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A Degenerate Big Bang Nucleosynthesis from CMB observations ?

S. Esposito, G. Mangano[1], A. Melchiorri[2,3], G. Miele[1], O. Pisanti[1]

[a]Dipartimento di Scienze Fisiche, Universitá "Federico II", Napoli, and INFN Sezione di Napoli, Italy.
[2] Dipartimento di Fisica, Universitá "La Sapienza", Roma, Italy.

We report the results of a likelihood analysis combining the primordial nucleosynthesis and Cosmic Microwave Background Anisotropies experiments. We discuss both the standard and degenerate BBN scenarios.

The four parameters Ω_B, Ω_{CDM}, Ω_ν and Ω_Λ, giving, respectively, the baryon, cold dark matter, neutrino and cosmological constant contributions to the total energy density, in unit of the critical density, and the Hubble constant, $H_0 = 100h\ Km\ s^{-1} Mpc^{-1}$, enter as crucial parameters in several cosmological observables.

An increasing interest has been devoted to many issues as Big Bang Nucleosynthesis (BBN), structure formation and the anisotropy of the Cosmic Microwave Background Radiation (CMBR). As for our theoretical understanding of the BBN, to test the theoretical models which describe these aspects of the hot Big Bang model, it is essential to have precise measurements of the several $\Omega_i h^2$. Furthermore, combining different cosmological observables, and comparing the way they are able to constrain the $\Omega_i h^2$, allows for a check of the consistency of our present understanding of the evolution of the universe. This can provide new hints on phenomena which took place at the macroscopic cosmological level, or rather related with the very microscopic structure of fundamental interactions.

This work represents a contribution in this direction. In particular, we do perform a combined analysis of the dependence 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) of CMBR anisotropies and BBN. 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 [3–7]. Concerning the CMBR experimental data, after the COBE satellite first detection of CMBR anisotropies, at scales larger than 5^o, and more than 20 independent detections at different frequencies and scales, see e.g. [8], 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. 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 [9], 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 far as BBN is concerned, in the last few years many results have been also obtained on light element primordial abundances. 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 $Y_p^{(l)} = 0.234 \pm 0.003$ [10], and a high one $Y_p^{(h)} = 0.244 \pm 0.002$ [11], which are compatible at 2σ level only, may be due to large sys-

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tematic errors. As in [4], in our analysis we adopt the more conservative value $Y_p = 0.238\pm0.005$. A similar controversy holds in D measurements, where observations in different Quasars Absorption line Systems (QAS) lead to the incompatible results $Y_D^{(l)} = (3.4\pm0.3)\,10^{-5}$ [12], and $Y_D^{(h)} = (2.0\pm0.5)\,10^{-4}$ [13]. We will perform 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 $Y_{^7Li} = (1.73\pm0.21)\,10^{-10}$ [14]. The light nuclide yields strongly depend on the baryon matter content of the universe, $\Omega_B h^2$. High values for this parameter result in a larger ^4He mass fraction and a lower deuterium number density. In particular, assuming a standard BBN scenario, i.e. vanishing neutrino chemical potentials, the likelihood analysis gives, at 95% C.L. [4],

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

As already pointed out by several authors [15–17], these values 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, as mentioned, while the narrow first peak around $l \sim 200$ is a confirmation of the inflationary paradigma, a flat universe with adiabatic perturbations, the lack of observation of a secondary peak at smaller scales raises new intriguing questions about the values of the cosmological parameters. In particular, this result 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. In this respect the measurement of the third peak at larger multipole moments is extremely important. Though it is fair to say that a further analysis of the BOOMERanG and MAXIMA-1 data, as well as new data from future experiment, are needed to clarify this issue, it is however timely to study how our theoretical understanding of BBN can be reconciled with the larger values of $\Omega_B h^2$ suggested by CMBR data.

It has already been stressed [17,4] 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 [18]. 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 as

$$N_\nu = 3 + \Sigma_\alpha \left[\frac{30}{7}\left(\frac{\xi_\alpha}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi_\alpha}{\pi}\right)^4 \right] \quad , \qquad (2)$$

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 (negative) value for ξ_e means a larger (smaller) number of ν_e with respect to $\bar{\nu}_e$, thus enhancing (lowering) $n \to p$ processes.

To test the degenerate BBN scenario we have 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*,

$$\mathcal{L}_{Nucl}(N_\nu, \Omega_B h^2, \xi_e) = L_D \; L_{^4He} \; L_{^7Li} \quad , \qquad (3)$$

as described in Ref.[4]. For a fully degenerate BBN, since the effect of a positive ξ_e can be compensated by larger N_ν, $\mathcal{L}_{Nucl}(N_\nu, \Omega_B h^2, \xi_e)$ may sensibly differ from zero in a region with rather large values of N_ν. We have chosen to constrain this parameter to be $N_\nu < 16$. This upper limit has been considered after checking that it is well outside the 95% upper limit on N_ν from the BOOMERanG and MAXIMA-1 data (again, see below). The other two parameters are chosen in the following ranges, $-1 \leq \xi_e \leq 1$ and $0.004 \leq \Omega_B h^2 \leq 0.110$.

Since CMBR spectrum is not sensible to ξ_e alone, we have marginalized over ξ_e. All nuclide abundances have been evaluated using the new BBN code described in [4], while the theoretical uncertainties $\sigma_i^{th\,2}(N_\nu, \Omega_B h^2)$ are found by linear propagation of the errors affecting the various nuclear rates entering in the nucleosynthesis reaction network [6].

The CMBR data analysis methods have been already extensively described in various papers [15]. Our database of models is sampled in *physical variables* as in [15], but we only consider flat models, $h = 0.65\pm0.2$ and the effective number of neutrinos is allowed to vary up to $N_\nu = 20$. Following [22] we can therefore constrain the parameter of interest, $\Omega_B h^2$ and N_ν, by finding the remaining "nuisance" parameters which maximize them. As mentioned, at 95 and 99% C.L. we found $N_\nu \leq 13$ and $N_\nu \leq 16$, respectively. A similar bound, using BOOMERanG data only, has been obtained in [23].

In the figure we have summarized 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.

As a first comment, 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:

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

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.

In conclusion, we have shown how a precision analysis of BBN and CMBR data is able to tell us about possible new features of the cosmological model describing the evolution of the universe. We have quantitatively discussed how larger values for the baryonic matter content $\Omega_B h^2$ may be reconciled with BBN predictions in a degenerate scenario. In this respect the observed low value of deuterium more easily fits with the constraints given by BOOMERanG and MAXIMA-1 data. The crucial aspect of our analysis is that this agreement is realized with an effective neutrino degrees of freedom larger than 4 at 95%. This represents an indication in favour of a degenerate neutrino background and/or new particle species contributing to relativistic matter in the universe. As final remark, we should note that our CMB analysis was restricted on a specific class of models with a limited numbers of parameters.

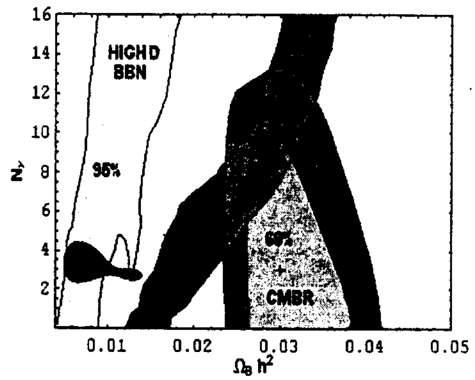

Figure 1. The 95% C.L. contours in the $\Omega_B h^2 - N_\nu$ plane compatible with degenerate BBN (large bands) and standard BBN (small regions) are plotted for both high D (left) and low D (right). The same contours for 68% and 95% C.L. from BOOMERanG and MAXIMA-1 CMBR data are also reported.

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