Variations in the Na-O anticorrelation in globular clusters: Evidence for a deep mixing episode in red giant branch stars

Jae-Woo Lee1⋆

1Department of Astronomy and Space Science, ARCSEC, Sejong University, Seoul 143-747, Korea

Submitted 12 January 2010

ABSTRACT

The Na-O anticorrelation seen in almost all globular clusters ever studied using high-resolution spectroscopy is now generally explained by the primordial pollution from the first generation of the intermediate-mass asymptotic giant branch stars to the proto-stellar clouds of the second generation of stars. However, the primordial pollution scenario may not tell the whole story for the observed Na-O anticorrelations in globular clusters. Using the recent data by Carretta and his collaborators, the different shapes of the Na-O anticorrelations for red giant branch stars brighter than and fainter than the red giant branch bump can be clearly seen. If the elemental abundance measurements by Carretta and his collaborators are not greatly in error, this variation in the Na-O anticorrelation against luminosity indicates an internal deep mixing episode during the ascent of the low-mass red giant branch in globular clusters. Our result implies that the multiple stellar population division scheme solely based on $[O/Fe]$ and $[Na/Fe]$ ratios of a globular cluster, which is becoming popular, is not reliable for stars brighter than the red giant branch bump. Our result also suggests that sodium supplied by the deep mixing may alleviate the sodium under-production problem within the primordial asymptotic giant branch pollution scenario.

Key words: globular clusters: general – stars: abundances – stars: atmospheres

1 INTRODUCTION

Variations in lighter elements, including oxygen and sodium, in globular cluster (GC) red giant branch (RGB) stars have been known for more than three decades, pioneered by Cohen (1978) and extensively studied by Lick-Texas group (see for example, Sneden et al. 1997). It is very clear that anticorrelations between oxygen and sodium abundances persist in almost all GCs ever studied using high-resolution spectroscopy (Carretta et al. 2009).

The physical processes involved in the Na-O anticorrelation appear to be certain; oxygen is depleted by the CNO cycle while sodium is enriched from the $^{22}\text{Ne}(p, \gamma)^{23}\text{Na}$ reaction in the hydrogen-burning shells of evolved stars. The key issue has been the origin of this Na-O anticorrelation and two viable scenarios has been debated: the evolutionary and the primordial scenarios (see Kraft 1994).

The evolutionary scenario is that a non canonical deep mixing in low-mass stars during their ascent of RGB phase can supply freshly synthesized nuclides to their photospheres (Langer et al. 1993). The annoying trouble with the deep mixing scenario is that Na-O anticorrelations does not appear to exist in field halo stars with comparable metallicities to GCs.

The primordial scenario requires at least two generations of star formation history in GCs. Chemical pollution from the first generation intermediate-mass asymptotic giant branch (AGB) stars (Ventura et al. 2001) or the fast rotating massive stars (Decressin et al. 2007) to the proto-stellar clouds of the second generation of stars can produce the observed anticorrelations. Although both the evolutionary and the primordial scenarios are required to fully explain the detailed elemental abundance variations seen in GC stars, consensus is in favor of the AGB pollution scenario due to the presence of the Na-O anticorrelation in main sequence and subgiant branch stars in GCs (Gratton et al. 2001), where the deep mixing can not be developed. However, it should be noted that the AGB pollution scenario also has a drawback that the amount of sodium synthesized in AGB stars is not enough to explain the observed Na-O anticorrelations, partly due to the uncertain cross-section of the $^{22}\text{Na}(p, \alpha)^{21}\text{Ne}$ reaction rate, which can destruct sodium in the later stage of AGB stars (Ventura & D’Antona 2006). To explain the observed Na-O

⋆ E-mail:jaewoolee@sejong.ac.kr
Table 1. Slopes in $[\text{Fe}/\text{H}]_I$ and $[\text{Fe}/\text{H}]_{II}$ versus $K$ mag.

| Name     | $\langle[\text{Fe}/\text{H}]_I\rangle$ | $\langle[\text{Fe}/\text{H}]_{II}\rangle$ | $[\text{Fe}/\text{H}]_{I}$ | $[\text{Fe}/\text{H}]_{II}$ |
|----------|-----------------------------------------|------------------------------------------|-----------------------------|-----------------------------|
| Metal-poor GCs |                                             |                                           |                             |                             |
| N6409    | $-1.97$                                  | $-1.93$                                  | $0.010$                     | $0.003$                     |
| N6397    | $-1.99$                                  | $-1.98$                                  | $0.003$                     | $0.002$                     |
| N4590    | $-2.23$                                  | $-1.85$                                  | $0.010$                     | $0.004$                     |
| N7078    | $-2.34$                                  | $-2.35$                                  | $-0.001$                    | $0.002$                     |
| N7095    | $-2.35$                                  | $-2.29$                                  | $-0.002$                    | $0.003$                     |
| Intermediate metallicity GCs |                                           |                                           |                             |                             |
| N6171    | $-1.06$                                  | $-1.05$                                  | $0.009$                     | $0.008$                     |
| N2608    | $-1.10$                                  | $-1.16$                                  | $-0.013$                    | $0.010$                     |
| N6121    | $-1.20$                                  | $-1.20$                                  | $-0.002$                    | $0.002$                     |
| N2828    | $-1.22$                                  | $-1.23$                                  | $0.007$                     | $0.003$                     |
| N6219    | $-1.31$                                  | $-1.35$                                  | $0.010$                     | $0.003$                     |
| N5694    | $-1.35$                                  | $-1.35$                                  | $0.000$                     | $0.001$                     |
| N3201    | $-1.49$                                  | $-1.40$                                  | $0.008$                     | $0.004$                     |
| N1994    | $-1.54$                                  | $-1.48$                                  | $-0.001$                    | $0.003$                     |
| N6254    | $-1.56$                                  | $-1.56$                                  | $0.020$                     | $0.004$                     |
| N6772    | $-1.56$                                  | $-1.48$                                  | $0.011$                     | $0.004$                     |
| Metal-rich GCs |                                             |                                           |                             |                             |
| N6441    | $-0.33$                                  | $-0.29$                                  | $0.091$                     | $0.051$                     |
| N6388    | $-0.31$                                  | $-0.35$                                  | $0.015$                     | $0.011$                     |
| N1010    | $-0.74$                                  | $-0.77$                                  | $0.001$                     | $0.001$                     |
| N6838    | $-0.81$                                  | $-0.80$                                  | $-0.003$                    | $0.008$                     |

Figure 1. A comparison of $[\text{Fe}/\text{H}]_I$ and $[\text{Fe}/\text{H}]_{II}$ against $K$ mag for RGB stars in NGC 4590 (Carretta et al. 2009). The slope in $[\text{Fe}/\text{H}]_{II}$ versus $K$ may imply that the surface gravities adopted by Carretta et al. are systematically in error.

anticorrelations in GCs within the AGB pollution scenario, either an ad-hoc assumption of a lowering $^{23}\text{Na}(p, \alpha)^{23}\text{Ne}$ reaction rate (Ventura & D’Antona 2006) or a fine tuning of the AGB mass spectrum (Ventura & D’Antona 2008) are required.

Recently, Carretta and his collaborators (Carretta et al. 2004, 2007; Gratton et al. 2007) provided a spectroscopic study for an unprecedented sample of RGB stars in 19 GCs, collected in a homogeneous way. Their work confirmed that the Na-O anticorrelations exist in all 19 GCs. Furthermore, they devised a scheme to distinguish multiple stellar populations by using $[\text{O}/\text{Fe}]$ and $[\text{Na}/\text{Fe}]$ ratios on the assumption that the primordial AGB pollution is entirely responsible for the observed Na-O anticorrelations in GCs.

In this Letter, using data provided by Carretta and his collaborators, we show that different Na-O anticorrelations in GCs can be clearly seen for RGB stars brighter than and fainter than the RGB bump. It is believed that this variation in the Na-O anticorrelations against luminosity is a strong evidence of the deep mixing episode during their ascent of RGB phase of low-mass stars, if the elemental abundance measurements by Carretta and his collaborators are not greatly in error. Therefore, the primordial AGB pollution scenario may not tell the whole story for the observed Na-O anticorrelations in GCs and the evolutionary deep mixing scenario should be resurrected.

2 NEW INTERPRETATION OF THE SODIUM-OXYGEN ANTICORRELATION

2.1 Slopes in the plots of $[\text{Fe}/\text{H}]_{II}$ versus $K$

The widely used local-thermodynamic equilibrium (LTE) analysis depends on appropriate stellar atmosphere model grids and input parameters, such as effective temperature, surface gravity and turbulent velocity. The derivation of stellar elemental abundances is not a trivial task even for nearby bright stars. The recent study of Baines et al. (2004) may highlight the current situation. They showed that the interferometric effective temperatures for nearby K giant stars do not agree with those from spectroscopic observations, suggesting a missing source of opacities in stellar atmosphere models. The situation would be even worse for fainter stars, such as those in GCs.

The recent studies by Carretta and his collaborators (Carretta et al. 2004, 2007; Gratton et al. 2007) provide $[\text{O}/\text{Fe}]$ and $[\text{Na}/\text{Fe}]$ ratios of RGB stars in 19 GCs, collected and analyzed in a homogeneous way. Their oxygen abundances were based on the forbidden lines of neutral oxygen at 6300.3 and 6363.8 ˚mag. However, line departures from the LTE can not explain this slope either, since $\text{Fe I}$ lines are more vulnerable to be affected than $\text{Fe II}$ lines are.

We examined the iron abundances of Carretta et al. (2004, and references therein) to see if their $[\text{Fe}/\text{H}]_{II}$ ratios are consistent with $[\text{Fe}/\text{H}]_I$ ratios, which will validate their $[\text{O}/\text{Fe}]$ measurements based on $\text{Fe I}$. We found a surprising discrepancy between $[\text{Fe}/\text{H}]_I$ and $[\text{Fe}/\text{H}]_{II}$ for many GCs. Figure 1 shows distributions of $[\text{Fe}/\text{H}]_I$ and $[\text{Fe}/\text{H}]_{II}$ against $K$ mag for RGB stars in NGC 4590, as an extreme example. The figure clearly shows that the iron abundance derived from $\text{Fe II}$ lines has a substantial slope against $K$ mag, where $K$ mag of RGB stars in a GC is related to the effective temperature and surface gravity (i.e. a bright RGB star has lower effective temperature and lower surface gravity; see for example Lee et al. 2004). In Table 1 we show the slopes in $[\text{Fe}/\text{H}]_I$ and $[\text{Fe}/\text{H}]_{II}$ against $K$ mag for 19 GCs studied by Carretta et al. (2004), assuming following relations,

$$[\text{Fe}/\text{H}]_I = a_I \times K + b_I,$$

1 Since NGC 4590 is very metal-poor ($[\text{Fe}/\text{H}]_I = -2.24$, see Table 1), $\text{Fe II}$ absorption lines would be very weak. However, line absorption measurement errors can not produce such a slope seen in Figure 1 unless their $\text{Fe II}$ line measurements are systematically in error with luminosity (i.e. S/N ratios of data). The departure from the LTE can not explain this slope either, since $\text{Fe II}$ lines are more vulnerable to be affected than $\text{Fe I}$ lines are. Note that, in terms of $[\text{Fe}/\text{H}]_I$, NGC 4590 is not monometallic, but has a metallicity spread of $> 1$ dex.
[O/Fe] and [Na/Fe] ratios may not be affected by potential
differences for 6 GCs in common and we obtained the magnitude
of $\Delta K_{\text{bump}}$ as $0.00 \pm 0.1$ mag for the faint RGB group
and $0.12 \pm 0.02$ mag for the bright RGB group. The difference
in [O/Fe] and [Na/Fe] ratios between the bRGB and the fRGB
groups persist for most GCs, in particular for those with sufficient number
of stars in each subgroup ($n \geq 10$). The differences in $\langle [\text{O/Fe}] \rangle$ and $\langle [\text{Na/Fe}] \rangle$ between the bRGB and the fRGB
groups for above mentioned 8 GCs are at $2.71 \pm 0.4$ mag.
Therefore, it is expected that Na-O anticorrelations between the bRGB
and the fRGB are different. In addition to differences in $\langle [\text{O/Fe}] \rangle$ and $\langle [\text{Na/Fe}] \rangle$, the scatters in the bRGB group
are slightly larger than those in the fRGB group, which makes
sense if the internal deep mixing is partly responsible for the
Na-O anticorrelation in the bRGB group. If the measurement
errors were responsible for these scatters, an opposite
would be expected.

In Figure 3, we show plots of $[\text{O/Fe}]$ versus $[\text{Na/Fe}]$ for

$$[\text{Fe/H}]_{\text{II}} = a_{\text{II}} \times K + b_{\text{II}}.$$ 

We also examined the variations in $[\text{Fe/H}]_{\text{I}}$ and $[\text{Fe/H}]_{\text{II}}$
against effective temperatures of RGB stars in individual GCs. Substantial slopes in the plots of $[\text{Fe/H}]_{\text{II}}$ versus effective
temperature can be seen in many GCs, in sharp contrast to what
Carretta et al. (2009) claimed (see their Figure 5).

It is beyond the scope of our work to explain such discrepancy
between $[\text{Fe/H}]_{\text{I}}$ and $[\text{Fe/H}]_{\text{II}}$ in Carretta et al.
(2009). However, as a first approximation, the gradient in
$[\text{Fe/H}]_{\text{II}}$ with respect to $[\text{Fe/H}]_{\text{I}}$ may indicate that their
adopted surface gravities are systematically in error. For
example, surface gravities of RGB stars in NGC 4590 could
be systematically larger with increasing $K$ mag. The modification
of surface gravity also tends to affect other input parameters,
such as effective temperature and turbulent velocity. Therefore, the results presented by Carretta et al. (2009) may not be as accurate as they claimed with apparently very small measurement errors. Furthermore, their final results may not be as homogeneous as they claimed, since the discrepancy between $[\text{Fe/H}]_{\text{I}}$ and $[\text{Fe/H}]_{\text{II}}$ varies one cluster to the other and the break in the slope between
$[\text{Fe/H}]_{\text{II}}$ versus $K$ mag or effective temperature can be seen in some GCs. We note that if this discrepancy is entirely due to incorrect surface gravity and other parameters adopted by Carretta et al. (2009), their derivations of other elemental abundances, such as oxygen and sodium, may not be reliable. Also importantly, if the limited number of available Fe II lines is responsible for this discrepancy (see Carretta et al. 2009), their $[\text{O/Fe}]$ and $[\text{Na/Fe}]$ ratios would be in the same situation since only few lines are available for both elements. We await their careful re-analysis of their data with keen interest.

2.2 Variations in the Na-O anticorrelation against luminosity

As we mentioned above, Carretta et al. 2004 derived
$[\text{O/Fe}]$ ratios based on Fe I and a substantial slope in the
$[\text{Fe/H}]_{\text{II}}$ versus $K$ mag may imply that their $[\text{O/Fe}]$ ratios
could be in error. In Table 1, eight GCs (NGC 6838, NGC 6121,
NGC 288, NGC 6218, NGC 5904, NGC 3201, NGC 6809 and NGC 7078) have negligibly small gradients in their
$[\text{Fe/H}]_{\text{II}}$ and $[\text{Fe/H}]_{\text{I}}$ versus $K$ mag. Therefore, it is expected that potential systematic errors in surface gravity adopted by Carretta et al. (2009) do not significantly affect differential $[\text{O/Fe}]$ ratios against $K$ mag in these GCs.

In Figure 2 we show oxygen and sodium distributions
against $K - K_{\text{bump}}$ for RGB stars in NGC 3201 and NGC 6218.
As shown in the figure, differences in $[\text{O/Fe}]$ and $[\text{Na/Fe}]$ distributions between the upper RGB and the lower
RGB stars are notable. The mean $[\text{O/Fe}]$ ratio for the lower
RGB stars is larger than that for upper RGB stars in NGC 3201 and NGC 6218, while the mean $[\text{Na/Fe}]$ ratio for the lower RGB stars is smaller than that for upper RGB stars. If the results by Carretta et al. (2009) are not greatly in error, are these variations in $[\text{O/Fe}]$ and $[\text{Na/Fe}]$ ratios between the lower and the upper RGB stars a signature of the internal deep mixing episode, so that oxygen is depleted by the CNO cycle while sodium is enriched from the $^{22}\text{Ne}(p, \gamma)^{23}\text{Na}$ reaction in upper RGB stars of NGC 3201 and NGC 6218?

Table 2 summarizes the mean $[\text{O/Fe}]$ and $[\text{Na/Fe}]$ for

$$[\text{Fe/H}]_{\text{II}} = a_{\text{II}} \times K + b_{\text{II}}.$$ 

We also examined the variations in $[\text{Fe/H}]_{\text{I}}$ and $[\text{Fe/H}]_{\text{II}}$
against effective temperatures of RGB stars in individual GCs. Substantial slopes in the plots of $[\text{Fe/H}]_{\text{II}}$ versus effective
temperature can be seen in many GCs, in sharp contrast to what
Carretta et al. (2009) claimed (see their Figure 5).

It is beyond the scope of our work to explain such discrepancy between $[\text{Fe/H}]_{\text{I}}$ and $[\text{Fe/H}]_{\text{II}}$ in Carretta et al.
(2009). However, as a first approximation, the gradient in
$[\text{Fe/H}]_{\text{II}}$ with respect to $[\text{Fe/H}]_{\text{I}}$ may indicate that their
adopted surface gravities are systematically in error. For
example, surface gravities of RGB stars in NGC 4590 could
be systematically larger with increasing $K$ mag. The modification
of surface gravity also tends to affect other input parameters,
such as effective temperature and turbulent velocity. Therefore, the results presented by Carretta et al. (2009) may not be as accurate as they claimed with apparently very small measurement errors. Furthermore, their final results may not be as homogeneous as they claimed, since the discrepancy between $[\text{Fe/H}]_{\text{I}}$ and $[\text{Fe/H}]_{\text{II}}$ varies one cluster to the other and the break in the slope between
$[\text{Fe/H}]_{\text{II}}$ versus $K$ mag or effective temperature can be seen in some GCs. We note that if this discrepancy is entirely due to incorrect surface gravity and other parameters adopted by Carretta et al. (2009), their derivations of other elemental abundances, such as oxygen and sodium, may not be reliable. Also importantly, if the limited number of available Fe II lines is responsible for this discrepancy (see Carretta et al. 2009), their $[\text{O/Fe}]$ and $[\text{Na/Fe}]$ ratios would be in the same situation since only few lines are available for both elements. We await their careful re-analysis of their data with keen interest.
Jae-Woo Lee

Figure 3. (a – b) A comparison of Na-O anticorrelations between the bRGB \((K - K_{\text{bump}} < -0.1 \text{ mag})\) and the fRGB \((K - K_{\text{bump}} \geq -0.1 \text{ mag})\) groups in 19 GCs. (c – d) As (a – b) but for eight GCs (NGC 6838, NGC 6121, NGC 288, NGC 6218, NGC 5904, NGC 3201, NGC 6809 and NGC 7078) with negligibly small gradients in \([\text{Fe/H}]_1\) versus \(K\) mag. Lack of RGB stars with small \([\text{O/Fe}]\) and large \([\text{Na/Fe}]\) ratios in the fRGB group is notable. This can not be explained by the chemical pollution from the first generation AGB stars in GCs.

Figure 4. (a & b) Cumulative \([\text{O/Fe}]\) and \([\text{Na/Fe}]\) distributions for the bRGB (solid red lines, 583 stars) and the fRGB (dashed blue lines, 370 stars) groups in 19 GCs. The probabilities of being drawn from identical parent populations are 0.00% for both \([\text{O/Fe}]\) and \([\text{Na/Fe}]\), indicating that the bRGB and the fRGB groups have different parent populations. (c) Cumulative \([\text{Na/Fe}]\) distributions for all available stars in bRGB (799 stars) and fRGB (688 stars) groups. (d & e) As (a & b) but for the bRGB (272 stars) and the fRGB (201 stars) groups in 8 GCs. The probabilities of being drawn from identical parent populations are also 0.00% for both \([\text{O/Fe}]\) and \([\text{Na/Fe}]\). (f) As (c) but for the bRGB (377 stars) and the fRGB (319 stars) groups in 8 GCs.

occurred in bRGB stars is responsible for different Na-O anticorrelations seen in the bRGB and the fRGB groups.

3 SUMMARY

We have shown that there exist variations in the Na-O anticorrelation against the luminosity of RGB stars in GCs. These variations can not be explained by chemical pollution from the first generation intermediate-mass AGB stars in GCs and are most probably due to the internal deep mixing during the ascent of RGB phase, unless oxygen and sodium abundance measurements by Carretta et al. (2009) are not greatly in error.

If the internal deep mixing can supply freshly synthesized sodium, via the \(^{22}\text{Ne}(p, \gamma)^{23}\text{Na}\) reaction, to the photospheres of low-mass RGB stars in these GCs, the trouble with the intermediate-mass AGB pollution scenario, which requires more sodium production rate, can be alleviated. However, the absence of the Na-O anticorrelation in the field halo stars is still an open question.

Although, ejecta from the first generation of the intermediate-mass AGB stars can significantly change primordial oxygen and sodium abundances of the second generation of stars in GCs, the multiple stellar population division scheme devised by Carretta et al. (2009), which is solely based on \([\text{O/Fe}]\) and \([\text{Na/Fe}]\) ratios of individual GCs, is not correct for bright RGB stars. It is because when the internal deep mixing in low-mass RGB stars in GCs is involved, one needs to disentangle the internal deep mixing effect from the primordial intermediate-mass AGB contribution to the
Variations in the Na-O anticorrelation

Table 2. Comparisons of $\langle [O/Fe] \rangle$ and $\langle [Na/Fe] \rangle$ between bRGB and fRGB.

| Name   | $K_{\text{bump}}$ | bRGB | fRGB | bRGB | fRGB |
|--------|-------------------|------|------|------|------|
|        |                   | $\langle [O/Fe] \rangle$ | $\sigma [O/Fe]$ | $\langle [Na/Fe] \rangle$ | $\sigma [Na/Fe]$ |
|        |                   | n    |      | n    |      |
|        |                   |      |      |      |      |
| Metal-rich GCs |                   |      |      |      |      |
| N6441  | 14.51             | 21   | 0.041| 0.168| 0.072|
| N6388  | 14.15             | 25   | -0.009| 0.255| 0.209|
| N0104  | 12.03             | 83   | 0.139| 0.186| 0.131|
| N6838  | 11.82             | 15   | 0.305| 0.108| 0.400|
|         |                   |      |      |      |      |
| Intermediate metallicity GCs |                   |      |      |      |      |
| N6171  | 12.63             | 3    | 0.169| 0.129| 0.198|
| N2608  | 13.37             | 83   | 0.041| 0.394| 0.072|
| N6121  | 10.13             | 35   | 0.193| 0.116| 0.259|
| N6288  | 13.16             | 24   | 0.075| 0.301| 0.072|
| N6218  | 11.78             | 24   | 0.150| 0.226| 0.353|
| N5904  | 12.57             | 68   | 0.131| 0.306| 0.219|
| N3120  | 11.80             | 28   | -0.036| 0.340| 0.211|
| N1904  | 13.74             | 21   | 0.016| 0.231| 0.136|
| N6254  | 11.39             | 24   | 0.133| 0.285| 0.295|
| N6752  | 11.15             | 37   | 0.218| 0.283| 0.287|
|         |                   |      |      |      |      |
| Metal-poor GCs |                   |      |      |      |      |
| N6809  | 11.61             | 52   | 0.202| 0.212| 0.360|
| N6397  | 9.73              | 3    | 0.252| 0.118| 0.236|
| N4590  | 12.87             | 18   | 0.280| 0.185| 0.480|
| N7078  | 12.86             | 21   | 0.188| 0.180| 0.422|
| N7099  | 12.40             | 8    | 0.027| 0.291| 0.454|
|         |                   |      |      |      |      |
| Mean   |                   | 0.134| 0.022| 0.283| 0.153|
|        |                   | ±0.026| ±0.026| ±0.017| ±0.017|
| Mean²  |                   | 0.160| 0.231| 0.299| 0.173|
|        |                   | ±0.031| ±0.030| ±0.019| ±0.019|
| Mean³  |                   | 0.129| 0.240| 0.285| 0.188|
|        |                   | ±0.032| ±0.030| ±0.033| ±0.031|

17 GCs (without NGC 6441 and NGC 2808)
12 GCs (without NGC 6441, NGC 6388, NGC 104, NGC 6171, NGC 2688, NGC 6397 and NGC 7099)
8 GCs (NGC 6838, NGC 6121, NGC 2688, NGC 5904, NGC 3201, NGC 6809 and NGC 7078)

observed Na-O anticorrelations in GCs. An alternative approach by using additional photometric information, such as the $hk$ index which is known to be not affected by the variations in lighter elemental abundances, is more appropriate to distinguish the multiple stellar populations in GCs, as Lee et al. (2002) have discussed in detail.

ACKNOWLEDGMENTS
This work was supported by the faculty research fund of Sejong University in 2008. Support for this work was also provided by the National Research Foundation of Korea to the Astrophysical Research Center for the Structure and Evolution of the Cosmos (ARCSEC).

REFERENCES
Baines E.K. et al., 2009, arXiv:0912.5491v1
Carretta E., Bragaglia, A., Gratton, R.G., Cantanzaro G. et al., 2007a, A&A, 464, 939
Carretta E., Bragaglia A., Gratton R. G., Leone F., Recio-Blanco A., Lucatello S., 2006, A&A, 450, 523
Carretta E., Bragaglia, A., Gratton, R.G., Lucatello S., Cantanzaro G. et al., 2009a, A&A, 505, 117
Carretta E., Bragaglia A., Gratton R., Lucatello S., Mooney Y., 2007b, A&A, 464, 939
Cho D.-W., Lee S.-G., 2002, AJ, 124, 977
Cohen, J.G., 1978, ApJ, 223, 487
D'Antona, F., Ventura, P., 2007, A&A, 379, 1431
Decressin, T., Charbonnel, C., Meynet, G., 2007, A&A, 475, 859
Gratton R.G., Bonifacio P. et al., 2001, A&A, 369, 87
Gratton R.G., Lucatello S. et al., 2007, A&A, 464, 953
Ivans I.I. et al., 2001, AJ, 122, 1438
Kraft R.P., 1994, PASP, 106, 553
Kraft R.P., Ivans I.I., 2003, PASP, 115, 143
Langer G.E., Hoffman R., Sneden C., 1993, PASP, 105, 301
Lee J.-W., Carney B.W., Balachandran S.C., 2004, AJ, 128, 2388
Lee J.-W., Carney B.W., Habgood M.J., 2005, AJ, 129, 251
Lee J.-W., Kang Y.-W., Lee J., Lee Y.-W., 2009, Nature, 426, 480
Sneden C. et al., 1997, AJ, 114, 1964
Ventura, P., D’Antona, F., 2006, A&A, 457, 995
Ventura, P., D’Antona, F., 2006, A&A, 479, 805
Ventura, P., D’Antona, F., Mazzitelli, I., Gratton, R. 2001, ApJ, 550, L65