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Lithium in a metal-poor external galaxy: ω Centauri

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Abstract. ω Centauri is a massive stellar system which is currently going through the Galactic Halo. Its compact aspect and spheroidal shape have for a long time led to it being classified as a Globular Cluster. However the fact that its stars cover a wide metallicity range ($-0.6 <$[Fe/H]< -2.1), points to this object as an external galaxy, satellite of the Milky Way. Lithium among warm metal-poor stars shows a roughly constant abundance, the "Spite Plateau". This has been interpreted as evidence for a primordial origin of the lithium nucleus, at the time of nucleosynthesis. After the physical conditions under which nucleosynthesis occurred, have been constrained by the observations of the fluctuations of the Cosmic Microwave Background, we are facing a "cosmological lithium problem", namely the primordial lithium was a factor of three to four higher than what observed in the Spite plateau. Several avenues may be taken to solve this conundrum, either relying on fundamental physics or on stellar physics, however the realm of possibilities may be considerably narrowed by observing stellar populations in different galaxies, which have experienced different evolutionary histories. Some of the proposed "solutions" may be clearly ruled out, depending on the observation of lithium in the metal-poor populations of external galaxies. ω Centauri is the only external galaxy amenable to such an investigation in the era of 8m telescopes. We have pushed to its limits FLAMES at the ESO 8.2m telescope to obtain high resolution spectra of the Li I doublet in 91 Turn-Off and Sub-Giant stars at V$\sim$ 18 in ω Centauri. We present our preliminary results on this data which suggest that the Li content in ω Centauri warm stars is comparable to that observed in Galactic Halo field stars of similar metallicities and temperatures. This may effectively rule out a whole class of models which invoke a severe Li depletion through processing of material in an early generation of massive stars.

Keywords. Nuclear reactions, nucleosynthesis, abundances – stars: abundances, Population II – Galaxy: globular clusters: individual (ω Cen) – galaxies: abundances, Local Group – cosmology: observations

1. Introduction

The Spite plateau is the constant Li abundance, observed in warm metal-poor stars of different effective temperature and metallicity. This remarkable feature in the abundance pattern of metal-poor stars was discovered by Monique and François Spite in 1982

(1982a,1982b) and was immediately interpreted as a signature of Big Bang Nucleosynthesis (BBN) and a mean to measure the baryonic density of the Universe. See the review of Spite & Spite (2010) on lithium and that of Steigman (2010) on nucleosynthesis in this volume, for an updated view of the problem. The most striking development came from the accurate measurement of the baryonic density from the WMAP satellite (Dunkley *et al.* 2009) which, coupled with standard BBN, implied a primordial Li abundance a factor of three to five higher than the Spite plateau. This discrepancy is often referred to as the "cosmological lithium problem".

Many solutions for this discrepancy have been proposed, including new physics at the time of the Big Bang (see for example Jedamzik 2004, 2006, Jittoh *et al.* 2008, Hisano *et al.* 2009), astration in the pristine Galaxy (Piau *et al.* 2006) and turbulent diffusion to deplete lithium in the stellar atmospheres (Richard *et al.* 2005). A fresh look at the problem can be afforded by the study of lithium in metal-poor populations of external galaxies. Theories like that of Piau *et al.* (2006) can be immediately tested and also theories which invoke stellar phenomena can be seriously constrained by the observation of stellar populations with different star formation histories. Unfortunately even nearby galaxies, like the Magellanic Clouds or the Sagittarius dwarf spheroidal are too far to allow such a study with existing telescopes, although they will be within the reach of the next generation of 40m class telescopes.

There is, however, one external galaxy which is, just about, within reach of our telescopes: ω Cen. The complexity of its colour magnitude diagram clearly testifies the existence of multiple stellar populations with a range of metallicities. It is currently generally accepted that ω Cen is not a globular cluster, but a satellite galaxy of the Milky Way. It is more massive than all other globular clusters (about 2.5×10^5 $M_\odot$, Van de Ven *et al.* 2006), but was probably more massive in the past and has lost mass due to tidal interaction with the Galaxy. In a galaxy which has such a different mass and history with respect to the Milky Way, one should expect a very different lithium content of the metal-poor populations, if the "cosmological lithium problem" is due to astration by an early population. Also in the case of stellar phenomena, such as diffusion, one may expect different lithium content, if the stars show a consistent age spread. Finally we might be able to capture the results of Li production by super-AGB stars, with A(Li) up to 4 (Ventura & D'Antona 2010, D'Antona & Ventura 2010).

2. Observations

We have selected targets on the turn-off and sub-giant branch of ω Cen, mainly from the high precision FORS/VLT photometry of Sollima *et al.* (2005) and from the spectroscopic survey of Villanova *et al.* (2007). Ten targets were selected to trace the faint subgiant branch, called SGB-a in Sollima *et al.* (2005). Our targets are shown in Fig. 1, where we have used the wide field photometry of Bellini *et al.* (2009).

The targets were observed on three nights from April 27th to 29th 2007 at ESO Paranal with FLAMES at the Kueyen 8.2m telescope. The fibres in Medusa mode fed the GIRAFFE spectrograph, configured in the HR15n setting, which covers both Hα and the Li I resonance doublet at 670.8 nm at a resolution of 17 000. The same plate configuration was observed for all the three nights, with integration times between one hour and slightly over two hours. Both plates were used alternatively and configured in such a way as to minimise the light loss due to atmospheric refraction. One further plate configuration was observed, with a partial overlap with the main plate configuration. We thus obtained a total integration time between 17 and 19 hours for 91 stars on the MS/SGB

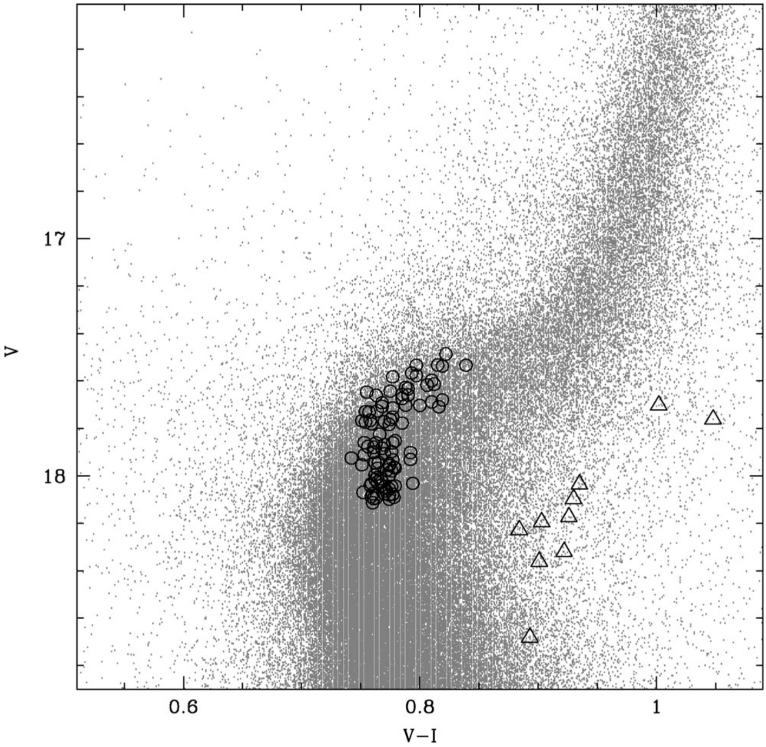

Figure 1. Colour-magnitude diagram of ω Cen from the WFI/2.2m photometry of Bellini *et al.* (2009) Our targets are shown as open circles, except for the targets on the SGB-a of Sollima *et al.* (2005), which are shown as open triangles.

and 10 stars on the SGB-a. After data reduction the spectra achieved S/N ratios in the range 30 to 90 with a mean around 60.

3. Analysis

Our analysis is based on one dimensional model atmospheres computed with version 9 of the ATLAS code (Kurucz 2005) in its Linux version (Sbordone 2005, Sbordone *et al.* 2004). The effective temperature of the stars has been determined by fitting the wings of Hα. The theoretical profiles were computed with a modified version of the BALMER code † which uses the Barklem *et al.* (2000a,b) self broadening theory and Stehlé & King (1999) Stark broadening. At this stage we assumed log g = 4.0 and a metallicity of −1.5 for all stars, thus ignoring the dependence of the Balmer line profiles on metallicity and surface gravity. The equivalent widths of the Li I resonance doublet were measured by fitting synthetic profiles, as done in Bonifacio *et al.* (2002). When we could not detect the Li line we estimated an upper limit as $2\sigma_{EW}$, where σ_{EW} was estimated from the Cayrel formula (Cayrel 1988). A model atmosphere with the appropriate effective temperature, log g = 4.0 and metallicity −1.5 was computed for each star and synthetic profiles were iteratively computed with SYNTHE until the equivalent width of the Li doublet matched the measured equivalent width. A microturbulent velocity of 1 kms^{-1} was assumed, this, like the assumed surface gravity and metallicity, have effects of a few hundredths of

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† The original version of R.L. Kurucz is available at `http://kurucz.harvard.edu/`

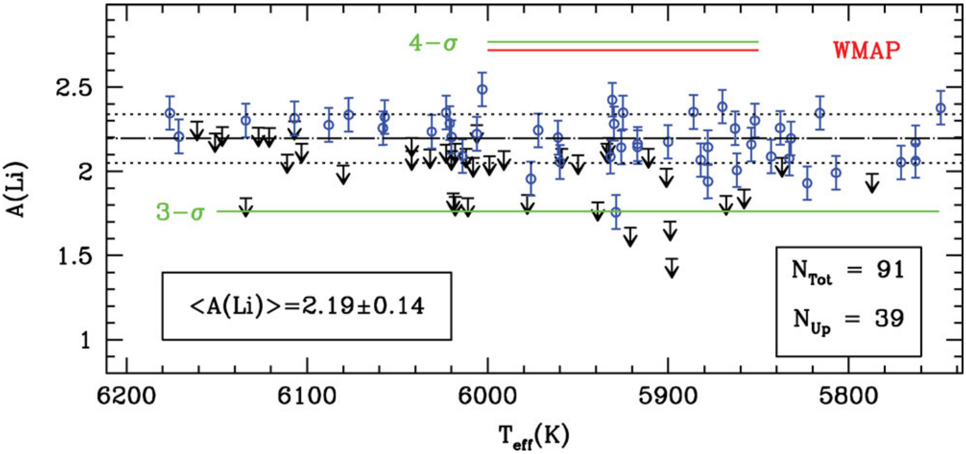

Figure 2. Li abundances in sub-giant and turn-off stars of ω Cen as a function of effective temperature.

dex on the derived Li abundance, this is totally negligible in the current context. Our S/N ratios are high enough that the error on Li abundances is totally dominated by the uncertainty in effective temperatures. The latter is of the order of 150 K and is dominated by the uncertainty in the correction of the blaze function of GIRAFFE. Our estimated total uncertainty on the Li abundance is 0.1 dex.

4. Results

For none of the stars of the SGB-a did we detect the Li doublet. For the other stars our results are summarised in Fig. 2, out of a total of 91 MS/SGB stars for 39 we could not detect any lithium. For the stars with measured Li the abundance appears to be uniform without any trend with effective temperature, the mean value is A(Li)=2.19 with a dispersion of 0.14 dex. We verified that if we use effective temperatures based on the V–I colour the mean Li abundance is similar (2.21) and the dispersion is a little smaller (0.11).

The spectral region covered by our observations is not rich of metallic lines, nevertheless we used the Fe I and Ca I to derive the metallicity of the stars, assuming [Ca/Fe]=+0.4. For the stars in common we get a rather good agreement with the results of Villanova *et al.* (2007) although we note a small offset of the order of 0.1 dex. Although this is, perhaps, not surprising, given the different spectral range, resolution, model atmospheres and spectrum synthesis codes used, we consider these metallicities yet preliminary and we plan to further investigate these differences in the future. However, even with these preliminary metallicities it is clear that there are no obvious trends of Li abundance with metallicity. Also for the upper limits, there does not appear to be present any clustering of upper limits at a particular range of metallicities.

5. Discussion

It appears that the stars of ω Cen lie on the Spite plateau. Comparison with the Galactic field stars, on the same effective temperature scale (see Sbordone *et al.* 2010) shows that the stars of ω Cen occupy the same zone of the Galactic stars, both in the A(Li)–$T_{\rm eff}$ and in the A(Li)–metallicity planes. This brings us to two robust conclusions:

- the Spite plateau exists also in other galaxies;
- the mechanism(s) which cause the "cosmological lithium problem" are the same in the Milky Way and in other galaxies.

Although this has only been established for ω Cen, it is simpler to assume that this is true for all galaxies than to assume that all galaxies behave differently and that only ω Cen behaves like the Milky Way. Until Li is measured in further external galaxies, this is an acceptable working hypothesis.

These facts immediately tell us that explanations of the "cosmological lithium problem" which require a special evolution for the Milky Way Halo are immediately ruled out. This is the case of the model by Piau *et al.* (2006), which requires that from one third to one half of the Galactic Halo ($\sim 10^9 \mathrm{M}_\odot$) has been processed through massive stars which effectively depleted lithium from the primordial value to the current observed Spite plateau. It would be extremely contrived to assume that another galaxy, of current mass $2.5 \times 10^6 \mathrm{M}_\odot$, thus of very different type and evolution from the Milky Way, has undergone a similar process with a fine tuning of the mass fraction processed through massive stars so that the Spite plateau results identical to that of the Milky Way. Occam's razor requires that this theory be discarded.

Among other solutions of the "cosmological lithium problem" all which invoke stellar atmospheric phenomena, such as diffusion might also be tightly constrained by our observations. All such phenomena are time dependent and they may produce a uniform Spite plateau in the Galactic Halo, only because the age-spread in the Halo is very small. So the question is: what is the age spread among the stars observed by us in ω Cen? For the stars in common with Villanova *et al.* (2007) we may use their age estimates, based on theoretical isochrones, their metallicity estimates and the requirement that, in the colour-magnitude diagram, each sub-giant branch be associated to a Main Sequence which contains the same relative number of stars. Such ages are given in their table 2 and for the stars in common with our study we find the age spread is 5.6 Gyr. If the age spread in ω Cen is indeed so large, then all theories which invoke time-dependent phenomena, such as diffusion, would be ruled out, since it would be impossible for stars of such different ages, which have started their lives with the same (primordial) Li abundance, to still show the same Li abundance.

However the actual age spread in ω Cen is still a matter of debate and the relative ages of Villanova *et al.* (2007) stand out in the literature for providing the largest spread. Our sample of stars captures essentially the metal–poor population of ω Cen. According to the vast majority of studies, the intrinsic age spread of this population is consistent with zero, from the first photometric estimates (e.g., Hughes *et al.* 2004, Hilker *et al.* 2004), to the most recent spectro-photometric studies based on high precision HST CMDs and low resolution spectroscopy of vast samples of SGB and TO stars (such as Sollima *et al.* 2005, Stanford *et al.* 2006, Kayser *et al.* 2006). Theoretical work supports these findings, implying that a first, coeval generation of stars (the metal–poor population) is responsible for at least part of the pollution of the subsequent generations (see e.g., Norris 2004, Lee *et al.* 2005, Romano *et al.* 2009). The uncertainties of the experimental age spread determination procedures still allow to accommodate for a maximum spread – within the metal–population – of about 1 Gyr. Besides Villanova *et al.* (2007), also the spectroscopic study by Johnson *et al.* (2009), supports a consistent age spread. In this study the metal-poor stars show different degrees of s-process enrichment (see their Figure 13), implying some 0.1–3 Gyrs (Schaller *et al.* 1992) for intermediate-mass AGB stars to pollute part of the metal-poor group, depending on the actual mean mass of the AGB population.

It is thus clear that at the present state of understanding of the age spread in ω Cen our observations do not provide a strong constraint on the viability of diffusion-like mechanisms for Li depletion. Future spectroscopic and photometric observations are likely to better pinpoint this issue. It is possible that even a spread of 1 Gyr would prove a strong constraint on possible Li depletion mechanisms

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