HOW TO GET LESS HELIUM AND MORE NEUTRINOS FROM BBN

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We discuss BBN in the presence of a non-minimally coupled quintessence model. In some of these models, the gravitational constant and cosmic expansion rate are smaller than standard model predicts. The Helium abundance is then smaller, possibly resolve the marginal disagreement between theory and observation. Furthermore, the constraint on neutrino species may also be relaxed.

The predicted primordial $^4$He abundance $Y$ increases with the expansion rate of the Universe during the big bang nucleosynthesis (BBN). This has been used to put limits on the number of neutrinos, quintessence models, and other new physics.

At present, there are still large systematic errors in measurement of the primordial helium abundance. Oliver and Steigman obtained $Y = 0.234 \pm 0.003$ (stat.), while Izotov and Thuan obtained a higher value $Y = 0.244 \pm 0.002$ (stat.). Obviously these two data sets are statistically inconsistent with each. In this paper, I shall adopt a midway value of $Y_p = 0.239 \pm 0.005$, or, $0.229 < Y_p < 0.249$ at 95% C.L.

The helium abundance also depends on the baryon to photon ratio $\eta$. We can determine $\eta$ by either measuring deuterium abundance, or fit CMB data with varying cosmological parameters. Burles and Tytler found $D/H = (3.3 \pm 0.25) \times 10^{-5}$, the lower bound on $\eta$ at 2$\sigma$ level is $\eta_{10} \equiv 10^{10}\eta < 6.3$. On the other hand, a recent analysis of the CMB data yields $\Omega_b h^2 = 0.030 \pm 0.004$, or $\eta_{10} = 8.2 \pm 1.0$. If we assume that there are three neutrino species, and adopt $\eta \approx 4.5$ as inferred from the deuterium abundance, then the standard BBN $^4$He abundance is in disagreement with the result of Oliver and Steigman. It is in marginal agreement with our “midway” result, but still at the higher end. Even this “midway” limit is exceeded if the $\eta$ inferred from CMB is adopted (see Fig. 1).

Furthermore, in addition to the three standard model neutrinos, a sterile neutrino may be needed to explain the results from neutrino oscillation experiments. If either or both of these were confirmed, or if there are any other light particles in the Universe, the breach between theory and observation on $^4$He would become even wider.

Here, I show that with non-minimally coupled quintessence model, the pre-

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dicted helium abundance could be lowered, thus alleviate the breach between theory and observation. Alternatively, in such a model the cosmological bound on neutrino number is relaxed, making room for a possible fourth neutrino.

The action for the NMC model is given by

$$S = \int d^4x \sqrt{-g} \left[ \frac{1}{2} F(Q) R - \frac{1}{2} Q^\mu Q_{\mu} - V(Q) + L_{\text{fluid}} \right], \quad (1)$$

with $F(Q) = 1 - \xi (Q^2 - Q_0^2)$, where $Q_0$ is a constant, and $V(Q) = V_0 Q^{-\alpha}$. It is known that in this model the cosmic expansion accelerates at late time, consistent with the recent type Ia supernova measurement.

In this model, the expansion rate of the Universe is

$$H^2 = \frac{1}{3 F} \left( \rho_f + \frac{1}{2} \dot{Q}^2 + V(Q) - 3 H \dot{F} \right), \quad (2)$$

where $\rho_f = \rho_m + \rho_r$ is the density contribution from matter and radiation (including neutrino). The change in expansion rate could be parametrized by a speed-up factor $\zeta$:

$$\zeta \equiv \frac{H}{\bar{H}} \approx \xi (Q^2 - Q_0^2). \quad (3)$$

Figure 1: The Helium abundance as a function of $\eta_{10}$. The Solid curve shows standard BBN result with three neutrinos, the two short-dashed curves denotes the cases of two and four neutrinos respectively, and the long-dashed curve is the result of the NMC model discussed in text. The three horizontal lines shows the center value and $2\sigma$ bound on observed helium abundance ("mixed result"), while the three vertical lines indicate the center value and $2\sigma$ bounds on $\eta$ from CMB.

The effect of a constant speed up factor on helium abundance has been investigated in the context of neutrino number limit. We have

$$Y = (0.2378 + 0.0073 \ln \eta_{10})(1 - 0.058/\eta_{10})$$
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$$+0.013\Delta N_\nu + 2 \times 10^{-4}(\tau - 887), \quad (4)$$

the speed up factor is related to neutrino number by

$$\zeta^2 = 1 + \frac{7}{43} \Delta N_\nu, \quad (5)$$

so we have

$$\Delta Y = 0.08(\zeta^2 - 1) \approx 0.16(\zeta - 1). \quad (6)$$

Thus, for example, in a model with $\alpha = 10, \xi = 0.004$, we find $\zeta - 1 \approx -0.06, \Delta Y \approx -0.96\%$. In terms of neutrino number, this corresponds to a reduction of $\Delta N_\nu \approx 0.74$.

The coupling constant $\xi$ is limited by solar system experiment. For a model with $\alpha = 10, \xi = 0.004$, which is within solar system limit, $\xi < 0.022Q_0^{-1}$, the helium abundance is reduced by 0.96%. If there is indeed a breach between the observed helium abundance and the standard BBN theory as indicated by Olive and Steigman, it could be explained by this NMC model. Alternatively, such a shift in $Y$ corresponds to a shift in neutrino number $\Delta N_\nu = -0.74$. The current cosmological limit on neutrino number is $1.7 < N_\nu < 4.3$ at 95% C.L., for the model described above, the upper limit would be relaxed to 5.0, making sufficient room for a non-standard model neutrino.

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References

1. K. A. Olive and G. Steigman, Astrophys. J. Supp. 97, 49 (1995).
2. Y. I. Izotov and T. X. Thuan, Astrophys. J. 500, 188 (1998).
3. S. Burles and D. Tytler, Astrophys. J. 499, 699 (1998); Astrophys. J. 507, 732 (1998).
4. A. H. Jaffe et al., astro-ph/0007333.
5. For a recent review, see K. Scholberg’s article in this volume and references therein.
6. J. P. Uzan, Phys. Rev. D 59, 123510 (1999); F. Perrotta, C. Baccigalupi, S. Matarrese, Phys. Rev. D 61, 023507 (1999).
7. C. Baccigalupi, F. Perrotta, S. Matarrese, astro-ph/0005543.
8. A. G. Riess et al., Astron. J. 116, 1109 (1998); P. M. Garnavich et al., Astrophys. J. 509, 74 (1998); S. Perlmutter et al., Astrophys. J. 517, 565 (1999).
9. D. E. Groom et al. (PDG), Euro. Phys. J. C15, 1 (2000).