FIRST LIGHT

The left-over radiation from the Big Bang has given up what may be its last great secret about the early Universe, but astronomers are determined to mine more from this primordial prize.

by Joanne Baker

Cosmologists couldn't have wished for a better anniversary present. Almost 50 years to the day after the first detection of the Big Bang's afterglow — a faint glimmer of long-wavelength photons known as the cosmic microwave background (CMB) — the field has been galvanized by what may be the last major discovery from the radiation.

On 17 March, astronomers announced that a microwave detector at the South Pole had recorded the first signs of primordial 'B modes': subtle, swirling patterns in the CMB data that were imprinted during the early history of the Universe. The result was hailed as direct evidence of gravitational waves, ripples in the fabric of space-time that were produced by a sudden 'inflation' of the Universe a split second after the Big Bang.

The most obvious question — is the B-mode signal real? — has sparked a race among teams running telescopes on the ground, in space and carried by balloons. "The name of the game is confirmation," says experimental cosmologist Amber Miller of Columbia University in New York City.

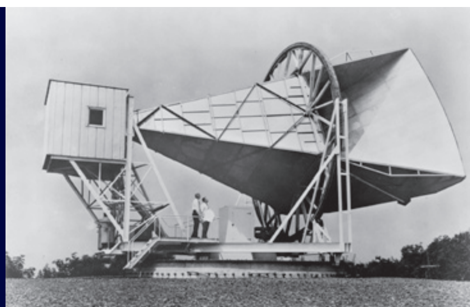
Should the results check out, and most in the field think they will, the focus will shift to the next frontier. Scientists would like to see a new era of B-mode astronomy that would collect more extensive and more precise measurements of the patterns. Through such data, researchers hope to reach back in time to better understand the Universe's first moments, as well as how galaxies formed and clustered together in the aftermath of the Big Bang. The B-mode data may even help to reveal the origins of mysterious factors such as dark matter and dark energy that control the form and fate of the cosmos.

"The CMB has been our best window on the early Universe by a long shot," says George Efstathiou, a cosmologist at the University of Cambridge, UK. But a rich new B-mode era is not guaranteed. Funding is scant, the existing surveys have little coordination with each other, and the available instruments are limited. What's more, theorists still need to pin down exactly what the new views of the CMB can reveal. Even as

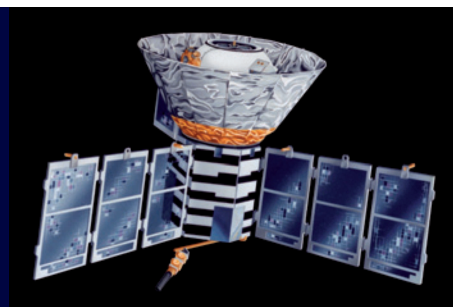
1964, NASA; 1990, NASA/COBE SCIENCE TEAM; 1992, NASA

50 YEARS OF DISCOVERY

Half a century after astronomers first detected the cosmic microwave background (CMB) radiation, it continues to be their clearest window on the early Universe.



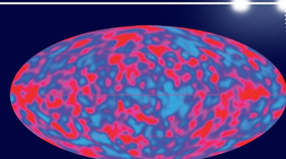
1964
Arno Penzias and Robert Wilson detect the CMB radiation and measure its temperature to be roughly 3 kelvin.



1990
NASA's Cosmic Background Explorer (COBE) satellite measures the CMB from space and pins its temperature at 2.725 kelvin.

1946–1948
Several scientists predict that the Universe should be filled with remnant radiation from the Big Bang, and that this would have a temperature of just a few kelvin.

1992
COBE data reveal minuscule variations in the CMB's temperature, a sign of density fluctuations in the early Universe that would later condense into galaxies.



they celebrate this year's discovery, CMB researchers are fretting over the future of their field. Decisions made over the next few months will determine whether astronomers can hope to realize the scientific promise of this new vista in the next decade or more.

EARLY DAYS

The discovery of the Big Bang's afterglow came as a happy accident, when Arno Penzias and Robert Wilson, two astronomers at Bell Labs in Holmdel, New Jersey, set out to map radio emissions from the Milky Way. On 20 May 1964, they noticed a faint signal that seemed to come from every direction. Penzias and Wilson assumed it was an artefact from some local source until a conversation with a colleague led them to conclude that the radiation was not earthly but cosmic.

Theorists, they learned, had long predicted such a signal: it was strong evidence in favour of the Big Bang theory, which holds that the Universe exploded into existence at a moment in the past, rather than having existed forever in an unchanging 'steady state'. By observing it, Penzias and Wilson had proved that the Universe was once much hotter than it is today. The photons they had recorded were released about 380,000 years after the Big Bang, when the expanding cosmic fireball had cooled enough for electrons and protons to combine to form hydrogen atoms. The photons have been travelling ever since, cooling as the Universe expands and preserving a snapshot of the Universe at the moment they were liberated (see '50 years of discovery').

In 1990, NASA's Cosmic Background Explorer (COBE) satellite made the first precise measurement of the CMB's temperature — 2.725 kelvin — and showed that the value was the same in every direction, implying that the primordial plasma was similarly uniform[1].

But it soon became apparent that the CMB is not perfectly smooth. In 1992, COBE scientists found that the temperature of the CMB varies across the sky by roughly 1 part in 100,000 (ref. 2). These tiny 'anisotropies' turned out to provide crucial information about the evolution of the Universe. The hot and cold spots reflect small variations in the density of the gas when the CMB photons were released. Most cosmologists think that gravity later magnified these fluctuations, pulling together denser regions to form galaxies and clusters of galaxies.

Seeing the anisotropies also inspired theorists, says Marc Kamionkowski, a cosmologist at Johns Hopkins University in Baltimore, Maryland. A prime example was the recognition that the warm and cold blotches in the CMB have characteristic sizes determined by vast waves of pressure and density that reverberated through the infant cosmos in much the same way that sound harmonics echo inside a violin. These dominant frequencies, or acoustic peaks, in the CMB allow astronomers to infer many physical properties of the Universe. For example, the biggest peak, akin to the loudest harmonic, lies at a scale of about 1°, or about twice the diameter of the full Moon. This is exactly as would be expected if the expanding Universe is geometrically flat, so that parallel light rays never cross as they traverse space. The location and relative strength of the second peak, at roughly 0.4°, allows astronomers to infer that ordinary matter — the kind found in atoms, planets and stars — comprises less than 5% of the cosmic total. Everything else is in the form of invisible dark matter and dark energy.

POLARIZATION PATTERNS

CMB research entered a new phase a decade ago, with the advent of detectors sensitive enough to measure its polarization — the direction of vibration in the photons coming from each point in the sky. Polarization in the CMB results from photons scattering off free-roaming electrons in the cosmic plasma, and the potential scientific pay-off from measuring it was huge: one component, the swirling B modes, promised to give astronomers the first direct evidence that the Universe had undergone an extreme form of inflation when it was just 10^{-36} to 10^{-32} seconds old. Theorists proposed the idea in the early 1980s to explain why the Universe is both smooth at the largest scales and geometrically flat[3]. The rapid expansion, in which the cosmos grew by a factor of at least 10^{26}, would have smoothed out most irregularities and flattened out any curvature. The few remaining irregularities — visible as the CMB temperature anisotropies — were vastly magnified vestiges of tiny quantum fluctuations in energy.

But that was all theory until researchers developed the capacity to measure B modes. That required them to find a way to identify a minuscule signal that is easily masked by polarized emissions from dust and magnetic fields in our Galaxy. The first detection wasn't announced until 2013 (refs 4, 5) — and even then, the measurements were made on a small angular scale, at which polarization patterns are distorted by the gravitational fields of galaxies in front of the CMB.

The real prize arrived in March, when astronomers working with the BICEP2 detector at the South Pole announced that they had measured B modes on scales of about 1°, large enough to avoid the signal from intervening galaxies and to probe fundamental polarization patterns such as those from inflationary gravitational waves[6].

After so many years of searching for inflationary B modes, BICEP2's results triggered widespread elation in the cosmology community. "It has injected a whole lot of adrenaline into the endeavour," says experimental cosmologist Shaul Hanany of the University of Minnesota in Minneapolis.

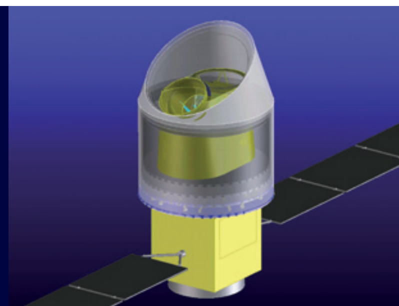
But with that excitement came a puzzle. The patterns detected by BICEP2 are considerably stronger than most cosmological models

1999, BOOMERANG/NASA/NSF; 2013, ESA/PLANCK COLLABORATION

2014, STEFFEN RICHTER/HARVARD UNIV.; 2020S, LITEBIRD

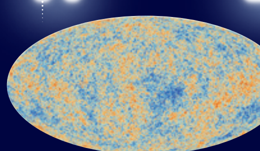
1999
Balloon-borne detectors characterize CMB fluctuations accurately enough for scientists to do a statistical analysis, which reveals information on the Universe's geometry and energy content.

2014
The BICEP2 experiment at the South Pole detects strong evidence of gravitational waves in the CMB's polarization.



2020s
Next-generation CMB observatories could use the radiation to track galaxy evolution and probe the earliest instants of the Universe.

2003
NASA's Wilkinson Microwave Anisotropy Probe (WMAP) charts the CMB in increased detail.



2013
Europe's Planck satellite picks up first hints of gravitational waves from the infant Universe.

predicted. And it exceeds limits set by the European Space Agency's now-deactivated Planck satellite on the degree to which gravitational waves might have contributed to the CMB temperature fluctuations. "The BICEP2 result was a bit of a shock for me," says Efstathiou, who is a member of the Planck science team. "I think the jury is still out" on what it means, or if it's even real.

In the next year, half a dozen experiments in Antarctica and Chile will try to confirm the findings. Members of the BICEP2 team are working on two new South Pole telescopes. The Keck Array, which is already operational, has five times as many detectors as BICEP2 and covers two frequency bands. A second, called BICEP3, is an upgraded version of the previous detector that is scheduled to start collecting data in December 2014. One or two US-funded balloon-borne experiments may also fly later this year from McMurdo Station in Antarctica; last year's flights were cancelled because of the US government shutdown.

But cosmologists are most eager to see this autumn's planned release of the full data set from Planck — findings that will include polarization maps. Planck has the advantage of monitoring a wider range of frequencies than ground- and balloon-based experiments, which can measure only within the narrow bands of radiation frequencies that are not absorbed by water vapour in the atmosphere. Planck's improved sight will give astronomers much more confidence in subtracting foreground polarization from our Galaxy. And instead of being restricted to the portion of sky visible from a given latitude, Planck has an unobstructed view.

If Planck confirms BICEP2's results, the champagne will come out. But if it does not, cosmologists will have to resolve the discrepancy, which will pose a challenge. To take just one example, gravitational waves as strong as those recorded by BICEP2 should have had a noticeable effect on the acoustic peaks — yet the limited Planck data currently available have shown no evidence for that.

"How can you reconcile it?" wonders Efstathiou. The ideas put forward so far seem contrived, he says. Kamionkowski is more optimistic, and counsels patience. "It may take years to really understand what the most promising models are and how to distinguish them."

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NEXT-GENERATION EXPERIMENTS

In the meantime, most CMB scientists are focusing on developing their capability for measuring B modes. For example, there are many theories for precisely how inflation unfolded, each making its specific prediction about how the gravitational wave B modes are distributed across the sky. Being able to measure B modes at the largest scales would allow astronomers to weed out the theories that are obviously wrong.

At smaller scales, the B modes are sensitive to how mass is distributed around the Universe, and how vast galaxy clusters have grown over time. Such a signal would help astronomers to constrain stubborn cosmological unknowns, including the nature of dark energy — a mysterious force that is causing the Universe's expansion to speed up — and the identity of the invisible dark-matter particles that make up most of the Universe's mass.

Combining B-mode maps with surveys of hydrogen across the Universe could also allow observers to probe the epoch in which the first stars and galaxies switched on their ionizing radiation. Electron scattering from this period should have left a large-scale mark in the B-mode polarization of the CMB.

Unfortunately, limited money is constraining choices about what comes next. A UK competitor to BICEP2 was cancelled in 2009 (see *Nature* http://doi.org/fnsdc3; 2009) as its funding council struggled to meet commitments to international bodies such as CERN, Europe's particle-physics laboratory near Geneva in Switzerland. Europe as a whole, meanwhile, has focused its CMB research programme almost exclusively on Planck — a policy that Efstathiou describes as a "big mistake". With no follow-on mission in the pipeline and little ground-based activity, the concern is that hundreds of postdocs and students will have to move to new fields when the research programme ends.

In the United States, CMB work falls into the cracks between grant-agency panels. Space and balloon work competes against planetary and X-ray astronomy missions at NASA, and ground-based arrays go up against particle-physics experiments at the Department of Energy (DOE) and the National Science Foundation (NSF). Philanthropic donations from the Keck and Simons foundations, among others, are helping fill the gap.

A solution suggested by some astronomers would be to cut back on the number of ground-based CMB experiments with similar aims. Critics contend that ground-based CMB experiments rarely share their data, which undermines calls for more projects. Most space-science missions are required to make their data public, says Jean-Loup Puget, an astronomer at the University of Paris-South and a principal investigator on Planck. "Ground-based experiments should do so too," he says.

But others argue that the ground experiments are cheap and that diversity makes for a healthy field. The one thing that everyone agrees on is that the science case for another CMB space mission is compelling. Efforts are afoot to make that happen after 2020.

It may be an uphill battle. No CMB probe was ranked highly in NASA's 2010 Decadal Survey, a community-led review that sets scientific priorities to guide future mission selection. But there was a clause recommending a mid-decade review in the event that B modes were discovered. After BICEP2, the US CMB community, led by Hanany and Jamie Bock of the Jet Propulsion Laboratory in Pasadena, California, is urging that the case for such a mission be reappraised and funding be redirected from existing missions that have suffered delays.

A consortium of US experimenters is proposing a follow-up to the present South Pole and Atacama telescopes. Known as CMB-S4, it would have hundreds of thousands of detectors and could come online after 2020 if it is given a high priority in a particle-physics review currently being carried out by the DOE and the NSF. Balloons could also play a part. "A coherent programme is warranted," Hanany says.

In Europe, a higher-resolution successor to Planck has not so far been selected by the European Space Agency. A revised mission is being drawn up for the next round of proposals, and if successful might be launched in the mid-2020s.

But such complicated proposals are expensive and difficult to realize, Efstathiou says. 'Keep it simple' is now his mantra. He would like to see a small mission dedicated to observing B modes on large angular scales, thus targeting the gravitational-wave signature alone. In effect, it would be a BICEP2 experiment in space, says Peter Ade at Cardiff University, UK, who has built detectors for ground-based experiments and Planck. The technology is mature and he thinks such a mission could be ready in five years.

A Japanese-led satellite proposal called LiteBIRD could be just such a mission. Proposed by physicists in Japan, in collaboration with experimenters in the United States, Germany and Canada, the project could be launched in the early 2020s if it received some US$100 million in funding. In the meantime, the researchers are developing a ground-based experimental version, called GroundBIRD.

For all the uncertainties about the future, CMB scientists are in bullish mood. "Nature has been kind to us in giving us this clear view of the early Universe," Efstathiou says. "With a gift like that we should exploit it as much as we can." ■

Joanne Baker *is a Comment editor for* Nature.

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