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The role of super–AGB and supernovae for the formation of Globular Clusters

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Abstract. Globular Clusters, although aged 12–13 Gyr, may provide information on stellar evolution at typical times of ~30–150 Myr, if their second generation stars are formed by gas including the ejecta of super–AGBs, massive AGBs and possibly late supernovae events occurring in binaries belonging to the first generation. Here we discuss the timeline of formation of the second generation, in the light of the recent HST-UV Legacy survey of Galactic Globular Clusters and of a recent dynamical model which studies the globular clusters forming in the disk of high–z dwarf galaxies. The AGB – super–AGB – supernovae boundaries and the stellar evolution of single and binary stars in the range of masses which limit the timeline of the second generation formation determine the variety and discreteness of the chemical properties of these objects.

Key words. Stars: abundances – Stars: Population II – Galaxy: globular clusters –

1. Introduction

In old Globular Clusters (GCs) of our Galaxy, ubiquitous "multiple populations" show, inter alia, chemical anomalies due to hot CNO and other p-capture reactions. The structure of Asymptotic Giant Branch subject to "Hot Bottom Burning" (HBB) is the most favorable environment to achieve these nucleosynthesis products, and both chemical models (D'Ercole et al. 2010, 2012) and dynamical simulations (D'Ercole et al. 2008; Bekki 2010) provide a reasonable basis for its success, in spite of difficulties still existing with the reproduction of all the details of chemistry in the second generation stars (Renzini et al. 2015; D'Antona et al. 2016). In this talk I describe how the AGB scenario is constrained by the details and timing of the supernovae events which occur in the clusters. In fact, not only the second generation formation must take place in between the end of the single type II supernovae (SN II) epoch and the onset of the type Ia supernovae (SN Ia) epoch, but also the binary "delayed" SN II explosions may play a fundamental role in achieving the multple–iron populations present in about 20% of GCs (e.g. Marino et al. 2015).

2. The discreteness and variety of multiple populations in the HST UV observations

Milone et al. (2012) introduced a spectrophotometric two-color ore pseudo-colors diagram based on the HST photometry including UV and optical bands whose combination amplifies the differences in C, N and O abundances in the spectral distribution of stars. This allowed Milone et al. (2017) to show that all

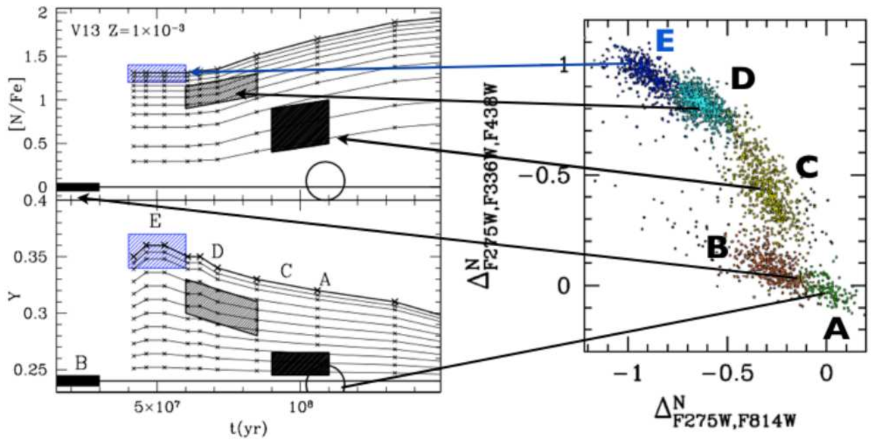

Fig. 1. On the right: distribution of data for the giants of NGC 2808 in the pseudocolor plane (m_{F275W}–m_{F336W})–(m_{F336W}–m_{F438W}) versus m_{F275W}–m_{F814W}. The ordinate is mostly sensible to the nitrogen abundance in the stellar atmosphere, while the abscissa is sensible to the oxygen (increasing with increasing color) and helium (decreasing). The points are distributed in at least 5 clumps, hinting at the presence of five chemically different populations, named from A to E (Milone et al. 2015). In the left panel, the five populations are identified along the timeline defined by Ventura et al. (2013) abundances in the ejecta of super–AGBs and AGBs for Nitrogen (top) and helium (bottom panel). The yields correspond to the top lines in the panels, and the initial abundances in the gas forming the "first generation" stars are the horizontal lines at the bottom of each panel. The different curves represent "diluted" abundances, for values of dilution 0.05, 0.1, 0.2... 0.9 from top to bottom. The timeline defines the acronym "BEDCA". Clump **B**: first generation stars; **E**: first born second generation stars, fully made from super–AGB ejecta, undiluted; **D**: clump with dilution with 25-60% of pristine gas; **C**: clump with dilution with 80–90% of pristine gas; **A**: uncertain, possibly stars polluted by the first SN 1A ejecta.

galactic GCs examined in the HST-UV Legacy survey of Galactic Globular Clusters (Piotto et al. 2015) show the presence of multiple populations. These have two main characteristics: they vary very much passing from one cluster to the other, and are very often in discrete (separated) groups. D'Antona et al. (2016) showed that the timeline of AGB evolution can be at the basis of the different chemical patterns of multiple populations, if the second generation formation lasts a relatively long interval of time between the end of the single stars SN II and the SN Ia epoch, because different modalities can favor or hamper the star formation and produce different patterns of chemical abundances. D'Antona et al. (2016) took as example case the observations of the cluster NGC 2808, where Milone et al. (2015) showed that at least five chemically different populations could be identified. In figure 1 we show the pseudo-color diagram by Milone et al. (2015) with the five groups identified with letters from A to D, while in the left side we show their interpretation in terms of the AGB timeline (see caption of Fig. 1). The groups B, D and E are easily identified as the helium normal, intermediate and extreme groups already known (e.g. D'Antona et al. 2005; Piotto et al. 2007). Two more groups are present: C, nitrogen richer than B, and the small group A. Group C can be identified with stars formed after group D. Its stars could not be easily identified spectroscopically, because they have small sodium overabundances and no other ev-

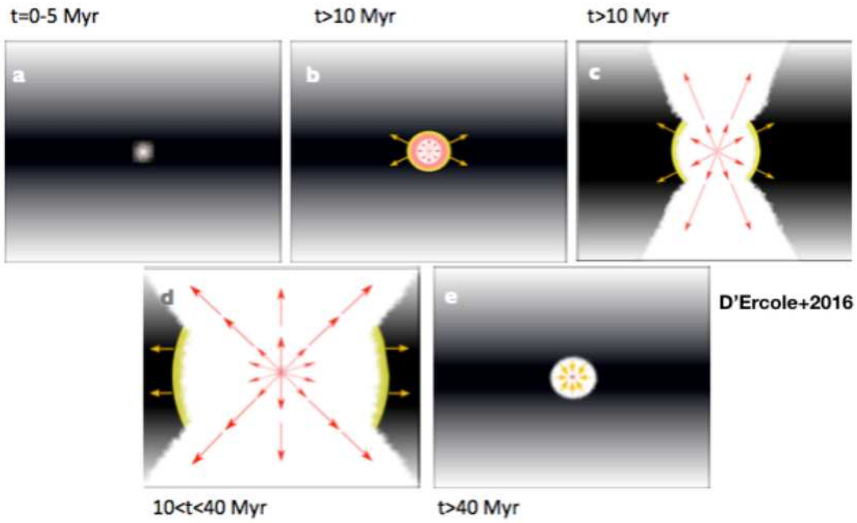

Fig. 2. Schematic model (D'Ercole et al. 2016) describing the formation of the first generation stars in the disk of primordial dwarf galaxies (panel a), followed by the beginning of the expansion of the bubble powered by the explosions of type II SN (panel b). The local gas swept up by the bubble is confined in a cool, dense, thin shell, while the free expanding wind powered by the SNs is thermalized; in panel c, the bubble expands beyond the disk scale height and the SN wind is lost from the disk; panel d: the hole on the disk expand as long the SNs keep exploding; panel e: after the end of the SN II explosions, the disk matter closes up again into the cluster, and star formation of the second generation occurs in a mixture of pristine and AGB gas.

ident peculiarities Carretta (2015). On the contrary, the nitrogen overabundance is well highlighted in the spectrophotometric pseudo-color diagram, and it may be due to star formation in gas in which there is a small contamination from the nitrogen rich ejecta of AGBs at late times ($\sim 10^8$yr), just prior to the onset of SN Ia. For group D, D'Antona et al. (2016) propose a contamination by a single SN Ia, but this should be tested by appropriate spectral analysis of the stars in the group.

3. A proposal for the dynamical evolution leading to discrete and varied multiple populations

D'Antona et al. (2016) simply analyze whether it is possible, in principle, to achieve the different chemistry of multiple populations in NGC 2808 by *assuming* that the group E is formed from pure super-AGB ejecta, and the other groups suffer different degrees of dilution, at increasing times, with pristine gas not polluted by the SN II ejecta of the first generation. This model may not be valid for the formation of GCs in the present day temperature and densities of the molecular clouds, so that most of young massive clusters will not develop this same kind of multiple populations. D'Ercole et al. (2016) studied a model for the formation of GCs in the disk of the primordial dwarf galaxies, finding that the conditions for the SN II gas ejection through the disk could be met, but re–accretion would be possible from the denser disk regions, so that the possibility of having a "pure ejecta" population (such as

E in NGC 2808) could be limited to the most massive clusters, as it is (see Figure 2 and its caption).

In the D'Ercole et al. (2016) scheme, the resulting second generations will differ one cluster from the other. Smaller clusters will have only milder second generation stars. On the contrary, if formation occurs in a more massive dwarf galaxy, dominated by dark matter, the ejecta may not escape and multiple populations differing in metallicity like in ω Cen, or nuclear star clusters may be the outcome. Re–accretion is (practically) not possible for low density of ambient gas (typical conditions for many Young Massive Clusters), but favorable local conditions may allow formation of multiple populations also in a more evolved universe, although this should not be the rule.

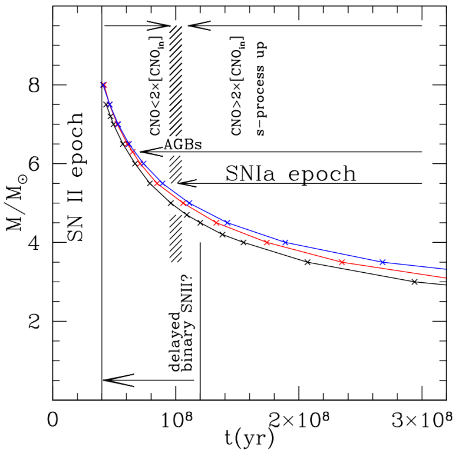

Fig. 3. Timeline of events following the first burst of star formation in a globular cluster. The end of the single SN II supernovae, the dividing line between CNO normal and CNO rich AGB ejecta, the end of delayed SN II epoch and the beginning of the SN Ia era are shown.

4. The delayed SN II

In addition, the presence of a cooling flow and the actual star formation in the model depends on the other energy sources disturbing the cooling flow. For instance, consider the binary "delayed" SN II. In principle, SNII explosions may continue after the single stars SN II epoch, if the critical mass for explosion (M_{mass}=8–9$M_\odot$) is reached by mass transfer during binary evolution. The existence of this kind of evolutionary path is necessary to explain the presence of young non-recycled pulsars in eccentric orbit with a companion white dwarf (van Kerkwijk & Kulkarni 1999). In these systems the neutron star formation must have occurred after the formation of the white dwarf, through mass accretion on the lighter companion (Portegies Zwart & Yungelson 1999; Tauris & Sennels 2000). D'Antona et al. (2005) suggested that binary SN II may influence the formation of multiple populations in GCs. A strict time limit to binary SN II explosions is obtained by noticing that the more massive (primary) star evolving in the binary may, in the best case, transfer all its envelope, leaving a white dwarf remnant $M_{\rm WD}$. Until the evolving primary M_1 is massive enough, mass transfer may push the mass accreting component beyond the limit for explosion, M_{mass}. The end of such delayed SN II is set by the time of evolution of this minimum possible mass

$$M_1 > (M_{\rm mass} + M_{\rm WD})/2$$

The limiting time for the possible occurrence of these events in our own stellar models is at 4.5$M_\odot$. For a more complete description see, e.g. Tauris & Sennels (2000).

How many delayed SN II will explode in a cluster will depend on cluster structural parameters and on the fraction of primordial binaries in the appropriate range of masses and initial separations. Nevertheless, a variety of situations is possible, hampering second generation star formation at different times and for different amounts of time.

5. The case of multiple iron clusters

Figure 3 shows the evolving mass versus time lines for three different composition, from Ventura et al. (2013). Times are dependent on the assumptions made in the models, especially on the core overshooting during the core H–burning phase. The end of the SN II epoch

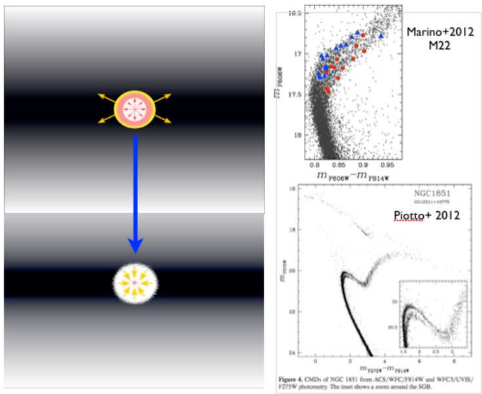

Fig. 4. Schematic effect of delayed type II supernovae on the star formation. The bubble triggered by repetitive delayed SN II events is not able to expand out of the disk, so both the SN ejecta (iron and oxygen rich) and the AGB ejecta collect at the bubble limit. When the delayed SN II epoch ends, the bubble closes, and star formation takes place in gas polluted by both AGB ejecta and SN ejecta. The formation of clusters with multiple iron and increased C+N+O abundances, like M22 (right top panel, Marino et al. 2012) or NGC 1851 (bottom right panel, Piotto et al. 2012) may be done through this path.

in these models is at ~40 Myr, is followed by the epoch of super–AGB evolution which lasts ~20 Myr, and then followed by the evolution of the most massive AGBs, in which the third dredge up is limited. The average locus at which the AGB ejecta become CNO enriched is marked. The SN Ia epoch begins at about 100 Myr, and ends forever the possibility of cooling flow and star formation. If there are delayed SN II, their epoch will end *when the AGB ejecta are already well affected by C+N+O enhancement due to the third dredge–up*. The age at which SNIa begin to explode is uncertain, but it is dependent on the age at the end of the super–AGB phase, which tags the beginning of formation of C-O white dwarfs.

A natural extension of the standard GC model studied by D'Ercole et al. (2016) can deal with the multiple–iron clusters. In these clusters, the O–Na anticorrelation is already present in the fraction of stars having the smaller, and homogeneous, iron content. This anticorrelation is very unlikely to occur, if the iron contamination is due to SN II of the single SN II epoch. So we suggest that the first phases of evolution of these clusters are similar to what happens in GCs which are fully chemically homogeneous in heavy elements, but, at later times, we must account for contamination by further supernova explosions, those from delayed SN II in binaries. Let us assume:

1. delayed SN II begin exploding after the first SG, homogeneous in iron, is born, providing the typical O–Na anti correlation for the stars with first generation iron content;
2. afterwards, delayed SN II begin exploding with some regularity in a cluster, destroy the cooling flow, which would have included both AGB ejecta and pristine gas;
3. these events (which are much less frequent than the single SN II were) are not able to inject into the gas enough power to definitely push it out of the cluster vicinity (see top panel of figure 4.

When, at last, the delayed events become rare, possibly several tens of Myr later, the pristine plus AGB gas will re-accrete and induce a new SG formation burst (bottom panel of Figure 4). In these hypotheses, *the pristine gas will now be contaminated by the delayed SN II ejecta, and by the AGB ejecta which were lost during this time span*. Further, the contaminating AGBs will be the masses in which the 3DU has been very effective, so this population will have the characteristics of the multiple iron clusters: larger iron and s–process abundances, and associated C+N+O enhancement. An appealing feature of this scenario is that it explains the features of the multiple iron clusters, without the need for additional hypotheses, such as the merging of two different clusters.

The time gap of a few 10^7yr between the formation of the 'first', standard SG, and the 'second' one, s-Fe and CNO enriched, also justifies another important characteristics of some clusters: the presence of separate subgiant branches (see Figure 4, right panels). While this time break is negligible in terms of location of isochrones with identical chemical composition, this short time is sufficient to shift the AGB ejecta composition to the CNO enriched stage, which, also with the help of the small iron increase, will result in distinct subgiant branches (for the case of NGC 1851, see Cassisi et al. 2008; Ventura et al. 2009). Finally notice that the formation epoch of this s-Fe-CNO enriched SG can not be very extended, as it occurs close to the beginning of the SN Ia era, which will definitely end star formation.

6. Conclusions

It is evident that the AGB–supernovae boundaries are of extreme importance in defining the characteristics, and the same existence, of multiple populations in Globular Clusters. We have shown that the presence of delayed SN II may be linked to the formation of the elusive category of multiple iron GCs. Further work applying binary population synthesis to these clusters is necessary.

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