VESTO SLIPHER, NEBULAR SPECTROSCOPY, AND THE BIRTH OF MODERN COSMOLOGY, 1912–22

Craig Fraser

This article looks at Vesto Slipher's work on nebular spectroscopy between 1912 and 1922 as well as related research by other astronomers of the period, and it examines the dissemination of their results more widely. Slipher's observations are viewed as marking the dividing line between speculation about the universe in traditional astronomy and the advent of modern cosmology and the theory of an expanding universe. The intent is to document the dissemination of Slipher's results in the period leading up to the publication of studies of relativistic cosmology by Willem de Sitter in 1917 and Alexander Friedmann in 1922. Themes touched on in the article include the unprecedented character of Slipher's findings and the interaction of observation and theory in modern cosmology. A prominent concern is the role of technology in astronomical science over the past century and a half. Here reference is made to the writings of Paul Forman on historical shifts that have taken place in our understanding of the relationship of science and technology.

> Science is embodied in its technologies, and technologies determine what is science. (David M. Kaplan, *Readings in the Philosophy of Technology* [2004])

1. Introduction

The beginning of modern cosmology and a new era in thinking about the universe opened up in the second decade of the twentieth century. The most remarkable

Contact Craig Fraser at the University of Toronto, Canada (craig.fraser@utoronto.ca).
I am grateful to Toby Reid and Nichole Levesley for helpful conversations. I would like to thank the reviewers for their comments on an earlier draft. My original interest in the history of cosmology developed out of reading John North's *Measure of the Universe* (1965).

Electronically published April 1, 2022.

HOPOS: The Journal of the International Society for the History of Philosophy of Science, volume 12, number 1, Spring 2022. Published by The University of Chicago Press for the International Society for the History of Philosophy of Science. https://doi.org/10.1086/718804

discovery in the history of cosmology took place with the identification by Vesto Slipher in 1914 of large spectral shifts in several celestial objects known as spiral nebulae. The spectral shifts indicated that these nebulae possessed very large radial motions. Most of the shifts were to the red end of the spectrum, indicating that the observed radial motions were predominately recessional.

In work unrelated to what was happening in astronomy, Albert Einstein in 1917 published a geometric model of the universe based on the field equations of general relativity (Einstein 1917). Einstein's work stimulated other researchers such as Willem de Sitter in 1917 and Alexander Friedmann in 1922 to develop cosmological solutions to the field equations.

The present study looks at Slipher's spectroscopic investigation of spiral nebulae and its reception up to 1922. Particular attention is paid to what de Sitter and Friedmann did know or may have known when they composed their theoretical studies in relativistic cosmology.

2. Before Slipher

A common view at the end of the nineteenth century was that the universe was made up of the Milky Way galaxy, possibly with some satellite objects. The Milky Way system was the whole universe. The universe was sidereal, composed of stars. This belief was sometimes presented as if it were a settled truth.

Small, compact, oval-shaped white nebulae proliferate in the sky, particularly as one moves away from the band of the Milky Way. Very large telescopes were built in the nineteenth century, the most famous being the giant reflector of the British astronomer William Parsons, the 3rd Earl of Rosse. Viewed in this great instrument, many of the white nebulae exhibited a spiral structure, and the term *spiral nebula* was sometimes applied to the whole class of white nebulae. The island-universe hypothesis or theory held that each of these nebulae was a galaxy in its own right, comparable to the Milky Way. The theory, which was highly speculative, had been put forward first in the eighteenth century by Thomas Wright, Immanuel Kant, and Johann Lambert. It enjoyed periods when it was less or more popular, and at the end of the nineteenth century it was at a low ebb. The Heidelberg astronomer Max Wolf wrote in 1908, "We are now entitled to assume as probable that star clusters and nebulae are an essential part of our stellar system, and are relatively close to us. They all form with the stars of the Milky Way an organic whole, and distant Milky Way systems have likely never been sighted" (Wolf 1908, 28).[1]

1. "Nach allem sind wir heutzutage berechtigt, als wahrscheinlich anzunehmen, daß die Sternhaufen und Nebelfleckchen einen wesentlichen Bestandteil unserer Sterneninsel darstellen und

In both conceptions the universe was viewed as more or less static, because it seemed to be that way and there was no particular reason to think it would be otherwise. Certain cosmological questions arose that remained unanswered. These came up for any view that posited that the universe was composed of an unbounded or very large collection of massive luminous bodies. There were two problems or paradoxes associated with such a world. The first problem, called Olbers's paradox, arose from the fact that the amount of radiation reaching any point in the universe would be extremely large, much larger than what we know to be the case. The second problem concerned the action of gravity in an indefinitely extended universe. It seemed that such a universe would be unstable and there would be an inherent tendency for gravitational implosion to occur, which from established astronomy of course was not known to be happening.[2]

In the first part of nineteenth century new geometries different from Euclid's were developed by mathematicians. The question arose as to which geometry described the physical space of the universe. It was evident that the world was locally Euclidean, but it was possible that at the scale of the astronomical distances of stars and nebulae there might be deviations. A founder of non-Euclidean geometry, the Russian mathematician Nikolai Lobachevsky, even proposed that the parallax of the star Sirius could be used to determine empirically the geometry of physical space (Bonola 1912, 94–96). However, the quantities in question were too small for any experimental verification to succeed.

The advent of new geometries stimulated a great deal of reflection about the foundations of mathematics and the very nature of space and time. One thinker who wrote on this subject in the last part of the century was the French mathematician Auguste Calinon. He composed an essay in 1889 introducing a general geometry that would be characterized by a numerical parameter. Different values of the parameter would give rise to different geometries; Euclidean geometry would be given for one of these values. Calinon (1889, 588) considered the possibility that the parameter might itself be a function of time.

In 1949 the cosmologist Howard P. Robertson published an essay titled "Geometry as a Branch of Physics." Robertson (1949, 322) wrote, "It is of interest to mention in passing, in light of recent cosmological findings, the possibility raised by A. Calinon (in 1889!) that the space-constant *K* might vary with time." In a footnote to his history of modern cosmology, the historian John North (1965, 113 n. 11) cited Calinon in reference to Alexander Friedmann's introduction

uns vielleicht relativ nahe lagern. Sie alle bilden mit den Sternen der Milchstraße ein organisches Ganzes, und ferne Milchstraßeninseln hat der Mensch wohl noch niemals zu Gesicht bekommen."

2. For a history of Olbers's paradox, see Harrison (1987). For work at the end of the nineteenth century on problems with the gravitational potential in an infinite or large universe, see North (1965, chap. 2).

of a dynamical model of the universe in 1922. Milič Čapek (1971, 380) asserted in a book on Henri Bergson that Calinon had anticipated the theory of the expanding universe in a specific way.

However, much more on track is Helge Kragh (2004, 26), who writes that Calinon's "discussion was of a general philosophical nature and he made no attempt to place it within an astronomical context. It has been suggested that Calinon 'anticipated the theory of the expanding universe,' but this is to read much too much into his article." Kragh rightly describes the article as obscure. Calinon's article belonged to a specialized nineteenth-century tradition of writing about the foundations of geometry. We have devoted some attention to it because it appears to be the only work before 1900 that has ever been adduced as a precursor of (or at least consistent with) the idea of a dynamic universe. And even here it would be dubious to characterize it in this way.

3. Slipher

Philanthropic and government support led at the end of the nineteenth century to the construction in the western United States of high-altitude observatories with excellent seeing conditions. Such facilities were built at the Lick Observatory on Mount Hamilton, the Mount Wilson Observatory, and the Lowell Observatory in Flagstaff, Arizona. In the early years of the new century nebular spectroscopy was pioneered by Max Wolf at the Heidelberg Observatory and Edward A. Fath at Mount Wilson. Observations revealed that spiral nebulae possessed dark-line spectra, suggesting they were made up of stars, different from diffuse nebulae with bright-line spectra characteristic of glowing gases. It was also found that the number of spiral nebulae was very large and seemed to grow ever larger as increasingly powerful telescopes were trained on the sky.

The line of scientific investigation that would lead to the creation of modern cosmology began with the work of Vesto Slipher at Lowell between 1912 and 1922.[3] Slipher faced daunting instrumental challenges in obtaining good spectrograms of faint nebulae. Percival Lowell had acquired a spectrograph built by the Pittsburgh instrument maker John A. Brashear and attached it to the main 24″ refractor. This spectrograph turned out to be the crucial instrument in deciphering the spectra of the nebulae. Because of the low-intensity spectral images of the nebulae, it was necessary to increase the speed of the camera, and Slipher accomplished

3. For accounts of Slipher's work on the radial velocities of spiral nebulae, see North (1965, chap. 3), Hoyt (1980), Smith (1982, 17–22), Osterbrock (1990), Nussbaumer (2013), Peacock (2013), Smith (2013), and Thompson (2013).

this with a Voigtländer f2.5 commercial lens. His work on improving the instrument was aided by a skilled machinist at Lowell named Stanley Sykes. Slipher replaced the three prisms in the existing spectrograph by a single high-dispersion prism and used a wider slit.[4] The exposures were very long, lasting up to 60 hours over several nights. While astronomers at Lick and Mount Wilson were also engaged in a program of spectrographic investigation, it was Slipher who was successful in deciphering the spectra of a range of spiral nebulae.

Slipher first examined the Andromeda Nebula in the fall of 1912 and made four plates of its spectrum. He found that the latter was shifted to the blue, indicating a radial velocity toward the sun of 300 km/sec., a large and unexpected result. Learning of this result, William Campbell, director of the Lick Observatory, wrote to him, "Your high velocity for [the] Andromeda Nebula is surprising in the extreme" (Smith 2013, 157). The recorded velocity was an order of magnitude higher than any of the stellar and nebular radial velocities that astronomers had thus far observed. Slipher even wondered whether such a high value could even be the result of a Doppler velocity, but he could find no other explanation. Such a velocity was also at odds with the prevailing theory that the spiral nebulae constitute solar systems in the making (according to the nebular hypothesis).

Slipher's finding was confirmed by Francis Pease at Mount Wilson, Joseph Moore at Lick, and Max Wolf at the Heidelberg Observatory. Slipher subsequently found that Andromeda was atypical and that the large majority of spiral nebulae possessed recessional radial motions away from the sun, and of a magnitude even larger than Andromeda's. A critical event in the founding of modern cosmology took place in March of 1914 with the publication in *Popular Astronomy* of a short note by Slipher (1914). Here he reported that he had determined the radial velocities of three spiral nebulae and certain others with values "of the order of one thousand kilometers per second." The three spirals were NGC1068 in Cetus, NGC4565 in Coma Berenices, and NGC4594 in Virgo. They had been known to astronomers since the eighteenth century and were situated in the northern and central parts of the celestial sphere, ideal for observation from Flagstaff. Historical drawings and modern photos of these nebulae are given in figures 1–3.[5]

4. Concerning the spectrographs of Edward Fath at Mount Wilson and Slipher at Lowell, Thompson (2013, 139) writes, "So both the Fath and Slipher instruments were working as nebular spectrographs at very low spectral dispersion with wide slits. Only in this way could they attain adequate signal-to-noise ratios on the final photographic image." Further details concerning Slipher's spectrograph are given by Smith (2013).

5. NGC1068 was discovered by Pierre Mechain in 1780 and is M77 in the Messier catalog. Its spiral character was noted by William Parsons in 1850. NGC4565 was discovered by William Herschel in 1785 and has no Messier number probably because of its faintness. NGC4594 was discovered by Pierre Mechain

A B

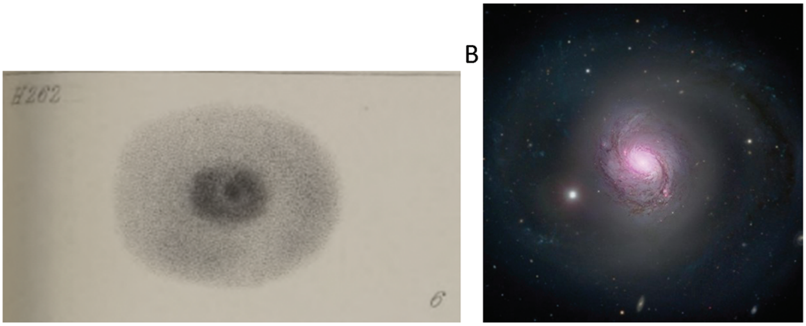


Figure 1. NGC1068, M77, Cetus. *A*, Drawing by William Parsons (3rd Earl of Rosse), 1861. *B*, Modern photo from Hubble Space Telescope. Radial velocity: +1,100 km/sec., Slipher (1914).

Slipher's initial motivation was to investigate spiral nebulae as instances of the nebular hypothesis for the formation of solar-planetary systems.[6] Both Percival Lowell and Slipher himself concluded that the huge radial velocities ruled out this interpretation—whatever the spiral nebulae were, they were not that. Slipher delivered a more complete report of his findings in the summer of 1914 at a meeting in Illinois of the American Astronomical Society. Following his presentation, he received a standing ovation, recognition by the audience of the remarkable achievement embodied in his spectrographic work. Campbell of the Lick Observatory stated that Slipher's "results compose one of the greatest discoveries which astronomers have encountered in recent times" (Osterbrock 1990, 262). Indeed, the observations constituted one of the most significant discoveries in the entire history of science.

Slipher at an early stage conjectured that there might be a relation between radial velocity and the developmental stage of the nebula, with the velocity increasing with age. This line of investigation did not turn out to be fruitful. In his spectroscopic studies he was also interested in the direction of rotation of a spiral nebula and over the years did a good deal of work in this direction. Again, this part of his work did not possess the same significance as his findings on radial recessional velocities.

---

in 1781 and was not in the original Messier catalog; its Messier number, 104, is a modern addition. Today, it is called the Sombrero galaxy. (Steinicke [2010] is a very detailed source for catalogs of nebulae from Messier to the New General Catalogue.) In *Norton's Star Atlas* (Norton and Inglis 1964) one finds the following descriptions: NGC1068, "small, round, faintish nebula, centrally condensed"; NGC4565, "a much elongated nebula, 15′x1′, with bright centre, and dark longitudinal centre streak." The edgewise spiral NGC4594 is not listed.

6. Smith (2013) provides an account of the place of the nebular hypothesis in Slipher's initial work on nebular spectroscopy.

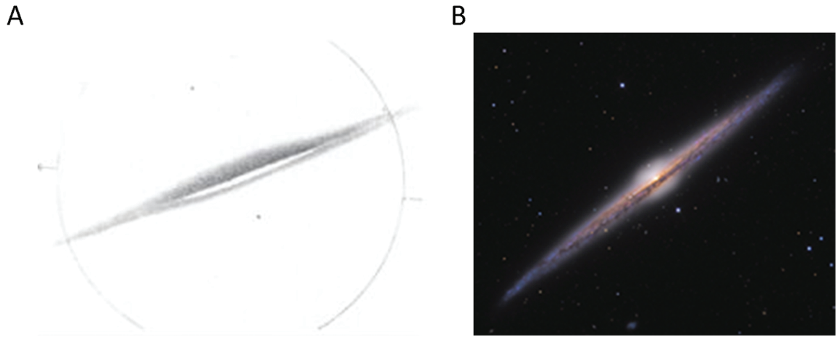


Figure 2. NGC4565, Coma Berenices, Needle galaxy. *A*, Drawing by William Lassell, 1867 (Steinicke 2010, 213). *B*, Modern photo from Hubble Space Telescope. Radial velocity: +1,100 km/sec., Slipher (1914).

The results Slipher reported on in Illinois were published in March of 1915 in the journal *Popular Astronomy*. Slipher published a table containing results for 11 new nebulae in addition to the four presented the year before. (Figure 4 is one of the new nebulae, NGC3623 in Leo, that appeared in this table.) Two years later in an article published by the National Academy of Sciences he expanded this list to 29 nebulae. By 1921 he had identified two further very large spectral velocities. In 1922 he supplied yet further data to Arthur Eddington, with a table containing the radial velocities of 41 nebulae. Eddington published this table in the following year in his book *The Mathematical Theory of Relativity*.

One line of investigation that was stimulated by Slipher's findings concerned the possible motion of the solar system relative to the spiral nebulae. Using Slipher's measurements, the astronomers Reynold Young and William Harper (1916) of the Dominion Astrophysical Observatory in Canada inferred that the solar system was moving relative to the nebulae and that the apex of this motion was located

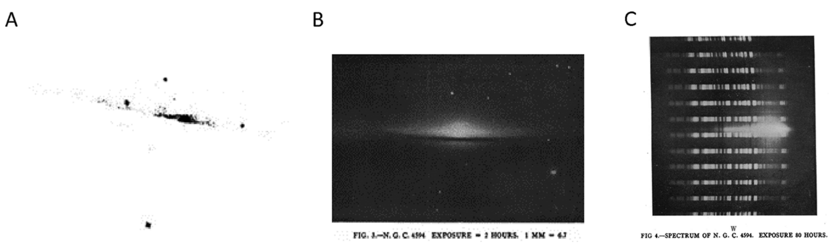


Figure 3. NGC4594, M104, Sombrero galaxy, Virgo. *A*, Drawing by William Lassell, 1867. *B*, Photo in Pease (1916), *C*, Spectrogram in Pease (1916). Radial velocity: +1,100 km/sec., Slipher (1914).

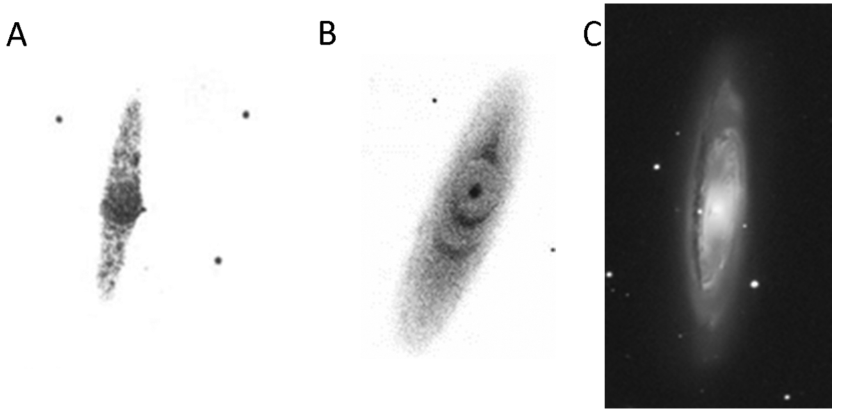


Figure 4. NGC3623, M65, Leo. *A*, Image by Johann Lamont, 1837 (Steinicke 2010, 92). *B*, Image by Hermann Vogel, 1867 (Steinicke 2010, 280–81). *C*, Modern photo from Hubble Space Telescope. Radial velocity: +800 km/sec., Slipher (1915).

at right ascension $20^h\ 24^m$ and declination $-12°10'$. They supplemented Slipher's findings with radial values for the Magellanic Clouds. Another attempt in the same year of this sort was made by O. H. Truman (1916) of the University of Iowa.

In 1916 George F. Paddock of the Lick Observatory contributed the article "The Relation of the System of Stars to the Spiral Nebulae" to the *Publications of the Astronomical Society of the Pacific*. Here he drew attention to two classes of nebulae, the diffuse nebulae, which have small radial velocities comparable to those of stars, and the spiral nebulae, which have exceedingly large and mostly positive radial velocities. Paddock's primary concern was the latter, and he presented Slipher's results including independent verifications in a couple of cases by Pease at Mount Wilson. Paddock divided the spiral nebulae into three distinct groups corresponding to their distinct places on the celestial sphere. He wrote,

> These objects, however, can hardly be considered to form a unitary system of associated objects, for it must be noticed that the average velocity of each of the three groups of objects is decisively positive, which means that they are receding not only from the observer or star system but from one another. Accordingly, a solution for the motion of the observer thru space should doubtless contain a constant term to represent the expanding or systematic component whether there be actual expansion or a term in the spectroscopic line displacements not due to velocities. This brings up the question whether these large displacements are to be interpreted as due entirely to velocities. (Paddock 1916, 113)

In certain parts of stellar astrophysics, it was found useful to introduce a systematic "K" term in the radial velocity of the star, representing a common velocity that should be added to the radial velocity characteristic of each star (Duerbeck and Seitter 1993). Paddock proposed that something similar might be done for spiral nebulae, except that the K term would be an order of magnitude larger than the corresponding K term in the stellar case. Following Young and Harper (1916) but making use of the K term, Paddock attempted to compute the motion of the sun relative to the spirals by expressing the radial velocity in terms of a component for the solar motion and the K term. A natural question concerned the source or physical explanation for the mysterious term. Paddock suggested that it could simply be a result of insufficient data and would be found to diminish as more observations were made. On this point his intuition turned out to be completely wrong.

In 1916 the English astronomer Hugh Frank Newall reviewed recent work in stellar spectroscopy in the *Monthly Notices of the Royal Astronomical Society*.[7] Here he called attention to some of the nebular spectroscopic observations of American astronomers, noting in particular the negative radial velocity of 300 km/sec. found for the Andromeda Nebula and the large positive radial velocity for NGC1068. Taking the average of the values found by Slipher (1915) at Lowell, Pease (1915) at Mount Wilson, and J. H. Moore (1915) at Lick, Newall (1916, 358) arrived at a positive or recessional velocity of 910 km/sec. for NGC1068. He did not dwell on the significance of this measurement, but its extraordinary magnitude could hardly have escaped the attention of the reader.

In the next year Arthur Eddington (1917) reviewed for the *Monthly Notices* recent spectroscopic work on spiral nebulae and gave a much more detailed report than had Newall.[8] Some additional facts were adduced in the next section on stellar spectroscopy. Eddington discussed Slipher's measurements of large radial velocities. While leading American astronomers such as Campbell had expressed confidence in Slipher's results, Eddington implied that they still needed to be independently checked. This qualification may have represented not so much doubts about Slipher as an observer as it did questions arising from the improbably large radial motions. Eddington provided values for the radial velocities of M77 (−300), NGC1068 (+900), and NGC4594 (+1,100), all of which had been confirmed by other observers. He also noted that the average radial velocity in Slipher's table of 15 spirals was between +300 and +400 km/sec.

7. The report does not appear in the table of contents by name. It is instead in a section titled "Notes on Some Points Connected with the Recent Progress of Astronomy."

8. As with Newall's (see n. 7), Eddington's report does not appear in the table of contents by name. It is in a section titled "Notes on Some Points Connected with the Recent Progress of Astronomy."

Eddington also reported on results concerning the proper motions of nebulae. Unlike the large and unambiguous radial velocities, the proper motions were small and at the very limit of measurement. Eddington (1917, 376) noted, "It seems to be very doubtful whether or not spiral nebulae show any detectable proper motions." Nevertheless, he called attention to some work of Heber Curtis of the Lick Observatory, who placed confidence in the value he determined of 8″ per century for the proper motion of the nebula NGC253. (We know today that NGC253 is a galaxy at a distance of 10.4 million light-years, and the reported value of 8″ per century would imply that it is moving with a velocity greater than the speed of light relative to the solar system.) Eddington was well abreast of the recent American literature on nebular spectroscopy.[9] He concluded that observations of nebulae overall "show that a new field of astronomical investigation is rapidly being opened up, and we may hope to acquire a more definite knowledge in the near future" (377).

By 1917 Slipher's discoveries had been discussed in several journals and periodicals. Among them were *Publications of the Astronomical Society of the Pacific*, *Proceedings of the American Philosophical Society*, *Popular Astronomy*, the *Monthly Notices of the Royal Astronomical Society*, the *Journal of the Royal Astronomical Society of Canada*, and others.

In 1916–17 Willem de Sitter published three papers on Einstein's general theory of relativity in the *Monthly Notices*. De Sitter was the director of the University of Leiden Observatory. During this period Einstein visited Leiden, and de Sitter had some conversations with him. In early 1917 Einstein published his famous foundational paper on relativistic cosmology in which he presented a mathematical model of a static universe based on the field equations of general relativity. In the third of de Sitter's papers, "On Einstein's Theory of Gravitation and Its Astronomical Consequences," he presented a new relativistic model of the universe (de Sitter 1917). The models of Einstein and de Sitter became known as solution A and solution B, respectively.[10]

Einstein and de Sitter posited a three-dimensional spatial universe that was finite and Riemannian or spherical, with constant positive curvature. Einstein apparently adopted this model because of his adherence to Mach's principle, which he believed required a finite universe (Belenkiy 2013, 83). The curvature of the

9. Here are the sources Eddington cited for nebular radial velocities: Slipher (1913), Moore (1915), Pease (1915, 1917), Truman (1916), and Young and Harper (1916). Eddington also cited Wolf's (1916) confirmation of the radial velocity of the Andromeda Nebula. Although Eddington discussed briefly Slipher's table of 15 radial velocities, he did not cite Slipher (1915) or produce the table itself. However, the table was given in Young and Harper (1916).

10. On these solutions and the reception of the work of Einstein and de Sitter in the 1920s, see Kerszberg (1989).

universe is the reciprocal of the radius of curvature. The radius of curvature, which is conventionally designated as R, is constant with respect to time in solution A of Einstein and solution B of de Sitter.

As indicated in the title of the paper, de Sitter differed from Einstein in attempting to relate his model to current observational work in astronomy. As director of an astronomical institute, he would have had informal contact with the professional community, and he presumably received news of the western American observatories, which were at the forefront of everything that was happening in stellar astronomy. In particular, he drew attention to Eddington's report earlier in the year on the large recessional velocities of spiral nebulae found by Slipher and verified by the Pacific observers. He also included specific numerical measurements for three nebulae given by Eddington. De Sitter suggested they provided possible support for his static relativistic model of the universe, in which the spectral shifts of objects increase as their distances from the observer increase. The data on spiral nebular redshifts indicated a certain degree of correlation between spectral shifts and apparent magnitude, with the fainter nebulae showing larger redshifts. If apparent magnitude is inversely proportional to distance, one has a correlation between redshift and distance, what became known as the "de Sitter effect."[11]

In de Sitter's paper, the mathematical expression of the de Sitter effect took the form

$$1 + \delta = \sec\left(\frac{r}{R}\right), \tag{1}$$

where δ is the fractional redshift, r is the distance of the particle, and R is the radius of the universe (North 1965, 99). Equation (1) implies that δ increases monotonically with r. Expressed as a series, equation (1) becomes

$$\delta = \frac{1}{2}\left(\frac{r}{R}\right)^2 + \frac{5}{24}\left(\frac{r}{R}\right)^4 + \frac{61}{720}\left(\frac{r}{R}\right)^6 + \dots . \tag{2}$$

For $r \ll R$, equation (2) would imply no detectible redshift, and for a somewhat larger range of values of r, $\delta \propto r^2$, with equation (2) giving the exact dependence of δ on r as r approaches R. Of course, in de Sitter's development of

11. Hubble (1936, 109) would later write that "Slipher's list of 13 velocities, although published in 1914, had not reached De Sitter, probably as a result of the disruption of communications during the war." (Slipher's list was published in 1915 and was also reproduced with some supplementary data in Paddock [1916] and Young and Reynolds [1916].) Hubble's comment may have been motivated by a desire to defend his priority in the discovery of the distance-redshift law. It should also be noted that Carl Wirtz (1918) writing in 1917 in wartime Germany presented Slipher's table and was well acquainted with the American work.

the theory the redshifts do not represent recessional velocities but are a relativistic effect related to the dilation of time.[12]

A noteworthy aspect of de Sitter's paper is that he ascribed a clear cosmological meaning to the spectroscopic nebular data. The measurements were typically analyzed by astronomers in terms of determining the motion of the solar system relative to the spirals. The high radial velocities were sometimes viewed as evidence for the island-universe theory but did not in themselves have further cosmological meaning. The "absurdly high" size of these velocities was a source of perplexity to observers.[13] De Sitter's interpretation of the radial motions as a relativistic effect brought in cosmology as a natural explanatory factor. In this respect his article was a harbinger of much that would come in the next 15 years. An undeniable contribution of the relativistic theorists in the 1920s was to give a cosmological interpretation to the results in nebular astronomy, which were not so viewed by the observers themselves.

Carl Wirtz of Strasbourg was one of the first astronomers outside of North America and the United Kingdom to consider Slipher's discovery of extraordinarily high nebular radial velocities.[14] While in military service he wrote an article in late 1917 for the *Astronomische Nachrichten* (Wirtz 1918) in which he discussed the American data. The table that he presented was the one in Paddock (1916, 109) in the *Publications of the Astronomical Society of the Pacific*. This in turn was simply Slipher's (1915) table adjusted in some cases to take into account the observations of other observers and supplemented by some data about the Magellanic Clouds. (Wirtz referred by name to Pease, Paddock, Moore, Wright, Adams, Truman, and Slipher.) Wirtz noted the huge leap from the radial velocities of stars, which averaged 14 km/sec., to the radial velocities of the spiral nebulae, which averaged 400 km/sec. He asked rhetorically, "Are therefore the spiral nebulae fundamentally different and separate from the system of stars?" (Wirtz 1918, 114).[15] Following Paddock (1916), he suggested that it was necessary to include a systematic velocity k in the expression for the radial velocity of each nebula. On the basis of the data in Slipher's table, he estimated k to be +656 km/sec.[16]

12. North (1965, 92–104) gives a detailed account of the de Sitter effect in relativistic cosmology from de Sitter into the early 1920s.

13. The words "absurdly high" for Slipher's values of the radial velocities of spiral nebulae were used by Campbell in 1914 (Osterbrock 1990, 262).

14. For Wirtz's career and his work on nebular spectral shifts, see Seitter and Duerbeck (1990).

15. "Sind demnach die Spiralnebel grundverschieden und getrennt vom System der Sterne?"

16. During wartime, German astronomers continued to receive astronomical literature, at least from the United States, which was neutral until April of 1917. It is sometimes stated that central Europe in World War I was cut off from news of the great developments in American astronomy (see, e.g., the remark by Hubble in n. 11), and this fact explains why Einstein in 1917 developed a cosmological model that was static. However, it may simply be the case that Einstein was not very engaged in general with observational astronomy and considered his model to be primarily of theoretical interest.

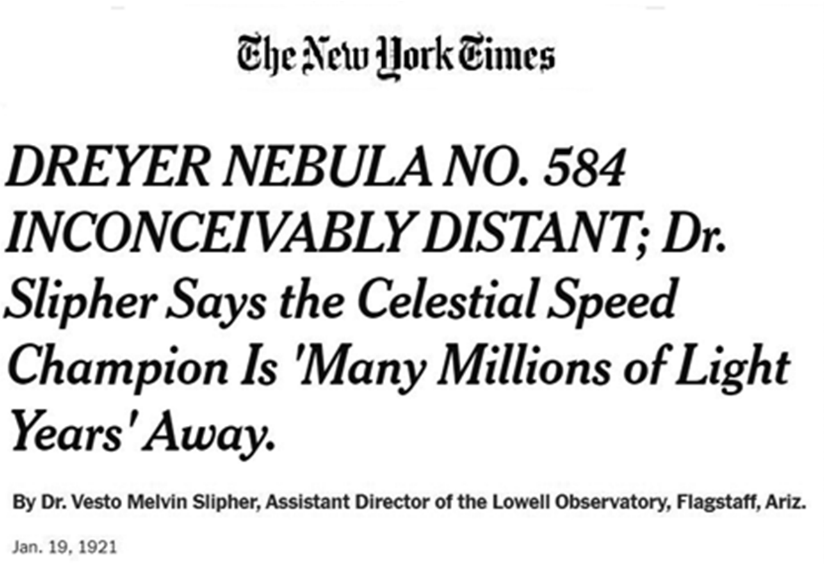
Wirtz was simply continuing his own earlier investigations of the proper motions of nebulae. There is no indication in the article that Wirtz had read de Sitter (1917), which just came out about the time he was writing but may not have made its way to Germany. The large radial velocities of the spirals raised questions that did not arise in the case of diffuse, gaseous, or planetary nebulae. Like Slipher and others before him, he considered the possibility that the spectral shifts did not represent Doppler velocities at all. He qualified his discussion with the proviso, "All in the tacit premise, that the full amount of the line shift is interpreted in the Dopplerian sense as radial motion" (Wirtz 1918, 115).[17]

At the conclusion of the article Wirtz recalled that William Herschel's original determination of the apex of the sun's motion relative to stars in its neighborhood was based on only a few observations. This preliminary work was confirmed by later observers and then integrated into a consistent mathematical theory by Hermann Kobold. Wirtz (1918, 116) asserted, "Also in the case of the nebulae, we can expect that we hold only isolated threads of the fabric, whose pattern we are not yet able to unravel. However, we are able to see how observations should proceed in order to arrive at a simpler description of quantitative results concerning the nebulae."[18]

Between 1916 and 1919 Harlow Shapley published a series of articles in the *Astrophysical Journal* on stellar clusters, a term that he took to encompass open clusters, globular clusters, and even spiral nebulae. The fourteenth installment in 1919 was written with his wife Martha and titled "Further Remarks on the Structure of the Galactic System" (Shapley and Shapley 1919). In section 7 they considered spiral nebulae and presented Slipher's (1917) table of radial velocities. The values in the latter were in marked contrast to the very low numbers that had appeared in the earlier tables for the radial velocities of globular clusters. The authors noted "that essentially without exception, on both sides of the Galaxy, spiral nebulae recede" (Shapley and Shapley 1919, 116). They made the following prescient observation: "The speed of spiral nebulae is dependent to some extent upon apparent brightness, indicating a relation of speed to distance or, possibly, to mass" (116). However, they believed that globular clusters and spiral nebulae were both systemically connected to the Milky Way galaxy, and they attempted to correlate the radial motions of the spirals to their positions within the galaxy. Needless to say, this line of investigation went nowhere.

17. "Alles in der stillschweigenden Voraussetzung, daß der volle Betrag der Linienverschiebung im *Doppler*schen Sinne als Radialbewegung gedeutet wird."

18. "Auch im Falle der Nebel darf man erwarten, daß wir vereinzelte Fäden des Gewebes in Händen halten, dessen Muster wir noch nicht zu entwirren vermögen. Man sieht aber, nach welcher Richtung die Beobachtungstatigkeit voranzustoßen ist, um uns zu einer einfachsten Beschreibung der mit den Nebeln verknüpften Rechnungsergebnisse zu verhelfen."


The New York Times

DREYER NEBULA NO. 584 INCONCEIVABLY DISTANT; Dr. Slipher Says the Celestial Speed Champion Is 'Many Millions of Light Years' Away.

By Dr. Vesto Melvin Slipher, Assistant Director of the Lowell Observatory, Flagstaff, Ariz.

Jan. 19, 1921

Figure 5. Headline, *New York Times*, January 19, 1921

Eddington in his 1920 book *Space, Time, and Gravitation* noted that the distances of the spiral nebulae may be in the millions of years. He displayed greater confidence in Slipher's findings here than he had in 1917. Concerning the shifts observed in their spectra, he stated, "The motions in line-of-sight of a number of nebulae have been determined, chiefly by Prof. Slipher. The data are not so ample as we should like; but there is no doubt that large receding motions greatly preponderate" (Eddington 1920, 161). Acknowledging de Sitter's work, Eddington considered the possibility that the spectral shifts may not have represented real radial velocities but have been the consequence of some other effect, possibly of the relativistic sort suggested by de Sitter. In 1921 Eddington's book was translated into French with a second mathematical part on the general theory of relativity that was not included in the English edition.[19]

News of the new observations of spiral nebulae was being disseminated more broadly in the popular press. In January of 1921 Slipher (1921a) published a story in the *New York Times* on the large recessional velocity of the nebula NGC584 in Cetus (fig. 5). Slipher stated that the observations at the Lowell Observatory had revealed "the quite unexpected fact that spiral nebulae are far the most swiftly moving objects in the universe." The nebula NGC584 was thousands of times

19. This second part was a draft of Eddington (1923).

fainter than M31 in Andromeda, indicating that it was likely very distant in comparison to the latter. Its faintness made it difficult to identify its spectral lines and determine their shifts, but Slipher was able to do so. He wrote, "The lines in its spectrum are greatly shifted, showing that the nebula is flying away from our region of space with a marvelous velocity of 1,100 miles per second [1,770 km/sec.]." The radial velocity of NGC584 was an order of magnitude higher than any that had been observed for stars. Slipher noted that if NGC584 left the vicinity of the earth at the time the latter was formed, then based on geological estimates of the earth's age, it would have traveled millions of light-years distant. This fact indicated that the nebula was very large and also implied a major increase in the estimated size of the universe.[20]

Heber Curtis investigated nebulae at the Lick Observatory from 1910 to 1920. In 1921 he published a vigorous defense of the island-universe theory in the *Bulletin of the National Research Council*. This was the written record of his contribution to the "great debate" with Harlow Shapley, a debate in which Curtis arguably had the upper hand.[21] Here he drew attention to the enormously large radial velocities of the spiral nebulae, much larger than those of objects in the Milky Way system such as stars, diffuse nebulae, and globular clusters. Such velocities indicated that the spirals were very probably external and likely comparable to the Milky Way. In fact, this possibility had been noted by Slipher himself and by others. The increasing support in the early 1920s for the island-universe theory was based in no small part on the growing body of nebular spectroscopic data.

Wirtz, now at the Kiel Observatory, considered the latest nebular data in an article that was dated October 1921 and was published the following April (Wirtz 1922). He produced the table from Slipher (1917) supplemented with additions in Slipher (1921b), as well as radial velocities for two other nebulae, for a total of 29 nebular velocities. The nebulae were regarded as objects external to the Milky Way but possibly connected to it in some way. Wirtz carried out a statistical study of the data. Among other things he considered the relationship between the brightness of the nebulae on the standard stellar magnitude scale and their radial velocities. Viewing faintness as a proxy for distance, he inferred that there was a tendency for nearby nebulae to approach the Milky Way system and distant nebulae to move away from it.

By 1922 the new results about the large positive radial motions of spiral nebulae had been presented in leading American, British, and German astronomical

20. Slipher's story also appeared in other newspapers, e.g., the *Salt Lake Telegram*, in which it was published in the Sunday edition of February 13, 1921, under the title "Celestial Speeder Long Distance Off Dreyer Nebula No. 584 Is Aloof from Earth."

21. On the "great debate," see Smith (1982) and Crowe (1994).

and scientific periodicals.[22] Alexander Friedmann's famous article was dated May 29, 1922, and was received by *Zeitschrift für Physik* one month later. At the beginning of the article, he cited both de Sitter's piece in the *Monthly Notices* and the 1921 French edition of Eddington's book. One finds on page 200 of the latter, "Les mouvements dans la direction radiale d'un grand nombre de nébuleuses ont été déterminés, en particulier par le Prof. Slipher . . . sans aucun doute ce sont les grandes vitesses d'éloignement qui sont prépondérantes" (Eddington 1921, 200). Although Friedmann did not refer to nebular radial velocities or to any other astronomical data (the specific reference to Eddington was to the second part of the book), it is safe to assume that he had some knowledge of them, at the very least from de Sitter's explicit discussion of the matter.

Recall that the radius of curvature R of the universe was constant with respect to time in solution A of Einstein and solution B of de Sitter. Friedmann's innovation in 1922 was to consider a model in which R varies with time and in particular is a monotonic function of time. He thereby obtained a dynamic model of the universe. The idea seems conceptually and mathematically a very natural one to pursue, and apparently it had not been taken up by Einstein simply because the thought had never occurred to him that the geometry of the universe might change with time.

At the conclusion of the article Friedmann (1922, 385–86) wrote, "Our knowledge is completely insufficient to carry out numerical calculations and decide what world our universe is."[23] This comment would indicate that he was probably not writing with any explicit attention to astronomical knowledge. Nevertheless, given that he was responding in part to de Sitter's earlier article and had consulted Eddington's book in preparing his study, one might conclude that he was influenced if only indirectly and perhaps somewhat generally by the latest work in nebular astronomy.

4. After Slipher

In 1923 Eddington published his mathematical treatise on general relativity, which included the latest nebular data (sent by Slipher to Eddington), listing the radial velocities of 41 nebulae, about 90% of which were recessional.

22. Slipher's (1915) table of radial velocities of spiral nebulae in either its original or supplemented form had appeared in Paddock (1916), Young and Harper (1916), Slipher (1917), Wirtz (1918, 1922), Shapley and Shapley (1919), and Eddington (1921). The findings were also summarized in a number of other publications. The conclusion of Shapley and Shapley (1919, 126) would have been apparent to anyone who looked at the data: "The speed of spiral nebulae is dependent to some extent upon apparent brightness, indicating a relation of speed to distance."

23. "Unsere Kenntnisse sind vollständig ungenügend, um Zahlenrechnungen auszuführen und zu entscheiden, welche Welt unser Weltall ist."

Eddington provided a detailed discussion of this data in terms of the de Sitter effect. Slipher's spectroscopic work was also noted in the Soviet Union, where the article "Fast-Moving Nebulae" was published in 1923 in the general journal of science *Mirovedeniye* (World science; Tropp et al. 2006, 217).

In the early 1920s Slipher largely moved away from nebular spectroscopy as he took on more administrative duties and turned his attention to areas of planetary astronomy for which the Lowell Observatory is famous. Edwin Hubble's biographer Gale Christianson (1995, 189) comments, "Slipher found that his telescope could not measure up to the task of photographing the increasingly smaller and dimmer objects he encountered." The center of research on nebular spectroscopy shifted to Mount Wilson, where the Hooker 100″ reflector became the preeminent instrument for the investigation of faint objects. The place of Hubble and Milton Humason in the formative events of the decade have been well documented in the historical literature.[24]

In 1921 Slipher was elected to the National Academy of Sciences in recognition of his contributions to astronomy. In accepting the Henry Draper Medal from the academy in 1933, he credited "good instrumental equipment and favorable skies for observation" (Hoyt 1980, 432). Slipher was never someone who rushed into print, and he published nothing at all in the last 25 years of his life.[25] When he died in 1969, the *New York Times* obituary headlined his involvement in the search that led to the discovery of the planet Pluto.

5. Discussion

The present study has focused on the observational contributions of Slipher and their dissemination both scientifically and more broadly, leading up to Friedmann's monotonic relativistic model of 1922. The intent is to document precisely what was known in astronomical science at this critical moment in the emergence of modern cosmology.

Richard F. Hirsch (1983, 9) begins his history of X-ray astronomy with the observation, "X-ray astronomy is a gift of technology." This observation might be extended to much of the history of astronomy since the late eighteenth century. There was of course highly significant work in celestial mechanics and mathematical methods that owed little to technology. Nevertheless, for the revolution in modern cosmology the role of technology was paramount. One need turn no

24. For these developments, see North (1965), Smith (1982), Christianson (1996), Kragh (1996, 2007), and Nussbaumer and Bieri (2009). A somewhat revisionist appraisal of the relationship of the research of Slipher to that of Hubble and Humason is given in Peacock (2013) and Thompson (2013).

25. The last publication listed in Hoyt (1980) was in 1944.

further than to Hubble (1936, vii–viii), who wrote, "The conquest of the Realm of the Nebulae is an achievement of great telescopes." Hubble was referring here to work that led to the identification of the extragalactic nature of spiral nebulae (which owed nothing to relativistic theorists), as well as progress that had been made in determining distances to a substantial class of the nebulae. In addition, the spectroscopic work that he carried out with Humason extended the pioneering achievements of Slipher and led to the celebrated redshift-distance law.

Insofar as Slipher himself was concerned, the key actors in the history were the master opticians at Alvan Clark & Sons who crafted the 24″ lens for the main Lowell refractor, the instrument maker John A. Brashear of Pittsburgh, who designed and built the spectrograph, the manufacturers of the fast Voigtländer f2.5 camera lens, and finally Slipher himself and the technician Stanley Sykes, who worked so diligently to apply this technology to nebular spectroscopy.

Astronomers who posited that the galactic redshifts arose not from radial motions but from some other cause were not able to develop an adequate physics to support this theory.[26] Given that the redshifts do represent radial velocities that increase with distance, it follows that we live in an expanding universe. Unlike many other great ideas of modern science, this fact is without precedent or anticipation in the history of science. In quantum physics the idea of the quantum was foreshadowed in earlier speculation about the discrete character of physical reality. In molecular biology the idea of the molecular code was anticipated by various ideas of preformation and cellular prototype. By contrast, there seems in history before the twentieth century no anticipation or imaginative foreshadowing of the idea of an expanding universe.

The expansion of the universe is a fundamental observational fact about the universe in which we live. The discovery of expansion was the product of developments in observational astronomy. Mathematical models that posited a distance-redshift relation or a distance-velocity relation were developed only after it had become generally known that spiral nebulae exhibit large positive radial velocities that on average increase with faintness of the nebulae. Furthermore, to the degree that the relativistic models were independent of observation, they were regarded by their creators and the scientific community at large as primarily of mathematical interest.[27]

26. Perspectives on cosmology outside of the mainstream, including ones that reject universal expansion, may be found in Arp et al. (1993).

27. Examples of such mathematical research were Weyl (1919) and Lanczos (1922). Referring to relativistic cosmology in the 1920s, North (1965, 110) writes, "Astronomy was not entirely unprepared for the ideas involved in this new conception [a nonstatic universe], but . . . liaisons between astronomer and mathematician were weak."

It is indeed a striking coincidence that relativistic cosmology appeared at the same time as the revolution in nebular astronomy.[28] And it is also true historically that relativistic models and theorizing from the 1920s on were a part of the burgeoning science of cosmology. Certainly the early relativists played a part in suggesting that Slipher's redshifts were cosmological in nature. However, their research was not essential to the basic discovery of expansion. The revelation that we live in an expanding universe would have emerged in the absence of contributions from relativistic theorists, however important they may have been in the subsequent development of cosmology.

John North's *Measure of the Universe* (1965) remains the most detailed historical account of relativistic cosmology in the 1920s. The question of who discovered universal expansion has been examined in some detail by the historians Kragh and Smith (2003). The astrophysicist Michael Way (2013) provides an account of the positive interaction between mathematical physicists and astronomers in theorizing about cosmology in the 1920s. As we saw for de Sitter, fairly abstract theorizing about redshifts contributed to a cosmological interpretation of these quantities. In 1923 Hermann Weyl published a relativistic cosmological model in which there is a linear relationship between distance and recession (Weyl 1923). Eddington (1933, 12) declared that the linear velocity-redshift law had been "predicted by relativity theory," although he conceded that it was Hubble and Humason (1929) that alerted him to this finding. Arthur Milne (1933) attempted to develop an "explanation" for the redshift law without using relativity. Such theoretical predictions or explanations of universal expansion reduced at their core to logical deductions of the following form: if the universe expands, then the universe expands. Universal expansion is a primary empirical fact about the world around us and not the implication of a theory. Of course, mathematical models were developed in which expansion takes place, but these (sometimes curious) theoretical constructions showed only that it was possible to devise a geometric model in which expansion occurs. Furthermore, the place of the general theory of relativity in modern cosmology is based not so much on these models as it is simply on the status of this theory as the best available account of gravity. The general theory of relativity originated not in cosmology but in the investigation of such anomalies in Newtonian theory as the motion of the perihelion of mercury and the behavior of electromagnetic radiation in gravitational fields.

In the historiography of modern cosmology considerable weight is given to the contributions of theorists. The identification of high nebular radial velocities and the subsequent discovery of the linear distance-redshift relation are implicitly

28. This historical coincidence is discussed by Fraser (2006) in an educational book on the history of cosmology.

viewed (with some justification) as events that were more or less inevitable with the construction of large observatories and the development of sophisticated telescopes, photography, and spectroscopy. The focus of critical historical analysis has been on the underlying principles that made it possible to integrate the observational findings into a coherent mathematical theory of the universe.

North's *Measure of the Universe* (1965) emphasizes the creative intellectual work of mathematicians and mathematical physicists. North's perspective is reflected in the ordering of his chapters, in which a chapter on formal work on the expanding universe is followed by a chapter documenting the astronomers' contribution. This attitude is also echoed in Pierre Kerszberg's (1989, 56) study of cosmology in the 1920s: "That a relatively consistent picture of the universe, on a new and gigantic scale, could be finally attained by the astronomers came at least as much from the purely theoretical side of the whole endeavor. Ultimately it was the totally new view of structure brought into play by the relativity theory which allowed evolutionary considerations to recover their full legitimacy."

The developments in nebular astronomy in the early twentieth century were so singular and of such an enormous historical magnitude that their significance was difficult for contemporary thinkers to fully grasp. The remarkable temporal coincidence of the breakthrough in nebular astronomy and the invention of the theory of general relativity created a kind of illusion in the minds of some of the historical actors themselves. Eddington is a case in point. His general attitude was already apparent in 1920 in his remark that "a geometer like Riemann might almost have foreseen the more important features of the actual world" (Eddington 1920, 167). In reference to the discovery by Hubble and Humason of the redshift-distance law, he later wrote, "These observational results are in some ways so disturbing that there is a natural hesitation in accepting them at their face value. But they have not come upon us like a bolt from the blue, since theorists for the last fifteen years have been half expecting that a study of the most remote objects of the universe might yield a rather sensational development" (Eddington 1933, 2).

The historian of science Paul Forman (2007) maintains that an epochal historical shift occurred at the end of the twentieth century, from a conception of science and theory as primary relative to technology, to a conception of technology as primary relative to science. Forman sees the shift from the primacy of science before 1980 (a primacy that he repeatedly refers to as "preposterous") to the primacy of technology after 1980 as the defining feature of a wider shift in the cultural zeitgeist from modernity to postmodernity. In his lengthy study Forman cites as one example Munich's Museum of Masterworks of Natural Science and Technology, founded in 1903. The museum's initial exhibition was devoted to astronomy. Forman (2007, 35) writes, "While we today would regard astronomy as well suited to illustrate a view of science as based in and dependent upon technology, such was by no means the museum's message. Rather, here as elsewhere, 'the technical artifacts stood above all else for scientific disciplines or were scientific ideas materialized'—with the astronomer who conceived and employed the instrument, not the exceptionally skilled and ingenious instrument-maker who created it, accorded the role of its 'inventor.'"[29]

In the writings of astrophysicists such as Eddington and Milne, and even later historians such as John North, one finds an unequivocal commitment to the primacy of theory relative to technology, of science relative to practice. The emphasis on theory among cosmologists from the 1920s through to the 1960s is consistent with the broader cultural and historical schema identified by Forman. The shift that Forman claims took place around 1980 is apparent in the outlook of an astronomer today such as Martin Harwit (2013), who sees the technological character of modern astronomy as its defining and redemptive feature.[30] The present study with its emphasis on the essential place historically of observational technology naturally issues from the postmodern side of Forman's temporal cultural divide.

REFERENCES

Arp, Halton C., Roy Keys, and Konrad Rudnicki, eds. 1993. *Progress in New Cosmologies beyond the Big Bang*. New York: Plenum.

Belenkiy, Ari. 2013. "'The Waters I Am Entering No One Yet Has Crossed': Alexander Friedman and the Origins of Modern Cosmology." In Way and Hunter 2013, 71–96.

Bertotti, B., R. Balbinot, S. Bergia, and A. Messina, eds. 1990. *Modern Cosmology in Retrospect*. Cambridge: Cambridge University Press.

Bonola, Roberto. 1912. *Non-Euclidean Geometry: A Critical and Historical Account of Its Development*. Trans. H. S. Carlaw. Chicago: Open Court.

Calinon, Auguste. 1889. "Les espaces géométriques." *Revue philosophique de la France et de l'étranger* 27:588–95.

Čapek, Milič. 1971. *Bergson and Modern Physics: A Reinterpretation and Re-evaluation*. Boston Studies in the Philosophy of Science 7. Dordrecht: Reidel.

Christianson, Gale E. 1995. *Edwin Hubble: Mariner of the Nebulae*. Chicago: University of Chicago Press.

Crowe, Michael. 1994. *Modern Theories of the Universe from Herschel to Hubble*. New York: Dover.

Curtis, Heber D. 1921. "The Scale of the Universe." *Bulletin of the National Research Council*, vol. 2, pt. 3, no. 11, 194–217.

29. The words 'the technical artifacts stood above all else for scientific disciplines or were scientific ideas materialized' are translated from Hashagen et al. (2003, 22).

30. Harwit's book is reviewed by Fraser (2014).

de Sitter, Willem. 1917. "On Einstein's Theory of Gravitation and Its Astronomical Consequences." *Monthly Notices of the Royal Astronomical Society* 78 (1): 3–28.

Duerbeck, Hilmar W., and Waltraut C. Seitter. 1993. "K-effect." In *Encyclopedia of Cosmology*, ed. Norriss S. Hetherington, 333–34. New York: Garland.

Eddington, Arthur S. 1917. "The Motions of Spiral Nebulae." *Monthly Notices of the Royal Astronomical Society* 77 (4): 375–77.

———. 1920. *Space, Time, and Gravitation: An Outline of the General Theory of Relativity*. Cambridge: Cambridge University Press.

———. 1921. *Espace, temps et gravitation. La théorie de la relativité généralisée dans ses grandes lignes. Exposé rationnel. Suive d'une étude mathématique de la théorie*. Trans. and introduction by P. Langevin. Paris: Libraire scientifique J. Hermann.

———. 1923. *The Mathematical Theory of Relativity*. Cambridge: Cambridge University Press.

———. 1933. *The Expanding Universe*. Cambridge: Cambridge University Press.

Einstein, Albert. 1917. "Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie." *Sitzungberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin*, 142–52.

Forman, Paul. 2007. "The Primacy of Science in Modernity, of Technology in Postmodernity, and of Ideology in the History of Technology." *History and Technology* 23 (1): 1–152.

Fraser, Craig. 2006. *The Cosmos: A Historical Perspective*. Westport, CT: Greenwood.

———. 2014. Review of *In Search of the True Universe: The Tools, Shaping, and Cost of Cosmological Thought*, by Martin Harwit. *Isis* 105:828–29.

Friedman, A. 1922. "Über die Krümmung des Raumes." *Zeitschrift für Mathematik und Physik* 10:377–86.

Harrison, Edward. 1987. *Darkness at Night: A Riddle of the Universe*. Cambridge, MA: Harvard University Press.

Harwit, Martin. 2013. *In Search of the True Universe: The Tools, Shaping, and Cost of Cosmological Thought*. Cambridge: Cambridge University Press.

Hashagen, Ulf, Oskar Blumtritt, and Helmuth Trischler. 2003. "Artefakte *circa* 1903: Methodische Konzepte-Überlegungen-Ergebnisse." In *Circa 1903:Artefakte in der Gründungszeit des Deutschen Museums*, ed. Ulf Hashagen, Oskar Blumtritt, and Helmuth Trischler, 9–30. Abhandlungen und Berichte (Deutsches Museum). N.F., Bd. 19. Munich: Deutsches Museum.

Hirsch, Richard F. 1983. *Glimpsing an Invisible Universe: The Emergence of X-Ray Astronomy*. Cambridge: Cambridge University Press.

Hoyt, William Graves. 1980. "Vesto Melvin Slipher, 1875–1969." *Biographical Memoirs of the National Academy of Sciences*. Washington, DC: National Academy of Sciences.

Hubble, Edwin. 1936. *The Realm of the Nebulae*. New Haven, CT: Yale University Press.

Hubble, Edwin, and Milton Humason. 1929. "A Relation between Distance and Radial Velocity among Extra-galactic Nebulae." *Proceedings of the National Academy of Sciences* 15 (3): 168–73.

Kerszberg, Pierre. 1989. *The Invented Universe: The Einstein–de Sitter Controversy (1916–17) and the Rise of Relativistic Cosmology*. Oxford: Oxford University Press.

Kragh, Helge. 1996. *Cosmology and Controversy: The Historical Development of Two Theories of the Universe*. Princeton, NJ: Princeton University Press.

———. 2004. *Matter and Spirit in the Universe: Scientific and Religious Preludes to Modern Cosmology*. London: Imperial College Press.

———. 2007. *Conceptions of Cosmos: From Myths to the Accelerating Universe; A History of Cosmology*. Oxford: Oxford University Press.

Kragh, Helge, and Robert W. Smith. 2003. "Who Discovered the Expanding Universe?" *History of Science* 41:141–62.

Lanczos, Kornel. 1922. "Ein vereinfachendes Koordinatensystem für die Einsteinschen Gravitationsgleichungen." *Physikalische Zeitschrift* 23:537–39.

Milne, Edward Arthur. 1933. "World-Structure and the Expansion of the Universe." *Zeitschrift für Astrophysik* 6:1–95.

Moore, Joseph H. 1915. "Note on the Radial Velocity of the Nebula 1068." *Publications of the Astronomical Society of the Pacific* 27:192.

Newall, Hugh F. 1916. "Stellar Spectroscopy in 1915." *Monthly Notices of the Royal Astronomical Society* 76 (4): 357–63.

North, John D. 1965. *The Measure of the Universe: The History of Modern Cosmology*. Oxford: Clarendon.

Norton, Arthur P., and J. Gall Inglis. 1964. *A Star Atlas and Reference Handbook for Students and Amateurs*. Cambridge, MA: Sky; Edinburgh: Gall & Inglis.

Nussbaumer, Harry. 2013. "Slipher's Redshifts as Support for de Sitter's Model and the Discovery of the Dynamic Universe." In Way and Hunter 2013, 97–134.

Nussbaumer, Harry, and Lydia Bieri. 2009. *Discovering the Expanding Universe*. Cambridge: Cambridge University Press.

Osterbrock, Donald. 1990. "The Observational Approach to Cosmology: U.S. Observatories Pre-World War II." In Bertotti et al. 1990, 247–89.

Paddock, George F. 1916. "The Relation of the System of Stars to the Spiral Nebulae." *Publications of the Astronomical Society of the Pacific* 28:109–15.

Peacock, John A. 2013. "Slipher, Galaxies, and Cosmological Velocity Fields." In Way and Hunter 2013, 3–23.

Pease, Francis G. 1915. "The Radial Velocity of the Nebula N. G. C. 1068." *Publications of the Astronomical Society of the Pacific* 27:133–34.

———. 1916. "The Rotation and Radial Velocity of the Spiral Nebula N. G. C. 4594." *Proceedings of the National Academy of Sciences* 2:517–21.

———. 1917. "The Rotation and Radial Velocity of the Spiral Nebula N.G.C. 4594." *Popular Astronomy* 25:26–27.

Robertson, Howard P. 1949. "Geometry as a Branch of Physics." In Schilpp 1949, 313–32.

Schilpp, Paul A., ed. 1949. *Albert Einstein: Philosopher-Scientist*. Library of Living Philosophers 7. Evanston, IL: Library of Living Philosophers.

Seitter, Waltraut C., and Hilmar W. Duerbeck. 1990. "Carl Wilhelm Wirtz—a Pioneer in Observational Cosmology." In Bertotti et al. 1990, 365–99.

Shapley, Harlow, and Martha B. Shapley. 1919. "Further Remarks on the Structure of the Galactic System." Studies Based on the Colors and Magnitudes in Stellar Clusters 14. *Astrophysical Journal* 50:107–40.

Slipher, Vesto M. 1913. "The Radial Velocity of the Andromeda Nebula." *Lowell Observatory Bulletin*, no. 58, 2 (8): 56–57. Repr. in *Popular Astronomy* 22 (1914) :19–21.

———. 1914. "Spectrographic Observations of Nebulae." *Popular Astronomy* 22:146.

———. 1915. "Spectrographic Observations of Nebulae." *Popular Astronomy* 23:21–23.

———. 1917. "Nebulae." *Proceedings of the American Philosophical Society* 56 (5): 403–9.

———. 1921a. "Dreyer Nebula No. 584 Inconceivably Distant." *New York Times*, January 19.

———. 1921b. "Zwei Nebelflecke mit außerordentlicher Bewegung." *Astronomische Nachrichten* 213:47–48.

Smith, Robert. 1982. *The Expanding Universe: Astronomy's "Great Debate," 1900–1931*. Cambridge: Cambridge University Press.

———. 2013. "The Road to Radial Velocities: V. M. Slipher and Mastery of the Spectrograph." In Way and Hunter 2013, 143–64.

Steinicke, Wolfgang. 2010. *Observing and Cataloguing Nebulae and Star Clusters: From Herschel to Dreyer's New General Catalogue*. Cambridge: Cambridge University Press.

Thompson, Laird A. 2013. "V. M. Slipher and the Development of the Nebular Spectrograph." In Way and Hunter 2013, 135–41.

Tropp, Eduard A., Viktor Ya. Frenkel, and Artur D. Chernin. 2006. *Alexander A. Friedmann: The Man Who Made the Universe Expand*. Trans. Alexander Dron and Michael Burov. Cambridge: Cambridge University Press.

Truman, O. H. 1916. "The Motions of Spiral Nebulae." *Popular Astronomy* 24:111–12.

Way, Michael J. 2013. "Dismantling Hubble's Legacy?" In Way and Hunter 2013, 97–134.

Way, Michael J., and Deidre Hunter, eds. 2013. *Origins of the Expanding Universe: 1912–1932*. ASP Conference Series 471. San Francisco: Astronomical Society of the Pacific.

Weyl, Hermann. 1919. "Über die statischen kugelsymmetrischen Lösungen von Einsteins 'kosmologischen' Gravitationsgleichungen." *Physikalische Zeitschrift* 20:31–34.

———. 1923. "Zur allgemeinen Relativitätstheorie." *Physikalische Zeitschrift* 24:230–32.

Wirtz, Carl. 1918. "Über die Bewegungen der Nebelflecke." *Astronomische Nachrichten* 206 (4933): 109–16.

———. 1922. "Einiges zur Statistik der Radialbewegungen von Spiralnebeln und Kugelsternhaufen."*Astronomische Nachrichten* 215 (5153): 349–54.

Wolf, Max. 1908. *Die Milchstraße*. Leipzig: Barth.

———. 1916. "Andromeda-Nebel." *Vierteljahrschrift der Astronomischen Gesellschaft* 51:115.

Young, Reynold K., and William E. Harper. 1916. "The Solar Motion as Determined from the Radial Velocities of Spiral Nebulae." *Journal of the Royal Astronomical Society of Canada* 10:134–35.