Arthur Stanley Eddington, Georges Lemaître and the Discovery of the Expanding Universe

Cormac O'Raifeartaigh FRAS

Eddington Conference, Observatoire de Paris. 29/05/2019

EDDINGTON CONFERENCE

27-29 May 2019, Paris

Arthur S. Eddington: From Physics to Philosophy and Back Again

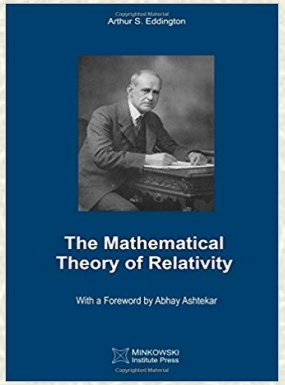
The centenary of the 29 May 1919 eclipse is a great opportunity for specialists to gather in Paris from **27 to 29 May 2019**. This international conference aims to bring together physicists, philosophers and historians, in order to discuss the works and achievements of Arthur S. Eddington.

It is jointly organised by IPC-Facultés Libres de Philosophie et de Psychologie and Paris Observatory, in partnership with the Institut d'Astrophysique de Paris, the International Astronomical Union, the British Society for the History of

Overview: a historical puzzle

- **Arthur Stanley Eddington**

  Outstanding astronomer
  Outstanding theorist

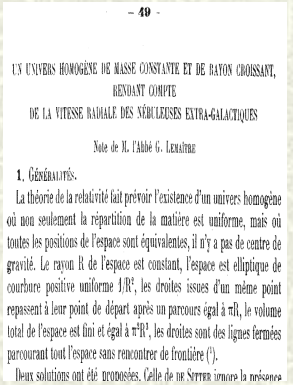


- **Eddington and relativity**

  Key proponent of the general theory
  Leading role in 1919 expedition

- **Georges Lemaître**

  An expanding universe from relativity (1927)
  Connection with the redshifts of the nebulae

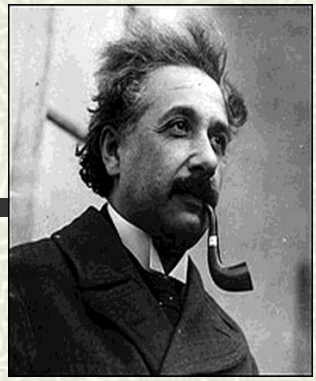


- **No impact**

  Model ignored at first by Eddington and others
  Later accepted and redistributed (1930)

Why?

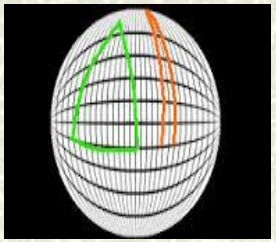
Context: cosmology (1917-30)



- **The general theory of relativity**

  A new theory of gravitation (Einstein 1915)

$$G_{\mu\nu} = -\kappa\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right)$$



- **The Einstein World (1917)**

  Static, matter-filled universe

  Closed spatial curvature

$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right)$$

$$\lambda = \frac{\kappa\rho}{2} = \frac{1}{R^2}$$

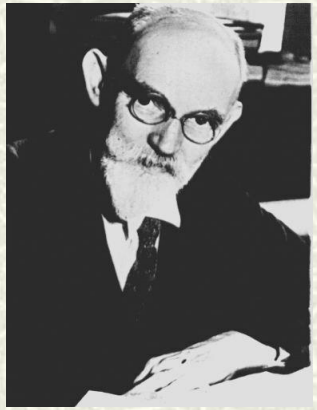
- **The de Sitter model (1917)**

  'Static', empty universe

  Closed spacetime curvature

  Prediction of redshifts: connection with astronomy?

$$\rho = 0;\ \lambda = \frac{3}{R^2}$$

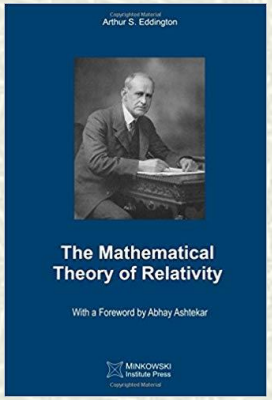


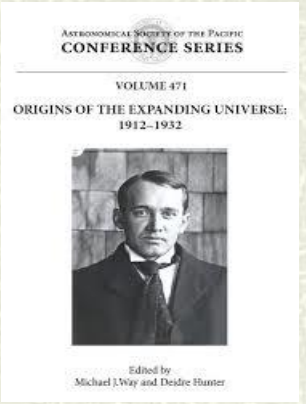
- **<u>A cosmic debate</u>**

  Einstein, de Sitter, Weyl, Klein, Lanczos

Context: astronomy (1917-1930)

- **Slipher's study of light from spiral nebulae**
  24-inch refractor at Lowell Observatory
- **Light from many spirals redshifted (1915, 17)**
  Doppler shift representing recession velocity?
- **Outstanding puzzle in astronomy**
  Republished by Eddington in 1923
- **A relation between redshift and distance?**
  Silberstein, Wirtz, Lundmark, Strömberg
  Nebular distances not known



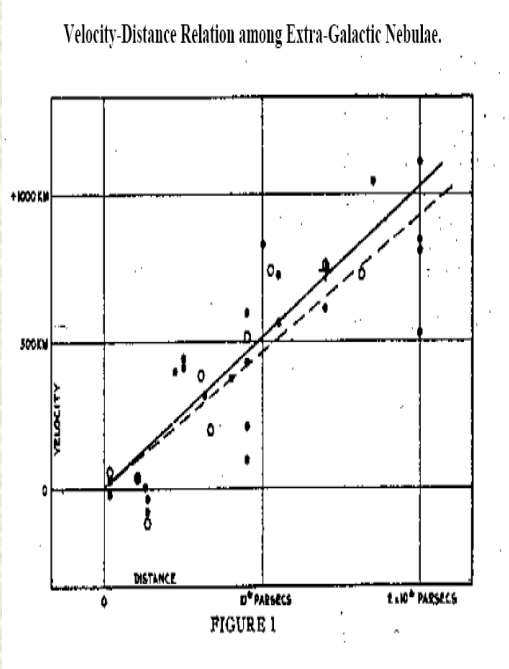


Connection to cosmology?

Two astronomical advances

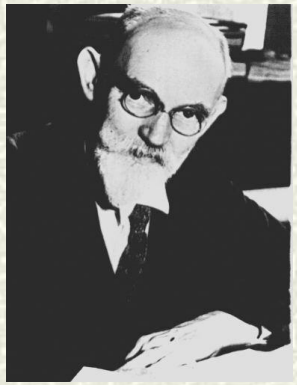
Edwin Hubble

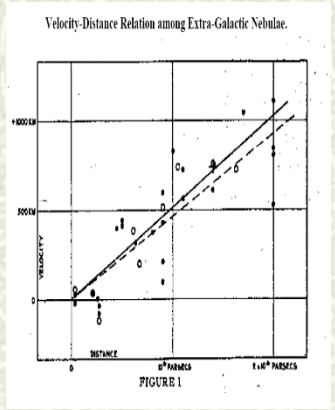
- **Edwin Hubble (Mt Wilson)**
  100-inch Hooker telescope
- **Resolved Cepheid stars in nebulae (1925)**
  Employed Leavitt method to measure distance
  Spiral nebulae far beyond Milky Way!
- **A relation between redshift and distance?**
  Combine Slipher redshifts with nebular distances
- **The Hubble graph (1929)**
  A linear relation for the galaxies!
  Most important data point not shown



The paradigm shift (1930)

- **RAS meeting (January)**
  Data conflict with Einstein, de Sitter models
  Should alternative cosmologies be considered?
- **Report**
  de Sitter (The Observatory)
- **Reaction from Georges Lemaître**
  Letter to Eddington
  Reminder of Lemaître (1927)
- **Accepted by Eddington**
  Lemaître paper shared and cited
  Republished in English in MNRAS (1931)





A historical puzzle

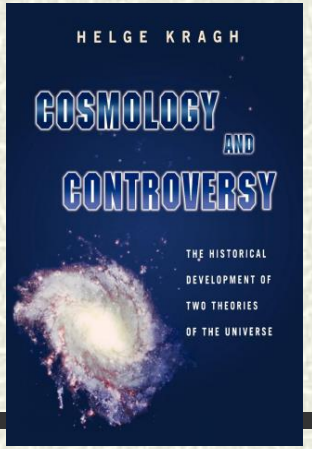
A witness to the puzzle

- **McVittie recollection (1967)**
  Research student in Eddington group

  "Eddington confessed that although he had seen Lemaître's paper in 1927 he had forgotten completely about it until that moment" QJRAS 8: 294-97

- **Additional McVittie account (1978)**
  Oral interview (DeVorkin) AIP

  "I'm sure Lemaître must have sent me a reprint, , he's just sent me another, but I'd forgotten about it"



- **A historical puzzle**
  How did Eddington 'forget' Lemaître's paper?

Standard explanations

- **Sociology of science**

  Status of researcher
  Status of journal
  Language of journal

- **Philosophy of science**

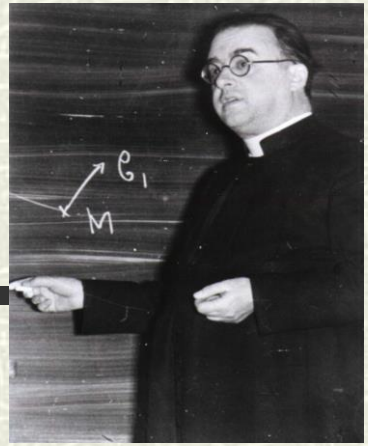
  Difficult concept
  The transition to a new paradigm

- **<u>CO'R: don't neglect the physics</u>**

  (i) Mathematical complexity of Lemaître's paper
  (ii) Nature of observational evidence

<u>Extraordinary claims require extraordinary evidence</u>

Status of researcher



1894-1966

- **Early career**
  Engineering → physics (1918)
  Talent in general relativity

- **RA at Cambridge (1923)**
  Astronomy and cosmology (Eddington)

- **RA at Cambridge MA (1924-5)**
  Astronomy at Harvard Observatory (Shapley)
  PhD (GR) at MIT (Heymans)
  Exposure to work of Slipher and Hubble

- **Lemaître (1925)**
  Static de Sitter model has a centre!
  Homogeneous version not static

NOTE ON DE SITTER'S UNIVERSE

By G. LEMAITRE [1]

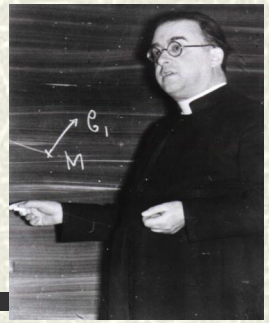
The equations of the element of interval of a four-dimensional universe of constant positive curvature have been given by de Sitter in the form

$$ds^2 = R^2[-d\chi^2 - \sin^2\chi(d\theta^2 + \sin^2\theta d\phi^2) + \cos^2\chi d\tau^2], \qquad (1)$$

where R is a constant called the radius of the four-dimensional universe and χ, θ, ϕ, τ are coördinates. When the division of time and space is made as suggested by these coördinates, the space is itself of constant curvature and has the same radius as the universe.

Early-career researcher of the front rank

Status of journal

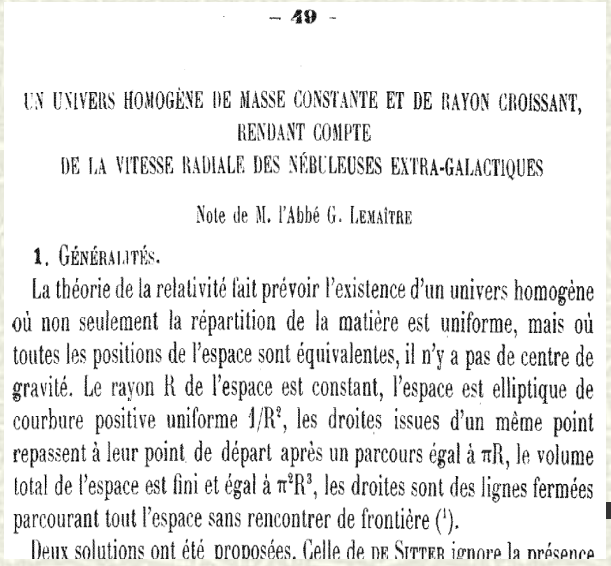


- **National journal**
  Annales de la Société Scientifique de Bruxelles
  Well-known; well-read?

- **Relevance of status?**
  Paper received by Eddington, Einstein and others

- **Subtle factor**
  More likely to read received paper in major journal

- **The language factor**
  Was Eddington fluent in French?
  Impact factor in second language



– 49 –

UN UNIVERS HOMOGÈNE DE MASSE CONSTANTE ET DE RAYON CROISSANT, RENDANT COMPTE DE LA VITESSE RADIALE DES NÉBULEUSES EXTRA-GALACTIQUES

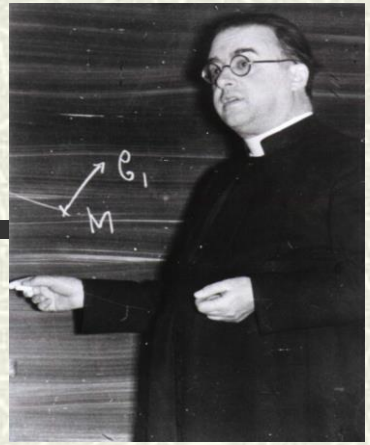
Note de M. l'Abbé G. Lemaître

1. Généralités.

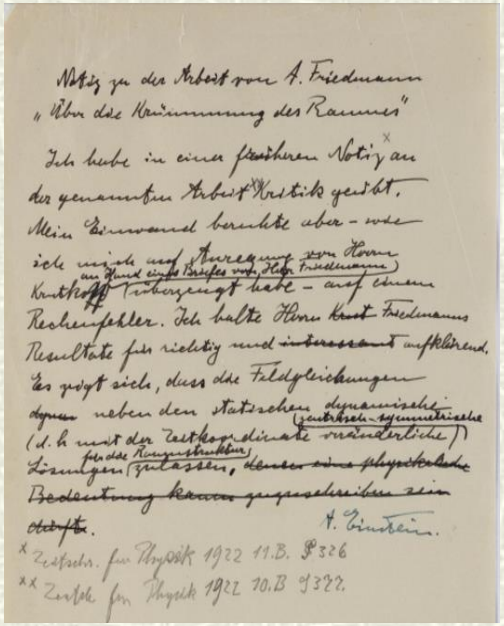
La théorie de la relativité fait prévoir l'existence d'un univers homogène où non seulement la répartition de la matière est uniforme, mais où toutes les positions de l'espace sont équivalentes, il n'y a pas de centre de gravité. Le rayon R de l'espace est constant, l'espace est elliptique de courbure positive uniforme $1/R^2$, les droites issues d'un même point repassent à leur point de départ après un parcours égal à πR, le volume total de l'espace est fini et égal à $\pi^2 R^3$, les droites sont des lignes fermées parcourant tout l'espace sans rencontrer de frontière (1).

Deux solutions ont été proposées. Celle de de Sitter ignore la présence

The philosophical factor



- **Einstein's static universe**
  'A bottomless pit of speculation' (1945)
- **Einstein's reaction to Friedman**
  Considered 'suspicious' (1922)
  Mathematical correction; retracted (1923)
  "To this a physical reality can hardly be ascribed"
- **An important insight**
  Extraordinary claims require extraordinary evidence
- **Reluctance towards time-varying cosmologies**
  Lanczos, Weyl, de Sitter, Tolman, Robertson (1920s)

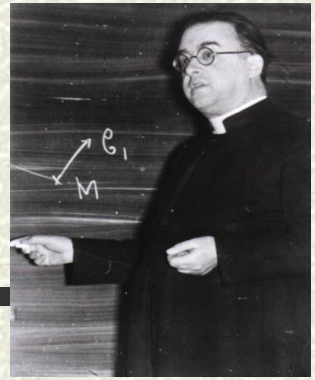

Notiz zu der Arbeit von A. Friedmann
„Über die Krümmung des Raumes"

Ich habe in einer früheren Notiz* an der genannten Arbeit Kritik geübt. Mein Einwand beruhte aber – wie ich mich auf Anregung von Herrn Krutkoff überzeugt habe – auf einem Rechenfehler. Ich halte Herrn Friedmanns Resultate für richtig und aufklärend. Es zeigt sich, dass die Feldgleichungen neben den statischen dynamische (zentrisch-symmetrische) (d.h. mit der Zeit kugelsymmetrisch veränderliche) Lösungen zulassen, denen eine physikalische Bedeutung kaum zugeschrieben werden darf.

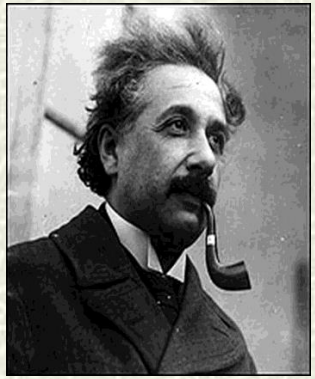
A. Einstein.

* Zeitschr. für Physik 1922 11.B. S 326
** Zeitschr. für Physik 1922 10.B S 377

Einstein *v* Lemaître

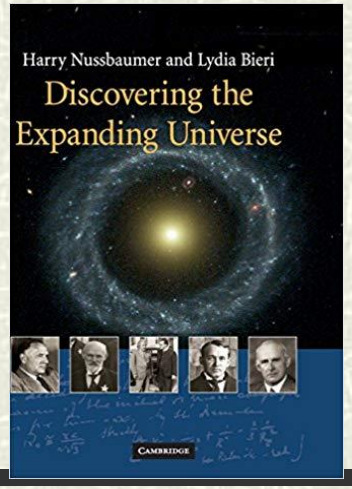


- **Lemaître meets Einstein**
  Solvay Conference 1927



- **Einstein's reaction**
  'Apres quelques remarques techniques favorables, il conclut…
  du point de vue physique cela lui paraissait tout a fait abominable'

- **Discussion continued in taxi**
  Einstein mentions similar model by Friedman



- **Setback for Lemaître**
  No further work on cosmology (1927-30)

Einstein not au fait with astronomy?
(Lemaître 1958)

New factor (i): complexity

- **Mathematical framework of GR**
  Einstein's struggle 1910-1915
  Physicists doing cutting-edge mathematics

$$G_{\mu\nu} = -\kappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right)$$

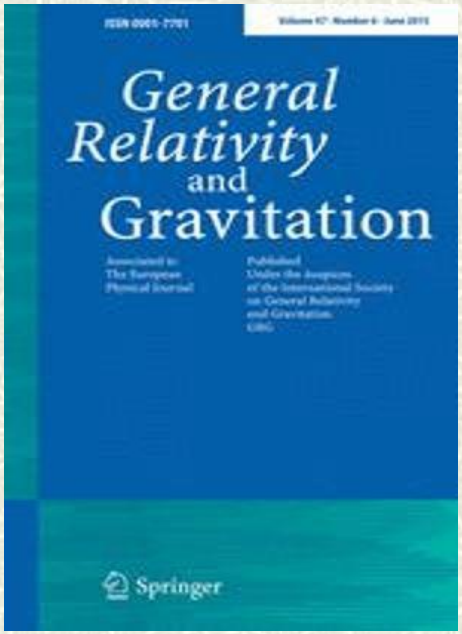
- **Mathematics of relativistic cosmology**
  Einstein's static universe: unstable
  de Sitter's universe: non-static

$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right)$$

$$\lambda = \frac{\kappa \rho}{2} = \frac{1}{R^2}$$

- **Friedman's cosmology**
  Formally rejected by Einstein (ZP)
  Mathematical error on Einstein's part

- **Lemaître's cosmology**
  Similarly difficult to grasp at first sight?



Gen Relativ Gravit (2013) 45:1619–1633
DOI 10.1007/s10714-013-1547-4

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

Jean-Pierre Luminet

Published online: 13 June 2013

Keywords Expanding Universe · Generalised Friedmann models · Georges Lemaître · Golden Oldie

Gen Relativ Gravit
DOI 10.1007/s10714-013-1548-3

GOLDEN OLDIE

Republication of: A homogeneous universe of constant mass and increasing radius accounting for the radial velocity of extra-galactic nebulae

Georges Lemaître

An editorial note to this paper can be found in this issue preceding this Golden Oldie and online via doi:10.1007/s10714-013-1547-4.

Original paper: Georges Lemaître, Un univers homogène de masse constante et de rayon croissant, rendant compte de la vitesse radiale des nébuleuses extra-galactiques, *Annales de la Société Scientifique de Bruxelles* **47A**, pp. 49–59 (1927). Translated from French by Jean-Pierre Luminet, Laboratoire Univers et Théories, Observatoire de Paris-CNRS, Université Paris Diderot, France, e-mail: jean-pierre.luminet@obspm.fr.

Editorial responsibility: A. Krasiński, e-mail: akr@camk.edu.pl.

G. Lemaître (Deceased June 20, 1966)
Louvain, Belgium
e-mail for correspondence: akr@camk.edu.pl

Published online: 13 June 2013

Springer

Read through
the eyes of 1927

Derivations
not shown

We identify ρ and $-p$ with the components T_4^4 and $T_1^1 = T_2^2 = T_3^3$ of the material energy tensor, and δ with T. Working out the contracted Riemann tensor for a universe with a line-element given by

$$ds^2 = -R^2 d\sigma^2 + dt^2 \tag{1}$$

where $d\sigma$ is the elementary distance in a space of radius unity, and the radius of space R is a function of time, we find that the field equations can be written

$$3\frac{R'^2}{R^2} + \frac{3}{R^2} = \lambda + \kappa\rho \tag{2}$$

and

$$2\frac{R''}{R} + \frac{R'^2}{R^2} + \frac{1}{R^2} = \lambda - \kappa\rho \tag{3}$$

Accents denote derivatives with respect to t; λ is the cosmological constant whose value is unknown, and κ is the Einstein constant whose value is $1,87 \times 10^{-27}$ in C.G.S. units (8π in natural units).

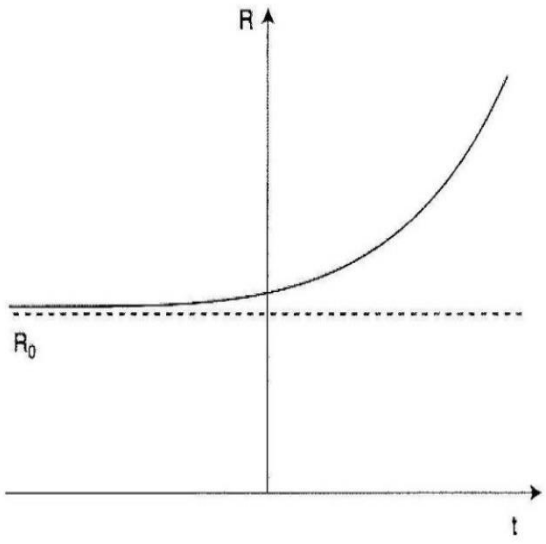
The four identities expressing the conservation of momentum and of energy reduce to

$$\frac{d\rho}{dt} + \frac{3R'}{R}(\rho + p) = 0 \tag{4}$$

which is the conservation of energy equation. This equation can replace (3). It is suitable for an interesting interpretation. Introducing the volume of space $V = \pi^2 R^3$, it can be written

$$d(V\rho) + pdV = 0 \tag{5}$$

No skimming!



and put in (11) $\beta = 0$ and $\alpha = 2R_0$, it follows that

$$t = R_0\sqrt{3}\int \frac{dR}{R - R_0}\sqrt{\frac{R}{R + 2R_0}} \tag{16}$$

For this solution the two equations (13) are of course no longer valid. Writing

$$\kappa\delta = \frac{2}{R_E^2} \tag{17}$$

we have from (14) and (15)

$$R^3 = R_E^2 R_0 \tag{18}$$

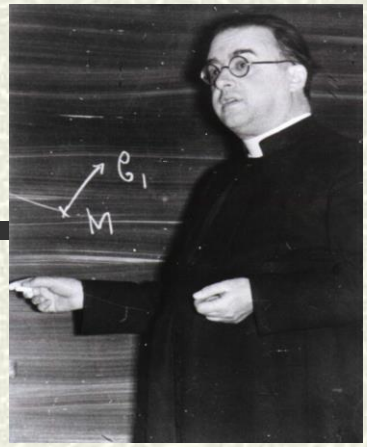
The value of R_E, the radius of the universe computed from the average density by Einstein's equations (17), has been found by Hubble to be

$$R_E = 8,5 \times 10^{28}\text{cm.} = 2,7 \times 10^{10}\text{parsecs} \tag{19}$$

We shall see later that the value of R_0 can be computed from the radial velocities of the nebulæ; R can then be found from (18). Finally, we shall show that a solution introducing a relation substantially different from (14) would lead to consequences not easily acceptable.

Conclusion: not an easy read in 1927!

New factor (ii): data



- **Un univers de rayon croissant…**

  Cosmos of expanding radius from GR
  Accounts for the recession of the nebulae

- **Redshift/distance data for the nebulae**

  Redshift data from Slipher (Strömberg,1925)
  Distance data from Hubble

- **How was the distance data established?**

  Distance data from Hubble (1926)
  Not established using Cepheid variables
  Method of apparent magnitude
  Many assumptions

Log r = 0.2m +4.04

Later verified

Hubble's paper of 1926

EXTRA-GALACTIC NEBULAE[1]

By EDWIN HUBBLE

ABSTRACT

This contribution gives the results of a statistical investigation of 400 extra-galactic nebulae for which Holetschek has determined total visual magnitudes. The list is complete for the brighter nebulae in the northern sky and is representative to 12.5 mag. or fainter.

The classification employed is based on the forms of the photographic images. About 3 per cent are irregular, but the remaining nebulae fall into a sequence of type forms characterized by rotational symmetry about dominating nuclei. The sequence is composed of two sections, the elliptical nebulae and the spirals, which merge into each other.

Luminosity relations.—The distribution of magnitudes appears to be uniform throughout the sequence. For each type or stage in the sequence, the total magnitudes are related to the logarithms of the maximum diameters by the formula,

$$m_T = C - 5 \log d ,$$

where C varies progressively from type to type, indicating a variation in diameter for a given magnitude or vice versa. By applying corrections to C, the nebulae can be reduced to a standard type and then a single formula expresses the relation for all nebulae from the Magellanic Clouds to the faintest that can be classified. When the minor diameter is used, the value of C is approximately constant throughout the entire sequence. The coefficient of log d corresponds with the inverse-square law, which suggests that the nebulae are all of the same order of absolute luminosity and that apparent magnitudes are measures of distance. This hypothesis is supported by similar results for the nuclear magnitudes and the magnitudes of the brightest stars involved, and by the small range in luminosities among nebulae whose distances are already known.

Distances and absolute dimensions.—The mean absolute visual magnitude, as derived from the nebulae whose distances are known, is -15.2. The statistical expression for the distance in parsecs is then

$$\log D = 4.04 + 0.2\, m_T ,$$

where m_T is the total apparent magnitude. This leads to mean values for absolute dimensions at various stages in the sequence of types. Masses appear to be of the order of 2.6×10^8 ⊙.

Distribution and density of space.—To apparent magnitude about 16.7, corresponding to an exposure of one hour on fast plates with the 60-inch reflector, the numbers of nebulae to various limits of total magnitude vary directly with the volumes of space

ponent parts of their organization. Definite evidence as to distances and dimensions is restricted to six systems, including the Magellanic Clouds. The similar nature of the countless fainter nebulae has been inferred from the general principle of the uniformity of nature.

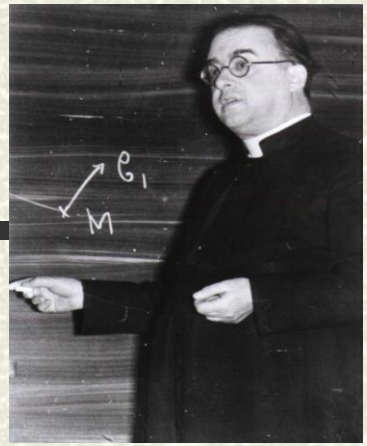
The various types are homogeneously distributed over the sky, their spectra are similar, and the radial velocities are of the same general order. These facts, together with the equality of the mean magnitudes and the uniform frequency distribution of magnitudes, are consistent with the hypothesis that the distances and absolute luminosities as well are of the same order for the different types. This is an assumption of considerable importance, but unfortunately it cannot yet be subjected to positive and definite tests. None of the

These considerations lead to the hypothesis that the nebulae treated in the present discussion are all of the same order of absolute magnitude; in fact, they lend considerable color to the assumption that extra-galactic nebulae in general are of the same order of absolute magnitude and, within each class, of the same order of actual dimensions. Some support to this assumption is found in the observed absence of individual stars in the apparently fainter late-type nebulae. If the luminosity of the brightest stars involved is inde-

Once the assumption of a uniform order of luminosity is accepted as a working hypothesis, the apparent magnitudes become, for statistical purposes, a measure of the distances. For a mean absolute magnitude of -15.2, the distance in parsecs is

$$\log D = 0.2\, m_T + 4.04. \qquad (8)$$

Lemaitre (1927): data section



where r is the distance of the source. We have therefore

$$\frac{R'}{R} = \frac{v}{cr} \tag{23}$$

Radial velocities of 43 extragalactic nebulæ are given by Strömberg ([6]).

The apparent magnitude m of these nebulæ can be found in the work of Hubble. It is possible to deduce their distance from it, because Hubble has shown that extragalactic nebulæ have approximately equal absolute magnitudes (magnitude = −15.2 at 10 parsecs, with individual variations ±2), the distance r expressed in parsecs is then given by the formula $\log r = 0,2m+4,04$.

One finds a distance of about 10^6 parsecs, varying from a few tenths to 3,3 megaparsecs. The probable error resulting from the dispersion of absolute magnitudes is considerable. For a difference in absolute magnitude of ±2, the distance exceeds from 0,4 to 2,5 times the calculated distance. Moreover, the error is proportional to the distance. One can admit that, for a distance of one megaparsec, the error resulting from the dispersion of magnitudes is of the same order as that resulting from the dispersion of velocities. Indeed, a difference of magnitude of value unity corresponds to a proper velocity of 300 Km/s, equal to the proper velocity of the sun compared to nebulæ . One can hope to avoid a systematic error by giving to the observations a weight proportional to $\frac{1}{\sqrt{1+r^2}}$, where r is the distance in megaparsecs.

Using the 42 nebulæ appearing in the lists of Hubble and Strömberg ([7]), and taking account of the proper velocity of the Sun (300 Km/s in the direction $\alpha = 315°$, $\delta = 62°$), one finds a mean distance of 0,95 megaparsecs and a radial velocity of 600 Km/sec, i.e. 625 Km/sec at 10^6 parsecs ([8]).

We will thus adopt

$$\frac{R'}{R} = \frac{v}{rc} = \frac{625 \times 10^5}{10^6 \times 3,08 \times 10^{18} \times 3 \times 10^{10}} = 0,68 \times 10^{-27} \text{cm}^{-1} \tag{24}$$

This relation enables us to calculate R_0. We have indeed by (16)

$$\frac{R'}{R} = \frac{1}{R_0\sqrt{3}}\sqrt{1 - 3y^2 + 2y^3} \tag{25}$$

where we have set

$$y = \frac{R_0}{R} \tag{26}$$

On the other hand, from (18) and (26)

$$R_0^2 = R_E^2 y^3 \tag{27}$$

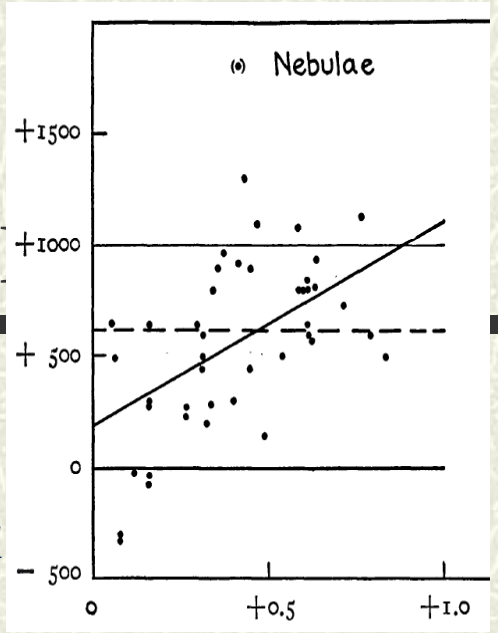
and therefore

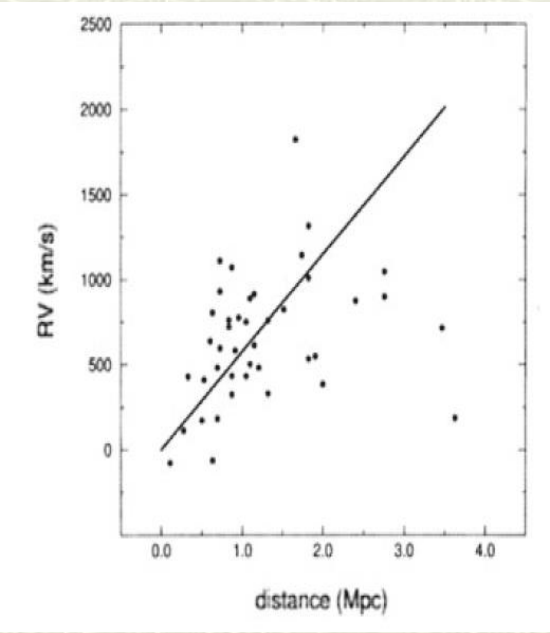
$$3\left(\frac{R'}{R}\right)^2 R_E^2 = \frac{1 - 3y^2 + 2y^3}{y^3} \tag{28}$$

With the adopted numerical data (24) for $\frac{R'}{R}$ and (19) for R_E, we have

$$y = 0,0465.$$

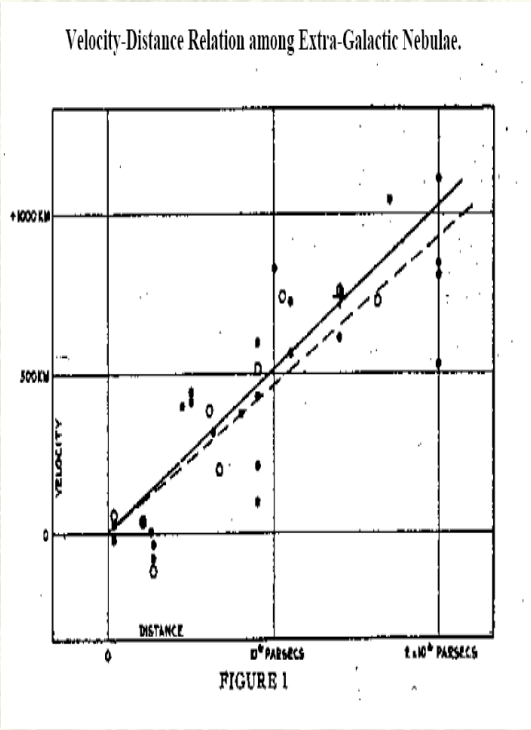
Lemaître (27) *v*





- **Lemaître's data (1927)**
  42 redshifts from Slipher (Strömberg 1
  42 distances from Hubble (1926)
  Distances using apparent magnitude
  Expansion rate = mean redshift/mean distance

- **Hubble's data (1929)**
  44 redshifts from Slipher
  24 distances using Cepheid variables
  22 distances using apparent magnitude
  Most important point not shown



Apparent magnitude data shown as one data point
Preliminary data: also true of Lemaître 1927

Supporting evidence

- **Lemaître (1927) republished in 1931**
  English translation (MNRAS)
- **Obs. section removed**
  No discussion of redshifts, distances
- **Abridgements by Lemaître**
  Established by Mario Livio
- **Explanation for removal**
  'Of no actual interest'

From a discussion of available data, we adopt

$$\frac{R'}{R} = 0{\cdot}68 \times 10^{-27}\ \text{cm.}^{-1} \quad . \quad . \quad . \quad (24)$$

and find from (16)

"I send you a translation of the paper.
I did not find it 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"

Preliminary data of 1927 paper superseded!

Letter to MNRAS

In conclusion..

- **Lemaître (1927)**

  Vanguard of theory
  Vanguard of observation

- **Paper overlooked – why?**

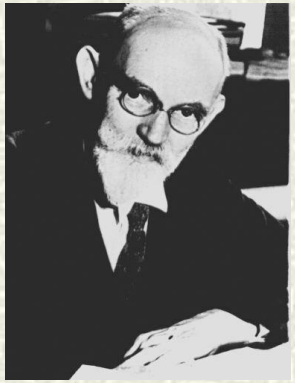
  Sociological factors
  Philosophical factors

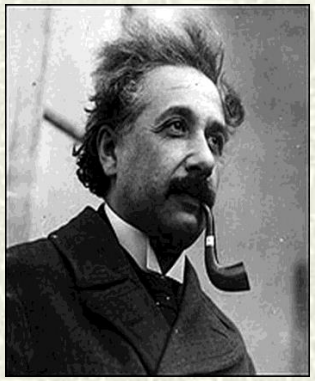
- **New: considerations of physics**

  Complexity of analysis
  Obs. data not well established

- **<u>An idea ahead of its time</u>**

  The brilliance of Georges Lemaître!





The greatest cosmologist of them all

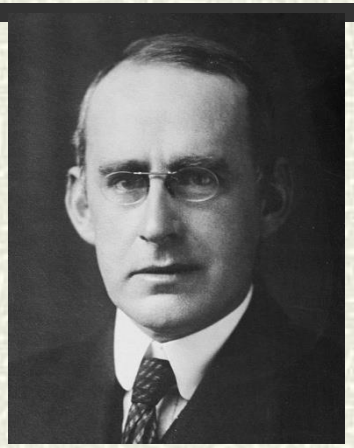
Epilogue

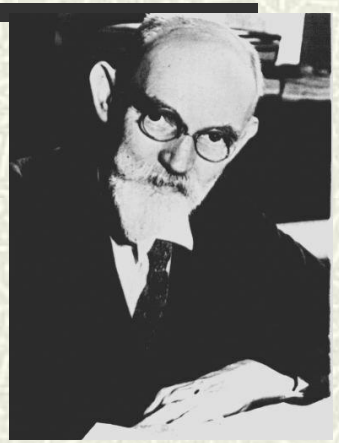
- **Eddington (1930, 31)**
  On the instability of the Einstein universe
  The Eddington-Lemaître model

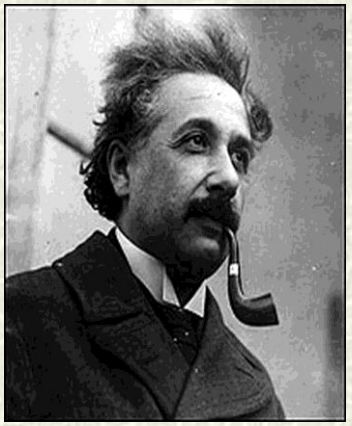
- **de Sitter (1930, 31)**
  Further remarks on the expanding universe

- **Tolman (1930, 31)**
  On the behaviour of non-static models

- **Einstein (1931, 32)**
  Friedmann-Einstein model $\lambda = 0, k = 1$
  Einstein-deSitter model $\lambda = 0, k = 0$
  Cosmology review of 1933







<u>If</u> redshifts represent velocities…
<u>If</u> effect is non-local ….

De Sitter effect and astronomy

- **Karl Wirtz** (1922,24)

  Redshifts of nebulae increasing with distance

  Dispersal effect? v = 2200 – 1200 log (Dm)

- **Ludwik Silberstein** (1924)

  Relation between redshifts, distance, curvature

  Δλ/λ = +/- r/R (global clusters)

- **Knut Lundmark** (1924,25)

  Velocity against distance; clusters, nebulae

KNUT LUNDMARK
Foto LUB

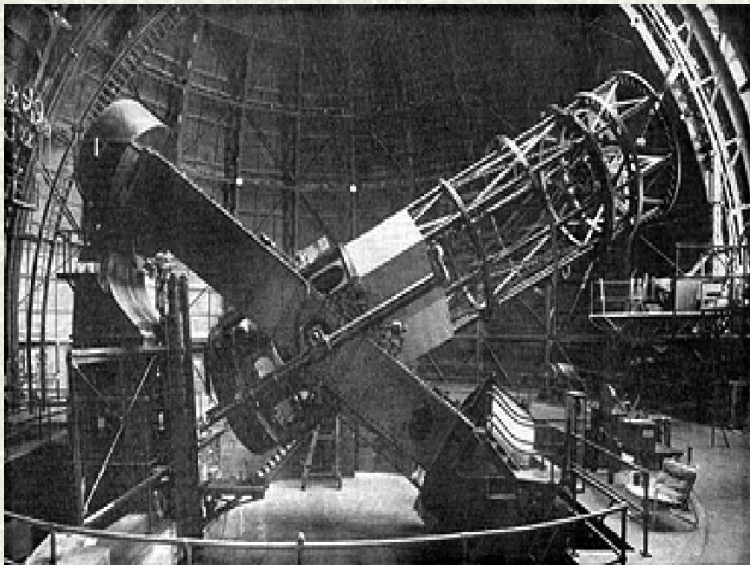
- **Gustav Strömberg** (1925)

  Vel/dist relation for globular clusters, nebulae?

The distances of the nebulae (1925,26)

- **Hooker telescope (Mt Wilson)**
  100-inch reflector (1917)
- **Edwin Hubble (1921)**
  Ambitious and dedicated astronomer
- **Resolved Cepheids in nebulae (1925)**
  Leavitt's period-luminosity relation
- **Spirals beyond Milky Way (1925, 26)**
  End of the 'Great Debate'

Edwin Hubble (1889-1953)



Paradigm shift or slow dawning?

- **Hubble/Slipher** *Empirical law for nebulae*
- **Friedmann** *Time-varying solutions*
- **Lemaître** *Theory and observation*

Obs: Parsons, Huggins, Leavitt, Shapley
Models I: Einstein, de Sitter, Weyl, Lanczos, Robertson
Models II: Einstein, de Sitter, Eddington, Tolman, Robertson

Slow emergence of theory and evidence
Slow acceptance: no upsurge of interest 1935-65

Lemaître's universe (1927)

Fr Georges Lemaître

- **Redshifts of galaxies = cosmic expansion?**

  Rate of expansion from ave. distance and redshift

  H = 585 km/s/Mpc

- **Matter-filled *U* of increasing radius**

  de Sitter model not static (1925)

  New evolving solution : Einstein → deS

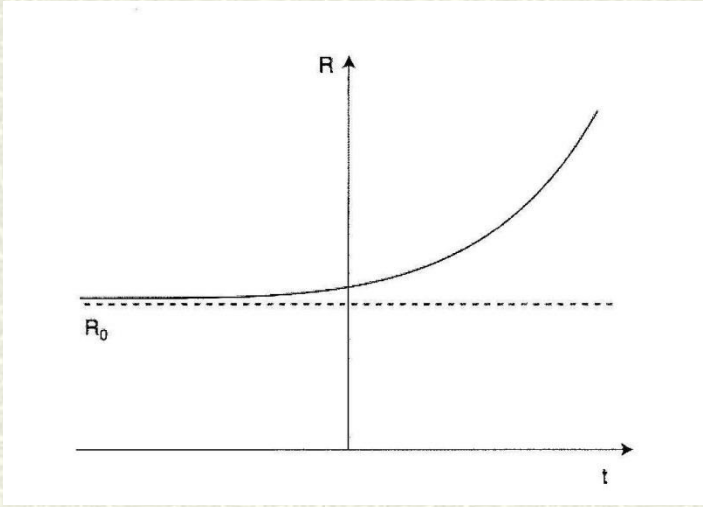
Not an empirical law
Edited in 1931 translation

- **No beginning: indefinite age**

  Starts from Einstein universe at t = - ∞

- **Rejected by Einstein**

  An idea whose time had not yet come



The Einstein World

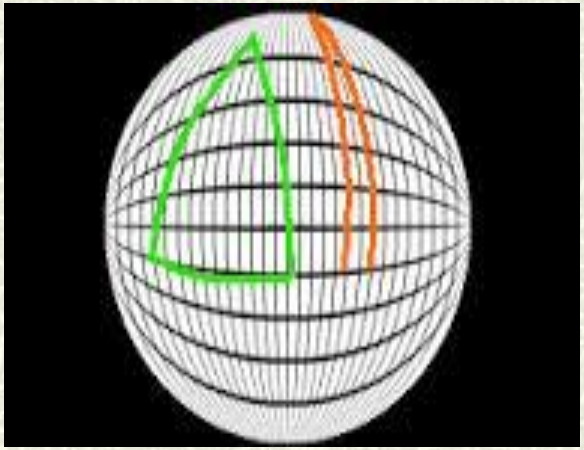
- **Assume static universe** *(observation)*

  Non-zero, static, uniform density of matter

- **Assume closed spatial curvature**

  To conform with the relativity of inertia

  Solves problem of $g_{\mu\nu}$ at infinity



- **New term necessary in GFE***

  Allowed by relativity

  Needed for non-zero solution

$$G_{\mu\nu} = -\kappa\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right)$$

$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right)$$

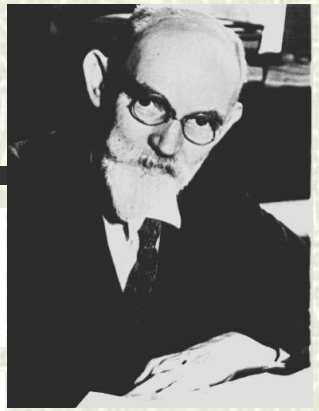
- **Quantitative model of the universe**

  Cosmic radius related to matter density

  Cosmic radius related to cosmological constant

$$\lambda = \frac{\kappa\rho}{2} = \frac{1}{R^2}$$

The de Sitter universe



$$G_{\mu\nu} - \frac{1}{2} g_{\mu\nu} G + \lambda g_{\mu\nu} = 0$$

$$\rho = 0; \quad \lambda = \frac{3}{R^2}$$

Willem de Sitter

- **Alternate cosmic solution**

  A universe empty of matter (1917)

  Curvature of spacetime determined by cosmic constant

- **Einstein's reaction**

  Unrealistic; conflict with Mach's principle

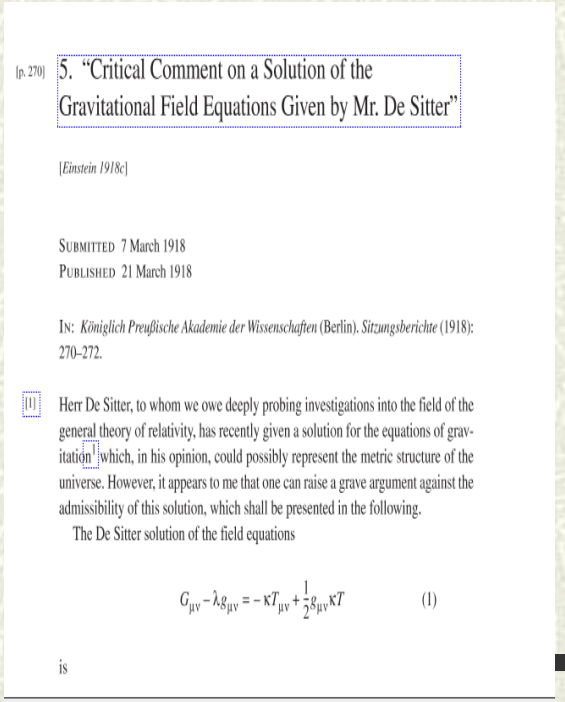
  Mathematically unsound? Singularity?

- **Interest from astronomers**

  Prediction of redshifts

- **The Einstein-deSitter-Weyl-Klein debate**

  Static or non-static - a matter of co-ordinates?



[p. 270] 5. "Critical Comment on a Solution of the Gravitational Field Equations Given by Mr. De Sitter"

[*Einstein 1918c*]

SUBMITTED 7 March 1918
PUBLISHED 21 March 1918

IN: *Königlich Preußische Akademie der Wissenschaften* (Berlin). *Sitzungsberichte* (1918): 270–272.

[1] Herr De Sitter, to whom we owe deeply probing investigations into the field of the general theory of relativity, has recently given a solution for the equations of gravitation[1] which, in his opinion, could possibly represent the metric structure of the universe. However, it appears to me that one can raise a grave argument against the admissibility of this solution, which shall be presented in the following.

The De Sitter solution of the field equations

$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa T_{\mu\nu} + \frac{1}{2} g_{\mu\nu} \kappa T \qquad (1)$$

is

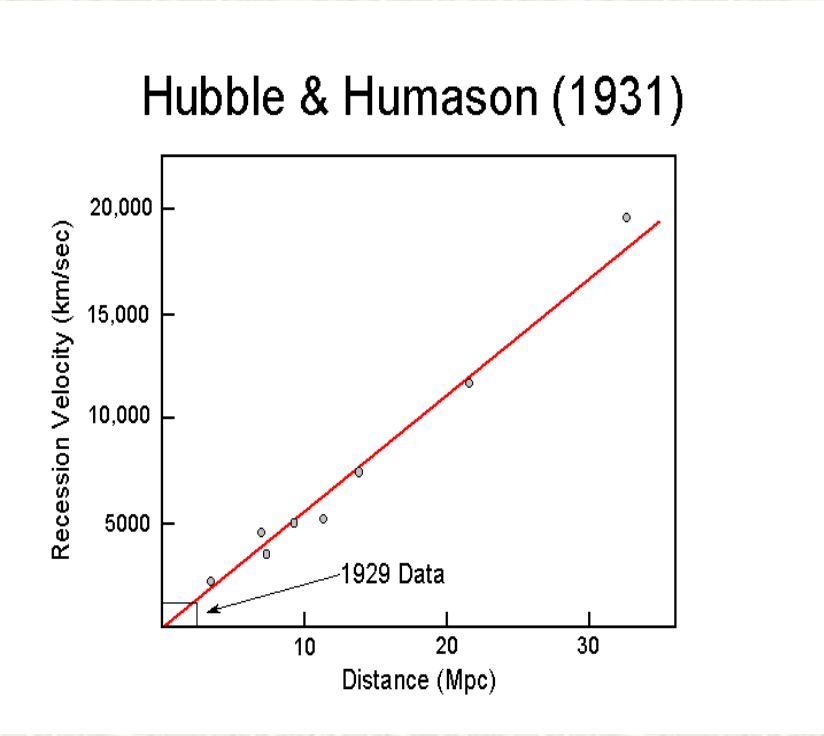
The justification

- **The Hubble-Humason graph**
  Context of justification (1931)

- **Different methods**
  Redshifts by Humason
  Distances by apparent magnitude

- **Acceptable in 1931**
  Justified by Hubble graph of 1929

- **Not acceptable in 1927?**
  Apparent magnitude method not established



$H = 585\ kms^{-1}Mpc^{-1}$

A redshift/distance relation (1929)

- **Is there a redshift/distance relation for galaxies?**

  Motivation: establishing distance to the galaxies

- **Combine 24 nebular distances with redshifts**

  Redshifts from Slipher : not acknowleged

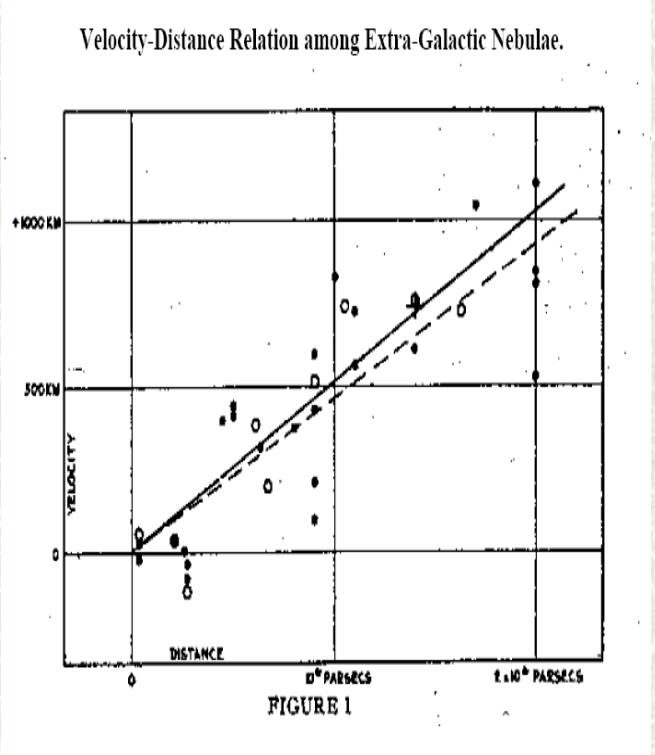
- **Approx linear relation (Hubble, 1929)**

  Some errors (Peacock)

  Most important point not shown

- **What do the redshifts mean?**

  Reference to de Sitter universe



$H = 585\ kms^{-1}Mpc^{-1}$

Act III An expanding universe? (1930-)

- **RAS meeting (1930)**

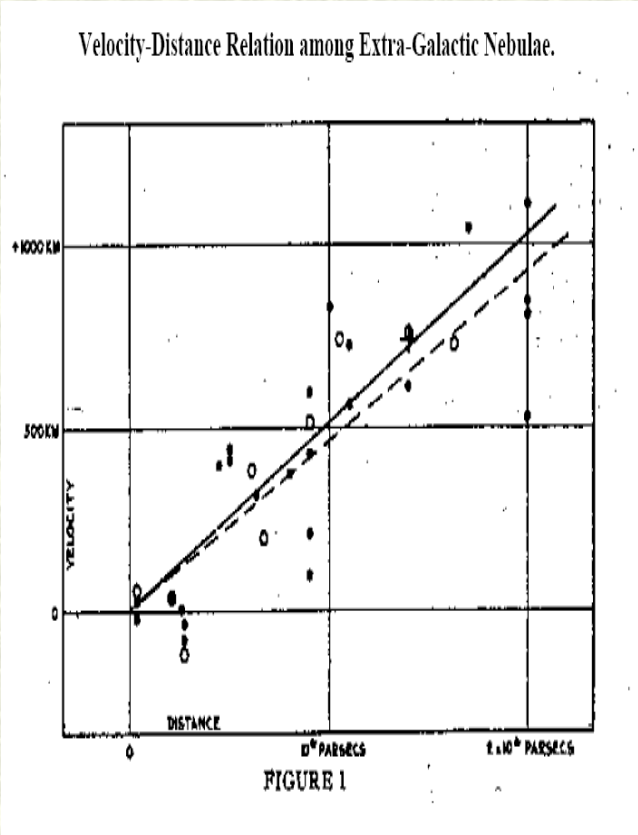
  Eddington, de Sitter
  Redshift/distance relation of the nebulae
  Static models don't fit
  New model required

- **Letter from Lemaître**

  Reminds Eddington of his 1927 model
  Eddington, de Sitter impressed

- **Expansion of space?**

  Considered by many theoreticians
  If redshifts are velocities (Zwicky)
  If effect is non-local
  Not accepted by astronomers (Hubble)



Expansion of space?

6. Conclusion.

We have found a solution such that:

1. The mass of the universe is a constant related to the cosmological constant by Einstein's relation

$$\sqrt{\lambda} = \frac{2\pi^2}{\kappa M} = \frac{1}{R_0}$$

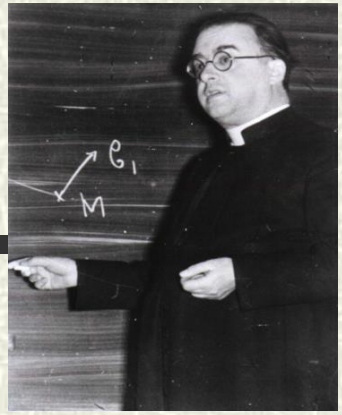
2. The radius of the universe increases without limits from an asymptotic value R_0 for $t = -\infty$.

3. The recession velocities of extragalactic nebulæ are a cosmical effect of the expansion of the universe. The initial radius R_0 can be computed by formulæ (24) and (25) or by the approximate formula $R_0 = \frac{rc}{v\sqrt{3}}$.

4. The radius of the universe is of the same order of magnitude as the radius R_E deduced from density according to Einstein's formula

$$R = R_E \sqrt[3]{\frac{R_0}{R_E}} = \frac{1}{5} R_E$$

A historical puzzle

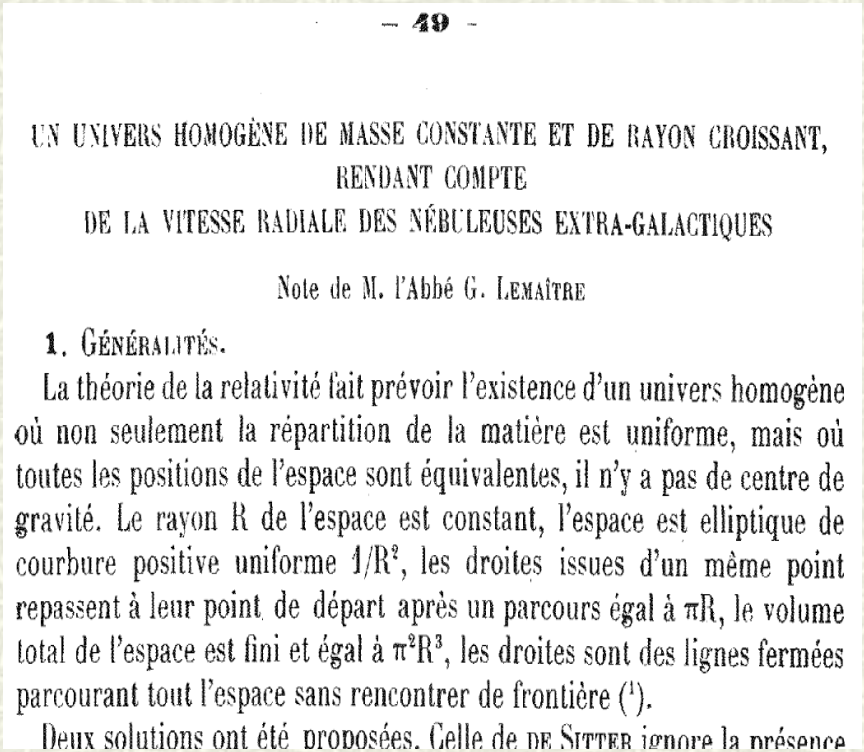


- **Georges Lemaître (1927)**
  Cosmos of expanding radius from GR
  Accounts for the recession of the nebulae

- **Distributed**
  Copy received by Eddington
  Copies received by Einstein, others

- **No reaction**
  'Set aside' by Eddington
  Not read or read and forgotten?

- **Accepted in 1930**
  After Lemaître contacts Eddington



– 49 –

UN UNIVERS HOMOGÈNE DE MASSE CONSTANTE ET DE RAYON CROISSANT, RENDANT COMPTE DE LA VITESSE RADIALE DES NÉBULEUSES EXTRA-GALACTIQUES

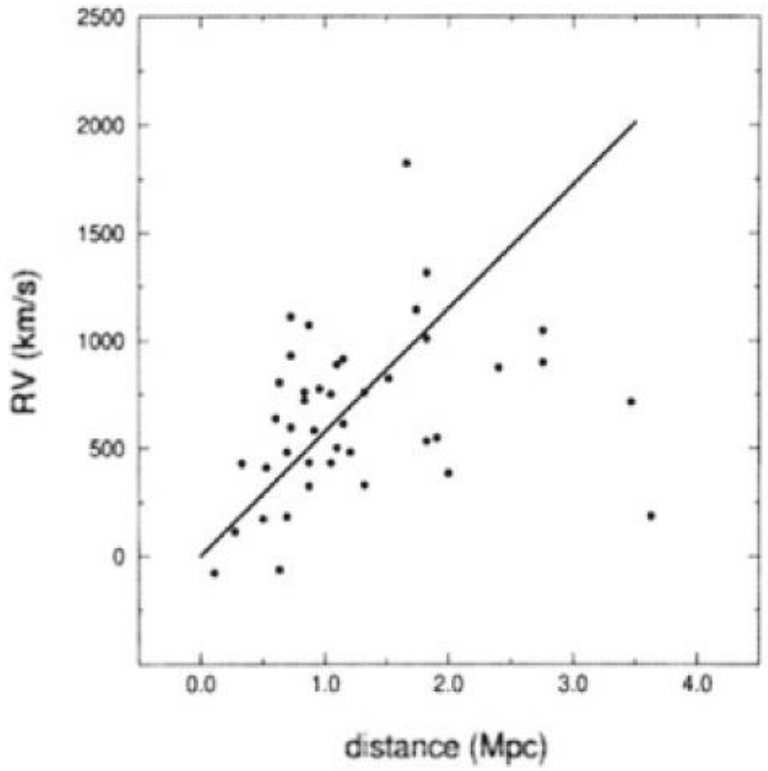
Note de M. l'Abbé G. LEMAÎTRE

1. GÉNÉRALITÉS.

La théorie de la relativité fait prévoir l'existence d'un univers homogène où non seulement la répartition de la matière est uniforme, mais où toutes les positions de l'espace sont équivalentes, il n'y a pas de centre de gravité. Le rayon R de l'espace est constant, l'espace est elliptique de courbure positive uniforme $1/R^2$, les droites issues d'un même point repassent à leur point de départ après un parcours égal à πR, le volume total de l'espace est fini et égal à $\pi^2 R^3$, les droites sont des lignes fermées parcourant tout l'espace sans rencontrer de frontière (1).

Deux solutions ont été proposées. Celle de DE SITTER ignore la présence

Comparison of Lemaître 1927 and Hubble 1929



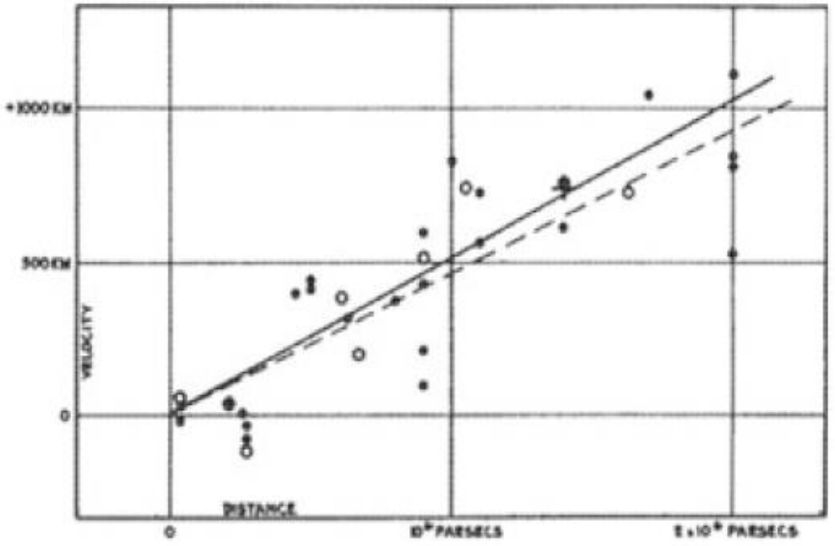


Fig. 3 Comparison between the data used by Lemaître in 1927 (*left*) to yield the first empirical value of the rate of expansion of the Universe as 575 km/s/Mpc (reconstructed in [31]), and the radial velocity–distance diagram published by Hubble in 1929, with a best slope of 530 km/s/Mpc (*right*)