Building BICEP2: A conversation with Jamie Bock

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Caltech Professor of Physics Jamie Bock. Credit: Seth Hansen

Caltech Professor of Physics Jamie Bock and his collaborators announced on March 17, 2014 that they have successfully measured a B-mode polarization signal in the cosmic microwave background (CMB) using the BICEP2 telescope at the South Pole. This signal is an important confirmation of key aspects of the theory of cosmic inflation, about how the universe may have behaved in the first fractions of a second of its existence to create the universe we live in today. Inflation was first proposed in 1980 by Alan Guth, a theoretical physicist at the Massachusetts Institute of Technology (MIT), to explain some unusual features of our universe, especially its surprising homogeneity. For all the clumping of stars and galaxies we see in the night sky, the universe seen through the CMB is extremely uniform—so much so that it has been difficult for physicists to believe that the various pieces of the sky were not all in immediate contact with one another at an earlier point in the universe's development.

Since the theory of cosmic inflation was first advanced, most physicists have come to agree that inflation is the best explanation we have for the observable universe. Yet the hope of acquiring direct evidence of inflation was for a long time regarded as a vain one. In 1997, MIT physicist Alan Lightman wrote that since "the extremely rapid cosmic expansion . . . happened so long ago, we will probably never know with certainty whether that event in fact occurred."

And yet now, thanks to a set of bold experiments undertaken with the BICEP telescopes, we seem to be closing in on direct confirmation of the theory of inflation. Bock recently discussed the design of the BICEP instrumentation and how it detected a signal from the dawn of time.

How did the BICEP program begin?

It all started with tennis. In 2001 I played tennis every week with Brian Keating, a Caltech postdoc who is now at UCSD. After a few sets, Brian and I would talk about science for a while. He kept bugging me about doing a CMB polarization experiment that would study structures on degree angular scales—portions of the sky larger than the full moon. Brian was pretty engaged with theoretical astrophysicists, and I liked to design new experiments, so it was a nice combination. Once we got going, our ideas for a new project came together quickly. We knew we were going to need a great team to pull it off, so we wrote a concept proposal that we brought to my colleague at Caltech, the late physicist Andrew Lange. Brian remembers Lange saying, "What you're proposing will cost 10 million dollars . . . but that's okay . . . that's okay!"

The last 13 years have been all about the hard work of designing and running the experiment, building and perfecting the technologies, and analyzing the data. You don't get anywhere in experimental physics without building a team, and what a great team we have! John Kovac came to Caltech as a postdoc shortly thereafter and was a relentless force to organize our team of students, to make sure everything—and I do mean everything—was working as well as it possibly could. Chao-Lin Kuo, also a postdoc at JPL and Caltech, came up with some great ideas, especially new designs to improve the detectors. Both have now gone on to professorships, at Harvard and Stanford, respectively, and are central players in our program. Clem Pryke, now at the University of Minnesota, organized and led the data analysis, a gargantuan task that he's done brilliantly. Our students stepped up to each fill major roles, and the collaboration has been simply amazing. I have never worked with a better group of individuals and am proud to consider myself a member of the team.

What can BICEP see that other telescopes cannot?

BICEP was the first experiment of its kind to go after just the gravitational wave B-modes. This was scientifically risky, because on large degree scales there was no guaranteed signal. It was "B-modes or bust." As a result, we were out in Antarctica running our BICEP instrumentation years before we had any real competition. That has certainly changed now. The field is hypercompetitive! But those first years were really valuable as a learning experience about how to make these difficult measurements.

How does BICEP differ from a traditional large-scale optical or sub-millimeter telescope?

First of all, I should say I love small telescopes. I've done four projects that use small telescopes, each for a unique purpose. Small telescopes have an overlooked capability to gather a lot of light with a wide field of view. This capability keeps on opening doors to new experiments, and especially applications in space where smaller, lighter telescopes are a great advantage. The BICEP telescope is based on a refractor with two lenses. This is not exactly a new idea in optical astronomy; it is similar to Galileo's telescope. But it was a novel approach in CMB measurements and gave us an enormous 20-degree field of view. In fact the light-gathering power of BICEP is not so different from that of the 10-meter telescope looming over us at the South Pole, but BICEP's aperture is just 26 centimeters.

What are the technical challenges involved in looking at a broader rather than a smaller piece of the sky?

To make accurate measurements over a wide area, the challenge is to control false signals. I especially worry about the instrument having a tiny response to the earth, which is a billion times brighter than the signal we want to detect. Our small telescope design works like a champ! We have surrounded the whole telescope with absorbing surfaces cooled to 4 degrees above absolute zero. Then we use an absorbing screen around the primary lens to soak up remaining radiation. Finally, to remove from the system any effects that might arise from having a preferred direction, we spin our telescope around its axis every day. These are things you just can't do with a big telescope.

How is BICEP2 different from the first BICEP instrument, BICEP1?

When the BICEP experiment first began, I was already working on some radical and long-term ideas for building detectors. But it was clearly going to be unrealistic to create completely new detectors while we were also fielding a completely new experiment. So BICEP1 used detectors that were similar to those that Andrew Lange and I developed for the European Space Agency's Planck satellite. These are "spider-web" bolometers. Bolometers are instruments that measure electromagnetic radiation by turning it into heat and measuring the temperature. Spider-web bolometers are made from a fine mesh standing in free space, with just enough material to catch millimeter-wave radiation. These devices that Lange and I developed were made at JPL's Microdevices Laboratory from a micromachined membrane. BICEP1 was a new version of this that we cooked up to detect polarization. But it was designed from the very beginning to accommodate the new technology we were already developing. The new detectors fit right into the telescope.

BICEP2 gets to the same sensitivity as BICEP1 in a tenth of the time. It would have taken BICEP1 30 years to get to where we are with the BICEP2 results that just came out. I really like working at the South Pole, but 30 years? That's a bit much.

How do you achieve this technological improvement?

The name of the game in making a more sensitive CMB polarization experiment is observing with more detectors. But a CMB detector is more than that. It is really a light-gathering, filtering, detection, and readout system. So the challenge is not like going from 35-mm film to a digital chip in your camera, it's like producing the entire camera on a chip. Our approach was basically to make a camera that detects both intensity and polarization via a printed circuit board.

The original inspiration for these ideas came from Caltech physics professor Jonas Zmuidzinas. We feed the detector with an array of little antennas. The radiation goes to a little bolometer at the end of the antenna where it is converted into heat and measured with a superconducting thermometer. Finally multiple detectors are read out together with a superconducting amplifier called a SQUID, developed at the National Institute of Standards and Technology.

Did you expect that BICEP2 would be able to detect B-mode polarization if it were in the CMB?

Honestly, I thought we would continue for decades to drill down to lower and lower levels of signal from the CMB, and never see the B-mode polarization. I was psychologically prepared for that, even expecting it. Our team was becoming increasingly discouraged. Then at a group meeting last March, we saw our first result from BICEP2 showing a B-mode polarization. We reviewed a plot on a projector screen that looked just like the signal we were trying to find, only a lot bigger. There was a sudden transition in the room, from "What on earth are we doing wrong?" to "Maybe this is real!"

For an entire year following this, we debated all the effects that could cause a false signal. There were weeks at a time where we chased a subtle effect that might compromise the data, only to find out that fixing it didn't really make much of a difference. In the end, what finally put us over the top was comparing the BICEP2 maps against the BICEP1 maps, and then against two full years of observations from the new Keck Array experiment at the South Pole, equivalent to an array of five BICEP2 instruments. They all matched.

Over the past months, we gradually became more and more certain that the signal we were seeing was real. It is a strange experience to be going through the activities of daily life, all the while carrying around this gem of knowledge in your head.

How does it feel to be engineering optics that can visualize the remnants of the earliest events in our universe?

It is mind-boggling that we can infer anything about the very instant of the birth of our universe nearly 14 billion years ago. I feel this measurement of the B-mode polarization of the CMB is ahead of its time. The process that produced the polarization involves physics we don't understand, energies beyond the Standard Model, and detecting gravitational waves that were born from quantum fluctuations. I hope this is just the beginning for getting to a real understanding of the exotic physics powering inflation.

But most of all, it is amazing to me that our little band of intrepid scientists, students, postdocs—all of whom I consider colleagues and friends—could build a machine that could actually tell us about the birth of the universe.

Provided by California Institute of Technology

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