# The Cosmological Lithium Problem

Sharba Bhattacharjee
National Institute of Science Education and Research, Bhubaneswar

Supervisor: Dr. Dhruba Gupta
Associate Professor, Bose Institute, Kolkata

July 13, 2015

**Abstract**

The light nuclei such as deuterium, helium and lithium were produced during Big Bang Nucleosynthesis (BBN). The relevant nuclear reaction rates and other parameters required for the light element abundance calculations have been determined over the years. The baryon-to-photon ratio of the universe ($\eta$) was the last free parameter of Big Bang Nucleosynthesis calculations. This ratio has been determined independently from observation of the anisotropies in the Cosmic Microwave Background (CMB). The most recent measurements were carried out by the *WMAP* and *Planck* satellites. Once $\eta$ is known, the primordial abundances of the nuclei can be predicted. The primordial elemental abundances can also be measured from astronomical observations and compared with the predictions based on CMB and BBN. Most of the nuclei have shown good agreement between the abundances estimated from the observations, and the predictions based on the CMB value of $\eta$ and the standard model of BBN. However, it has been found that the abundance of $^7$Li as predicted from CMB and BBN is about 3 times the abundance determined from the observation of metal poor halo stars. This is the long standing cosmological lithium problem or the $^7$Li abundance anomaly. This anomaly may be due to systematic errors in the measurements, errors in the reaction rates, incomplete understanding of stellar processes which may deplete lithium, or new physics beyond the standard BBN model. All of these possible factors have been studied, but new developments have been unable to resolve the lithium abundance anomaly. The origin, present status and possible directions for a solution are discussed in the project.

# Contents

# Chapter 1

# Introduction

While most of the elements were created in stars and supernovae, the lightest nuclei ($^2$H, $^4$He, $^3$He and $^7$Li) were produced in Big Bang Nucleosynthesis (BBN), during the first 20 minutes after the Big Bang [1]. BBN was first predicted by Gamow and his collaborators Alpher and Herman [2]. Their primordial abundances have been estimated from the model of standard Big Bang Nucleosynthesis and compared with astronomical observations. Most of the parameters for determining the primordial abundances have been determined from theory or from laboratory experiments [3]. The nuclear reaction rates have also been determined over the years from theoretical calculations, or from laboratory experiments. The remaining free parameter was $\eta$, the baryon-to-photon ratio of the universe, which could be determined only from astronomical observations. This has been determined from the observation of the cosmic microwave background. While studies of the CMB had been carried out previously from ground and balloon based observations or from the *COBE* satellite, precise values of the cosmological parameters such as $\eta$ have been obtained from the *WMAP* satellite observations [4]. More recent measurements have been made by the *Planck* satellite [3], but the *WMAP* data can still be used to study Big Bang Nucleosynthesis. Based on the *WMAP* value of $\eta$, the light element abundances have been predicted. While we get very good agreement between the predicted and observed abundances for deuterium and fairly good agreement for helium, the observed lithium abundance has been found to be about one-third of the predicted value.

In Chapter 2, the determination of the baryon-to-photon ratio from observation of the cosmic microwave background has been discussed. In Chapter 3, it has been shown how the primordial abundances are predicted based on the CMB data and nuclear reaction rates. In Chapter 4, the methods of determining elemental abundances from astronomical observations has been discussed. In Chapter 5, the predicted abundances have been compared with the measured values, and the lithium problem has been discussed.

# Chapter 2

# Determination of the baryon-to-photon ratio from the CMB

To study Big Bang Nucleosynthesis, it was required to find the baryon-to-photon ratio of the universe, usually denoted by $\eta$. Previously, the ratio was derived based on the light element abundances and the standard BBN model. But to verify the BBN theory, it was necessary to find $\eta$ from an independent method, and this was made possible by the observation of the Cosmic Microwave Background.

## 2.1 Origin of the CMB

The Big Bang Theory predicts that the universe was initially in a hot and dense state, which then started to expand and cool. According to this theory, the universe should be filled with radiation from the remnant heat left over from the Big Bang. This is the Cosmic Microwave Background (CMB), which was predicted by Alpher in 1948 along with Gamow and Herman in connection with their research on BBN, and observed in 1965 by Penzias and Wilson [5]. The present temperature of the CMB radiation is $(2.725 \pm 0.002)$ K [6], and its intensity is highest in the microwave spectrum. Its temperature is almost uniform in all directions.

In the early universe, the CMB temperature was much higher. at this high temperature, neutral atoms could not form, and there were free nuclei and electrons. The photons used to scatter off this charged particles multiple times, giving rise to a blackbody spectrum [5, 7]. About 380,000 years after the Big Bang, the universe cooled down enough that the nuclei and electrons could combine to form neutral atoms (epoch of recombination) [5]. Since photons interact very weakly with neutral atoms, the CMB photons were no longer scattered and could travel in straight lines (photon decoupling). The present observation of the CMB gives the "surface of last scattering", called so because it was the last time the photons scattered off matter. From observing the CMB, i.e. the surface of last scattering, we can gain information about the matter in the universe 380,000 years after the Big Bang [5, 9].

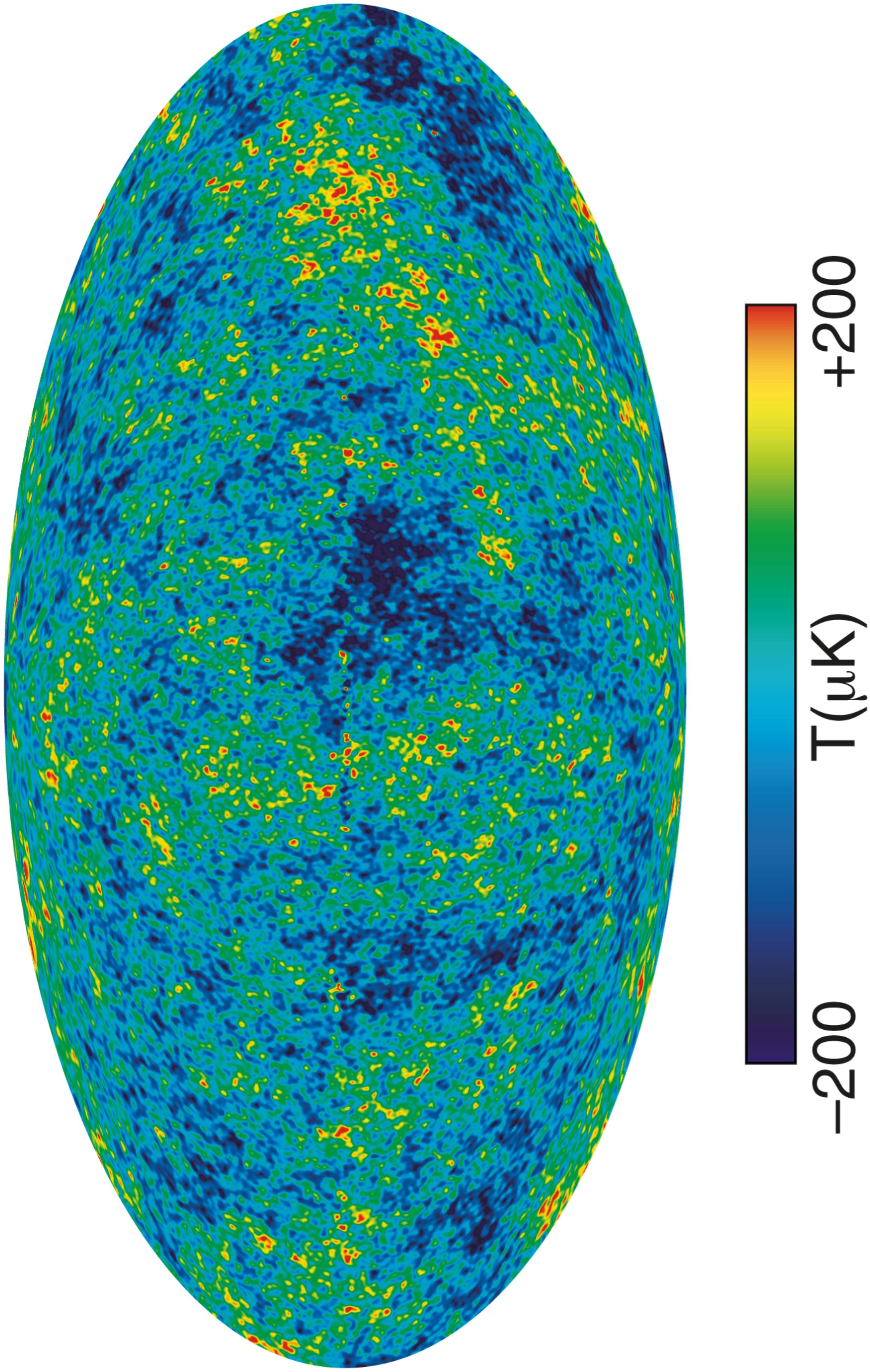


Figure 2.1: Sky map of the Cosmic Microwave Background based on *WMAP* observations (Reproduced from Ref. [8])

.

## 2.2 Anisotropies in the CMB

Though the CMB is almost uniform, there do exist fluctuations or anisotropies in the temperature. The basic observable of the CMB is its intensity as a function of frequency and direction on the sky. Since the CMB spectrum is an extremely good blackbody with a nearly constant temperature across the sky, this observable is generally described in terms of a temperature fluctuation [7]. Primary anisotropies are due to a combination of acoustic, Doppler, gravitational redshift and photon diffusion effects [9]. They can be analysed to obtain a number of cosmological parameters, such as the baryon density, the dark matter density, the cosmological constant, the Hubble constant, and the curvature of the universe. There are also secondary effects generated at later times, which provide clues behind the process of structure formation [9].

Before recombination, the photons were coupled to the electrons by Compton scattering, and the electrons were coupled to the baryons by electromagnetic interactions. Thus electrons acted as a glue between the photons and the baryons, and the system can be dynamically described as a photon-baryon fluid [7, 9]. Photon pressure resisted gravitational compression of the fluid and set up acoustic oscillations. At the time of recombination, neutral atoms formed and the photons last scattered. Regions of compression and rarefaction at this epoch represented hot and cold spots respectively. Photons also suffered gravitational redshifts from climbing out of the potentials on the last scattering surface. The resultant fluctuations appear to the observer today as primary anisotropies on the CMB [9]. The combination of intrinsic temperature fluctuations and gravitational effects is called the Sachs-Wolfe effect. There are other effects such as baryon drag (due to the mass of the baryons), Doppler effect owing to motion relative to the observer, driving effects because of the radiation dominated energy density, damping of the fluctuations by photon diffusion, and projection effect. These effects have been studied, and it is clear that the temperature anisotropies in the CMB depend on a number of parameters including the baryon density of the universe. Baryon density mainly affects the CMB anisotropies through baryon drag. It increases the compression, causing enhancement of peaks from compression over those of rarefaction, i.e. alternate peak amplitudes are enhanced [9]. In this regard, mention must be made of the secondary anisotropies arising from intervening effects between recombination and the present. These are mainly of two types: gravitational effects, and rescattering effects from reionization. They provide details on the evolution of structure in the universe. All factors affecting the CMB fluctuations have been discussed in Refs. [7] and [9].

## 2.3 Measurement of the cosmological parameters from CMB observations

As discussed in the previous subsection, the parameters of the Big Bang can be obtained from the anisotropies in the CMB. As these fluctuations are very small, they can be studied only using sensitive instruments, from satellite-based observations. The *COBE* (*Cosmic Background Explorer*) was at first launched in 1989 to map the entire sky from near earth orbit in the microwave spectrum [10]. The *WMAP* (*Wilkinson Microwave Anisotropy Probe*) satellite was launched in 2001 to obtain more accurate, precise and reliable data [10]. The instrument observes the temperature difference between two directions using two nearly identical sets of optics. These optics focus radiation into horns that feed differential microwave radiometers. Full sky maps are produced in five frequency bands (23 to 94 GHz) from the radiometer data of temperature differences measured over the full sky [6]. The mission has been carefully designed to limit systematic errors [4]. The basic approach in this analysis is to identify the simplest model of the universe that fits the *WMAP* data and determine the best fit parameters for this model using the data [4]. The overall error may be due to the exclusion of several effects, such as gravitational lensing of the CMB, the spatial variations in the effective beam of the *WMAP* experiment due to variations in the scan orientation between the ecliptic pole and plane regions, statistical uncertainties and non-Gaussianity in the noise maps [4]. The systematic errors can be classified into calibration errors, map-making errors, sidelobe response, baseline errors and striping [11]. Observations have been made in five frequency ranges: K-band ($\sim$ 23 GHz), Ka-band ($\sim$ 33 GHz), Q-band ($\sim$ 41 GHz), V-band ($\sim$ 61 GHz) and W-band ($\sim$ 94 GHz) [6]. Their combined map is given in Fig. 2.1.

The baryon-to-photon ratio, $\eta$, is the ratio between the baryon density and the photon density of the universe. Since the photon density can be obtained from the CMB temperature, $\eta$ depends on the baryon density as [12]

$$\Omega_{\mathrm{b}} h^2 = 3.6521 \times 10^7 \eta$$

Here $\rho_{\mathrm{b}}$ is the baryon density, $\Omega_{\mathrm{b}} = \rho_{\mathrm{b}}/\rho_{\mathrm{crit}}$ and $\rho_{\mathrm{crit}} = 3H_0^2/8\pi G$, with $H_0$ the present value of the Hubble parameter and $G$ the gravitational constant [13]. In the expression, $h = H_0/100\ \mathrm{km\,s^{-1}\,Mpc^{-1}} = 0.72 \pm 0.08$ [14].

From analysis of the *WMAP* data, the baryon density is obtained to be $\Omega_b h^2 = 0.02249 \pm 0.00056$, which gives the baryon to photon ratio as $\eta = (6.079 \pm 0.090) \times 10^{-10}$ [3]. The *Planck* satellite, launched in 2009, has given $\Omega_b h^2 = 0.02218 \pm 0.00026$ and has reduced the error margin in $\eta$ to some extent [15]. However, the change is not too large, and *WMAP* data can still be considered for studying Big Bang Nucleosynthesis.

# Chapter 3

# Prediction of the primordial abundances based on BBN calculations and the CMB value of $\eta$

The production of light nuclei during Big Bang Nucleosynthesis has been studied extensively. The theoretical model is referred to as Standard BBN, which is characterized by [13]:

1. Gravity governed by General Relativity.
2. A homogeneous and isotropic universe (cosmological principle).
3. The microphysics of the Standard Model of particle physics.
4. The particle content of the Standard Model, supplemented by dark matter and dark energy.

The nuclear physics and the reactions involved in Big Bang Nucleosynthesis have been studied and observed experimentally. There are a large number of reactions, but only the following 12 are found to have significant influence on the primordial abundances [1, 3]:

$$\begin{array}{cccc}
n \longleftrightarrow p & {}^1\mathrm{H}(n,\gamma)^2\mathrm{H} & {}^2\mathrm{H}(p,\gamma)^3\mathrm{He} & {}^2\mathrm{H}(d,n)^3\mathrm{He} \\
{}^2\mathrm{H}(d,p)^3\mathrm{H} & {}^3\mathrm{H}(d,n)^4\mathrm{He} & {}^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li} & {}^3\mathrm{He}(n,p)^3\mathrm{H} \\
{}^3\mathrm{He}(d,p)^4\mathrm{He} & {}^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be} & {}^7\mathrm{Li}(p,\alpha)^4\mathrm{He} & {}^7\mathrm{Be}(n,p)^7\mathrm{Li}
\end{array}$$

The other reactions have insignificant effect because of small cross-section and scarcity of reactants. The important reactions have been shown schematically in Fig. 3.1. The rates of the weak reactions involved in the $n \longleftrightarrow p$ equilibrium are derived from the standard theory of weak interaction. The ${}^1\mathrm{H}(n,\gamma)^2\mathrm{H}$ cross section is obtained in the framework of Effective Field Theory [1]. The cross sections of the remaining ten reactions have been measured in the laboratory at the relevant energies [1]. The other parameters of Big Bang Nucleosynthesis calculations such as neutron lifetime ($\tau_n$) have also been determined ($\tau_n = (880.1 \pm 1.1)$ s) [3]. The effective number of neutrino species ($N_{\mathrm{eff}}$) is also determined from CMB observations ($N_{\mathrm{eff}} = 3.36 \pm 0.34$) [3], but it does not affect the abundances significantly and we can use $N_{\mathrm{eff}} = 3$ as predicted by the Standard Model of Particle Physics. It has also been determined from laboratory experiments at CERN [1]. The baryon-to-photon ratio is the only free parameter controlling primordial light element abundances in the standard model of BBN. Based on the theoretical and

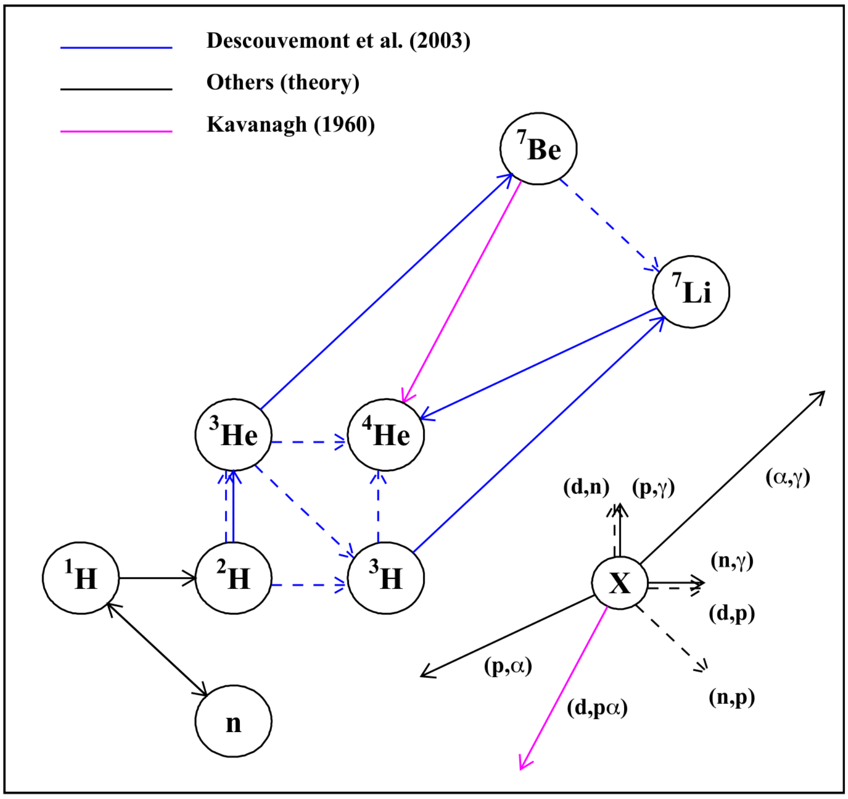


Figure 3.1: Important nuclear reactions relevant to primordial nucleosynthesis (Reproduced from Ref. [16]).

experimental inputs, the abundances of the light elements have been plotted as functions of the baryon-to-photon ratio (Fig. 3.2). The uncertainties in the curves are derived from the nuclear uncertainties by a Monte-Carlo calculation [1]. Once $\eta$ is known, the primordial abundances can be calculated.

## 3.1 Expressing the nuclear abundances

Before going into how the nuclear abundances are predicted from BBN theories or measured from astronomical observations, it should be clarified how the abundances are quantified. The abundance of a nucleus $^A$M can be expressed in two ways:

1. **As the ratio of the number of $^A$M nuclei in the universe to the number of hydrogen nuclei ($^A$M/H):** This is the most common measure of abundance. The abundances of all nuclei other than $^4$He are measured in terms of this ratio. This is also convenient to determine from observations, since the abundances of the elements are generally determined by comparing the intensities of their emission or absorption spectra with that of hydrogen [17]. Since hydrogen is the most abundant element, this ratio is less than one for all nuclei.

2. **As the fraction of the total baryonic mass of the universe which is contributed by $^A$M nuclei ($X_{\mathrm{M}}$):** This is another measure of nuclear abundance, which depends on the mass rather than the number of nuclei. In particular, the mass fraction of hydrogen is usually denoted by $X$, helium by $Y$ and all heavier nuclei together by $Z$. Clearly, $X + Y + Z = 1$. $Z$ is less than 1%, and we can

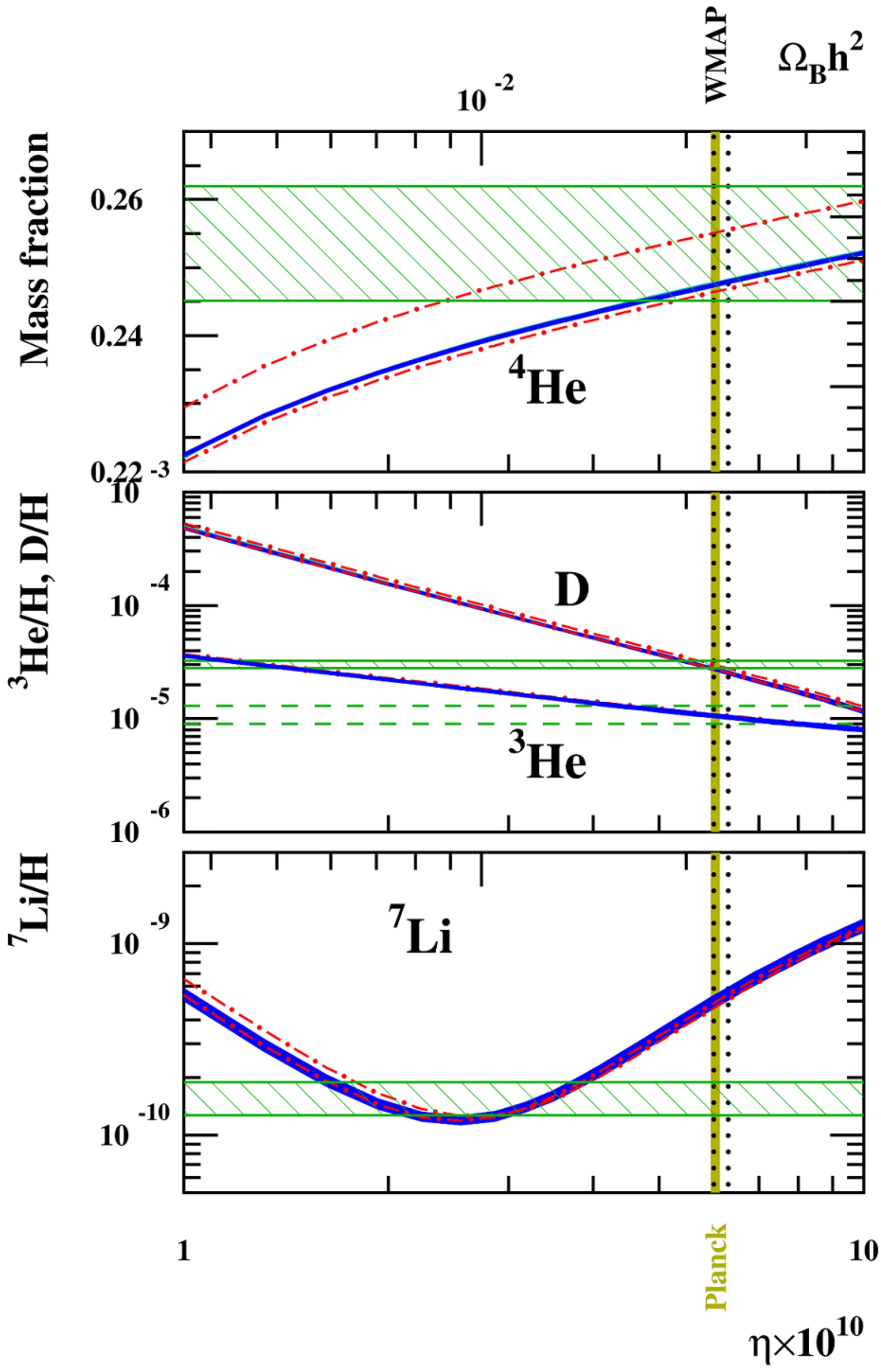


Figure 3.2: Predicted nuclear abundances as functions of $\eta$, reproduced from Ref. [3]. The width of the curves give the error margin. The horizontal green hatched regions give the primordial abundances as estimated from different astronomical studies (discussed in Chapter 4). The vertical areas correspond to the *WMAP* (dot, black) and *Planck* (solid, yellow) baryonic densities. The red dot-dashed lines correspond to the extreme values of the effective neutrino families coming from the CMB *Planck* study, $N_{\text{eff}} = (3.02, 3.70)$, and they can be ignored for the present discussion.

generally neglect it when considering the total baryonic mass. The primordial mass fraction of $^4$He, represented by $Y_P$, is taken to be the measure of the primordial helium abundance, instead of the number ratio to hydrogen ($^4$He/H).

While it is customary to express the abundance of $^4$He in terms of the mass fraction $Y$ and that of the other nuclei as the number ratio to hydrogen, I did not find any particular reason behind this convention. For example, some studies regarding the photospheric abundance of $^4$He do measure the abundance in terms of $^4$He/H [18]. Also, Spite & Spite (1982) have given their observed abundance of $^7$Li in terms of both $^7\text{Li/H} = 1.12 \times 10^{-10}$ and $X_{\text{Li}} = 5.96 \times 10^{-10}$ [19] (further details of Spite & Spite's observation are given in §4.4).

In any case, the two quantities are related, and one can be calculated if the other is known. The relation between the mass fraction $X_{\text{M}}$ of any nucleus $^A$M (having $A$ nucleons) and its abundance ratio $^A$M/H is given by:

$$X_{\text{M}} = AX(^A\text{M/H}),$$

where $X$, the mass fraction of hydrogen, is about 75%. For example, if $X_{\text{He}} = Y = 0.25$, we get $^4\text{He/H} \approx \frac{1}{12}$. The proton and neutron masses are taken to be equal in this equation. The mass fraction is a monotonic increasing function of the number ratio, which can be taken to be almost linear if the variation in $X$ is neglected. Therefore, if we measured the abundance of $^4$He in terms of $^4$He/H or that of the other nuclei as their respective mass fractions, we would get different numerical values of the abundances, but their relation with $\eta$ would be similar.

## 3.2 Beginning of Big Bang Nucleosynthesis

The first nucleus to be formed in Big Bang Nucleosynthesis is the hydrogen isotope deuterium ($^2$H or D). At the time of BBN, the temperature ($T$) decreased with time ($t$) as $t \propto 1/T^2$ [13]. The binding energy of deuterium is $B_D = 2.22$ MeV [13]. Hence, one would expect $^2$H formation to start when the temperature of the universe decreases to $kT = 2.2$ MeV, where $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant. However, because there are about a billion photons per nucleon ($\eta \approx 10^{-9}$), there are still a large number of photons at the high-energy tail of the blackbody distribution which can photodissociate any deuterium that is formed [13]. Deuterium synthesis starts when the temperature further falls to $kT \approx 0.07$ MeV [13], about 2 minutes after the Big Bang.

The relative abundance of the neutrons and protons are determined from the weak $n \longleftrightarrow p$ reactions ($p + e^- \longleftrightarrow n + \nu_e$, $n + e^+ \longleftrightarrow p + \bar{\nu}_e$ and $n \longleftrightarrow p + e^- + \bar{\nu}_e$) [20]. Initially, these interactions were rapid, driving the neutrons and protos to an equilibrium ratio

$$n/p = e^{\frac{-Q_{np}}{kT}},$$

where $Q_{np} = (m_n - m_p)c^2 = 1.293$ MeV is the neutron-proton mass difference expressed in energy units [13, 21]. ($m_n$ = neutron mass, $m_p$ = proton mass, $c$ = speed of light). As the temperature dropped to $kT \approx 1$ MeV, the equilibrium broke, and the neutron-proton ratio "froze out" to $n/p \approx \frac{1}{6}$ [13, 20, 21]. This value depends on the various physical interactions. After the freeze-out, neutrons still decayed by $\beta$-decay. By the time deuterium synthesis started ($kT \approx 0.07$ MeV), the ratio had further decreased to $n/p \approx \frac{1}{7}$ [13, 21].

## 3.3 Helium ($^4$He) mass fraction, $Y_P$

The reaction $^1\mathrm{H}(n,\gamma)^2\mathrm{H}$ ($n + p \to \mathrm{D} + \gamma$) as well as the reactions processing D into $^4$He are fast. So almost all neutrons in the universe go to $^4$He (also represented by $\alpha$) [22]. Let us suppose there were $P$ protons and $N$ neutrons at that time ($N < P$, and the neutron-proton ratio is $n/p = \frac{N}{P}$). If we assume that all neutrons go into $^4$He, and because each such nucleus has 2 protons and 2 neutrons, we see that $N$ protons and $N$ neutrons go into $\frac{N}{2}$ $^4$He nuclei (total mass of $^4\mathrm{He} = N(m_n + m_p)$), while the remaining $(P - N)$ protons remain as $^1$H nuclei. Therefore, taking $n/p = \frac{1}{7}$, the primordial $^4$He mass fraction is predicted to be [14]

$$Y_P \approx \frac{N(m_n + m_p)}{Nm_n + Pm_p} \approx \frac{2(n/p)}{1 + n/p} \approx 0.25 \ (m_n \approx m_p),$$

and the primordial helium-hydrogen atom ratio is

$$^4\mathrm{He/H} \approx \frac{\frac{N}{2}}{P - N} = \frac{n/p}{2(1 - n/p)} \approx \frac{1}{12},$$

assuming the abundances of the heavier nuclei to be negligible. To be more precise, the predicted value of helium abundance is $Y_P = 0.2463 \pm 0.0003$ [3]. It is almost independent of the other nuclear reaction rates. It depends weakly on the baryon-to-photon ratio, and $Y_P$ is predicted to increase slightly with $\eta$ [1]. This is because for higher $\eta$, deuterium synthesis begins sooner, and we have more neutrons to go into helium nuclei. The uncertainty in $\eta$ is the main contributor to the uncertainty ($< 1\%$) in the predicted value of $Y_P$ [13, 22].

## 3.4 Deuterium (D) abundance, D/H

A small fraction of deuterium ($^2$H, denoted by D or $d$) is not processed into heavier nuclei, giving rise to a small deuterium abundance [22]. Unlike $^4$He, the deuterium abundance is strongly dependent on $\eta$, because of which it was generally used to measure $\eta$ before independent measurements could be made from the CMB. With increasing baryon density, the deuterium nuclei have less chance of escape, so the abundance decreases strongly with $\eta$ [13, 22]. At the *Planck* value of $\eta$, the primordial deuterium abundance is predicted to be $(\mathrm{D/H})_P = (2.67 \pm 0.09) \times 10^{-5}$ [3]. The error ($\sim 7\%$) is partly due to the uncertainty in $\eta$, and partly due to BBN errors, especially $d(p,\gamma)^3$He, $p(n,\gamma)d$ and $d(d,n)^3$He [13, 23].

## 3.5 Helium ($^3$He) abundance, $^3$He/H

A small amount of $^3$He and $^7$Li were also produced during primordial nucleosynthesis. Its abundance is predicted to be $^3\mathrm{He/H} = (1.05 \pm 0.03) \times 10^{-5}$ [3]. $^3$He is a fragile nucleus, and its abundance decreases substantially with $\eta$. The error in $^3$He/H ($\sim 7\%$) is dominated by the uncertainties in the reactions $d(p,\gamma)^3$He and $^3\mathrm{He}(d,p)^4$He [13, 23].

## 3.6 Lithium ($^7$Li) abundance, $^7$Li/H

Another product of BBN is lithium, $^7$Li. Its predicted primordial abundance is $^7\text{Li/H} = (4.89^{+0.41}_{-0.39}) \times 10^{-10}$ [3]. $^7$Li abundance shows a "dip" behaviour with respect to $\eta$. This is because during BBN, lithium is produced directly as well as from decay of $^7$Be by electron capture. The $^7\text{Be}(n,p)^7\text{Li}$ reaction occurs long after the other reactions of BBN cease, but the lithium abundance plotted in the studies is after $^7$Be decay [13]. For low $\eta$, the abundance is dominated by $^7$Li production, while at high $\eta$, $^7$Be production dominates. The uncertainty in the $^7$Li prediction ($\sim 12\%$ for high $\eta$) is dominated by uncertainties in the nuclear cross sections, in particular the $^3\text{He}(\alpha,\gamma)^7\text{Be}$ reaction.

## 3.7 Heavier nuclei; end of BBN

There exists no stable nucleus having 5 or 8 neutrons. Because of this, even though $^1$H and $^4$He are the most abundant nuclei, stable nuclei can not be formed by fusion of hydrogen with helium or helium with helium. Very small amounts of some nuclei like $^7$Be (which mostly decays to $^7$Li) and $^6$Li are formed other than the ones mentioned above. Heavier nuclei are not produced during Big Bang Nucleosynthesis. In stars, nuclei such as $^{12}$C can be produced by the "triple-$\alpha$" reaction ($3^4\text{He} \rightarrow {}^{12}\text{C}^*$), but this requires high temperature and density, which is attained only in stars [22]. By about 20 minutes after the Big Bang, the temperature drops low enough that the nuclei can not easily overcome the Coulomb barrier. Also, because the lifetime of a free neutron is $\tau_n = (880.1 \pm 1.1)$ s [3], any neutron that had not been incorporated in the nuclei has turned into a proton by this time. Therefore, nucleosynthesis ceases at this time [21, 24].

# Chapter 4

# Determination of light element abundances from astronomical observations

The primordial elemental abundances can also be estimated from astronomical observations. Nuclear reactions have also taken place after Big Bang Nucleosynthesis, such as in stars or novae, and hence the observed light element abundances may have changed from their primordial values. It is required to observe the astronomical systems in which these changes have been insignificant. This is checked by measuring the abundances of the heavier elements (such as oxygen, nitrogen etc.) which are produced in later periods in the universe but not during Big Bang Nucleosynthesis. These heavy elements are called metals, and their abundance is called the metallicity. We measure the light elements in the most metal-poor systems, and obtain the primordial abundances by extrapolation to zero metallicity [1, 13].

## 4.1 Helium from HII regions of dwarf galaxies

$^4$He is one of the major products of Big Bang Nucleosynthesis. It is also produced in stellar nuclear fusion. Its primordial abundance is obtained from nearby dwarf blue compact galaxies. They have low oxygen and nitrogen abundance, and are considered to be primitive. Within these galaxies, astronomers observe gas clouds consisting of a plasma of protons ($^1$H) and electrons, called HII regions. In these gas clouds, emission lines can be observed for various atoms, and their intensities can be compared with that of hydrogen to get the abundances of helium, oxygen or nitrogen. If this is done for a number of gas clouds and a number of galaxies, the helium mass fraction $Y$ can be plotted as a function of the abundance of heavier atoms such as oxygen (O/H) to get a linear fit. This can be extrapolated to zero oxygen abundance to ascertain the primordial helium abundance, $Y_P$. The calculation is affected by systematic uncertainties such as plasma temperature or stellar absorption, as well as errors in the extrapolation and statistical uncertainties [1]. It is difficult to say how much of the observed helium is $^4$He and how much is $^3$He. However, because of the extremely low abundance of $^3$He as observed in our galaxy, we may take the entire measured helium abundance to be owing to $^4$He alone without much error. $Y_P$ was found to lie somewhere between 23.2% and 25.8% [1, 17]. Recent measurements have given the primordial helium mass fraction as $Y_P = 0.2534 \pm 0.0083$ [3].

## 4.2 Deuterium from distant quasars

Deuterium is not produced after Big Bang Nucleosynthesis, and it is destroyed in stars. Consequently, the deuterium abundance D/H decreases with time, and any observed abundance gives a lower limit of the primordial value. The primordial deuterium abundance is estimated from neutral hydrogen gas clouds at high redshift, on the line of sight of distant quasars [1, 13]. Analysing the radiation from the quasars, we can find absorption lines due to deuterium and ordinary hydrogen, and compare them to determine D/H. The absorption spectra of deuterium can be detected from an isotope shift in the Lyman series of neutral hydrogen. Deuterium abundance had been found to be $D/H = (3.02 \pm 0.23) \times 10^{-5}$ [3]. More recent observations have given $D/H = (2.53 \pm 0.04) \times 10^{-5}$ [12].

## 4.3 Helium isotope $^3$He from observaions within the galaxy

$^3$He is both produced and destroyed in stars [3]. This makes observation of the primordial $^3$He abundance difficult. Also, the properties of $^3$He and $^4$He atoms are very similar, making detection of $^3$He practically impossible outside our galaxy. Because of this, HII clouds within the Milky Way are studied. According to the current models of stellar evolution, more $^3$He is created in the stars than destroyed, and the overall $^3$He abundance should increase with stellar nuclear fusion. This is not completely supported by observations, for although the abundances of other elements within our galaxy show a decrease in the influence of stellar nucleosynthesis on element abundances with distance from the galactic centre, the $^3$He abundance is found to be almost same everywhere inside the galaxy [17]. Still, if the current models are assumed to be correct in general, the observations give an upper limit on the primordial value of $^3$He/H. It is found to be $(1.1 \pm 0.2) \times 10^{-5}$ [1].

## 4.4 Lithium from metal poor halo stars; Spite plateau

Lithium, $^7$Li, is produced after BBN in spallation, asymptotic giant branch (AGB) stars and novae, but is destroyed in the interior of most stars [1]. The nuclear fusion reactions take place in the inner regions of the star but not the outermost layers. Hence the composition of the outermost layers of the star indicate the element abundances in the matter from which the star was created, and they should be close to the primordial abundances for very old stars. From studying the absorption and emission lines (e.g. the 670.7 nm line of lithium), we can find the abundances of elements such as lithium, as well as heavy elements like iron. Low iron content (low "metallicity") indicates the star is old, and such metal poor stars can be found in the spheroidal region of the galaxy called the galactic halo or Population II. It is seen that for stars with high amount of iron (young stars), the $^7$Li content varies widely, because the amount of lithium produced or destroyed in the stars depends on several factors such as the mass, temperature and initial composition of the star. But for stars with iron content Fe/H less than 0.01 times that of the sun, the lithium abundance becomes almost independent of the metallicity (Fig. 4.1). This is called the Spite plateau after its discoverers F. Spite and M. Spite [16, 19], and this indicates that the $^7$Li abundance in these stars is primordial. Spite & Spite (1982) had found a value of $^7\mathrm{Li/H} \approx (1.12 \pm 0.38) \times 10^{-10}$ [19]. Recent observations have given $^7\mathrm{Li/H} = (1.58 \pm 0.31) \times 10^{-10}$ [3]. These measurements may have systematic errors. For example, lithium can be drawn into the hotter central regions of the stars by convection, where it is destroyed, causing depletion of lithium. This effect is seen in cool halo stars, but not in the hottest (most massive) stars [13]. The lithium abundance is considered only in the hot stars. The main source of error in the determination of the abundance is the uncertainty in determining the temperature of the stars [19].

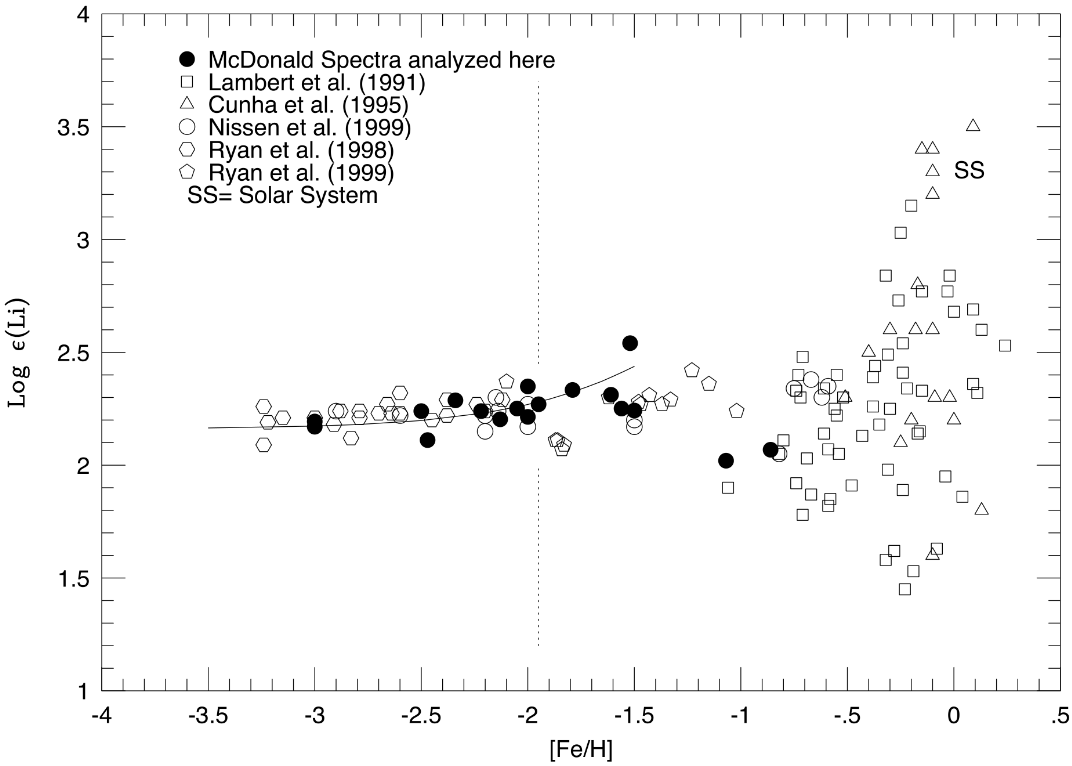


Figure 4.1: Lithium abundance, $\epsilon(\mathrm{Li}) = 10^{12}(^7\mathrm{Li/H})$ as a function of metallicity, $[\mathrm{Fe/H}] = \log\left(\frac{\mathrm{Fe/H}}{\mathrm{Fe/H_{sun}}}\right)$. The Spite plateau is observed for $[\mathrm{Fe/H}] \lessapprox -2$. (Reproduced from Ref. [20])

# Chapter 5

# Comparison between the CMB predictions of elemental abundances and the astronomical observations; the lithium problem

Once the abundances are predicted from the CMB value of $\eta$, they can be compared with the observed values. The comparison is given in Table 5.1. For deuterium, we get perfect agreement between the two values. $^4$He predictions are also in good agreement with the observations. The predicted $^3$He value is close to its galactic value, showing that its abundance has not changed much during galactic chemical evolution. On the contrary, for $^7$Li, the CMB+BBN calculated abundance is significantly higher than the spectroscopic observations by a factor of 2.4–4.3 [13]. This is the $^7$Li abundance anomaly. For $^6$Li, on the other hand, the BBN $^6$Li yield at *WMAP* baryonic density is about two orders of magnitude below the reported observations in some halo stars [1].

Table 5.1: Comparison between the predicted and observed abundances

| Abundance | Predicted value | Observed value |
|---|---|---|
| $Y_P$ | $0.2463 \pm 0.0003$ | $0.2534 \pm 0.0083$ |
| D/H | $(2.67 \pm 0.09) \times 10^{-5}$ | $(2.53 \pm 0.04) \times 10^{-5}$ |
| $^3$He/H | $(1.05 \pm 0.03) \times 10^{-5}$ | $(1.1 \pm 0.2) \times 10^{-5}$ |
| $^7$Li/H | $(4.89^{+0.41}_{-0.39}) \times 10^{-10}$ | $(1.58 \pm 0.31) \times 10^{-10}$ |

Possible solutions to the lithium problem fall into three broad classes [13]:

1. *Astrophysical* solutions revise the measured primordial lithium abundance.

2. *Nuclear Physics* solutions alter the reaction flow.

3. Solutions beyond the *Standard Model* invoke new particle physics or nonstandard cosmological physics.

## 5.1 Astrophysical solutions

We first consider the possibility that the measured value of the primordial lithium abundance is in error. Standard cosmology and particle physics, as well as the nuclear physics are considered to be correct. The true value of primordial $^7$Li/H must be more than the observed value by a factor of 3–4 [13].

One possible scenario is that systematic errors exist in the $^7$Li/H measurements of the metal poor stars. The lithium abundances are estimated from the absorption lines (670.8 nm) in the photospheres of the low-metallicity stars. However, the 670.8 nm line is sensitive to only neutral $Li^0$, while most of the lithium in the stars of interest is as $Li^+$ [13]. Therefore it is necessary to introduce an ionization correction $Li^+/Li^0$ to find the total lithium abundance, which is exponentially sensitive to stellar temperature. Thus, a systematic rise in the temperature scale for halo stars would increase all stellar $^7$Li abundances and alleviate the lithium problem. Accurate determination of stellar temperatures is non-trivial, because the emergent radiation does not follow a perfect Planck curve, and local thermodynamic equilibrium is also not completely attained in the stellar atmospheres [13]. For example, some studies have given a higher value of the Spite plateau value of $^7$Li/H due to a new effective temperature scale [25]. However, later detailed studies of the stellar temperature scale agree with the previous measurements, leaving the lithium problem unresolved [13].

Another possibility is that the present lithium content of the stars is different from the initial abundance. Because of the low nuclear binding of $^7$Li, destruction of lithium is possible at relatively lower stellar temperatures [13]. The major effect is convection, which draws the photospheric lithium deep into the interior where nuclear destruction can occur. Numerous mixing effects are considered for low-metallicity stars, such as convective motions, turbulence, rotational circulation, diffusion and gravitational settling, and internal gravity waves [13]. However, observations have not confirmed these effects. The possibility of the observed lithium abundance being less than the primordial value due to stellar depletion is also strengthened by the fact that observations of interstellar $^7$Li in the low-metallicity gas of the Small Magellanic Cloud, a nearby dwarf galaxy with a quarter of the Sun's metallicity, have been found to be nearly equal to the BBN predictions [26]. However, the lithium destruction processes can not explain the thinness of the Spite plateau. While some stars with very low metallicity have lithium abundances *below* the Spite plateau, no star has been observed to have $^7$Li/H *above* the plateau. Finally, $^6$Li has been detected in at least some of the stars. But if there has indeed been a significant depletion in the $^7$Li content, $^6$Li should have been completely destroyed [13]. Hence, the lithium problem has not been resolved astrophysically till now, and other possible solutions need to be considered.

## 5.2 Nuclear Physics solutions

Another possibility is that the measured primordial lithium abundance is correct, and the Standard Model of particle physics and the standard cosmology are also sound. The lithium problem is considered to be due to errors in the BBN light element predictions, in the form of incorrect implementation of standard cosmological and/or Standard Model physics. However, the standard BBN calculation is based on very well-determined physics. The principles of homogeneous universe (verified by the uniformity of CMB), General Relativity, Standard Model, Bose-Einstein and Fermi-Dirac statistics are all well understood

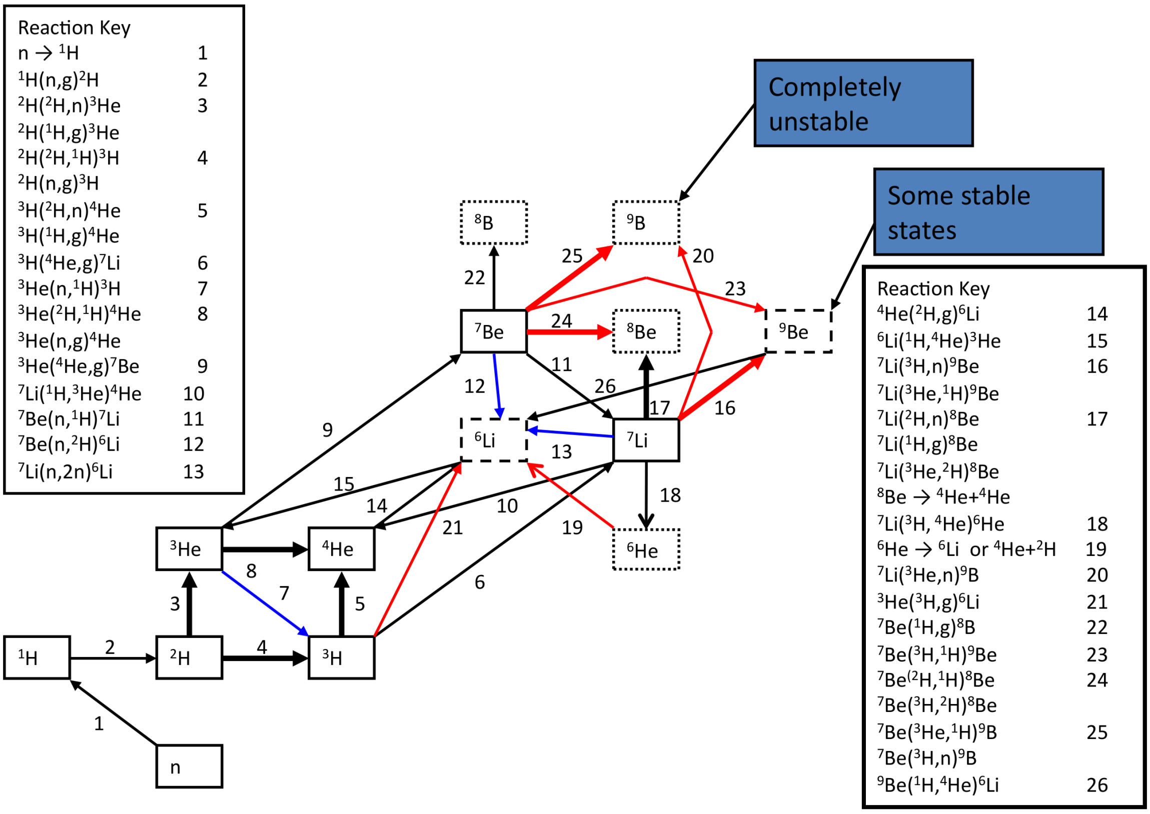


Figure 5.1: Reaction chain of Big Bang Nucleosynthesis with some of the new reactions. The nuclei indicated in dotted boxes are completely unstable, whereas those in dashed boxes have some stable states and some others that are relevant to BBN that undergo particle decay to some other nuclei. Red lines indicate reactions newly added to the BBN code, and blue lines indicate reactions studied in the context of non-thermal neutrons. Double thickness lines indicate more than one possible reaction. (Reproduced from Ref. [28])

with exact expressions [13]. The nuclear interactions are also well studied and calibrated empirically, but are still the only possible sources of error in the BBN calculations due to the complicated physics of the of the large nuclear network.

One possibility is that the weak and nuclear reactions in the BBN calculations have been miscalculated due to reactions that are entirely missing, or that which have been considered with incorrect rates [13]. However, all the reactions have been studied in the laboratory at the relevant energies [1], and only a relatively small number of reactions have been found to influence the light element abundances. Their uncertainties have also been calculated and taken into account when measuring the uncertainties in the predicted abundances [13]. Moreover, the BBN calculations use a much more extended reaction network than the simplified reaction chain in Fig. 3.1, also including the reactions which are insignificant in light element production. Thus, the primordial lithium predictions will change only if the cross sections of the known important reactions have larger uncertainties than quoted, or if the cross section of some normally unimportant reaction has been vastly underestimated [13].

The most important reaction behind $^7$Be production is $^3$He$(\alpha, \gamma)^7$Be. Though its absolute cross-section is difficult to measure, this reaction also occurs in the sun, and the experimental results are confirmed by solar neutrino flux measurements [13, 27]. Among the subdominant reactions, it had been proposed that if the $^7\mathrm{Be}(d,p)2\alpha$ cross-section was higher by a factor of $\sim 100$ than previously estimated, the $^7$Li problem would be resolved. However, the cross-section was experimentally found to be a factor $\sim 10$ *smaller* than thought before [25]. The possibility of entirely new reactions has been studied in Ref. [28], but they do not affect the primordial abundances. In fact, even though more than 400 reaction and decay rates have been studied [3], they have been unable to alleviate the lithium problem. An extended reaction chain with some (not all) of the new reactions added is given in Fig. 5.1. Other factors such as the weak interaction rates, effects of nonthermal particles, plasma effects and electron Coulomb scattering have been studied but found to be unimportant [13, 28]. The only other possible nuclear physics solution can be through resonances which were not detected experimentally or whose effects had been underestimated. The possible resonances such as $^7\mathrm{Be} + d \to {}^9\mathrm{B}^*$ are being studied experimentally [13, 29].

## 5.3 Solutions beyond the Standard Model

If it is assumed that the primordial $^7$Li/H has been measured correctly and the nuclear physics of BBN has also been calculated correctly, the only remaining possibility is to go beyond the Standard Model of particle physics and/or standard cosmology [13]. The existence of dark matter demands physics beyond the standard model, but it is ordinarily assumed not to have any influence on BBN. However, some theories involving the decay of massive nonstandard particles have been put forward, which may resolve the lithium problem. The photons emitted by this decay may photodissociate the BBN nuclei such as $^7$Be, reducing the lithium abundance [30]. Another possibility is that the value of a fundamental constant such as the deuteron binding energy was different during BBN from the present measured value. One possibility arises from nonstandard cosmology rather than particle physics, such as a scenario where the universe has large-scale homogeneities in the cosmic density. For example, while D/H and the CMB have been observed in the distant universe, $^7$Li/H has been measured locally. The lithium problem is resolved if, due to inhomogeneities in the universe, the local $\eta$ is lower than the distant value, though this has not been supported by observations [13]. Other cosmological solutions include photon cooling (which gives a smaller $\eta$ during BBN than the present value) or a primordial magnetic field (which increases the neutron-to-proton ratio) [30]. Nonstandard physics is being probed in collider and dark matter experiments [13].

## 5.4 Discussion: the baryon-to-photon ratio

Even though a number of possible solutions to resolving the $^7$Li abundance anomaly have been studied, all these studies have assumed that the baryon-to-photon ratio as measured from CMB observations is correct. The possibility that the ratio is lower than the CMB value, as indicated from the lithium abundance, is not considered. In this context, let us once again discuss $\eta$, the baryon-to-photon ratio of the universe.

The baryon-to-photon ratio is the only free parameter of Big Bang Nucleosynthesis that can not be obtained from theory or from laboratory experiments. It can only be determined from astronomical observations. There are two methods of estimating $\eta$: one from the observed light element abundances based on BBN, and the other from observation of the anisotropies in the Cosmic Microwave Background.

Since the primordial abundances of the light elements depend on $\eta$ (as discussed in Chapter 3), one way to find the ratio is to observe the abundance of one such element and then estimate the baryon-to-photon ratio which would yield the obtained abundance based on standard BBN calculations. It is assumed that the observed abundances are indeed primordial, and the standard BBN model is correct. Because the abundances of more than one nuclides were known, $\eta$ could be calculated from all of them and compared with one another. We get

$$\eta = (5.6 \pm 0.5) \times 10^{-10} \text{ from D/H} = (3.0 \pm 0.4) \times 10^{-5} \text{ [31]}$$

$$1.8 \times 10^{-10} \leq \eta \leq 18 \times 10^{-10} \text{ from } 0.232 \leq Y_P \leq 0.258 \text{ [32]}$$

$$\eta = (5.4^{+2.2}_{-1.2}) \times 10^{-10} \text{ from } ^3\text{He/H} = (1.1 \pm 0.2) \times 10^{-5} \text{ [33]}$$

$$1.6 \times 10^{-10} \leq \eta \leq 5 \times 10^{-10} \text{ from } ^7\text{Li/H} = (1.12 \pm 0.38) \times 10^{-10} \text{ [19]}$$

As we can see, a larger value of $\eta$ is obtained from the abundances of D and $^3$He (though $^3$He is not generally considered due to the large error in its observed primordial abundance), and a smaller value from $^7$Li abundance. $Y_P$ depends weakly on $\eta$, and it does not put much constraint on its value. Combining the calculations based on all the nuclei, the baryon-to-photon ratio is found to be $2.6 \times 10^{-10} \leq \eta \leq 6.2 \times 10^{-10}$ [21].

An independent measure of $\eta$ was possible from observation of the CMB. While the photon density was obtained from the CMB temperature, the baryon density was measured from the CMB anisotropies, from the *WMAP* and later the *Plank* satellites. From *WMAP* observations, we got $\eta = (6.079 \pm 0.090) \times 10^{-10}$ [3]. As BBN took place within 20 minutes of the Big Bang, and the CMB occurred 380,000 years later and involves different physics, we get a completely independent measure of $\eta$ which can be used to verify the BBN predictions.

As we saw, the CMB observation agrees perfectly with deuterium, fairly well with helium, but does not agree at all with lithium abundance observations. Therefore, we get two candidates for the value of $\eta$: a larger value ($\sim 6 \times 10^{-10}$) which is supported by CMB observations and deuterium abundance, and a smaller value ($\sim 4 \times 10^{-10}$) which is supported by lithium abundance. The helium isotopes are not being considered here. This is because $^3$He observations are not reliable, and $^4$He depends too weakly on $\eta$ to give any reasonable constraint. In fact, while older measurements of $Y_P$ constraints on $\eta$ conformed more with lithium than with deuterium [34], later measurements show it to agree more with the deuterium and CMB predictions [14]. In this context, it should also be borne in mind that even though we get a good overall agreement between the BBN and CMB measures of $\eta$, a number of assumptions had to be made to find the baryon-to-photon ratio from the CMB observations, some of which did not have any clear justification [21]. Since large amounts of data are now available, all possible models should be checked to determine the parameters beyond doubt.

Thus, if the smaller value of $\eta$ turned out to be the correct one, the predicted value of $^7$Li/H would decrease to agree with the Spite plateau observations, resolving the lithium problem. But the deuterium abundance prediction would increase to about twice its observed value (Fig. 3.2). Hence the lithium problem is replaced with a 'deuterium problem', and changing $\eta$ does not resolve the BBN problem completely. While it is true that deuterium is destroyed in stars, D/H is estimated from absorption lines in the light from distant quasars, in systems having metallicity 0.001 to 0.01 times the solar value. Thus it can be supposed with confidence that the measured deuterium abundance is equal to the primordial value. Also, all BBN reactions affecting deuterium abundance also affect lithium abundance [1]. So if any of the nuclear cross sections is taken wrong, we should get a wrong value of $^7$Li/H as well. This would mean that the lithium prediction matching with the Spite plateau value is incorrect, and there is still a lithium problem. ($^7$Li abundance, on the other hand, depends on a number of reactions such as $^3$He$(\alpha, \gamma)^7$Be which do not affect the other nuclei at all [1].) The lower value of $\eta$ would imply increase in the predicted $^3$He/H and lowering of the predicted $Y_P$, but they would still agree with the observed abundances within the error margin. This would also mean that the CMB value of the baryon density is higher than the true value. But the theory behind the CMB anisotropies has been studied thoroughly [7, 9]. The sources of error have been taken into account [11, 15], and the *WMAP* and *Planck* observations have agreed extremely well. Even if we assume that both deuterium abundance and CMB observations give wrong values of $\eta$, it is very improbable that these two completely independent methods will have errors yielding the *same* wrong value of $\eta$. Because of this, even though the $^7$Li abundance anomaly has not been resolved yet, it is generally considered that the CMB value of $\eta$ is correct. In this regard, mention must be made of two ideas involving Physics beyond the standard model which have been put forward as a possible solution to the lithium problem. According to one idea, which involves photon cooling, $\eta$ may have been less than the present value at the time of BBN. But it can not solve the lithium problem alone unless we assume along with photon cooling the radioactive decay of a hypothetical long lived particle [30]. Another idea proposes an inhomogeneous universe, where our position is nearly at the centre of a spherically symmetric cosmic underdensity. If the local $\eta$ is lower than the distant value, the $^7$Li prediction (which is measured locally) will decrease, while the D and CMB measurements (which are observed in the distant universe) will also agree. However, this idea has not been supported by the local measurements of D/H [13].

# Chapter 6

# Outlook

We discussed Big Bang Nucleosynthesis and the predictions of the light nuclei abundances based on BBN calculations. The methods of determining the baryon-to-photon ratio $\eta$ from the Cosmic Microwave Background as well as determination of the primordial abundances from astronomical observations were also discussed. The lithium abundance anomaly was studied, and its possible solutions were considered. None of them have been able to resolve this problem till now. Further experiments (astrophysical, nuclear physics, collider and dark matter) are under way to find a solution to the lithium problem.

# Bibliography


[1] Alain Coc and Elisabeth Vangioni, "Big-Bang Nucleosynthesis with updated nuclear data", Journal of Physics: Conference Series 202 (2010) 012001.

[2] David N. Schramm and Michael S. Turner, "Big-Bang Nucleosynthesis Enters the Precision Era", *Rev. Mod. Phys.*, 70(1): 303–318, Jan 1998, Preprint: arXiv:astro-ph/9706069v1.

[3] Alain Coc, Jean-Philippe Uzan and Elisabeth Vangioni, "Standard Big-Bang Nucleosynthesis and primordial CNO abundances after *Planck*", *J. Cosmol. Astropart. Phys.*, 2014(10): 050, 2014, Preprint: arXiv: 1307.6955v1 [astro-ph.CO].

[4] D. N. Spergel, L. Verde et al., "First Year Wilkinson Microwave Anisotropy Probe (*WMAP*) Observations: Determination of Cosmological Parameters", *Astrophys. J.*, 148: 175–194, Sep 2003, Preprint: arXiv:astro-ph/0302209v3.

[5] "Wilkinson Microwave Anisotropy Probe", NASA (`http://map.gsfc.nasa.gov`)

[6] C. L. Bennett et al., "First-Year Wilkinson Microwave Anisotropy Probe (*WMAP*) Observations: Preliminary Maps and Basic Results", *Astrophys. J. Supplement Series*, 148(1): 1–27, Sep 2003, Preprint: arXiv:astro-ph/0302207v3.

[7] Wayne Hu and Scott Dodelson, "Cosmic Microwave Background Anisotropies", *Annu. Rev. Astron. Astrophys.*, 40: 171–216, Sep 2002, Preprint: arXiv:astro-ph/0110414v1.

[8] C. L. Bennett et al., "Nine-Year Wilkinson Microwave Anisotropy Probe (*WMAP*) Observations: Final Maps and Results", *Astrophys. J. Supplement Series*, 208: 20 (54pp), Oct 2013, Preprint: arXiv:1212.5225v3 [astro-ph.CO].

[9] Wayne Hu, Naoshi Sugiyama and Joseph Silk, "The Physics of Microwave Background Anisotropies", *Nature*, 386: 37–43, March 1997, Preprint: arXiv:astro-ph/9604166v1.

[10] Lecture Notes, University of St Andrews (`http://star-www.st-and.ac.uk/~spd3/Teaching/PHYS3303/obs_cos_lecture3.pdf`).

[11] G. Hinshaw et al., "First Year Wilkinson Microwave Anisotropy Probe (*WMAP*) Observations: Data Processing Methods and Systematic Error Limits", *Astrophys. J. Supplement Series*, 148(1): 63–95, 2003, Preprint: arXiv:astro-ph/0302222v1.

[12] Alain Coc and Elisabeth Vangioni, "Primordial Nucleosynthesis", Proceedings of Science (XIII Nuclei in the Cosmos) 022, 7–11 July, 2014.

[13] Brian D. Fields, “The Primordial Lithium Problem”, *Annu. Rev. Nucl. Part. Sci.*, 61(1): 47–68, 2011, Preprint: arXiv:1203.3551v1 [astro-ph.CO].

[14] J. Beringer et al. (Particle Data Group), “Review of Particle Physics”, *Phys. Rev. D*, 86, 010001 (2012).

[15] P. A. R. Ade et al., “*Planck* 2013 results. XVI. Cosmological parameters”, *Astron. Astrophys.*, 571 A16 (2014), Preprint: arXiv:1303.5076v3 [astro-ph.CO].

[16] Coc et al., “Updated Big Bang Nucleosynthesis Compared with Wilkinson Microwave Anisotropy Probe Observations and the Abundance of Light Elements”, *Astrophys. J.*, 600:554–552, Jan 2004.

[17] Achim Weiss, “Elements of the past: Big Bang Nucleosynthesis and observation”, Einstein Online Vol. 02 (2006), 1019.

[18] Gerald H. Share and Ronald J. Murphy, “A Method for Determining the Photospheric $^4$He abundance”, E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington DC 20375.

[19] F. Spite and M. Spite, “Abundance of Lithium in Halo Stars and Old Disk Stars: Interpretation and Consequences”, *Astron. Astrophys.*, 115: 357–366, 1982.

[20] G. Steigman, “Big Bang Nucleosynthesis: Probing the First 20 Minutes”, Carnegie Observatories Astrophysics Series, Vol. 2: Measuring and Modelling the Universe, 2004, arXiv:astro-ph/0307244v1.

[21] Subir Sarkar, “Measuring the baryon content of the universe: BBN vs CMB”, Proceedings of 13th Rencontres de Blois on Frontiers of the Universe (C01-06-17.3), 53–63, eprint: arXiv:astro-ph/0205116v1.

[22] Course Notes, A5682: Introduction to Cosmology, Ohio State University (`http://www.astronomy.ohio-state.edu/~dhw/A5682/notes7.pdf`)

[23] Richard H. Cyburt , Brian D. Fields and Keith A. Olive, “Primordial Nucleosynthesis in Light of *WMAP*”, *Phys. Lett. B*, 567(3–4): 227–234, Aug 2003, Preprint: arXiv:astro-ph/0302431.

[24] Course notes, Theory of the Big Bang Nucleosynthesis, University of Maryland, College Park (`http://www.astro.umd.edu/~miller/teaching/astr422/lecture24.pdf`)

[25] C. Angulo, E. Casarejos, M. Couder, P. Demaret, P. Leleux, and F. Vanderbist, “The $^7$Be$(d,p)2\alpha$ cross section at Big Bang energies and the primordial $^7$Li abundance”, *Astrophys. J.*, 630: L105–L108, Sep 2005.

[26] J. Christopher Howk, Nicolas Lehner, Brian D. Fields & Grant J. Mathews, “Observation of interstellar lithium in the low-metallicity Small Magellanic Cloud”, *Nature*, 489: 121–123, 2012.

[27] Adelberger et al., “Solar fusion cross sections”, *Rev. Mod. Phys.*, 70(4), 1265–1291, Oct 1998.

[28] Richard N. Boyd, Carl R. Brune, George M. Fuller and Christel J. Smith, "New Nuclear Physics for Big Bang Nucleosynthesis", *Phys. Rev. D*, 82: 105005, Nov 2010, Preprint: arXiv:1008.0848v1 [astro-ph.CO].

[29] Richard H. Cyburt and Maxim Pospelov, "Resonant enhancement of nuclear reactions as a possible solution to the cosmological lithium problem", *Int. J. Mod. Phys.* E, 21(01): 1250004, Jan 2012, Preprint: arXiv:0906.4373v1 [astro-ph.CO].

[30] Dai G. Yamazaki et al., "Cosmological solutions to the Lithium problem: Big-bang nucleosynthesis with photon cooling, X-particle decay and a primordial magnetic field", *Phys. Rev. D*, 90(2): 023001, Jul 2014, Preprint: arXiv:1407.0021v1 [astro-ph.CO].

[31] John M. O'Meara et al., "The Deuterium to Hydrogen Abundance Ratio Towards a Fourth QSO: HS 0105+1619", *Astrophys. J*, 552(2), 718–730, May 2001, Preprint: arXiv:astro-ph/0011179v2.

[32] Keith A. Olive, "A Realistic Determination of the Error on the Primordial Helium Abundance: Steps Toward Non-Parametric Nebular Helium Abundances", *Astrophys. J.*, 617(1): 29–49, Dec 2004, Preprint: arXiv:astro-ph/0405588v1.

[33] T. M. Bania, Robert T. Rood & Dana S. Balser, "The cosmological density of baryons from observations of $^3\mathrm{He}^+$ in the Milky Way", *Nature*, 415: 54–57, 2002.

[34] Richard H. Cyburt, Brian D. Fields and Keith A. Olive, "Primordial Nucleosynthesis with CMB Inputs: Probing the Early Universe and Light Element Astrophysics", *Astropart. Phys.*, 17(1): 87-100, Apr 2002, arXiv:astro-ph/0105397v1.