An Examination of Galactic Polarization with Application to the Planck TB Correlation

J. L. Weiland1, G. E. Addison1, C. L. Bennett1, M. Halpern2, and G. Hinshaw3

1 Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218, USA; jweilan2@jhu.edu
2 Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, V6T 1Z1, Canada

Abstract

Angular power spectra computed from Planck HFI 353 GHz intensity and polarization maps produce a TB correlation that can be approximated by a power law. Whether the observed TB correlation is an induced systematic feature or a physical property of Galactic dust emission is of interest both for cosmological and Galactic studies. We investigate the large angular scale E- and B-mode morphology of microwave polarized thermal dust emission, and relate it to physical quantities of polarization angle and polarization fraction. We use empirical models of polarized dust to show that dust polarization angle is a key factor in producing the TB correlation. A small sample of both simulated and observed polarization angle maps are combined with 353 GHz intensity and dust polarization fraction to produce a suite of maps from which we compute TB and EB. Model realizations that produce a positive TB correlation are common and can result from large-scale (>5°) structure in the polarization angle. The TB correlation appears robust to introduction of individual intensity, polarization angle, and polarization fraction model components that are independent of the 353 GHz observations. We conclude that the observed TB correlation is likely the result of large-scale Galactic dust polarization properties.

Unified Astronomy Thesaurus concepts: Observational cosmology (1146); Dust continuum emission (412); Galaxy structure (622)

1. Introduction

Cosmic microwave background (CMB) research is currently focused on obtaining high sensitivity observations of the polarized CMB, as characterized by divergence free B-modes and curl-free E-modes (Kamionkowski et al. 1997; Zaldarriaga & Seljak 1997). B-modes are sensitive to the imprint of primordial gravitational waves sourced by inflation with an amplitude denoted by the tensor-to-scalar ratio parameter, r. Detection of these inflationary B-modes would constrain the energy scales of inflation and provide unique insight into the early universe. E-modes observed on large spatial scales provide a direct constraint on the reionization optical depth parameter, τ, and are important for cosmological neutrino mass constraints (e.g., Allison et al. 2015). Current and upcoming experiments are targeting high multipole (up to l ~ 3000–5000) polarization measurements to more stringent test the ΛCDM model and provide tighter constraints on the gravitational lensing of the CMB by large-scale structure (e.g., Benson et al. 2014; Henderson et al. 2016; Ade et al. 2019).

Because the signal from the polarized CMB is subdominant to the Milky Way’s polarized foreground emission, it has become increasingly important to both quantify and understand these foregrounds. At microwave frequencies, the two significant emission mechanisms are synchrotron and thermal dust emission (Page et al. 2007; Bennett et al. 2013; Planck Collaboration X 2016; Planck Collaboration IV 2018). The polarized foregrounds are usually observed and characterized in terms of the Stokes parameters I, Q, U, and V, but of primary interest are the linear polarization parameters Q and U. While Stokes Q and U are observationally convenient, they are coordinate system dependent so they do not couple naturally to the underlying physics. For this, the E-mode and B-mode representation of orthogonal polarization components is ideal. Despite this, sky maps are usually shown in Q and U and foreground masking is generally implemented for Q and U maps before transforming and computing E and B power spectra.

A relatively recent foreground-related puzzle originates with analysis of Planck HFI data, where the dominant polarized foreground is that from thermal dust emission. Angular power spectra computed from HFI 353 GHz intensity and polarization maps show a significant positive signal in the Temperature B-mode (TB) cross spectrum, but an EB cross spectrum consistent with zero signal (Planck Collaboration Int. XXX2016; Planck Collaboration XI 2018; Planck Collaboration Int. LIV 2018). The TB spectrum is roughly consistent with a power law as a function of multipole moment l for l ≲ 600, although there is significant scatter in the data points about the fit. We refer to this characteristic as “nonzero TB” throughout this paper.

Physical arguments predict the TB and EB signals from the CMB to be statistically consistent with zero (e.g., Zaldarriaga & Seljak 1997). Thus the two most likely sources for the nonzero TB signal are residual systematics in the data, and/or a nonzero TB contribution from Galactic thermal dust emission. The reported detection of a nonzero TB signal in the HFI 353 GHz data is a finding of interest regardless of its origin, but carries different ramifications depending on the source of that signal. If the TB signal arises from Galactic emission processes, it has implications for magnetic field structure studies and for CMB experiments. Calibration of CMB observations may rely on hardware, astrophysical sources, and/or use “self-calibration,” in which assumptions of null EB and sometimes TB spectra define the detector polarization angles and indicate the presence of potential measurement systematics (e.g., Kaufman et al. 2014; Koopman et al. 2016). Characterization of a nonzero TB sky signal would be essential knowledge for self-calibration (Abitbol et al. 2016). Efforts to find physical mechanisms to reproduce the Planck TB correlation are

---

8 When expressed in temperature units, the intensity map I is often referred to as “the temperature map,” or T.
ongoing; the model of Huffenberger et al. (2019) predicts both positive $TB$ and $EB$ (at a lower level) based on alignment of diffuse ISM filaments with that of the Galactic magnetic field (GMF) orientation. Conversely, if the Planck 353 GHz $TB$ signal arises from residual systematics in the data, possible analysis bias in CMB as well as Galactic emission component studies may be introduced through the assumption that these maps are accurate templates of polarized Galactic dust emission.

This paper has two motivations: (1) obtaining some basic insights into the $E$ and $B$ morphology of polarized emission from Galactic foregrounds, and (2) attempting to understand the origin of the nonzero $TB$ signal in Planck data. In Section 2, we discuss the $[Q, U]$ to $[E, B]$ transformation, and show observations of polarized synchrotron and dust foregrounds in both representations in order to illustrate relevant spatial features in the $E$ and $B$ maps. The remainder of the analysis discussion (Sections 3–5) is devoted to constructing models of $Q$ and $U$ Galactic dust maps assembled from a variety of intensity, polarization fraction, and polarization angle map components, and examining how the nature of these components affects both $[E, B]$ and the resultant $TB$ power spectra. Varying individual components within empirical models allows us to test the stability of the observed nonzero $TB$ spectrum. Section 3 presents empirical models in which we examine the role of dust polarization angle and polarization fraction in the spatial structure of the $[E, B]$ maps. In Section 4, we compute $TB$ and $EB$ power spectra of the models from Section 3, relate the origin of the nonzero $TB$ spectrum to the polarization angle, and compute $TB$ spectra for additional models incorporating synthetic polarization angles. We discuss further tests of nonzero $TB$ in Section 5, including intensity map variants and the addition of Planck 217 GHz polarization data. Section 6 summarizes our conclusions.

### 2. Stokes $[Q, U]$ and Transformation to $[E, B]$

$E$ and $B$ maps may be expressed as second derivatives of the Stokes $Q$ and $U$ maps (e.g., Equation (9) of Zaldarriaga & Seljak 1997, see also Kamionkowski et al. 1997). As a result, the relation between the two systems in pixel space is nonlocal. In Figure 1 we show the transformation of a single pixel with $Q = 1, U = 0$ into $E$ and $B$ maps. The local $Q$ signal becomes a quadrupolar pattern in $E$ and $B$, where $B$ is rotated 45 degrees relative to $E$ (Hu & White 1997). In this example, the pixel scale sets the scale of the $[E, B]$ structure, but more generally the Hessian of the $[Q, U]$ maps determines the scale of structure in the $[E, B]$ maps. As a consequence of nonlocality, masks appropriate for $[Q, U]$ data are not necessarily suitable for the corresponding $[E, B]$ data. Similarly, note that simple characterizations of foreground structure in $[Q, U]$, such as spectral indices, will not necessarily carry over to the corresponding $[E, B]$ maps.

Throughout this paper, we utilize the healpy⁴ (Zonca et al. 2019) and HEALPix⁵ (Górski et al. 2005) analysis package. The package function `map2alm` is used to transform $Q$ and $U$ using the spin-2 spherical harmonic basis functions with coefficients $a^{E}_{lm}$ and $a^{B}_{lm}$, and then the function `alm2map` is used to evaluate $E$ and $B$ maps from the $a_{lm}$'s. The `healpy` transformation sets monopole and dipole ($l = 0, 1$) components to zero, so that all full-sky $[E, B]$ maps that we show have zero mean and dipole. Additionally, we retain the polarization convention adopted by WMAP and Planck data products, which differ from the IAU convention by the sign of Stokes $U$.⁶

In Figure 2, we show the temperature (unpolarized intensity) map Stokes $I$, polarized intensity $P = (|Q|^2 + |U|^2)^{0.5}$, and the transformation from Stokes $Q$ and $U$ to $E$ and $B$ for WMAP K-band (23 GHz) and Planck 353 GHz maps. All maps in this paper are shown in Galactic coordinates, following astronomical convention, with the Galactic center in the middle. The K-band $Q$ and $U$ maps are dominated by Galactic synchrotron emission and serve as a useful template for that foreground in polarization. Similarly, the 353 GHz $Q$ and $U$ maps may serve as templates describing polarized thermal dust emission. The same unfortunately is not true for the temperature maps, for while the 353 GHz $I$ map is dominated by thermal dust emission outside the Galactic plane, the K-band $I$ map represents a mix of CMB, synchrotron, free–free, and AME (anomalous microwave emission, generally assumed to arise from spinning dust) components. Contributions also arise from point sources and cosmic infrared background asymmetries, but these are not critical to the larger angular scales discussed here. Although we concentrate in this paper on the more easily separable dust emission, we briefly discuss K-band in order to draw certain parallels, since both the synchrotron and dust emission are influenced by the same GMF.

The Galactic plane is clearly visible in all maps of Figure 2, but the details of the structures off the plane are not necessarily physically intuitive, particularly in polarization. The signal from polarized CMB is present in these maps, but is subdominant to Galactic components, such that high Galactic latitude structure at these frequencies represents foreground

---

⁴ <https://github.com/healpy/healpy/>

⁵ <http://healpix.sourceforge.net>

⁶ <https://healpix.sourceforge.io/html/intro_HEALPix_conventions.htm>
behavior rather than that of the CMB. The E-mode maps for both K-band and 353 GHz show very similar large-scale structure. The B-mode maps are less alike, with the 353 GHz B-mode map showing a strong contribution from the \( l = 3 \), \( |m| = 3 \) spherical harmonic modes, evidenced as a regular +/− pattern alternating above and below the Galactic plane.

The above figures establish a general overview of the visual appearance of E- and B-mode maps for polarized microwave foregrounds. In the next section, we step through some simple models to gain insight into large angular scale E and B map structures.

### 3. Empirical Models

Stokes Q and U maps may be constructed from an empirical model expressed in terms of a polarization angle \( \gamma \) and polarization fraction \( f \) as follows:

\[
Q = I f \cos(2\gamma),
\]

\[
U = I f \sin(2\gamma),
\]

where \( I \) is the temperature map, such that \( f = P/I \) and \( \gamma = 0.5 \tan^{-1}(U/Q) \). We deal with models designed to represent only a single foreground emission component at a given frequency.

The polarization fraction is influenced by a number of factors. For example, a complex line-of-sight column containing multiple emission regions will result in a lower polarization fraction due to the decoherence of preferred directions (e.g., the magnetic field directions) and emission conditions along the column. The polarization angle is influenced by the spiral structure imposed by the global GMF and more localized phenomena (e.g., MHD turbulence), and particle-field alignment properties. An observed temperature map \( I \) is generally used to provide realistic small-scale information.

In this section, we construct models of \( [Q, U] \) in which we vary choices for \( f \) and \( \gamma \), keeping \( I \) constant, and note the effect of these individual parameters on the resultant \([E, B]\) spatial structure. We first examine the role that the polarization angle plays in the morphology of the \([Q, U]\) and \([E, B]\) maps, as illustrated in Figure 3. We start with three separate inputs of polarization angle, convert them via Equations (1) and (2) to \( Q \) and \( U \) maps assuming \( I \) and \( f \) are everywhere unity over the sky, and then transform those \([Q, U]\) maps to \( E \) and \( B \). Two of the three input polarization angle maps are constructed from observations discussed previously; WMAP K-band and Planck 353 GHz \( Q \) and \( U \) maps, smoothed to 4° FWHM resolution. The third polarization angle example is computed from a simple geometrical model of the GMF, as parametrized by the logarithmic spiral arm model described in Page et al. (2007). As discussed in Section 4 of that paper, we adopt a dust scale height of 100 pc, a spiral arm opening angle \( \phi_0 \approx 25° \) and tilt \( \chi_0 \approx 0° \), with the polarization angle \( \gamma \) as specified in their Equation (11). This representation, which we denote as “simple \( \gamma \),” provides a polarization angle map dominated by large angular scale morphology. The polarization angle as observed from the solar neighborhood does not represent the true magnetic field orientation as seen by an outside observer, but is rather a projection. The sign of \( \gamma \) wraps at the directions roughly corresponding the observer’s view looking in both directions down the local Orion arm, roughly at Galactic longitudes 65° and 240°.

We show each of these three polarization angle maps in the top row of Figure 3. The next two rows illustrate the \( \cos(2\gamma) \) and \( \sin(2\gamma) \) geometrical patterns that heavily influence the appearance of the \( Q \) and \( U \) maps shown in Figure 2. The \( E \)- and \( B \)-mode maps resulting from these \( Q \) and \( U \) maps are shown in the fourth and fifth rows respectively. All E-mode maps in this

**Figure 2.** Maps of unpolarized (\( I \)) and polarized (\( P \)) intensity at 23 GHz (left half of plot, WMAP K-band 9 yr data) and 353 GHz (right half, Planck/HFI 2018 data). The bottom two rows show the polarization components in the form of \( Q \) and \( U \) maps (middle row) and \( E \) and \( B \) maps (bottom row). The maps have been smoothed to reduce instrument noise. The CMB signal is negligible in the polarization maps, which are dominated by synchrotron emission at 23 GHz, and by thermal dust emission at 353 GHz. Note that the \( E \) maps of synchrotron and dust share many common features, whereas the \( B \) maps appear to have less in common. In particular, the \( B \)-mode dust map exhibits a strong \( l = 3 \), \( |m| = 3 \) component. We explore this further in Section 3.
The lobe structure is most obvious in the simple $\gamma$-mode map, but is strongly present both in the $\gamma = K$-band and 353 GHz $E$ maps as well. Comparing the $E$-mode maps derived from the $K$-band and 353 GHz polarization angle to those of the data in Figure 2, it is clear that much of this large-scale two-lobed structure is attributable to the polarization angle geometry, and in turn, the GMF. The $B$-mode map is not well predicted by $\gamma$ alone.

Comparison of the bottom row of Figure 3 with that of the data make it clear that the $B$-mode morphology is not sufficiently explained with polarization angle alone. Having examined the role of $\gamma$ in $[E, B]$ structure, we now look at the role played by the polarization fraction $f$ via a set of four empirical models shown in Figure 4. The figure concentrates on empirical models of the dust emission at 353 GHz only, because the maps of $I$ and $f$ for dust are more easily derived than those for $K$-band synchrotron, as explained earlier. We choose to vary the polarization fraction $f$ between two extremes: a constant $f = 0.05$ over the entire sky, and that produced from a lightly smoothed (0.2°) map of $P$ and $I$ as observed by Planck. The $P$ map is produced from Planck half-mission maps in order to avoid introducing noise bias. In addition, we choose two bracketing representations of $\gamma$: that from the simple geometric
GMF model and 353 GHz data shown previously in Figure 3. We permute these $f$ and $\gamma$ choices with a fixed thermal dust emission temperature map from Planck to form the four model combinations. Our versions of $\gamma$ and $f$ independently derived from 353 GHz data are in good agreement with those shown and discussed in Planck Collaboration XII (2018). Weals on et al. that the exact choice of 353 GHz intensity map does not significantly alter our results: for example, use of the Planck Commander 353 GHz dust map (Planck Collaboration IV 2018) rather than the 353 GHz $I$ map produces similar models.

In Figure 4 the $E$ and $B$ maps for the 353 GHz data are shown in the top row and may be compared with the $E$ and $B$ model maps in the four rows directly below. The two leftmost columns specify the $f$ and $\gamma$ maps used to produce the $E$ and $B$ models shown in each row. On very large scales, the dust $B$-mode structure takes the form of a quadrupole about the Local Arm viewing directions near $l = 65^\circ$ and $240^\circ$, and expresses itself as a strong $l = 3, |m| = 3$ $B$-mode pattern about the Galactic plane. The last two rows of the figure illustrate that the specific 353 GHz polarization fraction is necessary to most closely reproduce the observed $l = 3, |m| = 3$ $B$-mode pattern. There is strong geometrical suppression of the polarization fraction along the spiral arm viewing directions, which is expected because of the complex astrophysics from multiple emission regions along each line of sight.

4. $TB$ and $EB$ Spectra of Empirical Models

We use the four empirical models presented in the previous section to explore which geometrical factors contribute most to producing the nonzero $TB$ signal detected by Planck. We construct half-mission $Q$ and $U$ maps using $I, f$, and $\gamma$ components at HEALPix $N_{\text{side}} = 2048$ resolution, and evaluate the $TB$ and $EB$ power spectra using PolSpice$^7$ (Szapudi et al. 2001;)

---

$^7$ http://www2.iap.fr/users/hivon/software/PolSpice/
Chon et al. 2004). The resultant power spectra are shown in Figure 5. The use of half-mission splits is necessary to avoid noise correlations in the power spectra when generating model components based on the 353 GHz data. Because the $I$ component is always fixed to that of the 353 GHz data, a mask that excludes strong nondust emission sources present in the data is used. In order to compare our results with that of Planck Collaboration XI (2018), we adopt the masking recipe described in Planck Collaboration XI (2018) for their analysis mask designated “LR71.” This mask maximizes analyzed sky area while excluding regions of strong CO line emission (primarily near the Galactic plane) and high-latitude polarized point sources above a certain threshold. Due to inexactitudes in the published masking specifications, our mask is slightly different and permits roughly 75% of the sky to be analyzed after apodization (rather than 71%). For visual clarity, power spectra are plotted using multipole bins; the binning ranges are as defined in Table C.1 of Planck Collaboration XI (2018). Power spectra are expressed as $D_l = l(l + 1)c^2/2\pi$.

The bottom-most plot of Figure 5 shows binned $TB$ (red) and $EB$ (blue) produced from 353 GHz data half-mission cross-spectra, and represents the case where $f$ and $\gamma$ both arise from 353 GHz data. This image illustrates independent confirmation of the nonzero $TB$ signal and $EB$ spectrum roughly consistent with zero presented in Figure 6 of Planck Collaboration XI (2018). Planck Collaboration XI (2018) estimate uncertainties for their $TB$ and $EB$ spectra based on analysis of the full-focal plane simulations (FFP10) from the 2018 data release. Similarly, the uncertainties plotted in this panel are derived by applying the same analysis methods to the first 100 FFP10 simulations, which include noise, residual systematics, CMB, and dust emission components.

The approximate power-law fit derived by Planck Collaboration XI (2018) for their LR71 mask is shown in magenta, which we evaluate using their Equation (1), $D_l^{TB} = A^{TB}(l/80)^{2.44}$, with $\alpha_{TB} = -2.44$. The amplitude $A^{TB}$ is not directly tabulated, but can be computed from the product of the $EE$ amplitude and mean $TB/EB$ amplitude ratios in their Table 1, multiplied by the quoted $TB/EE$ power ratio of $\sim 0.1$. The magenta line serves as a fiducial when comparing with the other three model spectra.

The remaining panels in Figure 5 illustrate the effect on $TB$ and $EB$ of varying the polarization fraction and angle between extremes in complexity (simple versus data). $EB$ is little affected except for variations at low multipoles. A positive $TB$ signal approaching observed levels (represented by the same magenta line) is present only when a polarization angle $\gamma$ based on 353 GHz data is used. Thus a $\gamma$ with more complex spatial structure than that of the simple GMF model is required to produce the observed positive $TB$, although this does not indicate what particular property of $\gamma$ is the cause.

Planck Collaboration XI (2018) note that current understanding of instrument polarization angle measurement errors preclude a simple rotational angle error as the cause of the positive $TB$ signal. Additionally, a simple rotational angle error should also leak into the $EB$ spectrum, which is not observed. Since it is apparent that $\gamma$ is the crucial factor in producing nonzero $TB$, we explore additional simple models of $Q$ and $U$ in which we fix $I$ and $f$ components to match Planck 353 GHz observations, but substitute in a variety of simulated and data-based maps of $\gamma$ that are derived independently of the Planck observations. This allows us to evaluate how easily one may obtain $TB$ and $EB$ dust spectra which are similar to those observed by Planck at 353 GHz, but are not affected by possible residual systematics in the Planck dust polarization angle.

Simulated $Q$ and $U$ maps of polarized dust emission have recently been made public⁸ by Kim et al. (2019). These “TIGRESS sims” provide a suite of polarized dust maps for nine observer positions within the solar neighborhood covering multiple evolutionary time-steps and are generated numerically using a multiphase, turbulent, magnetized interstellar medium (MHD code and TIGRESS ISM framework). We create nine simulated polarization angle maps from smoothed versions of the $Q$ and $U$ realizations for the nine observer positions and the

---

⁸ https://lambda.gsfc.nasa.gov/simulation/tb_tigress_data.cfm
t = 360 Myr time-step in their several-hundred Myr evolutionary interval. In addition to these nine realizations, we include two representations of polarization angle based on data. The first of these is the WMAP K-band polarization angle, which actually represents synchrotron emission, but has some similarities to the dust polarization angle because both emission components are influenced by the same global magnetic field (synchrotron likely follows gas with a larger scale height than the dust, and will trace a magnetic field that is related but not identical to the field the dust experiences). For our second data-oriented polarization angle map, we adopt the polarization angle constructed from the WMAP dust polarization templates. This angle is derived from observations of the optical polarization of starlight by dust grains (Page et al. 2007), which may be expected to have some similarities to the dust polarization angle at 353 GHz, although more sparsely sampled over the sky. None of the 11 discussed options are available at high spatial resolution. We replicate the pixels in Q and U maps to create maps pixelized at HEALPix Nside = 2048, but then smooth to 5° FWHM resolution and compute the γ map from the smoothed Q and U maps. Thus all 11 of the γ map realizations used in our models possess information only on 5° scales or larger, but the I and f components of the models provide small-scale structure.

Figure 6 shows the TB and EB spectra computed from the 11 models of Q and U sky maps we constructed using the polarization angles described above. We use the same 75% sky map described at the beginning of this section. Spectra are labeled according the choice of γ, since I and f are the same for all realizations, with “T1–T9” in the first three rows referring to the nine TIGRESS simulations, and the last row showing the K-band and starlight polarization associated models, with the lower corner illustrating the 353 GHz data spectra (shown in Figure 5 with error bars) for comparison. Among the 11 models, there is a wide variation in TB spectrum amplitude with the choice of polarization angle map (see the Appendix and Table 1 for estimated amplitudes). Of the nine realizations that use the TIGRESS-derived polarization angle, two (observers 6, 9) show TB spectra consistently above zero, and one (observer 2) is consistently below zero. The two models that use data-based γ components both show a positive TB spectrum. Although these latter two appear on visual

---

Figure 6. TB (red) and EB (blue) spectra of 353 GHz I, Q, and U maps, computed for the 75% mask. All panels, except the lower right (“353 data”), show spectra derived from modeled Q and U realizations. Each realization is constructed from the same set of 353 GHz intensity and polarization fraction maps based on Planck data, but each possesses a unique polarization angle morphology. The nine panels labeled with the “T1–T9” prefix utilize nine TIGRESS realizations of polarization angle corresponding to different observer locations within the solar neighborhood (see the text). Also included are TB and EB spectra for two realizations built using data-based polarization angles that are independent of Planck observations. These are shown in the first two panels in the last row, and either use the WMAP K-band polarization angle (“K-band”), or γ from the polarization of dust by starlight (“Starlight,” Heiles 2000; Page et al. 2007). The bottom right panel shows the TB and EB spectra for the 2018 Planck 353 GHz data for comparison with the empirical models. The magenta line shown in each panel represents the approximate TB power-law fit found by Planck Collaboration XI (2018) for their LR71 mask. Although we show a small number of sample models, finding realizations that produce a consistently positive TB power spectrum is not difficult. The two models that used data-based polarization angle maps consistently show a positive TB signal. Our results suggest that the TB signal is likely a real feature of the Milky Way polarization structure.

---

9 https://lambda.gsfc.nasa.gov/product/map/dr5/templates_info.cfm
inspection to strongly correlate with the 353 GHz polarization angle, the $\gamma$ maps corresponding to observers 6 and 9 (Figure 7) do not. Although not shown, we also evaluated $TB$ and $EB$ for an additional nine TIGRESS-based models using the maps from the last time-step in their evolutionary sequence. In this case, three of the nine TB spectra showed nonzero $TB$ signals.

It therefore appears not to be difficult to generate nonzero $TB$ Galactic dust maps from simulations of the polarization angle constructed using current GMF models, and nonzero $TB$ seems robust to substitutions of $\gamma$ from other observational data. We also note that spatial variations in polarization angle need not be small-scale to produce a positive $TB$ signature, since the $\gamma$ maps here contain variations on $5^\circ$ scales or larger.

5. Additional Tests of $TB$ Signal Persistence

If nonzero $TB$ is a property of Galactic emission, then it is reasonable to expect the effect not to be confined to 353 GHz, nor to one specific mask. In this section, we briefly examine varying combinations of maps and masks that test for persistence of the $TB$ correlation.

Planck Collaboration XI (2018) presented evidence for persistence of a positive 353 GHz $TB$ correlation within the context of a series of six nested masks defined by dust emission intensity thresholds. These masks admit between 24% and 71% of the sky for analysis: signal from higher Galactic latitude sky regions becomes more dominant as the analyzed sky area grows smaller, with a concomitant decrease in signal-to-noise. Their Figure 6 illustrates consistently positive $TB$ power-law amplitudes that progressively decrease in magnitude with sky fraction, indicating higher correlation closer to the Galactic plane. As explained in Section 4, we have adopted a mask similar to their 71% mask when computing the $TB$ spectra presented in this paper. However, we also explored an alternative masking strategy designed to test for the presence of nonzero $TB$ in sky regions with the lowest expected contribution from Planck large-scale residual instrument systematics. We used the FFP10 simulations to determine $QQ$ and $UU$ variances from noise and systematics in the polarization maps and adopted masking thresholds favoring regions of low variance common to both $Q$ and $U$. Our most restrictive mask admitted $\sim22\%$ of the sky for analysis, in two regions very roughly approximating truncated caps about the ecliptic poles (the spatial truncation is due to the exclusion of CO emission near the Galactic plane described in Section 4). We found strong persistence of positive $TB$ signal when using this mask, whereas a null detection would have argued for a possible non-sky origin. This is supportive, but not a definitive test, as it can only be performed for 353 GHz data because of signal-to-noise constraints, and the mask definition relies on

Figure 7. Polarization angles used in forming the maps that produced the 12 $TB$ and $EB$ power spectra shown in Figure 6. A nonzero $TB$ spectrum can result from polarization angle morphologies that are visually different from that of the 353 GHz data. In Figure 6, 4 of the 11 empirical models showed a positive $TB$ signal. Two of these are taken from data (“$K$-band” and “Starlight”) and strongly correlate with the 353 GHz $\gamma$ morphology. However, realizations T6 and T9 from the TIGRESS simulations bear little resemblance to the 353 $\gamma$ and yet produce nonzero $TB$.
some understanding of where the instrument systematics are strongest.

We next compute \( TB \) power spectra for cases in which the 353 GHz polarization maps are retained, but the intensity map is adopted from observations other than the Planck 353 GHz \( I \) maps. The use of an alternate \( I \) map is designed to avoid possible leakage of instrument systematics between the intensity and polarization maps. We tried combinations including Planck 545 and 857 GHz intensity maps scaled to 353 GHz emission levels and the Planck dust intensity amplitude map derived from Commander multifrequency analysis (Planck Collaboration X 2016), but still recovered the \( TB \) correlation at observed levels. Because it is possible that there is some common-mode systematic between all Planck HFI frequencies, we also evaluated a model for the 353 GHz dust intensity (Schlegel et al. 1998, SFD dust model 8). Although an older model, the SFD intensity map is based on IRAS and COBE/DIRBE data that are completely independent of any Planck observations. The \( TB \) spectrum obtained from the SFD intensity map and 353 GHz \( Q, U \) maps is shown in the left panel of Figure 8. This recovered \( TB \) spectrum is similar to that for the 353 GHz data, as shown by the magenta line.

Finally, we attempted to examine dust polarization data from additional frequencies. This is a test of limited scope, because currently only Planck data provide the necessary sky coverage, and dust signal-to-noise is decreasing at the next available frequency of 217 GHz. Additionally, \( TB \) computation using only 217 GHz intensity and polarization data does not produce a significant result in part because the 217 GHz dust signal is diluted by CMB at higher latitudes. We instead evaluate \( TB \) for the 75% sky region using the 353 GHz half-mission 1 \( I \) map and 217 GHz half-mission 2 \( Q, U \) maps, shown in the first of two plots in the double panel on the right of Figure 8. In this panel, the cyan curve is the 353 GHz \( TB \) power law described previously. The magenta line is the extrapolation of the observed 353 GHz \( TB \) signal assuming the amplitude of the polarized dust emission follows a modified blackbody emission law described by a single physical dust temperature \( T_D = 20 \) K and spectral index \( \beta_D = 1.6 \). There are more data points below the magenta line than above, so that the extrapolation is not an exact predictor of the result. However, data points for the 217 \( \times \) 353 \( TB \) spectrum predominantly lie above zero, providing additional evidence for positive \( TB \) persistence beyond 353 GHz. In the rightmost panel of Figure 8, we evaluate a 217 \( \times \) 353 \( TB \) combination that does not include any Planck 353 GHz data. In this combination, the intensity map is the same 353 GHz SFD dust model 8 mentioned previously, and the polarization data are again the Planck 217 GHz half-mission 2 \( Q, U \) maps. Both right panels produce similar, and positive, \( TB \) spectra (see Table 1 in the Appendix).

6. Conclusions

We have explored the basic morphology of \( E \) and \( B \) maps of Galactic dust emission and have used intensity, polarization fraction, and polarization angle components to build simple empirical models of the dust emission. We computed \( TB \) and \( EB \) power spectra for these models and investigated how \( I, f \), and \( \gamma \) contribute to \( TB \). We find that:

1. Contributions to dust polarization map morphology from intensity \( (I) \), polarization angle \( (\gamma) \), and polarization fraction \( (f) \) components are more easily distinguished in the \( E \) and \( B \) maps than \( Q \) and \( U \). The \( E \) component is strongly dependent on the large angular scale polarization angle structure, reflecting the GMF orientation. Large-scale dust-\( B \)-mode structure takes the form of a quadrupole about the Local Arm viewing directions near \( l = 65^\circ \) and \( 240^\circ \), and expresses itself as a strong \( l = 3 \), \( |m| = 3 \) \( B \)-mode pattern about the Galactic plane. The exact morphology of the \( l = 3 \) mode is constrained by the dust polarization fraction.
2. Polarization angle is the key component in producing the observed Planck 353 GHz nonzero \( TB \) spectrum.
3. Intensity and polarization fraction maps with small-scale structure \( (l > 600) \), combined with large angular scale \( (>5^\circ) \) polarization angle morphology, are capable of producing a nonzero \( TB \) spectrum similar to that of the Planck PR3 353 GHz data.
4. Within the context of our empirical models, we use a small sample of polarization angle realizations taken from

![Figure 8](https://example.com/figure8.png)
the TIGRESS simulations to show that a nonzero $TB$ spectrum is a property of individual realizations. This implies a geometrical or spatial origin rather than a need for physics beyond that already incorporated in codes such as TIGRESS. Polarization angle maps derived from observational data independent of Planck (WMAP $K$-band, dust polarization of starlight) also produce a nonzero $TB$ spectrum.

5. The observed nonzero $TB$ spectrum is persistent with variations of masking and alternate choices for the intensity map, including a dust intensity model completely independent of Planck observations. We find additional evidence for persistence of nonzero $TB$ computed from 353 GHz $I$ and 217 GHz $[Q, U]$ maps.

We have substituted estimates of $I$, $f$, and $\gamma$ components within our empirical models that are independent of the Planck 353 GHz observations and found realizations for which nonzero $TB$ persists. Our findings support the conclusion that the Planck 353 GHz nonzero $TB$ spectrum is a physical property of Galactic dust polarization. In light of our studies in the paper, observing nonzero $TB$ due to the Galactic dust foreground is not unusual or surprising. It will be interesting to see if future experiments with higher sensitivity detect nonzero $EB$.

This research was supported in part by NASA grants NNX16AF28G, NNX17AF34G, and 80NSSC19K0526 and by the Canadian Institute for Advanced Research (CIFAR). This research has made use of NASA’s Astrophysics Data System Bibliographic Services. Some of the results in this paper have been derived using the healpy and HEALPix package. We acknowledge the use of the Legacy Archive for Microwave Background Data Analysis (LAMBDA), part of the High Energy Astrophysics Science Archive Center (HEASARC). HEASARC/LAMBDA is a service of the Astrophysics Science Division at the NASA Goddard Space Flight Center. We also acknowledge use of the Planck Legacy Archive. Planck is an ESA science mission with instruments and contributions directly funded by ESA Member States, NASA, and Canada.

Appendix

Summary Table of $TB$ Correlation Results

In Table 1, we provide a summary of the components comprising the simple empirical models and data combinations that were used to create the $TB$ spectra presented in Figures 4, 6 and 8. In Section 6, we summarize how these tests informed our conclusion that the observed $TB$ correlation is likely the result of large-scale Galactic dust polarization properties. Also in Table 1, we provide an approximate measure of the strength of the $TB$ signal in each of the example spectra shown in these figures. We could not develop a rigorous statistical representation of the binned $TB$ power spectrum uncertainties for many of our empirical realizations, because each realization represents a combination of Planck data with either noiseless models or components from other missions. As an approximation, we assume the statistical uncertainties in each bin are roughly equivalent to those that are derived from the Planck FFP10 simulations for the relevant Planck frequencies (see Section 4). We adopt these uncertainties and perform a weighted least

![Table 1]

| Description | Model | Polarization Fraction, $f$ | Polarization Angle, $\gamma$ | $TB$ Amplitude$^a$ |
|-------------|-------|---------------------------|-----------------------------|-----------------|
| Figure 4: $I$ fixed, vary $f$, $\gamma$ components | 1 | Constant | Simple | $-54$ (10) |
|             | 2 | Constant | Planck 353 | 90 (10) |
|             | 3 | Planck 353 | Simple | 2 (10) |
|             | 4 | Planck 353 | Planck 353 | 110 (10) |
| Figure 6: $I$ and $f$ fixed, vary $\gamma$ only | 1 | Planck 353 | TIGRESS 1 | $-12$ (10) |
|             | 2 | Planck 353 | TIGRESS 2 | $-156$ (10) |
|             | 3 | Planck 353 | TIGRESS 3 | $-29$ (10) |
|             | 4 | Planck 353 | TIGRESS 4 | 17 (10) |
|             | 5 | Planck 353 | TIGRESS 5 | $-6$ (10) |
|             | 6 | Planck 353 | TIGRESS 6 | 141 (10) |
|             | 7 | Planck 353 | TIGRESS 7 | 8 (10) |
|             | 8 | Planck 353 | TIGRESS 8 | $-51$ (10) |
|             | 9 | Planck 353 | TIGRESS 9 | 218 (10) |
|             | 10 | Planck 353 | $K$-band | 94 (10) |
|             | 11 | Planck 353 | Starlight | 59 (10) |

| Description | Model | Intensity Map | $Q$ and $U$ Maps | $TB$ Amplitude$^a$ |
|-------------|-------|---------------|------------------|-----------------|
| Figure 8: Different choices for IQU Maps | 1 | SFD 353 | Planck 353 | 73 (10) |
|             | 2 | Planck 353 | Planck 217 | 19 (2) |
|             | 3 | SFD 353 | Planck 217 | 13 (2) |

Note.

$^a$ As described in the Appendix, this is $A^{TB}$ in units of $K^2$ as derived from a power-law fit to the binned $TB$ spectrum computed for each model. Uncertainties per bin are estimated from FFP10 simulations including noise, residual systematics, dust emission, and CMB. Approximate uncertainties for $A^{TB}$ are provided in parentheses.
squares fit of a power law to the binned \( TB \) spectrum, where the power law takes the form \( D_f^{TB} = A^{TB} (I/80)^{\alpha_f + 2} \), with fixed \( \alpha_f = -2.44 \). In this case, the only free parameter is the amplitude \( A^{TB} \), which may be taken as a measure of \( TB \) strength. This is the same power-law parameterization adopted by the Planck Collaboration in presenting their original findings, and thus provides a common metric. In the last column of Table 1, we tabulate \( A^{TB} \) from the weighted fit to the binned spectrum. The derived statistical uncertainty for this parameter, assuming these approximations, is indicated in parentheses.

**ORCID iDs**

J. L. Weiland @ https://orcid.org/0000-0003-3017-3474  
G. E. Addison @ https://orcid.org/0000-0002-2147-2248  
C. L. Bennett @ https://orcid.org/0000-0001-8839-7206  
M. Halpern @ https://orcid.org/0000-0002-1760-0868  
G. Hinshaw @ https://orcid.org/0000-0002-4241-8320

**References**

Abitbol, M. H., Hill, J. C., & Johnson, B. R. 2016, MNRAS, 457, 1796  
Ade, P., Aguirre, J., Ahmed, Z., et al. 2019, JCAP, 02(2019), 056  
Allison, R., Caucaï, P., Calabrese, E., Dunkley, J., & Louis, T. 2015, PhRvD, 92, 123535  
Bennett, C. L., Larson, D., Weiland, J. L., et al. 2013, ApJS, 208, 20  
Benson, B. A., Ade, P. A. R., Ahmed, Z., et al. 2014, Proc. SPIE, 9153, 91531P  
Chon, G., Challinor, A., Prunet, S., Hivon, E., & Szapudi, I. 2004, MNRAS, 350, 914  
Görski, K. M., Hivon, E., Banday, A. J., et al. 2005, Apl, 622, 759  
Heiles, C. 2000, AJ, 119, 923  
Henderson, S. W., Allison, R., Austermann, J., et al. 2016, JLTP, 184, 772  
Hu, W., & White, M. 1997, NewA, 2, 323  
Huffenberger, K. M., Rotti, A., & Collins, D. C. 2019, arXiv:1906.10052  
Kamionkowski, M., Kosowsky, A., & Stebbins, A. 1997, PhRvD, 55, 7368  
Kaufman, J. P., Miller, N. J., Shimon, M., et al. 2014, PhRvD, 89, 062006  
Kim, C.-G., Choi, S. K., & Flauger, R. 2019, Apl, 880, 106  
Koopman, B., Austermann, J., Cho, H.-M., et al. 2016, Proc. SPIE, 9914, 99142T  
Page, L., Hinshaw, G., Komatsu, E., et al. 2007, ApJS, 170, 335  
Planck Collaboration Int. LIV 2018, arXiv:1801.04945v1  
Planck Collaboration Int. XXX 2016, A&A, 586, A133  
Planck Collaboration IV 2018, arXiv:1807.06208  
Planck Collaboration X 2016, A&A, 594, A10  
Planck Collaboration XI 2018, arXiv:1801.04945  
Planck Collaboration XII 2018, arXiv:1807.06212  
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, Apl, 500, 525  
Szapudi, I., Prunet, S., Pogosyan, D., Szalay, A. S., & Bond, J. R. 2001, ApJL, 548, L115  
Zaldarriaga, M., & Seljak, U. 1997, PhRvD, 55, 1830  
Zonca, A., Singer, L., Lenz, D., et al. 2019, JOSS, 4, 1298