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GOLDEN OLDIE EDITORIAL

Editorial note to: Georges Lemaître, A homogeneous universe of constant mass and increasing radius accounting for the radial velocity of extra-galactic nebulae

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1 Introduction

As already pointed out in a previous Golden Oldie devoted to the Lemaître's short note of 1931 which can be considered as the true "Charter" of the modern big bang theory [1], although the Belgian scientist was primarily a remarkable mathematician and a theoretical physicist, he stayed closely related to astronomy all his life and always felt the absolute need for confronting the observational data and the general relativity theory. This basic fact explains why as soon as 1927, while still a beginner in cosmology, he was the first one to be able to understand the recent observations on the recession velocities of galaxies as a natural consequence of *dynamical* cosmological solutions of Einstein's field equations.[1] Before examining in detail the contents of his outstanding article, let us summarize the road which, in the few preceding years, led the young Lemaître to the expanding universe (see e.g. [6]).

In 1923, the same year as he was ordained as a priest, Georges Lemaître obtained a 3-year fellowship from the Belgian government, enabling him to study abroad.

[1] A number of other authors such as Hermann Weyl [2], Carl Wirtz [3], Ludwig Silberstein [4], Knut Lundmark [5] had looked for a relation that fit into the context of De Sitter's static model which presented *spurious* radial velocities.

The republication of the original paper can be found in this issue following the editorial note and online via doi:10.1007/s10714-013-1548-3.

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He spent the first year at the University of Cambridge, England, where he studied stellar astronomy, relativistic cosmology and numerical analysis under the direction of Arthur Eddington. He spent the second year at Harvard College Observatory in Cambridge, Massachusets, directed by Harlow Shapley who worked on the problem of nebulae. Then he passed to the Massachusetts Institute of Technology (M.I.T.), where Edwin Hubble and Vesto Slipher were active. The first one measured the distances of nebulae by observing variable stars of the Cepheid type, the second one estimated their radial velocities from their spectral shifts.

While following closely the experimental work of the American astronomers, who were going soon to found observational cosmology, Lemaître undertook a PhD thesis at M.I.T. with his compatriot Paul Heymans as advisor, on the gravitational field of fluids in general relativity—a theoretical subject suggested by Eddington. At the end of 1924, he attended a meeting in Washington which remained famous since the discovery of Cepheids in spiral nebulae was announced there by Edwin Hubble; this made it possible to prove the existence of galaxies external to ours, and Lemaître understood at once that this new design of "island universes" would have drastic consequences for the theories of relativistic cosmology.

On July 1925, his American stay ended and Lemaître had to go back to Belgium. In this same decisive year for observational cosmology, Lemaître obtained his first notable scientific results, concerning the cosmological solution found by De Sitter [7]. In the first article [8] he demonstrated how he could introduce new coordinates for the De Sitter universe which made the metric no more static, with a space of zero curvature and a scale factor depending exponentially on time. This metric would be used twenty years later by the keenest adversaries of the theory of the expanding universe in the framework of "steady-state" models [9,10], and still later in the 1980's to describe the hypothetical inflationary phase of the very early universe, see e.g. [11]. In the second article [12] he deduced that the relation between the relative speed of test-particles and their mutual distances in the De Sitter universe was linear. It was the first time that the cosmological constant (when it is positive) was seen allotting the role of a "cosmic repulsion" forcing the worldlines of particles to recede with time. However, although he found this non-static feature to be promising because of its connection to the redshifts of nebulae, he also realized that the model resulted in an infinite Euclidean space, that he considered inadmissible: as a neo-Thomist he did not accept the actual infinite and remained faithful to the finitude of space and matter throughout his career. Thus he had to seek for an alternative explanation, involving a truly non-static and spatially closed solution of Einstein's equations.

In 1926–27, Lemaître went again to the United States, where he remained at M.I.T. during three quarters of the academic year. Back in Europe in June 1927, he was informed by letter that he got his PhD [13], having been exempted of oral defense. The same year, he was appointed professor at the University of Louvain and published his great article on the expanding universe.

2 Recession of galaxies and expanding universe

Since 1912, Vesto Slipher had undertaken a program of measurement of the radial velocities of spiral nebulae. Interpreted in terms of the Doppler effect, the shifts in frequency (or wavelength) implied a radial speed of displacement of the source compared to the observer. Radial speeds were thus indirectly measured by spectroscopy. By 1917, Slipher (see [14] and references therein) had analyzed the spectra of 25 spiral nebulae, which he had observed at Lowell Observatory in Flagstaff, Arizona; 21 of them presented redshifts that could be interpreted as a systematic motion of recession (the exceptions were M81 and 3 galaxies from the Local Group). However, nobody suspected yet the repercussions that these preliminary data would have soon for the whole of cosmology, mainly due to the fact that the debate on whether spiral nebulae were island universes went on. The evidence for the redshifts mounted mainly due to Slipher's efforts, and by 1923 reached a score of 36 among 41 spiral nebulae.

Slipher never published his final list,[2] but it was given in Arthur Eddington's book of 1923 [16], who noticed that "one of the most perplexing problems in cosmogony is the great speed of spiral nebulae. Their radial velocities average about 600 km. per sec. and there is a great preponderance of velocities of recession from the solar system". The influential British astronomer suggested that effects due to the curvature of space-time should be looked for and referred to De Sitter's model for a possible explanation.

Thanks to his various stays at Cambridge, England, and at M.I.T. (where he met Slipher personally), Lemaître was perfectly informed of these preliminary results, and he wanted to take account of the available data by using a *new* cosmological solution of Einstein's equations.

As the title of his 1927 article clearly states, Lemaître was able to connect the expansion of space arising naturally from the non-static cosmological solutions of general relativity with the observations of the recession velocities of extragalactic nebulae.

He begins to review the dilemma between the De Sitter and Einstein universe models. The De Sitter model ignored the existence of matter; however, it emphasized the recession velocities of spiral nebulae as a simple consequence of the gravitational field. Einstein's solution allowed for the presence of matter and led to a relation between matter density and the radius of the space—assumed to be a positively curved hypersphere; being strictly static due an adjustment of the cosmological constant, it could not, however, explain the recession of the galaxies. Lemaître thus looks for a new solution of the relativistic equations combining the advantages of the Einstein and De Sitter models without their inconveniences, i.e. having a material content and explaining at the same time the recession velocities.

For this, in the next section he assumes a positively curved space (as made precise in a footnote, with "elliptic topology", namely that of the projective space $\mathbf{P}^3$ obtained by identification of antipodal points of the simply-connected hypersphere $\mathbf{S}^3$; see [17] for an explanation of such a choice) with the radius of curvature R (and consequently the matter density ρ) being a function of time t, and a non-zero cosmological constant λ. From Einstein's field equations he obtains differential equations (Eqs. (2)–(3)) for $R(t)$ and $\rho(t)$ almost identical to those previously obtained by Friedmann [18] (at the time Lemaître was not aware of Friedmann's work, see below). The difference is that

[2] For details see [15].

Lemaître supposes the conservation of energy (Eq. (4))—this is the first introduction of thermodynamics in relativistic cosmology—and he includes the pressure of radiation as well as the term of matter density into the stress-energy tensor (he rightly considers the matter pressure to be negligible). Lemaître emphasizes the importance of radiation pressure in the first stages of the cosmic expansion. Now it is well known that, within the framework of big bang models, the approximation of zero pressure is valid only for times posterior to the big bang for approximately four hundred thousand years. Just like Einstein and De Sitter, Friedmann had made the assumption that the term of pressure in the stress-energy tensor was always zero. The equations derived by Lemaître are thus more general and realistic.

Lemaître shows how the Einstein and De Sitter models are particular solutions of the general equations. Next he chooses as initial conditions $R' = R'' = 0$, $R = R_0$ at $t = -\infty$ and he adjusts the value of the cosmological constant such that $\lambda = 1/R_0$, in the same way Einstein had adjusted the value of λ in his static model with constant radius.

As a consequence, the exact solution he obtains in Eq. (30) describes a monotonous expanding universe, which, when one indefinitely goes back in time, approaches in an asymptotic way the Einstein static solution, while in the future it approaches asymptotically an exponentially expanding De Sitter universe.

This model, deprived of initial singularity and, consequently, not possessing a definite age—as well as the "monotonous solution of second species" found earlier by Friedmann—will be later baptized the Eddington-Lemaître's model (see below).

Lemaître does not provide a graph for $R(t)$ but gives numerical values in a table going from $t = -\infty$ to $+\infty$. For the sake of clarity our Fig. 1 depicts such a graph.

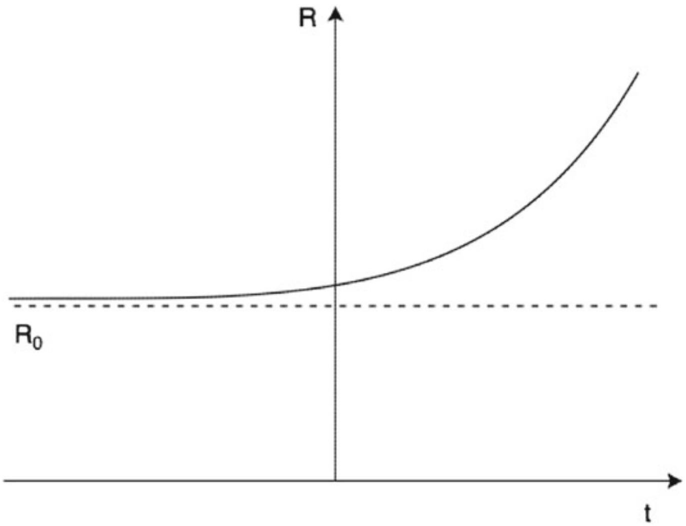

Fig. 1 The 1927 Lemaître's universe model, later named Eddington–Lemaître. The radius R_0 of the static Einstein hypersphere is reached asymptotically for $t = -\infty$. The origin of cosmic time is arbitrary, thus the model does not pose any problem of age

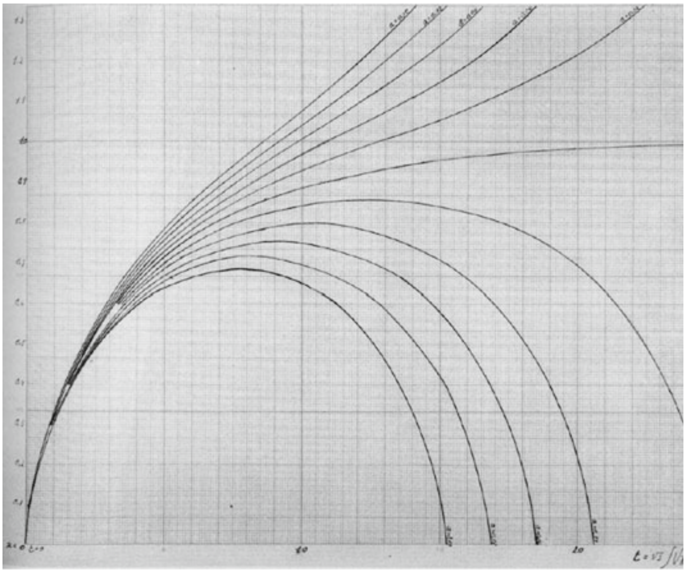

Fig. 2 Handwritten graph by Lemaître. This extraordinary diagram, plotted by Lemaître in 1927, but unpublished until 1998 [21], depicts the time evolution of the radius of the universe with the cosmological constant (denoted a), for a space of positive curvature. All the models start with a singularity in ($x = 0$, $t = 0$). For a sufficiently large cosmological constant a, the universe becomes open. The most recent cosmological data are compatible with a Lemaître's solution with positive curvature and accelerated expansion (*top curve*)

Lemaître conceived the static Einstein universe as a kind of pre-universe out of which the expansion had grown as a result of an instability. As a physical cause for the expansion he suggested the radiation pressure itself, due to its infinite accumulation in a closed static universe, but he did not develop this (erroneous) idea.

While giving preference to this particular model in his article, Lemaître nevertheless calculated separately the whole of dynamical homogeneous cosmological solutions, since he had the general formula (Eq. (11)) making it possible to calculate the time evolution of all the homogeneous isotropic models with positive curvature. The Lemaître archives at the University of Louvain keep a red pad with the inscription "1927", which contains the galley proofs of his article, some notes in handwriting connected with the paper, and two diagrams which (unfortunately) do not appear in any of his publications. These diagrams depict the time evolution of the space scale factor depending on the value of the cosmological constant for all homogeneous and isotropic solutions of Einstein's equations with positive curvature of space (Fig. 2).

As mentioned above, the 1927 article does not refer to the work of Friedmann, published in *Zeitschrift für Physik*—although it was one of the best known journals in theoretical physics at that time. This absence seems strange if one remembers the two notes by Einstein published in the same review [19], which had been largely discussed in the scientific community. A plausible explanation is that Lemaître could not read the German [20]. Friedmann's articles were pointed out to Lemaître by Einstein himself, during their meeting at the 1927 Solvay Conference. The reference to Friedmann thus appears for the first ime in a text of 1929 written in French, *La grandeur de l'espace*

[22], in which Lemaître thanks "Mr. Einstein for the kindness that he showed by announcing to me the important work of Friedmann which includes several of the results contained in my note on a homogeneous universe". The reference will also appear in the 1931 English translation of Lemaître's article, see below.

The exceptional interest of Lemaître's work is to provide the first interpretation of cosmological redshifts as a natural effect of the expansion of the universe within the framework of general relativity, instead of a real motion of galaxies: as it is written down in Eq. (23), space is constantly expanding and consequently increases the apparent separations between galaxies. This idea will prove to be one of the most profound discoveries of our time.

The relation of proportionality (23) between the recession velocity and the distance is an approximation valid at not too large distances which can be used "within the limits of the visible spectrum". Then, using the available astronomical data, Lemaître provides the explicit relation of proportionality in Eq. (24), with a factor 625 or 575 km/s/Mpc, depending on his choice of observations which presented an enormous scatter. This is the first determination of the so-called Hubble law and the Hubble constant, that should as well have been named Lemaître's law.

For this the Belgian scientist uses a list of 42 radial velocities compiled by Gustav Strömberg, a Swedish astronomer at the Mount Wilson Observatory,[3] and deduces their distance from a recent empirical formula between the distance and the absolute magnitude provided by Hubble [24], who himself took them from Hopmann [25]. Eventually, Lemaître is able to give the numerical figures for the initial and present-day values of the radius of the universe, resp. $R_0 = 2,7 \times 10^8\, pc$ and $R = 6 \times 10^9\, pc$. At the very end he points out that the largest part of the universe will be forever out of reach of the visible spectrum, since the maximum distance reached by the Mt Wilson telescope is only $R/120$, whereas for a distance only greater than $R/11,5$ the whole visible spectrum is displaced into the infrared—he could not imagine the space era with infra-red and submillimeter telescopes placed on board of satellites.

We have seen above that Lemaître knew already all the solutions of Einstein's equations for homogeneous and isotropic universes. The reason why he privileged a very particular model, adjusting the cosmological constant in order to have no beginning of time, is due to his overestimate of the Hubble constant: as is well known, the latter gives an order of magnitude of the duration of the expansion phase; with the estimate of about 600 km/s/Mpc found by Lemaître, this period is about one billion years only, a number less than the age of the Earth estimated by the geologists of the time. Thus the model with exponential expansion and no beginning allowed to reconcile the theory with both astronomical and geological data.

3 First reactions

The significance of Lemaître's work has remained mostly unnoticed for three years, not exclusively (but partly) due to the fact that it was published in French in an "obscure

[3] Strömberg [23] relied himself on redshifts measured by Slipher and included some globular clusters in addition to spiral nebulae.

and completely inaccessible journal", as is sometimes claimed [26], instead of one of the prestigious astronomical journals of the time.[4] As rightly pointed out by Lambert [27], the *Annales de la Société Scientifique de Bruxelles* published some articles in English, had an excellent scientific level and therefore were displayed in a large number of academic libraries and observatories all around the world; also French could be read by a much larger scientific audience than today. Indeed, the main obstacle to a larger diffusion of Lemaître's article was that most of the physicists of the time, such as Einstein and Hubble, could not accept the idea of a non-static universe. This was not the case with Eddington; unfortunately, his former mentor, to whom Lemaître had sent a copy, either forgot to read it in time, or he had not understood its importance.

From 24 to 29 October 1927 the Fifth Solvay Conference in Physics took place in Brussels, one of the great meetings of world science. The Solvay Conference was devoted to the new discipline of quantum mechanics, whose problems disturbed many physicists. Among them was Einstein. For Lemaître, it was the opportunity to discuss with the father of general relativity. He later reported himself on this meeting: "While walking in the alleys of the Parc Léopold, [Einstein] spoke to me about an article, little noticed, which I had written the previous year on the expansion of the universe and which a friend had made him read. After some favorable technical remarks, he concluded by saying that from the physical point of view that appeared completely abominable to him. As I sought to prolong the conversation, Auguste Piccard, who accompanied him, invited me to go up by taxi with Einstein, who was to visit his laboratory at the University of Brussels. In the taxi, I spoke about the speeds of nebulae and I had the impression that Einstein was hardly aware of the astronomical facts. At the university, everyone began to speak in German" [28]. Einstein's response to Lemaître shows the same unwillingness to change his position that characterized his former response to Friedmann (see e.g. [29]): he accepted the mathematics, but not a physically expanding universe!

In 1928 H. P. Robertson published an article [30] in which he wanted to replace De Sitter's metric by a "mathematically equivalent in which many of the apparent paradoxes inherent in [De Sitter's solution] were eliminated". He got the formula $v = cd/R$ where d is the distance of the nebula and R the radius of curvature of the universe, but in the framework of a *static* solution. Robertson used the same set of observations as had been taken by Lemaître[5] and that would be taken by Hubble one year later. From this he calculated $R = 2 \times 10^{27}$ cm, and a proportionality constant of 464 km/s/Mpc (that he did not calculate, the figure can be found in [31]). The main interest of Robertson's work (see also [32]) is that he was the first to search in detail for all the mathematical models satisfying a spatially homogeneous and isotropic universe—which imply strong symmetries in the solutions of Einstein's equations.

In 1929, Hubble [33] used the experimental data on the Doppler redshifts mostly given by Slipher (who was not quoted) and found a linear velocity-distance relation $v = Hr$ with $H = 465 \pm 50$ km/s/Mpc for 24 objects and 513 ± 60 km/s/Mpc

[4] The paper was reprinted later in 1927 in vol. 4 of *Publications du Laboratoire d'Astronomie et de Géodésie de l'Université de Louvain*, still less suited for widespread dissemination.

[5] He did not know the Lemaître's articles of 1925 and 1927.

for 9 groups. The law was strictly identical to Lemaître's Eq. (24), with almost the same proportionality factor, but Hubble did not make the link with expanding universe models. He stated "The outstanding feature, however, is the possibility that the velocity-distance relation may represent the De Sitter effect". In fact Hubble never read Lemaître's paper; he interpreted the galaxy redshifts as a pure Doppler effect (due to a proper radial velocity of galaxies) instead of as an effect of space expansion. And throughout his life he would stay skeptical about the general relativistic interpretation of his observations. For instance, in the 202 pages of his book of 1936 *The realm of the nebulae* [34], he tackled the theoretical interpretation of the observations only in a short ultimate paragraph on page 198, in which he quoted Einstein, De Sitter, Friedmann, Robertson, Tolman and Milne. As pointed out by his biographer G. Christianson, Hubble was chary of "all theories of cosmic expansion long after most astronomers and physicists had been won over. When queried about the matter as late as 1937, he sounded like an incredulous schoolboy: 'Well, perhaps the nebulae are all receding in this peculiar manner. But the notion is rather startling' " [35]. Indeed the fact that the expansion of the universe was discovered by Hubble is a myth that was first propagated by his collaborator Humason as soon as 1931 (see e.g. [36]) and Hubble himself, who was fiercely territorial; in a letter to De Sitter dated 21 August 1930, he wrote "I consider the velocity-distance relation, its formulation, testing and confirmation, as a Mount Wilson contribution and I am deeply concerned in its recognition as such" (quoted in [37]).

One month only after Hubble's article, Tolman joined the game of searching for an explanation of recession velocities, but still in the framework of a static solution [38], as he said "the correlation between distance and apparent radial velocity of the extra–galactic nebulae obtained by Hubble, and the recent measurement of the Doppler effect for a very distant nebula made by Humason at the Mount Wilson Observatory, make it desirable to consider once more the theoretical relations between distance and Doppler effect which could be expected from the form of line element for the universe proposed by De Sitter". One year later, Tolman published another article [39] where he suggested that the expansion was due to the conversion of matter into radiation, an idea already proposed by Lemaître in his 1927 article, who again was not quoted.

A new opportunity for the recognition of Lemaître's model arose early in 1930. In January, in London, a discussion between Eddington and De Sitter took place at a meeting of the Royal Astronomical Society. They did not know how to interpret the data on the recession velocities of galaxies. Eddington suggested that the problem could be due to the fact that only static models of the universe were hitherto considered; he nicely formulated the situation as follows: "Shall we put a little motion into Einstein's world of inert matter, or shall we put a little matter into De Sitter's Primum Mobile?" [40], and called for new searches in order to explain the recession velocities in terms of dynamical space models.

Having read the report of the meeting of London, Lemaître understood that Eddington and De Sitter posed a problem which he had solved three years earlier. He thus wrote to Eddington to remind him about his communication of 1927 and requested him to transmit a copy to de Sitter: "Dear Professor Eddington, I have just read the February n° of the *Observatory* and your suggestion of investigating non statical intermediary solutions between those of Einstein and De Sitter. I made these investigations two years ago. I consider a universe of curvature constant in space but increasing with time. And I emphasize the existence of solution in which the motion of the nebulae is always a receding one from time minus infinity to plus infinity."[6] Lemaître precised: "I had occasion to speak of the matter with Einstein two years ago. He told me that the theory was right and is all which needs to be done, that it was not new but had been considered by Friedmann, he made critics against which he was obliged to withdraw, but that from the physical point of view it was 'tout à fait abominable' " (quoted in [41]).

The British astrophysicist was one of the most prominent figures of science at the time, and was in the best possible position to play a key role in the recognition of the Lemaître's results. This time he paid attention to Lemaître's contribution, dispatched a copy to De Sitter in Holland and H. Shapley in the United States. Eddington was somewhat embarrassed. According to George McVittie, at the time a research student of Eddington working with him on the stability of the Einstein's static model, "[I remember] the day when Eddington, rather shamefacedly, showed me a letter from Lemaître which reminded Eddington of the solution to the problem which Lemaître had already given. Eddington confessed that although he had seen Lemaître's paper in 1927 he had forgotten completely about it until that moment" (quoted in [41]).

On March 19th, Eddington accompanied his invoice of Lemaître's paper to De Sitter in Leiden by the following comment: "It was the report of your remarks and mine at the [Royal Astronomical Society] which caused Lemaître to write to me about it. At this time, one of my research students, McVittie, and I had been worrying at the problem and made considerable progress; so it was a blow to us to find it done much more completely by Lemaître (a blow attenuated, as far as I am concerned, by the fact that Lemaître was a student of mine)" (reported in [42]).

De Sitter answered Lemaître very favorably in a letter dated March 25th, 1930, and the Belgian physicist replied to him on April 5th (these letters are fully displayed in [43]). In late May, De Sitter published a discussion about the expansion of the universe [44], where he wrote "A dynamical solution of the equations (4) with the line-element (5) (7) and the material energy tensor (6) is given by Dr. G. Lemaître in a paper published in 1927, which had unfortunately escaped my notice until my attention was called to it by Professor Eddington a few weeks ago."

On his side, Eddington reworked his communication to the following meeting of the Royal Astronomical Society in May, to bring Lemaître's work to the attention of the world [45]. Then he published an important article [46] in which he reexamined the Einstein static model and discovered that, like a pen balanced on its point, it was unstable: any slight disturbance in the equilibrium would start the increase of the radius of the hypersphere; thus he adopted Lemaître's model of the expanding universe—which will be henceforward referred to as the Eddington–Lemaître model—and calculated that the original size of the Einstein universe was about 1,200 million light years, of the same order of magnitude as that estimated by Lemaître in 1927. Interestingly enough, Eddington also considered the possibility of an initial universe with a mass M greater or smaller than the mass M_E of the Einstein model, but he

6 From a copy kept at the Archives Lemaître of Louvain-la-Neuve, quoted in [27].

rejected the two solutions, arguing that, for $M > M_E$, "it seems to require a sudden and peculiar beginning of things", whereas for $M < M_E$, "the date of the beginning of the universe is uncomfortably recent".

Eventually, Eddington sponsored the English translation of the 1927 Lemaître's article for publication in the *Monthly Notices of the Royal Astronomical Society* [47].

Then, with the support of Eddington and De Sitter, Lemaître suddenly rose to become a celebrated innovator of science. He was invited to London in order to take part in a meeting of the British Association on the relation between the physical universe and spirituality. But in the meantime he had considerably progressed in his investigations of relativistic cosmologies, and instead of promoting his model of 1927, he dared to propose that the Universe expanded from an initial point which he called the "Primeval Atom". Then cosmology experienced a second paradigmatic shift [48].

4 The English translation and discrepancies

A great deal has been written on the topic of who really discovered the expanding universe [49–56]. The French astronomer Paul Couderc [57] was probably the first one to rightly underline the priority of Lemaître over Hubble, but since Lemaître himself never claimed any priority (see [58] for more details), the case was not much discussed.

An intriguing discrepancy between the original French article and its English translation had already been quoted by various authors (e.g. [41–43]): the important paragraph discussing the observational data and Eq. (24) where Lemaître gave the relation of proportionality between the recession velocity and the distance (in which the determination of the constant that later became known as Hubble's constant appears) was replaced by a single sentence: "From a discussion of available data, we adopt $R'/R = 0,68 \times 10^{-27}\text{cm}^{-1}$". It was found curious that the crucial paragraphs assessing the Hubble law were dropped so that, either due to Eddington's blunder[7] or some other mysterious reason, Lemaître was never recognized as the discoverer of the expansion of the universe. *De facto* Lemaître was eclipsed and multitudes of textbooks proclaim Hubble as the discoverer of the expanding universe, although Hubble himself never believed in such an explanation [59].

Suddenly, in 2011, a burst of accusations has flared up against Hubble, from the suspicion that a censorship was exerted either on Lemaître by the editor of the M.N.R.A.S. [60] or on the editor by Hubble himself [37]—suspicion based on the "complex personality" of Hubble, who strongly desired to be credited with determining the Hubble constant.

The controversy was ended by Mario Livio, from the *Space Telescope Institute* [61], with the help of the Archives Lemaître at Louvain and the Archives of the Royal Astronomical Society (see also [27] for additional details). It is not the scope of the present note to enter into the explanations that solve the conundrum, it is sufficient to

[7] Until very recently the identity of the translator was not assessed, generally assumed to be that of Eddington himself.

say that it is now certain that Lemaître himself translated his article, and that he chose to delete several paragraphs and notes without any external pressure. On the contrary, he was encouraged to *add* comments on the subject; but the Belgian scientist, who had indeed new ideas, preferred to publish them in a separate article, published in the same issue of M.N.R.A.S. [62].

For the present purpose it is much more interesting to list in detail all the discrepancies—as far as we know a little work that has never been done—in order to better understand how the preoccupations of Lemaître had changed since 1927, and how the question which he had in mind in 1931 was less the expansion of space than the deep cause of it, how it started and how the first galaxies could form.

- Section 1, first paragraph
  The footnote "We consider simply connected elliptic space, i.e. without antipodes" is suppressed from the 1931 translation.
  As soon as 1917, De Sitter [18,63] distinguished the spherical space $\mathbf{S}^3$ and the projective space $\mathbf{P}^3$, that he called the elliptical space. As recalled by Lemaître in the first paragraph, $\mathbf{P}^3$ has a (comoving) volume $\pi^2 R^3$ instead of $2\pi^2 R_0^3$ for $\mathbf{S}^3$, and the longest closed straight line is πR instead of $2\pi R$. The main cosmological difference is due to the presence, in $\mathbf{S}^3$, of an antipodal point associated to any point, and in particular to the observer, at a distance of πR precisely. This was considered as an undesirable fact, so that cosmological models with $\mathbf{P}^3$ seemed preferable than those with $\mathbf{S}^3$.
  Eddington [16] also referred to elliptical space as an alternative more attractive than $\mathbf{S}^3$, and Lemaître also adopted this point of view.[8] We can infer that he suppressed his footnote because in any case, topology has no influence on the dynamics, which was the very purpose of his work, and because in the meantime he had published an extended discussion on the subject [62], which he merely points out in reference 4 of the 1931 version.
- Section 1, second paragraph
  In the 1931 translation, the original sentence "[...] it is of great interest as explaining the fact that extragalactic nebulae seem to recede from us with a huge velocity [...]" is replaced by "[...] it is of extreme interest as explaining quite naturally the observed receding velocities of extragalactic nebulae [...]" to acknowledge the fact that, due to the post–1927 observational work of Hubble and Humason, the receding velocities had acquired a firm observational status.
- Section 1, third paragraph
  The sentence "This relation forecasted the existence of masses enormously greater than any known when the theory was for the first time compared with the facts" is replaced by "This relation forecasted the existence of masses enormously greater than any known at the time".
- Section 1, third paragraph
  The footnote giving reference to Hubble's article of 1926 is suppressed because it is no more up-to-date.
- Section 1, sixth paragraph

[8] Note that elliptical space is not simply connected but multiply connected, see e.g. [17].

The two footnotes are suppressed. They both give geometrical details and subtleties about the De Sitter solution that Lemaître probably judged not appropriate for a journal such as *M.N.R.A.S*, more devoted to astronomy than to geometry. These details came mainly from an article by K. Lanczos and the 1925 articles of Lemaître himself. In the 1931 version, he added at the end of the article the bibliographic references to Lanczos and himself without development, and added references to H. Weyl and P. du Val.

– Section 2
Between Eqs. (4) and (5) the sentence "It is suitable for an interesting interpretation" has disappeared for the sake of economy.

– Section 4
The paragraphs from "Radial velocities of 43 extra-galactic nebulae [...]" up to "This relation enables us to calculate R_0", as well as the three footnotes, are suppressed and replaced by "From a discussion of available data, we adopt $R'/R = 0,68 \times 10^{-27}\text{cm}^{-1}$". This is precisely the part of the 1927 article where Lemaître discusses the astronomical data on the redshifts, the errors in the distance estimates, where he gives the relation of proportionality between the velocity and distance, and in footnotes, the references to Strömberg and Lundmark, as well as his calculation of two possible values of the constant of proportionality of 575 and 670, depending on how the data are grouped. The original Eq. (24) is truncated to a pure numerical one, whereas the original gives precisely what is called the Hubble law.
In a letter dated 9 March 1931 addressed to William H. Smart, the editor of *M.N.R.A.S.*, Lemaître writes: "I send you a translation of the paper. I did not find advisable to reprint the provisional discussion of radial velocities which is clearly of no actual interest, and also the geometrical one, which could be replaced by a small bibliography of ancient and new papers on the subject" (quoted in [61]). The choice of Lemaître is quite comprehensible because the data he used in 1927 gave only very imperfectly the linear relation $v = Hd$, whereas in 1931 the new data from Hubble allowed to validate this relationship in a much more precise manner, see Fig. 3 for comparative plots. Also because, as he explained himself in 1950, in 1927 he had not at his disposal data concerning clusters of galaxies, and he added that Hubble's law could not be proved without the knowledge of the clusters of galaxies" [64]. Here we find again one of the characteristic features of Lemaître's personality already mentioned, namely the crucial importance he always gave to experimental data.

– Section 6
The item 4 of the 1927's conclusions, giving the radius of the universe as 1/5th the radius of Einstein's hypersphere, is suppressed, and in the next sentence, Lemaître changes the range of the 100-inch Mount Wilson telescope estimated by Hubble from $R/120$ to $R/200$.

– Added references
Whereas the 1931 translation does not contain footnotes, it provides at the end new references that could not be given in the 1927 article: to Friedmann's article of 1922 and Einstein's comments on it, the article of Tolman about models of variable radius of 1923, the developments of his own model given by Eddington,

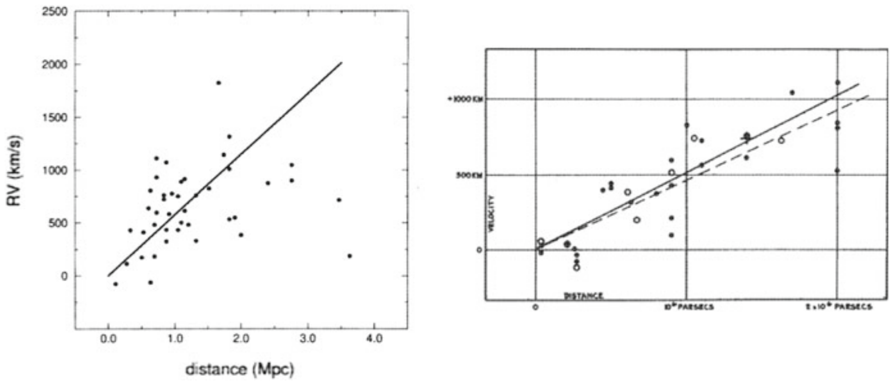

Fig. 3 Comparison between the data used by Lemaître in 1927 (*left*) to yield the first empirical value of the rate of expansion of the Universe as 575 km/s/Mpc (reconstructed in [31]), and the radial velocity–distance diagram published by Hubble in 1929, with a best slope of 530 km/s/Mpc (*right*)

De Sitter and himself in 1930, and eventually two popular expositions given by him in 1929 (in French) and by De Sitter in 1931.

Comment by the Golden Oldies editor: A brief biography of Georges Lemaître was printed together with another Golden Oldie by him, in *Gen. Relativ. Gravit.* **29**, 639 (1997), doi:10.1023/A:1018803604510.

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