Mem. S.A.It. Vol. 79, 508
© SAIt 2008

Memorie della

Surface abundances and constraints on extra-mixing in RGB field/GC stars

E. Carretta

Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy e-mail: `eugenio.carretta@oabo.inaf.it`

Abstract. I will review extant knowledge and observational evidences about mechanisms of extra-mixing and/or pollution concurring to produce chemical "anomalies" in population II red giants, both in clusters and in the field. I will discuss mixing in a broad sense, i.e. both internal to presently observed or already evolved stars and in the protocluster gas. Recent improvements in theoretical modeling and constraints as well as in observational surveys will be presented.

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

1. Introduction

Starting from early photometric and spectroscopic studies by Osborn (1971), Cohen (1978) and Peterson (1980), star-to-star abundance variations have been found in all galactic globular clusters (GCs) investigated so far. This also involves clusters of likely extragalactic origin, like the ones connected to Sagittarius.

On the other hand, field stars share some (but not all) abundance variations of cluster stars, in particular those involving the lightest nuclei (Li, C, N).

I want to give an update of previous extensive reviews (e.g. Gratton et al. 2004) by discussing very recent results and new problems raised. I will point out facts that we know for sure; in particular we now understand quite well the behaviour of the lightest elements in field and cluster giants. Observations of unevolved stars will be a bridge to the heavier elements along the increasing Coulomb barrier. And this is the part we still do not understand well and most difficult to model.

We know quite well which elements show intrinsic variations in cluster and field red giant branch (RGB) stars. In Fig. 1 filled, darker points are the averages I derived from the analysis of 215 RGB stars in 19 GCs, superimposed to a collection of data for field stars. The error bars are 1σ rms scatter and illustrate well that light elements such as O, Na, Mg and Al (as well as the new entry ^{19}F, not shown here, observed by Smith et al. 2005 in giants of M 4), show large star-to-star variations in GCs.

On the other hand, Li, C and N (and their isotopes) are know to vary also in field low mass giants, at least as a consequence of first-dredge-up.

We also know that α-elements, produced in massive Type II Supernovae, do not vary in globular clusters; iron group elements are pretty constant and in particular, iron is ho-

---

Send offprint requests to: E. Carretta

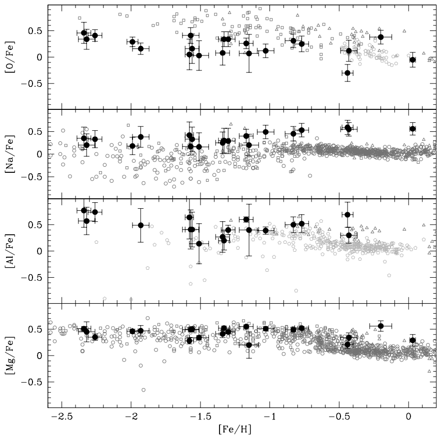

Fig. 1. Average abundances of light elements O, Na, Al, Mg derived from high resolution UVES-FLAMES spectra of RGB stars in 19 globular clusters (large dark points). Error bars are 1σ rms scatter around the mean. Samples of comparison field stars (open symbols in greytones) are from Gratton et al. (2003), Venn et al. (2004) and Reddy et al. (2003)

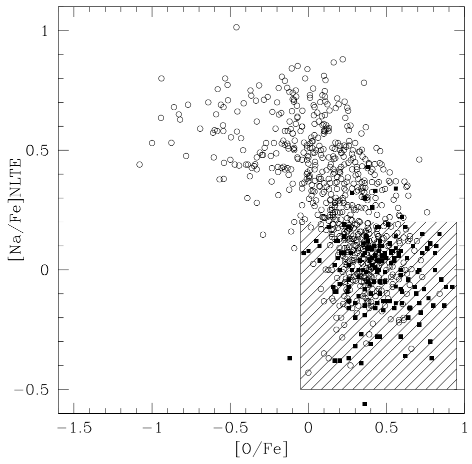

Fig. 2. Plot of Na, O abundances in GC red giants and unevolved stars (empty circles). The dashed square indicates the region populated also by field stars (filled squares)

mogeneous at a few percent level. Finally, neutron-capture elements generally follow the pattern of field stars of similar metallicity, although star-to-star variations are seen in a few metal-poor clusters (Gratton et al. 2004).

We also know that the environment plays a key role. In Fig. 2 the Na, O abundances of almost 700 RGB stars and about 40 unevolved stars in several clusters are shown (empty circles); references can be found in Carretta et al. (2006). Field stars (filled squares) are segregated in a well defined region (high O/low Na) reflecting typical supernovae nucleosynthesis. Cluster stars populate a larger part of this diagram, although the very O-poor tail is due to only two GCs: NGC 2808 and M 13.

Hence, at least some abundance variations **must** be prompted by the denser environment experienced by cluster stars.

2. Light elements and field stars

Let's begin with the lightest elements. Standard models predict only the classical first dredge-up (Iben 1964) after the main-sequence (MS), with alterations of surface abundances typical of products of the incomplete CNO-cycle, in agreement with observations: Li and C decrease, N increases, and the isotopic ratio ^{12}C/^{13}C falls from the solar value down to about 20-25.

However, these predictions were at odds with too much low values of Li, carbon isotopic and carbon-to-nitrogen ratios found in *evolved* stars both in field and in open and globular cluster as well as with Big Bang nucleosynthesis (see e.g., Charbonnel 1994, 1995). Hence extra-mixing mechanisms were soon invoked to explain the differences.

Briefly, a major observational step was the focused study by Gratton et al. (2000), whose homogeneous sample of stars of well known evolutionary status provided a good description of evolutionary changes in metal-poor, low mass field stars from the MS up to the RGB. Gratton et al. clearly highlighted two mixing episodes (the first dredge-up and a second episode after the RGB bump) for light elements (Li, C, N, and C isotopic ratios), whereas Na and O were found constant, at odds with what is seen in GC stars.

Smith & Martell (2003) showed that field and cluster giants share the same rate of declining C as a function of luminosity. They also noticed a rather large scatter among subgiant branch (SGB) stars in M 92 and that C abundances in M 13 seems to follow a somewhat different slope and reach larger C depletion.

The observed second mixing episode in low mass field and cluster giants is now fully taken into account in all stellar evolution models. According to Denissenkov & VandenBerg (2003) we may call this *canonical extra mixing* since it affects all low mass giants.

The exact physical mechanism is still not completely understood; this mixing is attributed to some kind of instability, Rayleigh-Taylor according to Eggleton et al. (2007) or thermohaline instability (Charbonnel & Zahn 2007). Anyway, the additional canonical extra-mixing also brings down from the envelope He-enriched matter, accounts for the observed pattern of light elements and isotopes and erases the conflict between predictions of stellar and Big Bang nucleosynthesis about the Galactic ^{3}He content, which is efficiently destroyed by these mechanisms in 95% of low mass stars (Charbonnel & Zahn 2007).

3. The role of unevolved cluster stars

So far we have seen that Pop II stars seem to follow a common evolution. However, (i) the canonical extra-mixing does not reach very inner regions: Na and O are untouched in field stars but not in GC stars, hence something is still missing, and (ii) in cluster giants we may see hints for a primordial range in C, as in M 92, well before the bump (see the discussion in Smith & Martell 2003)

Thus, the key role of unevolved stars in GCs stays in showing show us the composition of stars before any mixing might onset.

The two panels of Fig. 3, adapted from Briley and coworkers (see e.g. Briley et al. 2004) summarize the main features: large star-to-star spreads in N, anticorrelated with much smaller spreads in C all the way from the MS to the RGB, and the sum C+N increasing as C decreases. Hence, it follows that there is not simply a conversion of C into N; either O must be involved too or variable amounts of N must be taken into account.

However, when the complete set of CNO abundance is available in unevolved cluster stars (e.g., Carretta et al. 2005), we may see that the sum is quite constant, within errors. The conclusion is that we are seeing the outcome of complete CNO-cycle, likely coming from outside the stars we presently observe.

Another fact that we know for sure is that abundance anomalies affect a large fraction of the stellar structure, else a surface contamination would disappear due to dilution after the first dredge up. This does not happen, since these anticorrelations are seen all the way from the MS to the RGB (Cohen et al. 2002).

More insights come from heavier elements, like O and Na: the well know Na-O anticorrelation discovered in RGB stars by the Texas-Lick group (for a review, see Gratton et al. 2004) tells us that we are in the presence of proton-capture reactions at high temperature. This pattern (as well as the accompanying Mg-Al anticorrelation) is explained by the simultaneous run of the CNO, NeNa, and MgAl cycles in H-burning at the temperature of the oxygen shell where the other cycles are expected to efficiently operate, resulting in matter with Na enhanced, O depleted and N enhanced (Denisenkov & Denisenkova 1989; Langer et al. 1993).

The same Na-O anticorrelation observed also in dwarfs (Fig.4), coupled to the Mg-Al anticorrelation found in TO stars of NGC 6752 by Gratton et al. (2001), rules out the possibility of internal mixing because of the negligible convective envelopes and the too low central temperatures typical of these stars. Some other kind of stars must be responsible for the observed chemical pattern.

The best candidates must provide alterations in light elements, with no modification of heavier elements, in particular iron or α-elements.

At least three classes of stars are presently suggested: intermediate-mass asymptotic giant branch (IM-AGB) stars (e.g., Ventura et al. 2001), RGB stars between 0.8 and 2 solar masses (e.g., Denissenkov & VandenBerg 2003) and, very recently, fast rotating massive

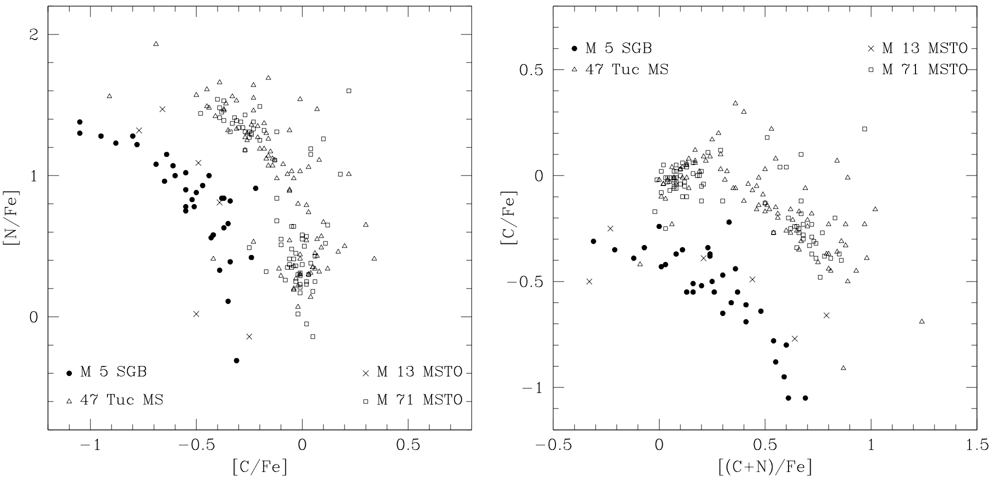

Fig. 3. C abundances as a function of the N abundances (left panel) and as a function of the C+N sum (right panel) for a collection of unevolved stars in several GCs (adapted from Briley and coworkers, see text).

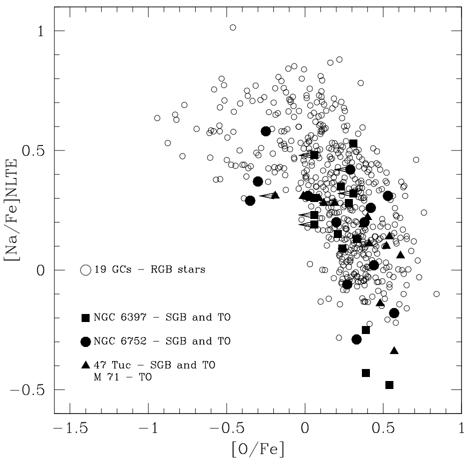

Fig. 4. Na-O anticorrelation for 215 red giants in 19 GCs (open circles; Carretta et al., in preparation) compared to the anticorrelation in unevolved stars (filled symbols) from Carretta et al. (2005), Ramirez & Cohen (2002).

stars (FRMS) (Decressin et al. 2007). In each class we find *i*) H-burning (in shell in RGB, in core burning in FRMS and at the base of convective envelope in AGB), *ii*) a mechanism to bring to the surface the processed material, and *iii*) a way to eject matter and pollute other stars.

Playing with the features of these candidates, several tentative scenarios have been proposed: self-enrichment, internal extra-mixing, or a combination of two, with multiple stellar generations involved. Scenarios resting on internal mixing are of course weakened by observations of abundance variations in unevolved cluster stars.

It is impossible to review all recent studies on these topics, hence in the following I will illustrate a few representative studies, useful to put constraints and show possible drawbacks for some of these scenarios.

4. New constraints and problems from a few selected studies

Constraints from nucleosynthesis- In a beautiful recent study Prantzos et al. (2007), with simple nucleosynthesis calculations, were able to pinpoint a narrow temperature range where the p-capture reactions could simultaneosly reproduce all the extreme abundances -from C to Al- observed in stars of NGC 6752. By assuming that O must be at its equilibrium value, the abundances of stars with more extreme signature of processing are reproduced after mixing the H-processed matter with 30% of unprocessed gas. Different dilution factors then allow the whole range of variations in NGC 6752 to be recovered.

Observations of Li in TO stars of NGC 6752 with signature of processing (Pasquini et al. 2005) allow Prantzos et al. to conclude that the unprocessed matter must be essentially interstellar matter (ISM).

Finally, according to the required temperatures, two main classes of stars may be selected as likely polluters of the early intra-cluster gas, namely massive AGB and the most massive MS stars. Notice that this study is able to provide quite robust constraints, due to the strong dependence of the nuclear rates on temperature.

On the other hand, still pending drawbacks of this approach are the well known uncertainties in yields from massive AGB stars (e.g. Fenner et al. 2004) as well as uncertainties, in some cases quite large, still affecting the nuclear reactions rates (Izzard et al. 2007).

He enhancement and extra-mixing- The issue of He-enhancement in cluster stars was called out by theoretical predictions of yields from IM-AGB stars (D'Antona et al. 2002), by photometric observations showing multiple main sequences (e.g., Piotto et al. 2007) and horizontal branches (HBs) with extremely long blue tails (Caloi & D'Antona 2007).

The current bottom line is that polluted (i.e., O-poor, Na-rich) stars should also be enriched in He (D'Antona et al. 2002), and He-rich stars evolve faster on the MS, so that polluted stars currently at the turn-off shuld be less massive (by about 0.05 $M_\odot$) than the normal He-poor stars. If these stars loose mass at the same rate as normal stars on the red giant branch, their descendants should become much hotter HB stars than objects with standard (unpolluted) composition. Hence, in this picture, He-enhanced stars are likely both to populate the blue extreme of HBs and to explain the extreme O-depletions observed in the surface abundance of RGB stars.

In fact, in a very recent study, D'Antona & Ventura (2007) come back to a combined scenario where normal values of O-depletion (down to [O/Fe]$\sim$ -0.4 as seen in most GCs) are due to self-enrichment by matter polluted by winds of FRMS or massive AGBs. Instead, more extreme depletions are possible assuming extra-mixing, occurring only in some already O-depleted *and* He-enriched stars. According to D'Antona & Ventura (2007) the rotational evolution of He-rich models has little or no molecular weight barrier. This allows extra-mixing to onset, explaining the largest depletion in O observed in peculiar clusters like M 13.

A first problem is that very high values of the helium mass fraction Y are required to both onset the extra-mixing and populate the blue tails on HB. Moreover, the required fraction of stars with enhanced Y is often quite large, as in the simulations to reproduce the whole HB morphology in NGC 6441 (Caloi & D'Antona 2007).

A second concern is that there is no way to satisfy at the same time the requirement of high He values and the constant CNO sum observed in GC stars (Carretta et al. 2005; Ivans et al. 1999). Using standard or ad hoc IMFs (enhanced in IM-AGB star content) Karakas et al. (2006) found that they were unable to obtain a large Y value while mantaining the C+N+O sum constant within the observational errors, using whatever set of yields of IM-AGB, namely Campbell et al. (2004) or Ventura et al. (2002).

Another puzzling issue lies in the rare observations of Mg isotopes. Yong et al. (2005) found the same pattern of correlations and anticorrelations with Al of the abundances of the ^{24}Mg, ^{25}Mg, and ^{26}Mg isotopes in both NGC 6752 (showing modest O-depletions) and M 13 (with large O-depletions). They conclude that in both clusters the mechanism at work (pollution of proto-cluster gas by two generations of IM-AGB stars) must be the same.

Finally, in their analysis of M 13 Sneden et al. (2004) noted that the super O-poor tail in this cluster is given only by high luminosity stars (near the RGB-tip). This evidence is confirmed by Johnson et al. (2005) who found that the incidence of high-Na stars

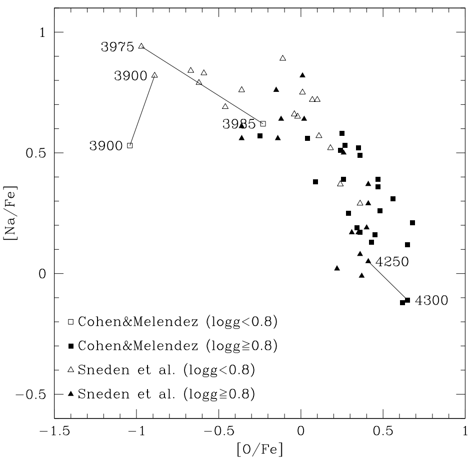

Fig. 5. Combined Na-O anticorrelation in M 13 using the samples by Sneden et al. (2004) (triangles) and by Cohen & Melendez (2005) (squares). Empty and filled symbols refer to low-gravity/high-luminosity stars and to high-gravity/low-luminosity stars, respectively. Solid lines connect stars in common between the two studies, with adopted effective temperatures labeled near the star symbol; notice the large discrepancy in the O abundance for some stars, even with very similar temperature.

is clearly weighted toward high luminosity stars; for warmer stars (see Fig. 5), the degree of chemical anomalies seems to be typical of most clusters (Cohen & Melendez 2005).

However, in the model by D'Antona and Ventura the extra-mixing of He-enhanced stars does not seem to have a luminosity threshold along the RGB.

On the other hand, in NGC 2808, the other GC showing very extreme values of O-depletions, such a trend is not observed. Carretta et al. (2003) found no significant variations in Na abundances as a function of magnitude in a sample of about 90 stars (Fig. 6, left panel), from the bump level up to the RGB-tip; the same behaviour is seen also (Fig. 6, right panel) for O abundances (Carretta 2006).

Despite these problems, is there any evidence of He-enhancement linked to abundance variations in light elements? A first spectroscopic detection of RGB stars with different He content was recently made by Carretta et al. (2007). From isochrones computed with a population mix of both normal composition and He-enhanced composition Salaris et al. (2006) predict a small difference in the location of the RGB bump (brighter for more He-rich sequences). Without going into details, in M 12 and NGC 6752 Carretta et al. (2007) noticed an abrupt change of O, Na abundances as a function of the temperature; this occurs not near the tip, but exactly at the magnitude of the RGB bump. By combining both samples to improve the statistics, they could highlights two bumps in the distribution function of Na abundances (used as proxy for He), differing of about 0.05 mag, just the amount predicted from models by Salaris et al.

5. Conclusions

A growing body of recent evidences presently points out that stellar populations with different He content do exist in GCs, very likely originated by primordial mixing of unprocessed and H-processed matter. At the same time, this complex early evolution of GCs left a fossil record, whose signature lies in the so-called chemical anomalies observed among stars currently climbing the red giant branch during their evolution.

In turn, the descendants of the fraction of very polluted stars may end up on a HB location quite different (bluer) than that populated by stars with more standard (unpolluted) composition.

To better quantify the relation between chemical anomalies and HB morphology a project was started (NAAAH, for NA-O Anticorrelation And HB) devoted to the homogeneous analysis of O and Na abundances from FLAMES-GIRAFFE spectra in more than 2000 RGB stars in 19 clusters with different metallicity, HB morphology, and global parameters. The project is presented in Carretta et al. (2006), for the interested reader.

Interestingly, in some key clusters, as for instance NGC 2808, which has an extreme Na-O anticorrelation and yet no luminosity dependence of Na, O abundances, a deficit of bright giants was recently observed by Sandquist & Martel (2007). A likely expla-

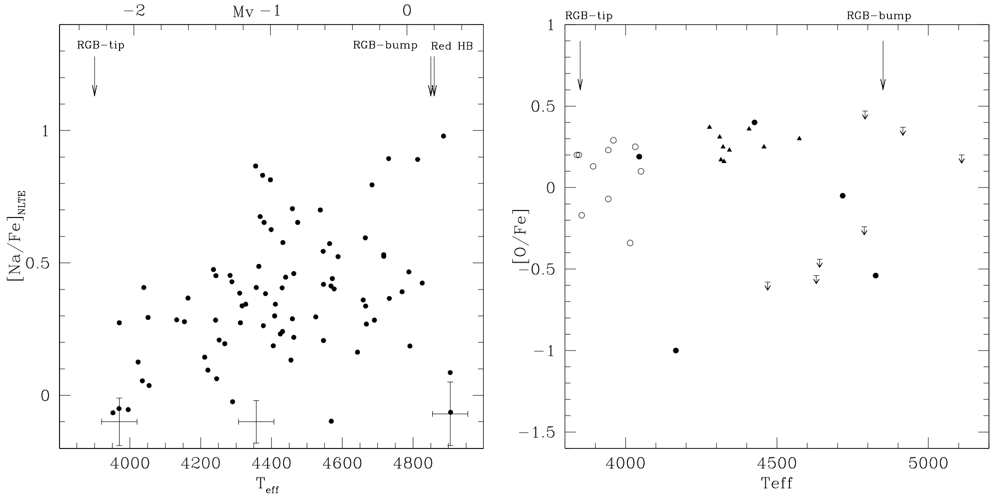

Fig. 6. Left panel: Na abundances as a function of effective temperature in NGC 2808 (Carretta et al. 2003). Right panel: the same, for O abundances from Carretta (2006) (circles) and Carretta et al. (in preparation). Empty symbols are used for stars with surface gravity log $g < 0.8$ dex; upper limits are indicated by arrows.

nation is that extreme mass loss for a fraction of stars near the tip of the RGB may reduce the envelope mass below a critical threshold, and that these stars may interrupt their RGB evolution well below the tip, igniting core He-burning only at higher temperature, as in the hot He-flashers scenario by Castellani & Castellani (1993). As a consequence, they end up on a very hot ZAHB location, contributing to build up a conspicuous blue tail on the HB.

The comparison of M 13 and NGC 2808 is illuminating, in this respect. As already said above, it is well known that the most O-depleted giants in M 13 are also among the brightest ones, all near the RGB-tip (Sneden et al. 2004). When coupled to the deficit of bright giants in NGC 2808, the inference from this comparison is that in M 13 we are probably seeing the *most He-poor among the Na/He-enhanced stars* that we can actually observe. Its is then possible that He self-pollution probably reached even higher levels in NGC 2808, so high that stars with most extreme composition left the RGB well in advance of approaching the classical tip level. They were able to decrease their envelope masses, experience an hot He-flash, and contribute to the clump of blue, extremely hot HB stars of this cluster, which is not present at all in M 13.

Thus, the link between chemical anomalies on RGB and HB morphology is not so direct, as we begin to understand, and a number of still unsolved problems is left to future investigations.

Acknowledgements. I am grateful to Angela Bragaglia and Raffaele Gratton for helping with the analysis of data and many fruitful discussions.

References

Briley, M.M., Harbeck, D., Smith, G.H., Grebel, E.K. 2004, AJ, 127, 1588

Caloi, V., D'Antona, F. 2007, A&A, 463, 949

Campbell, S. W., Fenner, Y., Karakas, A. I., Lattanzio, J. C., & Gibson, B. K. 2004, Memorie della Societa Astronomica Italiana, 75, 735

Carretta, E. 2006, AJ, 131, 1766

Carretta, E., Bragaglia, A., Cacciari, C., & Rossetti, E. 2003, A&A, 410, 143

Carretta, E., Bragaglia, A., Gratton R.G., Leone, F., Recio-Blanco, A., & Lucatello, S. 2006, A&A, 450, 523

Carretta, E., Gratton R.G., Lucatello, S., Bragaglia, A., & Bonifacio, P. 2005, A&A, 433, 597

Carretta, E. et al. 2007, A&A, 464, 939

Castellani, M., & Castellani, V. 1993, ApJ, 407, 649

Charbonnel, C. 1994, A&A, 282, 811

Charbonnel, C. 1995, ApJ, 453, L41

Charbonnel, C., & Zahn, J.-P. 2007, A&A, 467, L15

Cohen, J. G. 1978, ApJ, 223, 487

Cohen, J.G., Briley, M.M., & Stetson, P.B. 2002, AJ, 123, 2525

Cohen, J.G. & Melendez, J. 2005, AJ, 129, 303

D'Antona, F., Caloi, V., Montalbàn, J., Ventura, P., & Gratton, R. 2002, A&A, 395, 69

D'Antona, F., & Ventura, P. 2007, MNRAS, 379, 1431

Decressin, T., Meynet, G., Charbonnel C. Prantzos, N., Ekstrom, S. 2007, A&A, 464, 1029

Denissenkov, P.A., Denissenkova, S.N. 1989, A.Tsir., 1538, 11

Denissenkov, P. A., & VandenBerg, D. A. 2003, ApJ, 593, 509

Eggleton, P.P., Dearborn, D.S.P, Lattanzio, J.C.2007, ApJ, submitted, `arXiv:0706.2710`

Fenner, Y., Campbell, S., Karakas, A.I., Lattanzio, J.C., Gibson, B.K. 2004, MNRAS, 353, 789

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

Gratton, R.G., Carretta, E., Claudi, R., Lucatello, S., & Barbieri, M. 2003, A&A, 404, 187

Gratton, R.G., Sneden, C., & Carretta, E. 2004, ARA&A, 42, 385

Gratton, R.G., Sneden, C., Carretta, E., & Bragaglia, A. 2000, A&A, 354, 169

Iben, I. Jr. 1964, ApJ, 140, 1631

Ivans, I.I., Sneden, C., Kraft, R.P., Suntzeff, N.B, Smith, V.V., Langer, G.E., Fulbright, J.P. 1999, AJ, 118, 1273

Izzard, R.G., Lugaro, M., Karakas, A.I., Iliadis, C., van Raai, M. 2007, A&A, 466, 641

Johnson, C.I., Kraft, R.P., Pilachowski, C.A., Sneden, C., Ivans, I.I., Benman, G. 2005, PASP, 117, 1308

Karakas, A.I., Fenner, Y., Sills, A., Campbell, S.W., Lattanzio, J.C. 2006, ApJ, 652, 1240

Langer, G.E., Hoffman, R., & Sneden, C. 1993, PASP, 105, 301

Osborn, W. 1971, The Observatory, 91, 223

Pasquini, L., Bonifacio, P., Molaro, P., Francois, P., Spite, F., Gratton, R. G., Carretta, E., & Wolff, B. 2005, A&A, 441, 549

Peterson, R. C. 1980, ApJ, 237, L87

Piotto, G., Bedin, L., Anderson, J., King, I.R., Cassisi, S., Milone, A.P., Villanova, S., Pietrinferni, A., Renzini, A. 2007, ApJ, 661, L53

Prantzos, N., Charbonnel, C., & Iliadis, C. 2007, A&A, 470, 179

Ramirez, S. & Cohen, J.G. 2002, AJ, 123, 3277

Reddy, B.E., Tomkin, J., Lambert, D.L., Prieto, C.A. 2003, MNRAS, 340, 304

Salaris, M., Weiss, A., Ferguson, J. W., & Fusilier, D. J. 2006, ApJ, 645, 1131

Sandquist, E.L., & Martel, A.R. 2007, ApJ, 654, L65

Smith, G.H., & Martell, S.L. 2003, PASP, 115, 1211

Smith, V.V., Cunha, K., Ivans, I.I., Lattanzio, J.C., Campbell, S., Hinkle, K.H. 2005, ApJ, 633, 392

Sneden, C., Kraft, R.P., Guhathakurta, P., Peterson, R.C., & Fulbright, J.P. 2004, AJ, 127, 2162

Venn, K. A., Irwin, M., Shetrone, M. D., Tout, C. A., Hill, V., & Tolstoy, E. 2004, AJ, 128, 1177

Ventura, P., D'Antona, F., & Mazzitelli, I. 2002, A&A, 393, 215

Ventura, P. D'Antona, F., Mazzitelli, I., & Gratton, R. 2001, ApJ, 550, L65

Yong, D., Grundahl, F., Nissen, P.E., Jensen, H.R., & Lambert, D.L. 2005, A&A, 438, 875