Carnegie Observatories Astrophysics Series, Vol. 4:
Origin and Evolution of the Elements, 2004
ed. A. McWilliam and M. Rauch (Pasadena: Carnegie Observatories,
http://www.ociw.edu/ociw/symposia/series/symposium4/proceedings.html)

Abundances in LMC and SMC Globular Clusters

J. A. JOHNSON[1,2], M. BOLTE[3], J. E. HESSER[2], I. I. IVANS[4], and P. B. STETSON[2]
(1) Carnegie Observatories, Pasadena, CA, USA
(2) DAO/HIA/NRC, Victoria, BC, Canada
(3) UCO/Lick Obs., Santa Cruz, CA, USA
(4) California Institute of Technology, Pasadena, CA, USA

Abstract

We present abundances for four old LMC and SMC clusters based on high-resolution spectra of 2-3 red giants per cluster taken with the Magellan telescope. We find that in the two clusters close to the LMC bar, NGC 1898 and NGC 2019, the [Si/Fe] ratio is enhanced by $\sim$0.5 dex relative to solar, while [Ca/Fe] and [Ti/Fe] are between 0 and 0.2 dex, similar to what is seen in the inner halo Milky Way clusters. In contrast, [Ca/Fe] is 0.3 dex in the outer LMC cluster Hodge 11 and and the SMC cluster NGC 121, which is the canonical value for the old outer halo Milky Way clusters. The [Fe/H]'s found are in good agreement with those previously derived from the slopes of the red giant branches. This confirms that the inner LMC clusters systematically have horizontal branches which are too blue for their metallicities, and therefore the LMC has a second parameter problem similar to the Milky Way.

1.1 Introduction

The advent of large telescopes in the southern hemisphere have opened up more distant objects for observation. We can now study the abundances of many elements in red giants in Magellanic Cloud (MC) globular clusters in the same way that abundances in Galactic globular clusters (GGCs) have traditionally been studied. The oldest MC clusters, the ones discussed here, are interesting because they are the closest analogues to the GGCs. Recently we observed red giants in 6 old MC clusters with the MIKE (Bernstein et al. 2002) spectrograph on the Magellan telescope at Las Campanas. Our goal is to determine whether the abundance patterns in these clusters resemble those seen in the GGCs. Many of the well-studied, relatively nearby GGCs have [Ca/Fe]$\sim$0.3 dex. This has been interpreted the result of pollution by Type II SNe only, since they overproduce Ca relative to Fe compared with the solar ratios (Tinsley 1979; Carney 1996). This conclusion was reinforced when Brown, Wallerstein, & Zucker (1997) found that [Ca/Fe]$\sim$0 in two clusters, Rup 106 and Pal 12, that were 2-3 Gyr younger than the bulk of the GGCs. (Buonanno et al. 1990; Stetson et al. 1989). Presumably these clusters formed late enough to have Type Ia SNe pollute their gas with additional Fe. The situation with respect to other α elements, in particular Si and Ti, is more confusing. Lee & Carney (2002) found that [Si/Fe] in GGCs decreased as distance from the Galactic center increased, while the opposite was true of [Ti/Fe]. [Ca/Fe] alone did not have a noticeable slope as a function of R_{GC}. They suggest that perhaps the high [Si/Ti] ratios found in clusters in the inner Galaxy are due to a higher proportion of high-mass Type

II SNe contributing to the pollution of the interstellar medium in those regions. Ivans et al.'s (1999, 2001) study of a large number of giants in the GGCs M4 and M5 showed interesting differences in their abundance patterns from cluster to cluster. M4 had high [Si/Fe]=0.57, while M5 had [Si/Fe]=0.36. M4 has high [La/Eu], while M5's is again lower and much closer to the predicted value for the r-process. This leads to the questions of whether M4 has some s-processed material added before the stars formed, which raised its La abundance, and whether this related to differences in [Si/Fe].

The MCs provide an ideal laboratory for testing these explanations for the abundance patterns in the GGCs and detecting any environmental dependence on abundance ratios. The MC globular clusters are also worthy of study when trying to understand the formation of the Milky Way (MW) halo, since the MC clouds have been proposed as examples of the kind of dwarf galaxy that was accreted by the MW and helped form its halo (Zinn 1980, 1993). The LMC has $\sim$ 10 clusters which span a wide range of distances from the central bar. These clusters were studied by the *Hubble Space Telescope* by Olsen et al. (1998) (O98) and Johnson et al. (1999) who found that they had ages similar to the old GGCs such as M3, M5 and M92. The SMC, on the other hand, has only one cluster that is considered to be similar to the GGCs, NGC 121. Mighell, Sarajedini, & French (1998), also using *HST*, concluded it was $\sim$2-3 Gyr younger than the majority of GGCs, and so closer in age to clusters such as Rup 106 and Pal 12. We want to know the abundances of Si, Ca, Ti, La, and Eu for as many MC clusters as possible to see whether trends noted for the GGCs as a function of galactocentric distance and age hold for these clusters.

It is also important to determine the absolute [Fe/H]'s for these clusters in addition to their abundances ratios, since the age measurements of O98 and Johnson et al. 1999 rely on accurate abundances. O98 noticed that the red giant branches of some of their clusters were not as steep as they should have been if the metallicities measured by Olszewski et al. (1991) (O91) from low dispersion spectra were correct. So O98 determined new metallicities using the method of Sarajedini (1994) which relies on the slope of the red giant branch. For many of their clusters, the derived metallicity was larger than O91, by up to 0.5 dex. These new metallicities, combined with the horizontal branch (HB) morphologies they could determine from the *HST* images, revealed that the LMC had a second parameter problem with its HB morphologies similar to that seen in the MW. Lee, Demarque, & Zinn (1994) showed that the GGCs at R$<$ 8kpc tended to have bluer HBs than those with R$>$ 8kpc. The inner LMC clusters are more metal-rich than the outer LMC clusters, and so should have redder HBs, if their metallicities were the only parameter determining their appearance. Instead, O98 showed that the inner LMC clusters have similar HBs to the outer LMC clusters, so the inner cluster HBs are bluer than they should be. Since it would constrain theories for the second parameter in the MW if the LMC system had a similar trend of HB morphologies with distance, deriving [Fe/H] values and comparing them with O91 and O98 are other valuable results of our study.

1.2 Observations

We obtained spectra of red giants in six old Magellanic Cloud clusters on 27th-31st of December 2002. We chose to observe three inner ($< 4^o$ from the center) LMC clusters studied by O98, namely NGC 1898, NGC 2019, and NGC 2005. We also included two clusters further away from the LMC bar, Hodge 11 and Reticulum, so we will have some information on abundances as a function of distance. Finally, we observed giants in NGC

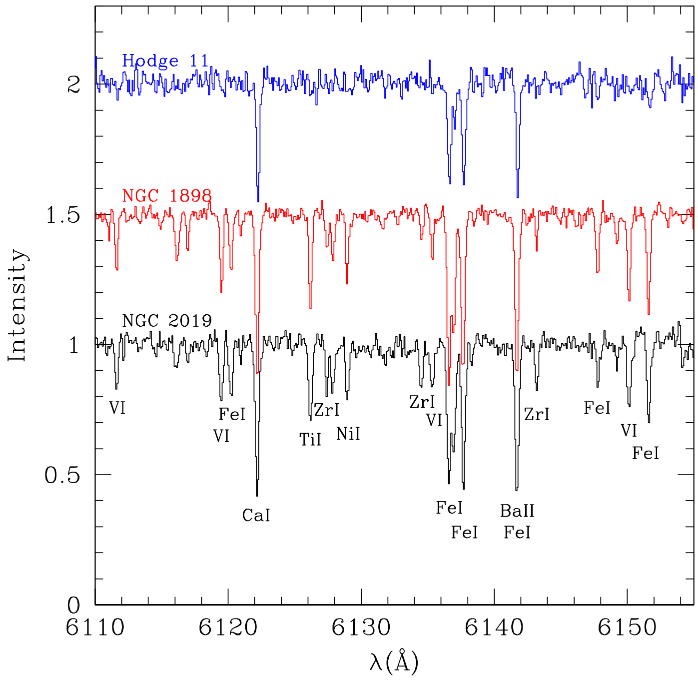

Fig. 1.1. Examples of MIKE spectra for red giants in three different clusters. These giants have similar effective temperatures so the differences in line strengths is mainly the result of metallicity differences. It is apparent that the Hodge 11 giant is the most metal-poor, while NGC 1898 and NGC 2019 giants have similar metallicities. A closer comparison of the bottom two spectra reveals that the Zr I lines in the NGC 2019 giant are stronger than those in the NGC 1898 giant. Finally, in the more metal-rich clusters, it is clear that we can measure many elements to compare in detail with GGCs.

121, the SMC cluster with a somewhat younger age. Our sample has 2 stars in NGC 1898, 3 stars in NGC 2019, 3 stars in NGC 2005, 2 stars in Hodge 11, 1 star in Reticulum and 3 stars in NGC 121. We used the new echelle spectrograph MIKE and a 1” slit, which results in R∼19,000. We exposed for a total of 1.5-3.0 hours each on targets with V∼ $16.5-17.5$. Our S/N at 6500Å was 30-50. Examples of the spectra are shown in Figure 1.1. MIKE has a red-side CCD and a blue-side CCD. The colors and the faintness of the stars in our sample limited our effective wavelength range to less than MIKE’s technical capabilities. We have useful data between 3700-7700Å. At the time of this proceeding, we have only reduced the red side data, concentrating on the lines visible between 5000Å and 7000Å. We have results for four of the six clusters at this point.

1.3 Abundances

We used Kurucz model atmospheres in our analysis. Initial estimates for the effective temperatures were derived by using color information and the calibration of Alonso,

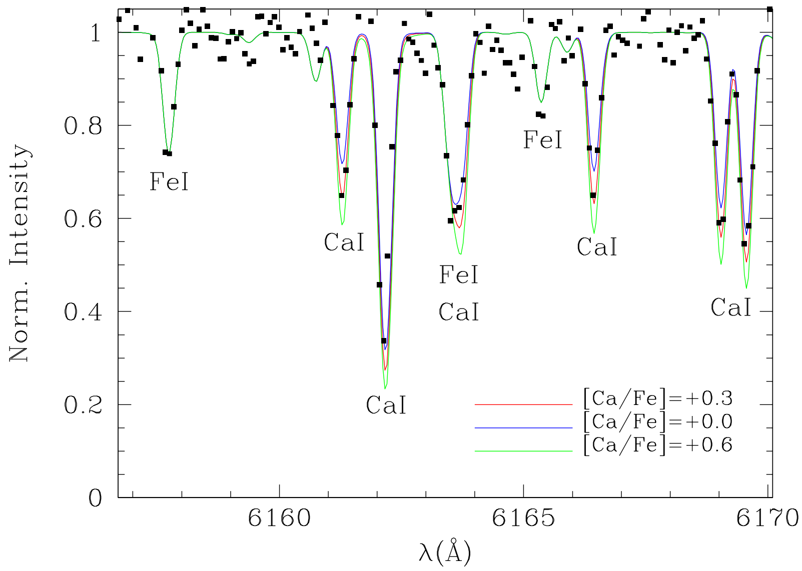

Fig. 1.2. Example of Ca in a red giant in NGC 121. While we did not use spectral synthesis to derive the Ca abundances, this plot illustrates how well we can determine it. The red line shows our best fit Ca abundances from the equivalent width analysis, while the other two lines show the Ca abundance up and down by a factor of two.

Arribas, & Martinez-Roger (1999); these were close to the adopted final temperatures, which were based on FeI lines of different excitation potentials. Gravities were calculated using FeI-FeII ionization balance, while the microturbulent velocity was calculated using FeI lines of different equivalent widths (EWs). For the present analysis, we have measured EWs for lines used in the studies of Ivans et al. (1999, 2001) for the GGCs M4 and M5 and by Shetrone, Cote, & Sargent (2001) in their study of abundances in dSphs. The gf-values were adopted from those studies as well. We include the effects of hyperfine splitting (HFS) on the abundances of La and Eu. While we only present results for Fe, Si, Ca, Ti, La, and Eu in this paper, Figure 1.1 makes it clear we can measure many other elements such as V, Ni, and Ba, at least in the more metal-rich clusters. Our abundances are listed in Table 1.1. In Figure 1.2, we have synthesized part of the spectrum of a giant in NGC 121 to illustrate how our derived abundances match the observations.

More work needs to be done to understand our absolute abundance scale relative to those for GGCs. We will examine the changes to the abundance ratios if we use MARCS models, log g's based on stellar evolution, or an FeII-based metallicity scales for example. In addition, analysis of the errors will be crucial for determining the significance of our results.

1.4 Results

Our average [Fe/H] values for Hodge 11 and NGC 1898 are close to what other authors have found. We find an average [Fe/H] of −2.27 for Hodge 11, while Cowley & Hartwick (1982) measured -2.1 ± 0.2 and O91 measured -2.06 ± 0.2, both with low-dispersion spectra. O91 measured [Fe/H]= −1.37 for NGC 1898, in excellent agreement

Table 1.1. *Preliminary Abundances for MC Globular Cluster Giants*

Star	[Fe/H]	[Ca/Fe]	[Ti/Fe]	[Si/Fe]	[La/Eu]
NGC 1898 #1	−1.30	+0.12	+0.01	+0.76	−0.16
NGC 1898 #2	−1.41	+0.09	+0.10	+0.70	−0.16
NGC 2019 #1	−1.34	+0.04	+0.10	+0.65	−0.61
NGC 2019 #2	−1.46	+0.01	−0.02	…	−0.28
NGC 2019 #3	−1.23	+0.11	+0.13	0.31	−0.55
Hodge 11 #1	−2.23	+0.50	…	…	…
Hodge 11 #2	−2.33	+0.33	…	…	…
NGC 121 #1	−1.47	+0.12	…	…	…
NGC 121 #2	−1.33	+0.37	…	…	…
NGC 121 #3	−1.44	+0.24	…	…	…

with our average value of −1.37. Our [Fe/H] value for NGC 2019 (−1.34), however, is closer to O98 (−1.23) than O91(−1.81) . This is not surprising in light of the discussion in O91 where the uncertainty in this cluster's metallicity was explicitly discussed. This confirmation of O98 abundances reinforces the conclusion that the LMC, with inner clusters that have similar HBs to outer, more metal-poor, clusters, has a second-parameter problem (Figure 1.3). For NGC 121, Da Costa & Hatzidimitriou measured [Fe/H] of -1.46 ± 0.10 on the Zinn & West (1984) scale using low resolution spectra of the Ca II triplet. We derive an average value of −1.41 based on our high-resolution data, another excellent match.

We have summarized our results for Ca and Ti in Figure 1.4. Unlike the young GGCs, Pal 12 and Rup 106, the young SMC NGC 121 has [Ca/Fe]=0.24, in good agreement with the bulk of the old GGCs. Hodge 11 also has high [Ca/Fe]. NGC 1898 and NGC 2019, which O98 found to be old clusters, both have low [Ca/Fe] and particularly low [Ti/Fe]. It is not easy to measure Si in these clusters, since the lines are weak. However, for four stars, we were able to measure an EW for one line of Si. The high Si values found, $+0.31 \leq$ [Si/Fe] $\leq +0.76$, suggests that we are witnessing the same phenomenon that Lee & Carney (2002) saw in the inner GGCs, rather than a contribution from Type Ia SNe in these old clusters.

Our MIKE data are of high enough quality that we can obtain La and Eu abundances for stars in NGC 1898 and NGC 2019. These abundances are each based on a single line, but one with a good laboratory-based gf-value and laboratory-based HFS constants (Lawler et al. 2001; Lawler, Bonvallet, & Sneden 2001). Our errors for these two abundances are not small enough to conclude that there is a difference between the clusters, but the [La/Eu] values for NGC 1898 and NGC 2019 fall among the values for the field stars from Simmerer & Sneden (2003, private communication) and probably are not as large as the average for M4 (Ivans et al. 1999).

1.5 Conclusions

We have several conclusions from the preliminary analysis of our data. First, not all young clusters in the MW halo are α-poor. This may be because NGC 121 at $\sim$ 70 kpc is more distant from the MW than Rup 106 and Pal 12 at 15 kpc, but we note that Pal 12 is thought to be a former satellite of the LMC (Lin & Richer 1992) or of Sagittarius (Martinez-

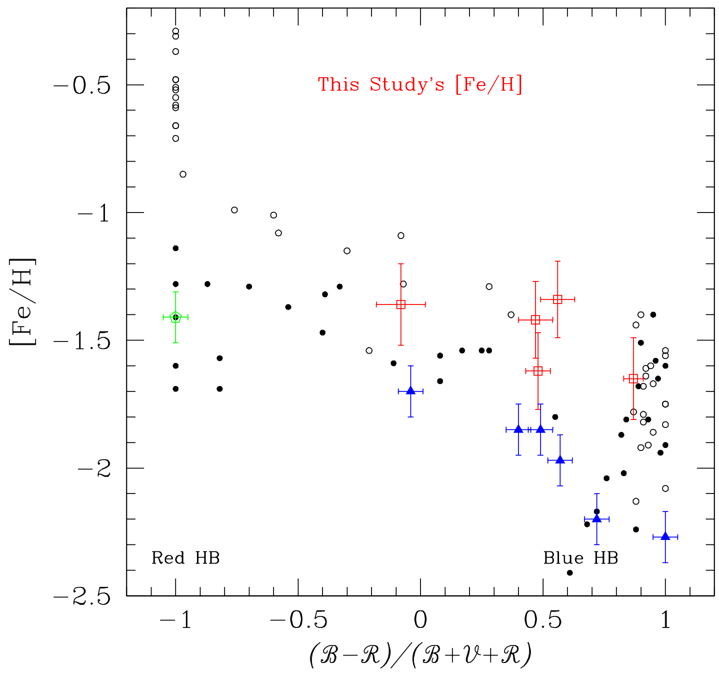

Fig. 1.3. HB morphology versus [Fe/H] for the GGCs and MC clusters. The HB morphology was defined by Lee (1989) and is the number of blue HB stars minus the number of red HB stars over the total number of stars on the horizontal branch, including variables. The data for the GGCs comes from Lee et al. (1994). The HB morphologies for the MC clusters come from Walker (1992) or O98. If we have determined new metallicities in this paper, we have used them. Otherwise, we adopt the values from Walker 1992 or O98. The open circles show the GGCs with R_{MW} <8 kpc, while the filled circles show those with R_{MW} >8 kpc. The red squares show the inner ($R_{LMC} < 4^o$) LMC clusters, and the blue triangles show those further away. The green pentagon shows the position of the SMC cluster NGC 121. The red squares fall close to the open circles, while the blue triangles fall close to the filled circles, illustrating the similarity between spatial distribution and HB morphology between the MW and the LMC. NGC 121 falls among the young clusters of the MW, such as Rup 106 and Pal 12, in this diagram.

Delgado et al. 2002). In fact, Bellazzini, Ferraro & Ibata (2003) point out that both Rup 106 and Pal 12 could have been members of the Sagittarius globular cluster system based on their phase-space distribution. If that is the case, it is not clear why the young clusters attached on one dwarf galaxy were polluted by Type Ia ejecta while NGC 121 attached to the SMC was not. The inner clusters of the LMC (NGC 1898 and NGC 2019) are very similar to the inner halo clusters in the MW in their ages, their HB morphologies, and their abundance ratios. Whatever mechanism is proposed for the high [Si/Fe] values in the MW must also work for the LMC. An open question is whether we see the same overall dependence on galactocentric distance in the LMC as in the MW. Although the outer LMC cluster Hodge

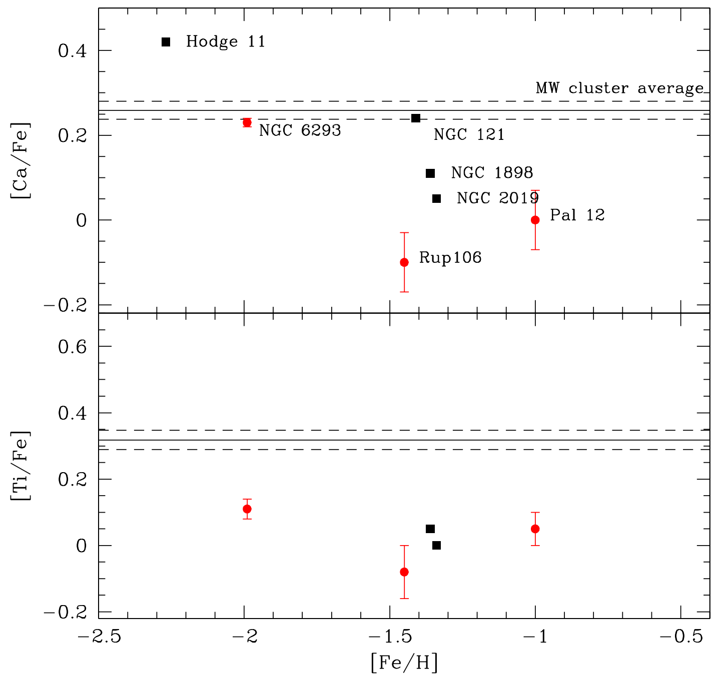

Fig. 1.4. The [Ca/Fe] and [Ti/Fe] values for the MC clusters compared with ratios in GGCs. The solid line indicates the mean value for a selection of well-studied GGCs, and the dotted lines show the standard deviation of the mean for that sample. There are several GGCs whose abundance ratios do not match the ratios of the majority of GGCs studied so far. Rup 106 and Pal are younger clusters, while NGC 6293 is representative of the three inner GGCs studied by Lee & Carney (2002). NGC 1898 and NGC 2019 have low [Ca/Fe] and [Ti/Fe] compared with "normal" GGCs, while Hodge 11 and NGC 121 both have more elevated [Ca/Fe].

11 has high [Ca/Fe], another outer cluster, NGC 2210 studied by Hill et al. (2000) has low [O/Fe], so the dependence on galactocentric distance with the α-elements may not be the same in the LMC. This discussion illustrates the fact that [α/Fe] is a simplification of the abundance patterns in globular clusters. It is preferable to measure O, Mg, Si, Ca , Ti and Fe separately.

Finally, the LMC has a second parameter problem like the MW. In their seminal paper on the MW second parameter, Searle & Zinn (1978) suggested that the second parameter was age, and that the inner, older MW clusters formed as part of the main MW, while the outer, younger clusters were accreted later from slowly forming dwarf galaxies. Such a theory is less appealing to explain the LMC, itself a dwarf galaxy. On the other hand, recent studies of the formation of MW-like galaxies suggest that the LMC could still be a prototype for MW building blocks. For example Bullock, Kravtsov, & Weinberg (2001) studied the fate of satellites accreted by the MW as it was being assembled in a cold dark matter Universe.

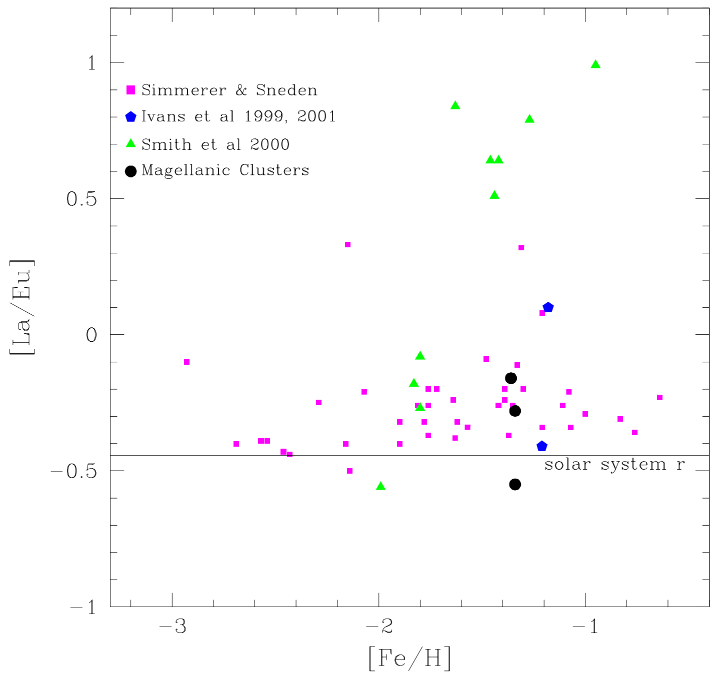

Fig. 1.5. [La/Eu] vs. [Fe/H] for the LMC clusters NGC 1898 and NGC 2019 red giants compared with the MW field stars from Simmerer & Sneden (private communication) and two well-studied GGC, M5 (Ivans et al. 2001) and M4 (Ivans et al. 1999). NGC 2019 and NGC 1898 do not have as high a [La/Eu] value as M4, and instead are in decent agreement with the field data and M5. Plotted as well are a solid line representing the predicted r-process [La/Eu] ratio from Arlandini et al. (1999) and the data for individual giants measured in ωCen by Smith et al. (2000). ωCen is a cluster that is probably self-enriched in the s-process elements by AGB stars, and is clearly distinct from the field stars and other globular clusters.

Satellites the mass of the LMC fell victim to dynamical friction. In these cases, the outer parts of the satellite would tend to remain in the outer parts of the MW, while the more tightly bound inner parts would join the inner MW. Therefore, accreting a galaxy with a globular cluster system like the LMC would still maintain the division in the HB properties seen in the MW. The Sagittarius dSph provides an example. Bellazzini et al. (2003) ascribe at least for outer halo MW clusters to the Sagittarius dSph, while it is presently adding clusters such as M54 and Arp 2 to the central regions of the MW (Da Costa & Armandroff 1995) . So accretion of dwarf galaxies may still be the explanation for the GGC system, but their contributions could include the inner MW clusters as well as the outer ones.

References

Alonso, A., Arribas, S., & Martinez-Roger, C. 1999, A&AS, 140, 261

Arlandini, C. Kappeler, F., Wisshak, K., Gallino, R., Lugaro, M., Busso, M., & Straniero, O. 1999, ApJ, 525, 886

Bellazzini, M., Ferraro, F. R., & Ibata, R. 2003, AJ, 125, 188
Bernstein, R. A., Shectman, S., Gunnels, S., Mochnacki, S., & Athey, A. 2002, Proc SPIE 481
Brown, J. A., Wallerstein, G., & Zucker, D. 1997, AJ, 114, 180
Buonanno, R., Buscema, G., Fusi Pecci, F., Richer, H. B., & Fahlman, G. G. 1990, AJ, 100, 1811
Bullock, J. S., Kravtsov, A. V., & Weinberg, D. H. 2001, ApJ, 548, 33
Carney, B. W. 1996, PASP, 108, 900
Cowley, A. P., & Hartwick, F. D. A. 1982, ApJ, 259, 89
DaCosta, G. S., & Armandroff, T. E., 1995, AJ, 109, 2533
Da Costa, G. S., & Hatzidimitriou, D. 1998, AJ, 115, 1934
Hill, V., Francois, P., Spite, M., Primas, F., & Spite, F. 2000, A&A, 364, 19
Ivans, I. I., Kraft, R. P., Sneden, C., Smith, G. H., Rich, R. M., & Shetrone, M. 2001, AJ, 122, 1438
Ivans, I. I., Sneden, C., Kraft, R. P., Suntzeff, N. G., Smith, V. V., Langer, G. E., & Fulbright, J. F. 1999, AJ, 118, 1273
Johnson, J. A., Bolte, M., Stetson, P. B., Hesser, J. E., & Somerville, R. S. 1999, ApJ, 527, 199
Lawler, J. E., Bonvallet, G., & Sneden, C. 2001, ApJ, 556, 452
Lawler, J. E., Wickliffe, M. W., Den Hartog, E. A., & Sneden, C. 2001, ApJ, 563, 1075
Lee, J.-W., & Carney, B. W. 2002, AJ, 124, 1511
Lee, Y.-W., Ph.D. thesis, Yale University
Lee, Y.-W., Demarque, P., & Zinn, R. 1994, ApJ, 423, 248
Lin, D. N. C., & Richer, H. B. 1992, ApJ, 388, L57
Martinez-Delgado, D., Zinn, R., Carrera, R., & Gallart, C. 2002, ApJ, 573, L19
Mighell, K. J., Sarajedini, A., & French, R. S. 1998, AJ, 116, 2395
Olsen, K. A. G., Hodge, P. W., Mateo, M., Olszewski, E. W., Schommer, R. A., Suntzeff, N. B., & Walker, A. R. 1998, MNRAS, 300, 665
Olszewski, E. W., Schommer, R. A., Suntzeff, N. B., & Harris, H. C. 1991, AJ, 101, 515
Sarajedini, A. 1994, AJ, 107, 618
Searle, L., & Zinn, R. J. 1978, ApJ, 225, 357
Shetrone, M. D., Cote, P., & Sargent, W. L. W. 2001, ApJ, 548, 592
Smith, V. V., Suntzeff, N. B., Cunha, K., Gallino, R., Busso, M., Lambert, D. L., & Straniero, O., 2000 AJ, 119, 1239
Stetson, P. B., VandenBerg, D. A., Bolte, M., Hesser, J. E., & Smith, G. H. 1989, AJ, 97, 1360
Tinsley, B. M. 1979, ApJ, 229, 1046
Walker, A. R. 1992, AJ, 104, 1395
Zinn, R. 1980, ApJ, 241, 602
Zinn, R. 1993, in ASP Conf. Proc. 48, The Globular Cluster-Galaxy Connection, ed. G. H. Smith & J. P. Brodie (San Francisco: ASP) 302
Zinn, R., & West, M. J. 1984, ApJS, 55, 45