THE FRACTION OF GLOBULAR CLUSTER SECOND-GENERATION STARS IN THE GALACTIC HALO

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ABSTRACT

Many observational studies have revealed the presence of multiple stellar generations in Galactic globular clusters. These studies suggest that second-generation stars make up a significant fraction of the current mass of globular clusters, with the second-generation mass fraction ranging from ~50% to 80% in individual clusters. In this Letter, we carry out hydrodynamical simulations to explore the dependence of the mass of second-generation stars on the initial mass and structural parameters and stellar initial mass function (IMF) of the parent cluster. We then use the results of these simulations to estimate the fraction fSG,H of the mass of the Galactic stellar halo composed of second-generation stars that originated in globular clusters. We study the dependence of fSG,H on the parameters of the IMF of the Galactic globular cluster system. For a broad range of initial conditions, we find that the fraction of mass of the Galactic stellar halo in second-generation stars is always small, fSG,H < 4%–6% for a Kroupa-1993 IMF and fSG,H < 7%–9% for a Kroupa-2001 IMF.

Key words: globular clusters: general

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1. INTRODUCTION

During the last decade, spectroscopic and photometric studies have provided strong evidence for multiple stellar populations in a number of Galactic globular clusters. In contrast to the standard formation scenario, according to which globular clusters are “simple stellar populations” composed of stars all with the same age and chemical composition, these studies have revealed star-to-star variations in the abundances of light elements in main-sequence and red giant stars, suggesting a second stellar generation (hereafter SG) that must have formed out of gas processed through a first generation (hereafter FG) of stars. SG stars are identified by their anomalous abundances of Na, O, Mg, and Al relative to normal halo field stars of similar age and chemical composition, these studies have revealed star-to-star variations in the abundances of light elements in main-sequence and red giant stars, suggesting a second stellar generation (hereafter SG) that must have formed out of gas processed through a first generation (hereafter FG) of stars. SG stars are identified by their anomalous abundances of Na, O, Mg, and Al relative to normal halo field stars of similar metallicity (see, e.g., Gratton et al. 2004; Carretta et al. 2009a, 2009b).

Accurate photometric studies of a few globular clusters have strengthened the evidence for multiple populations by showing their fingerprints (multiple main-sequences and sub-giant branches) in the color–magnitude diagram (see, e.g., Lee et al. 1999; Pancino et al. 2000; Bedin et al. 2004; Piotto et al. 2007; Milone et al. 2008; Marino et al. 2008; Anderson et al. 2009). The most striking main-sequence anomalies are populations with helium abundances much larger than the standard big bang value expected to be universally present in the oldest stars. The helium overabundance is interpreted as an evolutionary by-product of the progenitors of the anomalous SG stars. The leading models for the source gas from which SG stars formed involve rapidly rotating massive stars (e.g., Decressin et al. 2007; see also de Mink et al. 2009 for a more recent work suggesting massive binaries as a possible polluting source), or intermediate-mass asymptotic giant branch (AGB) stars (e.g., Ventura et al. 2001; see also Renzini 2008 for a review and references therein).

Prior to the discovery of the multiple main sequences, the presence of stars with helium anomalies had been predicted based on the very extended horizontal branches of some clusters (D’Antona et al. 2002; D’Antona & Caloi 2004). Analysis of horizontal branch morphologies of several clusters also led to the first suggestion that the second stellar generation could account for a high fraction—from 30% to 100%—of the total number of stars (D’Antona & Caloi 2008). While the high-quality photometric data necessary to detect multiple populations have been so far obtained for only a few clusters, a recent spectroscopic survey of about 2000 stars in 19 Galactic globular clusters has shown evidence of multiple populations in all the clusters observed, and in all cases SG stars account for a significant fraction (50%–80%) of the cluster mass (Carretta et al. 2009b).

D’Ercole et al. (2008) studied the formation and dynamical evolution of multiple populations in globular clusters, and found that two distinct evolutionary processes can cause stars to escape and populate the Galactic stellar halo during cluster dynamical evolution. At early times, stars escape over the tidal boundary as the cluster expands due to the loss of primordial gas and FG SN ejecta. Since SG stars form preferentially in the central regions of the cluster, almost all of the escapers at this stage are FG stars. The result is that the SG fraction among bound cluster stars increases dramatically. As the cluster evolution continues into the phase dominated by two-body relaxation, the two populations mix and the fractional escape rates of the FG and SG stars due to evaporation tend to equalize, stabilizing the SG fraction (see also Decressin et al. 2008 for another study of the mixing process). Thus, the vast majority of escapers from the cluster are FG stars. Two recent spectroscopic studies (Carretta et al. 2010; Martell & Grebel 2010) have found that the vast majority of halo stars studied have abundances typical of FG stars in clusters; only about 1.5%–2.5% of the stars are Na-rich (Carretta et al. 2010) and CN-strong (Martell & Grebel 2010), and hence classifiable as SG stars.

Many general studies have addressed the evolution of the Galactic globular cluster system and the dispersal of cluster
stars in the halo (see, e.g., Kroupa & Boily 2002; Baumgardt et al. 2008; Portegies Zwart et al. 2010; Vesperini 2010; and references therein). However, this Letter is specifically focused on SG stars. Our goals here are to estimate both the number of SG stars that may have formed in the Galactic globular cluster system and the fraction, $f_{\text{SG}}$, of SG stars formed in globular clusters that now populate the Galactic stellar halo, and to illustrate the link between SG formation, globular cluster evolution, and the formation history of the Galactic halo. In Section 2, we present the results of hydrodynamical simulations exploring the dependence of the mass of SG stars formed on cluster initial properties. In Section 3, we introduce our numerical framework to estimate the fraction of SG stars in the halo, and discuss its theoretical and observational ingredients. In Section 4, we present and discuss our results.

2. MASS OF SECOND-GENERATION STARS AS A FUNCTION OF A CLUSTER INITIAL PROPERTIES

In order to calculate the total mass of SG stars formed in a cluster as a function of cluster initial properties, we have carried out a series of one-dimensional hydrodynamical simulations modeling the SG formation process. The technical details of our simulations are described in D’Ercole et al. (2008). We outline here only the aspects relevant to this Letter.

We assume that the FG cluster initially follows a King (1962) density profile,

$$\rho = \rho_0 \left[ 1 + \left( \frac{r}{r_c} \right)^2 \right]^{-\frac{3}{2}},$$

out to some truncation radius $R$. Stellar masses are distributed in the range $0.1 < m/m_\odot < 100$ according to either a Kroupa et al. (1993, hereafter K93) or a Kroupa (2001, hereafter K01) stellar initial mass function (IMF). We model the formation of SG stars from the ejecta of AGB stars and assume that the SG formation phase extends from about 30 Myr after the FG cluster forms until $\sim 100$ Myr (should the SG star formation epoch extend to $\sim 150$ Myr, and hence include ejecta of stars down to $4 M_\odot$, the SG mass can be obtained by multiplying the values presented below by a factor $\sim 1.4$). As discussed in D’Ercole et al. (2008) and D’Ercole et al. (2010), in order to explain the chemical properties of SG stars, it is necessary to invoke the presence of pristine gas mixed in with the matter from which SG stars formed (see also Pfannm-Altenburg & Kroupa 2009 for a study of the possible accretion of gas from the ISM during the SG formation process). As shown by D’Ercole et al. (2008, 2010), a mass of pristine gas equal to about 50% of the total mass of SG star-forming gas is required to reproduce the abundance patterns (Na–O, Mg–Al anticorrelations and the helium distribution function) observed in the massive cluster NGC2808 and in the low-mass cluster M4 (see also Ventura et al. 2009; Ventura & D’Antona 2009).

However, additional systematic studies of the chemical properties of the individual clusters for which spectroscopic data are available will be required to explore the allowed mass range of pristine gas and any possible dependences on protocluster conditions. Here, we simply assume that pristine material makes up 50% of the total mass of gas forming the SG stars. Results for different pristine gas fractions can be easily obtained from those presented in this Letter.

The two panels of Figure 1 show the fractional mass of SG stars formed, $\xi \equiv (m_{\text{SG}}/m_{\text{tot}})$, as a function of the total cluster mass ($M$) for models with different combinations of values of the half-mass radius ($R_h = 1, 2$, and $4$ pc), of the truncation radius ($R = 20, 40,$ and $80$ pc; these values encompass the range of $R$ for the majority of Galactic globular clusters, for which the modal value is $R \sim 40$ pc; see, e.g., Mackey & van den Bergh 2005), and for a K93 or a K01 IMF. As the cluster mass increases for given values of $R$ and $R_h$, so too do the cluster escape speed, the fraction of AGB ejecta retained and the total mass of SG stars formed. For the structural parameters explored, only clusters initially more massive than $\sim 10^{4.8}$–$10^5 M_\odot$ can retain enough AGB ejecta to form an appreciable fraction of SG stars. The difference between the values of $\xi$ obtained for the K93 and the K01 IMF is a consequence of the fact that the K01 IMF contains a larger fraction of the cluster mass in the mass range of the polluting AGB stars.

3. SECOND-GENERATION STARS IN THE GALACTIC STELLAR HALO

A complete model for the determination of the fraction of SG stars in the Galactic halo would require accurate knowledge of the initial global properties of the Galactic globular cluster system as well as its dynamical history, the initial internal structure and subsequent dynamical evolution of clusters with
multiple stellar populations, and a comprehensive theory of how the stellar halo formed. Much work remains to be done on all of these problems. Considering the uncertainties involved in all of these key ingredients, we elect to proceed here in a simplified way, and our estimation of \( f_{\text{SG, H}} \) proceeds as follows.

For a given value of the total mass of the Galactic globular cluster system, \( M_{\text{GCS}}^{\text{init}} \), and a given initial globular cluster system mass function (IGCMF), we calculate the total mass of SG stars formed in the cluster system, \( M_{\text{SG, GCS}}^{\text{init}} \), using the results of the hydrodynamical simulations described in the previous section. \( M_{\text{SG, GCS}}^{\text{init}} \) may be written, in general, as an integral over cluster structural properties:

\[
M_{\text{SG, GCS}}^{\text{init}} = \int \int \int \xi(M, R_h, R) M f(M, R_h, R) dM dR_h dR,
\]

where \( f(M, R_h, R) \) is the joint distribution function of initial cluster mass and structural parameters.

We assume either a Schechter IGCMF (see, e.g., Burkert & Smith 2000)

\[
dN/dM \propto M^{-\alpha} e^{-M/M_c} \quad \text{for} \quad M_{\text{low}} < M < M_{\text{up}},
\]

or a simple power law (e.g., Whitmore 2003)

\[
dN/dM \propto M^{-\alpha} \quad \text{for} \quad M_{\text{low}} < M < M_{\text{up}}.
\]

With these assumptions, and for given values of \( R_h \) and \( R \) at the time of SG formation (30 Myr \( \lesssim t \lesssim 100 \) Myr), Equation (2) becomes

\[
M_{\text{SG, GCS}}^{\text{init}} = \int_{M_{\text{low}}}^{M_{\text{up}}} \xi(M, R_h, R) \int \frac{dN}{dM} dM dM.
\]

Neglecting mass loss due to stellar evolution, the total mass of the stellar halo in the form of SG stars, either from dissolved globular clusters or evaporated from those remaining, is the difference between \( M_{\text{SG, GCS}}^{\text{init}} \) and the current total mass of SG stars still in clusters, \( M_{\text{SG, GCS}}^{\text{now}} \).

A systematic observational study of SG stars in Galactic globular clusters is still lacking and will require significant effort. Currently, the only study affording an estimate of the fraction of SG stars in a significant number of Galactic clusters, as well as exploration of possible trends of the SG fraction with other cluster properties, is the spectroscopic survey of \( \sim 2000 \) stars in 19 Galactic globular clusters carried out by Carretta et al. (2009a, 2009b). They find that all clusters studied host SG stars, and that the fraction of individual cluster masses in SG stars ranges from about 50% to more than 80%. Hence, we define the current cluster SG mass fraction \( f_{\text{SG, GCS}}^{\text{now}} \) by

\[
M_{\text{SG, GCS}}^{\text{now}} = f_{\text{SG, GCS}}^{\text{now}} M_{\text{GCS}}^{\text{now}}
\]

where \( M_{\text{GCS}}^{\text{now}} \sim 2 \times 10^7 M_\odot \) is the current total mass of halo Galactic globular clusters (assuming \( M/L = 2 \); Mackey & van den Bergh 2005).

Most of the clusters studied are more massive than \( \sim 10^5 M_\odot \), and it is not known whether such a large SG fraction is common to all Galactic globular clusters or only to those currently more massive than some threshold. For purposes of this Letter, we simply assume as a reference value \( f_{\text{SG, GCS}}^{\text{now}} \simeq 0.5 \). Results for different values of \( f_{\text{SG, GCS}}^{\text{now}} \) can be very easily derived from those shown in this Letter.

To complete our calculation, we need an estimate of \( M_{\text{GCS}}^{\text{init}} \), the total initial mass of all stars in globular clusters. This is not easily determined from observations of the current Galactic globular cluster system. Here again, we simply parameterize the normalization of Equation (3) or (4) by defining the parameter \( \Phi = M_{\text{GCS}}^{\text{init}}/M_{\text{GCS}}^{\text{now}} \), where we take \( M_{\text{GCS}}^{\text{now}} = 10^9 M_\odot \) (see, e.g., Freeman & Bland-Hawthorn 2002).

The current fraction of SG stars in the stellar halo, \( f_{\text{SG, H}} \), then is

\[
f_{\text{SG, H}} = \frac{M_{\text{SG, GCS}}^{\text{init}} - M_{\text{SG, GCS}}^{\text{now}}}{M_{\text{GCS}}^{\text{now}}} \frac{M_{\text{GCS}}^{\text{now}}}{M_{\text{GCS}}^{\text{init}}}
\]

Finally, if we define \( \eta \) as the ratio of the total initial mass of SG stars in the Galactic globular cluster system to the total initial mass of the cluster system

\[
\eta \equiv \frac{M_{\text{SG, GCS}}^{\text{init}}}{M_{\text{GCS}}^{\text{init}}},
\]

and use the definition of \( f_{\text{SG, GCS}}^{\text{now}} \) in Equation (6) along with the values of \( M_{\text{GCS}}^{\text{now}} \), then we can rewrite Equation (7) as

\[
f_{\text{SG, H}} = \eta \Phi - 0.02 f_{\text{SG, GCS}}^{\text{now}}.
\]

The form of Equation (9) allows to easily identify the different theoretical and observational ingredients needed for the determination of \( f_{\text{SG, H}} \). We summarize them here.

1. \( \eta \), the ratio of the total initial mass of SG stars to the total initial mass of the Galactic globular cluster system, incorporates the dependency on the SG formation model (through the function \( \xi(M, R_h, R) \)), as well as on the stellar IMF, the cluster mass, and structural parameter distribution functions (see Equation (5) above).

2. \( \Phi \), the ratio of the total initial mass of the Galactic globular cluster system to the current halo mass, is not known. The simple linear scaling of \( f_{\text{SG, H}} \) with this parameter allows to easily explore the dependence of \( f_{\text{SG, H}} \) on the total initial mass of the Galactic globular cluster system.

3. \( f_{\text{SG, GCS}}^{\text{now}} \), the fraction of the total current mass of the halo cluster population composed of SG stars, is a parameter to be determined observationally. In our study, based on the spectroscopic survey of Carretta et al. (2009a, 2009b), we adopt as a reference value \( f_{\text{SG, GCS}}^{\text{now}} = 0.5 \). However, in this case too, the simple linear scaling of \( f_{\text{SG, H}} \) with \( f_{\text{SG, GCS}}^{\text{now}} \) allows to easily calculate \( f_{\text{SG, H}} \) for other values of \( f_{\text{SG, GCS}}^{\text{now}} \).

4. RESULTS AND DISCUSSION

In Figure 2, we show the dependence of \( \eta \) on the power-law index \( \alpha \) of the IGCMF. Different lines correspond to different pairs of values of \( R_h \) and \( R \), a K93 or a K01 IMF and different values for the parameters of the IGCMF (\( M_C \) and \( M_{\text{low}} \); \( M_{\text{up}} \) is fixed at \( 10^7 M_\odot \)).

Comparison of the results for models with different values of \( R \) shows no significant differences.

An increase in \( M_C \) and/or \( M_{\text{low}} \) increases the fraction of the total initial mass in clusters massive enough to form SG stars (\( M \gtrsim 10^{4.5} - 10^5 \); see Figure 1), and hence increases \( \eta \). Similarly, as \( \alpha \) decreases, the fraction of total mass in massive clusters increases, and so does \( \eta \).

For a fixed value of \( R \), decreasing the value of \( R_h \) adopted has the obvious consequence of increasing the fraction of AGB ejecta retained and the amount of SG stars formed in lower-mass clusters. The absolute upper limit (\( \eta_{\text{max}} \approx 0.08 \) for a K93
IMF and $\eta_{\text{max}} \simeq 0.125$ for a K01 IMF) would be attained by assuming (unrealistically) that all clusters (including the low-mass ones) were compact enough at the time of SG formation ($30 \, \text{Myr} \lesssim t \lesssim 100 \, \text{Myr}$) to retain all the AGB ejecta and reach a fraction of SG stars formed $\xi \simeq 0.08$ or $\xi \simeq 0.125$ for a K93 and a K01 IMF, respectively.

From the results shown in Figure 2, one can easily calculate $f_{SG, H}$ as a function of $\Phi$ and $F_{\text{low}}^\text{SG,GCS}$ for any of the combinations of IGCMF, cluster structural parameters, and IMF explored. For example, Figure 3 shows the dependence of $f_{SG, H}$ on $\Phi$ for a power-law IGCMF with $\alpha = 1.8$, for various values of $M_{\text{low}}, R, R_h$, and for either a K93 or a K01 IMF (and, as discussed above, we have adopted $F_{\text{low}}^\text{SG,GCS} = 0.5$). If clusters were at the time of SG formation ($30 \, \text{Myr} \lesssim t \lesssim 100 \, \text{Myr}$) more compact than assumed here, the lines of $f_{SG, H}$ versus $\Phi$ would fall between those shown in Figure 3 and that corresponding to the absolute upper limit easily obtained using Equation (9) and the maximum value of $\eta$ ($\eta_{\text{max}} \simeq 0.08$ for a K93 IMF and $\eta_{\text{max}} \simeq 0.125$ for a K01 IMF).

Figures 2 and 3 demonstrate that, for the broad range of values of the IGCMF parameters considered, the predicted fraction of SG stars in the halo is always small, $f_{SG, H} < 4\%–6\%$ for a K93 IMF and $f_{SG, H} < 7\%–9\%$ for a K01 IMF. This result is consistent with the small fraction ($\sim 1.5\%–2.5\%$) of halo stars identified as SG stars by Carretta et al. (2010; based on the stars’ sodium abundance) and Martell & Grebel (2010; based on CN and CH band strengths). For comparison, 50% of globular cluster stars are identified as SG when the same classification criteria are adopted (Kraft 1994; Carretta et al. 2010; Martell & Grebel 2010). We note that for these estimates of $f_{SG, H}$, using, for example, a power-law IGCMF with $\alpha = 1.8$ as a reference model, our calculations (Figure 3) with a K01 IMF (K93 IMF) imply that a fraction ranging from about 20% to about 40% (30% to about 60%) of the Galactic stellar halo must be composed of stars originally formed in globular clusters. Although this estimate is very uncertain and both more calculations and further observational studies of SG stars in the halo will be required to refine it, it is interesting to note how the fractions of SG stars in globular clusters and in the Galactic stellar halo connect and constrain both models for the formation and dynamical evolution of multiple stellar generations in globular clusters and the formation history of the Galactic halo.

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