BINARIES AS A POSSIBLE SCENARIO FOR THE FORMATION OF MULTIPLE STELLAR POPULATIONS IN GLOBULAR CLUSTERS

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ABSTRACT

Observations have revealed the presence of multiple stellar populations in globular clusters (GCs) that exhibit wide abundance variations and multiple sequences in the Hertzsprung–Russell (HR) diagram. We present a scenario for the formation of multiple stellar populations in GCs. In this scenario, initial GCs are single-generation clusters, and our model predicts that the stars with anomalous abundances observed in GCs are merged stars and accretor stars produced by binary interactions—rapidly rotating stars at the moment of their formation—and that these stars are more massive than normal single stars in the same evolutionary stage. We find that, due to their own evolution, these rapidly rotating stars have surface abundances, effective temperatures, and luminosities that are different from normal single stars in the same evolutionary stage. This stellar population of binaries reproduces two important points of observational evidence of multiple stellar populations: a Na–O anticorrelation and multiple sequences in the HR diagram. This evidence suggests that binary interactions may be a possible scenario for the formation of multiple stellar populations in GCs.

Key words: binaries: general – globular clusters: general – stars: evolution – stars: rotation

Online-only material: color figure

1. INTRODUCTION

Observational evidence of the existence of multiple stellar populations in globular clusters (GCs) challenges the traditional view of GCs hosting simple stellar populations that formed in a single generation from a cloud of uniform composition (single-generation cluster). One important point of evidence is the presence of star-to-star abundance variations. The most famous example of this is the Na–O anticorrelation wherein oxygen-depleted stars have higher abundances of sodium; this phenomenon is exhibited by main-sequence (MS) turnoff (TO) stars, sub-giant branch (SGB) stars, and red-giant branch (RGB) stars in some GCs (Carretta et al. 2004; Gratton et al. 2004). Another important point of evidence is that some GCs show multiple MSs (Piotto et al. 2007), multiple SGBs (Milone et al. 2008; Marino et al. 2009), or anomalously wide RGBs (Yong et al. 2008; Lee et al. 2009) in the Hertzsprung–Russell (HR) diagram. Several scenarios have been proposed to explain the formation of multiple stellar populations (Gratton et al. 2012), and they can be classified into two contrasting hypotheses: primordial scenarios versus evolutionary scenarios (Kraft 1994; Carretta et al. 2004). In a primordial scenario, multiple stellar populations in GCs are formed from the different components that make up primordial chemical inhomogeneities, for example, a merger of two separate GCs (Lee et al. 1999; Mackey & Broby Nielsen 2007) or the self-pollution of the intra-cluster gas occurring in the early evolution of clusters (D’Antona et al. 2002; Decressin et al. 2007; de Mink et al. 2009). However, a merger event would not be expected to occur in the halo of the Milky Way due to very large relative velocities of GCs (Gratton et al. 2012). For the self-enrichment of GCs, it is difficult to explain the high fraction of second-generation stars formed from the gas polluted by the first-generation stars (Bastian & de Mink 2009), and the nature of possible polluters remains unclear (Sills & Glebbeek 2010; Gratton et al. 2012).

In an evolutionary scenario, initial GCs are believed to be single-generation clusters, and multiple stellar populations in GCs are attributed to the evolution of stars affected by physical processes such as the first dredge-up, Sweigart–Mengel mixing (Sweigart & Mengel 1979), and primordial rotation (Bastian & de Mink 2009). However, it is necessary to explain why only some of the stars in GCs are affected by these physical processes. Moreover, Decressin et al. (2007) suggested that the MS TO stars in GCs are not hot enough for producing the observed Na–O anti-correlation because the central temperature (about $25 \times 10^6$ K) of a $0.85 \, M_\odot$ TO star is higher than the required temperature of the CNO cycle (about $20 \times 10^6$ K), but lower than that of the production of $^{23}$Na from proton capture on $^{20}$Ne (about $35 \times 10^6$ K).

Binary interactions have been used to explain the formation of multiple stellar populations in a primordial scenario. It has been proposed that chemically enriched material ejected from massive binaries forms a second population of stars (de Mink et al. 2009) or is accreted by low-mass pre-main-sequence stars (Bastian et al. 2013). However, binary interactions are not considered to be a kind of evolutionary scenario. They have not been directly investigated as a cause of the production of stars with anomalous abundances, but they have been proposed as an explanation for an extended MS in the HR diagrams of intermediate age clusters (Yang et al. 2011; Li et al. 2012).

Binary systems can produce more massive stars than normal single stars in the same evolutionary stage that are produced by binary interactions, e.g., merged stars or accretor stars. These stars are not hot enough for the production of $^{23}$Na from proton capture on $^{20}$Ne, but they are hot enough for proton captures on $^{16}$O and $^{22}$Ne, which respectively lead to the destruction of $^{16}$O and to the production of $^{23}$Na at temperatures $>20 \times 10^6$ K (Prantzos & Charbonnel 2006). Furthermore, these stars produced by binary interactions will be rapidly rotating because binary interactions can convert orbital angular momentum into their spin angular momentum (de Mink et al. 2013). Rotationally
induced mixing can bring part of the nuclear-processed products from the core to the surface (Decressin et al. 2007), and stellar rotation was used to explain the observed nitrogen enrichment found in several massive MS stars (Brott et al. 2009). Therefore, these rapidly rotating stars reproduce the properties of the stars with anomalous abundances observed in GCs (e.g., the Na–O anticorrelation), and binary interactions may be a possible evolutionary scenario for the formation of multiple stellar populations in GCs.

In this paper, we adopt a simple model for this scenario to investigate the formation of multiple stellar populations. In Section 2, we explore the formation of rapidly rotating stars from binary interactions by performing calculations of binary evolution, and we calculate the subsequent evolution of these rapidly rotating stars to obtain their parameters (e.g., effective temperatures, luminosities, and surface abundances). Then, we estimate the distributions of the binary population by performing a binary population synthesis study. In Section 3, we give a discussion and conclusions.

2. THE MODEL AND SIMULATION

In our scenario, the stars with anomalous abundances observed in GCs are merged stars and the accretor stars produced by binary interactions, and these binary products are rapidly rotating and more massive than the normal stars. These binary products have different effective temperatures, luminosities, and surface abundances from single stars in the same evolutionary stage due to their evolution. Thus, the stellar population with binaries (the binary population) can reproduce the observations of multiple stellar populations because this binary population includes two sub-populations: (1) normal single stars with normal abundance (the initial abundance of GCs) and (2) merged stars and accretor stars (produced by binary interactions) that have abnormal surface abundances through their own evolution.

2.1. Binary Evolution Calculations

We considered three evolutionary scenarios for the formation of rapidly rotating stars from binary interactions: (1) a binary evolves into contact and then merges into a rapidly rotating star (contact merger channel for the merged stars; Jiang et al. 2012; de Mink et al. 2013), (2) a binary evolves into Roche lobe overflow (RLOF) and experiences unstable mass transfer while both components are still MS stars then merges into a rapidly rotating star (unstable RLOF merger channel for the merged stars; Jiang et al. 2012), and (3) a binary evolves into RLOF and experiences stable mass transfer where the secondary obtains the mass and angular momentum transferred from the primary and subsequently becomes a rapidly rotating star (stable RLOF channel for the accretor stars; de Mink et al. 2013).

In these scenarios, a binary either evolves into the contact phase or an unstable RLOF phase while both components are still MS stars or it evolves into a stable RLOF phase while the secondary is still an MS star (Jiang et al. 2012; de Mink et al. 2013). This is because for MS stars, the binding energy of the envelope might be large enough to form rapidly rotating stars. To determine whether the binary evolves into any of these phases, it is necessary to perform detailed binary evolution calculations. We use Eggleton’s stellar evolution code (Eggleton 1971, 1972; Eggleton et al. 1973) which has been updated with the latest input physics during the last four decades (Han et al. 1994; Pols et al. 1995, 1998; Nelson & Eggleton 2001; Eggleton & Kiseleva-Eggleton 2002). In our calculations, we used the metallicity $Z = 0.001$ (corresponding to typical GCs) and considered the nonconservative effects, including a model of dynamo-driven mass loss, magnetic braking, and tidal friction for the evolution of stars with cool convective envelopes (Eggleton & Kiseleva-Eggleton 2002).

Altogether, we have calculated the evolution of 5200 binary systems, thus obtaining a large, dense model grid that covers the following ranges of initial primary mass ($M_{10}$), initial mass ratio ($q_0 = M_{20}/M_{10}$), and initial orbital period ($P_0$): $\log M_{10} = -0.3, -0.25, \ldots, 0.2$; $\log q_0 = \log (M_{20}/M_{10}) = 0.05, 0.10, \ldots, 0.5$; and $\log (P_0/P_{ZAMS}) = 0.05, 0.10, \ldots$, where $P_{ZAMS}$ is the orbital period at which the initially more massive component would just fill its Roche lobe on the zero-age MS. These ranges of initial parameters cover the systems that can form rapidly rotating stars in the old stellar population through case A binary evolution. According to these binary models, the parameters of rapidly rotating stars are established when the binary evolves into contact phase, unstable RLOF, or the end of stable RLOF. For simplicity, in the contact merger channel and the unstable RLOF merger channel, we assume that there is a 10% mass loss during the merger phase (Jiang et al. 2012; de Mink et al. 2013) and the binary products rotate at 80% of the break-up velocity. For the stable RLOF channel, we calculate the angular momentum obtained by the secondary, and then calculate its rotational velocity. We only consider the secondaries that can get enough angular momentum to rotate at 80% of the break-up velocity.

2.2. Rotation Evolution Calculations

To calculate the subsequent evolution of rapidly rotating stars produced by binary interactions, we have used the Modules for Stellar Experiments in Astrophysics code (version 4631; Paxton et al. 2011). This code implements the effects of rotation in the transport of angular momentum and chemical mixing, and it has been used to study the effects of rotational mixing (Chatzopoulos et al. 2012; Chatzopoulos & Wheeler 2012). We do not consider the effect of the helium-rich core of the original components on the subsequent evolution of rapidly rotating stars, and we assume that these rapidly rotating stars have abundances similar to zero-age MS stars. In addition, we consider that the effect of rotation on low-mass stars with convective envelopes might be weaker due to magnetic braking (Hurley et al. 2000; Bastian & de Mink 2009). We calculate the stellar evolutionary models with $M = 0.6, 0.7, \ldots, 1.6 \, M_\odot$ for $Z = 0.001$ which cover rapidly rotating stars produced by binary interactions in old stellar populations. For simplicity, these models run for two different degrees of rotation: non-rotating and 80% of break-up velocity, which are used to investigate the evolution of surface abundances of single stars and rapidly rotating stars produced by binary interactions. All evolutionary tracks have been computed up to the point of core helium ignition.

To illustrate the evolutionary tracks of these stars, we show four evolution of surface mass fractions (sodium versus oxygen abundances) in Figure 1. During the evolution of rapidly rotating stars with $M = 1.3 \, M_\odot$ (dotted line), the surface mass fraction of sodium ($X_{Na23}$) increases from $1.22 \times 10^{-6}$ to $5.95 \times 10^{-6}$ and that of oxygen ($X_{O16}$) decreases from $4.67 \times 10^{-4}$ to $9.54 \times 10^{-3}$. This is because the destruction of $O$ and the production of $^{23}Na$ in the central region result from proton captures on $^{16}O$ and $^{22}Ne$ (Langer et al. 1993; Prantzos & Charbonnel 2006; Decressin et al. 2007) and they are brought to the surface by rotational mixing. In other examples, rapidly
rotating stars with $M = 1.0, 1.1, 1.2 M_\odot$ evolve in a similar way as in the previous example although the variation ranges of surface abundances decrease with decreasing mass. Hence, these rapidly rotating stars can show oxygen depletion and sodium enhancement. For single stars with no rotation (open circles in Figure 1), the surface mass fractions of sodium and oxygen do not show significant variations.

2.3. Binary Population Synthesis

In the binary population synthesis study, we have performed a Monte Carlo simulation. We adopt the following input for the simulation (see Han et al. 1995). (1) The initial mass function of Miller & Scalo (1979) is adopted. (2) The mass–ratio distribution is taken to be constant. (3) We take the distribution of separations to be constant in log $a$ for wide binaries, where $a$ is the orbital separation. Our adopted distribution implies that $\sim 50\%$ of stellar systems are binary systems with orbital periods less than 100 yr. We follow the evolution of a million sample binaries according to grids of binary models and the evolution models of rapidly rotating stars described above.

The simulation gives the distributions of many properties of the binary population, e.g., masses, effective temperatures, luminosities, surface abundances. Figure 2 shows selected distributions of the binary population at 10 Gyr which may be helpful for understanding the scenario of binary interactions for the formation of multiple stellar populations. Figure 2(a) shows the distribution of single stars and binary products in the Na–O plane. Single stars (open circles) are concentrated at the bottom right corner and do not show significant variations. However, binary products have large star-to-star variations. The distribution of binary products first extends upward to the high sodium abundance region from the original abundance location, and then turns left to the oxygen depletion region. Thus, the binary population with binary interactions can show a Na–O anticorrelation.

To investigate the distributions of binary products with different abundances in the HR diagram, we classify them into four groups based on the surface mass fraction of Na and O, which are denoted as pluses with different colors. The distribution of the binary population with binary interactions in the HR diagram is shown in Figure 2(b). It is obvious that this population has at least two MSs, three TOs, three SGBs, and an extended RGB, which are produced by single stars (open circles) and binary products (pluses). More importantly, these sequences have a large spread in sodium and oxygen abundances. This is consistent with the fact that the Na–O anticorrelation is observed among MS TO stars, SGB stars, and RGB stars in some GCs (Carretta et al. 2004; Gratton et al. 2004). Observed red giants in 17 GCs given by Carretta et al. (2009) are shown in Figure 2(c), and they have a distribution similar to that of our simulated binary populations. If we assume that the binary populations (black line and blue lines) with different initial abundances, such as in different GCs, have the same variation ranges of surface abundances then we would find that these binary populations in the simulation are in good agreement with the observed stars in 17 GCs as shown in Figure 2(c).

We noted that single stars and binary products in the binary population have different mass distributions as shown in Figure 2(d), and binary products are more massive than single stars. For the binary population with log $L/L_\odot > 0$, the mass range of single stars is from 0.75 to 0.9 $M_\odot$, while the mass range of binary products is from 0.8 $M_\odot$ to 1.35 $M_\odot$, although these single stars and binary products have the same range of evolutionary stages. The maximum mass of binary products is larger than that of single stars by $\sim 0.45 M_\odot$. We do not compare stars with log $L/L_\odot < 0$ because the sample of very low mass binary products is not complete in our calculations. Although the effect of rotation on low-mass stars might be weaker due to magnetic braking (Hurley et al. 2000; Bastian & de Mink 2009), massive binary products could have significantly different surface abundances from single stars. Binary products are more massive than single stars in the same evolutionary stage, and they rotate rapidly, i.e., close to break-up velocity. The destruction of $^{16}$O and the production of $^{23}$Na in the central region result from proton captures on $^{16}$O and $^{22}$Ne, and the products of nuclear burning are brought to the surface by rotational mixing. This can explain why abundance variations occur in these stars but not in single stars in the same evolutionary stage.

3. DISCUSSION AND CONCLUSIONS

In this paper, we presented binary interactions as a possible scenario for the formation of multiple stellar populations in GCs. In this scenario, binary interactions can convert orbital angular momentum into spin angular momentum and produce rapidly rotating stars. These stars might have properties different from single stars such as surface abundances, temperatures, and luminosities because they experienced binary interactions and their evolution is affected by rotationally induced mixing. The existence of binary products and single stars results in multiple stellar populations in GCs, although the initial GCs are single-generation clusters. In our simple model, we carried out binary evolutionary calculations and constructed the evolutionary models of rapidly rotating stars formed by binary interactions. By performing a Monte Carlo simulation, we obtained the distributions of the binary population and investigated the formation of multiple stellar populations from binary interactions.

Stellar rotation have been shown that can explain the broad MS and spread TO observed in intermediate age stellar clusters (Bastian & de Mink 2009; Li et al. 2012). However, Bastian & de Mink (2009) suggested that this is unlikely to cause the
multiple stellar populations observed in old GCs because the stars in GCs are low mass and are not expected to be rapidly rotating stars. We show that the old binary population could exhibit multiple sequences in the HR diagram as shown in Figure 2(b) because binary interactions could produce rapidly rotating stars. Binary interactions, including mass transfer (Pols et al. 1991; de Mink et al. 2013) or mergers (Tylenda et al. 2011; Jiang et al. 2013), have been used to investigate the formation of rapidly rotating stars. Moreover, observed evidence has shown that binary interactions are very common in GCs. Many contact binaries have been observed in GCs (Rucinski 2000), and these binaries are believed to merge into a rapidly rotating star (contact merger channel). Mathieu & Geller (2009) show that many of blue stragglers are rotating faster than normal MS stars, which might be formed by mass transfer (Geller & Mathieu 2011). Therefore, binary interactions could explain the multiple sequences in the HR diagram, which is important evidence of multiple stellar populations.

Another important point of evidence of multiple stellar populations in GCs is the presence of star-to-star abundance variations, and the most famous example of this is the Na–O anticorrelation. We show that an old binary population can reproduce a Na–O anticorrelation as a result of the formation of rapidly rotating stars from binary interactions. If binary populations with different initial abundances, such as in different GCs, are assumed to have the same variation in their range of surface abundances, we found that these binary populations in the simulation are in good agreement with the observed stars in 17 GCs given by Carretta et al. (2009). In our scenario, this anticorrelation could be found in TO stars, SGB stars, and RGB stars, which is in agreement with observations that show the Na–O anticorrelation in these evolutionary stages (Carretta et al. 2004; Gratton et al. 2004). Moreover, our model predicts that the stars with anomalous abundances should be more massive than MS TO stars, and they should be blue stragglers or blue straggler progeny. Therefore, binary interactions could explain the existence of the Na–O anticorrelation in GCs. This suggests that binary interactions may be a possible scenario for the formation of multiple stellar populations, and the traditional view of a single-generation cluster could explain the photometric and spectroscopic observations of multiple stellar populations by considering the effects of binary interactions.

Observed multiple stellar populations show cluster-to-cluster variations (e.g., Carretta et al. 2009) and these variations also need to be explained (Sills & Glebbeek 2010). These cluster-to-cluster variations might be due to the dependence of binary interactions on cluster properties such as age, initial abundance, initial fraction of binaries, and initial orbital separation distribution. These parameters determine the nature of binary interactions and the subsequent evolution of binary products.
When the initial fraction of binaries is very low, the binary population would have few binary products and be similar to a simple, single stellar population. The investigation of the properties of binaries in 13 low-density GCs revealed that the fraction of binaries ranges from 0.1 to 0.5 in the core depending on the cluster (Sollima et al. 2007). Moreover, the stellar density in GCs is sufficiently high to affect the binaries that can be destroyed, created, or modified by dynamical interaction (e.g., Hut et al. 1992). Higher stellar densities could result in more efficient binary dissolution and thus a lower binary fraction (Marks & Kroupa 2011). Consequently, the binary population might have different distributions and different fractions of binary products in various clusters. A more detailed study of the binary population with binary interactions might help us to understand the dependence of binary interactions on cluster properties in further studies.

It is clear that our model is still quite simple and has not been investigated in much detail so far. In our investigation, we do not consider the effect of the helium-rich core of the original components on the subsequent evolution of binary products. Our simulation shows that 36% of all rapidly rotating stars are formed by binary mergers (including contact merger channels and unstable RLOF merger channels). These rapidly rotating stars formed by binary mergers might contain the helium-rich cores of the original primaries, and their remaining relative lifetimes are shorter than those of single stars with the same masses (e.g., Sills et al. 1997; Glebbeek & Pols 2008; de Mink et al. 2013). For rapidly rotating stars produced through stable RLOF, this effect does not need to be considered because they are the less massive components of binaries and their cores are still hydrogen-rich at the onset of mass transfer (e.g., Sills et al. 1997; Glebbeek & Pols 2008; de Mink et al. 2013). For rotating velocity, we simply assume that all binary products rotate initially at 80% of the break-up velocity. A lower initial rotating velocity or a faster spin down will lead to a weaker variation of surface abundances. These effects need more detailed investigation in future studies. In addition, observations have suggested that the fraction of binaries in GCs may be lower than that in field stars and open clusters (Rubeinstein & Bailyn 1997). This might be because GCs are much older than field stars and open clusters. Consequently, we do not expect more binaries in GCs to be recognized due to their large luminosity ratios and their large orbital periods; it is also possible they may not even be binaries due to mergers (de Mink et al. 2013).

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