

### **Analysis of CMB Polarization Data from the BICEP Observatory at the South Pole**

The study of gravitational waves produced by cosmic inflation will play a key role in our understanding of the origin of the universe. Ground-based pathfinders are essential for the development of NASA's Inflation Probe mission. This proposal is for the BICEP telescope at the South Pole to measure the imprint of the primordial gravitational waves on the cosmic microwave background polarization. Our team set up the telescope in fall 2005 and acquired over 2400 hours worth of high-quality data during 2006. We intend to detect or place the best constraint on the inflationary gravitational wave signal through my plan to carry out a full treatment of the noise in the data. This NASA fellowship will help me analyze these data to learn lessons for the next generation space telescopes like the Inflation Probe.

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### **Motivation: What Powered the Big Bang?**

We learned during the past century that the universe began with the Big Bang; the question for this century is how the Big Bang itself began. NASA's Beyond Einstein program addresses this mystery with its high-priority science question: "*What powered the Big Bang?*"<sup>1</sup>

Theories and observations suggest that the Big Bang started with a brief moment of accelerated expansion called "inflation", when the universe expanded exponentially by over 100 orders of magnitude in volume. Inflation is a testable scenario for the earliest event in the history of the universe (within the first  $\sim 10^{-30}$  second). It helps to answer various profound mysteries, including how the structures in the universe originated, why the universe appears so smooth on large scales, and why it appears to have no overall curvature.

Currently, the most direct way of studying inflation is through the CMB polarization. The rapid expansion during inflation is thought to have generated gravitational waves. These primordial gravity waves would be difficult to detect directly because their periods have redshifted to be comparable to the age of the universe. However, when the CMB photons were last scattering, the gravity waves must have induced motions in the photon-baryon fluid, imprinting unique curl patterns in the polarization of the background radiation. The CMB polarization is the only known feasible way of studying the gravity waves from inflation.


Detecting this relic from inflation in the CMB polarization would be a triumph and opportunity for fundamental physics. Studying it would allow us to explore energy scales approaching  $10^{16}$  GeV, possibly providing insight into the unification of gravity and the other fundamental forces. We could explore the first moments of the creation of the universe by learning about the physics behind inflation.

### **BICEP: A CMB Polarization Telescope for Probing Inflation**

This gravity-wave polarization signal is expected to be at least an order of magnitude smaller than the recently detected gradient-mode polarization. Sensitivities better than even the Planck Surveyor will likely be necessary to characterize this signal.

This proposal is for my work with the Robinson Gravitational Wave Background Telescope (as known as BICEP)<sup>2</sup>, which is the first experiment designed specifically to detect the signature of the inflationary gravity waves. Optimized for angular scales where this signal is expected to

peak, it is a simple and compact wide-field refractor, operating at 100 and 150 GHz (where the galactic foregrounds are at minimum). This instrument makes use of polarization-sensitive bolometers developed at JPL for the Planck Surveyor. The South Pole site allows it to observe a contiguous patch of the sky as long as possible while taking advantage of the stable dry weather with very low atmospheric loading.



BICEP SPECIFICATIONS	
Angular scales	$l = 30-300$ (where gravity-wave polarization should peak)
Sensitivity	480 $\mu\text{K}\sqrt{\text{s}}$ @ 100 GHz 420 $\mu\text{K}\sqrt{\text{s}}$ @ 150 GHz
Beam width	0.9° @ 100 GHz ( $\lambda = 3$ mm) 0.6° @ 150 GHz ( $\lambda = 2$ mm)
Field of view	17°
CMB coverage	$\sim 1000 \text{ deg}^2$ ( $\sim 3\%$ of sky)
Integration time	$> 2400$ hours/year
Aperture	25 cm
Bolometers	98 (49 feed horns x 2 polarizations)

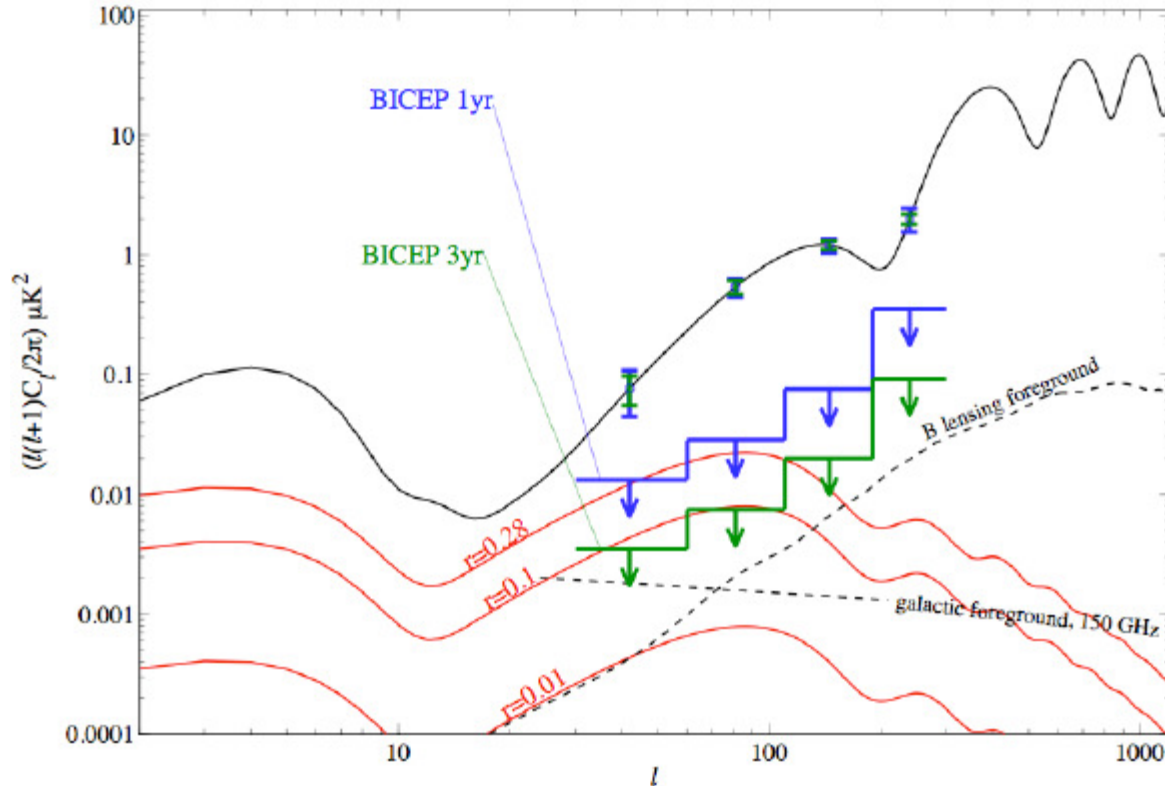
**BICEP at the South Pole**

Cosmology groups at Caltech/JPL and UC Berkeley began this program in 2002. We set up the telescope at the South Pole at the end of 2005 for observations in 2006. The telescope has been operating nearly flawlessly throughout the past year with the motion control system that I worked to integrate. We will continue observations through 2008.

BICEP is an important first step in probing inflation through the CMB. We will learn whether inflation was related to the grand unification of forces, or if it was due to some lower energy physics. An hour of integration with BICEP can lower the current upper limit on gravity waves (thus the energy scale of inflation). In a week, it should have reached the sensitivity that the Planck Surveyor will reach over our observation field. In a year, it should reach 1  $\mu\text{K}$  sensitivity in every pixel. Even a null result will tell us much about inflation and the associated energy scale of the unification of gravity with the other fundamental forces.

### **Ground-Based Precursor to NASA's Inflation Probe**

We designed BICEP as a prototype for a space-based version, the Inflation Probe in NASA's Beyond Einstein Roadmap<sup>3</sup>. Such a mission is recommended as the highest priority by the Cosmic Microwave Background Future Missions Working Group commissioned by NASA<sup>4</sup>. I work with key members of the design team for the Experimental Probe of Inflationary Cosmology (EPIC) space mission. BICEP has many essential similarities to a space-based version: a compact light-weight design, long duration of observation, remote operations with limited servicing, and sensitivity limited only by the photon background. We are testing methods and technologies for the next generation of experiments, providing a proof of concept for the space-based mission. Any detection or constraint on the inflationary energy scale we make will be essential in determining the observing strategy for the Inflation Probe. Data from our experiment will be also very useful in developing and testing analysis techniques for the Inflation Probe.



Expected sensitivity compared to the theoretical gravity wave polarization signal (red).<sup>2</sup>

### Proposed Research

This fellowship will allow me to fully engage myself in the operation of BICEP and its data analysis throughout the coming year. My main responsibilities for BICEP have included the ground shields, polarization calibration, the motion control system, optical star pointing, the vacuum window, and some essential electronics. During 2007, I will work with our team members to run BICEP and analyze the CMB polarization data in search of the inflationary gravity wave signature. At the beginning of 2008, I will travel to the South Pole again to make measurements essential for interpreting the data accurately and to prepare for the final year of observations.

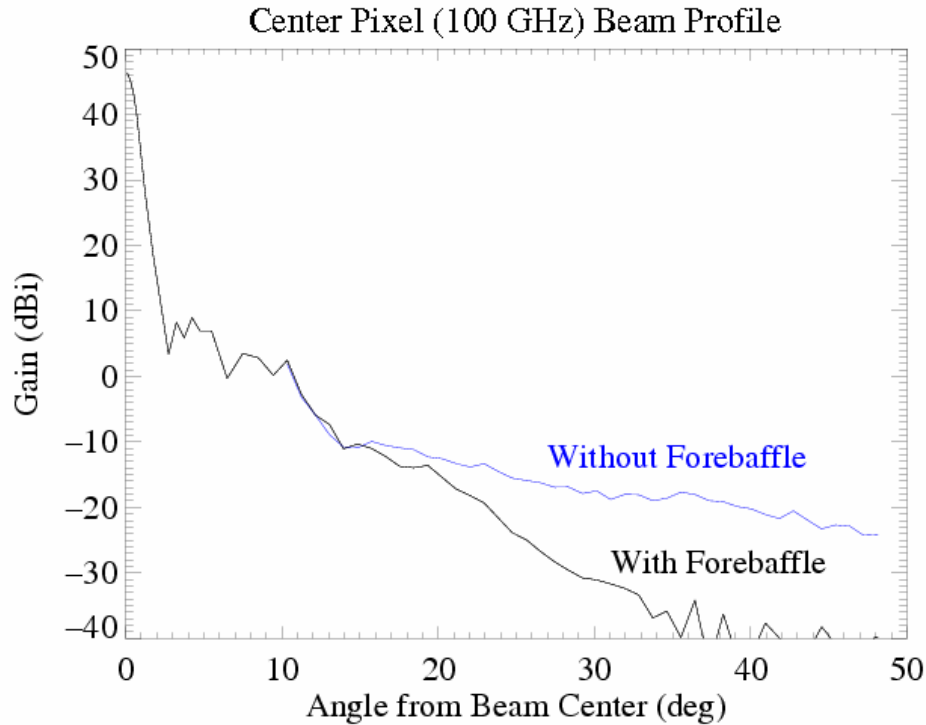
### Schedule

- |              |  |
|--------------|--|
| 2007 spring: | Complete instrument characterization.                          |
| 2007 summer: | Develop a noise estimation essential in the analysis.          |
| 2007 fall:   | Derive the CMB polarization power spectra and publish.         |
| 2008 winter: | Deploy to the South Pole to perform calibration measurements.  |
| 2008 spring: | Continue data analysis while running the 3rd year observation. |
| 2008 summer: | Complete data analysis and write thesis.                       |

### Far Sidelobe Profile Characterization

To detect polarization signals that are at least 7 orders of magnitude smaller than the background temperature, a telescope must reject beam spillovers very effectively, particularly polarized spillovers. I am responsible for BICEP's ground shield, and currently in the process of fully

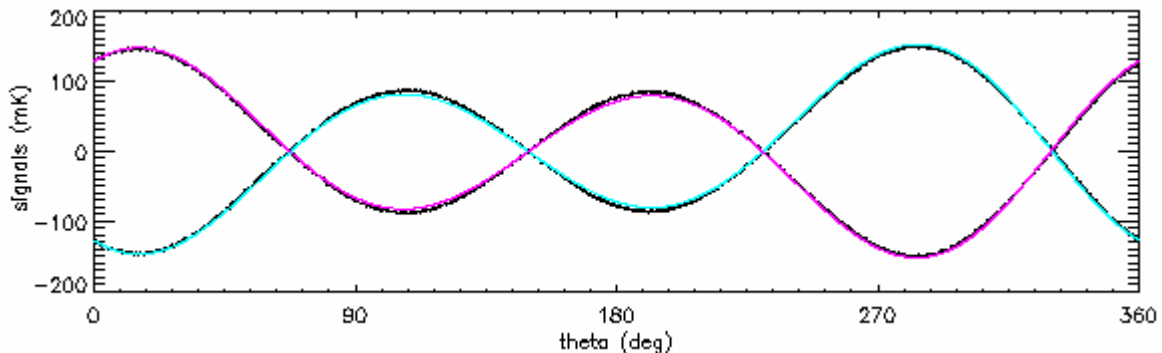
characterizing the far sidelobe of the beam. Our preliminary measurements last year indicated that my design meets the required -80 dB attenuation of the ground contamination. We have confirmed the superior sidelobe rejection by the absorptive baffle compared to a more conventional reflective version, which was only slightly better than having no forebaffle.



Preliminary characterization of the beam profile with an absorptive forebaffle, measured last year.

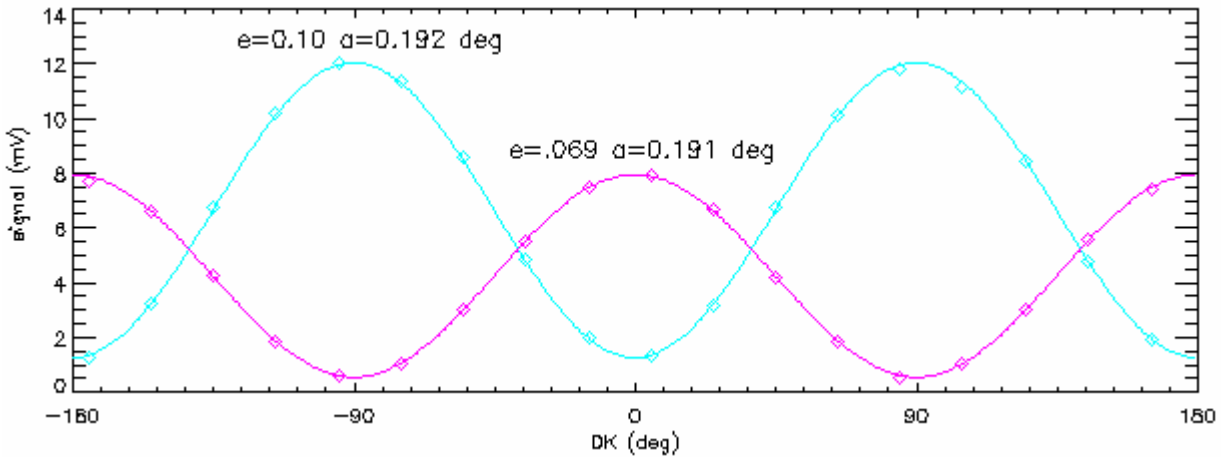
### Polarization Calibration: Orientation, Responsivity, and Leakage

To detect the faint polarization from inflationary gravity waves, probably the most crucial challenge is to minimize polarimetric systematic errors. Using a device that I developed, we calibrate the polarization orientation and responsivity of every bolometer on a monthly basis. The polarization orientation must be measured to within  $\sim 1^\circ$  to prevent the grad- to curl-mode leakage from obscuring the gravity wave signal at an  $r=0.1$  level.



Polarization calibration signal (black) and model fits (colored) for two orthogonal bolometers.

We also measure the leakage in polarization response by rotating a completely polarized source with respect to the bolometers. This method provides an additional way of measuring the bolometer orientations, and my current effort is to obtain consistent results with both approaches.



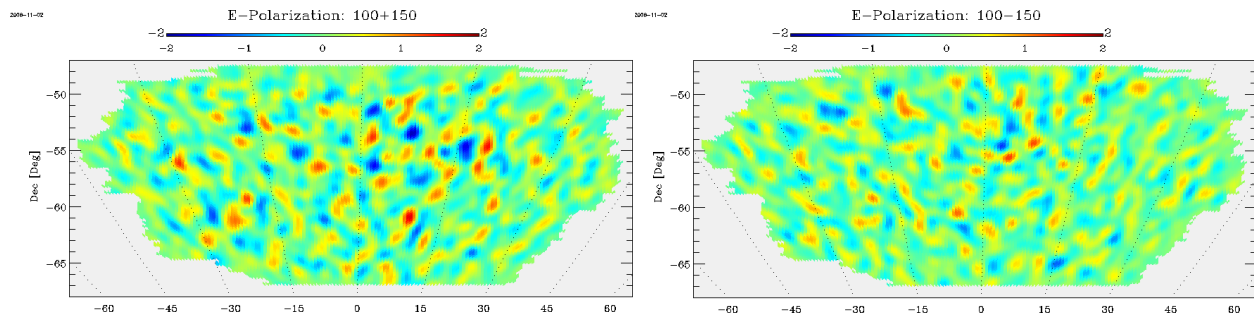
Measured response and sinusoidal fits for deriving polarization leakages ( $e$ ) and orientations ( $a$ ) for two orthogonal bolometers.

### Pointing Model Reconstruction

To limit contamination to the B-mode (curl) polarization, we routinely calibrate the telescope's pointing to better than 1% of the beam size using an optical star-pointing camera, which I am responsible for. The bi-daily star pointing data will be analyzed to accurately derive the sky coordinates from the telescope's axis encoder readings by fitting for parameters describing the dynamic state of the mount, including flexure, axis tilts, and encoder offsets. The resulting pointing information will be essential in constructing CMB maps free of false signals.

### Observation

During our 1st year of observation, we surpassed our goal of 2400 hours of CMB integration. We expect to acquire even more date during our 2nd year. Our observation strategy is to scan across a fixed azimuth range at each  $0.25^\circ$  elevation interval so that it is possible to completely remove any azimuth or scan synchronous contamination.



Preliminary map of the gradient component (E-mode) of the measured polarization pattern.

Left: Sum of the 100 GHz and 150 GHz maps, adding up the signal.

Right: Difference, subtracting out the signal.

The excess power in the sum map indicates detection of an actual gradient-mode polarization signal.

### **Analysis: Noise Estimation and Constraint on Gravity-Wave Polarization**

We intend to detect or place the best constraint on the gravity wave signal; for this, I propose to carry out a full treatment of noise in our data. Here I outline the proposed plan of data analysis leading up to CMB polarization power spectra:

1. Determine the transfer function of every bolometer to de-convolve the time stream.
2. Determine the relative responsivity calibrations from elevation nods and difference the time streams of bolometer pairs to reject (mostly atmospheric) common-mode signals.
3. Estimate noise:
  - a. For each bolometer pair, compute the spectral distribution of the differenced time stream during each 1-hour scan at fixed elevation.
  - b. Check that the noise is stationary during each 1-hour scan, and average over all the scans to establish the spectral model of the noise.
  - c. Use this model to create an ensemble of noise maps, and estimate the noise power spectrum in multipole space.
4. Subtract this noise power spectrum from the power spectrum of the data to obtain the CMB band power estimates.

The search for the inflationary gravity wave signature will require a complete understanding of foregrounds and sources of systematic error. BICEP is producing one of the largest data sets of any CMB experiment, adding to the challenge of analyzing its data.

### **Conclusion**

I am very interested in this fellowship as I would like to strengthen the tie between my current research activities and my broader interest in space exploration through NASA. With a NASA connection I develop through this fellowship, I sincerely hope to increase my opportunity for working with NASA after completing this project.

### **Acknowledgments**

At GSFC, I would like to thank Dr. Alan Kogut for discussing polarization calibration with me, Dr. Gary Hinshaw for providing me ideas on possible interactions with Goddard, and Dr. Edward Wollack for his helpful input for my ground shield study. I also thank my adviser William Holzapfel for helping me with this proposal (and my previous attempts for GSRP), and Bill Jones at Caltech for answering my questions about data analysis.

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