Dust, Distortions, and Shadows in the Universe’s Oldest Light

Half a century after its discovery, the cosmic microwave background remains a source of new knowledge and new controversies

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Fifty years ago, two radio astronomers working at Bell Labs in Holmdel, New Jersey, stumbled across a persistent unknown source of noise when they began taking measurements with a new horn antenna. The extremely sensitive apparatus was intended to receive radio waves from communications satellites but instead had received a signal from nearly the dawn of time: the cosmic microwave background (CMB) radiation, the thermal afterglow of the big bang. Arno Penzias and Robert Wilson later received the Nobel Prize for their discovery. Further characterization of the perfect blackbody spectrum of the CMB by NASA’s COBE satellite led to other Nobels in 2006.

The quest to pry every last secret from this radiation is a story that continues to this day, one that I am very humbled to take part in.

A window into the universe’s birth

The CMB has ancient origins; its photons are the oldest light ever seen in the universe. They were produced in the primordial brew of the big bang. For hundreds of thousands of years, they scattered frequently in a dense fog of electrons, protons, and helium nuclei that filled the universe. As the universe expanded, the fog cooled to progressively lower temperatures. Eventually, about 380,000 years after the big bang, the temperature was low enough for electrons and ions to combine. They formed neutral hydrogen and helium atoms, which no longer scattered the photons. The fog cleared.

Since that time, the photons have traveled, largely unimpeded. Their wavelengths stretched with the expansion of the universe, and they eventually arrived at our telescopes in the microwave band of the electromagnetic spectrum.

These CMB photons provide a window onto the conditions of the early universe, and thus a powerful tool with which to determine its fundamental properties, including its age, composition, geometry, and perhaps even its origin.

The prevailing theory describing the early universe, inflation, posits that the universe underwent a period of extremely violent expansion at its very beginning, growing in size by some 26 orders of magnitude in only $10^{-33}$ seconds—a truly audacious idea. Crucially, the theory makes specific predictions for CMB photons. It predicts the almost perfect uniformity of the photons’ temperature observed across the sky—2.726 Kelvin—as well as the ways in which temperature should slightly deviate from this uniformity. These temperature deviations, which are on the order of 1 part in 100,000, correspond to the differences in the density of the universe from place to place at the time the CMB photons were emitted. Most audaciously, inflation states that these small differences originated in quantum fluctuations that were stretched to macroscopic sizes during the initial violent expansion.

However, alternative theories, such as a cyclic or “bouncing” universe, might reasonably predict the properties of these temperature deviations as well. A key distinction of inflation is the prediction of a particular pattern in the CMB photon’s polarization, the direction of the light’s electric and magnetic...
fields. Inflationary expansion is thought to have been so violent that it disturbed the fabric of space-time itself, producing gravitational waves. These waves later manifest as “swirly” patterns in the polarization of the CMB photons (technically known as B-modes). The cyclic universe model does not predict this pattern, setting the stage for a powerful experimental test of our ideas about the origin of the universe.

**Promising polarization signal bites the dust**

In March 2014, the team behind the BICEP2 experiment dramatically announced a measurement of this highly sought B-mode polarization signal; an announcement met with international excitement. The pattern seemed to match theoretical expectations, but—very importantly—had been seen clearly at only one frequency, 150 gigahertz.

Dust grains in the Milky Way are known to emit thermal radiation around this frequency as they are heated by starlight. The grains are oriented by the galactic magnetic field, which leads to polarization in the emitted thermal radiation that could mimic a B-mode signal. But the strength of the polarized signal from dust was mostly unknown until the past two years, when high-frequency data from the Planck satellite began to shed light on its properties.

Using Planck data that had been publicly released, as well as other existing galactic surveys, I worked with a group at Princeton University (which included Raphael Flauger and David Spergel) in the months following the BICEP2 announcement, trying to understand whether the observed BICEP2 B-mode signal could be entirely explained by dust. The answer—unfortunately—turned out to be “yes,” although the uncertainties were large. Our reinterpretation was subsequently confirmed by the official joint analysis of the BICEP2 and Planck data released in February 2015. It showed that no statistically significant evidence for primordial B-modes remained after correcting for the dust.

Despite this disappointment, the path forward is clear. We need to understand the dust contaminating our measurements of the sky at microwave frequencies. A number of experiments have been planned or are already underway with this goal in mind, including the Advanced Atacama Cosmology Telescope (AdvACT), the Simons Array (with POLARBEAR-2 detectors), and BICEP3. By exploiting the different frequency spectra of the CMB and the dust (recall the perfect blackbody nature of the CMB), cosmologists might be able to effectively separate the two signals.

**Cosmic trash or treasures?**

But the dust in our galaxy is not the only thing obscuring our understanding of the universe’s birth. As CMB photons travel to our telescopes, they sometimes encounter distortions along the way that can warp our perspective. Fortunately, there is a silver lining. The signals produced by these encounters contain a wealth of information about the cosmos.

For example, the path of a CMB photon can be bent by gravitational fields encountered during its journey; the effect is called gravitational lensing. The twisting of light due to this lensing effect induces spurious B-modes in the CMB polarization, which must be accounted for (just like the dust B-modes) when searching for the primordial B-modes due to inflation. However, one can also use this gravitational lensing signal to reconstruct the gravitational fields themselves, and hence the distribution of matter (including both atomic matter and dark matter). This powerful technique has recently come of age and is now yielding precise constraints on the large-scale structure of the universe. Gravitational lensing maps from upcoming experiments such as AdvACT will unveil the precise distribution of dark matter at high resolution over more than half of the sky.

In addition to lensing distortions, CMB photons sometimes encounter large clouds of hot, ionized gas as they travel through the universe. The clouds cast “shadows” in our observed CMB maps because CMB photons scatter off of free electrons in the gas, a process known as the Sunyaev-Zel’dovich (SZ) effect. Because the SZ effect leaves the photons’ polarization essentially unchanged, it does not contaminate B-mode searches in the way that dust and gravitational lensing do. Instead, SZ shadows in CMB temperature maps are helpful because they can be used to find the most massive structures in the universe: galaxy clusters, where most of the hot, ionized gas causing the shadows is located. These rare structures are very sensitive probes of the amount of dark matter in the universe, for instance, and the properties of the quantum fluctuations generated during inflation.

Much of my own work has focused on new ways to pry secrets from the CMB using SZ shadows or the combination of gravitational lensing and SZ effects.

Fifty years after its discovery, the CMB continues to yield unexpected surprises. It may soon confirm our best ideas about what happened during the first moments after the universe was born. However, achieving this goal will require understanding the dust, distortions, and shadows present in CMB maps. It is an exciting challenge.
Dark matter is so named because we cannot see it. So it’s ironic that much we have learned about dark matter has come from studying light, specifically, the cosmic microwave background (CMB). I often share with my students the story of its discovery, which paints a wonderful picture of how science works in practice and how we test scientific theory, although as an astroparticle physicist I do not study it directly.

The CMB story starts with Edwin Hubble, who made one of the most earth-shattering discoveries of the 20th century. In 1929 he found that the universe is expanding. After concluding that the “spiral nebulae” were “island universes” and not part of the Milky Way, Hubble measured their distances using Cepheid variable stars. Except for the nearby galaxies in our Local Group, all of the galaxies he observed were moving away from us, and the farthest galaxies were moving away the fastest.

The relationship of the velocity and distance for galaxies is linear and its slope is known as the Hubble constant, $H_0$. Hubble found its value to be about 500 km/s/Mpc, which means a galaxy one megaparsec from us will be observed to be receding at 500 km/s. The modern value is 69.32 +/- 0.80 km/s/Mpc. Hubble’s high value was due to errors in distances to galaxies. Distances in astronomy are notoriously hard to measure. This universal recession immediately suggested that the universe was nonstatic and evolving, and perhaps had a beginning.

Hubble’s discovery came at a time when a flurry of work was being done to model the universe at large using Einstein’s recently developed theory of general relativity. Einstein first favored a static, nonevolving model. However, Georges Lemaître, a Belgian scientist and Catholic priest, showed that an expanding universe was also a valid solution to Einstein’s field equations. Inspired by the phenomenon of radioactivity, Lemaître proposed that the universe as we see it began from the “decay” of a primeval atom. In his view cosmic remnants from this atom formed the seeds of stars, galaxies, and the other structures in the universe we see today. Lemaître viewed this as a cold process.

In the famous paper published in 1948, Ralph Alpher, Hans Bethe, and George Gamow proposed a model explaining the abundances of the elements that incorporated the expansion of the universe. The early universe, they argued, was hot and dense, and expanded from an initially ultradense state. They successfully calculated hydrogen and helium abundances; however, they erroneously postulated that all heavier elements were created in the early universe through combining neutrons. We now understand that all elements heavier than lithium are created in the core of stars.

One of the most important predictions they made was too quickly forgotten: the initial hot, dense state of the universe should exhibit a leftover radiation field. In their theory, particles were created and annihilated in the early universe, and energy was transferred back and forth to a background of photons or light. Those frequent interactions meant that the universe could be modeled as a perfect blackbody, characterized by some temperature, $T$. As the universe expanded, this background of photons redshifted (i.e., lost energy). In essence, Gamow and his collaborators predicted the CMB and postulated that this background radiation should have a temperature today of about 5 K.

By the early 1960s cosmology had become a showdown between two competing theories. The big bang model gave the universe a problematically young age, two billion years. This age problem led Fred Hoyle, Hermann Bondi, and Thomas Gold to propose the steady-state theory, which explained Hubble’s expansion by proposing new physics and a static universe that continuously created new matter.

The two theories, big bang and steady state, gave very different predictions about the universe. In a way, the steady-state model was conceptually simpler; it had fewer variable parameters and made more concrete predictions. One of these predictions was the distribution of radio sources at large distances. Measurements of radio sources seemed to disfavor the steady-state model, but the results were not conclusive at that time.

In 1964 astronomers Arno Penzias and Robert Wilson found the smoking gun that finally gave unequivocal evidence for the big bang model. While trying to calibrate a horn antenna at Bell Labs, developed to detect radio waves from satellites, they noticed excess noise in the sky corresponding to a uniform signal 100 times stronger than any background they had expected.

At first this signal frustrated them to no end. They went to extreme lengths, even removing bird droppings from the antenna, to determine the source of this background. After painstaking work, they found that the background was neither from the sun nor our own galaxy. It was extragalactic in nature, but its source remained mysterious.

Finally, when a friend pointed out the work of astronomers at Princeton University who were searching for the CMB, Penzias and Wilson realized what they had discovered. The two groups published joint articles in The Astrophysical Journal describing the discovery and interpreting it as the long-predicted cosmic microwave background radiation.
In 1989 NASA launched the Cosmic Background Explorer (COBE) satellite, which verified two fundamental properties of the CMB. The first was that the radiation is remarkably uniform (isotropic) across the sky; hence the early universe was a nearly perfect blackbody. This discovery vindicated the use of statistical thermodynamics to describe the early universe.

But cosmologists were still puzzled by the uniform nature of the CMB. An extremely uniform CMB suggested an extremely uniform early universe. Why, then, is there structure today? Why isn’t the universe a dilute, uniform cloud of gas?

John C. Mather and George Smoot answered this question with COBE, which also revealed the second fundamental property of the CMB: although the CMB is remarkably isotropic, fluctuations (anisotropies) in temperature do exist. Some of the anisotropies discovered by COBE’s differential microwave radiometer (DMR) were due to our motion relative to the CMB frame and foregrounds, such as emissions from dust in the Milky Way. Once these anisotropies and other backgrounds were removed, fundamental anisotropies on the level of one part in 10^5 remained. In other words, one patch of the CMB sky differs in temperature from another at the fundamental level by only one 100,000th of a degree.

Those fundamental anisotropies were the seeds of early structure formation; they allow us to figure out the composition and state of the early universe. For instance, the scale of these temperature fluctuations hints at the necessity of dark matter; it is too small to allow ordinary matter time to coalesce into the structures we see today without the help of something like dark matter. The problem is time; ordinary matter becomes charge neutral only at the epoch of recombination, and before that, due to electrostatic forces, matter cannot effectively clump into gravitational wells to begin forming structure. The COBE results showed a need for an electrically neutral form of matter that could jump-start the structure formation process well before recombination.

Mather and Smoot were awarded the Nobel Prize in Physics in 2006 for their measurements of the CMB.

After COBE, we have continued to learn a great deal more about the CMB thanks to the Wilkinson Microwave Anisotropy Probe (WMAP) and Planck satellite missions (among others). Experiments such as BICEP-2 (featured in this issue) are probing cosmic inflation shortly after the big bang using the polarization of the CMB. As a particle theorist, I continue to be amazed by the amount of information about the early universe that can be extracted from the cosmic microwave background.

References


Reading list for more information


Wayne Hu of the University of Chicago also has a wonderful introduction to the CMB for beginners: http://background.uchicago.edu/~whu/beginners/introduction.html.

You don’t need a time machine to see what the universe looked like more than 13 billion years ago. You just need the right camera, one good enough to take photos of the faint cosmic microwave background (CMB) radiation left over from the big bang.

Each photon in this radiation is a time capsule that carries information about the face of the universe in its infancy. Collect enough of them and you have a snapshot—specifically, a snapshot of temperature.

**Portrait of a young universe**

Just as a hot iron glows red with visible light, the early universe glowed with microwave radiation as it cooled. The peak wavelength of this glow, about 2 millimeters, corresponds to a specific temperature derived from the blackbody spectrum: about 2.7 Kelvin. This temperature is extremely consistent in all parts of the sky. Though it has interesting cosmological implications, it is very boring to look at.

Subtract this 2.7 Kelvin signal, and something exciting happens. Slight differences in the microwave radiation become visible, and the map of the CMB attains structure.

To take a picture of this structure, you need a very sensitive camera. The CMB signal is already very weak, and the interesting variations within the overall signal are fainter still. The polarization of light from the CMB is interestingly nonuniform as well, but measuring polarization anisotropy requires even more sensitive detection.

**Condensed matter meets cosmic microwaves**

As an undergraduate majoring in physics and mathematics at Drexel University, I spent two six-month internships at Argonne National Laboratory just outside of Chicago, Illinois, working on detectors for the South Pole Telescope. My devices will be deployed this year to map the CMB at small angular scales. There’s a very good chance that I will also be going to the South Pole in the future!

The pixels in this telescope’s cameras are similar to those in other telescopes investigating the CMB. They are superconducting devices called transition-edge sensors (TES). A TES detector is so sensitive that it can resolve the energy of a single photon.

My task as part of the detector fabrication team was to construct the next generation of detectors to be deployed in the telescope. I spent lots of quality time in a clean room forging 150-pixel TES arrays on six-inch silicon chips. I was also involved in the design and testing of the early devices.

A TES detector consists of three small parts, all with sizes on the order of microns. Detection occurs when a photon heats an absorber. The temperature is then measured by a thermometer. Finally, the heat is dissipated through a thermal link. Our thermometers are special because they are superconductors. The special properties of the superconducting transition give TES detectors their sensitivity.

Superconductors have zero resistance below the superconducting transition temperature. Cool aluminum down from room temperature, for instance, and at around 1.2 Kelvin the resistivity of the metal drops from a finite value to zero. This transition is often quick; it can occur in less than a millikelvin.

A TES thermometer is a superconductor cooled precisely to its transition temperature. Smack dab in the middle of its transition, the material is not quite superconducting and not quite normal metal. In this state a very small variation in temperature, such as that created by an incoming photon, generates a sizable shift in resistivity. Measuring this shift in resistance probes the temperature of the absorber. From the temperature of the absorber, the energy of the photon can be deduced.

My research has focused on controlling and tailoring this transition. I’ve worked on new TES designs that will be used in conjunction with antennae that couple to CMB radiation. The antennae are specifically designed to couple a broad band of frequencies and discriminate between different kinds of CMB polarization of interest to cosmologists. By incorporating band-pass filters into the new pixel designs, this broadband signal can be divided into smaller frequency bands, allowing each pixel to measure multiple frequencies.

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Measuring the largest features in the universe, I’ve learned, requires a deep understanding of materials at much smaller scales. Condensed matter physics and observational cosmology are permanently entangled. This cosmic connection between two seemingly separate worlds has and will continue to provide insight into the beginning of it all. 

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**A Camera for the Cosmos**

Undergraduate work in materials science sharpens photos of early universe

by Sam Ciocys  
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Formed in the crucible of the early universe, the light that composes the cosmic microwave background (CMB) contains an abundance of information about the formation and composition of the universe in both its temperature and polarization. The faintest signal from the CMB is the B-mode polarization signal, which has two potential sources: the gravitational lensing by intervening matter on small angular scales or anisotropies induced by inflationary gravity waves on large angular scales.

Inflationary B-modes have a magnitude of less than 100 nK, so noise is a constant adversary. Noise can originate from the atmosphere, the instrument itself, and galactic dust emission. To reach the sensitivity necessary for measuring B-mode polarization, experiments not only need highly sensitive detectors but also cutting-edge instrumentation and a skilled team of experimentalists and analysts.

To curtail atmospheric contamination, ground-based CMB experiments are conducted in some of the highest and driest places in the world: the Atacama Desert in Chile and the South Pole. High elevations decrease the amount of atmosphere the CMB photons must travel through before detection, and dry locations minimize the amount of water vapor in the air, which is one of the main culprits because it absorbs and emits at microwave frequencies. While these locations are ideal for ground-based observations, their remoteness makes daily operation a monumental effort, which would not be possible without strong local support from skilled local engineers and constant fuel supplies.

Members of CMB experiments work under difficult conditions to ensure the success of years of development and observation. At the beginning of an experiment, they must assemble a telescope, install its systems, and deploy its detector arrays. During nominal observations, they must perform telescope maintenance; plan and implement a 24-hour observation schedule; and run calibration measurements to ensure that the instrument and the detectors are thoroughly characterized. Supplies are scarce, so observers must find imaginative and durable solutions to malfunctions. They must have a deep understanding of all the experimental systems, including the computers, detectors, readout and biasing systems, cryogenic systems, and motion control systems. I myself have worked many months over the past few years on the Atacama B-mode Search (ABS) at its site 17,000 ft. up in the Atacama Desert.

Even in these extreme locations, atmospheric noise can still be an issue due to its nonuniformity, especially for observations at large angular scales. Sections of the unpolarized atmosphere can change on the timescale of minutes, causing fluctuations of tens of mK in the signal. Pioneered by the balloon CMB experiment MAXIPOL, a continuously rotating half-wave plate (HWP) can further reduce atmospheric noise by modulating the incident polarization signal. The rapid polarization modulation acts as a lock-in amplifier for the polarized signal and also mitigates systematic effects. ABS, the first ground-based telescope to use a continuously rotating HWP, showed that using a HWP to decrease atmospheric noise was extremely effective. ABS also demonstrated that a HWP can recover CMB polarization data at large angular scales, which are typically obscured from the ground by atmospheric fluctuations. Now other ground-based CMB experiments, including the Advanced Atacama Cosmology Telescope polarization receiver (AdvACT), are adding HWPs to their optics.
Noise can also come from the instrument itself. The optical elements of telescopes that couple the detectors to the sky must be optimized and well characterized in the field to minimize cross-polarization and the creation of spurious polarized signals. Experimentalists must also design and deploy electromagnetic shielding for the electrical systems and cables to minimize electrical noise. Future experiments will increase the packing density and number of detectors to increase sensitivity by decreasing statistical variation. To maximize the signal, CMB polarization experiments employ transition-edge sensor (TES) bolometers as detectors and read them out with a series of inductors and superconducting quantum interference devices, which provide low-noise amplification of the signals. (See Sam Ciocys’ story on page 13 for more information about TES detectors.) Improvements to these readout systems are crucial for future applications as arrays gain more detectors and the noise requirements become more stringent.

Some of the largest sources of instrumental noise are thermal. Vibrations within the telescope during motion must be minimized, as they can cause excess thermal noise. To further reduce thermal noise, the critical temperatures of the bolometers must be tuned to 100–500 mK for most experiments, which requires advanced cryogenic and readout technologies. In the past decade, cryogenic systems large enough to house many full detector arrays and even entire telescope optics (as in the case of ABS) have made great technological strides and can now reliably reach base temperatures below 100 mK for extended periods of time. Additionally, readout and feedback lines can carry thermal energy from warmer cryogenic stages to the detectors. To minimize the number of cryogenic wires, the detectors are multiplexed so that many detectors can be read out on a single wire.

Dust from our galaxy is a major source of signal contamination, as mentioned in Colin Hill’s story on page 9. To remove this contamination, the spectrum of the polarized dust emission must be well characterized, which requires observations at several frequencies. Today’s experiments usually link two TES bolometers to orthogonal polarizations at a single frequency. Future experiments will employ multichroic pixels, which use on-chip filters that allow several frequency bands to be detected by a single pixel. Upgrading to multichroic detector arrays necessitates the development of efficient wide-band elements, including lenses, filters, antireflective coatings, and HWPs. The Atacama Cosmology Telescope Polarization receiver (ACTPol) has already successfully deployed a 90/150 GHz multichroic array, which is currently observing, and AdvACT will use low-, mid-, and high-frequency multichroic arrays to observe with five frequency bands.

Competition in the CMB field can be fierce, as teams search for evidence related to everything from inflation to the curvature and content of the universe, and the growth of structure to the sum of neutrino masses. However, the competition between projects dissolves in the field. We observers face harsh conditions, including high UV exposure, low temperatures, low oxygen levels, long hours, and even llama traffic. Overcoming those obstacles requires camaraderie, with groups working together to push the boundaries of our scientific understanding of the universe.