Mem. S.A.It. Vol. 75, 377

Memorie della

The Horizontal Branch morphology in Globular Clusters: consequences for the selfpollution model

Francesca D'Antona

INAF Osservatorio di Roma, via di Frascati 33, 00040 Monteporzio e-mail: dantona@mporzio.astro.it

Abstract. The Joint Discussion 4 of the Sydney IAU General Assembly takes place at a very interesting stage for the Globular Cluster (GC) astrophysics, when it is becoming clear that many –if not all– of the inhomogeneities in the chemical composition of GC stars are due to some mechanism of primordial enrichment. The best candidate for "self–pollution" is identified with the matter lost in winds of low velocity from Asymptotic Giant Branch (AGB) stars, especially of high mass, evolving during the first phases of life of the Clusters, and cycling their envelope material through hot CNO-cycle at the bottom of their convective envelopes (Hot Bottom Burning –HBB). Recognition that Globular Clusters showing large chemical anomalies are also peculiar in their Horizontal Branch (HB) stars distribution, led D'Antona et al. (2002) to suggest that extended blue tails are directly linked to the enhanced helium in the matter, processed through HBB, from which these stars are born. Here we show that other HB peculiar morphologies —such as the lack of stars in the RR Lyrae region, in clusters like NGC 2808, whose red and blue side of the HB are both well populated— can be attributed to the helium enrichment of the matter from which the stars populating the whole blue HB in this cluster were born.
This interpretation lends credit to the idea that the GC stars are formed in two main generations, the first one having the composition of the primordial gas cloud, the second one formed *directly* from the AGB ejecta over a span of time lasting $\sim 2\times10^8$yr. This hypothesis provides a useful and conceptually simple key not only to interpret some —but not all— HB peculiarities, but also to understand the distribution of abundance anomalies. If the model is correct, in the end we can use the abundance anomalies to falsify (or calibrate) our AGB models.

Key words. Abundances in Globular Cluster stars – AGB models – self–pollution

1. Introduction

The recent observations of abundance spreads among Globular Clusters stars, now observed also at the turnoff (TO) and among the subgiants (e.g., Gratton et al. 2001; Gratton 2003) show that these anomalies must be attributed to some process of "self–pollution" occurring at the first stages of the life of the cluster, during the epoch in which the Supernova explosions were already finished (carrying easily away

Send offprint requests to: Francesca D'Antona
Correspondence to: INAF Osservatorio di Roma, 00040 Monteporzio

from the clusters their high velocity ejecta) and the massive Asymptotic Giant Branch (AGB) stars were evolving. At an epoch starting less than $\sim 10^8$yr from the birth of the first stellar generation, the massive AGBs lose mass through low velocity winds, so that it has been reasonably speculated that these winds remain into the cluster where they are either accreted on the already formed stars (D'Antona, Gratton, & Chieffi 1983) or mixed with residual gas and give origin to a new stellar generation (Cottrell & Da Costa 1981).

I outline the line of reasoning which led us to suggest that the spreads in chemical abundances are actually due to the birth of successive generation of stars *directly* from the ejecta of the massive AGBs of the first generation. If this is the explanation, we also require that the Initial Mass Function (IMF) of the first stellar generation should have been considerably "flat" (with a power law index close to –1, in the notation in which Salpeter's index is –2.35) in the mass range 3–8$M_\odot$, or we must envision some ways by which only a fraction of the low mass stars first formed are retained in the cluster.

This new self–pollution hypothesis is based on several evidences, of which we only consider in this work the interpretation of the morphology of extended HBs in some globular clusters in terms of a spread in the initial helium content of the cluster stars.

2. The AGB models for Population II

The most striking abundance anomaly in GC stars is the spread in Oxygen which can reach a factor $\sim$ 10 in the intermediate metallicity clusters like M13 and NGC 6752 (e.g. Kraft et al. 1993). This spread extends to the TO and subgiant stars, as shown by Gratton et al. (2001), and therefore can not be inputed to 'in situ' mixing. At the same time of the Gratton et al. (2001) observations, Ventura et al. (2001) found that the process of 'Hot Bottom Burning' (HBB), that is the nuclear processing which occurs at the basis of the convective envelope of massive AGBs, takes place at such large temperatures ($\simeq 10^8$K) that the full CNO cycle operates and converts Oxygen into Nitrogen. Therefore the envelopes of these stars have an Oxygen abundance much smaller than the initial. The processing is more efficient in the most massive AGBs, and progressively less efficient in the lower masses, which have smaller temperatures at the basis of the convective envelope. Further, the ON processing is possible only at low metallicities, and thus for the HBB conditions typical of the massive AGBs in GCs. With this knowledge, it is natural to attribute the spread in Oxygen to HBB and to some "self–pollution" mechanism from the envelopes of AGB stars. More recent computations show that there are still problems in the global quantitative scenario. In particular, it is not yet clear whether the reduction in Oxygen can occur together with an increase in the ^{23}Na abundance (Denissenkov & Herwig 2003; Ventura et al. 2003), explaining the O-Na anticorrelation, nor whether present models can be consistent with the anticorrelation Oxygen – Nitrogen (Ventura et al. 2003). On the other hand, the computation of AGB models is subject to severe uncertainties, due to the approximations made both for convection and mass loss, and some nuclear reaction rates are still quite uncertain, so that the quantitative results are still uncertain and must be carefully explored (see also Lattanzio 2003), before we have a clear and fully satisfactory scenario — or before we reject it.

3. A hint on the modalities of self–pollution

As remarked by Ventura et al. (2001) and Ventura, D'Antona, & Mazzitelli (2002), the models of AGB which show Oxygen depletion, also show a noticeable helium enhancement: the helium content can be as high as Y=0.30 or more, for the most massive AGB ejecta, although starting from a mere Y=0.24 (the Big Bang abundance) –see Figure 1. This result is particularly robust, as it is due primarily to the so called 'second dredge up' phase, which is much less model dependent than the third dredge up associated with the thermal pulses. Now, if self-pollution is due to the matter lost from AGBs, the low mass stars (M $\lesssim 0.8 M_\odot$) presently evolving in GCs

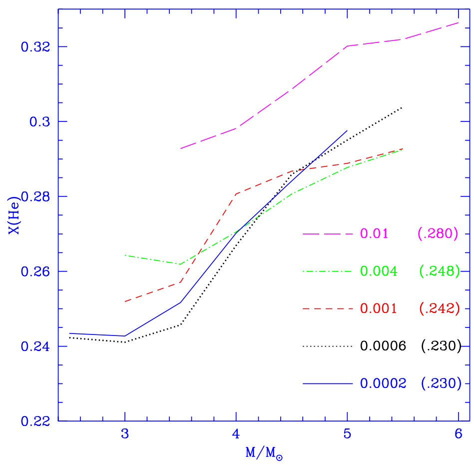

Fig. 1. The average helium abundance, X(He), in the ejecta from AGB stars, as function of the evolving initial mass, is shown for different metal contents from Ventura, D'Antona, & Mazzitelli (2002). The metal mass fraction Z and the initial helium mass fraction Y (in parenthesis) are labelled in the figure.

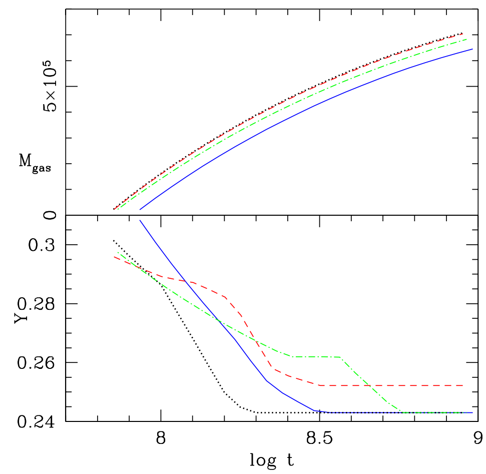

Fig. 2. Assuming an initial population of 10^6 stars, born at time zero, with an IMF following a power law $dN/dM \propto M^{-1}$, we plot as a function of time, the cumulative mass of gas ejected during the evolution of the first generation AGBs (top) and the corresponding helium abundance Y in the ejecta (bottom). The mass coordinate of Figure 1 is converted into a time coordinate, by adopting the evolutionary times appropriate to the evolving masses from the same computations by Ventura, D'Antona, & Mazzitelli (2002). The line styles (and colors) follow the caption of Figure 1: Z=2×10^{-4} (full line); Z=6×10^{-4} (dotted line); Z=1×10^{-3} (dashed line); Z=4×10^{-3} (dot-dashed line).

should be a mixture of two populations, the first one, born together with the intermediate mass population, and having the initial helium content, and a second, additional, population more or less enriched in helium. By looking at models with high helium, we first notice that the isochrone location is not very sensitive to variations in Y (D'Antona et al. 2002). But for all the isochrones there is a small but significant difference in the evolving mass: the most relevant feature is that, the larger is the helium content, the smaller is the mass. For Z close to $\sim 10^{-3}$), a simple interpolatory formula based on our models ((D'Antona et al. 2002; D'Antona & Caloi 2003)) provides, for the mass at the helium flash at age t:

$$\log M/M_\odot \simeq [-0.282 + 0.092(Y-0.24)]\times$$
$$\log t - 1.693(Y-0.24) + 2.768 + 12(Z-10^{-3})$$

The mass differs by $\sim 0.05\mathrm{M}_\odot$ for a difference in helium by 0.04. This difference is important for the $T_{\rm eff}$ distribution on the HB. In fact, if the same mechanism of mass loss operates on the "standard Y" and on the "enhanced Y" stars along the giant branch and at the helium flash, the final mass in HB will be several hundredths of solar mass smaller, and therefore will have a *bluer* location. This has been remarked by D'Antona et al. (2002), who also show that the hypothesis of a population of stars having enhanced Y *from the start* (that is, from the main sequence) can explain the existence of extended blue tails in the HB of some clusters, like NGC 6752 or M13, whose red giants show the mentioned huge Oxygen spreads. In this hypothesis, the helium abundance of the matter lost from the AGB *must not be diluted* with other residual matter in the cluster, and the helium enrichment must be present also *in the core* of the main sequence stars, in order to affect their lifetimes and pro-

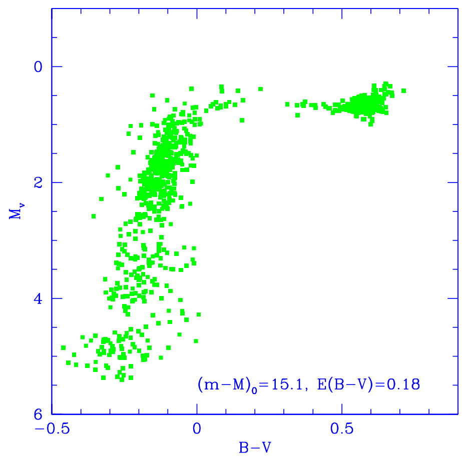

Fig. 3. The HB in the data by Bedin et al. (2000) for the GC NGC 2808. It consists of a "red" clump plus a composite blue part, along which two main gaps are well evident.

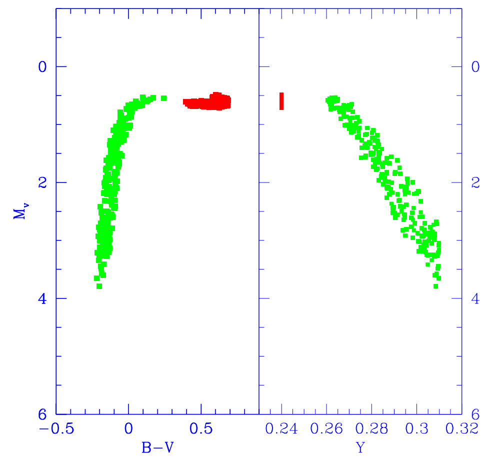

Fig. 4. The HB distribution of NGC2808 is simulated by assuming an age of 14Gyr, Z=2 $\times$ 10^{-3} and a population of 250 HB stars having uniform Y=0.24, plus a population of 250 HB stars having Y uniformly distributed in the range 0.26<Y<0.31. A Gaussian distribution is assumed for the mass loss along the whole red giant evolution , with a mean of 0.185 $M_{\odot}$, and a standard deviation σ = 0.004 $M_{\odot}$. Notice that this very small deviation well reproduces the distribution of stars on the red to star helium variation, shown by plotting Y as function of the absolute M_v magnitude on the right side of the figure. Notice that the hotter (dimmer) part of the HB is not reproduced by this naive simulation. We suggest that it can be reproduced by assuming that the red giants having the highest Y –and thus the smallest initial mass– uffer a delayed helium flash followed by mixing, as proposed by Sweigart (1997a)

vide the mass difference for a fixed value of the cluster age. So, we are led to think about a second phase of star formation, directly occurring from the AGB ejecta!

4. Gaps in the Horizontal Branches

Fig. 2 shows an example of the mass of gas ejected from AGBs (top) and its helium content (bottom) as function of time for several metallicities. The evolutionary times and helium yields of the ejected matter are taken from our models in Ventura, D'Antona, & Mazzitelli (2002). We see that the helium content variation can even be not fully monotonic with time. Further, it is possible that the star formation stops abruptly at some epoch (due, e.g., to the presence of strong UV sources such as the planetary nebulae from relatively low mass progenitors). For these reasons, we will have a discontinuity between the helium content of the first generation (probably the Big Bang abundance) and the *lowest* helium content of the second generation. This can justify a discontinuity in mass along the red giant branch, which reflects in a discontinuity in mass along the HB. After suggesting that this discontinuity is a possible reason for the existence of gaps along the very blue HB, we have been exploring the possibility that the helium variation and discontinuity provide an interesting explanation for other kind of gaps, e.g. for the very peculiar distribution of stars in the HB of NGC 2808 (D'Antona & Caloi 2003).

The HB of NGC 2808 has been studied recently in many works (e.g., Sosin et al. 1997; Bedin et al. 2000), which have been mostly interested in discussing the appearence of gaps at the blue side of the HB. In particular, the clear separation of the most extreme clump in the blue tail is satisfactorily explained by assuming that some stars have suffered a late helium core flash, followed by flash–induced

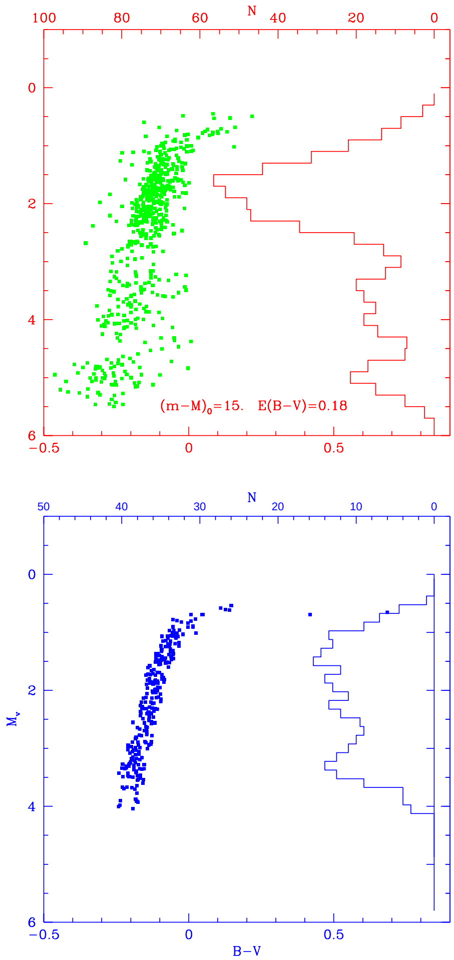

Fig. 5. Top: number-magnitude distribution histograms for the blue HB of NGC 2808; bottom: the same for the simple simulation of figure 4. A 'calibration' of the number of stars born with different Y between 0.26 and 0.31 can allow a much better reproduction of the observations, and provide us with a tool to understand the corresponding distribution of abundance anomalies at the main sequence or along the giant branch.

mixing (Sweigart 1997a) whose final effect is to raise the HB $T_{\rm eff}$, producing a discontinuity between the $T_{\rm eff}$ of the stars with canonical and late helium flash (e.g. Brown et al. 2001). Scarce attention has been given to the huge gap which the HB shows exactly at the position of the RR Lyrae. We have simulated the HB distribution for mixed HB populations starting from models of Y=0.24, and Y=0.30, for Z=2×10^{-3}. Details will be given by D'Antona & Caloi (2003), and an example is shown in Figure 4. Due to the combination of metallicity and age for this cluster, we suggest that indeed the gap at the RR Lyrae separates the HB cluster stars which belong to the original first population, born at t=0 with the cosmological helium abundance Y=0.24 and the helium enriched population born from the ejecta of the HB, which, in this case, must have a *minimum* helium abundance Y=0.26 to produce the gap. In our proposed model for selfpollution, the AGB winds should be able to form new stars up to an age of $\sim 2\times10^8$yr, when the evolving mass in the cluster was $\sim 3.5 M_\odot$. We notice two interesting characteristics of the synthetic HB distribution which are obtained when we assume that there is a helium spread.

First of all, *a much smaller width of the Gaussian mass loss distribution in the red giant evolution is sufficient to reproduce HB distributions which may even be very extended in color* or $T_{\rm eff}$. Generally, in synthetic HB distribution it is assumed $\sigma \sim 0.15-0.20$ (e.g. Catelan et al. 1998), while the distribution in Figure 4 is obtained with $\sigma = 0.004$, which well reproduces the small spread of the red HB, and is adequate for the blue HB, whose color spread is due to the *helium* variation and not to the mass loss spread.

Second, the helium spread, although not altering in a significant way the absolute luminosity of the RR Lyrae in clusters in which there is a consistent "first generation" population (D'Antona et al. 2002) will produce, in the particular case of NGC 2808, a small but noticeable difference in luminosity between the cool side of the blue HB and the hot side of the red HB. There are other clusters showing a marked bimodality, such as the metal rich ones NGC 6388 and NGC 6441 (Rich et al. 1997). These clusters show a marked slope of the horizontal part of the HB (the bluer stars being more luminous), which is easy to attribute to the same selfpollution mechanism described here: the luminosity increases with $T_{\rm eff}$ just because the helium abundance of the stars increases.[1]

When we assume this key interpretation of the HB stars distribution, we may also speculate that there may be external factors which may be responsible for gaps in the HB distribution[2]. In particular, if the Globular Cluster passes through the galactic disk, it can be deprived of all the gas lost by the AGB, and it will be necessary to wait until the newly lost gas accumulates again before the second phase of star formation resumes. In the meantime, the helium abundance of the gas declines, leaving a small gap in the helium content which is reflected into a gap in the HB distribution.

We spend a few words to contrast our interpretation with other models proposed in the recent literature and invoking the helium content of HB stars to explain (a part of) the second parameter problem.

1) A helium enrichment *in the envelope* as a consequence of deep mixing in today evolving red giants was suggested as a way to obtain blue and very blue HBs, and an increasing luminosity of bluer HB stars (Langer & Hoffman 1995; Sweigart 1997b). As a matter of fact, an increased helium abundance can help in reaching a HB position bluer than the RR Lyrae variables (at the expense of a more or less substantial increase in luminosity), but the extremely blue locations *always* require an extreme mass loss, because the envelope mass has to be in any case *smaller* than 0.01 $M_{\odot}$ —see the discussion in Caloi (2001). In addition, Weiss et al. (2000) have shown that the helium enhancement needed to explain the exclusively blue HB morphology would be related to chemical inhomogeneities much stronger than observed in red giants. So an increase in the *envelope* Y is a model less satisfactory than the increase in the global Y.

2) We have to acknowledge that Norris, Cottrell, Freeman, & Da Costa (1981), twenty years ago, have proposed the same model which we are appraising again today, to explain the HB anomalies of NGC 6752, and correlate them to the abundance anomalies of the red giants. Their model was incomplete only because it was not yet so clear that AGB winds have the ability to fulfill these abundance anomaly requirements: good ideas seem to need a mature period to be fruitfully explored.

5. Is there enough matter to form the second generation stars?

Cluster stars showing abundance anomalies represent grossly a half of the cluster population. If we make the simple hypothesis that the IMF of the first generation stars follows a power law of the type $dN/dM \propto M^{-(1+x)}$ (x is 1.35 for Salpeter's IMF) and look at the fraction of gas ejected from the AGBs as function of time, with respect to the initial total mass of the gas, we easily realize that the index must be much smaller than Salpeter's –about 0– if we wish to get some 40-50% of gas in the ejecta, to justify the chemical anomalies. In other words, the IMF of the first generation of stars born in dense stellar systems should have been "flat".[3] A simpler point of view is the following: let us suppose that the proto–GC IMF actually follows Salpeter's IMF (Elmegreen 2003). Nevertheless, on a dynamic timescale, which for the intermediate mass stars is shorter than their evolution timescale, these stars concentrate in the central regions of the cluster, where they evolve and produce the second generation. It is well possible that the most external parts of the cluster, those containing many of the low mass stars of the *first* generation, are lost, so that the cluster as we see it today maintains the first generation stars only as a fraction of $\sim 50\%$ of the total.

[1] The anomalous distribution of the period of the RR Lyrae in NGC 6388 and NGC 6441, which does not allow to fit them into the Oosterhoff type classification (Pritzl, Smith, Catelan, & Sweigart 2000), may also have the same explanation.

[2] We warn, however, that first of all one must carefully understand *which* gaps are due to atmospheric phenomena, see, e.g. the discussion in Caloi (1999).

[3] Notice that a flat IMF of the first generation, if extended to somewhat more massive stars, can also explain the embarrassing large number of neutron stars present in clusters and revealed as millisecond pulsars.

6. Conclusions

A lot of work remains to be done to understand the chemical abundances in Globular Clusters, but we think that the outline described here is in a correct direction and may provide a key for the interpretation of several characteristics, both of abundance anomalies and of the HB distribution. A consequence of this proposal is that we have dismissed as wrong our own, 20 year old, model of self–pollution, based on the accretion of the AGB winds on already formed stars (D'Antona, Gratton, & Chieffi 1983), and have revitalized the model by Cottrell & Da Costa (1981) on the birth of a second generation of stars. The present model is actually more extreme, as it does not envision mixing with remnant gas from the first generation. Cottrell & Da Costa (1981) had recognized as a weak point of their model that they could evaluate in at most 10 – 20% the recycling of the matter ejected from the first generation AGBs into a second generation, starting from a standard, Salpeter like, IMF for the first generation: we see that this is also a difficult point of our proposal. Finally, we must stress that the problem of the so called 'second parameter' in Globular Clusters can not be entirely solved by the inclusion of this further parameter (a helium spread and gap between a first and a second generation), but it is possible that this way of looking at the problem may help to discriminate among the possible second parameter candidates.

One very evident problem for the second parameter issue is that, in our model, the first generation stars should *always* be present in all clusters. Therefore, e.g., we can not get rid of the red HB stars of M3, in order to obtain a fully blue HB like that of M13, by invoking simply two stellar generations with different helium content. Johnson & Bolte (1998) proposed that the initial helium content of M13 stars is larger than that of M3 to explain the second parameter problem of the two clusters. They did not discuss either the origin of the larger helium abundance, nor have envisioned helium abundance spreads, but it could be interesting to modify their suggestion in the framework of our model: this would require, e.g., that the first generation low mass stars of M13 have been *totally lost* from the cluster, so that today there is no population of red HB stars left.

Acknowledgements. I thank Bruce Elmegreen, who suggested to me that mass segragation could be an easy escape to the problem of the IMF of the stars belonging to the first generation. It is a pleasure to acknowledge friends and collaborators who have contributed to understand, develop, and correct the described scenario. In particular, I thank Paolo Ventura, who is responsible for the computation of the AGB models in our group, Josefina Montalbán, who shared the first phases of enjoyment and discussion on the properties of horizontal branches, Vittoria Caloi whose insight on HB evolution has been fundamental, and Raffaele Gratton, with whom I first proposed, and now reject, the selfpollution – accretion scenario. Part of this work was supported by the COFIN 2001-2002 funding for the project "Evolution of millisecond pulsars in the Galaxy and in Globular Clusters".

References

Bedin, L. R., Piotto, G., Zoccali, M., Stetson, P. B., Saviane, I., Cassisi, S., & Bono, G. 2000, A&A, 363, 159
Brown, T. M., Sweigart, A. V., Lanz, T., Landsman, W. B., & Hubeny, I. 2001, ApJ, 562, 368
Caloi, V. 1999, A&A, 343, 904
Caloi V., 2001, A&A, 366, 91
Catelan, M., Borissova, J., Sweigart, A. V., & Spassova, N. 1998, ApJ, 494, 265
Cottrell, P. L. & Da Costa, G. S. 1981, ApJ, 245, L79
D'Antona, F. & Caloi, V. 2003, in preparation
D'Antona, F., Gratton, R., & Chieffi, A. 1983, Memorie della Societa Astronomica Italiana, 54, 173
D'Antona, F., Caloi, V., Montalbán, J., Ventura, P., & Gratton, R. 2002, A&A, 395, 69
Denissenkov, P. A. & Herwig, F. 2003, ApJ, 590, L99
Elmegreen, B. 2003, in these Proceedings
Gratton, R. G. 2003, in these Proceedings
Gratton, R. G. et al. 2001, A&A, 369, 87
Johnson, J. A. & Bolte, M. 1998, AJ, 115, 693
Kraft, R. P., Sneden, C., Langer, G. E., & Shetrone, M. D. 1993, AJ, 106, 1490

Langer G.E., Hoffman R.D., 1995, PASP 107, 1177
Lattanzio, J. 2003, in these Proceedings
Norris, J., Cottrell, P. L., Freeman, K. C., & Da Costa, G. S. 1981, ApJ, 244, 205
Pritzl, B., Smith, H. A., Catelan, M., & Sweigart, A. V. 2000, ApJ, 530, L41
Rich, R. M. et al. 1997, ApJ, 484, L25
Sosin, C. et al. 1997, ApJ, 480, L35
Sweigart, A. 1997, Third Conference on Faint Blue Stars, ed. A. G. D. Philip, J. Liebert, R. Saffer and D.S. Hayes, (Schenectady, L. Davis Press), p.3
Sweigart, A. V. 1997, ApJ, 474, L23
Ventura, P., Zeppieri, A., Mazzitelli, I., & D'Antona, F. 1998, A&A, 334, 953
Ventura, P., D'Antona, F., Mazzitelli, I., & Gratton, R. 2001, ApJ, 550, L65
Ventura, P., D'Antona, F., & Mazzitelli, I. 2002, A&A, 393, 215
Ventura, P., Mazzitelli, I. & D'Antona, F. 2003, in these Proceedings
Weiss A.,Denissenkov P.A., Charbonnel C., 2000, A&A, 356,181