynamical evolution models presented in D'Ercole et al. (2008) and in Vesperini et al. (2013), SG stars are more concentrated in the cluster inner regions (Bellini et al. 2009, Carretta et al. 2010a, Lardo et al. 2011, Kravtsov et al. 2010, 2011 Nataf et al. 2011, Johnson & Pilachowski 2012, Milone et al. 2012).

4. Binary disruption in multiple population clusters

As discussed above, the structural properties of multiple population clusters are characterized by the presence of a compact SG subsystem in the cluster inner regions and differ from those of simple Plummer or King models usually adopted in the study of globular clusters dynamical evolution. In Vesperini et al. (2011), we have explored the implications of the presence of a concentrated SG subcluster on the evolution of FG and SG binary stars. Binary stars play a key role in many different aspects of the evolution of globular clusters and their stellar content (see e.g. Heggie & Hut 2003 for a review) and it is important to understand their evolution in multiple-population clusters. By means of a combination of N-body simulations and analytical expressions for binary interaction rates we have explored the SG and FG binary disruption during a cluster evolution. The results of our study show that the structural properties of multiple population cluster significantly affect the properties and disruption rate of binary stars.

Our calculations show that SG binaries are, in general, disrupted at a larger rate than FG binaries and the SG population is expected to have a smaller binary fraction than the FG. The first observational study aimed at exploring the differences between the SG and FG binary fraction has been carried out by D'Orazi et al. (2010) and suggests that the fraction of SG binaries is smaller than the FG binaries in agreement with our theoretical results.

Further exploration of the evolution of binary stars in multiple population clusters by means of simulations including the self-consistent treatment of binaries are currently in progress.

5. Second generation stars in the Galactic halo and the contribution of globular clusters to the Galactic halo assembly

During a cluster long-term evolution driven by two-body relaxation some SG stars may escape and populate the Galactic halo. In Vesperini et al. (2010) we have carried out a survey of hydrodynamical simulations to estimate the number of SG stars that may have formed in Galactic globular clusters as a function of the cluster mass, structural properties and stellar initial mass function. Using the results of these simulations (see Fig. 1 in Vesperini et al. 2010) we have explored for a number of different initial structural parameters, stellar initial mass function (IMF) and initial mass function of the Galactic globular cluster system (IGCMF) the possible fraction of the Galactic halo composed of SG stars escaped from clusters.

Our study shows that for a broad range of IGCMF parameters the expected fraction of SG stars in the halo is small. In particular, assuming a Kroupa (1993) stellar IMF the fraction of SG stars in the halo is smaller than about (4-6)% while for a Kroupa (2001) stellar IMF the fraction of SG stars in the halo is smaller than about (7-9)%. The small fraction of SG halo stars predicted by our calculations are consistent with the fraction (1.5% – 2.5%) of SG stars identified in the Galactic halo by Carretta et al. (2010b) and Martell & Grebel (2010). In our study we also show the relation between the fraction of cluster SG stars in the halo and the general contribution of cluster stars (from clusters now completely dissolved and from stars escaped from clusters still surviving) to the halo population (see Fig.3 in Vesperini et al. 2010). Assuming a power-law IGCMF with index $\alpha = 1.8$, the observational values of the fraction of SG stars in the halo imply that a fraction ranging from about 20 % to about 40% of the Galactic halo must come from stars formed in globular clusters if a Kroupa (2001) IMF is adopted (30-60 % if a Kroupa (1993) IMF is adopted).

It is interesting to note that the fraction of SG stars in globular clusters and in the halo can constrain the formation and evolution of multiple population clusters and their role in the Galactic halo assembly.

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