The Beginning of the World: Georges Lemaître and the Expanding Universe

by

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Scientific cosmology is largely a child of this century. Today the field is dominated by the standard Big Bang theory, a class of cosmological models which have in common that the universe expanded to its present state from a singularity in spacetime some ten billion years ago. In view of the fact that this theory ranks among the greatest conceptual innovations ever made in science it is remarkable that it has only received a relatively modest attention from historians of modern science.[1] Compared with quantum mechanics, probably the only other theory which can match cosmology as regards generality and conceptual greatness, the history of modern cosmology is an underdeveloped field.

Modern Big Bang cosmology is constituted around two key features, the idea of the expanding universe and the idea of a beginning of the universe. These ideas are logically distinct since the expanding universe does not necessarily imply a beginning in spacetime. All the same, from the point of view of history of science they are closely related. The concepts were first introduced in the period 1922–32, the decade in which modern cosmology was born. The idea of a beginning of the world is indebted to Georges Lemaître who developed it as an extension of his earlier theory of an expanding universe. In order to evaluate the contributions of Lemaître in this period it is necessary to place them in their proper historical context. For that purpose I will briefly outline the main developments of cosmology up to around 1927. It is not obvious that the development of early relativistic cos-

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mology relates to the development of quantum theory, but in the case of Lemaître this relationship should not be ignored. It turns out that Lemaître's revolutionary idea of a beginning of the world was indebted to the current situation in quantum theory.

1. Cosmology in the Early Twenties

When Lemaître first entered relativistic cosmology the field was new and unfamiliar to astronomers. It was founded by Einstein in an epoch-making article of 1917 in which he applied his new theory of general relativity to the entire universe.[2] Einstein based his cosmological considerations on a tensor equation in which the spacetime curvature was expressed by the energy density of the universe. He showed that the equation represented a spherically bounded, isotropic universe homogeneously filled with matter. The solution considered by Einstein was static in the sense that the curvature of the universe was independent of time. In order to secure the static nature Einstein introduced in his equations the so-called cosmological constant (Λ) the effect of which was to produce a repulsive force counteracting the gravitational attraction. Shortly after the appearance of Einstein's work the Dutch astronomer Willem de Sitter analyzed and criticized the theory in an important paper.[3] De Sitter proved that for zero mass density Einstein's field equations had also static solutions. The model proposed by de Sitter was an empty universe which would only remain stable in the absence of matter. In the early twenties there were thus two rival cosmological theories founded on the general theory of relativity, associated with the names of Einstein and de Sitter. Both theories were designed so as to be static.

At first the astronomers did not pay much attention to the theories of Einstein and de Sitter. The merging of theory and observation in cosmology came into being primarily through the study of displacements of the spectral lines from distant nebulae. Such studies were initiated by V. M. Slipher before World War I and in the early twenties several researchers felt justified to conclude from their observations that the redshifts of the light from the spiral nebulae are correlated to their distances.[4] Since the redshifts were generally interpreted as a result of a Doppler effect this indicated a velocity-distance relation.

However, there was much uncertainty about the nature of the relationship, if it existed at all. The uncertainty was mainly due to unreliable determinations of the distances of the spiral nebulae. It should be recalled that at the time the extra-galactic nature of the spiral nebulae was not yet commonly accepted. For example, in Einstein's work of 1917 the universe was still believed to be identical with our own galactic system, the Milky Way.

The increasing confidence in a redshift-distance relation supplied de Sitter's model with considerable appeal. While the Einstein model did not agree with a redshift-distance relation, it was predicted by de Sitter's model. According to de Sitter the frequency of light would be expected to decrease with increasing distance of the source. However, this effect was not due to a recession of the nebulae, but was explained as a slowing down of distant atomic vibrations caused by the structure of spacetime. To the extent that the redshift-distance relation was acknowledged, astronomers tended to conceive it as a matter of observation and were generally sceptical to arguments based on theoretical cosmology. In 1924 Ludwik Silberstein argued for a linear redshift-distance relation of the form $d\lambda/\lambda = \pm r/R$ where r is the distance of the luminous source and R the curvature of radius of the universe; as indicated by the double sign the formula was supposed to be valid for blueshifts as well as redshifts.[5] Silberstein claimed that his formula was supported by observations of globular clusters but few astronomers followed him. On the contrary, his theory was seriously criticized by leading astronomers who rather ridiculed the 'Silberstein effect'. Partly as a result of the negative reaction to Silberstein's formula most astronomers were very cautious to propose redshift-distance relations. They rather expected some such relation but they wanted to base it on more reliable measurement and thus had to wait for new methods of determining galactic distances.

2. *Lemaître: Education and Early Career*

Georges Édouard Lemaître was born in 1894 in Charleroi, Belgium, where he attended a Jesuit school. Attracted by the exact sciences as well as by theology he started engineering studies in 1911 at the Catholic University of Louvain but did not finish them because of the war.

Lemaître served as a soldier in the Belgian army throughout the entire war, 1914–18, but after the war had ended he returned to the peaceful university life. He then changed from engineering to mathematics and physics in which subjects he graduated in 1920. At the same time he studied theology and was ordained as an abbé in 1923.[6]

While until 1920 Lemaître's main study had been mathematics, in the following years he specialized in theoretical physics, including a close study of the general theory of relativity. At that time Belgium was somewhat at the periphery of physics and Einstein's theory of gravitation was largely unknown to the physicists at Louvain. Consequently Lemaître had to learn the difficult subject by himself. In order to master it and to unfold his talent of theoretical physics Belgium was too far away from the scientific centres of the world. It was therefore most fortunate that he received in the summer of 1923 a travelling grant from the Belgian government and also a Committee for Relief in Belgium Fellowship, the latter donated by the Educational Foundation in the USA. He was now in a position to widen his scientific horizon and chose to go to Cambridge, England.

In Cambridge he wanted to study under Eddington, the fountainhead of relativity in England and internationally known for his role in the famous solar eclipse expedition of 1919 which did so much to confirm and propagate Einstein's theory. Eddington's personality and approach to physics greatly inspired Lemaître who decided to specialize in general relativity. While staying in Cambridge Lemaître wrote his first research paper on the theory of relativity.[7] The paper, which carried a lengthy introduction by Eddington, dealt with a problem intermediate between the special and general theory of relativity, viz. how to define simultaneity relative to a moving solid body. Lemaître was able to improve on previous results obtained by Born and Herglotz and demonstrated that he mastered the subtle mathematical methods of the theories of relativity.[8] Eddington was impressed by the Belgian post-graduate student. After Lemaître had left Cambridge Eddington wrote to Théophile de Donder, professor at the Free University of Brussels:

> I found M. Lemaitre a very brilliant student, wonderfully quick and clear-sighted, and of great mathematical ability. He did some excellent work whilst here, which I hope he will publish soon. I hope he will do well with Shapley at Harvard. In case his name is considered for any post in Belgium I would be able to give him my strongest recommendations.[9]

While at Cambridge Lemaître did not yet pursue problems of astronomy or cosmology. But as a student of Eddington he could not avoid to make acquaintance with the new relativistic cosmologies of Einstein and de Sitter. The subject was treated by Eddington in his recently published *The Mathematical Theory of Relativity* which Lemaître studied with interest. At that time Eddington preferred Einstein's solution because it fitted better with his, Eddington's, idea of a deep interconnection between cosmology and atomic physics; but he also recognized the force of de Sitter's theory, in particular its ability to account for the observed redshift. Referring to this question, Eddington wrote: "It is sometimes urged against de Sitter's world that it becomes non-statical as soon as any matter is inserted in it. But this property is perhaps rather in favour of de Sitter's theory than against it".[10] This remark was read with particular interest by Lemaître who quoted it in full in his first paper on cosmology, published in the spring of 1925.[11]

In July 1924 Lemaître crossed the Atlantic and reached Harvard after a brief stay in Canada, where he attended the Toronto meeting of the BAAS (British Association for the Advancement of Science). Present at the meeting was also Silberstein with whom Lemaître discussed the question of a redshift-distance relation. Lemaître was attached to Harvard College Observatory and at the same time he prepared for a Ph.D. in astronomy at MIT.[12] During his stay in USA, from July 1924 to April 1925, Lemaître was introduced to the latest developments in astronomy and initiated his career as a theoretical astrophysicist. The environment in Harvard was particularly stimulating in this respect, no least because of the director of the observatory, the specialist in galactic astronomy Harlow Shapley.

In December 1924 Lemaître attended an important meeting in Washington DC arranged by the American Astronomical Society and the American Association for the Advancement of Science. At this meeting Edwin Hubble's observations of Cepheids in spiral galaxies were announced on the first day of 1925. The discovery was soon accepted by most astronomers with the result that the 'Great Debate' was now finally settled: at the end of the year it was generally agreed that the spiral nebulae are 'island universes' outside the Milky Way. Lemaître at once realized the importance of Hubble's discovery for relativistic cosmology and decided to investigate its consequences for the cosmological theories of Einstein and de Sitter. He recognized that a realistic cosmology had to contain a redshift-distance relation and visited Slipher at the Lowell Observatory in Arizona and the Mount Wilson Observatory in California (where Hubble worked) in order to learn about the most recent measurements. In March 1925 he submitted his first paper on cosmology and a few months later he returned to Belgium.[13]

3. Non-static Universes

The work that Lemaître published in the *Journal of Mathematics and Physics* was hardly noticed by other scientists in the field. Yet it is historically significant since it can be regarded as a preparation for his later work on the expanding universe.

Lemaître investigated the coordinates used in de Sitter's model of 1917 which he criticized for introducing a centre to the universe. Such a feature is intolerable, Lemaître objected: it conflicts with the requirement of the four-dimensional universe that every point is equivalent with any other. In order to remove the difficulty Lemaître introduced another division of space and time than that used by de Sitter. He derived a model in which the radius of curvature depended on the time. "The radius of space is constant at any place, but it is variable with time".[14] The solution obtained by Lemaître was thus non-static, a feature which he, following Eddington, did not find disturbing. On the contrary: "Our treatment evidences this non-statistical character of de Sitter's world which gives a possible interpretation of the main receding motion of spiral nebulae".[15] He showed that in his version of de Sitter's theory the observed redshift could be reproduced by the Doppler expression (with $c = 1$)

$$d\lambda/\lambda = -r/t_0$$

where r is the distance between the light-source and the observer and t_0 the time measured by the observer. Lemaître's redshift formula thus corresponded to Silberstein's ill-fated formula of the previous year.

Although Lemaître found the non-static character of the de Sitter world promising because of its connection to the redshift-distance relation, he was not satisfied with his model. To get rid of the centre in de Sitter's original theory he was forced not only to accept a non-static universe but also, and much worse, a space with no curvature. This he regarded as inadmissible:[16]

> We are led back to the euclidian space and to the impossibility of filling up an infinite space with matter which cannot but be finite. De Sitter's solution has to be abandoned, not because it is non-static, but because it does not give a finite space without introducing an impossible boundary.

Lemaître thus reached the negative conclusion that neither of the two world models discussed by Einstein and de Sitter could be adequate descriptions of the real universe. In order to solve the dilemma he had to find a solution which combined the advances of the two theories. In 1925 he seems to have realized that such a solution, if it existed, would imply an expanding universe; but he still did not draw this conclusion explicitly.

Lemaître's contribution of 1925 was essentially to propose a mathematically transformed version of de Sitter's line element. Although equivalent, the two line elements invited very different physical interpretations. Apparently unknown to Lemaître a similar transformation to a non-static form had been proposed by Kornelius Lanczos at Freiburg University a couple of years arlier.[17] In 1928 H. P. Robertson suggested still another non-static version of de Sitter's cosmology which was equivalent to Lemaître's and showed that it yielded a recession of the galaxies.[18] Robertson did not mention the works of Lanczos and Lemaître and neither did he realize that his line element was implicitly contained in the 1923 edition of Hermann Weyl's *Raum, Zeit, Materie.* This was pointed out by Weyl who in the spring of 1929 had discussed the matter with Robertson at a conference in Princeton.[19] Weyl also drew attention to the fact that Robertson's coordinates had already been discovered by Lemaître in 1925. Although non-static universes were discussed prior to 1927, by Weyl, Lanczos, Friedmann and others, these were treated as mathematical solutions and not given any particular physical significance.

After his return to Belgium Lemaître resumed his work at the University of Louvain where he was appointed associate professor in 1926 and full professor the following year. He continued his studies in cosmology but now under less stimulating conditions. When he published his next contribution to cosmology it was in the French language. The place of publication was the *Annales de la Société Scientifique de Bruxelles*, a relatively obscure journal which was not widely read outside Belgium. Lemaître was at that time unaware that the cosmological implications of general relativity had received full treatment five years earlier by the Russian mathematician and meteorologist Alexander Friedmann.[20] The almost complete neglect of Friedmann's work is puzzling. True, Friedmann was outside the professional community of astrophysicists and unknown to those specializing in cosmology. But his two papers were published in what was probably the most respected journal of theoretical physics and even received a comment by Einstein.[21] His papers must have been seen by many astronomers and physicists of whom at least some studied them. But to the extent Friedmann's theory was read it was not appreciated or understood. At any rate it left no trace at all until years later when the climate in cosmology had changed. At that time Friedmann had died and his great contribution was partly overshadowed by the work of Lemaître.[22]

Friedmann analyzed the solutions of Einstein's field equations and showed that apart from the static worlds of Einstein and de Sitter the equations also allow for a non-static world. For this case the basic equations governing the time variation of the size of the universe were found to be

$$\left(\frac{R'}{R}\right)^2 + \frac{2\dot{R}R''}{R^2} + \frac{c^2}{R^2} - \Lambda = 0 \tag{1}$$

and

$$3\left(\frac{R'}{R}\right)^2 + 3\,\frac{c^2}{R^2} - \Lambda = \varkappa c^2 \varrho, \tag{2}$$

where R' denotes dR/dt and Λ is the cosmological constant; ϱ is the mean density of matter in the universe and $\varkappa$ is the Einstein gravitational constant. Friedmann analyzed the solutions to these equations in considerable detail and generality. He showed that equation (1) yields an elliptic integral of the form

$$t = \frac{1}{c}\int_a^R \sqrt{\frac{x}{A - x + (\Lambda/3c^2)x^3}}\,\mathrm{d}x + B, \tag{3}$$

where a, A and B are constants. As Friedmann demonstrated, this, depending on the value of Λ, leads to either a homogeneously expanding universe or a cyclical universe. In a formal sense the expanding universe was introduced with Friedmann's work in which the essentials of all later theories were given. However, from the point of view of history and sociology Friedmann's work was ineffective. This was partly a result of its mathematical rather than astronomical character. It was presented as a purely theoretical contribution and no attempt was made to connect it with astronomical observations. In the final section Friedmann stated that "Unsere Kenntnisse sind vollständig ungenügend, um Zahlenrechnungen auszuführen und zu entscheiden, welche Welt unser Weltall ist". For the sake of illustration he used $\Lambda = 0$ and a mass of the universe equal to $5 \cdot 10^{21}$ sun masses which gives an age of the world around 10^{10} years. But he stressed that "Diese Ziffern können aber gewiss nur als eine Illustration für unsere Rechnungen gelten".[23]

Friedmann's work introduced two concepts in cosmology of revolutionary importance, viz. the age of the world and the creation of the world. "Die Zeit seit der Erschaffung der Welt", wrote Friedmann, "ist die Zeit, die verflossen ist von dem Augenblicke, als der Raum ein Punkt war ($R = 0$) bis zum gegenwärtigen Zustande ($R = R_0$)".[24] In the case of an expanding universe – a 'monotonic world of the first kind' in Friedmann's terminology – the age of the world was written as the above integral with $a = 0$ and $R = R_0$. However, Friedmann did not attach much importance to this result. He added that "diese Zeit darf auch unendlich sein". To Friedmann the age of the universe was a mathematical curiosity, not a possible physical reality. The same may be said of Lanczos's contributions to cosmology which contained in a formal way a spacetime singularity. Even that was regarded a blemish at a time when a universe expanding from a singularity was almost unthinkable. In 1924 Weyl argued that his own version of cosmology "has the great advantage [over Lanczos's] of not introducing a singular initial moment, of conserving the homogeneousness of time".[25]

4. *The Expanding Universe*

The point of departure of Lemaître's paper of 1927 was the conclusion reached two years earlier, that a solution intermediate between the Einstein world and the de Sitter world would be desirable: "When we use co-ordinates and a corresponding partition of space and time of such a kind as to preserve the homogenity of the universe, the field is found to be no longer static; the universe becomes of the same form as that of Einstein, with a radius no longer constant but varying with the time according to a particular law".[26] Applying a line element of the form

$$ds^2 = -R(t)^2 d\sigma^2 + dt^2,$$

where $d\sigma$ comprises the space coordinates, Lemaître found the following field equations

$$3\left(\frac{R'}{R}\right)^2 + \frac{3}{R^2} = \Lambda + \varkappa\varrho \tag{4}$$

and

$$2\frac{R''}{R} + \left(\frac{R'}{R}\right)^2 + \frac{1}{R^2} = \Lambda - \varkappa p. \tag{5}$$

Here p is the pressure which Lemaître took to be given by the radiation pressure as he regarded the matter pressure to be negligible. The universe considered was one of constant mass, satisfying energy conservation. For such a universe Lemaître found as a solution of equation (4) that

$$t = \int \frac{\mathrm{d}R}{\sqrt{\frac{\Lambda R^2}{3} - 1 + \frac{\alpha}{3R} + \frac{\beta}{R^2}}}, \tag{6}$$

where α and β are constants. He observed that this solution entails both the Einstein solution (for $\beta = 0$ and $R = \text{constant}$) and Lanczos's version of the de Sitter solution (for $\alpha = \beta = 0$) as special cases. But the case to which he called special attention was that of $\beta = 0$ and $R = R(t)$. For this case he found the solution

$$t = \sqrt{3}\,R_0 \int \sqrt{\frac{R}{R + 2R_0}} \cdot \frac{dR}{R - R_0}, \tag{7}$$

where R_0 is related to the cosmological constant by $\Lambda = 1/R_0^2$. Lemaître thus showed that the field equations of general relativity could be satisfied by an expanding universe in which "The radius of the universe increases without limit from an asymptotic value R_0 for $t = -\infty$".[27] Lemaître only discussed solutions corresponding to an open universe. However, at the time he was aware that there were other solutions, including a class corresponding to closed universes.[28] As to the value of R_0 he calculated it "from a discussion of available data" to be about $2.7 \cdot 10^8$ parsec while he estimated the current radius of the world to be twenty times as large.

It is seen at once that Lemaître's cosmological differential equations, equations (4) and (5), are the same as Friedmann's. The only difference is that Lemaître included the radiation pressure and used a system of units in which $c = 1$. The general solution, given by equation (6), was also published by Friedmann (with $\beta = 0$). However, while mathematically Lemaître's theory added nothing new to Friedmann's work, in approach and perspective it was very different. First of all it was a serious attempt to give a physically realistic cosmology, not only a mathematical exercise in general relativity. Throughout the paper Lemaître was prepared to relate the mathematics to astronomical observations. His expanding universe was within the realm of physics and hence requiring a cause for its explanation, a notion foreign to Friedmann and other researchers. Lemaître proposed tentatively that "the expansion has been set up by the radiation" but at the time he was unable to develop this rather obscure suggestion.

Contrary to Friedmann, Lemaître connected explicitly his theory with the recession of the nebulae. "The receding velocities of extragalactic nebulae are a cosmical effect of the expansion of the universe".[29] He derived the Doppler effect formula which gives a proportionality between the velocity of the receding galaxies and their distance from the earth. For the proportionality factor, later known as the Hubble constant, he adopted the value $2 \cdot 10^{-17}$ sec^{-1} from a discussion of current redshift-distance measurements.

5. From Neglect to Prominence

In the scientific literature of the late twenties Lemaître's contributions were ignored to an even larger extent than Friedmann's. As far as I know, his works were not cited at all in recognized journals until 1930.[30] This is as puzzling as is the neglect of Friedmann's works, though for somewhat different reasons. It is true that *Annales Scientifique Bruxelles* was a rather obscure journal which would easily be overlooked outside Belgium and France. But unlike Friedmann, Lemaître was not really isolated in Louvain and was not outside the community of astrophysicists and cosmologists. From his travels in 1923–25 he had personal contacts with key persons in England and USA like Eddington, Shapley, Slipher and Hubble. In the spring of 1927 he returned to MIT in order to complete his Ph.D. degree. What would have seemed more natural than using this opportunity to discuss his new ideas with people in USA? Then in July 1928 Lemaître attended the third General Conference of the International Astronomical Union in Leiden, organized by de Sitter. Surely he would contact de Sitter concerning the expanding universe? As far as we can tell, he did not.[31] Apparently he did not even send reprints of his article to other astronomers (except perhaps to Eddington) or letters explaining his theory.

Lemaître was not invited to the 1927 Solvay Congress in Brussels but during the congress he met with Einstein and discussed briefly his cosmological ideas with him. According to Lemaître's recollections Einstein told him that he had read his paper and that he had no objections to its mathematics; but he did not believe in its physics and dismissed the expanding universe. "Après quelques remarques techniques favorables, il conclut en disant que du point de vue physique cela lui parassait tout à fait abominable … je parlais de vitesses des nébuleuses et j'eus l'impression qu'Einstein n'était guère au courant des faits astronomiques".[32] Einstein recognized the similarity between Lemaître's theory and that of Friedmann to which he drew Lemaître's attention.[33] It was only then that Lemaître was made aware of Friedmann's work. When Lemaître surveyed the science of cosmology in January 1929 he mentioned Friedmann's work but did not emphasize the idea of the expanding universe. The vehicle of publication was again a Belgian journal not well known outside the country.[34]

In the meantime observational cosmology made rapid progress. In the summer of 1929 Hubble published the preliminary results of a still unfinished research programme which argued a linear relation between recessional velocity and distance.[35] Hubble's conclusion was generally accepted and soon confirmed by new observations. At first the Hubble relation appeared as a purely observational fact and was not connected with any of the mathematically based models of the universe. It is uncertain whether Hubble knew about the prediction of Robertson but it is almost certain that he did not know about the contributions of Friedmann and Lemaître.[36] In effect, in the fall of 1929 the velocity-distance relation was recognized but not, as yet, the expanding universe.

At the end of 1929 theoretical cosmology reached a state of crisis as it became increasingly clear that some break with the static universe had to be made. Several astronomers felt that in order to admit for cosmological evolution in some form or another, a non-static metric had to be introduced. To mention just one example, Richard Tolman concluded that "our assumption of a static line element takes no explicit recognition of any universal evolutionary process which may be going on. The investigation of non-static line elements would be very interesting".[37] At about the same time Robertson, Eddington and de Sitter reached similar conclusions. At a meeting of the *Royal Astronomical Society* in London on 10 January 1930 Eddington pointed out that since both the Einstein solution and the de Sitter solution proved inadequate, interest should focus on non-static solutions. De Sitter, who was present at the meeting, agreed.[38] However, the conclusion that the universe is actually expanding was still not drawn.

When the report of the London meeting, published in *The Observatory*, reached Louvain, Lemaître wrote to Eddington and reminded him about his theory of 1927 which offered a solution to the dilemma. Probably Eddington had received a copy of Lemaître's paper but either he had not read it or he had not, in 1927, fully understood its importance. Now, three years later, the situation was different and the stage set for an acceptance of the expanding universe. Eddington at once realized that Lemaître's forgotten theory provided an answer to the problem he had recently discussed with de Sitter.[39] He sent a copy of Lemaître's paper to de Sitter in Leiden and immediately incorporated the expanding universe in a paper which appeared in May.[40] With Eddington's enthusiastic endorsement Lemaître's theory was discovered by the international community of astronomers. Eddington praised "Lemaître's brilliant solution", an evaluation which was shared by de Sitter. In April 1930 de Sitter told Shapley about the new theory which in de Sitter's opinion was "the true solution, or at least a possible solution, which must be somewhere near the truth".[41] With the support of Eddington and de Sitter, Lemaître suddenly rose to become a celebrated innovator of science. Eddington arranged an English translation of the 1927 paper which helped to make Lemaître's theory better known.[42]

With the 'discovery' of Lemaître's work in 1930–31 cosmology experienced a paradigmatic change. Works which were not able to incorporate the new idea of universal expansion became obsolete.[43] Tolman was investigating the non-static line elements in a series of papers when de Sitter and Eddington informed him of Lemaître's work.[44] It was also through de Sitter and Eddington that Otto Heckmann in Göttingen learned of the expanding universe.[45] Both Tolman and Heckmann at once began to develop the new theory. It was endorsed by Einstein in early 1931 and got wide public notice through the popular works of Jeans, Eddington and de Sitter.[46]

It was, however, evident from the very start that the idea of the expanding universe posed as many problems as it solved. One of these was the beginning of the expansion, a problem which was particularly emphasized by Eddington. Analyzing the various mathematical possibilities he ended up with favouring as "the most attractive" the case in which the mass of the universe is equal to the mass of the Einstein universe. "There is at least a philosophical satisfaction in regarding the world as beginning to evolve infinitely slowly from a primitive uniform distribution in unstable equilibrium".[47] Eddington also considered the possibility of a universe of mass larger than the Einstein universe. But he rejected this possibility on the ground that "it seems to require a sudden and peculiar beginning of things".[48] In 1930 the world model of Eddington was in harmony with the one proposed by Lemaître. The Lemaître-Eddington universe was an expanding universe, evolving gradually from an already existing pre-universe and thus without a proper beginning. The agreement between Eddington and Lemaître on this point did not last long.

6. The Beginning of the World

Following the translation of Lemaître's 1927 work there appeared in the same issue of *Monthly Notices* an article by Lemaître in which he elaborated on various aspects of his theory of the expanding universe.[49] He deduced the equations of his theory in a new way and examined the question of how the expansion originally started from a universe in equilibrium. This question had earlier been considered by Tolman and Eddington. Tolman argued that annihilation processes, i.e. conversion of matter into radiation, might explain the recession of the nebulae.[50] Eddington criticized this idea and suggested instead that formation of condensations in the Einstein world might be the mechanism involved.[51] Lemaître did not consider the annihilation suggestion (which was hinted at in his work of 1927) but developed a theory which partly agreed with Eddington's idea. Lemaître's theory was based on what he called 'stagnation', a sort of condensation process in which the total pressure diminishes. He concluded: "If, in a universe in equilibrium, the pressure begins to vary, the radius of the universe varies in the opposite sense. Therefore stagnation processes include expansion".[52] He further considered the case in which the pressure of the equilibrium (p_0) suddenly, at $t = 0$, drops to zero as a result of an instantaneous stagnation. In this case he found that the time since the stagnation would have been infinitely long: "If p_0 tends to zero, t tends to infinity, the limiting case being the solution emphasized in our 1927 paper. As was pointed out by Eddington, such logarithmic infinities have no real physical significance".[53]

In March 1931 Lemaître then still worked with a model of the universe in which there was a beginning of the expansion but no creation of the world. At about that time he made another great conceptual innovation, introducing into scientific cosmology for the first time the audacious notion of the beginning of the world in a realist sense. The step seems to have been inspired by an address which Eddington delivered in early January as President of the British Mathematical As-

Figure 1. Drawing of Lemaître while lecturing before the Kapitza Club, Cambridge University, in 1933. Unknown artist. Lemaître says, "But I don't believe in the finger of God agitating the ether", a reference to Jeans who used this phrase in connection with the expanding universe. Churchill College Archive.

sociation.[54] The text of Eddington's address was published under the dramatic title "The End of the World: from the Standpoint of Mathematical Physics". Eddington dealt in a popular fashion with one of his favourite themes, the role of universal entropy as an arrow of time. In accordance with earlier authors, like Boltzmann and Kelvin, Eddington discussed the 'heat death' of the universe, that is the state of maximum entropy and dissolution of the directionality of time assumed to take place in the far future. Such discussions were far from new in 1931 but Eddington also considered briefly what the state of the world would be like if time was traced backwards to a state in which the entropy tends to zero. Would the universe of zero entropy correspond to 'the beginning of the world'? Eddington answered that this question probably laid outside the range of scientific reasoning, but that "philosophically the notion of a beginning of Nature is repugnant to me".[55]

This remark, rather taken out of its context, spurred Lemaître to state that the concept of the beginning of the world did not have to rest on personal or philosophical views. A few weeks after Eddington's address there appeared in *Nature* a brief paper entitled "The Beginning of the World from the Point of View of Quantum Theory".[56] In this note Lemaître stated that "the present state of quantum theory suggests a beginning of the world very different from the present order of nature". It is remarkable that he argued for the primeval atom (a term not yet used) by means of quantum theory. At that time Eddington attempted to link cosmology and quantum theory by means of his idiosyncratic interpretation of Dirac's wave equation of the electron, but Eddington's programme did not appeal to Lemaître.[57] His inspiration came from the current discussion of the philosophical implications of quantum mechanics. The *Nature* note was probably indebted to the views of Niels Bohr who had recently argued that in the quantum domain the concepts of space and time have only statistical validity.[58] Lemaître was deeply interested in these questions which involved how to extend and interpret Heisenberg's uncertainty principle. In 1933, in connection with a lecture given to the Kapitza Club in Cambridge, Lemaître discussed quantum mechanical indeterminacy with, among others, Dirac.[59]

Echoing Bohr, Lemaître claimed in 1931 that "in atomic processes, the notions of space and time are no more than statistical notions". He went on:[60]

> If the world has begun with a simple quantum, the notions of space and time would altogether fail to have any meaning at the beginning; they would only begin to have a sensible meaning when the original quantum had been divided into a sufficient number of quanta. If this suggestion is correct, the beginning of the world happened a little before the be-

> ginning of space and time. I think that such a beginning of the world is far enough from the present order of nature to be not at all repugnant ... we could conceive the beginning of the universe in the form of a unique atom, the atomic weight of which is the total mass of the universe. This highly unstable atom would divide in smaller and smaller atoms by a kind of super-radioactive process.

Lemaître was well aware of the problems which followed his scenario of the beginning of the world. Could our present world in all its diversity really be the causal result of causes embedded in a single, undifferentiated quantum? Again he took resort to quantum mechanics:[61]

> Clearly the initial quantum could not conceal in itself the whole cause of evolution; but, according to the principle of indeterminacy, that is not necessary. Our world is now understood to be a world where something really happens; the whole story of the world need not have been written down in the first quantum like a song on the disc of a phonograph. The whole matter of the world must have been present at the beginning, but the story it has to tell may be written step by step.

A more elaborated version of the idea was presented at the BAAS meeting of October 1931 where one of the sessions covered the topic "The Question of the Relation of the Physical Universe to Life and Mind".[62] At first Lemaître was not invited to attend the conference but as a result of Eddington's intervention it was arranged that Lemaître delivered a talk following Jeans. At the end of his talk Jeans had remarked that if some infallible oracle offered to give a 'yes' or 'no' answer to just one question, he would like to ask it, "is the universe expanding at about the rate indicated by the spectra of the nebulae"? To Lemaître there was no doubt. He considered the cosmic expansion to be a scientific fact for which an oracle was not needed: "The expansion of the universe is a matter of astronomical facts interpreted by the theory of relativity, with the help of assumptions as to the homogenity of space, without which any theory seems to be impossible".[63]

Jeans and other speakers at the meeting had emphasized the conflict between stellar theory and the new cosmology as far as the time needed for evolution was concerned. The time-scale difficulty was this: according to currently accepted theories of stellar evolution the age of stars was much higher than the age of the universe as estimated from the value of the Hubble constant. This paradox became "the nightmare of the cosmologists", to quote North.[64] De Sitter felt that it was a genuine dilemma which forced him to accept a universe with

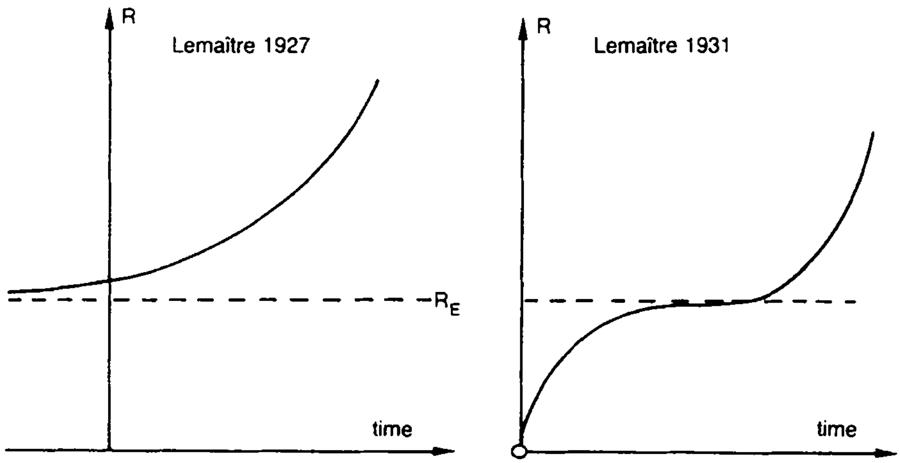

Figure 2. Lemaître's two universes. In Lemaître's model of 1927, also known as the Lemaître-Eddington model, the universe expands from the static Einstein universe of radius R_E. In the 'fireworks universe' of 1931 the expansion begins at $t = 0$ with an explosion of the primeval super-atom and runs through a stagnation phase in which expansion is halted.

contradictory properties. He concluded reluctantly that "the expansion of the universe on one hand, and the evolution of stellar systems and stars on the other hand, are two different processes, taking place side by side, but without any apparent connexion between them. The expansion has only been going on during an interval of time which is as nothing compared with the duration of the evolution".[65]

Lemaître recognized the difficulty but believed that it could be resolved if a "fireworks theory" of evolution was introduced in cosmology: "The last two thousand million years are slow evolution: they are ashes and smoke of bright but very rapid fireworks".[66] He argued that the cosmic radiation was to be conceived as the remnants of the disintegration of the primeval super-atom from which the stars were once formed. If such a view was adopted the time-scale difficulty did not need to arise, Lemaître claimed. He pictured the evolution of the universe as follows:[67]

> "At the origin, all the mass of the universe would exist in the form of a unique atom; the radius of the universe, although not strictly zero, being relatively small. The whole universe would be produced by the disintegration of this primeval atom".

Lemaître's fireworks theory required that the cosmic rays consist of high-energy charged particles, including atomic nuclei, and not merely of high-energy photons. He believed that investigations of the cosmic radiation, then only at their beginning, would supply an observational test of his theory. Later in the thirties he engaged in studies of the cosmic radiation and concluded that they did indeed support his view.[68]

7. *Conclusion*

The cosmological hypothesis which Lemaître suggested in 1931 was the first example of what later became known as Big Bang cosmology. However, unlike modern Big Bang theories Lemaître's universe did not evolve from a true singularity but from a material pre-universe, the primeval atom. A cosmical singularity is a non-physical notion in which neither space nor time exist and Lemaître always emphasized that cosmology could and should be understood in physical terms. In his later cosmological works he retained the model he had introduced in 1931. He developed it in various ways but never abandoned the idea of a physically comprehensible primeval atom.[69]

The most important innovation of Lemaître's cosmology, the notion of a creation of the entire universe, may be considered to be in conspicuous harmony with the notion of creation in Christian theology. Lemaître was an abbé and it may well be that indirectly his Christian belief helped him in formulating a creation cosmology. In 1929 as well as on later occasions he stated that God had given man intellectual faculties so as to be able to discover every aspect of the universe.[70] Lemaître was an epistemic optimist who believed that God would hide nothing for the human mind and that consequently there could be no contradiction between Christian belief and scientific cosmology. "There is no natural limitation to the power of the mind", he said in 1958 at the Solvay Congress. "The Universe does not make an exception, it is not outside its grip".[71] This does not mean that Lemaître's cosmology was designed to fit theological views or that he used it in defending such views. Contrary to some other scientists (like Milne and Whittaker) he believed that science and theology were separate fields which, though ultimately leading to the same goal, should not be mixed.[72] He was not happy at all when Pope Pius XII in 1951 declared that the new cosmology confirmed the fundamental doctrines of Christian theology. As a catholic priest Lemaître did not object to the Pope's address, but he left no doubt that he thought differently about the relationship between cosmology and religion: "As far as I can see, such a theory [of the primeval atom] remains entirely outside any metaphysical or religious question. It leaves the materialist free to deny any transcendental Being. He may keep, for the bottom of space-time, the same attitude of mind he has been able to adopt for events occurring in non-singular places in space-time. For the believer, it removes any attempt to familiarity with God, as were Laplace's chiquenaude or Jeans' finger. It is consonant with the wording of Isaias speaking of the 'Hidden God' hidden even in the beginning of the universe".[73]

NOTES AND REFERENCES

1. Historical surveys on modern cosmology, relevant to the present paper, include the following works: J. North, *The Measure of the Universe*, Oxford: Oxford University Press, 1965. J. Merleau-Ponty, *Cosmologie du XX^e Siècle*, Paris: Gallimard, 1965; *La Science de l'Univers à l'Age du Positivisme*, Paris: Vrin, 1984. R. W. Smith, *The Expanding Universe*, Cambridge: Cambridge University Press, 1982. P. Kerzberg, "Le principe de Weyl et l'invention d'une cosmologie non-statique", *Arch. Hist. Exact Sciences* 35 (1986), 1–89.
2. A. Einstein, "Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie", *Sitzungsber. Kön. Preuss. Akad: Wiss.* (1917), 142–152.
3. W. de Sitter, "On Einstein's theory of gravitation and its astronomical consequences. Third paper", *Mon. Not. Roy. Astr. Soc.* 78 (1917), 3–28.
4. See Smith (ref. 1) for references. Also R. W. Smith, "The origins of the velocity-distance relation", *J. Hist. Astronomy* 10 (1979), 133–165.
5. L. Silberstein, "The curvature of de Sitter's space-time derived from globular clusters", *Mon. Not. Roy. Astr. Soc.* 84 (1924), 363–366.
6. There exists no full biography of Lemaître and no autobiography. For biographical information the best source is A. Deprit, "Monsignor Georges Lemaitre", pp. 363–392 in A. Berger (ed.), *The Big Bang and Georges Lemaitre*, Dordrecht: Reidel, 1984. *Revue des Questions Scientifiques* 155 (1984), 139–224, is a special issue on Lemaître with informative contributions by O. Godart and A. Deprit. See also H. Kragh, "Lemaître, Georges Édouard" in F. L. Holmes (ed.), *Dictionary of Scientific Biography*, Supplement II, New York: Charles Scribner's Sons (forthcoming) and the literature cited therein.
7. G. Lemaître, "The motion of a rigid solid according to the relativity principle", *Phil. Mag.* 48 (1924), 164–176.
8. M. Born, "Die Theorie des starren Elektrons in der Kinematik des Relativitätsprinzips", *Annalen der Physik* 30 (1909), 1–56; G. Herglotz, "Über den vom Standpunkt des Relativitätsprinzips aus als 'starr' zu bezeichnenden Körper", *Annalen der Physik* 31 (1910), 393–415.

9. Eddington to de Donder, 24 December 1924. Quoted from A. V. Douglas, *The Life of Arthur Stanley Eddington*, London: Thomas Nelson and Sons, 1956, p. 111.
10. A. S. Eddington, *The Mathematical Theory of Relativity*, Cambridge: Cambridge University Press, 1923, p. 161.
11. G. Lemaître, "Note on de Sitter's universe", *Journal of Mathematics and Physics* 4 (1925), 188–192.
12. Lemaître submitted his dissertation, entitled "The gravitational field in a fluid sphere of uniform invariant density according to the theory of relativity", in November 1925. In order to complete the courses required to obtain the Ph.D. degree at MIT, Lemaître returned for a couple of months to MIT in the spring of 1927.
13. Ref. 11. Shortly after his return to Belgium, Lemaître attended the Second General Assembly of the International Astronomical Union which took place in Cambridge in July 1925.
14. *Ibid.*, p. 188.
15. *Ibid.*, p. 192.
16. *Ibid.*, p. 192.
17. K. Lanczos, "Bemerkung zur de Sitterchen Welt", *Phys. Zs.* 23 (1922), 539–543; "Über die Rotverschiebung in der de Sitterchen Welt", *Zs. f. Phys.* 17 (1923), 168–189. Referring to Dirac's memorial article on Lemaître, Kerzberg claims that Lemaître was directly influenced by Lanczos. See Kerzberg (ref. 1), p. 84 and P. A. M. Dirac, "The scientific work of Georges Lemaître", *Pontificia Academia delle Scienze, Commentarii*, 11 (1968), 1–20. However, since Dirac does not mention Lanczos and Lemaître did not refer to him in 1925 (although he did in 1927) the claim seems to lack documentation. Lemaître's work of 1925 contained only one reference, to Eddington's *Mathematical Theory of Relativity*.
18. H. P. Robertson, "On relativistic cosmology", *Phil. Mag.* 5 (1928), 835–848.
19. H. Weyl, "Redshift and cosmology", *Phil. Mag.* 9 (1930), 936–943; *Raum, Zeit, Materie*, 5th edn., Berlin: Springer-Verlag, 1923, p. 323. Weyl's contributions to non-static cosmology are analyzed in Kerzberg (ref. 1) and also in P. Kerzberg, "La découverte du temps cosmique en physique contemporaine", *Fundamenta Scientiae* 7 (1986), 1–23.
20. A. Friedmann, "Über die Krümmung des Raumes", *Zs. f. Phys.* 10 (1922), 377–386; "Über die Möglichkeit einer Welt mit konstanter negativer Krümmung des Raumes", *Zs. f. Phys.* 21 (1924), 326–332.
21. A. Einstein, "Bemerkung zu der Arbeit von A. Friedmann", *Zs. f. Phys.* 11 (1922), 326; "Notiz zu der Arbeit von A. Friedmann", *Zs. f. Phys.* 16 (1923), 228. While in the first note Einstein criticized Friedmann's work, in the second he admitted to have based his criticism on a mathematical error.
22. Friedmann's work of 1922 was listed in the *Astronomischer Jahresbericht* under relativity theory. Cf. N. S. Hetherington, "The delayed response to suggestions of an expanding universe", *J. Brit. Astr. Ass.* 84 (1973), 22–28; "Philosophical values and observation in Edwin Hubble's choice of a model of the universe", *Hist. Stud. Phys. Sci* 13 (1982), 41–68, on p. 44. According to *ISI Physics Citation Index 1920–1929*, Philadelphia: ISI, 1982, the work was cited at least five times in the period 1922–29. Apart from its modest impact on publications it was of course known to other people who discussed it informally, in particular scientists in Leningrad. Thus Friedmann acknowledged in his second work discussions with Tamarkine and V. Fock. That Friedmann's theory was not completely forgotten may also be seen from a letter which D. Iwanenko, another Leningrad physicist, wrote to P. A. M. Dirac on 11 De-

cember 1929 (Churchill College Archive). Iwanenko referred to Friedmann's works which he thought might be relevant to Dirac's recent idea of negative-energy electrons.

23. Ref. 20 (Friedmann, 1922), p. 385.
24. *Ibid.*
25. H. Weyl in *Phil. Mag.* 48 (1924), 348–349. Weyl's note was a reply to L. Silberstein, "Determination of the curvature invariant of space-time", *Phil. Mag.* 47 (1924), 907–917.
26. G. Lemaître, "Un univers homogène de masse constante et de rayon croissant", *Ann. Soc. Sci. Bruxelles* 47 (1927), 49–56. The quotations and references given here are from the English translation, "A homogeneous universe of constant mass and increasing radius", *Mon. Not. Roy. Astr. Soc.* 91 (1931), 483–490.
27. *Ibid.*, p. 489.
28. This is known from unpublished sources dating from 1927. See M. Heller, "Questions to infallible oracle", 199–210 in M. Demianski (ed.), *Physics of the Expanding Universe*, Berlin: Springer-Verlag, 1979.
29. Lemaître (ref. 26), p. 489.
30. None of Lemaître's works are listed in the *Physics Citation Index, 1920–29* (ref. 22). The index includes citations from *Astrophysical Journal, Monthly Notices* as well as the major physics periodicals.
31. According to Deprit (ref. 6, p. 371), Lemaître approached de Sitter in Leiden, but "basking as he [de Sitter] was then in the vain glory of President of the Union, de Sitter had no time for an unassuming theorist without proper international credentials". Deprit provides no source for this information.
32. G. Lemaître, "Rencontres avec A. Einstein", *Revue des Questions Scientifiques* 129 (1958), 129–132; on p. 130. In 1929 Lemaître acknowledged Einstein's references to Friedmann's work, see ref. 33, p. 216. See also O. Godart and M. Heller, "Einstein-Lemaître: Rencontre d'idées", *Revue des Questions Scientifiques* 150 (1979), 23–43.
33. G. Lemaître, "La grandeur de l'espace", *Revue des Questions Scientifiques* 15 (1929), 189–216; on p. 216. Article based on address delivered at a conference of the Brussels Scientific Society on 31 January 1929.
34. *Ibid.* It is remarkable that apparently Lemaître did nothing to make his theory known outside Belgium. Later in 1927 his paper was reprinted as vol. 4 of *Publications du Laboratoire d'Astronomie et de Géodésie de l'Université de Louvain*, hardly a site of publication which would secure dissemination.
35. E. Hubble, "A relation between distance and radial velocity among extra-galactic nebulae", *Proc. Nat. Acad. Sci.* 15 (1929), 168–173. For details, see Smith (ref. 1), pp. 180 ff.
36. Smith (ref. 1), p. 200.
37. R. Tolman, "On the possible line elements for the universe", *Proc. Nat. Acad. Sci.* 15 (1929), 297–304; on p. 304.
38. *The Observatory* 53 (1930), 38–39. Also W. de Sitter, "On the distances and radial velocities of extra-galactic nebulae, and the explanation of the latter by the relativity theory of inertia", *Proc. Nat. Acad. Sci.* 16 (1930), 474–488.
39. G. McVittie, "Georges Lemaitre", *Quart. J. Roy. Astr. Soc.* 8 (1967), 294–297.
40. A. S. Eddington, "On the instability of the Einstein world", *Mon. Not. Roy. Astr. Soc.* 90 (1930), 668–678.
41. De Sitter to Shapley, 17 April 1930. Quoted from Smith (ref. 1), p. 187.
42. Ref. 26.

43. One such example was Silberstein's already controversial conception of cosmology which he summed up in his *The Size of the Universe,* Oxford: Oxford University Press, 1930, written shortly before Lemaître's work became known. When Eddington reviewed Silberstein's book he called attention to Lemaître's "very substantial advance" which "renders obsolete the contest between Einstein's and de Sitter's cosmogenies" on which Silberstein built. A. S. Eddington, "Space and its properties", *Nature* 125 (1930), 849–850.
44. R. C. Tolman, "Discussion of various treatments which have been given to the non-static line element for the universe", *Proc. Nat. Acad. Sci.* 16 (1930), 582–594; on p. 582. In an earlier work Tolman had derived the general form of the non-static line element and proved that it was equivalent to that published by Robertson in 1929. R. C. Tolman, "The effect of the annihilation of matter on the wave-length of light from the nebulae", *Proc. Nat. Acad. Sci.* 16 (1930), 320–337. He now proved the equivalence between the line elements suggested by Robertson, Lemaître, Friedmann and himself.
45. O. Heckmann, "Über die Metrik des sich ausdehnenden Universums", *Nachr. Ges. Wis. Göttingen,* Math.-Phys. Klasse, 1931, 126–130. Heckmann showed that the expanding universe may refer to both open and closed spaces. This result was already contained in Friedmann's paper of 1924 which, however, remained unnoticed for some time even after the 'discovery' of Lemaître and Friedmann. When Pauli made Heckmann aware of Friedmann's second paper, Heckmann replied: "Als ich im Winter 1930/31 die ersten Arbeiten von de Sitter und Eddington über den Gegenstand las, habe ich aus ihnen auch die Hinweise auf frühere Literatur übernommen. Damals war man gerade auf Friedmann und Lemaître aufmerksam geworden. Und offenbar haben auch de Sitter und Eddington die von Ihnen angegebene Arbeit Friedmanns nicht beachtet". Heckmann to Pauli, 13 May 1932. Quoted from K. v. Meyenn (ed.), *Wolfgang Pauli, Wissenschaftlicher Briefwechsel,* vol. 2, Berlin: Springer-Verlag, 1985; on p. 112.
46. A. Einstein, "Zum kosmologischen Problem der allgemeinen Relativitätstheorie", *Sitzungsberichte,* Preussische Akademie der Wissenschaften, 1931, 235–237. J. Jeans, *The Mysterious Universe,* Cambridge: Cambridge University Press, 1930. W. de Sitter, *Kosmos,* Cambridge (Mass.): Harvard University Press, 1932. A. S. Eddington, *The Expanding Universe,* Cambridge University Press, 1933.
47. Eddington (ref. 40), p. 672.
48. *Ibid.*
49. G. Lemaître, "The expanding universe", *Mon. Not. Roy. Astr. Soc.* 91 (1931), 490–501. Also G. Lemaître, "On the random motion of material particles in the expanding universe. Explanation of a paradox", *Bull. Astr. Inst. Netherlands* 5 (1930), 273–274.
50. R. Tolman, "The effect of the annihilation of matter on the wavelength of light from the nebulae", *Proc. Nat. Acad. Sci.* 16 (1930), 320–337. The annihilation processes discussed by Tolman were believed to be, for example, proton-electron annihilation. Such hypothetical processes were considered by several astrophysicists in the period, including Nernst, Millikan, Jeans and Eddington. They should of course not be confused with annihilation processes in the modern sense (electron-positron annihilation) which only appeared with Dirac's theory of 1931.
51. Eddington (ref. 40).
52. Lemaître, 1931 (ref. 49), p. 499.
53. *Ibid.*, p. 501.
54. *Nature* 127 (1931), 447–453.

55. *Ibid.*, p. 453.
56. *Nature* 127 (1931), 706.
57. A. S. Eddington, "On the value of the cosmical constant", *Proc. Roy. Soc.* (London) A133 (1931), 605–615. Lemaître was fascinated by the Dirac equation which he, like many others, suggested to state in a generalized version. This was Eddington's programme too, but Lemaître did not believe that the Dirac equation could be given a cosmological significance. G. Lemaître, "Sur l'interpretation de l'equation de Dirac", *Ann. Soc. Sci. Bruxelles* 51 (1931), 83–93; "Sur l'interpretation d'Eddington de l'equation de Dirac", *Ann. Soc. Sci. Bruxelles* 57 (1937), 165–172.
58. N. Bohr, "The use of the concepts of space and time in atomic theory", *Nature* 127 (1931), 43. A more elaborated attempt to apply Bohr's quantum philosophy to cosmology was made the following year by the Leningrad physicist M. Bronstein in "The expanding universe", *Phys. Zs. Sowietunion* 3 (1933), 73–82.
59. G. Lemaître, "The uncertainty of the electromagnetic field of a particle", *Phys. Rev.* 43 (1933), 148. Letter from Dirac to Churchill College, 1 September 1979 (Churchill College Archive). Dirac recalled that Lemaître's lecture took place "around 1930" but the minute book of the Kapitza Club shows that the date was 25 April 1933 and that the title of the lecture was "The primeaeval atom hypothesis" (Churchill College Archive). According to Dirac's recollection Lemaître emphasized in his lecture that he did not believe God influenced directly the course of atomic events. The Kapitza Club was an informal but distinguished series of seminars initiated in 1922 by P. Kapitza, the Russian phycisist who worked in Cambridge in the period 1918–34.
60. Ref. 56.
61. *Ibid.*
62. *Nature* 128 (1931), 700–722.
63. *Ibid.*, p. 704.
64. North (ref. 1), p. 125.
65. Ref. 62, p. 708. See also de Sitter (ref. 46), 131–133.
66. Ref. 62, p. 705.
67. *Ibid.*, 706.
68. G. Lemaître and M. S. Vallarta, "On Compton's latitude effect of cosmic radiation", *Phys. Rev.* 43 (1933), 87–91. In 1932 A. H. Compton was able to detect that cosmic rays are deflected in the earth's magnetic field and hence that they consist of charged particles. Lemaître interpreted Compton's discovery as giving support to the theory of a super-radioactive origin of the cosmic radiation.
69. G. Lemaître, "Evolution of the expanding universe", *Proc. Nat. Acad. Sci.* 20 (1934), 12–17; *L'Hypothèse de l'Atome Primitif*, Neuchatel: Éditions du Griffon, 1946; "Cosmological applications of relativity", *Rev. Mod. Phys.* 21 (1949), 357–366.
70. Ref. 33, p. 216. See also O. Godart and M. Heller, "Un travail inconnu de Georges Lemaître", *Rev. d'Hist. Sci.* 31 (1978), 346–359, on p. 359.
71. G. Lemaître, "The primaeval atom hypothesis and the problem of the clusters of galaxies", pp. 1–25 in R. Stoops (ed.), *La Structure et l'Évolution de l'Univers*, Brussels: Institut International de Physique Solvay, 1958; on p. 7.
72. E. A. Milne, *Modern Cosmology and the Christian Idea of God, Oxford:* Oxford University Press, 1952; E. T. Whittaker, *Space and Spirit: Theories of the Universe and the Arguments*

for the Existence of God, London: Nelson & Sons, 1946. Deprit (ref. 6, p. 387) claims that Einstein was suspicious to Big Bang cosmology, "if only for the reason that it was proposed by a Catholic priest and seconded by a devout Quaker (Eddington), hence highly suspect of concordism". The claim is undocumented and also, I think, unfounded. In general Einstein's view of Big Bang theory was remarkably close to Lemaître's. For example, Einstein did not accept space-time singularities as physically real, a conclusion also drawn by Lemaître. In his last comment on Big Bang cosmology, Einstein wrote: "One may not ... assume the validity of the equations for very high density of field and matter, and one may not conclude that the 'beginning of the expansion' must mean a singularity in the mathematical sense ... This consideration does, however, not alter the fact that the 'beginning of the world' really constitutes a beginning, from the point of view of the development of the new existing stars and systems of stars, at which those stars and systems of stars did not yet exist as individual entities". A. Einstein, *The Meaning of Relativity*, 5th edn., Princeton: Princeton University Press, 1956, p. 129 (appendix for the second edition of 1945).

73. Ref. 71, p. 7. For the reaction to the speech of Pope Pius XII, see E. McMullin, "How should cosmology relate to theology?", pp. 17–57 in A. R. Peacocke (ed.), *The Sciences and Theology in the Twentieth Century*, London: Oriel Press, 1981. See also O. Godart and M. Heller, "Les relations entre la science et la foi chez Georges Lemaître", *Pontificia Academia delle Scienze, Commentarii*, 3 (1979), 1–12.