The Lithium content of Globular Clusters

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Resumen / El litio es uno de los pocos elementos producidos durante la breve fase de la nucleosíntesis cosmológica, unos minutos después del big bang. Por lo tanto, el estudio de su abundancia en estrellas viejas y pobres en metales revela detalles de las condiciones físicas del universo en esta fase temprana. Describiré cómo el estudio de la abundancia de litio en cúmulos globulares proporciona información sobre sus proceso de formación y el valor cosmológico.

Abstract / Lithium is one of the few elements produced during the brief phase of cosmological nucleosynthesis, a few minutes after the big-bang. Therefore, the study of its abundance in old, metal-poor stars reveals details of the physical conditions of the universe in this early phase. I will describe how the study of the lithium abundance in globular clusters provide information about both their formation process and the cosmological value.

Keywords / stars: abundances — stars: atmospheres — primordial nucleosynthesis — globular clusters: general

1. Introduction: the cosmic lithium problem

According to standard cosmology, only a few light elements (H, D, ^{3}He, ^{4}He and traces of ^{7}Li) were produced in appreciable amount during a brief phase of nucleosynthesis (standard big-bang nucleosynthesis, SBBN) which took place a few minutes after the big-bang (Coc et al., 2014). It is from this simple chemical composition, that the first stars (population III) formed a few hundreds of million years afterwards and, soon after, started enriching the interstellar medium (ISM, Bromm & Larson, 2004).

In their seminal papers, Spite & Spite (1982b,a) showed that warm, un-evolved halo stars present the same lithium abundance, within the measurement errors, over a wide range of temperatures and metallicities. The interstellar medium from which these, presumably old, stars formed should not have had time to be enriched in lithium by galactic sources (Romano et al., 1999; Prantzos, 2012; Molaro et al., 2016) and the constant lithium abundance (A(Li)*) measured in their atmospheres (the so called "Spite plateau") was suggested to reflect the cosmic production occurred during the SBBN phase. In fact, since the production of elements during SBBN is determined by the baryon to photon ratio (the η parameter), a cosmological parameter not constrained by first principles, the lithium level at the Spite plateau was used as a tool to determine the η parameter.

However, when η was measured from the cosmic microwave background data of the *WMAP* first and the *Plank* satellites later (Hinshaw et al., 2013; Planck Collaboration et al., 2014), it became possible to predict the amount of lithium produced during the SBBN. This resulted to be three times in excess to the value of the Spite plateau (A(Li)=2.69±0.03 against A(Li)=2.2±0.1 dex, Coc et al., 2014). This discrepancy is usually referred to as the cosmic lithium problem.

*A(Li)=$\log\frac{n(Li)}{n(H)}+12.0$.

2. Searching for a solution

Once the existence of a discrepancy between the lithium abundance at the plateau and the SBBN predictions was acknowledged, the community started to look for a solution to this riddle. To further complicate the observational scenario, a "meltdown" of the Spite plateau was evidenced at metallicities [Fe/H]<-2.8 dex (Bonifacio et al., 2007; Aoki et al., 2009; Sbordone et al., 2010; Bonifacio et al., 2018), where an increase in the scatter, no longer compatible with the measurement errors, together with a lower mean abundance, was observed.

It is worth mentioning that no discrepancy emerged between the prediction and observations, for the elements produced during the SBBN other than lithium (Coc et al., 2014). Therefore, any proposed solution should be able to reconcile the lithium discrepancy, while preserving the agreement achieved for the other elements. At the same time, it should be able to account for a plateau having a dispersion in abundance compatible with the measurement errors and flat over a wide range in temperature (T_{eff} > 5900 K) and metallicity (-2.8 to -2 dex, Spite et al., 2012). It should also account for the meltdown of the plateau at [Fe/H]<-2.8 dex.

Solutions to the cosmic lithium problem have been searched for following different routes, either requiring modification to the SBBN theory, investigating the cross section of the nuclear reactions involved, or considering stellar processes which may affect the lithium abundance measured in the stellar atmospheres. We refer the reader to the reviews on the subject by Spite et al. (2012) and Iocco (2012) summarizing both the observational and theoretical aspects of the problem.

Particular interest into solutions outside the standard cosmological model was triggered by the claim of the detection of a significant amount of ^{6}Li in a sample of metal-poor stars by Asplund et al. (2006). SBBN does not, in fact, produce this isotope in any appreciable amount. On the other hand, the production of ^{6}Li is an outcome of many theories outside the standard model (Iocco, 2012). The abundance of ^{6}Li is measured as an asymmetry in the red wing of the lithium resonance doublet at 6707.8 Å. Such an asymmetry may, however, also be the signature of convective motions in the stellar atmospheres, as readily noticed (Cayrel et al., 2007). Indeed, it seems now well established from state of the art analysis, that the great majority of the claimed ^{6}Li detections were, in fact, due this affect (Steffen et al., 2012; Lind et al., 2013).

3. Stellar solutions

If we accept the SBBN predictions, we may search for solutions to the cosmic lithium problem related to the stellar astrophysics theory.

Diffusion may deplete the lithium content in the stellar atmosphere from its original value. In fact, being heavier than hydrogen, lithium is susceptible to sink into the stellar atmospheres (Michaud et al., 1984). The constant lithium observed at the Spite plateau, suggested that diffusion was inefficient in the atmospheres of metal-poor stars. Furthermore, the lithium depletion in the stellar atmosphere of a metal-poor dwarf is temperature/mass dependent as a consequence of the different extension of the convective envelope (Salaris & Weiss, 2001). Therefore, the inclusion of diffusion in the stellar models is unable to simultaneously reduce the lithium abundance while at the same time produce a plateau similar to the observed one (but see Bressan et al., 2013; Fu et al., 2015).

Richard et al. (2005) tried to remedy the situation including some turbulent mixing phenomenon in their models, beside diffusion, which could be activated at some specific temperature and could bring material, more or less efficiently, down to regions at temperatures $T>2.5\times10^6$ K, where ^{7}Li is readily destroyed. This way, they were able to produce a plateau at a value compatible with observations, starting from the SBBN lithium abundance accepted at that time.

Piau et al. (2006), on a different approach, searched for a solution in the local conditions of formation of the Milky Way halo. They proposed that a first generation of massive population III stars might have efficiently depleted in lithium the material from which population II halo stars observed at the Spite plateau formed. A fraction between one third to one half of the halo material should have been processed in order to obtain a $\sim$0.3 dex depletion in the lithium abundance. An additional, in situ depletion was needed, though, to reconcile the observed value with the cosmological predictions. Prantzos (2007), however, noticed that the enrichment of the ISM caused by these Pop III stars would have led to a metallicity larger than observed in extremely metal poor stars.

We notice that lithium depletion may occur already during the pre-main sequence phase, when temperatures high enough to destroy lithium may be reached in the stellar core, and when the convective envelope extends down to these regions. Standard models indicate this should be significant for masses lower than $\sim0.7\,M_\odot$ only (Salaris & Weiss, 2001). Fu et al. (2015), on the contrary, proposed a model in which lithium is totally destroyed during the pre-MS phase for masses as high as $0.8\,M_\odot$, and then restored in the stellar atmosphere through a phase of late accretion from the ISM. They were able to reproduce a plateau compatible with the observations.

From the observational point of view, Nissen & Schuster (2012) were able to put into evidence a dependence of the lithium abundance with metallicity and stellar mass. Their sample, however, comprises stars at [Fe/H]$\geq$-1.6 dex only. Meléndez et al. (2010) also showed a similar dependence of the lithium depletion with stellar mass on a sample of stars extended down to [Fe/H]=-3.5 dex. These latter authors found the trend of depletion with mass to be similar to the predictions of Richard et al. (2005) models.

4. Information from globular clusters

Globular clusters (GCs) are among the oldest objects known in the Galaxy (Marín-Franch et al., 2009). They are, thus, precious cosmological probes and witnesses of the early epochs of formation of the Galaxy. For a long time they have been considered the prototype of simple stellar populations and have been a key testbed of the stellar evolution theory (Renzini & Fusi Pecci, 1988). This peculiar combination of properties has made GCs interesting tools to investigate the cosmic lithium problem.

Korn et al. (2006) used high resolution, high signal-to-noise spectra to measure the abundances of main sequence (MS), sub-giant branch (SGB) and red giant branch (RGB) stars in the GC NGC 6397. They detected variations in the abundances of Li, Fe, Ca and Ti, as a function of the evolutionary phase compatible with Richard et al. (2005) models. This lead to suggest those models to provide a "probable" solution to the cosmic lithium problem. It should be noticed, though, that Richard et al. (2005) do not identify the physical origin of the turbulent mixing phenomenon they introduce in their models and the temperature at which this is activated is determined by the comparison with the observations only.

González Hernández et al. (2009), investigated two groups MS and SGB stars at the same temperature in NGC 6397. They found the equivalent widths of the lithium resonance doublet to be stronger among SGB than in MS stars confirming, thus, that the primitive Li abundance was alterer by diffusion. On the other hand, the very same model used by Korn et al. (2006) was unable to simultaneously reproduce the abundance trends with temperature observed among SGB and MS stars.

Richard et al. (2005) models were further employed to study the behavior of the abundance with the evolutionary phase in M30 and NGC 6752. Different values of the temperature parameter at which the additional turbulent mixing phenomenon is activated may be required in different clusters (Mucciarelli et al., 2011; Nordlander et al., 2012; Gruyters et al., 2014, 2016). These observations and models recover an original lithium abundance $\sim 0.1-0.2$ dex lower with respect to SBBN predictions, although with errors of the order of ± 0.1 dex.

Interestingly, the lithium abundance measured among MS stars in GCs, with the exception of 47 Tuc, was found at the same level of halos stars, i.e. A(Li)$\simeq$2.2 dex (Dobrovolskas et al., 2014). This includes ω Centauri (Monaco et al., 2010), commonly considered as the remnant of a dwarf galaxy accreted by the Milky Way (see Ibata et al., 2019, and references therein). Indeed, the need of high resolution, high signal-to-noise spectroscopy of un-evolved stars, has largely limited, until recently, the investigation of the cosmic lithium problem to Milky Way stars, with the only exception of ω Cen. In fact, even in the closest galaxy, the Sagittarius dwarf spheroidal (Sgr dSph, Ibata et al., 1994), MS stars are too faint to be observed with the current instrumentation on 8-10 m class telescopes. Howk et al. (2012) managed to measure the lithium abundance in the ISM of the Small Magellanic Cloud (SMC). This has the advantage of not being affected by the phenomena at play in the atmosphere of dwarf stars. These authors measured a lithium level compatible with the SBBN predictions. However, at the SMC metallicity ([Fe/H]>-1), contamination from galactic sources should already be affecting the observed abundances. This is particularly evident when comparing the A(Li) in the SMC with the trend with metallicity of galactic stars (Howk et al., 2012). Therefore, one has to conclude that either the measured value is larger than the primordial one, due to the enrichment by galactic sources, or that this latter should have been very limited in the SMC.

5. Pristine abundances from RGB stars

When a star evolves from the MS to the SGB and RGB, the deepening of the convective envelope bring to the surface material which was exposed to high temperatures and is, hence, depleted in lithium. This dilution causes an overall decrease of the surface lithium abundance. An additional decrease in A(Li) occur when the star cross the RGB-bump luminosity level, where an additional extra-mixing episode is known to take place (Gratton et al., 2004).

Mucciarelli et al. (2012) showed that RGB stars which have already completed the dilution, and evolving still below the luminosity of the RGB-bump (lower RGB stars, LRGB), can be used to infer their initial surface abundance. The amount of dilution is, in fact, reliably predicted by standard stellar models and LRGB stars lie at a plateau that resembles the (dwarf) Spite plateau but at a lower level (A(Li)$\simeq$1.0 dex, Mucciarelli et al., 2012). Furthermore, the resulting A(Li) level of LRGB stars is largely independent of the details of the diffusion processes affecting the surface abundance in dwarf stars. Therefore, the use of LRGB stars has the double advantage of removing one of the main uncertainties about the physical processes in the stellar atmospheres, while at the same time allowing for the use of brighter stars and, thus, reaching further distances. The lower temperatures of LRGB with respect to MS stars also helps at obtaining stronger lines, while dealing with surface Li levels over 1 dex lower than in MS.

Indeed, the use of LRGB stars has allowed Mucciarelli et al. (2014), to measure the lithium abundance of M54, a massive GC lying within the nucleus of the Sgr dSph galaxy (Monaco et al., 2005; Bellazzini et al., 2008). By averaging the spectra of 51 LRGB stars, Mucciarelli et al. (2014) were able to measure A(Li)$_{LRGB}$=0.93$\pm$0.11 dex, corresponding to a initial abundance in the range A(Li)=2.29-2.35 dex, hence again significantly lower than SBBN predictions. The results obtained for ω Cen and M54 indicate, thus, that the cosmic lithium problem is not limited to the Milky Way, but it is common to other, admittedly close, (dwarf) galaxies.

6. Lithium and the formation of globular clusters

GCs revealed to be more complex than thought, hosting multiple stellar populations (MPs) characterized by variations in the content of their light elements (C, N, O, Na, Mg, Al). Most GCs hosts at least two stellar populations: one usually termed "first generation" (FG) presenting a chemical composition similar to typical halos stars, and an additional "second" (SG) or polluted generation, presenting trends in their chemical patterns which can be explained by processing by the CNO cycle and other high temperature hydrogen burning chains, namely the NeNa and MgAl cycles. When these patterns were identified in low-mass main sequence stars, it was realized that they are a birthmark (Gratton et al., 2001). However, the identity of the polluters which contaminated the ISM from which the second stellar generation formed is still matter of an intensive and lively debate. A completely satisfactory and accepted model for the GC formation is still lacking and we refer the reader to the recent review by Bastian & Lardo (2018) for a description of the current state of affairs.

One of the most notable features marking the presence of MPs in GCs is the Na-O anti-correlation (Carretta et al., 2009b,a), with FG stars presenting an enhancement in oxygen, typical of the [α/Fe] enhancement of halo stars, and about solar [Na/Fe] abundance ratios, while SG stars have enhanced [Na/Fe] and lower [O/Fe] abundance ratios. Since the NeNa cycle likely responsible for the Na-O anti-correlation is activated at temperatures significantly larger than required to destroy lithium, one may expect anti-correlations between both Na-O and Na-Li. However, some polluter may have a significant lithium yield acting in the opposite direction. Therefore, the study of the lithium content of GCs, may hold crucial information about the polluters of the ISM from which SG stars formed and, hence, into the formation process of GCs.

Among the main candidates as polluters, fast rotating massive stars (FRMS, Decressin et al., 2007) do not produce lithium, while asymptotic giant branch

(AGB) and super-AGB (~6.5—8 $M_\odot$) stars may produce significant amount of lithium through the Cameron & Fowler (1971) mechanism during hot bottom burning (D'Antona et al., 2012). Pollution from AGB stars, would tend to generate a Na-O correlation, rather than an anti-correlation. For this reason models considering AGB stars as polluters also include some level of dilution of the AGB ejecta with the pristine gas of the cluster (D'Ercole et al., 2010).

Indeed, Li correlations and anti-correlations with light elements were detected in a few GCs and not detected in others (Pasquini et al., 2005; Lind et al., 2009; Shen et al., 2010; Monaco et al., 2012; Dobrovolskas et al., 2014; D'Orazi et al., 2014, 2015; Mucciarelli et al., 2018). Modeling has been attempted in some cases without, however, succeeding at univocally identifying the polluters responsible for the observed Li-Na patterns (D'Antona et al., 2012), although indications in favor of the AGB scenario were also found (D'Antona et al., 2019).

Monaco et al. (2012) identified a dwarf star in M4 (#37934) presenting a lithium content compatible with the cosmological value. While it is possible that this star, at odds with the others, was able to preserve the primordial abundance of lithium, the fact that it is a SG star rather suggests that its high lithium content is the result of pollutions. In D'Antona et al. (2012) models, a limited number of stars may form from the pure ejecta of super-AGB stars, before dilution with the pristine gas. These stars may present A(Li) similar or even larger than observed in #37934, depending on the mass of the polluter super-AGB. Stars formed from the pure ejecta of super-AGB stars would also present enrichment in He and Na. This latter at a level significantly higher than observed in #37934. No other chemical peculiarities were identified in this star, other than its high lithium abundance (Spite et al., 2016). A lithium rich MS star was also identified in NGC 6397 at a level significantly higher even than the meteoritic abundance (A(Li)≃4.03 dex, Koch et al., 2011) again supporting the pollution scenario. At variance with the M4 case, this star belongs to the FG and no radial velocity variations greater than $0.95\,\mathrm{km\,s^{-1}}$ were detected over 8 years (Pasquini et al., 2014). Li et al. (2018) also identified MS and SGB metal-poor field stars having A(Li)>4 dex, suggesting that a pollution mechanism may be at work already among MS stars and not necessarily related to the environment, at odds to what the M4 and NGC 6397 cases might have indicated. Notice that, similarly to the case of #37934 in M4, also the Li-rich dwarfs in NGC 6397 and among metal-poor field stars do not present any other chemical anomaly other than in their Li abundance (Pasquini et al., 2014; Li et al., 2018), a situation which resembles that of Li-rich giants observed in the field (Castilho et al., 2000; Ruchti et al., 2011).

Mucciarelli et al. (2018) used again LRGB stars to study the lithium content in the various stellar populations (of different metallicity) of ω Cen. They found well defined Al-Li and Na-Li anti-correlations. This latter more extended than usually seen in other clusters. While most of the stars present a lithium abundance similar to that of field LRGB stars, a significant number of Li-depleted (upper limits or measures lower than A(Li)=0.8 dex) stars were found at all metallicities. All of them are SG stars. FRMS may be a viable polluters for the ISM from which these stars were born. On the other hand, both FG and SG stars having normal lithium abundance are present in ω Cen. The normal lithium content in SG, Na enhanced stars, suggest a polluter which had a significant lithium yield, like super-AGB stars. Hence, different kind of stars may have polluted the ISM from which SG stars formed (see also D'Orazi et al., 2015; Carretta et al., 2018). Notice that upper limits only could be measured at [Fe/H]>-1.3 dex.

Mucciarelli et al. (2019) detected two Li-rich stars in ω Cen, having A(Li)=1.65 and 2.40, to be compared with the normal halo value of A(Li)≃1.0 dex. It should be noted that, unless they resulted from mass-transfer form a companion (Casey et al., 2019), these A(Li) are to be corrected for the dilution process the stars went through and correspond to original lithium abundances over one dex larger. The most Li-rich of these stars, #25664, belong to the dominant metal-poor ω Cen population and presents a Na content larger than the rest of the distribution, namely [Na/Fe]=+0.87 dex. This is similar to what predicted for stars formed by the pure ejecta of super-AGB stars by the D'Antona et al. (2012) models. Together with its large original lithium abundance, this makes this stars a strong candidate of this, so far, theoretical type of stars.

Notice that Li-rich stars were detected in GCs in the MS, SGB and RGB, both above and below the RGB-bump level (see Kirby et al., 2016; Gruyters et al., 2016, and references therein).

7. Conclusions

A discrepancy emerged between the constant lithium abundance measured in warm metal-poor halo dwarf stars (A(Li)≃2.2±0.1 dex, the Spite plateau level) and the predictions of SBBN coupled with the baryon to photon ratio measured by the *WMAP* and *Plack* satellites (A(Li)≃2.69±0.03 dex, Coc et al., 2014). The origin of this cosmic lithium problem is still an unsolved riddle. Various mechanisms were proposed as possible solutions, but no consensus has been reached yet on none of them (see Spite et al., 2012; Iocco, 2012; Fu et al., 2015, and references therein).

GCs, being old and close to simple stellar populations, played an important role in this controversy. GCs observations put into evidence the effects of diffusion in the stellar atmosphere of MS stars (González Hernández et al., 2009). However, modeling the diffusion process and possible additional phenomena still represent a mayor uncertainty when trying to recover the primordial lithium level.

LRGB stars allow to recover the pristine lithium abundance, being only marginally influenced by the details of the diffusion processes affecting the atmospheres of MS stars. Field metal-poor LRGB stars imply a pristine lithium abundance significantly lower than SBBN predictions (Mucciarelli et al., 2012). LRGB allowed to infer the formation lithium abundance of stars in M54, a

GC belonging to the Sgr dSph (Mucciarelli et al., 2014). This and the measures in ω Cen (Monaco et al., 2010) are both compatible with the Spite plateau level, indicating that the cosmic lithium problem exists also in other galaxies.

The formation process of GCs is also a matter of debate. GCs host multiple populations, but the nature of the polluters of the ISM from which SG stars are formed is unclear. Different polluters may or may not have a significant lithium yield. Lithium is a fragile element destroyed at relatively low temperatures ($T>2.5\times10^6$ K) while significantly hotter temperatures are required to generate the observed abundance patterns. In this respect, the study of the lithium content in GCs is a precious tool to understand the nature of the polluters which gave rise to SG stars. Observations seem to support the idea that different polluters may be simultaneously at play (D'Orazi et al., 2015; Carretta et al., 2018; Mucciarelli et al., 2018).

The Li-Na-rich LRGB star recently discovered in ω Cen (Mucciarelli et al., 2019) may be the first detection of a star formed by the pure ejecta of super-AGB stars before dilution with the residual pristine gas in the cluster (D'Antona et al., 2012).

Lithium rich MS stars were detected in GCs (Koch et al., 2011; Monaco et al., 2012) and field metal-poor stars (Li et al., 2018). The mechanism(s) producing such enrichment are yet to be isolated (see, e.g., Pasquini et al., 2014).

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