Primordial Nucleosynthesis in the New Cosmology

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Big bang nucleosynthesis (BBN) and the cosmic microwave background (CMB) anisotropies independently predict the universal baryon density. Comparing their predictions will provide a fundamental test on cosmology. Using BBN and the CMB together, we will be able to constrain particle physics, and predict the primordial, light element abundances. These future analyses hinge on new experimental and observational data. New experimental data on nuclear cross sections will help reduce theoretical uncertainties in BBN’s predictions. New observations of light element abundances will further sharpen BBN’s probe of the baryon density. Observations from the MAP and PLANCK satellites will measure the fluctuations in the CMB to unprecedented accuracy, allowing the precise determination of the baryon density. When combined, this data will present us with the opportunity to perform precision cosmology.

1. Introduction

Big bang nucleosynthesis (BBN) theory predicts the abundances of the light elements, deuterium (D), helium (\(^3\)He and \(^4\)He), and lithium (\(^7\)Li) produced during the first three minutes after the big bang. Anisotropies detected in the cosmic microwave background (CMB) contain information about the universe at the time of last scattering, about 300,000 years after the big bang. Both of these pillars of cosmology, probing two different epochs in the early universe offer independent determinations of the cosmic baryon density. Comparing their results will provide a fundamental test of cosmology. There is tentative agreement between current observations of the CMB anisotropies and the light element abundances, and their respective baryon density determinations adding confidence to the cosmic “standard model” \cite{1, 2, 3}.

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\footnote{Note in press: with the new WMAP data, precision cosmology is at hand and the concordance between BBN and the CMB is tested in astro-ph/0302431}
2. BBN and the CMB

In standard BBN, primordial abundances are sensitive to only one parameter, the baryon-to-photon ratio, $n_B/n_\gamma \equiv \eta \propto \Omega_B h^2$. Light element observations are used to determine their primordial abundances [4, 5, 6]. These in turn, are convolved with BBN theory to determine the baryon density. The uncertainties in the theory lie entirely with the nuclear reaction cross sections that govern the formation of the light nuclei [1, 7].

Figure 1 shows the 95% confidence predictions of BBN theory. Combined with observational constraints, shown with dark boxes, they pick out an $\eta \sim 5.0 \times 10^{-10}$. Current CMB measurements by DASI and BOOMERANG [8] tentatively agree with this baryon density, as shown by the vertical band.

With the advent of precision measurements of the anisotropies in the CMB by MAP and PLANCK, we are obliged to go out of our way to improve both theory and observations in order to make the best comparison between BBN and the CMB.

3. Data Needed

The reactions listed in Table 1 dominate the uncertainties in the light element abundance predictions from BBN. The uncertainties listed are from [1], see also [7] for different and complimentary methods. It is important to measure these key reactions to less than 4% so that BBN theory’s predictions are more precise, making BBN a sharper probe of nuclear and particle astrophysics [2, 9, 10].

Besides improving the nuclear reaction uncertainties, it is important to reduce the errors in the light element abundance observations. A large number of $^4$He and $^7$Li observations exist from extragalactic H\textsc{ii} regions and the atmospheres of population II stars in the Galactic halo, respectively. Both of these abundance determinations suffer from large systematic uncertainties. Improvements in theoretical models of these regions are needed.
to reduce these systematics, and possible new observational strategies should be attempted.

Deuterium however, consists of only a handful of observations. This small sample prevents us from analysing systematic uncertainties and exploring possible trends. Only with more observations in high-redshift damped Lyman-α systems will D be put on the same statistical footing as $^4$He and $^7$Li.

4. BBN with the CMB

With the direct comparison of the baryon densities derived from BBN and the CMB, we will fundamentally test the very framework cosmology is built upon. Assuming concordance is established we can use BBN and the CMB together to place stronger constraints on physics [1,2]. With the CMB baryon density, we can predict the light element abundances with high precision. Using the observations of light element abundances we can address their evolution in universe. We can test new particle physics (reviewed in [3]) and non-standard cosmology (e.g. dark radiation [10]). With new analyses of observational data determining the primordial light element abundances and updated nuclear cross section data, we will be able to perform precision cosmology.

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