‘The Wildest Speculation of All’: Lemaître and the Primeval-Atom Universe

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Abstract Although there is no logical connection between the expanding universe and the idea of a big bang, from a historical perspective the two concepts were intimately connected. Four years after his pioneering work on the expanding universe, Lemaître suggested that the entire universe had originated in a kind of explosive act from what he called a primeval atom and which he likened to a huge atomic nucleus. His theory of 1931 was the first realistic finite-age model based upon relativistic cosmology, but it presupposed a material proto-universe and thus avoided an initial singularity. What were the sources of Lemaître’s daring proposal? Well aware that his new cosmological model needed to have testable consequences, he argued that the cosmic rays were fossils of the original radioactive explosion. However, this hypothesis turned out to be untenable. The first big-bang model ever was received with a mixture of indifference and hostility. Why? The answer is not that contemporary cosmologists failed to recognize Lemaître’s genius, but rather that his model was scientifically unconvincing. Although Lemaître was indeed the father of big-bang cosmology, his brilliant idea was only turned into a viable cosmological theory by later physicists.

About 80 years ago, in a little known letter to *Nature*, Georges Lemaître introduced the audacious hypothesis that the entire universe had come into being a finite time ago in a cataclysmic explosion of what he picturesquely called a ‘primeval atom.’ Today his idea is widely recognized as the conceptual beginning of what much later became known as the big-bang theory of the universe. Although Lemaître’s version of the explosive universe differed in important respects from the modern one, there are enough similarities to justify the claim that the conceptual foundation of relativistic big-bang cosmology goes back to the spring of 1931. Yet, to appreciate the true nature of his seminal contributions to physical cosmology it is important

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not to read history backwards and judge them by the standards of modern theory. One needs to understand them within the context of Lemaître's own time, which primarily means the decade 1925–1935. For example, it is only by adopting a contemporaneous perspective that one can understand why his theory, today hailed as a revolution in cosmological thought, only had a very limited impact on the further development of the science of the universe. This lack of appreciation was basically justified, simply because Lemaître's theory was not scientifically convincing in its original formulation.

While there are good historical reasons to celebrate Lemaître as the founding father of what eventually became the big-bang standard cosmology, this does not imply that our present conception of the universe can be traced back to his work in some direct way. Far from, for there is little continuity in the historical development of cosmology between the emergence of the primeval atom in 1931 and the reborn big-bang theory of the 1960s. If Lemaître's cosmological hypothesis merits historical attention it is not because it was the seed from which our modern view of the universe grew, but because it was a remarkable and interesting theory in own right and at its own time.

The Expanding Universe

'I found M. Lemaître a very brilliant student, wonderfully quick and clear-sighted, and of great mathematical ability' (Douglas 1956, p. 111). Thus wrote Arthur Eddington in a letter of 24 December 1924 to Théophile de Donder, a Belgian physicist and specialist in the general theory of relativity. The following year, while staying as a Ph.D. student at the Massachusetts Institute of Technology, Lemaître made his debut in theoretical cosmology with an examination of Willem de Sitter's empty world de Sitter model proposed in 1917. By introducing a division of space and time coordinates other than the one used by de Sitter, he derived a de Sitter-like world model in which' the radius of space is constant at any place, but is variable in time.' However, although he found the non-static model promising because it suggested an interpretation of the nebular redshifts in terms of the Doppler effect, he dismissed it on the ground that the constant space curvature had to be zero. His reason was philosophically and probably also theologically rooted, namely 'the impossibility of filling up an infinite space with matter which cannot but be finite' (Lemaître 1925, p. 192). Lemaître did not suggest an expanding universe in 1925, but his paper anticipated his masterpiece two years later and prepared him mentally for the idea of a closed universe growing in time.

It is unknown precisely how Lemaître arrived at his theory of the expanding universe announced in his classical paper in the *Annales de Société Scientifique de Bruxelles*, except that his earlier paper of 1925 undoubtedly served as an inspiration. One might speculate that he knew of Alexander Friedmann's ill-fated work of 1922, in which the expanding universe was discussed as one mathematical possibility among others, but this is a speculation that lacks foundation. He only became aware of Friedmann's paper in the fall of 1927, when he had the opportunity to discuss his theory with Einstein, who was attending the fifth Solvay congress in Brussels. At any rate, from an examination of the relationship between the rival models of Einstein and de Sitter, both of them conceived as static at the time, Lemaître was led to 'consider an Einstein universe where the radius of space (or of the universe) varies in an arbitrary way' (Lemaître 1927, p. 51; Nussbaumer and Bieri 2009). Yet he was not interested in arbitrary variations of the world radius, but in just the variation that agreed with astronomical data for the one and only real universe. Guided by Vesto Slipher's data of extragalactic redshifts he focused on the solution of the Friedmann-Lemaître equations that corresponded to a closed universe expanding from an Einstein state of radius $R_0 = 1/\Lambda^{1/2} \cong 270$ Mpc $\cong 9 \times 10^8$ light years, where Λ is the cosmological constant.

As indicated by the title of the paper – 'A Homogeneous Universe of Constant Mass and Increasing Radius Accounting for the Radial Velocity of Extragalactic Nebulae' – Lemaître realized that the observed redshifts are a cosmical effect of the expansion of the universe and not caused by galaxies moving through a fixed space. On this basis he derived a linear relationship between recession velocity and distance, $v = kr$, and even estimated a value for the expansion constant, namely $k \cong 625$ km s^{-1} Mpc^{-1}. In other words, he found what later became known as the Hubble relation and the Hubble constant, and he did so two years before Edwin Hubble famously obtained a linear relation between the recessional velocities of spiral nebulae and their distances. On the other hand, Lemaître's derivation was theoretical and not supported by convincing empirical evidence – no such evidence existed at the time. He never claimed that priority to Hubble's relation or law belonged to him. In a later book review (Lemaître 1950) he referred to how his work of 1927 related to those of Friedmann and Hubble:

> If my mathematical bibliography was seriously incomplete because I did not know the works of Friedmann, it is completely up to date from an astronomical point of view; I calculate the expansion coefficient (575 km sec^{-1} per megaparsec, 625 with a doubtful statistical correction). Naturally, before the discovery and study of galactic clusters, there could be no question of establishing Hubble's law, but only to determine its coefficient. The title of my note left no one in doubt of my intentions.

If one insists that the expansion of the universe was discovered by a particular scientist, then Lemaître is undoubtedly a better choice than either Friedmann or Hubble (Kragh and Smith 2003). Yet, although Lemaître explicitly predicted the expansion, he could not justify the prediction with observational data that convincingly supported the linear law he suspected. In so far as Lemaître did not establish observationally that the universe is in fact expanding, he did not make a discovery; but in so far as he gave theoretical as well as observational reasons for it, he did discover the expansion of the universe. As to Hubble, he established the empirical redshift-distance relation, but he did not clearly interpret the redshifts as caused by the recession of the galaxies. Nowhere in his paper of 1929 did Hubble conclude that the galaxies recede from us or otherwise suggest that the universe is expanding. In fact, words such as 'recession' and 'expansion' do not occur in his paper. Throughout his life Hubble maintained an agnostic attitude with respect to the reality of the expansion of the universe.

From a sociological point of view it makes sense to date the discovery of the expanding universe to 1930 rather than 1927. The reason is that Lemaître's paper, published in a somewhat obscure journal, was thoroughly ignored until Eddington belatedly drew attention to this 'very substantial advance' in a book review in *Nature* of 7 June 1930 (Eddington 1930). Only then was it 'rediscovered' and quickly recognized as a pioneering contribution to theoretical cosmology. In the wake of the rediscovery followed the recognition of Friedmann's important papers of 1922 and 1924. While there were a few citations to Friedmann's papers in the scientific literature in the 1920s, there may only have been a single one, a self-citation, to Lemaître's. In a survey article of early 1929 he briefly referred to his work two years earlier, and also used the occasion to refer to Friedmann's theory, but this article did not attract any attention either (Lemaître 1929; Hetherington 1973).

Towards a Universe of Finite Age

In his work of 1927 Lemaître assumed an expanding universe with the properties $R \rightarrow R_0$ for $t \rightarrow -\infty$ and $R \rightarrow \infty$ for $t \rightarrow \infty$. There was no proper beginning of the universe, which consequently could not be ascribed a definite age. On the other hand, he conceived the static Einstein universe of radius R_0 as a kind of pre-universe out of which the expansion had grown as the result of some instability. As a physical cause for the expansion he noted that the pressure of radiation does work during the expansion, which 'seems to suggest that the expansion has been set up by the radiation itself.' He suggested the following picture: 'In a static universe light emitted by matter travels round space, comes back to its starting point, and accumulates indefinitely. It seems that this may be the origin of the velocity of expansion [which] … in our interpretation is observed as the radial velocity of extragalactic nebulae' (Lemaître 1927, p. 56). The role of light as a possible mechanism for the initial instability of the Einstein world would reappear a few years later in a different context, namely when Lemaître took the crucial step of extrapolating this kind of pre-universe to a primeval 'atom' from which the entire universe originated in an explosive act.

The general idea of a finite-age universe was considered strange and unwelcome by almost all astronomers and physicists, but of course Lemaître was not the first to suggest the possibility by means of scientific (rather than philosophical or theological) arguments. In his paper of 1922 Friedmann had considered the idea within the framework of relativistic cosmology and written about 'the time since the creation of the world' as the time that had passed from the initial singularity to the present. In the case of a cyclical universe with $\Lambda = 0$ he even calculated 'a world period of about ten billion years.' However, to the Russian physicist this was merely a mathematical curiosity, not a possible physical reality. Lemaître undoubtedly received some inspiration from Friedmann, but there were other and probably more important sources, of which I shall call attention to two. One of them was radioactivity, such as Lemaître (1949a, p. 452) explicitly mentioned in a work of 1949:

> The idea of this [primeval-atom] hypothesis arose when it was noticed that natural radioactivity is a physical process which disappears gradually and which can, therefore, be expected to have been more important in earlier times. If it were not for a few elements of average lifetimes comparable to T_{H} [the Hubble time], natural radioactivity would be completely extinct now. ... The hypothesis that all the actually existing elements have resulted from the disintegration of heavier elements now extinct finds some support, therefore, in nuclear physics.

This line of reasoning can be found much earlier, probably first in 1911 when the Austrian physicist Arthur Haas argued that the existence of radioactive elements is incompatible with an eternal universe. The argument was taken up by the Belgian neo-scholastic philosopher Desiré Nys, who advocated it in a book of 1913, and it also appeared in some of Eddington's writings (Kragh 2007). According to Lemaître, it was no coincidence that the age of the universe was comparable to the lifetimes of uranium and thorium, for had the universe been much older the two elements would no longer exist. He inferred that our present world is the nearly burned-out result of a previous highly radioactive universe, such as he first suggested in the fall of 1931 (Lemaître 1931a). The argument from radioactivity is closely connected to the so-called entropic creation argument (Kragh 2008), which is an argument for the finite-age universe based on another irreversible process, namely the continual increase of entropy in the universe. Lemaître was familiar with this argument, which appeared prominently in the neo-scholastic literature as a possible proof of God's existence. He later said that in formulating the primeval-atom hypothesis he was 'guided by thermodynamic considerations while attempting to interpret the law of the degradation of energy within the framework of quantum theory' (Lemaître 1946, p. 147).

The idea that light plays a crucial cosmological role, and may even be thought of as the primordial medium of the world, is old and can be found in both theological and scientific versions (Kragh 2006). *Fiat lux*. It was an idea that fascinated Lemaître, who in early 1931 – before his note on the primordial atom – imagined the possibility of a static proto-universe in which 'all the energy was in the form of electromagnetic radiation and suddenly condensed into matter' (Lemaître 1931b, p. 501). This picture of a primordial radiation universe, which at some moment underwent a gigantic phase transition or materialization, had a certain similarity to contemporary ideas proposed by James Jeans and Robert Millikan, among others. In a little known paper of 1930, in which he discussed Millikan's view of cosmic rays within the framework of the expanding universe, Lemaître speculated that 'One could concede that the light had been the original state of matter, and that all the matter condensed in the stars was formed by the process proposed by Millikan,' namely a kind of photon-to-matter pair creation (Lemaître 1930). However, while Millikan argued that the enigmatic cosmic rays consisted of high-energy photons, Lemaître thought they were corpuscular, mainly consisting of protons, electrons and alpha particles. Although there is no solid documentation for it, it seems reasonable to assume that Lemaître initially thought of the original state of the universe in terms of light or photons, and that he only switched the imagery from light to atoms in the early months of 1931 (Kragh and Lambert 2007).

The Primeval-Atom Hypothesis

Lemaître's note of 9 May 1931 to the letter section of *Nature*, comprising a mere 457 words, is one of the most remarkable communications in the history of modern science. It was not an ordinary scientific paper, but rather a spirited scenario of a possible cosmic beginning, a visionary piece of cosmo-poetry that was meant to open the eyes of the readers rather than convince them. The unusual form of the communication is underlined by the fact that Lemaître chose to write as a private person and not in his capacity as professor of the University of Louvain: he signed it with his name and private address – 'G. Lemaître, 40 rue Namur, Louvain.' The very title of the note indicated the essence of his daring hypothesis, an argument for the beginning of the world in part based on quantum theory and also, if only indirectly, on thermodynamics. The fundamental indeterminacy of quantum mechanics helped him explain how the present world in all its colourful diversity could be the result of a single, undifferentiated atomic entity, for 'the whole story of the world need not have been written down in the first quantum like the song on the disc of a phonograph' (Lemaître 1931c). About a month later he gave an oral presentation of his idea to the Belgian Astronomical Society.

Whereas the letter to *Nature* did not qualify as a scientifically based hypothesis, and was not intended to do so, later the same year Lemaître presented a better argued and more elaborate version. At the London meeting of the British Association for the Advancement of Science in October 1931, the astrophysicist Herbert Dingle had organized a session on 'The Question of the Relation of the Physical Universe to Life and Mind' with the participation of Eddington, de Sitter, Jeans and Millikan, among others. Lemaître, who was invited to give a talk at the session, argued that the cosmic rays were the remnants of the disintegration of the primeval superatom from which the stars were once formed. 'At the origin, all the mass of the universe would exist in the form of a unique atom,' he said. 'The whole universe would be produced by the disintegration of this primeval atom.' At about the same time he further developed his ideas into a definite model of the universe, which he presented in the pages of *Revue des Questions Scientifiques*:

> The first stages of the expansion consisted of a rapid expansion determined by the mass of the initial atom, almost equal to the present mass of the universe. . . . The initial expansion was able to permit the radius [of space] to exceed the value of the equilibrium radius. The expansion thus took place in three phases: a first period of rapid expansion in which the atom-universe was broken down into atomic stars, a period of slowing-down, followed by a third period of accelerated expansion (Lemaître 1931a, p. 422).

Although Lemaître's universe of 1931 counts as a big-bang model (*avant le mot*), it was not a universe originating from a singularity, that is, from the physically impossible state of infinite space curvature and mass density. He always resisted the idea of an initial singularity in the strict meaning of the term. According to him, at

$t = 0$ the universe already 'existed' in the shape of the material primeval atom that contained within it the entire mass of the universe and the radius of which he estimated to be about one astronomical unit. The matter density would correspond to that of an atomic nucleus, of the order 10^{15} g cm^{-3}. At least in principle, such a hypothetical superatom was comprehensible and would, immediately after its disintegration, be subject to the laws of physics. On the other hand, Lemaître insisted that it was physically meaningless to speak of time (and hence existence?) in the primeval atom before the initial explosion. Apparently adopting an operationalist methodology, he found it impossible to define a physical state for a system when there was no conceivable method of time measurement.

Nearly 30 years later, in a presentation given to the eleventh Solvay congress in 1958, Lemaître elaborated on his view of a 'natural beginning' of the universe. With this phrase he wanted to emphasize that it was not a supernatural event, and also that the primeval atom could not have evolved from some even simpler state. Because of the random character of the explosion, being a quantum event, 'from the same beginning, widely different universes could have evolved.' This was a view agreeing with the one held by Leibniz, while it disagreed with the so-called indifference principle on which Descartes had based his cosmogonical theory. 'The splitting of the Atom,' said Lemaître, 'can have occurred in many ways and there would be little interest to know their relative probabilities. The one which really occurred might have been very improbable' (Lemaître 1958, p. 6 and p. 8). Not only was the beginning of the universe natural, it was also inaccessible in the sense that it can never be reached but only approached in some asymptotic manner – because, 'in absolute simplicity no physical questions can be raised.'

Whereas Lemaître considered the superdense primeval atom to be real, he denied that the cosmic singularity formally turning up in big-bang cosmology at $t = 0$ could be ascribed physical reality. When running the movie of the cosmic development backwards in time, at some stage physical conditions would prevent the unwelcome singularity scenario. However, as a specialist in general relativity theory he also realized that the hypothetical 'annihilation of space' was not easily got rid of. When in 1933, at the request of Einstein, he made calculations of anisotropic models to see if the singularity would then disappear, the result was disappointing (Lemaître 1933). Yet neither he nor Einstein considered the calculations as proof that the initial singularity was therefore physically inevitable. As he declared, 'Matter has to find a way to avoid the annihilation of its volume.' Another point worth emphasizing is that Lemaître was always careful in describing his universe as one that had originated in the past, had exploded, or had begun expanding, while he never spoke of the beginning as a *creation*. The initial explosion of the primeval atom was not a creation of the universe out of nothing, not a physical representation of what is described in Genesis. In this area as in others, he was careful in keeping science and theology apart.

Two more features of Lemaître's 1931 model need to be emphasized. Like the earlier Lemaître-Eddington model it was a closed universe with a positive space curvature, meaning that it was finite in space and material content. Ever since his first encounter with cosmological theory in 1925, he was convinced that the one and

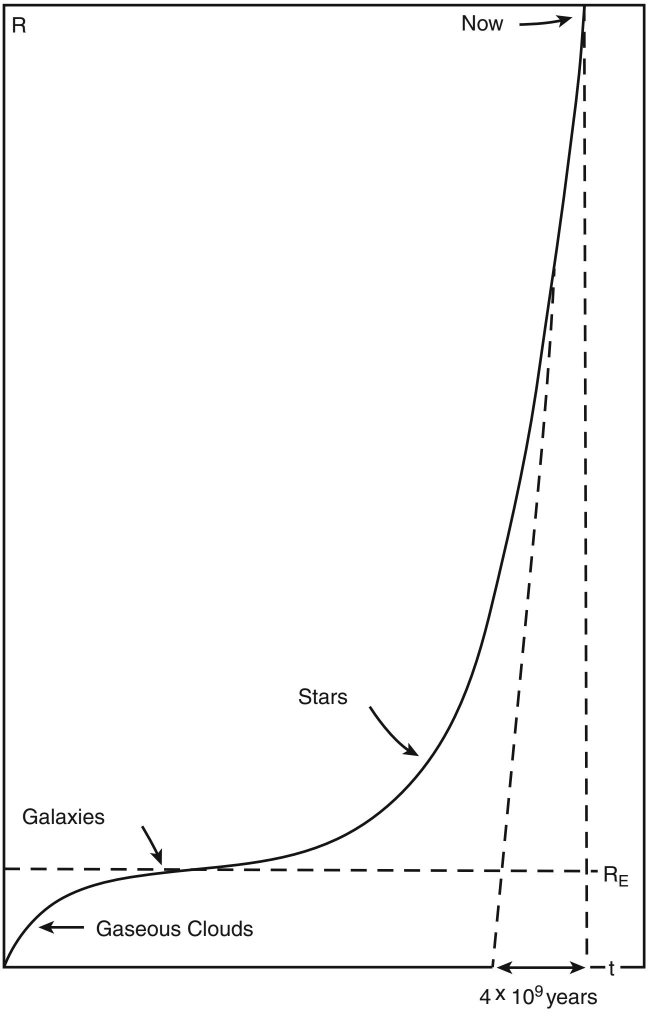

Fig. 1 Lemaître's world model of 1931, here in a version he presented in 1958. The radius of the closed world is plotted against the time since the beginning of the world

only real universe has to be finite. This was not so much for scientific reasons, but rather for reasons of epistemology. There was in Catholic philosophy a long tradition of rejecting 'infinitism' as epistemically meaningless and theologically heretical, and Lemaître saw no reason to depart from this tradition. He strongly believed that the universe was comprehensible to the human mind, a belief he could not reconcile with an infinite space populated with an infinity of objects. In a conversation with Richard Tolman he said that a closed model was preferable because 'an infinite universe could not be regarded in its totality as an object susceptible to scientific treatment' (Tolman 1934, p. 484).

Another feature common to the two models of 1927 and 1931 was the crucial role played by the cosmological constant (Λ). Whereas after 1930 most cosmologists followed Einstein in abandoning the constant as superfluous, Lemaître remained convinced that a non-zero Λ was essential for cosmology. In his exploding model of 1931 the constant determined the length of the so-called stagnation phase and thereby provided the model with an age long enough to avoid problems with the age of the stars (Fig. 1). Moreover, he found it methodologically convenient to operate with a cosmological constant because it gave relativistic cosmology greater flexibility and an increased empirical content. In his address to the 1958 Solvay congress he said, almost prophetically: ‘If some extension of relativity towards a broader field, such as quantum theory, has to be achieved the superfluous [Λ] term shall be very much welcomed’ (Lemaître 1958, p. 15). Although Lemaître recognized the objections against Λ, which he discussed in his correspondence with Einstein, he found that the advantage of keeping a non-zero cosmological constant greatly outweighed the disadvantages (Kragh 1996, pp. 53–54). This view, unorthodox at the time, he kept until his death in 1968.

Cosmic Rays as Fossils of the Past

Lemaître realized that his scenario of an exploding atom constituting the beginning of the cosmic expansion was hypothetical and might even appear bizarre to many of his colleagues in physics and astronomy. In order to convince them that it was more than an airy hypothesis he needed some physical evidence from the original explosion. If the universe had really once been in a highly compact and hot state, would it not have left some traces that could still be subjected to analysis? Lemaître thought that there were indeed such traces or fossils from the ultimate past, and that these were to be found in the cosmic rays that had been discovered in about 1912 but were still badly understood. In his address to the British Association he argued that the rays had their origin in the disintegration of the primeval superatom, that they were ‘ashes and smoke of bright but very rapid fireworks.’ He imagined that the primeval atom would first disintegrate into ‘atomic stars’ of mass comparable to those of the presently observed stars, and that the further disintegration of these atomic stars would produce the cosmic rays and, eventually, the ordinary matter now observed. Thus, the cosmic rays were not direct products of the original explosion but had their origin in the early formation of stars, which he dated some ten billion years back in time:

> Cosmogony is atomic physics on a large scale – large scale of space and time – why not large scale of atomic weight? Radioactive disintegration is a physical fact, cosmic rays are like the rays from radium. Have they not escaped from a big scale super-radioactive disintegration, the disintegration of an atomic star, the disintegration of an atom of weight comparable to the weight of a star. . . . Cosmic rays would be glimpses of the primeval fireworks of the formation of a star from an atom, coming to us after their long journey through free space (Lemaître 1931d, p. 705).

The hypothesis of cosmic rays as the descendants of the primeval atom had the advantage that it had testable consequences. As a possible test of his cosmological theory Lemaître proposed that 'cosmic rays cannot be formed uniquely of photons, but must contain, like the radioactive rays, fast beta rays and alpha particles, and even new rays of greater masses and charges.' In his article in *Revue des Questions Scientifiques* from about the same time he dealt with the cosmic rays in largely the same way as he had done at the meeting of the British Association. The rays, he wrote poetically, were 'one of the most curious of the hieroglyphs of our astronomical library.'

Lemaître's interest in the cosmological implications of the cosmic rays predated his primeval-atom hypothesis. He first considered the cosmic rays in the context of the expanding universe in a paper of 1930, arguing that the radiation energy of cosmic photons would originally have been much greater than that presently observed. He estimated that the original frequency was at least 20 times greater than the observed, a result of the redshift caused by the expansion of space. While in 1930 he seems to have considered cosmic rays as primarily made up of photons, with the primeval-atom hypothesis he changed to the view that a substantial component of them consisted of charged atomic particles. At the time there were two rival conceptions of the cosmic rays, one principally advocated by Millikan and the other by Arthur Compton. While Millikan held the rays to consist of high-energy photons, Compton and his collaborators argued that they were charged particles of extragalactic origin. Understandably, Lemaître preferred the latter hypothesis.

In collaboration with the Mexican physicist Manuel Vallarta he engaged in complicated calculations of the energies and trajectories of charged particles in the Earth's magnetic field, concluding in favour of Compton's hypothesis. Moreover, the two physicists concluded optimistically that Compton's data and their own calculations gave 'some experimental support to the theory of super-radioactive origin of the cosmic radiation' (Lemaître and Vallarta 1933, p. 91). The Lemaître-Vallarta theory was well known in the 1930s when it attracted scientific as well as public attention. It was the most cited of Lemaître's papers in the period. According to *The New York Herald Tribune* of 3 September 1933, 'Abbé Lemaître, he of the expanding universe, . . . links up the cosmic rays with the birth of the universe and the beginning of time.'

Although Lemaître was correct in his belief that cosmic rays consist mainly of charged particles, he failed in convincing the majority of physicists and astronomers that the radiation stemmed from the original explosion of the universe. One of the few physicists who seriously considered the hypothesis was Paul Epstein, a theoretical physicist at the California Institute of Technology and a colleague of Millikan. In an early survey of cosmological models, Epstein (1934, p. 77) included Lemaître's explosion theory and his idea that the corpuscular cosmic rays 'are the messengers of some super-radioactive materials which existed once but have long since disappeared in the solar system.' Although he found the idea interesting, he did not endorse it.

As the knowledge of the content of the cosmic radiation gradually improved, it became more and more clear that it could not be explained as the result of a singular explosive act in the distant past. Most of the rays turned out to have a more local origin, either solar or galactic. Yet Lemaître kept to his idea, which he defended on various occasions in the 1940s and 1950s. For example, at a conference of the Astronomical Society of Anvers in January 1949 he gave an address on ‘Cosmic Rays and Cosmology’ (Lemaître 1949c). In a paper published on the occasion of Einstein’s seventieth birthday, he repeated his favourite hypothesis, now connecting it to the formation of the original gaseous clouds out of which the stars were assumedly formed. These clouds would absorb the cosmic rays and thereby increase their size and mass until they gravitationally condensed into stellar bodies. According to Lemaître, some of the mass increase would be caused by the transformation into hydrogen atoms of the kinetic energy of the original cosmic rays particles, whose energy he estimated to have been about 10,000 times that of the observed cosmic rays (Lemaître 1958). He did not specify the mechanism of the process. Since he found the energy-mass density of the cosmic rays to be of the order 10^{-34} g cm^{-3}, and the mass density of the universe was known to be about 10^{-30} g cm^{-3}, he concluded that the cosmic rays were indeed the primordial form of matter (Lemaître 1949c).

In the view of Lemaître, there was no fundamental difference between stars and cosmic rays. ‘All kind of matter,’ he said in 1949, ‘must be present in the cosmic rays and matter is nothing else than condensed cosmic rays’ (Lemaître 1949b, p. 366). Moreover, he thought that what he called ‘super alpha-rays’ – nuclei of atomic number up to about 40 recently found in the cosmic radiation – supported his idea that the rays do not consist of light particles only but that ‘all atomic elements exist in the rays.’ These speculations about cosmic rays and matter were unfruitful and left no mark on the further development of either astrophysics or cosmology. In spite of Lemaître’s clear recognition that there might still today exist fossils of the cosmic past, he failed to understand that the abundance distribution of the chemical elements, and particularly the abundance of helium, makes up such a fossil.

Early Responses

Whereas Lemaître’s theory of the expanding universe was received very favourably after it became generally known in 1930, responses to the primeval atom hypothesis were quite different. As to the expanding universe, not only was the concept accepted at an early time by leading scientists such as Eddington, Einstein, de Sitter, Robertson and Tolman, it was also disseminated to the public through a number of popular books, including Jeans’ *The Mysterious Universe* (1930), de Sitter’s *Kosmos* (1932), and Eddington’s *The Expanding Universe* (1933). By the late 1930s the expansion of the universe had secured a nearly paradigmatic status among astronomers and cosmologists. Alternative explanations of the redshifts, for example in terms of tired-light cosmologies, did not disappear, but they were no longer taken seriously by mainstream astronomers.

When it comes to the reception of the finite-age universe in Lemaître’s physical version, one needs to distinguish between popular and scientific responses. Newspapers and popular science magazines found the primeval-atom hypothesis fascinating and in some cases described it in detail and at an early date. Thus, Lemaître's note to *Nature* of 9 May 1931 found its way to *The New York Times* only 10 days later, where it was quoted nearly *in extenso*. In July 1932 the theory featured in the widely read American magazine *Popular Mechanics*, and later the same year *Popular Science* included an article by the Harvard astronomer Donald Menzel dramatically entitled 'Blast of Giant Atom Created Our Universe.' Menzel could inform readers of the magazine that Lemaître's theory did away with the old query of what happened before the beginning, for 'nothing can happen where there is no room for it to happen.' As to the future of the cosmos, Menzel mentioned the possibility of a later contraction, as in Einstein's cosmological model of 1931, but 'Dr. Lemaître prefers to believe that the whole universe was born in the flash of a cosmic sky-rocket and that it will keep expanding until the showering sparks which form the stars have burned to cinders and ashes' (Menzel 1932, p. 105).

The positive attention that Lemaître's explosion theory received in the popular press contrasted strongly with the cool and sometimes hostile response from the scientific community. It took some time until his theory was noticed at all, probably a result of Lemaître's unfortunate decision to publish it in French in *Revue des Questions Scientifiques*, a journal most physicists and astronomers outside Belgium and France would not even be aware of. On the other hand, many would know the theory from lectures and conferences. During the years 1931–1934, Lemaître lectured widely on the expanding universe and the primeval-atom hypothesis, about which he spoke at meetings in London, Paris, Chicago, Princeton, Montréal, Pasadena and elsewhere. For example, on 25 April 1933 he lectured on 'The Primaeval Atom Hypothesis' before the Kapitza Club, Cambridge University, in front of Paul Dirac and other Cambridge physicists.

At any rate, when the theory did become known, the general response was either dismissal or neglect. Consider Richard Tolman, who in his authoritative textbook of 1934, *Relativity, Thermodynamics and Cosmology*, found it necessary to warn against 'the evils of autistic and wishful thinking' in cosmology, in which he counted the belief that the universe was created in the past. There can be little doubt that he thought of Lemaître, when he wrote: 'The discovery of models, which start expansion from a singular state of zero volume, must not be confused with a proof that the actual universe was created at a finite time in the past.' As far as he was concerned, 'no definiteness could now be attached to any idea as to *the* beginning of the physical universe' (Tolman 1934, pp. 486–488; Tolman 1932) (Fig. 2).

The beginning of the world was a radical concept, which was difficult to accept, and to which scientists had to accustom themselves. Eddington belonged to those who never became accustomed with it, indeed never wanted to. Like most other scientists he felt uneasy about a created universe, a notion he found to be 'repugnant.' While Eddington's opposition was philosophically (and possibly also religiously) based, the reluctance of Hubble was rooted in his cautious empiricist attitude to science. Although he did not refer to Lemaître in his classical study of 1936, *The Realm of the Nebulae*, he did consider the explosive universe in the Rhodes Memorial Lectures he delivered in Oxford the same year. Hubble showed that with a particular value of the cosmological constant, about 6×10^{-18} (light years)$^{-2}$, Lemaître's model might be brought in agreement with observational data,

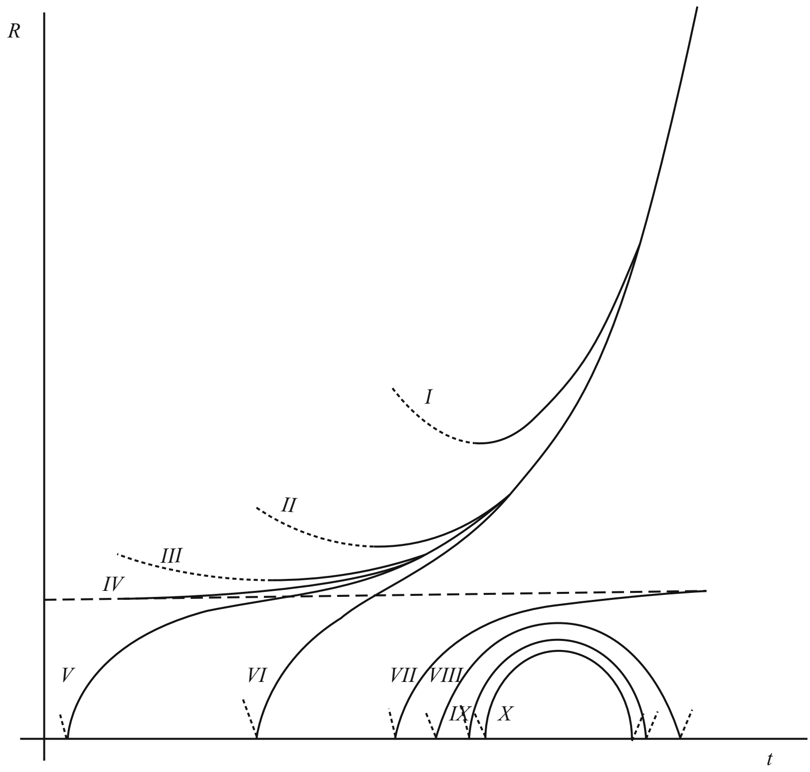

Fig. 2 Graphical representations of physically realistic world models, as of 1934. The Lemaître-Eddington model is shown by the curve IV, whereas curves V and VI correspond to Lemaître's primeval-atom universe (Source: Tolman 1934, p. 411)

but then the density would have to be suspiciously high (~ 10^{-26} g cm^{-3}) and the size of the universe suspiciously small (4.7×10^8 light years). The model he considered was 'the type that will always be associated with the name of Lemaître,' and for this model he concluded that although it could not be ruled out, it was unattractive and 'rather dubious' (Hubble 1937, p. 62; Hubble 1936).

The eminent Princeton cosmologist Howard Robertson basically agreed with the scepticism expressed by Tolman and Hubble. In an address of 1932, he mentioned the theoretical possibility of an initial singularity; but he found it unattractive and preferred 'emotionally more satisfactory' solutions such as the non−singular Lemaître-Eddington model. At this occasion he mentioned Lemaître only in connection with the appealing Lemaître-Eddington model, whereas he associated the finite-age possibility with Friedmann's solution. The following year, in an influential survey in *Reviews of Modern Physics*, he specifically excluded from what he considered plausible universe models those which have 'arisen in finite time from the singular state $R = 0$' (Robertson 1933, p. 80). In his extensive bibliography he included a reference to Lemaître (1931a), but in the text he ignored the primeval-atom model. Also the German astronomer Otto Heckmann found the Lemaître-Eddington model to be attractive 'because it allows the possibility of a world without catastrophic behaviour either in the past or in the future' (Heckmann 1932, p. 106). In his survey of cosmological models, he did not mention Lemaître's exploding universe.

In a few cases the responses to the primeval-atom hypothesis bordered on ridicule. John Plaskett, a Canadian astronomer who shared Hubble's empiricism, credited Lemaître, in an address of 1933, as the effective pioneer of the expanding universe, adding that 'Unfortunately this important paper was buried in a little read publication and entirely escaped attention.' While Plaskett was willing to take the expanding universe seriously, when it came to its beginning in an explosive event he had no more patience. Lemaître's hypothesis, he said, was 'the wildest speculation of all, even 'an example of speculation run mad without a shred of evidence to support it' (Plaskett 1933, p. 252). The verdict of Ernest Barnes, the mathematically trained Bishop of Birmingham, was not much different. In a book of 1933 he opined, probably correctly: 'I do not think that many cosmogonists have yet been persuaded by this theory of Lemaître. It is usually regarded as a brilliantly clever *jeu d'esprit* rather than a sober reconstruction of the beginning of the world' (Barnes 1933, p. 408). He was unwilling to 'bring in God ... to let off the cosmic fire-work of Lemaître's imagination' – but then, so was Lemaître, apparently unknown to Barnes.

Generally speaking, during most of the 1930s big-bang solutions of the Friedmann equations – which, in addition to Lemaître's, also included Einstein's cyclical model of 1931 and the Einstein-de Sitter model of 1932 – were part of the cosmological literature, but they were rarely taken seriously or assigned physical reality. In the few cases where researchers entertained ideas somewhat similar to Lemaître's, such as did Paul Dirac in England (1938), Hans Ertel (1935) and Carl Friedrich von Weizsäcker (1938) in Germany, and George Gamow and Edward Teller in the United States (1939), they did not refer to Lemaître's primeval-atom hypothesis. The German pioneer of quantum mechanics, Pascual Jordan, was perhaps the only scientist who subscribed to a version of Lemaître's big-bang universe before World War II and actually referred to it. In a book of 1936 he summarized: 'Ten billion years ago – Lemaître especially deserves credit because of the closer execution of this representation – the initially small universe arose from an original explosion' (Jordan 1936, p. 152). The following year he gave a brief but sympathetic account of the *Urexplosion* suggested by Lemaître (Jordan 1937). The model favoured by Jordan was clearly inspired by Lemaître's fireworks model, and like his Belgian source it was finite in space as well as in time. However, contrary to Lemaître, Jordan preferred to put the cosmological constant equal to zero.

Conclusion: The Fate of Lemaître's Model

Given the later success of big-bang cosmology one may find it strange, almost embarrassing, that physicists and astronomers received Lemaître's pioneering contribution with such indifference. But there were good reasons for the cool reception and the marginal role that the primeval-atom hypothesis played in the period. For one thing, the hypothesis was simply not well known, since Lemaître did not communicate it in a clear and quantitatively developed form in one of the major scientific journals. More importantly, from the perspective of the 1930s it could not help appearing speculative and unconvincing. The only testable consequence of Lemaître’s primeval atom was the composition of the cosmic rays, which he claimed to be fossils of the original explosion, and this alone was far from enough to make it acceptable. Contrary to other models of the big-bang type, such as the Einstein-de Sitter model, Lemaître’s explosive model had the advantage that it avoided the so-called time-scale difficulty of a universe being younger than its constituent parts. This was a conceptual advantage, but one that relied solely on adopting a positive cosmological constant and not on the postulated primeval explosion. From the perspective of the period there were no good reasons to prefer the explosion scenario over, say, the smoothly expanding Lemaître-Eddington model.

This situation only changed after World War II, first with Gamow’s independent development of a big-bang theory based on the nuclear reactions in the early universe and later with the prediction and discovery of the cosmic microwave background. However, rather than considering Gamow’s nuclear-physical approach to cosmology as a realisation of his own ideas, Lemaître chose to ignore it, claiming that ‘It is not very profitable to insist on [the detailed nature] of the extreme physical conditions which arose at the very beginning’ (Lemaître 1949a, p. 453). As it turned out, in this evaluation Lemaître was plain wrong: it was precisely investigations of the detailed nature of the very early universe that transformed big-bang cosmology from a somewhat speculative *jeu d’ esprit* to an advanced and empirically convincing theory of the origin and development of the universe. This transformation, principally due to Robert Dicke, James Peebles and Yakov Zel’dovich, occurred about 1965 and was largely independent of the earlier works of Lemaître or Gamow. Our present hot big-bang standard theory has its *conceptual roots* in Lemaître’s old primeval-atom speculation, but otherwise it is a very different theory and one which in its actual development owes little to the work of the ‘father of the big bang.’

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