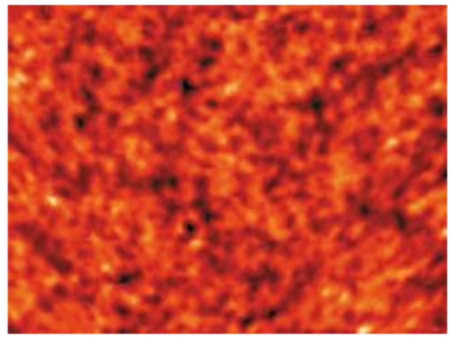
Case Study: The Cosmic Microwave Background Radiation

Part of the Cosmic Horizons Curriculum Collection.



The cosmic microwave background radiation is the faint remnant glow of the big bang. This false color image, covering about 2.5 percent of the sky, shows fluctuations in the ionized gas that later condensed to make superclusters of galaxies. Photo courtesy of the BOOMERANG Project.

In 1929, Edwin Hubble showed that the light from distant galaxies is shifted to longer wavelengths in proportion to their distances from the Milky Way.

The modern interpretation is that space itself is expanding, carrying the galaxies along for the ride. In 1931, Georges Lemaître imagined running such an expansion backwards in time. At some remote point in the past, he reasoned, everything in the universe would have been packed together at enormous density. Lemaître suggested that all the matter and energy in the observable universe originated in an explosion of space, now called the Big Bang, which launched the expansion that continues to this day.

In 1948, Hermann Bondi, Thomas Gold, and Fred Hoyle published an alternative cosmological theory, which accounted for the observed expansion without invoking a beginning in time. They proposed that matter is continually created, to form new galaxies, so that the expanding universe maintains the same average density and appearance through infinite time. In this "steady state" theory, matter is created continuously. In the Big Bang theory, all the matter in the universe is created at once, at a definite point in the past.

In the same year, the physicists George Gamow, Ralph Alpher, and Robert Herman developed a detailed theoretical picture of the Big Bang. They realized that the universe immediately after the explosion would have been not only extremely dense but also extremely hot. At such high temperatures most of the contents of the universe would be in the form of intense light (radiation) rather than in the form of matter. This early period is now called the radiation era.
As the universe expanded, the total amount of light and matter had to fill a continually increasing volume of space, so the density of each had to decrease. But the expansion of space also stretched out the waves of the light traveling through it. And the longer the wavelength of light, the lower its energy. So the expansion of space caused the energy density of light to decrease even faster than the density of matter. Consequently, most of the energy of the universe was soon in the form of matter instead of radiation, and today we live in a matter-dominated universe.

The three scientists recognized that the radiant energy of the Big Bang must still exist in the universe today, although greatly reduced in intensity by the expansion of space. Alpher and Herman went on to calculate the present temperature corresponding to this energy. The answer they got was 5 K, which means 5 degrees above absolute zero on the Kelvin scale. (At absolute zero, the lowest possible temperature, molecular motion and thermal radiation come to a complete stop.) Radiant energy at a temperature of 5 K is mostly in the frequency band of microwaves.

Alpher and Herman in effect predicted that the universe today should be awash in a faint but uniform bath of microwave energy coming from every direction—the remnant glow from the Big Bang. But they made no attempt to search for it. As theoretical physicists, not observational astronomers, they perhaps assumed that the technology required for such an observation did not yet exist. Furthermore, radio astronomy was in its infancy in those days, and the handful of radio astronomers who might have known how to use the available technology to search for the microwave background radiation were unaware of the published theoretical prediction. So for several years the debate between the steady state and Big Bang theories continued, in the absence of any strong observational evidence in favor of one over the other.

In 1964, Arno A. Penzias and Robert W. Wilson at the Bell Telephone Laboratories in New Jersey began investigating the microwave radio emissions from the Milky Way and other natural sources. They had a very sensitive detector connected to a large horn-shaped antenna, previously used for satellite communication. When the two scientists tuned their equipment to the microwave portion of the spectrum, they discovered an annoying background static that wouldn't go away. No matter where they pointed the antenna, or when, the microwave static was the same. They spent months running down every possible cause for the static, including pigeon droppings inside the antenna, but they couldn't find a source or a solution.

At about the same time, Princeton physicist Robert H. Dicke had come to his own conclusion that residual radiation from the Big Bang must still be present in the universe. He did not know about the previously published work by Gamow, Alpher, and Herman. So Dicke independently calculated that the lingering radiation should have a temperature of about 10 K. He realized that it should be observable in the microwave portion of the spectrum. His research team was in the process of building an antenna to search for it when he learned that Penzias and Wilson had discovered a persistent microwave background noise. Dicke turned to his colleagues and said simply, "They've got it."

Penzias and Wilson had stumbled on the first observational evidence to support the Big Bang theory of the origin of the universe. For this discovery they shared the Nobel Prize for Physics in 1978. Subsequent observations of the microwave background at different wavelengths have refined the value of the radiation temperature of the universe to 2.73 K. This is about half the value calculated by Alpher and Herman in 1948, but their result is widely regarded as a successful prediction in view of the approximations required by the calculation. The discovery of the cosmic microwave background radiation led most astronomers to accept the Big Bang theory.

The few who dissent from Big Bang theory include, among others, the authors of the original steady state theory. They suggest that ordinary starlight, not the Big Bang, produced the microwave background radiation. If this were true, there would have to be a mechanism, as yet unverified, to convert the visible starlight into the observed microwave spectrum. The dissenters continue to investigate such possibilities.

GUIDED QUESTIONS:

1. How did Georges Lemaître and the concept of the Big Bang differ from the steady state theory proposed by Bondi, Gold, and Hoyle?
2. Explain the significance of the "radiation era" in the early universe and how it transitioned to a matter-dominated universe (this has already been discussed in the intro lessons).
3. Describe how Penzias and Wilson discovered the cosmic microwave background radiation and the significance of their findings.
4. How did the discovery of cosmic microwave background radiation impact the acceptance of the Big Bang theory among astronomers?
5. Compare and contrast the Big Bang theory and the steady state theory. What evidence supports the Big Bang theory over the steady state theory?
6. Consider the role of technology in scientific discoveries. How might advancements in technology have influenced the discovery of cosmic microwave background radiation?