When we sought permission from Sir William McCrea he wrote back: I am only too happy for you to use it in the way you propose. However, I have revised my views on a number of problems I wrote about in the article and would have expressed things different were I to be writing at this point of time.

– Editor

Physics and cosmology: Some interactions

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Introduction

Georges Lemaître (1894–1966) was one of the founders of modern cosmology – expanding universe cosmology, as it may be called. He was *the* founder of modern physical cosmology – big bang cosmology, as it has come to be called. His ideas in this field seem to have become well-defined by 1933, although any date for their inception is harder to identify, and now, 50 years later, we are invited to commemorate this historic scientific adventure. Particularly for those of us who knew Lemaître, it is a high privilege to participate and to do so in Lemaître's own University in the Institute that bears his name.

After half-a-century of enormous developments in physics and astronomy, most of the particulars of Lemaître's model have been superceded. Probably he expected this to happen, and he did not in fact pursue them in much detail. Nevertheless the clarity and sureness with which he recognized the basic problems and the general lines along which they should be approached remain astonishing. The purpose of this paper is to sketch in some of the background to Lemaître's cosmology, to recall its main features, briefly to review the development of observational cosmology since the time when Lemaître proposed his model, and then to note some sequels to his ideas in some of the most recent models. Finally, since Lemaître sought to relate the physics and the cosmology of his day, it seems appropriate to end with some attempt to assess the present-day state of the relationship.

Lemaître's lifetime

Lemaître published his now famous first paper on the expanding universe in 1927 in Belgium. At the time he did not know that the Russian mathematician and meteorologist Alexander A. Friedman (1888–1925) had published similar work in 1922 in Germany. The names of these two men will evermore be together linked with one of the most audacious developments in physical thought. They were near contemporaries, but each lived as though the other had never been.

To notice when that was, it may help if we remember that one of the great founders of astrophysics – who must seem to most people a figure in the distant past – E. Arthur Milne (1896–1950) was actually about two years *younger* than Lemaître. By contrast, one of the great founders of geophysics, Harold Jeffreys (b. 1891), was three years *older* than Lemaître, and he is still an active scientist!

Natural philosophy

The general procedure of natural philosophy seems inevitable. *Observations* of something recognized as being observable suggest a *mathematical model* of that something; the model serves to predict the outcome of *further observations*; the actual outcome suggests an *improved model*, and so forth.

In the Newtonian approach, a model consists of the (model) system being studied + a reference frame (which models the rest of the Universe) + universal time + laws (of motion, of electromagnetism, ...) obeyed by the (model) system and regarded as unchanging with time.

Cosmology is the study of the Universe as a whole. It is therefore not amenable to the Newtonian approach. The aim of cosmology must be to construct cosmological models, not to 'discover' laws. This is the Einsteinian approach, as realized in general relativity (GR). Every GR model is a universe of its own; there is no 'rest of the universe'.

In GR any completely defined Riemann 4-space (of suitable signature) is a universe. It can be interpreted as a conceivable system of mass and stress under self-gravitation, again with no 'rest of the Universe'. This is what Einstein himself appears first to have appreciated when he wrote his paper 'Cosmological considerations on the general theory of relativity' (Einstein 1917). Of

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Reproduced from *The Big Bang and Georges Lemaître* (ed. A. Berger), D. Reidel Publishing Company, Dordrecht/Boston/Lancaster.

course, in general the mass and stress in such a model could not be reproduced by any real matter. There is no way of ensuring *a priori* that the contents are real in this sense.

Status of GR in cosmology

The comparison between the Newtonian and Einsteinian approaches in the preceding section shows that the latter must be preferred for use in cosmology. But GR presents problems and limitations that have to be recognized. To start with, a GR model is the whole history of the 'universe' concerned all laid out before us. It is a frozen picture; nothing happens in four dimensions; an observer in the model gets the illusion of things happening because he is supposed to experience a succession of spatial sections in a certain sequence. Such a model cannot, in particular, depict itself coming into existence; that would require another time-dimension, and so on.

If a model has simple topology, it is possible self-consistently to admit an *arrow of time* and an associated *causality* concept. But it is difficult to see how it can admit thermodynamic *irreversibility* or quantum theory *uncertainty*.

It appears to be a recommendation for GR that according to the well-known work of Hawking and Penrose (1970) (see also Hawking and Ellis 1973), every GR spacetime of physical interest has at least one singularity. The case of one singularity is that of a big-bang cosmological model. Penrose (1982) quotes an example for which the big-bang singularity has 'degree of specialness' of general order one part in $10^{10^{123}}$, suggesting, as he says, 'very precise physical laws in operation at the big-bang itself. The new physics involved is necessarily time-asymmetric.' This is a difficult concept since any such laws could themselves have originated only from the big-bang along with whatever is assumed to obey them.

We must in fact think of there coming into existence from the big-bang

the content of the Universe
physics
mathematics and logic
existence itself

but, if we do entertain the notion of existence coming into existence, we seem to be embarking upon an infinite regress.

It is at any rate the plain fact that current cosmological models are in general based upon GR.

GR and cosmology

It is interesting to examine the extent to which cosmology has tested specifically Einstein's theory of gravitation. Some predictions of relativistic cosmology depend only upon the postulation of a Robertson–Walker metric without saying anything about gravitation. This is involved only if the predictions concern energy and stress in the cosmological model. In that case relations of these to the expansion factor $R(t)$ of the metric are needed. If the relations are those given by Einstein's theory, the Friedman–Lemaître cosmological models result. The simplest of these is the well-known Einstein–de Sitter (ES) model. This is commonly employed as a standard of comparison. In particular, for any other model the density parameter $\Omega(t)$ is defined as the ratio of the density of that model at cosmic epoch t to the density at the same epoch in an ES universe having the same Hubble constant at that epoch.

Barrow and Ottewill (1983) have shown that Friedman–Lemaître type universes exist for gravitation theories derived from a Lagrangian of a form more general than Einstein's. This may be significant because, if we do not regard Einstein's form of general relativity as the only one to be considered, then we need not assign special status to the ES model, i.e. that having $\Omega = 1$ for all t.

It is known that, on Einstein's theory, unless in the very early big-bang universe the value of Ω is unity to fantastic accuracy, the model would explode or collapse within the 'very early' time and never reach the state that we observe. This is the same as saying that the spatial section of the very early Universe must be *flat* to fantastic accuracy. The problem of how this comes about is the well-known 'flatness' problem. The solution is generally sought in a combination of particle physics and Einsteinian gravitation. But maybe it is the use of Einsteinian gravitation that creates the problem.

One recent suggestion is Adler's (1983) that Einstein's theory should be regarded as a 'long-wavelength effective field theory' arising from a 'fundamental theory' more like other quantum field theories. The difference from Einstein would be significant only in the very early universe. It is not yet known, so far as I am aware, whether this would have any immediate bearing upon the flatness problem. But it certainly has bearing upon the fundamental problem of gravity in the very early Universe – that of quantization. Physicists conclude that quantization must occur then, even if it is significant only before cosmic time of the order of the Planck time, that is $t \approx 10^{-43}$ s. There is no accepted scheme for this. At any rate in part this must be owing to the basic feature of relativistic treatments of gravitation that it and space-time itself are inextricably interrelated. So quantization of gravitation presumably requires quantization of space-time. This has often been mentioned, but never achieved.

To return to the question at the beginning of this section: Going back to the work of Friedman and of Lemaître, it was a tremendous triumph for GR to predict the expansion of the Universe. But the success was and remains essentially qualitative. No relativistic cosmological model has ever been tested in a way that a physicist could regard as quantitatively crucial. Also for the reasons mentioned we expect GR to demand modification sufficiently near to the big-bang singularity. There are, too, the conceptual difficulties to which allusion has been made. Most of these perplexities should be resolved before long; none of them calls in question any of the 'confirmation' of quantitative predictions of GR on the scale of, say, the Solar System or a binary pulsar.

Cosmology of G. Lemaître

In the paper already quoted Einstein (1917) introduced his cosmical constant Λ that enabled him to formulate his static model universe (assuming $\Lambda > 0$). In the same year de Sitter (1917) produced his model, which is properly regarded as the first non-static model. Then Friedman (1922) and Lemaître (1927) produced their more general non-static models. Friedman pointed out that if a non-static model be regarded as acceptable, the need for a non-zero Λ has disappeared; in due course Einstein agreed, and thenceforth dropped Λ from his theory. Using Lemaître's treatment, Eddington showed that the original Einstein model is unstable; if disturbed so that expansion commences, it goes on expanding forever, and this was the model adopted by Eddington. Lemaître took the commonsense attitude for a mathematical physicist; in effect, he said, keep Λ in the equations until we find observations that contradict some two of the hypotheses $\Lambda < 0$, $\Lambda = 0$, $\Lambda > 0$.

Lemaître identified three basic problems for the expanding universe which he discussed for homogeneous, isotropic relativistic models:

A. *Age of the Universe*

Let t_0 be cosmic time at the observer, i.e. the age of the universe at the observer; let T_0 be the Hubble time as measured by the observer at t_0. If $\Lambda = 0$ then for the model $t_0 < T_0$. The value of T_0 inferred by Hubble was smaller than current values of geological ages. So the model would imply that the age of the universe is less than the age of the Earth. Therefore Lemaître rejected $\Lambda = 0$. Other arguments led him to reject also $0 < \Lambda \lesssim \Lambda_E$ where Λ_E corresponds to an Einstein static universe of 'radius' R_E. If $R(t)$ is the Robertson–Walker expansion factor normalized to $R = R_E$ for the Einstein model, then $R(t)$ for a Lemaître model having $\Lambda > \Lambda_E$ has a graph as shown qualitatively in Figure 1. It is drawn for Λ relatively little more than Λ_E. It is seen that $R(t) \to 0$, $dR/dt \to \infty$, as $t \to 0$ so that $t = 0$ is a singularity in the density and in dR/dt. Three phases of the expansion may be recognized, the 'first expansion' from $R = 0$ to R only a little less than R_E, an interval of near-'stagnation' in which R increases to only a little more than R_E, the 'second expansion' in which R moves increasingly rapidly away from R_E. Lemaître showed that he could find a case for which $t_0 \approx 10\,T_0$ and $R(T_0) \approx 10\,R_E$, and these appeared plausible values, i.e. giving a plausible age and a plausible mean density of the Universe.

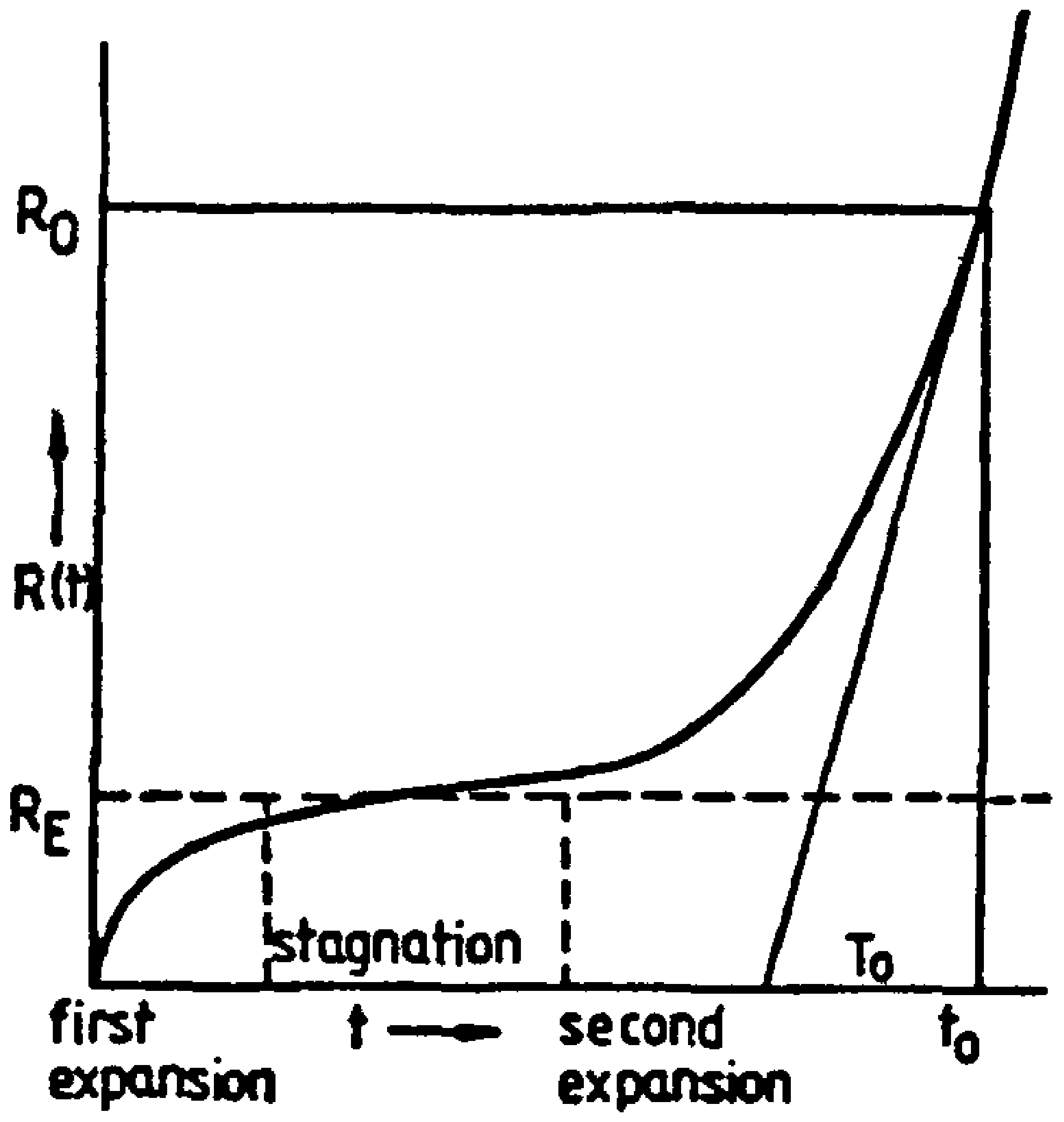

Figure 1. Lemaître cosmological model (schematic diagram).

In this way Lemaître was the first to propose a resolution of the *age problem* in cosmology.

B. *Galaxy-formation*

Lemaître was also the first explicitly to recognize that the culminating problem of cosmology is the origin of the structure of the Universe, as composed of galaxies and clusters of galaxies, within the time available. In Lemaître's model this last meant the time allowed under A.

He presented a rather qualitative scheme starting apparently early in the 'stagnation' phase with 'small accidental fluctuations in the original distribution' of matter. These he saw as producing clouds which by processes of agglomeration, collision and merging would lead to concentrations of material sufficient to produce galaxies or clusters of galaxies. Stars would result by gravitational contraction of portions of the material of a proto-galaxy. He estimated that all this could take place within 'a few' Hubble times. Such an inadequate summary makes it appear even more speculative than in Lemaître's own presentation. Even so it does read much like a summary of the modern theory of 'isothermal fluctuations' (see below). Speculative it undoubtedly was, but it had all the right ingredients, and not all modern attempts take account of the time available, as it did seek to do.

C. *Interpretation of the big-bang; origin of the raw material for galaxy-formation*

Lemaître was the first to appreciate the possibility of a singularity as $t \rightarrow 0$ and to attempt to assign physical significance to this. He postulated that the Universe began as a single 'primeval atom' – which he supposed to undergo disintegration by *cosmic radioactivity*. In fact Lemaître (1946) entitled his small volume of essays on the subject *L'Hypothèse de l'atome primitif* and the English translation (1950) was called *The primeval atom*. It should be scarcely necessary to remark that the picture is of the *entire* Universe being initially (whatever that may mean) this one 'atom', not of an atom existing somewhere in space; so the disintegration is to be pictured as a fragmentation accompanying the initial expansion. Lemaître wrote, 'if matter existed as a single atomic nucleus, it makes no sense to speak of space and time in connection with this atom. Space and time are statistical notions which apply to an assembly of a great number of individual elements; they were meaningless notions, therefore, at the instant of first disintegration of the primeval atom'.

As must be remarked, there may be some inconsistency in speaking of 'the instant of the first disintegration' after asserting that 'it makes no sense to speak of space and time ....' That apart, Lemaître must be credited with the first attempt to contend with the notion of a singularity in space-time. Our reference to the consequences of any quantization of gravity for the meaning of space-time in the very early Universe shows that this was another instance of Lemaître recognizing a basic problem that is still with us.

The picture that he proceeded to develop was the disintegration of his primeval atom – which he described as an 'isotope of the neutron' – first into supermassive nuclei, the further disintegration of which resulted in both the *cosmic-ray background*, that in his picture is still with us, and the normal atoms that then constituted the gas which provided the *raw material* for the processes in B.

All this was Lemaître's invention of the big-bang, which we are now celebrating. The details are greatly different from those that are now generally accepted. Nevertheless, yet again he produced features of broadly the right character – a present background surviving from the early Universe and a process in the early Universe that yielded the raw material for the present galaxies. As we shall see the most essential change since Lemaître's work is that cosmologists now contemplate a *hot* big-bang; his picture assigned no particular significance to any cosmic temperature.

The observed cosmos

At this point it is necessary briefly to review the changes in empirical knowledge of the cosmos between the time when Lemaître developed his cosmology and the time of this commemoration.

About 1933 such knowledge was much what Hubble (1936) described in his book *The Realm of the Nebulae*. This gave for the Hubble time $T_0 \lesssim 2 \times 10^9$ years, whereas it is now almost certain that $10^{10} \lesssim T_0 \lesssim 2 \times 10^{10}$ years. The then current estimate of the mean density of galactic matter was quite reasonable. The age of the Earth was inferred to be more than 2×10^9 years, but by how much was not known. Compared with more recent times, knowledge about cosmic rays was rudimentary. As regards the structure of the Universe, the hypotheses of large-scale homogeneity and isotropy were not contradicted by observation, while on a smaller scale the clustering of galaxies was well recognized although there was not much systematic information.

It has to be appreciated that Hubble had started publishing his observations of the 'expanding Universe' only in 1929 and that hitherto there had been little systematic work in extragalactic astronomy. So we are in fact looking back to the very early days of such astronomy. Two things now may strike us as surprising: (a) that nobody raised an insistent call for 'more observations', (b) that everybody in the business seemed to accept Hubble's measurements quite uncritically. The reason for both of these was that Hubble had the use of the Mt. Wilson 100-inch telescope, and no other existing telescope could compete.

Moving on to the time of this celebration in 1983, there is vastly more information than there was 50 years earlier, and most of it – like results from radioastronomy – is of sorts that were unknown around 1933. From the standpoint of cosmology it is in the following categories, as compared with information accessible to Lemaître:

1. Improvements upon old results
2. New results having cosmological applicability
3. New results without present cosmological applicability
4. Results awaited.

To take these briefly in turn:

1. As we mentioned above, Hubble's value for T_0 was too small by a factor of order 10, but the actual value is still uncertain to within a factor about 2.

Various estimates of *mean densities* in the Universe at the present cosmic epoch are now available; they include that for the galactic matter, baryonic matter, total energy (including rest mass). Some of the values are independent of the Hubble time T_0 and some are proportional to T_0^{-2}. Comparisons may therefore set bounds upon the value of T_0. For some purposes it is more convenient to express results in terms of the density-parameter Ω_0 rather than in mass per unit volume.

Particularly in the last few years there have been extensive studies of the *large-scale structure of the Universe*. Statistical studies employing 2-point or higher order correlation functions, particularly those of Peebles (1980) and his school have yielded much more systematic quantitative knowledge of the clustering of galaxies. The work of Abell (1958) had earlier provided far more descriptive knowledge than had been available in Lemaître's day. All such work supports the early hypothesis of the large-scale homogeneity and isotropy of the Universe.

Special studies strongly indicate, however, that there exists a detailed structure more complex than had ever before been envisaged. If they are broadly correct galaxies and clusters of galaxies are arranged in the form of a rough network that outlines great voids each of the order of a million cubic megaparsecs in which there are effectively no bright galaxies. Some workers are still inclined to doubt whether the 'strings' of galaxies and clusters are significantly different from features that occur fortuitously in any random distribution. Others seem to be so convinced of the non-random character of the structure that they wish to regard it as the 'fossil' of some structure in the early Universe.

2. All observations using electromagnetic radiation outside the optical and near infrared wavelength-range have come since Lemaître's time, as well as the bulk of cosmic-ray observations. Some of these observations have assisted in improving results in category 1. But others apply to new discoveries. Of these probably the most important is the *micro-wave background radiation*. It provides the only known means of observing the Universe before any galaxies had been formed – if the standard interpretation is correct. In that case it shows that the Universe at that epoch was isotropic to an exceedingly high degree. As we have seen, in a general sense it plays the role envisaged by Lemaître for a cosmic-ray background.

Another empirical parameter of cosmological significance is the baryon: photon ratio η, estimated to be about 10^{-9} and believed to have remained effectively constant since the beginning of the 'radiation era' of the Universe.

Quantities also of cosmological importance are the relative abundances of the atomic nuclei ^{1}H, ^{2}D, ^{3}He, ^{4}He that are inferred to have been 'frozen in' to the cosmos from the end of about the first 3 minutes until the first stars were formed. Significant empirical values of these primordial abundances are now claimed. They form the best basis we have for estimating the present mean density of baryonic matter.

3. Radio-galaxy and quasar number-counts have been expected to yield important cosmological information particularly with the object of selecting a cosmological model. It seems now that their usefulness from that aspect is obscured by what are classed as 'evolutionary effects'. Sooner or later the information will have to be adequately analysed.

In the same general category, but far more pressing and important, is the evidence that has been discussed now over many years regarding the existence and quantity of 'dark matter' in the Universe. If the amount is near the upper bound that has been considered, then the Universe is an almost totally different place from what astronomers had hitherto thought. All their past endeavours would have been concentrated upon less than 1 per cent of its content. The other 99 per cent of the mass could almost certainly not mainly be ordinary (baryonic) matter; it might be 'massive' neutrinos or more exotic particles. On the other hand, if the amount of dark matter is near the lower bound considered, then it need imply nothing more alarming than that some galaxies may be surrounded by rather many faint stars or 'jupiters', and some clusters may contain rather more inter-galactic matter than had been thought. The resolution of this uncertainty has become surely the central problem for present-day astronomy.

To quote an example of a discovery which, when correctly interpreted, must be a clue to the evolution of the Universe, we cite that of the so-called Lyman-alpha clouds. These were evidently scattered through inter-galactic space before a few 10^9 years ago and they produced most of the absorption lines in the spectra of quasars. They seem not to contain an important mass of the matter in the cosmos, but since their material was apparently left over after the formation of galaxies they should help to reveal the nature of the formation process.

4. It is well known that a very small positive rest mass of the neutrino, no more than the energy of a few electron volts, would suffice to ensure that at the present cosmic epoch the neutrinos in the Universe should furnish most of its mass. [Different neutrino species might have different positive rest masses, unless all have zero mass.] It is therefore of the utmost importance to know if the rest mass of any neutrino is non-zero. The experimental evidence seems still to be inconclusive.

Cosmology since Lemaître

Lemaître himself after about 1933 worked mainly in fields other than cosmology. Although he was always generous about responding to invitations to expound in lectures and essays his views on the subject, he did not develop them much further during the rest of his life.

In the 1930s Eddington was developing his ideas regarding the constants of physics; his scheme demanded a positive Λ. Lemaître was practically the only other worker to retain Λ. Almost everyone else at the time regarded an isolated constant of this sort as being out of keeping with the spirit of GR. It has then to be asked why they were not concerned as much as Lemaître was about the age paradox. Strangely enough for most astronomers at the time the paradox worked the other way. I think that because the Hubble time was so short they took the view that not much more could be inferred from Hubble's result than that the Universe had been in a rather highly congested state at a time about T_0 before the present. T_0 being so much less than the ages assigned to the stars and galaxies, they had to suppose that these would have retained their identities while experiencing that state. A Friedman–Lemaître model as they saw it, was a grossly simplified representation of the actual Universe, in which all the elaborate system of stars, galaxies and clusters was replaced by a uniform stress-free dust. So the model need not be taken seriously anywhere near its singularity.

Other aspects of relativistic cosmology and alternatives to it continued to be studied until after World War II. Then in 1948 Bondi and Gold, and to some extent independently, Hoyle propounded *steady-state cosmology*, necessarily implying *continual creation*. While it would be incorrect to say that this was ever widely *accepted*, it was certainly the case that its concepts continued to have a dominating influence upon cosmological thinking until about 1965. This is not an occasion to attempt to recount the history of those years. For one thing, steady-state concepts seem never to have had much impact upon Lemaître. Historically what for most astronomers was the strongest reason for rejecting steady-state cosmology in the form in which it had been presented was the discovery in 1965 of the microwave background radiation. This was taken as evidence of an explosive start for the Universe. It is recorded that Lemaître expressed satisfaction about this feature a short while before he died in 1966. It is an irony of history that the general acceptance of big-bang cosmology is to be dated from the year of the death of its inventor. However, two comments must be made: When big-bang cosmology regained favour, for most cosmologists this meant a *hot* big-bang. The current version cannot be final, and it is conceivable that whatever succeeds it will contrive to combine some of its concepts with some of the more attractive concepts of steady-state theory.

Meanwhile hot big-bang cosmology has furnished a history of the cosmos that in general terms seem to be acceptable on all the available evidence. Briefly it is:

Early Universe – from say 10^{-43} s to 10^{-3} s, forming the 'particle era', beginning with a quark-gas, followed by hadrons.

Radiation era – about 10^{-2} s to 10^{13} s (about 4×10^5 years), up to about 3 minutes in regard to nuclear reactions there is effective thermodynamic equilibrium at each instant, but approaching about 3 minutes nuclear abundances are determined by reaction rates after which they become 'frozen in'; effectively only ^{1}H, ^{2}D, ^{3}He, ^{4}He remain. At about 4×10^5 years matter and radiation decouple.

Matter era – after about 4×10^5 years the energy-density is predominantly from the rest-mass of matter. The fact that decoupling works out to occur about the end of the radiation era appears to be an arithmetical coincidence brought about by the property $\eta \approx 10^{-9}$.

All this gives a self-consistent picture using a Robertson–Walker metric with expansion factor $R(t)$ satisfying the Friedman–Lemaître equations. These follow from GR and they may first be derived with the retention of Λ. They may then be solved for Λ, which is thus expressed in terms of the Hubble constant, the acceleration parameter, the function $R(t)$, the mean density and pressure at epoch t. For the actual Universe at the present epoch bounds may be set to all these quantities and they are found to imply $|\Lambda| \lesssim 10^{-120}$ in absolute units. But since Λ is by definition a universal constant, this result must hold good at all epochs. Λ is thus the quantity in physics most accurately measured to be zero (Hawking 1983).

Inflation

Several properties of vacuum (quantum) states have closely the same effect as non-zero values of Λ. They are significant only at very high energies. There has been a suggestion that a phase transition occurred when an original unified 'electroweak' force split into electromagnetic and nuclear-weak constituents. Times of order 10^{-35} s from the big-bang have been mentioned for this. During the transition a vacuum effect of the sort mentioned is inferred to have produced an enormous 'cosmic repulsion' that caused the Universe to inflate by a factor estimated at 10^{20}. When the transition was complete and the two kinds of force had been 'frozen out' with their familiar characters, the repulsion would vanish. This would, of course, be consistent with using $\Lambda = 0$ for the subsequent normal expansion. Consistently with GR, the repulsion cannot then be exactly equivalent to having a non-zero value of Λ for part of the time; even so Guth (1981) noted that it is hard to represent a smooth return to non-inflation.

One important consequence appeared to be that the huge inflationary expansion would smooth away any initial irregularities in the universe and so produce the high degrees of homogeneity and isotropy which are inferred to have existed at an early stage of the normal expansion. Another would be that it would explain why the homogeneity can hold good between regions that otherwise could not have been in causal contact when their contents were determined.

Unfortunately it now appears that this original inflationary model has to be rejected as depending upon a too naive interpretation of the particle physics. Physicists seem now to favour a 'bubbly' early Universe. One version envisages the observable Universe as arising from the inflation of one small bubble of an early state. Another regards even the present Universe as 'bubbly' on a micro-scale, but very smooth on the scale on which we observe it.

Even the latest models thus invoke an essential role for cosmical repulsion – as did Lemaître's model half-a-century ago – but now only for the very early Universe, whereas Lemaître had an effect of his Λ that became relatively more important as the expansion proceeded.

Galaxy formation

As already mentioned, Lemaître very properly saw the formation of galaxies – or maybe clusters of galaxies as the culminating problem of cosmology. Here we shall briefly review the current approach to this problem.

A well-known argument shows that since there are now fluctuations in the density of matter in the Universe, there must always have been fluctuations. More specifically, if what is basically a Friedman–Lemaître model possesses galaxies at some epoch after decoupling there must have been fluctuations of density at any epoch before decoupling. So the 'modern' approach to the problem of the origin of galaxies is to consider arbitrary fluctuations $\delta\rho/\rho$ before decoupling, and to enquire how they develop as the model expands into the matter era. If some such fluctuations are inferred in due course to produce galaxies, then we can ask what fluctuations in some earlier era could lead to these fluctuations before decoupling. The aim is then to discover what were the most primitive significant fluctuations.

This approach implicitly supposes that a FL model was a better match to the actual Universe in the past than it is in our era. In particular, it is assumed that in the radiation era the matter and radiation were almost uniformly distributed in space. So far as the actual Universe is concerned this is strongly supported by the high degree of isotropy of the micro-wave background radiation.

Two sorts of fluctuations are studied; the names they have acquired should not be taken literally:

'Adiabatic' fluctuations

The initial fluctuation is taken to apply to both the matter and the radiation. So long as the matter is to a considerable extent ionized – that is, until decoupling is largely complete – *radiation damping* is strong for condensations of relatively small mass. This leads to the conclusion that condensations surviving recombination are mostly in the range 10^{12} to 10^{14} solar masses. It is inferred that such a condensation then collapses first as a 'pancake', which proceeds to fragment into clusters of galaxies. Peebles (1980) identifies three characteristic lengths associated with the process.

'Isothermal' fluctuations

These are taken to involve the matter alone. Radiation causes less damping in this case. No characteristic lengths emerge; some astronomers consider that this is in better agreement with observation. The first condensations, after decoupling, may be on the scale of globular clusters; if so, these would merge to form galaxies.

Neither picture leads to a quite convincing account of how a condensation of the raw material is transformed into a real galaxy as it is seen in the sky. Some phenomenon besides gravitational instability seems to be required to play some crucial part. This could be the occurrence of *shocks* either between condensations or within a collapsing condensation (McCrea 1982, 1983).

Primeval fluctuations

The work that has been done on adiabatic and isothermal fluctuations, whatever may be its inconclusiveness in detail, is almost certainly sufficient to show that the existence of galaxies in the matter era implies the existence in the preceding era of fluctuations $\delta\rho/\rho$ in a certain range of size and amplitude. As regards amplitude appeal may then be made to the observed absence of anisotropy, exceeding a certain very small amount, in the observed microwave background radiation. This leads to the inference that, in the region in the radiation era in which most of this radiation last interacted significantly with matter, that matter must have been of uniform density ρ to within fluctuations not exceeding $\delta\rho/\rho \approx 10^{-4}$. On the other hand, fluctuations weaker than this would not be expected to lead to galaxy formation. It is therefore generally inferred that fluctuations of this amplitude existed in the cosmos at an epoch of order 10^5 years after the big bang.

Astronomers ask, Is this a fundamental property of the Universe that, at any rate in our present state of knowledge, has simply to be accepted as such? Or can it be traced to something more primitive?

As regards the latter question, among possibilities contemplated are:

Quantum fluctuations as an inherent element in the concept of the very early Universe. Some cosmologists have discussed how these might leave an imprint that could survive through all subsequent phases.

Primeval chaos, part of which somehow achieved considerable homogeneity at an early epoch but never without some irregularities.

Primeval turbulence as a possibly more comprehensible version of 'chaos'.

Astronomers also ask, Do we learn anything about primeval fluctuations from the present large-scale structure of the Universe as observed? If significant, is the 'cellular' or 'network' structure that is claimed to exist a fossil of the early Universe? It seems unlikely that this can be true in any simple way, for I am told that what evidence there is from numerical simulations shows that such structure would be unlikely to survive from an early stage. Nevertheless, in a very general sense it seems that it *must* be true. For the existence of condensations at any stage depends upon the existence of condensations at an earlier stage, and in the same way the existence of any general structure at any stage would depend upon the existence of structure at an earlier stage. But there remains the question as to whether significant general structure does actually exist.

In summary, the whole problem of condensations in the cosmos is still beset by uncertainties, the most serious being at the two ends, the one concerning the nature of the most primitive condensations, the other concerning the process by which a condensation of the raw material is converted into stars, stellar clusters, nebulae ... to make a galaxy.

Physics

Cosmology, observational and theoretical, and particle and high energy physics, experimental and theoretical, all seem at the present time to have arrived at a peak of activity and discovery. This is partly a cause and partly a result of the interaction of all these elements. It is resulting in a review of the foundations of physics that is more profound than any previously possible. It would have been highly desirable that this essay should have dealt with the most profound aspects of all these developments. But anyone attempting to do this would need to understand much more about modern physics than the writer. He can only mention a few of the aspects that have immediate significance for cosmology.

Here we mention a few cosmological considerations specially concerned with the *constants of physics*. It is the existence of these that makes physics what it is. They arise basically because everything in physics is quantized, so that the physical world itself provides *natural units* ('Planck units') in which it can be described. If our physical concepts are valid, this would in principle permit us to exchange precise physical information with physicists anywhere in the Universe. Consistently with this, it should be noted that a constant of physics has an *operational existence* that transcends any particular theoretical model. The experience that there exist operations that always yield the same outcome is a way of defining the 'external' world of physics. This is a paraphrase of the remark that the constants of physics make physics. Not surprisingly, therefore, it can be seen that properties of the world of astrophysics depend upon the values of a few constants. For example it can be shown that the mass of an asteroid, of a planet, of a star each lie within a particular interval dictated by these constants – the same constants that determine, say, the range of possible physical capabilities of the human animal.

What is at first surprising about the resulting situation is the sensitivity of its features to the values of the constants. The whole world of experience could be made so different by relatively small changes in one or two constants that we could not have evolved to observe it (Carr and Rees 1979; Press and Lightman 1983).

Such considerations are embodied in what have been called *anthropic principles*. The 'weak' principle asserts that man's experience of the Universe depends upon the circumstance that he can exist only within a restricted region of space-time. In itself this is self-evident; but it is obviously necessary for the cosmologist to appreciate that, when he thinks that he is discovering an important property of the cosmos, he may be doing no more than noticing a feature that happens to be present when he himself happens to be around to observe it. Thus the weak principle may issue useful cautions, but in the form stated it cannot serve as a basis for making predictions about the cosmos. Also it is to be noted that it assigns no properties to the observer other than the existence of an ability to receive and record signals.

The 'strong' principle, on the other hand, takes note of the properties of the observers that actually exist, and it asserts that the constants of physics have to possess values such that the cosmos must cause these beings to exist. Again the assertion is self-evident, but now it is one that may lead to predictions. It seems almost certain that, if we suppose the familiar constants of physics simply to exist, then such a principle should impose *bounds* upon their values. But it is hard to see how it can be inferred that such constants *must* exist and that they must possess certain *precise* values.

It is interesting to remark that inferences of this last sort were something of what Eddington (1936, 1946) was trying to achieve in the work described in his last two books. Nowadays it has become more fashionable to ask, Do there in any sense 'exist' other universes in which the constants of physics have values different from those in 'our' Universe? This appears to be broadly the same problem.

There are two other problems related to all this. One is, in a big-bang model universe, how and when do the constants of physics come into existence? So far as one knows, nobody has made any useful approach to a solution.

The other is, Are there constants of cosmical physics that are not related to those of microphysics – at least in any way that we can discover at present. It is to this that we finally turn.

Cosmical numbers

According to the usual view of the constants of *physics* they concern, of course, entities that exist. But they tell us nothing about the amounts of these entities that exist and that would thus serve to specify the Universe that exists. We have remarked that the constants of physics make *physics* what it is. Are there additionally *cosmical numbers* that make the *Universe* what it is?

The number of dimensions of space-time seems to be a 'given' constant of the Universe. The Universe would be fundamentally different were the number other than 4, so that an observer experiences one time dimension and three space dimensions (Barrow 1983). Actually some recent unified theories employ space-times with dimensions up to 11. But whatever the number it may be best to regard it as both a constant of physics and a cosmical number.

Rees (1983), who has given most explicit consideration to the question, has indicated 'three basic numbers that characterize our Universe'. In the terminology used here, these are: (i) The Robertson–Walker curvature radius at our cosmic epoch, $R(t_0) \approx 10^{60}$ Planck lengths. (ii) The baryon: photon ratio, $\eta \approx 10^{-9}$. (iii) The amplitude of the fluctuations that triggered galaxy formation $\delta\rho/\rho \approx 10^{-4}$. We do not know why they should have these values, or whether to expect any discovery of any dependence upon the values of the constants of physics.

If indeed, as mentioned above, 'our Universe' resulted from the inflation of one small bubble in a very early Universe, then we might conclude that the constants of physics arose from the latter, and that the cosmical numbers were determined by what happened to be the content of that one particular bubble.

This paper is largely a catalogue of unsolved problems. The present developments in physics seem to promise some imminent further progress. We may hazard the view that progress as a whole is likely to be gradual. For example, as regards the constants of physics the trend naturally seems to be to seek some new theory such that the constants of existing theory become expressible in terms of a smaller number of constants in the new theory (Weinberg 1983). It may be a long time before the number has been reduced to zero.

Abell, G. O., The distribution of rich clusters of galaxies, *Astrophys. J. Suppl.*, 1958, **3**, no. 31.

Adler, S. L., *Philos Trans. R. Soc. London*, 1983, **A310**, 273–278.

Barrow, J. D., *Philos. Trans. R. Soc. London*, 1983, **A310**, 337–346.

Barrow, J. D. and Ottewill, A C., *J. Phys A Math. Gen.*, 1983, **16**, 2757–2776

Carr, B J. and Rees, M. J., *Nature*, 1979, **278**, 605–612.

Eddington, A. S., *Relativity Theory of Protons and Electrons*, 1936.

Eddington, A. S., *Fundamental Theory*, 1946.

Einstein, A., 1917 in *The Principle of Relativity* (eds. Lorentz, H. A *et al.*), 1923, pp. 177–188.

Friedman, A. A., *Z. Phys.*, 1922, **10**, 377–386.

Guth, H. A., *Phys. Rev.*, 1981, **D23**, 347–356.

Hawking, S. W., *Philos. Trans R.. Soc. London*, 1983, **A310**, 303–310.

Hawking, S. W. and Ellis, G. F. R., *The Large-Scale Structure of Space-Time*, 1973.

Hawking, S. W. and Penrose, R., *Proc. R. Soc. London*, 1970, **A314**, 529–548.

Helfand, D. J., *Physics Today*, 1983, **36**, pp. 17–20.

Hubble, E. P., *The Realm of the Nebulae*, 1936.

Kibble, T. W. B., *Philos. Trans. R. Soc. London*, 1983, **A310**, 293–302.

Lemaître, G., *Ann. Soc. Scient. Brux.*, 1927, **A47**, 49–59, also in *Mon. Not. R Astron. Soc.*, 1927, **91**, 483–490

Lemaître, G, *The Primeval Atom*, 1950, French edition republished 1972 *L'hypothèse de l'atome primitif.*

McCrea, W. H, *Progress in Cosmology* (ed. Wolfendale, A. W.) 1982, pp. 239–257.

McCrea, W. H., *Early Evolution of the Universe and its Present Structure* (eds Abell, G. O. and Chincarini, C) 1983, pp. 383–385.

Peebles, P. J. E., *The Large-Scale Structure of the Universe*, 1980

Penrose, R., *Progress in Cosmology* (ed. Wolfendale, A W.), 1982, pp. 87–88.

Press, W. H. and Lightman, A. P., *Philos. Trans R. Soc London*, 1983, **A310**, 326–336

Rees, M J., *Philos. Trans. R. Soc. London*, 1983, **A310**, 311–322.

Sitter, W. de, *Mon. Not. R. Astron Soc.*, 1917, **78**, 3–28

Weinberg, S., *Philos Trans. R Soc. London*, 1983, **A310**, 249–252.