

Polarization measurement detects primordial gravitational waves

Cosmic inflation is bolstered, but some inconsistencies await resolution.

The theory of cosmic inflation makes the extraordinary assertion that within the first 10^{-35} seconds or so, the universe underwent a dramatic quasiexponential expansion, doubling in size more than 60 times, before ending in an episode of “reheating” that produced the basic stuff that evolved into the universe as we see it today.

There are good reasons for believing that seemingly outrageous proposition. As Alan Guth pointed out when he introduced the idea,¹ it solves several problems that otherwise plague Big Bang cosmology. Furthermore, quantum fluctuations are magnified by inflation and lead to inhomogeneities that seed the observed structure of the universe.

Among the quantum fluctuations are those of the gravitational field itself. They are predicted to imprint a unique signature on the polarization of the cosmic microwave background (CMB), the light emitted when the universe was 380 000 years old and cool enough for atoms to form. If the gravitational fluctuations were sufficiently strong during inflation, that signal, known as *B*-mode polarization, should be detectable. It would be both a triumph of inflationary theory and the first real evidence of the quantum nature of the gravitational field.

Thus the excitement in March of this year, when the BICEP2 collaboration announced the unambiguous detection of a *B*-wave polarization signal in the CMB.²

The CMB polarization can be decomposed into two distinct types, usually called *E* modes and *B* modes. The *E* modes are gradient-like and parity even, and they can be produced by the scalar field, the “inflaton,” whose energy density drives inflation. The *B* modes are curl-like and parity odd, and they can be produced only by a tensor field—that is, the gravitational field itself.

E-mode polarization in the CMB was first detected more than a decade ago. Within the past two years, experiments have also detected *B*-mode polarization,³ but it was not due to inflation—rather, it was a consequence of perturbation of the *E* modes by the process of gravitational lensing, a so-called foreground effect. (Gravitational lensing occurs when the light from a distant source is bent by an object, such as a galaxy, between the source and the observer.) The elusive primordial *B*-mode polarization, expected at the level of parts per million or less, awaited detection.

That was the state of play as the nation and the world awaited the announcement from the BICEP2 collaboration on the morning of 17 March. Led by John Kovac of Harvard University, Clement Pryke of the University of Minnesota, Jamie Bock of NASA’s Jet Propulsion Laboratory, and Chao-Lin Kuo of Stanford University, BICEP2 is an experiment dedicated to detection of

the primordial *B*-mode polarization. Located in the Dark Sector Laboratory at Amundsen-Scott South Pole Station, it incorporated a small-aperture (26-cm) telescope with 500 polarization-sensitive bolometric detectors mounted at the focal plane. The entire apparatus was cooled by liquid helium, with the detectors cooled further to 270 mK using a sorption refrigerator.

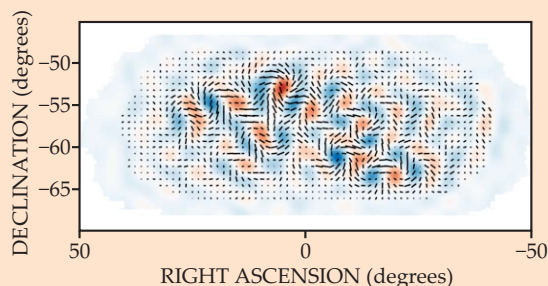
Data were taken over three years, from early 2010 to late 2012. Conditions are especially favorable during the austral winter, given the extremely low humidity and stable atmosphere. In addition, the telescope was aimed at the “Southern Hole,” an unusually clear line of sight out of our galaxy.

The researchers observed radiation in a band at 150 GHz, looking for degree-scale polarization effects over an effective area of 380 square degrees. The measurements corresponded to angular multipoles ranging between $l = 20$ and $l = 340$. The range of l was carefully chosen, because the *B*-mode polarization was predicted to exhibit a peak at an l of about 80, whereas the *E*-mode polarization (and the *B* modes that come from lensing of the *E* modes) peaks at l of approximately one thousand. Figure 1 shows a map of the *B*-mode signal obtained by BICEP2, restricted to multipoles between 50 and 120.

Key parameter

Perhaps the most important single parameter that the BICEP2 researchers extracted from their data is r , the ratio of the power in tensor modes to that in scalar modes. The best fit to the BICEP2 data is $r = 0.2^{+0.07}_{-0.05}$, and the data exclude $r = 0$ at 7σ . BICEP2 also estimates the possible effect of foreground dust; with that taken into account, r might be slightly reduced, but $r = 0$ is still excluded at the level of almost 6σ . Unlike all previous experiments, the results from BICEP2 establish not an upper bound but a value for the *B*-mode signal inconsistent with zero. Figure 2 plots the *B*-mode power found by BICEP2 as a function of angular multipole, compares it with the signal to be expected if $r = 0.2$, and shows the upper bounds from other experiments that have now been superseded.

Figure 1. A map of the BICEP2 *B*-mode polarization signal in the cosmic microwave background (CMB). The axes represent the celestial coordinates of the observation patch over which the measurements were made. The data are truncated to include only angular multipoles l between 50 and 120. (The multipoles are inversely related to the angular scale.) The red color indicates a twist of the polarization in one direction; the blue color is a twist in the opposite direction. The black lines indicate the direction of linear polarization, and the length of the lines is a measure of its strength. The signal strength is about a part in 10 million of the CMB. (Adapted from ref. 2.)



Since gravity couples directly to the energy density, the BICEP2 value for r can be used to deduce an energy scale for inflation of about 2×10^{16} GeV. Thus BICEP2 is measuring an effect produced at energies about a trillion times higher than those at the Large Hadron Collider.

Much as with the discovery of the Higgs boson two years ago, the announcement by the BICEP2 collaboration was the cause for great celebration, a milestone that validated almost 35 years of theoretical and experimental efforts. But, just as with the Higgs, once the initial excitement had died down, it was time for interpretation and evaluation of possible problems and contradictions.

Prior to BICEP2, the best information about gravitational fluctuations was the upper limit $r < 0.11$ at 95% confidence level, which came from an analysis by the *Planck* collaboration.⁴ The *Planck* spacecraft, launched by the European Space Agency, made extensive measurements of the anisotropies of the CMB, improving on the earlier *Wilkinson Microwave Anisotropy Probe* mission. Although *Planck* did take polarization data, the quoted bound comes from the temperature measurements only, augmented with data from other experiments; the polarization results are still to be released.

Different models of inflation predict different amounts of tensor power. The *Planck* bound led to increased attention for models compatible with r less than about 0.1, and it disfavored those with r much bigger than that. But with the release of the BICEP2 results, the situation was suddenly reversed.

Winners and losers

On one hand, $r = 0.2$ is easily accommodated by the simplest version of the chaotic inflation scenario, introduced by Andrei Linde.⁵ Chaotic inflation, like many other models, possesses the property of “eternal inflation”: inflation does not end everywhere at once. Bubbles of the postinflationary phase can condense out at different places and times, but the bulk of the universe continues to inflate forever. Our own observed universe is presumably one of the bubbles.

On the other hand, among the losers was the venerable Starobinsky model,⁶ in which the inflation appears as part of a modification of the Lagrangian describing general relativity. It produces a very small amount of tensor power, seemingly inconsistent with the BICEP2 result.

Of course, there is tension between the BICEP2 results and the *Planck* bound. That raises a pair of related

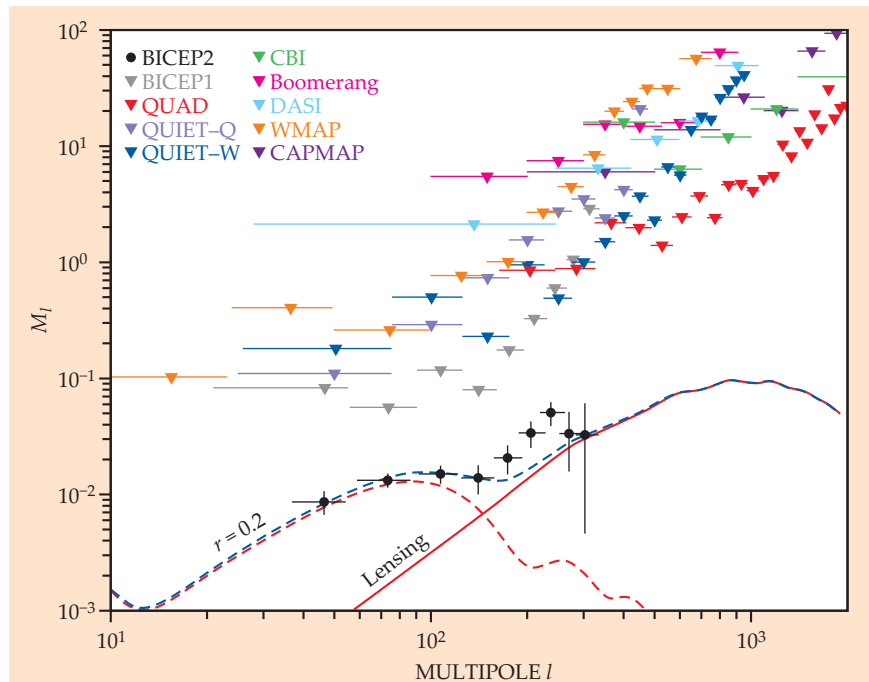


Figure 2. The BICEP2 B -mode signal as a function of angular multipole (black points). Plotted on the vertical axis is a suitably normalized measure M_l of the tensor power in the l th multipole. The dashed red line is the prediction for primordial B -wave polarization with $r = 0.2$, where r is the ratio of tensor to scalar power, and the solid red line is the signal to be expected from gravitational lensing of the E -mode polarization. The dashed blue line is the sum of the two contributions. Also shown are the upper limits on the signal derived from a set of previous experiments. (Adapted from ref. 2.)

questions: Will the BICEP2 results hold up? And if so, how can BICEP2 and *Planck* be reconciled?

Over the several weeks since the BICEP2 announcement, many ideas have been advanced to address the second question. In addition to r itself, two relevant parameters are the spectral indices n_s and n_t , which determine how the scalar and tensor power vary with the scale being measured. One difficulty is that reconciliation of BICEP2 with *Planck* seems to favor a positive value for n_t , which is hard to achieve theoretically. Allowing n_s to vary with scale is another way of trying to improve the agreement.

Yet another possibility is to introduce into the mix a “sterile” neutrino that interacts only gravitationally with other particles. Such a particle, it is claimed, also alleviates various other sources of tension for the now-standard concordance cosmological model that are independent of the B -mode measurement. (See PHYSICS TODAY, October 2010, page 14.)

The good news is that many experiments are poised not to repeat the measurement exactly but to add potentially confirmatory or contradictory evidence. Eagerly awaited are *Planck*’s po-

larization data. Additional experiments include one other at the South Pole and several in the Atacama Desert of Chile. In addition, at least 3 balloon-borne experiments are in the works.

With the additional observational data from those experiments, and with the ongoing theoretical and phenomenological efforts to make sense of them, researchers hope that a consistent and well-determined inflationary scenario will emerge. It would be ironic in the extreme if, to the contrary, the information gained from the B -mode polarization of the CMB, often referred to as “smoking gun” evidence in favor of inflation, ended up instead as an agent of the theory’s demise.

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References

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