Long, cold stare. From its South Pole perch, BICEP2 (foreground) peers at the sky.

COSMOLOGY

First Wrinkles in Spacetime Confirm Cosmic Inflation

Few cosmologists were surprised on Monday, when observers announced that they had spotted traces of gravitational waves—undulations in the fabric of space and time—rippling through the infant universe. Rumors of the discovery had circulated for days. Yet, the observation electrified scientists the world over. That's because, if it holds up, it clinches the idea that in its first sliver of a second, the cosmos expanded like a gargantuan balloon in a faster-than-light growth spurt known as inflation—a wild idea proposed more than 30 years ago. It also shows for the first time that gravity must follow the same rules of quantum mechanics that other forces such as electromagnetism do. Forging a quantum theory of gravity may be the grandest goal in theoretical physics.

Some cosmologists say the discovery is the biggest in their lives. "Never has the boundary of human understanding been pushed back so far," says Max Tegmark of the Massachusetts Institute of Technology (MIT) in Cambridge, who was not involved in the work. Researchers had good evidence of how the first atomic nuclei formed a second after the big bang. But now they have probed the first 10^{-32} seconds, says Marc Kamionkowski, a cosmologist at Johns Hopkins University in Baltimore, Maryland. "It's not every day that you wake up and find out what happened one trillionth of a trillionth of a trillionth of a second after the big bang."

The discovery comes from a study of the big bang's afterglow, the cosmic microwave background (CMB). Cosmologists with the Background Imaging of Cosmic Extragalactic Polarization (BICEP), a small but sophisticated telescope at the South Pole, mapped how the arrowlike polarization of those microwaves varies from place to place across the sky. In data taken from January 2010 to December 2012, they found faint pinwheel-like swirls called B modes. "We believe that gravitational waves could be the only way to introduce this B-mode pattern," says John Kovac, a cosmologist at Harvard University and one of the four principal investigators of BICEP. The results were announced in a talk at the Harvard-Smithsonian Center for Astrophysics in Cambridge.

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Many cosmologists also consider B modes the smoking gun for inflation. According to the standard model of cosmology, when the universe sprang into existence it contained one thing: a quantum field, similar to an electric field, made up of particles called inflatons. That field blew up spacetime so that within 10^{-32} seconds the cosmos doubled and redoubled its size 60 times. In the process, it pulled itself "flat" like a bed sheet snapping taut and evened out in temperature. Inflation stopped as the inflatons decayed into other particles, ultimately including photons, electrons, and quarks. That inflationary scenario was invented in 1980 by Alan Guth, a cosmologist at MIT.

The inflaton field roiled with tiny quantum fluctuations. Inflation magnified those fluctuations to enormous size, seeding variations in the density of energy and matter that eventually grew into galaxies. The fluctuations also created part-in-100,000 variations in the temperature of the CMB across the sky. By measuring the statistical distribution of hot and cold spots of different sizes, researchers have determined the content of the universe in terms of ordinary matter, mysterious dark matter whose gravity binds the galaxies, and weird space-stretching dark energy (*Science*, 29 March 2013, p. 1513).

That much of the evolution of the universe has been traced, and it all appears to be consistent with the idea of inflation. But with the new results, researchers have gone a big step further and tested a particular prediction of inflation. Thanks to quantum mechanics, not only did the stuff inside the infant universe fluctuate—so did spacetime itself. Or so it must have if spacetime and gravity are quantum mechanical. Inflation stretched that jittering into gravitational waves billions of light-years in wavelength that left their own imprint on the CMB. Whereas the density variations caused a simple sloshing of matter and energy from more dense spots to the less dense ones, gravitational waves stirred up a more complex twisting motion called "tensor modes." Only that type of motion can give rise to B modes, says Uros Seljak, a cosmologist at the University of California, Berkeley.

Spotting those modes wasn't easy.

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The B modes are only 1% as strong as the already-faint temperature variations. To see them, the BICEP team deployed BICEP2, a 26-centimeter telescope with 500 exquisitely sensitive microwave detectors called bolometers, each cooled to within a fraction of a degree of absolute zero. Researchers got a little help from nature, as the B-mode signal appears about 20 times stronger than many cosmologists had expected.

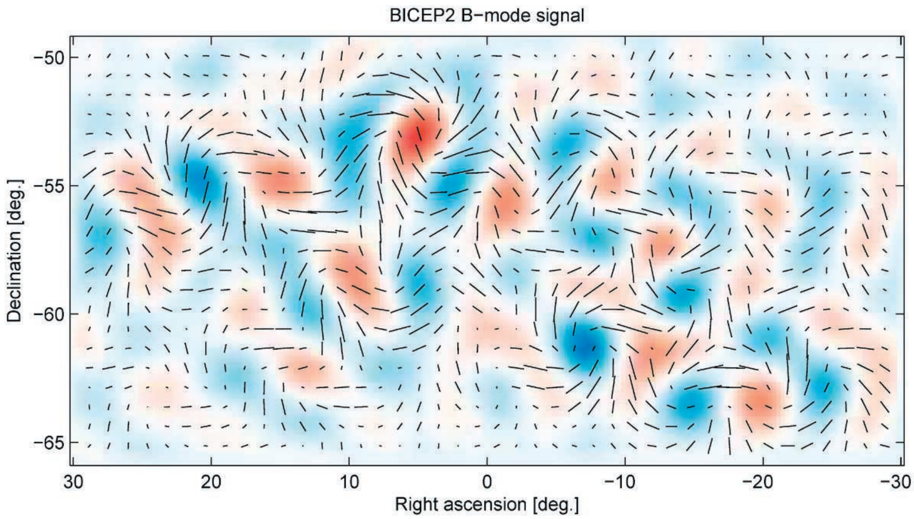
BICEP scooped a gaggle of other experiments, including the European Space Agency's Planck spacecraft, which took data from 2009 until last year and is expected to present polarization data soon. Ironically, Kovac says, BICEP owes its success in part to detectors made by Jamie Bock and colleagues at the California Institute of Technology in Pasadena, who also developed detectors for Planck. Suzanne Staggs, a cosmologist at Princeton University who works on the Atacama B-mode Search in Chile, says she was shocked when she heard of BICEP's success. "The more I think about this, the more excited I am because the signal is so big," she says.

In particular, the big signal suggests that cosmologists may soon be able to test the idea of inflation in earnest. If nothing else, many researchers say, it should silence doubters of the faster-than-light stretching. That's because alternative theories do not produce B modes, says Scott Dodelson, a cosmologist at Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois. "All of the alternatives that have been proposed are dead," he says. "This is a done deal."

Now cosmologists hope to probe the characteristics of the inflaton field—particularly how the field interacted with itself to give itself energy. Cosmologists think of the field like a marble on a hillside, with height denoting the field's energy and horizontal position denoting its amplitude. The field started somewhere up on the hill and rolled down toward zero energy and amplitude. BICEP's result reveals the marble's initial height, Dodelson says, which is equivalent to the energy density of the universe during inflation—3 trillion times any energy achieved with a particle accelerator. Cosmologists' next big goal is to determine the shape of the energy landscape, or "potential."

Many cosmologists say that the signal strength reported by BICEP jibes nicely with a model of that landscape proposed in 1982 by Andrei Linde of Stanford University in California, which is a parabola. "Suddenly this very simple model works very well," says MIT's Tegmark.

A few cosmologists remain inflation holdouts, however. Paul Steinhardt of Princeton University has called inflation "contrived" and says the BICEP results just make it worse. BICEP's B-mode signal implies that the tensor churning in the early universe is twice as strong as the upper limit inferred from Planck's temperature measurements, he says. To make those two observations mesh, the spectrum of shorter and longer quantum fluctuations in the infant universe must have been a lot more complicated than standard theory assumes, he argues: "That's not good for inflation."



Twisted. Pinwheel-like swirls in BICEP's polarization map of the microwave background are the prized B modes.

CREDIT: BICEP2 COLLABORATION

Steinhardt acknowledges that the discovery rules out his own noninflationary models—in which big bangs occur over and over again within a much older spacetime. But when the dust settles, he predicts, theorists may still find themselves searching for an alternative to inflation.

Only more observations can settle the issue, scientists say. First off, researchers need to confirm the BICEP result, which may happen fairly quickly if the signal is as large as reported. Beyond that, to trace the inflaton's energy landscape, observers must measure the statistical distribution of the swirling B modes in exactly the same way they measured the statistical distribution of the hot and cold spots. Researchers break the hot and cold spots down into overlapping spots of bigger and smaller sizes on the sky, and the spectrum of different size spots encodes the recipe for the universe.

In much the same way, the spectrum of larger and smaller B modes should reveal the shape of the inflaton potential, says Berkeley's Seljak. The BICEP team has measured the modes in a patch of sky measuring 15° by 60° and has observed B modes that make pinwheels about a degree wide. Primordial gravitational waves should also produce B modes stretching about 10° across. Spotting those bigger B modes would most likely require another more sensitive spacecraft, which, like Planck, could map the whole sky. "The community will probably make the case for another satellite mission to measure polarization," Seljak says. "That's where I expect we will go."

Perhaps most tantalizing, such a mission might finally enable physicists to test theories that attempt to meld quantum mechanics and Einstein's general theory of relativity, which says that gravity arises when mass and energy bend spacetime. The BICEP result proves that gravity must be quantum mechanical, says Fermilab's Dodelson, as B modes originate from quantum fluctuations in spacetime itself.

Moreover, Dodelson says, theories of quantum gravity, such as string theory, predict modifications to the shape of the inflaton energy landscape. So if that landscape can be measured precisely, he suggests, physicists might finally put string theory—long mocked as an untestable "theory of anything"—to a concrete test.

Even if that dream doesn't come true, the observation of primordial gravitational waves has shaken up cosmology almost as much as the waves did the fledging universe.

–ADRIAN CHO AND YUDHIJIT BHATTACHARJEE