Multiple Populations in Globular Clusters: The Possible Contributions of Stellar Collisions

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ABSTRACT

Globular clusters were thought to be simple stellar populations, but recent photometric and spectroscopic evidence suggests that the clusters’ early formation history was more complicated. In particular, clusters show star-to-star abundance variations, and multiple sequences in their colour-magnitude diagrams. These effects seem to be restricted to globular clusters, and are not found in open clusters or the field. In this paper, we combine the two competing models for these multiple populations and include a consideration of the effects of stellar collisions. Collisions are one of the few phenomena which occur solely in dense stellar environments like (proto-)globular clusters. We find that runaway collisions between massive stars can produce material which has abundances comparable to the observed second generations, but that very little total mass is produced by this channel. We then add the contributions of rapidly-rotating massive stars (under the assumption that massive stars are spun up by collisions and interactions), and the contribution of asymptotic giant branch stars. We find that collisions can help produce the extreme abundances which are seen in some clusters. However, the total amount of material produced in these generations is still too small (by at least a factor of 10) to match the observations. We conclude with a discussion of the additional effects which probably need to be considered to solve this particular problem.

Key words: globular clusters: general – stellar dynamics

1 INTRODUCTION

Globular clusters have long been viewed as the epitome of simple stellar populations. Their stars have a common age, a common distance, and a common metallicity; there is no interstellar gas and little else to get in the way of studying the stars directly. These systems are the closest we can come to a “controlled experiment” in stellar astrophysics, and as such they have proved incredibly valuable for studies of both stellar evolution and stellar dynamics in the past.

However, in recent years, cracks have been appearing in this simple picture. Both photometric and spectroscopic studies of clusters have started to unearth puzzles and inconsistencies. At first, these problems were thought to be an oddity in one particular cluster, or evidence of some details of stellar physics that we didn’t quite understand. Over the last five years or so, however, it is becoming clear that our picture of a globular cluster needs to change. They cannot have formed instantly out of a single molecular cloud, removing all their leftover gas immediately, and then evolved passively for the next 10 billion years. Their history is more complicated.

1.1 Observational Background

Hints that something strange was going on in globular clusters came first from spectroscopic studies of their red giants. For an excellent review, see Gratton, Sneden & Carretta (2004). The general results have not changed since that review was written, although we now have observations of more stars per cluster, and more stars observed with high-resolution spectra. Most globular clusters have a constant iron and iron-peak element abundances, with the notable exception of ω Centauri (Freeman & Rodgers 1975) and hints of a very small spread in M22 and M92 (Marino et al. 2009; Langer et al. 1998). However, it has been known since the late 1970s that lighter metals, particularly carbon, nitrogen and oxygen, do vary from star to star in many clusters (Cohen 1978). Other light elements also show star-to-star variations in clusters, including Na, Al and Mg. The most striking piece of evidence to date that this abundance variation phenomenon occurs in all clusters is the spectroscopic...
study of sodium and oxygen by Carretta et al. (2009a,b). A general anti-correlation is seen, with oxygen-depleted stars having higher sodium abundances. Aluminum and magnesium have been studied in fewer clusters, but they also show similar trends (Shetrone 1996; Carretta et al. 2009a). With a large range in aluminum, a smaller spread in magnesium, and some evidence for high-aluminum stars having lower magnesium abundances.

Carretta et al. (2008) also looked for correlations between the extent of the Na-O anti-correlation and cluster properties. The strongest correlation was between the extent of the correlation and the maximum temperature of stars on the horizontal branch, in the sense that clusters with very hot (or blue) horizontal branches had a large spread in Na and O. They also found a weaker trend with the total mass (or magnitude) of the cluster, and a trend with galactic orbit, in the sense that clusters which have spent more of their lifetime in the outskirts of the halo and not interacting with the galaxy, have a larger spread in abundances.

One of the main reasons that globular clusters have been so useful to stellar astrophysics is that their colour-magnitude diagrams are very clean. Other than the blue stragglerstars and a few other unusual objects, the stars fall onto a single isochrone (see e.g. Sarajedini et al. 2007). Again, the exception has been ω Centauri. Its colour-magnitude diagram shows a large amount of structure beyond a single age/composition isochrone. The spread of the giant branch of this cluster was understood in the context of the measured differences in iron abundance of the stars, and so it did not come as much of a surprise to the community when the main sequence of this cluster was found to contain more than one sequence as well (Bedin et al. 2004). However, the most intriguing result from this detailed study of ω Centauri was the determination that the iron abundance of the bluest main sequence was not, as one would expect, the lowest in the cluster, but was in fact the highest (Piotto et al. 2003). The only possible way to reconcile the spectroscopic abundances with the photometric information was to infer a high helium content for these stars, perhaps even as high as Y=0.4. Because the abundance anomalies are found in light elements only but not iron, researchers have been casting this as a problem of ‘pollution’ from an early generation of stars in the cluster.

The globular cluster community finally came to realize that multiple populations were ubiquitous when D’Antona et al. (2003) discovered an intrinsic spread in the main sequence NGC 2808, which was later confirmed to be three separate main sequences (Piotto 2007). The turnover region in this cluster is quite tight without much evidence for a spread, but starting about one magnitude below the turnover, the sequences become obviously separated.

At about the same time, we saw the first CMDs showing multiple subgiant branches (e.g. the ACS observation of NGC 1851 (Milon et al. 2008)). Similar observations have since been seen in M22, NGC 6388, and M54 (Piotto 2009) and many intermediate age clusters in the LMC and SMC (Mackev et al. 2008; Milone et al. 2006). NGC 1851 is an interesting case, is that it does not show any evidence for a splitting of the main sequence, even in very careful observations including proper-motion cleaning of the CMD. It does, however, show a split in its giant branch when observed in $U - I$ (Han et al. 2004) which is not seen in $V - I$, highlighting the importance of observing in multiple bands.

Understanding the horizontal branch (HB) morphology in globular clusters has been a problem for decades, commonly referred to as the ‘second parameter problem.’ Because the position of HB stars in the CMD is sensitive to both helium and metal abundances, they are a very useful population with which to discuss both pollution and multiple populations (e.g. D’Antona & Caloi 2008).

### 1.2 Possible Explanations

Many of the models to date have attempted primarily to understand the source of the pollution. The work of Prantzos, Charbonnel, & Iliadis (2007) showed that the general abundance patterns could be explained by invoking the products of hot hydrogen burning, at a temperature of 70-80 × 10⁶ K. At these temperatures, the hydrogen is burned in a series of cycles – the standard CNO cycle, as well as the neon-sodium cycle and the aluminum-magnesium cycle. Conveniently, the second two cycles work to give the abundance patterns that are needed: higher sodium, lower Mg and higher Al. This processed material must be removed from the star before helium burning can proceed. Otherwise, the helium will be converted to carbon and oxygen. We will not have the large amount of helium that is required at the surface, and the constraint of (almost) constant C+N+O abundance will be violated.

A number of polluters have been proposed. The leading contender is a population of intermediate-mass (3-10 $M_\odot$) asymptotic giant branch (AGB) stars (for a review, see Renzini 2008). These stars can reach the appropriate high temperatures in their hydrogen burning shells, and the processed material is brought to the surface by the outer convection zone as it reaches into the burning shell during the hydrogen burning portion of the thermal pulse phase. AGB stars have strong but low-velocity winds, which means that any mass that is removed from the star has a good chance of remaining in the cluster. Indeed, there is recent evidence that giant stars in this mass range do show surface abundances which are consistent with the necessary pollution (Villanova, Carraro, & Saviane 2009).

An alternative source of pollution is a population of fast-rotating massive stars (Depresset al. 2007). Massive stars reach sufficiently high temperatures in their hydrogen-burning cores. These stars also have substantial winds, but under normal circumstances, the core regions are not exposed until very late in the stars’ lives, well past the helium-burning phase. If a star is rotating rapidly, however, then meridional circulation and other rotational instabilities will mix material from the core to the surface, bringing these hydrogen-burning products up to a region where the wind can take them away from the star. Also, if the star is rotating rapidly enough that it is close to its break-up velocity, material can escape from the equator of the star in a slow outflowing disc or slow wind. This material in particular has a slow enough velocity that it will stay in the cluster, and there are even indications that low mass stars could form in situ in the disc.

Both AGB and fast-rotating massive star models have some difficulties in explaining the pollution of globular cluster gas and the formation of the second generation of stars.
In both cases, the amount of material that is required to form the second generation is quite large. Observations of clusters such as NGC 2808 suggest that the mass of the second generation is approximately equal to the first (within a factor of 2-3 or so), which puts a limit on the amount of ejecta that the first generation must produce. Early versions of both models (D’Antona & Caloi 2004; Decressin et al. 2007) suggested non-standard IMFs, heavily weighted towards the polluter in question, but these IMFs are difficult to justify. Current versions suggest that in fact the first generation needed to be significantly larger than what is observed today, and that the cluster needs to have lost approximately 90% of its first generation, while retaining all of the gas and the second generation of stars (Ventura & D’Antona 2009; Decressin, Baumgardt, & Kroupa 2008). Both models also require a certain amount of dilution of the polluted ejecta with primordial gas, in order to match the observed abundances of light elements, including lithium.

The work of Pietrinferni et al. (2009) looked at the effect of both enhanced helium abundance, and enhanced C+N+O abundance, on isochrones appropriate for globular clusters. They confirm that multiple main sequences are caused by a change in helium abundance at constant metal abundance (both iron and light elements). Multiple subgiant branches, on the other hand, are caused by a difference in total C+N+O abundance at constant helium, constant iron, and constant age. Han et al. (2009) show that the split subgiant and giant branches of NGC 1851 are best explained in both $U - I$ and $V - I$ by a small change in both helium and metal abundance. The alternative explanation is a difference in age of the two populations of $\sim 1$ Gyr and constant abundances. It is, however, difficult to explain in a delay in star formation of such a long time, and difficult to understand where the gas for the second generation came from.

Only a few groups have tried to put together the entire scenario. The most successful is the work of D’Ercole et al. (2005), which incorporated hydrodynamic simulations to study the flow of the AGB and supernovae ejecta in the vicinity of the proto-cluster. They find that the ejecta collects in a cooling flow and returns to the core of the cluster. They also look at a scenario in which pristine gas, which was pushed out of the cluster vicinity by the supernovae and massive stars, returns to the cluster after a few million years and mixes with the ejecta. Similar to Prantzos, Charbonnel, & Iliadis (2007); D’Antona & Ventura (2007); Ventura & D’Antona (2009), they find that the combination of pristine gas and ejecta is necessary. They also find that much of the first generation in the cluster may be lost if the cluster is tidally limited. Finally, both D’Ercole et al. (2008) and Decressin, Baumgardt, & Kroupa (2008) use N-body dynamical models to study the subsequent evolution of this two-generation cluster and the mixing of the two populations. They concur with the general results of Downing & Sills (2007) that, at the current time, a two-generation cluster will not be dramatically different from a single-generation cluster in terms of the dynamics and distribution of stars.

2 A TOY MODEL CALCULATION

In this paper, we investigate a modified version of the scenarios presented in the introduction. First, we will consider the case where both fast-rotating massive stars and asymptotic giant branch stars contribute to the pollution of material which forms the subsequent generation(s). Second, we include the possible effects of stellar collisions.

Recall that the multiple populations phenomenon is only seen in globular clusters and not in the field or in open clusters. Dense globular clusters are one of the few places in the universe where stellar collisions are expected to be prevalent (Hills & Dey 1976). There are three relevant outcomes of stellar collisions: runaway collisions, modification of the rotational properties of stars, and creation of intermediate mass stars.

Dynamical calculations of dense stellar systems have shown that there can be dozens of direct stellar collisions between massive stars within the first few million years of the cluster’s life (Portegies Zwart et al. 2004). These runaway collisions involved stars with a total mass of up to 1000 $M_\odot$ and occur in any cluster which undergoes a core collapse within the first 3 Myr or so (Freitag, Rasio, & Baumgardt 2006). The runaway collision dramatically modifies the upper end of the initial mass function. The most massive stars in the cluster will not follow their normal isolated evolution, but will merge to create the collision product. Therefore, there will be fewer supernovae and fewer neutron stars and black holes created. Secondly, the evolution of these very massive stars must include substantial mass loss, but the mass loss history of the collision product is very different from that of the sum of the stars which go into the collision. As shown by Glebbeek et al. (2009), the total amount of mass ejected by the collision product can be up to a factor of $\sim 1.5$ larger than that ejected by the collision parents individually.

At the same time that the runaway collision is happening, other collisions will also be going on in the cluster. Some of them will produce massive collision products, and others will be between very small and very large stars, which will produce rapidly-rotating stars. Unless two stars collide exactly head-on, most of angular momentum of the original trajectory is deposited into the collision product, producing an object which is spinning rapidly (Lombardi, Rasio, & Shapiro 1996). Many of them could be rotating with a substantial fraction of their break-up velocity. Therefore, the population of fast-rotating massive stars should be larger in a cluster with a high collision rate.

And finally, collisions between low and intermediate mass stars could increase the number of stars in the 3-10 $M_\odot$ range. Some of the original stars in this range will have been removed due to collisions themselves, and so determining the total number of intermediate mass stars is not a trivial calculation. However, these stars will not segregate quickly enough to become part of the sub-cluster which creates the runaway collision. This population does not start contributing to the gas of the subsequent generation until the stars reach the AGB phase, around 30-100 Myr after the formation of the cluster.

To try to get a handle on the abundances of the gas which could possibly form the second and third generations of stars, we calculate a very simple chemical evolution model
based on the scenario described above. We also follow the mass function of stars as they form, evolve to remnants, and are modified by collisions. We begin with a gasless star cluster at \( t=0 \). We assume some typical quantities for a globular cluster: the total mass of stars in the system is \( 1 \times 10^5 \ M_\odot \), its half-mass radius \( r_h=3 \) pc, and the stellar velocity dispersion is 10 km s\(^{-1}\). According to the simulations of Freitag, Rasio, & Baumgardt (2004), a runaway velocity will occur if the cluster has an initial \( W_0 \) (the dimensionless central potential of a King model) of 8 or higher, corresponding to a concentration parameter \( c = \log(r_c/r_h) = 2 \) or higher (Binney & Tremaine 2008, figure 4.10). For King models, \( r_h/r_c \) is approximately constant, with a value of 0.12 at \( c = 2 \) (Spitzer 1987, p. 16), and therefore this globular cluster must have a core radius \( r_c = 0.25 \) pc, tidal radius \( r_t = 25 \) pc, and a central density of \( 2.5 \times 10^5 \ M_\odot/pc^3 \) in order for this scenario to be valid. These quantities are not unreasonable for dense globular clusters seen today. We assume the stars are formed with a Salpeter mass function between 0.1 and 120 \( M_\odot \) and have \( Z=0.001 \), \( Y=0.24 \) and an alpha-enhanced abundance mixture with [\( \alpha/Fe \)] = +0.4.

Early in the cluster’s life, we assume that one runaway collision occurs. We remove each of the stars which participate in this collision from the initial mass function. The yields from this collision are based on the low-metallicity sequence in the calculations of Glebbeek et al. (2009). The original calculation used a simplified nuclear network that could only follow a small number of species. We have recalculated the yields of the Glebbeek et al. (2009) calculation using the nucleosynthesis routines of Stancliffe et al. (2003) with reaction rates from Angulo et al. (1999) and Herwig, Austin, & Lattanzio (2006). The reaction network includes proton, neutron and \( \alpha \) captures on stable isotopes up to \( ^{34}\text{S} \) and some iron group elements.

Material leaves the runaway collision products in two ways. First, during each collision, the product loses a few percent of its total mass because of the energy of impact of the collision itself. The amount of each element ejected in this way, summed over all collision in the runaway sequence, are listed in table 1 as ‘ejecta’. Between collisions, the collision product is evolving as a relatively normal massive star, and exhibits strong mass loss. In our calculations, we assume that this loss is from a radiative wind, although LBV-like mass loss may also be important. The total amount of material lost by the runaway collision product in winds is listed in table 1. There are two wind channels, listed separately: the wind of the collision product in between collisions ‘Wind’), and the wind of the collision product during its remaining lifetime after the last collision (‘Rem. wind’). These winds should leave the parent star with velocities which are typical of O stars and luminous blue variables, which range from a few hundred to a few thousand km s\(^{-1}\). In a dense stellar system with many other massive stars present, it is plausible that these winds will collide with the winds of other stars, shock, and slow down sufficiently to remain trapped in the centre of the cluster and contribute to the second stellar generation. We assume that is the case initially, but also perform the calculation under the assumption that all the wind material is lost from the cluster.

As in Glebbeek et al. (2009) we were only able to follow the evolution of the collision product about half way through core helium burning due to numerical difficulties during this evolution phase. We calculate the final remnant mass of the collision product as described in Glebbeek et al. (2009) and estimate the yields for the remaining core helium burning lifetime by assuming that the remainder of the envelope is ejected without undergoing additional processing. The results are listed in table 1 under ‘Rem. remaining’.

This particular runaway is only one possible combination of parent stars, impact velocities, etc. It was chosen in the study of Glebbeek et al. (2009) to be representative of the collisions seen in N-body simulations. The details of exactly how much mass, and the exact composition of the ejecta, will change slightly if the details of the runaway collision changes. This must be kept in mind when interpreting the results of the chemical evolution calculations presented below. A comparison of the three runaway collision sequences studied in Glebbeek et al. (2009) show that the yields are consistent to within 10-20\% depending on the element. The total amount of mass which can be released varies by up to a factor of two (up to approximately 1000 \( M_\odot \)). As we will discuss below, the results do not change dramatically if we adopt the upper limit of these values.

While the runaway collision is going on, other stellar collisions will spill up some of the massive stars in the cluster. Following Gurkan, Freitag, & Rasio (2004), we assume that the massive stars in the cluster segregate towards the centre, and form a decoupled dynamical cluster which undergoes core collapse. This cluster, until very close to the time of core collapse, has the same core radius and central density as the original cluster. However, the mass function becomes much more weighted towards massive stars, so that the average stellar mass in this sub-cluster is more like 20 \( M_\odot \) (compared to \( \sim 0.35 \) \( M_\odot \) for a normal cluster). Using these parameters and the equation for the average time between collisions from Leonard (1989), we find that approximately 1100 stellar collisions should occur during this first 5 Myr in this initial sub-cluster of stars. There are approximately 200 stars in this cluster with masses above 20 \( M_\odot \), forming approximately 35\% of the stars in the sub-cluster. Therefore, it is likely that every high-mass star has undergone at least one stellar collision.

Following Decressin et al. (2007), we define “rapidly rotating” to mean having a rotation rate that is at least 80\% of

Table 1. Abundances, in mass fraction, from the runaway collision. The total amount of mass in each component is given.

| Element | Ejecta | Wind | Rem. wind | Rem. remaining |
|---------|--------|------|-----------|----------------|
| \(^1\text{H}\) | 5.97e-01 | 3.09e-01 | 1.21e-01 | 5.70e-02 |
| \(^{4}\text{He}\) | 4.02e-01 | 6.90e-01 | 8.78e-01 | 9.50e-01 |
| \(^{12}\text{C}\) | 1.89e-05 | 1.02e-05 | 8.78e-06 | 7.48e-06 |
| \(^{13}\text{C}\) | 2.16e-06 | 2.24e-06 | 2.31e-06 | 2.12e-06 |
| \(^{14}\text{N}\) | 6.66e-06 | 7.10e-04 | 7.09e-04 | 7.21e-04 |
| \(^{16}\text{O}\) | 5.03e-05 | 1.79e-05 | 1.21e-05 | 7.40e-06 |
| \(^{19}\text{F}\) | 2.09e-09 | 4.44e-10 | 1.56e-10 | 2.12e-11 |
| \(^{20}\text{Ne}\) | 7.03e-05 | 4.31e-05 | 2.85e-05 | 2.41e-05 |
| \(^{23}\text{Na}\) | 2.20e-05 | 1.29e-05 | 3.94e-06 | 2.16e-06 |
| \(^{24}\text{Mg}\) | 3.60e-05 | 7.50e-05 | 9.75e-05 | 9.97e-05 |
| \(^{25}\text{Mg}\) | 3.82e-07 | 7.65e-08 | 3.14e-08 | 3.31e-09 |
| \(^{26}\text{Mg}\) | 2.31e-06 | 7.35e-07 | 2.37e-07 | 1.30e-07 |
| \(^{26}\text{Al}\) | 1.95e-06 | 1.20e-06 | 7.16e-07 | 5.73e-07 |
| \(^{27}\text{Al}\) | 4.01e-06 | 5.62e-06 | 6.11e-06 | 6.24e-06 |
of the critical rotation rate. We expect that some fraction of massive stars are primordial fast rotators (i.e. they were born that way and not spun up by collisions). The models of Decressin et al. (2007) assume that all massive stars are rotating rapidly enough to contribute polluted material to the second generation. Observations of stars in young clusters (e.g. Dufton et al. 2006) suggest that cluster stars are more rapidly rotating than those in the field, and that the fraction of rapid rotators is more like 20%. Initially, we make the extreme assumption that every collision will turn a slow rotator into a rapid rotator. This assumption is unlikely to be completely correct, as the amount of angular momentum which can be added to a high-mass star depends on the mass of the impactor, its velocity and its position of impact on the high mass star. However, the highly collisional environment of the mass-segregated sub-cluster means that high mass stars will likely undergo more than one collision. The net effect of these collisions will be to spin up the population.

We use the yields of Decressin et al. (2007) to determine the contribution of this population to the ejected gas. We use the yields of their case C reaction rates for 40, 60 and 120 M⊙ fast-rotating stars. These yields come from a set of reactions in which the reactions involving 26Ne through 27Al are set to their experimental upper or lower limits in such a way to produce the most favourable set of yields for this work. However, we do not use the yields from the models in which the 24Mg(p,γ) reaction rate is increased by a factor of 1000 at 5 × 10⁷ K (case D). This fudge was required to produce the lower range of the observed [Mg/Al] values in NGC 6752. However, for this toy model, we prefer to use the ‘standard’ set given by Decressin et al. (2007). The models presented in that paper assumed a metallicity of Z=0.0005 and are initially alpha-enhanced. The yields for the runaway collisions and the AGB stars are for Z=0.0001, so we should be using different yields to be consistent. Unfortunately higher metallicity yields for fast-rotating massive stars are not available. We do not expect our results to be dramatically different if we had used other reasonable yields or models.

Like the runaway collisions, these fast-rotating massive stars also lose material in two ways. One, a slow wind is present, primarily from the equator of the stars, as the surface material reaches an angular velocity higher than the local stellar escape velocity. This material will remain in the cluster, and those yields are assumed to be those up to the time the star has reached the end of central H burning, following Decressin et al. (2007). These stars also have a fast wind, with velocities typical for O and B stars (a few hundred km s⁻¹), and is dominant between the end of central H burning and the time when the helium-burning products appear at the surface of the fast-rotating stars. We make the same assumptions as for the winds of the runaway collision: initially we assume these winds shock and remain in the cluster, and then we will present a calculation in which they are assumed to be removed entirely from the cluster.

The time of the first supernova is set by the most massive star which is not involved in a runaway collision, or the lifetime of the runaway itself, whichever comes first. At this time, which is approximately 5 Myr, we assume that all the gas in the cluster forms the second generation of stars, and any subsequent gas is removed from the cluster until the AGB stars begin to contribute. For this reason, we neglect the contribution of rapidly rotating 20 M⊙ stars, as their main sequence lifetimes are closer to 10 Myr. We calculate the total mass in ejecta from both the runaway collision and the fast rotating massive stars, under the assumption that both fast and slow winds are retained in the cluster. We find that we have 3459 M⊙ of material, which we assume forms the second generation of stars with 100% efficiency. We populate a Salpeter IMF from 0.1 to 120 M⊙, as was done with the initial cluster.

The abundances of this second generation are quite extreme. In Figure 1, we show the helium abundance of each generation, labelled as “primordial”, “runaway & FRMS” for this second generation, and “all AGB” and “high mass AGB” for different possibilities of the third generation, to be discussed below. This figure also shows the calculated number of low mass stars, with masses less than 0.8 M⊙, which are expected to be observable members of the cluster today. Note that we plot the logarithm of the number of stars. The runaway collision, which contributes only 539 M⊙ of material to the cluster, is strongly enhanced in helium, with an overall Y of 0.68. The fast-rotating massive stars are also strongly helium enhanced, with Y=0.43 for the 2920 M⊙ ejected. This results in an overall helium abundance for this first generation of Y=0.47. This is much higher than is inferred in even the most extreme globular cluster second generation.

The abundances of other elements, however, match the observations reasonably well. Figures 2 and 3 compare the calculated abundances of each generation or pollution mechanism, as labelled, to the observations. The shaded region on each diagram encompasses most of the observed abundance trends, as taken from the figures in Carretta et al. (2009a) and Carretta et al. (2009b). The runaway collisions alone seem to be the only way to reach significant oxygen depletion ([O/Fe] ~ -0.9) and sodium enhancement ([Na/Fe] ~ 1.0). The fast-rotating massive stars do deplete oxygen and enhance sodium as well, although to a lesser extent. Because the runaway collision produces so little mass, the overall abundances of the second generation are oxygen-poor and sodium-rich at levels which are consistent with all but the most extreme observations in clusters (e.g. in NGC 2808).

Magnesium and aluminum abundances from this second generation are also consistent with most of the observations. Again, none of our models are able to reproduce the most extreme populations (the high aluminum, low magnesium portion of the diagram). It should be noted, however, that there are very few stars in that region and they are all in NGC 2808; the bulk of the stars in other clusters lie in the vertical region of this plane, and we argue that magnesium depletion needs to be confirmed in more clusters before this diagnostic is used to rule out particular models. We also note that this generation does not produce very much aluminum, despite the interestingly high helium yields and the good agreement with the bulk of the Na-O observations.

Next, we consider the likelihood that collisions in this early stage will produce additional intermediate-mass AGB stars later in the cluster’s life. We used the properties of the entire cluster core rather than that of the sub-cluster of massive stars because the low to intermediate mass stars that we were considering here have not had time to mass segregate. Using equation 13 of Leonard (1989), we found that only 4 collisions should have occurred in the first 5 Myr. Even if...
we assume that the cluster conditions remain the same until the stars of this mass reach the AGB phase (about 30 Myr), only a few dozen collisions will occur, and only approximately 5% of those will produce stars with masses between 3 and 8 M\(_\odot\). Therefore, we will neglect the contribution of collisionally-created AGB stars.

Now we calculate the contribution of the AGB stars from both the first and second stellar generations. We use yields for Z=0.001 for both the first and second generation populations (Ventura & D’Antona 2008, 2009). These yields will be incorrect for the AGB stars formed from the ejecta of the runaway collision and fast rotating massive stars, as the helium and light element content of these stars is initially increased. The structure of helium-rich stars is different than that of normal stars, and the hydrogen-burning cycles are dependent on the abundances of the catalyst elements. Therefore, we should not simply scale the yields from the normal AGB stars to estimate the yields of high-helium stars. The helium abundances will be higher than given by the normal star yields because even unprocessed material will be enriched in helium. However, the number of second-generation AGB stars is low (~ 65), and so we will take the conservative assumption that their yields are the same as the first generation population. In addition, helium-rich AGB stars have lifetimes which are \(\approx 50-70\%\) shorter than stars of the same mass but normal helium. In our simple model, this does not affect our results because we simply sum up all the contributions from AGB stars with lifetimes shorter than our cutoff. However, a more detailed model will need to include this lifetime effect.

First, we assume that all AGB stars between 3 and 6 M\(_\odot\) contribute to the material which forms the third generation. The AGB stars produce almost twice as much material as the massive stars (6084 M\(_\odot\)). The helium abundance of this population is Y=0.29, which is higher than the standard value but still not as high as the Y=0.4 inferred for clusters such as NGC 2808. The AGB ejecta is slightly enhanced in oxygen compared to the initial value ([O/Fe] = 0.55, up from 0.4), and is significantly enhanced in sodium ([Na/Fe] = 1.04, up from -0.2). The sodium enhancement is much larger than that seen in most globular clusters, and the AGB stars alone do not produce stars with low oxygen/high sodium values that are seen in globular clusters. Dilution with primordial material reduce both the sodium and oxygen abundances, but an oxygen depletion of approximately 1 dex is impossible to accomplish with these AGB yields. Similarly, this population produces some aluminum without much change in magnesium. This population is labelled ‘all AGB’ in figures 1–3.

However, 3 M\(_\odot\) AGB stars have lifetimes of over 300 Myr. This time is long enough that SNIa may have started to pollute the cluster and disrupt the gas. Also, the most massive AGB stars started losing their mass after only \(\approx 50\) Myr, and it is not clear that this material would have remained in the cluster, waiting for the ejecta of the lower mass stars. It is more likely that the longest possible time for the AGB ejecta to collect is more like 100 Myr, which is the lifetime of a 5 M\(_\odot\) AGB star. If we restrict ourselves to only the most massive AGB stars (5-6 M\(_\odot\)), then the sodium and oxygen yields are more consistent with the observations, and in fact are very similar to those from the runaway + FRMS population. Under this assumption, AGB stars only contribute \(\sim 2100\) M\(_\odot\) to the new generation, an amount of mass which is comparable to that of the first generation. This population also produces more aluminum and shows a very slight magnesium dilution. This population is labelled ‘high mass AGB’ in figures 1–3.

If we combine the second and third generation, we have \(9.5 \times 10^5\) M\(_\odot\) of material, or less than 10% of the initial cluster. If we compare the number of stars that will still be in the globular cluster at current time (less massive than 0.8 M\(_\odot\)), the two new generations have created 25 000 stars and there are approximately \(2.6 \times 10^6\) stars from the first generation. We are still required to lose 90% of the initial low-mass stars in order to have our younger generations form half the cluster at the current day. These numbers assume that all AGB stars contribute to the third generation, which is the most generous assumption one can make about total mass, but is almost certainly an overestimate as discussed above.

The other way to mitigate this mass problem is to allow primordial material to mix into the gas which will form either the second or third generation (or possibly both). While this will certainly help boost the mass of that generation, it will also change the abundances. In figures 2 and 3 we have drawn lines of dilution for the second and the two possible third generations. The amount of dilution ranges from almost none near the points labelled by the polluters, to a huge amount of mass as the line nears the primordial abundance. We feel that it is more likely that the second generation would be polluted than the third, and so we calculated the total amount of mass needed to bring the helium abundance down to some values of interest. For example, only 1500 M\(_\odot\) is needed to bring the helium abundance to Y=0.4, but 77 000 M\(_\odot\) brings Y to 0.25. This is comparable to the mass of the initial generation.

The previous results assume that both the “slow” and “fast” winds from runaway collision products and fast-rotating massive stars contribute to the second generation in the globular cluster. Fast winds, with velocities between a few hundred and a thousand km/s, may not be retained in the potential well of the initial cluster. We have calculated the total mass of gas, and its abundances, using only the slow winds from the two contributors to the second generation. As expected, the total amount of mass available is reduced (\(\approx 1900\) M\(_\odot\) instead of \(\approx 3500\) M\(_\odot\)), and the abundances are different. In particular, the helium content is much lower (Y=0.321) because the fast wind is thought to be occurring when the stars are predominantly helium stars. The oxygen and sodium abundances are both approximately 0.1 dex lower, while the aluminum and magnesium abundances are lower by more like 0.15 dex. These abundances are still consistent with the observed abundances in clusters. The oxygen and sodium abundances are closer to the extreme values observed, while the aluminum/magnesium values are closer to the primordial values.

For comparison, we have also calculated the expected contributions from our three pollution processes if we neglect the effects of stellar collisions entirely. In this case, runaway collisions do not contribute at all. We assume that only 20% of massive stars are rotating rapidly enough to produce any polluting material (but we do include both slow and fast winds from fast-rotating massive stars). We assume that the other 80% of massive stars are not rotating...
Figure 1. Histogram of helium abundance of the three stellar generations, and the number of low-mass (i.e. observable) stars in each generation. The polluter(s) of each generation is marked: primordial abundance, all asymptotic giant branch stars, high mass asymptotic giant branch stars only, and runaway collision product & fast-rotating massive stars. Note that the y axis is logarithmic.

Figure 2. Sodium vs. Oxygen abundances for the three stellar generations. The shaded region shows the extent of the observations, as taken from Carretta et al. (2009a,b). The abundances of the runaway collision products, the population of fast rotating massive stars, and the population of high-mass AGB stars only, are also marked. The curved lines connecting the generations to the primordial abundances show the effects of dilution.

Figure 3. Aluminum vs. Magnesium abundances for the three stellar generations. The shaded region shows the extent of the observations, as taken from Carretta et al. (2009a,b). The abundances of the runaway collision products, the population of fast rotating massive stars, and the population of high-mass AGB stars only, are also marked. The curved lines connecting the generations to the primordial abundances show the effects of dilution.

at all, and we neglect any contribution of their winds to the second generation. This is reasonable because their surface abundances have not been modified by nuclear burning. The effects of AGB stars are reduced as well, since we have much less mass with which to make second-generation AGB stars. Therefore, the total amount of mass in the subsequent generations is only 6500 $M_\odot$, a mere 6.5% of the initial mass of the cluster. Of this material, the bulk is from the AGB stars of all masses, and so is very high in oxygen, sodium, and aluminum, and only mildly enhanced in helium.

3 DISCUSSION AND CONCLUSIONS

In this paper, we take another theoretical look at the problem of multiple populations in globular clusters. In particular, we tried to address the observational constraint that this is specifically a dense old cluster phenomenon. We concentrated on the effects of stellar collisions, which is one of the only physical mechanisms which affects clusters much more strongly than anywhere else in the universe. We also combined two previous models for multiple populations – the fast-rotating massive stars and the asymptotic giant branch stars – to determine if having more polluters would help with either abundances or with the total mass in the subsequent generations.

We included the effects of collisions in three ways: the impact of a runaway collision, an increase in the number of fast-rotating massive stars, and an increase in the number of intermediate mass AGB stars. We also allowed for two subsequent generations. One is formed within a few million years of the first cluster formation, from the ejecta of run-
away collisions and fast-rotating massive stars. The other is formed approximately 100 million years later, from the ejecta of the AGB stars.

Our results are not substantially different from those of other groups who are modeling the early evolution of multiple population clusters. We still find that the mass produced by the polluters alone is insufficient. Loss of a large fraction of the initial cluster, dilution by primordial gas, or both, is required. However, stellar collisions do produce material with abundances which are interestingly extreme in all elements, and may well be a substantial contribution to the extreme populations in the most massive clusters.

It is clear, from this work and others, that we do not yet have a complete understanding of the multiple populations issue. Here, we try to highlight a number of the largest remaining problems, starting with those specific to our model and then discussing the puzzle more generally.

So far, there have been no simulations of star formation in the environment(s) envisioned here. Star formation typically occurs in cores in molecular clouds, an environment which is cold, dark, dense, and shielded from the outside universe. In the centre of a dense cluster, a cloud of ejecta will be subject to the radiation field of the first generation stars. No simulations of star formation in a region with this kind of external radiation bath have been done, and so we do not really understand the properties of the second generation. We have assumed a Salpeter mass function for our subsequent generations, for example, with a maximum mass of 120 M⊙. It may be reasonable to postulate that high mass stars could never form in the second generation (as was suggested by D’Ercole et al. 2008), which would mean that the second generations have more low-mass stars then in our toy model. For a Salpeter mass function between 0.1 and 120 M⊙, 44% of the mass is found in stars more massive than 0.8 M⊙. Under the assumption that only stars of mass 0.8 M⊙ or less form in the subsequent generations, we can increase the predicted mass of these generations by approximately a factor of two.

If the cluster needs to be substantially more massive initially than assumed in this paper, then we should consider how the different polluter channels scale with cluster mass. For fast-rotating stars and AGB stars it is reasonable to assume that the yields scale with the total cluster mass. For the collision runaway this is not so clear. The mass of the collisional runaway as a function of the cluster mass has not been considered in detail in the literature. If the mass of the collision runaway scales with cluster mass, then it behaves as the other two polluter models. However, if the mass of the collision runaway depends more steeply on the mass of the cluster, then it will become relatively more important with increasing initial cluster mass. In that case the number of stars that need to be lost from the cluster can be smaller than when either of the other two scenarios alone are considered. If the total mass of the runaway is only a weak function of cluster mass the other polluter scenarios will become relatively more important for increasing cluster mass.

In these models, we have neglected the effects of binary stars. We know that globular clusters do have binaries, although work suggests that the fraction may be lower than in the field and open clusters (Davis et al. 2003; Rubenstein & Bailyn 1997). Binary stars can modify our toy model in a number of ways. Collisions between binary stars are more likely than between single stars (Leonard 1984) because of the larger cross section of the binary, and many of those interactions can result in more than two stars merging. Binaries can also increase the likelihood of having more than one runaway collision (Gürkan, Fregeau, & Rasio 2004). There are indications that massive stars have a higher binary fraction than low mass stars in the field (Lada 2008) and so it may not be unreasonable to expect that interacting binary stars may have a significant impact on the mass lost from massive stars. Following suggestions by de Mink et al. (2009), Vanbeveren (2004) goes as far as to suggest that interacting massive binaries are responsible for all the pollution in globular clusters, not fast-rotating massive stars or AGB stars.

All models of multiple populations need to be refined substantially in order to explain the cluster-to-cluster variations. While it is clear that something is going on in almost every well-studied cluster, it is not clear that we understand how that effect depends on the cluster properties. In our scenario, we would argue that the cluster-to-cluster variations were caused by different collision rates early in the clusters’ lives, perhaps driven by slightly different formation conditions and initial densities. In fact, it may be that we can use the extreme abundances produced in runaway collisions to determine which clusters hosted a runaway all those years ago. Only some clusters show evidence for extremely high Y values (Y ≈ 0.4) and very extreme sodium-oxygen anticorrelations, such as ω Centauri and NGC 2808. Perhaps only those clusters were formed with sufficiently high initial density to induce a runaway. A more detailed study of the abundance patterns in the individual pollution mechanisms may help disentangle these processes.

It has become clear that the epochs of globular cluster formation and very early evolution are crucial pieces of the puzzle when disentangling the present-day properties of these ancient objects. It is also clear that our understanding of the dominant processes and effects during these epochs is not as strong as we would like. Learning about the early lifetimes of dense clusters is not easy – the stellar archaeology required is quite intricate. We are looking at small changes in current surface abundances and brightnesses of very old, low mass stars, and inferring a significant amount of action involving more massive stars over 10 billion years ago. However, we have learned a great deal about this phenomenon since it first was identified only a few years ago, and progress will continue to be made.

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