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The problem of Lithium and the other Light Elements Deuterium, Beryllium and Boron

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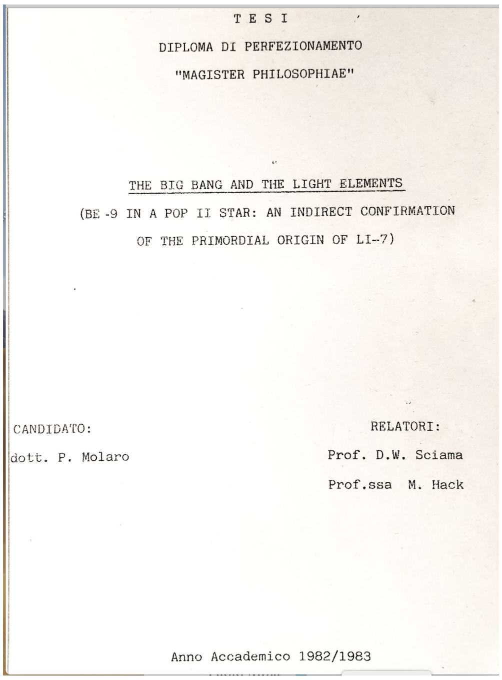
Abstract. In this tribute to Margherita Hack I will consider her work in connection to the problem of the light elements Li, Be B and D and with a brief overview of their current state. The title itself is taken from a review she wrote in 1965 when the origin of these element was quite mysterious. Seeking a Li source she found an excess of Li in magnetic stars, which was a first evidence of a non thermal synthesis of this element. Li in Ap stars was a topic to which she returned in the last years of her scientific life. D comes all form the Big Bang. It is the best measured primordial element and the baryometer of choice. Be and B are made by spallation processes in the interstellar but mainly close to SNe. ^{7}Li is the most problematic one. There is a striking mismatch between the primordial prediction and what measured which has been standing since more than two decades. ^{7}Li has multiple sources but the one making most of it is still missing. However, the recent detection of ^{7}Be in the outburst spectra of Novae makes them the most probable source.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: globular clusters – Galaxy: abundances – Cosmology: observations

1. Introduction

The variety of scientific interests of Margherita Hack is well covered in this volume in particular in the contribution by Selvelli, Ferluga and Messerotti. Here we consider a specific topic of her activity dealing with Lithium and more in general with the light elements Beryllium, Boron and Deuterium. The interest of Margherita Hack on these topics dates back to the early 60s with two reviews dedicated to their astronomical origins and abundances (Hack 1965a,b, 1968). Burbidge et al. (1957) in their monumental paper realized that the light elements were bypassed by stellar nucleosynthesis and burned inside the stars at the temperature of few millions degrees, thus requiring a non-thermal process for their synthesis. They could not identify the process that they called **X-process** suggesting Li, Be and B could come from breaking heavier elements such as CNO around supernovae or onto the surfaces of Flare stars. Faraggiana & Hack (1963) found a *Probable Excess of Lithium in the Atmosphere of the Magnetic Star β Coronae Borealis* quiantified by Wallerstein & Hack (1964) as being about 1000 more abundant in the atmosphere of Ap star β Coronae Borealis. In fact this was the first evidence of non thermal synthesis of a light element in a stellar surface which confirmed the earlier suggestion by Burbidge et al. (1957). In her reviews on the origin of the light elements Hack suggested that the Li destruction by convection could be related to the age of the star and correctly interpreted the anti-correlation between the presence of ^{13}C and the absence of ^{7}Li as due to ^{7}Li destruction in the mixing of stellar layers required to make ^{13}C. She also drawn the attention onto the Li-rich carbon stars WZCas, WX Cyg and Tara suggesting that some specific stars could make Li by their own. The specific mechanism was disclosed only few years later by Cameron & Fowler (1971). Since 1996 M. Hack joined the international collaboration *Lithium in magnetic AP stars* formed by N. Polosukhina, A. Shavrina, N.A. Drake, P. North, P. Quinet, J. Zverko, Ya Pavlenko,V. Tsymbal, V. Khalack, A. Veles, P. Wood, R. de La Reza, D. Shakhovskoy. Between 1996 and 2004 the project produced 25 papers. Li was found to vary with the rotational phase of the Ap stars and shown to be produced and accumulated in magnetic spots onto the stellar surface. The isotopic $^6Li/^7Li$ ratio was found ≈ 0.3 with a significant presence of the ^{6}Li isotope. This value is the smoking gun of spallation production of Li in the magnetic regions proving what suggested in the 60s by Faraggiana & Hack (1963); Wallerstein & Hack (1964). In 1983 under the supervision of Margherita Hack and Dennis Sciama I discussed my *Magister Philosophie*, a passage thesis between the 2nd and 3rd year of the International School of Advanced Studies. In this unpublished work, whose front page is shown in Fig. 1, the first significant upper limit on the ^{9}Be abundance in a population II star was derived. At the time I ignored Hack's work on the topic, a circumstance that caused some embarrassment when I discovered it. In those years there were models that with very active star formation in the early stages could make easily all the ^{7}Li observed in the halo stars (Dravins & Hultqvist 1977). The absence of ^{9}Be showed that ^{7}Li observed in the halo stars was indeed made in the Big Bang. The result was published in Molaro & Beckman (1984) where also Li was first used to bound the η value and together with the available upper bound to the primordial helium to constrain the number of neutrino families to less than 4. I am grateful to the organizers of Hack100 conference which gives me the opportunity to express my gratitude to Margherita for her continuous support and encouragement in the study of light elements. In Fig. 2 Margherita Hack celebrates her 90th birthday.


T E S I

DIPLOMA DI PERFEZIONAMENTO

"MAGISTER PHILOSOPHIAE"

THE BIG BANG AND THE LIGHT ELEMENTS

(BE -9 IN A POP II STAR: AN INDIRECT CONFIRMATION

OF THE PRIMORDIAL ORIGIN OF LI-7)

CANDIDATO: RELATORI:

dott. P. Molaro Prof. D.W. Sciama

Prof.ssa M. Hack

Anno Accademico 1982/1983

Fig. 1. Front page of my thesis for the Magister Philosophie of SISSA of the year 1982/1983. This is the first ^{9}Be upper limit in a population II star showing that the Li observed in halo dwarfs was not produced by spallation and therefore likely primordial. The results of this thesis have been published in Molaro & Beckman (1984).

2. The long standing Cosmological ^{7}Li problem

(Wagoner et al. 1967) were the first to elaborate in detail the primordial nucleosynthesis considering all the relevant reactions which assemble the nuclei of D, ^{4}He, ^{3}He and ^{7}Li within the first three minutes. Since then cross sections have been much improved, but the essential physics remains. Among the recent

Fig. 2. Margherita Hack celebrating her 90's birthday at the Observatory of Trieste together with the author of this notes (courtesy of Gabriella Schiulaz).

updates the LUNA experiment in the underground laboratory of Gran Sasso measured the cross section of the of $D(p,\gamma)^3He$ at BBN energies (Mossa et al. 2020). Along the years also the neutron half-life has been also precisely measured along with better measurements of ^4He and an impressive improvement in the D measurements. While the ^4He abundance is particularly sensitive to the speeding up of the expansion, and therefore to the number of effective relativistic neutrino families, the abundances of the other primordial nuclei are a function of the baryon to photon ratio. The concordance of the measured primordial abundances for a unique value of η has been one of the main support to the Big Bang cosmology, but in the era of precision cosmology some problems emerged. Observations of D received an impressive improvement in the recent years reaching a precision of about 10%. Considering all the 16 extant D/H determinations in high redshift QSO's absorbers, the weighted mean is $(D/H)_p \cdot 10^6 = (25.36 \pm 0.26)$. The metallicities of the Damped Lyman Alpha absorbers are in between 0.001 and 0.03 solar, i.e. at a level where absence of significant astration or depletion onto dust grains is expected. The concordance of the η value when derived from D within SBBN or the CMB shown in Fig 3 is quite impressive providing a robust support to the theory.

The best objects suited to provide the value of the primordial ^7Li are the metal-poor stars in the Galactic halo. Observations have long shown that ^7Li does not vary significantly in halo dwarfs with metallicities $[Fe/H] < -1.5$, i.e. the Spite plateau (Spite & Spite 1982). A puzzling drop is observed in the Li abundances in metal-poor stars with $[Fe/H] < -3.0$. This becomes particularly acute at the very low metallicity end where only one star out of the seven most metal poor dwarfs shows ^7Li abundance close to the Spite Plateau, while in the others, where it ought to be present, it is either lower or totally absent. Most of these stars are CEMP-no stars with a peculiar progenitors which may have destroyed ^7Li. The reason for the increase in scatter at low metallicity is unknown and prevents derivation of the primordial ^7Li value by extrapolating to zero metallicity. This is better estimated in stars with metallicity in the range $-2.8 < [Fe/H] < -1.5$, where there is no scatter, and has a value of $(Li/H)_p = 1.6 \pm 0.3 \cdot 10^{-10}$ (Sbordone et al. 2010).

As it can be seen in Fig. 3, the stellar Li measurements are inconsistent with the D. Since D agrees with the CMB, the odd element is likely ^7Li. The theoretical primordial ^7Li is $(Li/H)_p = 5.623 \pm 0.247 \cdot 10^{-10}$, which is a factor 3.5 higher than what measured in the halo dwarfs and with a significance of 10 σ. Interestingly, the Li abundance in stars belonging to the Gaia-Enceladus Galaxy shows a similar abundance and behaviour of the Galactic ones showing that the problem is rather universal and not dependent on the kind of galaxy or the chemical evolution type Molaro et al. (2020). The question is now whether this mismatch comes from uncertainties in stellar astrophysics or nuclear inputs, or whether there might be new and unknown physics behind it.

Strictly speaking, the observed primordial ^7Li abundance should be considered a lower

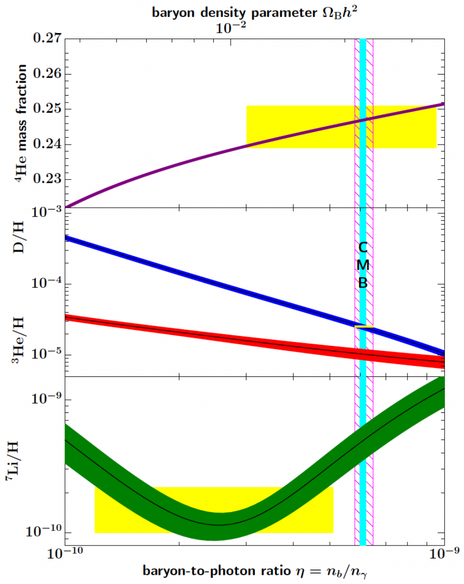


Fig. 3. The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis — the bands show the 95% CL range. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN D+4He concordance range (both at 95% CL). Figure from Workman et al. (2022).

bound rather than a measure. In fact, ^{7}Li in Pop II stars may have been partially destroyed due to mixing of the outer layers with the hotter interior.

The depth of convection a metal-poor dwarf is lower than solar metallicity stars allowing Li survival in the atmosphere (Cayrel et al. 1999). However, non standard models which include rotational mixing (Pinsonneault et al. 2002), or diffusion (Salaris & Weiss 2001), or both (Richard et al. 2002) predict a mild Li depletion. However, common feature of such models is the prediction of a sizable star to star variation in Li abundances and the probable existence of a small number of outliers with either higher or lower abundance. Thus, while a stellar solution to the cosmological Li problem is possible and also probable, a satisfactory physical explanation of the observed behaviour is still to be provided. On a different line Fu et al. (2015) suggested the possibility of Li destruction in the pre-main sequence phases followed by a partial Li restoring in the matter accretion process. A pre-main sequence Li destruction could also explain why Li in young clusters never reaches the meteoritic value.

3. Is the riddle of the origin of Li solved?

Whether Big Bang Li is, either taken from the theory or from halo stars, both values are much smaller than the meteoritic abundance of A(^{7}Li)=3.3± 0.02. This requires the existence of one, or more, Li source to make most of Li present in the Galaxy. Spallation processes are certainly present but their contribution is constrained to about less than 15% by the abundance of elements such as ^{9}Be and B which are produced in the same way (Reeves et al. 1970). Stellar production is limited to the AGB stars, which are too few and can contribute to a level up to few percent (Romano et al. 2001). Neutrino breaking heavy ions in SNe explosions predicted by Woosley et al. (1990) is also limited by chemical evolution models since they should act very soon at low metallicities, which is not observed. In the thermo-nuclear-runaway of Novae the reaction ^{3}He(α,γ)^{7}Be leads to the formation of ^{7}Be which if transported by convection to cooler zones could survive from destruction and decay into ^{7}Li Starrfield et al. (1978).. With the theoretically derived yields by José & Hernanz (1998), the novae contribution is of 30-40% and are not sufficient. An additional source is required. Romano et al. (2001) suggested that red-giants could be the missing source. However, the observational evidence is that only 0.1% of red giants show A(Li) > 3.3 and it is very unlikely that they can do the job. After decades of observational failures, the first, and so far unique, detection of Li was reported in nova V1369 Cen (Izzo et al. 2015). Moreover, the ^{7}Li parent nucleus ^{7}Be was discovered in classical novae by Tajitsu et al. (2015); Molaro et al. (2016). The non detection of neutral Li in the outburst spectra of novae could be explained if ^{7}Be de-

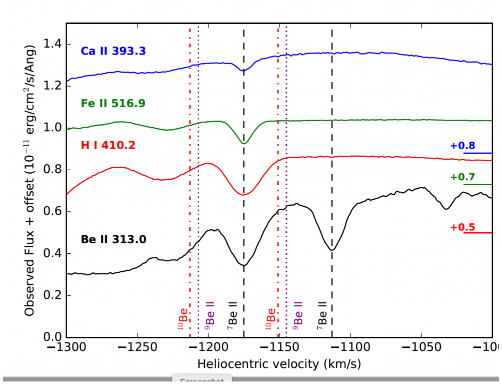


Fig. 4. Portions of Nova Sgr 2015 outburst spectra around the −1175 kms^{-1}expanding component of few metal lines. The ^{7}Be $\lambda\lambda$ 313.0583, 313.1228 nm are shown with a black dashed line. The positions of the expected ^{9}Be II $\lambda\lambda$ 313.0442, 313.1067 nm and ^{10}Be II $\lambda\lambda$ 313.0484, 313.1129 nm are also shown. Figure from Molaro et al. (2016)

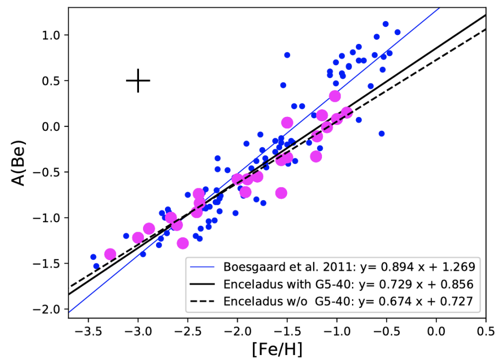


Fig. 5. A(Be) abundances versus iron abundances. A(Be) abundances from literature are in blue dots. The Gaia-Enceladus star candidates are highlighted in magenta. The cross on the top left corner shows the mean errors in the abundances. The solid and dashed black lines are the best fit through the Gaia-Enceladus stars with and without G5-40,which holds an uncertain membership, respectively. From Molaro et al. (2020).

cays via e— capture in 52.3d by capturing one internal K-electron and ending as ionised Li, which has no lines in the optical. So far ^{7}Be has been detected in all the dozen of novae where it was searched for, including also the Recurrent Nova RS Oph, see Molaro et al. (2022) and references there in. The mean yield is estimated as $< A(Li) >$ = 7.4, which is 4 orders greater then the meteoritic Li abundance. To note that the theoretical yields are about one order of magnitude lower than those observed. This tension is a crucial aspect, because only yields as derived from the observations are capable to make all the ^{7} Li in the Galaxy and to solve the riddle as shown by Cescutti & Molaro (2019); Kemp et al. (2022).

4. First extragalactic Beryllium

The process for the synthesis of ^{9}Be, as well as of ^{10,11}B, ^{6}Li and a fraction of ^{7}Li was defined by Reeves et al. (1970). The process is that of spallation of heavy elements such as energetic CNO nuclei breaking when colliding with protons and alpha particles at rest in the interstellar medium. The reverse process is also possible with energetic protons and α particles hitting CNO nuclei at rest in the interstellar medium.

On this basis, a secondary behaviour was predicted for the increase of Be abundance with Fe. Instead, the first observations revealed a primary trend suggesting that only one of the two processes was the dominant one (Rebolo et al. 1988; Molaro et al. 1997). This is that related to the formation of light elements near the SNe as originally suggested by Burbidge et al. (1957) in 1957. Observation also revealed a remarkable dispersion of the beryllium values at the same metallicity which is difficult to explain. Recently the beryllium measurements in stars belonging to the Gaia-Enceladus galaxy have been isolated showing not only a different slope in the trend with iron, but also the absence of any dispersion as shown in Fig. 5 (Molaro et al. 2020). This suggests the interesting possibility that the observed dispersion in the Galaxy is actually the result of several evolutionary traces in the synthesis of these elements in small galaxies that have been later engulfed by the Galaxy. Beryllium could therefore be a useful element for the chemical differentiation of these mergers. To note that the possibility of extragalactic observations of ^{9}Be will be very challenging if not impossible also with the next generation of gigantic telescopes. Thu, the possibility to isolate stars in the Galaxy coming from mergers with external galaxies will provide a unique way to probe the evolution of this element in an environment which differs from that of our own Galaxy.

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