The Celestial Buffet: multiple populations and globular cluster formation in dwarf galaxies

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ABSTRACT
We present a framework that explains the commonly observed variation in light element abundances in globular clusters. If globular clusters form in the centres of dwarf galaxies, they will be pumped on to larger orbits as star formation progresses. The potential well will only retain the moderate velocity asymptotic giant branch (AGB) ejecta, the expected source of enrichment, but not supernova ejecta. There is no need to increase the initial cluster mass, a requirement of self-enrichment scenarios, as all the stars within the dwarf can contribute. As the clusters move through the dwarf centre they sweep up a mix of AGB ejecta and in-falling pristine gas to form a second generation of stars. The specific mix will vary in time and is thus able to explain the spread in second generation abundances observed in different clusters. The globular clusters will survive to the present day or be stripped as part of the hierarchical merging process of larger galaxies. We illustrate how this process may operate using a high-resolution simulation of a dwarf galaxy at high redshift.

Key words: globular clusters: general — galaxies: dwarf — galaxies: evolution — galaxies: formation — galaxies: star clusters: general

1 INTRODUCTION

Until recently, the standard picture of a globular cluster was that of a simple stellar population. It was thought that all the stars formed in one time, in one place, and from a single cloud with a uniform chemical abundance. However, high-precision photometry from the Hubble Space Telescope (e.g. Bedin et al. 2004; D'Antona et al. 2003, 2005a, 2005c) revealed split main sequences and sub-giant branches in many massive clusters, such as NGC 2808, M22, 47 Tuc, and NGC 1851. Simultaneously, high-resolution spectroscopic studies of globular cluster stars (e.g. Ramírez et al. 2001, Carretta et al. 2000b) showed that almost all globular clusters have no star-to-star variations in iron abundance. The variation in lighter elements, however, which had been characterized in bright giants for decades (e.g. Carretta & Gratton 1994; Cohen 1998; Gratton et al. 2003, 2007a), was shown to extend down to stars on the main sequence (e.g. Gratton et al. 2001, Ramírez & Cohen 2002, Carretta et al. 2003, 2004). Most surprisingly, a high He content is required to explain some of the observed properties of several of these clusters (e.g. Piotto et al. 2005, D’Antona et al. 2005, Carretta et al. 2007b, Piotto et al. 2012).

The ubiquity of this light element spread in all well-studied globular clusters (see the review by Gratton, Sneden, & Carretta 2004) suggests globular clusters undergo a more complex formation process than that of a single burst of star formation. The chemical patterns, the split photometric sequences, and extended horizontal branches (e.g. Bedin et al. 2004) of globular clusters can be explained if, within the first few hundred million years of a cluster’s existence, two or more populations of stars were formed (e.g. Ventura et al. 2001, D’Antona & Caloi 2008).

The commonly accepted explanation for these abundances is a sequence of events that a nascent globular cluster must undergo (e.g. D’Antona & Caloi 2008; Ventura & D’Antona 2008). First, the proto-globular cluster forms from pristine gas. After some time, the most massive stars explode as supernovae, but their ejecta have
sufficient velocity to escape unhindered from the potential well of the cluster. Later, a population of polluting stars ejects their hot hydrogen-burnt material into the cluster at much lower velocities, so that the material is retained by the cluster. Shortly thereafter, the second population forms from a mixture of this material and additional pristine material that has fallen into the cluster, in order to reproduce the observed abundance variations (e.g. Carretta et al. 2009b, Ventura et al. 2014). These two populations then passively evolve to become the present-day cluster. This scenario broadly matches the observational constraints on the problem of multiple populations and extended horizontal branches in globulars, but there are two problems which we describe below.

The majority of recent papers currently favour asymptotic giant branch (AGB) stars as the polluters (e.g. Ventura & D'Antona 2005, D'Ercole et al. 2010) since the bottom of their convective envelopes can produce the required overabundance of Na and N versus O and C (e.g. Denissenkov & Denisenkova 1989). However, the nucleosynthetic yields from AGB stars need to be carefully tuned (e.g. Denissenkov & Herwig 2003, James et al. 2004), and there is still some uncertainty in the AGB evolution models (e.g. Ventura & D'Antona 2005a, 2005b, 2008b). Due to these problems, other polluters have been proposed: rapidly rotating massive stars (e.g. Decressin et al. 2007), massive binary stars (e.g. de Mink et al. 2009), and even stellar collisions (Sills & Glebbeek 2010).

The second problem has to do with the mass budget for the polluted population, which can make up to 50 per cent of the present cluster mass (e.g. Carretta et al. 2009, Piotto et al. 2012). If one assumes a normal initial mass function (IMF) and an initial cluster mass that is close to its present-day mass (~ 10⁶ M☉), then the population of polluting stars can only produce at most a few per cent of the cluster mass as material with which to form the polluted population (e.g. Cohen, Briley & Stetson 2005). Most papers to date have addressed this issue by requiring the proto-cluster be at least 10 times more massive than the present cluster (e.g. D'Antona & Caloi 2008, Ventura & D'Antona 2008a, D'Ercole et al. 2010, Vesperini et al. 2013), added more enriched gas to the ejecta by flattening the AGB range of the IMF (e.g. D'Antona & Caloi 2004, D'Antona et al. 2005), or both. Furthermore, highly unlikely star formation efficiencies of 100 per cent are required in the formation of the second population, or the mass-budget problem becomes even worse.

Bekki (2010, 2011) simulated the formation of a second generation of stars from AGB ejecta within a cluster. As expected (e.g. D'Antona & Caloi 2004, D'Ercole et al. 2008), a second population formed soon after the first starburst, but with a spatial and kinematic distribution completely different from the first population. The simulations showed that the second population would be centrally condensed and show considerable rotation due to the dissipative processes required to drive the enriched material to realistic star-forming conditions. The initial cluster mass required to retain the AGB ejecta exceeded 6×10⁶ M☉, and even the best case scenario was only able to form 4×10⁵ M☉ in second population stars. Yet, an order of magnitude increase in initial stellar mass would only produce enough AGB ejecta to form the present-day mass of second generation stars. Self-enrichment thus requires the cluster to be tidally stripped on time-scales much shorter than their relaxation times (e.g. Vesperini et al. 2013), since the first generation stars would have distributions initially extending to larger radii.

The most straightforward solution to this problem was suggested by Bekki (2006): instead of treating the formation of globular clusters as simple stellar populations condensing from homogenous isolated gas clouds, they were treated as forming within the centres of dwarf galaxies at high redshift (z ≥ 4). This alleviated the mass budget problem, since now AGB ejecta from the surrounding dwarf galaxy spheroid would cool and settle to the centre, mix with the pristine material, and form the second population in the newly formed globular cluster. However, even this scenario failed to reproduce the observed trends (Bekki et al. 2007).

The problem is that the simple approach of Bekki (2006) would not make up the majority of globular clusters with variance only in the light elements. Bekki (2008) assumes the stellar nucleus of a dwarf progenitor is accreted on to a Milky Way (MW) sized halo, observable as a halo globular cluster. However, the likelihood that SNe ejecta will be retained by the dwarf increases as its halo mass grows, imposing a limit on how long the stellar nucleus can be considered uniform in abundance. This is evident in the broad range of Fe-enrichment exhibited by many of the Local Group Dwarfs, such as Fornax (e.g. Pont et al. 2004). Many globular clusters show very little dispersion in the Fepeak elements (e.g. Ramirez et al. 2001, Carretta et al. 2009c), which suggests at least two possible constraints not discussed in Bekki (2006). Either all globular clusters formed in dwarf progenitors that were accreted by larger haloes extremely early, or some process halted star formation in the nucleus on long time-scales, preserving the uniform iron abundances.

There do exist peculiar globular clusters with dispersion in their heavy elements which would fit this model (Bekki & Norris 2006). ω Cen is one example of a globular cluster with variations in [Fe/H] (e.g. Norris & Da Costa 1995, Piotto et al. 2003), which can be explained if it is the remnant stellar nucleus of an accreted dwarf galaxy (e.g. Gnedin et al. 2002). Another is M54, located at the centre of the Sagittarius dwarf galaxy (Ibata, Gilmore & Irwin 1995) and likely an example of ω Cen in an earlier accretion phase (Carretta et al. 2010). NGC 2419 has similarly been argued to be the core of a stripped dwarf galaxy (Mackey & van den Bergh 2005, Cohen et al. 2011, Cohen, Huang & Kirby 2011, Cohen & Kirby 2012).

Clearly, what is lacking in the Bekki (2006) model is a clear understanding of how the uniform heavy element abundance is preserved, if dwarf progenitors are the true sites of globular cluster formation.

In this paper, we provide a new framework in which we can understand the formation of all globular clusters that exhibit abundance variations. Like Bekki (2006), this new framework assumes the site of globular cluster formation is within the centres of dwarf galaxies. Unlike previous work, our framework proposes that these clusters are removed from the dwarf centres through dynamical evolution and end up on wide orbits, like those of the Fornax dwarf (e.g. Hodge 1961, Mateo 1998, Letarte et al. 2006), where they may be easily stripped. By proposing a physically motivated mechanism for globular cluster removal, our
new framework provides a consistent solution to the problem of abundance spreads with the cluster and links the probability of a spread in [Fe/H] to the amount of time spent in the dwarf centre. We describe our new framework in \(^2\) and provide an illustration of it in \(^3\) using a highly resolved simulation of a dwarf galaxy at high redshift (Mashchenko, Wadsley & Couchman 2008). We describe the setup in \(^3\) with results in \(^3\).

\section*{2 A NEW FRAMEWORK FOR FORMING MULTIPLE POPULATIONS IN DWARF GALAXY GLOBULAR CLUSTERS}

The framework that will be outlined here rests on one key assumption: all globular clusters exhibiting abundance spreads formed near the centre of high-redshift dwarf galaxy progenitors and were later accreted during the hierarchical build-up of present-day massive galaxy haloes. As gas accretes on to the dwarf galaxy progenitor, it cools and collapses to the centre. Once the gas reaches sufficient densities ($\gtrsim 100$ m$^{-3}$) to form molecular clouds, star formation begins. This will lead to feedback from massive stars in the form of radiation, winds, and supernova explosions that suppress star formation for about 30 Myr. As gas builds up of present-day massive galaxy haloes, there should be plenty of gas in fall to lend itself to dilution (e.g. Maxwell et al. 2012). Eventually, the gas within the centre will become predominantly pristine and the cluster formation process can begin anew. A single dwarf galaxy could make several mixed abundance globular clusters within a few hundred Myr, long before Type Ia SNe begin to enrich the gas with Fe. This is in sharp contrast to the work of Bekki (2006) which would be more suitable for producing the more unusual objects that show clear [Fe/H] variations, such as $\omega$ Cen.

Current models of the formation of the second population require some sort of dilution (e.g. Carretta et al. 2009a) of the polluted material with pristine gas in order to create the observed abundance anticorrelations. Since our framework places the formation site of the mixed abundance clusters within progenitor dwarf galaxies at high redshift, there should be plenty of gas in fall to lend itself to dilution (e.g. Maxwell et al. 2012). Eventually, the gas within the centre will become predominantly pristine and the cluster formation process can begin anew. A single dwarf galaxy could make several mixed abundance globular clusters within a few hundred Myr, long before Type Ia SNe begin to enrich the gas with Fe. This is in sharp contrast to the work of Bekki (2006) which would be more suitable for producing the more unusual objects that show clear [Fe/H] variations, such as $\omega$ Cen.

\section*{3 AN ILLUSTRATION}

We use the cosmological simulation of a well resolved dwarf galaxy by Mashchenko, Wadsley & Couchman (2008) to demonstrate the salient points of our framework. This simulation has been extensively studied in the context of the cusp–core problem (for a recent review see de Blok 2010) and the formation of Fornax-like spheroidal systems (Maxwell et al. 2012). The 12 pc force softening used in the simulation is comparable in scale to globular clusters and molecular clouds hosting star formation, but is still adequate for our purposes. Within the simulation, Maxwell et al. (2012) identified four bound star clusters over 100 times denser than the surrounding stellar spheroid that could be traced over 100 Myr.

However, the resolution was not high enough to resolve the internal structure of the clusters, and so we cannot measure dynamical properties such as their mass distribution or velocity dispersion. At these scales, accurate treatment of the formation of stars and the resultant feedback is re-
quired, which prevents us from directly studying the accretion of gas on to the cluster and the true mass of the clusters themselves. Since our framework applies to any collisionless component of matter, we need only use a suitable globular cluster tracer throughout the simulation to illustrate it in a cosmological context. Therefore, in the following setup, we use only the orbital properties of these clusters and treat the cluster mass as a free parameter.

3.1 Accretion

Since we cannot directly measure accretion on to a star cluster as it passes through the gas-rich centre of the dwarf, we use the first-order estimate of Bondi & Hoyle (1944):

\[ \dot{M} \simeq 2\alpha\pi\frac{G^2M^2}{(\vec{v}_{\text{rel}} + \vec{v}_{\text{com}})^3}\bar{\rho}, \]

(1)

where \(M\) is the mass of the cluster, \(\bar{\rho}\) is the ambient gas density, \(\vec{v}_{\text{rel}}\) is the relative velocity between the cluster and the gas, and \(\alpha\) is the sound speed of the gas. The numerical factor \(\alpha\) lies between 1 and 2 for most cases (Bondi & Hoyle 1944; Bondi 1952), but we have assumed unity so that we may be conservative in our estimate of the accretion rate. Since we cannot directly measure the local gas density and temperature, we average the gas particle properties over a 35 pc sphere around the centre of mass of each cluster in each simulation snapshot. This is the typical tidal radius for the MW clusters (Harris 1996) derived from the King surface density profiles (King 1962, 1966), and similar to the maximum accretion radius derived from Equation (1) for a 10^6 M_☉ cluster and a sound speed of 10 km s^{-1}. To compute the bulk relative velocity, we use the mass-weighted relative velocity with respect to the centre of mass velocity of the cluster:

\[ \bar{v}_{\text{rel}} = \frac{\sum m_i(\vec{v}_i - \vec{v}_{\text{com}})}{\sum m_i}, \]

(2)

for all gas particles within the 35 pc sphere whose temperature is below 1.5 × 10^4 K.

The original derivation of Equation (1) was for spherically symmetric accretion of a point mass moving through a uniform medium whose properties were measured very far from the point mass. Lin & Murray (2007) have shown that for extended mass distributions whether Equation (1) applies to the cluster as a whole, or to individual stars within the cluster, depends on the internal velocity distribution of the stars. Although we cannot directly measure the velocity distribution of the stars within the four clusters, the functional form of the accretion rate is preserved in both scenarios (Lin & Murray 2007). Any uncertainty will be contained mainly in \(\alpha\), which requires detailed numerical study (e.g. Naiman, Ramirez-Ruiz & Lin 2011). Since each of the four clusters spends significant time with relative speeds of 20–30 km s^{-1} with respect to the surrounding gas, and given the spherical symmetry of globular clusters, Equation (1) should give a good estimate of the amount of gas accreted by a globular cluster moving through regions of dense gas (Conroy & Spergel 2011).

Once the gas has accreted on to the ‘surface’ of a globular cluster, it should disperse throughout the cluster on a very short time-scale. Using a mean half-mass radius of 4.3 pc (Harris 1996) and a typical sound speed of 10 km s^{-1} yields a crossing time of 0.4 Myr. This is significantly shorter than the cooling time for the accreted gas and the onset of star formation, which is expected to last 2–3 Myr (e.g. D’Ercole et al. 2008; Bekki 2011), and that the winds from these stars distribute the pollutants. However, our framework is not tied to a specific polluter and so will be applicable regardless of whether AGB stars are the true culprit; all that we require is that the source is present within the dwarf galaxy. Most of the stars within the dwarf galaxy are found within 1 kpc (Maxwell et al. 2012) and the escape velocity from this radius is 60 km s^{-1}, so we can safely assume that the AGB wind will stay bound to the galaxy.

Recently, Larsen, Strader & Brodie (2012) suggested that the star formation history of Fornax placed severe constraints on the AGB mass available. Although the simulation of Mashchenko, Wadsley & Couchman (2008) did not track the light element abundances of individual gas particles due to AGB feedback, we can verify that the star formation history of the dwarf galaxy would satisfy even the highest observed fraction of second generation – in other words, polluted – stars by mass. Since the star particles formed in the Mashchenko, Wadsley & Couchman (2008) simulation represent many stars, we must integrate over the IMF to obtain the fraction of each star particle that would be expected to contribute to enriching the surrounding gas. Given the uncertainties in AGB yields, we will focus only on the 3–6 M_☉ mass range (e.g. Ventura et al. 2001), although 6–8 M_☉ stars may also be a contributor (e.g. D’Ercole et al. 2012). Using a typical power-law index \(\alpha = -2.3\) (Salpeter 1955; Miller & Scalo 1979; Kroupa 2001; Chabrier 2003) over the mass range 0.1–100 M_☉, approximately 8 M_☉ per 100 M_☉ will undergo the AGB phase; increasing the upper limit to 8 M_☉ would add roughly an extra 3 M_☉ per 100 M_☉. Assuming AGB stars lose at least 10 per cent of their initial mass over a period of 30–100 Myr yields a mean wind-loss rate of 10^{-2} M_☉ Myr^{-1}. Converting the star formation history of the dwarf into an AGB ejecta history yields over 10^6 M_☉ of pure AGB ejecta within 1 kpc over a few Myr.

In order to determine if this satisfies the observational constraints, we searched the literature (Ramirez & Cohen 2002, 2003; Cohen & Meléndez 2005a,b; Carretta et al. 2006, 2007a,b,c, 2009a,b) for spectroscopic measurements of the Na–O anti correlation, and follow Carretta et al. (2009a) by splitting the stars into three components. We then used their simple dilution model to estimate that ~7 per cent of the accreted mass needs to be composed of pure AGB ejecta in order to reproduce the global Na–O anticorrelation. In other words, a cluster whose final mass is 4 × 10^6 M_☉ with half of the stars showing signatures of enrichment would only require 1.5 × 10^5 M_☉ of AGB ejecta. Further-
more, the diffusion time of the AGB ejecta through the inner 1 kpc of the dwarf galaxy is

\[ t_{\text{diff}} \sim \frac{1 \text{kpc}}{v_{\text{wind}}} \approx 24 \text{ Myr}. \]

This suggests that there may be inhomogeneity in the amount of enrichment within the gas pool from which a cluster may accrete, further diversifying the amount of dispersion a given cluster will exhibit.

### 3.2 Results

In order to find the potential mass growth of the four clusters traced within the simulation, we numerically integrate Equation (1):

\[ M(t) = \int_{t_0}^{t} \dot{M} \, dt. \tag{3} \]

We start the integration 30 Myr after the formation of each cluster since this represents the end of the SNe phase which will sweep out any residual gas from the formation of the initial stellar population. This allows sufficient time for the gas that formed the first generation cluster stars to be swept away by Type II supernovae. This is supported by the observation that the majority of the star formation within the simulation occurs in bursts separated by 50–100 Myr (Maxwell et al. 2012).

Since the mass growth is highly non-linear, we will represent it as the percentage increase in mass as a function of time:

\[ \frac{M(t) - M(t_0)}{M(t_0)} \times \text{per cent}, \tag{4} \]

where \( M(t_0) \) corresponds to the initial cluster mass. This is shown in Fig. 1 for three different initial masses: \( 5 \times 10^5 \, M_\odot \) as the solid line, \( 10^6 \, M_\odot \) as the short dashed line, and \( 2 \times 10^6 \, M_\odot \) as the long dashed line. The abscissa has been set to start at the formation time of each cluster. Each cluster experiences wildly different growth rates, despite living in the same dynamic halo.

First, the most massive clusters will accrete the most material at later times. It has been observed that the strength of the Na–O anticorrelation in globular clusters is correlated with the cluster mass (e.g. Recio-Blanco et al. 2006; Carretta et al. 2009b,c). Furthermore, the extent of the Na–O anticorrelation can be reproduced using a model wherein one source of material, either the pure AGB ejecta or the pristine gas, is diluted by the other. In other words, there exist two time-scales: one for the accumulation of pristine material, and one for the accumulation of AGB ejecta. Presumably, pristine material will accumulate at a rate dependent on the dwarf galaxy merger history, whereas the AGB ejecta will accumulate depending on the star formation history. If the most massive clusters can accrete more gas for a longer time during each pass through the centre, then our framework applied to the Mashchenko, Wadsley & Couchman (2008) simulation suggests that the pristine gas accumulates first, so that the more massive clusters can accumulate more AGB ejecta later.

Secondly, the orbit of a cluster through its host dwarf progenitor primarily determines its mass growth. The orbits of the clusters, shown in grey in Fig. 2, grow with time due to the fluctuations in the gravitational potential induced by the re-distribution of the central dark matter mass. This is a purely stochastic process, since it depends on both the rate of gas accumulation in the dwarf progenitor centre, the star formation rate, and the supernovae rate. Each cluster will have a unique accretion history, even within the same dwarf galaxy progenitor, due to the varying number of AGB stars and their location within the dwarf, as well as the changing orbit. This is consistent with the observation that the amount of light element enrichment per MW globular cluster varies between 10 and 50 per cent by mass (e.g. Piotto et al. 2012).

Thus, we can consider the ratio of gas density to relative gas velocity as the accretion efficiency; a massive cluster
passing quickly through a dense gas region may experience an accretion rate much lower than that of a lower mass cluster passing slowly through sparse pockets of gas. The mass increase experienced by a cluster is a discontinuous process: clusters experience ‘growth spurts’ as they pass through the centre of the dwarf galaxy progenitor where the densest gas is found. The split main sequences within the globular clusters (e.g. Piotto et al. 2004) would arise over time through the gradual combination of enriched and pristine material (e.g. Bedin et al. 2004; Piotto et al. 2005, 2007). The mass increase cannot continue indefinitely, however, as each boost in the cluster’s orbit means that its relative velocity through the dwarf progenitor centre will increase, as shown in Fig. 1. The black lines show the accretion rate given by Equation (1) as a function of time for an initial mass of $2 \times 10^6 \, M_\odot$.

Increasing the relative velocity of a cluster through dense gas also increases the probability that the clusters may experience ram pressure stripping. Although Equation (1) does not take this into account, we can use the temporal behaviour of $v_{\text{rel}}$ of each cluster through the dense gas, shown in Fig. 3, to determine whether the accreted gas is susceptible to removal by hydrodynamic forces. Stripping will occur for globular clusters when the pressure of the accreted gas is less than the ram pressure of the ISM as it flows past the cluster. Ignoring the cooling and gravitational collapse of the accreted gas, this condition is satisfied when $v_{\text{rel}} \gtrsim v_{\text{esc}}$, the cluster escape velocity, for most situations (Mori & Burkert 2000). In Fig. 3 this is represented by the three horizontal lines which correspond to the escape velocity from 10 pc for each of the cluster masses used in Fig. 1. It is clear that each cluster spends a significant amount of time within 35 pc of gas with relative speeds of 20–30 km s$^{-1}$.

In general, the initial orbit of the cluster will significantly affect the ability for enriched gas to be accreted. The three clusters with the largest orbits would have accreted 10–20% of their initial mass, despite making multiple passes through the inner 100 pc of the dwarf galaxy progenitor. The cluster with the highest estimated mass growth accretes much of its material during the 100 Myr when its orbit is least eccentric. Finally, it experiences a huge energy boost that ejects the cluster past 300 pc, and were the simulation continued, it would probably experience a cut-off similar to that exhibited by the other three clusters.

4 SUMMARY

We have proposed a new framework for the formation of multiple populations in dwarf galaxies. In this framework, the high-redshift progenitors of dwarf galaxies are the formation sites of globular clusters with light element abundance dispersions. The deeper potential well of the dwarf progenitors can easily retain the winds from AGB stars, thought to be the most likely source of the polluting material. Fluctuations in the gravitational potential, caused by the re-distribution of matter by star formation feedback occurring at the centres of dwarf galaxies, will drive growth in the clusters orbit. In time, it will make multiple passes through the gas-rich dwarf centre, accreting a combination of pristine and polluted material.

We have examined this framework in the context of the first cosmological simulation of a highly resolved dwarf galaxy. Our results suggest that this framework broadly matches the mounting observational evidence of multiple populations in many, if not all, globular clusters. It suggests a timeline for enrichment that matches the dilution models used to explain the observed light element anticorrelations, such as that in Na–O, with the observation that more massive clusters have the largest abundance spreads. It also connects the stochastic nature of star formation and feedback to the observed spread in the number of second generation stars within each cluster, which is between 10 and 50 per cent by mass. Finally, it provides the clearest difference between our new framework and those previously proposed, since our framework provides the blueprint to form the whole population of globular clusters, not just those with heavy element abundance spreads. Thus, there exists at least two modes of stellar cluster formation within dwarf galaxies: the globular cluster channel and the stripped stellar nucleus channel.

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REFERENCES

Bedin L. R., Piotto G., Anderson J., Cassisi S., King I. R., Momany Y., Carraro G., 2004, ApJL, 605, L125
Bekki K., 2006, MNRAS, 367, L24
Bekki K., 2010, ApJ, 724, L99
Ventura P., D’Antona F., 2008a, MNRAS, 385, 2034
Ventura P., D’Antona F., 2008b, A&A, 479, 805
Ventura P., D’Antona F., Mazzitelli I., Gratton R., 2001,
ApJ, 550, L65
Ventura P., Di Criscienzo M., Carini R., D’Antona F., 2013,
MNRAS, 431, 3642
Vesperini E., McMillan S. L. W., D’Antona F., D’Ercole
A., 2013, MNRAS, 429, 1913
Woitke P., 2006, A&A, 452, 537