Polarization of the Cosmic Infrared Background Fluctuations

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Received 2019 September 21; revised 2020 April 28; accepted 2020 May 3; published 2020 July 10

Abstract

The cosmic infrared background (CIB) is slightly polarized. Polarization directions of individual galaxies could be aligned with tidal fields around galaxies, resulting in nonzero CIB polarization. We use a linear intrinsic alignment model to theoretically predict angular correlations of the CIB polarization fluctuations and find that electric-like and curl-like (B-mode) polarization modes are equally generated with power four orders of magnitude less than their intensity. The CIB B-mode signal is negligible and not a concerning foreground for the inflationary B-mode searches at nominal frequencies for cosmic microwave background measurements, but could be detected at submillimeter wavelengths by future space missions.

Unified Astronomy Thesaurus concepts: Infrared galaxies (790); Cosmic background radiation (317); Cosmic inflation (319)

1. Introduction

The angular correlation pattern of cosmic microwave background (CMB) polarization fluctuations was predicted shortly after the CMB discovery in 1965 (Rees 1968; Nanos 1979; Negroponte & Silk 1980; Bond & Efstathiou 1984; Polnarev 1985; Tolman 1985). In 2001, the Degree Angular Scale Interferometer experiment for the first time detected an electric-like component (E-mode) of the predicted polarization signal (Kovac et al. 2002) and opened up a window for CMB polarization science. Since then, the E-mode polarization has been detected with great precision by current ground-based CMB experiments (Chiang et al. 2010; Naess et al. 2014; Polarbear Collaboration et al. 2014; Crites et al. 2015) and the most recent space-borne Planck mission (Planck Collaboration et al. 2016). As also predicted by perturbation theory, there is the existence of another, curl-like, component of the polarization signal—the so-called B mode, which can be created by both inflationary gravitational waves and gravitational lensing of the E-mode component, corresponding to B-mode fluctuations at large and small angular scales, respectively. The lensing B-mode, caused by large-scale structure, has been detected by many experiments (Hanson et al. 2013; Ade et al. 2014; BICEP2 Collaboration et al. 2014; Polarbear Collaboration et al. 2014; Keisler et al. 2015; POLARBEAR Collaboration et al. 2017). With sophisticated low-temperature detection technologies, cosmologists have gained a good understanding of the CMB on linear scales, although the inflationary B modes remain a mystery.

Future high sensitivity and high resolution (HSHR) CMB experiments (Benson et al. 2014; Galitzki et al. 2018; Abazajian et al. 2019; Sehgal et al. 2019) will enter a new era when the CMB is measured at very small and even nonlinear scales with unprecedented precision, and the secondary CMB fluctuations—radio galaxies, the thermal/kinetic Sunyaev–Zel’dovich (tSZ/kSZ) effects, and the cosmic infrared background (CIB)—will be precisely measured. As one of the precursors to the HSHR experiments, the South Pole telescope collaboration analyzed 2500 deg$^2$ data taken at 90, 150, and 220 GHz and found that the CIB emission due to the dusty star-forming galaxies is much stronger than the tSZ and kSZ at scales smaller than 4$'$ (George et al. 2015). Above 95 GHz the radio galaxies have little contributions to the secondaries (Iacobelli et al. 2014). Moreover, the CIB intensity anisotropies at high CMB frequencies—217, 353, 545, and 857 GHz—are also measured by the Planck satellite and are found to dominate the primary fluctuations (Planck Collaboration et al. 2014).

The secondary fluctuations can also be polarized. Fluctuations from polarized synchrotron radiation from radio galaxies are negligible at >150 GHz (Iacobelli et al. 2014) and the power of polarized tSZ signal is theoretically predicted to be $\mathcal{O}(10^{-5}) \mu K^2$ and behave like white noise (Deutsch et al. 2018). The CIB dominates the secondaries in intensity at small scales but its polarization has not been investigated.

CIB emission arises from thermal dust emissions of individual galaxies. The dust emission of individual galaxies is known to be polarized and different physical mechanisms have been proposed to explain it (Stein 1966; Hildebrand 1988a; Kritsuk et al. 2018). One basic theory is that asymmetric dust grains are aligned by the magnetic field of the host galaxy, leading to polarized emission that is perpendicular to the alignment direction (Stein 1966; Hildebrand 1988a). Turbulence is also thought to introduce Galactic dust polarization, as found from numerical simulations (Kritsuk et al. 2018). Although differences lie in various theories, the average polarization fraction of an individual galaxy is estimated to be 1%–2% of its intensity (Stein 1966; Hildebrand 1988b). From the Planck 353 GHz data, the polarization of the Galactic dust indicates that the dust is polarized at the $\sim$10% level along individual lines of sight, not averaged over the whole galaxy (Planck Collaboration et al. 2015, 2018).

The CIB arises from the superposition of emissions from many galaxies. The CIB polarization should be less than that of individual galaxies as misalignments between galaxies will lead to the averaging down of polarization fluctuations. Thus the CIB is usually assumed to be unpolarized and fully described by its intensity fluctuations. However, it is unclear how much polarization remains after this averaging. The polarization vectors of galaxies trace magnetic fields and directions of magnetic fields are correlated with galaxy...
morphologies, such as galaxy shapes (Hiltner 1958; Golla & Hummel 1994; Berkhuijsen et al. 2003; Chyży & Buta 2008; Fletcher et al. 2011). Galaxy shapes are known to be correlated with local tidal fields (Okumura & Jing 2009; Okumura et al. 2009; Singh et al. 2015; Martens et al. 2018; Johnston et al. 2019). Therefore, the averaged polarization direction could be correlated with the tidal fields on a megaparsec scale. This implies that galaxy polarization vectors may be preferentially aligned with the tidal fields.

If the CIB polarization signal were detectable, it would complement the current polarization surveys with much shorter wavelengths and open up a new window into structure formation. If the CIB polarization is not curl-free but contains a B-mode signal, it could become a new challenge to CMB inflationary B-mode searches, depending on its strength. As a science return, it is even possible that the CIB polarization will bring new cosmological information. In this work, we will theoretically calculate the CIB polarization signal with the linear alignment model for galaxy shapes proposed in Hirata & Seljak (2004).

2. Intrinsic Alignment Induced Polarization

CIB polarization requires a long-range coherence mechanism between galaxies, which could be caused by galaxy intrinsic alignment (IA). A spatial coupling $T(x)\gamma(x)$ between the CIB intensity $T(x)$ and the tidal field $\gamma(x)$ generates the CIB polarization. Here $x$ denotes space coordinates. Theoretical models for the linear IA are proposed in Hirata & Seljak (2004). The tidal fields are related to the gravitational potential $\Psi(x)$

$$\gamma(x) = -\frac{C_1}{4\pi G}(\nabla^2 - \nabla^2 \delta_x) \Psi(x),$$  

and in the Fourier domain, it is

$$\gamma(k) = -\frac{C_1}{4\pi G}e^{i\phi_x} \Psi(k).$$  

Here $k_i = (k_x, k_y, k_z)$, $k_i = k_z$, $C_1$ is a free parameter and $\delta$ is a covariant derivative. Rotational invariance is imposed on the tidal field by a phase factor $e^{i\phi_x}$, so the tidal field can be decomposed into the Stokes parameters via $\gamma = \gamma^Q + i\gamma^U$. Specifically, $\phi_x$ is a projected angle between $k_z$ and $k_i$ on the $k_i$ plane so the phase factor $e^{i\phi_x} = (k_x^2 - k_y^2)/k_z^2 + i2k_xk_y/k_z^2$ where $|k_z| = k_z$. The gravitational potential is created by the matter distribution $\delta(x)$ via the Poisson equation $\nabla^2 \Psi(x) = -4\pi G\rho/\text{D}a^2 \delta(x)$, where $a$ is the cosmological scale factor, $\rho$ is the matter density, and $D$ is a growth factor. In this work, we only consider the linear alignment model, and assume that the higher order corrections, such as the quadratic alignment, are negligible.

The CIB is the emission from dust surrounding star-forming regions in distant galaxies. The amount of CIB polarization $P$ at a location $x$ is determined by a polarization fraction $p$, and is an intrinsic property of a particular galaxy that forms its polarization due to complicated processes, such as magnetic field (Fletcher et al. 2011), supernovae activity (Bulla et al. 2015), and thermal dust dynamics (Levrier et al. 2018). Therefore, the polarization fraction is actually a spatially varying and frequency-dependent field, which can be described as $p(x) = p_0 + \Delta p(x)$. For measurements at linear angular scales, the CIB polarization fluctuation at arcminute level resolution is an average of many individual galaxies, so the residual polarization fraction should be negligible. In this work we are assuming that each galaxy has a constant polarization fraction $p_0$ coming from the bit associated with large-scale structure, along with fluctuations from other effects that we treat as a random variable within each galaxy.

In addition to the amplitude of the polarized emission, a polarization direction is another important property of an individual galaxy. If each galaxy’s polarization direction is randomly aligned, the polarization signal from the extragalactic dust will behave like white noise. However, an averaged polarization direction on scales larger than $k_\text{d}$ is expected to be aligned with the tidal field, although the polarization direction of each galaxy may not be perfectly correlated with the stretching direction of the local tidal field on scales smaller than $k_\text{d} \sim O(1)\text{ Mpc}^{-1}$ which is a typical coherence length of a tidal field. Therefore, if the polarization vector is aligned with the local tidal field which simultaneously modulates its polarization intensity, the polarization signal of the extragalactic dust will behave differently from white noise. Furthermore, the three fields—CIB intensity $T(x)$, tidal field $\gamma(x)$, and polarization fraction $p(x)$—are not expected to be correlated at linear angular scales due to their different coherence lengths and intrinsic properties.

Given the assumptions discussed above, we propose the IA-induced CIB polarization model

$$P(x) = (Q + iU)(x) = p(x)T(x)\gamma(x),$$

from which it is seen that the CIB temperature modulation by the IA field is the key to generating a polarization signal. Next, we will use Equation (3) to predict the CIB polarization power spectra. We assume that the CIB emissivity is linearly proportional to the underlying density field, i.e., $T(x) = b_x T_0 \delta(x)$. The galaxy bias $b_x$ is fixed by the Planck CIB temperature power spectrum at a specific frequency, and the mean CIB intensity $T_0$ is calculated by integrating the flux distribution up to a certain flux threshold. We note that in this work the monopole value $T_0$ is absorbed in the CIB redshift distribution $dN/dz_c$, which is fitted from the measured CIB auto- and cross-power spectra at different frequencies (Viero et al. 2013).

2.1. Constant Polarization Fraction and Completely Correlated Polarization Angle

We first assume that the polarization fraction is a constant $p_0$ and the polarization angle is completely correlated with the tidal field, and will discuss implications of spatial fluctuations of these two fields in Section 2.2.

Expanded by plane waves, Equation (3) becomes

$$P(k) = F(z)p_0 \int \frac{d^3k_1}{(2\pi)^3} e^{i\phi_1} \delta(k_1) \delta(k_2),$$

where $k = k_1 + k_2$ and $e^{i\phi_1} = f_\text{IA}(k) + if_\text{SB}(k)$. We adopt a prefactor $F(z) = -A C_1 p_0 \Omega_m/D(z)$ following the definition of Joachimi et al. (2011) and Heymans et al. (2013), which is slightly different from the original definition in Hirata & Seljak (2004). Here $A$ and $C_1$ are both free parameters, $\rho_\text{crit}$ is the critical density today and $D$ is the growth factor normalized to unity today. It is seen from this equation that the CIB polarization essentially arises from a two-point matter density correlation, and its 3D power spectrum can be thus derived as
Here, $P^{\nu}(k)$ is the 3D matter power spectrum that governs the spatial clustering of CIB intensity anisotropies $P^{TT} = \langle T(k)T^*(k)\rangle = h_c^2P^m$ via a linear bias $b_c$. The fiducial parameter set is $\{A, C_s, \Omega_m, H_0\} = [1, 5 \times 10^{-14}h^{-2}M_{\odot}^{-1} \text{ Mpc}^3, 0.27, 67.5 \text{ km s}^{-1} \text{ Mpc}^{-1} \}$ with a reduced Hubble constant $h = H_0/100$. The $k$ cutoff in Equation (5) is set to $2 \text{ Mpc}^{-1}$, which is sufficiently large for convergence. This 3D polarization power spectrum can also be computed using a halo model (Schneider & Bridle 2010).

Different from the 3D characterization, the HSHR experiments essentially measure a projected CIB field, which is an integration of all redshift slices weighted by a redshift distribution $W_s(z)$, i.e.,

$$P(n) = \int d\chi W^\text{CIB}_\nu(\chi) P(\chi, n),$$

and the CIB temperature and polarization angular power spectra at frequency $\nu$ are derived using the Limber approximation $k = \ell/\chi$, i.e.,

$$C_{\ell,XX(,\nu)} = \int \frac{d\chi}{\chi} W^\text{CIB}_\nu(\chi) W^\text{CIB}_\nu(\chi) P_{XX}(k, z).$$

Here $X = \{T, E, B\}$, $n$ is a direction in the sky, $\chi$ is the comoving distance, and the CIB redshift distribution $W^\text{CIB}_\nu(z)$ is taken from Viero et al. (2013).

To calculate the CIB intensity and polarization power spectra at a broad range of frequencies, we make a few approximations. The CIB source redshift distributions $dN/dz$ are poorly constrained at lower CMB frequencies, especially 217 and 143 GHz. Instead of using various empirical redshift distributions at different frequencies, we adopt the same shape of $dN/dz$ for a lower frequency but allow the amplitude to change. Specially, we derive a ratio of the Planck CIB temperature and polarization power spectra is shifted by the flux cuts as well. In Figure 1 (left), we show the theoretical power spectra of the CIB polarization at a polarization fraction $p_0 = 1\%$ from frequencies 143 to 545 GHz. We note that this is only a representative case for the polarization fraction, which could be as high as 20% (Planck Collaboration et al. 2015, 2018). But its uncertainty does not add complexity and new features to the CIB polarization power spectrum calculations in this work because it is only a multiplicative factor. One remarkable feature of the CIB polarization is that the IA produces equal power on the $E$ and $B$ modes, whereas for the Galactic dust, the ratio of $E$ to $B$ is $\sim2$ (Planck Collaboration et al. 2018). The shape of the polarization power spectrum is nonwhite at small scales. The power of CIB polarization anisotropy $\sqrt{\ell(\ell+1)/2\pi}C_\ell$ is about four orders of magnitude fainter than its intensity anisotropy, whereas the CMB polarization is relatively much brighter—one order of magnitude fainter than its temperature. The calculation of the $B$-mode power spectrum indicates that the inflationary CMB $B$-mode signal will not be contaminated at observing frequencies $\nu < 353$ GHz and if the tensor-to-scalar ratio $r > 0.001$.

We show the polarization power spectra at 857 GHz, where CIB emission is expected to dominate the extragalactic sky, in Figure 1 (right). As seen from Figures 1 and 2, the CIB $B$-mode signal is increasing as the frequency increases and becomes comparable to the CMB lensing $B$-mode signal at 857 GHz. The measured signal is a sum of the IA-induced polarization signal, shot noise, and instrumental noise. Polarization signals of other secondaries, such as the polarized tSZ, are ignored in this work. Also, Galactic foregrounds will not be a problem for the CIB polarization detection. Optical surveys in the future will make direct measurements of the intrinsic alignment, which can be cross-correlated with the CIB polarization data to more robustly detect the CIB polarization signals.

### 2.2. Spatial Fluctuations of the Polarization Fraction and Angle

In the previous section, we have assumed that the polarization fraction is a constant and the polarization angle is completely correlated with the tidal fields. However, dust polarization is complicated, the mean polarization fraction of each galaxy is an average over many clumps of star-forming regions with strong local variations in polarization properties. In the following, we consider the impact of a random polarization fraction $\Delta p$ by sampling a small Gaussian fluctuation from a normal distribution $N(0, \sigma^2_{\Delta p})$, where $\sigma^2_{\Delta p}$ is the variance of the spatially varying polarization fraction. The uncorrelated polarization fraction $\Delta p$ will not change the mean polarization fraction, i.e., $\langle p \rangle = p_0$, but it will contribute to the variance $\langle p^2 \rangle = p_0^2 + \sigma^2_{\Delta p}$.

Moreover, it is unlikely that each galaxy’s polarization direction will exactly track the large-scale tidal field within the coherence length. Thus, the polarization angle $\phi_k$ is a combination of the dominant tidal field direction and a random angle $\Delta \phi$ due to its intrinsic properties, and the latter behaves
like a source of noise. To quantify how the polarization angle fluctuation can affect the CIB polarization, we introduce the component $\Delta \phi$ for the polarization angle $\phi_k$. The field $\Delta \phi$ is also sampled from a normal distribution $N(0, \sigma_{2\Delta \phi}^2)$, where $\sigma_{2\Delta \phi}^2$ is the variance of the spatially varying polarization angle. At a single $k$ mode, the polarization angle $\phi_k$ is determined by the rotation phase $e^{i2\phi_k} = (k_+^2 - k_0^2)/k^2 + i2k_0 k_x/k^2 = \cos[2\phi(k)] + i\sin[2\phi(k)]$, where the real and imaginary parts are referred to as $f_+(k) = \cos[2\phi(k)]$ and $f_0(k) = \sin[2\phi(k)]$.

For the polarization power spectra $EE/BB$ in Equation (5), a random angle $\Delta \phi$ to the intrinsic angle $\phi$ of each galaxy will modify the angle-related part, which is

$$\Gamma_{AB}(\mathbf{k}_1, \mathbf{k}_2) \equiv [f_{A/B}(\mathbf{k}_1) + f_{A/B}(\mathbf{k}_2)] \times f_{A/B}(\mathbf{k}_2)$$

$$= \cos^2[\phi(\mathbf{k}_1) - \phi(\mathbf{k}_2)] \pm \cos[4\Delta \phi + \phi(\mathbf{k}_1) + 3\phi(\mathbf{k}_2)],$$

by replacing $\phi$ by $\phi + \Delta \phi$. Here $A$ and $B$ refer to $EE$ and $BB$, respectively. Using the trigonometric relationship, we can express the above equation as

$$\Gamma_{EE/BB}(\mathbf{k}_1, \mathbf{k}_2) = \alpha[\alpha \pm \cos(4\Delta \phi)\beta \mp \sin(4\Delta \phi)\gamma],$$

where $\alpha = \cos[\phi(\mathbf{k}_1) - \phi(\mathbf{k}_2)]$, $\beta = \cos[\phi(\mathbf{k}_1) + 3\phi(\mathbf{k}_2)]$, and $\gamma = \sin[\phi(\mathbf{k}_1) + 3\phi(\mathbf{k}_2)]$, and we omit $(\mathbf{k}_1, \mathbf{k}_2)$ in the following text unless it is needed.

Defining $\epsilon = e^{-2\Phi_{2\Delta \phi}/2}$, we obtain the mean value of the angle-related component in Equation (9) as

$$\langle \Gamma \rangle_{\Delta \phi} = \alpha(\alpha \pm \epsilon \beta),$$

and the variance as

$$\sigma^2(\Gamma_{EE/BB}) = \langle \Gamma^2 \rangle_{\Delta \phi} - \langle \Gamma \rangle^2$$

$$= \alpha \alpha'[\alpha \alpha' \pm (\alpha \beta' + \alpha' \beta)\epsilon + \beta\beta'[1 + \epsilon^4] + \gamma\gamma'[1 - \epsilon^4]} - \langle \Gamma \rangle^2,$$

(12)

where the prime $'$ denotes $(\mathbf{k}_1', \mathbf{k}_2')$.

With perturbations of the polarization fraction and angle, the polarization power spectra now become

$$\langle P_{EE/BB}(k, \Delta p, \Delta \phi) \rangle_{\Delta p, \Delta \phi} = F^2(\mathbf{z})[p_0^2 + \sigma_{2\Delta \phi}^2] \int \frac{d^3k_1}{(2\pi)^3} \left[ \frac{1 + \epsilon}{2} f_A(k_1)f_A(k_2) \right.$$

$$\left. + \left(1 + \frac{\epsilon}{2}\right)f_B(k_1)f_B(k_2) \pm \epsilon f_A^2(k_2) \right.$$  

$$\left. + \left(1 + \frac{\epsilon}{2}\right)P^m(k_1)P^m(k_2) \right].$$

(13)

The numerical calculations show that the averaged power spectrum with random fields $\Delta p$ and $\Delta \phi$—$P_{EE/BB}(k, \mathbf{z}, \Delta p, \Delta \phi)$—is just a rescaled version of the one with no perturbations, i.e., $\langle P_{EE/BB}(k, \mathbf{z}, \Delta p, \Delta \phi) \rangle_{\Delta p, \Delta \phi} = (1 + \sigma_{2\Delta \phi}^2/p_0^2)P_{EE/BB}(k, \mathbf{z}, \Delta p = 0, \Delta \phi = 0)$, where $P_{EE/BB}(k, \mathbf{z}, \Delta p = 0, \Delta \phi = 0)$ is Equation (5). However, the power spectrum with a single realization of the random $\Delta \phi$ and $\Delta p$ fields could deviate from the averaged one, leading to variance.

Figure 1. (Left) CIB polarization power spectra with respect to the observing frequencies. The CIB polarization is nonzero and its power [$\sqrt{(\ell+1)/(2\pi)C_\ell}$] is about four orders of magnitude lower than its intensity. Also the polarization power is equally divided into $E$ and $B$ modes, and is not distributed like white noise. The polarization power increases as the intensity increases. The CMB $B$-mode signal is much fainter than the CMB inflationary $B$-mode at frequencies $\nu < 353$ GHz. The CMB tensor $B$-mode is generated with a tensor-to-scalar ratio $r = 0.001$. Two CIB flux cuts ($S_1$ and $S_2$) are applied to the CIB-related power spectrum calculations. (Right) CIB polarization power spectra at 857 GHz. At this frequency, the CIB is the dominating fluctuation and its $B$-mode signal becomes comparable to that of the CMB lensing. Future space submillimeter experiments could detect the CIB $E$- and $B$-mode signals.
in the power spectrum:
\[
\sigma^2[P^{EE/BB}(k, z, \Delta p, \Delta \phi)] = F^4(z) \left( p_0^6 + 6 p_0^2 \sigma_{2p}^2 + 3 \sigma_{2p}^4 \right) \times \int \frac{d^3k_1}{(2\pi)^3} \int \frac{d^3k_2}{(2\pi)^3} P^m(k_1) P^m(k_2) \times P^m(k_1') P^m(k_2') \left[ \alpha \alpha' \pm (\alpha \beta' + \alpha' \beta) \epsilon + \beta \epsilon' \left( \frac{1 + \epsilon^2}{2} + \gamma \gamma' \left( \frac{1 - \epsilon^2}{2} \right) \right) \right] \times \alpha \alpha' - \left< P^{EE/BB}(k, z) \right>^2, \tag{14}
\]

using the variance term Equation (12). Here \(\alpha = u_1^{(1)} u_2^{(2)} + u_2^{(1)} u_1^{(2)}\), \(\beta = u_1^{(1)} v_2^{(2)} - u_1^{(2)} v_2^{(1)}\), \(\gamma = u_3^{(1)} v_2^{(2)} + u_3^{(2)} v_2^{(1)}\), \(v_2 = u_3^2 u_s - u_3^3 + 3 u_s^2 u_3\), \(u_s = k_s / k\), and \(u_3 = k_s / k\). The superscript (1) or (2) refers to \(k_1\) or \(k_2\), respectively. The variance of the 2D power spectrum (Equation (7)) thus can be easily derived with Equation (14). We have numerically checked that the extra variance induced by spatial variations is much smaller than the cosmic variance, and the CIB polarization power spectra are not significantly affected by including the spatially varying components for the polarization fraction and angle. Thereby, the assumption (Section 2.1) of a constant polarization fraction and a polarization angle completely correlated with the tidal fields is found to be a good approximation.

3. Conclusions

In this work, we establish a theoretical model for polarization of the CIB, in which polarization directions of individual galaxies are aligned with tidal fields. Theoretical calculations show that both the CIB E and B modes are created with an equal power that is about four orders of magnitude less than the CIB intensity anisotropy. The CIB B-model signal will not become a concerning foreground for the CMB inflationary B-mode searches at frequencies \(\nu > 545\) GHz. However, at the CIB dominated frequencies, such as 545 and 857 GHz, the CIB polarization signals could be detected by space submillimeter observations in the future and could become a new probe of structure formation.

This research was supported in part by Perimeter Institute for Theoretical Physics. Research at Perimeter Institute is supported by the Government of Canada through the Department of Innovation, Science, and Economic Development, and by the Province of Ontario through the Ministry of Research and Innovation. This research is supported by the Brand and Monica Fortner Chair.

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References
Abazajian, K., Addison, G., Adshedd, P., et al. 2019, arXiv:1907.04473
Ade, P. A. R., Akiba, Y., Anthony, A. E., et al. 2014, PhRvL, 113, 021301
Benson, B. A., Ade, P. A. R., Ahmed, Z., et al. 2014, Proc. SPIE, 9153, 915312
Berkhuijsen, E. M., Beck, R., & Hoernes, P. 2003, A&A, 398, 937
Béthermin, M., Dole, H., Lagache, G., Le Borgne, D., & Penin, A. 2011, A&A, 529, A4
BICEP2 Collaboration, Ade, P. A. R., Aikin, R. W., et al. 2014, PhRvL, 112, 241101
Bond, J. R., & Efstathiou, G. 1984, ApJL, 285, L45
Bulla, M., Sim, S. A., & Kroner, M. 2015, MNRAS, 450, 967
Chiang, H. C., Ade, P. A. R., Barkats, D., et al. 2010, ApJ, 711, 1123
Chyży, K. T., & Buta, R. J. 2008, ApJL, 677, L17
Crites, A. T., Henning, J. W., Ade, P. A. R., et al. 2015, ApJ, 805, 36

Figure 2. CIB polarization power with respect to frequencies. Two cases are evaluated at \(\ell = 100\) (left) and \(\ell = 1000\) (right) at which the inflationary B modes and gravitational lensing B modes have peak contributions. It is seen that the CIB B-mode signal will exceed the CMB lensing B-mode at higher frequencies \(\nu > 545\) GHz, but will not contaminate the CMB inflationary B-mode signal at \(\nu < 535\) GHz.
Deutsch, A.-S., Johnson, M. C., Münchmeyer, M., & Terrana, A. 2018, JCAP, 2018, 034
Fletcher, A., Beck, R., Shukurov, A., Berkhuijsen, E. M., & Horellou, C. 2011, MNRAS, 412, 2396
Galitzki, N., Ali, A., Arnold, K. S., et al. 2018, Proc. SPIE, 10708, 1070804
George, E. M., Reichardt, C. L., Aird, K. A., et al. 2015, ApJ, 799, 177
Glenn, J., Conley, A., Béthermin, M., et al. 2010, MNRAS, 409, 109
Golla, G., & Hummel, E. 1994, A&A, 284, 777
Hanson, D., Hoover, S., Crites, A., et al. 2013, PhRvL, 111, 141301
Heymans, C., Grocutt, E., Heavens, A., et al. 2013, MNRAS, 432, 2433
Hildebrand, R. H. 1988a, ApL&C, 26, 263
Hildebrand, R. H. 1988b, QJRAS, 29, 327
Hiltner, W. A. 1958, ApJ, 128, 9
Hirata, C. M., & Seljak, U. 2004, PhRvD, 70, 063526
Iacobelli, M., Burkhart, B., Haverkorn, M., et al. 2014, A&A, 566, A5
Joachimi, B., Mandelbaum, R., Abdalla, F. B., & Bridle, S. L. 2011, A&A, 527, A26
Johnston, H., Georgiou, C., Joachimi, B., et al. 2019, A&A, 624, A30
Keisler, R., Hoover, S., Harrington, N., et al. 2015, ApJ, 807, 151
Kovac, J. M., Leitch, E. M., Pryke, C., et al. 2002, Natur, 420, 772
Kritsuk, A. G., Flauger, R., & Ustyugov, S. D. 2018, PhRvL, 121, 021104
Lagache, G., Dole, H., & Puget, J. L. 2003, MNRAS, 338, 555
Levrier, F., Neveu, J., Falgarone, E., et al. 2018, A&A, 614, A124
Martens, D., Hirata, C. M., Ross, A. J., & Fang, X. 2018, MNRAS, 478, 711
Naess, S., Hasselfield, M., McMahon, J., et al. 2014, JCAP, 2014, 007
Nanos, G. P., Jr. 1979, ApJ, 232, 341
Negroponte, J., & Silk, J. 1980, PhRvL, 44, 1433
Okumura, T., & Jing, Y. P. 2009, ApJL, 694, L83
Okumura, T., Jing, Y. P., & Li, C. 2009, ApJ, 694, 214
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2014, A&A, 571, A30
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2015, A&A, 576, A104
Planck Collaboration, Aghanim, N., Arnaud, M., et al. 2016, A&A, 594, A11
Planck Collaboration, Akrami, Y., Ashdown, M., et al. 2018, arXiv:1801.04945
POLARBEAR Collaboration, Ade, P. A. R., Aguilar, M., et al. 2017, ApJL, 848, 121
Polarbear Collaboration, Ade, P. A. R., Akiba, Y., et al. 2014, ApJ, 794, 171
Polnarev, A. G. 1985, SvA, 29, 607
Rees, M. J. 1968, ApJL, 153, L1
Rowan-Robinson, M. 2009, MNRAS, 394, 117
Schneider, M. D., & Bridle, S. 2010, MNRAS, 402, 2127
Sehgal, N., Aiola, S., Akrani, Y., et al. 2019, arXiv:1906.10134
Singh, S., Mandelbaum, R., & More, S. 2015, MNRAS, 450, 2195
Stein, W. 1966, ApJ, 144, 318
Tolman, B. W. 1985, ApJL, 290, 1
Viero, M. P., Wang, L., Zemcov, M., et al. 2013, ApJ, 772, 77