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The lithium content of the globular clusters ω Centauri and M 4

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Abstract. Globular clusters (GCs) are among the oldest objects in the universe. By studying their Li content, insights can be gained about both the cosmological lithium problem and about the ubiquitous multi-population identified in GCs and, hence, about their chemical enrichment history. We will present the results of two spectroscopic campaigns aimed at studying the Li content of un-evolved stars in the GCs ω Cen and M 4.

Key words. nuclear reactions, nucleosynthesis, abundances, stars: abundances, stars: Population II, (Galaxy:) globular clusters: individual (M 4), globular clusters: individual (ω Cen), galaxies: abundances, (galaxies:) Local Group, cosmology: observations

1. Introduction

The study of the lithium content of globular clusters (GCs) presents several levels of interest. Galactic GCs are among the oldest objects in the universe. As such, the study of their lithium content can provide insights into the so-called "cosmological lithium problem", namely the discrepancy between the constant lithium abundance measured in warm metal-poor dwarf stars in the halo (Spite & Spite 1982, the "Spite plateau"), and the significantly higher primordial value predicted from the standard models of big-bang nucleosynthesis (SBBN) coupled with the measurement of the baryon to photon ratio made by using data obtained from the WMAP satellite (Cyburt et al. 2008).

Additionally, the fragile nature of lithium, which is destroyed at relatively low temperatures (2.5×10^6 K), can also provide informations about the formation of GCs. These are now commonly accepted to host at least two stellar populations. In fact, the variations observed in the light element abundances, and in particular the sodium-oxygen anti-correlations observed in all GCs studied so-far, are observed both among evolved stars and at the main sequence level, hence suggesting their origin as connected to the phase of formation of the cluster, and not on stellar evolution. The Na-O anti-correlation is sometimes observed to be accompanied by a Li-Na anti-correlation in main sequence stars (Pasquini et al. 2005; Bonifacio et al. 2007). This is not surprising, as at the temperatures necessary for Na production, lithium is destroyed. A debate is currently in place about the nature of the polluters of the gas from which the second generation of stars was formed. In particular, Asymptotic Giant Branch (AGB, D'Ercole et al. 2010, 2011; Ventura & D'Antona 2010) stars and Fast Rotating Massive Stars (FRMS Decressin et al. 2007, 2010) are considered as viable candidates. While FRMS would

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only destroy the original lithium, AGB stars may have also important yields of lithium, which can be produced through the Cameron-Fowler mechanism (Cameron & Fowler 1971). Indeed, lithium rich red giant branch (RGB) and AGB stars were observed in different environments (see, e.g. Monaco & Bonifacio 2008; Monaco et al. 2011, and references therein). Any lithium production would, however, tend to erase the presence of a Na-Li anti-correlation. The study of the lithium and sodium abundance in GCs, represents, hence, a useful tool to investigate the origin of the multi-populations in GCs.

We summarize here the results of two observational campaigns conducted to study the lithium content in the GCs ω Centauri and M 4 (Monaco et al. 2010, 2012).

2. The lithium content of ω Centauri: the first stellar measure in an extra-galactic system?

ω Centauri is the most massive among the galactic GCs and is commonly considered as the remnant of dwarf galaxy accreted by the Milky Way (MW). While the detection of metallicity spread has been claimed at the level of a few tenth of dex for several GCs (see, e.g., Carretta et al. 2010; Marino et al. 2011), ω Cen is the only one to present a sizeable range, covering almost 2 dex in [Fe/H] (Johnson & Pilachowski 2010). A less extreme case is also constituted by Ter 5, for which two populations with a Δ[Fe/H]$\simeq$0.5 dex were identified both photometrically and spectroscopically (Ferraro et al. 2009). Also the position of ω Cen in the integrated magnitude *vs* surface brightness or half light radius planes is intermediate between that of GCs and the ultra-compact dwarf spheroidal galaxies (Tolstoy et al. 2009). It is also worth noticing the early suggestion by Gnedin et al. (2002) that the present day mass of ω Cen would not be enough to allow a significantly more efficient retention of the heavy element dispersed by AGB stars during stellar evolution, with respect to the rest of GCs, which, however, do not present the complex stellar content of ω Cen. This would suggest that ω Cen might have been significantly more massive in the past. Indeed, its radial velocity dispersion profile tend to remain flat at large distances. This may be due to past dynamical interactions (Da Costa 2012) which might have also caused a partial disruption of ω Cen. Indeed, Majewski et al. (2012) identified stars having kinematics and chemistry compatible with them belonging to a tidal stream originated from ω Cen. A similarity was also proposed between ω Cen and the massive GCs M 54 (Bellazzini et al. 2008; Carretta et al. 2010) at the center of the disrupting Sagittarius dwarf spheroidal galaxy (see also Ibata et al. 1994; Monaco et al. 2005).

At a distance of $\sim$5 kpc (Harris 1996), ω Cen, may represent the closest extra-galactic system and most likely, the only one accessible for a study of the lithium content among un-evolved stars with the currently available instrumentation.

Studying the lithium content of an extra-galactic system has implications about the universality of the "Spite plateau", so far observed only among MW stars. Additionally, models identifying the solution of the cosmological lithium problem in the local conditions of formation of the MW halo, will also be challenged by these observations.

For these reasons, we decided to study the lithium content among un-evolved stars in ω Cen. Observations were conducted with the FLAMES (Pasquini et al. 2002) facility at the Very Large Telescope of ESO (Paranal Observatory, Chile). Details of the observations, data reduction and abundance analysis can be found in Monaco et al. (2010).

Figure 1 shows the observed stars on top of the ω Cen color-magnitude diagram (CMD) from Bellini et al. (2009). Figure 2 presents the measured lithium abundances as a function of the stellar effective temperatures and the iron content. Clearly, the average lithium level is perfectly compatible with the Spite Plateau (Spite & Spite 2010), with a dispersion around the mean compatible with the expected measurement errors and no trend with temperature or metallicity are visible. It is worth to notice that a small range of metallicity was sampled, and hence our measures are representative of the dominant, metal-poor populations of ω Cen. A small sample of stars was observed also on the most metal-rich population of ω Cen, the so called SGBa (Ferraro et al. 2004; Pancino et al. 2011) but only upper limits on the lithium abundance could be measured for these stars. Notice, however, that at their relatively cold temperature some depletion from the original value is expected.

A significant number of upper limits are present among our measures, some of them are due to the quality of the data, and several are compatible with the measured mean lithium abundance. However, a few of them may indeed represent stars with a lower lithium content. This may be due to several reasons. As mentioned above, GCs may present Na-Li anti-correlations, hence, some of them may be second generation stars having an high Na content and a correspondingly low lithium abundance. Some can also actually be blue stragglers stars, which are known to present low lithium abundances (Ryan et al. 2001). Additionally, several authors have suggested that some of the ω Cen sub-population may be helium enriched (see, e.g., Norris 2004; Piotto et al. 2005). At the temperatures at which helium production can take place lithium would be destroyed. Thus, the low lithium content of some of our stars would find a natural explanation in case they would be enriched in helium.

The fact that un-evolved stars with lithium abundances similar to that in the MW halo are observed in a system with a very likely extra-galactic origin, point in the direction of the universality of the Spite plateau, even though, of course, this suggestion waits for confirmation in an extended sample of extra-galactic objects. The same lithium abundance level was also recently observed for one dwarf star in the galactic bulge (Bensby et al. 2010), and Molaro et al. (1997) observed the Spite plateau in a sample of stars belonging to the galactic thick disk. All these indications would suggest the universality of the Spite plateau. It is however now accepted that at the lowest metallicities and, hence, likely at the oldest ages and chemical compositions the most similar to the outcome of the big-bang nucleosynthesis, significant deviations from the plateau level show-up (Aoki et al. 2009; Sbordone et al. 2010). This is particularly evident in the case of the extremely metal-poor stars SDSS J102915+172027 and HE 1327-2326 (Caffau et al. 2011, 2012; Frebel et al. 2005, 2008). The reasons for this observational fact are not identified yet, but they may reside in some depletion mechanism becoming effective at the lowest metallicities (Caffau et al. 2011) or may lie in a not well-mixed interstellar medium from which these stars formed, where the effect of depletion from single supernovae events may become important (Piau et al. 2006; Sbordone et al. 2010). Several models were proposed to solve the cosmological lithium problem, among them Piau et al. (2006) suggested that part of the observed discrepancy might be due to efficient depletion of the cosmic lithium abundance by a population of massive Pop III stars which processed a significant part of the MW halo (one third to one half of the Galactic halo). Our observations disfavor this model, as a fine tuning of the mass fraction processed through massive stars would be required for different galaxies to end up with Li abundances similar to those of Milky Way stars. Additional inconsistencies of this model with the observed abudandance pattern in halo stars were also noted (Prantzos 2007).

Our observations show that the Spite plateau exists in other galaxies and suggest that the mechanisms which produce the cosmological lithium problem, are the same in the MW and in other galaxies.

3. The lithium and sodium content of M 4 and the discovery of a lithium rich dwarf

M 4 is one of the closest galactic GCs. It was found by Marino et al. (2008) to present a well defined Na-O anti-correlation. Hence, it is a natural place to search for the possible presence of a Na-Li anti-correlation.

Observations were obtained for main sequence and sub-giant branch stars using FLAMES/VLT in settings which allowed to measure both the lithium and sodium abundances. Details of the observations, data reduction and analysis can be found in Monaco et al. (2012). The observed target stars are plotted in

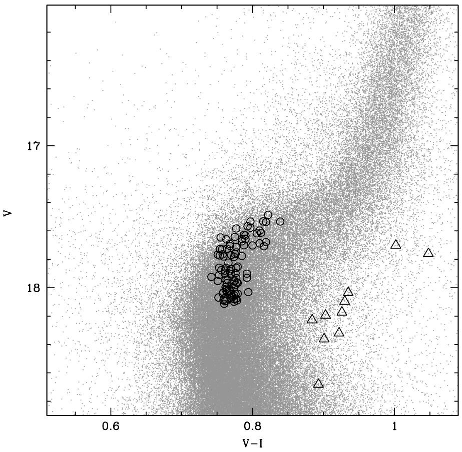

Fig. 1. Target stars are plotted on top of the ω Centauri V *vs* V – I color-magnitude diagram. Open circles mark main sequence/sub-giant branch stars, open triangles mark SGB-a stars. Credit: Monaco et al., A&A, 519, L3, 2010, reproduced with permission © ESO.

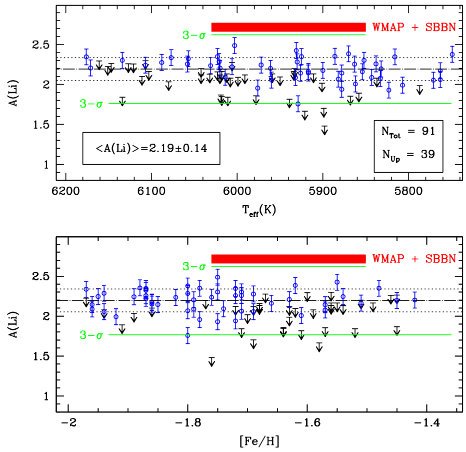

Fig. 2. Measured lithium abundances for targets on the main sequence/sub-giant branch as a function of the effective temperature (upper panel) and the star metallicity (lower panel). The mean Li abundance and dispersion derived for ω Cen, the number of stars analyzed (N_{Tot}) and the number of stars for which we derived upper-limits (N_{Up}) only are indicated in the upper panel. The mean Li abundance (dot-dashed line), the 1–σ (dotted lines) and 3–σ (continuous lines) levels from the mean and the primordial lithium level implied by WMAP measures plus standard big-bang nucleosynthesis (SBBN) theory (shaded area) are also marked for reference. Credit: Monaco et al., A&A, 519, L3, 2010, reproduced with permission © ESO.

Fig. 3 (right panel) as open symbols on top of the cluster CMD. The left panel in the figure presents a sample of the obtained spectra for a few target stars. Figure 4 presents the measured lithium abundances as a function of the stellar effective temperature (upper panel) and of the sodium content (lower panel, only stars at T_{eff} >5880 K).

Figure 4 shows the presence of a Na-Li anti-correlation among the sample of stars observed in the main sequence of M 4. The correlation is detected non-parametrically with a probability of 0.02 of being spurious, according to the calculated Spearman rank correlation coefficient (C_S=-0.34). Nevertheless, the variation in the measured lithium abundance, as a function of the sodium abundance is very small. This suggests that lithium production should have been in place in this cluster. In fact, at the temperatures necessary to produce the sodium increase we observe in the second generation of stars (arbitrarily defined at [Na/Fe]>0.25) we do expect that lithium would be destroyed and yet we see an abundance level quite similar all over the range of the measured [Na/Fe] values. This is consistent with the results of Mucciarelli et al. (2011) and D'Orazi & Marino (2010a), who did not observe any Li-O correlation among main-sequence/sub-giant stars or Na-Li anti-correlation among their sample of giant stars, respectively. The fact that a production of lithium has taken place in the cluster, suggests AGB stars as the most likely polluters of the interstellar medium (ISM) from which the second generation stars were formed.

We can also observe in Fig. 4 the presence of one star, # 37934, presenting a lithium content significantly higher than the rest of the cluster population. In Fig. 3 the position of this star in the CMD and the strong lithium line of this star can be appreciated. The lithium con-

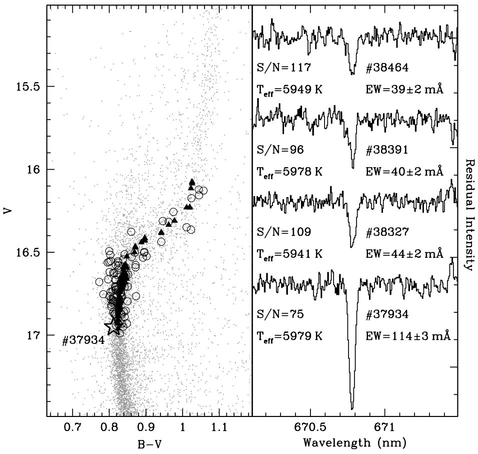

Fig. 3. Left panel: V *vs* B-V M 4 color-magnitude diagram. Target stars are marked by open circles. Filled triangles mark the location of the targets as projected on the cluster mean ridge line. Target # 37934 is marked by the star symbol. Right panel: summed spectra for a sub-sample of the target stars. Credit: Monaco et al., A&A, 539, A157, 2012, reproduced with permission © ESO.

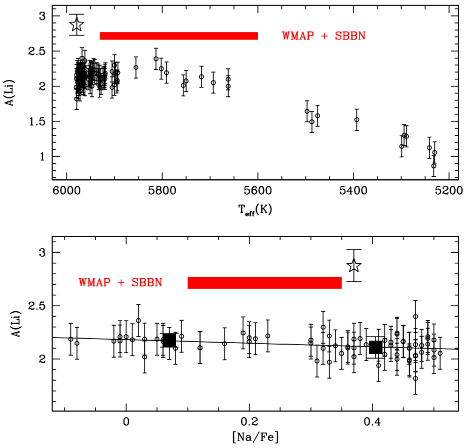

Fig. 4. Measured lithium abundances for targets on the main sequence/sub-giant branch as a function of the effective temperature (upper panel) and the sodium content (lower panel, stars at T_{eff} >5880 K only). The primordial lithium level implied by WMAP measures plus SBBN theory (shaded area) is also marked for reference. In the lower panel, filled squares indicate the mean Li content for the Na-rich/Na-poor sub-samples. The continuous line is a least square fit to the individual data. In both panels, the big open star marks the position of star # 37934. Credit: Monaco et al., A&A, 539, A157, 2012, reproduced with permission © ESO.

tent of star # 37934 is indeed compatible to the cosmological value. Nevertheless, indirect evidence suggests that the high lithium abundance presented by this star is due to pollution of the IMS from which this star formed from the previous generation of stars. In fact, it belongs to the groups of stars with a high sodium content (the second generation of stars) and, as we have just discussed, lithium production has happened in the cluster, as indicated by the shallow slope of the Li-Na anti-correlation. Furthermore, a lithium rich dwarf star has also been identified in the GC NGC 6397 by Koch et al. (2011). This star has a significantly higher lithium abundance (A(Li)=4.21), and certainly represents a case of pollution. This reinforces the pollution hypothesis for the case of stars # 37934 as well. However, all of this evidence is indirect and the possibility that this star has actually been able to preserve the cosmological lithium abundance cannot be discarded.

4. Conclusions

We have presented the results of two spectroscopic campaign conducted using the multi-object facility FLAMES/VLT and aimed at studying the lithium content of the GCs ω Centauri and M 4.

ω Centauri is commonly considered as the remnant of a dwarf galaxy accreted by the MW. Its lithium content is similar to that of the warm, metal-poor dwarfs in the galactic halo, i.e the Spite plateau (see Fig. 2). This suggests that the Spite plateau exists also in other galaxies and favors the idea that it is a universal feature. Hence, the same mechanisms that take place and generate the cosmological lithium problem hold in different environments. At the same time, our results disfavor models which attempt to solve the cosmological lithium problem starting from the particular condition of formation of the MW and the galactic halo in particular.

Our observations have revealed the presence of a very shallow Na-Li anti-correlation among un-evolved stars in M 4 (see Fig 4). This suggests production of lithium took place during the fist phase of formation of the cluster. Therefore, AGB stars appear a more suitable polluter of the ISM from which the second generation of stars formed in this cluster with respect to FRMS.

Additionally, a lithium-rich dwarf (# 37934) was detected in this cluster. This star and the super lithium-rich dwarf detected in NGC 6397 (Koch et al. 2011) currently represent the two only known examples of lithium rich dwarfs in globular clusters. Star # 37934 has a lithium content compatible with the cosmological value. However, the most likely explanation for the nature of star # 37934 in M 4 is an important pollution of the ISM from which it formed from a previous generation of stars. Examples of lithium-rich RGB and AGB stars, reaching up to super meteoritic values have been observed in various environments (see Monaco et al. 2011, and references therein).

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