Abundances of Big Bang elements

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Abstract. In this paper we review the present status of observations of
the Big Bang elements D, $^3$He, $^4$He and $^7$Li and of their extrapolation
to the primordial values. It is shown that, within the errors, the abundances
are consistent with the predictions of the standard Big Bang nucleosynthesis
for $1 \leq \eta_{10} \leq 6$, which corresponds to $0.004 \leq \Omega_b h^2 \leq 0.02$.
Narrower consistencies in $\eta_{10}$ are still possible at $\approx 1.7$ or $\approx 4$, but in
this case some of the observations of D and $^4$He should be incorrect. Finally,
that extragalactic Li may have already been detected in a star possibly accreted
by the Galaxy.

1. Introduction

In the standard hot homogeneous Big Bang model with 3 neutrino flavours the
elemental yields of primordial nucleosynthesis depend only on the ratio between
the number of baryons and photons at that epoch, namely:

$$\eta = \frac{n_b}{n_\gamma}$$

The value of $\eta$ is not predictable by the physics of the early universe. It can
only be fixed from the observations of the primordial abundances of the light
elements D, $^3$He, $^4$He and $^7$Li. Unlike $^4$He, where the yields are sensitive to the
speeding up of the expansion, the other three elements $^3$He, D and $^7$Li must
show consistency with the same value for $\eta$, whatever the number of relativistic
particles at the nucleosynthesis. More details can be found in Salati (1997) and
Sarkar (1996). There are four overall observables, i.e. the four light element
abundances, and one variable, i. e. $\eta$, which make the Big Bang theory fully
testable. This redundancy turns out to be particularly useful since the determina-
tion of the primordial values of the four elements from the observations is not
so straightforward.

The number of photons $n_\gamma$ at the epoch of the nucleosynthesis can be ob-
tained by scaling back the present number density of photons of the cosmic
background radiation ($T=2.73$ K) since the stellar photon production is negligi-
ble, and, therefore, a simple relation holds between $\eta$ and the the global baryonic
density, namely:

$$\Omega_b = 0.0037 h^{-2} \eta_{10}$$
where $\eta_{10} = 10^{10} \eta$ and $h_0$ = is the Hubble constant in units of 100 km s$^{-1}$ Mpc$^{-1}$, with possible values between 0.5 and 1. When compared with the luminous and dynamical matter this value has important bearings for assessing the presence and relative amount of baryonic and non baryonic dark matter respectively.

The uncertainties in the theoretical yields of SBBN come mainly from uncertainties in the nuclear cross-sections. They have been considerably reduced in the recent years after the accurate determination of the neutron half-life decay of $887(\pm 2)$ sec. The uncertainties are rather small for $^4$He with $\approx 0.5 \%$ at 95 C.L., with $\approx 15\%$ for D and $^3$He, but as large as $\approx 50 \%$ for Li (Krauss and Kernan 1995). In the following we are using the approximate relations to the theoretical yields over the range of $\eta_{10}$=1-10 provided by Sarkar (1996), which are accurate enough for our purpose. These are:

$$Y_p = 0.2462 + 0.01 \ln\left(\frac{\eta}{5 \cdot 10^{-10}}\right)\left(\frac{\eta}{5 \cdot 10^{-10}}\right)^{-0.2} \pm 0.0012$$  \hspace{1cm} (1)$$

$$\frac{D}{H} = 3.6 \cdot 10^{-50.06}\left(\frac{\eta}{5 \cdot 10^{-10}}\right)^{-1.6}$$  \hspace{1cm} (2)$$

$$\frac{^3He}{H} = 1.2 \cdot 10^{-50.06}\left(\frac{\eta}{5 \cdot 10^{-10}}\right)^{-0.63}$$  \hspace{1cm} (3)$$

$$\frac{Li}{H} = 1.2 \cdot 10^{-110.2}\left[\left(\frac{\eta}{5 \cdot 10^{-10}}\right)^{-2.38} + 21.7\left(\frac{\eta}{5 \cdot 10^{-10}}\right)^{2.38}\right]$$  \hspace{1cm} (4)$$

Determining a primordial abundance is a two-step process. The first one involves a measurement of $^3$,$^4$He, D and Li in an environment, or at least the closest one, were pristine material has been preserved. A measurement of HI is also required since the significant abundances are those relative to hydrogen. In fact, the HI determination is often, in particular for deuterium, the most difficult part. Unfortunately, there is no uncontaminated material available around and even the Ly$\alpha$ clouds, supposed to be made up of unprocessed material, have revealed the presence of metals at the deep Keck observations. Probably the sites with the material closest to the primordial one are the atmospheres of the extreme halo stars, where the metallicities can be as low as 0.0001 solar. Therefore, the second step necessarily requires corrections for the 15 Gyr or so of the cosmic stellar pollution. Recent reviews of the subject are those of Reeves (1994) and Pagel (1995).

2. The Helium Universal Floor

Jakobsen et al. (1994) made a remarkable detection of the HeII 304 Å line in absorption towards the QSO 0202-003 at $z_{em} = 3.286$ showing that helium is indeed pervasive in the universe but, unfortunately, uncertainties in the photoionization preclude precise helium measurements. Helium can be measured by a number of means and in a number of environments such as the study of the solar interior, solar prominences, He absorption lines in hot stars, the position of subdwarfs main sequence, the globular clusters morphology and the
recombination of He lines in planetary nebulae and HII regions. Among these techniques the HII regions provide the most accurate helium determination with an accuracy that can be as small as ±2%. In the HII nebulae hydrogen and helium emission lines are formed by electronic recombination of H+ and He++. For the abundance determination the necessary physical quantities are the electronic temperatures and densities, that can be obtained by specific line ratios (for instance: $T_e$ from the $[OIII]_{4363}/(3959+5007)$ and $n_e$ from the $[SII]_{6717/6731}$ ratios). Searle and Sargent (1972) first recognized that the extragalactic HII regions IZw18 and IIZw40 showing low metal abundances are the best sites for primordial helium determination. The extragalactic HII regions or blue compact galaxies (BCG) are dwarf irregular galaxies undergoing an intense burst of star formation but characterized by low abundances. The burst is not necessarily the first one and some of the BCG show presence of red stars or Wolf Rayet revealing previous older generations of stars which may have contributed to the elemental production and as well as to a small fraction of helium.

These objects are those specifically used for cosmological purposes since they have the virtues of being the closest objects to the primordial material and at the same time of permitting accurate measurements for helium. So far about 80 BCG with a metallicity range between $Z/50 < Z < Z/3$ have been studied for helium. Following Peimbert-Torres and Peimbert (1974) the stellar production of helium is given by the correlation among helium and the "metallicity", namely:

$$Y = Y_p + Z \frac{dY}{dZ}$$

where Y stands for helium, Z for oxygen, or nitrogen as suggested by Pagel and co-workers, and the primordial value is obtained by an extrapolation at zero metallicity. Since the time scales for oxygen production are much shorter than for helium an often followed alternative approach is that of taking the mean of the most metal poor galaxies. Strictly speaking this is just an upper limit to the primordial value.

From the first determination of the mass fraction of primordial helium of $Y_p=0.230 \pm 0.004$ made by Lequeux et al. (1979) to the most recent one of 0.228 $\pm 0.005$ by Pagel et al. (1992), the determinations have remained rather stable around these values with the focus on the value of the third decimal place (see Pagel 1995 for a detail account of the works). More recently Izotov Thuan and Lipovetsky (1994, 1997) claimed a primordial helium considerably higher than generally assumed earlier. The two papers are based on the analysis of 10 and 27 new extragalactic HII regions from the I and II Byurokan objective prism surveys. The Izotov et al. most recent value is:

$$Y_p = 0.243 \pm 0.003.$$  

The same result is obtained by using either O or N, and it is also not sensitive to the inclusion of objects with W-R features. According to the authors, the $Y_p$ value rises up with the use of the new HeI recombination coefficients by Smits (1996). However, as pointed out by Peimbert 1996 and Olive, Skillman and Steigman (1997), Smits’ coefficients are almost the same of the old ones by
Brocklehurst (1972), with the exception of the He 7065 Å line, which has been used by Izotov et al. but not by previous authors. Olive et al. reanalyzed the whole data set of available extragalactic HII regions comprehensive of Izotov et al.’ ones for a total of 78 BCG. From the linear regression at zero metallicity they obtained

$$Y_p = 0.234 \pm 0.002$$

The result does not change when the sample is reduced to the 62 objects of better data quality, but when the subsample of the most metal poor galaxies ([O/H]<-1) is considered, the linear regression gives a somewhat lower value $Y_p=0.230\pm0.003$. The same value ($Y_p = 0.230\pm 0.004$) is obtained by averaging the multiple independent determinations of IZw18 which, with [Fe/H]=-1.8, is the most metal poor known among the blue compact galaxies. Thus the problem seems to be related to the absence of very metal poor objects in the Izotov et al. sample. Unless they are giving lower helium values for some unknown systematics, the more likely value for the primordial helium ranges between 0.230-0.234. In Fig 1 the $Y_p$ abundances are compared with the SBBN predictions for 3 types of neutrinos and a $\tau_n=887$ sec. The Olive et al. value in terms of $\eta_{10}$ gives $1.8^{+0.9}_{-0.8}$, considering a significance of $2\sigma$ both in the observations and in the theoretical uncertainties. By comparison the Izotov et al. value corresponds to a $\eta_{10} = 3.7^{+4.1}_{-1.6}$ at the same value of confidence.

3. The $^3$He puzzle

$^3$He is an element presenting many difficulties for its measurement and interpretation. The pre-solar system abundance is derived from the non solar component in the meteorites and is:

$$\frac{^3He}{H} = 1.5(\pm0.3) \cdot 10^{-5}$$

(Eberhardt 1974).

A new datum has been recently acquired with the solar wind ion composition spectrometer (SWICS) on Ulysses spacecraft which measured the $^3He/^4He$ ratio in the interstellar gas entering the solar system (Gloeckler and Geiss 1996) along 40 months of integration. Relative to hydrogen the value becomes:

$$\frac{^3He}{H} = 2.1^{+0.9}_{-0.8} \cdot 10^{-5}$$

This measure refers to the present composition of $^3He$ and it shows that the $^3He$ abundance has not changed significantly in the last 4.5 Gyrs.

$^3He$ is also detected in emission through the 3.46 cm hyperfine transition of $^3He^+$ in Galactic HII regions. Data from a heroic project started in the early ‘80s at the 43m Green Bank radiotelescope by Rood and collaborators have been obtained from about 14 nebulae (Rood et al. 1995). The derived abundances are in the range of $0.68 \cdot 10^{-5}$ up to $6.03 \cdot 10^{-5}$, probably with a real dispersion.
Figure 1. SBBN yields for $^4He$ with the observations of Izotov et al. (1997) and Olive et al. (1997), errors at 2σ of CL.
In addition, the data suggest an anticorrelation with the galactocentric radius, with the more distant nebulae showing also the largest abundances.

$^3$He is produced in small mass stars ($M \leq 2M_\odot$) but it is destroyed in more massive stars (Iben 1967). All chemical evolution models predict a net increase of $^3$He with time, and therefore we should have at any time $^3He_p < ^3He$. But, if we take the value for the S209 nebula, which is the lowest value observed in the Galactic HII regions, we get a lower limit on $\eta_{10} > 5$, which is inconsistent with the bounds coming from the other elements.

According to the review of Tosi (1996), a common feature of all the chemical models is an astonishing overproduction of $^3$He by a factor 10 to 40 when compared to the observed one. Furthermore, these models cannot reproduce the constancy of the element from the solar birth up to the present time and predict a galactocentric gradient which is opposite to the observed one. Only non standard models which incorporate some $^3$He destruction in low mass stars (Hogan 1995, Charbonnel 1995) can reproduce the observations. However, counterexamples came from the observations of $^3He/H$ at the level of $10^{-3, -4}$ in six PNe with low mass progenitors in agreement with the theoretical predictions of $^3He$ production in low mass stars (Rood et al. 1995).

In summary $^3$He is the most elusive and ambiguous among the quartet of Big Bang elements both for what concerns the observations and the understanding of its theoretical behaviour; therefore, it is of little use for cosmology. Under the assumption that it has not changed very much we have a

$$^3He_p \approx 2 \cdot 10^{-5}$$

which is slightly more than a guess at its primordial value.

4. The Deuterium controversy

Primordial nucleosynthesis is the only known source of deuterium, and the mere presence of deuterium is an important proof for BBN. After all D has been produced in the first three minutes or so, it is slowly destroyed in the stellar recycling along the following 15 Gyrs. Correspondingly, the primordial deuterium is higher than any observed value, i.e. $(D/H)_p > (D/H)_o$.

The (pre)-solar system abundance is indirectly deduced by using the fact that when deuterium is burnt, it is all converted into $^3$He (Geiss and Reeves, 1972). By subtracting the present $^3He$ abundance obtained from solar flares from the $^3He$ pre-solar value obtained from the meteorites, we obtain the deuterium abundance originally present in the sun prior to deuterium burning:

$$\frac{D}{H} = \left( \frac{^3He}{H_\odot} - \frac{^3He}{H_{pre-\odot}} \right) = 2.6(\pm 1) \cdot 10^{-5}$$

This is in substantial agreement with the various determinations in the giant planets of the solar system, all in the range between 2 and $5 \cdot 10^{-5}$ (see Griffin et al. 1996, and references therein).

In the interstellar medium deuterium is measured in absorption from the DI Lyman series in the spectra of ultraviolet background sources, blushed by
Figure 2. Top figure: SBBN $^3He$ yields with $2\sigma$ errors. Observations are the solar $^3He$ and S209 nebula from Rood et al. (1995). Bottom: The SBBN yields for $(D + ^3He)$ and the upper limit for the sum, see text for details.
\[ \approx 82 \text{ km s}^{-1} \] with respect to the corresponding HI Lyman serie. A summary of the best data from the Copernicus and IUE satellites towards hot and relatively distant stars gives a value of \(1.5 \cdot 10^{-5}\), but variations of a factor 2 among the different lines of sight are not ruled out (McCullough 1992). Note that in few cases the D/H ratio was found at a level of \(\approx 5.8 \cdot 10^{-6}\) towards δ and ε Ori, λ Sco and θ Car and there is not a clear understanding of such a low values.

Historically these determinations of low deuterium abundance in the interstellar medium and solar system provided the first evidence that \(\Omega_b \leq 0.04h^{-2}\), i.e. that the universe cannot be closed by baryons (Reeves et al. 1973).

High quality data have been recently supplied by HST. Measurements of the DI Lyα have been performed towards the closeby cool stars Capella, Procyon and α Cen where the DI and HI Lyα are detected in absorption on the stellar chromospheric Lyman emission (Linsky et al. 1993, 1995, Linsky and Wood 1996). Lemoine et al. (1996) measured the D/H towards the featureless continuum of the hot white dwarfs G191-B2B at a distance of 48 pc. Three independent clouds are detected along this line of sight and all of them give an abundance of \(D/H \approx 1.3 \cdot 10^{-5}\). Towards Capella the interstellar medium is remarkably simple with only one component, and it probably provides the most accurate measure for D/H in the local interstellar medium. From Linsky et al. (1995):

\[
\frac{D}{H} = 1.6(\pm 0.09)_{\text{stat}}(0.05)_{\text{syst}} \cdot 10^{-5}
\]

In general, difficulties may arise from the modelling of intervening clouds. The binary system α Cen the system is only 1.34 pc away, which is the shortest line of sight one may think, and nevertheless a model with two clouds is required, with a second component contributing to HI but not to deuterium. The D/H abundance would be a factor 2 lower (i.e. \(D/H = 0.61 \cdot 10^{-5}\)), ignoring this second component, which Linsky and Wood associate with the compression of the interstellar gas by the solar wind near the heliopause. The case of α Cen is a good example of how difficult it may be measuring exactly deuterium within a complex interstellar structure.

An important detection is the long search for the 92 cm DI hyperfine emission line reported by Chengalur et al. (1997). The detection is at a significance of \(4 \sigma\) and implies an abundance of

\[
\frac{D}{H} = 3.9 \pm 1.0 \cdot 10^{-5}
\]

The Chengalur et al. (1997) measure is obtained in the direction of the Galactic anticenter in a region of the Galaxy that should be less affected by stellar recycling than the solar neighborhood. This measure is certainly the measure of deuterium closest to the primordial value we may get in the Galaxy.

The extrapolation to the primordial value from the measurements of the abundance in the interstellar medium requires the understanding of the amount of matter recycled into stars (astration). The ratio between the observed deuterium and the primordial value \(\frac{D}{D_p}\) is the fraction of gas that has never been
Figure 3. SBBN D yields with 2 σ errors. Observations are for the QSOs, the Galactic anticenter, and the LISM, see text for details.
through stars. According to Tosi’s review the most likely value for this fraction is 0.5, whereas a value of 0.3 seems a safe bound. However, the presence of infall in the Galaxy is an additional variable since it requires pre-knowledge of the amount of deuterium there. Less conventional models can destroy D up to a factor of 10, without overproducing metals or $^3He$ (Vangioni-Flam et al. 1994). However, the problem of $^3He$ overproduction in models with large D depletion is relaxed if extra destruction for $^3He$ is required, as discussed in the previous section.

4.1. Primordial ($^3He + D$)

Some of the problems in the understanding of D evolution may be circumvented by considering the sum (D+$^3He$) instead of the separated elements. This is because any D destruction leads to $^3He$ production, some of which survives stellar processing. Following Yang et al. (1984) at any time the sum

$$
\frac{(D + ^3He)}{H}|p < \left[\frac{(D + ^3He)}{H}\right]_\odot + \left(\frac{1}{f} - 1\right)^3He_\odot
$$

where $f$ is the fraction of survival of $^3He$. Stellar evolution theory predicts $f > 0.25$, with a likely value of 0.5. Thus:

$$
\frac{(D + ^3He)}{H}|p < 8.6(\pm 0.3) \cdot 10^{-5}
$$

which implies $\eta_{10} \geq 2.5$. This argument was used in combination with an upper bound in primordial helium to set a limit at four for the number of neutrino flavours (Yang et al. 1984). However, most surprisingly, (D + $^3He$) computed at the solar birth has not changed in comparison with the value of the present epoch, which can be obtained by combining the data for D and $^3He$ from the local interstellar medium (3.6$\cdot 10^{-5}$). This again reflects the poor understanding of the $^3He$ evolution, with the possible presence of unrecognized $^3He$ sinks. Thus, the (D + $^3He$) argument does not appear a very safe one anymore for setting a lower bound to $\eta$.

4.2. Deuterium in high z QSO absorption systems

Adams (1976) first suggested the possibility of measuring the D/H ratio in high redshift absorption systems. They are supposed to be unevolved systems which offer the advantage of a deuterium abundance before a considerable as well as uncertain, stellar destruction. The first positive results, which came out only in the 1994, show that the measure is not straightforward at all.

Simulations have been presented by Webb et al. (1991) and Jenkins (1996). The most propitious case seems to be the detection of the D Ly$\alpha$ or Ly$\beta$ of a relatively simple, i.e. one-component absorption system, with negligible kinematic broadening along the line of sight. The total column density has to be rather low to avoid the saturation of the line, so that the best candidates are the Limit Lyman System (log $N(HI) \leq 17.5$). A second possibility suggested by Jenkins involves the higher members (Ly$\theta$ to Ly$\pi$) of Damped Ly$\alpha$ absorbers, which are systems with log $N(HII) \geq 20.6$. Such a possibility is particularly interesting.
since these objects are believed to be the progenitors of the present day spirals, and specific programs are under way.

So far detections for D/H have been claimed for eight systems, but research is developing very fast. The first was the system in the QSO Q0014-813 at redshift z=3.32 (Songaila et al. 1994, Carswell et al. 1994 and Rugers and Hogan 1996). This system has log $N(HI)$=17.3, no metal lines detected which imply $[C/H]$, $[Si/H] < -3.0$, and is composed of at least 7 hydrogen clouds. A deuterium line is identified for the most blueward of the seven components which form the absorption complex, and the abundance is:

$$\frac{D}{H} \approx 2 \cdot 10^{-4}$$

The crucial question, here and in general for other deuterium identifications towards QSOs, is to discriminate the feature against the possibility of a Ly$\alpha$ cloud. For QSO0014-813 the redshift coincidence is of ± 5 km s$^{-1}$, but the argument is not definitive, in particular if there is some clustering in the system. Rugers and Hogan (1996) from the reanalysis of the Keck data used by Songaila et al. claimed that the deuterium feature is made of two resolved clouds. The measured line broadening is of $b \approx 8$ kms$^{-1}$, ($b = (2KT/m)^{1/2}$), which is rarely found (less than 2%) in Ly$\alpha$ clouds thus making the case for a Ly$\alpha$ interloper less likely. However, new Keck data of the same system by Tytler (1997) are challenging the double nature of the deuterium line.

Carswell et al. (1996) proposed a tentative detection of deuterium in the system at $z_{abs} = 3.08$ towards QSO 0420-388. The hydrogen column density of the system is of about $10^{18}$ and the metallicity is rather high at $\approx 0.1$ solar. They acknowledge that the presence of the deuterium line improves the fit in the Lyman lines but that there is not any compelling evidence for a deuterium line and an interloper Ly$\alpha$ can do the same job. Carswell et al. by-pass the uncertainty on the hydrogen column density by using the oxygen abundance assumed constant for all components of the system and obtain $D/H \approx 2 \cdot 10^{-4}$.

Wampler et al. (1996) claimed a deuterium detection in a system at $z=4.672$ towards BR 1202-0725. This system is likely dominated by a single absorption, it shows the high ionization features of CIV and SiIV and it may have a rather high abundance with $[O/H] \approx -0.3$. This would indicate a potentially embarrassing higher D/H. Other tentative but somewhat more uncertain detections, all giving high D/H of $\approx 10^{-4}$, have been reported for another system at $z=2.79$ towards Q0014-813 by Rugers and Hogan (1996b) and towards Q0956+122 and GC 0636+680 (cfr. Hogan 1996).

In contrast with the high values of D/H, Tytler et al. (1996) and Burles and Tytler (1996) found D/H about one order of magnitude lower towards Q1937-1009 and in the $z=2.54$ system towards Q1009+2956. Both systems, which show several similarities, have two components barely resolved with the HIRES-Keck resolution in several metal lines. For Q1937-1009 the column densities are of 17.94± 0.05 and the carbon abundances for the two components are $[C/H] = -3$ and -2.2. For Q1009+2956 the hydrogen column density is of 17.46 and $[C/H] = -2.9$ for both the components. The two systems have a very similar deuterium abundance, with an average of:

$$\frac{D}{H} = 2.4(\pm 0.3)(\pm 0.3_{sys}) \cdot 10^{-5}$$
Figure 4. The Li plateau from Bonifacio and Molaro (1997); $[\text{Li}] = \log(\text{Li/H}) + 12$.

However, Wampler (1996) showed that an alternative model for Q1937-1009 with 3 components may lead to a reduction in the total hydrogen column density by a factor 3 or even 4, having as a side effect weaker damping wings and a 25\% increase in the flux below Ly$\alpha_2$, which are both consistent with the data. In fact, a residual flux below the Lyman break was detected in new Keck observations of Q1937-1009 by Songaila et al. (1997). From an estimation of the continuum in that region which takes into account the contribution of the Ly$\alpha$ forest, the hydrogen column density is of $N(\text{HI}) = 5(\pm0.1)\cdot10^{17}$, i.e. about a factor 2 lower than Tytler et al.’s estimation. This increases the deuterium value in this system at $\approx 5 \cdot 10^{-5}$, and shows that small errors in the (D/H) measured towards QSOs are probably unrealistic. Considering the revised D/H for one of the two Tytler et al. measurements, and the determination towards the Galactic anticenter, the most likely value for primordial deuterium is around:

$$\left(\frac{D}{H}\right)_p \approx 4 \cdot 10^{-5}$$

This value also reconciles the determination of the local interstellar medium measurement with the conventional chemical evolution prescriptions.
5. Lithium in halo subdwarfs

Francois and Monique Spite (1982) discovered the presence of Li and its remarkably constant value in the warm \( T_{\text{eff}} \geq 5600 \text{K} \) and metal poor stars in an amount very close to the minimum of the SBBN yields. Since then several groups have increased up to about one hundred the number of halo stars studied for lithium, including very metal poor stars with metallicity down to \([\text{Fe/H}] \approx -4\).

Recently the results from the field stars have found support in the turn off stars of globular clusters of NGC 6397 (Pasquini and Molaro 1996). Deliyannis et al. (1995) made Keck observations of few turn-off stars in the globular cluster M92 and found six stars with about normal Li except one with higher abundance (M92-18). However, this star has shown some chemical peculiarities and should not modify the general result.

The main problem concerning the cosmological use of lithium is to understand whether the value measured in population II stars truly represents the primordial value or has been depleted from a higher value. Lithium is a fragile element which is destroyed in the stellar interiors by \((p,\alpha)\) reactions at \( \approx 2.6 \cdot 10^6 \) K. Thus it survives on the surfaces of F and G stars but is depleted in later type stars with deep convection zones. In addition, other processes, not clearly identified, should be present depleting further Li and producing the large scatter of about 3 orders of magnitude, which is observed in the Li abundances of stars with solar composition. At variance with population I, the Li abundances in population II stars are closely gathered, with the natural inference that analogous depletion mechanisms are not active in these stars. The different extent of the convection zones in the two types of stars is probably responsible for the different behaviours. In halo stars the decrease in the opacity creates a shallower and more superficial convection zone, preserving Li from nuclear burning.

Standard stellar models predict no destruction but various mechanisms such as diffusion, rotational mixing and stellar winds have been investigated as a way to deplete Li still preserving a plateau shape (Vauclair and Charbonnel 1995). Gravitational settling or thermal diffusion operate in very stable atmospheres, while in the case of rotational mixing the exchange of material between the surface and the interior is produced by the loss of angular momentum which creates a rotational instability inside the star. According to Vauclair and Charbonnel (1995) these processes can deplete the original Li content by a factor 2 or 3, but they have some distinct features such as a downturn at the hot edge of the plateau, a small anticorrelation of Li abundance with the effective temperature of the star and a dispersion of the order of at least 0.3 dex. Stellar mass loss produces a readjusting of the stellar structure which is able to produce Li dilution when Li-free layers enter into the photosphere. A mass loss higher than \( 10^{-13} M_\odot \text{yr}^{-1} \) starts bringing up Li depleted layers while higher values \( (\gg 10^{-12}) \) lead to complete Li destruction. The sun has a mass loss of \( 10^{-14} M_\odot \text{yr}^{-1} \) and since no direct observations of winds are possible in population II stars, this proposal remains rather speculative. With stellar winds of \( \approx 10^{-12.5} M_\odot \text{yr}^{-1} \) a positive slope is predicted in the plateau as well as a considerable dispersion, unless they are strictly identical in all the stars.
As a consequence of these claims the question of the real flatness in the Spite plateau becomes rather important. Trends of Li-Teff and Li-[Fe/H] and of intrinsic dispersion have been claimed by some authors (Deliyannis et al. 1993, Thorburn 1994, Ryan et al. 1995), supporting the presence of some Li depletion. On the other hand the plateau has been found really flat, without any intrinsic dispersion or trend with temperature and metallicity in the analysis of Molaro et al. (1995), Spite et al. (1996) and Bonifacio and Molaro (1997). The different results are probably due to the different ways to derive the stellar effective temperature for the stars, which is a rather critical point for Li abundances. From an accurate reanalysis of 41 stars in the plateau \((T_{\text{eff}} > 5700 \text{ and } [\text{Fe/H}] < -1.5)\), with available good \(T_{\text{eff}}\) determinations obtained from the Infrared Flux Method, Bonifacio and Molaro (1997) have obtained a very small dispersion of \(\pm 0.088\) around the mean, which is of the same order of the observational accuracy. The observations are shown in Fig 4. No trends are found either with the effective temperature or metallicity, and there is no evidence for a downturn for the Li abundances of the warmer stars. These results argue against any kind of depletion predicted by diffusion, rotational mixing or stellar winds, so that there are no real observational features which may support the case for Li depletion. On the contrary, also the Li measurements in tidally locked binaries and the detection of the more fragile \(^6\text{Li}\) isotope in the atmosphere of few halo stars suggest the absence of Li depletion.

Averaging over all the measurements and after correction for small Non-LTE effects the primordial Li becomes:

\[
\left( \frac{\text{Li}}{H} \right)_p = 1.73 (\pm 0.05_{\text{stat}})(\pm 0.11_{\text{sys}}) \cdot 10^{-10}
\]

where the small statistical error is the error of the mean, and the systematic error, which is dominant, follows from the uncertainty in the zero point of the \(T_{\text{eff}}\) scale of cool stars (Bonifacio and Molaro 1997). Our ultimate ability to model stellar atmospheres is the only area left in which other systematic errors can be hidden.

In Fig. 5 the SBBN theoretical Li yields together with the primordial Li from Bonifacio and Molaro (1997) are shown. The Li Pop II value corresponds to two possible values for \(\eta\): \(\eta_{10} = 1.7^{+0.6}_{-0.3}\) or \(\eta_{10} = 4.0^{+0.9}_{-1.0}\). The minimum theoretical Li yield is left out when one considers 1\(\sigma\) errors in the theoretical predictions and 1\(\sigma\) errors, plus the full systematic error, in the Li abundances. However, considering the 2\(\sigma\) errors, the minimum of the Li curve is allowed thus considerably increasing the allowed \(\eta\) range to \(1.2 < \eta_{10} < 5.5\).

6. Already detected ”extragalactic” Li?

Among the Big Bang elements only D and \(^4\text{He}\) have been observed in extragalactic objects. Most of the \(^4\text{He}\) measures come from the local universe at redshifts typically of 0.01 to 0.1 at most, and deuterium is observed up to a redshift of 3 or even 4. The difficulties of observations makes \(^4\text{He}\) a definitely Galactic element. The same applies to Li, since solar type stars in external galaxies are out of reach even for the 10m class telescopes. Only upper limits for the interstellar Li towards the SN1987A in the LMC were obtained when the
supernova was as bright as V=4 mag. However, Li has been detected in Galactic stars, which might possibly have been born in other galaxies.

Preston et al. (1994) in their HK objective prism survey of metal poor stars identified a population of stars which they called the blue metal poor main sequence stars (BMP). This population is composed by hot and metal poor objects that should have already evolved from the main sequence if coeval with the halo stars. The space density for the BMP stars is about one order of magnitude larger than that of blue stragglers in globular cluster, thus suggesting that field BS are a minor component of this population. Moreover, the kinematical properties of the BMP are intermediate between those of halo and thick-disk populations. The Preston et al.’s suggestions is that the BMP population has been accreted from a low luminosity satellite of the Milky Way in the recent past.

One of these stars is CS 22873-139, which has a remarkably low metallicity [Fe/H]=-3.1. This object is a spectroscopic binary with a period of 19.16 days, and Preston (1994) was able to derive an upper limit to the age for the system at < 8 Gyr, which again is inconsistent with a halo origin. Li has been already measured in CS 22873-139 by Thorburn (1994) who derived a value of (Li/H)=1.9 \cdot 10^{-10}, i.e. at the canonical halo value. Under the assumption that the object has been truly accreted by our Galaxy, this may be considered the first extragalactic Li detection giving support to the universality of the Li observed in the population II of the Galactic halo.
7. Crisis or concordance

Whether or not concordance exists between the observations of the light element abundances and the standard Big Bang nucleosynthesis depends on the errors one is willing to associate to the different measurements. It is evident that most of the different determinations for a specific element are in conflict with one another by a factor that exceeds the claimed errors.

For deuterium both high and low D/H measures towards QSOs are clearly conflicting. The high value may be affected by Ly\(\alpha\) interlopers, while the low value may adopt a too simple cloud model and/or underestimate the hydrogen column density. On the other hand, if they were both accurate, then the two classes of objects may have had very different chemical histories. It must be realized that the real nature and chemical evolution of the systems originating the QSO absorption systems are not clearly understood, and what we know today is only that they are probably the progenitors of the present day galaxies. It has also been pointed out that the total mass covering the QSO image is rather small \((\leq 1 M_\odot)\), and local effects as those from deuterium-free winds of massive stars may have depleted deuterium significantly along the line of sight. Deuterium is the only light element of the quartet observed on cosmological scales, but the possibility that the different D/H abundances reflect inhomogeneities in the baryon number at the epoch of nucleosynthesis on very large scales has been found inconsistent with the CRB isotropy (Copi et al. 1996).

Concerning Li, there is no dispute about its abundance among the observers, and the agreement among the measurements carried out by different authors with different theoretical atmospheric models is excellent. The controversial issue is the possible depletion, but despite several claims there is no observational support for any depletion. It is a very unfortunate circumstance that the theoretical uncertainties associated with the SBBN yields are much larger than the observational ones.

Since intrinsic variations in the primordial abundances are cosmologically unlikely, unrecognized systematics are probably affecting the elemental measurements. Adopting the most conservative approach to take the different values as an indication of the systematics errors involved in the measurements, all the abundances agree with each other for

\[ 1 \leq \eta_{10} \leq 6 \]

This consistency although not particularly tight has to be regarded as a success of the Big Bang theory which is able to predict the right absolute abundances for all the four primordial elements, which differ from one another by something as nine orders of magnitude. This corresponds to:

\[ 0.004 \leq \Omega_b h^2 \leq 0.02 \]

As it is possible to see in Fig. 6, where the ranges in \(\eta\) for the most likely abundance are shown, there may be room for two narrower ranges for \(\eta_{10}\), where concordance is realized by particular choices for D and \(Y_p\). The two narrower bands are centered roughly in correspondence of the two intersections of the primordial Li value taken from the Pop II observations at face value, and the valley of the SBBN Li yields.
Figure 6. Comparison of theory and observation. $Y_p$ is from Olive et al. (1997) and Izotov et al. (1997); D is from Chengalur et al. (1997), considered at 1 $\sigma$, and Li from Bonifacio and Molaro (1997); first choice measurements are shown by continuous lines.
One narrow band is centered at $\eta_{10} \approx 1.7$. This is in excellent agreement with the high deuterium suggested by several measurements in QSO absorption systems and it is also in perfect agreement with a primordial helium at $Y_p = 2.34$ as derived by Olive et al. (1997) from the analysis of the whole data sample of extragalactic HII regions. Two basic problems affect this consistency. One is the low deuterium observed by Tytler et al., which holds even if we take the value revised by Songaila et al. (1997) of $\approx 4 \cdot 10^{-5}$. The second one is the difficulty of the conventional chemical evolution models to explain an original D/H abundance at a level of $10^{-4}$ starting from the value of the interstellar medium, which is one order of magnitude lower.

A slightly higher band centered at $\eta_{10} \approx 4$ shows the concordance of deuterium at $4 \cdot 10^{-5}$ as it is measured by Chengalur et al. (1997) from the anticenter region of the Milky Way. This is about the same value shown by the distant quasar systems of Tytler et al., once we take into account the new hydrogen column density of Songaila et al. (1997), but the high value of D/H observed in some QSO requires some contamination from Ly$\alpha$. On this value of $\eta_{10}$ there is also the concordance of the Izotov et al. (1997) determination of helium at $Y_p = 0.243$, which is also shown in Fig 6. But this would imply that the most metal poor extragalactic HII regions lead to a systematic underestimation of primordial helium by about 0.014 in mass.

However, it is rather unsatisfactory that first choice measures for helium at $Y_p = 0.234$ and deuterium at $\langle \text{D/H} \rangle \approx 4 \cdot 10^{-5}$ denotes some friction among them since they do not strictly match the same value for $\eta_{10}$ as they are expected to do. An alternate solution suggested by Hata et al. (1997) would be to consider a lower primordial production of helium, which may be achieved by relaxing the hypothesis of 3 relativistic neutrinos as assumed in the standard model.

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