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The Polarization of Dust Thermal Radiation as a Foreground to the CMB

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Galactic dust is known to cosmologists as the dominant foreground to CMB measurements above ~ 100 GHz, especially when dealing with polarization. In this paper, we summarize how the size of dust grains affects their alignment properties and therefore both the optical polarization and the polarization of their radiation. We compare theoretical expectations and experimental measurements. At the present time there is a lack of precise experimental information to predict to what level exactly dust can be removed from CMB data in our quest for the primordial B modes.

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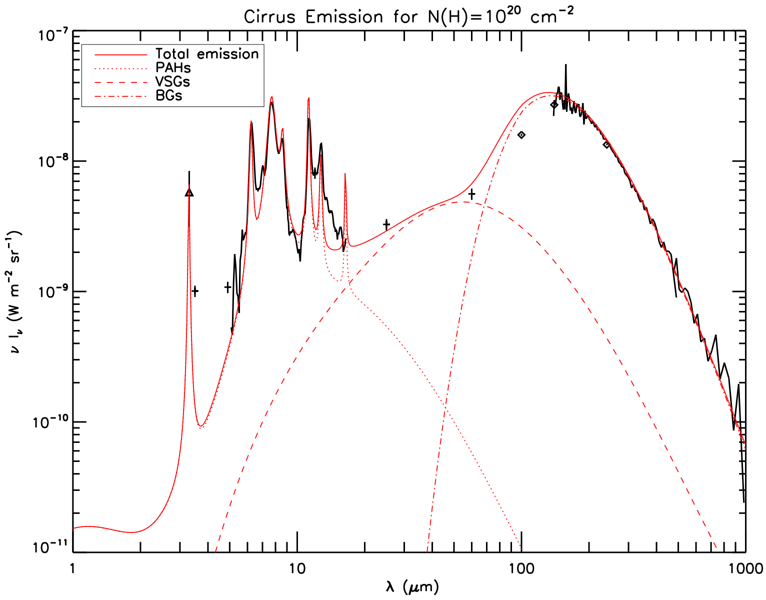

Figure 1: Spectral energy distribution vs frequency of observation. Individual contributions of three grain populations are presented by broken lines. Following [6], courtesy of M. Compiègne.

1. Introduction

The polarization of optical starlight was attributed to aligned aspherical dust grains as early as the 1950's [15, 14, 5]. It is an interesting coincidence that the first publication about its polarized counterpart in the IR and submillimeter (hereafter submm) [38] appeared almost at the same time as the discovery of the CMB [31]. Forty years later, the large fraction of time allocated to foregrounds in this conference on "CMB and physics of the early universe" is not a coincidence. Synchrotron is reviewed by Burigana in this volume. We focus here on dust and why it is a significant foreground to the CMB, especially its polarization.

In sect. 2 we review the nature of the grain populations in the InterStellar Medium (ISM) (2.1) and the main ideas about grain alignment (2.2). Taken together with observational evidence, it appears that the large silicate grains could by themselves be responsible for the near-infrared to ultraviolet interstellar polarization and by extension for the polarization of dust emission which becomes predominant at frequencies above 100 GHz (2.3). We compare observational results on submm polarization to these predictions in sect. 3 and discuss the prospects of component separation in sect. 4.

2. The polarization of dust thermal radiation

Dust participates to the life cycle of the ISM as a whole and comes in different forms and abundances with specific physical properties. The distinction between grain populations is essential to the prediction and/or interpretation of the polarization of their radiation.

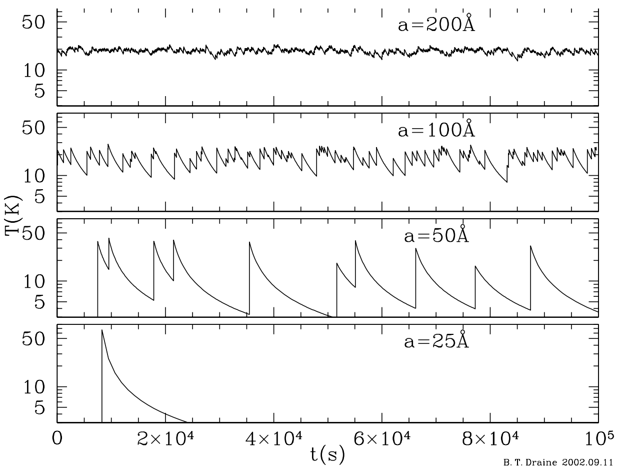

Figure 2: Thermal behaviour of dust grains as a function of their size. Whereas large grains are at thermal equilibrium, small grains with small heat capacity can reach high temperatures when they absorb UV photons. They cool down between successive photon absorptions.

2.1 Grain populations as revealed by their emission

Desert et al. [6] fit the spectrum of Galactic radiation between 1 and 10^3 μm by a mixture of three grain components (Fig. 1). Below ~ 10 μm, the spectrum is dominated by small carbonaceous grains (~ 1 nm) in the form of Polycyclic Aromatic Hydrocarbons (PAH). Above ~ 100 μm, the emission is well understood as the radiation of "big" (~ 0.1 μm) grains, in thermal equilibrium with the radiation bath. Between ~ 10 and ~ 100 μm, the emission cannot be explained by the sum of PAH emission and thermal radiation by the big grains. A population of intermediate-size grains is required. They have very small heat capacity so that they attain high temperatures when they absorb a single UV photon. This is not a thermal equilibrium behaviour (see Fig. 2), nor is the spectrum of emission at the elevated temperatures attained like the thermal equilibrium emission of the big grains.

The chemical composition of dust grains, their size, and thermal behaviour are key elements to understand their alignment, which in turn is a key element to understand the polarization properties of the radiation of these grains.

2.2 Grain alignment

Dust grain alignment theory has been making constant progress over the past fifty years. An extensive review of the subject is beyond the scope of this section and can be found in, e.g., [25]. We only give a summary here.

Following the observation that starlight was polarized by [14, 15], Davis & Greenstein [5] (DG hereafter) proposed an alignment mechanism based on paramagnetic dissipation. The unpaired electrons of the paramagnetic material get oriented by the magnetic field which produces grain magnetization. The magnetization varies with respect to the grain when it rotates. This causes paramagnetic loss (at the expense of grain rotation energy) unless the grain's rotation velocity $\vec{\omega}$ is parallel to $\vec{B}$, in which case magnetization no longer varies. This tends to cancel out the component of $\vec{\omega}$ orthogonal to $\vec{B}$: the longest axis of the grains gets therefore aligned perpendicular to $\vec{B}$, in

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agreement with observations at this time. For this mechanism to be viable, the characteristic time of DG alignment must be shorter than the time of randomization through gaseous bombardment, which appears to be difficult to achieve (e.g., [21]). This mechanism can, however, be enhanced by magnetic inclusions as proposed by [16]. At the same time as DG, Gold [13] proposed a mechanism based on the gaseous bombardment. Atoms deposit angular momentum in the grain perpendicular to both the grain's longest axis and the gas flow. If the flow is supersonic the alignment is not disrupted by collisions coming from other directions. The difficulty is therefore to provide the supersonic drift and in practice this cannot explain the grain alignment in the diffuse ISM.

In the 1970's, new mechanisms were proposed. Purcell [36, 37] suggested that H_2 formation at the surface of the grains or differential photoelectric yield could induce torques that would rotate the grains much faster than first expected from Brownian estimations. This fast rotation of the grain body transfers angular momentum to its electrons and this induces a magnetization (Barnett effect) with the same direction as $\vec{\omega}$. Internal dissipations lead to the alignment of the angular momentum $\vec{J}$ of the grain with its main axis of inertia (i.e., orthogonal to the longest axis of the grain). As $\vec{\omega}$ precesses about $\vec{J}$, the magnetization precesses about $\vec{J}$ too which leads to paramagnetic dissipation with the magnetic field. In the end, the grains are aligned and orthogonal to $\vec{B}$ as in DG, but the characteristic times are much more favorable.

Differential scattering of left and right hand polarized light by irregular shaped grains was proposed by Dolginov & Mytrophanov [10] as an alternative mechanism to Purcell's to provide the necessary fast rotation to the grains to seed paramagnetic dissipation. To be effective, this rotation must be supported long enough for paramagnetic dissipation to take place. This was shown to be possible numerically by Draine & Weingartner twenty years later [7, 8], even in an environment with anisotropic radiation [9]. Lazarian & Draine found that this alignment should survive despite randomization during cross-overs provided that the grains are larger than $\sim 0.1\ \mu$m, i.e., big grains [21]. Ongoing work is testing the analog to the Barnett effect but with nuclei [23] that could lower this critical grain size by an order of magnitude.

The above mentioned alignment mechanisms rely on the orientation of the angular momentum $\vec{J}$ of the grains. Polarization itself is linked to the asymmetry of the grain and to preferential extinction (in the optical and UV) and emission (in the IR and submm) along the longest axis of the grain. To observe polarization, both the stability of $\vec{J}$'s orientation in space and with respect to the grain body is needed. While the latter is likely to be true in big grains that can reach thermal stability, Lazarian & Roberge [22] showed that is not the case for small grains. Figure 2 shows the typical thermal behaviour of dust grains in the ISM. Small grains, with small heat capacity, reach very high temperatures when they absorb UV photons and then the alignment between $\vec{J}$ and the axis of maximal inertia of the grain is broken. This is a strong theoretical argument that small grains are not well aligned and therefore produce very little polarization.

2.3 Polarization by the silicates

This low degree of alignment of small grains is supported empirically. Indeed, whereas the extinction curve (Fig. 3) shows a continuous rise in the UV that requires smaller and smaller grains, the polarization curve decreases in the same wavelength domain. The 2175Å feature characteristic

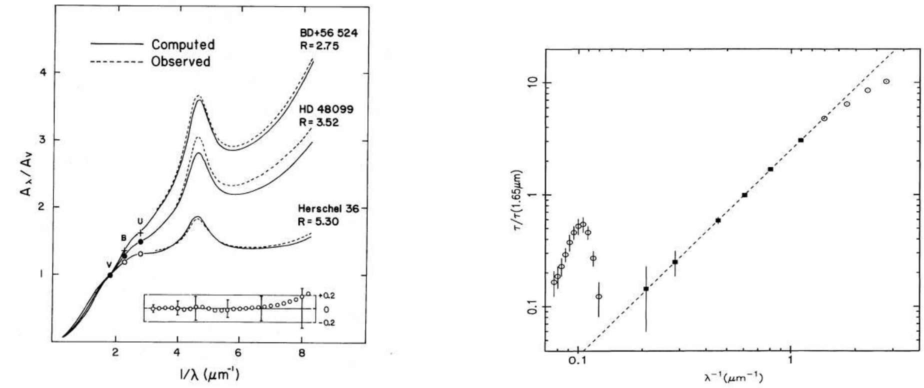

Figure 3: Frequency dependence of interstellar extinction. Left: Extinction curves in the optical and ultraviolet showing a range of behaviour as a functon of R_V [4]; in the diffuse medium $R_V \sim 3.1$. The sole spectral feature is the prominent "bump" at 2175 Å. Right: In the infrared there is a power-law decrease, plus a distinctive 10 μm silicate feature [28]. From [26].

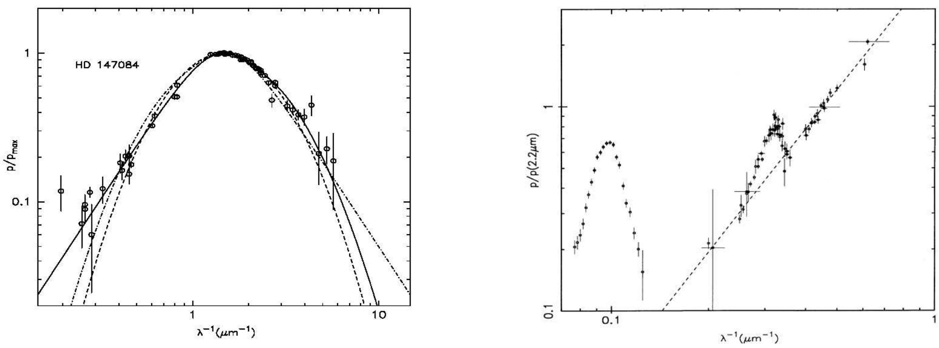

Figure 4: Frequency dependence of interstellar polarization. Left: Polarization curve from the near-infrared to the ultraviolet, normalized to the maximum polarization in the visual [27]. There is no strong ultraviolet polarization "bump" as in the extinction curve. Right: In the infrared there is a power-law decrease, plus a distinctive polarized 10 μm silicate feature [28]. In lines of sight to an embedded source, such as this toward the Becklin-Neugebauer object in OMC 1, there is polarization at 3.1 μm ice band, interpreted as a thin frost on the aligned silicates. From [26].

of carbonaceous grains does not show in polarization curves either[1], leading to the conclusion that small carbonaceous grains are generally not aligned. This, together with the associated "anomalous emission" is discussed in greater detail by Davis & Verstraete in this volume (see also [26]).

Experimental evidence, however, supports that silicate grains are aligned. The 10μm feature, typical from Si-O stretch is prominent in the polarization curve (Fig. 4), and big aligned silicate grains can also explain the power law rise in polarization in the infra-red [18]. It therefore seems reasonable to focus on these grains and assume that they alone are responsible for the polarized

[1] A small bump is reported in [27] in a few lines of sight, but two orders of magnitude too low to require significant grain alignment.

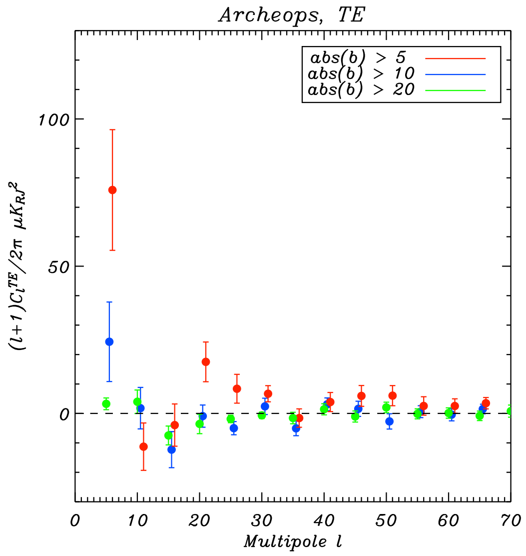

Figure 5: Dust TE angular power spectra measured by ARCHEOPS at 353GHz on 20% of the sky and removing latitudes lower than 5, 10, 20 degrees (red, blue and green respectively).

emission in the IR and submm [26]. The prediction of the polarization of these grains in the diffuse ISM, most relevant for CMB component separation, is described in detail in [26]. We only mention here that the net polarization predicted at 350 GHz for a range of realistic grain shapes is between 7.5 and 9.4%. This is a large degree of polarization compared to what was predicted in the literature in the past, but we see in the next section that this agrees with recent experimental measurements.

3. Observational results

The observation of far-infrared and submm polarization on small angular scales in dense clouds in or close to the Galactic plane has been very active for many years. We do not talk about these observations here but refer the interested reader to the most recent reviews, e.g., [40]. We present recent measurements obtained in the context of CMB measurements that illustrate the foreground aspect of dust.

The first CMB experiment to report the observation of dust polarization was ARCHEOPS [1]. ARCHEOPS was a balloon-borne experiment dedicated to the measurement of the CMB temperature anisotropy from angular scales $\ell \sim 15$ to $\ell \sim 600$. It had 6 spider-web bolometers operating at 143 GHz, 8 at 217 GHz, and 1 at 545 GHz. An additional 6 bolometers at 353 GHz were assembled in pairs as Ortho-Mode Transducers and were sensitive to polarization. The analysis of their data lead to several important results.

Galactic dust was observed to be significantly polarized, about 5% on average, but some regions were coherently polarized up to ~ 10% or more over several degrees on the sky (therefore compatible with theoretical estimations [26]). The general direction of polarization in the fraction of the Galactic plane observed is consistent with the expectation that submm and optical polarization should be orthogonal to each other. If 5% polarization is observed in the Galactic plane where

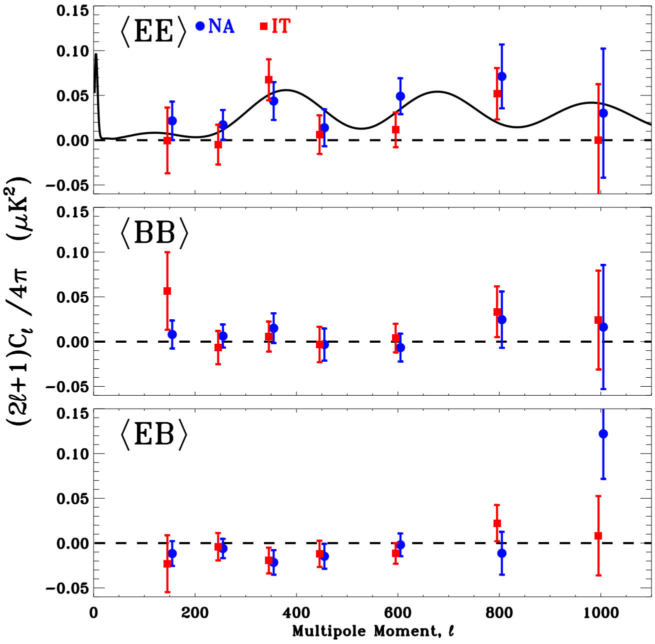

Figure 6: Angular power spectra derived by BOOMERanG. The absence of *B* provides evidence that dust polarization has been filtered out properly.

the potential for cancellation along the line of sight is the highest, then we must expect at least as much polarization at high latitudes where the CMB is analyzed.

The large sky coverage of ARCHEOPS enabled the first estimation of dust polarization angular power spectra (Fig. 5) [34]. These spectra confirmed the broad picture of a Galactic magnetic field following the spiral arms of the Galaxy on large angular scales and dust being aligned orthogonally to it, with a degree of polarization between 5 and 10%. They also showed that even extrapolated to 100 GHz [20, 11] where CMB dominates, dust TE angular power is significant compared to the CMB TE on large angular scales and must therefore be carefully accounted for in cosmological interpretations.

More recently, BOOMERanG [29, 32] reported the measurement of the CMB scalar polarization power spectra. Although they do detect dust polarization in their 245 and 353 GHz channels, they claim that dust polarization has negligible effects on their results. This is supported by the fact that dust is expected to produce as much B as E type polarization. As their measure of B is compatible with 0 (see Fig. 6), this suggests that dust polarization does not contribute to the measured E and TE spectra. They do further cross checks on their filtering and sky cuts using IRAS data.

However, this does not rule out ARCHEOPS conclusions. First, it must be noted that BOOMERanG observes a very limited fraction (0.22%) of the sky selected to have low dust column density. Dust contamination in this region may indeed be small, but this patch is not representative of dust polarization on the rest of the sky. Second, ARCHEOPS had low signal to noise on the degree angular scale outside the Galactic plane and mainly constrained dust polarization on large angular scales, therefore saying nothing on BOOMERanG's angular scales. The angular power spectrum of dust remains to be measured by more sensitive experiments (e.g., PILOT, see below). Third, the common argument about dust producing as much B as E must be taken with a grain of salt. While this may be true on small angular scales as suggested by simulations [35], nothing guarantees that this remains true on larger angular scales. The reason is that the shape of the Galaxy and the orientation of the magnetic field essentially parallel to the Galactic plane break the symmetry on which this statement relies.

To illustrate this, Figure 7 shows dust angular power spectra from a very naive model. This is based on a map of 100 GHz radiation predicted from Finkbeiner-Davis-Schlegel (FDS) model 8 [12]. A uniform degree of polarization of 5% is assumed, and the grains are aligned orthogonally to the magnetic field. The latter is oriented along our spiral arm and so the apparent degree of polarization has a simple modulation according to the orientation of the line of sight with respect to this field[2]. Note that on medium angular scales, the predicted E spectrum is about an order of magnitude larger than B. While this pedagogical example is perhaps conservative and pessimistic, it does provide a warning against sweeping generalization concerning these foregrounds.

We conclude that the BOOMERanG results are encouraging in that dust contamination can be limited and filtered out on some small patches of the sky where interesting cosmology can be done. However, ARCHEOPS showed that on large angular scales, dust should be more problematic. Large angular scales are needed if one wants to measure the two bumps of the CMB B mode spectrum (reionization $\ell < 10$ and primordial $\ell \simeq 100$); this would be the most (if not only) convincing argument that any detected B type signal is that of the CMB and not some foreground contamination, imperfect de-lensing or systematic effect.

4. Component separation

Component separation is really where ISM and CMB physics meet. Several questions arise. To what level do we need to subtract foregrounds from CMB polarization data? Do we have enough information on foregrounds to reach this level?

Suppose we are interested in the characterization of the CMB E mode. We already know its amplitude with enough confidence to fix a target for foregrounds cleaning. On the other hand the amplitude of the CMB B mode is poorly constrained and so we cannot similarly fix a target. There is another consideration, however. The ability to subtract the lensing-induced B mode (the distortion of the CMB E field by large scale structures) is limited by cosmic variance in the estimation of both the E mode and the large scale structures angular power spectra. Knox & Song [19] estimate that the lensing-induced contribution to the B mode angular power spectrum could be removed down to a few 10^{-4} μK^2 at $\ell \simeq 100$, allowing a detection of the CMB primordial B mode if the energy scale of inflation is not lower than 2×10^{15} GeV. There is then no need to ask for foregrounds removal much lower than this limit.

Is this level of foreground cleaning achievable? Tucci et al. [39] address this problem by studying how uncertainties in the spectral index produce a residual when then the foreground is subtracted. From Figure 8 a residual level of 2.5×10^{-5} μK^2 at $\ell \sim 100$ might be achieved. This

[2] Polarization is along the main axis of the grain which is orthogonal to the magnetic field. Since the observed polarization is projected onto the plane of sky, it is also orthogonal to the line of sight. The resulting observed polarization (for a degree of polarization of 5%) is therefore $\vec{p} = 0.05\vec{B} \times \vec{n}/|\vec{B} \times \vec{n}|$

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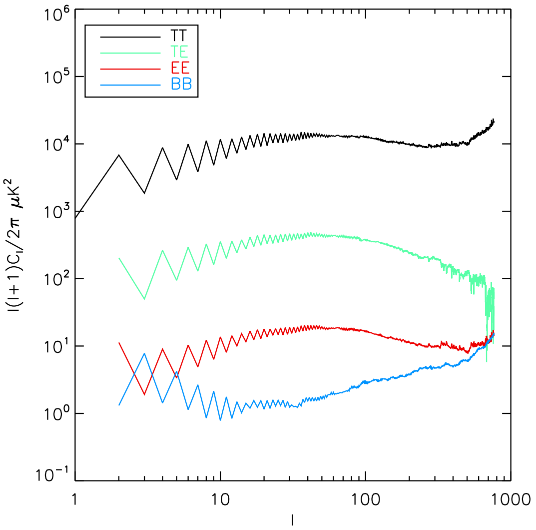

Figure 7: Dust angular power spectra for a very naive Galactic model with systematic polarization. The FDS model number 8 [12] is used to simulate dust radiation at 100 GHz. The Galactic magnetic field is assumed to have constant orientation in the direction of our local spiral arm. The dust grains are aligned with respect to this field; the degree of polarization is taken to be 5% everywhere but is modulated according to the direction of the field with respect to the line of sight. This crude model aims at illustrating that the Galactic disk and the overall orientation of the magnetic field on large angular scales produce more Q than U (tilted at 45 degrees) in the Galactic plane where total emission is the highest. This breaks the symmetry between dust E and B polarization modes on medium angular scales. The general statement that "dust produces as much B as E" must be tempered by angular scale considerations.

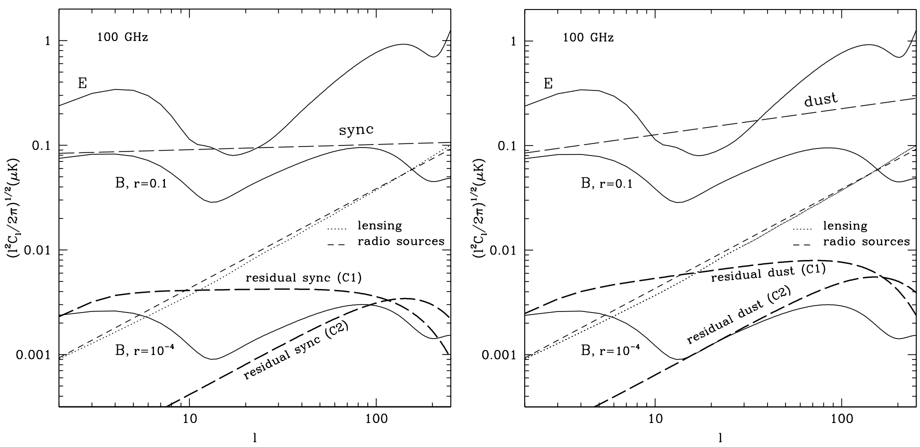

Figure 8: Polarization power spectra at 100 GHz from Tucci et al. [39]. Of special interest here are the thick dashed lines showing the estimated residual after subtraction of the synchrotron (left) and dust (right) emission; the residual arises from spectral index uncertainties applied to the foreground templates (following two extreme cases C1 and C2) in extrapolating to the frequency at which the CMB polarization is to be detected.

level is even lower than the Knox & Song lensing residual, though we regard this as optimistic. It must also be pointed out that the models used for dust polarization, in particular [35], tend to be optimistically low compared to ARCHEOPS results, even considering only TE on angular scales lower than $\ell = 70$ [34], and so conclusions must be drawn with care. Recent theoretical results (see [26] for a review) also suggest that dust polarization could have a more complex frequency dependence than those assumed. Thus, even though this limit could be reached in theory, subtracting polarized foregrounds to such a low level remains quite a challenge in practice.

5. Conclusion

Dust has been known to polarize starlight in the optical domain, since the 1950's. In the 1960's, it was predicted that this polarization by extinction should have a counterpart in emission in the IR and submm. This polarization has been detected in Galactic clouds and in the diffuse ISM since then. The involved grain alignment mechanisms are not clear yet although great progress has been achieved. Now with the advent of CMB anisotropy experiments, cosmologists have become interested in dust. At this stage, several conclusions can be drawn:

- The degree of submm dust polarization is high, above 5% and perhaps closer to 10% in well aligned diffuse regions with favorable orientation of the field. This is expected theoretically and has been measured experimentally.

- On large angular scales, the amplitude of the dust TE angular power spectrum is comparable to that of the CMB (ARCHEOPS).

- On a limited sky patch, selected for low column density, dust polarization can however be filtered out from CMB data, at least to a sufficient level to measure EE (BOOMERanG).

- Optimistic component separation modelling suggests that foreground dust polarization is removable in the angular power spectrum to a level a few times 10^{-3} μK at ℓs of interest for detecting primordial B modes [39].

- Recent dust modelling indicates that the frequency dependence of the dust polarization spectrum could be more complex than a single power law, therefore making component separation more challenging [26].

More information is expected to come from current and forecast CMB experiments. BICEP [3] and QUaD [2]) operate at 100 and 150 GHz each which can give an estimate of dust near the peak of the CMB, although on a limited sky patch. EBEX [30] will have channels at higher frequencies and therefore will place tighter constraints on the frequency spectrum of dust polarization. PLANCK will bring polarized maps of the whole sky at 100, 143, 217 and 353 GHz and will thoroughly address the component separation problem. These are CMB experiments that are sensitive to dust. By contrast, PILOT [33] is dedicated to the characterization of dust polarization, observing at 550 and 250 μm where dust emission is more intense. These experiments will bring significant improvements to our current understanding of dust polarization, and will be milestones on the road to the design, building, and exploitation of a satellite dedicated to CMB polarization.

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