

Distant foreground and the *Planck*-derived Hubble constant

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ABSTRACT

It is possible to reduce the discrepancy between the local measurement of the cosmological parameter H_0 and the value derived from the *Planck* measurements of the cosmic microwave background (CMB) by considering contamination of the CMB by emission from some medium around distant extragalactic sources, such as extremely cold coarse-grain dust. Though being distant, such a medium would still be in the foreground with respect to the CMB, and, as any other foreground, it would alter the CMB power spectrum. This could contribute to the dispersion of CMB temperature fluctuations. By generating a few random samples of CMB with different dispersions, we have checked that the increased dispersion leads to a smaller estimated value of H_0 , the rest of the cosmological model parameters remaining fixed. This might explain the reduced value of the *Planck*-derived parameter H_0 with respect to the local measurements. The signature of the distant foreground in the CMB traced by supernovae (SNe) was previously reported by the authors of this paper – we found a correlation between the SN redshifts, z_{SN} , and CMB temperature fluctuations at the SNe locations, T_{SN} . Here we have used the slopes of the regression lines $T_{\text{SN}} / z_{\text{SN}}$ corresponding to different *Planck* wavebands in order to estimate the possible temperature of the distant extragalactic medium, which turns out to be very low, about 5 K. The most likely ingredient of this medium is coarse-grain (*grey*) dust, which is known to be almost undetectable, except for the effect of dimming remote extragalactic sources.

Key words: dust, extinction – intergalactic medium – cosmic background radiation – cosmological parameters.

1 INTRODUCTION

The first and consecutive releases of the *Planck* mission results revealed a statistically significant discrepancy between the cosmological parameter H_0 as calculated by using the *Planck* measurements of the cosmic microwave background (CMB) radiation within the standard Λ cold dark matter (Λ CDM) cosmological model, $H_0 = (67.37 \pm 0.54) \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Planck Collaboration VI 2018), and the values of this parameter obtained by using other methods – mostly from direct local measurements (see the review by Riess 2020). One of these local measurements is based on optical and infrared (IR) observations of Cepheid variable stars, with the recent calculation of H_0 based on this method being $H_0 = (73.48 \pm 1.66) \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Riess et al. 2018).

Both local and *Planck*-derived estimates of H_0 have passed a number of rigorous tests by considering many possible sources of systematic errors (Efstathiou 2014; Planck Collaboration LI 2017; Zhang et al. 2017; Feeney, Mortlock & Dalmaso 2018; Follin & Knox 2018), but the discrepancy still remains, which has resulted in active discussions in the literature. Most authors seek to explain this discrepancy by implicating either unknown systematic effects in the observations or by focusing primarily on the possibility of new physics beyond the standard cosmological model and/or beyond the standard model of particle physics.

Possible modifications of the Λ CDM model include a new kind of dark energy (Planck Collaboration XIV 2016d; Guo, Zhang & Zhang 2019) or an increase of the number of parameters in this model – for example, from 6 to 12, as was proposed by Di Valentino, Melchiorri & Silk (2016). There are many other exotic proposals, like decaying dark matter, dark radiation, modified gravity, etc., most of which are based on some departure from basic cosmological principles.

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On the particle physics side, there are advocates for the existence of new relativistic particle species, such as hypothetical sterile neutrinos (Dvorkin et al. 2014; Wyman et al. 2014; Sakstein & Trodden 2019), which could lead to a smaller expansion rate at early times and, thus, explain the H_0 discrepancy. But this is at the expense of departing from the standard model of particle physics.

It is worthwhile mentioning that the baryon acoustic oscillation probe based on galaxy surveys combined with big bang nucleosynthesis data gives an independent estimate of $H_0 = 68.3^{+1.1}_{-1.2}$ km s⁻¹ Mpc⁻¹ (Schöneberg, Lesgourgue & Hooper 2019), which is close to the *Planck*-derived H_0 value. These are important results, but discussing them goes beyond the scope of this paper.

Di Valentino, Melchiorri & Silk (2019) have found that the Λ CDM parameters derived from the *Planck* data can be brought into agreement with each other and with the Cepheid-based H_0 value by assuming our Universe to be closed with the curvature parametrized by the energy density parameter $\Omega_K = -0.091 \pm 0.037$. According to these authors, such a fit requires drastic changes in the Λ CDM model, unless there exists an obvious possible solution to this problem in the form of hitherto undetected systematics in the CMB data.

In our view, it is preferable to find a solution to the H_0 discrepancy problem from within more conventional physics, perhaps by using some additional observational data and/or re-examining the interpretation of the existing measurements in terms of biases and systematics. The main systematic effects in the *Planck* data (e.g. the Galactic foreground radiation) are removed during the pipeline processing (Planck Collaboration II 2016a), whereas the residual effects are analysed and removed by simulations and numerical modelling of the instruments (Planck Collaboration 2016b). All the procedures for removing systematic effects have been rigorously checked and validated. Extragalactic foregrounds are usually modelled by a set of power spectrum templates (Planck Collaboration XIII 2016c) that include fluctuations in the number density and clustering of extragalactic point sources, as well as the thermal and kinetic Sunyaev–Zel’dovich components.

However, despite taking into account all these sources of contamination, the lower value of H_0 derived from the *Planck* measurements persists in contrast to the local measurements. This means that there might still exist an additional component (or various components) contaminating the CMB.

Here we shall explore such a possibility based on our previous work (Yershov, Orlov & Raikov 2012, 2014) that revealed that the CMB temperature fluctuations could be affected by emission from the medium around remote clumps of matter (e.g. galaxy clusters or superclusters). This conclusion came from finding a statistically significant correlation between the supernova (SN) redshifts, z_{SN} , and CMB temperature fluctuations at the SNe locations, T_{SN} . In this paper, we compare and contrast our predicted change in the CMB power spectrum and in the estimated value of H_0 due to the increase in the dispersion σ_T of contaminated CMB temperature fluctuations ΔT – contaminated with respect to the theoretically clear case of the standard Λ CDM model.

2 POSSIBLE DISTORTIONS OF THE CMB POWER SPECTRUM

In order to quantify the corresponding changes in the CMB power spectrum we have used the code for anisotropies in the microwave background (CAMB) created by Lewis (2013) in its 2014-version

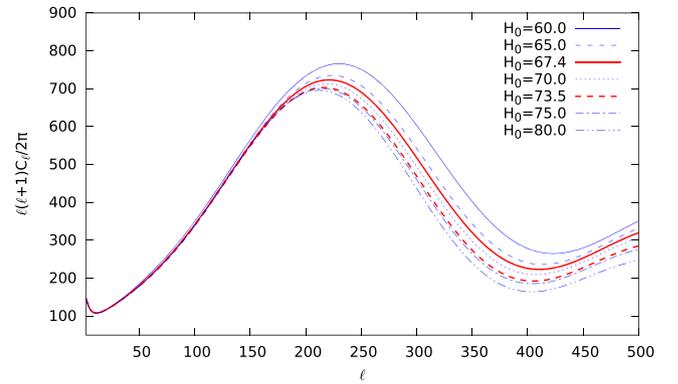


Figure 1. CMB power spectra (in the standard normalized presentation) generated by using the CAMB tool for seven different values of H_0 .

from GITHUB,¹ which allows extracting different cosmological parameters from theoretical CMB power spectra generated by the same code.

By fixing the parameters Ω_Λ and Ω_M and varying the value of the parameter H_0 we have produced a set of theoretical CMB power spectra, part of which is shown in Fig. 1. The fixed parameters have been given the standard default values of $T_0 = 2.7255$ K, $\Omega_{\text{baryon}} = 0.0462$, $\Omega_{\text{CDM}} = 0.2538$, and $\Omega_\Lambda = 0.7$ (which corresponds to $\Omega_M = \Omega_{\text{baryon}} + \Omega_{\text{CDM}} = 0.3$ for the flat Universe).

In this code, the coefficients C_ℓ of the CMB power spectrum are calculated as sums of the integrals $a_{\ell m}$, $|m| \leq \ell$, which include temperature fluctuations $\Delta T(x, \phi)$ over the celestial sphere, where $x \in [-1, 1]$ is the cosine of the latitude and $\phi \in [0, 2\pi]$ is the longitude. Reversely, the functions $\Delta T(x, \phi)$ are calculated by summing up the integrals $a_{\ell m}$.

For a given CMB power spectrum, we have calculated a set of corresponding values of $\Delta T(x, \phi)$ over a 1/1024th part of the celestial sphere by using random $a_{\ell m}$ for $\ell = 0, 1, \dots, \ell_{\text{max}}$ with the restriction $\ell_{\text{max}} = 500$ (the use of the whole sphere is not needed here, as the angular sizes of distant cosmic structures in question are not expected to be large). In these calculations, we have taken five equal-spaced values of H_0 , namely, 60, 65, 70, 75, and 80 [km s⁻¹ Mpc⁻¹] plus the values 67.4 and 73.5 [km s⁻¹ Mpc⁻¹] corresponding, respectively, to the *Planck* result (Planck Collaboration VI 2018) and to the local measurements of H_0 (Riess et al. 2018). Fig. 1 shows the CMB power spectra generated in this way.

Additionally, for checking the consistency of our calculations we have taken a few sets of normally distributed randomized values of $a_{\ell m}^i$, $i = 1, 2, \dots, 5$, so that for each of the selected values of H_0 , we have obtained five samples of $a_{\ell m}^{H_0, i}$ and, correspondingly, five samples of values $\Delta T^{H_0, i}$. For each of them, we have calculated the average of the CMB temperature fluctuations $\overline{\Delta T}$ and its standard deviation σ_T .

Here we are mainly interested in the way the values σ_T change when the parameter H_0 is varied. For each of these generated sequences, the trend of the calculated values σ_T was practically the same. Namely, when the dispersion of the CMB temperature fluctuations increases, the value of the estimated H_0 diminishes, the difference between the two discussed H_0 values 73.5 and 67.4 [km s⁻¹ Mpc⁻¹] being related to $\Delta\sigma_T = -0.60 \pm 0.04$ μK . This supports our proposition that if the CMB is contaminated by photons from the medium surrounding remote clumps of matter,

¹<https://github.com/cmbant/CAMB/releases/tag/Apr2014>

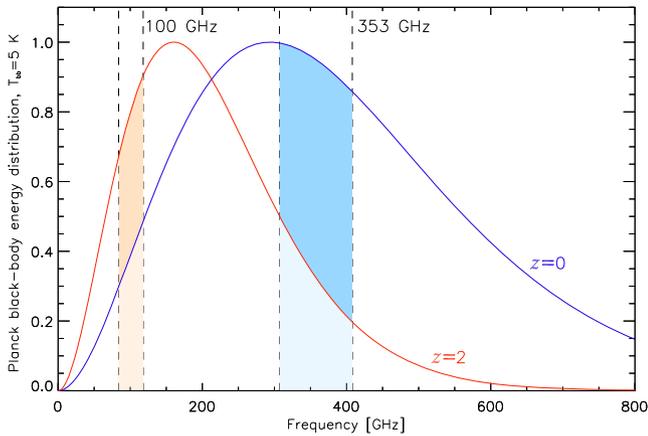


Figure 2. Changes in the blackbody energy fraction observed in two *Planck* High Frequency Instrument (HFI) bands (100 and 353 GHz) due to redshifting the radiating matter with $T_{\text{bb}} = 5$ K from $z = 0$ (right-hand curve) to $z = 2$ (left-hand curve). The observed energy is redistributed from the band 353 GHz (the shaded area below the right-hand curve) to the 100 GHz band (the shaded area below the left-hand curve). The Planck blackbody curves are normalized here to their maxima. The thermal equilibrium threshold corresponding to the CMB temperature at $z = 2$ is taken into account.

then the *Planck*-derived parameter H_0 extracted from such contaminated CMB data would be underestimated with respect to the same parameter derived from a theoretically clean CMB case or from local observations not related to the CMB.

3 CONTAMINATING EMISSION IN DIFFERENT FREQUENCY BANDS

Let us estimate the possible range of temperatures of the medium from which the contaminating photons might emanate. In our previous work, Yershov et al. (2014), we confidently excluded the possibility of the correlation between the SN redshifts and the CMB temperature fluctuations being caused by the Sunyaev–Zel’dovich (SZ) effect by comparing the signs of the correlation in different frequency bands. The SZ effect should cause a decrease in the CMB intensity at frequencies below 218 GHz and an increase at higher frequencies. Therefore, if the observed anomaly was caused by this effect, we would expect a higher positive anomaly for the 353 GHz band. However, the effect was exactly the opposite: the anomaly in the 353 GHz band was negative, and the slope of the regression line for this band was negative as well, $\xi_{353} = -61.8 \pm 30.0 \mu\text{K}$. The remaining possibility is the existence of contaminating emission from a cold medium residing in and around the SN host galaxies.

As an illustration, let us calculate the Planck blackbody energy distribution for the photons coming from some cold ($T_{\text{bb}} = 5$ K) medium at two different redshifts, as shown in Fig. 2. The right and left curves in this plot correspond to $z = 0$ and 2, respectively. The dashed vertical lines indicate the average limits [84.4, 117.36] and [306.8, 408.22] GHz of the 100 and 353 GHz *Planck* frequency bands, respectively (Planck Collaboration IX 2014). Of course, the real shapes of the *Planck* band transmission curves are not rectangular, so for our further estimations we have used the actual transmissions available at the ancillary data folder of the *Planck* legacy archive.²

²https://irsa.ipac.caltech.edu/data/Planck/release_1/

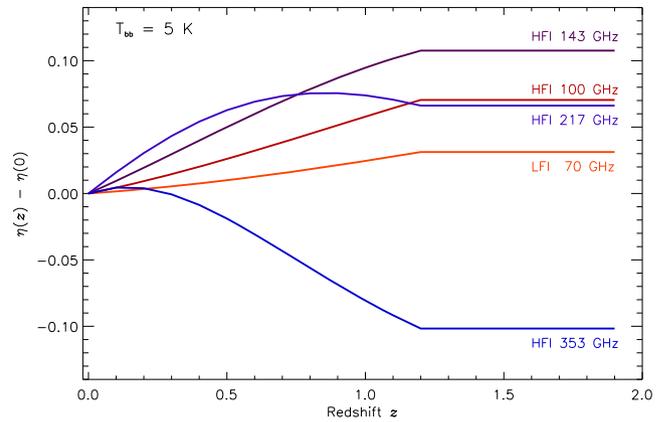


Figure 3. Redshift dependences of the blackbody radiation energy fraction $\eta(z)$ as observed in five *Planck* frequency bands for $T_{\text{bb}} = 5$ K. The constant shifts of the curves with respect to each other have been normalized at $z = 0$ by subtracting from them their individual values $\eta(0)$.

Fig. 2 schematically illustrates the effect of redistribution of photons from the band 353 GHz to the band 100 GHz if these photons are redshifted to $z = 2$ (for simplicity the Planck blackbody curves in this plot are normalized to their maxima). The fraction of the blackbody photons observed in the instrumental band of 353 GHz and coming from $z = 0$ (the shaded area below the right-hand curve in the plot) become essentially smaller if the photons with the same blackbody temperature are redshifted to $z = 2$ (the lower part of this shaded area) because these photons are now observed in the 100 GHz band (the shaded area below the left-hand curve) that is smaller for this band at $z = 0$. This would lead to a positive slope of the 100 GHz band signal with increasing redshift and to a negative slope for the 353 GHz band signal. In Fig. 2, we have taken into account the temperature threshold for a medium in thermal equilibrium with the CMB whose temperature at $z = 2$ is higher than 5 K, which shifts the peak of the left-hand curve to higher frequencies, compared to the pure 5-K blackbody redshifted to $z = 2$.

In this way, for this particular blackbody temperature of $T_{\text{bb}} = 5$ K, we can calculate the fraction of photons, $\eta(z)$, detected in each instrumental frequency band for a range of redshifts of interest. The results of such a calculation are shown in Fig. 3 for the five selected frequency bands of 70, 100, 143, 217, and 353 GHz and for the redshifts ranging from $z = 0$ to 2. Here, the threshold corresponding to thermal equilibrium with the CMB at different redshifts is also taken into account, which can be seen in the shapes of the curves. The linear regression coefficients (slopes) $\eta(z)$ corresponding to these curves indicate how the redshift dependence would look in different frequency bands if the contaminating emission were coming from different redshifts. Since here we are interested only in the slopes of these curves and not in their absolute values, we have normalized their constant shifts with respect to each other at $z = 0$ by subtracting from them their individual values $\eta(0)$.

By comparing Fig. 3 with our previously published results, namely, with fig. 3 and table 5 from Yershov et al. (2014), we can see that the pattern of slopes of the calculated functions $\eta(z)$ for the five selected *Planck* frequency bands matches the pattern of the observed slopes of the functions $T_{\text{SN}}(z)$ for the same frequency bands.

The calculated theoretical slopes of $\eta(z)$ and the experimental slopes of $T_{\text{SN}}(z)$ are expressed in different units: the former is a dimensionless ratio between the blackbody energy integrated

Table 1. Theoretical slopes ξ_ν of the function $\eta_\nu(z)$ normalized to the values of $\xi_{100\text{GHz}}(z)$ for different temperatures of the blackbody emitter, and the experimental slopes derived from the *Planck* data taken from Yershov et al. (2014), table 5.

Band (GHz)	Slopes for the blackbody temperatures					Experimental slopes
	3 K	4 K	5 K	6 K	7 K	
70	0.49	0.46	0.44	0.42	0.39	0.96 \pm 0.63
100	1.00	1.00	1.00	1.00	1.00	1.00 \pm 0.39
143	1.21	1.42	1.56	1.67	1.84	1.09 \pm 0.31
217	-0.17	0.52	1.04	1.56	2.26	0.61 \pm 0.36
353	-1.84	-1.77	-1.41	-0.89	-0.10	-0.99 \pm 0.48

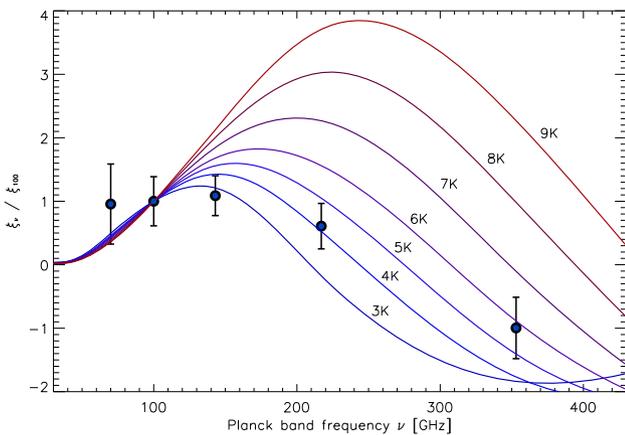


Figure 4. Theoretical (solid curves) and observed (points with error bars) slopes of the regression characterizing the relationship between T_{SN} and z_{SN} for different *Planck* frequency bands. The slopes are normalized to the slope magnitude for the High Frequency Instrument (HFI) 100 GHz band.

within the limits of a given *Planck* band and the total blackbody energy, whereas the latter is expressed in Kelvins per unit redshift. Therefore, in order to be able to compare these functions we have to normalize them by choosing a reference curve corresponding to one of the frequency bands, say, 100 GHz. The theoretical slopes ξ_ν of the functions $\eta(z)$ calculated in this way for different *Planck* bands, normalized to the slope of the function $\eta(z)$ for the band 100 GHz, are given in Table 1 for temperatures of 3, 4, 5, 6, and 7 K. The measured experimental slopes taken from table 5 of Yershov et al. (2014), also normalized to the experimental slope corresponding to the 100 GHz band, are given in the last column of Table 1. The data from Table 1 are illustrated by Fig. 4, where the experimental slopes are shown as black points with error bars.

We can see that these experimental slopes match various theoretical slopes corresponding to the blackbody emission with temperatures from 3 to 6 K, different temperature columns matching 1σ experimental tolerances for different *Planck* bands, and all of the 5 K column slopes matching all of the experimental slopes within $\sim 1.1\sigma$ tolerance (hence the choice of 5 K for the illustrations in Figs 2 and 3). This temperature is the lowest possible for a medium in thermal equilibrium with the CMB radiation at a redshift $z \approx 0.8$ (see also Sato et al. 2013). So we can speculate that the major part of the contaminating emission comes from approximately this distance or, more likely, from a range of intermediate distances corresponding to $z \in (0, 1.5)$.

4 DISCUSSION

The fact that the remote contaminating medium must be at a very low temperature (see Fig. 4) can give clues as to the nature of the medium. Obviously, hot intergalactic gas with its temperatures reaching 10^7 K can be disregarded as a candidate for the contaminating agent, as well as dust in star-forming regions whose temperatures are too high, being of the order of 20–100 K (Galamez et al 2016). This leaves us with the most likely contaminating ingredient being cold dust that for some time has been suspected to populate intergalactic space.

Eigenson (1938, 1949) and Zwicky (1951, 1952, 1957) were the first to notice the existence of intergalactic extinction due to dust when studying the Coma Cluster of galaxies. They have demonstrated that intergalactic dust could be detected by counting high-redshift objects in the directions of lower redshift clusters of galaxies. The presence of extragalactic dust was later traced by measuring the attenuation of distant background galaxies by foreground galaxies (González et al. 1998; Alton, Bianchi & Davies 2001).

The possibility of grey intergalactic extinction was debated just after the discovery of the Type Ia supernova (SN Ia) dimming, see e.g. the review by Riess (2000) who wrote that ‘*dust which is greyer than Galactic-type dust could challenge the cosmological interpretation of high-redshift SNe Ia*’. At the time of that discussion, there was not sufficient evidence supporting such a possibility. But more recently, the theories of interstellar and intergalactic dust have been substantially revised (see Voshchinnikov 2012; Hutton, Ferreras & Yershov 2015; Schultheis et al. 2015; Vavryčuk 2019). It has become clear that at the peripheries of galaxies and possibly further away in the intergalactic medium, the fraction of coarse-grain dust is larger than in the galactic discs, which leads to this dust resembling the theoretical ‘grey’ dust that leaves little or no imprint on the spectral energy distribution of background sources. It also creates the long-known excess of radiation from some extragalactic objects in the far-IR at $\lambda \approx 500 \mu\text{m}$, which extends up to centimetre wavelengths and which was confirmed and measured by the *Herschel* and *Planck* space observatories (Galliano et al. 2011; Planck Collaboration XVII 2011).

In the 1990s, this excess was interpreted as an elevated spatial mass density of cold dust with temperatures of 4–7 K (Reach et al. 1995). At that time such an interpretation was considered to be impossible. However, the observed anticorrelation between the $500 \mu\text{m}$ emission and the density of the medium (Galliano et al. 2003, 2005) supports this interpretation because if the radius of dust grains in an environment with a constant spatial mass density grows by an order of magnitude, then the number density of grains will be reduced by three orders of magnitude, which would dramatically increase the transparency of the medium and would reduce the interactions of dust particles with radiation, rendering them difficult to detect. The angular sizes of the observed regions with the $500 \mu\text{m}$ emission range from 0:02 (Lisenfeld et al. 2002) to 0:5 (Galliano et al. 2011). So this emission would effectively distort the CMB power spectrum at the multipole moments $\ell \approx 360$ and higher, near the first trough of the curves shown in Fig. 1, where the effect of the CMB distortion on the calculated parameter H_0 is quite strong.

More observational evidence supporting our hypothesis comes from the directional dependence of the Universe acceleration parameter as estimated from the SNe Ia data (Cai & Tuo 2012; Bernal, Cárdenas & Motta 2017; Colin et al. 2019), which is currently interpreted as an artefact of us, observers, being located in a local bulk flow. However, it would be more logical to assume

a non-homogeneous distribution of intergalactic dust rather than anisotropy of Universe's acceleration.

We conclude that the mechanism proposed here for contamination of CMB radiation by some distant cold foreground emission can explain the discrepancy between the local measurements of H_0 and the *Planck*-derived value, without invoking assumptions that would require modifications of the standard cosmological model or the standard model of particle physics.

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