Search intensifies for primordial gravitational waves

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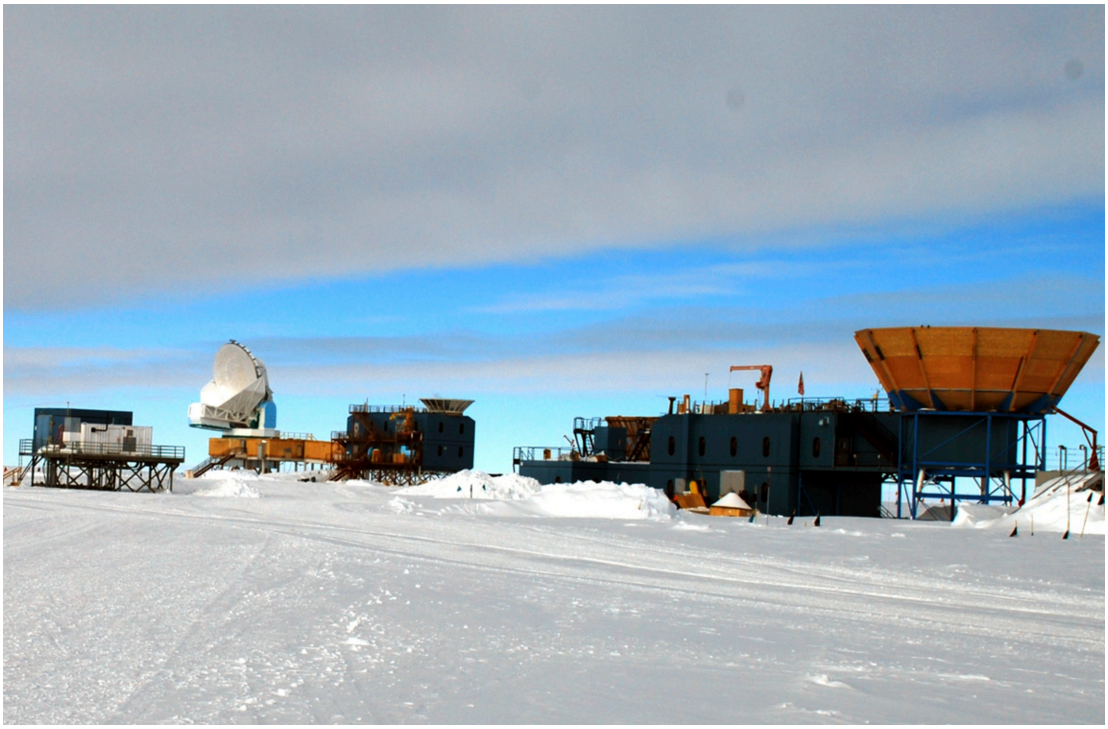
In March 2014, researchers who had been working at the South Pole made a stunning announcement: With a telescope called BICEP2 (Background Imaging of Cosmic Extragalactic Polarization), they had found evidence of primordial gravitational waves, or ripples in the fabric of spacetime produced in the first fractions of a second after the Big Bang. This discovery seemed to be our first glimpse of a critical moment in the birth of the universe (1).

The publicity that followed the announcement surprised the team. "All hell broke loose," recalls observational cosmologist John Kovac, a coleader of the BICEP2 collaboration at Harvard University in Cambridge, MA. Unfortunately, it turned out to be a case of mistaken identity. "The signal was consistent with being just from galactic dust," says Kovac. But the search has not ended by any means. Since then, the BICEP team has redoubled its efforts, making bigger, better, and faster instruments to search for primordial gravitational waves.

Wave Back

Figuring out whether these waves exist is crucial for our understanding of how the universe came to be. "This isn't just me and a handful of other theorists sitting around in our offices saying this will be a very nice thing to measure," says Marc Kamionkowski, a theoretical physicist at Johns Hopkins University in Baltimore, MD.

If cosmologists are correct, primordial gravitational waves would have been produced during a key epoch



Following on the BICEP2 telescope's failure to find a signature of gravitational waves in the cosmic microwave background, the South Pole telescope (left) and the Keck Array (right) and have joined BICEP2 (middle, small upturned dome) at the South Pole to investigate further. Image credit: Anil Ananthaswamy.

in the evolution of the universe called inflation. During inflation, spacetime is thought to have expanded rapidly for a fraction of a second. This theory was posited to explain certain puzzling features of our cosmos, for example, why the curvature of spacetime at cosmological scales is nearly zero—in other words, why spacetime is almost flat. "It's by far the best theory that we have for explaining how the universe [looks]. . .on the largest possible scales," says Clem Pryke a coprincipal investigator of the BICEP2 collaboration at the University of Minnesota in Minneapolis.

Many of the predictions of inflation fit our observations of the universe, but a key prediction remains unverified. Inflation should have roiled spacetime, generating gravitational waves that would have rippled through the cosmos ever since. Evidence of these waves would be concrete proof of inflation and provide clues to how it happened.

Gravitational waves from merging black holes and neutron stars have already been detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO). But the waves from inflation would be much weaker and have much longer wavelengths, putting them outside LIGO's range of sensitivity.

Instead, our window for seeing signatures of primordial gravitational waves is the cosmic microwave background (CMB): the universe's first light emitted when the cosmos was about 380,000 years old. If there were ripples in spacetime caused by inflation, they would have affected the photons of the CMB, and the signature of that interaction would be discernible today.

BICEP2 was looking for this signature. A photon has a property called polarization, the orientation of its electric field, and the average polarization of CMB photons at each point on the sky can be shown as a line matching that orientation. If primordial gravitational waves polarized the photons, these lines today should have a characteristic swirl known as the B-mode polarization signal. This is what BICEP2 saw. Unfortunately, dust in our galaxy can create a similar pattern (2).

Bigger BICEPs

Since that case of mistaken identity, the collaboration has built five more BICEP2-class telescopes, put them all on a single mount at the South Pole, and called it the Keck Array (3). The original BICEP2, which had a 26-centimeter aperture, was replaced with the 55-centimeter-aperture BICEP3, which collects an order of magnitude more data (4). The team is now working on replacing the Keck Array with four BICEP3 telescopes on one mount. This along with a lone BICEP3 in its own mount will together constitute the BICEP Array.

Astronomers build such telescopes at the South Pole because of the excellent atmospheric conditions. The air is cold and dry (thus lacking much of the water vapor that absorbs microwaves). The polar atmosphere during the long winter months is also very stable. There are no day–night temperature variations, the winds over the Antarctic Plateau have relatively low speeds, and there are no jet streams in the upper atmosphere—all of which make for a clear view.

In each BICEP2/BICEP3 telescope, lenses corral photons down a tube and toward an array of superconducting detectors. Each detector looks at one part of the sky and measures the power contained in photons that are polarized in two different directions. As the telescope rotates about its axis, this power measurement is repeated for each detector to work out the net polarization of the CMB photons in each patch of the sky. The process involves being sensitive to temperature differences of mere microkelvins, which could be easily swamped by much larger temperature fluctuations in the surroundings.

The collaboration tackled this by putting all the temperature-sensitive components, including lenses and sensors, in a vacuum-sealed tube cooled to 0.25 kelvin. For BICEP3, the team also replaced the original plastic lenses with a ceramic material that filters out some of the infrared radiation entering the telescope. This material can also be kept colder, reducing its own thermal emissions.

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—Marc Kamionkowski

These data-hungry telescopes presented new challenges. The signals from the sensors are carried out of the vacuum tube by a system of wires. With four BICEP3 telescopes close together, the sheer number of wires becomes a problem because they conduct heat from the room-temperature outer electronics into the cooled sensors.

One solution is to reduce the number of wires. Zeeshan Ahmed, project scientist at the SLAC National Accelerator Laboratory in Menlo Park, CA, led the team that designed, constructed, and deployed BICEP3. Ahmed is working on using microwave frequencies to squeeze up to a thousand signals on one wire. "It's not a completely mature technology, so there is a bit of risk," he says.

Dust Busting

Although BICEP2 studied the sky only at one frequency (150 gigahertz), the BICEP Array will span 30 to 270 gigahertz. The wide range of frequencies will help the astronomers separate contamination from dust, which tends to be at higher frequencies, and from electrons and other charged particles spiraling around galactic magnetic fields, a problem at lower frequencies.

At the sensitivity of BICEP3, another source of B-mode polarization becomes significant. The photons of the CMB get polarized by the bending of light due to the gravity of galaxies and galaxy clusters along our line of sight, a phenomenon called weak lensing. To subtract this signal, the BICEP3 collaboration will use data from the nearby 10-meter South Pole Telescope, which looks at smaller patches of the sky with far greater sensitivity.

BICEP3 won't be alone. In the Atacama Desert in Chile, an instrument called the Simons Array will look for the same signals. Meanwhile, a collaboration called CMB-S4 is planning a fourth-generation instrument that will operate at both the South Pole and Chile. The plan for CMB-S4 is to collect data by using about 500,000 detectors, a huge step up from the third generation of telescopes, such as BICEP3, that have on the order of 10,000 detectors each.

The question is whether these new telescopes will see signals that can be unambiguously traced to inflationary gravitational waves. "If we don't find something convincing in generation 3 or generation 4, will there be a generation 5?" says Ahmed. "Will we have the resolve to go after this for another order of magnitude?"

The latest results were published in October 2018 by using data collected until the end of the 2015 observing season by BICEP2 and the Keck Array (5). The data already show that primordial gravitational waves are not as strong as the simplest models of inflation predicted. Other models, which predict weaker waves, are still in the running, but they can be more complicated. Although the simplest models drive inflation with just one ingredient—a field that contributes some energy per unit volume to spacetime—some of the more complex models that entail several interacting fields can reproduce current observations. But these models then imply weaker gravitational waves.

Answers could be hiding in the 3 years of data from BICEP3 that await analysis. That dataset, or the powerful new instruments to come, may finally find B-modes from the early universe, verifying inflation. And if they see nothing, that would be just as important. "If 10 years from now, we have not yet detected these B modes, then we have to go back to our models of inflation and seriously rethink what we have been telling people about how inflation works," says Kamionkowski. "If we don't see primordial gravitational waves, then in spite of the other successes that the models have had, there is something fundamentally wrong. Somehow nature has been misleading us."

1 Harvard and Smithsonian Center for Astrophysics (2014) First direct evidence of cosmic inflation. Available at https://www.cfa.harvard.edu/news/2014-05. Accessed December 26, 2018.

2 Ade PAR, et al.; BICEP2/Keck and Planck Collaborations (2015) Joint analysis of BICEP2/Keck Array and Planck data. *Phys Rev Lett* 114:101301, 101301.

3 Ade PAR, et al. (2015) BICEP2/KECK Array V: Measurements of B-mode polarization at degree angular scales and 150 GHz by the KECK Array. *Astrophys J* 811:126.

4 Kang JH, et al. (2018) 2017 upgrade and performance of BICEP3: A 95GHz refracting telescope for degree-scale CMB polarization. arXiv:1808.00567.

5 Ade PAR, et al. (2018) BICEP2/Keck Array X: Constraints on primordial gravitational waves using Planck, WMAP, and new BICEP2/Keck observations through the 2015 season. arXiv:1810.05216. Preprint, posted October 11, 2018.