


Primordial nucleosynthesis constraints on high- z energy releases

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ABSTRACT

The cosmic microwave background (CMB) spectrum provides tight constraints on the thermal history of the universe up to $z \sim 2 \times 10^6$. At higher redshifts, thermalization processes become very efficient so that even large energy releases do not leave visible imprints in the CMB spectrum. In this paper, we show that the consistency between the accurate determinations of the specific entropy at primordial nucleosynthesis and at the electron–photon decoupling implies that no more than 7.8 per cent of the present-day CMB energy density could have been released in the post-nucleosynthesis era. As pointed out by previous studies, primordial nucleosynthesis complements model independent constraints provided by the CMB spectrum, extending them by two orders of magnitude in redshift.

Key words: cosmic background radiation – primordial nucleosynthesis – cosmology: theory.

1 INTRODUCTION

The spectrum of the cosmic microwave background (CMB) carries unique information/constraints on the thermal history of the universe since energy releases occurring over many redshift decades can leave their imprint on it (Zeldovich & Sunyaev 1969; Sunyaev & Zeldovich 1970; Illarionov & Sunyaev 1975; Danese & de Zotti 1977; Burigana, Danese & de Zotti 1991; Chluba, Khatri & Sunyaev 2012; Khatri & Sunyaev 2012; Chluba & Jeong 2014; Tashiro 2014; Chluba 2016; De Zotti et al. 2016; Chluba et al. 2019). However, at very high redshifts such imprints are erased by thermalization effects due to the combined action of photon emission processes and of Compton scattering. Small distortions are completely thermalized at $z > \text{few} \times 10^6$ (Danese & de Zotti 1982; Burigana et al. 1991; Hu & Silk 1993; Chluba 2014). The thermalization is less efficient for large distortions that can keep some visibility up to redshifts higher by factors of several (Chluba, Ravenni & Acharya 2020).

At still higher redshifts, releases of very large amount of energy could have occurred without leaving any visible track in the CMB spectrum. On the other hand, the outcomes of primordial nucleosynthesis (or big-bang nucleosynthesis, BBN) are sensitive to the radiation energy density. Indeed, just the consideration of the production of light elements in the early universe led to the prediction of the CMB (Gamow 1948; Alpher & Herman 1949).

The present-day accurate determinations of cosmological parameters entail strong constraints on the CMB energy density both at the BBN epoch and at electron–photon decoupling, hence on the additional amount of energy that could have been released after the BBN, at high enough redshifts to ensure a tight coupling between electrons and radiation. Such constraints are quantified in Section 2. Our conclusions are summarized in Section 3.

2 CONSTRAINTS ON THE RADIATION ENERGY DENSITY AT BBN

The results of BBN calculations can be presented as a function of the present-day dimensionless baryon-to-photon number density ratio $\eta = n_b/n_\gamma$ (Steigman 2007; Cyburt et al. 2016; Fields et al. 2020). The BBN redshift ($z_{\text{BBN}} \sim 3 \times 10^8$) is much higher than the CMB thermalization redshift even in the case of strong deviations from equilibrium (Chluba et al. 2020). Hence, the CMB photon number density is $n_{\gamma,\text{BBN}} = 20.28 T_{\text{BBN}}^3$ and the energy density is $\epsilon_{\gamma,\text{BBN}} = a T_{\text{BBN}}^4$, $a = 7.5657 \times 10^{-15} \text{ erg cm}^{-3} \text{ K}^{-4}$ being the black-body radiation density constant and T_{BBN} the CMB temperature at BBN.

The present-day baryon number density $n_{b,0}$ is related to the baryon density parameter $\omega_b = h^2 \Omega_b$ by

$$\omega_b = \frac{\langle m_b \rangle n_{b,0}}{h^{-2} \rho_{\text{crit},0}}, \quad (1)$$

where $h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_b = \rho_b/\rho_{\text{crit}} = 8\pi G \rho_b/3H_0^2$, G being the gravitational constant, and $\rho_b = \langle m_b \rangle n_b$. The mean mass per baryon is very well approximated by Fields et al. (2020) $\langle m_b \rangle = (1 + \delta)m_{\text{H}}$, where $\delta = -[1.744 + 7.119(Y - 0.245)] \times 10^{-3}$ accounts for the reduction of the mass due to helium binding; Y is the primordial helium mass fraction. Combining the above relations, we get (Fields et al. 2020)

$$\eta_{\text{BBN}} = \frac{273.754 \times 10^{-10}}{1 - 7.131 \times 10^{-3}(Y - 0.245)} \left(\frac{2.7255 \text{ K}}{T_{\text{BBN},0}} \right)^3 \omega_b, \quad (2)$$

where $T_{\text{BBN},0}$ is T_{BBN} redshifted to $z = 0$. Note that this expression does not contain the Hubble parameter and therefore is not affected by the current discrepancy between the value derived by *Planck* CMB anisotropy measurements (Planck Collaboration VI 2020) and the local value derived by Riess et al. (2019).

The excellent agreement between the values of η inferred from BBN and from CMB anisotropies (Fields et al. 2020; Planck Collab-

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oration VI 2020) implies a tight upper limit to the amount of energy that could have been released to the CMB after the nucleosynthesis epoch. Fields et al. (2020) found $\eta_{\text{BBN}} = (6.084 \pm 0.230) \times 10^{-10}$ and $\eta_{\text{CMB}} = (6.090 \pm 0.060) \times 10^{-10}$, allowing for variations of the number of neutrino species [$\eta_{\text{BBN}} = (6.143 \pm 0.190) \times 10^{-10}$ and $\eta_{\text{CMB}} = (6.104 \pm 0.058) \times 10^{-10}$ for three neutrino species]. The latest *Planck* best-fitting value of the baryon density for the TT+TE+EE+lowE+BAO data combination is $\omega_b = 0.02242 \pm 0.00014$ (table 2 of Planck Collaboration VI 2020).

We define $\delta\eta/\eta = (\eta_{\text{BBN}} - \eta_{\text{CMB}})/\eta_{\text{CMB}}$. Then, after equation (2) and the analogous equation at decoupling, the fractional difference, $\Delta\epsilon/\epsilon_\gamma$, between the photon energy density at decoupling ($\epsilon_{\gamma,\text{CMB}}$) and at BBN ($\epsilon_{\gamma,\text{BBN}}$), can be written as

$$\frac{\Delta\epsilon}{\epsilon_\gamma} \equiv \frac{\epsilon_{\gamma,\text{CMB}} - \epsilon_{\gamma,\text{BBN}}}{\epsilon_{\gamma,\text{CMB}}} \approx 1 - \left(\frac{\eta_{\text{CMB}}}{\eta_{\text{BBN}}}\right)^{4/3} \simeq \frac{4}{3} \frac{\delta\eta}{\eta}, \quad (3)$$

where we have assumed $(\Delta\epsilon/\epsilon_\gamma, \delta\eta/\eta) \ll 1$ and used the fact that $\epsilon_\gamma \propto n_\gamma^{4/3} \propto \eta^{-4/3}$.

$\Delta\epsilon/\epsilon_\gamma$ is consistent with zero with an rms uncertainty of

$$\sigma(\Delta\epsilon/\epsilon_\gamma) \simeq \frac{4}{3} [(\delta \ln \eta_{\text{BBN}})^2 + (\delta \ln \eta_{\text{CMB}})^2]^{1/2} \simeq 0.039, \quad (4)$$

so that the 95 per cent confidence upper limit to the fractional amount of energy density that could have been added to the CMB after the BBN is 0.078.

A different approach to derive model independent constraints on electromagnetic energy releases after primordial nucleosynthesis was adopted by Chluba et al. (2020). Their argument goes as follows. Deep in the radiation dominated era, but after the electron/positron annihilation, the expansion time-scale is controlled by the energy density of photons and neutrinos, $\rho = \rho_\gamma + \rho_\nu$. A difference, $\delta\rho$, between the value of ρ at BBN and its standard value, due to a subsequent energy injection, leads to a non-standard expansion rate, impacting on the primordial production of lig elements.

Such difference can be parametrized by a variation of the effective number of neutrino species, N_{eff} (Simha & Steigman 2008). For $\delta \ln(N_{\text{eff}}) \ll 1$, Chluba et al. (2020) found $|\delta\rho/\rho| \lesssim |0.2417\delta \ln(N_{\text{eff}})/(f_\nu - 0.4089)|$, where f_ν is the fraction of energy injected going into neutrinos. *Planck* measurements of the CMB anisotropy power spectra yielded $N_{\text{eff}} = 2.99 \pm 0.17$ (1 σ error). Using the 95 per cent confidence uncertainty, $\delta \ln(N_{\text{eff}}) = 0.112$, Chluba et al. (2020) found $\Delta\epsilon/\epsilon_\gamma \lesssim 0.11^1$ in the case of a release of pure electromagnetic energy ($f_\nu = 0$), and $\Delta\epsilon/\epsilon_\gamma \lesssim 0.25$ for $f_\nu = 0.5$, both limits being at the 95 per cent confidence level. Chluba et al. (2020) also point out that if $f_\nu \simeq 0.4089$ the energy release is unconstrained by measurements of N_{eff} .

A more precise calculation of constraints on $\Delta\epsilon/\epsilon_\gamma$ should take into account that they depend on the difference between the effective number of neutrino species derived from BBN (2.86 ± 0.15 ; Fields et al. 2020) and that derived from CMB anisotropies, referring to the much later decoupling epoch (Simha & Steigman 2008). The error on the $N_{\text{eff, BBN}} - N_{\text{eff, dec}}$ is a factor of 1.33 higher than the error on $N_{\text{eff, dec}}$ used by Chluba et al. (2020). This also implies that the future strengthening of the constraints on $\Delta\epsilon/\epsilon_\gamma$ depends on decreasing the uncertainty on N_{eff} at both epochs.

The 95 per cent confidence limit on $\Delta\epsilon/\epsilon_\gamma$ derived in this paper is illustrated by the black horizontal line in Fig. 1. Also shown, for

¹The value $\Delta\epsilon/\epsilon_\gamma \lesssim 0.077$ quoted in that paper is a misprint (Jens Chluba private communication).

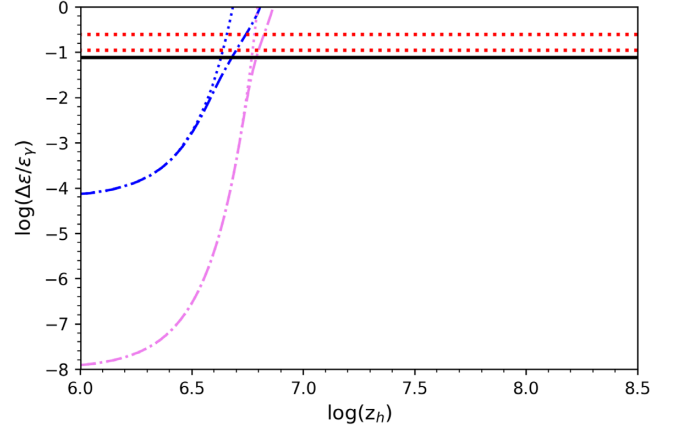


Figure 1. Upper limit (95 per cent confidence level) to the fractional amount of energy that could have been added to the CMB after the primordial nucleosynthesis epoch, derived in this paper (black horizontal line), compared with constraints derived by Chluba et al. (2020). The red dotted horizontal lines show the limits obtained from the effective number of neutrino species, assuming that a fraction f_ν of the total injected energy goes into neutrinos. The lower and upper lines refer to $f_\nu = 0$ and $f_\nu = 0.5$, respectively; note that the value for $f_\nu = 0$ has been corrected as mentioned in the text. Constraints from CMB spectral measurements, as computed by Chluba et al. (2020), are also shown. The upper (blue) and lower (pink) dot-dashed lines show the 95 per cent confidence upper limits implied by CMB spectral measurements from *COBE/FIRAS* ($\delta\epsilon/\epsilon_\gamma < 6 \times 10^{-5}$) and from a future *PIXIE*-like experiment ($\delta\epsilon/\epsilon_\gamma < 10^{-8}$), respectively. The dotted lines deviating from the dot-dashed lines at their right end, again from Chluba et al. (2020), show the corresponding limits obtained under the small-distortion approximation.

comparison, are the limits obtained by Chluba et al. (2020) from the uncertainty on N_{eff} , for two values of f_ν . The lines on the left part of the figure show the constraints implied by upper limits on μ -type distortions, again from Chluba et al. (2020).

At $z \lesssim 4-5 \times 10^6$ constraints from *COBE-FIRAS* supersede those from BBN. At higher redshifts, thermalization of additional energy injected into the CMB smooths out distortions, thus weakening or erasing constraints on the thermal history of the universe. Even releases of very large amounts of energy, $\Delta\epsilon/\epsilon_\gamma \sim 1$, occurring at $z \geq 6.5-7.5 \times 10^6$ would not leave imprints detectable by *COBE/FIRAS* (Fixsen 2009) or by a *PIXIE*-like experiment (Kogut & Fixsen 2020), orders of magnitude more sensitive.

3 CONCLUSIONS

The constraint from primordial nucleosynthesis, derived in this paper, implies that no more than 7.8 per cent of the present-day CMB energy density could have been released after primordial nucleosynthesis. Much stronger constraints are set by *COBE/FIRAS* measurements of the CMB spectrum, but these are limited to $z \lesssim 5 \times 10^6$ (Chluba et al. 2020), i.e. to redshifts about two orders of magnitude lower than the nucleosynthesis redshift.

Comparable constraints on post-BBN energy releases have been derived by Chluba et al. (2020) from measurements of the effective number of neutrino species. As pointed out by these authors, such constraints are affected by uncertainties on the fraction, f_ν , of energy going to neutrinos. They are weak for $f_\nu \approx 0.3-0.5$ and can be completely avoided for $f_\nu \approx 0.409$, a value close to the typical amount of energy carried by neutrinos in TeV scale dark matter annihilations.

Constraints on the contribution to N_{eff} by high-energy neutrinos from dark matter decay in the early universe have been obtained by Acharya & Khatri (2020).

Tighter constraints on early energy releases from specific processes have been inferred from measurements of the light element abundances. Examples are Hawking evaporation of primordial black holes (e.g. Keith et al. 2020) and decaying particles (e.g. Kawasaki et al. 2020). However, these constraints are somewhat model dependent as they rest on the details of hadronic and electromagnetic interactions involved. On the contrary, the limit presented here is general and model independent.

Above $z \sim 5 \times 10^6$ thermalization effects wash out spectral distortions induced by energy injections into the CMB. Planned next-generation experiments like PIXIE (Chluba et al. 2019; Kogut et al. 2019), PRISM (André et al. 2014), PRISTINE² or the microwave spectropolarimetry mission proposed by Delabrouille et al. (2019) will reach sensitivities orders of magnitude higher. However, the redshift range over which spectral distortions are visible will be only marginally extended.

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DATA AVAILABILITY

The research described in this letter does not make use of any data base. The data used are those available in the references cited when the data are introduced. The data generated are given in the text.

²<https://www.ias.u-psud.fr/en/content/pristine>

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