Chapter 4  The ‘big bang’

With the concept of an expanding universe supported by both theory and experiment, physicists began to speculate about its past. Georges Lemaître was the first to suggest that the present universe may have originated in a tiny, dense volume. George Gamow et al. applied principles of nuclear physics to this idea, leading to the hot ‘big bang’ model and two important predictions.

Following Hubble’s observations of the runaway galaxies, Lemaître’s prediction of an expanding universe from relativity became widely known. The concept of an evolving, expanding universe was gradually accepted amongst the physics community, marking a great paradigm shift in cosmology.

*Lemaître’s primeval atom*

In 1931, Lemaître took another giant step forward. Pointing out that something that is expanding now must have been smaller in the past, he suggested that the entire universe – space, time, energy and matter - was once constrained to a tiny volume, expanding from that compressed state ever since (one can see this by backtracking along the graphs of figure 5). Indeed, the relativistic models of Friedmann and Lemaître seem to imply a universe with an abrupt beginning.

What was the physical mechanism for this process? Lemaître suggested that the origin of the universe might be explicable in terms of the new quantum physics. Basing his ideas on what was known of radioactivity at the time, he conjectured that the universe originated as a gigantic *primeval atom*. Just as the atoms of some unstable elements decay into atoms of lighter elements by the process of radioactivity, perhaps the universe began as a giant atom that decayed by some as-yet unknown process into the matter and radiation we see today. Intriguingly, Lemaître suggested that the newly discovered cosmic rays might constitute evidence for this primordial
The age of the universe

One exciting implication of Lemaître’s idea of a finite beginning was that one could immediately estimate the age of the universe. If the runaway galaxies represented the expansion of the universe, then the slope of the Hubble graph (or Hubble constant) would give an estimate of timespan of the expansion. Unfortunately, estimates of the age of the universe obtained in this manner suggested a value of about 2 billion years! This value was a major problem as it was less than the estimated age of many stars (calculated from astrophysics) and indeed the age of the earth (calculated from radioactivity). The ‘age paradox’ was to dog cosmology for decades – it was later discovered that the problem lay in Hubble’s estimation of the distance to the galaxies.

With his background in astronomy, Lemaître was keenly aware of the age problem. His solution was to propose that the universe had not always expanded at the same rate. Instead, he proposed a model in which the universe undergoes an initial rapid expansion, followed by a slower period, followed by another accelerated expansion. To this end, he re-instated Einstein’s cosmological constant in the equations of relativity, interpreting it as an energy of the vacuum. As we shall see, this model of the expanding universe is in some ways remarkably similar to today’s models.

Reception

Lemaître’s ‘primeval atom’ was the first draft of what later became known as the ‘big bang’ model of the origin of the universe. However, few physicists took his hypothesis seriously. One

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1 Since velocity is distance travelled per unit time, it follows that a graph of velocity versus distance has a slope that is the inverse of the time elapsed i.e. \( t = 1 / H_0 \)
reason was that the only concrete prediction made – the age of the universe – was greatly in doubt. Another was that developments in nuclear physics soon showed that the physical process envisioned, a huge, super-radioactive atom, could not be correct.

A third reason may have been that few physicists were comfortable discussing an origin for the universe – it seemed more like philosophy than physics. It didn’t help that Lemaître was a priest; he was suspected of being biased towards a creation-type model of the universe. This accusation was rather unfair, as Lemaître was careful to distinguish between the idea of a beginning for the universe as predicted by science, and the concept of creation. A brilliant scientist with impressive credentials in mathematics and astronomy, he strove throughout his career to keep his science untainted by ideology. He was not at all a fundamentalist, and had little time for literal interpretations of the bible. Indeed, he once reprimanded the Pope for claiming that the big bang model was evidence of creation.2

Another problem concerned the theory of relativity itself. Studying the models of Friedmann and Lemaître in detail, physicists noted that relativity in fact predicts a universe that begins in what is called a singularity. Winding the clock back towards the origin (figure 5), one approaches a point of zero volume and infinite density. Mathematicians are used to the concept of singularities, but physicists consider them a poor description of the real world. How could our universe have begun in such a strange state? Some suggested that this problem implied that general relativity was not the correct framework for models of the universe. This avenue was explored by physicists such as Edward Milne and William McCrea. Another possibility was that the problem lay in the marriage of relativity with the new quantum physics. By the 1930s, it had become clear that processes on the atomic scale are indeed described by the strange laws of quantum physics, a micro-world in which the rules are very different from those of the macro-

2 See (Farrell 2005) chapter 6.
world of ordinary physics. If the universe really began in a state of atomic dimensions, an analysis of its origins would have to wait until a clearer picture of the quantum world emerged.\(^3\)

![Einstein and Lemaître in discussion in Pasadena in 1933](image)

**The universe according to George Gamow**

One physicist who took Lemaître’s model seriously was the maverick Russian theorist George Gamow. Gamow spent his formative years at the University of Leningrad (formerly St Petersburg) in the 1920s, as a member of a small group of brilliant young minds that were quickly absorbing the new ideas emerging in quantum physics. He attended Friedmann’s courses in relativistic cosmology as a student, but his research interests focused on applications of the new quantum theory to nuclear physics. After Leningrad, Gamow spent time at the major centres of quantum physics in Gottingen, Copenhagen and Cambridge. He scored his first major success by showing that quantum physics provides a successful explanation for alpha decay in radioactivity.

In 1933, Gamow defected to the West, taking up a position at George Washington University in the United States. There, he became interested in applying quantum theory to the

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\(^3\) This problem remains to this day, as we will see in chapter 8.
phenomenon of *nucleo-synthesis*, the formation of the chemical elements. It was widely believed at the time that all the chemical elements of the Periodic Table are formed by nuclear fusion processes in the interior of stars, and Gamow joined the attempt to see whether the quantum view of nuclear reactions could give a quantitative description of this process. By the early 1940s, a major problem had emerged – the theory simply could not explain the abundance of the two lightest elements, hydrogen and helium. This was a serious setback as these elements are by far the most abundant in the universe.

At this point, Gamow’s training in relativity came to the fore. According to the relativistic models of Friedmann and Lemaître, the universe was once confined to a tiny volume of space and thus would have been extremely dense and extremely hot. *Was it possible that the chemical elements were formed, not in the hot interior of stars, but in the furnace of the infant universe?* Gamow set his PhD student, Ralph Alpher, the problem of constructing a mathematical model that could depict the creation of the chemical elements under such conditions. In 1948, they published a landmark paper in which the early universe was described as an extremely hot, highly compressed gas of subatomic particles that subsequently decays into protons and electrons, leading to the formation of the chemical elements. (Alpher named this gas the *ylem*, a word used in ancient cultures for a primordial substance from which the world is made). Over the next few years, the model was refined with the help of Robert Herman, a colleague at the John Hopkins laboratory. In particular, the group hit on the key idea that the early universe was dominated not by matter, but by radiation. In 1953, Gamow *et al.* published their definitive model, a theory of nucleo-synthesis in the early universe that predicted that today’s universe should be almost entirely made of Hydrogen (75%) and Helium (25%), a

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4 See (Gamow et al 1953).
prediction that was in excellent agreement with astronomical observation!

This was a spectacular advance. The Gamow group had shown that the puzzling abundance of the lightest elements could be explained in the context a hot, dense epoch in the early universe. Their theory offered a second line of evidence for a universe with a cataclysmic beginning and became known as the ‘hot big bang’ model. (However, it should be noted that the model could not describe the synthesis of the heavier elements; today, it is thought that the lightest elements were formed in the infant universe, while the heavier elements are formed in the stars). Nevertheless, Gamow’s group had made a vital leap forward - best of all, their model contained the seeds of a third line of enquiry.

Figure 6. Alpher (L) and Herman (R), with Gamow emerging from a bottle containing the primordial material ‘ylem’.

A cosmic fossil

In 1948, Alpher and Herman noted a startling prediction of their ‘hot big bang’ model. If the universe began with a hot, radiation-dominated early epoch, might some of that radiation not be present today? Analyzing the behavior of the primordial radiation as the universe expands and cools over time, they calculated that some remnants might indeed still be observable. (The reason
is simple: when the expanding universe reaches a point that it is cool enough for stable atoms to form, the scattering of radiation by individual particles is greatly reduced. From this point onwards, the radiation travels unimpeded i.e. the universe becomes transparent. Hence radiation released at the time of the formation of atoms should still be detectable today. Of course, any such radiation would be enormously cooled and red-shifted by the expansion of the universe ever since (the first atoms were formed when the universe was about one hundred thousand years old). From their analysis,⁵ Alpher and Herman made a quantitative prediction: our universe should exhibit a ubiquitous, background radiation of cosmic origin, of extremely long wavelength and low temperature (about 3 degrees Kelvin above absolute zero). As we shall see, just such radiation was discovered almost twenty years later, offering a third plank of support for the hot big bang model.

**On the philosophy of science**

Lemaître’s explanation of the phenomenon of the runaway galaxies in terms of an expanding universe was a great advance, but his hypothesis of a ‘primeval atom’ was not well received. In the late 1940s, Gamow et al. showed that a hot, dense epoch in the early universe could give a satisfactory explanation for the abundance of the lightest elements, and predicted that our universe might exhibit a ubiquitous background radiation dating from its early years. This was a significant advance and one might have expected a great upsurge of interest in ‘big bang’ cosmology during the 1950s; in fact, the field remained a topic of minor interest.

It is not entirely clear why this occurred, but it is probably linked to a decline of interest in general relativity. In the years 1930 to 1955, there was a remarkable decrease in research in this field. Many reasons for this phenomenon have been offered, from the difficulty in making

⁵ See (Alpher and Herman 1948).
connection to experiments to the impact of anti-relativity sentiments in both Nazi Germany (in the 1930s) and Stalinist Russia (in the 1940s and 1950s). Even in the United States, courses in general relativity were mainly confined to mathematics departments during this period. Another factor may have been the exciting progress being made in other fields, in particular the spectacular successes in both nuclear and particle physics. By comparison, most physicists were not terribly interested in the concept of an origin for the universe; it was still seen more as metaphysics than physics.

A sociological factor may have been the community’s perception of the group’s leader. Despite his great successes, Gamow had an unenviable reputation as a joker, a drinker and a physicist of unlimited imagination but limited mathematical ability. Worst of all, he was an émigré Russian in 1950s America (Alpher and Herman were also of Russian heritage).

As regards the relativists themselves, even Einstein did not seem greatly interested in the new model of the cosmos. From this time onwards, Einstein’s interest in what relativity (and indeed quantum theory) had to say about the universe became totally eclipsed by his work in unified field theory.\(^6\) Similarly, Lemaître took no interest in the Gamow model, much to the surprise of his colleagues. A likely factor here is that Lemaître knew nothing of nuclear physics and had very little interest in the subject. This is also true of Einstein, so perhaps this story is one of a reluctance of the relativists to stray into territory they had no expertise in.

Whatever the reasons, there is no doubt that the work of Gamow, Alpher and Herman was effectively ignored by the mainstream physics community for decades. Even after the discovery of the cosmic background radiation (chapter 5), it was many years before the group was given due credit. Today, the members of the group are greatly admired for their pioneering

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\(^6\) Unified field theory is the attempt to describe the four fundamental forces of nature in a single, unified framework.
contribution. By applying principles of nuclear physics to Lemaître’s analysis, they moved from
the model of a ‘primeval atom’ to a ‘hot big bang’. The latter model described not only the
expansion of the universe, but made two important predictions; the abundance of the lightest
chemical elements and the presence of a cosmic microwave background.