Gamow Legacy and the Primordial Abundance of Light Elements

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Abstract

The presently accepted “Theory of the Universe” was pioneered 60 years ago by Gamow, Alpher and Herman. As a consequence of the, later dubbed, Hot Big-Bang, matter was neutrons, and after some decay protons, and a history of successive captures built up the elements.

It wasn’t until some 15 years later (with the discovery of the Cosmic Microwave Background radiation) that Gamow and colleagues theories were validated and present day Standard Big-bang Nucleosynthesis theory was developed.

We will discuss the importance of state of the art observations and modelling in the quest to determine precise values of the primordial abundance of D and \(^{4}\)He, using observations of astrophysical objects and modern day atomic parameters. In particular, we will present the search for understanding and coping with systematic errors in such determinations.

Keywords: Cosmology, Big Bang Nucleosynthesis, Light elements abundance

1 Introduction

The principles of the Standard Big Bang (SBB) model of the universe were laid down by Gamow, Alpher and Herman in work produced between 1945 and 1953 (\cite{gamow1, gamow2, gamow3, gamow4}). Their work placed Friedmann’s and Lemaitre’s conception of the universe on a physically observable basis. They had the advantage of knowing already about the expansion of the universe, discovered by Hubble (\cite{hubble}). Their ideas proposed a way to create all the chemical elements.

SBB states that the Big Bang was hot and dense, and that the conditions were ripe for nucleosynthesis during a short time window of a few minutes. Before that moment the radiation was too hard to permit any nucleide to survive, after that the temperature had gone too low. Therefore the first light nucleides were formed only in a time window of approximately 15 minutes, and the relative abundances that
result depend on the production and the destruction rates during the nucleosynthesis period, which are a function of the baryon-to-photon ratio \( \eta \) (see, e.g. [6]).

Hayashi in 1950 ([7]) suggests that at the high density and temperature reached close to the discontinuity, a freezing of the ratio neutrons to protons would have occurred. Considering as well that there are no stable nuclei with atomic weight \( A=5,8 \), lead researchers to the conclusion that there was no nucleosynthesis after \(^4\)He. Successes in stellar evolution and nucleosynthesis then lead to Big Bang Nucleosynthesis theory (BBNS) to be all but abandoned for 10 years, until Penzias and Wilson ([8]) discovered Cosmic Microwave Background radiation (CMB) that had already been predicted by Gamow and colleagues. People then turned back their attention to Standard Big Bang Nucleosynthesis (SBBN) and a very comprehensive model was developed by Peebles, Wagoner, Fowler, Hoyle, Schramm, Steigman, etc. (e.g. [6]).

A schematic illustration of how the first light nucleides were synthesized in a very short time interval following the Big Bang is shown in Figure 1.

![Figure 1](image-url)

Figure 1: The figure shows how the first light nucleides where synthesized in the first 1000 seconds after the Big Bang. Deuterium, \(^4\)He and traces of \(^7\)Li and Bo nuclei were formed. After 1000 seconds, and when temperature was \(3.10^8\) degrees, BBN stopped.

SBBN has been very successful at least in three predictions:

- it very well predicts primordial abundances of Deuterium, Helium 4, Helium 3, Lithium 7 covering 9 orders of magnitude, a commendable achievement.
• it predicts the number of neutrino species.
• it predicts the neutron half life.

There is a very delicate balance between the reaction rates and the expansion of the universe, therefore on the density and temperature, and hence, the primordial abundances of the first elements can be used to determine the baryon-to-photon density $\eta$. Figure 2 shows the relationship between the primordial abundances of $^4\text{He}/\text{H}$, $^3\text{He}/\text{H}$, D/H and $^7\text{Li}/\text{H}$ and the ratio of the density of baryons-to-photons in units of $10^{-10}$ ($\eta_{10}$). One element alone should be enough to determine $\eta$, but consistency with the others would make the theory very robust, while confirming the parameters of atomic physics used in deriving the predictions.

Of all the light elements, $^4\text{He}$ is the easiest to measure, but, as Figure 2 shows, it is the least sensitive to $\eta$, and therefore, in order to be used as a diagnostic, it has to be measured with very high precision.

![Figure 2: Relationship between the primordial abundances of $^4\text{He}/\text{H}$, $^3\text{He}/\text{H}$, D/H and $^7\text{Li}/\text{H}$ and the ratio of the density of baryons-to-photons in units of $10^{-10}$ ($\eta_{10}$). Notice on the right, the 9 orders of magnitude that the abundances cover.](image)

## 2 Primordial helium ($Y_p$)

Abundances of $^4\text{He}$ and its primordial value ($Y_p$), have been inferred for many years by different authors. Analysing their results, it becomes apparent that the different
determinations are progressively converging, although a significant scatter remains. In order to see where this scatter comes from, we will review the method used to determine $Y_p$.

2.1 The method

The method, essentially devised by Manuel Peimbert and Silvia Torres-Peimbert in 1974 ([10]) was based on the realization, by Searle and Sargent ([11]) that the so-called HII galaxy most metal poor known (then and still now, more than 30 years later, but that is another story) – I Zw 18 – still has a finite He/H abundance, around 0.24, which therefore had to be primordial. The thought behind [10, 11] is that if the universe was born with zero metallicity (Z=0), the metals we see today were created by nucleosynthesis inside stars, and by the same process, helium abundance grows. Therefore, if we collect a sample of objects, measure their chemical abundances, and extrapolate the relation $Y(Z)$ back to $Z=0$, we can determine $Y_p$. An up-to-date representation of this concept can be seen in figure 3 from a compilation by [9]. It is clear from the figure that a reliable determination of $Y_p$ rests entirely on accurate values of Y and O/H abundances.

Figure 3: Helium abundance (Y) versus oxygen abundance (O/H) for HII galaxies. The dashed line is a linear fit. Figure taken from Fields & Olive [9].
2.2 $^4\text{He}$ abundance

Many efforts have concentrated over the years on $Y_p$ determinations, and although the value obtained seems to be converging, substantial scatter still remains. Given that the determination of $Y_p$ relays on a good determination of heavier elements abundance, let’s review the method commonly used for that purpose.

Chemical abundances in ionized regions of the interstellar medium (HII regions) are determined from their optical spectra, (an example of which is represented in Figure 4) applying relations of the type of equation 1 to the emission-line spectrum as the intensity of a line is linked to the ionic abundance through a function of the electron temperature ($T_e$).

![Figure 4: Optical blue spectrum of an HII galaxy. The intense recombination and collisional forbidden lines are indicated. G. Hägele, private communication.](image)

$$\frac{N(X)}{N(H^+)} = f(T_e) \frac{I(\lambda)}{I(H\beta)}$$  \hspace{1cm} (1)

$T_e$ is found by the analysis of suitable temperature sensitive spectral features, e.g. the $[\text{OIII}]\lambda\lambda 4363/4959,5007$ ratio as it is easy to understand from atomic physics first principles. The ionic abundances are then summed to obtain the chemical abundance of a particular element. For example,

$$\frac{N(He^+)}{N(H^+)} \sim T^{a_1} \frac{I(\lambda5876)}{I(H\beta)}$$  \hspace{1cm} (2)
\[
\frac{N(He^{++})}{N(H^+)} \simeq T^{\alpha_2} \frac{I(\lambda 4686)}{I(H\beta)}
\]  
(3)

\[
\frac{N(He)}{N(H)} = \frac{N(He^+)}{N(H^+)} + \frac{N(He^{++})}{N(H^+)}
\]  
(4)

gives the total abundance of He.

### 2.3 Photoionization models

In cases where the $T_e$ cannot be rigorously determined, one can resort to more empirical methods, in particular, to photoionization models. A schematic view of how they work is presented in figure 5.

![Figure 5: Schematic view of the way in which photoionization models help us to deduce physical conditions of nebular gas.](image)

The inputs to a photoionization code are an ionizing spectrum, a nebular geometry and a chemical composition. The outputs are an emission line spectrum, and the structure of the nebula (ionization structure, electron density and temperature $N_e, T_e$). If we succeed in reproducing the emission line spectrum of an observed object, we can use the predicted structure to estimate properties such as the ionization structure.
3 Uncertainties in $Y_p$ determinations

The uncertainties affecting $Y_p$ can be identified in terms of the individual steps that the method includes and can be grouped into three broad categories: the physics, the stellar parameters and the nebular parameters. We can list some of them, but several others exist (e.g., observational errors). In table 1 they are listed in three categories, according to the ingredient of the method where they originate. As it can be seen, some of them are intertwined. We will discuss all of them, except the physics that affect our abundance determinations through atomic parameters. There is nothing we astrophysicists can do about it, but to wait for better laboratory results.

| Category       | Source of error                      |
|----------------|--------------------------------------|
| physics        | atomic parameters                    |
| stellar        | underlying stellar absorption        |
| parameters     | ionization structure                 |
| nebular        | temperature structure                |
| parameters     | H I collisional enhancement          |

3.1 Underlying absorption

The stars that photoionized the nebulae also show their own spectra. They are young hot stars, with H and He lines in absorption, therefore the nebular emission measured is underestimated. One solution is to subtract from the spectra a good estimate (obtained from theoretical stellar models) of the stellar population. One is then left with the pure emission spectrum. Nowadays, state-of-the-art stellar population synthesis models with high spectral resolution allow us to perform a good underlying absorption correction.

3.2 Ionization structure

The simplest assumption to derive the He abundance from the HeI and HeII abundances is that the ionized He and the ionized H spheres coincide. If this is not the case, and the effect is not taken into account, the He abundance is either underestimated or overestimated depending on whether neutral helium is contained in the ionized hydrogen sphere, or $H^0$ is contained within the He$^0$ sphere. If HII regions were density-bounded in all directions, the problem would not exist.

There are several ways to deal with the uncertainty associated with the ionization structure:
• 1. applying selection criteria to the object sample.
• 2. building tailored photoionization models.
• 3. using narrow long-slit data.

A first possibility is applying selection criteria to the regions analyzed. Since the ionization structure depends on the shape of the ionizing spectrum, the selection criteria depend on the stellar population. One can therefore exclude those regions ionized by stellar clusters that do not guarantee ionization correction factors $ICF(\text{He}) \sim 1$. This has the disadvantage that precious data points are lost, methods are not so robust as they should be, and selection criteria are VERY model-dependent.

A second possibility is building tailored ionization models and assuming that the ionization structure of the model reflects the one of the real region. Disadvantages of this method are that it is time-consuming, and that the model must really be very constrained to ensure that the predicted ICF is a good assessment.

A third possibility is using long-slit data. In this way, although the problem is not solved, its impact is lessened owed to geometrical reasons (the relative volume of the transition zone is smaller than in the case of a complete sphere, about $2/3$).

### 3.3 Temperature fluctuations

Temperature fluctuations inside the H II regions can bias the abundance determinations. We use equation (1) to link the abundance of an element with the relative intensities of its lines to a hydrogen recombination line, and the relation depends on a function of the electron temperature. But, does one value of $T_e$ fit all? The answer is no, as each ion is associated to a typical temperature, and adopting one for all introduces a bias in the derived abundance.

The dependence of the line intensity on $T_e$ varies from recombination to collisionally excited lines. Recombination lines (like, e.g. HeI) weight smoothly the $T$ structure according to

$$\frac{I(\lambda5876)}{I(H\beta)} \simeq T^{-\alpha} \frac{N(\text{He}^+)}{N(H^+)}$$

while collisional lines (like, e.g. [OIII] $\lambda$ 5007Å) are enhanced in $T$ peaks as

$$\frac{I(\lambda5007)}{I(H\beta)} \simeq T^{-\beta} \times e^{\Delta E/kT} \times \frac{N(\text{O}^{++})}{N(H^+)}$$

Therefore, if there are temperature fluctuations in the region and the temperature is determined from the ratio of collisional lines, as it is often the case, the inferred temperature will be biased towards the peaks. On the other hand, recombination lines may give an estimate closer to the average values. The problem is that recombination lines are weaker than collisional lines, so they are more difficult to observe.

In any case, this becomes a very hairy problem. The temperature used to find the ionic abundances must be determined with care, otherwise the abundances will be over or underestimated.
3.4 Collisional enhancement of Balmer lines

Another problem is caused by the collisional enhancement of Balmer lines. The expression here

$$\frac{N(He^+)}{N(H^+)} \simeq T^\alpha \frac{I(\lambda)}{I(H\beta)}$$

(7)

holds under the hypothesis that the intensities derive from recombination only. Helium intensities have an important collisional part, which is routinely computed and subtracted out. Balmer lines have a much smaller collisional part, which is nevertheless important at the present required state of precision. To have an idea of the relative importance of collisions in Balmer lines, let us consider the collisional-to-recombination ratio of H\(\beta\): the ratio depends on the ionic fractions of neutral and ionized hydrogen and on the Boltzmann factor of the transition from the ground state to the upper level of the line.

$$\frac{j(H\beta)_C}{j(H\beta)_R} \propto \frac{N(H^0)}{N(H^+)} e^{-\Delta E/KT}$$

(8)

Typical values for the ionic ratio are around \(10^{-4}\), values for the Boltzmann factor are listed below for the typical range of HII temperatures.

| \(T_e\)  | \(e^{-\Delta E/KT}\) |
|--------|----------------|
| 10000  | 3.7E-7         |
| 12500  | 7.2E-6         |
| 15000  | 5.2E-5         |
| 17500  | 2.1E-4         |
| 20000  | 6.1E-4         |

Table 2: Boltzmann factor as a function of Temperature

Due to the Boltzmann factor, the collisional contribution to the Balmer lines is particularly important in high-temperature regions. This is a big difficulty because the hottest regions are the most metal poor ones, that is the most important ones from the point of view of the determination of primordial helium given that the amount of (unseen) He\(^0\) is minimal, and so is the extrapolation to \(Z=0\).

An additional difficulty is that the collisional contribution is higher for H\(\alpha\) than for H\(\beta\), and thus it mimicks (and can be misunderstood for) the reddening due the interstellar attenuation. Therefore, unrecognized collisions have two main effects, one direct and one indirect. The direct one is that the relative hydrogen contribution is overestimated, therefore the He/H ratio is underestimated. The indirect one is that if the Balmer decrement is interpreted in terms of pure extinction, the lines blueward of H\(\beta\) are overestimated, and those redward of H\(\beta\) are underestimated. The global effect on helium abundance depends on which lines are used, but since the most intense ones (\(\lambda \) 5876 and 6678 \(\AA\)) are redward of H\(\beta\), the net effect is usually that He is underestimated.

As an example, [12] used tailored photoionization models to study quantitatively the effect of collisional excitation of Balmer lines on the determination of the helium
abundance (Y) in individual photoionized regions. The geometry of the model is very complex, simulating a filamentary structure with stellar sources spread everywhere. The revised Y values for the five objects in their sample yield an increase of +0.0035 in Y_p, giving Y_p = 0.2391 ± 0.0020.

Other recent results, [13] use a numerous sample of good signal-to-noise spectra, in an effort to take into account all the possible systematics. They obtain Y_p = 0.2391 ± 0.0020.

In a novel approach, [14] use the recent determinations of the baryon density by the experiment WMAP (e.g. [15]) and the standard BBNS model to determine quite precise predictions of the primordial light-element abundances. They argue that the discrepancies between the observationally determined Y values and the value favoured by WMAP results are significant if only the statistical errors are considered. They examine in detail some likely sources of systematic uncertainties that may resolve the differences between the determinations and conclude “that the observational determination of the primordial helium abundance is completely limited by systematic errors and that these systematic errors have not been fully accounted for in any published observational determination of the primordial helium abundance”. They advocate for a nonparametric approach to the analysis of the observed metal-poor H II region spectra such that the physical conditions and the helium abundance are derived solely from the relative flux ratios of the helium and hydrogen emission lines. The data and the selected objects for the task should be very specific and of inexistent (at present) quality. In practice, the solutions at present are parametric with underestimated error bars. [14] obtain a value of Y_p = 0.249 ± 0.009. They consider as their main result the increase in the size of the uncertainty rather than the shift in the primordial value and go on to claim that most of the spectra analyzed to date do not significantly constrain Y_p. Rather, they argue that a range of allowed values would be 0.232 ≤ Y_p ≤ 0.258. Figure 6, taken from their work, shows that this last consideration allows for the eagerly searched concordance between measurements of the baryon-to-photon ratio (η) from WMAP and deuterium and helium abundances. It also shows that individual error bars in D/H do not overlap. As a consequence, averaging the five best absorption system determinations may not be correct.

Finally, figure 7 summarises the state-of-the-art concerning the determination of η vs. the primordial abundances of the light elements.

It is interesting to note that the Songaila 1994 point for D/H has been included just for historical reasons, as it was soon recognised to be wrong.

4 Concluding remarks

Given the concordance obtained with WMAP D/H determination (e.g. [13]), is the η value secure? The answer is no. Cosmic Microwave Background results constraint combinations of cosmological parameters, therefore independent individual determinations of them are still very important.

Concordance of primordial abundances has been considered a triumph of modern cosmology; regaining it represents an important goal.

In the process, as the community has done in the past, we are sure to learn a
Figure 6: Concordance between WMAP derived light element abundances and observationally determined ones (from [15] and references therein).

lot about chemical evolution of galaxies and about systematic effects in abundance determinations.

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