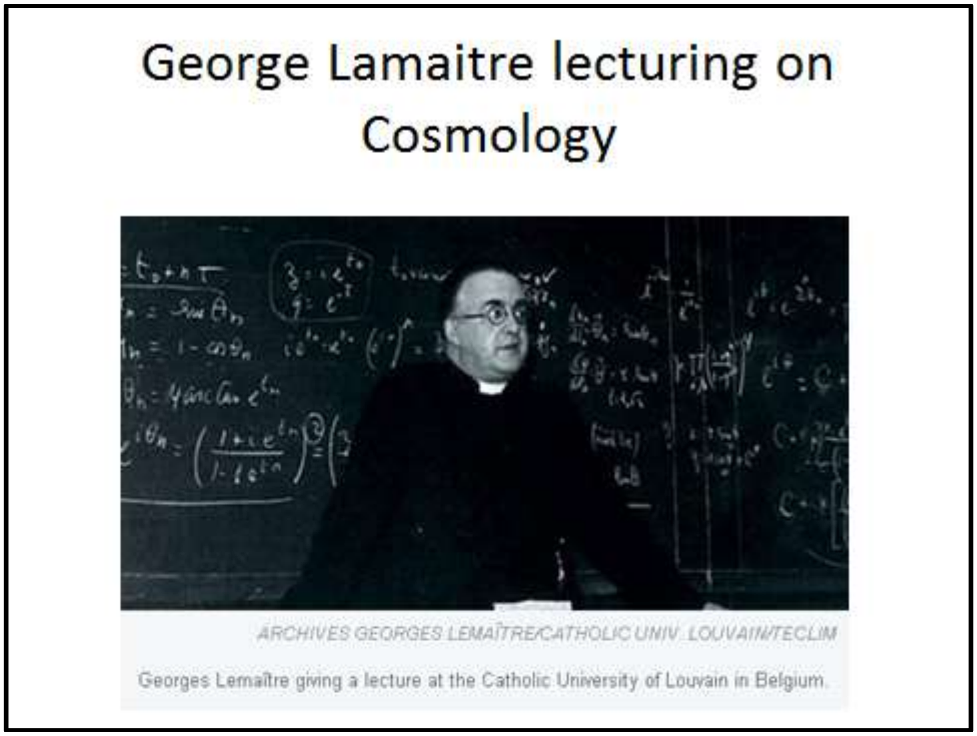
The Big Bang Theory of the Early Universe

Today astronomers agree that Hubble's Law is an observational fact and is beyond dispute – anyone who doubts it can duplicate the measurements for him or herself and will obtain the same results as Hubble did. The idea of expanding space, however, is not a fact. Rather, expanding space is the theoretical explanation of a fact, and as a theory, it is possible for it to be scientifically doubted. Perhaps there is an alternative, completely different explanation for Hubble's Law.

The ability to explain known facts is an important criterion that a theory must pass in order to be accepted among scientists. But there is an even more important criterion – the ability to predict facts that are not known at the present time. If these predictions turn out to be accurate, the theory still is not categorically proven true, since it is always possible that a later prediction of the theory will fail. However, with each new successful prediction made by a theory, scientific confidence in the theory is strengthened. The concept of expanding space has made many such successful predictions, and as a result, it is tentatively accepted, by the majority of scientists, to be true. And because it is such an integral part of any explanation of the nature of the universe, we can assume, for the purposes of discussion in later readings, that it is true.

Georges Lemaitre

If the universe is expanding, the question arises as to what the universe was like in the past. The first person to address this question seriously was the Belgian cosmologist-theologian Georges Lemaitre. In 1927 Lemaitre showed that Einstein's attempt to eliminate the prediction of an expanding or contracting space from his general theory of relativity did not work. Lemaitre's paper received little attention; discouraged, he turned his research in other directions. However, with the arrival of Eddington's explanation of Hubble's Law, Lemaitre returned to cosmology in the 1930s.



Georges Lemaître giving a lecture at the Catholic University of Louvain in Belgium.

Lemaitre reasoned that if space is expanding, then the universe must have been denser in the past than it is now. Using the physics of the general theory of relativity, he realized that there would have been a time in the finite past when the universe would have been infinitely dense – and, therefore, that our universe must have had a beginning in time. This was contrary to the prevailing opinion among Lemaitre's contemporaries.

Most scientists at the time assumed that the universe was infinitely old; that it had always existed and always would exist. Although Lemaitre's model represented a significant philosophical and cosmological breakthrough, it was inadequate in terms of physics. There was little that could be done with the model to see if it could, in fact, evolve into the present universe – that would have required a knowledge of nuclear physics that did not exist at the time. There was another reason why scientists were skeptical of Lemaitre's idea of a universe that had a beginning in time. He was a Catholic priest, and thus possibly predisposed to believing that the universe had been created in the finite past. When science is used to predict something that the predicting scientist probably already believes to be true, fellow scientists and students of science should be skeptical.

George Gamow and the Big Bang

George Gamow was born in Odessa, Russia, in 1904. He received his doctorate in physics from the University of Leningrad in 1928 and in 1931 accepted a professorship there. This was a time of increasing oppression in the Soviet Union, and Gamow and his wife made several unsuccessful attempts to defect. After years of refusing to give them permission to leave, the government of the U.S.S.R. unexpectedly allowed them to attend the 1933 Solvay Congress in Belgium. The couple used this opportunity to defect from the Soviet Union, and Gamow spent the rest of that year at various scientific institutions in Europe. He was appointed professor of physics at George Washington University in Washington, D.C., in 1934.

Gamow's first major contribution to physics was to explain the nature of alpha decay using the new theory of quantum mechanics. By 1942 he had turned his attention to astrophysics, developing a theory of the internal structures of red giant stars. He became interested in Lemaitre’s ideas concerning the early universe, and as early as 1946 Gamow began to believe that the high temperatures of the early universe could provide the appropriate conditions for the creation of the chemical elements in their proper ratios. Since the time Lemaitre had first addressed the problem, significant advances in nuclear physics had occurred. In 1948, Gamow and Ralph Alpher (Gamow’s doctoral student) developed a model of an early universe consisting of neutrons at a very high temperature.

When their work was published in 1948, the eminent astrophysicist Hans Bethe was surprised to find himself listed as a co-author. Although Bethe had nothing to do with the work, Gamow – a practical joker – thought it would be funny to have an important paper authored by Alpher, Bethe, and Gamow, a pun on the first three letters of the Greek alphabet: *alpha*, *beta*, and *gamma*. To Gamow’s delight, the paper appeared in the April 1, 1948, issue of *The Physical Review*.

George Gamow

Gamow with Wolfgang Pauli

1948 - Gamow used new knowledge of nuclear physics along with the GTR to describe the early universe.

He assumed (like LeMaitre) that the early universe was much hotter and denser than it is today and that the expansion of space cooled it and allowed structures to form.

He intended to show how the hot, dense conditions of the early universe could produce all the chemical elements present in the universe today.

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This theory (and its subsequent versions) is now known as the Big Bang theory. Ironically, the name was coined by Fred Hoyle in a BBC radio interview in 1949. Hoyle was co-author of an alternative cosmological theory known as the Steady State theory and was a strong critic of Gamow's theory. It is commonly reported that Hoyle intended the term *Big Bang* to be pejorative, but Hoyle explicitly denied that this was the case. He said the term was just a striking image meant to emphasize for radio listeners the difference between his and Gamow's theories.

Indeed, the Big Bang is an unfortunate term for the theory because it may be interpreted incorrectly. It suggests the occurrence of an explosion; that is, matter flying out in all directions from a central point into previously unoccupied space. In reality, the Big Bang was not an explosion of matter; if anything, it was an explosion of space. Matter has filled all of space more or less uniformly since the beginning of time.

In 1953, the Big Bang model was modified by Gamow so that it began with matter in the form of protons, neutrons, and electrons. The revised theory assumed that the early universe was extremely hot and dense, and that the temperature was continuously decreasing due to the expansion of space. These assumptions led to two unavoidable predictions. The first prediction was that the early universe essentially contained only the elements hydrogen and helium. Gamow proposed that through a series of nuclear reactions, the protons and neutrons of this matter fused to form nuclei, a process called *nucleosynthesis*. Gamow's revised model readily explained the high percentages of hydrogen and helium present in the universe, but it completely failed to account properly for the heavier elements that are present. No matter how many times Gamow recalculated his model, nucleosynthesis was shown to essentially stop after the creation of helium. This observation was considered at the time to be a fatal flaw in Gamow's theory. This was a disappointment to Gamow. His motivation for beginning the calculations was to show that the relative abundances of chemical elements present in the universe now could be explained by the hot, dense conditions of the early universe. Also, if the heavier elements were not produced in the early universe neither he, nor anyone else at the time, knew where they could have come from.

Gamow also predicted that the universe should be filled with electromagnetic radiation left over from the events of the early universe, but which would have cooled significantly due to the subsequent expansion of space. Shortly after the 1948 paper, Ralph Alpher and Robert Herman calculated the present temperature of the radiation at to be about 5 K (5 degrees above absolute zero on the Kelvin temperature scale), but at the time this was an untestable prediction. For this and other reasons, the work of Gamow and his students Alpher and Herman was not taken very seriously.

Predictions of the Big Bang model

- The early universe contained only hydrogen and helium. Because of the expansion of space and its cooling effect, nucleosynthesis only occurred between 3 to 4 minutes after the big bang (A.B.B.) and essentially stopped after helium.
- The universe is filled with a background radiation whose temperature is a few degrees above absolute zero. When neutral atoms formed (about 370,000 yrs A.B.B.), the electromagnetic radiation essentially stopped interacting with matter. The expansion of space cooled the radiation from its initial value of about 3000 K to its present low value.

It is important to note that the Big Bang theory is not a theory of the origin of the universe, as it is often described. Neither when it was first proposed nor now does the theory say anything about the universe's origin. The earliest temperatures and densities are far too great to be described using our current understanding of physics. Rather, the Big Bang theory is a description of the very early universe.

Over the course of his scientific career, Gamow switched his interests from nuclear physics to astrophysics to cosmology. In the 1950s he turned his attention to the origin of life. He quickly recognized the significance of the DNA model proposed by Crick and Watson in 1953, and realized that the bases contained a code for amino acids. Gamow is best known to the public for his excellent books popularizing abstract physical theories, several of which are still in print.

The first step toward confirming Gamow's first prediction to arise from the Big Bang theory was solving the problem of the origins of the heavier elements. The solution came in 1957, ironically due in part to Fred Hoyle, the most prominent scientific opponent of the Big Bang theory. Hoyle and his colleagues were able to show that heavier elements could be produced later in the universe's evolution, within the interiors of massive stars. Since Hoyle's findings, observations of the oldest stars in our galaxy and of very distant galaxies early in their evolution have completely confirmed Gamow's prediction that the early universe was essentially pure hydrogen and helium.

The confirmation of Gamow's second prediction – the existence of what is now called the cosmic background radiation -- constitutes one of the most important discoveries in the history of science. The story starts in the early 1960s. Robert Dicke and his colleagues at Princeton University began to rethink the consequences of a Big Bang-like beginning to the universe. Working through the physics, Dicke, like Gamow before him, realized that the early universe had to be nearly pure hydrogen and helium.

This was no longer a problem as it was by then known that heavier elements are produced in stars.

Dicke also realized that if the universe had passed through a uniformly hot stage in its compressed past, then the present universe would necessarily be filled with electromagnetic radiation, cooled from its initial high temperature by the expansion of space – Gamow's second prediction. But when Gamow predicted it, radio technology was not sufficiently advanced to detect radiation associated with such a low background temperature. As a result, Gamow's original prediction was soon forgotten.

In 1975, Dicke wrote:

> There is one unfortunate and embarrassing aspect of our work on the fireball radiation. We failed to make an adequate literature search and missed the more important papers of Gamow, Alpher, and Herman. I must take the major blame for this, for the others in our group were too young to know these old papers. In ancient times I had heard Gamow talk at Princeton, but I had remembered his model universe as cold and initially filled only with neutrons.

The technological situation had improved by the time the Princeton group reached Gamow's earlier conclusion. It was now clear that such a background radiation should be observable, and the Princeton experimentalists, then unaware of the earlier prediction, immediately set about building an appropriate radio receiver. If something like the Big Bang had occurred, the background radiation must exist, and although it would not be an easy experiment, Dicke and his colleagues were confident they would be able to detect it.

The Princeton physicists were in a situation all scientists dream of. They were addressing a question of fundamental scientific importance. They would either discover the background radiation and provide extremely strong evidenced in favor of the Big Bang, or they would show that the background radiation did not exist and thereby disprove the Big Bang theory. In either case, a contribution to science worthy of its highest honor, the Nobel Prize, would result.

Arno Penzias and Robert Wilson

At the same time that the Princeton group was setting up their experiment to search for the background radiation, two radio astronomers were working on Bell Laboratories' horn-shaped radio telescope in nearby Homedale, New Jersey. The instrument was intended for use in trans-Atlantic telephone communication, and Arno Penzias and Robert Wilson were assigned to evaluate the performance of the telescope. In return for this rather mundane work, they would be allowed to use the telescope for their own scientific work.

Penzias and Wilson ran their tests at a wavelength of 7.35 centimeters, in the microwave region of the radio spectrum. They quickly found that no matter what direction in the sky the antenna was pointed, some signal was received. This was a totally unexpected result. Because there should be nothing in space producing radiation at this wavelength, Penzias and Wilson at first assumed that the signal was being generated within the instrument itself.

Although the level of the noise was not sufficient to significantly interfere with telephone conversations, Penzias and Wilson were conscientious scientists and wanted to understand where the noise was coming from. They carefully inspected the electronics, covered all the rivets in the telescope horn with aluminum tape, and even took the horn itself apart and removed the “white dielectric material” left behind by pigeons – but there was still far too much unaccounted-for background noise. Penzias and Wilson were completely stumped. They had eliminated every conceivable source of the radiation, and yet there it was, always present no matter where the antenna was pointed.

In 1965, a friend of Penzias, Bernard Burke of the Massachusetts Institute of Technology, told Penzias about a preprint paper he had seen by Jim Peebles, an experimental colleague of Robert Dicke’s at Princeton, on the possibility of finding radiation left over from the early universe. Penzias and Wilson began to realize the significance of their discovery and called Dicke. After Dicke hung up the phone, he reportedly said to his colleagues, “Well boys, we’ve been scooped.” Penzias and Wilson had unknowingly discovered Gamow’s predicted cosmic background radiation.

The two groups decided to publish their results jointly. Companion letters were rushed to *The Astrophysical Journal Letters*, with Penzias and Wilson announcing their observations and Dicke and his colleagues providing the cosmological interpretation. The Princeton group soon completed their measurements verifying the work of Penzias and Wilson. The detection of the cosmic background radiation is regarded as the second most significant (after Hubble’s Law) observation ever made concerning the nature of the universe. In 1978, Penzias and Wilson received the Nobel Prize for this discovery. Unfortunately, and many scientists think unfairly, Gamow was not included.

Arno Penzias and Robert Wilson

Early 1960s - Penzias and Wilson are hired by Bell Labs to evaluate the performance of the new radio telescope to be used in trans-Atlantic telephone communications.

They find a small, unexplained signal regardless of the direction the telescope is pointed. It is not enough to be a problem, but they are curious.

1964 - They become aware that the noise in their telescope is the cosmic background radiation predicted by the Big Bang theory.

Bell Labs’ radio telescope. Image Credit: AIP Niels Bohr Library