



A Population III–Generated Dust Screen at $z \sim 16$

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Abstract

The search for alternative cosmological models is largely motivated by the growing discordance between the predictions of Λ CDM and the ever-improving observations, such as the disparity in the value of H_0 measured at low and high redshifts. One model in particular, known as the $R_{\text{H}} = ct$ universe, has been highly successful in mitigating or removing all of the inconsistencies. In this picture, however, the anisotropies in the cosmic microwave background (CMB) would have emerged at a redshift $z \sim 16$, rather than via fluctuations in the recombination zone at $z \sim 1080$. We demonstrate here that a CMB created in the early universe, followed by scattering through a Population III–generated dust screen, is consistent with all of the current data. Indeed, the Planck measurements provide a hint of an $\sim 2\%$ – 4% frequency dependence in the CMB power spectrum, which would be naturally explained as a variation in the optical depth through the dust but not a Thomson scattering–dominated recombination environment. Upcoming measurements should be able to easily distinguish between these two scenarios, e.g., via the detection of recombination lines at $z \sim 1080$, which would completely eliminate the dust-reprocessing idea.

Unified Astronomy Thesaurus concepts: [Cosmic microwave background radiation \(322\)](#); [Population III stars \(1285\)](#); [Reionization \(1383\)](#); [Cosmological parameters \(339\)](#); [Large-scale structure of the universe \(902\)](#)

1. Introduction

Given how well we understand the origin of the cosmic microwave background (CMB) and the underlying physics of the medium where it was produced, it might seem surprising to suggest that the anisotropies we observe in its temperature distribution perhaps emerged at a redshift of only ~ 16 rather than the conventional $z \sim 1080$. And yet, as we shall demonstrate in this paper, there are good reasons for considering such a radical possibility. Even more to the point, we shall show that none of the data available today clearly rule out a scenario in which the CMB, though produced in the early universe, was subsequently reprocessed by dust created in the ejecta of Population III stars at the lower redshift. As revolutionary as this alternative picture may appear to be, an early version of it was actually seriously considered in the 1970s before the current paradigm was established. We aim to resurrect it here because there are growing indications that the tension developing between the predictions of Λ CDM and the ever-improving observations may be completely resolved by an expansion history in which this Population III dust screen scenario becomes viable.

We begin by motivating this proposal in Sections 2 and 3 and then proceed in Section 4 to systematically examine why the current data do not yet rule out this picture. We also provide some indication of how future, more precise observations may be able to clearly distinguish between the recombination and dust-reprocessing models, e.g., via the detection of recombination lines in the CMB spectrum. We end with our conclusion in Section 5.

2. Background

A pivotal development in our understanding of how the CMB was produced in the standard model occurred with COBE’s discovery of a near-perfect blackbody in its spectrum (Mather et al. 1990). All succeeding measurements of this relic signal have bolstered the view that the background radiation must therefore have been thermalized within 1 yr of the Big Bang, diffused through a scattering-dominated medium, and eventually streamed freely after the protons and electrons combined (Hinshaw et al. 2003; Planck Collaboration et al. 2014).

Prior to this period, however, the CMB was thought to have been produced by dust at lower redshifts, probably injected into the interstellar medium (ISM) by Population III stars (Rees 1978; Rowan-Robinson et al. 1979; Wright 1982). In the absence of any indication to the contrary, it was also assumed that the radiation rethermalized by this dust was itself emitted by the same stars.

But in the context of Λ CDM, there are several fundamental reasons why the CMB must have been produced at the epoch of recombination, $z_{\text{cmb}} \sim 1080$. The dust screen scenario we consider here cannot alter this situation. The surface of last scattering (LSS) had to lie at this redshift because (i) the characteristic scale observed in the CMB’s power spectrum, interpreted as an acoustic horizon, requires a decoupling of the radiation and the baryonic fluid $\sim 380,000$ yr after the Big Bang, corresponding to the aforementioned $z_{\text{cmb}} \sim 1080$ (Spergel et al. 2003), and (ii) assuming that the CMB propagated freely after this time, its temperature must have scaled according to $T(z) \propto (1+z)$. One may therefore use the Saha equation to estimate the LSS temperature (T_{cmb}), and hence the redshift, at which the ionization fraction dropped to $\lesssim 50\%$. Thus, using $T_{\text{cmb}} \sim 3000$ K and a CMB temperature today of 2.728 K, one infers that z_{cmb} must have been ~ 1100 , confirming the value implied by the acoustic horizon. On the other hand, if dust were somehow involved, the implied

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temperature ($T \lesssim 50$ K) would correspond to a redshift $z \lesssim 20$, which is clearly in conflict with the acoustic-scale interpretation of the CMB power spectrum. Subsequent work has provided even more reasons to abandon the dust scenario, given that Population III starlight scattered by the ejected dust could not produce the observed CMB spectrum (Li 2003). This conclusion has been affirmed with more recent work showing that the original formalism used to calculate the thermalization of starlight by metallic needles is probably not correct, requiring a reevaluation of the absorption cross section of these dust particles over a wide wavelength range (Xiao et al. 2020).

So the issue is not whether the conventional recombination picture for the formation of the CMB needs to be modified in the standard model. Rather, the growing tension between the predictions of Λ CDM and the new observations is motivating us to consider alternative cosmologies, one of which—the $R_h = ct$ universe (Melia & Shevchuk 2012; Melia 2020)—has been particularly successful in resolving these inconsistencies. As we shall see beginning with Section 3, the origin of the CMB would have been quite similar in these two models, but the interpretation of the temperature anisotropies in $R_h = ct$ requires them to have emerged at $z \sim 16$, rather than the conventional $z_{\text{cmb}} \sim 1080$. Ironically, the most likely origin of these anisotropies would thus be fluctuations in a dust screen at that redshift, echoing the original (though now abandoned) scenario proposed for the standard model.

A well-known example of the standard model’s inability to account for all of the cosmological data arises from the inconsistency of the Hubble constant measured at high and low redshifts. The analysis of the CMB observed with Planck (Planck Collaboration et al. 2020a) indicates a value, $H_0 = 67.6 \pm 0.9$ km s⁻¹ Mpc⁻¹, lower than that measured locally, with a corresponding matter fluctuation amplitude, σ_8 , higher than that derived from the Sunyaev–Zel’dovich effect. In fact, the Hubble constant measured by Planck in the context of a flat (i.e., $k=0$) Λ CDM disagrees by $\sim 4.4\sigma$ with that measured using Type Ia supernovae, calibrated via the Cepheid distance ladder, which instead implies a value $H_0 = 74.03 \pm 1.42$ km s⁻¹ Mpc⁻¹ (Riess et al. 2018).

But these are not the only measurements that show evidence of discordance in the interpretation of H_0 within the standard model. Clustering, weak lensing, and baryon acoustic oscillations (BAOs) have yielded results similar to the CMB (Abbott et al. 2018), in contrast to a local distance ladder calibrated with the tip of the red giant branch, which implies yet a different value of H_0 (Freedman et al. 2020). A broader discussion of this tension may be found in Verde et al. (2019). Clearly, the 4.4σ disparity in the expansion rate of the universe at low and high redshifts refutes the expansion history predicted by the standard model. Several other reasons for questioning the expansion history in the standard model are presented in Melia (2023).

Yet it would not be unreasonable to argue that such tensions are due to astrophysical reasons rather than the cosmology itself. This is certainly a possibility, and further scrutiny will help determine whether this position is tenable in the long run. But unfortunately, the inconsistencies extend well beyond merely the measurement of H_0 , as described at length in Melia (2020). For example, it is now becoming quite evident that the measured angular correlation function requires a cutoff in the primordial power spectrum (see Section 3.2 below) that makes

it impossible for slow-roll inflation to have seeded the fluctuations while simultaneously solving the temperature horizon problem (Melia & Lopez-Corredoira 2018; Liu & Melia 2020). A recent compilation of tests such as this and a direct comparison between the standard model and $R_h = ct$ may be found in Table 2 of Melia (2018a).

The success of $R_h = ct$ in resolving many of the observed inconsistencies in Λ CDM motivates us to probe the consequences of its expansion history more deeply, particularly with regard to the CMB. As we shall see shortly, a firm prediction of this model is that the CMB temperature anisotropies must have emerged at $z \sim 16$ if the acoustic scale inferred from the multi-peaked power spectrum coincides with the BAO scale measured at lower redshifts (see Section 3). But this redshift is special for other reasons. It sits well within the period of Population III star formation, just prior to the epoch of reionization, which began at $z_{\text{EoR}} \sim 14$ –15. This was a time when dust was likely being ejected into the ISM.

If there is any validity to the $R_h = ct$ cosmology, this overlap between the redshift at which the CMB temperature anisotropies must have emerged and the era of Population III star formation cannot be a coincidence. So, while our goal in this paper is not to question the established recombination picture for the origin of the CMB in Λ CDM, we shall examine in detail how the (now dated) dust model is still viable in the context of $R_h = ct$. Indeed, we shall demonstrate that, while recombination does not work in this model, the dust model is unavoidable. A principal difference between the original dust scenario and that developed here, however, is that reprocessing of radiation emitted by the Population III stars plays no role in creating the CMB we observe today. Instead, the background radiation would still have originated in the early universe, as it did in Λ CDM, but would have been reprocessed through the dust screen prior to the epoch of reionization. Thus, a critical difference between these two cosmologies is that the CMB anisotropies would reflect the large-scale structure at $z \sim 16$ in $R_h = ct$, while they would be a consequence of the conventional fluctuation spectrum at $z \sim 1080$ in the context of Λ CDM.

3. CMB Anisotropies at $z \sim 16$

There are several independent observational indicators suggesting that the CMB anisotropies originated at $z_{\text{dust}} \sim 16$ in the context of $R_h = ct$. We discuss the two most prominent ones below.

3.1. Equality of the Acoustic and BAO Scales

The first of these is based on the conventional assumption that the acoustic horizon responsible for the CMB multi-peaked power spectrum is equal to the BAO scale measured at much lower redshifts.

Planck has identified a scale, r_s , in the temperature and polarization power spectra (Planck Collaboration et al. 2014) corresponding to an angular size $\theta_s = (0^\circ.596724 \pm 0^\circ.00038)$. This is interpreted as an acoustic horizon, dependent on how far sound waves could have traveled in the comoving frame before matter and radiation decoupled. The specifics of how this scale was established are not central to the argument made here, other than the requirement that it remained constant in the comoving frame once the radiation began to stream freely following recombination.

In parallel with the scale θ_s seen by Planck, a peak has also been identified in the two-point correlation function of galaxies and the Ly α forest. The growth of fluctuations in the matter density is still linear at the BAO scale, allowing one to model it with low-order perturbation theory (Meiksin et al. 1999; Seo & Eisenstein 2005; Crocce & Scoccimarro 2006; Jeong & Komatsu 2006; Eisenstein et al. 2007b; Takahiro et al. 2007; Matsubara 2008; Padmanabhan & White 2009; Taruya et al. 2009; Seo et al. 2010). The peak measured via large galaxy surveys is thought to be due to the aforementioned acoustic scale.

In other words, one assumes that the acoustic horizon established at decoupling remains fixed in the comoving frame, reappearing much later in the guise of the BAO feature. Of course, the proper size of the BAO “ruler” is not the same as the proper size of the acoustic scale. These lengths may be identical in the comoving frame, but the acoustic scale expands as the universe evolves at a rate consistent with the expansion factor $a(t)$. The physical BAO scale is thus much bigger than the acoustic length at the LSS, given by the ratio $a(t_{\text{BAO}})/a(t_{\text{cmb}})$, which depends critically on the cosmological model. As we shall see shortly, it is this ratio that eliminates any possibility of the CMB scale having been set at recombination in $R_h = ct$, implying instead that it must have been established at a redshift much smaller than ~ 1080 .

The BAO peak positions can now be measured to better than $\sim 1\%$ accuracy with galaxies and $\sim 1.4\%–1.6\%$ with the Ly α forest, thanks to the introduction of reconstruction techniques (Eisenstein et al. 2007a; Padmanabhan et al. 2012) that enhance the quality of the correlation functions. The recent galaxy measurements at $z \lesssim 0.7$ (Alam et al. 2017), in combination with the Ly α forest observation at $z = 2.34$ (Font-Ribera et al. 2014; Delubac et al. 2015), indicate that the BAO scale is ~ 147 Mpc in the case of a flat Λ CDM, and $r_{\text{BAO}} \sim 131 \pm 4$ Mpc for $R_h = ct$ (Melia & Lopez-Corredoira 2022). One should emphasize that these measurements exclude the use of BAO observations based on photometric clustering and the WiggleZ survey (Blake et al. 2011), which have much larger errors.

In the $R_h = ct$ cosmology, the angular diameter distance is simply given as (Melia & Shevchuk 2012; Melia 2020)

$$d_A(z) = \frac{c}{H_0} \frac{1}{(1+z)} \ln(1+z), \quad (1)$$

while the Hubble distance is

$$d_H(z) = \frac{c}{H_0} \frac{1}{(1+z)}. \quad (2)$$

One can therefore see that the ratio $\mathcal{D}(z) \equiv d_A(z)/d_H(z)$ has the form

$$\mathcal{D}(z) = \ln(1+z), \quad (3)$$

which is free of any parameters.

If we now set the acoustic and BAO scales equal to each other in the comoving frame, we find that

$$\mathcal{D}(z) = \ln(1+z) = \frac{r_{\text{BAO}}}{R_h(t_0)\theta_s}, \quad (4)$$

where $R_h(t_0) = c/H_0$ is the gravitational (or Hubble) radius today (Melia 2018b). One therefore infers that the dust screen must lie at

$$z_{\text{dust}} = 16.05_{-2.0}^{+2.4} \quad (\text{acoustic} = \text{BAO}), \quad (5)$$

corresponding to a cosmic time $t_{\text{dust}} \approx 849$ Myr in the evolutionary history of the $R_h = ct$ universe. In deriving this value, we have simply used the Hubble constant (i.e., $H_0 = 67.6 \pm 0.9$ km s $^{-1}$ Mpc $^{-1}$) measured by Planck, though the actual optimization for $R_h = ct$ may differ by several percentage points. The error in z_{dust} has been propagated from the uncertainties in θ_s , r_{BAO} , and H_0 . The second indicator that confirms this redshift is based on an entirely different analysis of the CMB spectrum, which we discuss next.

3.2. Angular Size of the Largest Mode in the CMB Fluctuations

Several large-angle anomalies have been observed in the CMB fluctuation spectrum by every major satellite flown to study the CMB since the 1990s (COBE, Mather et al. 1990; WMAP, Hinshaw et al. 2003; and Planck, Planck Collaboration et al. 2016). One of the most prominent among them is the lack of large-scale angular correlations in the temperature distribution, contrasting with basic inflationary theory, which is disfavored by the measured angular correlation function at a confidence level exceeding 3σ (Copi et al. 2015).

An in-depth analysis of the latest Planck data focusing on this particular issue (Melia & Lopez-Corredoira 2018; Melia et al. 2021; Sanchis-Lozano et al. 2022) has shown that the paucity of large-angle correlations is best explained by the presence of a cutoff,

$$k_{\text{min}} = (3.14 \pm 0.36) \times 10^{-4} \text{ Mpc}^{-1}, \quad (6)$$

in the primordial power spectrum, $P(k)$. The value of k_{min} can easily discriminate between inflationary (e.g., Λ CDM) and noninflationary (e.g., $R_h = ct$) models because the quasi-de Sitter expansion in the former would have stretched all the quantum fluctuations beyond the Hubble horizon, thereby producing strong correlations at all angles upon reentry (i.e., $k_{\text{min}} \approx 0$). Noninflationary cosmologies, on the other hand, would have created a CMB power spectrum with wavelengths no bigger than the size of the Hubble horizon at the time the background radiation was produced.

In addition to its impact on the angular correlation function, the existence of $k_{\text{min}} \neq 0$ also signals the time at which inflation could have started. And the delayed initiation time implied by Equation (6) makes it difficult to account for the origin of the primordial power spectrum while allowing the universe to have expanded by a sufficient number of e-folds to overcome the horizon problem. This issue has been explored elsewhere (Destri et al. 2008; Ramirez & Schwarz 2012; Handley et al. 2014; Remmen & Carroll 2014; Scacco & Albrecht 2015; Santos da Costa et al. 2018; Liu & Melia 2020), however, so we shall not revisit it here. Instead, our primary focus is on how k_{min} could represent a measurable angular scale for non-inflationary models.

In $R_h = ct$, the mode wavelengths grew at the same rate as the Hubble radius, both proportional to $a(t)$, so quantum fluctuations never crossed back and forth across the Hubble horizon (Melia 2019). The mode with the smallest wavenumber in this cosmology, and hence the longest wavelength,

$$\lambda_{\text{max}}(t) \equiv \frac{2\pi a(t)}{k_{\text{min}}}, \quad (7)$$

corresponds to the first fluctuation to have emerged out of the Planck domain into the semiclassical universe. Thus, the ratio

$\lambda_{\max}(t)/R_h(t)$, where $R_h(t) = c/H(t)$ is the Hubble radius at time t , would have remained fixed throughout cosmic evolution.

One can see right away that this essential concept is well supported by the Planck data. In the $R_h = ct$ cosmology, quantum fluctuations began to form at about the Planck time, t_{Pl} , with a maximum wavelength

$$\lambda_{\max}(t_{\text{Pl}}) = \eta \, 2\pi R_h(t_{\text{Pl}}), \quad (8)$$

where η is a multiplicative factor $\sim O(1)$ (Melia 2019). The measured value of k_{\min} (Equation (6)) confirms this basic theory by showing that the ratio $\lambda_{\max}(t)/R_h(t)$ has not changed over the universe's entire expansion since the Planck era, corresponding to an increase in $a(t)$ by over 60 orders of magnitude. Putting $t = t_0$ in Equation (7), one finds that $\lambda_{\max}(t_0) \approx 2.0 \times 10^4$ Mpc, which is to be compared with $\eta 2\pi R_h(t_0) \approx \eta 2\pi \times 4.5 \times 10^3$ Mpc. These two lengths are equal as long as $\eta = 2/3$. But it must be emphasized that any expansion different from that in $R_h = ct$ would have produced highly divergent values of $\lambda_{\max}(t_0)$ and $R_h(t_0)$ today. In other words, the near equality of $\lambda_{\max}(t_0)$ and $R_h(t_0)$ would be extremely unlikely if it were random, so already we see that the basic premise underlying the origin of quantum fluctuations in $R_h = ct$ is borne out by the Planck measurements.

This outcome is highly relevant to our identification of where the anisotropies in the CMB were produced because it provides an entirely new length scale (i.e., λ_{\max}) one may use to estimate z_{dust} . The optimization that completely removes the angular correlation anomaly is given as $u_{\min} = 4.34 \pm 0.50$, where $u_{\min} \equiv k_{\min} r_{\text{dust}}$ in terms of the comoving radius (r_{dust}) to the dust screen (Melia & Lopez-Corredoira 2018; Sanchis-Lozano et al. 2022). It is easy to see that one may therefore write

$$u_{\min} = \frac{1}{\eta} \frac{R_{\text{dust}}}{R_h(t_{\text{dust}})}, \quad (9)$$

where R_{dust} is the proper distance to the dust screen, and $R_h(t_{\text{dust}})$ is the corresponding Hubble radius at that time. Therefore,

$$\ln(1 + z_{\text{dust}}) = \eta u_{\min}, \quad (10)$$

which yields

$$z_{\text{dust}} = 17.05_{-5}^{+8} \quad (\text{largest CMB mode}). \quad (11)$$

Equation (11) is to be compared with Equation (5), which provided an independent measurement of this redshift. Clearly, these two estimates of the dust screen's location are highly consistent with each other, even though they follow from two entirely different length scales in the CMB anisotropies: (i) the acoustic peak in the CMB power spectrum and (ii) the (unrelated) size of the largest fluctuation mode. These results affirm our conclusion that the CMB anisotropies emerged during the Population III era when interpreted in the context of $R_h = ct$.

4. Impact of a Dust Screen at $z \sim 16$

4.1. Recombination Lines

One of the most straightforward tests to distinguish between a model in which the CMB propagated freely out of recombination at $z_{\text{cmb}} \sim 1080$ versus one in which the

background radiation subsequently diffused through a dust screen at $z_{\text{dust}} \sim 16$ involves the search for recombination lines. These should be present at some level in the microwave spectrum if the standard scenario is correct, but dust reprocessing would have completely wiped them out. Extensive simulations have already been carried out to predict the intensity of the lines in the standard model (Rubino-Martin et al. 2006, 2008). They show that the impact of line emission on the angular power spectrum of the CMB is probably quite small, $\sim 0.1\text{--}0.3 \mu\text{K}$. Nevertheless, the recombination lines may still be distinguished from other effects because of their peculiar frequency and angular dependence. Thus, if future high-sensitivity experiments measure such deviations with narrowband spectral observations, the dust screen scenario we are proposing in this paper would almost certainly be ruled out.

4.2. The Dust-reprocessed CMB Spectrum

Within the standard model, the plasma near the LSS is dominated by hydrogen and helium ions and their electrons, so its opacity is heavily influenced by Thomson scattering. This process can dilute the Planck spectrum produced at large optical depths, though not its shape, as the CMB photons diffuse through a progressively thinning photosphere. In other words, though the CMB intensity may differ somewhat from a true Planck function, its "color" temperature cannot change (Melia 2009).

In contrast to this relatively simple scenario, one must take into account the fact that the efficiency of dust absorption, Q_{abs} , is frequency-dependent (Wright 1982) within the hypothesized dust screen at $z_{\text{dust}} \sim 16$ in the $R_h = ct$ universe. As we shall see shortly, however, the reprocessed radiation field can still be quite simple and featureless if the physical conditions bring the dust particles into thermal equilibrium with the background light. To gauge its impact on the CMB's spectral shape, we begin by assuming a density $n_d(\Omega, t)$ of thermalizers at a temperature $T_d(\Omega, t)$ in the direction $\Omega \equiv (\theta, \phi)$. As is well known, the Q_{abs} of the thermalizers depends on several factors, including composition, orientation, geometry, and frequency.

In terms of the intensity $I(\nu, \Omega)$, I/ν^3 is invariant, so if we assume Kirchoff's law with isotropic emission by each radiating surface along the line of sight, we may write the intensity observed at frequency ν_0 in the direction Ω as

$$\begin{aligned} I(\nu_0, \Omega) &= \langle \sigma \rangle \frac{2h\nu_0^3}{c^2} \int_0^{t_0} \frac{dV(t)}{dt} n_d(\Omega, t) \\ &\times \frac{\langle Q_{\text{abs}}(\nu[\nu_0, t]) \rangle}{d_L(t)^2} P(\nu[\nu_0, t]), \\ &T_d[\Omega, t] e^{-\tau(\nu_0, \Omega, t)}, \end{aligned} \quad (12)$$

where $\langle \sigma \rangle$ is the average cross section of the thermalizers, $\langle Q_{\text{abs}} \rangle$ is an average over the randomly oriented thermalizers in the field of unpolarized radiation, d_L is the luminosity distance, dV is the comoving volume element, and

$$P(\nu, T) \equiv \frac{1}{\exp(h\nu/kT) - 1} \quad (13)$$

is the mean number of photons per mode. In writing $\langle \sigma Q_{\text{abs}} \rangle \approx \langle \sigma \rangle \langle Q_{\text{abs}} \rangle$, we have assumed that one type of dust

is dominant. The blackbody intensity is correspondingly

$$B(\nu, T) \equiv \frac{2h\nu^3}{c^2} P(\nu, T). \quad (14)$$

In these expressions (and all that follow below), the quantity

$$\tau(\nu_0, \Omega, t) = \langle \sigma \rangle \int_t^{t_0} dt \langle Q_{\text{abs}}(\nu[\nu_0, t]) \rangle n_d(\Omega, t) \quad (15)$$

is the optical depth due to thermalizers along the line of sight between time t and t_0 .

For simplicity, we assume a scaling law

$$n_d(\Omega, t) = n_d(\Omega, 0)(1+z)^\epsilon. \quad (16)$$

Then, for convenience, we recast these integrals in terms of the redshift z :

$$\begin{aligned} I(\nu_0, \Omega) &= \tau_0(\Omega) \frac{2h\nu_0^3}{c^2} \int_0^\infty dz' \frac{(1+z')^{\epsilon-1}}{cE(z')} \\ &\times \langle Q_{\text{abs}}(\nu_0[1+z']) \rangle P(\nu_0[1+z']) T_d[\Omega, z'] \\ &\times e^{-\tau(\nu_0, \Omega, z')}, \end{aligned} \quad (17)$$

with

$$\tau(\nu_0, \Omega, z) = \tau_0(\Omega) \int_0^z dz' \frac{(1+z')^{\epsilon-1}}{cE(z')} \langle Q_{\text{abs}}(\nu_0[1+z']) \rangle. \quad (18)$$

Here we have defined the quantities,

$$\tau_0(\Omega) \equiv \frac{c}{H_0} \langle \sigma \rangle n_d(\Omega, 0) \quad (19)$$

and

$$E(z) \equiv \frac{H(z)}{H_0}. \quad (20)$$

But notice that

$$\begin{aligned} \frac{d}{dz} e^{-\tau(\nu_0, \Omega, z)} &= -\tau_0(\Omega) \times \frac{(1+z)^{\epsilon-1}}{cE(z)} \\ &\times \langle Q_{\text{abs}}(\nu_0[1+z]) \rangle e^{-\tau(\nu_0, \Omega, z)}, \end{aligned} \quad (21)$$

and so Equation (17) may be written in the form

$$\begin{aligned} I(\nu_0, \Omega) &= -\frac{2h\nu_0^3}{c^2} \int_0^\infty dz' P(\nu_0[1+z'], T_d[\Omega, z']) \frac{d}{dz'} \\ &\times e^{-\tau(\nu_0, \Omega, z')}. \end{aligned} \quad (22)$$

Integrating this expression by parts then yields

$$\begin{aligned} I(\nu_0, \Omega) &= B(\nu_0, T_d[0]) + \frac{2h\nu_0^3}{c^2} \int_0^\infty dz' e^{-\tau(\nu_0, \Omega, z')} \\ &\times \frac{d}{dz'} P(\nu_0[1+z'], T_d[\Omega, z']). \end{aligned} \quad (23)$$

The dust-reprocessed CMB intensity, $I(\nu_0, \Omega)$, is therefore a true blackbody (the first term on the right-hand side of Equation (23), unless the second term—arising from modifications to the background radiation as it diffuses through the dust—is significant compared to the Planck function $B(\nu_0, T_d[0])$). Very critically, however, it is not difficult to see that $I(\nu_0, \Omega)$ does not deviate at all from the Planck function when

$T_d(z) \propto (1+z)$, regardless of how the optical depth $\tau(\nu_0, \Omega, z)$ varies with ν_0 .

To fully understand this point, consider that the temperature of free-streaming radiation scales simply as

$$T(z) = T_0(1+z). \quad (24)$$

Thus, if the dust and the radiation it rethermalizes are in equilibrium (we shall discuss what is required for this to happen in Section 4.3 below), T_d is also expected to follow Equation (24). But the frequency itself scales as $\nu \propto (1+z)$, and so $P(\nu, T)$ is independent of redshift. The term $(d/dz')P$ in Equation (23) is thus strictly zero, leaving $I(\nu_0, \Omega) = B(\nu_0, T_d[0])$ at each and every frequency (see Rowan-Robinson et al. 1979 for the introduction of such ideas).

4.3. Temperature of the Dust Screen

We thus see that our intuition concerning the impact of dust reprocessing based on our local Galactic environment may not apply to a dust screen at $z_{\text{dust}} \sim 16$. The key issue is not that the dust opacity is frequency-dependent but rather whether the physical conditions at this redshift may have induced the dust to reach local thermal equilibrium with the background radiation. If the answer is yes, then, according to Equation (23), the frequency dependence of the dust opacity is irrelevant to the final reprocessed radiation spectrum.

In this section, we shall first consider whether Population III stars could have generated enough dust particles to produce an optical depth $\tau(\nu_0, \Omega, z) \gg 1$ at $z_{\text{dust}} \sim 16$ and then see if the condition $T_d = T$ could have realistically been met. In preparation for this analysis, we should remind ourselves that the early work on this possibility, though framed in the context of Λ CDM, already demonstrated that a medium could be rendered optically thick just by dust, even if the latter represented a mere percentage density compared to other constituents in the cosmic fluid (Rees 1978; Rowan-Robinson et al. 1979; Rana 1981; Wright 1982; Hawkins & Wright 1988).

A remnant trace of Population III stars seeded prior to $z \sim 15$ appears to have been found in the guise of extremely metal-poor stars in the Galactic bulge (Howes et al. 2015), consistent with the conventional picture of a very low metal abundance in the ISM prior to stellar nucleosynthesis during the Population III era. The actual metallicity between Population III and Population II star formation has not yet been identified, however, so we parameterize it as f_Z relative to solar abundance. As we shall see shortly, the dust was created prior to $z \sim 16$ and then subsequently destroyed by Population II supernovae, coinciding with the beginning of the epoch of reionization (at $z_{\text{EoR}} \sim 14$ –15). It is the dust’s existence within this relatively narrow range of redshifts that motivates us to refer to it as a “dust screen.”

The expansion profile in the $R_h = ct$ universe is similar, though not identical, to that in Λ CDM, so the optimized cosmological parameters, such as the Hubble constant, can differ by several percentage points between these two models. Nevertheless, for simplicity, let us assume the concordance values for the most essential variables, notably, $H_0 = 67.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and a baryon fraction $\Omega_b \sim 0.04$ (Planck Collaboration et al. 2016). With these quantities, we estimate that the comoving metal mass density at $z = 16$ was $\rho_s(z = 16) \sim 4 \times 10^{-29} f_Z \text{ g cm}^{-3}$. Thus, with a bulk density

of silicate grains of $\sim 2 \text{ g cm}^{-3}$, each of which had an average radius $r_s \sim 0.1 \mu\text{m}$, the dust number density would have been $n_s(z=16) \sim 5 \times 10^{-15} f_Z \text{ cm}^{-3}$.

We can thus estimate the metallicity f_Z required for all of the CMB photons to have been absorbed at least once by the dust screen by noting that, at $z=16$, its spectrum ranged from $\lambda_{\min} \sim 0.003 \text{ cm}$ to $\lambda_{\max} \sim 0.02 \text{ cm}$, corresponding to a dust absorption efficiency $Q(\lambda_{\min}) \sim 0.02$ and $Q(\lambda_{\max}) \sim 0.003$ (Draine 2011). Thus, the photon mean free path due to dust absorption would have fallen in the range $3 \times 10^{25} f_Z^{-1} \text{ cm} \lesssim \langle l_\gamma \rangle \lesssim 2 \times 10^{26} f_Z^{-1} \text{ cm}$. This is to be compared with the gravitational (or Hubble) radius at that redshift, $R_h(z=16) \sim 10^{27} \text{ cm}$ (Melia 2018b). We therefore see that every CMB photon would have been absorbed by dust prior to $z \sim 16$ if $f_Z \gtrsim 0.2$, representing $\sim 20\%$ of the solar value—a very reasonable number indeed. Moreover, a more recent investigation (Huang et al. 2021) has shown that the absorption efficiency may be even larger—by a factor of up to 10—compared to that reported by Draine (2011), so the required metallicity at $z \sim 16$ is probably even smaller than 20% of the solar value.

The second issue concerns whether this absorption process was sufficient to bring the dust particles into thermal equilibrium with the radiation, for which we must consider two additional factors. First, the average cooling $K(T_d)$ and heating $H(T)$ rates determine the energy flow to and from the radiation. Second, one must take into account the fact that each photon absorption may have produced a jump in the dust particle's temperature, depending on its size (Draine & Li 2001; Weingartner & Draine 2001). The dust was heated by an isotropic radiation field with an angle-averaged intensity $J_\lambda = B(\lambda, T)$ (see Equation (14)), with $T(z=16) \approx 46 \text{ K}$ in the cosmological context. Note that this differs from our local Galactic neighborhood, where the primary heating agent is instead UV light. In this environment, a typical dust particle was heated at a rate $H(T) = 4\pi r_s^2 \int_0^\infty d\lambda \pi B(\lambda, T) Q(\lambda)$, calculated from the previously defined absorption efficiency $Q(\lambda)$. Kirchoff's law then gives its emissivity $\propto B(\lambda, T_d) Q(\lambda)$. Similarly, its cooling rate was $K(T_d) = 4\pi r_s^2 \int_0^\infty d\lambda \pi B(\lambda, T_d) Q(\lambda)$. These two integrals are identical only when $T_d = T$.

The dust temperature evolves according to the equation

$$C(T_d) dT_d/dt = H(T) - K(T_d), \quad (25)$$

where $C(T_d)$ is the heat capacity. At $T_d \sim 46 \text{ K}$, we have approximately $C(46 \text{ K}) \sim 0.2 k_B N_s$, where k_B is Boltzmann's constant, and N_s is the total number of atoms in the dust grain (Draine & Li 2001). For the aforementioned grain size $r_s \sim 0.1 \mu\text{m}$, one estimates that $N_s \sim 3 \times 10^8$ (Weingartner & Draine 2001), and with $\langle Q(\lambda) \rangle \sim 0.012$, one therefore finds that

$$dT_d/dt \sim 10^{-7} (T^4 - T_d^4) \text{ K s}^{-1}. \quad (26)$$

Let us assume that either $H(T)$ or $K(T_d)$ was dominant when $T_d \neq T$. We then see that it would have taken a mere 50 s for the dust to reach equilibrium with the background CMB field at $T = T_d \sim 46 \text{ K}$. Subject to possible limitations from the second factor we shall consider shortly, this result thus clearly shows that the dust at $z \sim 16$ would have been fully thermalized with the background radiation.

There is a caveat to this result, however, which constitutes the second factor we must take into account. This outcome

would be unrealistic if the dust grains were so small that each absorption event would have changed their temperature in quantum jumps, rather than continuously. The absorption of a photon with wavelength λ changes the temperature of a dust grain containing N_s atoms by an amount $\Delta T_d = hc/\lambda C(T_d) \sim 7.2(\lambda N_s)^{-1} \text{ K}$ (Draine & Li 2001; Weingartner & Draine 2001). Larger grains (i.e., those with radius $r_s \sim 0.1\text{--}0.3 \mu\text{m}$) would thus have avoided this problem because they contain $N_s \sim 3 \times 10^8\text{--}10^{10}$ atoms, for which ΔT_d is a minuscule fraction ($\sim 10^{-9}\text{--}10^{-8}$) of $T_d = 46 \text{ K}$ at all wavelengths of interest, $\lambda \sim 0.003\text{--}0.02 \text{ cm}$. For them, the evolution in T_d at $z \sim 16$ would have proceeded smoothly, as described above. But smaller grains have less heat capacity and a reduced radiating area, so each CMB photon absorption would have produced spikes in temperature (Draine & Li 2001).

The assumption of a smooth evolution in T_d thus breaks down for grains smaller than $r_s \sim 0.003 \mu\text{m}$, for which thermal equilibration would have proceeded via stochastic heating. So, in summary, the dust temperature in this model could very easily have been equilibrated to the background radiation temperature as long as the dust particles were silicates of size $\sim 0.003\text{--}0.3 \mu\text{m}$. Larger grains would have violated the previous estimate of $n_s(z=16)$ and $f_Z \sim 0.2$, requiring an unreasonably large fraction of the mass in the form of dust at $z \sim 16$.

Interestingly, the ultrasmall grains are destroyed faster than their bigger counterparts when exposed to the shock waves produced by the supernovae of Population III stars (see Section 4.4), so there may be a natural motivation for expecting an absence of these ultrasmall particles during the principal time when the CMB was rethermalized.

To complete our self-consistency check, we need to demonstrate that these estimates do not violate our assumption of a negligible contribution to the overall background radiation field by the Population III stars. These stars were much more massive ($500 M_\odot \gtrsim M \gtrsim 21 M_\odot$) than those forming today (Bromm & Larson 2004; Glover 2005) and emitted copious high-energy radiation that ionized the halos within which they grew (Johnson et al. 2007). We can estimate the fluence of radiation they emitted by calibrating it to how much metallicity they contributed to the ISM.

A large fraction of the Population III stars exploded as supernovae following their brief ($\sim 10^6\text{--}10^7 \text{ yr}$) lives (Heger et al. 2003), creating the dust screen (Whalen et al. 2008) we are proposing in this paper. From the dust particle size and number inferred above, we estimate that these stars must have injected roughly $9 \times 10^{44} \text{ g Mpc}^{-3}$ (comoving volume) of dust into the ISM during their principal epoch ($20 \gtrsim z \gtrsim 15$) of formation.

Whether a Population III star ended its life as a supernova depended on its preexplosion mass. Its mass also provided an indication of how much metallicity it created prior to ending its life: for $M \lesssim 40 M_\odot$, it ejected $\sim 20\%$ of its mass into the ISM, and for $M \gtrsim 140 M_\odot$, the explosion was much more powerful, dispersing $\gtrsim 50\%$ of its mass (Heger & Woosley 2002). For simplicity, we adopt a typical mass $M \sim 100 M_\odot$ and an ejection fraction of 30% (representing an average between these two limits). In the $R_h = ct$ universe,

$$1 + z = 1/tH_0, \quad (27)$$

implying an interval of time $\Delta t \sim 200$ Myr between $z = 15$ and 20. And so we estimate that, during the principal Population III era, an amount of dust required to render the ISM optically thick could have been produced if $\sim 1.5 \times 10^8$ Mpc $^{-3}$ of the stars exploded as supernovae.

A typical Population III star with mass $M \sim 100 M_{\odot}$ also emitted radiation as a blackbody with radius $R_* = 3.9 R_{\odot}$ and a surface effective temperature $T_* = 10^5$ K, implying a bolometric luminosity of $\sim 4 \times 10^{39}$ erg s $^{-1}$. The total stellar energy density radiated during the Population III era would thus have been $U_{\text{III}} \sim 4 \times 10^{63}$ erg Mpc $^{-3}$. At $z \sim 16$, however, the CMB energy density was $U_{\text{cmb}} \sim 8 \times 10^{65}$ erg Mpc $^{-3}$. Therefore, $U_{\text{III}}/U_{\text{cmb}} \sim 0.5\%$, a negligible fraction that would have easily been thermalized and absorbed into the background Planck distribution. And if we consider photon number density instead of radiative energy density, this ratio would have been even smaller, since the average stellar photon energy was much higher than that of its CMB counterpart.

4.4. Frequency-dependent Power Spectrum

A less discussed, though equally important, consequence of a dust screen for the CMB is that, unlike the frequency-independent optical depth in a Thomson scattering environment, the depth to which our instruments “see” the radiation through the dust screen does change with frequency. This could result in a measurably different fluctuation pattern as a function of wavelength.

Such photospheric depth effects would probably not change the shape and size of the larger fluctuations observed at different frequencies, but they could alter the anisotropy observable on (smaller) scales comparable to the angular diameter displacement of the dust screen at two different frequencies. At some level, these differences would alter the CMB power spectrum constructed at one wavelength compared to that at another.

Before we consider the expected differences in this effect between the recombination and dust-reprocessing scenarios, let us first gather the observational evidence concerning a possible frequency dependence of the power spectrum. Such a detailed analysis was reported most recently by the Planck collaboration (Planck Collaboration et al. 2016), following an earlier assessment of the WMAP first-year release (see, e.g., Figure 2 in Hinshaw et al. 2003).

Generating the Planck maps at different frequencies is challenging due to the wavelength dependence of the foreground conditions themselves, making it difficult to cross-correlate the patterns. In spite of this, Planck has shown that residuals in the half-mission TT power spectra, sampling a frequency range 70–217 GHz, clearly vary from one power spectrum to the next. The caveat here, of course, is that this variation could merely be due to noncosmological factors, such as foreground systematics.

On a more technical level, one may also estimate the dependence of the multipole power coefficients on the chosen frequency by extending the range of multipole numbers used in the analysis, up to a maximum value l_{max} . Allowing l_{max} to vary from ~ 900 to several thousand permits one to search for a greater variation in the observed anisotropies on small scales compared to the larger ones. Interestingly, this type of analysis shifts the optimized cosmological parameters by up to $\sim 1\sigma$, whose interpretation cannot always be made in terms of noncosmological effects. Perhaps even more importantly, the

cross-power spectrum at lower frequencies ($\lesssim 100$ GHz) reveals variations in the overall amplitude D_{ℓ} by as much as $\sim 4\sigma$ compared to that inferred from measurements at higher frequencies.

As of today, the Planck analysis reveals that the CMB multipole power varies by an amount $\Delta D_{\ell} \sim 40 \mu\text{K}^2$ at $\ell \sim 400$, all the way up to $\sim 100 \mu\text{K}^2$ at $\ell \gtrsim 800$. Aside from the fact that these variations appear to be real, it should also be noted that ΔD_{ℓ} increases with multipole number ℓ across the frequency range ~ 70 –200 GHz, as one would expect if a variable optical depth were preferentially affecting the smaller fluctuations. Given that $D_{\ell} \sim 2000 \mu\text{K}^2$ over this range, the maximum variation of the power spectrum due to a frequency-induced change in the optical depth in the emission region appears to be $\sim 2\%$ at $\ell \sim 400$, increasing to $\sim 5\%$ at $\ell \gtrsim 800$. In other words, based on what we know so far, the frequency dependence of the power spectrum is modest but not absent. We therefore conclude that the evidence does not appear to clearly favor a CMB produced within a purely Thomson scattering environment.

This frequency dependence of the power spectrum instead appears to be qualitatively consistent with what one would expect in the dust screen scenario we are exploring in this paper. Let us also see if the current limits quoted above stand up to more quantitative scrutiny. In order for it to be consistent with the observations, the angular diameter distance to the dust screen should not vary with frequency so much that it causes unacceptably large variations in the inferred comoving BAO scale at $z_{\text{dust}} \sim 16$. As discussed in Section 3 above, any variation in the optical depth through the dust screen would be limited to the range of angular diameter distances between $z \sim 14$ and 16, which we shall justify more fully in this section.

Though nucleosynthesis and mass ejection in Population III stars were somewhat different than those occurring later, our current understanding of the life cycle of dust suggests it was quite similar then and now: (i) dust particles formed primarily in the ejecta of evolved stars and (ii) were subsequently destroyed much more rapidly than they were formed in supernova-generated shock waves. This story line was established over half a century ago (Routly & Spitzer 1952; Cowie 1978; Seab & Shull 1983; Welty et al. 2002) with the earliest observations of shock-induced dust destruction, which severely constrains how much dust can possibly exist near young, star-forming regions. The early-type stars emit most of the UV light and evolve on a timescale of only 10–20 Myr, ending their lives as supernovae. Their shocks completely destroy all the grains in the ISM on a timescale $\lesssim 100$ Myr (Jones et al. 1994, 1996).

If we adopt the view that the dust screen was created by Population III stars prior to $z_{\text{dust}} \sim 16$, we can then estimate the redshift, $z_{\text{dust}} - \Delta z$, by which subsequent Population III and Population II supernovae would have completely destroyed it. According to Equation (27), 100 Myr at z_{dust} corresponds to $\Delta z \sim 2.0$, while $\Delta z \sim 1.0$ is roughly 53 Myr. The dust destruction scenario thus corresponds very closely to the other observational requirements we have discussed thus far, which see the creation of the dust screen due to Population III stars by $z_{\text{dust}} \sim 16$ and the beginning of the epoch of reionization by $z_{\text{EoR}} \sim 14$ –15.

Then, using Equation (4) with $z = z_{\text{dust}}$, we can easily estimate the impact of such a dust screen width on the inferred angular scale θ_s . Assuming the medium was optically thick at

Table 1
Width of the Dust Screen at $z_{\text{cmb}} \sim 16$ and Its Maximum Impact on θ_s

Δz	Δt (Myr)	$\Delta\theta_s$ (deg)	Percentage of θ_s
1	53	0.013	2.2%
2	100	0.025	4.2%

$z_{\text{dust}} \sim 16$ and that it became transparent by $z_{\text{dust}} - \Delta z$, one can show that θ_s would have changed by an amount

$$\Delta\theta_s = \frac{r_{\text{BAO}}}{R_h(t_0)} \left[\frac{1}{\ln(1 + z_{\text{dust}} - \Delta z)} - \frac{1}{\ln(1 + z_{\text{dust}})} \right]. \quad (28)$$

The range of possible outcomes is shown in Table 1. Since the angular diameter distance in the $R_h = ct$ universe changes very slowly with redshift near z_{dust} , the maximum possible impact on θ_s of optical depth effects across the dust screen is quite small, no more than a few percent—fully consistent with the current observational limits discussed above.

4.5. E- and B-mode Polarization

We next consider what the detection (or nondetection) of E- and B-mode polarization can reveal about the medium where the CMB is produced and (possibly) reprocessed by dust. We focus on linear polarization, which has already been measured at some level and promises to probe inflationary physics at an unprecedented level of detail via several upcoming missions, e.g., LiteBIRD (Hazumi et al. 2019), CORe (Delabrouille et al. 2018), PRISM (André et al. 2014), PICO (Hanany et al. 2019), and ECHO (Adak et al. 2022).

Linear polarization is geometrically decomposed into two rotational invariants, known as the E (gradient) mode and the B (curl) mode (Kamionkowski et al. 1997; Zaldarriaga & Seljak 1997). The Thomson scattering of anisotropic radiation associated with the scalar density fluctuations responsible for the temperature hot spots also creates E-mode polarization. This process does not produce B-mode polarization, however, because the modes are longitudinal density compressions aligned perpendicular to the direction of propagation, resulting in a pattern with zero curl. In contrast, tensor (or gravity) modes redshift the wavelength of the incident anisotropic radiation along diagonals to the propagation vector, resulting in a polarization pattern with a nonzero curl. The presence of B-mode polarization in the CMB could thus signal a possible origin in tensor fluctuations of a quantized scalar field in the early universe.

But the detection of these modes is quite challenging, because the foreground polarized intensity due to dust in the Galaxy is orders of magnitude larger than that expected in the CMB (Planck Collaboration et al. 2020b). Aspherical dust particles in our neighborhood align with an ambient magnetic field and produce both E- and B-mode polarization. Unfortunately, a simple modeling of this emission is not possible because the relative power in the E- and B-mode components is a complex function of the underlying physical conditions, especially (i) the magnetic field \mathbf{B} , (ii) its geometry (i.e., turbulent versus smooth), and (iii) its energy density relative to that of the plasma. And there have been some surprises. The naive prediction had been that the E- and B-mode polarizations would be oriented randomly in the foreground map, with roughly equal intensities (Caldwell et al. 2017). Planck instead

measured a factor of ~ 2 E/B anisotropy (Planck Collaboration et al. 2020b).

The signal remaining after this foreground polarization is subtracted contains only an E-mode pattern that one may assign to the CMB, with no evidence of any B-mode polarization. An additional significant clue is provided by stacking the CMB peaks, which uncovers a characteristic ringing pattern in the temperature due to the first acoustic peak (on scales of $\lesssim 1^\circ$), with an associated strong pattern in the E-mode stack (see, e.g., Figure 20 in Planck Collaboration et al. 2020b). In the context of Λ CDM, such a correlation in the temperature and E-mode anisotropies supports the standard picture in which the CMB anisotropies were created in the recombination zone.

As we now discuss, however, neither the temperature-E-mode (TE) correlation nor the absence of B-mode polarization in the foreground-subtracted signal rule out a reprocessing of the CMB by a dust screen at z_{dust} . We shall demonstrate (i) that the current observations are not sufficiently precise to do this, and (ii) that our theoretical understanding of dust polarization is not complete enough for us to conclude that B-mode polarization should or should not be present in the foreground-subtracted CMB map.

For dust to emit polarized light, its grains need to be nonspherical so that they can spin about their semimajor axis. In addition, there must be an organized magnetic field present to align them. We have no evidence regarding whether or not the earliest dust grains produced in Population III ejecta were spherical, but observations in other dust environments suggest that they probably were not. We similarly have no hard evidence for the existence of an intergalactic magnetic field, but our current measurements suggest that, if present, it was weaker than those found in galaxies, where $|\mathbf{B}_G| \sim 3\text{--}4 \mu\text{G}$ (Grasso & Rubinstein 2001).

Nevertheless, it is certainly not ruled out. For example, fields within the Abel clusters appear to have amplitudes $|\mathbf{B}_{\text{ICM}}| \sim 1\text{--}10 \mu\text{G}$. Other lines of evidence include high-resolution measurements of the rotation measure in high- z quasars, which indicate that weak magnetic fields must have been present in the early universe. Radio observations of 3C 191 at $z = 1.945$ (Kronberg 1994) imply that $|\mathbf{B}_{\text{IGM}}| \sim 0.4\text{--}4 \mu\text{G}$.

Interesting limits may also be derived from the ionization fraction in the intergalactic medium (IGM) and reasonable assumptions regarding the magnetic coherence length. The largest reversal scale (~ 1 Mpc) seen in galaxy clusters implies that $|\mathbf{B}_{\text{IGM}}| \lesssim 10^{-9}$ G (Kronberg 1994; Grasso & Rubinstein 2001). If their coherence length is much larger, however, these fields could be as small as $\sim 10^{-11}$ G.

This range of values for $|\mathbf{B}_{\text{IGM}}|$ is also supported by less direct arguments. For example, the galactic dynamo origin for \mathbf{B}_G is still controversial. Some maintain that the galactic field was produced by the adiabatic compression of $|\mathbf{B}_{\text{IGM}}|$ when the protogalactic cloud collapsed. If so, then $|\mathbf{B}_{\text{IGM}}|$ would have been $\sim 10^{-10}$ G at $z > 5$, around the time when galaxies were forming. This argument is consistent with the limits placed by the rotation measures of high- z objects (Grasso & Rubinstein 2001).

The magnetic field within the halos where Population III stars formed and ejected their dust could have been even stronger than $|\mathbf{B}_{\text{IGM}}|$. The issue here is whether it was strong enough to align the dust grains. But other mechanisms have also been proposed to assist with this process, such as

mechanical alignment (Dolginov & Mytrophanov 1976; Lazarian 1994; Roberge et al. 1995; Hoang & Lazarian 2012) and radiative alignment (Dolginov & Mytrophanov 1976; Draine & Weingartner 1996, 1997; Weingartner & Draine 2003; Lazarian & Hoang 2007), which are not so sensitive to the magnetic field amplitude. It is fair to say that our experience with dust grain alignment and their polarized emission within our Galaxy is probably not general enough to encompass such processes during the Population III era at $z_{\text{dust}} \sim 16$.

This uncertainty is relevant to the question of why polarized dust emission has never been seen from the IGM and whether the CMB polarization constraints already available today may nevertheless still be consistent with the dust screen scenario. There are several good reasons to suspect that this may be the case. First, the dust particles in the screen at $z_{\text{dust}} \sim 16$ would have been destroyed by redshift $z \sim 14$. As such, the nondetection of polarized dust emission from the IGM at $z < 14$ does not necessarily imply an absence of a magnetic field in the IGM.

Second, detailed theoretical studies of dust emission and its polarization (motivated in part by the Planck data) show that the dust polarization fraction is typically $\sim 6\%$ – 10% for a broad range of physical conditions (see, e.g., Draine & Fraise 2009). This outcome is remarkably similar to the $\sim 10\%$ fraction measured in the CMB (Planck Collaboration et al. 2020b). In other words, the dust screen at $z_{\text{dust}} \sim 16$ could very well have accounted for all of the E-mode polarization fraction measured in the CMB thus far.

The relative E- and B-mode intensities depend on several detailed properties of the dust particles and the background magnetic field (see, e.g., Caldwell et al. 2017; Kritsuk et al. 2018; Kim et al. 2019). Indeed, an alignment between the density structures and the magnetic fields generates more E-mode power than B-mode (Zaldarriaga 2001). Thus, a third reason why the dust screen may have produced the observed CMB polarization features is that the E/B asymmetry depends heavily on the randomness of this alignment; a higher degree of randomness produces less E/B asymmetry. If \mathbf{B} within the Population III halos was highly organized, the E/B asymmetry produced by the dust would have been quite large.

Caldwell et al. (2017) considered this feature of the E/B emissivity in the context of magnetized fluctuations comprised of slow, fast, and Alfvén magnetohydrodynamic waves. They concluded that the ratio E/B could emerge within quite a broad range, from the factor of ~ 2 observed in the Galaxy by Planck all the way to ~ 20 , when the medium is threaded by weak fields and fast magnetosonic waves. But these are precisely the conditions that would have been present in the dust environment at $z_{\text{dust}} \sim 16$ (see their Figure 3 for a summary of these results).

Thus, contrary to what conventional wisdom would have us believe, polarized dust emission need not automatically produce detectable B-mode emission along with E-mode. As such, the current nondetection of B-mode polarization in the foreground-subtracted CMB intensity does not rule out reprocessing of the background radiation by dust within the Population III screen. Interestingly, an eventual detection of B-mode polarization could work both ways; it could constrain either inflation in Λ CDM or the physical conditions within a magnetized dusty environment at $z_{\text{dust}} \sim 16$.

Finally, we acknowledge the fact that a TE correlation has also been detected by Planck in the foreground dust emission,

not just the direct CMB signal. This means that the overlap between the temperature and E-mode stacks of the foreground-subtracted CMB intensity need not necessarily be due solely to Thomson scattering in a recombination zone. It apparently could have been produced by polarized dust emission in a dust screen at $z_{\text{dust}} \sim 16$.

4.6. Weak Lensing of the CMB

Aside from the observational signatures associated with a dust screen in the Population III era that we have discussed thus far, several other lesser known characteristics of the CMB can potentially distinguish between an interpretation of the anisotropies originating at the LSS ($z \sim 1080$) versus $z_{\text{dust}} \sim 16$. One of these is lensing of the CMB, which has been measured to very high precision. The observed deflections appear to be consistent with the transfer of the background radiation over a comoving distance stretching from $z \sim 1080$ to zero (for an early review, see Lewis & Challinor 2006). But this is only true in the context of Λ CDM. In the $R_h = ct$ universe, one can show that the current CMB lensing data are instead fully consistent with the analogous transfer of background radiation across a comoving distance from $z_{\text{dust}} \sim 16$ to zero.

Although the LSS ($z \sim 1080$) and dust screen ($z_{\text{dust}} \sim 16$) redshifts differ considerably in these two scenarios, what matters most in establishing the lensing effects are (i) the comoving distance to the location of the CMB anisotropies, (ii) the size of the potential wells along the line of sight, and (iii) the actual pattern of anisotropies where the CMB radiation is released. Quite critically, the time–redshift relation between these two models differs by a factor of up to ~ 2 , which accounts for the majority of the differences, as we shall see.

The calculations completed thus far for the formation of structure in the $R_h = ct$ universe (Melia 2017; Yennapureddy & Melia 2018) show that the typical potential well in this model had a size of ~ 265 Mpc, compared with ~ 300 Mpc in Λ CDM. The comoving distance between $z_{\text{dust}} \sim 16$ and zero is correspondingly $\sim 12,200$ Mpc. Thus, the CMB radiation would have traversed approximately 46 potential wells from the dust screen to $z = 0$. Ironically, this is almost exactly the same number as that from $z \sim 1080$ to zero in the standard model (Lewis & Challinor 2006), a similarity that continues to affirm the suspicion that the various free parameters in Λ CDM are optimized by the data to mimic the expansion profile predicted by the zero active mass condition in $R_h = ct$ (Melia 2020).

We therefore estimate that weak lensing from $z_{\text{dust}} \sim 16$ to zero in $R_h = ct$ would have produced an average deflection angle very similar to that from $z \sim 1080$ to zero in Λ CDM. Assuming that the potentials are uncorrelated, we find that the total deflection angle should be $\sim \sqrt{46} \times 10^{-4}$ rad based on the deflection angle due to each single well. Quite remarkably, the overall deflection angle is therefore $\sim 2'$ in both models. Of course, the detailed remapping of the CMB temperature profile by weak lensing is much more complicated than this and ought to be done in the near future. Since the scales are so similar, however, we already know that the observed weak lensing profile probably cannot distinguish between an origin of the CMB within a recombination zone at $z \sim 1080$ and one due to subsequent reprocessing by a Population III–generated dust screen in the context of $R_h = ct$.

4.7. Growth of Structure

Finally, we consider whether density fluctuations corresponding to the CMB temperature anisotropies at $z_{\text{dust}} \sim 16$ would have had enough time to grow into the large-scale structure we observe today. The fluctuations in the CMB temperature correspond to $\sim 10^{-5}$ amplitude variations in density that are believed to have grown gravitationally into galaxies and clusters. In the standard model, linear growth between $z \sim 1080$ and today may account for the formation of structure beginning with such initial conditions, though the early appearance of galaxies and quasars is creating some tension with the standard timeline (Melia 2013, 2014, 2023; Yennapureddy & Melia 2018, 2021).

But if the CMB anisotropies were instead indicative of features emerging at $z_{\text{dust}} \sim 16$, the standard picture would be entirely unworkable, given that there would have been barely enough time to accomplish this starting at $z \sim 1080$. The time-redshift relation in $R_{\text{h}} = ct$ is sufficiently different, however, to fully compensate for the shorter range in z . With a timeline $t(z) = t_0/(1+z)$ (Melia 2017), the duration from $z_{\text{dust}} \sim 16$ to today is ~ 13 Gyr. This is to be compared with the time elapsed since $z \sim 1080$ in Λ CDM, which is ~ 13.7 Gyr. These two times are clearly indistinguishable, which suggests that galaxies and clusters could have grown with equal viability in the comoving frames of these two scenarios.

5. Conclusion

We have demonstrated in this paper that the dust model proposed in the 1970s for the origin of the CMB may still be relevant today, albeit in the context of the $R_{\text{h}} = ct$ cosmology rather than the standard model, Λ CDM. Indeed, for a noninflationary history, such as that expected in the former, the anisotropies measured in the CMB could not have been established at the time when protons and electrons combined and liberated the CMB relic photons. Instead, all of the current observational constraints point to a model in which the CMB photons were subsequently reprocessed by dust at a redshift $z_{\text{dust}} \sim 16$.

This period is interesting but, even more importantly, was followed directly by the epoch of reionization, which began at $z_{\text{EoR}} \sim 14$ –15. The alignment of these two redshifts cannot and should not be viewed as a mere coincidence, because this transition can be easily understood based on what we see in the local universe. The rapid formation of stars would have filled the universe with dust during the Population III era, which presumably peaked at $z \sim 16$, followed by an ~ 100 Myr period during which subsequent supernova explosions would have destroyed all of the dust particles. Together with the correlated rapid increase in UV emissivity, one expects this transition to have heralded the reionization phase.

We are fortunate in that the observational signatures of the recombination and dust scenarios should be easily distinguishable with the improved sensitivities of future experiments. We should be able to definitely rule out one or the other of these models over the next few years, either (i) from the detection of recombination lines at $z \sim 1080$, providing compelling evidence in favor of Λ CDM, or (ii) by confirming the current hint of frequency dependence in the CMB power spectrum, which would favor $R_{\text{h}} = ct$. An $\sim 5\%$ variation in the anisotropy spectrum across the sampled frequency range could be naturally explained as a change in the optical depth through

the dust screen but not in the Thomson scattering-dominated recombination zone.

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