Binary Star Disruption in Globular Clusters with Multiple Stellar Populations

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ABSTRACT
The discovery of multiple stellar populations in globular clusters raises fundamental questions concerning the formation and dynamical history of these systems. In a previous study aimed at exploring the formation of second-generation (SG) stars from the ejecta of first-generation (FG) AGB stars, and the subsequent dynamical evolution of the cluster, we showed that SG stars are expected to form in a dense subsystem concentrated in the inner regions of the FG cluster. In this paper we explore the implications of the structural properties of multiple-population clusters, and in particular the presence of the inner SG subsystem, for the disruption of binary stars. We quantify the enhancement of the binary disruption rate due to the presence of the central SG subsystem for a number of different initial conditions. Our calculations show that SG binaries, which are assumed to be more concentrated in the cluster inner regions, are disrupted at a substantially larger rate than FG binaries. Assuming a similar initial fraction of FG and SG binaries, our dynamical study indicates that the SG population is now expected to contain a significantly smaller binary fraction than the FG population.

Key words: globular clusters:general, stars:chemically peculiar, methods:N-body simulations

1 INTRODUCTION
Spectroscopic and photometric observations reveal that globular clusters host multiple stellar populations. Spectroscopic studies show star-to-star variations in the abundances of light elements, such as Na, O, Al, and Mg, indicating that a significant fraction (50-80\%) of globular cluster stars must have formed out of matter processed through a high-temperature CNO cycle in a first generation (hereafter FG) of stars (see e.g. Carretta et al. 2009a, 2009b and references therein). Photometric studies reveal the presence of multiple main sequences, subgiant, and red-giant branches in numerous clusters, supporting the spectroscopic evidence for multiple populations (see e.g. Piotto 2009 and references therein). Photometric measurements also provide evidence for a population of very He-rich stars among the second-generation (hereafter SG) stars of some clusters (see e.g. Piotto et al. 2007). These findings confirm the predictions of previous studies (D’Antona et al. 2002; D’Antona & Caloi 2004, D’Antona & Caloi 2008) that suggested the existence of a population of stars with a strong He enhancement on the basis of the extension of the horizontal branch.

The origin of the gas out of which SG stars formed is still an open question: in addition to the scenario involving AGB stars (Cottrell & Da Costa 1981, Ventura et al. 2001) described in more detail below, possible gas sources proposed in the literature also include rapidly rotating massive stars and massive binary stars (Decressin et al. 2007, De Mink et al. 2009; see also Renzini 2008 and references therein for a review). Many fundamental questions concerning globular cluster star formation and cluster chemical and dynamical history are raised by the discovery of multiple populations, and are targets of ongoing investigations (see e.g. D’Ercole et al. 2008, 2010, Vesperini et al. 2010, Bekki 2011 and references therein).

D’Ercole et al. (2008) explored the formation and dynamical evolution of multiple populations in globular cluster by means of hydrodynamical and N-body simulations, focusing on a model in which SG stars form from the ejecta of FG AGB stars. Our simulations show that the AGB ejecta form a cooling flow and rapidly collect in the innermost regions of the cluster, forming a concentrated SG stellar subsystem.
In order to form the numbers of SG stars observed today, the FG cluster must have been considerably more massive than it is now, and the majority of stars in the cluster initially belonged to the FG population. The N-body simulations presented in D’Ercole et al. (2008) show that the early expansion triggered by the loss of mass in the form of SNII ejecta and primordial gas leads to a strong preferential loss of FG stars.

According to our models, during this early evolutionary phase the cluster evolves from a configuration in which FG stars dominate to one in which the numbers of FG and SG stars are similar (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, 2009b). At the end of this early phase, the SG subsystem, although now composed of a number of stars similar to that of the FG population, is still concentrated in the cluster inner regions. The system thus begins its long-term, relaxation-driven evolution with a structure characterized by the superposition of a compact SG inner cluster and a more extended FG cluster. In the initial simulations discussed in D’Ercole et al. (2008) we showed that, as the cluster evolves, the two populations tend to mix and the characteristic structure imprinted by the SG formation process is slowly erased.

Such a peculiar structure differs significantly from the simple King or Plummer models usually adopted as initial conditions in studies of globular cluster evolution. It is therefore important to explore the implications of this unusual initial state for the long-term evolution of a cluster’s structural and kinematic properties, as well as its stellar content. This paper focuses on the effects of this new class of initial structural properties on the survival of binary stars, and on the differences in the evolution of the numbers of FG and SG binaries.

Binary stars play a crucial role in cluster evolution, both as an energy source supporting the cluster’s post-core collapse dynamics (see e.g. Gao et al. 1991, Goodman & Hut 1989, Vesperini & Chernoff 1994, Heggie et al. 2006, Trenti et al. 2007, Hurley et al. 2007; see also Heggie & Hut 2003 for a review), and as potential seeds for the formation of a variety of exotic objects (e.g. LMXBs, CVs, blue stragglers etc.; see e.g. Ivanova et al. 2006, 2008, Ferraro & Lanzoni 2008 and references therein). Exploring the evolution of binaries in the environment resulting from the formation of FG stars, and understanding whether or not observed binary properties and abundances contain any imprint of a cluster’s formation, are fundamental problems to be addressed. Here we present an initial study of this problem that combines the results of a set of N-body simulations of clusters hosting multiple populations with analytical expressions for binary interaction rates, to estimate the net binary disruption rate during cluster evolution.

The structure of this paper is as follows: in Section 2 we describe the N-body simulations and the analytical framework used for our study; in Section 3 we present our results; and in Section 4 we discuss our results and summarize our main conclusions.
Finally, for clusters with a significant fraction of primordial binaries, binary heating will delay deep core collapse and the binary disruption occurring during that high-density phase. (Notice, however, that a larger fraction of binaries delaying deep core collapse will increase the number of binary-binary interactions, again leading to significant binary disruption).

In order to quantify the binary disruption rate, we define the radial profile of the ionization rate

$$I(r,a) = n_s(r)\pi a^2 V_{th}(r) R(x)$$

and the volume-integrated disruption rate for SG (FG) binaries

$$\frac{1}{N_{\text{SG}}} \frac{dN_{\text{SG}}}{dt} = \Delta_{\text{SG}}(a,t) = \frac{1}{N_{\text{SG}}} \int n_s,\text{SG}(r) n_s(r)\pi a^2 V_{th}(r) R(x) \times 4\pi r^2 dr;$$

and similarly for $\Delta_{\text{FG}}$, where $a$, $x$, and $V_{th}$ are defined above.

Finally, we calculate the time integral of Eq.3 to obtain the time evolution of the number of SG binaries with a given semi-major axis $a$ as

$$\frac{N_{\text{SG}}(a,t)}{N_{\text{SG}}(a,0)} = \exp \left[ -\int_0^t \Delta_{\text{SG}}(a,\tilde{t}) d\tilde{t} \right]$$

and similarly for $N_{\text{SG}}(a,t)$.

### 2.2 N-body simulations

As discussed in Section 1, our previous hydrodynamical and N-body simulations (D’Ercole et al. 2008) predict that SG stars form in a compact subsystem concentrated in the inner cluster regions (see also Bekki 2011 for additional simulations confirming our prediction), and that early cluster expansion triggered by the loss of SNII ejecta and primordial gas is responsible for the loss of a significant fraction of FG stars.

In order to explore the long-term evolution of a multiple-population cluster, driven by two-body relaxation, we have followed the evolution of four different systems each containing equal numbers of SG and FG stars. In all cases, the initial state of the FG system is modeled as a single-mass King (1966) model with central dimensionless potential $W_0 = 7$ and truncation radius $R_t$ equal to the cluster Jacobi radius. The initial SG subsystem is also modeled as a $W_0 = 7$ King model, but one that is concentrated in the inner regions of the FG cluster. We have explored the evolution of the resulting two-population cluster for four values of the initial ratio of the FG to SG half-mass radii: $R_{\text{FG}}/R_{\text{SG}} = 2.5$, 5, 10, 25. We refer to these simulations as $r_{25}$, $r_{5}$, $r_{10}$, and $r_{25}$, respectively. The different ratios represent clusters with the same initial mass and total radius ($R_t$) but different internal structures, as measured by the degree of concentration of the SG subsystem.

All simulations start with a total number of particles $N = 10,000$, and our analysis focuses on the evolution of the system until $t \approx 40t_{\text{h,SG}}(0)$, where $t_{\text{h,SG}}(0)$ is the initial half-mass relaxation time of the SG subsystem. For all initial conditions considered, the system undergoes core collapse at $t \approx 17 - 25t_{\text{h,SG}}(0)$. More detailed discussion of the structural evolution of the FG and SG systems will be presented in a separate paper (Vesperini et al. 2011, in preparation).

### 3 RESULTS

We consider a common range of binary semi-major axes, $10^{-2} R_t / N < a < 10^{-1} R_t / N$, for all simulations. To illustrate the effect of the inner SG substructure in our multiple-population clusters, in some cases we compare quantities related to binary disruption with those calculated for a ‘standard’ $W_0 = 7$ King model with no multiple populations and hence no additional substructure due to the presence of the SG system (hereafter we will refer to this system as the SP -Single Population- system). For the SP system, $R_t \sim 0.1 R_t$ and the above range of $a$ corresponds to binaries that are close to the hard/soft boundary or are hard everywhere in the cluster; specifically for the widest binary considered, $x > 2.8$ in the SP cluster.

Fig. 1 shows the radial profile of the ionization rate $I(r)$ for $a = 5 \times 10^{-2} R_t / N$ in each of the models explored.

The profiles are calculated using the cluster properties after about 5-6 dynamical times, in order to allow the initial two-population configuration to come into dynamical equilibrium. This figure illustrates how the presence of the inner SG system greatly enhances the ionization rate over that in the simple SP system. Even for the system ($r_{25}$) with the least concentrated SG population, the ionization rate in the cluster inner regions is about an order of magnitude larger than that in the SP system.

As the system evolves, the ionization rate reaches a maximum at the time of core collapse and decreases again in the post-core-collapse phase. However, the ionization rate
in all multiple-component models is always larger than that in the reference SP system. Fig. 2 shows the time evolution of the volume-integrated ionization rate for SG ($\Delta_{SG}(a,t)$) and FG ($\Delta_{FG}(a,t)$) binaries, for $a = 5 \times 10^{-2} R_t/N$. Fig. 3 shows the time evolution of the ratio of the SG to the FG volume-integrated ionization rate $\Delta_{SG}(a,t)/\Delta_{FG}(a,t)$, for $a = 5 \times 10^{-2} R_t/N$.}

As the cluster evolves and the two populations tend to mix, $\Delta_{SG}(a,t)/\Delta_{FG}(a,t)$ tends to decrease. However, the mixing is not complete by the end of the time interval spanned by this study ($t \sim 40 t_{rh,SG}(0)$), so the SG binary disruption rate is always larger than that of FG binaries.

Fig. 4 plots $N_{b,SG}(a)/N_{b,FG}(a)$, calculated at the end of each simulation, as a function of binary semi-major axis. In all cases, SG binary disruption is significantly enhanced compared to that of the FG binary population. Fig. 5 shows the ratios of the final to the initial number of binaries for the SG and the FG population, $N_{b,SG}(a)/N_{b,SG}(a)_{init}$ and $N_{b,FG}(a)/N_{b,FG}(a)_{init}$, and illustrates the extent of the binary disruption in our multiple population clusters, as well as the preferential disruption of SG binaries.

Finally, in Fig. 6 we plot the time evolution of $N_{b,SG}(a,t)$, $N_{b,FG}(a,t)$, and their ratio, for two different values of $a$ for simulation $r10$. This figure illustrates the extent of the early (pre-core collapse) disruption of binaries due to the presence of the high-density SG subsystem. Binary disruption further increases during core collapse, and finally slows down during the post-core collapse phase. The preferential disruption of SG binaries continues for the whole simulation.

4 DISCUSSION AND CONCLUSIONS

The results presented in this paper show that the properties of binary stars are significantly affected by the initial structure of a cluster hosting multiple populations, and may contain important clues to the formation and evolutionary history of multiple populations.

The central result of our study is that significant differences in the numbers of FG and SG binaries is a fingerprint of the structural properties predicted by our models.
of SG star formation and dynamical evolution (D’Ercole et al. 2008; further investigation of the long-term evolution of multiple population clusters will be presented in Vesperini et al. 2011, in preparation). Specifically, we showed in our previous studies that SG stars forming from AGB ejecta tend to form in a strongly concentrated subsystem in the FG cluster inner regions (see also Bekki 2011); we have now shown in this paper that in a cluster with such a structure, SG binaries are preferentially disrupted and that, more generally, binary disruption is enhanced compared to a standard cluster with similar mass and size but without an inner SG subsystem.

Our calculation is based on analytical calculations combined with the results of N-body simulations of cluster structural and kinematical evolution. Further refinement of the calculations presented in this paper will require simulations including full treatment of binary stars; simulations including the self-consistent treatment of binaries are very computationally expensive and are beyond the scope of this initial exploratory study. Future studies based on simulations with binaries will allow us to incorporate additional effects (e.g. binary-binary interactions, binary segregation, binary heating) not included in our simple analytical treatment of binary disruption.

The first observational indication of the preferential disruption of SG binaries, as found in our analysis, comes from a recent study of Ba stars in globular clusters (D’Orazi et al. 2010). Ba stars are thought to be the result of the accretion of matter processed by a thermally pulsing AGB onto the secondary component of a binary system. The Ba-rich envelope of the AGB component contaminates the companion via wind accretion, possibly followed by stable Roche lobe overflow, or by common envelope evolution, depending on the mass ratio at the time the donor AGB fills its Roche lobe (see Han et al. 1995 for a detailed study of the binary channels for the formation of Ba stars; see also Jorissen et al. 1998, McClure & Woodsworth 1990 for two observational studies of the Ba stars orbital properties).

In order for this process to occur, the initial binary separation must be larger than approximately 1 AU (smaller separations would affect the primary component evolution before it reaches the AGB phase). D’Orazi et al. find that Ba stars belong predominantly to the FG population. This result is consistent with a dynamical history in which the SG Ba star binary progenitors are disrupted more efficiently than those of the FG population.

We note that the larger binary interaction rate of SG binaries can also lead them to harden more rapidly. By tightening a binary below the minimum separation for the formation of Ba stars, the more rapid hardening of SG binaries may represent an additional channel for the suppression of Ba stars in the SG population. Another interesting possible consequence of an enhanced binary interaction rate is that a binary might be disrupted after the mass transfer episode that led to the formation of the Ba star, resulting in a single Ba star.

The sample of Ba stars discussed in D’Orazi et al. is still very small, and further observational studies aimed at exploring the relative abundance of FG and SG binaries will be extremely important to test the predictions of our study and, more generally, to shed further light on the interplay
between the dynamics of multiple population clusters and their binary star content.

Many observational studies cover only a limited region of a cluster, and thus could provide only local information on the SG-to-FG binary number ratio. A detailed comparison between observations and theoretical results will entail a more detailed accounting of the radial variation of the SG and FG binary fractions. The results presented here illustrate a clear general trend in the evolution of the total numbers of SG and FG binaries, but the interplay between binary segregation and binary disruption, along with possible initial differences in the spatial distributions of FG and SG binaries, will presumably result in radial gradients in the SG-to-FG binary number ratio. (For example, in the innermost regions, the binary population might be dominated by SG binaries even though FG binaries may dominate globally.) As discussed above, future simulations including self-consistent treatments of binaries will include these effects, allowing us to further explore these issues.

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