Primordial Nucleosynthesis, Cosmic Microwave Background and Neutrinos

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We report the results of a recent likelihood analysis combining the primordial nucleosynthesis and the BOOMERanG and MAXIMA-1 data on cosmic microwave background radiation anisotropies. We discuss the possible implications for relic neutrino background of a high value for the baryonic matter content of the universe, larger than what is expected in a standard nucleosynthesis scenario.

In this contribution we report on a combined analysis of the dependence of CMBR anisotropies and BBN on the energy fractions $\Omega_B h^2$ and $\Omega_\nu h^2 = N_\nu \Omega_\nu^0 h^2$ for *massless* neutrinos (N_ν standing for the effective neutrino number and $\Omega_\nu^0 h^2$ for the energy contribution of a single $\nu - \overline{\nu}$ specie). This is aimed to test the standard and degenerate BBN scenario, using the recent results of the BOOMERanG [1] and MAXIMA-1 [2] CMBR experiments and the measurements of ^4He, D and ^7Li primordial abundances.

The theoretical tools necessary to achieve this goal are nowadays rather robust. A new generation of BBN codes have been developed [3–5], which give the ^4He mass fraction Y_p with a theoretical error of few per mille, this effort being justified in view of the small statistical error which is now quoted in the Y_p measurements. On the other hand, the theoretical predictions on the CMBR anisotropies angular power spectrum have also recently reached a 1% level accuracy. An important new insight is represented by the recent results obtained by the BOOMERanG Collaboration [1]. For the first time, in fact, multifrequency maps of the microwave background anisotropies were realized over a significant part of the sky, with $\sim 10'$ resolution and high signal to noise ratio. In the last few years many results have been obtained on light element primordial abundances as well [6]. The ^4He mass fraction Y_p, has been measured with a 0.1% precision in two independent surveys, from regression to zero metallicity in Blue Compact Galaxies, giving a *low* value $Y_p^{(l)} = 0.234 \pm 0.003$, and a high one $Y_p^{(h)} = 0.244 \pm 0.002$, which are compatible at 2σ level only, may be due to large systematic errors. In our analysis [7] we adopted the more conservative value $Y_p = 0.238 \pm 0.005$. A similar controversy holds in D measurements, where observations in different Quasars Absorption line Systems (QAS) lead to the incompatible results $Y_D^{(l)} = (3.4 \pm 0.3)\, 10^{-5}$, and $Y_D^{(h)} = (2.0 \pm 0.5)\, 10^{-4}$. We performed our analysis for both low and high D data. Finally, the most recent estimate for ^7Li primordial abundance, from the *Spite plateau* observed in the halo of POP II stars, gives $Y_{^7Li} = (1.73 \pm 0.21)\, 10^{-10}$. The light nuclide yields strongly depend on the baryon matter content of the universe, $\Omega_B h^2$. In particular, assuming a standard BBN scenario, i.e. vanishing neutrino chemical potentials, the likelihood analysis gives, at 95% C.L. [4],

$$\begin{array}{lll} \text{low D} & \Omega_B h^2 = .017 \pm .003 & 1.7 \leq N_\nu \leq 3.3, \\ \text{high D} & \Omega_B h^2 = .007^{+.007}_{-.002} & 2.3 \leq N_\nu \leq 4.4. \end{array} \quad (1)$$

Regarding CMBR data, the anisotropy power spectrum, C_ℓ, was measured in a wide range of angular scales from multipole $\ell \sim 50$ up to $\ell \sim 600$, with error bars of the order of 10%, showing a peak at $\ell_{peak} = (197 \pm 6)$ with an amplitude $DT_{200} = (69 \pm 8) \mu K$. While the presence of such peak, compatible with inflationary scenario, was already suggested by previous measurements [8], the absence of secondary peaks after $\ell \geq 300$ with a flat spectrum with an amplitude of $\sim 40 \mu K$ up to $\ell \sim 625$ was a new and unexpected result. This result obtained then an impressive confirmation by the MAXIMA-1 [2] experiment up to $\ell \sim 800$.

As already pointed out [9], the values in Eq. (1) for $\Omega_B h^2$, though in the correct order of magnitude, are however somehow smaller than the baryon fraction which more easily fit the CMBR data. In fact, the lack of observation of a secondary peak in the anisotropy power spectrum at small scales may be a signal in favour of a larger $\Omega_B h^2 \sim 0.03$, since increasing the baryon fraction enhances the odd peaks only.

It has been stressed [4] that a simple way to improve the agreement of observed nuclide abundances with $\Omega_B h^2 \geq 0.02$ is to assume non vanishing neutrino chemical potentials at the BBN epoch, a scenario already extensively studied in the past [10]. The effect of neutrino chemical potentials μ_α, with α the neutrino specie, is twofold. A non-vanishing $\xi_\alpha = \mu_{\nu_\alpha}/T_\nu$, contribute to N_ν implying a larger expansion rate of the universe with respect to the non-degenerate scenario, and a higher value for the neutron to proton density ratio at the freeze-out. Furthermore, a positive value for ξ_e means a larger number of ν_e with respect to $\bar{\nu}_e$, thus enhancing $n \to p$ processes.

Increasing N_ν also weakly affects the CMBR anisotropy spectrum in two ways. The growth of perturbations inside the horizon is in fact lowered, resulting in a decay of the gravitational potential and hence in an increase of the anisotropy near the first peak. Moreover, the size of horizon and sound horizon at the last scattering surface is changed, and this, with additional effects in the damping, varies the amplitude and position of the other peaks.

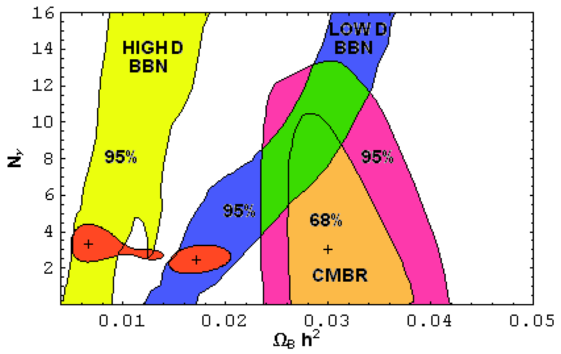

Figure 1. The 95% C.L. contours in the $\Omega_B h^2 - N_\nu$ plane compatible with degenerate BBN (large bands) and standard BBN (small regions) are plotted for both high D (left) and low D (right). The same contours for 68% and 95% C.L. from BOOMERanG and MAXIMA-1 CMBR data are also reported.

To test the degenerate BBN scenario we performed a likelihood analysis of the data. First, to constrain the values of the parameter set (ξ_e, N_ν, $\Omega_B h^2$) from the data on ^4He, D and ^7Li we define a *total likelihood function*, $\mathcal{L}_{Nucl}(N_\nu, \Omega_B h^2, \xi_e)$ [4,7]. Since the effect of a positive ξ_e can be compensated by larger N_ν, we have chosen to constrain this parameter to be $N_\nu < 16$, well outside the 95% upper limit on N_ν from the BOOMERanG and MAXIMA-1 data (see below). The other two parameters are chosen in the following ranges, $-1 \leq \xi_e \leq 1$ and $0.004 \leq \Omega_B h^2 \leq 0.110$.

In the figure we summarize the main result of our analysis. In the $\Omega_B h^2 - N_\nu$ plane we show the 95% C.L. likelihood regions for both the high and low D measurements, as well as the analogous contours for standard BBN, obtained running our code with $\xi_e = 0$. In the same plot we show the 68 and 95 % C.L. regions obtained by CMBR data.

We observe that the standard BBN, $\xi_e = 0$, and CMBR data analysis lead to quite different values for $\Omega_B h^2$. This can be clearly seen from the reported 95% results, but we have verified that the 99% C.L. contour for high D has no overlap with the region picked up by BOOMERanG and MAXIMA-1 data, and a very marginal one for low D.

For the degenerate scenario, increasing N_ν, the allowed intervals for $\Omega_B h^2$ shift towards larger values. However the high D values require a baryon content of the universe energy density which is still too low, $\Omega_B h^2 \leq 0.018$, to be in agreement with CMBR results. A large overlap is instead obtained for the low D case, whose preferred $\Omega_B h^2$ span the range $0.012 \leq \Omega_B h^2 \leq 0.036$. As expected, a larger N_ν helps in improving the agreement with the high CMBR $\Omega_B h^2$ value, but is important to stress that a large value for N_ν is not preferred by the CMBR data alone, being, in this case, the best fit $N_\nu \sim 3$. If we only consider the 95% overlap region we get the following conservative bounds[1]:

$$4 \leq N_\nu \leq 13 \quad , \qquad 0.024 \leq \Omega_B h^2 \leq 0.034. \quad (2)$$

In this region ξ_e varies in the range $0.07 \leq \xi_e \leq 0.43$. As we said, values $N_\nu \geq 3$, as suggested from our analysis, can be either due to weak interacting neutrino degeneracy, or rather to other unknown relativistic degrees of freedom.

REFERENCES

1. P. de Bernardis et al. (Boomerang Coll.), *Nature* **404** 955 (2000).
2. S. Hanany et al. (Maxima Coll.), *Astrophys. J.*, *submitted*, (2000).
3. S. Esposito, G. Mangano, G. Miele, and O. Pisanti, *Nucl. Phys.* **B540** 3 (1999); S. Esposito, G. Mangano, G. Miele, and O. Pisanti, *Nucl. Phys.* **B568** 421 (2000).
4. S. Esposito, G. Mangano, G. Miele, and O. Pisanti, *JHEP* **0009** 038 (2000).
5. R.E. Lopez and M.S. Turner, *Phys. Rev.* **D59** 103502 (1999).
6. K.A. Olive and G. Steigman, *Astrophys. J. Suppl.*, **97** 49 (1995), and references therein; Y.I. Izotov and T.X. Thuan, *Astrophys. J.*, **500** 188 (1998); S. Burles and D. Tytler, *Astrophys. J.*, **499** 689 (1998); J.K. Webb, R.F. Carswell, K.M. Lanzetta, R. Ferlet, M. Lemoine, A. Vidal-Madjar, and D.V. Bowen, *Nature*, **388** 250 (1997); P. Bonifacio and P. Molaro, *Mon. Not. Roy. Astron. Soc.*, **285** 847 (1997).
7. S. Esposito, G. Mangano, A. Melchiorri, G. Miele, and O. Pisanti, astro-ph/0007419.
8. P. D. Mauskopf et al, *Astrophys. J.*, **L59** 536, (2000); A. D. Miller et al., *Astrophys. J.*, **L1** 524, (1999).
9. J. Lesgourgues and M. Peloso, astro-ph/0004412.
10. H. Kang and G. Steigman, *Nucl. Phys.*, **B372** 494 (1992).
11. S. Hannestad, *Phys. Rev. Lett.*, **85**, 4203 (2000).

[1]The result $N_\nu \leq 13$ has also been obtained in [11] using BOOMERanG data only.