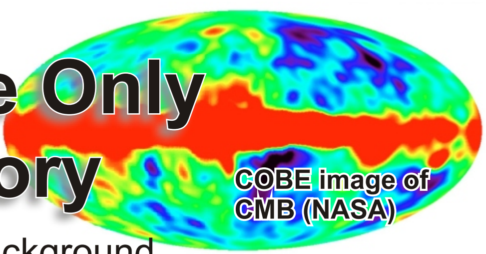
Data Makes Sense Only in Light of Theory


COBE image of CMB (NASA)

The Story of Cosmic Microwave Background

The recognition of the Cosmic Microwave Background (CMB) has been hailed for many achievements. First, it was a triumphant agreement between theory and observation. Second, it was a key to understanding nucleosynthesis (the fusing of smaller elements in stars to produce larger nuclei). Third, it was the point at which cosmology became an authentic "science." Building off of Hubble's expanding universe and the 1950s work on nucleosynthesis, the detection of a background radiation permeating the universe is often cited as the clinching evidence for the Big Bang. Through decades of observation that agree with predicted values, the CMB is the most accurately measured and mapped stellar phenomenon known to scientists.

The importance of the CMB to scientists rests in their interpretation of what it means about the early universe. According to the Big Bang theory, a very hot soup of elementary particles flew apart at an astonishing rate and filled the universe. The universe cooled as it expanded, but for about 100,000 years it was so hot that photon radiation had a devastating effect on primordial matter. At temperatures hotter than 3,000 K, energized photons smashed apart all elementary hydrogen atoms into their charged particles of protons and electrons. After further expansion and cooling, photons no longer had the energy to break apart elemental atoms, and particles recombined to make the first hydrogen. The photon background radiation, now transparent to the electrically neutral atoms, "froze out" and has never since reacted with matter in the same way. What we call the CMB is the remnant of this relic radiation from about 100,000 years after the Big Bang. Looking at the CMB provides clues as to the composition of the early universe and how matter and radiation interacted at these fantastically high temperatures.

Despite all the attention given to the CMB, the history surrounding its early detection and later confirmation is generally distorted. Credit for its detection goes to two physicists from New Jersey's Bell Laboratories in 1963 – Arno Penzias and Robert Woodrow Wilson. The story of their work illustrates much about how science can be serendipitous and requires theory to inform both observations and conclusions.

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This last sentence is important for understanding how science works. Good science theories guide observation and makes sense of observations and conclusions. Science textbooks often wrongly portray observation as unbiased and neutral. That is not the case!


Arno Penzias and Robert Woodrow Wilson. *Photo by Ted Thai*

At the time, the two scientists couldn't make sense of the background 'noise' they kept picking up. They worked for nearly a year to identify the source of what they thought was irrelevant readings picked up by their instruments. They even scrubbed the inside of the antenna to remove pigeon waste. Insisting that something was wrong with their instrument, they never thought radiation from the Big Bang could explain the 'noise'. But the cosmologists with whom they communicated immediately recognized the 'noise' as something spectacular. At the time of the 'noise' detection, two ideas were being debated concerning the origin and state of the universe – the Big Bang and the Steady-State models. Fifteen years earlier, scientists working from the Big Bang theory had predicted the 'noise' that Wilson and Penzias had detected. Only upon learning this did the two understand that the source of their 'noise' was of great importance. The story of how Cosmic Microwave Background came to be recognized and accepted raises questions concerning how science works – what does it mean to "make a discovery," and what roles do theory, philosophy, technology, history, and interdisciplinary discussions play in making sense of data.

When Penzias and Wilson initially detected the radiation in 1963, they had just begun a survey of the Milky Way using a relatively new instrument called a radio telescope. Radio astronomy, particularly accurate radio astronomy, was a fairly new discipline, having become popular only in the previous decade or so. Radio telescopes use super-sensitive antennas and receivers, the later models looking like satellite dishes. In a very real sense, radio astronomers 'saw' by 'listening.' This permitted scientists to detect stellar phenomena that emitted energy at wavelengths other than the narrow visible region (which later included quasars and black holes) and penetrate the dust and gas that permeated interstellar space and obstructed views of the Milky Way. As physicists working in radio astronomy, Penzias and Wilson didn't expect to make any significant breakthroughs. Their intended task was to increase the accuracy of existing measurements of radio sources in the Milky Way. The signals they expected to find would be measurable with the same characteristics of visible light: intensity, frequency, and temperature. However, they detected a signal that was 3 degrees Kelvin 'warmer' than expected, no matter where they pointed their telescope.

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Technological advances often come from our growing understanding of the natural world. However, technologies also play an important role in furthering scientific work.

Here, it's important to note the disciplinary differences between astronomy and cosmology. While these terms are often used interchangeably, in practice they do not mean precisely the same discipline. Understanding this will help when thinking about why scientists like Penzias and Wilson didn't make connections between their data and theory. Astronomy is a discipline that deals with positions, velocities, temperatures, compositions, and makeup of stellar objects. Astronomy deals with phenomena like the temperature of the sun, the orbital period of Pluto, the number of stars in the Andromeda Galaxy, and the distance to the farthest quasars. Cosmology, on the other hand, is the study of the universe as a whole, from its size, shape, and density, to its evolution. The grandest examples of cosmology include the Big Bang and the Steady-State theories, which address the beginnings and ends of the cosmos. In the 1960s, cosmology classes simply didn't exist – those who published theories about the origins of the universe tended to be the most respected astronomers with well-established careers who could afford to make entirely theoretical statements concerning the universe. As well educated physicists, Penzias and Wilson both had sound astronomy backgrounds, but they would only learn cosmology from isolated lectures. Their observation of excess radio noise meant very little to them because the prior knowledge they did and did not bring to their observations. A scientist having knowledge of both astronomy and cosmology would be required to make sense of the 'noise'.

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Scientific knowledge is often seen as simply a product. But note how knowledge also affects the sense that scientists make out of data. Data doesn't tell scientists what to think! Data must be interpreted, and it is made sense of in light of previous knowledge. In that sense, knowledge is also a process.

The first prediction that linked background radiation with the origins of the universe came in 1948 with the work of Ralph Alpher and Robert Herman. At the time, Alpher was a doctoral student under the mentorship of George Gamow, an ardent proponent of the Big Bang. Following the publication of the famous Alpher-Bethe-Gamow paper on neutron capture in nucleosynthesis, Robert Herman teamed up with Alpher to continue the work. The Alpher-Bethe-Gamow paper claimed that elements could be built up via neutron capture. The authors admitted the limitations of the process, namely the famous 'mass gap' problem at masses 5 and 8, where no stable nuclei existed in which to add another nuclei. Another limitation, however, was the temperature required for these processes to go on. At the time, Gamow thought the Big Bang began 'hot,' meaning that the early universe existed in a dense, pressurized, and hot state. Gamow realized, however, that in the moments immediately following the Big Bang the temperatures would be too hot for matter creation. In other words, the universe needed to cool down a bit before protons and neutrons could even exist. This need for cooling led him to formulate two stages of the very early universe: one dominated by radiation that would cool to the next stage dominated by matter. Gamow tried in vain to figure out the importance of matter and radiation densities, but was ultimately stymied. He prepared an article with some ideas and sent it off to Nature in 1948 before going on vacation.

Checking the preprint, Alpher and Herman realized their mentor's paper was off-base. They wired him on vacation to relate the news, and Gamow encouraged them to send corrections via express mail. The two students went to work, and here's how they remembered it many years later (writing in the third person):

> It was in the course of these considerations that Alpher and Herman found it possible to integrate the full relativistic equations of the expansion, not only finding a correct crossover or decoupling time [when elementary particles could not 'couple' into atoms], but also realizing that they were in a position to examine the time dependence of all the relevant physical variables over the entire evolution of the universe. In particular they were able for the first time to predict the existence of a cosmic background blackbody radiation and to calculate its temperature and contribution to the density in the present universe. The calculation, based in a relatively simple way on the then-known values of the pertinent parameters, yielded a present cosmic background blackbody radiation at a temperature of ~5 K.

George Gamow

Notice how the passage said "blackbody radiation," a vital subject to understanding the CMB. A blackbody is a theoretical object that absorbs all incoming radiation and reflects none of it. A blackbody also emits radiation at all wavelengths. The shape and intensity of a blackbody spectrum is a function of temperature, so the temperature of a blackbody can be used as a shorthand describing the intensity of the radiation at all wavelengths. The peak wavelength is given by Wien's displacement law:

$$\lambda_{max} = b/T$$

where λ_{max}= peak wavelength, b = constant of proportionality (0.29 cm) and T = temperature. So a temperature of 5 K gives a peak wavelength of 0.06 cm, which lies in the microwave spectrum. This would be the best place to "hunt" for the CMB since it would be the brightest at these wavelengths.

The blackbody radiation discussed by Alpher and Herman was theorized as a result of the Big Bang. The radiation that had fueled nucleosynthesis had ever since been cooling and, they predicted, should still be permeating the universe with a spectrum identical to a very cool 5 K blackbody. However, many scientists wrote off their words as just another estimate of the temperature of interstellar space and not the temperature of the then theoretical CMB.

Gamow's group also knew that 1950s technology wasn't capable of measuring the microwave realm very precisely, so they never engaged in a full campaign to experimentally verify their prediction, nor did they try to make their message available and comprehensible to working astronomers. Instead of publishing their results in an astronomical journal, they published in a physics journal, the *Physical Review*. To make matters worse, they couldn't nail down a precise temperature for the CMB. In 1948 they began at 5 K. The next year they used a new estimate of matter density to arrive at an estimate of 28 K. In his 1952 book *The Creation of the Universe*, Gamow mentioned that the background radiation should be 50 K! Such confusion made many physicists and astronomers reluctant to indulge their predictions.

In 1963, Penzias and Wilson began their project at Bell Labs in Murray Hill, NJ. Using hand-me-down parts, they built a radio receiver that they planned to slowly upgrade as they collected basic data about the Milky Way. The configuration they ended up using picked up signals from the microwave spectrum, a region of light that hadn't been thoroughly investigated at the time. As they pointed the antenna at their first objects, they picked up a signal 3 K warmer than expected, and most mysteriously, it came from everywhere. Thinking something must be wrong with their second-hand equipment, they gave it a complete overhaul. They determined that a pair of pigeons had taken to roosting in their antenna, covering the receiver in bird droppings, but cleaning the antenna had no effect on the noise. Being physicists, they weren't familiar with cosmology and did not think to employ the Big Bang theory as an explanation – here's what Robert Wilson had to say about it:

> In fact, I do not think that either of us took the cosmology very seriously at first. We had been used to the idea of steady-state cosmology; I had come from Caltech and had been there during many of Fred Hoyle's visits. Philosophically, I liked the steady-state cosmology [which needed no Big Bang and therefore no background radiation]. So I thought that we should report our result as a simple measurement; the measurement might be true after the cosmology was no longer true!

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Wilson's private thoughts concerning his support for the Steady-State model influenced the way he interpreted the 'noise' he and Penzias had detected. Thus he decided to simply publish the results as observed measurements and nothing more. Notice the difference between the private ideas a scientist has and those they decide to make public.

1. Note how Wilson and Penzias were not cosmological theoreticians – they were not concerned with ideas such as the Big Bang and the Steady-State models. Conversely, Alpher, Herman, and Gamow were very much working on theoretical understandings of the universe. Both groups were missing important pieces of their respective puzzles. Wilson and Penzias were missing a theoretical framework to interpret their data. Gamow and company were missing an observable test. How does this illustrate the close relationship between theory and making sense of data?

Meanwhile, about 40 miles away in Princeton, New Jersey, the physicist Robert Dicke had been working on a very different view of the Big Bang that answered Penzias and Wilson's mystery. Dicke made his career by trying to meld Quantum Mechanics and General Relativity, resulting in a radical redefinition of gravity made with one of his graduate students called the Brans-Dicke Theory of Gravity.

In 1963, Dicke had been contemplating the possibility of an oscillating universe. This possibility, which has since been prominently advocated by the eminent astrophysicist John Wheeler, entertained the idea that the universe undergoes cycles of expansion and contraction. Dicke didn't want to talk about original creation – he left the origins of the universe to an incidental quantum fluctuation that expanded and quickly contracted. At this point of collapse, a critical density would be reached, and a new Big Bang would occur, and everything would start over again. The only thing that would survive the big crunch would be radiation, which would sort of 'plant the seeds' for the hydrogen in the next expansion. With each 'bang-crunch' cycle the universe got bigger and contained more mass. The radiation surviving the bang was essentially Dicke's version of the CMB.

He gave the job of calculating the temperature of this radiation to his graduate student James Peebles, who estimated it to be about 10 K. They sent a paper off to the *Astrophysical Journal*. Imagine their surprise when it was rejected on account that a paper had already been written on the subject by Alpher, Herman, and Gamow! Neither Dicke nor Peebles had any idea such a paper had been written. They had already enlisted their colleagues Peter Roll and David Wilkinson to find a way to look for this radiation. Fortunately, the data they needed was located just upstate.

Peebles had been giving lectures based on his predictions, and word got out that he was looking for data on background radiation. A Princeton colleague had heard of Penzias and Wilson's mystery noise, and connected the two groups in March 1965. Penzias and Wilson were relieved to be in touch with people who finally understood cosmology and what their data might represent. After reading Gamow's paper and noting the lack of emphasis on the significance of his calculations, Peebles made sure to emphasize that the New Jersey scientists had detected evidence for a relic blackbody radiation in agreement with the Big Bang theory, not the temperature of interstellar space.

In June 1965, the two groups published companion papers in the *Astrophysical Journal*. Penzias and Wilson reported their measurement of a temperature of about 3.5 K at the 7.3cm wavelength. Dicke and Peebles followed, addressing the implications of this temperature for the Big Bang theory. Despite having read Alpher, Herman, and Gamow's work, the authors of the two 1965 papers remained confused about the importance of the 1948 predictions. The New Jersey scientists mentioned the Alpher-Bethe-Gamow paper and another paper written in 1953 by Alpher, Herman, and their colleague James Follin, but neither of these references said anything about background radiation.

Gamow was understandably angry at the omission. When the New Jersey scientists wrote him an apology, Gamow replied by summarizing his existing work in the field, and finished, “Thus, you see the world did not start with the almighty Dicke”. Gamow, Alpher, and Herman got together to write a review of their work, but acknowledgement of their role in the recognition of the CMB was slow in coming. In a 1990 symposium on the history of cosmology, Alpher and Herman wrote:

> Nevertheless, accounts continue to appear, both in the archival literature and in popularizations, that deal incorrectly with the early work by us and by Gamow. Too many authors evidently rely on more recent publications, many of which continue to propagate errors, rather than consulting original source material… We do not accept the argument of some that correct attribution does not matter, but that only the furtherance of science matters. This view does not reflect the ideals and realities of the scientific enterprise. A correct history of science as a human endeavor does matter, both for the present and for the future.

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Notice the sense of frustration that Alpher, Herman, and Gamow demonstrate because their work was not correctly recognized as the seminal work in CMB. While scientists work to better understand the natural world, they are not unlike the rest of us. Science is done by human beings who are also often driven by and express intense emotions.

2. Each group of scientists seems to have thought they were working on isolated problems, yet if they had read different publications or mingled with different groups, they may have collaborated and perhaps solved their problems more quickly. Based on this story, what role does communication play in the scientific enterprise?

To this day, recognition for the discovery of the CMB has been controversial. Nobel Prizes were awarded only to Penzias and Wilson. For certain, Alpher, Herman, and Gamow had been snubbed for their role in predicting the discovery of the CMB. However, they did a very poor job in making their work understandable and available to those that most needed it. Dicke and Peebles, despite independently predicting and recognizing the CMB, also never received a Nobel Prize.

3. Use examples from this story to show that science is not a matter of simple "discovery."

After the recognition of the CMB, many scientists were quick to jump aboard and announce the Big Bang triumphant and the Steady-State dead. Wilson remained calm though, concerned that, just maybe, the detection could mean something else entirely. As he wrote in 1982:

> Some of the steady-state people were pleased by the way we had gone about things. We felt that, at least until they had had a chance to think about our results, we shouldn't go out on a theoretical limb that we couldn't support. For me, the last nail in the coffin of the steady-state theory wasn't driven in for quite a while – not until the blackbody curve was really verified. That's the point when I stopped worrying about it.

For the rest of the scientific world, though, the CMB became the hot topic of study. The 'discovery' thrust the Big Bang to the forefront of cosmological theories. Most remarkably, the radiation was almost perfectly even in all directions, or isotropic. Study of the degree of isotropy in the CMB jumpstarted the careers of many famous scientists, including Stephen Hawking. Members of the original detection team continued to work on the topic throughout their lives. Take for example the Wilkinson Microwave Anisotropy Probe (WMAP) project, named after the Princeton physicist David Wilkinson, enlisted by Robert Dicke to find the background radiation. These and many other satellite projects are directed at furthering our understanding of the CMB.

The history of the CMB's detection and significance, however, has only been cleared up in the past decade or so, and the valuable lessons tend to be glossed over. For instance, what would have happened if Alpher and Herman had made it entirely clear that they were looking for something different than the temperature of interstellar space? What if they had published their articles in the *Astrophysical Review* instead of the *Physical Review*? What would have happened if Penzias and Wilson had attended a few of Gamow's Big Bang lectures in addition to Hoyle's Steady-State lectures? These 'what-if' questions throughout scientific work illustrate the unpredictable, dynamic and human-negotiated aspects of the scientific endeavor.

4. The detection of CMB is often touted as the turning point in the debate between the Big Bang and the Steady-State theories. Yet, even after the CMB had been confirmed, the matter was not considered settled for several decades – after additional significant work had been done supporting the Big Bang. Why do you think acceptance of one scientific idea over another often takes so much time?

Data Makes Sense Only in Light of Theory: The Story of Cosmic Microwave Background written by Blair Williams, Jerrid W. Kruse, Michael P. Clough, Matthew Stanley, & Charles Kerton

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