Light-element abundance variations in globular clusters∗

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Star-to-star variations in abundances of the light elements carbon, nitrogen, oxygen, and sodium have been observed in stars of all evolutionary phases in all Galactic globular clusters that have been thoroughly studied. The data available for studying this phenomenon, and the hypotheses as to its origin, have both co-evolved with observing technology; once high-resolution spectra were available even for main-sequence stars in globular clusters, scenarios involving multiple closely spaced stellar generations enriched by feedback from moderate- and high-mass stars began to gain traction in the literature. This paper briefly reviews the observational history of globular cluster abundance inhomogeneities, discusses the presently favored models of their origin, and considers several aspects of this problem that require further study.

1 Introduction

Light-element abundance inhomogeneities in globular clusters have been a subject of active study for the past thirty years. The phenomenon was first noticed as anticorrelated variations in the broad CN and CH absorption features in red giants in a few clusters, and with the development of larger-aperture telescopes and higher-resolution spectrographs, the data set has expanded in several directions. Star-to-star abundance variations have been found in stars from the main sequence to the tip of the red giant branch, the set of abundances involved has expanded to include carbon, nitrogen, oxygen, sodium, magnesium and aluminium, and individual studies often survey tens of clusters rather than one or two.

Intriguingly, stars with these unusual abundances are found universally in globular clusters, but are apparently only formed in that environment. The overall picture that has developed is that stars at all evolutionary phases in all Galactic globular clusters occupy a wide range in light-element abundance that is not observed in any other Galactic stellar population, or in the fields of Local Group dwarf galaxies. This abundance range is typically observed in anticorrelated abundance pairs, C vs N or O vs Na, because roughly half of cluster stars have abundance patterns like Population II field stars while the other half are relatively depleted in carbon, oxygen and magnesium and enhanced in nitrogen, sodium and aluminium, with no variations in any other elemental abundances.

There are a few globular clusters known to exhibit metallicity variations along with light-element variations, such as ω Cen and M54, and they are unusual in other ways as well, with large masses and likely extragalactic origins (e.g., Carretta et al. 2010). However, they are an exception, while clusters with only light-element variations appear to be the rule. Comparative studies of light-element abundances in globular cluster stars and halo field stars (e.g., Langer, Suntzeff & Kraft 1992) find that the field star population shows very little or no light-element abundance variation. The field-star studies of Piłachowski et al. (1996a) and Gratton et al. (2000) found no stars with cluster-like abundance variations in the field, and concluded that the cluster environment must play a vital role in creating or permitting light-element abundance variations.

A similar paucity of stars with cluster-like light-element abundances has been reported in nearby dwarf galaxies. McWilliam & Smecker-Hane (2005) and Sbordone et al. (2007) both report quite unusual abundance patterns in the Sagittarius dwarf galaxy, but no stars with cluster-like C-N or O-Na anticorrelations. Shetrone et al. (2003) surveyed stars in Sculptor, Fornax, Carina and Leo I and found none with cluster-like light-element abundances, and Letarte et al. (2010) confirm that result with more stars in Fornax. More recently, Marettl & Grebel (2010) searched a sample of field giants from the SEGUE survey (Yanny et al. 2009) and found that 2.5% of those stars have strong CN and weak CH features relative to the majority of the field at the same metallicity and luminosity, suggesting that they may have the full cluster-like light-element abundance pattern. Those authors claim that the CN-strong field stars formed in globular clusters and later migrated into the halo as a result of cluster mass-loss and dissolution processes.

Studies of Galactic globular cluster abundances are experiencing something of a revival at present, driven by the discovery that the (presently) most massive clusters have complex color-magnitude diagrams (CMDs). There is a variety of unexpected behavior found in carefully constructed,
highly accurate CMDs: multiple main sequences in M54 (e.g., Siegel et al. 2007; Carretta et al. 2010), ω Centauri (e.g., Bedin et al. 2004; Sollima et al. 2007; Bellini et al. 2010) and NGC 2808 (Piotto et al. 2007), multiple subgiant branches in M54, ω Cen, 47 Tucanae (e.g., Anderson et al. 2009), NGC 1851 (e.g., Cassisi et al. 2008; Milone et al. 2008; Yong & Grundahl 2008), NGC 6388 (Piotto 2009) and M22 (Piotto 2009), and broadened red giant branches (RGBs) in M4 (Marino et al. 2008) and NGC 6752 (Milone et al. 2010).

There are several tantalizing potential connections between the photometric multiplicity in clusters and light-element abundance variations. Following the suggestion in Cassisi et al. (2008) that the two distinct subgiant branches discovered in NGC 1851 by Milone et al. (2008) have very similar ages but total [C+N+O/Fe] abundances that differ by a factor of two, Yong et al. (2009) measured abundances of carbon, nitrogen and oxygen in four bright red giants in NGC 1851. The total [C+N+O/Fe] abundance in their data set does vary fairly widely, which is consistent with a model in which NGC 1851 contains two populations in total light-element abundance. The case of NGC 1851 also provides a useful illustration of the importance of a careful choice of photometric systems: while the division of the subgiant branch is visible in the Milone et al. (2008) (F336W, F814W) and (F606W, F814W) color-magnitude diagrams, and in the Johnson-Cousins (U, I) color-magnitude diagram presented in Han et al. (2009b), it is not visible in the Han et al. (2009b) (V, I) color-magnitude diagram or the Strömgren (uby) color-magnitude diagram presented in Yong et al. (2009).

In M4, there is also RGB multiplicity that is found or not depending on the filter set used to construct a color-magnitude diagram: Marino et al. (2008) report a split of the red giant branch in the Johnson-Cousins (U, B) color-magnitude diagram, which had not been observed in previous color-magnitude diagrams based on redder photometric passbands. However, in M4, the two giant branches appear to correlate with typical globular cluster variations in [O/Fe] and [Na/Fe] abundances rather than variations in total [C+N+O/Fe] abundance.

It is of course not surprising that abundance variations with significant spectral effects should have noticeable effects on photometry, particularly in UV-blue photometric bands where CN and NH molecular bands can be dominant. Photometric determinations of stellar parameters and iron abundance were the motivation for defining medium-band filter systems like Strömgren (Strömgren 1963), DDO (McClure 1973) and Washington (Cantera 1976). It is, however, unexpected that the oxygen-sodium anticorrelation would affect photometry, particularly in the very broad Johnson/Cousins system, and it is unclear whether variations in oxygen and sodium abundance, which are observed in all Galactic globular clusters (e.g., Carretta et al. 2009), correlate with variations in U − B color.

The complex phenomenology of photometrically multiple globular clusters, and the excitement about them, serve to underline the importance of the rhetorical framework used in discussing an observed phenomenon: as an anomaly, star-to-star abundance variations are a curiosity to be catalogued, but as a result of light-element self-enrichment and multiple star-formation events they are powerful markers of the conditions in early Galactic history. The present challenge is to understand the connections between the new photometric observations and the well-studied abundance variations. This requires that we develop a comprehensive model for the origin of chemical and photometric complexity in globular clusters, and further that we ground that model in the larger cosmological environment to enable studies of the effects of formation time and environment on the ability of a star cluster to self-enrich and to form a second stellar generation.

2 Development of the observational data set

Photographic color-magnitude diagrams constructed for globular clusters (e.g., Arp & Johnson 1955; Sandage & Wallerstein 1960) revealed simple stellar populations: unlike the wide variety found in surveys of the Solar neighborhood, stars in globular and open clusters all apparently shared a single age and metallicity. The clusters were quickly recognized as ideal laboratories for testing theories of stellar structure and evolution (e.g., Sandage 1958, Preston 1961), and are used to the present day as anchors for metallicity scales (e.g., Kraft & Ivans 2003; Carretta et al. 2009).

2.1 Carbon and nitrogen in bright red giants

It was therefore surprising when these orderly, predictable stellar systems turned out to host a number of stars with wide variations in the strength of molecular features. Unusually weak absorption in the CH G band (the phenomenon of “weak-G-band stars”) was noted among giants in M92 (Zinn 1973; Butler, Carbon & Kraft 1975), in NGC 6397 (Mallia 1975), in M13 and M15 (Norris & Zinn 1977), in ω Cen (Dickens & Bell 1976), in M5 (Zinn 1977), and in 47 Tuc (Norris 1978). It was quickly shown (Norris & Zinn 1977; Zinn 1977) that most of the weak-G-band stars were on the asymptotic giant branch, implying the existence of some process that dramatically reshapes the surface abundances of stars between the RGB and the AGB, described as the “third dredge-up” by Iben (1975).

It was also noted (by, e.g., Norris & Cottrell 1979; Norris et al. 1981; Hesser et al. 1982; Norris, Freeman & Da Costa 1984) that those RGB stars with unusually weak CH bands also had relatively strong CN absorption at 3883Å and 4215Å. Since molecular abundance is controlled by the abundance of the minority species, CH traces carbon abundance, while CN reflects nitrogen abundance. This general association of bandstrength and abundance was confirmed
by spectral-synthesis studies such as Bell & Dickens (1980), which implies that the CN-strong, CH-weak stars found only in globular clusters have atmospheres that are depleted in carbon and enriched in nitrogen.

Since the CNO cycle, operating in equilibrium, tends to convert both carbon and oxygen into nitrogen, stars with strong CN and weak CH bands were interpreted as having some amount of CNO-processed material in their atmospheres. Several theories were put forward to explain this extra CNO-cycle processing: McClure (1979) surveyed the data available at the time and concluded that internal mixing, specifically the meridional circulation described by Sweigart & Mengel (1979), could be responsible for “some or all” of the surface abundance variations. The connection between angular momentum and the efficacy of meridional circulation prompted Suntzeff (1981) to propose that different rotational velocities might explain the different levels of carbon depletion seen in giants in M3 and M13, an idea further explored in the Norris (1987) study of the relation between CN anomalies and overall globular cluster ellipticity. Langer (1985) suggested that a uniform mixing efficiency, in combination with star-to-star variations in CNO-cycle fusion rates, could produce the observed ranges in surface carbon and nitrogen abundance. Cohen (1978) proposed that star-to-star scatter in [Na/Fe] and [Ca/Fe] in M3 giants required a non-homogeneous initial gas cloud, a scenario that implies a primordial origin for [C/Fe] and [N/Fe] variations as well. In addition, D’Antona et al. (1983) proposed that light-element abundance variations were merely surface pollution, a consequence of mass loss from evolved stars and the high density of globular clusters.

### 2.2 Other elemental abundances

Hoping to learn more about the source of apparently CNO-processed material in the atmospheres of some globular cluster giants, researchers began obtaining higher-resolution spectra for cluster giants. These were difficult observations to make with the 4-m-class telescopes available at the time, and as a result the data sets were typically small and limited to stars brighter than $V \approx 14$. Despite these challenges, it was quickly discovered that stars depleted in carbon and enhanced in nitrogen were also depleted in oxygen and magnesium, and enhanced in sodium and aluminium. CN-strong giants in M5 were found by Sneden et al. (1992) to have systematically lower oxygen abundances and higher sodium abundances than their CN-normal counterparts. Cottrell & Da Costa (1981) found positive correlations between CN bandstrength and both sodium and aluminium abundances in NGC 6752. A correlation between aluminium and sodium abundances, and anticorrelations between aluminium and both oxygen and magnesium, were found by Shetrone (1996) in M92, M13, M5 and M71, clusters that span the range of halo globular cluster metallicity.

Oxygen depletion was consistent with an evolutionary explanation, as the hydrogen-burning shell of a red giant is hot enough to host the CNO-cycle reactions $^{14}$N $+2p \rightarrow ^{12}$C$+\alpha$. However, changes in the abundances of heavier elements were unexpected from fusion reactions occurring within $0.8M_{\odot}$ red giants: the NeNa and MgAl cycles operate similarly to the CNO cycle, with the nuclei acting as catalysts to convert hydrogen into helium, but both require significantly higher temperatures. Some authors (e.g., Pilachowski et al. 1996b) interpreted the extension of the light-element abundance variations to sodium, magnesium and aluminium as a sign that the hydrogen-burning shells in red giants must have the ability to operate the hotter hydrogen-fusion cycles, while others (e.g., Peterson 1980) considered it a sign that the initial gas cloud from which globular clusters formed must have been inhomogeneous.

### 2.3 Main-sequence and turnoff stars

With the construction of 8-meter-class telescopes came access to fainter stars within globular clusters. Harbeck et al. (2003) observed around 100 stars at or below the main-sequence turnoff in 47 Tuc, and found clear bimodality in the distribution of CN bandstrength in those stars, implying variations in C and N abundance as large as those already known in red giants in the cluster. Main-sequence and turnoff stars in M13 were observed by Briley et al. (2004), and significant, anticorrelated ranges in C and N abundance ($\Delta$ [N/Fe] $\approx 1.0$, $\Delta$ [C/Fe] $\approx 0.5$) were also found among those stars.

These discoveries had a major impact on theoretical explanations for light-element abundance variations in globular clusters, and prompted a serious evaluation of the possibility that they are not simple stellar populations. While evolutionary explanations could conceivably be stretched to include modifications of surface aluminium abundance, they could not accommodate abundance variations in low-mass main-sequence stars, which are not capable of either high-temperature hydrogen fusion or mixing between the surface and the core. Additionally, the fact that the abundance ranges are as large above the “bump” in the RGB luminosity function as below it indicates that the abundance variations cannot be mere surface pollution, because such a signal would be greatly diminished at the first dredge-up (Iben 1965), when the surface convective zone briefly deepens well into the interior of the star.

### 3 Current models for globular cluster formation

The presently favored explanation for the presence of primordial light-element abundance variations in globular clusters is that the CN-strong, N- and Na-rich, C- and O-poor stars are a second generation formed from material processed by intermediate- or high-mass stars in the first generation. There have been several types of stars proposed as the source of this feedback material, each with its own strengths and weaknesses. AGB stars with masses between

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[Note: The text contains various scientific terms and references, which are typical in astrophysics and astrochemistry literature. The context suggests discussions about the origin and evolution of stars within globular clusters, focusing on light-element abundance variations, and the role of the CNO cycle in these phenomena. The text integrates theoretical and observational data, highlighting the complexity and diversity of explanations for stellar abundances.]
4 and $8M_\odot$ (e.g., Parmentier et al. 1999) are popular because they are relatively common, they are known to have slow, massive winds, they are a site of hot hydrogen burning, and they evolve on timescales of $\sim 10^8$ years, quite fast compared to the lifetime of a globular cluster. In addition to AGB stars, rapidly rotating massive stars (Decressin et al. 2007b) and massive binary stars undergoing mass transfer (De Mink et al. 2009) have been proposed as alternative sources of feedback material, and both could deliver more feedback mass in a shorter amount of time than AGB stars, though the stars themselves are less common. As is pointed out by Sills & Glebbeek (2010), while it may be observationally determined that one particular feedback source is dominant, they all certainly contribute to the cluster ISM at some level.

In a present-day globular cluster with a mass of $5 \times 10^3 M_\odot$ and a 1 : 1 ratio of first- to second-generation stars, assuming a 30% star formation efficiency, the second generation of stars must have formed from $\sim 8 \times 10^3 M_\odot$ of gas. The first stellar generation, with a mass of $2.5 \times 10^5 M_\odot$, clearly cannot have produced enough feedback material to form the second generation (indeed, typical values for AGB mass loss are $\leq 10\%$). There have been four solutions proposed for this “mass budget problem”: a top-heavy first-generation mass function (e.g., Decressin et al. 2007b), a second-generation mass function that is truncated above $0.8 M_\odot$ (e.g., D’Ercole et al. 2008), a first generation that is initially 10 to 20 times as massive as at present (e.g., D’Ercole et al. 2010), and infall of pristine gas (e.g., Carretta et al. 2010b; Conroy & Spergel 2010).

A top-heavy first generation would alleviate the mass budget problem by placing more $5 - 15 M_\odot$ feedback sources in the first generation. A truncated (bottom-heavy) second generation would require the first generation to produce less feedback material: assuming a Kroupa IMF (Kroupa et al. 1993) and a mass range from 0.1 to 100$M_\odot$, half of the mass is in stars with $M \leq 0.8 M_\odot$. However, it is unclear what physical process would cause overproduction of massive stars in the first generation or underproduction in the second, and neither effect is significant enough to solve the mass budget problem. Additionally, observations of young star clusters (e.g., Boudreault & Caballero 2010; Gennaro et al. 2010) do not find either of these effects, and present-day globular clusters do not contain unusually large populations of neutron stars or other compact remnants of massive first-generation stars relative to the number of low-mass first-generation stars still on the main sequence (e.g., Bogdanov et al. 2010; Lorimer 2010).

Massive first generations and significant gas infall, in contrast, are central to the leading theoretical models of globular cluster formation. In the model of D’Ercole et al. (2008), the first stellar generation has a mass 10 to 20 times its present mass, and produces all the material needed for the formation of the second generation from AGB winds. The authors assume that Type Ia supernovae begin occurring 40 Myr after the formation of the first generation. The supernovae conclusively end star formation in the cluster, meaning that all second-generation stars must have formed within that time. The second generation stars form near the cluster center, and as a result, when the cluster expands in response to the supernovae, the stars that become disassociated from the cluster are mostly or exclusively first-generation stars. The authors also consider a model with infall of pristine gas from near the globular cluster, and find that it prolongs star formation significantly beyond the onset of Ia supernovae.

The globular cluster formation model of Conroy & Spergel (2011) also relies on AGB stars to provide the chemical inhomogeneities between the first and second stellar generations, but requires significantly more gas accretion to provide the mass for second-generation stars. The authors justify this by speculating about the cosmological environment of proto-globular clusters, namely self-gravitating, gas-dominated proto-galactic systems with gas masses between $10^7 M_\odot$ and $10^{10} M_\odot$. They find that globular clusters orbiting in such systems can accrete significant amounts of gas over $10^8$ years, through a combination of Bondi accretion and “sweeping up” of material in the cluster’s path, with little vulnerability to ram-pressure stripping for clusters above $10^4 M_\odot$. In this model, Lyman-Werner flux $(912 \lambda \leq 1100 \AA)$ from massive first-generation stars prevents the gathering gas from forming stars by dissociating $H_2$ molecules, creating a gap of roughly $10^8$ years between the two generations and allowing time for the mass in accreted gas to become large enough to create a second generation as massive as the first.

Any globular cluster formation model that requires significant gas accretion implicitly assumes that the accreted gas must have a metallicity very similar to that of the first stellar generation, since systematic [Fe/H] differences are not observed between first- and second-generation cluster stars. There are a few models that are explicit about the importance of this coincidence, such as Carretta et al. (2010a) and Smith (2010). Both of these models incorporate supernova material into the second generation but require that it mix well with accreted lower-metallicity gas before the formation of the second generation in order to make the metallicity of the second stellar generation be the same as the first. While these conditions are certainly conceivable for certain proto-globular clusters, they are unlikely to hold for all globular clusters in the Milky Way.

4 Recent observational progress

There have recently been several large-scale light-element abundance studies, which have the distinct advantage over smaller-scale studies that the abundance behavior of multiple clusters can be directly compared within homogeneous observations, data reduction and analysis. The low-resolution study of Kaysar et al. (2008) measured CN and CH bandstrengths in stars from the main sequence to the red giant branch in 8 Southern globular clusters. Those au-
thors confirmed the presence of RGB CN bandstrength variations and CN-CH anticorrelations, as found in previous single- and few-cluster studies. They also demonstrated that CN bandstrength variations can be found on the main sequence in the clusters NGC 288, NGC 362, M22 and M55, clusters that had not previously been observed to contain main-sequence abundance variations. To explore the question of the source of light-element abundance variations, they also evaluate possible correlations between the ratio of CN-strong to CN-weak stars and several cluster parameters, and find mild positive correlations to cluster luminosity and tidal radius. These trends are interpreted as signs that globular clusters with larger masses or outer-halo orbits would be more efficient at producing second-generation stars.

The comprehensive study of Carretta et al. (2009b) reported homogeneous oxygen and sodium abundances for 1958 stars of all evolutionary phases in 19 Southern globular clusters. This study made a significant statement about the universality of light-element abundance variations in globular clusters, and also explicitly adopted the language of self-enrichment and multiple stellar generations. By identifying groups of stars as “primordial”, “intermediate” or “extreme” depending on oxygen and sodium abundances, this study made the claim that the degree of abundance variation can differ between clusters, and may be a function of environment and feedback source. Main-sequence stars in many of the same clusters were observed by Pancino et al. (2010), who measured CN and CH bandstrength variations from low-resolution spectra. These authors found that the fraction of CN-strong (second-generation) stars was \( \sim 30\% \), distinctly lower than the 70% reported in Carretta et al. (2009b). This discrepancy is curious, and Pancino et al. (2010) suggest that it may indicate that C-N abundance variations are contributed, at least in part, by a different feedback source from the O-Na abundance variations studied by Carretta et al. (2009b).

From recent large-scale studies it appears that light-element abundance variations are universal in Galactic globular clusters, but the question of the dominant first-generation feedback source remains unsolved. Future studies will need to measure the C-N and O-Na variations simultaneously in order to address the mismatch in frequency of second-generation stars found in low- versus high-resolution spectroscopic studies, and will need to measure other specific elemental abundances to evaluate various aspects of cluster formation scenarios. For example, abundances of s-process elements like Ba would be useful for placing limits on AGB contributions (e.g., Smith 2008; Yong et al. 2008), and the abundance of Li carries a great deal of importance in understanding the importance of infalling pristine gas (e.g., D’Orazi & Marino 2010; Shen et al. 2010).

The APOGEE survey (Allende Prieto et al. 2008), one of four components of the SDSS-III project, will obtain high-resolution near-infrared spectra for 100 000 stars in all components of the Galaxy, including red giants in globular clusters. The data reduction pipeline will automatically determine 14 elemental abundances, including overall [Fe/H] metallicity, \( \alpha \) elements, and most of the light elements that vary in globular clusters. It will provide a database for studying cluster light-element variations that is unparalleled in sample size, amount of abundance information per star, and start-to-finish homogeneity, and ought to shed significant light on many aspects of cluster light-element abundance variations.

5 Evolution of the Galactic globular cluster system

Although efforts have been made to understand the presence or degree of light-element abundance variations as a function of present-day globular cluster properties, correlations with present-day mass, concentration or ellipticity are loose at best. While we expect the total mass or central density of a cluster during the formation of the first and second generations to have an influence on its ability to self-enrich, those properties have clearly evolved significantly over each cluster’s lifetime.

5.1 Self-enrichment and escape velocity

One of the more perplexing elements of the question of globular cluster light-element self-enrichment is the fact that most of the Galactic globular cluster population is unable to retain AGB or massive-star winds at the present day. This is observable both in the lack of intracluster material in globular clusters (Evans et al. 2003; van Loon et al. 2006; Boyer et al. 2006), and in low present-day escape velocities. The census of Galactic globular clusters conducted by McLaughlin & van der Marel (2005) includes values for \( v_{esc} \), and roughly half of the clusters have \( v_{esc} \) below 20\,km\,s\(^{-1}\). Since these clusters all have light-element abundance variations, and since all proposed sources of feedback material have wind speeds \( \geq 20\,km\,s^{-1} \), these clusters must have had higher escape velocities in the past. The massive first generation in the D’Ercole et al. (2008) model provides one natural solution to this problem, as do suggestions (e.g., Palouš et al. 2009; Sills & Glebbeek 2010) that collisions between winds from multiple stars should result in a lower bulk wind velocity, trapping wind material that otherwise would escape in the dense inner regions of proto-globular clusters. It seems clear that the Galactic globular cluster population has evolved strongly since its formation, both in terms of the overall cluster mass function (e.g., Parmentier & Gilmore 2005) and in the structural properties of individual clusters (e.g., de Marchi et al. 2010).

5.2 The initial cluster mass function

It is curious that light-element abundance variations are apparently universal among present-day Galactic globular clusters, considering that the initial cluster mass function included many low-mass clusters that should not have been
able to self-enrich according to current globular cluster formation models. There are two possible explanations for this coincidence that are quite simple: that self-enrichment in globular clusters is very common, and occurs at lower cluster masses than we expect, or that cluster dissolution was extremely effective early in the lifetime of the Milky Way, with only a small percentage of the highest-mass clusters surviving to the present day. Globular cluster formation scenarios that rely on significant gas infall tend to promote the first generation, allowing clusters with lower-mass first generations to form a second stellar generation. The numerical study of Marks & Kroupa (2010) found that the expulsion of residual gas following star formation is very effective at destroying globular clusters with low initial masses and concentrations. This result both supports the second explanation and implies that globular clusters have contributed significant numbers of stars with first-generation abundances to the construction of the stellar halo of the Milky Way, as is also suggested by the result of Martell & Grebel (2010).

If it is simply coincidental that the minimum mass for a globular cluster to survive to the present day in the Milky Way is larger than the minimum mass for a globular cluster forming in the Milky Way to host two stellar generations, then it is instructive to consider environments where those conditions are not met. In galactic environments that are more hospitable to long-lived low-mass globular clusters, the present-day cluster populations ought to include Milky Way-like, high-mass, two-population clusters along with lower-mass, chemically homogeneous globular clusters. In galactic environments in which it is more difficult for clusters to self-enrich, there would be some fraction of high-mass globular clusters with homogeneous light-element abundances. Regarding the first possibility, the theoretical study of Conroy & Spergel (2011) suggests that intermediate-aged clusters in the Large Magellanic Cloud with masses between $10^4 M_\odot$ and $10^5 M_\odot$ should be able to retain first-generation winds and self-enrich because of the relatively low ram pressure they experience. This claim is bolstered by the observational study of Milone et al. (2009), in which clearly broad and/or bifurcated main-sequence turn-offs were found to be common in intermediate-aged LMC clusters.

6 Future challenges

In order to correctly interpret the photometric complexities observed in some globular clusters (e.g., Marino et al. 2008; Milone et al. 2008; Han et al. 2009; Lardo et al. 2011), we must understand the photometric shifts caused by changes in light-element abundances and helium, in addition to those caused by age, overall metallicity and [$\alpha$/Fe]. Current theoretical isochrones (e.g., Bertelli et al. 2008; Dotter et al. 2008; Han et al. 2009) are built from stellar models that allow variations in age, overall metallicity, and sometimes the abundances of $\alpha$-elements and helium. Considering the correlations between light-element abundances and $U$-band photometry reported by, e.g., Marino et al. (2008), it seems prudent to expand the theoretical grid of stellar models to test for photometric sensitivity to light-element abundance variations. The study of Dotter et al. (2007) considered exactly this question, constructing isochrones with enhancements in one of C, N, O, Ne, Mg, Si, S, Ca, Ti, or Fe while maintaining a constant overall heavy-element abundance Z in order to explore the effects of individual-element abundance variations on stellar structure. They find that enhancement in C, N or O abundance caused the isochrones to shift to the blue and reduced main-sequence lifetimes by as much as 15%, while an enhanced Mg abundance caused isochrones to be redder but had a minimal positive effect on main-sequence lifetimes. They did not calculate isochrones for the anticorrelated light-element abundance pattern found in globular clusters, but such an exercise would be extremely helpful to our understanding of photometric complexity in globular clusters.

It will also be important to understand whether photometric variations are a generic result of light-element abundance variations, or if not, which globular cluster properties permit or prohibit them from being observed. As an example, large variations in CN and CH bandstrength are almost certainly responsible for $U$-band variations among red giants in relatively high-metallicity ([Fe/H] $\geq -1.5$) globular clusters, but not all relatively high-metallicity clusters are known to have complex $U-B,B-V$ CMDs. Additionally, multiplicities in different regions of the CMD do not always correspond. For instance, the cluster $\omega$ Cen has three main sequences and five distinct subgiant branches (Villanova et al. 2007), making it unclear how many distinct populations it contains. A search by Piotto (2009) of archival HST/ACS photometry uncovered multiple turnoffs in several clusters, and further searches for UV-blue photometry of globular cluster stars in public databases (as done in SDSS by Lardo et al. 2011) or observatory archives could be a quick and profitable way to confirm or deny the presence of photometric complexity in a large number of Galactic globular clusters.

Developing tools for interpreting integrated spectra of extragalactic globular clusters will dramatically expand our ability to study the effects of cosmological environment on globular cluster formation and self-enrichment. Methods for deriving ages and mean elemental abundances from low-resolution spectra have been adapted from galactic stellar populations studies (e.g., Puzia et al. 2006; Schiavon 2007), and techniques for extracting mean abundances from high-resolution integrated spectra of extragalactic globular clusters have been developed by Colucci et al. (2009). A merger of the two approaches, matching high-resolution spectroscopic data to synthetic spectra that are a sum over multiple distinct populations, will allow detailed searches for abundance variations in extragalactic globular clusters to very large distances.

It is becoming an accepted paradigm that the majority of, if not all, “normal” Galactic globular clusters contain
stars with a range of light-element abundances, although they are resolutely mono-metallic. This requires that clearly multi-metallic, multi-age clusters like ω Cen and M54 formed in different environments, and not as subsystems of the Milky Way. Rather, their extended star formation histories and ability to retain supernova feedback indicate that their early development occurred in a fairly high-mass environment. M54 lies quite close to the core of the Sagittarius dwarf galaxy, prompting some to claim that it formed as the nucleus of the galaxy (e.g., Layden & Sarajedini 2000), while others argue that M54 formed as a normal globular cluster but is being trapped in the galactic nucleus (e.g., Bellazzini et al. 2008). One group (Carretta et al. 2010a) has made the claim that M54 and ω Cen both originated as nuclear star clusters in dwarf galaxies, with ω Cen having been captured by the Milky Way earlier while M54 is still being removed from its galaxy of origin. The schematic model of multi-metallicity globular clusters having formed as nuclear star clusters in dwarf galaxies (e.g., Georgiev et al. 2009) is attractive: the dark-matter halo of the galaxy would permit the cluster to experience extended feedback and star formation, and present-day nuclear star clusters are similar to multi-metallicity globular clusters in several properties such as half-light radius, escape velocity and horizontal branch morphology.

Recent announcements of mild [Fe/H] and [Ca/Fe] variations in NGC 2419 (Cohen et al. 2010), along with the discovery of photometric complexity (which may be a result of age or metallicity variations) in several otherwise unexceptional globular clusters (e.g., Piotto 2009), raise the question of whether there is a class of globular clusters intermediate between “normal” mono-metallic, light-element-variable globular clusters and the more massive multi-metallicity clusters. Theoretical studies of supernova feedback in extremely massive proto-globular clusters would help to clarify the feasibility of claiming that clusters with mild metallicity variations constitute the high-mass end of typical globular cluster self-enrichment. Numerical simulations of interactions between nucleated dwarf galaxies and the Milky Way would provide an estimate of how many nuclear star clusters may have been captured into Milky Way orbit, and whether clusters like NGC 2419 can be considered as examples of captured nuclear star clusters with a history of low-efficiency feedback.

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