The Abundance of Lithium Measured for the First Time Beyond Our Galaxy

Alessio Mucciarelli[1]
Maurizio Salaris[2]
Piercarlo Bonifacio[3]
Lorenzo Monaco[4]
Sandro Villanova[5]

[1] Dipartimento di Fisica & Astronomia, Universitá degli Studi di Bologna, Italy
[2] Astrophysics Research Institute, Liverpool John Moores University, Liverpool, United Kingdom
[3] GEPI, Observatoire de Paris, CNRS, Univ. Paris Diderot, Meudon, France
[4] ESO
[5] Universidad de Concepcion, Casilla, Concepcion, Chile

The discrepancy between the primordial lithium abundance derived from Population II dwarf stars and from the predictions of standard Big Bang nucleosynthesis is one of the most intriguing and challenging open questions in modern astrophysics. The use of lower red giant branch stars, instead of the usual method of observing dwarf stars, represents a new approach to attacking the problem. Lithium in distant, extragalactic stellar systems, for which observations of dwarf stars are precluded because of their faintness, becomes open for investigation. From observations with FLAMES at the VLT, we have been able to derive for the first time the initial lithium abundance in an extragalactic globular cluster, namely M54 in the Sagittarius galaxy.

Lithium, together with hydrogen and helium, is synthesised during the early phase of the Universe, in the first few minutes after the Big Bang. All the elements heavier than lithium are produced later, mainly during the nucleosynthesis occurring in the stellar interiors. In particular, the primordial lithium abundance is strictly linked to the baryonic density (Ω_B), a cosmological parameter that quantifies the amount of ordinary matter. Hence, the study of the lithium abundance in the oldest stars is crucial for several different astrophysical topics, i.e., cosmology, stellar evolution and globular cluster formation.

In a seminal paper, Spite & Spite (1982) first noted that dwarf Population II stars in the Solar Neighbourhood (with [Fe/H] < –1.5 and effective temperatures > 5800 K) share the same lithium abundance, regardless of their metallicity and temperature, a feature known as the Spite Plateau. The derived lithium abundance turns out to be in the range *A*(Li) = 2.1–2.4 dex, depending on the adopted temperature scale. The existence of a narrow lithium plateau has been confirmed by three decades of observations, both in halo field stars and in globular cluster stars.

The results obtained with the Wilkinson Microwave Anisotropy Probe (WMAP; Spergel et al., 2007) and Planck (Planck collaboration, 2013) satellites have provided an alternative route to inferring Ω_B. In fact, these high precision measurements of the cosmic microwave background (CMB) have allowed Ω_B to be estimated with unprecedented accuracy. The derived value of Ω_B, coupled with the standard Big Bang nucleosynthesis (SBBN) model, provided a lithium abundance of 2.72 ± 0.06 dex (Coc et al., 2013). This value is significantly higher, by at least a factor of three, than the lithium abundance derived from dwarf stars. Such a discrepancy is referred to as the cosmological lithium problem.

At present, the discrepancy between the Spite Plateau and the CMB + SBBN results is still unexplained. Three possible explanations appear to be especially promising:

1) the effect of atomic diffusion and some competing additional mixing, the combined effect of which decreases the lithium abundances in the atmospheres of dwarf stars (see e.g., Korn et al., 2006);
2) inadequacies in the SBBN models used to calculate the lithium abundance (Iocco et al., 2009);
3) lithium depletion driven by Population II stars during early Galaxy evolution (Piau et al., 2006).

Whatever the solution of the lithium problem is, the investigation of this discrepancy (and its solution) is a formidable chance to understand SBBN in greater depth and refine our description of the processes occurring in the first few minutes after the Big Bang. In fact, if the primordial lithium abundance derived from the CMB results is incorrect, the current SBBN model would have to be drastically re-thought, introducing "new physics", e.g., the inclusion of "new" high-energy, non-thermal particles and the annihilation/decay of dark matter particles. On the other hand, if the initial lithium content in Population II stars is depleted by transport processes, the measurement of the lithium abundance in these stars could provide robust constraints on the efficiency of turbulent mechanisms occurring at the bottom of the stellar convective envelope (which is a free parameter in the stellar models).

An alternative route: The lower RGB stars

Mucciarelli, Salaris & Bonifacio (2012) proposed an alternative/complementary route to investigate the initial lithium abundance in Population II stars (with respect to the observations of dwarf stars), by measuring the surface lithium abundance in lower red giant branch (RGB) stars. These stars are defined as the giants evolving between the first dredge-up and the luminosity level of the RGB Bump. When a star evolves off the main sequence, the convection propagates inward (first dredge-up) reaching hot regions where lithium has been burned. Lithium-free material is dredged up to the surface, with the main effect of reducing the surface lithium abundance. When the convective envelope attains its maximum penetration, depletion of the surface lithium abundance ends. Afterwards the lithium abundance remains constant until the star reaches the luminosity level of the RGB Bump; then, an additional mixing episode occurs, further reducing the surface lithium abundance down to virtually zero, or to effectively non-measurable values (see Figure 1).

The lower RGB stars (both in the Galactic field and globular clusters) display a constant lithium abundance, defining a plateau that mirrors the Spite Plateau, but at a lower abundance (*A*(Li) ~ 0.9–1.0 dex). Since the amount of lithium depletion after the first dredge-up can be predicted easily from stellar models, the lithium abundance measured among the lower RGB stars can be used to infer or

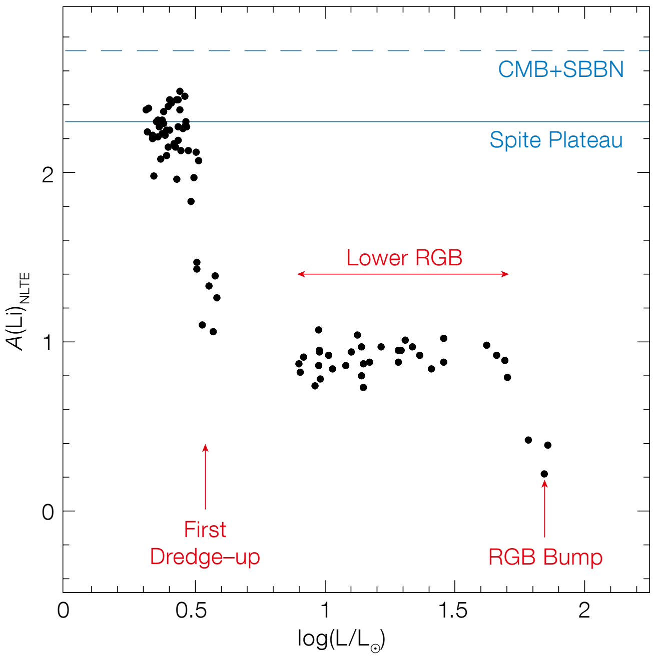


Figure 1. Behaviour of the surface lithium abundance as a function of luminosity for the stars in the globular cluster M4 (from Mucciarelli et al., 2011). The value of the initial lithium abundance as derived by the CMB + SBBN is marked as a blue dashed line. The value of the lithium abundance as derived from dwarf stars (the Spite Plateau) is marked by the blue solid line.

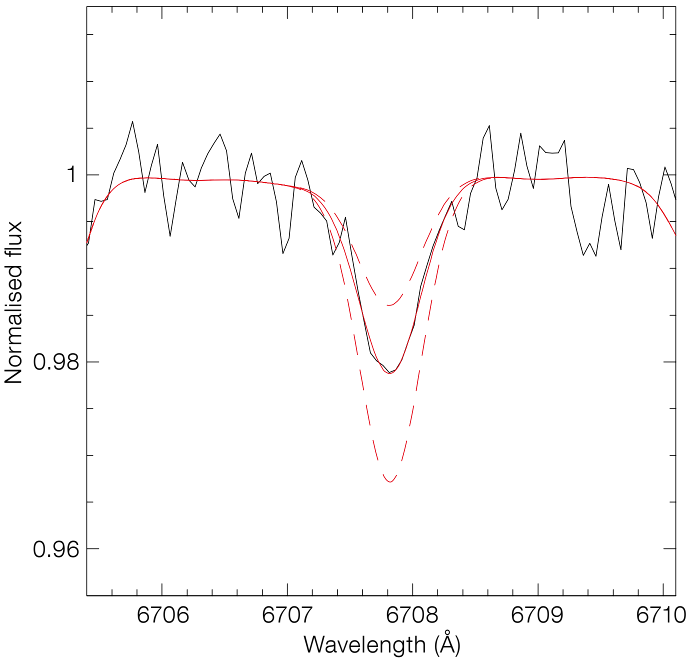


Figure 2. The observed lithium doublet of the average spectrum obtained by combining 51 member stars of M54 observed with FLAMES GIRAFFE. Superimposed are the best-fit synthetic spectrum and two synthetic spectra calculated with lithium abundance variations of ± 0.2 dex.

constrain the initial lithium abundance of those stars.

This new diagnostic has extraordinary potential and advantages. In particular:
1) The derived abundance of lithium is totally independent of the abundances obtained from dwarf stars and therefore does not suffer from the large uncertainties on the turbulent mixing affecting that evolutionary stage. Note that the uncertainties related to the efficiency of diffusion processes amount to 0.4 dex or more for the lithium abundance in dwarf stars, while they are smaller than 0.07 dex for lower RGB stars;
2) The use of lower RGB stars will allow estimates of the lithium content in stellar populations more distant than those usually observed to investigate the Spite Plateau. The obvious benefits are not only to enlarge the sample of Galactic field and cluster stars to study the primordial lithium abundance, but also to offer the formidable opportunities to investigate the initial lithium abundance in extragalactic systems where the observation of dwarf stars is precluded because of their distance.

Lithium abundance in M54

We have recently approached the lithium problem by adopting this new diagnostic. We used the lower RGB stars to investigate for the first time the lithium abundance outside the Milky Way (Mucciarelli et al., 2014). We obtained high-resolution spectra of 51 member stars of the globular cluster M54, with the FLAMES facility mounted at the Kueyen Unit Telescope of the Very Large Telescope (VLT) and the GIRAFFE spectrometer. M54 is a massive globular cluster located at ~ 25 kpc from the Sun and immersed in the nucleus of the Sagittarius dwarf galaxy. The dwarf stars in M54 and the Sagittarius galaxy are too faint (at *V* ~ 22 mag) to measure their lithium abundance, even with the VLT, hence the study of lower RGB stars currently represents the only possible route to infer the lithium abundance in this galaxy.

Figure 2 shows the lithium doublet at 6707 Å observed in an average spectrum, obtained by combining together the spectra of the 51 stars, in order to enhance the spectral quality. Superimposed are the best-fit synthetic spectrum and two synthetic spectra calculated with lithium abundance variations of ± 0.2 dex.

We measured *A*(Li) = 0.93 ± 0.11 dex, in agreement with measurements in lower RGB stars of the Galactic Halo. By considering the dilution due to the first dredge-up, we established that the initial lithium abundance of this stellar system (in the range *A*(Li) = 2.29–2.35 dex) was compatible with those derived in dwarf stars. This is the most distant measurement of the initial lithium abundance in old, metal-poor stars obtained so far. In fact, all the previous studies of the lithium abundance in dwarf stars are restricted to distances within ~ 8 kpc from the Sun.

Figure 3 summarises the state of the art of our current knowledge of the lithium abundance. The initial lithium abundance obtained in M54 matches the Spite Plateau well but is lower than the CMB + SBBN value by ~ 0.3 dex. This demonstrates that old stars, regardless of their birthplace, were born with the same initial lithium abundance.

Also, an important question can be addressed by our study: is the lithium problem a local problem, limited to our Galaxy, or is it independent of the environment? The analysis of M54 confirms the findings in ω Centauri (Monaco et al., 2010) considered as the remnant of an accreted dwarf galaxy: the lithium problem seems to be a universal problem, regardless of the parent galaxy.

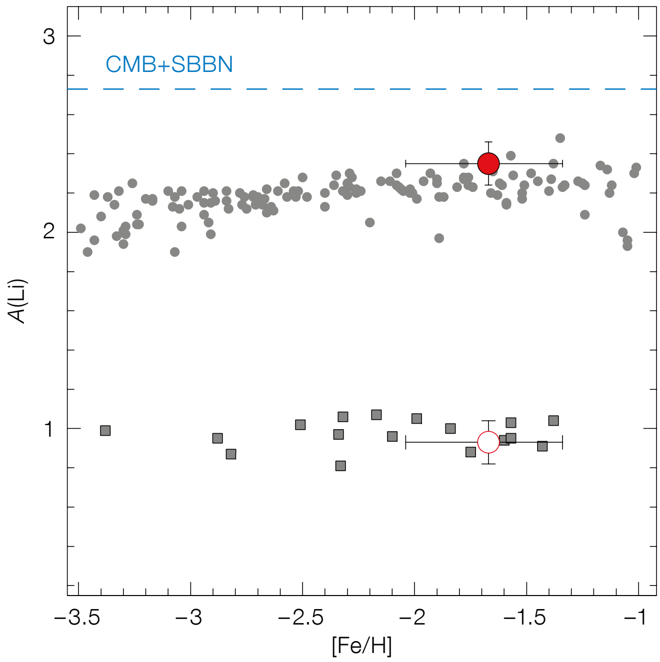


Figure 3. Abundance of lithium as a function of [Fe/H] for the Spite Plateau (grey circles) and lower RGB stars (grey squares) of the Galactic field. The empty red circle denotes the surface lithium abundance measured in the lower RGB stars of M54, while the filled red circle shows the initial lithium abundance of M54. The blue dashed line is the initial lithium abundance from CMB + SBBN.

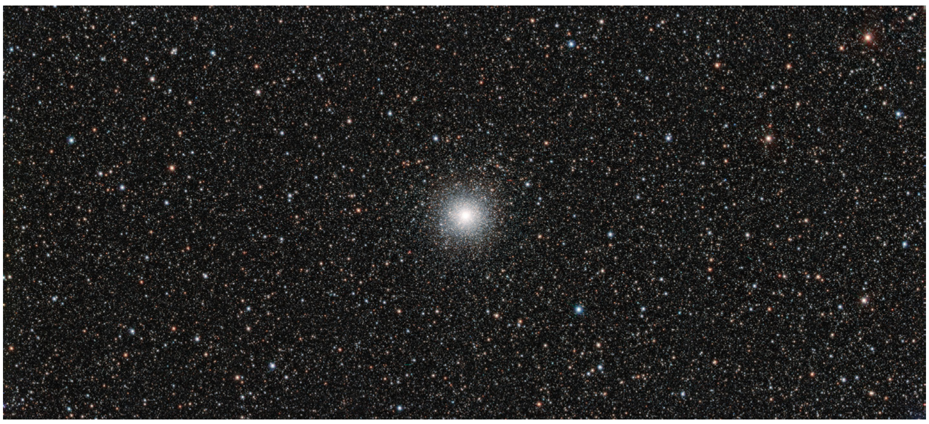
A new tool for new instruments

The result obtained for M54 demonstrates the potential of lower RGB stars in the investigation of the initial lithium abundance in stellar systems for which the observation of dwarf stars is precluded. This study has allowed a giant leap in this kind of study, pushing our view to ~ 25 kpc from the Sun. Besides the natural impact on the theoretical SBBN model and stellar evolutionary models, the accurate investigation of the lithium abundance in lower RGB stars also has an important benefit in terms of the definition of science cases for the next generation of spectroscopic instrumentation. In fact, the proper calibration of this diagnostic using a wide sample of Galactic stars is a fundamental step in the process of observing very distant lower RGB stars with the next generation of 30–40-metre-class telescopes (such as the European Extremely Large Telescope or the Giant Magellan Telescope).

The current generation of high-resolution spectrographs mounted on 8–10-metre-class telescopes (like the VLT, Keck and Subaru) allows us to reach lower RGB stars in stellar systems out to ~ 25 kpc from the Sun, with a typical magnitude of *V* ~ 18.5. The advent of the 30–40-metre-class telescopes will allow observation of lower RGB stars out to the closest dwarf spheroidal galaxies (~ 80 kpc), while dwarf stars will be observed out to the Magellanic Clouds (~ 50–60 kpc). Thus, this new diagnostic represents a powerful science case for the future giant telescopes.

References

Coc, A., Uzan, J.-P. & Vangioni, E. 2013, arXiv1307.6955
Korn, A. J. et al. 2006, Nature, 442, 657
Iocco, F. et al. 2009, Phys. Rev., 472, 1
Monaco, L. et al. 2010, A&A, 519L, 3
Mucciarelli, A. et al. 2011, MNRAS, 412, 81
Mucciarelli, A., Salaris, M. & Bonifacio, P. 2012, MNRAS, 419, 2195
Mucciarelli, A. et al. 2014, MNRAS, 444, 1812
Piau, L. et al. 2006, ApJ, 653, 300
Planck Collaboration, 2013, arXiv1203.5076
Spergel, D. N. et al. 2007, ApJS, 170, 377
Spite, M. & Spite, F. 1982, Nature, 297, 483



VLT Survey Telescope *u*-, *g*- and *r*-band colour image of the globular cluster M54 situated at the core of the Sagittarius Dwarf Galaxy. See eso1428 for details.