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Helium-rich stars in globular clusters: constraints for self-enrichment by massive stars

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Abstract. Globular clusters exhibit peculiar chemical patterns where Fe and heavy elements are constant inside a given cluster while light elements (Li to Al) show strong star-to-star variations. This pattern can be explained by self-pollution of the intracluster gas by the slow winds of fast rotating massive stars. Besides, several main sequences have been observed in several globular clusters which can be understood only with different stellar populations with distinct He content. Here we explore how these He abundances can constrain the self-enrichment in globular clusters.

Keywords. stars: abundances, evolution, horizontal-branch, mass loss – globular clusters: general

1. Chemical enrichment of globular clusters

Globular clusters are self-gravitating aggregates of tens of thousands to millions of stars that have survived over a Hubble time. Many observations show that these objects are composed of (at least) two distinct stellar populations. The first evidence rests on the chemical analysis that reveals large star-to-star abundance variations in light elements in all individual clusters studied so far, while the iron abundance stays constant (for a review see Gratton *et al.* 2004). These variations include the well-documented anticorrelations between C-N, O-Na, Mg-Al, Li-Na and F-Na (Kraft 1994; Carretta *et al.* 2007; Gratton *et al.* 2007; Carretta *et al.* 2006; Pasquini *et al.* 2007; Bonifacio *et al.* 2007; Lind *et al.* 2009). This global chemical pattern requires H-burning at high temperature around 75×10^6 K (Arnould *et al.* 1999; Prantzos *et al.* 2007). As the observed chemical pattern is present in low-mass stars both on the red giant branch (RGB) and at the turn-off that do not reach such high internal temperatures, the abundance anomalies must have been inherited at the time of formation of these stars.

Further indications for multiple populations in individual GCs come from deep photometric studies that have revealed multiple giant branches or main sequences. In ω Cen a blue main sequence has been discovered (Bedin *et al.* 2004) that is presumably related to a high content in He (Piotto *et al.* 2005; Villanova *et al.* 2007). A triple main sequence has been discovered in NGC 2808 (Piotto *et al.* 2007). The additional blue sequences are explainable by a higher He content of the corresponding stars which shifts the effective temperatures towards hotter values. He-rich stars have also been proposed to explain the morphology of extended horizontal branch (hereafter HB) seen in many globular clusters (see e.g., Caloi & D'Antona 2005). Whereas no direct observational link between abundance anomalies and He-rich sequences has been found, this link is easily understood theoretically as abundance anomalies are the main result of H burning to He.

These observed properties lead to the conclusion that globular clusters born from giant gas clouds first form a generation of stars with the same abundance pattern as field stars. Then a polluting source enriches the intracluster-medium with H-burning material out of which a chemically-different second stellar generation forms. This scheme can explain at the same time the abundance anomalies in light elements and He-enrichment.

Two main candidates that reach the right temperature for H-burning have been proposed to be at the origin of the abundance anomalies (Prantzos & Charbonnel 2006): (a) intermediate mass stars evolving on the thermal pulses along the asymptotic giant branch (hereafter TP-AGB), and (b) main sequence massive stars. After being first proposed by Cottrell & Da Costa (1981) the AGB scenario has been extensively studied (see e.g., Ventura & D'Antona 2008b,a, 2009, see Ventura, this volume) and has been seriously challenged by rotating AGB models that predict unobserved CNO enrichment in low-metallicity globular clusters (Decressin *et al.* 2009).

On the other hand, as being suggested by Brown & Wallerstein (1993) and Wallerstein *et al.* (1987), massive stars can also pollute the interstellar medium (ISM) of a forming cluster (see Smith 2006; Prantzos & Charbonnel 2006). In particular Decressin *et al.* (2007b) show that fast rotating massive stars (with a mass higher than ~ 25 $M_\odot$) are good candidates for the self-enrichment of globular clusters. In this wind of fast rotating massive stars (WFRMS) scenario, rotationally-induced mixing transports H-burning products (and hence matter with correct abundance signatures) from the convective core to the stellar surface, and, providing initial rotation is high enough, the stars reach the break-up on the main sequence evolution. As a result a mechanical wind is launched from the equator that generates a disk around the star similar to that of Be stars (e.g. Townsend *et al.* 2004). Later, when He-burning products are brought to the surface, the star has already lost a high fraction of its initial mass and angular momentum, so that it no longer rotates at the break-up velocity. Matter is then ejected through a classical fast isotropic radiative wind. From the matter ejected in the disk, a second generation of stars may be created with chemical pattern in agreement with observations.

2. He-rich stars evolution

As explained in Decressin *et al.* (2007a), matter stored in the discs around massive stars is heavily enriched with He. If the second generation stars form locally around each massive star from a mixture of matter stored in the slow winds and the ISM, we expect the following distribution: a main peak is present at normal He-abundance (Y = 0.245, in mass fraction) and it extends up to 0.4. However a long tail toward higher Y-values is also present with around 12% of the stars with initial He value between 0.4 and 0.72. Here we want to explore in more details the consequence of the super He-rich stars for the properties of globular clusters.

To assert these implications we have computed a grid of low-mass stellar models from 0.2 to 0.9 $M_\odot$ at a metallicity of $Z = 0.0005$ (similar to the metal-poor globular cluster NGC 6752) for initial He mass fraction between 0.245 and 0.72 with the stellar evolution code STAREVOL V2.92 (see Siess *et al.* 2000; Siess 2006, for more details). These models have been computed without any kind of mixing except for an instantaneous mixing in convection zones. All models have been computed from the pre-main sequence to the end of the central He-burning phase.

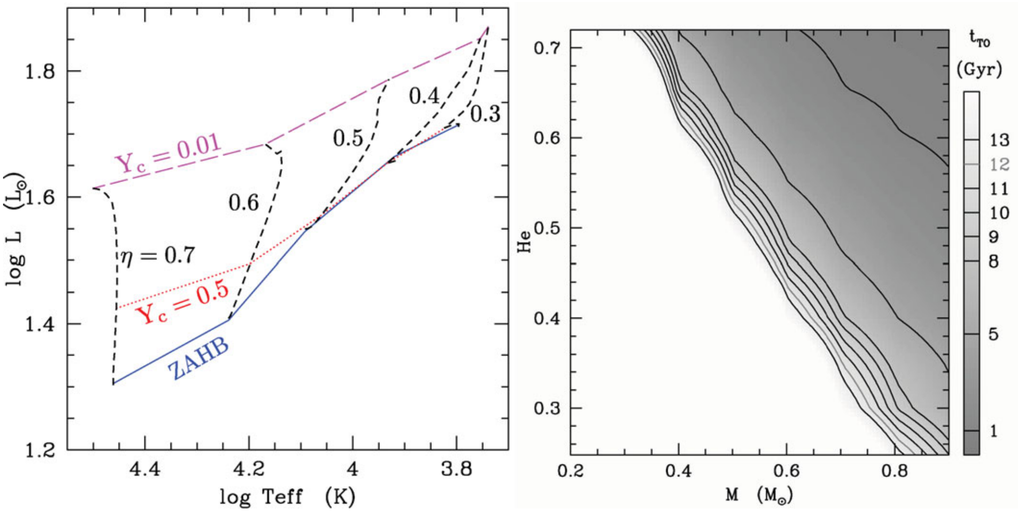

Figure 1. *Left:* Location of central He-burning stars with initial mass of 0.83 $M_\odot$ reaching the TO after 13 Gyr. with various mass loss parameters on the RGB ($\eta_R = 0.3$ to 0.7). Full, dotted, and long-dashed lines indicate respectively places where the stars arrive on the HB and where the central He abundance is 0.5, and 0.01. *Right:* Age at the turn-off for low-mass stars as a function of their initial mass (0.2–0.9 $M_\odot$) and initial He value (0.245-0.72, mass fraction). White area indicates stars still on the main sequence after 15 Gyr of evolution.

The mass-loss rate is the only physical parameter that can change the evolution of standard stellar models. This is of peculiar importance in globular clusters as both mass-loss and He-enrichment can produce blue HB. Here we adopt the mass-loss rate following Reimers (1975) prescription (without metallicity dependence). In Fig. 1 (left panel) we present the location of the stars on the HB used to calibrate the mass-loss. Models with He-normal composition ($Y_{\rm ini} = 0.245$) are computed with different values, from 0.3 to 0.7, for the η parameter in Reimers (1975) prescription. A high value for η (i.e., a high mass-loss rate on the RGB) gives bluer stars on the HB. Below $\eta = 0.5$ the stars stay near the ZAHB in the first part of central He-burning phase. As time passes the luminosity of the H-burning shell (hereafter HBS) decreases while the luminosity of the He-burning core increases, leaving almost no variation of surface luminosity. On the other hand stars with high mass loss have a weak HBS on the ZAHB and the increase of surface luminosity reflects the one in the He-core.

From the observational point of view only few studies have been able to assess the He abundance for HB stars. In the GC M 3, Catelan *et al.* (2009) show that for stars with effective temperature below 10 000 K, only normal He abundance agreed with the surface gravity. Besides in NGC 6752, Villanova *et al.* (2009) find through spectroscopic measurements that stars with effective temperature in the range 9 000–8 500 K have a He composition compatible with normal He abundance. From Fig. 1 (left panel) we see that a value of η around 0.4 implies HB stars with standard He abundance and effective temperature below 10 000 K. If we assume the same mass-loss rate for He-rich stars, they will have a smaller mass on the HB and hence will only have hotter temperature. Therefore, higher η values than 0.4 will produce too hot HB stars without stars in the red part of the HB. On the other hand, lower η values will require high He abundance HB stars with effective temperature below 10 000 K in contradiction with the observations. In our computation we use $\eta = 0.4$ for the parameter of Reimers (1975) law for all models independently of the initial He content.

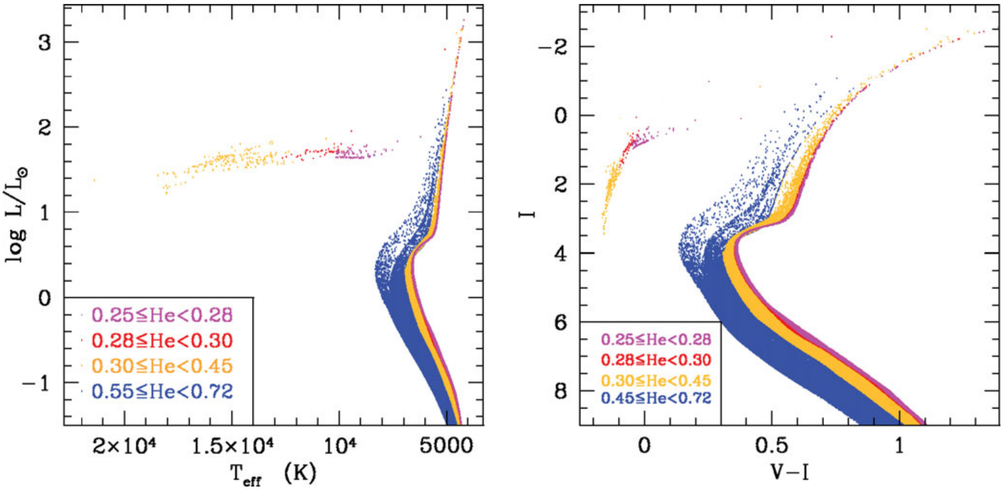

Figure 2. Synthetic diagram of a 13 Gyr old globular cluster in HR diagram (right) and CMD (left). Magenta, red, orange and blue colours (from right to left) indicate the initial abundance of He. He-rich stars are present on the blue part of the MS, RGB and HB, while super-He rich stars are only seen on the MS and RGB.

For a given stellar mass, He-rich stars evolve faster on the main-sequence due to their lower initial H-content and to their higher luminosity. Figure 1 (right panel) illustrates this point showing the turn-off age as a function of the initial mass and He mass fraction of stars. After 12 Gyr, stars of 0.85 $M_\odot$ with standard helium (Y = 0.245) as well as He-rich stars of 0.4 $M_\odot$ (Y = 0.6) are leaving the main sequence. Thus the distribution of the initial He abundance will be reflected by a distribution of stellar mass for stars at the same evolutionary stage.

3. Effects on colour-magnitude diagram of GCs

Figure 2 shows synthetic colour-magnitude diagrams (in the $T_{\rm eff}$ vs. $\log L$ and I vs. V-I planes) of a 13 Gyr old globular cluster with the initial spread in He following the distribution obtained by Decressin *et al.* (2007a) for a cluster enriched by fast rotating massive stars. The age is chosen to be of 13 Gyr, in agreement with that determined for NGC 6752 (13.8 ± 1.1 Gyr, Gratton *et al.* 2003). This CMD has been computed with a modified version of the program used by Meynet (1993) to investigate supergiant populations. We use the colours transformation from VandenBerg & Clem (2003) which considered only He-normal abundance. This adds another uncertainty to the position of He-rich stars in right panel of Fig. 2.

The spread in He converts into a spread in mass at the turn-off. The luminosity increase of He-rich stars is mainly compensated by their shorter lifetime so that the turn-off luminosity is almost constant. Besides due to their differences in opacity and to their compactness they are also hotter. Thus the He-rich main-sequence and RGB stars are shifted to the left side of the CMD.

While being present on blue side of MS and RGB, super He-rich stars are not laying in the blue part of the HB. This is due to the combined effects of mass-loss during the RGB phase with a smaller initial mass which produce a He-core too light to be able to start He-burning. Thus stars with He content higher than ∼ 0.45–0.5 will end as He-WD instead of blue HB stars and CO-WD.

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Recently Milone *et al.* (2009) analyse deep photometry of NGC 6752, revealing a broadening of the main sequence which could be attributed neither to binaries nor to photometric errors. If we compare our theoretical CMD with the one observed by those authors we note some discrepancies. In particular the theoretical width of the main sequence at the turn-off is too large compared to that observed for this cluster. Let us stress however that we use calibration relations for normal He content while stars of different He content are present. This might artificially distort the MS. Interestingly the extended blue loop of NGC 6752 can be reproduced by our theoretical CMD with different He-value ranging from 0.245 to 0.45.

A possibility to avoid super He-rich stars is to consider stronger dilution factors. For instance, if we assume a global dilution to produce a mean value we will have Y$\sim$0.37, which is quite consistent with the blue main sequence in ω Cen and the triple main sequences detected in NGC 2808. However this situation is not completely satisfactory as it leads to a reduction of the amplitude of star-to-star variations of light elements that may then disagree with the observations.

Another way to solve the discrepancy comes from the stellar evolution models of fast rotating massive stars. As already explained, during the main sequence the star reaches the break-up velocity and we assume that the matter is ejected through a slow equatorial wind. However the matter with a very high He-abundance is released only at the end of the main-sequence and the beginning of the central-He burning phase. During these phases, the stars is still at the break-up velocity but this time the radiation pressure contribute significantly to it. This is the so-called $\Omega\Lambda$ limit (Maeder & Meynet 2000). In previous studies we have assumed that the matter released has still a small velocity and will be stored also in the disc to maximise the amount of H-burning processed matter released by fast rotating massive stars. However if the radiation starts to dominate we can instead expect faster winds that will escape the cluster potential well so that this super He-rich matter is lost for the self-enrichment of globular clusters. In this case it would be possible to produce both large abundance variations in light elements along with a moderate increase in He abundance.

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