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Detection of second-generation asymptotic giant branch stars in metal-poor globular clusters

D. A. García-Hernández[1,2]

[1] Instituto de Astrofísica de Canarias, C/ Via Láctea s/n, 38205 La Laguna, Spain
[2] Departamento de Astrofísica, Universidad de La Laguna, 38206 La Laguna, Spain

Abstract

Multiple stellar populations are actually known to be present in Galactic globular clusters (GCs). The first generation (FG) displays a halo-like chemical pattern, while the second generation (SG) one is enriched in Al and Na (depleted in Mg and O).Both generations of stars are found at different evolutionary stages like the main-sequence turnoff, the subgiant branch, and the red giant branch (RGB), but the SG seems to be absent - especially in metal-poor ([Fe/H] < -1) GCs - in more evolved evolutionary stages such as the asymptotic giant branch (AGB) phase. This suggests that not all SG stars experience the AGB phase and that AGB-manqué stars may be quite common in metal-poor GCs, which represents a fundamental problem for the theories of GC formation and evolution and stellar evolution. Very recently, we have combined the H-band Al abundances obtained by the APOGEE survey with ground-based optical photometry, reporting the first detection of SG Al-rich AGB stars in several metal-poor GCs with different observational properties such as horizontal branch (HB) morphology, metallicity, and age. The APOGEE observations thus resolve the apparent problem for stellar evolution, supporting the existing horizontal branch star canonical models, and may help to discern the nature of the GC polluters.

1 Introduction

Nowadays, it is well known that all Galactic globular clusters (GCs) host multiple (at least two) stellar populations (see [8] and references therein). First-generation (FG) stars display the normal Na (and Al) abundances typical of the halo field stars, while second-generation (SG) stars - which may have additional subpopulations - show Na (and Al) enhancements. These SG additional subpolutations of stars are also characterized by He overabundances (e.g., [15]). FG and SG GC stars are found in the main sequence, subgiant branch, and red giant branch (RGB) phases (e.g., [7]; [4]) but they are not found in more evolved evolutionary stages like the asympotic giant branch (AGB; e.g., [10]; [2]; [11]), representing a challenge for stellar evolution and the formation/evolution models of these complex stellar systems [5]; [3].

Recent spectroscopic observations of AGB stars in the metal-poor ([Fe/H]≈-1.56) GC NGC 6752 [2] found no Na-rich (SG) AGB stars in this cluster; see also [10] and [11] for the non-detection of SG-AGBs in M 13 (a twin of NGC 6752) and M 62 (a slightly more metal-rich cluster with [Fe/H]≈-1.2). In [2] explain these puzzling observations as due to the fact that all SG stars do not ascend the AGB (failed AGB stars). They suggest that a stronger mass-loss in SG horizontal branch (HB) stars could explain their observations and that AGB-manqué stars may be very common in metal-poor ([Fe/H]<-1) Galactic GCs. The Na-poor nature of all AGB stars analyzed in NGC 6752 (also in M 13 and M 62) poses an apparent problem for stellar evolution. This is because the canonical theoretical models of HB stars do not predict the lack of SG-AGB stars. More recently, [3] have critically discussed such mass-loss scenario during the core He-burning stage. They show that the required mass-loss rates are much higher than any of the current theoretical and empirical constraints and that their synthetic simulations of HB stars can reproduce the number ratio of AGB to HB stars in NGC 6752 and a few other clusters with similar/dissimilar observational properties. Thus, at present there is no simple explanation for the apparent lack of SG-AGB stars in these metal-poor GCs.

In [6] we have recently reported the first detection of SG-AGB stars in the GC M 13 - a twin of NGC 6752 - and another three GCs (M 5, M 3, and M 2) of similar metallicity but distinct observational properties such as HB morphology and age. For this, we combined the H-band Al abundances measured by the Apache Point Observatory Galactic Evolution Experiment (APOGEE) and the most recent ground-based photometry of these GCs.

2 APOGEE abundances and ground-based photometry

The APOGEE survey observed ten northern GCs, covering metallicity [Fe/H] from -0.8 down to -2.4, including cluster members with well-characterized stellar parameters and abundances from existing high-resolution optical spectra as well as many additional cluster giant stars currently lacking such detailed abundances [14]. The stellar parameters and chemical abundances of nine elements (Fe, C, N, O, Mg, Al, Si, Ca, and Ti) for 428 cluster star members in these ten GCs have been recently reported by us (see [14] for more details).

The APOGEE abundances are measured from neutral lines of Fe, Al, Mg, etc.; the H-band single-ionized lines are not detected in metal-poor GC giants. The main advantages of the APOGEE H-band data with respect to previous optical spectroscopic studies of GC giants are that they enable us to analyze these ten clusters in a homogeneous way (covering almost the full extent of the RGB) and non local thermodynamic equilibrium (NLTE) effects on the spectral lines of neutral species like Fe, Al, Mg, etc. are expected to be less important than in the optical range because in the H-band these lines are formed deeper in the atmosphere.

Ground-based U,B,V,I photometry is available for six out of the ten GCs observed by APOGEE. The ground-based photometry is taken from the private collection by P. Stetson, which is based upon a large corpus of the most recent observations obtained mainly from public astronomical archives (see [6] for more details).

3 CMDs and the (V, $C_{u,b,i}$) pseudo-CMD

We constructed several color-magnitude diagrams (CMDs) for each GC observed by APOGEE in order to separate the AGB and RGB stars. We find that the combination of the U−(U-I), I−(U-I), and V−(B-I) CMDs gives an efficient RGB/AGB separation (Fig. 1).

We used an extreme-deconvolution method to identify FG and SG stars in the Al−Mg distributions (see [14] for more details). This translates in FG and SG stars displaying [Al/Fe]<0.50 dex (Al-poor) and [Al/Fe]≥0.50 dex (Al-rich), respectively, although the exact cut in [Al/Fe] may be slightly different from one cluster to another. Thus, we combined our FG and SG stars classification (mainly driven by the Al abundances) with the U−(U-I), I−(U-I), and V−(B-I) CMDs. We note that FG- and SG-AGB stars display [Al/Fe]<0.50 dex (Al-poor) and [Al/Fe]≥0.50 dex (Al-rich), respectively.

From the CMDs, four GCs: M 13 ([Fe/H]≈-1.53), M 5 ([Fe/H]≈-1.29), M 3 ([Fe/H]≈-1.50), and M 2 ([Fe/H]≈-1.65) - those clusters with more than 50 members observed plus M 2 with only 18 members - contain SG Al-rich AGB stars (Fig. 1). The AGB stars are clearly separated from the RGB ones in the U−(U-I), I−(U-I), and/or V−(B-I) CMDs (Fig. 1). The number ratio of AGB to RGB stars is very similar for M 13, M 5, and M 3 (∼0.21, 0.16, and 0.20, respectively) but it is higher for M 2 (∼0.39). We identify a total of 4, 5, 3, and 2 SG Al-rich AGB stars in M 13, M 5, M 3, and M 2, respectively (see Table 1 in [6]).

The Al−O anticorrelation is clearly seen in our APOGEE data for all clusters (see Fig. 2 in [6]) and the SG Al-rich AGB stars are among the most O-poor stars, as expected. Only a few (5 out of 14) of the SG Al-rich AGB stars have Na abundances from optical spectroscopy available in the literature (see Table 1 in [6]). Remarkably, all of them are Na-rich ([Na/Fe]∼0.3−0.6 dex; see Fig. 3 in [6]), supporting their identification as truly SG-AGB stars. Another indication of the Na-rich nature of the identified SG-AGB stars is offered by the (V, $C_{u,b,i}$) pseudo-CMDs (where $C_{u,b,i}$=(U-B)-(B-I); [16]). It has been clearly shown by [16] that the $C_{u,b,i}$ index is very sensitive to any change in the relative distributions of CNO elements and since SG stars are N-rich/O-poor/Na-rich/Al-rich with respect FG stars, it is a powerful tool for tracing the distribution of FG/SG stars along the RGB and AGB evolutionary stages. The (V, $C_{u,b,i}$) pseudo-CMD of all GCs in our sample (see Fig. 4 in [6]) provide an independent confirmation of present results.

Another interesting feature from Fig. 1 is the hint for the presence of a splitting (i.e., different photometric sequences) along the AGB between the FG and SG stars in M 13 and M 5. However, the number of stars is small and this AGB splitting is not seen in M 3 and M 2 where we have even less stars observed. In the CMDs, the M 13 and M 5 SG-AGB stars seem to define bluer (and/or brighter) photometric sequences than the FG ones.

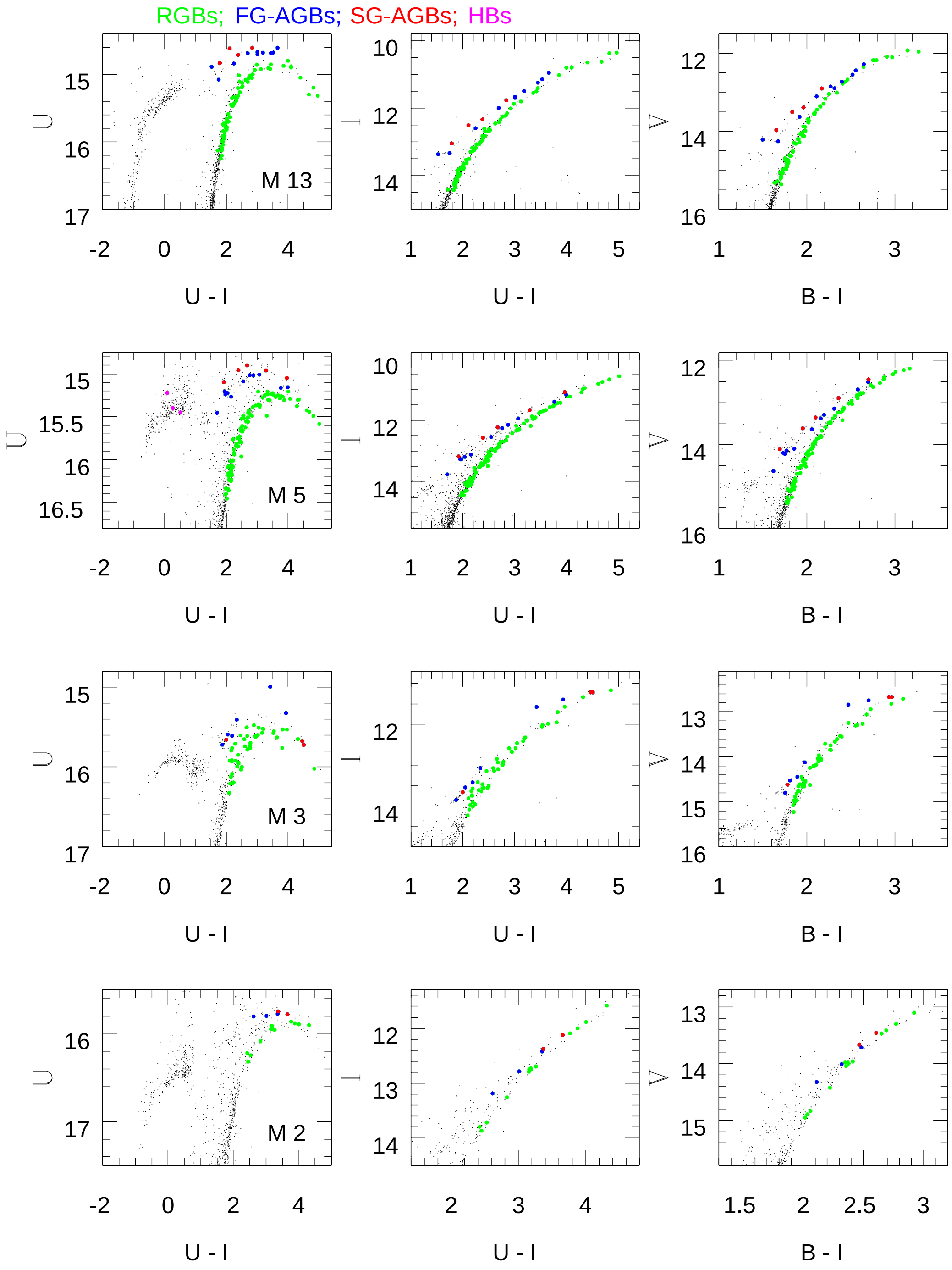

Figure 1: Color-magnitude (CMD) diagrams U vs.(U-I) (left panels), I vs. (U-I) (middle panels), and V vs. (B-I) (right panels) for metal-poor GCs (from top to bottom: M 13, M 5, M 3, and M 2). Ground-based photometry for the cluster stars is indicated with black dots, while the RGB, FG-AGB, and SG-AGB stars observed by APOGEE are indicated with green, blue, and red dots, respectively. The three M 5 stars marked with magenta dots (left panel) are HB stars (updated from [6]).

4 Discussion

The non detection of SG-AGB stars in several metal-poor GCs (such as NGC 6752, M 13, and M 62) from previous optical spectroscopic surveys may be just coincidental (bias in the sample selections, small stellar samples) or due to the non use of recent (and precise) optical photometry and appropriate combinations of several CMDs for efficient RGB/AGB separation (see [6] for more details).

The lack of Na-rich SG-AGB stars in NGC 6752 [2] is puzzling (also in M 62 but only six AGB stars were analyzed; [11]. Here we report for the first time SG-AGB stars in the GC M 13; a twin of NGC 6752 with very similar HB morphology, metallicity, and age. Our work demonstrate that SG-AGB stars are present in metal-poor GCs with different observational properties, showing that they are not uncommon in these stellar systems. This resolves the previous apparent problem for stellar evolution and support the existing canonical HB star models.

An alternative explanation for the Na-poor character of all AGBs surveyed in NGC 6752 (as well as for the no previous detection of Na-rich SG-AGBs in several metal-poor GCs) is the fact that NLTE effects in AGB stars may be larger than in RGB stars, underestimating more severely the correct Na abundances in the AGB stars ([11] and references therein). Higher NLTE effects in AGB stars are suggested by the differences (up to $\sim$0.1$-$0.2 dex) in the Fe (and Ti) abundances measured from neutral and single-ionized lines in the AGB stars, which otherwise are negligible in the RGB stars (e.g., [9]; [11]); e.g., the Fe abundances derived from optical neutral lines in AGB stars are systematically $\sim$0.1$-$0.2 dex lower than in the RGB stars. As we mentioned above, the APOGEE abundances are measured from neutral lines and we find no significant differences for the Fe (Al, Mg, O) abundances in the AGB and RGB stars (see Fig. 2 in [6]), which seem to confirm that the H-band spectral lines are formed deeper in the atmosphere and NLTE effects on the neutral lines of Fe, Al, Mg, etc. are less severe than in the optical domain. The H-band thus open a new (and safer) window to systematically study the AGB and RGB stellar generations in Galactic GCs.

Interestingly, our first detections of SG-AGB stars in metal-poor GCs have been recently confirmed by other authors. For example, [13] and [19] have confirmed the presence of Na-rich SG-AGBs in M 3 and NGC 2808, respectively. More interesting is that fact that [12] have finally found SG-AGB stars in the GC NGC 6752; at least eleven SG-AGB stars have been identified.

Finally, our observations may have also an impact on the GC formation/evolution theories, which usually explain the origin of the chemical anomalies (e.g., the Na$-$O and Mg$-$Al anticorrelations) in these stellar systems as due to a first generation of polluters; i.e., massive AGB stars, fast rotating massive (FRM) stars, massive interacting binaries, or supermassive stars (but see also [1]). For example, [5] proposed that the He-Na correlation needed to explain the lack of Na-rich AGB stars in NGC 6752 corresponds to the one predicted by the FRM stars models, suggesting that these stars may explain the formation of subpopulations within GCs. Our observations (and particularly the recent identification of SG-AGB stars in NGC 6752 by [12] would thus disfavour FRM stars as the GC polluters. Indeed, [18] have very recently shown that the Mg-Al anticorrelations observed by the APOGEE survey further support the idea that massive AGB stars are the intra-cluster medium polluters responsible for the formation of additional stellar generations in GCs.

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References

[1] Bastian, N., Lamers, H. J. G. L. M., de Mink, S. E., et al. 2013, MNRAS, 436, 2398

[2] Campbell, S. W., D'Orazi, V. Yong, D. et al. 2013, Nature, 498, 198

[3] Cassisi, S., Salaris, M., Pietrinferni, A., Vink, J. S., Monelli, M. 2014, A&A, 571, A81

[4] Carretta, E., Bragaglia, A., Gratton, R., & Lucatello, S. 2009, A&A, 505, 139

[5] Charbonnel, C., Chantereau, W., Decressin, T., Meynet, G., & Schaerer, D. 2013, A&A, 557, L17

[6] García-Hernández, D. A., Mészáros, Sz., Monelli, M. et al. 2015, ApJ, 815, L4

[7] Gratton, R. G., Bonifacio, P., Bragaglia, A., et al. 2001, A&A, 369, 87

[8] Gratton, R. G., Carretta, E., & Bragaglia, A. 2012, A&ARv, 20, 50

[9] Ivans, I. I., Kraft, R. P., Sneden, C. et al. 2001, AJ, 122, 1438

[10] Johnson, C. I., & Pilachowski, C. A. 2012, ApJ, 754, L38

[11] Lapenna, E., Mucciarelli, A., Ferraro, F. R. et al. 2015, ApJ, 813, 97

[12] Lapenna, E., Lardo, C., Mucciarelli, A. et al. 2016, ApJ, 826, L1

[13] Massari, D., Lapenna, E., Bragaglia, A. et al. 2016, MNRAS, 458, 4162

[14] Mészáros, Sz., Martell, S. L., Shetrone, M. et al. 2015, AJ, 149, 153

[15] Milone, A. P., Marino, A. F., Dotter, A., et al. 2014, ApJ, 785, 21

[16] Monelli, M., Milone, A. P., Stetson, P. B. et al. 2013, MNRAS, 431, 2126

[17] Renzini, A., D'Antona, F., S. Cassisi, S. et al. 2015, MNRAS, 454, 4197

[18] Ventura, P., García-Hernández, D. A., Dell'Agli, F. et al. 2016, ApJ, 831, L17

[19] Wang, Y., Primas, F., Charbonnel, C. et al. 2016, A&A, 592, A66