Abundances of Li in clusters

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Abstract

Taken individually, stellar clusters offer the possibility of studying a population of stars that have approximately the same age and the same chemical composition. This allows to highlight the effects of stellar evolution on the properties of the stars. In this context the fragile element lithium is a very good indicator of mixing that occurs as the star evolves, but also of less well-understood phenomena, such as the appearance of lithium-rich stars. Taken collectively, stellar clusters span more than two orders of magnitude in metallicity and ages from extremely young to as old as the Universe. In this context the lithium abundances in stellar clusters are an interesting alternative to field stars to study the chemical evolution of Li. Since this conference is in hounour of Luca Pasquini I shall highlight some of his many important contributions to this field, as well as a few aspects that I find interesting.

1 Introduction

The fact that Li is destroyed by nuclear reactions at temperatures above 2.5×10^6 K is at the root of the deficiency of Li in the solar photosphere, A(Li)= 1.01 (Caffau et al., 2011), with respect to the meteorites, A(Li)= 3.28 (Lodders et al., 2009). The convection brings material to temperatures above the Li destruction temperature and this Li-depleted material is then brought back to the photosphere, resulting in a decrease of the Li abundance in the latter. This effect is obviously expected to increase with age, the longer the process has been going on and the more the Li is depleted. One also expects an effect on metallicity, since the depth of the convection zone is metallicity dependent. For these reasons observing the Li abundances in a star cluster, in which all the stars share the same age and metallicity, allows one to focus on the dependence on the stellar mass, or effective temperature, the two are equivalent variables for main sequence stars, like the Sun. One of the early attempts of this was by Wallerstein et al. (1965), who observed the Hyades and obtained two important results: the overall Li content of the Hyades is higher than that of the Sun, and the lower the mass (or effective temperature) the lower the Li abundance. The first result is a practical demonstration of the dependence of Li abundance with age, the Hyades have an age of 0.625 Gyr (Perryman et al., 1998) and the Sun, 4.6 Gyr (Bonanno et al., 2002). The second is consistent with the theoretical prediction that lower mass stars have deeper convective regions. Wallerstein et al. (1965) also noticed several warm stars for which they could not detect the Li 670.7 nm doublet, but did not identify these stars as a special group in terms of colour or luminosity. The first modern investigation of the same cluster was that of Cayrel et al. (1984), who used a high-resolution spectrograph at the coudé focus of the 3.6 m CFHT telescope and a RETICON detector. The effective resolving power was probably around R=45 000[1], a factor of two higher than (Wallerstein et al., 1965), based on a photographic spectrograph. Two years later with the same spectrograph and detector, but a different camera and grating that provided a slightly higher resolving power R=61 000, Boesgaard & Tripicco (1986)[2] confirmed the results of Cayrel et al. (1984), but extended the observations to warmer F-type dwarfs and found, like Wallerstein et al. (1965), that some stars had no detectable lithium. However, thanks to better photometry, they demonstrated that all stars with no lithium occupied a small range in colour (effective temperature), in stars that are to the blue of this range the Li reappeared with the same abundance it had to the red of this range (see figure 2 of Boesgaard & Tripicco 1986). This feature is called the lithium dip and is observed

[1] Since all the authors of this paper are now deceased it is difficult to know the exact resolving power. What is quoted, as customary at the epoch, is the dispersion of 71 mÅ/pixel, but the slit width is not provided. The estimated resolving power comes from assuming a point-spread function of 2.1 pixels FWHM.

[2] In this case the resolution is provided explicitly and there is no doubt. Boesgaard & Tripicco (1986) also used somewhat lower resolution data (R=42 000) obtained with the University of Hawaii 2.2 m telescope.

in many open clusters, esssentially in all that are young enough to have F stars on the main sequence. The origin of this feature is much debated in the literature, however I believe we still do not have good explanation for it. For further reading, I suggest François et al. (2013); Deliyannis et al. (2019); Aoki et al. (2021, and references therein) and of course, the excellent review by Charbonnel & Prantzos (2026).

Earlier in the 1980's Spite & Spite (1982a,b) discovered that warm halo stars had the same lithium abundance, whatever their metallicity or effective temperature. This feature was later called the Spite plateau. This finding came as a big suprise, since the known dependence of Li abundance on age, induced people to expect that in stars with ages of 10 Gyr or older, like most of the halo stars, Li should be completely depleted, or in any case depleted to a level which prevented the detection of the Li I 670.7 nm doublet. Instead Spite & Spite (1982a) correctly pointed out that the lack of dependence of the lithium abundance on metallicity, considered as a proxy of age, and effective temperature, considered as a proxy of mass, suggested that these metal-poor warm stars likely preserved their birth lithium content. Under this assumption they interpreted the Spite plateau as the lithium formed during primordial nucleosynthesis. The lithium produced in the big bang nucleosyntheisis, under standard hypothesis[3] depends only on the baryon-to-photon ratio η (or equivalently on the baryonic density), thus for many years the Spite plateau was considered to be one of the main constraints on this quantity. This was until we began to have available accurate and precise measurements of the power spectrum of the anisotropy of the comsic microwave background (de Bernardis et al., 2002; Hinshaw et al., 2013; Planck Collaboration et al., 2020). These measurements provided an independent measurement of the baryonic density, which is inconsistent with the Spite plateau. In fact the prediction of SBBN is for a lithium abundance about a factor of three higher than that of the Spite plateu. This tension is called the cosmological lithium problem, and I shall come back to possible solutions to this problem. Ages for field stars are difficult to obtain; however, fairly robust ages can be obtained for clusters from their colour-magnitude diagrams. After the discovery of the Spite plateau it became a major goal to measure Li in Globular Clusters (GCs). However this is observationally challenging since the nearest GC, NGC 6397, as a Turn-Off (TO) around magnitude 16.1. This had to wait several more years and it was Molaro & Pasquini (1994), with EMMI on the ESO 3.5 m NTT telescope, who succeded to measure Li in one TO star in NGC 6397. This was a very challenging observation, which was followed by observations of six more stars in the same cluster (Pasquini & Molaro, 1996) and five stars in 47 Tuc (Pasquini & Molaro, 1997). This was the maximum that could be done with 4-m class telescopes and soon the scene was taken by observations on the 8-10-m telescopes, the pioneering observation being that of Boesgaard et al. (1998), who measured Li in M 92 TO stars, with HIRES on the Keck telescope. These observations were followed by many others, mainly with VLT, but this is another story. By and large these early observations already showed that Li in TO stars of GCs is consistent with the Spite plateau. After this concise historical introduction I shall turn to a few specific results that I would like to discuss.

2 Pal 12 observed with ESPRESSO 4-UT

The design of the VLT telescopes included an incoherent combined Coudé focus that was thought to host a high resolution-spectrograph. This materialised over 20 years after the first light of the first Unit Telescope (Giacconi, 1998) with ESPRESSO (Pepe et al., 2021), that can collect the light coming from the four Unit Telescopes, formally the equivalent of a 16.4-m diameter telescope. Although this is the largest collecting area currently available for an optical telescope, there is a price to pay: the coudé optics have a cost in terms of the efficiency of the instrument, the injection into the spectrograph is non-trivial. For this reason Luca Pasquini decided to submit a Science Verification proposal to see how faint a star one could observe, obtaining a scientifically useful spectrum for absorption line spectroscopy. The target was the GC Pal 12, which is associated to the Sgr dwarf spheoridal galaxy (Ibata et al., 1995) and is moderately metal-poor. If the Spite plateau is universal we expect warm metal-poor stars in other galaxies and their associated GCs to share the same Li abundance. This has already be demonstrated for ω Centauri, the bulge of a disrupted galaxy, (Monaco et al., 2010), using TO stars. Mucciarelli et al. (2014) etsablished that another GC, belonging to the Sgr dSph, M 54, has a Li content consistent with the Spite plateau using giant stars[4]. However, up to now, nobody has been able to measure Li in a TO star of Sgr or

[3] Standard Big Bang Nucleosynthesis (SBBN): the Universe is homogeneous, isotropic, it is expanding and there are three light neutrinos. See Coc & Vangioni (2017) for further details on Standard Big Bang Nucleosyntheisis.

[4] They used the fact that giant metal poor stars, less luminous than the bump, display a plateau in Li abundance at A(Li)=1. This corresponds to an initial Li on the Spite plateau, followed by the effect of Li dilution as the star expands and climbs up the Red Giant Branch (RGB). I usually call this the Mucciarelli plateau, since, although it was known for many years it was the idea of A. Mucciarelli to use it systematically to probe the Li abundance of a stellar population, providing also the theoretical arguments for its existence (Mucciarelli et al., 2012).

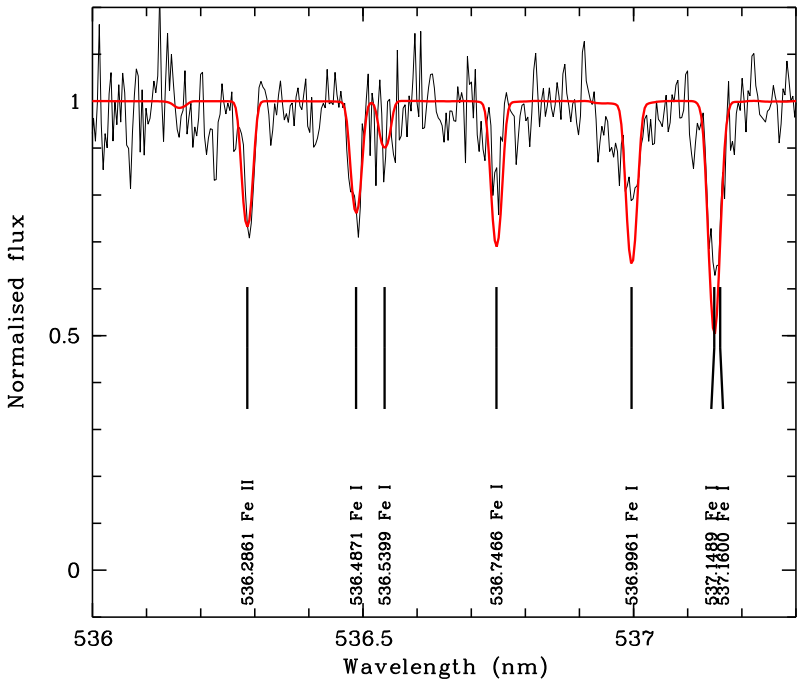


Figure 1: A portion of the combined ESPRESSO spectrum of the BSS 1336in Pal 12 used by (Pasquini et al., 2022). The red spectrum is the best fit from MyGIsFOS (Sbordone et al., 2014).

of any of its GCs, since these stars are too faint. For this reason, Pal 12 seemed a fairly good case. Nevertheless, the TO is probably too faint even for the 4 UT mode, thus Pasquini et al. (2022) observed a Pal 12 Blue Straggler Star (BSS) that at $G = 19.01$, is almost one magnitude brighter than the cluster TO. The scientific case was to try and determine if the BSS was formed by a stellar collision or by mass transfer in a binary system. According to Glebbeek et al. (2010) in the first case one should observe A(Li) $\approx$ 1.0, while in the latter, lithium should be depleted by about 5 dex, making it unobservable. Despite the brighter magnitude, Pasquini et al. (2022) had to confront the problem that the star is very warm, with $T_{\rm eff} = 7042$ K, which means that all lines are considerably weaker than those of cooler stars of the same metallicity. However, they managed to determine abundances of 16 ionic species and 13 elements. A portion of the ESPRESSO 4-UT spectrum is shown in Fig. 1. To compare the abundances with those of RGB stars in the same cluster, they analysed the HIRES Keck spectrum of an RGB star of the sample of Cohen (2004). They concluded that the abundances of the two stars are the same within the errors, with the notable exception of Mg, which is depleted by 0.5 dex in the BSS. For the lithium, however, they could not obtain a meaningful upper limit, A(Li) $\leq$ 3.1 is inconclusive for the test they proposed. The low Mg abundance may suggest a case B or C[5]mass transfer, with the donor being an RGB or Asymptotic Giant Branch (AGB) star that transferred material which has experienced high enough temperatures to deplete Mg, by forming Al through proton capture. Mass transfer from an RGB star should result in a low [C/O] ratio as observed in some BSS of 47 Tuc (Ferraro et al., 2006). Mass transfer from an AGB star should be acompanied by a carbon enhancement and, in some cases, by an enhancement of neutron-capture elements as observed in some field BSS (Sneden et al., 2003). Given the high temperature of the star, there is no indication on the C abundance. Among the four neutron-capture elements observed (Sr, Y, Zr, Ba), only Zr is enhanced by about 0.5 dex, however this relies on a single Zr II line. Sr, on the other hand, is under-abundant by about 0.4 dex relative to iron, again, this is based on a single Sr II line. So from the chemical point of view, there is no clear indication as to whether the star was formed through mass transfer or through a collision. Pasquini et al. (2022), did not mention the mass of the star. However, by looking at the isochrone they used to determine the atmospherc parameters of the star, the star has a mass of 1.12 $M_\odot$. This is a typical mass for a BSS. The survey of De Marco et al. (2005), of BSS in four GCs provided a mean mass of 1.07 $M_\odot$. For BSS, the masses derived from isochrones agree very well

[5]Kippenhahn & Weigert (1967) proposed to divide the mass transfer in three cases: Case A, the star that is initially more massive fills the Roche lobe while still on the main sequence; Case B, mass transfer takes place after the initially more massive star has evolved off the main sequence, it is in the Subgiant branch (SGB) or Red Giant Branch (RGB) phase; case C, mass transfer begins after the initially more massive star has started central helium burning, it is in the Horizontal Branch (HB) or Red Clump (RC) or Asymptotic Giant Branch (AGB) phase.

with pulsational masses (Fiorentino et al., 2014), because, after an initial adjustment following the mass accretion episode, the BSS evolves like a normal star.

From the point of view of science verification, these observations were very succesful. In the first place, because they demonstrated that a usable spectrum can be obtained in two hours for a $G = 19.01$ star using the 4-UT mode. In the second place, they highlighted a limitation in the use of ESPRESSO in a crowded field, such as a GC. The sky fibre is placed in a fixed position $7''$ from the main target, its position on the sky depends on which UT is used to feed ESPRESSO. In fact, Pasquini et al. (2022) obtained three exposures of 55 minutes each for their target. However, one of the exposures could not be used because the sky fibre was placed too close to a star and thus the level of sky could not be confidently determined. Following this experience, ESO developed a visualisation tool that allows one to see the area spanned during the exposure for each of the four UTs. This tool is now part of the P2 observing block preparation tool. It may happen that some faint stars cannot be observed by ESPRESSO, if they are in a crowded region.

3 Li in Globular Clusters

From the very first observations of Li in GCs, it was clear that they were around the Spite plateau. However, a certain dispersion was immediately noted and Pasquini et al. (2005) showed for the GC NGC 6752 that the lithium abundance anti-correlates with sodium, making this element one of the elements that characterise the multiple populations in GCs. For this cluster Shen et al. (2010) also highlighted the existence of a Li-O correlation[6], which is a logical consequence of the Li-Na anti-correlation and the Na-O anti-correlation. The nearest GCs have been extensively observed with FLAMES and for 47 Tuc, Kučinskas et al. (2014) showed that there is also a slight radial gradient, the more external stars display a slightly higher Li abundance. This implies that the multiple populations of the GC are not homogenously distributed, and that the first generation is preferentially located at larger distances from the cluster centre. The inhomogeneity of Li abundances was recently confirmed for the two clusters M 13 and M 71 by Boesgaard & Deliyannis (2024), a challenging observation of stars around the 18^{th} magnitude with the HIRES spectrograph at the Keck telescope. One of the take-away messages is that, even if one takes the most Li-rich stars in all clusters one is well below the value predicted by SBBN.

There are groups that have extensively used GCs to validate models that could solve the cosmological lithium problem. In particular, Korn et al. (2006) used FLAMES observations to study Li in NGC 6397 and concluded that turbulent diffusion models can explain a uniform depletion in Li, in stars of all masses, from the SBBN value to the currently observed Spite plateau. This work was also done for NGC 6752 (Gruyters et al., 2014) and M 4 (Nordlander et al., 2024). This is a possible solution, however, these turbulent diffusion models are phenomenological and depend on a parameter that cannot be derived from first principles. It has to be adjusted to fit the observations, and each cluster needs a different parameter. I wish to draw attention to what is, in this context, a troubling observation. Molaro et al. (2024) used 27 h of ESPRESSO at the VLT to observe the O star Sk143 in the Small Magellanic Cloud (SMC). This star provides access to the interstellar medium (ISM) absorption lines of metal-poor gas in the SMC. The lithium abundance inferred from the Li I resonance doublet at 670.7 nm is A(Li)= 2.16 ± 0.12, which is consistent with the Spite plateau value. This is troubling because even if we accept that Li, starting from the SBBN value, has been uniformly depleted in stars we need to find another mechanism that depletes it to the same value in the ISM. Abundances from absorption lines in the ISM need to be corrected for the fraction of the element that is locked in dust and for the fraction in unseen ionisation stages. These have been taken into account by Molaro et al. (2024). Observationally, it would be desirable to probe other metal-poor gas clouds. However, I am afraid we have stretched the VLT to the limit its possibilities. Perhaps with the ELT and ANDES (Marconi, 2026) we may be able to probe the gas along the line of sight of young massive stars in the Phoenix irregular galaxy (see, e.g. Battaglia et al., 2012) or perhaps even further.

4 Open clusters as tracers of Li evolution

Open cluster can be found in the Galactic disc at distances as large as 11 kpc from the Galactic centre. This makes them precious probes of the evolution of the disc. The Gaia-ESO survey (Randich et al., 2022; Gilmore et al., 2022), carried out at the VLT with FLAMES, provided an unprecedented sample of high-quality data for a large number of open clusters of different ages and at different distances from the Galactic centre. Randich et al. (2020) used a carefully chosen sample of 18 open clusters showing that they trace the Li evolution very well over the

[6]Not anti-correlation, as incorrectly stated in the title of that paper!

metallicity range –0.4 to +0.3. The data also show a decrease in Li abundance for the outermost clusters. This, however, may also be an age effect, since the outermost clusters are also the oldest, and it is difficult to disentangle the effect of age from that of a possible Galactic gradient.

5 Li-rich stars in clusters

A star is defined as Li-rich if it has a higher Li content than stars of the same metallicity and evolutionary status. Therefore, a metal-poor giant with A(Li)=1.5 is Li-rich, while a dwarf with the same metallicity and Li content would be considered Li-depleted. While commissioning the FEROS spectrograph (Kaufer et al., 1997) on the ESO 1.5 m telescope Hill & Pasquini (1999) discovered a Li-rich giant in the open cluster Berkely 21. This cluster is metal-poor ([Fe/H]≈ -0.5) and this was the first time a Li-rich giant was observed in an open cluster. Normal giants deplete lithium, due the expansion and the deepening of the convection zone, thus, the Li observed in such a star must be somehow produced. Monaco et al. (2014) discovered a Li-rich Red Clump (RC) star in the open cluster Trumpler 5. This is certainly surprising, because RC stars are burning He in the core, they have already reached the tip of the RGB, where they must have destroyed the Li in their atmospheres. It is difficult to understand why, when they reach the RC, some of them show a high Li content. One hypothesis is that the ignition of He in degenerate matter (the He flash) leads to Li production, although the detailed physics of this process has not been worked out. Thanks to the Gaia-ESO survey Magrini et al. (2021) discovered many Li-rich stars among RC stars in a sample of 57 Open Clusters, showing that the star in Trumpler 5 is not unique.

Among GCs, I want to mention the discovery of a main sequence star in NGC 6397 with A(Li)$\sim$ 4 (Koch et al., 2011). One hypothesis is that the star acquired material from a companion when the latter was in the AGB phase. Yet the chemical composition of this star, except for Li, is perfectly compatible with that of other TO stars in the cluster, so this hypothesis seems difficult to accept. Another possibility is that the star engulfed a substellar companion, brown dwarf or planet. Luca Pasquini decided to test this hypothesis by measuring the Be abundance in this star. In the case of engulfment, the Be abundance should also be increased. The observation was very challenging: a total of 10.5 hours of integration with UVES at the VLT for a $G = 16.2$ star did not achieve a detection of the BeII doublet at 313 nm (Pasquini et al., 2014). The upper limit derived is consistent with a Be abundance similar to that measured in other TO stars in this cluster (Pasquini et al., 2004), but in any case, the scenario of an engulfment can be ruled out.

While the Li-rich star in NGC 6397 has a Li abundance that is well above the primordial Li abundance predicted by SBBN, and therefore requires a Li production, the case of a Li-rich dwarf star in M 4 with A(Li)= 2.87 (Monaco et al., 2012) is more ambiguous. In fact this Li abundance is tantalisingly near to the prediction of SBBN, opening the possibility that for some reason this star has preserved the primordial Li abundance, while all the others in the cluster have depleted their lithium.

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