A Survey of Big Bang Cosmology, Part I: Cosmic Geography

ELEGANT CONNECTIONS IN PHYSICS

by Dwight E. Neuenschwander

In November 1915, Albert Einstein finished his decade-long struggle to develop the General Theory of Relativity (GR), in which he envisioned gravitation geometrically as the "curvature of spacetime." Immediate observational confirmation for the theory was significant but slim. In 1915 this consisted of the successful accounting of the anomalous precession of Mercury's orbit. Tests of other early predictions, all on the solar system scale, would have to wait. Measurement of the deflection of light rays grazing the sun occurred with the 1919 solar total eclipse; measuring gravitational redshift and radar echo delay required high-speed electronics that appeared about 1960. Some measurements, such as gyroscope precession and gravitational waves, are only now being carried out for the first time.[1]

Despite limited early opportunities to test the theory, in 1917 Einstein hitched his wagon to the stars and brazenly launched modern cosmology by applying GR to the *entire universe*. In so doing he started a discussion that, over the next dozen years, blossomed into the genesis of big bang cosmology.

The years between 1900 and 1930 saw a confluence of observation and theory that matured cosmology into a science. On the theoretical side was the advent of GR. Newtonian cosmology was spectacularly inconsistent with Newtonian gravitation concerning the boundary conditions at infinity, and in 1917 GR offered a way out of the impasse. On the observational side, the realization that the spiral nebulae lay far outside the Milky Way galaxy was a necessary insight before modern cosmology could be possible. We take up a synopsis of the latter story here, and return to the former in subsequent installments of this series.

"...A CONGERIES OF INNUMERABLE STARS..."

In 1610, Galileo Galilei published The Sidereal Messenger, which offered humanity its first glimpse of the innumerable quantity of stars:[2]

> *"...the Milky Way itself...with the aid of the spyglass, may be observed so well that all the disputes that for so many generations have vexed philosophers are destroyed by visible certainty, and we are liberated from wordy arguments. For the Galaxy is nothing else than a congeries of innumerable stars distributed in clusters. To whatever region of it you direct your spyglass, an immense number of stars immediately offer themselves to view, of which very many appear large and conspicuous but the multitude of small ones is truly unfathomable."*

Not all the "disputes were destroyed by visible certainty," as we shall see. But from now on they would be resolved with data understood through theoretical models. By the end of the seventeenth century, the enormous successes of the Newtonian paradigm at the solar system scale gave Newtonian cosmologists, beginning with Isaac Newton himself, reason to turn with confidence to the large-scale structure of the universe. When Newton wrote the Principia in 1687, and republished its Book 3 as *A Treatise on the System of the World* in 1728, no mechanisms were known for turning stars on or off; presumably the universe was eternal. Euclidian space was the only geometry imaginable. Space was assumed infinite because an edge or boundary would raise more questions than it answered. The cosmos was thought to be essentially static because the stars exhibited little perceptible motion relative to one another. There was only one tiny problem. An infinite, static, eternal universe was *impossible to reconcile* with Newtonian gravitation.

Gravity only attracts; so why doesn't Galileo's "congeries of innumerable stars" collapse? To explain the non-occurrence of that catastrophe Newton invoked a symmetry argument. He suggested that the star population extends to infinity, with a uniform number density:[3]

> *"The fixed stars, being equally spread out in all points of the heavens, cancel out their mutual pulls by opposite attractions."*

Leaving aside the subtle (and fatal) question of such a system's instability against local density fluctuations, the model was also famously plagued with the so-called Olbers Paradox, first discussed by Edmund Halley in 1720, then J. P. de L. de Cheseaux in 1744, and Heinrich Olbers in 1823 (demonstrating that sometimes it pays to be third).[4] In an infinite universe populated uniformly with stars, every line of sight eventually terminates on a star. The stars far away appear dimmer than nearby ones, but there are more of them. For the stars in a spherical shell of given radius centered on the observer, the distance-dependent factors cancel, giving a each shell a common brilliance, not to mention infinite intensity when integrating over all shells.

Much of what Galileo saw through his small refractor and took to be stars turned out to be diffuse gas illuminated by starlight. A century later, Emanuel Swedenborg (1734), Thomas Wright (1750), Immanuel Kant (1755), and Jean

(continued on next page)

Lambert (1761) commented on the existence of the fuzzy patches called "nebulae," not yet resolved into spirals or any other definite shape.[5] Whatever they are, about a hundred nebulae were listed by Charles Messier in his famous catalog "*Mémoires de l'Academie*," published in 1774. Thomas Wright had postulated that the Milky Way is a disc-shaped array of stars around us, and starry hosts might extend beyond our range of observation. In *An Original Theory or New Hypothesis of the Universe*, he wrote

> *"...That this [endless immensity] in all probability may be the real case, is in some degree made evident by the many cloudy spots, just perceivable by us, as far without our starry Regions...."*

William Herschel, a.k.a, Fredrich Wilhelm Herschel, was a musician who emigrated from Germany to England in 1759, having had enough of the Seven Years War. While teaching music in England he took up astronomy, and became one of the most skilled of telescope makers. Among his many astronomical accomplishments, Herschel attempted to map the Milky Way in a procedure he called "star gauging." By assuming the stars had the same intrinsic luminosities, he proposed relative distances to the stars from the relative intensities of their light that we receive on Earth. Thus he mapped the Milky Way by counting stars of various magnitudes, in hundreds of fields of view.

While making his systematic surveys of the sky Herschel discovered Uranus in 1781. This got him elected to the Royal Society, and he could devote his full time to astronomy, which was good for astronomy if not for music (CDs of his symphonies are available). Presented that same year with a copy of Messier's catalog, Herschel, with his sister Caroline, his steadfast partner in observing, began to systematically study the nebulae. Over the years they discovered thousands of them.

Messier had suggested that 29 of his nebulae held no stars. However, with his excellent telescopes Herschel was able to resolve 18 of these into what we now call "globular clusters," most of which seem to congregate in the direction of Sagittarius, suggesting we are not surrounded by them; and in 1790 he found a nebula that contained a central star surrounded by what appeared to be a gaseous atmosphere. Today we call the latter "planetary nebulae" in which the star has puffed off its outer layers. However, with the persistence of some diffuse nebulae (think of the Orion or the Crab nebulae), Herschel became convinced that not all nebulae would be resolved into stars.[6]

A distinctive spiral shape for a nebula was first seen in M51 in 1845 by William Parsons, third Earl of Rosse, with "Leviathan," his 72-inch telescope that surpassed Herschel's 48-inch instrument as the world's largest at the time, and remained so for the next seventy years.[7] Few believed his remarkable drawings of spirals until photographs offered confirmation.

WHAT ARE THE SPIRALS?

In his *General Natural History and Theory of the Heavens* of 1755, Immanuel Kant proposed two far-reaching ideas.[8] One hypothesized that stars and their planets form in the condensation of nebulae.[9] His second hypothesis suggested that the nebulae are "island universes," galaxies in their own right, of which the Milky Way happens to be the example in which we reside. Kant wrote, "It is much more natural and reasonable to assume that a nebula is not a unique and solitary sun, but a system of suns."[10] Kant's "island universe" hypothesis was at the time pure speculation, and raised a controversy that continued until 1924.

Kant was a formidable philosopher, though not trained in advanced mathematics. So he could not express his concepts in the language of mathematical models that could lead to testable quantitative inferences. That step was taken in 1796 by Pierre-Simon Laplace, who made quantitative the nebula collapse concept as the mechanism of solar system formation.[11] After 1845 it was suggested that in the vortex of the spiral nebulae we are seeing solar system formation in progress. Until 1924 astronomers tended to be either Kantians or Laplacians. Kantians supposed that the nebulae were "island universes," other galaxies like the Milky Way. Laplacians supposed that the nebulae, especially the spirals, were solar systems under construction.

The Island Universe hypothesis received its first observational support from the inexhaustible William Herschel. In two papers of 1784 and 1785 he presented the results of has "star gauging" surveys from 683 regions over the sky. In some fields he would see only one star, in others there would be hundreds. His map of the Milky Way shows roughly a wheel-shaped region with the Sun placed near the center. The Milky Way, according to Herschel's map, was not infinite in extent. So if the Milky Way was just a proper name for the universe, that would offer a sharp contrast to the assumptions of Newtonian cosmology. In any case, the galaxy's finite size supported the island universe notion.

Herschel's early map is all the more remarkable because he did not entertain the notion of absorption of light by interstellar dust, or allow for diverse luminosities among stars. The ubiquitous John Michell had shown in 1767 that the stars could not all have the same luminosity.[12] For instance, the stars in the Pleiades appear with unequal brightnesses, yet their grouping gives every appearance of the members being close proximity to one another.

The main problem was measuring distances with any reasonable accuracy and precision. Stars are so far away that distances to only a very few nearby ones can be measured by parallax using the Earth's orbit diameter as the baseline. Such a trigonometric parallax was first published by Friedrich Wilhelm Bessel in 1838, finding 0.31 seconds of arc for 61 Cygni, which puts it about 10 light-years (LY) from Earth.[13] These incredibly skinny triangles are good for probing distances on the order of less than 100 LY.

Herschel hoped to use as a distance calibrator the parallax of "optical double stars," two stars that happen to lie on

(continued on next page)

essentially the same line of sight. Herschel proceeded to catalog all the optical double stars he could find. He was not successful in using them as distance indicators, but he did show for the first time (with Castor in Gemini, in 1804) that gravitationally bound true binaries occur, where one star orbits another, and therefore Newton's laws apply outside the solar system. Herschel's quest for binaries also showed, by 1802, that some of his true binary stars had differing brightness, whereupon he reluctantly acknowledged that stars exhibit diverse luminosities.

As Herschel began to question his own assumptions for mapping the Milky Way, he began to doubt the island universe model. The Laplacian scenario of the spirals being stars condensing from nebulae seemed to receive dramatic support with the sudden appearance in 1885 of a bright new star, or "nova," seen in M31, the Andromeda nebula.

Throughout the 19th century, estimates for the size of the Milky Way ranged from about 6,000 to over 20,000 LY.[14] These were Herschel's figures early (1785) and later (1806) in his star-gauging career. Several other surveys were attempted by other astronomers. For instance, Giovanni Celoria in 1879 proposed a finite galaxy of two or more concentric rings. Not until 1900 was the first map of the Milky Way drawn that that endows it with spiral arms. This was done by Cornelius Easton, who placed the Sun in the center and the spirals off the sides.[15] Karl Schwarzschild estimated the galaxy to be about 10 kpc (1 pc = 3.26 LY) in diameter, 2 pc thick, with the Sun at the center. Johannes Kapteyyn and P. J. van Rhijn in 1920, and Kapetyn again in 1922, put the diameter of the galaxy about double Schwarzschild's, and the latter survey put the Sun about 3 kpc off-center.[16]

But even if the Milky Way was a spiral, it was not yet clear whether the spiral nebulae were sovereign galaxies, or merely satellites of the Milky Way. By the time Easton drew his Milky Way spiral, over 100,000 spiral nebulae had been found. I suppose it is hard for us nowadays to appreciate how difficult it must have been at that time to be asked to stretch one's mind around the vastness of space required for the spiral nebulae to be as remote and large as the island universe required. In addition, the brightness of the "new stars" (novas), such the Andromeda event of 1885 and Tycho's nova of 1572, overwhelmed the imagination if they were supposed to occur in other, distant island universes not part of the Milky Way (although by 1920 there was talk of there possibly being more than one kind of nova). The astronomer and historian Agnes Clerke perhaps echoed this reluctance accurately when she wrote in *A Popular History of Astronomy During the Nineteenth Century* (1890), "No competent thinker, with the whole of the available evidence before him, can now, it is safe to say, maintains any single nebula to be a star system of coordinate rank with the Milky Way."[17] If that sentiment was right, then the Milky Way was the universe. As late as 1922 when H. G. Wells ambitiously wrote *A Short History of the World*, it was still possible to think of the spirals as solar systems in the process of forming:[18]

> *"The telescope reveals to us in various parts of the heavens luminous spiral clouds of matter, the spiral nebulae, which appear to be in rotation about a centre. It is supposed by many astronomers that the sun and its planets were once such a spiral, and that their matter has undergone concentration into its present form."*

STANDARD CANDLES AND REDSHIFTS

If a "standard candle" were available, then the ratio of received flux to the candle's intrinsic luminosity would give a fairly accurate measure of the distance to it, thanks to the inverse square diminishment of light intensity. The first reliable standard candles were provided in 1908 by Henrietta Swan Leavitt, after working for four years with photographic plates from Harvard's new Arequipa observatory in Peru.[19] The plates carried images of light from Cepheid variable stars residing in the Small Magellanic Cloud. She reinforced her results with more data in 1912.[20]

All stars exhibit some mechanical vibrations, and several kinds of variable stars exist. Cepheid are massive, young stars that take this periodic swelling to such amplitudes that the oscillations in the star's surface area give its luminosity measurable periodicity. Cepheids are bright enough to probe intergalactic distances, and have periods that range from 2 to 40 days.[21] However, their average luminosities vary from star to star. For the 1908 paper, from the Arequipa plates Leavitt found and measured hundreds of variable stars. Of these she highlighted sixteen Cepheids for which she could say, "It is worthy of notice [that] the brighter variables have the longer periods." Her discovery of the period-luminosity relation of the Ceheids, with its subsequent tentative calibration via statistical methods by Henry Norris Russell[22], Einar Hertzsprung[23], Harlow Shapley,[24], and Ralph Wilson[25], released the brake on measuring deep space distances.

Compared to distance measurements, velocity measurements of nebulae were relatively robust. About 1912 Vesto Melvin Silpher, working with the 24-inch refractor at the Lowell Observatory, started measuring the spectra of several dozen spiral nebulae. Percival Lowell, the observatory director, expected these studies to show that spiral nebulae were indeed solar systems being formed.[26] But Silpher, who had previously analyzed the spectra of the planets, became convinced that the spirals were not planetary systems, but full-fledged galaxies, because their spectra were more like those of stars.

Silpher's spectra were also the first empirical evidence of a systematic redshift among the nebulae. By 1922 he had collected data from 41 nebulae. Of these, 36 showed redshifts, fractional stretches of wavelength that ranged up to $\Delta\lambda/\lambda \approx 0.006$. Only five nebulae showed blueshifts, the largest being Andromeda with $\Delta\lambda/\lambda \approx -0.001$. If these red and blue shifts were interpreted as Doppler effects due to relative motion between the source and our own system (and not due to other interpretations, such as Fritz Zwicky's "tired light" hypothesis), then to first order in velocity, the Doppler effect for light gives$\Delta\lambda/\lambda \approx v/c$. The dominance of redshifts suggested that the spirals, whatever they were, are not gravitationally bound to the Milky Way galaxy. The significance of this pattern

(continued on next page)

would become apparent after 1917, increasingly so throughout the 1920s, and would be understood as a *cosmological* redshift.

THE "GREAT DEBATE"

Scientific controversies are not settled by verbal debates, but by evidence. Nevertheless, a debate can be useful for focusing the issues. The National Academy of Science's annual William Ellery Hale Lectures featured for 1920 a "debate" between Harlow Shapley of the Mt. Wilson Observatory, and Heber D. Curtis of the Lick Observatory. Their topic was "The Scale of the Universe." The island universe model may have seemed far-fetched in 1890, but by 1920 much informed opinion was swinging in its favor.

In the 1920 Debate,[27] Curtis was the Kantian. He had spent much of his time at the Lick Observatory photographing and measuring the spirals. Shapley was the Laplacian. Using Leavitt's Cepheid variables—and several extrapolations beyond them—Shapley attempted to measure the size and shape of the Milky way, and obtained answers so large that he became convinced that the Milky Way was the entire universe. Among his extrapolations, on one end of the distance scales Shapley lumped RR Lyre stars (older periodic stars with pulsation periods less than a day) along with W Virginis stars (with periods similar to the Cepheids but different chemical compositions and ages)[28] into a single period-luminosity relation; on the other end of distance scale he valiantly attempted to use entire star clusters as standard candles. It would take Walter Baade and others, working into the 1950s, to sort out the different kinds of variable stars and complete separate calibrations for all of them.

Shapley argued that the Milky Way was essentially the Universe. He put its diameter at some 200,000 LY with the Sun about 65,000 LY from the center, with the globular clusters hovering about the center. Curtis cited for these dimensions about 32,000LY and 10,000 LY respectively (the modern value is over 100,000 LY for the diameter of the visible disc and roughly 25,000 LY for our distance from the center). The upshot was that Shapley's Milky Way was thought to be so enormous that it was essentially the entire Universe; at best the spirals were satellites of it. Curtis' universe, in contrast, shrank the Milky Way down to a size where it might be but one of many spiral nebulae. That two leading astronomers could come to quite different conclusions shows that the measurements were tedious and difficult, and filled with compounded uncertainties. Improved technology in the form of larger telescopes, and thus less ambiguous data, was just around the corner.

The ink was barely dry on Wells' 1922 book of world history when the new 100 inch telescope at Mt. Wilson saw first light. This instrument was able to resolve individual stars within some of the spiral nebulae. On the night of October 4, 1923, Edwin Hubble took another round of time exposures of the Andromeda spiral nebula, looking for novae, and confirmed when comparing that night's run to previous plates that Andromeda held a sample of Henrietta Leavitt's Cepheid variable stars.[29] Hubble's measurements and Leavitt's period-luminosity relation put the distance to Andromeda on the order of a million LY, an order of magnitude more remote than the outer regions of even Shapley's swollen Milky Way (modern, re-calibrated distance: ~2 MLY). The Kantian-Laplacian question of the spirals was settled. The spiral nebulae were galaxies.

Hubble's paper reporting the results was read by Henry Norris Russell at the December/January 1924-25 meeting of the American Association for the Advancement of Science. *The New York Times* beat the peer-reviewed journals to press with an article on November 24, 1924 that said, "Dr. E. Hubble confirms view that spiral nebulae are stellar systems." Before the AAAS meeting, Hubble broke the news to Shapley in a letter. Cecilia H. Payne-Gaposchikin recalled being in Shapley's Harvard office when the letter arrived. Shapley held it out to her and said, "Here is the letter that destroyed my universe."[30] Hubble's student Allan Sandage would later recall, "What are galaxies? No one knew before 1900. Very few people knew in 1920. All astronomers knew after 1924."[31]

RETURN TO EINSTEIN AND 1917

Whether the universe was a "gas" of individual stars or of nebulae, in 1917 the boundary conditions at infinity and cosmological kinematics were still open questions. At the largest scales the distribution seemed to be reasonably isotropic and homogeneous. As we will discuss in the next installment of this series, Newtonian gravitation was wonderfully inconsistent with the cosmological boundary conditions at infinity. The redshift measurements of the time gave speeds small compared to light, suggesting the contents of the universe to be static in the main. Seeking consistency with contemporary data, in his 1917 cosmology Einstein took his model universe to be static, homogeneous, and isotropic. Most remarkable, Einstein solved the problem at infinity by abolishing infinity, by postulating a spherical closed geometry! However, to his chagrin he found that to make the model work he had to modify his original equations by introducing a "cosmological constant," Λ, that effectively opposed gravity to maintain a static universe. The 1917 paper[32] started a discussion that, through the work of mathematicians and astronomers in Russia, England, Belgium, America, and England, and elsewhere, led by 1930 to an observational and theoretical understanding that the universe is expanding.

After the expansion of the universe was discovered, Einstein urged that Λ be dropped and his equations restored to their pristine form. However, Λ could not be so jauntily dismissed. A nonzero Λ remains a *logical* possibility within GR, thereby allowing the *most general* version of the field equations. But Λ remains an enigma: what principle determines its value? If nonzero, must Λ be a *fundamental* constant, or could some non-gravitational physics produce an *effective* Λ?

As a serious contender for the latter, consider that most of the universe is "empty" space, or "vacuum." The vacuum, practically by definition, has zero energy density. But according to quantum theory, "zero" means only that the *average*

(continued on next page)

energy vanishes—there are always statistical fluctuations about the average. They would arise through the continual production and annihilation of virtual particle-antiparticle pairs. If these statistical processes endow the energy density of the vacuum with a nonzero variance, in an expanding universe it would eventually dominate the cosmic energy density budget. These vacuum fluctuations could provide an *effective* cosmological constant.

Unfortunately for our present understanding, all attempts to *calculate* an effective Λ from quantum theory give answers that are ridiculously larger than observational limits on Λ allow. This dilemma must be taken seriously today because two independent lines of recent research lead to the conclusion that a non-zero Λ, or something mimicking it, seems to account for about 70 percent of the energy density of the universe! This exciting development reveals a crisis of incompatibility between GR and quantum theory, which separately have proved to be our most successful theories. In our next article we return to 1917 and see how Λ entered cosmology.

ACKNOWLEDGMENTS

Any short telling of a topic as rich in personalities and events as the history of cosmology will skim the surface at best. I am indebted to Professor Virginia Trimble for priceless suggestions, criticisms, and much-appreciated advice.

REFERENCES

[1] For a comprehensive comparison of GR to evidence see Clifford Will, *Theory and Experiment in Gravitational Physics* (Cambridge, 1981, 2000). Gravitational wave interferometers are now being realized; see the Fall 2005 *Radiations* which describes how your screen saver can help analyze LIGO data. The Gravity Probe B experiment, measuring the geodetic and frame-dragging effects on orbiting gyroscopes, released initial results earlier this year; see http://einstein.stanford.edu/ .
[2] Galileo Galilei, *Siderus Nuncius* (1610), Tr. by A. van Helden (Univ. of Chicago, 1989), p. 62.
[3] Newton in the *Principia*, quoted by E. R. Harrison, *Cosmology* (Cambridge, 1981), p. 10.
[4] J. D. North, *The Measure of the Universe: A History of Modern Cosmology* (Dover, 1965), Ch. 1; see also Charles W. Misner, Kip S. Thorne, and John A. Wheeler, *Gravitation* (Freeman, 1973), p. 756; and Edward Harrison, "Olbers' Paradox in recent times," *Modern Cosmology in Retrospect*, edited by B. Bertotti, R. Balbinot, S. Bergia, and A. Messina (Cambridge, 1990), p. 33.
[5] J. D. North, *The Measure of the Universe: A History of Modern Cosmology* (Dover, 1965), p. 3 offers a brief survey. The original sources are E. Swedenborg, *Principia Rerum Naturalium* (Dresden, 1734), tr. by J. R. Rendall and I. Tansley as *The Principia* in two volumes (London, 1912); T. Wright, *An Original Theory, or New Hypothesis of the Universe, founded upon the Laws of Nature, etc.* (London, 1750); I. Kant, *General Natural History and Theory of the Heavens* (1755), tr. by W. Hastie (Glasgow, 1900); J. Lambert, *Kosmologischen Briefe* (Augsburg, 1761). See also the collection of Bertotti et. al, ref. 4.
[6] North, ref. 6, Ch. 1. For biographies of the Herschels see M. A. Hoskin, *William Herschel and the Constructions of the Heavens* (Oldbourne Press, 1964) or C. A. Lubbock, *The Herschel Chronicle* (Cambridge, 1933).
[7] North, p. 7.
[8] Kant :Bef http://www.friesian.com/kant.htm#note-1 .
[9] Swedenborg suggested a similar idea a few years earlier; cf. North, p. 7.
[10] George Johnson, *Miss Leavitt's Stars: The Untold Story of the Woman Who Discovered How to Measure the Universe* (Norton, 2005), p. 59.
[11] P. S. Laplace, *Mécanique Céleste*, in five volumes, 1799-1825.
[12] North, p. 4.
[13] Bessel was the first to publish a triangulation parallax result. That same year Thomas Henderson, working at the Cape of Good Hope, measured the parallax of Alpha Centauri; and Friedrich Struve in Russia measured a parallax for Alpha Centauri and Vega. See George O. Abell, David Morrison, and Sidney C. Wolff, *Exploration of the Universe*, 6th ed. (Saunders 1993) Ch. 21; also North (ref. 4.).
[14] V. Trimble, "The 1920 Shapley-Curtis Discussion: Background, Issues, and Aftermath," *Publications of the Astronomical Society of the Pacific* **107**, 1133-1144, Dec. 1995.
[15] *ibid.*; also North, p. 9.
[16] *ibid.*
[17] Johnson,, ref. 10, p. 60.
[18] H. G. Wells, *A Brief History of the World* (Macmillan, 1922) p. 5.
[19] H. S. Leavitt, "1777 Variables in the Magellanic Clouds," *Annals of the Astronomical Observatory of Harvard College*, **60**, No. 4, 87-108 (1908).
[20] Edward C. Pickering, "Periods of 25 Variable Stars in the Small Magallenic Cloud," *Harvard College Observatory Circular **173**.* Although this paper was published under the name of Pickering's name as the Director of the Observatory, the first sentence says, "The following statement regarding the periods of 25 variable stars in the Small Magellanic Cloud has been prepared by Miss Leavitt."
[21] See any introductory text; e.g., Abell et. al., (ref. 13), Ch. 29; Niel F. Comins and William J. Kaufmann III, *Discovering the Universe*, 5th ed. (Freeman, 2000), Ch. 11; Michael A. Seeds, *Horizons: Exploring the Universe*, 6th ed. (Brooks/Cole, 2000), Ch. 12.
[22] H. N. Russell, *Science* **37**, 651 (1913),
[23] E. Hertzsprung, *Astron. Nachr.* **196**, 201 (1913).
[24] H. Shapley, *Astrophysical Journal* **48**, 89 (1918).
[25] R. E. Wilson, *Ap. J.* **35**, 35 (1923); Ap. J. 89, 218 (1939).
[26] V. Trimble, "H_0: The Incredible Shrinking Constant 1925-1975," *Pub. Ast. Soc. Pacific* **108**: 1073-1082, Dec. 1996, p. 1076; also North, ref. 4, p. 142.
[27] For a thorough and lively account, see Trimble, ref. 14. Johnson, ref. 10, Ch. 6, provides an engaging synopsis.
[28] Cepheids are "Population I" and W Virginis stars are "Population II" stars.
[29] Hubble's colleague, Milton Lasell Humanson, may have been the first to detect Cephids in M31, while Shapley was the Mt. Wilson director. See refs. 26 and 17.
[30] Trimble, ref. 14, pp. 1142-1143.
[31] Johnson, ref. 17, p. 98.
[32] A. Einstein, "Cosmological Considerations on the General Theory of Relativity," pp. 177-188 in the Dover reprint of original papers by Einstein, Lorentz, Weyl, and Minkowski: *The Principle of Relativity*, tr. by W. Perrett & G. B. Jeffrey (Dover, 1952). The original article appeared as "Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie," in *Sitzungsberichte der Preussischen Akad. d. Wissenschaten*, 1917.

◆