Volume Title
*ASP Conference Series, Vol. **Volume Number***
Author
*© **Copyright Year** Astronomical Society of the Pacific*

The contribution of V. M. Slipher to the discovery of the expanding universe

C. O'Raifeartaigh

Department of Computing, Maths and Physics, Waterford Institute of Technology, Waterford, Ireland

Abstract. A brief history of the discovery of the expanding universe is presented, with an emphasis on the seminal contribution of V. M. Slipher. It is suggested that Hubble's 'discovery graph' of 1929 could also be known as the Hubble-Slipher graph. It is also argued that the discovery of the expanding universe matches the traditional view of scientific advance as a gradual process of discovery and acceptance, and does not concur with the Kuhnian view of science progressing via abrupt paradigm shifts.

1. Introduction

The discovery of the expanding universe marks one of the great advances of 20th century science. It lies at the heart of today's cosmology and forms a cornerstone of the evidence underpinning the modern 'big bang' model of the origin of the universe. Several comprehensive accounts of the discovery are available (North 1965; Smith 1982; Kragh 1999; Nussbaumer & Bieri 2009); however, the seminal contribution of V. M. Slipher remains relatively unknown to the scientific community and to the wider public.

A brief overview of the discovery of the expanding universe is presented, with an emphasis on Slipher's contribution. The review is presented as distinct narratives of theory and observation, as much of the key astronomical work was carried out independently of emerging theory. From the analysis, we conclude that 'Hubble's law' is a reasonable name for an empirical relation between velocity and distance for the spiral nebulae, but suggest that Hubble's 'discovery graph' of 1929 could alternately be known as the Hubble-Slipher graph. We also argue that the brief history presented matches the classic view of scientific progress as a slow, cumulative process of theory and experiment, followed by a long period of persuasion and gradual acceptance, and does not support a view of science progressing by an abrupt transition to a new paradigm, as suggested by Thomas Kuhn (1962).

2. A brief history of observation

In 1909, Vesto Melvin Slipher, a young astronomer working at the Lowell Observatory in Flagstaff, Arizona, was set the task of studying the spectrum of light from the Andromeda nebula. The motivation for this study was the belief among many astronomers that the spiral nebulae constituted solar systems in early stages of evolution. In particular, Percival Lowell, the founder and director of the observatory, hoped that a study of the spiral nebulae might yield important information about the origins of our own solar system (Hoyt 1976). For this work, young Slipher had at his disposal a 24-inch refracting telescope by Alvan Clark and a spectrograph made by John Brashear (Slipher 1927).

The use of spectroscopy to study the composition and motion of celestial objects was an established tool in astronomy by this time. In particular, the measurement of the velocity of stars by means of the Doppler effect had been well established by observers such as William Wallace Campbell at the Lick Observatory (Campbell 1906). In this effect, the spectral lines of light emitted by an object moving towards an observer are measured by the observer as shifted in frequency towards the higher (or blue) end of the spectrum, and shifted towards the lower (or red) end if the object is moving away. However, the study of the spectra of the spiral nebulae had proved problematic even for the world's largest telescopes, due to the faintness of their light. Experienced astronomers such as Julius Scheiner and Max Wolf at the Heidelberg Observatory and Edward Fath at the Lick Observatory had obtained spectrograms that suggested the spirals contained stellar systems, but the images were not clear enough to study the spectral lines in detail (Scheiner 1899; Fath 1909; Wolf 1912). Thus, Slipher set about the task with some trepidation (Hoyt 1980). Experimenting carefully over many months, he found that good spectra of the nebulae could be obtained using a spectrograph fitted with a camera lens of very short focus, a prism of high angular dispersion and a wide collimator slit. His key discovery was that the results depended critically on the speed of the spectrograph, rather than the aperture of the telescope (Hoyt 1980). Thus, useful measurements of the faint nebulae could be carried out at the relatively modest telescope at the Lowell Observatory.

In September 1912, Slipher obtained the first clear spectrum of Andromeda, and by January 1913, he had four plates on which the spectral lines of the nebula were clearly visible. His analysis of the plates gave a surprising result; the spectral lines were significantly blue-shifted, suggesting that the spiral was approaching at a radial velocity of 300 km s^{-1} (Slipher 1913). This was the first measurement of the velocity of a spiral nebula and it was greeted with some skepticism because it was much larger than the known velocities of stars (Campbell 1913). However, the measurement was soon confirmed by well-known astronomers such as William H. Wright at the Lick Observatory and Francis Pease at Mt. Wilson (Pease 1915).

By 1917, Slipher had measured spectra for 25 spiral nebulae (Slipher 1917). Of these, four were blue-shifted (indicative of a radial velocity towards the observer) and the remainder were red-shifted, indicative of objects receding from the observer. Of particular interest were the speeds of recession, ranging from 150 to 1100 km s^{-1} (see Fig. 1). Such large recession velocities were a great anomaly and suggested to some that the spirals could not be gravitationally bound by the Milky Way. Thus, Slipher's redshift observations became well-known as one argument for the 'island-universe' hypothesis, the theory that the spiral nebulae constituted distinct galaxies far beyond the Milky Way.[1] As he put it himself, *"It has for a long time been suggested that the spiral nebulae are stellar systems seen at great distances. This is the so-called "island universe" theory, which regards our stellar system and the Milky Way as a great spiral nebula which we see from within. This theory, it seems to me, gains favour in the*

[1]In fact, Slipher's argument was rather more subtle. He derived a mean velocity of 700 km s^{-1} for the Milky Way galaxy from his observations of the spirals, from which he concluded that the nebulae were similar astronomical objects.

present observations" (Slipher 1917). However, the debate could not be settled until the distances to the spirals had been measured.

Radial Velocities of Twenty-five Spiral Nebulæ.

Nebula.	Vel.	Nebula.	Vel.
N.G.C. 221	− 300 km.	N.G.C. 4526	+ 580 km.
224	− 300	4565	+1100
598	− 260	4594	+1100
1023	+ 300	4649	+1090
1068	+1100	4736	+ 290
2683	+ 400	4826	+ 150
3031	− 30	5005	+ 900
3115	+ 600	5055	+ 450
3379	+ 780	5194	+ 270
3521	+ 730	5236	+ 500
3623	+ 800	5866	+ 650
3627	+ 650	7331	+ 500
4258	+ 500		

Figure 1. Radial velocities in km s^{-1} of 25 spiral nebulae published by V. M. Slipher in 1917. Negative terms indicate velocities of approach while positive velocities are receding.

Meanwhile, Slipher continued his spectrographic observations of the nebulae. By 1922, he had amassed radial velocities for 41 spirals, almost all of which were redshifted. Unfortunately, he did not formally publish the full dataset in a journal; they became known to the community when they were published in an early textbook on general relativity (Eddington 1923) and in a paper by the astronomer Gustav Strömberg (1925).

The problem of measuring the distances to the spiral nebulae was solved by the astronomer Edwin Hubble in the 1920s.[2] Working at the world's largest telescope, the 100-inch Hooker reflector at the Mt Wilson Observatory, Hubble was able to resolve stars known as *Cepheid variables* in three of the nebulae. Such stars have the unusual property that their intrinsic luminosity can be determined by measuring a periodic variation in their brightness, a phenomenon that was first discovered by Henrietta Leavitt of the Harvard College Observatory (Leavitt 1908), and developed into a powerful technique for measuring stellar distance by Ejnar Hertzsprung and Harlow Shapley (Hertzsprung 1913; Shapley 1918). Hubble's observations of Cepheids in three nebulae allowed him to measure the distance to those spirals, and the results indicated that they lay far beyond the limits of the Milky Way, settling the 'island universe' debate at last (Hubble 1925, 1926).

The confirmation that the spiral nebulae are distinct galaxies far beyond our own led to renewed interest in the puzzle of Slipher's redshifts. The next step was to investigate whether there was a simple relation between the distance to a given galaxy and its

[2]The astronomer Ernst Öpik was the first to give a reliable estimate of the distance to a spiral nebula (Öpik 1922). However, he used a theoretical method that was not appreciated for many years.

velocity of recession.[3] By 1929, Hubble had amassed reliable estimates of the distances to 24 spirals; combining these with the corresponding redshifts from Slipher, and four redshift measurements acquired at Mt. Wilson by his assistant Milton Humason, Hubble obtained the velocity/distance graph shown in Fig. 2. Despite considerable scatter, a linear relation between radial velocity and distance was discernible. Hubble calculated a value of 500 km s^{-1} Mpc^{-1} for the slope of the solid line shown, and noted that it was consistent with preliminary studies of a more distant nebula (a spiral of velocity 3995 km s^{-1} at an estimated distance of 7 Mpc). The graph was published in the prestigious *Proceedings of the National Academy of Sciences* and it became very well known (Hubble 1929). Unfortunately, Hubble did not acknowledge his use of Slipher's velocity measurements in the paper, and this is perhaps one reason the result later became known as Hubble's law.

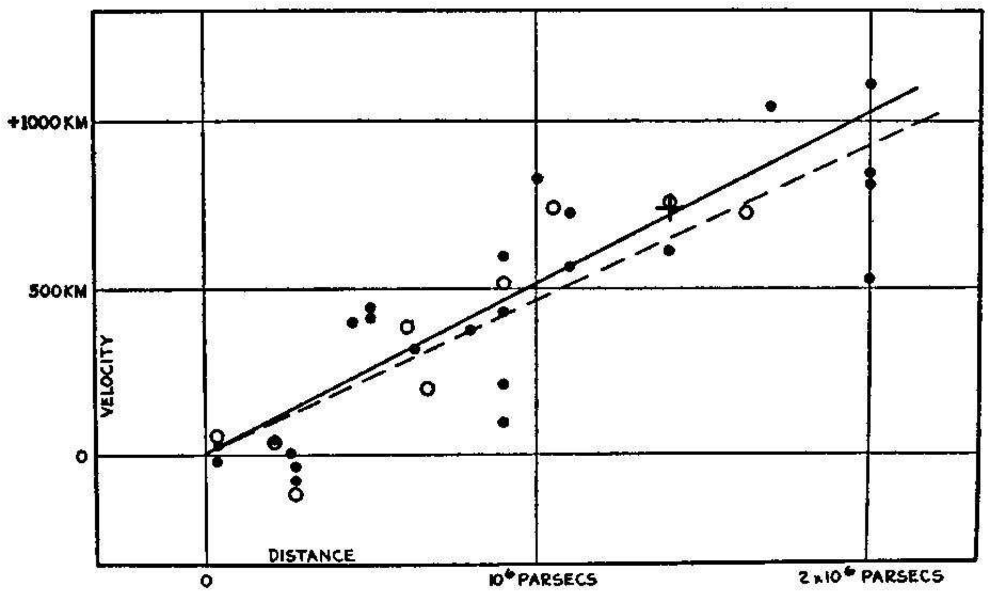

Figure 2. Graph of radial velocity versus distance for the spiral nebulae. Reproduced from Hubble (1929). Black data points represent 24 individual nebulae; almost all but four of the velocities are from Slipher, as listed by Eddington in 1923.

By the time the graph of Fig. 2 was published, Hubble had embarked on a program to extend the study to even more distant nebulae. Using a state-of-the-art spectrograph with a specially designed 'Rayton' camera lens in conjunction with the great 100-inch reflecting telescope at Mt Wilson, he and Humason measured distances and redshifts for forty more spirals, demonstrating a linear relation between velocity and distance out to a distance eighteen times that of Fig. 2 (Hubble & Humason 1931).[4]

---

[3]There were several early attempts to establish a relation between velocity and distance for the nebulae, notably by Knut Lundmark in 1924; however the distances to the spirals were not well established at this point.

[4]In the 1931 study, the distances of the nebulae were estimated from their apparent magnitudes, as individual stars could not be resolved.

It should not be concluded from this section that "Hubble discovered the expanding universe", as is sometimes stated in the popular literature. Such a statement confuses *observation* with *discovery*, as a linear relation between recessional velocity and distance for the distant galaxies does not in itself suggest an expanding universe. It is much more accurate to say that the 1929 graph provided the first experimental evidence in support of the hypothesis of an expanding universe. But what was this hypothesis?

3. A brief history of theory

The publication of Einstein's general theory of relativity in 1915 led to a new view of the force of gravity; according to relativity, gravity was not an 'action at a distance' between two objects, but a curvature of space and time caused by matter or energy (Einstein 1915a,b). Thus the earth does not interact directly with the sun, but follows a path in a space that has been warped by the sun's great mass. This new view of gravity, space and time led theorists to a number of mathematical models for the universe as a whole.

Einstein himself attempted the first model (Einstein 1917). Assuming a uniform distribution of matter on the largest scales, he discovered that relativity predicts a universe that is *dynamic*, i.e. whose radius expands or contracts in time. Like most scientists of the day, Einstein presumed that the universe is *static*, i.e. unchanging in time (no astronomical evidence to the contrary was known at this point). Given that gravity is an attractive force that could cause the universe to contract, he added a small term to his equations that could counterbalance the effect, a term he named the 'cosmological constant.' This analysis led Einstein to a model of the cosmos that is static in time and of closed spatial geometry - a finite universe whose radius could be calculated from the density of matter.[5]

The Dutch astronomer Willem de Sitter also applied Einstein's field equations to the cosmos. Assuming a universe empty of matter, de Sitter found a second solution that also appeared to be static (de Sitter 1917). A curious feature of the model was the prediction that any matter introduced into this universe would recede from the observer, observable as a redshift. A second redshift effect due to an apparent slowing down of atomic vibrations was also predicted. The 'de Sitter effect' became quite well-known in the 1920s, and astronomers such as Ludwig Silberstein, Carl Wirtz, Knut Lundmark and Gustav Strömberg sought to measure the curvature of space from the redshifts of stars, global clusters, planetary and spiral nebulae (e.g. Silberstein 1924; Wirtz 1924; Lundmark 1924; Strömberg 1925). In general, these attempts to match theory with observation were not successful, due to a flaw in de Sitter's analysis (see below). However, it's worth noting that Lundmark provided the first velocity/distance plot for the *spirals*, although the results were not very clear (Lundmark 1924). A description of the work of Silberstein, Wirtz, Lundmark and Strömberg and can be found in the essay by Harry Nussbaumer in this book.

---

[5]Constants of integration occur naturally in the solution of differential equations such as the Einstein field equations. The size of the cosmological constant is constrained by the requirement that relativity predicts the motion of the planets, but there is no reason it should be exactly zero. Einstein's suggestion was that a small, non-zero constant of integration could simultaneously render the universe static and give it a closed curvature, neatly removing the problem of boundary conditions. It was later shown that this solution is in fact unstable (Eddington 1930).

In 1922, the Russian theoretician Alexander Friedman published solutions to the Einstein field equations that included not only the static solutions of Einstein and de Sitter, but also a universe of time-varying radius (Friedman 1922). In the language of relativity, he was the first to allow the possibility of a *dynamic* space-time metric for the universe. With another paper in 1924, Friedman established almost all the main possibilities for the evolution of the cosmos and its geometry (Friedman 1924), an analysis that provides the framework for the models of today. However, little attention was paid to Friedman's work at the time because most people, including Einstein, considered time-varying models of the universe to be unrealistic.[6]

Friedman himself made no attempt to connect his theory to experiment as he was unaware of Slipher's observations, and he died four years before the publication of the Hubble-Slipher graph. A full discussion of Friedman's contribution is given in the essay by Ari Belenkiy in this book.

Unaware of the earlier work of Friedman, the Belgian theoretician Georges Lemaître also discovered that the application of Einstein's field equations to the cosmos gives time-varying solutions. In his first contribution to the field, he spotted a significant inconsistency in de Sitter's analysis; correcting the error showed that de Sitter's empty universe is not static (Lemaître 1925). A theoretician with significant training in astronomy, Lemaître was well aware of Slipher's redshifts and Hubble's emerging measurements of the vast distances to the spiral nebulae (Kragh 1987). His great insight was to link the recession of the spirals with a relativistic expansion of space-time. (Note that as an expansion of space-time *metric*, the effect would be detectable only on extra-galactic scales, not in the earlier studies of stars, globular clusters and planetary nebulae). In a pioneering paper in 1927, Lemaître derived a universe of expanding radius from Einstein's equations, and then estimated the rate of expansion using average values of velocity and distance for the spirals from Slipher and Hubble respectively (Lemaître 1927). He obtained a value of 575 km s^{-1} Mpc^{-1} for the coefficient of expansion (as well as an alternate estimate of 625 km s^{-1} Mpc^{-1} using a statistical weighting method): these values were in good agreement with Hubble's estimate two years later (see above). Thus Lemaître was undoubtably the first to connect the theory of the expanding universe with observation. However, his work went unnoticed because it was published in French in a little-known Belgian journal. Lemaître did little to promote his model, perhaps due to a negative reaction from Einstein; the latter declared the expanding model 'abominable', and added that such models had in any case already been suggested by Alexander Friedman (Lemaître 1958)!

It should be noted that during these years, other theoreticians such as Hermann Weyl (Weyl & Ehlers 1918; Weyl 1919, 1923), Cornelius Lanczos (1922, 1923), Howard Percy Robertson (1929) and Richard Tolman (1929a,b) also applied Einstein's field equations to the study of the cosmos. All of them spotted the inconsistency in the model of de Sitter; however, Friedman and Lemaître were the first to make the key step of specifically allowing time-varying solutions for the radius of the universe.

[6]Einstein first accused Friedman of a making a mathematical error (Einstein 1922). He later withdrew the comment (Einstein 1923b), but a draft copy of his retraction contains the revealing phrase *'denen eine physikalische Bedeutung kaum zuzuschreiben sein dürfte'* or '*to this a physical significance can hardly be ascribed'* (Einstein 1923a).

4. A convergence of theory and observation

The publication of Hubble's velocity/distance graph of 1929 did not cause a major stir in the scientific community at large, but the relativists paid close attention. At a seminar at the Royal Astronomical Society in January 1930, de Sitter admitted that a linear relation between distance and radial velocity for the nebulae could not be explained in the context of his own model or that of Einstein. In the ensuing discussion, the eminent British astronomer Arthur Stanley Eddington suggested that a new model of the cosmos was needed. Their discussion was published in the proceedings of the meeting (de Sitter 1930) and came to the attention of Lemaître, who wrote to Eddington to remind him of his 1927 paper. Eddington immediately grasped the significance of Lemaître's work and quickly made others aware of it (Eddington 1930). He also arranged for it to be translated and republished in the widely-read *Monthly Notices of the Royal Astronomical Society*. The paper duly appeared (Lemaître 1931a) although the section where a coefficient of expansion is estimated from observational data was not included. It has recently been confirmed that this revision was carried out by Lemaître himself in the light of Hubble's 1929 paper (Livio 2011; Lemaître 1931b).

Supported by the empirical data of Hubble's 1929 paper, Lemaître's model of a universe of expanding radius became widely known (e.g. de Sitter 1931). Einstein publicly accepted the expanding model during a visit to the United States in early 1931, drawing worldwide attention to the work of Hubble, Humason, Lemaître and Tolman (Einstein 1931a); he also published a short academic paper on the expanding universe later that year (Einstein 1931b). Thus by the early 1930s, it seemed to many relativists and some astronomers that an astonishing new phenomenon, the expanding universe, had been discovered that could be explained in a natural way in the context of the general theory of relativity.

5. On the naming of laws and equations

In time, the velocity/distance graph of Fig. 2 became known as 'Hubble's law.' It is not entirely clear when or why this nomenclature became the norm. One factor may have been Hubble's failure to acknowledge Slipher's data in the 'discovery' paper of 1929 (Hubble 1929). Lemaître also neglected to cite Slipher directly in his seminal 1927 and 1931 papers (Lemaître 1927, 1931a); these omissions may have set a precedent for authors of subsequent papers. A second factor may have been Hubble's well-known vigilance in defending and promoting the contribution of Mt Wilson astronomers,[7] an attitude that was in marked contrast with Slipher's reticence in such matters (Hoyt 1980). Indeed, it is remarkable that Slipher never formally published the full set of his painstaking redshift measurements, but allowed them to be circulated by Eddington and Strömberg instead. However, the most important factor in the naming of Hubble's law is undoubtedly one of social context; Hubble was a famous astronomer working at the world's foremost observatory, while Slipher was a lesser-known figure working at a smaller facility best known for controversial claims concerning the observation of

[7]Hubble's accusation of plagiarism on the part of Lundmark (Hubble 1926) and his aggressive letter to de Sitter (Hubble 1931) are good examples of this attitude.

canals on Mars.[8] Thus, the graph of 1929 became known as 'Hubble's law' and its slope as the 'Hubble constant.'

It could be argued that Hubble fully merits this recognition, given his ground-breaking measurements of the distances to the nebulae (Hubble 1925, 1926), his combination of distance measurements with Slipher's data to obtain the first evidence for a velocity/distance relation (Hubble 1929), and his subsequent extension of the relation to much larger distances (Hubble & Humason 1931). We find this a reasonable argument; however, in order to recognize that almost all the velocity data in the 'discovery' graph of 1929 are from Slipher, we suggest that this particular graph could also be known as the 'Hubble-Slipher graph.' As Hubble once wrote in a letter to Slipher *"I have obtained a velocity/distance relation for the nebulae using your velocities and my distances"* (Hubble 1953). It is one of the great ironies of science that Hubble's measurements of distance were later substantially revised due to significant systematic errors,[9] while Slipher's redshift data have stood the test of time remarkably well.

It is sometimes argued that Hubble's law should be known as the 'Hubble-Lemaître law' (Farrell 2006), or even 'Lemaître's law' (Block 2011), given the pioneering contribution of Georges Lemaître in 1927. We do not find this a reasonable argument simply because Hubble's law is understood as an empirical relation between velocity and distance for the nebulae. Lemaître did not provide any measurements of velocity or distance, nor did he establish the linearity of the velocity/distance relation. Instead, he *predicted* a linear relation between velocity and distance from theory, and, assuming that such a relation existed, used average values of observational data for the spiral nebulae to estimate a coefficient of expansion for the universe. That this calculation was something of a provisional 'guesstimate' can be seen from the fact that it is included only as a footnote in the 1927 paper (Lemaître 1927), and not at all in the translated version (Lemaître 1931a). Lemaître's attitude can be clearly seen in a recently-discovered letter that accompanied his 1931 manuscript when he states; *"I do not think it is advisable to reprint the provisional discussion of radial velocities which is clearly of no actual interest"* (Lemaître 1931b). Thus, it seems to us that to credit him with the discovery of a velocity/distance relation for the nebulae confuses theory with observation. As he remarked many years later in a discussion of his 1927 paper, *"Naturellement, avant la découverte et l'étude des amas de nebuleuses, il ne pouvait être question d'établir la loi de Hubble"* or "*Naturally, before the discovery and study of the clusters of nebulae, it was not possible to establish Hubble's law*" (Lemaître 1952).[10]

The above is not to understate Lemaître's seminal contribution; he is recognized as the first to connect the recession of the spiral nebulae with a relativistic expansion of space-time, an expansion that he derived himself from the Einstein field equations. He is also recognized for his retention of the cosmological constant; where Einstein and de Sitter quickly disposed of the term in constructing a new model of the cosmos (Einstein & de Sitter 1932), Lemaître retained it as an important component of cosmological models (not least because of its potential to circumvent a conflict between the age of the

---

[8]Lowell's persistent claims of the observation of canals on Mars damaged the reputation of the Lowell observatory (Hoyt 1976).

[9]Due to an error in the classification of Cepheid variables, Hubble's cosmological distance ladder was later substantially revised by Walter Baade (1956) and Allan Sandage (1958). Hubble's distances of 1929 may also have contained some observational errors, as suggested in the essay by John Peacock in this book.

[10]This passage is mistranslated in a recent paper by David Block (2011).

universe estimated from the expansion and from the known age of stars). This approach led Lemaître to a model of a universe whose rate of expansion first de-accelerates and then accelerates (Lemaître 1934), remarkably similar to the best-fit models of today. Finally, Lemaître's characteristic blending of theory and experiment also led him to become the first physicist to postulate a physical model for the origin of the universe - the 'primeval atom' (Lemaître 1931c). It is for this model, the forerunner of today's big bang model, that he is best known.

As regards Friedman, his time-varying solutions provided a template for all subsequent models of the evolution and geometry of the universe. Thus it could be said that Friedman derived the possibility of an *evolving* universe from Einstein's equations, while Lemaître, guided by observational data, derived an *expanding* universe. (Note that our universe could one day contract, depending on the nature and time-evolution of dark energy). Today, the 'Friedman equations' appear in the first chapter of every cosmology textbook, as do 'Friedman universes.' Indeed, the contributions of both Friedman and Lemaître are recognized in the naming of the Friedman-Lemaître -Robertson-Walker (FLRW) metric, a fundamental tool of today's theoretical cosmology.

In summary, we note that references to 'Hubble's law' and 'the Hubble constant' are to be found throughout the scientific literature, while the work of Friedman and Lemaître is recognized in every modern textbook on cosmology. By contrast, Slipher's contribution seems destined to be consigned to the footnotes of history, although his pioneering observations provided a crucial part of the first evidence for the expanding universe. This contribution was neatly summarized by the President of the Royal Astronomical Society in 1933, in his closing remarks on the occasion of the awarding of the society's Gold Medal to Slipher (Stratton 1933):

> In a series of studies of the radial velocities of these island galaxies, he laid the foundations of the great structure of the expanding Universe, to which others, both observers and theorists, have since contributed their share. If cosmogonists today have to deal with a universe that is expanding in fact as well as in fancy, at a rate which offers them special difficulties, a great part of the initial blame must be borne by our medallist.

6. A note on paradigm shifts in science

By the early 1930s, a new phenomenon, the expansion of the universe, had been observed that could be explained in the context of the general theory of relativity. In *retrospect*, this fusion of theory and experiment marked a watershed in modern cosmology, and it was a key step in the development of today's 'big bang' model of the origin for the universe.

However, the scientific community did not shift to a new view of the universe overnight. In fact, it was many years before most physicists accepted that the redshifts of the spiral nebulae truly represented recessional velocities, and that an explanation for the recession could be found in terms of a relativistic, expanding universe (North 1965; Kragh & Smith 2003). During this time, many alternate models were considered.

One such model was the 'tired light' hypothesis of Fritz Zwicky. In this theory, the redshifts of the nebulae were not due to an expansion of space, but to a loss of energy as starlight travelled the immense distance to earth (Zwicky 1929). Many scientists took the theory seriously, although it was later ruled out by experiment. Other nonrelativistic models of the universe emerged (McCrea & McVittie 1930; Milne 1933), and astronomers carried out many observations in order to test the models (North 1965, chapter 11; Kragh 1999, chapter 7). Thus, it could not be said that, after 1931, astronomical results were interpreted in terms of one model only, the relativistic expanding universe.

For example, it's worth noting that Hubble declined to interpret the velocity/distance relation in terms of an expanding universe throughout his life. This is not to say that he was unaware of relativistic models of the cosmos; in his paper of 1929, he remarks that *"the outstanding possibility is that the velocity/distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of space*" (Hubble 1929). However, in subsequent years, Hubble declined to interpret his empirical data in the context of any particular model, in case the theory might later prove wanting (Hubble 1958). This approach was quite common among professional astronomers at the time, particularly in the United States (Kragh & Smith 2003), and it is somewhat in conflict with the modern hypothesis of the 'theory-ladeness' of scientific observation (Hanson 1958).

We also note that our narrative does not match Thomas Kuhn's view of science progressing via long periods of 'normal science' interspersed by relatively abrupt 'paradigm shifts' (Kuhn 1962). Instead of an abrupt transition to a new cosmological paradigm incommensurate with the old,[11] there was a long period from 1930-1960 when many models were considered, as described above. Secondly, a paradigm shift to a relativistic, expanding universe might have been expected to trigger a great upsurge of interest in cosmology, relativity and the expanding universe. Nothing of the kind happened; it can be seen from the citation record (Marx & Bornmann 2010) that few in the wider physics community took an interest in the expanding universe in the years 1930-1960, despite exciting developments such as Lemaître's 'primeval atom' (Lemaître 1931c) or the fiery infant universe of Gamow, Alpher and Herman (Gamow 1948; Alpher & Herman 1948). It seems likely that this indifference is linked to an overall decline of interest in general relativity. Physicists found the new theory very difficult mathematically and, outside of cosmology, it made few predictions that differed significantly from Newtonian physics. In consequence, the study of general relativity became consigned to mathematics departments, with little interest from physicists and astronomers (Eisenstaedt 1989; Eisenstaedt 2006, chapter 15). Where a paradigm shift to the notion of a relativistic, expanding universe might have been expected to cause a great upsurge in the study of general relativity, the opposite happened; cosmology remained a minority sport within the physics community for decades (North 1965, chapter 11; Kragh 1999, chapter 7; Kragh 2006, chapter 3), a situation that did not change until the discovery of the cosmic microwave background in 1965.[12]

In conclusion, one can describe the discovery of the expanding universe as a slow, parallel emergence of theory and observation, with many false starts, wrong turns and re-discoveries. Once accepted among a small band of relativists, the discovery experienced an equally slow acceptance among the wider physics community, with alternate

[11]The concept of 'incommensurability' refers to Kuhn's belief that a new scientific paradigm cannot be meaningfully compared with previous models, because the underlying assumptions of the worldviews are different Kuhn (1962).

[12]The discovery of a ubiquitous cosmic background radiation of extremely long wavelength offered strong support for the hypothesis of a universe that has been expanding and cooling for billions of years.

models being considered for many years. This behavior mirrors the traditional model of scientific discovery as a quasi-linear process of gradual evolution and persuasion, and does not match the Kuhnian view of an abrupt shift to a new paradigm that becomes incommensurate with the old. This point shall be discussed further in a forthcoming paper.

Acknowledgments. The author would like to thank Dr. Michael Way of the NASA Goddard Institute for Space Studies, Dr. Simon Mitton of St. Edmund's College of Cambridge University and Dr. Joseph Tenn of Sonoma State University for many helpful suggestions. He would also like to thank the Dublin Institute of Advanced Studies for access to the Collected Papers of Albert Einstein (Princeton University Press).

References

Alpher, R. A., & Herman, R. 1948, Evolution of the Universe, Nature, 162, 774
Baade, W. 1956, The Period-Luminosity Relation of the Cepheids, PASP, 68, 5
Block, D. L. 2011, Georges Lemaitre and Stiglers Law of Eponymy, ArXiv e-prints. 1106.3928
Campbell, W. W. 1906, The Radial Motions of Polaris, PASP, 18, 307
— 1913, Letter from W. W. Campbell to V. M. Slipher, 09 April 1913. Lowell Observatory Archives
de Sitter, W. 1917, Einstein's Theory of Gravitation and its Astronomical Consequences. Third paper, Monthly Notices of the Royal Astronomical Society, 78, 3
— 1930, Proceedings of the RAS, Observatory, 53, 37
— 1931, Contributions to a British Association Discussion on the Evolution of the Universe., Nat, 128, 706
Eddington, A. S. 1923, The Mathematical Theory of Relativity (the University Press). URL http://books.google.ie/books?id=pgi9OAAACAAJ
— 1930, On the Instability of Einstein's Spherical World, MNRAS, 90, 668
Einstein, A. 1915a, Die Feldgleichungen der Gravitation, Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), 844
— 1915b, Zur Allgemeinen Relativitätstheorie, Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), 778
— 1917, Kosmologische Betrachtungen zur Allgemeinen Relativitätstheorie, Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), 142
— 1922, Bemerkung zu der Arbeit von A. Friedmann Über die Krümmung des Raumes, Zeitschrift fur Physik, 11, 326
— 1923a, A. Einstein to Zeitschrift der Physik, 1923, The Albert Einstein Archives, Hebrew University of Jerusalem. Additional comment unpublished
— 1923b, Notiz zu der Arbeit von A. Friedmann Über die Krümmung des Raumes, Zeitschrift fur Physik, 16, 228
— 1931a, The Expanding Universe, New York Times, 1
— 1931b, Kosmologische Betrachtungen zur Allgemeinen Relativitätstheorie, Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), 235
Einstein, A., & de Sitter, W. 1932, On the Relation between the Expansion and the Mean Density of the Universe, Proceedings of the National Academy of Science, 18, 213
Eisenstaedt, J. 1989, in Einstein and the History of General Relativity, edited by D. Howard, & J. Stachel, 277
— 2006, The Curious History of Relativity: How Einstein's Theory of Gravity Was Lost and Found Again, CNRS editions (Princeton University Press). URL http://books.google.ie/books?id=d2bnXTOtCD8C
Farrell, J. 2006, The Day Without Yesterday: Lemaître, Einstein, and the Birth of Modern Cosmology (Basic Books). URL http://books.google.ie/books?id=G-IXzhkTcS4C
Fath, E. A. 1909, The Spectra of Some Spiral Nebulæ and Globular Star Clusters, PASP, 21, 138

Friedman, A. 1922, Über die Krümmung des Raumes, Zeitschrift fur Physik, 10, 377

— 1924, Über die Möglichkeit einer Welt mit Konstanter Negativer Krümmung des Raumes, Zeitschrift fur Physik, 21, 326

Gamow, G. 1948, The Evolution of the Universe, Nat, 162, 680

Hanson, N. 1958, Patterns of Discovery: An Inquiry Into the Conceptual Foundations of Science (At the University Press). URL `http://books.google.ie/books?id=XD44AAAAIAAJ`

Hertzsprung, E. 1913, Über die räumliche Verteilung der Veränderlichen vom δ Cephei-Typus, Astronomische Nachrichten, 196, 201

Hoyt, W. G. 1976, Lowell and Mars (University of Arizona Press). URL `http://books.google.ie/books?id=6ofvAAAAMAAJ`

— 1980, Vesto Melvin Slipher, Biographical Memoirs, 52, 411

Hubble, E. P. 1925, Cepheids in Spiral Nebulae, The Observatory, 48, 139

— 1926, Extragalactic Nebulae, ApJ, 64, 321

— 1929, A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae, Proceedings of the National Academy of Science, 15, 168

— 1931, Letter from E.Hubble. to W. de Sitter, 21 Aug 1931. Huntington Library Archives, HUB 617

— 1953, Letter from E. Hubble. to V. M. Slipher, 06 March 1953. Lowell Observatory Archives

— 1958, The Realm of the Nebulae, Dover books (Dover Publications). URL `http://books.google.ie/books?id=uu45AAAAMAAJ`

Hubble, E. P., & Humason, M. L. 1931, The Velocity-Distance Relation among Extra-Galactic Nebulae, ApJ, 74, 43

Kragh, H. S. 1987, The Beginning of the World: Georges Lemaître and the Expanding Universe, Centaurus, 30, 114

— 1999, Cosmology and Controversy: The Historical Development of Two Theories of the Universe (Princeton University Press). URL `http://books.google.ie/books?id=eq7TfxZOzSEC`

— 2006, Conceptions of Cosmos:From Myths to the Accelerating Universe: A History of Cosmology: From Myths to the Accelerating Universe: A History of Cosmology (OUP Oxford). URL `http://books.google.ie/books?id=MeC9pc4Yk1QC`

Kragh, H. S., & Smith, R. W. 2003, Who Discovered the Expanding Universe?, History of Science, 41, 141

Kuhn, T. S. A. 1962, The Structure of Scientific Revolutions, International encyclopedia of unified science (University of Chicago Press). URL `http://books.google.ie/books?id=xnjS401VuFMC`

Lanczos, C. 1922, Bemerkung zur de Sitterschen Welt, Physikalische Zeitschrift, 23, 539

— 1923, Über die Rotverschiebung in der de Sitterschen Welt, Zeitschrift für Physik A Hadrons and Nuclei, 17, 168

Leavitt, H. S. 1908, 1777 Variables in the Magellanic Clouds, Annals of Harvard College Observatory, 60, 87

Lemaître, G. 1925, Note on de Sitters Universe, Journal of Mathematics and Physics, 4, 188

— 1927, Un Univers Homogène de Masse Constante et de Rayon Croissant Rendant Compte de la Vitesse Radiale des Nébuleuses Extra-Galactiques, Annales de la Societe Scietifique de Bruxelles, 47, 49

— 1931a, Expansion of the universe, A Homogeneous Universe of Constant Mass and Increasing Radius Cccounting for the Radial Velocity of Extra-Galactic Nebulae, MNRAS, 91, 483

— 1931b, Letter from G. Lemaitre to RAS, 09 March 1931. RAS Correspondence

— 1931c, The Beginning of the World from the Point of View of Quantum Theory., Nat, 127, 706

— 1934, Evolution of the Expanding Universe, Proceedings of the National Academy of Science, 20, 12

— 1952, Clusters of Nebulae in an Expanding Universe, Monthly Notes of the Astronomical Society of South Africa, 11, 110

— 1958, Rencontres avec A. Einstein, Revue des questions scientifiques, 129, 129
Livio, M. 2011, Lost in Translation: Mystery of the Missing Text Solved, Nat, 479, 171
Lundmark, K. 1924, The Determination of the Curvature of Space-Time in de Sitter's World, MNRAS, 84, 747
Marx, W., & Bornmann, L. 2010, How Accurately Does Thomas Kuhns Model of Paradigm Change Describe the Transition from the Static View of the universe to the Big Bang Theory in Cosmology?, Scientometrics, 84, 441
McCrea, W. H., & McVittie, G. C. 1930, Relativity: On the Contraction of the Universe, MNRAS, 91, 128
Milne, E. A. 1933, World-Structure and the Expansion of the Universe. Mit 6 Abbildungen., ZAp, 6, 1
North, J. 1965, The Measure of the Universe: A History of Modern Cosmology (Clarendon Press). URL `http://books.google.ie/books?id=wFVAAAAAIAAJ`
Nussbaumer, H., & Bieri, L. 2009, Discovering the Expanding Universe (Cambridge University Press). URL `http://books.google.ie/books?id=RaNOJkQ4l14C`
Öpik, E. 1922, An Estimate of the Distance of the Andromeda Nebula, ApJ, 55, 406
Pease, F. G. 1915, Radial Velocity of the Andromedæ Nebula, PASP, 27, 134
Robertson, H. P. 1929, On the Foundations of Relativistic Cosmology, Proceedings of the National Academy of Science, 15, 822
Sandage, A. 1958, Current Problems in the Extragalactic Distance Scale, ApJ, 127, 513
Scheiner, J. 1899, On the Spectrum of the Great Nebula in Andromeda, ApJ, 9, 149
Shapley, H. 1918, Studies Based on the Colors and Magnitudes in Stellar Clusters. VI. On the Determination of the Distances of Globular Clusters, ApJ, 48, 89
Silberstein, L. 1924, The Curvature of de Sitter's Space-Time Derived from Globular Clusters, MNRAS, 84, 363
Slipher, V. M. 1913, The Radial Velocity of the Andromeda Nebula, Lowell Observatory Bulletin, 2, 56
— 1917, Nebulae, Proceedings of the American Philosophical Society, 56, 403
— 1927, The Lowell Observatory, PASP, 39, 143
Smith, R. 1982, The Expanding Universe: Astronomy's "Great Debate," 1900-1931 (Cambridge University Press). URL `http://books.google.ie/books?id=jVjFmzLJdQAC`
Stratton, F. J. M. 1933, Society Business: Presidential Address on Presenting the Gold Medal to Dr. V. M. Slipher, MNRAS, 93, 476
Strömberg, G. 1925, Analysis of Radial Velocities of Globular Clusters and Non-Galactic Nebulae, ApJ, 61, 353
Tolman, R. C. 1929a, On the Astronomical Implications of the de Sitter Line Element for the Universe, ApJ, 69, 245
— 1929b, On the Possible Line Elements for the Universe, Proceedings of the National Academy of Science, 15, 297
Weyl, H. 1919, Uber die Statischen Kugelsymmetrischen Lösungen von Einsteins Kosmologischen Gravitationsgleichungen, Phys. Z, 20, 31
— 1923, Zur allgemeinen Relativitätstheorie, Physikalische Zeitschrift, 24, 230
Weyl, H., & Ehlers, J. 1918, Raum, Zeit, Materie: Vorlesungen über allgemeine Relativitätstheorie (Springer). URL `http://books.google.ie/books?id=g6EgAQAAMAAJ`
Wirtz, C. 1924, De Sitters Kosmologie und die Radialbewegungen der Spiralnebel, Astronomische Nachrichten, 222, 21
Wolf, M. 1912, Unknown, Sitzungsberichte der Heidelb. Akad. der Wissenschaffer Abt; Vol. 3, 3
Zwicky, F. 1929, On the Red Shift of Spectral Lines through Interstellar Space, Proceedings of the National Academy of Science, 15, 773