Imprint of primordial gravitational waves detected

C. Frederick Graves
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In the first instants after the Big Bang, it is theorized that the universe underwent a short, rapid phase of exponential expansion known as inflation, which set the conditions for the subsequent development of all structure in the universe. On March 17, the inflationary hypothesis received an important confirmation, with the announcement of the first indirect detection of primordial gravitational waves, an important prediction of the theory.

The detection was announced by the BICEP2 collaboration, an international team of astronomers working at the South Pole. If confirmed by other ongoing experiments, the detection is an important confirmation of the basic picture of cosmology that has been developed over the last five decades.

By studying the polarization of the cosmic microwave background, the BICEP2 team was able to identify so-called “B-modes,” thought to be produced by primordial gravitational waves. These primordial gravitational waves are a natural consequence of the interaction of gravity and quantum mechanics in the first moments of the universe’s history. The new detection is important not only because it confirms inflationary cosmology, the idea that the universe expanded exponentially in the first instants, but also because it gives a window to study the interplay of gravity and quantum mechanics, two fundamental theories of physics which have yet to be fully reconciled.

In order to explain the BICEP2 collaboration’s result, a bit of background is necessary.

The Cosmic Microwave Background

When astronomers look out into the universe, they are peering into the past. Light from more distant regions of the universe takes longer to reach us, so we see more distant objects as they looked long ago. The farther out we look, the further into the past we are looking. Some astronomers liken this to “cosmological archeology.” Looking out farther into the universe is like digging deeper into the ground—dig deeper and you find older remains. Traveling outward, we see at first nearby stars, then nearby galaxies, then progressively more distant and older galaxies. We eventually reach a distance at which we are looking at a time when there were as yet no stars or galaxies.

As the universe is expanding and cooling, the further back we look, the smaller, denser and hotter the universe was when the light we see was emitted. If we travel far enough out in space, and therefore back in time, we reach a point when the universe was so hot and dense that it was made up of opaque plasma. We run up against an opaque boundary, called the surface of last scattering, beyond which we cannot see. This surface is the farthest—and therefore oldest—thing we can observe in the universe. Since the universe has been largely transparent since the time when the surface of last scattering existed, the light it emitted has been free to stream throughout the universe. This is how the surface of last scattering gets its name—it is the last medium that the light of the hot, early universe ever scattered off of. The expansion of the universe has caused that light to become dimmer and to shift to lower energies, but it can still be seen as microwave radiation. This light, emitted by the universe when it transitioned from opaque plasma to neutral atoms, is called the Cosmic Microwave Background (CMB).

The CMB shows us how the universe appeared at the time of last scattering, 380,000 years after the Big Bang, at a time when the universe was not only much hotter and denser than it is now, but also nearly perfectly homogeneous. This means that the CMB is of almost uniform intensity and temperature in every direction on the sky. However, the deviations from perfect uniformity allow cosmologists to glean information on the early history and composition of the universe. Up until now, cosmologists have primarily studied variations in the temperature of the CMB across the sky. The BICEP2 team has measured a different property of the CMB, namely its polarization.

Gravitational waves

A second key concept involved in the BICEP2 collaboration’s finding is that of gravitational waves, a prediction of Einstein’s gravitational theory, called General Relativity. When Newton first postulated the law of gravitation, he assumed that it acted instantaneously across great distances. If the Sun were to disappear this instant, the Earth would immediately be released from its orbit and fly off into the darkness of space. In General Relativity, however, gravity does not act instantaneously.

If the Sun were to disappear, we wouldn’t know until eight minutes later, the time it takes light to travel from the Sun to the Earth. Gravity propagates at the speed of light, the maximum speed that information can travel. The example given here is unphysical—the Sun’s mass and energy could not vanish from existence in this way—but it illustrates that gravitational changes are not felt immediately at a distance.

Gravity itself is an effect of the curvature of spacetime—matter curves spacetime, and the curvature of spacetime guides the motion of matter. This interplay is what we observe as gravity. Small perturbations in the curvature of spacetime travel at the speed of light, and are called gravitational waves. These ripples can be generated by the acceleration of large masses, but may also be generated on very small scales by quantum fluctuations. The connection between these small gravitational perturbations and the cosmic microwave background is provided by a third concept, known as inflation.

Inflation

A number of previously unresolved problems in cosmology are resolved if one assumes that the universe underwent a short period of exponential expansion, much faster than the rate of expansion either before or after this short blip, a tiny fraction of a second after the Big Bang.

"Inflation" was proposed by Alan Guth in the early 1980s, and developed further by Andrei Linde, in order to account for the nearly uniform temperature of the CMB and flatness of space. In the instant after the Big Bang, the rapid expansion caused by inflation would have flattened out the curvature of space, much like the surface of a balloon looks flatter on small scales as it is blown up. Inflation also expanded small regions of space that were homogeneous in temperature and density, creating vast regions, like our observable universe, with uniform properties. Without inflation, we would expect the CMB to look much more patchy, yet the CMB is nearly perfectly uniform across the entire sky.

Inflation is now favored by most cosmologists, although the details of how it happened are very uncertain. The universe at the time of inflation was incredibly hot and energetic. The high-energy physics that would have dominated the universe at that time is far beyond our ability to test directly, even in our most powerful particle accelerators, like the LHC. Nevertheless, there are some specific predictions of inflation that can be tested directly.

The early universe is assumed to have been remarkably homogeneous, but small quantum fluctuations would have been stretched by inflation to cover vast distances. This is thought to be the origin of the initial density fluctuations that eventually allowed the formation of structure in the universe, from stars and planets all the way to superclusters of galaxies.

Small-scale fluctuations in the curvature of space would also have been inflated to cover vast scales. These fluctuations continued to propagate as gravitational waves through the universe and left an imprint on the CMB that can now be observed. Because these gravitational waves were generated in the first instants after the Big Bang, they are known as "primordial" gravitational waves.

Observing the imprint of primordial gravitational waves

Detecting gravitational waves directly is a longstanding goal in astrophysics, and one which very well may be achieved soon by a number of large-scale experimental facilities. However, the primordial gravitational waves created by inflation are too weak to plausibly be directly detected on Earth. Rather, the newest announcement is based on an indirect detection of primordial gravitational waves, based on a particular signature they have imprinted onto the CMB.

Gravitational waves stretch and compress space as they propagate. As they do this, they distort a property of light known as "polarization." Light is an electromagnetic wave, comprised of oscillating electric and magnetic fields that vibrate in perpendicular directions. The polarization of light is the axis along which the electric field oscillates. Most light that we receive from space is unpolarized, meaning that its direction of polarization is constantly changing and random. The light of the CMB, however, is polarized, meaning that its polarization points slightly more often in one direction than in others.

This polarization came about because of the small temperature variations in the medium that emitted the CMB, the surface of last scattering. The CMB was also polarized ever so slightly by the stretching and compressing of the surface of last scattering by primordial gravitational waves that were generated by inflation.

Working at the South Pole, a prime location for astronomy because of its high altitude and dry air, the BICEP2 collaboration, led by Professor John Kovac of Harvard, measured the polarization of the CMB on one patch of sky. They used a custom-built telescope with a 26 cm diameter, with the electronics and focal plane cooled to near-absolute zero to enable the sensitive measurements the team required. BICEP2 conducted 590 days of observations between 2010 and 2012 of a small patch of sky, chosen because the relative lack of obscuring structure from our own Milky Way and other galaxies allowed a clearer view of the CMB. The team compiled a map of the polarization of the light from the CMB across this patch of sky.

They then looked for a specific type of curled pattern, called the B-mode, in their polarization maps. While other polarization patterns can be produced by density fluctuations in the early universe, B-modes are imprinted on the CMB by primordial gravitational waves. However, there are other sources of light between ourselves and the distant CMB, which could potentially produce B-mode polarization, masquerading as the signal of primordial gravitational waves. This is the reason why BICEP2 chose a region of the sky with a relatively unobscured view of the CMB.

In addition, the team was careful to account for possible foreground sources of B-mode polarization, such as dust in our Milky Way galaxy, and to verify that they were not strong enough to produce the observed signal. Monday's announcement comes after painstaking work by the BICEP2 collaboration members to verify that their observed signal was a solid detection of the imprint of primordial gravitational waves on the CMB.

Scientists now await confirmation of the BICEP2 result from other ongoing experiments. Later this year, results from a European space telescope, Planck, will be released. Planck observed the CMB from 2010 through late 2013, when its supply of liquid helium coolant ran out. The Planck team has already released their analysis of the temperature variations of the CMB, providing our most detailed look yet at the fluctuations in the early universe, but is still working to produce a full analysis of the polarization of the light of the CMB. Confirmation from Planck is of particular interest, as an early, incomplete analysis of Planck data suggested that the B-mode polarization of the CMB should be weaker than BICEP2 observed.

The BICEP2 collaboration's detection of B-modes in the CMB is a strong indication of the existence of primordial gravitational waves, and therefore an important confirmation of the inflationary hypothesis and our basic picture of the history of the cosmos. By observing the polarization of light emitted only 380,000 years after the Big Bang, a window has been opened up into the physics of an even earlier era, when the universe was only a fraction of a second old. That theories of physics developed by scientists bound to our planet can make successful predictions about such a physically and temporally remote era is a major achievement.

Press conference

Andrei Linde receives word that BICEP2's results confirm his theory

The BICEP2 collaboration's website

General background on cosmology

The First Three Minutes: A Modern View of the Origin of the Universe by Steven Weinberg