CMB Foregrounds: Problems, Parameterizations, and Progress

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Outline

• CMB Foregrounds

• Generalized Parameterizations
  - Application: PIXIE Spectral Distortions

• CMB Lensing: signal and foreground
CMB Foregrounds

Polarization

Temperature

+ Radio sources
+ Anomalous microwave emission? (+ Atmosphere)

Kogut+ (2016); Abitbol, Chluba, JCH, & Johnson (2017)
B-modes

BICEP2 Collaboration

BICEP2: B signal

\[0.3 \mu K\]

150 GHz
B-modes

Flauger, JCH, & Spergel (2014)
New Parameterizations

Flexible, general models are needed for ~nK precision data. Beam and line-of-sight averages are inevitable. Superposition of spectral shapes, leading to new behavior.
New Parameterizations

Flexible, general models are needed for \( \sim nK \) precision data, where beam and line-of-sight averages are inevitable.

\[ I_v(p) = I_v(\bar{p}) + \sum_i (p_i - \bar{p}_i) \partial_{\bar{p}_i} I_v(\bar{p}) + \frac{1}{2!} \sum_i \sum_j (p_i - \bar{p}_i)(p_j - \bar{p}_j) \partial_{\bar{p}_i} \partial_{\bar{p}_j} I_v(\bar{p}) \]
\[ + \frac{1}{3!} \sum_i \sum_j \sum_k (p_i - \bar{p}_i)(p_j - \bar{p}_j)(p_k - \bar{p}_k) \partial_{\bar{p}_i} \partial_{\bar{p}_j} \partial_{\bar{p}_k} I_v(\bar{p}) + \ldots \]

New SED behavior generated by beam- and LOS-averaging coupling to derivatives of fundamental SED can be captured by *moments* of underlying parameter distribution functions.

Chluba, *JCH*, and Abitbol (2017)
New Parameterizations

Flexible, general models are needed for ~nK precision data beam and line-of-sight averages are inevitable

→ superposition of spectral shapes, leading to new behavior

Example: modified blackbody SED

\[ I_{\nu}(A_0, \alpha, T) = A_0 \left( \frac{\nu}{\nu_0} \right)^\alpha \nu^3 / \left( e^{h\nu/kT} - 1 \right). \]

\[ \langle I_{\nu} \rangle = \frac{\bar{A}_0 \left( \frac{\nu}{\nu_0} \right)^{\bar{\alpha}} \nu^3}{e^x - 1} \left\{ 1 + \frac{1}{2} \omega_{22}^d \ln^2 \left( \frac{\nu}{\nu_0} \right) \right. \]

\[ + \omega_{23}^d \ln \left( \frac{\nu}{\nu_0} \right) Y_1(x) + \frac{1}{2} \omega_{33}^d Y_2(x) \]

\[ + \frac{1}{6} \omega_{222}^d \ln^3 \left( \frac{\nu}{\nu_0} \right) + \frac{1}{2} \omega_{223}^d \ln^2 \left( \frac{\nu}{\nu_0} \right) Y_1(x) \]

\[ + \frac{1}{2} \omega_{233}^d \ln \left( \frac{\nu}{\nu_0} \right) Y_2(x) + \frac{1}{6} \omega_{333}^d Y_3(x) + \ldots \}

\[ p = \{ A_0, \alpha, \beta = 1/T \} \]

\[ \bar{\alpha} = \frac{\langle A_0(r) \alpha(r) \rangle}{\overline{A}_0}, \quad \frac{1}{\bar{T}} = \frac{\langle A_0(r)/T(r) \rangle}{\overline{A}_0} \]

\[ \omega_{2\ldots23\ldots3}^d = \frac{\langle A_0(r)[(\alpha(r) - \bar{\alpha})^k [(\bar{T}/T(r) - 1]^m \rangle}{\overline{A}_0} \]

\[ Y_k = [(-\beta)^k \partial^k/\partial \beta^k I_{\nu}] / I_{\nu}, \]

\[ Y_1(x) = xe^x/(e^x - 1) \]

\[ Y_2(x) = Y_1(x) x \coth(x/2) \]

note cross-terms between spectral index and temp.

Chluba, JCH, and Abitbol (2017)
New Parameterizations

Example: two-component dust model

Chluba, JCH, and Abitbol (2017)
New Parameterizations

Example: suppose dust SED is simple modified blackbody everywhere, but spectral index varies on ~deg scales

Simple extrapolations can lead to highly inaccurate results

Moment method allows such variations to be captured without *a priori* assumptions

Chluba, JCh, and Abitbol (2017)
Application: *PIXIE* Forecasts

Primordial Inflation Explorer

~1000x more sensitive than COBE-FIRAS
15 GHz to 6 THz (400 channels)
High S/N detection of $<y> +$ relativistic tSZ
Primordial B-mode science: $\sigma(r) \sim 6 \times 10^{-4}$

Kogut+ (2011); JCH+ (2015); Calabrese+ (2016)
σ(T_{CMB}) \sim 100 \text{ nK} \\
(S/N \sim 1.3 \times 10^7)

Compton-\text{y} detection \\
S/N \sim 200

\mu \text{ limit (95\% CL): } |\mu| < 3.6 \times 10^{-7} \\
(250x \text{ better than } \text{FIRAS limit})

Relativistic thermal Sunyaev-Zel’dovich detection S/N \sim 10

Abitbol, Chluba, JCH, and Johnson (2017)
CMB Lensing

Re-mapping of CMB fluctuations (preserves blackbody form)

Many (∼50) small random deflections lead to a net deflection (∼2-3 arcmin), coherent on ∼deg scales

\[ T(\hat{n})_{\text{lensed}} = T(\hat{n} + d(\hat{n}))_{\text{unlensed}} \]

Quadratic reconstruction:

\[ \phi(\vec{L}) \sim T(\vec{\ell})T(\vec{L} - \vec{\ell}) \]

\[ \vec{d} = \nabla \phi \]
CMB Lensing: \( r \) Foreground

\[
B^{\text{lens}}(l) = \int \frac{d^2l'}{(2\pi)^2} W(l,l') E(l') \kappa(l-l')
\]

\[
W(l,l') = \frac{2l' \cdot (1-l')}{|l-l'|^2} \sin(2\varphi_{l,l'})
\]

Zaldarriaga & Seljak (1998); Lewis+ (2001); Kesden+ (2002); Knox & Song (2002)
**CMB Delensing**

estimate lensing B-mode using multi-tracer LSS data

\[
\hat{B}^\text{lens}(l) = \int \frac{d^2 l'}{(2\pi)^2} W(1, 1') f(1, 1') E^N(1') I(1 - 1') \quad B^\text{res} = B^\text{lens} - \hat{B}^\text{lens}
\]

Tracers = \{CIB [Planck GNILC 353 GHz], WISE galaxies, Planck \(\kappa\)\}

Yu, JCH, and Sherwin (2017)
CMB Delensing
determine optimal linear combination coefficients by fitting models to all auto- and cross-power spectra
delensing efficiency $\leftrightarrow$ correlation coefficient with true $\kappa$

$C^{\kappa\kappa}_l \rightarrow (1 - \rho^2_l)C^{\kappa\kappa}_l$

Yu, JCH, and Sherwin (2017)
CMB Delensing

Yu, JCH, and Sherwin (2017)

CIB + WISE

$f_{\text{sky}} = 0.43$

GNILC 353 GHz + WISE + Planck lens co-add

Highest-fidelity delensing maps to date

maps: http://www.astro.princeton.edu/~jch/delens/
CMB Delensing

delensing factor $\sim2$ on nearly half of the sky

$\sim2x$ decrease in $\sigma(r)$ for low-noise surveys

Yu, JCH, and Sherwin (2017)
CMB Delensing

delensing factor $\sim 2$ on nearly half of the sky

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Yu, JCH, and Sherwin (2017)
Conclusions

• Flexible, systematic foreground parameterizations are needed to robustly interpret upcoming polarization and spectral distortion measurements.

• *PIXIE* will detect Compton-$\gamma$ and relativistic tSZ distortions at high significance, even in the presence of foregrounds. $\mu$ constraints will improve upon *FIRAS* by factor of $\sim 250$.

• Multi-tracer maps from current data can delens B-mode foreground well enough to reduce $\sigma(r)$ by factor of $\sim 2$. 
Advanced ACTPol

Planck

SPT-3G

PIXIE

BICEP/Keck

LiteBird

Spider

CLASS

PolarBear/Simons Array

ABS

Thanks!