Small and Mighty

How cosmology has been dramatically changed by a telescope born and bred at Caltech and stationed at the literal end of the earth.

by Cynthia Eller

Caltech professor of physics Jamie Bock holds a dummy version of the focal plane for BICEP2, for use in thermal tests.

Even the most dedicated explorer of the cosmos needs the occasional diversion. When physicist Jamie Bock was a research scientist at JPL back in 2001, that diversion was tennis. Of course, if Bock had wanted a real diversion, he shouldn't have been playing tennis with Brian Keating, then a postdoc at Caltech. The two inevitably ended up talking about their work—measuring the early universe.

As Bock recalls, "Brian kept insisting we should build an experiment to search for direct evidence of the inflationary epoch at the beginning of the universe—a single brief, intense event that blew our observable universe up from a volume smaller than an atom, with space itself expanding faster than the speed of light. For a while I just listened to Brian. Of course this would be something worth finding, but technically it was an enormous challenge. But then I began to think, 'Maybe we really could do this.' Brian was pretty engaged with theoretical astrophysicists, and I liked to design new experiments, so it was a nice combination. I also like small telescopes, from my days flying compact instruments on sounding rockets and satellites. So we came up with the idea of building a simple refracting telescope with a wide field of view that gathers a lot of light."

By 2006, Bock and his colleagues at Caltech and JPL had built the experiment that Keating was pushing for. They called the project BICEP—and in March 2014, data from its second-generation telescope, BICEP2, was presented to the world. The findings were immediately hailed as the greatest cosmological discovery of the 21st century, or perhaps even since the 1920s, when Edwin Hubble realized that the universe is expanding.

Perhaps most impressive is the fact that this detection was achieved by a modest telescope—imagined, designed, and built at Caltech—whose eye on the sky was only 26 centimeters in diameter.

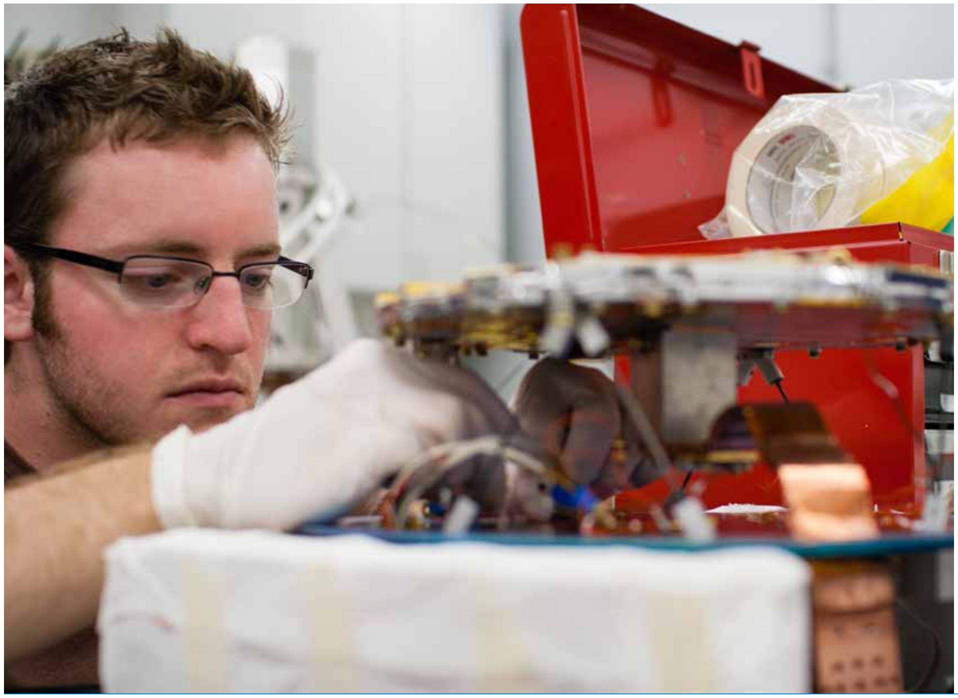
What BICEP Found

From less than a millisecond after the Big Bang until 380,000 years later, the universe was a soup of free electrons and ions. Light particles (photons) could not travel very far during this time before running into a free electron and being scattered. But at 380,000 years, the universe cooled enough so that free electrons combined with free protons to make neutral hydrogen, and the universe became transparent to light.

The earliest electromagnetic radiation we can observe from Earth is the cosmic microwave background (CMB). This light is not visible to the eye, but is observable in all directions from Earth by telescopes using specialized detectors tuned to microwave frequencies. When we make maps of the CMB, we are basically getting a view of the universe at an age of 380,000 years, when the primordial photons from the Big Bang last scattered.

While the CMB is one of the best ways to study the early universe, it also acts as a wall preventing a view of earlier times. It is a bit like looking at the sky on a cloudy day. You can see the surface of the cloud, which is lit up by the sun behind it, but you can't see into the cloud or see the sun itself. To gather evidence for inflation, which occurred behind the wall of the CMB, well before the universe was transparent to light, cosmologists must look for some type of signature that inflation left behind on a later era of the universe that is visible to us: namely, the CMB.

The theory of inflation was first proposed by Erast Gliner in the Soviet Union in 1965, and in 1975 Leonid Grishchuk predicted that massive gravitational waves would have been released in an inflationary scenario. The term itself, "inflation," was coined by MIT's Alan Guth in 1980, and theoreticians from that time forward—including Stanford's Andrei Linde—assumed that one consequence of their proposed inflationary period would be the highly energetic creation of gravitational waves, which squeeze and stretch space as they travel at the speed of light.



Left: Former Caltech graduate student Randol Aiken adjusts the BICEP2 telescope in the Caltech highbay laboratory.

Gravitational waves are notoriously difficult to detect, so it did not occur to cosmologists to try to confirm inflationary theory through the direct detection of gravitational waves. But then, in the late 1990s, theoreticians such as Marc Kamionkowski, on the Caltech faculty from 1999 to 2011, began to suggest that even if gravitational waves themselves could not be detected, perhaps their impact on the CMB, in the form of polarization patterns, could.

Polarization patterns in the CMB can be produced both by density variations, which are largely responsible for the temperature variations in the CMB, and by gravitational waves. But gravitational waves, because they squeeze and stretch space in a unique way, would create a special kind of polarization known as B-mode polarization: a swirly pinwheel pattern that can turn either clockwise or counterclockwise. The conclusion? Find this polarization pattern, and you have found primordial gravitational waves from inflation.

Sound simple? Maybe in concept, but not in execution. The predicted B-modes are such tiny fluctuations in the CMB that most scientists thought it would be impossible to ever detect them. "BICEP was the first experiment of its kind to go after just the B-mode polarization in the CMB," says Bock. "This was scientifically risky, because there was no guaranteed signal. But this was an appealing challenge for us. It was 'B-modes or bust.'"

Building BICEP

Using Kamionkowski's rationale, Bock and Keating took a proposal to the late Andrew Lange, the Marvin L. Goldberger Professor of Physics at Caltech, for the construction of a small refracting telescope, not unlike the one Galileo used over 400 years ago. The telescope would measure the CMB over a comparatively large portion of the sky—about 5,000 times larger than the face of the full moon—which is enormous compared to the usual targets of astronomical observation.

Lange was on board from the start. Although he knew B-mode detection was a long shot, he deemed the potentially revolutionary result worth the risk. In 2002, the Caltech-JPL team was granted seed money from the Caltech President's Fund, and they were on their way.

Since Kamionkowski had talked about the B-modes as "curls," Keating decided the telescope that searched for the curls should be named "BICEP." From there, he came up with the name to back up that acronym: Background Imaging of Cosmic Extragalactic Polarization.

BICEP involved a dual challenge: creating a new telescope and inventing a revolutionary detector technology to put inside it. Taking on both challenges at the same time was untenable, so Bock decided to use detectors they had successfully designed and deployed on an earlier instrument, BOOMERanG (Balloon Observations of Millimetric Extragalactic Radiation and Geophysics). These detectors were "spiderweb" bolometers, first developed in 1993, that used a fine mesh to absorb millimeter-wave light and convert it into heat sensed by a tiny thermometer.

BICEP2 Buzzwords

Inflation The expansion of space at the time of the Big Bang, when the early universe grew exponentially at a rate that was much faster than the speed of light. Inflation is believed to have happened over an extremely short period of time—mere fractions of a second—after which the universe settled into a much slower rate of expansion that continues today.

Cosmic microwave background (CMB) A relic glow from the early universe. The CMB emits energy at a microwave frequency and is not visible to the naked eye but is observable across the entire sky with the use of specialized telescopes.

Polarization The orientation of the electric field in a light wave. Polarization can be produced by scattering, such as when light glances off the hood of a car.

Gravitational waves Ripples in the fabric of space-time that stretch and squeeze space as they travel. Gravitational waves are created by explosive astronomical phenomena. Gravitational waves from the Big Bang are sometimes called primordial to differentiate them from gravitational waves produced by events like supernovae.

B-mode A pattern of **polarization** that has a characteristic pinwheel shape. BICEP2 detected a B-mode pattern imprinted on the **CMB** by **gravitational waves** produced during the epoch of **inflation**.

Bolometer A detector that absorbs electromagnetic radiation, converting it into heat, and then measures the temperature of the absorber with a sensitive thermometer. The bolometers in BICEP2 measure power at microwave frequencies to detect the **CMB**.

"Back in 2001 when the BICEP project began," says Bock, "we had revolutionary new detectors in mind. These detectors were the successor to the spiderweb bolometers, but they were just emerging, and we needed time to develop and test them. So the first stage was to build and field a practical instrument, BICEP1, with spiderweb bolometers onboard, but the telescope was designed to accommodate the new detectors when they were ready."

One Cool Telescope

BICEP was designed from the beginning to run in a cold environment, colder even than its planned location at the South Pole. Encased in a cryostat—a glorified thermos—the inner workings of BICEP are chilled to .27 kelvins (around –272 Celsius), close to absolute zero and even colder than the CMB itself, the average temperature of which is 2.7 kelvins.

But why so cold? "By cooling the telescope," Bock explains, "we reduce emission from the instrument that the detectors will sense along with the incoming CMB radiation that we want to measure."

The team installed its first telescope—BICEP1—at the South Pole in November 2005. Because the telescope was so small, all that was needed to install it was to cut a hole in the ceiling of the Dark Sector Laboratory, place the BICEP telescope on its mount, and point it at the CMB in a patch of the sky the team calls the "southern hole"—a region without much gas and dust from the Milky Way in the foreground.

By this time, the BICEP project was on a firmer financial footing, thanks to continued support from Caltech, which funded key postdoctoral fellows; the National Science Foundation, which gave major grants to BICEP1 in 2003 and BICEP2 in 2008; and generous gifts from the estate of John M. Robinson, the Gordon and Betty Moore Foundation, and the John B. and Nelly Llanos Kilroy Foundation. JPL supported instrument and technology development through its Research and Technology Development program.

With BICEP1 successfully deployed at the South Pole, Bock and his team, including Chao-Lin Kuo, then a postdoc at JPL and now a professor at Stanford, were back in Pasadena crafting the next-generation detector technology for BICEP2: a radically different, all-in-one detector made from an integrated circuit, a concept pioneered by Jonas Zmuidzinas, the Merle Kingsley Professor of Physics at Caltech and chief technologist at JPL. BICEP2's detector combined bolometers—which detect light—with imaging polarimeters that collect and filter light and analyze the polarization. "Our approach was basically to make a polarization-sensitive camera via a printed micro circuit board," says Bock.

Calibrating and testing BICEP2's flat detectors was a frenzied process in the run up to their deployment at the South Pole in 2009. Jeff Filippini, the Robinson Postdoctoral Fellow in Experimental Astrophysics, remembers that the entire team had doubts about whether or not they would be ready in time: "Even a month before deployment, we were afraid it was never going to work. It's a bit like theater: in the last days of rehearsal, you're sure it will never come together, but somehow it works on opening night."

Indeed, even when the construction of BICEP2 was under way, it seemed that everyone on the project believed that it would turn out to be simply a test run, a learning experience in how to use the detectors. According to Zak Staniszewski, a Caltech postdoc who joined the BICEP2 team shortly before deployment, John Kovac—a Caltech postdoc, now a professor at Harvard, whom Lange had named as the leader of the BICEP2 NSF proposal—urged on the new recruits, saying, "You guys need to learn how to make BICEP2 work so you can make the next telescope work."

But once deployed, the new detectors did their job brilliantly: "BICEP2 was able to get to the same sensitivity as BICEP1 in a tenth of the time," says Bock. "It would have taken BICEP1 30 years to get the results that BICEP2 gathered in just three."

A great advantage to the BICEP2 detectors-on-a-chip is that they can be fairly easily replicated—you print another circuit board—unlike the spiderweb bolometers with their individualized optics that were installed in BICEP1. So with BICEP2 in the field, a follow-on experiment was funded by the W. M. Keck Foundation in 2007 that would gather five BICEP2 telescopes in a cluster to take the most sensitive measurements of the CMB to date. The Keck Array began making observations at the South Pole in 2010.

Surprising Data

And so it was with more than a little surprise that the analysis team, led by Clem Pryke of the University of Minnesota, noticed something curious about the data BICEP2 had gathered in its three observing seasons at the South Pole from 2009 to 2012: it showed a pinwheel polarization pattern in the CMB.

At first, no one on the BICEP2 team believed this pinwheel polarization signal was anything other than a measurement artifact. "At the time, we were trying to get out a paper setting a maximum amplitude on the gravitational wave B-mode signal," recalls Bock. "So this extra signal was a source of some frustration." The situation came to a head at a project collaboration meeting when one of the postdocs compared the BICEP2 data with new data coming in from the Keck Array. The data matched. "That was a pivotal moment," says Bock. "We stopped trying to explain the excess away and started asking ourselves, 'How can we test if this signal is real?'"

The four senior members—Kovac, Pryke, Bock, and Kuo—held long phone calls to decide if there were other sources of error and how to tackle each potential source of error in sequence. "Ultimately the most convincing evidence," says Bock, "was seeing the B-mode polarization signal not only in BICEP2 but in the new Keck Array data. Also, given the BICEP2 map, we could find the B-mode polarization in the noisier BICEP1 data. Our result is really a testament to the full program of experiments, and if any of the stages were missing, we would not have been so confident."

BICEP2 team members deliver liquid helium to cool the telescope at the South Pole.

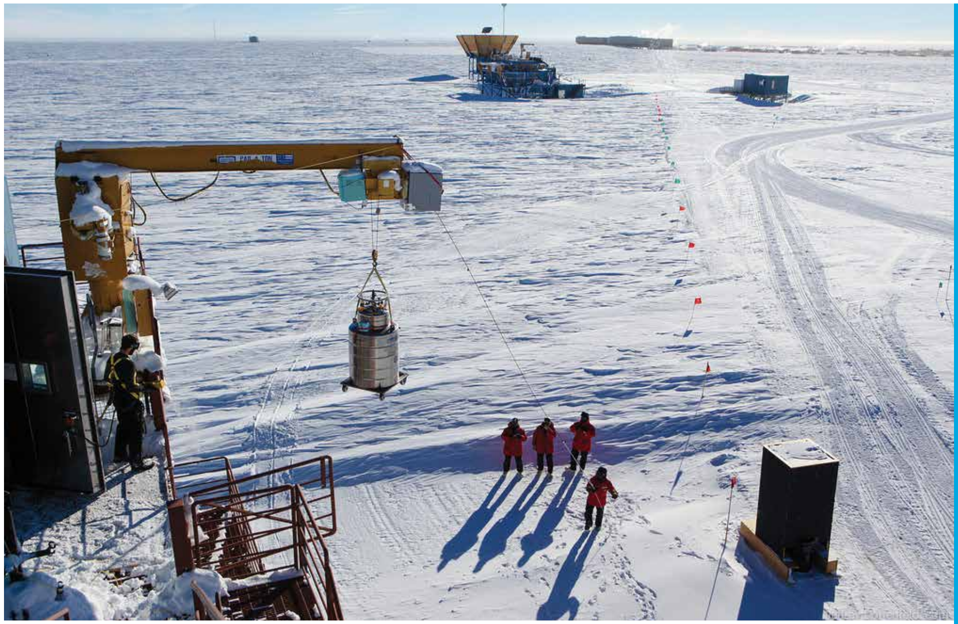
By late 2013, the BICEP2 team was finally ready to announce that they had found exactly what they were looking for and at a level stronger than expected. "Honestly, I had mentally prepared myself to continue this search for decades, drilling down to lower and lower signal levels and maybe never seeing B-modes from inflation," says Bock.

As Filippini puts it, "There was a finish line. We were trying to get there as fast as possible. We just didn't realize that the finish line was closer than we thought."

"Probably the most serious remaining concern," says Bock, "is that we are seeing polarized emission from our own galaxy. We have tight constraints against this because the spectrum of the CMB is different from that of the galaxy, but we recently installed two new telescopes in the Keck Array, observing at a different wavelength than BICEP2. These detectors are already reporting back data, and we expect they will improve our constraints on the spectrum still further."

News will also be available shortly from the Planck satellite mission, which used high-performance versions of the spiderweb bolometers developed for BOOMERanG and BICEP1. Planck has measured the whole sky at multiple wavelengths to search for the same signal.

There are many B-mode competitors out there that will test BICEP2's finding. Although BICEP pioneered the search for inflationary B-mode polarization, many other cosmologists joined the quest in the intervening years with their own experiments. "There are now about a dozen dedicated ground-based and balloon-borne CMB experiments under way," says Bock. "It has been quite a horse race."



BICEP2 team members lift a liquid helium cryostat to the second floor of the Dark Sector Laboratory to chill the telescope to a temperature near absolute zero.

We're looking forward to hearing the results from these experiments, and of course we are working as hard as we can on our own balloon experiment, Spider."

The Future of Observational Cosmology

It is hard to overstate the significance of BICEP2's findings. In the *New York Times*, Kamionkowski called BICEP2's findings "huge, as big as it gets."

The BICEP2 findings strongly support the theory of inflation (as opposed to non-inflationary cosmologies). Furthermore, only particular models of inflation can account for the abundance of gravitational waves found in the B-modes. So far the simplest models of inflation that were developed by Alan Guth and Andrei Linde match the data.

Primordial gravitational waves are very faint, but with an advanced gravitational-wave interferometer—a futuristic descendant of the Laser Interferometer Gravitational-Wave Observatory, or LIGO (see "Reflections in Research," page 20)—they might actually be detected one day as they pass by Earth.

"It is mind-boggling that we can infer anything about the very instant of the birth of our universe nearly 14 billion years ago," says Bock. "The process that produced the polarization involves physics we don't understand and energies beyond the standard model in particle physics. The primordial gravitational waves were born from quantum fluctuations that were expanded by inflation due to a connection between gravitation—in Einstein's theory of general relativity—and quantum mechanics. This is just the beginning for understanding the exotic physics powering inflation.

"Most of all," Bock continues, "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." E&S

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WHAT BICEP FOUND

BY SEAN CARROLL

The discovery by the BICEP2 experiment of the imprints of gravitational waves on the cosmic microwave background radiation is a historic moment for cosmologists. For the first time, we've directly learned something about the state of the universe one trillionth of a trillionth of a trillionth of a second after the Big Bang.

The result is a great example of the interplay of theory and experiment. Over 30 years ago, Alan Guth of MIT and others formulated the theory of cosmic inflation. In this model, the very early universe underwent a brief period of superfast expansion. That expansion works to smooth out the distribution of matter and energy through space, much like tugging on the edges of a bed sheet will smooth out any wrinkles. Unlike a bed sheet, however, the early universe is governed by the rules of quantum mechanics. And quantum mechanics says that we can't make anything *perfectly* smooth; there will always be some irreducible fluctuations from place to place.

According to inflation, quantum fluctuations are responsible for the tiny deviations in the density of matter that eventually grew into galaxies and clusters in the current universe. The cosmic microwave background, leftover radiation from the Big Bang, displays the influence of those deviations by having a slightly different temperature at different points in the sky. We have seen these temperature differences; what we haven't been sure about is whether inflation is the right theory to account for them. The temperature fluctuations match the prediction of inflation, but maybe there are other theories that would produce the same signature.

Fortunately, inflation makes an additional prediction: not only should the density of matter fluctuate, so should the gravitational field itself. Inflation, in other words, predicts a specific pattern of gravitational waves, which should leave a distinctive imprint on the microwave background. Seeing those waves would be strong evidence that inflation is on the right track.

And that's exactly what BICEP2 has done. In addition to measuring the temperature of the microwave background, the instrument also measured its polarization. Luckily for cosmologists, gravitational waves push and pull on the plasma of the early universe to produce a very particular kind of polarization pattern (the so-called B-modes). BICEP2 was designed to look for this signal, and it found precisely that.

The finding is noteworthy not only because it's a scientific and technological tour de force (although it is that), but also because the gravitational waves were actually relatively easy to find. Inflation predicts a particular pattern, but the overall amplitude of the signal is a free parameter—one that, according to BICEP2, turns out to be just about as big as it could be. That's very good news indeed for cosmologists, as it implies that inflation happened very quickly after the Big Bang. The scientists on BICEP2 have brought us quite a bit closer to understanding how our universe began.

Sean Carroll is a senior research associate in physics at Caltech and the author of From Eternity to Here: The Quest for the Ultimate Theory of Time *(Dutton, 2010) and* The Particle at the End of the Universe: How the Hunt for the Higgs Boson Leads Us to the Edge of a New World *(Dutton, 2012).*