Primordial Helium And the Cosmic Background Radiation

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Abstract

The products of primordial nucleosynthesis, along with the cosmic microwave background (CMB) photons, are relics from the early evolution of the Universe whose observations probe the standard model of cosmology and provide windows on new physics beyond the standard models of cosmology and of particle physics. According to the standard, hot big bang cosmology, long before any stars have formed a significant fraction (\(\sim 25\%\)) of the baryonic mass in the Universe should be in the form of helium-4 nuclei. Since current observations of \(^4\text{He}\) are restricted to low redshift regions where stellar nucleosynthesis has occurred, an observation of high redshift, prestellar, truly primordial \(^4\text{He}\) would constitute a fundamental test of the hot, big bang cosmology. At recombination, long after big bang nucleosynthesis (BBN) has ended, the temperature anisotropy spectrum imprinted on the CMB depends on the \(^4\text{He}\) abundance through its connection to the electron density and the effect of the electron density on Silk damping. Since the relic abundance of \(^4\text{He}\) is relatively insensitive to the universal density of baryons, but is sensitive to a non-standard, early Universe expansion rate, the primordial mass fraction of \(^4\text{He}\), \(Y_P\), offers a test of the consistency of the standard models of BBN and the CMB and, provides constraints on non-standard physics. Here, the WMAP seven year data (supplemented by other CMB experiments), which lead to an indirect determination of \(Y_P\) at high redshift, are compared to the BBN predictions and to the independent, direct observations of \(^4\text{He}\) in low redshift, extragalactic H\ II regions. At present, given the very large uncertainties in the CMB-determined primordial \(^4\text{He}\) abundance (as well as for the helium abundances inferred from H\ II region observations), any differences between the BBN predictions and the CMB observations are small, at a level \(\lesssim 1.5\sigma\).

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I. INTRODUCTION

In the first few minutes of the evolution of the Universe, during big bang nucleosynthesis (BBN), neutrons and protons are incorporated in astrophysically interesting (i.e., measurable) abundances into the light nuclides D, $^3$He, $^4$He, and $^7$Li. Of these nuclides, the relic abundance of $^4$He (mass fraction $Y_P$) is least sensitive to the nuclear reaction rates (and their uncertainties) and to the baryon density but, $Y_P$ is very sensitive to the early universe energy density through its effect on the expansion rate of the Universe during radiation-dominated epochs. As a result, a comparison of the BBN-predicted value of $Y_P$ with its observationally determined value has the potential to test the standard models of particle physics and cosmology and to constrain any new physics beyond the standard models (see, e.g., Steigman, Schramm, & Gunn [1], Boesgaard & Steigman [2], Steigman [3], and references therein). For several decades observations of $^4$He (and H) recombination lines in metal-poor, extragalactic H II regions have provided the data needed to infer the primordial $^4$He mass fraction which may be compared with the predictions of BBN in the standard model (SBBN). Over the years, the observationally inferred $^4$He abundance has varied (largely increasing) from $Y_P \lesssim 0.23$ to $Y_P \gtrsim 0.25$, the variations due, in large part, to better data and to better analyses of the data which, in particular, address the systematic uncertainties in using the observed hydrogen and helium recombination line intensities to derive the $^4$He abundances. Cosmological tests require that $Y_P$ be known to $\lesssim 0.4\%$. An independent determination of $Y_P$, with different systematics, would be of great value. Furthermore, the H II region observations of $^4$He are in low redshift, star-forming regions, polluted to some extent by the products of stellar nucleosynthesis. The CMB can play an important role by providing a completely independent determination of $Y_P$ in the high redshift, post-BBN, prestellar Universe, free from the systematic uncertainties affecting the direct observations of $^4$He in extragalactic H II regions.

II. STANDARD BBN AND PRIMORDIAL DEUTERIUM

Long before recombination, during the first few minutes in the evolution of the Universe, the light nuclides D, $^3$He, $^4$He, and $^7$Li are synthesized by BBN. For “standard” BBN (SBBN), with three flavors of light neutrinos ($N_\nu = 3$), the light element abundances depend
on only one adjustable parameter, the baryon (or nucleon) abundance, $\eta_B \equiv n_B/n_\gamma \equiv 10^{-10}\eta_{10}$. In the standard models of particle physics and cosmology, the numbers of nucleons and CMB photons in every comoving volume are preserved (post-$e^\pm$ annihilation), so that $\eta_B$ should be unchanged from BBN to recombination to the present. Of the relic nuclides, deuterium is the baryometer of choice since its post-BBN evolution is simple and monotonic. As gas is cycled through stars, deuterium is destroyed and no significant amounts of D are synthesized in stellar (or other) post-BBN nucleosynthesis [4]. The abundance of deuterium, observed anywhere in the Universe, at any time in its post-BBN evolution, is never any larger than the primordial D abundance. Furthermore, the BBN-predicted D abundance is sensitive to the baryon density parameter, varying (for $\eta_B$ in the range of interest) as $\eta_B^{-1.6}$, so that a $\sim 10\%$ determination of $y_{DP} \equiv 10^5(D/H)_P$ results in a $\sim 6\%$ measurement of the universal density of baryons.

Nearly primordial deuterium is seen in absorption against background UV sources in QSO Absorption Lines Systems (QSOALS). These observations are difficult, requiring significant time on large telescopes equipped with high resolution spectrographs. At present there are determinations of the deuterium abundance along only seven, high-redshift, low-metallicity lines of sight. The results, summarized in Pettini et al. [5], lead to a primordial D abundance $\log y_{DP} = 0.45 \pm 0.03$. For SBBN ($N_\nu = 3$), this corresponds to a baryon abundance $\eta_{10}(\text{SBBN,D}) = 5.80^{+0.27}_{-0.28}$ ($\Omega_B h^2 = 0.0212 \pm 0.0010$). For this baryon abundance, the SBBN-predicted primordial $^4$He mass fraction is $Y_P(\text{SBBN,D}) = 0.2482 \pm 0.0007\ [3, 6]$.

III. STANDARD BBN AND THE WMAP BARYON DENSITY

The CMB temperature anisotropy spectrum probes the baryon abundance (among many other cosmological parameters) at recombination. Using the WMAP Seven-Year data, Komatsu et al. [7] derive $\eta_{10}^{(\text{WMAP})} = 6.190 \pm 0.145$ ($\Omega_B h^2 = 0.02260 \pm 0.00053$). This determination of the baryon abundance at recombination, some $\sim 400$ kyr after BBN, provides an independent determination of $\eta_B$. Although somewhat higher than the value found from SBBN and deuterium (see III), the two determinations differ by only $\sim 1.3\sigma$: $\eta_{10}(\text{SBBN,WMAP}) - \eta_{10}(\text{SBBN,D}) = 0.39^{+0.32}_{-0.31}$. For SBBN with this baryon abundance, the primordial deuterium abundance is predicted to be $\log y_{DP}(\text{SBBN,WMAP}) = 0.405^{+0.020}_{-0.021}$, which differs from the observationally determined value [5] by only $\sim 1.1\sigma$. The
SBBN/WMAP-predicted primordial $^4\text{He}$ mass fraction is $Y_P(\text{SBBN, WMAP}) = 0.2488 \pm 0.0006$ [3, 6]. Whether SBBN and deuterium or SBBN and WMAP is used to find $Y_P$, the SBBN-predicted relic abundance is $Y_P \approx 0.248 - 0.249$, with a $\sim 0.2 - 0.3\%$ uncertainty.

IV. NON-STANDARD BBN AND WMAP

A non-standard early Universe expansion rate (Hubble parameter: $H' \neq H$; $S \equiv H'/H \neq 1$) characterizes a large class of non-standard cosmological and particle physics models. During the early evolution of the Universe, a non-standard expansion rate may be expressed in terms of an expansion rate parameter, $S$, as $S \equiv H'/H = (G'\rho'/G\rho)^{1/2}$, where $G$ is the gravitational constant and $\rho$ is the energy density, dominated at early epochs by the contribution from massless or extremely relativistic particles (“radiation”). One possibility is a non-standard energy density: $\rho \rightarrow \rho' \equiv \rho + \Delta N\nu \rho_\nu$, where the non-standard contribution is normalized to $\rho_\nu$, the total energy density from one, two-component, relativistic neutrino. The parameter $\Delta N\nu \equiv N\nu - 3$, the “effective number of equivalent neutrinos”, is a convenient way to characterize a non-standard ($\Delta N\nu \neq 0$), early Universe expansion rate, but it need not actually count new flavors of neutrinos [1, 3, 6]. In the standard model ($N\nu = 3$), at $T \gtrsim m_e$, prior to $e^\pm$ annihilation, $T_e = T_\nu = T_\gamma$, so that $\rho_e/\rho_\gamma = 7/4$, $\rho_\nu/\rho_\gamma = 7/8$, and

$$\rho = \rho_\gamma + \rho_e + 3\rho_\nu = 43\rho_\gamma/8.$$  (1)

For a non-standard cosmology, $S(\neq 1)$ and $\Delta N\nu(\neq 0)$ are related by $S = (1+7\Delta N\nu/43)^{1/2}$ [6].

The effect on BBN of a non-standard expansion rate is to modify the competition between the nuclear (and weak) reaction rates and the universal expansion rate. Since the primordial $^4\text{He}$ mass fraction is largely determined by the neutron to proton ratio when BBN begins in earnest, $Y_P$ is quite sensitive to the competition between the weak interaction rates (i.e., $\beta$-decay) and the expansion rate [1]. For $|\Delta N\nu| \lesssim 1$, $\Delta Y_P \approx 0.013\Delta N\nu$. There are relatively smaller, but non-negligible changes to the BBN-predicted abundances of the other light elements; see, e.g., Kneller & Steigman [6] and Steigman [3].

When $e^\pm$ pairs annihilate ($T \lesssim m_e$), the photons are heated with respect to the neutrinos. On the quite good assumption that the $e^-$, $\mu^-$, and $\tau$-neutrinos are decoupled (from the photon-$e^\pm$ plasma) when $T \approx m_e$, then after $e^\pm$ annihilation $T_\gamma/T_\nu = (11/4)^{1/3}$. In the radiation-dominated, post-$e^\pm$ annihilation Universe the energy density in the standard model
\[ \rho = \rho_\gamma + 3\rho_\nu = [1 + (21/8)(4/11)^{4/3}]\rho_\gamma = 1.68\rho_\gamma. \] (2)

For a non-standard model, in the approximation of complete neutrino decoupling, \( \rho' = [1 + (7/8)(4/11)^{4/3}\Delta N_\nu]\rho_\gamma \). A non-standard energy density or expansion rate affects the transition from radiation domination to matter domination, impacting the growth of perturbations, and leaving an imprint on the CMB temperature anisotropy spectrum. As a result, the CMB provides a probe of \( N_\nu \) which is independent of BBN.

However, since the e-, µ-, and τ-neutrinos are not fully decoupled at \( e^\pm \) annihilation, the effective number of equivalent neutrinos at recombination is not \( N_\nu \), but \( N_{\text{eff}} \equiv 3 + \Delta N_\nu \). Since Komatsu et al. [7] adopt \( N_{\text{eff}} \equiv 3.04 + \Delta N_\nu \), in the comparison here with the WMAP seven-year data, \( \Delta N_\nu \equiv N_{\text{eff}} - 3.04 \) will be used.

The CMB temperature anisotropy spectrum determines \( z_{\text{eq}} \), the redshift of the epoch of equal radiation and matter densities: \( 1 + z_{\text{eq}} = \Omega_M/\Omega_R \). Since \( \Omega_R \) depends on \( N_{\text{eff}} \), a CMB determination of \( N_{\text{eff}} \) is degenerate with the energy density in non-relativistic matter (\( \Omega_M h^2 \)) [7]. According to Komatsu et al. [7],

\[ N_{\text{eff}} - 3.04 = 7.44 \left( \frac{\Omega_M h^2}{0.1308} \frac{3139}{1 + z_{\text{eq}}} - 1 \right) \equiv \Delta N_\nu. \] (3)

To constrain \( N_{\text{eff}} \), the CMB data needs to be supplemented by independent, external data on the Hubble parameter (\( H_0 \)) and on \( \Omega_M \) (or, \( \Omega_M h \)) from observations of large scale structure (LSS). For their constraint on \( N_{\text{eff}} \), Komatsu et al. [7] adopt the improved measurement of \( H_0 \) from Riess et al. [9] and LSS data either from baryon acoustic oscillations (WMAP+BAO+\( H_0 \)) or from luminous red galaxies (WMAP+LRG+\( H_0 \)).

For WMAP+BAO+\( H_0 \), Komatsu et al. [7] find \( N_{\text{eff}} = 4.34^{+0.86}_{-0.88} \), corresponding to \( \Delta N_\nu(\text{WMAP+BAO+}H_0) = 1.30^{+0.86}_{-0.88} \), while for WMAP+LRG+\( H_0 \), they find \( N_{\text{eff}} = 4.25^{+0.76}_{-0.80} \), corresponding to \( \Delta N_\nu(\text{WMAP+LRG+}H_0) = 1.21^{+0.76}_{-0.80} \). At \( \sim 1.5\sigma \), these CMB/LSS results are consistent with the standard model value of \( \Delta N_\nu = 0 \) (\( N_\nu = 3 \)).

For the WMAP value of the baryon density parameter (\( \eta_{10}(\text{WMAP}) = 6.190 \pm 0.145 \)) and either the WMAP+BAO+\( H_0 \) or WMAP+LRG+\( H_0 \) determinations of \( \Delta N_\nu \) [7], the BBN-predicted deuterium abundance [3, 6] is \( \log y_{DP} = 0.47 \pm 0.05 \), in excellent agreement with the observationally-determined value [5], \( \log y_{DP} = 0.45 \pm 0.03 \). The BBN-predicted \(^4\text{He} \) mass fractions are \( Y_P(\text{WMAP+BAO+}H_0) = 0.2649^{+0.0099}_{-0.0108} \) and \( Y_P(\text{WMAP+LRG+}H_0) = 0.2649^{+0.0099}_{-0.0108} \).
0.2639$^{+0.0088}_{-0.0099}$, respectively. Although these values of $Y_P$ may seem high, the uncertainties are large (reflecting the large uncertainties in the WMAP determination of $\Delta N_\nu$) and these abundances are consistent with those for SBBN (see §II & §III) within $\sim 1.5\sigma$.

V. PRIMORDIAL HELIUM-4 FROM THE CMB

The suppression of the CMB temperature power spectrum on small angular scales due to Silk damping [10] provides an independent probe of the relic, prestellar $^4$He abundance, through its effect on the electron density at recombination. After helium recombination, but prior to hydrogen recombination, the number density of free electrons (which are responsible for Silk damping) is related to the baryon number density by $n_e = (1-Y_P)n_B \propto (1-Y_P)\eta_B$. The larger $Y_P$, the fewer free electrons, the further can the CMB photons free-stream, damping perturbations in the temperature anisotropy spectrum, reducing the CMB power spectrum on small angular scales. Since this effect is largest on the smallest angular scales, the WMAP data needs to be supplemented by data from small-scale CMB experiments such as ACBAR [11] and QUaD [12]. For WMAP data alone, Komatsu et al. [7] find a 95% upper limit to the primordial helium mass fraction of $Y_P^{(\text{CMB})} < 0.51$. When ACBAR and QUaD data are added, Komatsu et al. [7] find $Y_P^{(\text{CMB})} = 0.326 \pm 0.075$, a result which differs from zero at more than $3\sigma$ (but, apparently, not by the $5\sigma$ usually required to establish new discoveries).

Although the central value of this determination of $Y_P$ seems high, its uncertainty is large. For example, it is interesting to test the internal consistency of this independent, CMB determination by comparing it to the WMAP+BAO+$H_0$, BBN-predicted value (§IV).

$$Y_P^{(\text{CMB})} - Y_P^{(\text{WMAP} + \text{BAO} + H_0)} = 0.061 \pm 0.76.$$  \hspace{1cm} (4)

This result is consistent with zero at $\sim 0.8\sigma$ (as is that using WMAP+LRG+$H_0$). It is also interesting to compare the CMB result to the one determined by SBBN and the observed D abundance (§II),

$$Y_P^{(\text{CMB})} - Y_P^{(\text{SBBN}, D)} = 0.078 \pm 0.075,$$  \hspace{1cm} (5)

or, with that predicted by SBBN using the WMAP-determined baryon abundance (§III),

$$Y_P^{(\text{CMB})} - Y_P^{(\text{SBBN}, \text{WMAP})} = 0.077 \pm 0.075.$$  \hspace{1cm} (6)
These differences are consistent with zero at $\sim 1.0\sigma$. Within its currently large uncertainty, the CMB provides an independent measurement of $Y_P$ in the high redshift, prestellar Universe consistent with the SBBN and non-SBBN predicted primordial $^4$He abundances.

VI. PRIMORDIAL HELIUM-4 FROM EXTRAGALACTIC H II REGIONS

Historically, the primordial $^4$He mass fraction has been determined from observations of helium and hydrogen recombination lines in low-metallicity, extragalactic H II regions such as Blue Compact Galaxies (BCG) \[13–18\]. As the data set has become larger and more accurate, it has become clear that, at present, the systematic uncertainties in converting the recombination line intensities to helium abundances dominate over the statistical errors. Very recently, Izotov & Thuan \[19\] and Aver, Olive, & Skillman \[20\] have revisited the BCG data, paying special attention to the systematic errors. From a linear extrapolation to zero metallicity of the helium and oxygen abundances derived from 96 spectra in 86 H II regions, Izotov & Thuan \[19\] find $Y_P(\text{IT10}) = 0.2565 \pm 0.0010(\text{stat}) \pm 0.0050(\text{syst})$. In contrast, Aver, Olive, & Skillman \[20\] concentrate on the spectra from only nine, highly selected BCGs. A linear extrapolation of the helium and oxygen data for their 9 BCGs leads Aver, Olive, & Skillman \[20\] to $Y_P(\text{AOS10}) = 0.2528 \pm 0.0028$, where the uncertainty is the error in the mean which, since systematic errors dominate, may be an underestimate. Within the errors, Izotov & Thuan \[19\] and Aver, Olive, & Skillman \[20\] are in agreement. For comparison with the helium abundance predictions and the CMB-determined value discussed above, the central value of the BCG-inferred primordial mass fraction from Izotov & Thuan \[19\] is adopted here, and their statistical and systematic errors are combined linearly, leading to $Y_P(\text{IT10}) = 0.2565 \pm 0.0060$. Although this estimate of the primordial $^4$He abundance is larger than the SBBN-predicted values (see \[III\] and \[III\]), the differences are consistent with zero at $\sim 1.3 - 1.4\sigma$. In contrast, the Izotov & Thuan \[19\] helium mass fraction is smaller than the non-SBBN value predicted for the WMAP (and LSS) determined baryon abundance and $\Delta N_\nu$, but only by $\sim 0.6 - 0.7\sigma$. The CMB-determined primordial helium abundance is higher than the Izotov & Thuan \[19\] value but, given the large uncertainty, the difference is consistent with zero at $\sim 0.9\sigma$. 

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VII. SUMMARY AND OUTLOOK

For SBBN ($N_\nu = 3$), using the observationally-inferred primordial deuterium abundance or the WMAP data to constrain the universal density of baryons, the predicted primordial helium mass fraction is $Y_P^{\text{(SBBN)}} \approx 0.2482 - 0.2488$, with a $\sim 2 - 3\%$ uncertainty. These estimates agree, within $\lesssim 1.4\sigma$, with the primordial value inferred from observations of low metallicity extragalactic H II regions $^{19, 20}$, $Y_P^{\text{(H II)}} \approx 0.2528 - 0.2565$ ($\pm \approx 0.0060$). However, the CMB and LSS data provide some evidence in support of a non-standard cosmology with $N_\nu \neq 3$ $^7$. For the WMAP estimates of $\eta_B$ and of $\Delta N_\nu$, $Y_P^{\text{(BBN,WMAP)}} = 0.2639 - 0.2649$, with an uncertainty ranging from 0.0088 to 0.0108. Although higher than the SBBN estimates of $Y_P$, as well as those inferred from direct observations $^{19, 20}$, within the relatively large errors, they are consistent with them. By combining the WMAP temperature anisotropy power spectrum with data from other CMB experiments $^{11, 12}$, Komatsu et al. $^7$ have presented evidence for an independent, high redshift, prestellar detection of helium, $Y_P^{\text{(CMB)}} = 0.326 \pm 0.075$. Within its very large errors, this value too, is consistent with the others reviewed here.

It is anticipated that data from the Planck experiment $^{21}$ will result in significant reductions in the uncertainties in $\eta_B$ and $\Delta N_\nu$, as well as in the CMB estimate of $Y_P$. According to Hamann, Lesgourges, & Mangano $^{22}$, Planck will reduce the uncertainty in the baryon abundance parameter by more than a factor of two, from a WMAP value of $\sigma(\eta_{10}) \approx 0.145$ to $\sigma(\eta_{10}) \approx 0.063$ and, will reduce the uncertainty in $\Delta N_\nu$ by a factor of $\sim 3$, from $\sigma(\Delta N_\nu) \approx 0.76 - 0.88$, to $\sigma(\Delta N_\nu) \approx 0.26$. If Planck achieves these reductions, the uncertainty in the BBN-CMB predicted helium abundance will be reduced by a factor of $\sim 3$, to $\sigma(Y_P) \approx 0.0034$, resulting in a more accurate determination of $Y_P$ than is currently available from the direct observations of helium in extragalactic H II regions.

The Planck experiment will also have improved sensitivity to a direct detection of primordial helium $^{23}$. According to Hamann, Lesgourges, & Mangano $^{22}$ and Ichikawa, Sekiguchi, & Takahashi $^{23}$, the uncertainty in the CMB value of $Y_P$ will be reduced by a factor of $\sim 5 - 7$, from $\sigma(Y_P) \approx 0.075$ $^7$, to $\sigma(Y_P) \approx 0.011 - 0.014$. Although still large, this uncertainty should be small enough that truly primordial helium will be discovered at more than the $5\sigma$ confidence level.
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