Remarks on the Boomerang results, the baryon density and the leptonic asymmetry

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The very recent Boomerang results give an estimate of unprecedented precision of the Cosmic Microwave Background anisotropies on sub-degree scales. A puzzling feature for theoretical cosmology is the low amplitude of the second acoustic peak. Through a qualitative discussion, we argue that a scarcely considered category of flat models, with a leptonic asymmetry, a high baryon density and a low cosmological constant seems to be in very good agreement with the data, while still being compatible with big bang nucleosynthesis and some other observational constraints. Although this is certainly not the only way to explain the data, we believe that these models deserve to be included in forthcoming likelihood analyses.

I. INTRODUCTION

The measurement of Cosmic Microwave Background (CMB) anisotropies has been driving the attention of cosmologists over the past decade. Very recently, De Bernardis et al. [1] published the first results of the Boomerang balloon Antarctic flight. With these data, the (recent) story of precision cosmology climbs a new step. For the first time, the anisotropy power spectrum has been measured by a single experiment in a wide range of angular scales, from multipoles \( l \approx 50 \) up to \( l \approx 600 \), with many independent points, and error bars of order \( \pm 20\% \). The observation of a narrow peak, centered around multipoles \( l \approx 200 \), confirms the inflationary picture of an approximately flat Universe with adiabatic fluctuations.

This beautiful result was already suggested by previous CMB experiments (see [2] for a recent review). On the other hand, the Boomerang anisotropy spectrum exhibits a puzzling behavior on small scales (high multipoles): in the range in which a pronounced secondary peak was expected, the data points are rather low, with an almost flat shape. It seems that the cosmological model most favored during the past year, which is a flat Cold Dark Matter (CDM) model with a large cosmological constant and “standard” parameter values (see below), can hardly account for this feature, unless some new ingredient is added.

After this paper was submitted, a detailed analysis of the data by the Boomerang team was released in ref. [3], followed by another work [4] including also the new MAXIMA data [5]. We refer the reader to these works for a more exhaustive interpretation of this puzzling small–scale behavior. In the following discussion, we just intend to point out that a particular category of models, which are scarcely taken into account, seem to be in remarkable agreement with the new published data (as can be seen from Fig.1). We therefore believe that they deserve some attention, and should be included in future data analyses.

While this discussion was being completed, a nice paper by White et al. [6] was put on the preprint database, suggesting many possible explanations of the data, including a large baryon density \( \Omega_b \). The key point of this rapid communication is to recall that a large \( \Omega_b \) is still in agreement with the observed light element abundances, provided that a large neutrino asymmetry is also present [7]. With these two ingredients (large \( \Omega_b \) and neutrino asymmetry) the Boomerang data can be nicely fitted in a flat Universe context, especially with a low value of the cosmological constant. Interestingly, this class of models can satisfy some other cosmological requirements, such as the ones coming from the matter power spectrum and from the baryon fraction in clusters.

II. FLAT \( \Lambda \)CDM MODELS AND BOOMERANG DATA

As a starting point, we plot on Fig.1 (solid line) a \( \Lambda \)CDM model with the parameters which were recently the most favored: \( (\Omega_{\text{tot}}, \Omega_b, h^2\Omega_b, h, n) = (1, 0.70, 0.019, 0.68, 1) \), with no tensors and reionization neglected (\( h \) is the Hubble constant in units of \( 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( n \) stands for the scalar primordial spectrum tilt). This set is in agreement with standard BBN [8], supernovae [9], clusters [10], direct measurements of \( h \) [11], constraints on the matter power spectrum [12], and other observations. However, as we can see from Fig.1, once the Boomerang data are taken into account, the first and second peaks do not have the right shape and location. The problem is not so much with the overall amplitude of the peaks, which can be affected by

\[ * \] In addition, the possibility of explaining the data with a high \( \Omega_b \) was confirmed contemporaneously [13] and soon after [14] the release of this work.
calibration uncertainties, and which can be adjusted by changing the scalar tilt, the reionization optical depth \( \tau \) and the tensor amount. Most difficult is to accomplish the location, relative amplitude and shape of the peaks, which depend only slightly on the previous parameters. Rather, we must tune other parameters in order to shift the peaks to the left (smaller multipoles), and flatten the second peak. So, if we remain in the framework of a flat \( \Lambda \)CDM model with power-law primordial spectrum, the only way to get closer to the experimental data is by changing \( h^2 \Omega_b, \Omega_\Lambda \) or \( h \).

For instance, by lowering \( h^2 \Omega_b \), we could shift the peaks to the left. But a low baryon density would enhance even peaks with respect to odd ones. Clearly, this is not favored by the data: the large ratio between the first and second peak amplitude rather suggests a large baryon fraction. It seems that there are not many solutions to this interesting and new situation (at least if we avoid introducing a positive curvature or some “exotic” cosmological parameters): it is necessary, first, to decrease \( \Omega_\Lambda \) and/or increase \( h \) in order to have the first peak on the right scale, and, second, to take a high baryon density \( h^2 \Omega_b \), in order to suppress the second peak amplitude with respect to the first one. Then, the remaining parameters (scalar tilt, overall normalization, tensor amount, reionization) can enter into the game in order to adjust the overall peak amplitude with respect to the Sachs–Wolfe plateau (only in this last stage the uncertainty on Boomerang calibration and on COBE normalization play a role).

So, the Boomerang result is so characteristic (with its low and flat second peak) that even without a precise likelihood analysis, a quick glance brings evidence for a large baryon density \( h^2 \Omega_b > 0.02 \), together with \( h > 0.7 \) and/or \( \Omega_\Lambda < 0.70 \) (again, in the framework of flat \( \Lambda \)CDM models). It is intriguing that previous precise analyses of CMB data, which did not include the new Boomerang results and the related information concerning the shape of the secondary peak, also favored a high baryon density and a low cosmological constant \( \Omega_\Lambda \). After this communication was put on the database, the quantitative analyses based on Boomerang [3] and Boomerang + Maxima [4] results also pointed towards a high baryon density.

### III. INCLUDING BBN CONSTRAINTS

The large baryon density suggested by the previous analysis conflicts current estimates from standard BBN, which indicate \( h^2 \Omega_b \approx 0.019 \), with an error bar varying between \( \pm 0.001 \) and \( \pm 0.004 \) in the recent literature [3][4].

As pointed out by Kang and Steigman in 92 [3], a high value for \( h^2 \Omega_b \) can still lead to the observed light element abundances, provided there is a large asymmetry between neutrinos and antineutrinos in the primordial plasma (degenerate neutrinos).\(^1\) One of the main effects of this asymmetry is to enhance the relativistic energy density, usually parametrized by the number \( N_{\text{eff}} \) of effective relativistic neutrino families, with a consequent increase of the expansion rate of the Universe. If \( \mu_i \) and \( T_i \) denote, respectively, the chemical potential and the temperature of the \( i \)-th neutrino family (\( i = e, \mu, \tau \)), this effective number is linked to the degeneracy parameters \( \xi_i = \mu_i/T_i \) by:

\[
N_{\text{eff}} = 3 + \sum_i \left[ \frac{15}{7} \left( \frac{\xi_i}{\pi} \right)^4 + \frac{30}{7} \left( \frac{\xi_i}{\pi} \right)^2 \right].
\]

For what concerns BBN, \( N_{\text{eff}} > 3 \) leads to a higher neutron to proton ratio, since \( n, p \) decouple earlier from the primordial plasma. On the contrary, the presence of a positive asymmetry for the electronic neutrinos (\( \xi_e > 0 \)) tends to reduce this ratio, since it “shifts towards the proton direction” the reaction \( n \nu_e \leftrightarrow p e^- \) (and the crossed ones). The two effects can compensate each other in a wide region in the \( (\xi_e, \xi_\mu, \xi_\tau) \) parameter space, and the observed abundances of light elements can be achieved with a value of \( h^2 \Omega_b \) significantly higher than the bound coming from standard BBN (\( \xi_e = 0 \)).

For a quantitative analysis, one can apply the results of [3], which associate to any given value of the baryon density a region in the \( (\xi_e, \xi_\mu, \xi_\tau) \) plane where primordial nucleosynthesis is successful. In this work, the lower and upper bounds on \( N_{\text{eff}} \) come, respectively, from the requirement that \( ^7\text{Li} \) is not too abundant (\( ^7\text{Li}/\text{H} \geq 3 \cdot 10^{-5} \)) and that enough deuterium is produced (actually \( (\text{D} + ^3\text{He})/\text{H} \leq 10^{-4} \)). The most stringent limits on \( \xi_e \) come instead from the observed \( ^4\text{He} \) abundance (in [3] the helium–4 mass fraction \( Y \) is assumed to be in the conservative range \( 0.21 - 0.25 \)). While more recent observations put more severe bounds on this last quantity, the above estimates on lithium–7 and deuterium abundances are in good agreement with the latest ones (see for example [5] for a review). As a consequence, the allowed region in \( (h^2 \Omega_b, N_{\text{eff}}) \) given by [3] remains in good agreement with recent data (see also [6] for an updated analysis).

Cosmological implications of “degenerate BBN” have been the object of several recent studies. The importance

\(^1\)BBN bounds the number of baryon minus antibaryons to be very small with respect to the number of photons. Since the Universe appears to be electrically neutral, an asymmetry on the charged leptons is equally bounded to be vanishingly small. However, the possibility of a large asymmetry in the neutrino sector cannot be excluded. From a particle physics point of view, a large lepton asymmetry can be generated by an Affleck–Dine mechanism [13] without producing a large baryon asymmetry (see refs. [14]), or even by active–sterile neutrino oscillations [15]. In general, the asymmetry is different for each neutrino family.
of a large leptonic asymmetry for the formation of large–
scale structure (resp. CMB anisotropies) was pointed out
by [12] (resp. [13]), but the first comparison of ΛCDM
models with both CMB and large–scale structure data
was performed in [21]. Another question was addressed
by Kinney and Riotto [22], who calculated the sensitivity
of forthcoming CMB satellites to the neutrino degeneracy
parameter. The analysis was extended to the degenerate
nuineutrino mass in [12]. We should also stress that ref.
[24] proposed a lepton asymmetry for generating ultra–
high energy cosmic rays beyond the Greisen–Zatsepin–
Kuzmin cut–off.

In ref. [21], a ΛCDM model with large leptonic asymmetry
was compared with the CMB data available at that
time, plus a few constraints from large–scale structure,
the most restrictive being the matter power spec-
trum normalization to σ8 (the variance of mass fluctua-
tions in a sphere of radius R = 8h−1Mpc). The effect
of massless degenerate neutrinos is mainly to postpone
the time of equality, therefore boosting the first acous-
tic peak, shifting the peaks to higher multipoles, and
suppressing small–scale matter fluctuations. It can be
completely modeled with the effective neutrino number
Neff introduced above, in contrast with the case of mas-
dge degenerate neutrinos (for which simple modifications
to CMBFAST [23] must be performed). It was shown in
[21] that high values of the cosmological constant (such as
ΩΛ ≥ 0.80) are hardly compatible with Neff > 3, while for
ΩΛ ≤ 0.70 there are some allowed windows in the space
of cosmological parameters, ranging up to very large ef-
effective neutrino numbers. An interesting point is that in
refs. [20, 21], even with ΩΛ = 0, an agreement was found
with both CMB and large–scale structure constraints.

It is amazing that Boomerang data seems precisely to favor,
as one of the simplest possibilities, a high baryon
density combined with a low cosmological constant.
The high baryon density requires a leptonic asymmetry in or-
der to be compatible with the observed light elements
abundances (unless systematic errors have been under-
estimated in all recent analyses), and following ref. [21],
this large asymmetry is allowed precisely in presence of
a low cosmological constant. In Fig.1 we provide some
examples of such models (dashed and dotted lines).

IV. COMPATIBILITY WITH LARGE–SCALE
STRUCTURE AND OTHER CONSTRAINTS

There are several independent observations which sug-
gest the presence of a non–vanishing cosmological con-
stant. Very recently, supernovae data [11] motivated sev-
eral works in this direction. Also, indications for Ωm < 1
(and thus ΩΛ > 0 if the Universe is assumed to be flat)
are provided, for example, by the study of matter abun-
dance (baryons + cold dark matter) in clusters, by the
limits on the age of the Universe, or by constraints on
the matter power spectrum (see [24] for a recent review).
It seems to be particularly convincing that most of these
observations favor a common result Ωm ∼ 0.2–0.3. How-
ever, at present, none of them can be said to be conclusive
if considered separately from the others. Before firmly re-
lying on ΩΛ ≥ 0.7, it is thus legitimate to investigate if
some of the arguments listed above can be evaded. For
example, the model considered in the previous section,
with Ωm > 0.3, large h2Ωb and neutrino degeneracy,
is not excluded by constraints on the observed matter
power spectrum and on the fraction of baryonic mass in
clusters, which is one of the most robust arguments for a
low Ωm.

As far as the latter is concerned, the cosmological
baryon density can be constrained by the ratio of the baryonic mass to the total gravitational mass in clusters. Numerical simulations show that this ratio should be nearly equal (actually slightly lower) to the cosmological average. Thus one can evaluate the ratio in clusters (the baryon fraction in clusters can be deduced from X-ray emission, while the total matter can be extracted from the velocity dispersion curves) and gain a relation between the baryon and matter densities in the Universe. Tytler et al. report the following bound:

\[ h^2 \Omega_b \geq (0.025 - 0.060) h^{-3/2} \Omega_m, \]

where \( h_{70} \) is the Hubble constant in units of \( 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \). One usually assumes \( h^2 \Omega_b \) to be bounded by the values allowed by standard BBN. As a consequence, \( \Omega_m \) has to be smaller than one. However, the values for \( h^2 \Omega_b \) considered in the previous sections are compatible even with a Universe closed by matter alone.

Finally, ΛCDM models with a low (or vanishing) cosmological constant are known to be hardly compatible with large–scale structure data (what is also known as the “shape parameter” problem). Indeed, once the primordial spectrum has been normalized to COBE, there is an excess of power in small–scale matter fluctuation with respect to the bounds on \( \sigma_8 \). This issue cannot be solved by introducing a large red tilt (then, the shape of the power spectrum contradicts redshift surveys), neither with a large tensor amount (that would suppress the CMB acoustic peaks). On the other hand, it was shown in [21] that the neutrino degeneracy, by postponing matter domination and suppressing small–scale matter fluctuations, can reconcile CMB data with large–scale structure constraints, even for a zero cosmological constant (in other words, the “shape parameter” is consistent with current estimates). The proof was made for particular values of the cosmological parameters (\( h \), the tensor amount and the optical depth to reionization were not allowed to vary), but it indicates clearly that in a systematic analysis, agreement with COBE, Boomerang and other CMB data (including calibration uncertainties) is not exclusive from a correct shape and amplitude for the matter power spectrum.

V. CONCLUSIONS

In conclusion, we believe that models with a large neutrino asymmetry deserve to be included in forthcoming precise comparisons with experimental data. In practice, this amounts in including simultaneously higher values of \( N_{\text{eff}} \) and \( h^2 \Omega_b \) than the ones usually considered.

Since a high baryon density enhances odd peaks with respect to even ones, a natural outcome of these models is a large amplitude for the third peak. This will be probably the best way to test this scheme in a near future. If the third peak turns out to be also very low, the situation will be even more puzzling, and more complicated models (for instance, with a Broken–Scale–Invariant primordial spectrum or with topological defects) may have to enter into the game.

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