The lithium problem

A phenomenologist's perspective

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Abstract. Thirty years after the first observation of the ^{7}Li isotope in the atmosphere of metal-poor halo stars, the puzzle about its origin persists. Do current observations still support the existence of a "plateau": a single value of lithium abundance, constant over several orders of magnitude in the metallicity of the target star? If this plateau exists, is it universal in terms of observational *loci* of target stars? Is it possible to explain such observations with known astrophysical processes? Can yet poorly explored astrophysical mechanisms explain the observations or do we need to invoke physics beyond the standard model of Cosmology and/or the standard model of Particle Physics to explain them? Is there a ^{6}Li problem, and is it connected to the ^{7}Li one? These questions have been discussed at the Paris workshop "Lithium in the Cosmos", and I summarize here its contents, providing an overview from the perspective of a phenomenologist.

Key words. Lithium problem, chemical stellar evolution, primordial nucleosynthesis

-"I can't be waiting for death in a hotel room. [...] My life... my life has been spectacular."
-"Now, please, take your lithium."[1]

1. Introduction

The seminal observation of the ^{7}Li isotope in low-mass turn-off stars of our galactic halo, returned a surprising result: the lithium abundance observed in the atmosphere of the target stars -whose metallicity spanned more than one order of magnitude in [Fe/H]- exhibited a constant behavior, Spite & Spite (1982). This permitted the identification of a "plateau" of ^{7}Li in turn-off, metal-poor stars of our halo,

given the very little dispersion of observations around a single value, an observational evidence that was puzzling for reasons that can be summarized by the following questions. If the observed ^{7}Li has been processed by the host stars, how is it possible that it exhibits such a regular behavior over such a large interval in metallicity of the host star? If it has not been processed by the star, the ^{7}Li we observe is the same that was in the atmosphere from the very beginning of the stellar formation process. If depletion from intervening chemical evolution is negligible (as it safely turns out to be) the latter must be identified with what is leftover from primordial nucleosynthesis, but then, why is it the only element not to match the standard primordial nucleosynthesis predictions made using the latest

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[1] [P. Sorrentino, "The consequences of love", Fandango productions, 2004]

(independent) cosmological data on the baryon density? Thirty years later, the puzzle about the origin of the ^{7}Li observed in the atmosphere of such stars is far from being solved. In spite of the bigger sample of stars, better quality spectra and amazing progress in the determination of stellar atmospheres, we still struggle to understand the origin of the observed ^{7}Li. In these proceedings, I summarize the view that a phenomenologist (not an observer, not an hardcore cosmologist, not a stellar theorist) has on the problem, in light of the latest findings as discussed in the Paris workshop. Observations are summarized in the first section, and the leading stellar theory arguments invoked to explain the observations are shortly summarized in the second section. In the third, current issues regarding Primordial (or Big-Bang) Nucleosynthesis (BBN) are briefly exposed. A very short update on observations of ^{6}Li is provided before finally reporting the biggest open questions to date in the Conclusions section.

Throughout these proceedings the references to the original literature must be limited and therefore utterly incomplete; for each topic, I also address to the material presented at this workshop with the name of the author presenting such results: a more complete list of references for each topic, as well as more quantitative details can be found in their proceedings.

2. Observations

The abundance of ^{7}Li in stellar atmospheres is determined through the observation of this element's doublet line at 670.8 nm. In order to determine the relative abundance of ^{7}Li, the absorption strength of this line must be calibrated through a process that involves detailed knowledge of the temperature of the atmosphere, and a careful treatment of the latter. For as concerning these latter issues may be —with different groups using different temperature scales based on different atmosphere models— throughout the last thirty years they have been fully addressed by all the different observational groups.

For some differences in the results of different groups do arise in some cases, as thor-

oughly discussed at the workshop by W. Aoki, J. Meléndez, S.G. Ryan, and L. Sbordone, they are minor with respect to the issues which are going to be faced in the following.

Issues related to the temperature scale and its effects on retrieving the correct atmospherical abundances has been thoroughly discussed by S. G. Ryan in his talk at this conference. Over-summarizing its conclusions, the solutions to the problems raised in the following discussion seems to lie not in the atmospheric temperature scale, based on both LTE and NLTE calculations.

In the following the ^{7}Li abundance will be expressed in the customary dex unit A(Li)=12+Log[N(Li)/N(H)].

2.1. Halo stars

Turn Off point (TOP), metal-poor stars in the halo of our Galaxy are selected on the basis of their kinematics, in order to make sure they belong to the halo population and not to the younger one present in the disk, and on their temperature T_{eff} >5900K. This technique for selecting Population II stars is established and has been adopted throughout the last thirty years in a universal fashion.

The data presented by W. Aoki and L. Sbordone seem to converge for metallicities -2.8 ≤ [Fe/H] ≤ -2.0 : ^{7}Li abundance in dwarf, turn-off stars of the sample is contained, for these metallicities, in a band 2.1 ≤ A(Li) ≤ 2.4, Aoki et al. (2009), Sbordone et al. (2010). This is the old region of the "plateau", which appears, although with a somewhat increased spread around a central value to show little sign of depletion. The data presented by J. Melendez at this meeting, disagree with the latter, as he claims "strong evidence for lithium depletion at all metallicities", as well as a consistent spread of the former-thin "plateau", Melendez et al. (2010). The reason for this discrepancy is yet to be understood and will be very likely fully discussed in the forthcoming analysis by the author.

Even more compelling is the evidence for a "meltdown" of the plateau at metallicities below [Fe/H] ≤ -2.8. Such evidence appears clearly in the data of -and has been discussed

by- W. Aoki, J. Melendez, and L. Sbordone: whereas in no case the lithium abundance raises above the envelope of A(Li)=2.4, the scatter below such value is much more consistent, as it can clearly be seen in the recollection of data by all groups presented by L. Sbordone and here reported in Figure 1, not including the Melendez data.

The state of the art on ^{7}Li observations in the atmospheres of turn-off, halo-field stars can be summarized as follows:

i) throughout the metallicity range [Fe/H] ≤ -2.0, the ^{7}Li abundance A(Li) does not raise above the "envelope" of A(Li)=2.4 (see later in Subsection 2.3 for exceptions, which do not affect the generality of this statement);

ii) in the metallicity range -2.8 ≤ [Fe/H] ≤ -2.0, the abundance lies within the interval 2.1 ≤ A(Li) ≤ 2.4, with non-zero dispersion even within each single dataset, although the degree of such dispersion varies from group's dataset to group's dataset;

iii) at metallicities [Fe/H]≤-2.8, clear dispersion of several dexes is seen below the mentioned envelope of A(Li)=2.4. The entity and the possible dependence of this feature is yet to be entirely characterized, yet it emerges clearly from the analysis of all the group, to the point that the behavior has been named a "meltdown" of the plateau.

Regarding to the "plateau" itself, in light of the points summarized here, we wonder whether this term should now be used as referring to the envelope, rather than to a single value, which is clearly now unsupported by observational evidence. See more in the Conclusions.

2.2. Globular Clusters

Globular Clusters (GCs) are extremely valuable observation *loci* in light of their special characteristics with respect to stellar formation: stars born inside a given GC are approximately coeval, with a uniform initial chemical signature. The age of stars can be determined from photometry, therefore permitting to draw an evolutionary pattern for diffusion, throughout the whole sequence of the Population II stars observed. These characteristics permit to

use them as extremely important case studies, aimed at understanding the behavior of ^{7}Li throughout the whole evolutionary path, using the stellar population as a homogenous ensemble of given initial metallicity. In principle, this permits to test the lithium depletion mechanism at different metallicities, thus "sampling" the X-axis of the plateau plane, provided that the peculiar chemical history of each single cluster is understood, avoiding that contamination due to the local chemical history pollute more general results. Several individual GCs at different metallicities have been studied so far: 47 Tuc, NGC 6752, M4, M30, M92 Ω Centauri, and NGC 6397. The range of metallicities of these objects spans from -2.8 ≤ [Fe/H] ≤ -1.1, from the most metal poor M30, M92 up to the iron richest M4, thus covering (although in a non-continuous fashion) a big region of the range of halo-field stars. The case of the quite metal-poor NGC 6397 -[Fe/H]=-2.0- has been long debated in literature, as summarized by A. Korn in his review talk on GCs. In fact, stars at different evolutionary stages exhibit a clear trend on ^{7}Li abundance versus the effective temperature T_{eff} of target stars. The evolution of A(Li) from Turn-Off, through the Sub-Giant Branch and the Red Giant Branch shows a pattern which is compatible with theoretical models including atomic diffusion and microturbulence -see the following section for more details. It is worth stressing that the ^{7}Li abundance observed in turn-off stars is compatible with that of halo-field stars observed in the halo, as from the previous Section, remaining constrained within the 2.1 ≤ A(Li) ≤ 2.4.

2.3. Outliers in clusters and halo

On the top of this general view, whose strength relies on the strong statistics of the data sets, observations of single cases of ^{7}Li-rich stars seem to spice up some more the problem. It is necessary to stress that the following cases are statistically irrelevant, namely do not affect the conclusions that one may (or may not) have reached over the debate of the origin of the TOP ^{7}Li abundance. Even the richest samples, that in the RAVE survey presented here
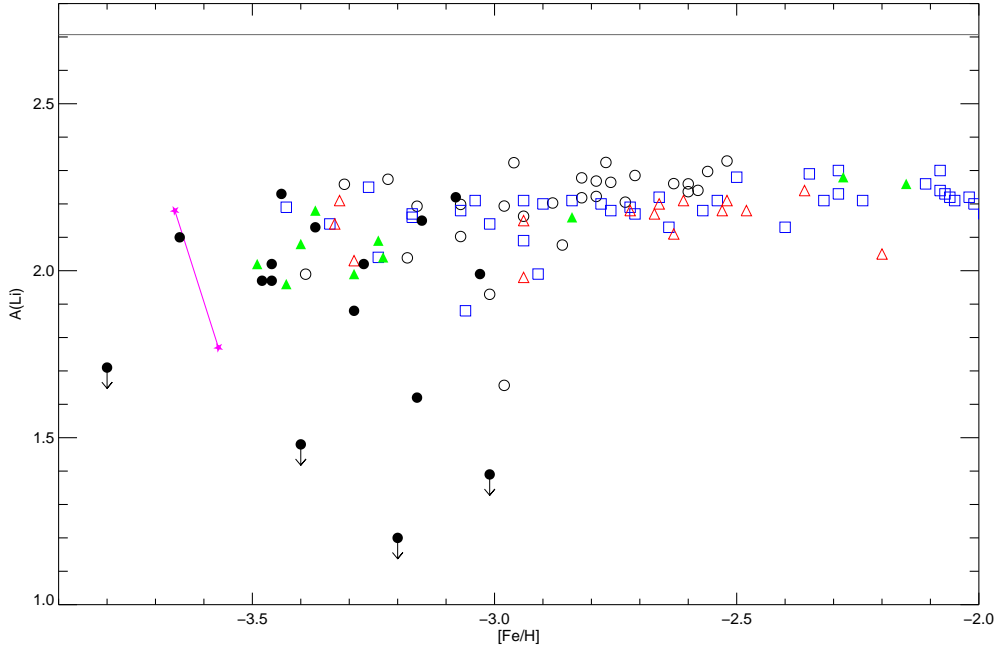
Fig. 1. The ^{7}Li "plateau", a. d. 2012. Courtesy of L. Sbordone. Filled black circles, Bonifacio et al. (2012); open black circles, Sbordone et al. (2010); green filled triangles, Aoki et al. (2009); red open triangles, Hosford et al. (2009); blue open squares Asplund et al. (2006); magenta stars: the two components of the binary star CS 22876-032 (González Hernández et al. 2008).

by G. Ruchti, and the giants in the Milky Way Dwarf Galaxy satellites presented by X. Fu, do not exceed the 0.44% of the total sample. In particular, a super-^{7}Li-rich turnoff star in NGC 6397 and one in M4 presented at this workshop respectively by A. Koch and L. Monaco, the existence of thirteen ^{7}Li-rich giants in the Dwarf Galaxies of the MW presented by X. Fu, of fourteen ^{7}Li-rich field halo giants presented by M. Adamow, of eight ^{7}Li-rich field stars in the RAVE survey, and of one ^{7}Li-rich in M68, presented by G. Ruchti, have been discussed, Koch et al. (2011), Monaco et al. (2012), Ruchti et al. (2011), Adamow et al. (2012). The nature of such anomalous lithium abundances -in most cases even above the BBN predicted floor is still a puzzle, but given the nature of the sample, much reduced with respect to the bulk of evidence discussed in the previous Sections- remain puzzling, but very likely disconnected from what is typically known as

the "lithium problem", thus very likely identifying some more Lithium problems, likely of different nature. Possible explanations proposed include ingestion of a planet or brown dwarf because of the star's expansion, mass transfer from an AGB companion, and self production of the ^{7}Li the giant itself through either cool-bottom processes, a lithium flash or a lithium circumstellar shell. All of these explanations do however present problems, as overviewed at this workshop by X. Fu.

2.4. Non-stellar abundances of lithium

In light of what described so far, and of the difficulties in convincing oneself on the actual nature of the ^{7}Li observed in the atmosphere of stars, there is most probably very little arguing that a measure of lithium in the most unpolluted regions of our sky, would most probably push the needle toward one solution or the

other. For as obvious as it seems, it is also as obviously difficult a measure to perform, given the very low abundance of ^{7}Li. C. Howk has presented at this meeting the first observation of ^{7}Li in a non-stellar, low-metallicity, extra-galactic medium: lithium in the interstellar material of the Small Magellanic Cloud, a Galaxy with a metallicity of one quarter that of the Sun, [Fe/H]~-0.6 , Howk et al. (2012). The observed abundance of ^{7}Li is A(Li)$_{SMC}$=2.68 ± 0.16; which is nicely compatible with the primordial abundance, see later section, and non compatible with the plateau envelope. It is however to be stated that this is the first measurement of the kind, although the region of such measurement has been chosen with great care in order to avoid possibilities of contamination and enrichment. This observation is clearly inconclusive with respect to the lithium problem, but is equally clear that such technique has an enormous potential to shed light on the problem, and observations of this type should be encouraged and supported by the whole community.

3. Stellar theory

The obvious question that arises after having overviewed the observations is the following: what is the origin of the lithium in the stellar atmospheres? This most probably constitutes the bulk of what is commonly named the "lithium problem".

On one hand one would *not* expect that elements in the stellar atmospheres resemble the original composition of the star: internal mechanisms as well as external ones can easily enrich or deplete the star of elements heavier than Helium and Hydrogen. On the other hand, it is clear that the seemingly bizarre behavior of Lithium is not easily explained in terms of known astrophysical processes, and the existence of a single value, i.e. the "plateau" has long compelled people toward the identification of that plateau value as the one in the original composition of the star. Such puzzle remains even if one drops the paradigm of a single plateau value (in light of the previously discussed observations) and decides to adopt the envelope value as a new plateau.

^{7}Li is a very fragile element, and proton capture easily destroys it at temperatures above ~2.5×10^{6}K; the atmospheres of the stars are much colder than this but convection can bring the lithium down from the cold atmosphere to hotter regions. However, for the stars which are customarily chosen -Turn Off Point, warm, metal-poor stars whose mass is estimated to be less than one solar mass- the convective region below the atmosphere is not deep, and it can therefore not drag lithium down to regions with temperatures in excess of the mentioned threshold.

In addition to this paradigmatic and yet simplistic view of the problem, one element must be added: atomic diffusion, which slowly brings heavier elements down in the stellar bosom. As written by G. Michaud in 1984, and reminded at this meeting by M. Spite: "*atomic diffusion can not be turned off, it can only be rendered inefficient by sufficient mass motion either due to meridional circulation or turbulence*". Nonetheless, this essential element has been almost thoroughly omitted for several years. As a matter of fact, whereas atomic diffusion does deplete the original ZAMS ^{7}Li abundance throughout the Main Sequence, it can not reproduce the observed abundances at the turn off point, if the ZAMS is evolved starting with a BBN abundance. See e.g. M. Spite and A. Korn in these proceedings series.

On the top of this, turbulence in the stellar atmosphere —caused by differential rotation, meridional circulation, gravity wave excitation and shear— mitigate the effects of atomic diffusion, stirring the material and hampering its fall. All these effects are extremely challenging to model in a self-consistent way, from first principles, in order to properly include it stellar evolution models. As discussed by C. Charbonnel, this is as of today yet challenging, although a better handle on the theory can be obtained by tuning the physics on the observations of metal-richer stars than the ones that are used for the determination of lithium abundances, Talon & Charbonnel (2004).

Therefore, when dealt with, such effects are generally referred to as of an effective turbulence (or *micro*turbulence), which is in some cases taken into account in chemical evolution

models of the star. It is however added as a parameter, whose value must be tuned rather than derived from first principles, as mentioned above; O. Richard has thoroughly discussed this, and the different types of models adopted in Richard et al. (2005). In particular, this technique is applied in order to reproduce the actually *observed* pattern of ^{7}Li -starting from the Standard BBN value at Zero Age Main Sequence- in Globular Clusters. This technique is successful in some cases, see e.g. NGC 6397, the most debated example, Korn et al. (2006), Nordlander et al. (2012); however, the very same parameters adopted for the reproduction of the NGC 6397 features fail to work in reconciling the observed evolutionary pattern, with the given initial conditions for other GCs, i.e. M30 and M4. This has been explicitly mentioned by A. Mucciarelli, and he has stressed that such "ad hoc" turbulence models (namely the same models with the very same parameters) which successfully reproduce the whole evolutionary trend of NGC 6397, fail to capture the subgiant enhanced abundance when applied to M30 observations, conversely those set of parameters able to explain the dredge-up predict a depletion not able to fill the gap between the BBN and the TOP abundance.

It is extremely interesting to notice the following: Mucciarelli et al can *not* reproduce the global trend of Li evolution in the open cluster M4 using atomic diffusion and microturbulence with the same parameters used by Korn et al. for the analysis of NGC 6397. However, they equally fail to reproduce the lithium trend if they adopt atomic diffusion only. If needed, this is clear and obvious indication that atomic diffusion can not be neglected when modeling the evolution of lithium in the atmospheres of target stars, nor is the only answer to the problem.

4. Primordial Nucleosynthesis

In order to understand the origin of the lithium observed in stellar atmospheres one piece of the puzzle must be clear: the initial conditions expected at the best of our knowledge. In the current framework of Lambda Cold Dark Matter (ΛCDM) cosmology, favored by a host of astrophysical data, Primordial nucleosynthesis (also known as Big Bang Nucleosythesis-BBN) is considered as one of the pillars of our understandings of modern cosmology. In its standard formulation (SBBN) predicts that the amount of light elements (essentially null for atomic numbers above 7) produced in the first hours after the Planck time depend on one and only cosmological parameter, the baryon density ω_b, which can nowadays be retrieved from the refined measurements of the Cosmic Microwave Background anisotropy spectrum, reading ω_b=0.02249 from WMAP 7 year data, Komatsu et al. (2011). SBBN is therefore a parameter-free theory, whose uncertainties on its final predictions —the light element abundances— depend on the uncertainties on the measured physical quantities which are used. In particular, as it is nowadays well established and presented at this meeting by A. Coc and F. Villante, the reactions necessary in the nuclear network used in SBBN calculations are well known, thus making the systematic uncertainty associated with neglecting potentially relevant reactions virtually null. On the other hand, uncertainties associated with the reactions rates of the relevant reactions do exist, and their estimate is a crucial element for the evaluation of the error budget of light element abundance predictions; the (very advanced) state of the art in this field has been presented at this meeting by A. Coc, and it is extremely satisfactory that estimates performed by several groups converge within the uncertainties, Coc et al. (2012), Serpico et al. (2004).

The elemental abundance which permits the best check of SBBN is deuterium: its extreme sensitivity to the baryon density has given the first historical test of the standard cosmological model. Today, observations of hydrogen rich clouds absorbing QSO's background light permit accurate observations of virtually uncontaminated environments, thus measuring what is estimated to be the primordially produced deuterium abundance, in light of this isotope's fragility which leads to its destruction by virtually every process. As reminded at this meeting by K. Olive, obser-

vations of deuterium abundance in the above mentioned environments, have a small spread around a central value, $D/H=2.82\pm0.20\times10^{-5}$, Pettini et al. (2008). This is compatible - within the uncertainties- with the one predicted by SBBN $D/H=2.56^{+0.11}_{-0.10}\times10^{-5}$, Iocco et al. (2009) rescaled for WMAP7 ω_b with the PArthENoPE code (2008), as all following theoretical BBN abundances.

Observations of ^{4}He in metal-poor, extragalactic HII regions, with the need for a subsequent regression to zero metallicity. As presented in this meeting by E. Skillman, it seems that after years of uncertainty, and of a bizarre trend of the central value which increased with the years, ^{4}He observations today converge towards a single value, $Y_p=0.2534\pm0.0083$, Aver et al. (2012) This value is broadly compatible with the one predicted by SBBN when using the very same value of baryon density ω_b from CMB observations as above, namely the same SBBN which predicts Deuterium compatible with observations, $Y_p=0.2467^{+0.0003}_{-0.0002}$.

The ^{7}Li predicted by this very configuration of SBBN is $X_{Li}/H=4.6^{+0.2}_{-0.5}\times10^{-10}$, which in the most common unit of *dex* adopted above reads A(Li) = 2.66 $^{+0.02}_{-0.05}$; this quoted number may vary slightly according to different groups and network, and all theoretical estimates are consistent with each other.

Therefore, if the value of the envelope is to be interpreted as the primordially produced lithium, there is a friction with SBBN. Namely, one would be faced with the situation in which SBBN is nicely compatible with Deuterium and ^{4}He observations, but is overproducing the ^{7}Li; in this scenario, a mechanism is therefore needed in order to reconcile ^{7}Li without destroying the concordance of the other elements. A. Coc has stated that "*no sensible modification of primordial ^{7}Li is possible through standard BBN*", and the possibility that an unknown, experimentally overlooked resonance in the destruction channels of beryllium-seven (which makes up approximately half of the ^{7}Li, by successive decay) has been described as "*requiring almost unphysical processes*" by F. Villante during this meeting, Broggini et al. (2012). Which leaves very little room for justifying the interpretation of the observed ^{7}Li

as primordial, unless exotic models of BBN - i.e. models with physics beyond the Standard Model of Particle Physics or Cosmology - are invoked.

The possibility that an astrophysical population (and its associated phenomena) intervening between BBN and Population II, may have modified the lithium abundance in such uniform way is today generally discarded as unphysical by the whole community.

4.1. Exotic BBN models

The injection of high-energy, non thermal particles during the Big Bang Nucleosynthesis is known to modify the final abundance of light primordial elements, as a consequence of nonthermal nuclear reactions, see e.g. Jedamzik & Pospelov (2009). The entity of the modification to the final light element abundances depends quite strongly on the nature and initial energy spectrum of the non-thermal particles injected, thus making a thorough discussion of such topic unfit for this proceedings. What is most compelling to report here, as discussed at the workshop by K. Olive and T. Kajino, is the fact that several Dark Matter candidate models exist that predict either the annihilation or decay of the Dark Matter particle into standard model particles —or either the decay of supersymmetric particles into the Dark Matter particle itself— during the BBN. In particular, different results are obtained for the injection of hadronic showers vs leptonic ones, e.g. . Additionally, thermal nuclear reactions can be modified if negatively charged massive particles (CHAMPs), with a lifetime comparable with the Hubble time at BBN epoch are present. Several regions of the SuperSymmetric parameter space (as well as of other extensions of the Standard Model), currently unconstrained by the LHC results as well as from indirect and direct DM detection, have as a result to destroy ^{7}Li to the level of the plateau roof, see e.g. Kusakabe et al. (2010). Many of these models do however also predict an increased production of primordial ^{6}Li —which in SBBN is produced in negligible amounts $X_{^6Li}=1.1\times10^{-14}\pm0.1$— which was considered a good feature of such mod-

els in light of the ^{6}Li observations in stellar atmospheres. The latter seem to be strongly challenged, see following section, and in order to obtain only ^{7}Li depletion at the plateau level one must restrict the region of the parameter space where a solution is available, although the price to pay is almost unavoidably Deuterium overproduction, see e.g. Olive et al. (2012). Other ways to deplete ^{7}Li synthesis during BBN are phenomenologically viable, including baryon inhomogeneous BBN, axion cooling mechanisms, variation of constants of nature, and have been discussed at this workshop by T. Kajino.

5. Lithium-six, or not?

^{6}Li detection in stellar atmospheres is extremely challenging: the isotopic shift makes its feature appear as a small depression in the redward region of the lithium doublet line. The precision needed in order to resolve such delicate feature, had made its detection impossible until very recently. However, the two-sigma detection of ^{6}Li in nine stars (or three-sigma detection in five stars), Asplund et al. (2006) had stirred much interest. The abundance $X_{^6Li}$ ~5% $X_{^7Li}$, seemingly the same in all of the objects of different metallicity, was 4 orders of magnitude above the predictions of SBBN, as well as in inexplicable with models of cosmic ray induced chemical evolution of the Galaxy, as thoroughly discussed by B. Fields in his talk, Prodanovic & Fields (2007). This circumstance brought to the claim of a ^{6}Li "plateau", ideally analogue to the ^{7}Li one, which was soon used to advocate the primordial nature of the observed ^{6}Li, the remarkable discrepancy with SBBN, and the need for exotic models. Many of the latter could self-consistently explain both the deficit in ^{7}Li and the overabundance in ^{6}Li, as reminded in previous section. However, as stated during this workshop by A. Korn: "*it is very unfortunate that we started talking of a ^{6}Li plateau in the first place*".

In fact, as it has been realized soon after the first claim of detection, the small depression in the red wing of the lithium doublet line line could be due to effects other than the isotopic shift. Motions in the atmosphere can easily produce features that in an LTE analysis of the line are interpreted as evidence for ^{6}Li, therefore not only the sum of the two isotopes abundance and their relative abundance must be adopted as parameters for the line fitting, but also others describing the line broadening because of motions of the gas in atmosphere. In particular, asymmetric flows in the atmosphere cause a line shape distortion comparable with the one expected by a blend of ^{6}Li/^{7}Li, with an assumed ^{7}Li symmetric shape. Several analysis exploring this scenarios have been carried on: K. Lind and M. Steffen have devoted their talks to this subject, and details can be found in their proceedings and references therein. What it seems compelling to report here is the fact that evidence for detection of ^{6}Li seems to be vanishing, or to put it in other words, ^{6}Li can not be safely claimed to have been detected in many of the stars of original sample, and detection is actually excluded for several others, depending on the type of atmospheres adopted. In particular, according to theoretical corrections based on 3D NLTE predictions of the line profile, Steffen et al. obtain a reduction from nine to five stars (under the two–sigma criterion) and from five to two (under the three sigma criterion). If they adopt results based three-dimensional simulations of the atmospheres with proper treatment of convection and line formation, they obtain that a single star (HD 84937) exhibits non-negligible ^{6}Li abundance. For this very same stars, Lind et al. obtain instead a vanishing ^{6}Li abundance, based on an 3D, NLTE analysis of both lithium and Ca line profiles.

Whereas this issue is clearly not yet established, it seems to go in the direction of telling us that what has been for few years the " ^{6}Li plateau", is now the measure of a non vanishing ^{6}Li abundance in a limited sample of stars. For as interesting as this can be, at the state of the art this can not be reasonably considered as an indication for a cosmological signature.

6. Conclusions

'What is the "lithium problem" today?' is the relevant question to be asked before look-

ing for its solution. Namely, what is it about lithium that state-of-the-art observations and theory fail to explain, and must therefore be regarded as a "problem"? Until very few years ago the "lithium problem" could have been phrased this way: "Observations of ^{7}Li in the atmosphere of field halo, turn-off stars — spanning almost two orders of magnitude in metallicity— exhibit a single value abundance, with virtually zero dispersion around the central (only) value. Such value is a factor 3 to 5 smaller than what is expected to be left-over by SBBN, and no known astrophysical mechanism is able to deplete the lithium with such a fine—tuned accuracy." Such formulation, would hint toward a solution in terms of either: *i)* an unknown, fine tuned astrophysical mechanism, at work with same strength in the atmospheres of very different stars, capable to level the lithium abundance starting from the SBBN value or *ii)* a modification of SBBN, which would be accurate in predicting all other light elements but ^{7}Li, by virtue of wither unknown nuclear processes, or exotic processes involving non—standard model particles of modifications of the constants of nature. For both of these explanations, viable physical models existed, however yet unfalsified in their predictions of other systems.

The observations and analysis of the last years, discussed at this workshop, display a somewhat more complicated observational evidence than only few years ago:

i) the abundance of ^{7}Li in turn-off stars in the halo of the Milky Way and in Globular clusters exhibit a "roof value" of A(Li)=2.4 throughout the range of metallicities [Fe/H]≤-2.0. Very few outliers can be found above such value, and their number is statistically irrelevant;

ii) below such envelope value, the observed abundances show:
iia) moderate dispersion of ~0.2 dex in the metallicity range -2.8≤[Fe/H]≤-2.0
iib) very big dispersion —down to vanishing abundances— in the metallicity range [Fe/H]≤-2.8.

In light of this, the "lithium problem" today may be rephrased in the following way: "Observations of ^{7}Li in the atmosphere of turn off stars spanning more than two orders of magnitude in metallicity, do not pass a roof/envelope abundance a factor ~3 smaller than what predicted from SBBN. Little, yet non-zero, dispersion is seen below such value at intermediate metallicities, and much more consistent dispersion -down to vanishing abundances- is seen from the lowest metallicities."

This is clearly a much more complicated scenario to be solved with a single answer. If the explanation is astrophysical, one shall envision a mechanism that from the SBBN value depletes the lithium of *at least* a factor 3 in the atmosphere of metal-poor stars, with little dispersion (with similar efficiency of the mechanism) at intermediate metallicities, and with very different efficiency at the lowest metallicities.

On the other hand, if one assumes that some exotic mechanism is at work during BBN, such to modify the abundance of the ^{7}Li isotope down to the plateau envelope value, additional problems would still to be faced. An astrophysical mechanism able to cause strong depletion at low metallicities, shall be invoked, yet capable of limiting such depletion at the observed level at higher metallicities, in a mechanism much resembling those that were so fine tuned, and be argued against when invoked as solution of the old formulation of the "lithium problem". Yet, it seems clear that in both scenarios astrophysical processes are at work, even if at low metallicities only, on the top of an unknown astrophysical, cosmological or particle process, and that the use of the plateau roof for cosmological use and constraints on non-standard processes seems riskier today than it was in the past.

A specular discussion of these arguments can be found in the proceedings of Sbordone et al. and of Spite et al., and examples of composite explanations have been discussed at the meeting, see e.g. P. Molaro's proceedings.

In spite —or maybe because of— all the novelties and elements discussed at the Paris workshop, I find impossible to write down any Conclusion about the lithium problem, and I prefer to end these proceedings with a some-

what pedantic, yet not inappropriate semantic thought.

Is the lithium problem Primordial, Cosmological, Cosmic or Astrophysical: which of the several adjectives that have been imposed to the problem is the most fitting to its nature? In light of the previous considerations, I suggest that either Astrophysical, Cosmological or Primordial would impose on the problem a shade of pre-concept solution, and that perhaps "Cosmic" is the least unfitting definition, given the universality of the problem itself with respect to galactic observation loci.

Note added— It is with much relief that — after completing this text— I read the proceedings of M. Spite, F. Spite, and P. Bonifacio in this volume, and I realize that a phenomenologist's perspective is after all not that different from an observer's one. We leave it to the reader to investigate the consequences of this worrisome finding.

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