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Bernard J. T. Jones
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PART I

100 YEARS OF COSMOLOGY

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Emerging Cosmology

> *The Universe is as it is because it was as it was*
>
> Herman Bondi,
> Lectures at King's College London, 1965

1.1 Introduction

Almost every civilisation throughout history has had a cosmology of some kind. By this we mean a description of the Universe in which they live based on their state of knowledge. The Vikings, for example, had a complex cosmology in which the world and its inhabitants were controlled by a set of Gods, both good and bad. Nature was ruled not by the laws of physics, but by the forces of nature controlled by the whims of these Gods. However bizarre that may seem to us now, at the time this belief-set dominated human behaviour: its social mores and values.

Today we live in a Universe that is described by physical laws. What is remarkable is that these laws have more often than not been discovered on the basis of laboratory experiments, and subsequently found to work on the vastest scales imaginable. That fact leads us to believe that our explanations of the Universe are a valid description of what is actually happening. We do not need to invoke special laws just to explain the cosmos and our position within it.

The physical laws governing the Universe and its constituents were discovered over a period of several centuries. Some might say this path to realisation started with Copernicus putting the Sun at the centre of everything rather than the Earth. Others might argue that this was merely descriptive and that knowledge of the laws started to emerge following on from the work of Kepler, Galileo and Newton. However one sees it, by the beginning of the 20th century, with Einstein's Theory of Relativity, the scene was set to embark on a journey of observational cosmology which 100 years later would lead to most scientists agreeing that we have a self-consistent theory of the Universe based on known laws of physics. Some, no doubt, would go as far as to say that the current view was incontrovertible.

Just as the early map makers measured and marked out our planet, the cosmographers of the 20th century marked out and mapped the Universe. Just as those map makers and those who used the maps showed that the Earth was round, the cosmographers of the 20th century have shown that the Universe we see is, in the large, homogeneous and isotropic,

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and, most remarkably, is expanding and began a finite time in our past. In addition, the evidence was that the birth of the Universe was phenomenally hot and so the theory of this origin became known as the Hot Big Bang theory.

The fact of the cosmic expansion from a hot singular state a finite time ago in our past must surely be one of the outstanding revelations of 20th century science. Some, myself included, might even argue that it is one of the most fundamental discoveries in all of science.

Acceptance of the finite age expanding model did not come easily. The idea of a finite age Universe had been around for over 50 years when, in 1965, there was a remarkable discovery that effectively set the seal on this notion. This was the discovery by Penzias and Wilson of a cosmic electromagnetic radiation field left over from the initial event. The radiation field is now referred to as the Cosmic Microwave Background Radiation (CMBR).

This radiation field served to establish the physical model of the Universe, and within a few years of the discovery many scientists were working on exploring the consequences of that model. Observation of the Universe went hand in hand with theoretical advances to clarify and test the Hot Big Bang Theory, and now this is one of the paradigms of modern science.

However, as it turned out, not everything was perfect: there were still surprises in store. Observers, while mapping out the furthest reaches of the Universe, discovered that the cosmic expansion was not quite as simple as had been first thought. It appears that although we can construct models of the Universe that are fully consistent with this observational data, that consistency can only be achieved by supposing that most of our Universe is made up of matter of an as yet unknown kind. The material we are familiar with, the atoms that make up the substances of everyday life, are but a small fraction of everything. We are as certain about the existence of this ‘dark matter’ as we are about the Big Bang itself.

The challenge is to understand the paradox that the dominance of dark matter presents us with. We have studiously avoided moulding the locally determined laws of physics to explain the phenomenon of cosmic expansion, yet we find we are forced to introduce something we did not know about before. Depending on who you are, this is either a disturbing or exciting situation.

In this book I will describe the story that leads to this remarkable conclusion, concentrating on the observations and the theoretical framework within which they are interpreted.

1.2 Pre-20th Century Cosmology

Big advances in science have often been driven by advances in technology, and this is no less true in astronomy and cosmology. Galileo with his telescope opened up the Solar System, Herschel built the largest telescopes of their time (see Figure 1.1) and produced the first great catalogue of galaxies. Hubble had access to the greatest telescopes of his day: first the Crossley 60″, followed by the Hooker 100″ and then the Hale 200″. That story continues right up to the present day, as we shall see in the chapters to come.

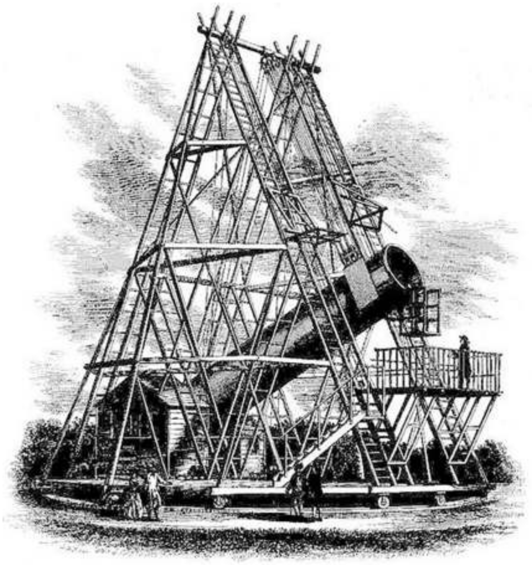

Fig. 1.1 The iconic picture of 19th century astronomy: William Herschel's great '40 foot' reflecting telescope. The telescope, designed and built by Herschel, first saw light in 1789 and was last used in 1815. This was the largest telescope ever built for a period of over 50 years when, in 1845, the Earl of Ross built his giant reflector having a 72″ mirror. Both telescopes had mirrors made of a reflective copper-tin alloy.
(From Encyclopædia Britannica, 1797.)

It is worth recounting the story of the people whose collective insight eventually led to an appreciation of one of the most remarkable discoveries made by humankind: that our Universe has a finite age. Scientifically, all the evidence points in this direction. That evidence has been accumulated as part of a century-long process bringing together the capabilities of observational astronomy and the fundamental physics of gravitation. However, the process starts long before that, arguably with Galileo turning his telescope to the heavens, and certainly with William Herschel who systematically studied the heavens beyond the stars with the most powerful telescopes of his day.

Short biography: **William Herschel** (1738–1822) came to England around 1759 and took up a career as a musician. Herschel became interested in astronomy in 1773, and very quickly went on to master the technology of building reflecting telescopes. In 1781 he discovered the planet Uranus and shortly after that became court astronomer to the King of England, George III. Much of his work was done in collaboration with his sister Caroline whose own work was acknowledged in 1828 by the Royal Astronomical Society with the award of the Society's Gold Medal.

The existence of objects in the sky that were neither stars nor planets was only appreciated towards the end of the 18th Century. Halley (1716) had listed six nebulous or diffuse objects, but the first serious catalogues were those of de la Caille (1755) and of Messier (1784). This latter catalogue was said to have been drawn up to help astronomers searching for comets from erroneously picking up known nebulae. It was a compilation of the work of others and has been occasionally added to since its first publication. The Messier

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catalogue has had a lasting impact on astronomy. Today, Messier's catalogue contains 110 objects of which 40 are galaxies.

The year following the publication of Messier's Catalogue, saw William Herschel's first catalogue of nebulae: it contained over 1000 objects. Over the following years that catalogue grew to list 2500 objects (Herschel, 1789, 1800). William Herschel's son, John Herschel, expanded his father's catalogue to create *The General Catalogue of Nebulae and Clusters* containing over 5000 nebulae (Herschel, 1864). This was soon used as the basis of several important studies of the all-sky galaxy distribution: Abbe (1867), Proctor (1869) and Waters (1873) (see Figure 1.2). Here, for the first time, was a map of the deep sky showing the zone of obscuration by the Milky Way and the clustered distribution of the nebulae (which had, by that time, started to be referred to as 'galaxies').

There is a more detailed overview of the history of this period in the article by Lundmark (1956) and the books by North (1965) and Saslaw (1999).

1.2.1 Observation in the Early 20th Century

By the early 1920s it was apparent that the Universe was mainly populated by galaxies, or, as they were referred to then, 'Island Universes'. Originally, the galaxies were thought by many astronomers to be parts of our own Galaxy of Stars, but early research showed that they were in fact distant stellar systems comparable in scale to our own Galaxy.

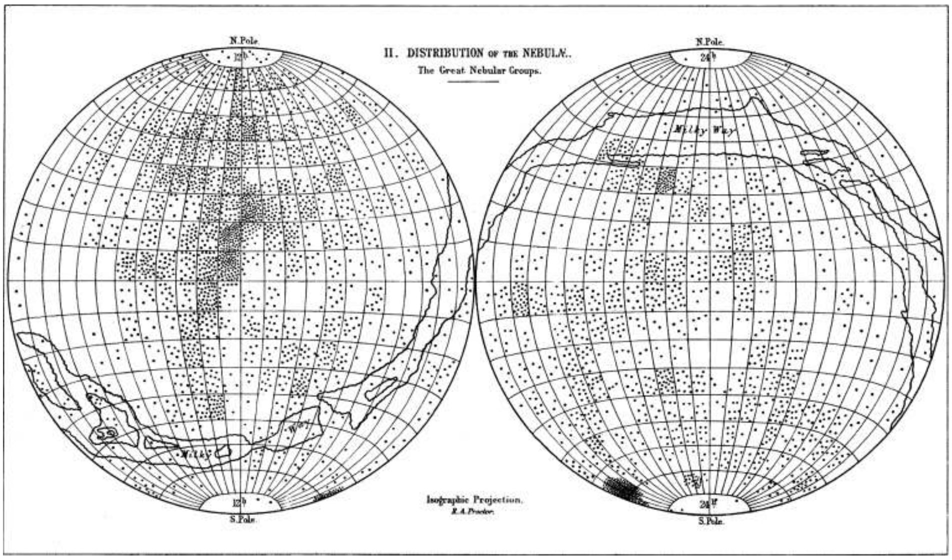

Fig. 1.2 R.A. Proctor's first all sky map showing the Milky Way and the distribution of nebulae (galaxies) over the sky (Proctor, 1869, Fig. 2). The obscuration from the Milky Way is quite evident, as is the clustered distribution of galaxies. The Virgo Cluster of Galaxies around (12^h, $+15°$) is clearly visible. The amateur astronomer Waters (1873) produced a similar map based on Abbe's (1867) refined analysis of the Herschel Catalogue (Herschel, 1864) *(© Royal Astronomical Society (1869).)*

The work of Henrietta Swan Leavitt in which she discovered that the period of Cepheid variable stars was related to their absolute magnitude (Leavitt, 1908; Leavitt and Pickering, 1912) is fundamental in establishing the cosmological distance scale.[1] She had been finding and studying variable stars in the Magellanic clouds and noticed that those which were identified as Cepheid variables having the longest period were the brightest, and since they were all at roughly the same distance they were the intrinsically brightest. Her data was shortly afterwards used by Hertzsprung (1913) to put the distance of the Small Magellanic Cloud (SMC) at 30 000 light years.[2] This makes the SMC the first object to be identified as extra-galactic.

Short biography: **Henrietta Leavitt** (1868–1921) graduated from what is nowadays known as Radcliffe College in 1892. During her senior year there she took a course in astronomy and went on to take an unpaid job at the Harvard Observatory in 1893 when the observatory was under the directorship of Edward C. Pickering. In 1902 her position became permanent and she was awarded a nominal salary of $0.30 per hour for her work, which consisted mainly of the tedious job of measuring and cataloguing variable stars in the Magellanic clouds. Pickering treated her as a mere lab assistant and did not allow her to follow up on this work. She died of cancer in 1921, after which her work was taken on by Hubble in determining the distances to nearby galaxies.

When Hubble (1926) estimated the distance to the nearby galaxy M33 he did not cite Leavitt's ground-breaking paper, referring instead to Shapley (1918a), citing it and referring to it as 'Shapley's period luminosity curve'. Shapley (1918a,b) in his work on distances makes no reference to Henrietta Leavitt as having discovered the relationship, but merely makes a passing reference: 'Some years ago Miss Leavitt found a similar relation between the apparent photographic brightness and the length of the period for the Cepheid variable stars in the Small Magellanic Cloud'.[3]

In recent years, Leavitt's period-luminosity relationship has played a fundamental role in establishing the extragalactic distance scale. A key goal of the Hubble Space Telescope (HST) was to determine the Hubble constant, H_0, to within ±10% using Cepheid variables as the fundamental calibrators of the secondary distance measures. There were three such

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[1] The first of these papers is a long-term study of 1777 variable stars in the Magellanic Clouds. She describes her photographic material and procedures in the first paragraphs of the first paper: this was evidently a formidable undertaking both in terms of the photometry and the data handling. The second of these papers starts 'The following statement regarding the periods of 25 variable stars in the Small Magellanic Cloud has been prepared by Miss Leavitt'. She then goes on to report that 'A remarkable relation between the brightness of these variables and the length of their periods will be noticed'.

[2] Hertzspring's paper has a misprint at this point, reporting 3 000 light years for an effective parallax of $0.0001''$. It was common in the early years of the 20th century to quote distances in terms of the parallax of the object when seen from the opposite points on the Earth's orbit. That defines the *parsec* unit of distance as D parsecs $= 1/p$ arc seconds ($''$) for a parallax p: A $1''$ parallax corresponds to a distance of 1pc, (hence the name *parsec*, attributed to Herbert Turner in 1913). 1pc = 3.261 . . . light years.

[3] The period luminosity data shown in Shapley (1918a, Fig. 1) for periods < 200 days is very similar to the data shown in Leavitt and Pickering (1912, Fig. 2). In both papers the period is displayed using the logarithm of the period. Leavitt, however, simply put a straight line through the points. That was enough to make her point, though on closer examination there is a manifest curvature in the data points (see Figure 1.3). Shapley (1918a, Table XI) provided a table of the curve he had fitted to the data values which would have made Hubble's task a little easier than using Leavitt's plot. It would be fair to say that Shapley's main contribution was the calibration of the Cepheid period luminosity relation using parallaxes and other methods, and that was what Hubble needed.

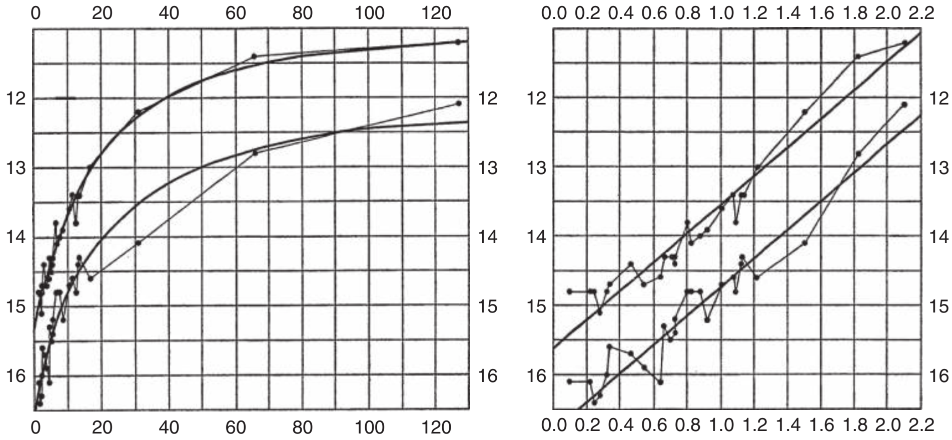

Fig. 1.3 Henrietta Leavitt's Period–Luminosity diagram for 25 Cepheid variable stars in the Small Magellanic Cloud (Leavitt and Pickering, 1912, Figs. 1 & 2). The vertical axis is the apparent magnitude (brightest at the top) and two curves are shown on each panel, one fitting the data for the brightness at maximum light and the other for the brightness at minimum. The horizontal axis is the period in days, linear in the left panel and logarithmic on the right. This is arguably one of the most important plots in the history of astronomy.
(Source: Harvard College Observatory Circular, 1912)

'Key projects' awarded to research groups in 1986. There were many advantages in using HST that would allow the study of Cepheids in galaxies outside of the Local Group and up to ten times the distance that could be achieved from ground-based observatories. The final summary of the achievements, as given in Freedman *et al.* (2001), is $H_0 = 72 \pm 2\ \text{km s}^{-1}\ \text{Mpc}^{-1}$, with a possible additional systematic error of some $\pm 7\ \text{km s}^{-1}\ \text{Mpc}^{-1}$. The largest contribution to the systematic error is the absolute zero point of the Cepheid period–luminosity relation. More recent use of the Spitzer Space Telescope has allowed a further increase in accuracy by reducing the systematic errors to give $H_0 = 74.3 \pm 2.1\ \text{km s}^{-1}\ \text{Mpc}^{-1}$ (Freedman *et al.*, 2012).

In those early years of the 20th century the quest for distance estimators for nebulae was intense. Although the Cepheid method could be locally calibrated and could take us to the nearest galaxies, it involved taking and calibrating numerous high resolution photographic plates and searching for Cepheid variable stars: Leavitt's achievement was indeed quite remarkable. There were at the time two alternatives to Cepheids: use of Novae and observations of the brightest stars. Lundmark (1956) has written an eyewitness review on the situation at that time. Lundmark was himself one of the first people to estimate the distances to several nearby galaxies: he provided a detailed overview in his paper of 1925 (Lundmark, 1925).

The year before, Lundmark (1924) had written a paper on distances to galaxies and, using Slipher's velocity data (Slipher, 1915, 1917), had plotted a velocity–distance diagram (*loc. cit.* Figure 5). He comments that 'Plotting the radial velocities against these relative distances (Fig. 5) we find that there may be a relation between the two quantities, although not a very definite one'. The situation was left to Hubble (1926, p.356 *et seq.*) to resolve.

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1.2.2 Who Discovered the Cosmic Expansion?

One of the key historical issues is the question of who did what and when? Who discovered the expansion of the Universe? That discovery is attributed to Hubble, but several people, notably Lundmark and Lemaitre, had considered cosmic expansion before his paper was published. Should they be credited with the discovery rather than Hubble?

This all happened in the brief period between around 1900 and 1930 and there are no witnesses left who can testify from experience. There is only the documentary evidence of the papers that were published and the letters and notes that were left. I want to take a slightly different approach in looking at this: I want to put myself as a researcher in the period 1925–1930 and address the questions of who knew what. What was the environment and the thinking that such a researcher would have found?

Two suggestions will emerge from this. Firstly: Hubble's approach used data that was not available to any others, so the others could not have done what he did. The others might have suspected the truth, but, unlike Hubble, they would have been unable to establish their claim convincingly. Secondly, there was an enormous gulf between 'observers', who gathered and analysed data and 'theorists', who at that time were often lost in the maze of complexities brought up by Einstein's theory. Hubble had never really come to terms with the interpretation of his discovery in terms of an expanding Universe. Conversely, few, if any, mathematicians of the time could relate the data to the coordinate systems used in their equations. Eddington in his book had noted, as others had done, the preponderance of positive radial velocities in the data available to him as 'very striking'. Yet he did not question the reason for this, he did not say 'the Universe seems to be flying apart', nor did Hubble in his famous paper of 1929.

1.2.3 General Relativity and Cosmology

It was apparent shortly after the publication of Einstein's General Theory of Relativity that this theory provided the appropriate framework for discussing mathematical models of the Universe.

Hubble (1929) discovered the relationship between redshift and distance that bears his name, but the interpretation of that result was not immediate. Hubble himself, in that important paper, never used either of the words 'expansion' or 'recession', but instead alluded to '. . . the possibility that the velocity–distance relation may represent the de Sitter effect . . . ', going on to explain briefly what the de Sitter effect was. The title of Hubble's paper was *A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae*. But, no matter what Hubble's thinking on the interpretation might have been, it was a landmark paper in cosmology: he had found direct evidence relating the redshift of the spectral lines with distance.[4]

[4] Given that Hubble did not conclude that the Universe was expanding, there then arises the question of 'Who discovered the expanding Universe?'. There are many interesting discussions on this point, focusing mainly

Soon after Einstein published his General Theory of Relativity (Einstein, 1915), a number of people, notably de Sitter (1917a, 1918) and Einstein (1917a) himself, produced solutions to his field equations that could describe a Universe governed by the influence of the force of gravity. There was little data with which to test these models, and so they remained just that, abstract mathematical models.

Prior to the publication of Hubble's 1929 paper several papers had been published presenting exact homogeneous and isotropic solutions to the Einstein Field Equations, notably by Einstein, by de Sitter, by Friedmann (1922, 1924) and by Lemaître (1927, 1931a).

The solutions of Friedmann[5] and Lemaître were non-static, expanding, solutions that now underpin all of modern cosmology. The work of Friedmann was certainly an important mathematical triumph, but it had absolutely no connection with data or with the real world (see Heller (1985)). Lemaître actually calculated a redshift–distance relationship for his solution and later championed the notion of the 'primeval atom' in which the Universe expanded from a denser state. But it was perhaps Robertson who first wrote about the expanding Universe, even before the publication of Hubble's 1929 paper (Robertson, 1928, 1929).

Four scientists, Friedmann, Lemaître, Robertson and Walker established the theoretical basis for modern cosmology within the framework of Einstein's General Theory of Relativity. They provided what should be referred to as the Friedman–Lemaître–Robertson–Walker equations for a homogeneous and isotropic expanding cosmological model that is derived from Einstein's theory of general relativity. The appropriate abbreviation should be 'FLRW models', though in the literature we variously see this referred to as the 'Friedmann–Lemaître solution' or the 'Robertson–Walker metric'. North (1965) gives the opinion that while Robertson wound up two decades of discussion on homogeneous and isotropic solutions to the Einstein equation, Lemaître set the pattern for the future of cosmology. There is a nice technical overview by Lemaître himself of how he saw his 'primeval atom' model in Lemaître (1958). My own opinion is that this vastly underestimates Robertson's contribution.

Short biography: **Georges Lemaître** (1894–1966) obtained his first degree in mining engineering at the University of Brussels in 1913. During the first World War he served as an artillery sergeant in the Belgian army, after which in 1919 he went to the University of Louvain to study physics and mathematics. During that period he studied the works of Einstein. He was ordained as a priest in 1923, and then spent a year in each of Cambridge University and the Massachusetts Institute of Technology (MIT), where he was awarded a PhD, before returning to Belgium and becoming Professor of Astrophysics at the Catholic University of Louvain in 1927. 1927 was the year in which he first published his relativistic solution describing an expanding Universe with a cosmological constant.

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on the paper of Lemaître (1927) and its English language translation (Lemaître, 1931a). That aspect of the question is discussed in the papers of Kragh and Smith (2003) and of Kragh (2008), and more recently by Livio (2011) and Nussbaumer and Bieri (2011).

[5] There is no consistent transliteration of the spelling of Friedman's name from the Russian. Hence we variously see Fridman, Friedmann, and Friedman. The lunar crater named after him is 'Fridman'. The ADS bibliographic database uses 'Friedmann', so this form will be used here.

1.3 The Expansion Law

The famous Curtis–Shapley debate on whether spiral nebulae were within the galaxy or external systems had taken place in 1920 (Curtis, 1920, 1921; Shapley, 1919, 1921). Not surprisingly, no conclusion was reached, both astronomers stuck to their position. It was not until December 1924 that the astronomical community really appreciated that galaxies, or 'nebulae' as they were referred to at that time, were systems outside of our Galaxy. Hubble had a paper read at a meeting of the American Astronomical Society giving distances for three local galaxies, M31, M33 and NGC6822 using the Cepheid variables as distance indicators.[6] Even conceptually, the notion of an expanding Universe populated by galaxies was far from the then-current thinking.

Several technological advances helped to provide the necessary data. Large reflecting telescopes were built and data could be acquired onto photographic plates. Despite the size of the telescopes, the photographic emulsions were not very sensitive and so acquiring data was a slow process. Moreover, the data could only be acquired by the few who had access to these instruments.

The first published list of galaxy redshifts was that of Slipher (1915) (see also Slipher (1917)). The list had 15 galaxies. Most of the velocities in the list were large and positive and this led astronomers of the time to add a so-called 'K-term' to the solution for the motion of the Sun relative to distant stars and nebulae. Remember, at that time astronomers were not even sure whether these objects were extragalactic, so it would have been difficult to reach any profound conclusions.

Short biography: **Vesto Slipher** (1875–1969) After getting his PhD at Indiana University in 1909, Slipher spent his entire professional career at the Flagstaff Observatory in Arizona. In 1912 he obtained the first spectrum of a galaxy, M31, with an exposure of 6^h50^m using a $24''$ refractor telescope, revealing a systematic shift in the position of the spectral lines towards the blue. The velocity of approach of M31 was $-300\,\text{km}\,\text{s}^{-1}$, this was, at the time, the highest velocity measured in an astronomical object. His conclusion was that *extension of the work to other objects promises results of fundamental importance*. Despite the difficulty of measuring fainter objects, Slipher had indeed obtained spectra for 15 galaxies by 1915, 11 of which were red-shifted, and added a further six galaxies by 1917, all of which showed red-shifted spectral lines at hitherto unprecedented velocities. The final list he gave to Eddington in 1923 contained 41 galaxies.

His 1913 spectrum of NGC4595 (the *Sombrero* galaxy) revealed, for the first time the tilted spectral lines that were indicative of systemic rotation in galaxies. Later spectra found the same phenomenon in other galaxies. Slipher had also discovered and measured the rotation of galaxies.

Slipher expanded the list, giving measured radial velocities for some 41 galaxies.[7] He, Wirtz, Lundmark and Hubble all noted that the galaxies in this sample, with

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[6] This is based on the comments of Sandage (1961b, p4.). The articles by Hoskin (1976) and Trimble (1995) are far more detailed, the former giving details and analysis of the talks as they were presented and the latter eloquently describing the important backdrop against which this was played out in 1920.

[7] Strictly speaking Slipher measured the redward shift of the spectral lines. It was natural to interpret this as a velocity since that is how they measured the radial velocities of stars. Thus the galaxies were assigned the velocities that corresponded to the observed redshift as if the redshift did reflect the radial velocity. However,