DO AGB STARS DIFFER CHEMICALLY FROM RGB STARS IN GLOBULAR CLUSTERS?

CHRISTOPHER SNE DEN1, INENE I. IVANS1, ROBERT P. KRAFT2
1Department of Astronomy and McDonald Observatory, University of Texas, Austin, TX 78712, USA
2UCO/Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA

ABSTRACT.
The recent improvements in globular cluster colour-magnitude diagrams, coupled with an increase in large-sample spectroscopic abundance studies of cluster giants, finally allow some attempts at a statistically meaningful comparison of the chemical compositions of red giant branch and asymptotic branch cluster stars. We review some of the extant data here, concluding that in a few clusters the AGB stars show on average smaller amounts of high-temperature proton-capture synthesis products (low oxygen, high sodium and aluminum) at their surfaces than do the first-ascent RGB stars. This suggests that those RGB stars with envelopes that have been enriched with proton-capture material also have high helium contents. Such stars after the He-flash then take up residence on the bluest parts of the HB (as a consequence of their high envelope helium), probably never to return to the AGB during subsequent evolutionary stages.

1. Introduction

Asymptotic giant branch (AGB) stars of all populations have basically the same interior structures, with shell fusion zones of He and H surrounding C-O cores. Most AGB stars will undergo episodes of mass loss that eject their outer envelopes, leaving the exposed cores to fade away as white dwarfs. Thus low mass, metal-poor halo AGB stars and their higher mass, metal-rich disk counterparts exist in the same evolutionary domains and share the same eventual fates; all these stars appear to be theoretically quite similar.

Observationally however, the properties of disk and halo population AGB stars are quite distinct. The high mass, high metallicity AGB stars are both extremely luminous and extremely cool. Sometimes they are surrounded by substantial gas/dust shells of their own making, and thus present unique photometric signatures (especially in the infrared). Often they exhibit spectroscopic peculiarities (strong carbon-containing molecular and neutron-capture element features) indicative of nuclear processing in their He fusion zones. These are the stars that are treated in most of the contributions to this workshop.

In contrast, the low mass, low metallicity stars that can be positively associated with the AGB are photometrically and spectroscopically somewhat difficult to distinguish from first-ascent red giant branch (RGB) stars. In globular cluster colour-magnitude
(c-m) diagrams the AGB is a thinly-populated stream of stars connecting the red end of the horizontal branch (HB) and the end of the RGB. Over the brightest 1–2 magnitudes, the AGB and RGB are separated by less than 0.2 in V magnitude at a given B–V colour (a particularly clear example is the M3 c-m diagram of Buonanno et al. 1986). Globular cluster AGB stars will not become extremely luminous because they are former HB stars, whose masses cannot in theory exceed $M \sim 0.6M_\odot$; the second-ascent AGB tip effectively merges with the first-ascent RGB tip. Unfortunately, for many globular clusters, photometry precise enough to cleanly separate the AGB from the RGB for most candidate stars still does not exist. The spectra of globular cluster AGB stars also do not differ radically from those of RGB stars. CH stars, those possessing spectroscopic evidence of having possibly mixed He shell burning products (carbon, neutron-capture elements) to their surfaces, are apparently very rare in globular clusters; only a handful have been discovered (e.g., McClure & Norris 1977; Cowley & Crampton 1985; Vanture & Wallerstein 1992; Côte et al. 1997).

In recent years photometrists and spectroscopists have combined efforts to substantially increase the quantity and quality of data on AGB stars in globular clusters. In this paper, we look for chemical composition differences between AGB and RGB stars in three globular clusters, concluding that there is some evidence suggesting that AGB stars have less chemically evolved surface layers. This suggestion is then related to the “second parameter problem” of globular clusters.

2. Inter- and Intra-Cluster Chemical Inhomogeneities: A Brief Sketch

Several decades of spectroscopic investigations have established the reality of large-scale star-to-star abundance variations among light elements in globular cluster stars. The variations are not of the same magnitude in all clusters, and indeed each cluster seems to have a chemical composition signature that is not repeated exactly in other clusters. Most of the abundance inhomogeneities observed in globular clusters involve some aspects of so-called “proton-capture” nucleosynthesis. Extensive reviews of these abundance variations have been published by e.g., Kraft (1979), Freeman & Norris (1981), Smith (1987), Suntzeff (1993), Briley et al. (1994), Kraft (1994), and Sneden (1998,1999). Some general statements about cluster nucleosynthesis are summarized here without attribution to specific papers, and the reader is strongly encouraged to consult the reviews and the original papers quoted in them for details on these abundance trends.

The CN cycle: The chief products of ordinary CN cycle fusion are observed at the surfaces of most RGB and AGB stars. That is, the carbon isotope ratios are uniformly low ($4 \leq ^{12}\text{C}/^{13}\text{C} \leq 10$), carbon abundances are usually low ($-0.3 \geq [\text{C/Fe}] \geq -1.3$), and nitrogen abundances are correspondingly very high ($+0.5 \leq [\text{N/Fe}] \leq +1.5$). However, the N overabundances are sometimes far greater than the amounts that would be predicted from simple $\text{C} \rightarrow \text{N}$ conversion.

The ON cycle: Globular cluster giants, unlike almost all halo field giants, often exhibit very depleted oxygen abundances ($-1.0 \leq [\text{O/Fe}] \leq +0.4$). This suggests that the ON cycle, which requires higher temperatures ($T \sim 40 \times 10^6$ K) in hydrogen fusion zones than does the CN cycle, has been active either in the giants that are being observed
or in an earlier cluster generation. This cycle’s major net effect is O→N conversion, and can therefore account for the anomalously large N abundances mentioned above. Finally, in nearly all cluster giants with complete CNO abundance data, the C+N+O abundance sum appears to be conserved, adding further weight to the idea that the variations in these elements are simply due to the combined CN and ON element re-shufflings.

**The NeNa cycle:** Sodium abundances also vary widely among globular cluster giants (−0.3 ≤ [Na/Fe] ≤ +0.4). The same globular cluster giants that have low O abundances almost invariably have high Na abundances; an anticorrelation between these abundances apparently occurs in all lower metallicity clusters ([Fe/H] < −1) studied to date. This anticorrelation suggests that the NeNa proton-fusion cycle, which can work efficiently at the same temperatures as does the ON cycle, has at some time in globular cluster histories converted Ne (undetectable in cluster giant spectra) into Na.

**The MgAl cycle:** Aluminum abundances also have large star-to-star variations that are anticorrelated with O abundances, and in some well-studied clusters the anticorrelation extends also to Mg abundances. Again, proton-capture fusion leading to Mg→Al conversion is the probable culprit (Shetrone 1996), but the burning temperature requirements (T ∼ 70×10^6 K) are large enough that it is difficult to imagine low mass globular cluster giants performing the MgAl cycle, unless such transmutations occur as the result of a thermal instability of the H or He shell source (Langer et al. 1997, Powell 1999). Alternatively, stars with abnormally large Al abundances might either have been born with them, created in previous higher mass stars, or have accreted them from the winds of higher mass AGB stars.

**Other Nucleosynthesis effects:** Some significant cluster-to-cluster abundance differences are seen in heavier elements that cannot be altered in proton-capture synthesis reactions. For example, the very heavy elements Ba, La, and Eu can have very different abundance ratios in different clusters, indicating varying contributions of slow and rapid neutron-capture synthesis reactions to the creation of these elements. Among the elements that participate in the major nuclear fusion chains, silicon should only be altered during the last stages of very high mass stars. But its mean abundance varies from cluster to cluster; some globular clusters have Si abundances nearly a factor of two larger than those of typical halo field giants. And in addition to the star-to-star variations of Al abundances within individual clusters, the Al mean abundance level also differs substantially from cluster to cluster. All of these abundance anomalies point to nucleosynthesis contributions of multiple generations of stars in a given cluster, either from stars that died before the present stars were born or during their formation. Also, the relatively small numbers of high mass stars that must have existed in or preceded formation of each cluster probably produced supernovae of different masses in each cluster, creating distinct “initial” abundance distributions in each cluster.

3. CN Bandstrengths in RGB and RGB Stars of NGC 6752

Perhaps the first suggestion that AGB and RGB stars in some clusters might on average have different compositions was made by Norris et al. (1981). In a large-sample study of CN bandstrengths among giants of NGC 6752, they found that there is a bi-modal distribution of CN bandstrengths that is nearly independent of RGB position. But they
suggested that there is a nearly uni-modal set of CN bandstrengths among the AGB stars: their CN bands are almost all weak. Norris et al. presented this situation in their Figure 3, plotting the CN absorption index S(3839) as a function of V magnitude and B–V colour.

We have used the formula developed by Norris et al. to convert S(3839) to a CN bandstrength indicator that is independent of stellar temperature/gravity effects, and in Figure 1 we show “boxplots” that illustrate the ranges in CN bandstrength found in RGB and AGB stars. The lower CN strengths of the AGB stars on average is obvious, but just as important is the near total lack of any CN strong AGB stars in this cluster. For comparison, we also show similar data for two other clusters, M4 and M13. The M4 CN bandstrength data are taken from either Norris (1981) or Suntzeff and Smith (1991), or the mean of both, where the variation of S(3839) with position in the c-m diagram has been removed according to Norris’ formula. The evolutionary status of the stars are those determined by Ivans et al. in their H-R diagram of Figure 12, which illustrates the reddening-free positions of the stars. For the M13 data, we referred to Suntzeff (1981), where we converted the photometric m(CN) indices to relative photometric bandstrengths δm(CN) using Suntzeff’s suggested relationship of the lower limit of m(CN) to B–V colour index. We further transformed the δm(CN) values to δS(3839) relative bandstrengths employing the relationship we derived for δm(CN) and δS(3839) found using stars in common between the studies of NGC 6752 stars by Langer et al. (1992), who used m(CN), and Norris et al. (1981) who used S(3839). The evolutionary status of the M13 stars were those determined by Suntzeff (1981) and, in the cases where the photometry made the status ambiguous, we supplemented the information using the stars in common studied by Pilachowski et al. (1996b). Thus, the distributions shown in Figure 1 are all, in effect, on the δS(3839) system of Norris et al. (1981) and only include the stars for which AGB vs RGB designations are unambiguous.

Norris et al. (1981) offered two possible explanations for the relatively weak CN bandstrengths in NGC 6752 AGB stars; both explanations involve an inability of the strong-CN RGB stars to ascend the giant branch a second time after HB evolution. In one scenario, some cluster stars would have been born with abnormally large C and/or N abundances, accompanied by larger-than-average He/H ratios (presumably from the CN and/or ON cycles). Stellar evolution computations (e.g., Lee et al. 1994, and references therein) have shown that RGB stars with higher He contents will, after they undergo the He flash, take up residence in bluer parts of the HB than do otherwise identical stars with lower He contents. In fact, these stars may arrive at such a blue HB position that they may eventually evolve directly to the white dwarf track, entirely avoiding the AGB stage. In the other scenario, larger internal mixing in CN-strong stars during RGB evolution might drive large amounts of mass loss, leading to lower-than-average envelope masses after the He flash. Again, such stars would wind up on the bluer end of the HB, possibly never to return as AGB stars. Thus the stars observed on the AGB of NGC 6752 may have weak CN bands because they are the former RGB stars that had little mixing of CN cycle products (N and He) into their envelopes; they are the ones that survived the HB stage to rise again toward the giant branch tip.

This latter hypothesis can be tested by comparing abundances of light proton-capture elements (C, N, O, Na, Mg, Al) in AGB and RGB stars of NGC 6752. Unfortunately, the
Fig. 1. Simple boxplots illustrating CN bandstrength ranges in RGB and AGB stars of NGC 6752, M13, and M4 are shown. For all of the individual abundance boxes, the horizontal line inside a box indicates the median value of $\delta S(3839)$. The vertical boundaries of a box show the interquartile range (the middle 50% of the data). The vertical tails extending from the boxes indicate the total range of $\delta S(3839)$, excluding outliers. Mild outliers (those between 1.5 and 3 times the interquartile range) are denoted by open circles. No severe outliers (those greater than 3 times the interquartile range) are present in these data. The number of stars included in each boxplot is noted in parentheses. The basic data (estimates of CN line blocking index $S(3839)$) were taken from the following sources: (a) NGC6752: Norris et al. (1981), and we have used their suggested relationship of the lower limit of $S(3839)$ to V magnitude to compute the relative CN bandstrengths $\delta S(3839)$; (b) M13: converted photometric CN index $m(CN)$ values obtained by Suntzeff (1981). We first removed the variation of the index due to position in the c-m diagram using Suntzeff’s formula, and then converted the results to $\delta S(3839)$ values using the relationship we found for the NGC 6752 stars in common to the $m(CN)$ values presented by Langer et al. (1992) and the $\delta S(3839)$ values of Norris et al. (1981). (c) M4: Norris (1981) or Suntzeff & Smith (1991), or the mean of both, using Norris’ suggested relationship of the lower limit of $S(3839)$ to V magnitude.
extant high resolution spectroscopic studies of NGC 6752 giants (Gratton 1987, Norris & Da Costa 1995, Minniti et al. 1996, Shetrone 1998) were only able to include the brightest stars near the RGB tip, where the distinction between RGB and AGB stars cannot be made.

4. Sodium Abundance Variations in M13 Giants

Pilachowski et al. (1996b) derived sodium abundances for 130 giants in M13; their program stars ranged from those at the RGB tip to ones about as faint as the HB. They showed that Na abundances of most M13 giants are greater than those of similar-metallicity halo field stars, but there are some significant differences between RGB and AGB stars in this cluster. We illustrate this situation in Figure 2 with another boxplot, in which we compare [Na/Fe] ratios for lower luminosity M13 RGB stars (those with log $g > 1$), RGB tip stars (log $g < 1$), and AGB stars, along with [Na/Fe] ratios for field stars in the metallicity range $-1.2 > [\text{Fe/H}] > -1.9$ (Pilachowski et al. 1996a). The higher Na abundances of M13 giants is obvious in this figure, but it is also clear that the AGB stars have lower mean Na abundances than do the RGB tip stars, and that they have a narrower range in Na. It is possible that the Na abundances for the very cool RGB tip stars must be corrected downward somewhat to correct for departures from LTE (e.g., Gratton et al. 1999). But oxygen abundances in cluster giants are always determined from the [O I] transitions, which do not suffer substantial departures from LTE. And in M13 not only do the RGB stars exhibit on average the largest Na abundances but they also have the lowest O abundances (Kraft et al. 1997). Therefore the difference between the the mean levels of Na in AGB and RB stars in M13 is probably real.

Pilachowski et al. (1996) followed a line of reasoning similar to that of Norris et al. (1981) in supposing that the presently observed AGB stars in M13 are those whose envelope He contents remained relatively low when they were RGB stars; the RGB stars with elevated He took up residence on the blue part of the HB and never arrived on the AGB. However, the Pilachowski et al. scenario differed from that of Norris et al. in one important respect: the RGB stars with elevated He were those that had contaminated their atmospheres with material that had been processed through the CNO hydrogen-burning shell, in accordance with the deep mixing scenario and nuclear transmutation calculations of Langer et al. (1993), Langer & Hoffman (1995) and Cavallo et al. (1998). Sweigart (1997a,b) showed that such “deep mixed” stars could indeed be moved sharply to the blue in their subsequent evolution onto the HB, largely as a result of increased mass loss prior to the helium core flash. Pilachowski et al. also noted that since M13 has the most extreme cases of Na and Al enhancements and O depletions among RGB stars, it also probably has a higher percentage of high-He stars than other globular clusters. If so, then the AGB of M13 ought to be relatively unpopulated. This view is supported by the statistics of Caputo et al. (1978) and Buzzoni et al. (1983), from which one finds that M13 has the lowest ratio (by a factor of $\sim 2$) of AGB to RGB stars among the 16 clusters studied.
Fig. 2. Boxplots of sodium abundances in M13 (Pilachowski et al. 1996b) and field giant stars (Pilachowski et al. 1996a). The statistical abundance distributions represented by each box’s vertical boundaries, etc., are as described in Figure 1. The different boxes illustrate the sodium abundance distributions found for RGB tip stars, lower luminosity giants, and AGB stars. For contrast, a boxplot representing sodium abundances in field giants is also shown in this figure.
5. Some Additional Comments

M13 and NGC 6752 represent the clearest cases for chemical composition differences between AGB and RGB stars in globular clusters. But truth in advertising compels us to admit that the situation is probably far more complex than we have suggested so far. Smith & Norris (1993) suggested that the AGB stars of M5 have a different CN bandstrength distribution: “... the observations reported in this paper yield no consistent picture of the CN distributions among stars in more advanced stages of evolution. The asymptotic giant branch appears to be deficient in CN-weak stars for M5, but deficient in CN-strong stars for NGC 6752.”

Consideration of these differences has been made possible by the existence of very large bandstrength or abundance samples in these two clusters. Unfortunately, most other globulars have not been studied in sufficient detail to assess the chemical compositions of AGB stars. In their study of a large number of bright giants in M4, Ivans et al. (1999) found some of the same correlated variations in proton-capture elements that have been seen in other clusters. Their data were most extensive for the determination of oxygen abundances, and they concluded that the mean oxygen abundance of M4 AGB stars is slightly larger than that of the RGB stars. This provides mild further support for the suggestion that AGB stars in globular cluster are on average less chemical evolved in the proton-capture elements than are RGB stars.

This problem cannot be effectively dealt with until stellar samples in many globular clusters include at least 10 AGB stars, as well as many more RGB stars over a large luminosity range. Enough detailed high resolution, large wavelength coverage spectroscopic studies of individual stars in selected globulars to make it clear that the proton-capture phenomenon is “universal”. Thus in addition to the continued full-scale abundance analyses of the brightest cluster members, it will be especially fruitful to now survey cluster giant branches with multi-object spectrometers (in the manner of Pilachowski et al. 1996b) that concentrate on fairly complete descriptions of the abundance trends of just one or two elements that will stand as surrogates for the behaviour of the whole set of proton-capture elements.

Acknowledgements

We thank Raffaele Gratton for helpful discussions on this work. This research was supported by NSF grants AST-9217970 to RPK AST-9618364 to CS. Travel support given by the Rome Observatory to CS is gratefully acknowledged.

References

Briley, M. M., Bell, R. A., Hesser, J. E., Smith, G. H.: 1994, Can. J. Phys. 72, 772.
Buonanno, R., Buzzoni, A., Corsi, C. E., Fusi-Pecci, F., Sandage, A. R.: 1986, Mem. Soc. Astron. It. 57, 391.
Cavallo, R. M., Sweigart, A. V., Bell, R. A.: 1998, Astrophys. J. 492, 575.
Côte, P., Hanes, D. A., Mclaughlin, D. E., Bridges, T. J., Hesser, J. E., Harris, G. L. H.: 1997, Astrophys. J. 476, L15.
Cowley, A. P., Crampton, D.: 1985, Publ. Astr. Soc. Pacific 97, 835.
Freeman, K. C., Norris, J.: 1981, *Ann. Rev. Astron. Astrophys.* **19**, 319.
Gratton, R.: 1987, *Astron. Astrophys.* **177**, 177.
Gratton, R. G., Carretta, E., Eriksson, K., Gustafsson, B.: 1999, *Astron. Astrophys.* **350**, 955.
Ivans, I. I., Sneden, C., Kraft, R. P., Suntzeff, N. B., Smith, V. V., Langer, G. E., Fulbright, J.: 1999 *Astron. J.* **118**, 1273.
Kraft, R. P.: 1979, *Ann. Rev. Astron. Astrophys.* **17**, 309.
Kraft, R. P.: 1994, *Publ. Astr. Soc. Pacific* **106**, 553.
Kraft, R. P., Sneden, C., Smith, G. H., Shetrone, M. D., Langer, G. E., Pilachowski, C. A.: 1997, *Astron. J.* **113**, 279.
Langer, G. E., Hoffman, R.: 1995, *Publ. Astr. Soc. Pacific* **107**, 1777.
Langer, G. E., Hoffman, R., Sneden, C.: 1993, *Publ. Astr. Soc. Pacific* **105**, 301.
Langer, G. E., Hoffman, R., Zaidins, C.: 1997, *Publ. Astr. Soc. Pacific* **109**, 244.
Langer, G. E., Suntzeff, N. B., Kraft, R. P.: 1992 *Publ. Astr. Soc. Pacific* **104**, 523.
Lee, Y. -W., Demarque, P., Zinn, R.: 1994, *Astrophys. J.* **423**, 248.
McClure, R. D., Norris, J.: 1977, *Astrophys. J.* **217**, L101.

Minniti, D., Peterson, R. C., Geisler, D., Claria, J.: 1996, *Astrophys. J.* **470**, 953
Norris, J.: 1981, *Astrophys. J.* **248**, 177.
Norris, J., Cottrell, P. L., Freeman, K. C., da Costa, G. S.: 1981, *Astrophys. J.* **244**, 205.
Norris, J. E., Da Costa, G. S.: 1995, *Astrophys. J.* **447**, 680.
Pilachowski, C. A., Sneden, C., Kraft, R. P.: 1996a, *Astron. J.* **111**, 1689.
Pilachowski, C. A., Sneden, C., Kraft, R. P., Langer, G. E.: 1996b, *Astron. J.* **112**, 545.
Powell, D. C.: 1999, *Publ. Astr. Soc. Pacific* **111**, 1186.
Shetrone, M. D. 1998, in *Fundamental Stellar Properties: The Interaction between Observation and Theory*, IAU Symp. 189, T. R. Bedding ed., School of Physics: Univ. of Sydney, p. 158
Shetrone, M. D. 1996, *Astron. J.* **112**, 2639.
Smith, G. H.: 1987, *Publ. Astr. Soc. Pacific* **99**, 67.
Smith, G. H., Norris, J. E.: 1993, *Astron. J.* **105**, 173.
Sneden, C.: 1998, in *Galaxy Evolution: Connecting the Distant Universe with the Local Fossil Record*, M. Spite ed., Kluwer Academic Publ., in press.
Sneden, C.: 1999, in *35th Liege International Astrophysics Colloquium: The Galactic Halo, from Globular Clusters to Field Stars*, P. Magain, A. Noels eds., in press.
Suntzeff, N. B.: 1981 *Astrophys. J. Suppl.* **47**, 1.
Suntzeff, N. B. 1993, in *The Globular Cluster-Galaxy Connection*, G. H. Smith and J. B. Brodie eds., ASP Conf. Ser. 48, p. 167.
Suntzeff, N. B., Smith, V. V.: 1991 *Astrophys. J.* **381**, 160.
Sweigart, A. V.: 1997a, *Astrophys. J.* **474**, L23.
Sweigart, A. V. 1997b, in *Third Conference on Faint Blue Stars*, A.G.D. Philip, J. W. Liebert and R.A. Safford eds., L. Davis Press, Schenectady, p. 3.
Vanture, A. D., Wallerstein, G.: 1992, *Publ. Astr. Soc. Pacific* **104**, 888.