MEASUREMENTS OF DEGREE-SCALE B-MODE POLARIZATION WITH BICEP2, KECK ARRAY, AND BICEP3

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BICEP2, the Keck Array, and BICEP3 are a series of small-aperture Cosmic Microwave Background (CMB) polarimeters operating from the South Pole. These telescopes search for evidence of inflation by targeting the recombination peak in the $BB$ spectrum. BICEP2 reported the first detection of degree-scale $B$ modes at 150 GHz, but the cross-correlation with high frequency polarization maps from the Planck satellite shows that most or all of this signal is due to Galactic dust foregrounds. New deep observations from the Keck Array at 95 GHz have significantly improved our ability to distinguish between CMB and foreground signals; these constraints will improve further with 220 GHz data from Keck Array and 95 GHz data from BICEP3. Future $B$-mode constraints on inflation will be boosted with multi-frequency data at large angular scales from the proposed BICEP Array and delensing in conjunction with the South Pole Telescope.

1 Constraining Cosmological Inflation with $B$-mode Polarization

While the Standard Model of Cosmology, ΛCDM, is extremely successful at explaining a wide range of observations, it is notably incomplete as we lack understanding of either the cosmological constant ($\Lambda$) or cold dark matter (CDM). Another unanswered question in ΛCDM is the origin of the Big Bang itself. The theory of inflation posits a period of exponential expansion of the space-time metric, which would explain the observed homogeneity of our universe, the source of initial perturbations, and other initial conditions. An unverified prediction of inflation is the existence of a stochastic background of gravitational waves, created from quantum fluctuations of the metric that were stretched to macroscopic length scales. The search for this Cosmic Gravitational Wave Background (CGB) is one of the most exciting topics in cosmology.

Direct detection of the CGB is likely impossible, but we may be able to measure the tensor perturbation (gravitational wave) contribution to the Cosmic Microwave Background anisotropies. The amplitude of the CGB is parametrized by $r$, the ratio of power between tensor and scalar (density) perturbations. The current best upper limit is $r_{0.05} < 0.07$ at 95% confidence, from BICEP2 and Keck Array data in combination with maps from the Planck and WMAP satellites. For such small ratios, sample variance from the dominant scalar perturbations limits our ability to detect tensors in the temperature or $E$-mode polarization fields, even with full sky observations. Fortunately, the odd parity of the $B$-mode polarization field means that it receives no contribution from scalar perturbations, making it an ideal “low background” channel to search for gravitational waves. The $B$-mode signal induced by gravitational waves at the time of recombination peaks at multipoles near $\ell = 80$, which corresponds to angular scales of 2–4 degrees.

This is referred to as the recombination bump. The reionization bump, present at very large scales $\ell < 10$, is due to gravitational waves scattering after the universe reionizes at lower redshift.
There are several obstacles to detection of gravitational waves via the degree-scale CMB $BB$ spectrum. First, the amplitude of the signal is very small, requiring large arrays of background-limited detectors integrating deeply from an excellent terrestrial site, high altitude balloon, or satellite. Our vantage point in the Milky Way means that all lines of sight must pass through some column of diffuse Galactic matter. In the microwave part of the electromagnetic spectrum, the two most important types of Galactic emission are synchrotron emission from free electrons (brighter at low frequencies) and thermal emission from dust (brighter at high frequencies). Both synchrotron and dust emission are partially polarized due to the Galactic magnetic field. Multicolor observations allow us to distinguish between the CMB blackbody spectrum and foregrounds, but we have only just begun to understand the properties of polarized foreground emission in the cleanest regions of the sky. Finally, the $E$-mode polarization pattern of the CMB, sourced by scalar perturbations, is distorted by gravitational lensing from large scale structure between us and the surface of last scattering, leaking part of that signal into $B$ modes. While techniques have been developed to identify and remove these lensing $B$ modes, a resulting improvement in sensitivity to $r$ has not yet been demonstrated on real data.

2 The BICEP/Keck Observational Program

BICEP2, the Keck Array, and BICEP3 make up a long-running program of microwave polarimeters operating at the Amundsen-Scott South Pole Station that have produced the best constraints to date on $B$-mode polarization from inflation. Beyond a common observing site, these experiments share similar optical designs, detector technology, survey strategy, and their data are analyzed jointly. The BICEP/Keck experimental strategy is to maximize sensitivity by packing a large number of detectors into high optical throughput telescopes with the minimum aperture size needed to target the signature of inflation at angular scales of a few degrees. Figure 1 summarizes the progression from BICEP2 and the Keck Array through BICEP3 and the planned BICEP Array. As the program proceeds, we have increased the number of deployed detectors and distributed them across three observing frequencies (95, 150, and 220 GHz) to improve our ability to separate CMB and foreground signals.

BICEP2 observed from 2010–2012 from the Dark Sector Laboratory (DSL), making use of a three-axis mount that was originally built for BICEP1. BICEP2 consisted of a single small-aperture telescope with a focal plane array of 512 transition edge sensor (TES) bolometers arranged into 256 dual-polarization pixels. All BICEP2 detectors operated in the 150 GHz observing window. Papers describing the cryostat, optics, and detectors and the optical calibrations contain further details.

The Keck Array was designed to use existing South Pole infrastructure by multiplying the successful BICEP2 design into a five telescope array on the mount originally built for the DASI experiment. The main design change was to upgrade the liquid Helium cooled BICEP2 cryostat to a more compact, pulse tube cooled design. A major advantage of the Keck Array’s modular design has been the ability to update the observing frequencies of individual telescopes from year to year. Table 1 summarizes the distribution of deployed detectors between 95, 150, and 220 GHz observing bands across seven years of the BICEP/Keck observing program.

BICEP3 represents a significant upgrade over BICEP2 and Keck Array, with a combination of larger telescope aperture and faster optics that yield five times the focal plane area. While the 95 GHz detectors in BICEP3 use a similar design to those from BICEP2 or Keck Array, the BICEP3 detector tiles have been packaged into modular units that can be individually installed on the focal plane. BICEP3 began full operations in 2016.

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Theory doesn’t provide a lower bound for $r$, but there is significant interest in the large-field regime, $r \gtrsim 10^{-3}$. 

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Figure 1 – Summary of the BICEP/Keck observing program. From left to right, the columns summarize BICEP2, the Keck Array, BICEP3, and the planned BICEP Array. The top row shows a photo of each instrument (CAD rendering for BICEP Array). The second row shows photos representing the focal planes of each instrument. These photos have approximately the same scale, demonstrating that BICEP3 and BICEP Array feature much larger focal planes. The bottom row contains diagrams of the focal planes projected on the sky. The focal plane projections are color coded to show various observing frequencies. Red represents 95 GHz; green represents 150 GHz; blue represents 220 GHz. For BICEP Array, we additionally include light red (35 GHz) and dark blue (270 GHz).

Table 1: Number of detectors deployed by year and observing frequency for BICEP2, Keck Array, and BICEP3. Each of the five Keck Array telescopes can field 288 detectors at 95 GHz or 528 detectors at 150 or 220 GHz. This table reflects the design detector count, not achieved yield. The right hand columns show the accumulated survey weight at each frequency. The 2012 survey weight includes BICEP2 only. The 2015 and 2016 survey weight values (in parentheses) are preliminary.

<table>
<thead>
<tr>
<th>Year</th>
<th>BICEP2</th>
<th>Keck Array</th>
<th>BICEP3</th>
<th>Survey weight $[\mu K^{-2}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>150 GHz</td>
<td>95 GHz</td>
<td>150 GHz</td>
<td>220 GHz</td>
</tr>
<tr>
<td>2010</td>
<td>512</td>
<td>512</td>
<td>2560</td>
<td>1024</td>
</tr>
<tr>
<td>2011</td>
<td>512</td>
<td>2560</td>
<td>2560</td>
<td>2048</td>
</tr>
<tr>
<td>2012</td>
<td>512</td>
<td>2560</td>
<td>2560</td>
<td>2048</td>
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</tr>
<tr>
<td>2015</td>
<td>576</td>
<td>512</td>
<td>2048</td>
<td>2560</td>
</tr>
</tbody>
</table>

In addition to showing deployed detector counts, Table 1 shows the accumulated survey weight by year for each observing frequency. Survey weight increases linearly with effort and is
calculated as
\[
\text{Survey weight} = 2 \times \frac{\text{map area}}{(\text{map depth})^2},
\]
with the factor of two included to count both the $Q$ and $U$ polarization maps. Survey weight represents the total sensitivity to signals with a CMB-like $3K$ blackbody spectrum; the 220 GHz data will provide considerable sensitivity to Galactic dust foregrounds, despite its apparently low weight.

3 Current Constraints on Cosmology and Foregrounds

Since the initial BICEP2 results publication\textsuperscript{15} in 2014, we have made significant progress on our understanding of Galactic foreground polarization. High frequency (353 GHz) polarization maps from the Planck satellite provided the first hints\textsuperscript{17,18} that the BICEP2 signal is dominated by Galactic dust emission. A joint analysis of BICEP2, Keck Array (2012–2013, 150 GHz only), and Planck data detected dust at 5.1$\sigma$ and set an upper limit on tensors, $r_{0.05} < 0.12$ at 95% confidence\textsuperscript{19} This joint analysis was ultimately limited by the noise level in the Planck 353 GHz map; further improvement requires better multi-frequency data. As shown in Table 1, Keck Array and BICEP3 are busy producing deep maps covering the same region of sky at 95 and 220 GHz to address this problem.

The first results including 95 GHz data from Keck Array\textsuperscript{2} were published this year (referred to here as BK14). This paper represents a milestone, as the constraint on $r$ from the BB spectrum has exceeded the CMB temperature-derived constraint\textsuperscript{c} for the first time. Figure 2 summarizes the BK14 constraints on $r$ as well as foreground nuisance parameters. To derive these results, we compute all BB auto and cross-spectra between a set of multi-frequency maps and calculate the likelihood of a parametrized model, using the Hamimeche-Lewis approximation for the likelihood of correlated Gaussian fields\textsuperscript{21} Prior to calculating the BB spectra, these maps have been purified by a matrix operation that removes the “ambiguous modes” that occur when an $E$-mode map is filtered and apodized in the data reduction process.\textsuperscript{22} This highly effective purification step is critical to fully take advantage of the deep BICEP2/Keck maps.

The data used in this analysis are:

- BICEP2 + Keck Array 150 GHz map, including all observations through 2014.
- Keck Array 95 GHz map (2014 data only).
- Planck full mission polarization maps\textsuperscript{23} at 30, 44, 70, 100, 143, 220, and 353 GHz. These maps have been smoothed to BICEP2/Keck resolution and reobserved with the same coverage as the BICEP2/Keck 150 GHz map.
- WMAP nine-year polarization maps\textsuperscript{24} at 23 and 33 GHz, which have been likewise reobserved.

The parametrized model includes the following components:

- Lensing $B$ modes, calculated assuming a standard $\Lambda$CDM model.
- Tensor $B$ modes with amplitude proportional to $r$.
- A dust component with spectral behavior corresponding to a modified blackbody with emissivity power law index $\beta_d$. The dust is assumed to scale with $\ell$ as $\ell(\ell+1)C_\ell \sim \ell^{\beta_d}$. We define $A_d$, the amplitude of the dust power spectrum, at $\nu = 353$ GHz and $\ell = 80$. We apply a Gaussian prior on $\beta_d$ that is centered at 1.59 with width 0.11. There is a weak

\textsuperscript{c}Planck $TT+lowP+lensing+ext$ yields $r_{0.062} < 0.11$ ($r_{0.05} < 0.12$) at 95% confidence.\textsuperscript{20}
uniform prior on the \( \ell \) scaling, \(-1 < \alpha_d < 0\), but the analysis is fairly insensitive to this parameter.

- A synchrotron component with power law spectral behavior governed by parameter \( \beta_s \). We also assume power law scaling in \( \ell \) for this component, with index \( \alpha_s \). The synchrotron amplitude, \( A_s \), is defined at \( \nu = 23 \) GHz and \( \ell = 80 \). The Gaussian prior on \( \beta_s \) is centered at -3.1 with width 0.3. The prior on \( \alpha_s \) is the same as for \( \alpha_d \).

- We allow for spatial correlation between the dust and synchrotron foreground components. The correlation coefficient, \( \epsilon \), is assumed to be constant in \( \ell \). We apply a uniform prior between 0 and 1 for \( \epsilon \) (positive correlation).

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**Figure 2 – Likelihood figure reproduced from the BK14 results paper.** Solid black lines show the BK14 results; solid red lines show previous results from the BICEP2/Keck Array/Planck joint analysis. One-dimensional marginalized posteriors are shown along the main diagonal for \( r \), \( A_d \), and \( A_s \). We also show the two-dimensional marginalized posteriors between these three parameters. The small panels in the upper right show posteriors for auxiliary parameters, \( \beta_d \), \( \beta_s \), \( \epsilon \), \( \alpha_d \), and \( \alpha_s \), with dashed red lines to indicate the priors that were applied on these parameters.
From Figure 2, we see that the dust component is detected at high significance (center panel). No synchrotron component is detected (bottom right panel), which suggests that deeper 95 GHz observations from BICEP3 will yield significant returns. As noted above, these data provide the tightest upper limit to date on $r$ (upper left panel). Comparing the BK14 result (solid black) with the previous BICEP2/Keck Array/Planck joint analysis (solid red) for the two-dimensional $r$ vs $A_d$ posterior (middle left panel), we can see the power of the Keck Array 95 GHz data; the red contours show a significant degeneracy between $r$ and $A_d$, which is broken with the new data.

4 Future Prospects

The last two lines of Table 1 promise great improvements in the foreground separation and constraint on $r$ for upcoming BICEP/Keck publications. The current experimental strategy employs Keck Array as a high frequency dust monitor while BICEP3 provides very high mapping speed at 95 GHz. For the 2017 observing season, we plan to experiment with 270 GHz focal planes in two of the Keck Array telescopes. South Pole atmospheric properties are less well known at that frequency, but models suggest that higher sky temperatures will be more than compensated by increased brightness of the dust signal. Additional high frequency channels will also increase the robustness of the component separation against foreground complexities, such as decorrelation of the dust signal.

To surpass the currently operating instruments, we are building the BICEP Array (right column of Figure 1), which will deploy to South Pole for observations starting in 2018. BICEP Array will be an upgrade of the Keck Array to four BICEP3-like telescopes. With this upgrade, we will retain the modularity of Keck Array but increase the throughput of the telescopes to match BICEP3. BICEP Array will operate at 35, 95, 150, 220, and 270 GHz.

While this summary of the BICEP/Keck program focuses on separation of CMB and foreground components, it will soon be equally important to be able to remove the lensing $B$ modes, which would otherwise contribute irreducible sample variance to attempts to measure tensors. With an estimate of the lensing-mass map, $\phi$, and maps of the CMB $E$ modes, it is possible to reconstruct a template of the lensing-induced $B$ modes. The auto and cross-spectra derived from this template can be folded into our likelihood analysis to help reduce lensing sample variance while simultaneously constraining foregrounds and tensors.

In the short term, our best estimate of $\phi$ might come from the Cosmic Infrared Background, which measures high redshift galaxies that are imperfect tracers of the lensing potential. A collaborative effort is currently underway to use a CIB-derived $\phi$ map together with $E$ modes from SPTpol\textsuperscript{25} (which are complete to much higher $\ell$ than the BICEP/Keck $E$-mode map) to delens BICEP/Keck $B$ modes. While this delensing exercise is expected to yield only a small improvement on the $r$ constraint, it will be an important first demonstration of the technique.

Ultimately, the best measurements of $\phi$ will be derived from the higher order statistics of the CMB maps themselves. There have already been publications demonstrating CMB-derived lensing maps from Planck,\textsuperscript{26} SPTpol,\textsuperscript{27} ACTpol,\textsuperscript{28} POLARBEAR,\textsuperscript{29,30} and BICEP/Keck,\textsuperscript{31} but the signal-to-noise per mode is still rather low. The South Pole Telescope 3rd Generation camera (SPT-3G), scheduled for deployment at the end of 2016, represents a huge upgrade in sensitivity which will provide critical assistance in delensing the BICEP Array data.\textsuperscript{32}

Acknowledgments

References
