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 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 $T_{SN}/z_{SN}$ corresponding to different Planck wave bands 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: cosmic background radiation – cosmological parameters – intergalactic medium – dust, extinction

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 (ΛCDM) cosmological model, $H_0 = (67.37 ± 0.54)\, \text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ (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 variable Cepheid stars, with the recent calculation of $H_0$ based on this method being $H_0 = (73.48 ± 1.66)\, \text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ (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; Zhang et al. 2017; Planck Collaboration LI 2017; Feeney, Mortlock, & Dalmasso 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 ΛCDM model include a new kind of dark energy (Planck Collaboration XIV 2016; 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.

On the particle physics side, there are advocates for the existence of new relativistic particle species, such as hypothetical sterile neutrinos (Wyman et al. 2014; Dvorkin 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 worth while mentioning that the baryon acoustic oscillation probe based on galaxy surveys combined with big bang nucleosynthesis data, gives an independent estimate of $H_0 = 68.4^{\pm 1.2}$ 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 $\Lambda$CDM parameters derived from the Planck data can be brought into agreement with each other with the Cepheid-based $H_0$ value by assuming a closed Universe with the curvature parametrised by the energy density parameter $\Omega_k = -0.091 \pm 0.037$. According to these authors, such a fit requires drastic changes in the $\Lambda$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 2016), whereas the residual effects are analysed and removed by simulations and numerical modelling of the instruments (Planck Collaboration III 2016). 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 2016) that include fluctuations in the number density and clustering of extragalactic point sources, as well as the thermal and kinetic Sunyaev-Zeldovich 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) which 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 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 $\sigma_T$ of contaminated CMB temperature fluctuations $\Delta T$ – contaminated with respect to the theoretically clear case of the standard $\Lambda$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 from github$^1$, which allows extracting different cosmological parameters from theoretical CMB power spectra generated by the same code.

By fixing the parameters $\Omega_A$ and $\Omega_M$ 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 Figure 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 $\Omega_A = 0.7$ (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 $\ell = 0, 1, \ldots, \ell_{\text{max}}$ 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). Figure 1 shows the CMB power spectra generated in this way.

$^1$ https://github.com/cmbant/CAMB/releases/tag/Apr2014
Additionally, for checking the consistency of our calculations we have taken a few sets of normally distributed randomised values of \( a_{\ell m}, i = 1, 2, \ldots, 5 \), so that for each of the selected values of \( H_0 \), we have obtained five samples of \( a_{\ell m} \) and, correspondingly, five samples of values \( \Delta T_{H_0} \). For each of them, we have calculated the average of the CMB temperature fluctuations \( \Delta T \) and its standard deviation \( \sigma_T \).

Here we are mainly interested in the way the values \( \sigma_T \) change when the parameter \( H_0 \) is varied. For each of these generated sequences, the trend of the calculated values \( \sigma_T \) 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 \( \Delta \sigma_T = -0.60 \pm 0.04 \mu K \). This supports our proposition that if the CMB is contaminated by photons from the medium surrounding remote clumps of matter, 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-Zeldovich (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 anomalous 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, \( \xi_{353} = -61.8 \pm 30.0 \mu K \). 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 (\( T_{bb} = 5 \) K) medium at two different redshifts, as shown in Figure 2. The blue and red curves in this plot correspond to \( z = 0 \) and \( z = 2 \), respectively. The dashed vertical lines indicate the average limits [84.4, 117.36] GHz and [306.8, 408.22] GHz of the 100 GHz 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 \(^2\).

Figure 2 schematically illustrates the effect of redistribution of photons from the band 353 GHz into the band 100 GHz if these photons are redshifted to \( z = 2 \) (for simplicity the Planck blackbody curves in this plot are normalised to their maxima). The fraction of the blackbody photons observed in the instrumental band of 353 GHz and coming from \( z = 0 \) (blue shaded area in the plot) becomes essentially smaller if the photons with the same blackbody temperature are redshifted to \( z = 2 \) (light-blue shaded area) because these photons are now observed in the 100 GHz band (salmon shaded area in the plot, which is smaller for this band at \( z = 0 \) and which is shaded with light-salmon colour). 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 red curve to higher frequencies, compared to the pure 5-K-blackbody redshifted to \( z = 2 \).

In this way, for this particular blackbody temperature of \( T_{bb} = 5 \) 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 Figure 3 for the five selected frequency bands of 70, 100, 143, 217 and 353 GHz and for the redshifts ranging from \( z = 0 \) to \( z = 2 \). 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 normalised their constant shifts with respect to each other at \( z = 0 \) by subtracting from them their individual values \( \eta(0) \).

By comparing Figure 3 with our previously published results, namely, with Figure 3 and Table 5 from

\(^2\) https://irsa.ipac.caltech.edu/data/Planck/release_1/
for the band 100 GHz, are given in Table 1 for temperatures of 3 K, 4 K, 5 K, 6 K and 7 K. The measured experimental slopes taken from table 5 of Yershov et al. (2014), also normalised 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 Figure 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 K 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 ~ 1.1σ-tolerance (hence the choice of 5 K for the illustrations in Figure 2 and Figure 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 Figure 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 K to 100 K (Galametz et al. 2016). This leaves us with the most likely contaminating ingredient being cold dust which 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 1998; Alton et al. 2001).

The possibility of grey intergalactic extinction was debated just after the discovery of the 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
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