Hands off Hubble’s Law

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IAU members vote to recommend renaming the Hubble law as the Hubble–Lemaître law

An electronic vote has been conducted among all members of the International Astronomical Union, and the resolution to recommend renaming the Hubble law as the Hubble–Lemaître law has been accepted. The Hubble–Lemaître law describes the effect by which objects in an expanding Universe move away from each other with a velocity proportionally related to their distance. This resolution was proposed in order to pay tribute to both Lemaître and Hubble for their fundamental contributions to the development of modern cosmology.
on a suggested renaming of the Hubble Law

Proposed by the IAU Executive Committee

The XXX General Assembly of the International Astronomical Union,

considering

1. that the discovery of the apparent recession of the galaxies, which is usually referred to as the “Hubble law”, is one of the major milestones in the development of the science of Astronomy during the last 100 years and can be considered one of the founding pillars of modern Cosmology;

2. that the Belgian astronomer Georges Lemaître, in 1927 published (in French) the paper entitled “Un Univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extra-galactiques” [1]. In this he first rediscovers Friedman’s dynamic solution to Einstein’s general relativity equations that describes an expanding universe. He also derives that the expansion of the universe implies the spectra of distant galaxies are redshifted by an amount proportional to their distance. Finally he uses published data on the velocities and photometric distances of galaxies to derive the rate of expansion of the universe (assuming the linear relation he had found on theoretical grounds);

3. that, at the time of publication, the limited popularity of the Journal in which Lemaître’s paper appeared and the language used made his remarkable discovery largely unperceived by the astronomical community;

4. that both Georges Lemaître (an IAU member since 1925 [2]) and the American astronomer Edwin Hubble (an IAU member since 1922 [3]) attended the 3rd IAU General Assembly in Leiden in July 1928 and exchanged views [4] about the relevance of the principle of dark energy to the evolution of the universe.
redshift vs distance observational data of the extragalactic nebulæ to the emerging evolutionary model of the universe;

5. that Edwin Hubble, in 1929 published the paper entitled “A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae” [5] in which he proposed and derived the linear distance-velocity relation for galaxies, ultimately including new velocity data in his 1931 paper with Humason [6]. Soon after the publication of his papers, the cosmic expansion became universally known as the “Hubble law”;

6. that, in 1931, on invitation by the Journal Monthly Notices of the Royal Astronomical Society, G. Lemaitre translated in English his original 1927 paper [7], deliberately omitting the section in which he derived the rate of expansion because he "did not find advisable to reprint the [his] provisional discussion of radial velocities which is clearly of no actual interest, and also the geometrical note, which could be replaced by a small bibliography of ancient and new papers on the subject" [8];

    desiring

7. to pay tribute to both Georges Lemaitre and Edwin Hubble for their fundamental contributions to the development of modern cosmology;

8. to honour the intellectual integrity of Georges Lemaitre that made him value more the progress of science rather than his own visibility;

9. to highlight the role of the IAU General Assemblies in fostering exchanges of views and international discussions;

10. to inform the future scientific discourses with historical facts;

    resolves

11. to recommend that from now on the expansion of the universe be referred to as the “Hubble-Lemaitre law”.

Hubble's law, also known as the Hubble–Lemaître law,[1] is the observation in physical cosmology that:

1. Objects observed in deep space—extragalactic space, 10 megaparsecs (Mpc) or more—are found to have a redshift, interpreted as a relative velocity away from Earth;
2. This Doppler shift-measured velocity of various galaxies receding from the Earth is approximately proportional to their distance from the Earth for galaxies up to a few hundred megaparsecs away.[2][3]

Hubble's law is considered the first observational basis for the expansion of the universe and today serves as one of the pieces of evidence most often cited in support of the Big Bang model.[4][5] The motion of astronomical objects due solely to this expansion is known as the Hubble flow.[6]. It is often expressed by the equation $v = H_0 D$, with $H_0$ the constant of proportionality—Hubble constant—between the "proper distance" $D$ to a galaxy, which can change over time, unlike the comoving distance, and its velocity $v$, i.e. the derivative of proper distance with respect to cosmological time coordinate. (See uses of the proper distance for some discussion of the subtleties of this definition of 'velocity'.)
Overview: the historical facts

- **A brief history of observation**
  *Redshifts and distances of the galaxies*

- **A brief history of theory**
  *Relativity and the expanding universe*

- **A paradigm shift**
  *Hubble’s law = manifestation of cosmic expansion*

- **Conclusion**
  *Hubble’s law should be Hubble’s law*

*Coda: bring clarity to contemporary $H_0$ puzzle*
The redshifts of the nebulae

- **Spectrum of light from spiral nebulae** (1909-)
  
  Good results with fast camera lens

- **Many nebulae red-shifted** (1912-1917)
  
  Doppler effect \( \Delta \lambda / \lambda = v / c \)

- **Largest redshifts for faintest nebulae**
  
  Relation between redshift and distance?

- **Distinct galaxies?**
  
  Not gravitationally bound by MW?

  Well-known puzzle (Edd 1923)
Further astronomical investigations

- **Silberstein (1923)**
  \[ \Delta \lambda / \lambda = +/- \ r/R \text{ (globular clusters)} \]

- **Von Wirtz (1924)**
  *Redshift/distance for nebulae?*

- **Lundmark (1924)**
  *Stars, globular clusters and nebulae*

- **Strömberg (1925)**
  *Redshift/dist relation for clusters and nebulae?*

*Uncertain distances*
The distances of the nebulae (1925)

- **Hooker telescope (Mt Wilson, 1917)**
  
  *Edwin Hubble (1921): ambitious astronomer*

- **Resolved Cepheid stars in nebulae (1925)**
  
  *Distance using Leavitt’s period-luminosity relation*

- **Spirals beyond Milky Way!**
  
  *Verdict soon accepted*

- **Nebulae = distinct galaxies**
  
  *What do nebular redshifts represent?*
Hubble’s Law (1929)

- A redshift/distance relation for the nebulae?
  *Motivation: establishing galactic distances*

- Combine 24 nebular distances with redshifts
  *Distances using Cepheids and involved stars
  Redshifts from Slipher: not acknowledged*

- ‘Approx linear relation’
  *Cross = mean value for another 22 nebulae
  Furthest data point not shown*

- An empirical relation
  *Nothing to do with cosmic expansion*

$$H = 585 \text{ km s}^{-1} \text{ Mpc}^{-1}$$
Explanation for runaway galaxies?

*Newton’s gravity*

Gravity pulls in not out

\[ F = G \frac{Mm}{r^2} \]

*What is pushing out?*
Einstein’s theory of gravity

General theory of relativity (1915)

• Space and time not fixed

• Affected by mass

Gravity = curvature of space (time)
Relativity and the universe

Apply Einstein’s gravity to Universe

- dynamic $U$
- expand or contract
- depends on mass

Alexander Friedmann
Lemaître’s cosmology

- **Georges Lemaître (1927)**
  Allow time-varying solutions (expansion)

- **Inspired by astronomical observation**
  Redshifts of the nebulae (Slipher)
  Extra-galactic nature of the nebulae (Hubble 1925)

- **Derives linear relation from theory**
  Extracts expansion parameter from data
  Mean velocity/mean distance
  \[ \frac{3R^2}{R^2} + \frac{3c^2}{R^2} - \lambda = \kappa e^2 \rho, \]
  \[ \frac{R^2}{R^2} + \frac{2RR''}{R^2} + \frac{e^2}{R^2} - \lambda = 0. \]

- **Einstein’s reaction**
  Expanding models ‘abominable’
  Einstein not ‘au fait’ with astronomy?

\[ H = 685 \text{ kms}^{-1}\text{Mpc}^{-1} \]
neighbourhood of the observer, because the period of the light emitted under
the same physical conditions has the same value everywhere when reckoned
in proper time. Therefore
\[ \frac{v}{c} = \frac{\delta t_2}{\delta t_1} - 1 = \frac{R_2}{R_1} - 1 \]
measures the apparent Doppler effect due to the variation of the radius of
the universe. It equals the ratio of the radii of the universe at the instants of
observation and emission, diminished by unity. \(v\) is that velocity of the ob-
server which would produce the same effect. When the source is near enough,
we can write approximately
\[ \frac{v}{c} = \frac{R_2 - R_1}{R_1} = \frac{dR}{R} = \frac{R'}{R} \frac{dt}{R} = \frac{R'}{R} r \]
where \(r\) is the distance of the source. We have therefore
\[ \frac{R'}{R} = \frac{v}{c r} \]
Radial velocities of 43 extragalactic nebulae are given by Strömberg (\(^6\)).
The apparent magnitude \(m\) of these nebulae can be found in the work of
Hubble. It is possible to deduce their distance from it, because Hubble has
shown that extragalactic nebulae have approximately equal absolute magni-
tudes (magnitude = \(-15.2\) at 10 parsecs, with individual variations \(\pm 2\)), 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 \(\pm 2\), 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 nebulae. 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 nebulae appearing in the lists of Hubble and Strömgren (7), and taking account of the proper velocity of the Sun (300 Km/s in the direction $\alpha = 315^\circ$, $\delta = 62^\circ$), 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

$$\frac{R'}{R} = \frac{v}{rc} = \frac{625 \times 10^5}{10^6 \times 3.08 \times 10^{18} \times 3 \times 10^{10}} = 0.68 \times 10^{-27} \text{cm}^{-1}$$

(24)

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

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

(25)

where we have set

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

(26)

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

$$R_0^2 = R_E^2 y^3$$

(27)

and therefore

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

(28)

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

$$y = 0.0465.$$
III The paradigm shift (1930)

- RAS meeting (January)
  Explanation for Hubble graph?
  Not compatible with static models of U

- Shift to non-static cosmologies
  U of expanding radius?
  Discussion reported in The Observatory

- Reaction from Georges Lemaître
  Reminder of Lemaître (1927)

- Accepted by community
  Lemaître paper published in English in MNRAS (1931)
  Experimental section omitted
  Replaced by expansion factor from Hubble (1929)

A paradigm shift delayed?
IV On eponmy in science

Who discovered the expanding universe?

- **Alexander Friedman**  
  *First non-static cosmologies*

- **Georges Lemaître**  
  *Non-static cosmologies and the galaxies*

- **VM Slipher**  
  *The redshifts of the nebulae*

- **Edwin Hubble**  
  *The distances of the nebulae*  
  *A linear relation between distances and redshifts*

*Answer: all of them!*
On eponymy and Hubble’s law

Note: *Hubble’s law ≠ cosmic expansion*

- **An empirical law**
  *Observed relation between redshift/distance of the nebulae*
  *Similar to Ohm’s law, Boyle’s law, Charles’ law*

- **Not interpreted by Hubble as cosmic expansion**
  *Others also hesitant*

- **Interpreted by some as manifestation of expansion**
  *Manifestation ≠ phenomenon itself*

- **Nothing to do with Lemaître!**
  *Exact law of cosmic expansion from theory*
  *Used mean values of redshift/distance to ground model*
Supporting evidence

- **Lemaître (1927) republished in 1931**
  
  *English translation (MNRAS)*

- **Data section removed**
  
  *No discussion of redshifts, distances*

- **Abridgements by Lemaître**
  
  *Established by Mario Livio*

- **Explanation for removal**
  
  *‘Of no actual interest’*

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**Preliminary data of 1927 superseded!**

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From a discussion of available data, we adopt

\[
\frac{R'}{R} = 0.68 \times 10^{-27} \text{ cm.}^{-1}
\]

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”

*Letter to MNRAS*
Lemaître (1950)

“Naturellement, avant la découverte et l’étude des amas de nébuleuses, il ne pouvait être question d’établir la loi de Hubble” or “Naturally, before the discovery and study of the clusters of nebulae, there could be no question of establishing Hubble’s law”

Lemaître (1952)

“Hubble and Humason established from observation the linear relation between velocity and distance which was expected for theoretical reasons and which is known as the Hubble velocity-distance relation”
“I propose to discuss the law of red-shifts—the correlation between distances of nebulae and displacements in their spectra. It is one of the two known characteristics of the sample of the universe that can be explored and it seems to concern the behaviour of the universe as a whole. For this reason it is important that the law be formulated as an empirical relation between observed data out to the limits of the greatest telescope. Then, as precision increases, the array of possible interpretations permitted by uncertainties in the observations will be correspondingly reduced.”

Hubble (1953)
A brief history of Hubble’s law

*When did Hubble’s observations become a law?*

- **Papers of the 1930s**
  - Hubble’s law and Hubble’s relation (theory and astronomy)

- **Papers of the 1940s**
  - Cited as Hubble’s law by astronomers (Mt. Wilson)
  - ‘Hubble’s law of the redshifts’ (Einstein)
  - Not accepted as cosmic expansion by many astronomers

- **Papers of the 1950s, 60s**
  - Conflict between ‘big bang’ and steady-state model
  - Copious references to Hubble’s observations
  - Hubble’s law and the Hubble expansion

*Hubble’s law becomes the Hubble expansion*
The rationale for renaming Hubble’s law

- **Rationale?**
  
  *To right a wrong!*

- ‘Hubble expansion’
  
  *Attributes too much to Hubble*

7. to pay tribute to both Georges Lemaître and Edwin Hubble for their fundamental contributions to the development of modern cosmology;

8. to honour the intellectual integrity of Georges Lemaître that made him value more the progress of science rather than his own visibility;

10. to inform the future scientific discourses with historical facts;

**Two wrongs don’t make a right!**
Conclusions

- Hubble’s law $\neq$ cosmic expansion
  *Empirical relation between redshift/distance of the nebulae*

- Manifestation of cosmic expansion
  *Like the cosmic microwave background*

- Renaming Hubble’s law misrepresents physics
  *Conflates observation and theory*
  *Conflates astronomy and cosmology*

- Renaming Hubble’s law misrepresents history
  *Hubble’s law $\neq$ law of cosmic expansion*

*Two wrongs don’t make a right!*
Coda: does it matter?

- Contemporary resonance
  
  *Tension in Hubble’s law*

- Expansion parameter from redshifts of supernovae
  
  \[ H_0 = 73.24 \pm 1.74 \text{ (km/s)/Mpc} \] (Riess et al. 2016)

- Expansion parameter from CMB
  
  \[ H_0 = 67.4 \pm 0.5 \text{ (km/s)/Mpc} \] (Aghanim et al. 2018).

- Redshift/distance is only one measure of expansion
  
  *Problem with \(\Lambda\)-CDM model of the cosmos?*

*Two wrongs don’t make a right!*
IV On the naming of laws

Who discovered the expanding universe?

- Friedman  *Evolving universe*
- Lemaitre  *Expanding U and experiment*
- Hubble/Slipher  *Empirical evidence*

All of them!

*FLRW metric, but nothing for Slipher*
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)
  - Accounts for the redshifts of the nebulae

- **No impact**
  - Model ignored at first by Eddington and others
  - Later accepted and redistributed (1930)

  **Why?**
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*

• **CO’R: don’t neglect the physics**
  (i) *Mathematical complexity of (Lemaître 1927)*
  (ii) *Nature of data used in (Lemaître 1927)*

*Extraordinary claims require extraordinary evidence*
Status of researcher

- **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*

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*NOTE ON DE SITTER'S UNIVERSE*  
*By G. Lemaître*

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

\[
ds^2 = R^2[-dX^2 - \sin^2 X (d\Theta^2 + \sin^2 \Theta d\Phi^2) + \cos^2 X d\tau^2],
\]

where \( R \) is a constant called the radius of the four-dimensional universe and \( X, \Theta, \Phi, \tau \) 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
*Standard at the time*
*Was Eddington fluent in French?*
*Impact factor in second language*
**The philosophical factor**

- **Einstein’s static universe**
  ‘A bottomless pit of speculation’ (1945)

- **Einstein’s reaction to Friedman (1922)**
  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)
Einstein v Lemaître

- **Lemaître meets Einstein**
  Solvay Conference 1927

- **Einstein’s reaction**
  ‘Après quelques remarques techniques favorables, il conclut...
  du point de vue physique cela lui paraissait tout à fait abominable’

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

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

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*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

- **Mathematics of relativistic cosmology**
  - Einstein’s static universe: unstable
  - Confusion over de Sitter’s universe

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

- **Lemaître’s cosmology**
  - Connection with astronomy
  - Analysis similarly difficult to grasp at first sight?
Gen Relativ Gravit

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@obs-pp.fr.

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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

Keywords Expanding Universe · Generalised Friedmann models · Georges Lemaître · Golden Oldie
We identify $\rho$ and $-p$ with the components $T^4_4$ and $T^T_1 = T^T_2 = T^T_3$ of the material energy tensor, and $\delta$ with $T$. Working out the contracted Riemann tensor for a universe with a line-element given by

$$ds^2 = -R^2d\sigma^2 + dt^2$$

(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

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

(2)

and

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

(3)

Accents denote derivatives with respect to $t$; $\lambda$ is the cosmological constant whose value is unknown, and $\kappa$ is the Einstein constant whose value is $1.87 \times 10^{-27}$ in C.G.S. units ($8\pi$ in natural units).

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

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

(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

$$d(V\rho) + pdV = 0$$

(5)
Is R a constant or a variable in eq 18?

Not an easy read!
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**
  - *Redshifts from Slipher (Strömberg, 1925)*
  - *Distances from Hubble*

- **How were 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
By EDWIN HUBBLE

ABSTRACT

This contribution gives the results of a statistical investigation of 400 extra-galactic nebulae for which Holtschek 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 types 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,

\[ m = C - 5 \log d, \]

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

\[ \log D = 4.04 + 0.3 m_T, \]

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 \( 10^{4} \) \( M_\odot \).

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.

Note caveats

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

\[ \log D = 0.2 m_T + 4.04. \]
Lemaître (1927)  
42 redshifts from Slipher  
42 distances from Hubble (1929)  
Most distances using apparent magnitude  
Mean redshift/mean distance = cosmic expansion rate

Hubble’s data (1929)  
44 redshifts from Slipher  
24 distances using Cepheid variables  
22 distances using apparent magnitude  
‘Roughly linear relation’

Most data points using involved stars  
Important data point not shown  
‘Preliminary data’: even more true of Lemaître (1927)
In conclusion..

- Lemaître (1927)
  Vanguard of theory
  Vanguard of observation

- Overlooked at the time – why?
  Sociological factors
  Philosophical factors

- New: considerations of physics
  Complexity of analysis
  Obs. data not well established
  An idea ahead of its time!

Final thought: did Eddington read his student’s paper?
TCD2020

4th International Conference on the History of Physics

4th in biennial conference series

Cambridge 2014, Pölleau 2016, San Sebastian 2018

Trinity College Dublin

Conference chair: Denis Weaire

‘On the road to modern physics’

Centenary of Eddington eclipse

Centenary of naming of proton

Many other topics/epochs

Call for abstracts: December 2019

17-19 June 2020
Further investigations

- **Silberstein** (1923)
  \[ \Delta \lambda/\lambda = +/- \ r/R \] (globular clusters)

- **Von Wirtz** (1924)
  *Redshift/distance for nebulae?*

- **Lundmark** (1924)
  *Stars, globular clusters and nebulae*

- **Strömgberg** (1925)
  *Redshift/dist relation for clusters and nebulae*
II A brief history of theory

The general theory of relativity
A new theory of gravitation (Einstein 1915)

The Einstein World (1917)
Static, matter-filled universe
Closed spatial curvature

The de Sitter model (1917)
‘Static’, empty universe
Closed spacetime curvature
Prediction of redshifts: connection with astronomy?

A cosmic debate
Einstein, de Sitter, Weyl, Klein, Lanczos
Friedman’s cosmology

Alexander Friedman (1922)
Allow time-varying solutions for the cosmos
Expanding or contracting universe

Evolving universe
Time-varying density of matter
Positive or negative spatial curvature

Einstein’s reaction
Declared solution mathematically invalid (1922)
Retracted one year later (1923)
Hypothetical (unrealistic) solution

“To this a physical reality can hardly be ascribed”
Models of the expanding universe (1930-32)

- **Eddington (1930, 31)**
  
  On the instability of the Einstein universe
  Expansion caused by condensation?

- **de Sitter (1930, 31)**
  
  Expanding universes of every flavour

- **Robertson and Tolman (1930, 31)**
  
  On the behaviour of non-static models
  Expansion caused by annihilation of matter?

- **Einstein (1931, 32)**
  
  Friedman-Einstein model  \( k = 1, \lambda = 0 \)
  Einstein-de Sitter model  \( k = 0, \lambda = 0 \)