Light Elements in the Universe
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Revisiting the helium abundance in globular clusters with multiple main sequences

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Abstract. For nearby K dwarfs, the broadening of the observed Main Sequence at low metallicities is much narrower than expected from isochrones with the standard helium–to–metal enrichment ratio $\Delta Y/\Delta Z \sim 2$. A much higher value, of order 10, is formally needed to reproduce the observed broadening, but it returns helium abundances in awkward contrast with Big Bang Nucleosynthesis. This steep enrichment ratio resembles, on a milder scale, the very high $\Delta Y/\Delta Z$ estimated from the multiple Main Sequences observed in some metal-poor Globular Clusters. We argue that a revision of low Main Sequence stellar models, suggested from nearby stars, could help to reduce the overwhelmingly high $\Delta Y/\Delta Z$ deduced so far for those clusters. Under the most favourable assumptions, the estimated helium content for the enriched populations may decrease from $Y \simeq 0.4$ to as low as $Y \simeq 0.3$, with intermediate values being plausible.

Keywords. Stars: fundamental parameters, late-type – subdwarfs – globular clusters: individual (ωCen, NGC 2808, 47 Tuc)

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1. Introduction

Helium (Y) is the second most abundant element in the Universe, having been produced by Big Bang Nucleosynthesis (BBN) with a universal mass fraction $Y_P = 0.24 - 0.25$ and topped up by successive stellar generations which also synthesize metals (Z). In spite of its large abundance, it is an elusive element. It can be measured directly, from spectroscopic lines, only for $T_{\rm eff} \gtrsim 8000$ K: young, massive stars or blue Horizontal Branch stars though, apart from a small temperature range, their surface abundance may not trace the original one, due to helium sedimentation and metal levitation (e.g. Villanova, Piotto & Gratton 2009). Only indirect methods can be used for stars of low mass and cooler temperatures, which constitute the bulk of the Galaxy's stellar population. One such method relies on the broadening of the low Main Sequence (MS), where evolutionary effects do not need to be taken into account. At a fixed metallicity Z, an increase of Y makes a given mass on the isochrone hotter and brighter, so that the net effect of varying $\Delta Y/\Delta Z$ is to affect the broadening of the lower MS (e.g. Faulkner 1967; Fernandes *et al.* 1996).

Previous studies based on Hipparcos parallaxes concluded $\Delta Y/\Delta Z = 2 - 3$ (Pagel & Portinari 1998; Jimenez *et al.* 2003). More recently, Casagrande *et al.* (2006, 2007) further improved the analysis by compiling a much larger sample of K dwarfs with bolometric magnitudes and effective temperatures derived via InfraRed Flux Method (IRFM). The implementation adopted for the IRFM resorted to homogeneous multi–band photometry to determine in a fully self-consistent, (almost) model independent way $T_{\rm eff}$ and $M_{\rm Bol}$. The study of the broadening of the lower MS could thus be performed in the theoretical

HR diagram where the effects of $\Delta Y/\Delta Z$ are more prominent, also bypassing uncertainties related to synthetic colour-temperature transformations†.

Around solar metallicities this analysis yielded $\Delta Y/\Delta Z \sim 2$ but at lower Z, Casagrande *et al.* (2007) found that the observed MS is narrower than expected from stellar models computed under this standard $\Delta Y/\Delta Z$ (i.e. the stars are cooler than the isochrones), rather implying a much steeper value of ~ 10. This change in slope is at odds with Galactic chemical evolution models, which predict a ratio substantially constant with Z (Carigi & Peimbert 2008; Casagrande 2008); a constant $\Delta Y/\Delta Z \sim 2$ is also found from HII regions (e.g. Peimbert *et al.* 2007). More importantly, $\Delta Y/\Delta Z \sim 10$ at low metallicities implies a helium content for nearby subdwarfs much lower than Y_P, in awkward contrast with the cosmological floor set by standard BBN.

This result points toward inadequacies in MS stellar models of low metallicity (see also Lebreton *et al.* 1999), an issue which is worth investigating since it may lead to reconsider the problem of the helium enrichment in Globular Clusters (GCs). In fact, at magnitudes comparable to those of the local stars studied in Casagrande *et al.* (2007, $M_V \sim 5.5-7.5$), multiple MSs have been discovered in some Globular Clusters and interpreted as evidence for huge helium enhancement in a sub-population (Piotto 2009 and references therein). The required $\Delta Y/\Delta Z \gtrsim 100$ is extremely difficult to explain for stellar nucleosynthesis and chemical evolution models (Yi 2009 and references therein). While it is likely that a significant helium enhancement is present in those stellar populations, our purpose is to show that the revision of low metallicity MS stellar models, needed to cure the problem of the high $\Delta Y/\Delta Z$ and sub-primordial Y deduced in nearby K dwarfs, may significantly reduce current estimates of $\Delta Y/\Delta Z$ in Globular Clusters with multiple MS, easing their theoretical interpretation. Full details on the work presented here are given in Portinari, Casagrande & Flynn (2010).

2. Homology relations

Homology relations, holding for largely radiative structures (Cox & Giuli 1968) such as MS stars of $M \lesssim 1\ M_\odot$, express the distance, in the theoretical HR diagram of a Zero Age Main Sequence (ZAMS) of composition (Y, Z) with respect to another reference ZAMS of composition (Y_r, Z_r):

$$\begin{aligned}\Delta \log T_{\rm eff} = \quad & -0.0935 \log \left[1 - \tfrac{\delta}{X_r}(Z - Z_r)\right] \\ & -0.196 \log \left[1 - \tfrac{5\delta+1}{(3+5X_r-Z_r)}(Z - Z_r)\right] \\ & -0.051 \log \left[1 - \tfrac{\delta}{(1+X_r)}(Z - Z_r)\right] \\ & -0.051 \log \left(\tfrac{100Z+1}{100Z_r+1}\right)\end{aligned} \tag{2.1}$$

where $\delta = 1 + \frac{\Delta Y}{\Delta Z}$ and $X_r = 1 - Y_r - Z_r$. Notice that the same relation holds also for a generic combination of (Y, Z) replacing $\delta\,(Z - Z_r) \rightarrow (Y - Y_r) + (Z - Z_r)$.

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† It is worth recalling that the adopted $T_{\rm eff}$ scale has been recently validated by interferometric angular diameters and HST spectrophotometry (Casagrande *et al.* 2010). Without entering into further details, suffice here to say that this scale is hotter than other IRFM renditions, and hotter than or close to various spectroscopic scales. Therefore, any other $T_{\rm eff}$ scale will just worsen the comparison with the isochrones discussed in this paper, with real stars even cooler than the models.

2.1. *Application to Globular Clusters*

In recent years, thanks to deep photometric observations, multiple, distinct MSs have been detected in ωCen and NGC 2808 (Piotto 2009 and references therein). Recent observations also seem to support a MS broadening in 47 Tuc (Anderson *et al.* 2009). Since helium crucially affects the morphology of the HR diagram, it is very tempting to interpret multiple stellar populations in terms of different helium contents (Catelan, Valcarce & Sweigart 2009 and references therein).

For ωCen, detailed isochrone analysis indicates that a helium enrichment of $\Delta Y \simeq 0.15$ is needed to reproduce the observed split between the blue (bMS, [Fe/H] $= -1.3$) and red (rMS, [Fe/H] $= -1.6$, $Y_{\rm rMS} = 0.246$) main sequence. Homology relations (Eq. 2.1) indeed yield a similar result: using the colour–temperature–metallicity scale of Casagrande *et al.* (2006) to translate the dereddened maximum observed colour split between the bMS and rMS returns $\Delta \log T_{\rm eff} = 0.0185$ implying $\Delta Y = 0.144$ and $Y_{\rm bMS} = 0.39$ (Fig. 2). These values are in excellent agreement with the results obtained by Norris (2004), Piotto *et al.* (2005), Lee *et al.* (2005) and Sollima *et al.* (2007) by means of isochrone analysis.

Another striking example of multiple populations is NGC 2808, where three MSs are found at virtually the same metallicity [Fe/H] $= -1.1\pm0.03$ dex (Carretta *et al.* 2006) and helium abundances of $Y = 0.248$ (the value assumed for the red MS, which includes the bulk of the population), $Y = 0.30$ (middle MS) and $Y = 0.37$ (blue MS; D'Antona *et al.* 2005; Lee *et al.* 2005; Piotto *et al.* 2007). In this case $\Delta Z \rightarrow 0$, and one should just focus on ΔY. Translating the dereddened maximum split of the bMS and rMS with respect to the mMS and using the $T_{\rm eff}$ scale of Casagrande *et al.* (2006) returns $\Delta \log T_{\rm eff} = \pm 0.009$. For an assumed $Y_{\rm rMS} = 0.248$, homology relations return $Y_{\rm mMS} = 0.31$ and $Y_{\rm bMS} = 0.37$ again in excellent agreement with isochrone analysis (Piotto *et al.* 2007).

Finally, if the observed broadening of the MS in 47 Tuc is interpreted in terms of helium variation, homology relations reproduce the measured $\Delta \log T_{\rm eff} = 0.003$ with $\Delta Y = 0.023$, again close to the conclusion based on isochrones (Anderson *et al.* 2009).

2.2. *Application to isochrones*

We have shown that theoretical homology relations, applied to the multiple (or broadened) MSs of Globular Clusters, provide a similar interpretation of the data in terms of ΔY and $\Delta Y/\Delta Z$ as detailed isochrone analysis. We now compare directly homology relations to current stellar models by fitting isochrones with a homology–like relation.

An interpolation formula for isochrones directly inspired by Eq. (2.1) involves at least 4 independent parameters, but for fitting purposes, a simplified form of Eq. (2.1) is more suitable. We verified that the result is still a very good approximation of the rigorous homology relations, especially for metallicities $Z \leqslant Z_\odot$ and even for extremely high $\Delta Y/\Delta Z > 100$, which are of interest for Globular Clusters. Therefore we seek a three–parameters fitting formula for isochrones (and, later below, for real stars) of the kind:

$$\begin{aligned}\Delta \log T_{\rm eff} = \; & -P_1 \log\left[1-\tfrac{\delta}{(0.6+X_r)}(Z-Z_r)\right] \\ & -P_2 \log\left(\tfrac{P_3 Z+1}{P_3 Z_r+1}\right)\end{aligned} \tag{2.2}$$

where P_i are 3 free fitting parameters. It is our experience that this formula provides an adequate fit to isochrones, as good as (and more robust than) other homology-like fitting formulæ with 4 or more parameters. This simplified formulation condenses together the first three (helium dependent) terms of the original relation and has a clearcut separation between the helium– and metallicity–dependent part, which proves to be handy for the empirical calibration discussed in Section 3.

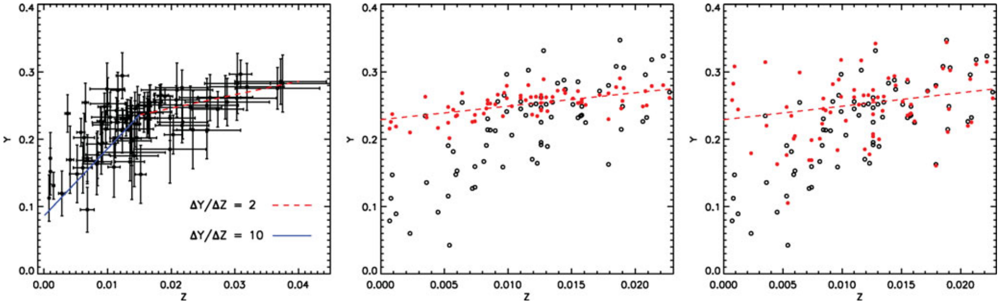

Figure 1. *Left panel:* metal versus helium mass fraction for nearby field dwarfs obtained from Casagrande *et al.* (2007). Lines with two values of $\Delta Y/\Delta Z$ (break at $Z = 0.015$) are plotted to guide the eye. *Central panel:* zooming on metallicities around and below solar. Open circles are derived applying *numerical homology relations* and look remarkably similar to those in the left panel. Full circles are obtained using *empirical homology relations* with $P_1 = 1.5$. *Right panel:* same as central panel, but using *empirical homology relations* with $P_3 \sim 150$.

We consider both the Padova isochrones computed specifically for the analysis in Casagrande *et al.* (2007), and the more recent release by Bertelli *et al.* (2008) with varying $\Delta Y/\Delta Z$ and $0.0001 \leqslant Z \leqslant 0.04$, which fully brackets the metallicity range relevant for the present study. In Casagrande *et al.* (2007) we had checked that other sets of isochrones (Yonsei–Yale, Teramo, McDonald) were very similar in the lower MS.

We find that the behaviour of isochrones, at least in the range $M_{\rm Bol} = 5.4 - 7.0$ (where the effect of $\Delta Y/\Delta Z$ is expected to be maximal) is well described by homology–like relations with the following set of parameters: $P_1 = 0.50 \pm 0.03$, $P_2 = 0.064 \pm 0.005$ and $P_3 = 670 \pm 200$. When using these parameters we will speak of *numerical homology relations*. In Casagrande *et al.* (2007) the metal and helium mass fraction of the stars were computed iteratively, with a star–by–star isochrone fitting: despite the less sophisticated approach provided by homology relations, with the aforementioned parameters nearly identical results are obtained, including the change in slope above and below $Z \sim 0.015$ (Fig. 1).

3. Empirical homology relations and Globular Clusters

In the previous section we have shown that theoretical homology relations agree very well with the isochrone–based interpretation of the MS splits observed in ωCen and NGC 2808, and adequately reproduce the behaviour of isochrones in general, as a function of $\Delta Y/\Delta Z$. However, isochrones are known to fail the interpretation of the HR diagram of nearby low–Z MS stars: while for $Z \gtrsim 0.015$ the broadening of the main sequence is well reproduced with the standard $\Delta Y/\Delta Z \sim 2$, with current isochrones a much higher $\Delta Y/\Delta Z \sim 10$ is needed to fit lower metallicities. While in principle $\Delta Y/\Delta Z$ may not necessarily be constant, taken at face value, this result implies a helium content in local metal poor stars as low as $Y = 0.1$. Such a striking contrast with BBN is to be ascribed to inadequacies of low metallicity MS stellar models.

While awaiting for a solution to this problem by improved stellar physics, we now define *empirical homology relations*, calibrated to reproduce the broadening of the local MS, and extrapolate the consequences for the interpretation of Globular Clusters. Here we adopt a very pragmatic approach: we *assume* $\Delta Y/\Delta Z \sim 2$ also for $Z < Z_{\odot}$, and empirically calibrate homology relations to fulfill this constraint for nearby stars. Our assumption is very reasonable, since HII region measurements and chemical evolution models support a constant $\Delta Y/\Delta Z \sim 2$ at all Z, as does the following simple argument: taking the solar

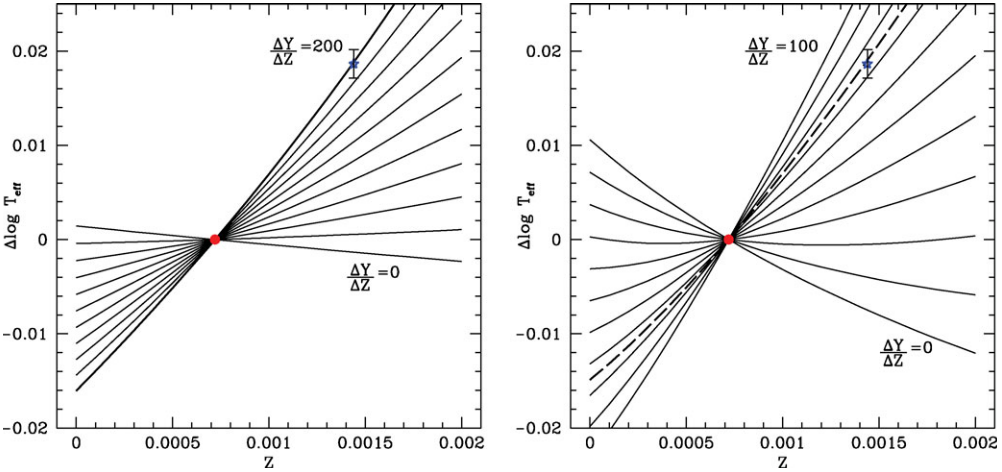

Figure 2. *Left panel:* $\Delta Y/\Delta Z$ obtained applying homology relations to the measured $\Delta \log T_{\rm eff}$ between the rMS (dot) and bMS (star) in ωCen. *Right panel:* same as left, but using *empirical homology relations* with maximized effect on helium (i.e. $P_1 = 1.5$)

bulk abundances (Asplund *et al.* 2009) and the primordial Y_P, one derives $\Delta Y/\Delta Z \sim 2$ for $Z < Z_\odot$.

To define *empirical homology relations*, one can act on either terms of Eq. (2.2). The first one includes the effects of the helium content, while the second term (stemming essentially from the metallicity dependence of opacity) is independent of $\Delta Y/\Delta Z$. The second term is therefore irrelevant for the multiple MSs in GCs, where metallicity differences are small or vanishing. Therefore, if we calibrate our empirical homology relations onto nearby stars acting only on the first term (via the parameter P_1), we maximize the change in the role of helium, and the consequences for the interpretation of GC's.

Keeping P_2 and P_3 fixed and optimizing P_1 so that the inferred helium content of nearby K dwarfs with $Z < Z_\odot$ follows $\Delta Y/\Delta Z = 2$ (Fig. 1, central panel) yields $P_1 = 1.5$ and the helium abundances required to describe the multiple MSs decrease to $Y_{\rm bMS} = 0.30$ (ωCen, Fig. 2), $Y_{\rm mMS} = 0.265$ and $Y_{\rm bMS} = 0.283$ (NGC 2808) and $\Delta Y = 0.006$ (47 Tuc).

Acting instead on the second term of the homology relations has no impact on the interpretation of the multiple MS of Globular Clusters. But for nearby K dwarfs and subdwarfs, the metallicity range is significant and exploring the effects of this second term is worthwhile. The parameters P_2 and P_3 are degenerate, in the sense that a given change in the second term can be obtained by modifying either of the two parameters. Therefore, we choose to discuss the role of the second term by optimizing P_3. Keeping P_1 and P_2 fixed we find that $P_3 \sim 150$ is the optimal value to obtain $\Delta Y/\Delta Z = 2$ for nearby low–Z stars. However, while we do obtain $\Delta Y/\Delta Z = 2$ on average, this solution has considerable scatter and many stars remain with uncomfortably low helium abundances (Fig. 1, right panel).

4. Conclusions

The purpose of the present exercise has been to draw attention on the possible connection between the HR diagram of Globular Clusters with multiple MSs and the broadening of the low MS defined by nearby stars. We estimate the possible extent of the required revision of low MS stellar models on the base of homology relations. First we show that theoretical homology relations properly reproduce the response of stellar models to the helium content. Then, since both isochrones and theoretical homology relations fail the interpretation of the nearby low–Z MS, we calibrate empirical homology relations to yield $\Delta Y/\Delta Z \sim 2$ for nearby stars of all metallicities, and inspect the consequences for the MS splits in Globular Clusters.

If we entirely impute the failure of the low MS stellar models to a wrong response to the helium abundance (and correspondingly re-calibrate the helium–sensitive term of the homology relations), the consequences for Globular Clusters are highly significant: the helium content of the blue sub-populations is reduced from 40% to 30%, which is far easier to explain with chemical evolution models (e.g. Yi 2009; Romano *et al.* 2009).

Alternatively, if stellar models for the lower MS are assumed to fail in their metallicity dependence (i.e. we re-calibrate only the homology term expressing the metallicity dependence of opacity) the consequences for Globular Clusters are negligible — as the metallicity differences between the subpopulations are minimal or vanishing.

As the solution for K dwarf models can be intermediate between these two extreme assumptions, we suggest that the helium rich populations in Globular Clusters are likely to have a helium content Y in the range 0.3–0.4; but altogether, there is room to decrease their estimated helium content from the extreme $Y = 0.4$ that is the commonly quoted value. Improvements in the physics of low MS stellar models are thus potentially important also for the riddle of the helium self-enrichment in Globular Clusters.

References

Anderson, J., Piotto, G., King, I. R., Bedin, L. R., & Guhathakurta P. 2009, *ApJ*, 697, L58
Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Bertelli, G., Girardi, L., Marigo, P., & Nasi, E. 2008, *A&A*, 484, 815
Carigi, L. & Peimbert, M. 2008, *RMxAA*, 44, 341
Carretta, E., Bragaglia, A., Gratton, R. G. *et al.* 2006, *A&A*, 450, 523
Casagrande, L. 2008, *PhD Thesis*, Annales Universitatis Turkuensis, Ser. A1 t., 382
Casagrande, L., Portinari, L., & Flynn, C. 2006, *MNRAS*, 373, 13
Casagrande, L., Flynn, C., Portinari, L., Girardi, L., & Jimenez, J. 2007, *MNRAS*, 382, 1516
Casagrande, L., Ramírez, I., Meléndez, J., Bessell, M., & Asplund, M. 2010, *A&A*, in press
Catelan, M., Valcarce, A. A. R., & Sweigart, A. V. 2009, *IAU Symp.* 266, (arXiv:0910.1367)
Cox, J. P. & Giuli, R. T. 1968, *Principles of Stellar Structure*, Gordon & Breach, New York
D'Antona, F., Bellazzini, M., Caloi, V., Pecci, F. F., Galleti, S., & Rood, R. T. 2005, *ApJ*, 631, 868
Faulkner, J. 1967, ApJ 147, 617
Fernandes, J., Lebreton, Y., & Baglin, A. 1996, *A&A*, 311, 127
Jimenez, R., Flynn, C., McDonald, J., & Gibson, B. 2003, *Science*, 299, 1552
Lebreton, Y., Perrin, M.-N., Cayrel, R., Baglin, A., & Fernandes, J. 1999, *A&A*, 350, 587
Lee, Y.-W., Joo, S.-J., Han, S.-I. *et al.* 2005, *ApJ*, 621, L57
Norris, J. E. 2004, *ApJ*, 612, 25
Pagel, B. E. J. & Portinari, L. 1998, *MNRAS*, 298, 747
Peimbert, M., Luridiana, V., & Peimbert, A. 2007, *ApJ*, 666, 636
Piotto, G. 2009, in The Ages of Stars *IAU Symp.* 258, 233
Piotto, G., Villanova, S., Bedin, L. R., Gratton, R., Cassisi, S. *et al.* 2005, *ApJ*, 621, 777
Piotto, G., Bedin, L. R., Anderson, J., King, I. R., Cassisi, S. *et al.* 2007, *ApJ*, 661, L53
Portinari, L., Casagrande, L., & Flynn, C. 2010, submitted
Romano, D., Tosi, M., & Cignoni, M. *et al.* 2009, *MNRAS*, in press (arXiv:0910.1299)
Sollima, A., Ferraro, F. R., Bellazzini, M. *et al.* 2007, *ApJ*, 654, 915
Villanova, S., Piotto, G., & Gratton, R. G. 2009, *A&A*, 499, 755
Yi, S.-K. 2009, in The Ages of Stars *IAU Symp.* 258, 253