

Standard Big-Bang Nucleosynthesis after Planck

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ABSTRACT

Primordial or Big Bang nucleosynthesis (BBN) is one of the three historical strong evidences for the Big-Bang model together with the expansion of the Universe and the Cosmic Microwave Background radiation (CMB). The recent results by the Planck mission have slightly changed the estimate of the baryonic density Ω_b , compared to the previous WMAP value. This article updates the BBN predictions for the light elements using the new value of Ω_b determined by Planck, as well as an improvement of the nuclear network and new spectroscopic observations. While there is no major modification, the error bars of the primordial D/H abundance ($2.67 \pm 0.09 \times 10^{-5}$) are narrower and there is a slight lowering of the primordial Li/H abundance ($4.89^{+0.41}_{-0.39} \times 10^{-10}$). However, this last value is still ≈ 3 times larger than its observed spectroscopic abundance in halo stars of the Galaxy. Primordial Helium abundance is now determined to be $Y_p = 0.2463 \pm 0.0003$.

Subject headings: Cosmology, Primordial Nucleosynthesis, Nuclear Reactions, Cosmological Parameters, Early Universe

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1. Introduction

There are three historical observational evidences for the Big-Bang Model: the cosmic expansion, the Cosmic Microwave Background (CMB) radiation and Primordial or Big-Bang Nucleosynthesis (BBN). Today they are complemented by a large number of evidences in particular from the properties of the large scale structures (see Peter & Uzan (2009) for a textbook description). BBN predicts the primordial abundances of the “light cosmological elements”: ^4He , D, ^3He and ^7Li that are produced during the first 20 mn after the Big-Bang when the Universe was dense and hot enough for nuclear reactions to take place. Comparing the calculated and observed abundances, there is an overall

good agreement except for the ^7Li . The essential cosmological parameter of the model is the baryon to photon ratio, $\eta \equiv n_b/n_\gamma$ where the photon number density is determined from the CMB temperature and n_b is related the baryonic density. Ω_b is now well measured from the angular power spectrum of the CMB temperature anisotropies. A precise value for this free parameter was provided by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite, $\Omega_b h^2 = 0.02249 \pm 0.00056$, (Komatsu et al. 2011) while the recent Planck mission updated it to $\Omega_b h^2 = 0.02207 \pm 0.00033$ (Ade et al. 2013).

The goal of this letter is to update our previous work (Coc & Vangioni 2010) to incorporate (i) the Planck results, (ii) nuclear network improvements and (iii) new spectroscopic observations. To trace the changes since Coc & Vangioni (2010), we follow, step by step, the effects of each

update to identify the key parameters. We first consider the update of the observational data (Section 2) while in Sections 3 and 4, we present the new results with the last nuclear and CMB data and with an extended network respectively.

2. Primitive observational abundances update

Deuterium is a very fragile isotope, easily destroyed after BBN. Its most primitive abundance is determined from the observation of clouds at high redshift, on the line of sight of distant quasars. Very few such observations are available. For $\eta = \eta_{\text{WMAP}}$, we previously determined a theoretical BBN deuterium abundance, $\text{D}/\text{H} = (2.59 \pm 0.15) \times 10^{-5}$ (Coc & Vangioni 2010).

From the observation of about 10 quasar absorption systems the weighted mean abundance of deuterium is $\text{D}/\text{H} = (3.02 \pm 0.23) \times 10^{-5}$ (Olive et al. 2012). However, the individual measurements of D/H show a considerable scatter and it is likely that systematic errors dominate the uncertainties. Most of the measurements available in the literature have been gathered in Pettini et al. (2008) to deduce $\text{D}/\text{H} = 2.82^{+0.20}_{-0.19} \times 10^{-5}$. Recently, the observation of a Damped Lyman- α (DLA) at $z_{\text{abs}} = 3.049$ has permitted (Pettini & Cooke 2012) a new determination of $\text{D}/\text{H} = 2.535 \pm 0.05 \times 10^{-5}$, leading to a mean determination lower than the previous one, $(2.60 \pm 0.12) \times 10^{-5}$. But, since the HI Ly- α absorption associated to this system is redshifted exactly on top of the Ly- α -Nv blend emission from the quasar, the errors on this measurement are probably underestimated. A new analysis is needed to clarify this question and we do not take into account this value presently to determine our weighted mean D abundance. Different star formation histories in the galaxies associated with the DLAs could explain this dispersion. For a recent analysis of the deuterium observations, we refer to Olive et al. (2012) and in this present study, we thus adopt their D/H mean abundance value,

$$\text{D}/\text{H} = 3.02 \pm 0.23 \times 10^{-5}. \quad (1)$$

After BBN, ${}^4\text{He}$ is still produced by stars, essentially during the main sequence phase. Its primitive abundance is deduced from observations in HII (ionized hydrogen) regions of compact blue galax-

ies. In a hierarchical structure formation model, these dwarf galaxies are more primitive than the galaxies. The primordial ${}^4\text{He}$ mass fraction, Y_p , is obtained from the extrapolation to zero metallicity but is affected by systematic uncertainties (Aver et al. 2010; Izotov & Thuan 2010) such as plasma temperature or stellar absorption. These determinations based on almost the same set of observations lead to

$$Y_p = 0.2561 \pm 0.0108. \quad (2)$$

Recently, Aver et al. (2012) have determined the primordial helium abundance using a Markov Chain Monte Carlo (MCMC) techniques. In this study, a regression to zero metallicity yields

$$Y_p = 0.2534 \pm 0.0083 \quad (3)$$

which corresponds to a narrower error bar than previously. We take this last value for comparison with our calculation.

Contrary to ${}^4\text{He}$, ${}^3\text{He}$ is both produced and destroyed in stars all along its galactic evolution, so that the evolution of its abundance as a function of time is subject to large uncertainties. Moreover, ${}^3\text{He}$ has been observed in our Galaxy (Bania et al. 2002), and gives only a 'local' constraint

$${}^3\text{He}/\text{H} = 1.1 \pm 0.2 \times 10^{-5}. \quad (4)$$

Consequently, the baryometric status of ${}^3\text{He}$ is not firmly established (Vangioni-Flam et al. 2003).

Primitive lithium abundance is deduced from observations of low metallicity stars in the halo of our Galaxy where the lithium abundance is almost independent of metallicity, displaying the so-called Spite plateau (Spite & Spite 1982). This interpretation assumes that lithium has not been depleted at the surface of these stars, so that the presently observed abundance can be assumed to be equal to the initial one. The small scatter of values around the Spite plateau is indeed an indication that depletion may not have been very effective. However, there is a discrepancy between the value i) deduced from these observed spectroscopic abundances and ii) the one calculated by BBN from Ω_b CMB observations. Many studies have been devoted to the resolution of this so-called *Lithium problem* and many possible "solutions", none fully satisfactory, have been proposed. For a detailed analysis see Fields (2011)

and the proceedings of the meeting “Lithium in the cosmos” (Iocco et al. 2012).

Astronomical observations of these metal poor halo stars (Ryan et al. 2000) have thus led to a relative primordial abundance of $\text{Li}/\text{H} = (1.23_{-0.16}^{+0.34}) \times 10^{-10}$ while more recent analysis (Sbordone et al. 2010) gives

$$\text{Li}/\text{H} = (1.58 \pm 0.31) \times 10^{-10} \quad (5)$$

which we use in our analysis. For reviews on the Li observations, we refer to Spite & Spite (2010) and Frebel & Norris (2011).

3. New results with nuclear and CMB data updated

Since our previous Monte-Carlo BBN calculations (Coc & Vangioni 2010), no change has been made concerning 11 of the 12 main BBN reactions rates. We thus use those from the the evaluation performed by Descouvemont et al. (2004) except for ${}^1\text{H}(n,\gamma)\text{D}$ (Ando et al. 2006) and ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ (Cyburt & Davids 2008).

The only modification of one of the main rates concerns the weak reactions involved in $n \leftrightarrow p$ equilibrium whose rates (Dicus et al. 1982) is determined from the standard theory of the weak interaction but needs to be normalized to the experimental neutron lifetime. The latter has recently been revised from 885.7 ± 0.8 s (Amsler et al. 2008), used in Coc & Vangioni (2010), to 880.1 ± 1.1 s (Beringer et al. 2012). This significant change is due to the re-consideration of the previously discarded (Serebrov et al. 2005) experimental value, now comforted by new analyses (see Wietfeldt & Greene (2011); Beringer et al. (2012) for more details). Comparison between columns 3 and 4 in Table 1 shows the effect of this change, which remains very small since it lowers Y_p by 0.44% and ${}^7\text{Li}/\text{H}$ by 0.39%, letting the other abundances unchanged.

Concerning the update of the CMB, a comparison between columns in Table 1 shows the effect of a change in $\Omega_b h^2$ from Spergel et al. (2007) to Komatsu et al. (2011) (columns 2, 3) and from Komatsu et al. (2011) to Ade et al. (2013) (columns 4, 5). It mostly affect ${}^7\text{Li}/\text{H}$ by about 4% and D/H by about 2.7% while the other changes are less than a percent.

A BBN evaluation has been done by Ade et al. (2013), using $\Omega_b \cdot h^2 = 0.02207 \pm 0.00027$; their prediction regarding the Y_p and D/H abundances are similar than ours (0.24725 ± 0.00032 and $2.656 \pm 0.067 \times 10^{-5}$ respectively) but they do not provide any ${}^7\text{Li}/\text{H}$ value.

4. Extended BBN network and correlated results

Recently, Coc et al. (2012) have extended the BBN network by including more than 400 reaction or decay rates in order to calculate the primordial CNO production during BBN. They performed a sensitivity study by changing each rate within three orders of magnitudes around their nominal rates or within their known uncertainties when available. None of these reactions have displayed a significant influence on the light isotope yields and in particular on ${}^7\text{Be}+{}^7\text{Li}$ (see also Hammache et al 2013, submitted to PRC). However the extension of the network with many new neutron producing or absorbing reactions slightly (-4%) modify the late neutron abundance, resulting in a moderate increase of the ${}^7\text{Li}$ yield, as seen comparing columns 3 and 6 in Table 1.

Concerning this new Monte-Carlo calculation, that involves reactions up to CNO¹, we follow the prescription by Sallaska et al. (2013). Namely the reaction rates x are assumed to follow a log-normal distribution with μ and σ , tabulated as a function of T and are deduced from the evaluation of rate uncertainties by Coc et al. (2012). The p 's in Eq. (22) of Sallaska et al. (2013), are sampled according to a normal distribution:

$$x = \exp(\mu + p\sigma) \equiv x_{\text{med}}(f.u.)^p \quad (6)$$

where $x_{\text{med}} \equiv \exp(\mu)$ is the median rate and $f.u. \equiv \exp(\sigma)$ the factor uncertainty. As discussed in Longland et al. (2010), for small σ the lognormal distribution used here is close to a normal distribution as used in Coc & Vangioni (2010). (For η , we use a normal distribution.) The values displayed in the last column of Table 1 correspond to the 0.16, 0.5 and 0.84 quantile of the ${}^4\text{He}$, D , ${}^3\text{He}$ and ${}^7\text{Li}$ distributions.

Hence, comparison between columns 2 and 7 in Table 1 shows the evolution of the yields from

¹The results concerning $A > 7$ nuclei are beyond the scope of this letter and will be published elsewhere.

Table 1: Primordial abundances. (Bold face displayed values highlight parameter changes.)

Nb. reactions	(a) 13	(b) 15	This work 15	This work 15	(b) 424	This work 424
$\Omega_b \cdot h^2$	$0.0223^{+0.00075}_{-0.00073}$ (c)	0.02249 (e)	0.02249 (e)	0.02207 (g)	0.02249 (e)	0.02207 ± 0.00033 (g)
τ_n	885.7 ± 0.8 (d)	885.7 (d)	880.1 (f)	880.1	885.7 (d)	880.1 ± 1.1 (f)
Y_p	0.2476 ± 0.0004	0.2475	0.2464	0.24617	0.2476	0.2463 ± 0.0003
D/H ($\times 10^{-5}$)	2.68 ± 0.15	2.64	2.64	2.71	2.59	2.67 ± 0.09
${}^3\text{He}/\text{H}$ ($\times 10^{-5}$)	1.05 ± 0.04	1.05	1.05	1.06	1.04	1.05 ± 0.03
${}^7\text{Li}/\text{H}$ ($\times 10^{-10}$)	5.14 ± 0.50	5.20	5.18	4.98	5.24	$4.89^{+0.41}_{-0.39}$

(a) Coc & Vangioni (2010); (b) Coc et al. (2012), (c) Spergel et al. (2007); (d) Amsler et al. (2008); (e) Komatsu et al. (2011); (f) Beringer et al. (2012); (g) Ade et al. (2013)

Coc & Vangioni (2010) with the first WMAP results (Spergel et al. 2007) to the recent Planck data (Ade et al. 2013). The reduced uncertainty on D/H is a direct consequence of the reduced uncertainty on $\Omega_b \cdot h^2$ while ${}^7\text{Li}$ uncertainty is still dominated by nuclear uncertainty on the ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ rate.

Figure 1 displays the abundances as a function of η and Table 2 those at Planck baryonic density, both for $N_{\text{eff}} = 3$. We do not use the $N_{\text{eff}} = 3.046$ value from Mangano et al. (2005) to account for non-instantaneous neutrino decoupling in the presence of oscillations. While this approximation works for ${}^4\text{He}$, the change for the other nuclides is exactly in the opposite direction of the true one. Hence, to implement these very small effects ($\approx 2 \times 10^{-4}$ for Y_p), we suggest to the interested reader, to correct $N_{\text{eff}} = 3$ results (i.e. Table 2) with the exactly calculated abundance changes (e.g. ΔY_p) given in the Tables of Mangano et al. (2005), rather than considering $N_{\text{eff}} = 3.046$ results. In Figure 1 we also display for visual inspection the results obtained for the limits on effective neutrino family numbers $N_{\text{eff}} = 3.36 \pm 0.34$ provided by the CMB only confidence interval (Ade et al. 2013). [Note that in Coc et al. (2013) we obtained $2.89 \leq N_{\text{eff}} \leq 4.22$ at WMAP baryonic density, with N_{eff} defined by eq. 3.12 of the same reference, as in this paper.] Finally in Table 2, a comparison between this work and the last observational data; an overall consistency between standard BBN calculation and the observational constraints is done except for lithium, as said above: the discrepancy remains of the order of 3.

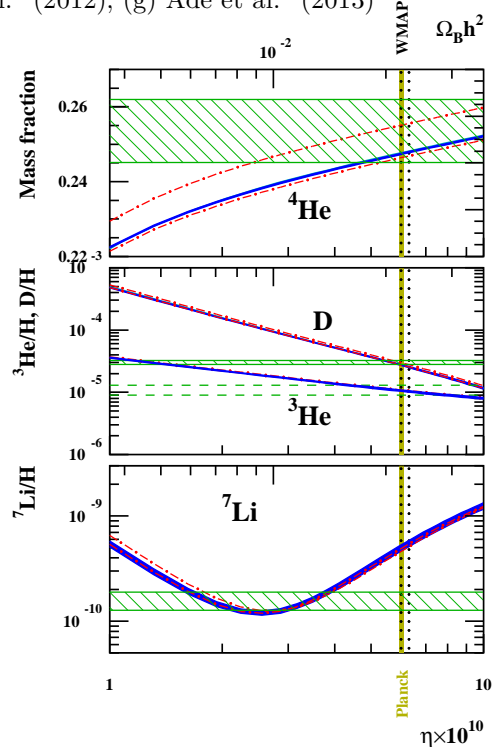


Fig. 1.— (Color online) Abundances of ${}^4\text{He}$, D, ${}^3\text{He}$ and ${}^7\text{Li}$ (blue) as a function of the baryon over photon ratio (bottom) or baryonic density (top). The vertical areas corresponds to the WMAP (dot, black) and Planck (solid, yellow) baryonic densities while the horizontal areas (green) represent the adopted observational abundances; see text. The (red) dot-dashed lines correspond to the extreme values of the *effective* neutrino families coming from CMB Planck study, $N_{\text{eff}} = (3.02, 3.70)$; see text.

5. Conclusion

This work has updated the BBN predictions in order to take into account the most recent developments concerning both the cosmological framework (i.e. the cosmological parameters determined from the recent CMB Planck experiment) and the microphysics. It demonstrates that these predictions are robust for the lightest elements. It shows also that the modification of these parameters in the range allowed cannot alleviate the lithium problem.

Table 2: Comparison with observations

	This work	Observations
Y_p	0.2463 ± 0.0003	0.2534 ± 0.0083
D/H ($\times 10^{-5}$)	2.67 ± 0.09	3.02 ± 0.23
$^3\text{He}/\text{H}$ ($\times 10^{-5}$)	1.05 ± 0.03	1.1 ± 0.2
$^7\text{Li}/\text{H}$ ($\times 10^{-10}$)	$4.89^{+0.41}_{-0.39}$	1.58 ± 0.31

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