CHAPTER 13

Revolutionizing Cosmology

WE TEND TO take the modern view of the cosmos and our place in it very much for granted. Modern astronomers regard the planet Earth as being an undistinguished planet, orbiting a fairly unremarkable star on the outer fringes of an unexceptional galaxy—one of an indefinitely large number of galaxies in an indefinitely large universe. In the words of Monty Python in *The Meaning of Life*:

> Our galaxy itself contains a hundred billion stars.
> It's a hundred thousand light years side to side.
> It bulges in the middle, sixteen thousand light years thick,
> But out by us, it's just three thousand light years wide.
> We're thirty thousand light years from galactic central point.
> We go 'round every two hundred million years,
> And our galaxy is only one of millions of billions
> In this amazing and expanding universe.

This view of the universe and of humans' place in it is, however, of very recent origin. Until the 1930s, there was no consensus among astronomers concerning the size and shape of the Milky Way (our own galaxy) or the planet Earth's position within it. There was no consensus over the question of either whether the Milky Way was a unique structure in the universe or whether other galaxies even existed. According to one astronomer at least, "the realization . . . that our galaxy is not unique and central in the universe ranks with the acceptance of the Copernican system as one of the great advances in cosmological thought" (Berendzen, Hart, and Seeley 1976).

From this perspective, then, the emergence of the modern view of the cosmos ranks as a scientific revolution comparable to one of the defining events of the Scientific Revolution itself. There are certainly parallels between the change in perspective entailed by the development of modern cosmology and the Copernican revolution—as it has traditionally been portrayed, at least. Copernicus challenged late medieval presumptions about humanity's place in the cosmos by removing the earth from the center of the universe. Modern cosmology completed the task and removed the last vestiges of human uniqueness by relegating even the galaxy that we inhabit to the backwaters of the universe. There are certainly senses in which this twentieth-century cosmological revolution might be taken as a classic case study of a Kuhnian scientific revolution. In particular, as we shall see, it illustrates Kuhn's point concerning the subjectivity of observational evidence. Astronomers engaged in debates about the size and shape of the universe interpreted data differently depending on their various views of what the cosmos was really like, just as Kuhn suggests that different observers with different views as to what is "really there" might see either a duck or a rabbit in the same picture (Kuhn 1962). It is also a good example of more recent sociological points concerning the importance of issues such as training, institutional affiliation, and personal relationship in the resolution of scientific controversies (Barnes 1974; Collins 1985).

As we have seen earlier, the predominant ancient Greek view of the universe was that it was finite, with the earth as its center and bounded by the sphere of fixed stars. By the late Middle Ages and Renaissance, this picture was coming under increasing attack with the advent of Copernicus's heliocentric system. As far as Newton was concerned, space—and therefore the universe—was infinite. During the eighteenth and nineteenth centuries, a range of opposing views concerning the structure of the universe was developed. Some, like Immanuel Kant, argued that nebulae represented other galaxies like the one in which the earth was located. Others argued that nebulae were clouds of gases from which other solar systems like our own would eventually develop. During the second half of the nineteenth century, new tools such as photography and spectroscopy were used to look deeper into space and to identify the elements that made up celestial objects. By the first decades of the twentieth century, arguments concerning the size and shape of the universe hinged on different views concerning the nature and distance of nebulae. The consolidation of Einstein's new theory of general relativity during the 1910s and 1920s also had important ramifications for arguments concerning the size of the cosmos. Einstein reckoned that he could use his relativistic field equations to understand the geometrical structure of space and time. Einstein's universe was static. Others disagreed, suggesting that evidence showed the universe to be expanding.

By the middle of the twentieth century, two opposing models of an expanding universe had been developed. According to one view, it was possible to use observations of the universe's rate of expansion to extrapolate back through time to the universe's beginnings. This was what came to be known as the "Big Bang" theory of the universe. Big Bang proponents argued that all the matter currently in the universe was originally concentrated at one point. It was the explosion and subsequent expansion of that point—the original Big Bang—that had brought the modern cosmos into being. Opponents of the Big Bang, such as the British astronomer Fred Hoyle, argued that the universe had no discrete beginning. It had always existed and would continue to exist indefinitely. New matter was continually being produced throughout the universe to fuel its steady expansion. This was the "steady state" model of the universe. By the closing decades of the twentieth century, however, the Big Bang model of the universe was increasingly dominant. In accounts of the universe, the modern cosmos was described as being populated by bizarre entities like black holes, pulsars, and wormholes. By the end of the twentieth century, new technologies had been developed that allowed astronomers to claim to be able literally to see back to the very beginnings of the cosmos. New observations meant that new concepts such as "dark matter" and "dark energy" were needed to fill in the gaps in the cosmological picture.

The Shape of the Universe

Is the universe something that can meaningfully be said to have a shape or a size? According to ancient Greek views of the cosmos, the answer would presumably have been yes. The universe was spherical, with the earth at its center and the orb of fixed stars as its outer boundary. As this basic Aristotelian model of the universe was adopted and adapted in medieval Europe, outside the sphere of the fixed stars was Heaven. By the end of the Scientific Revolution and the gradual adoption of first Copernicus's heliocentric universe and then Kepler and Newton's views of the mechanism of the heavens, the crystalline celestial spheres had long been abandoned as real physical entities (Kuhn 1966). By the middle of the eighteenth century, astronomers were largely agreed that Sir Isaac Newton's theory of gravitation provided the best explanation for the movements of celestial objects. Newton's universe was infinite, absolute, and unchanging. It had come into being at the moment of creation. It had no boundaries of any kind, it simply stretched to infinity. Beyond the confines of the earth's own system, where the earth along with the other planets orbited around the central sun, there was nothing except the stars, distributed more or less uniformly and in infinite numbers. From this perspective, it was certainly not at all clear that questions about the shape and size of the universe made any kind of sense at all.

In 1750, however, the Englishman Thomas Wright published *An Original Theory or New Hypothesis of the Universe*, in which he proposed a specific structure for the universe. In Wright's model, the universe consisted of two concentric spheres with the stars sandwiched between them. At the center of the universe was the throne of God. Wright had observational evidence to support his model. The highly luminous band of stars visible in the night sky—the Milky Way—was the result of looking along the tangent of the spheres. The German philosopher Immanuel Kant, better known as the author of the *Critique of Pure Reason*, published his *Universal Natural History and Theory of the Heavens* in 1755, in which he argued that the Milky Way was only one of a number of similar "island universes" scattered throughout the cosmos. Having read a slightly ambiguous account of Wright's theory, he understood him as suggesting that the Milky Way was a disk of stars seen lengthways and adopted the suggestion. When the Anglo-German astronomer William Herschel—famous for his discovery of the planet Uranus—started mapping the heavens with his powerful new telescopes and identifying a number of glowing stellar clouds, or nebulae, in the skies, these were often identified as being island universes. Herschel himself originally agreed that nebulae were extragalactic systems of stars but later observations led him to doubt the claim (Hoskin 1964).

The compendious observations of nebulae made by William and Caroline Herschel provided important evidence for a theory of the solar system's origins that became increasingly popular in some astronomical circles during the first half of the nineteenth century (Hoskin 2011; Winterburn 2017). The so-called nebular hypothesis put forward by the French physicist Pierre-Simon Laplace argued that nebulae were massive clouds of gaseous matter that formed the birthplaces of stars and planets. The swirling clouds of gases gradually coalesced over time, forming clumps of matter orbiting around a central mass. These eventually evolved into planets orbiting a star. The nebular hypothesis was particularly popular in Britain, where it was advocated by such radical popularizers as John Pringle Nichol and Robert Chambers. In his notorious *Vestiges of the Natural History of Creation* published in 1844, Chambers used the nebular hypothesis to argue that the universe was in a state of continuous evolution and progress, suggesting that the same applied to human beings and their societies. The nebular hypothesis depended on the claim that nebulae were clouds of stellar gas rather than collections of stars. The Anglo-Irish astronomer Lord Rosse, during the 1840s, famously used the enormous seventy-two-inch reflecting telescope built at Birr Castle, his Irish family seat, to resolve the Orion Nebula into its constituent stars in an effort to disprove the nebular hypothesis (fig. 13.1). Despite Rosse's efforts, however, doubts remained as to whether all nebulae could be resolved into collections of stars or whether some were "true" nebulae made up of clouds of gases (Jaki 1978).

Developments in photography and spectroscopy during the second half of the nineteenth century also provided new ammunition for ongoing debates about the true constitution of nebulae and other celestial objects. Some astronomers hoped that photography might be able to capture features of distant objects in the night skies that fallible human eyes might miss or misinterpret. Chemicals reacting to light might prove more sensitive than mere eyesight and provide a permanent and objective record of what was really there. They might be able to distinguish between clusters of stars and clouds of gases in a way that human senses could not. Spectroscopy, the other addition to astronomers' armory during this period, had its origins in the observation that different substances burned with different colors or gave off differently colored electric sparks when used as electrodes. When such light was viewed through a prism it gave a spectrum unique to each particular element. The German instrument-maker Josef von Fraunhofer had also noted that light from the sun exhibited characteristic lines in its spectrum when viewed through a prism (Jackson 2000). By turning their spectroscopes on celestial objects and comparing the spectra they produced to those produced by terrestrial elements, astronomers could try to identify the elements that made up stars and nebulae. As we shall see below, by examining the shift in these spectral lines toward the red end of the spectrum (the so-called red shift), thought to be caused by light sources moving away from the earth, astronomers could even come up with estimates of the speeds at which distant stars and other celestial objects

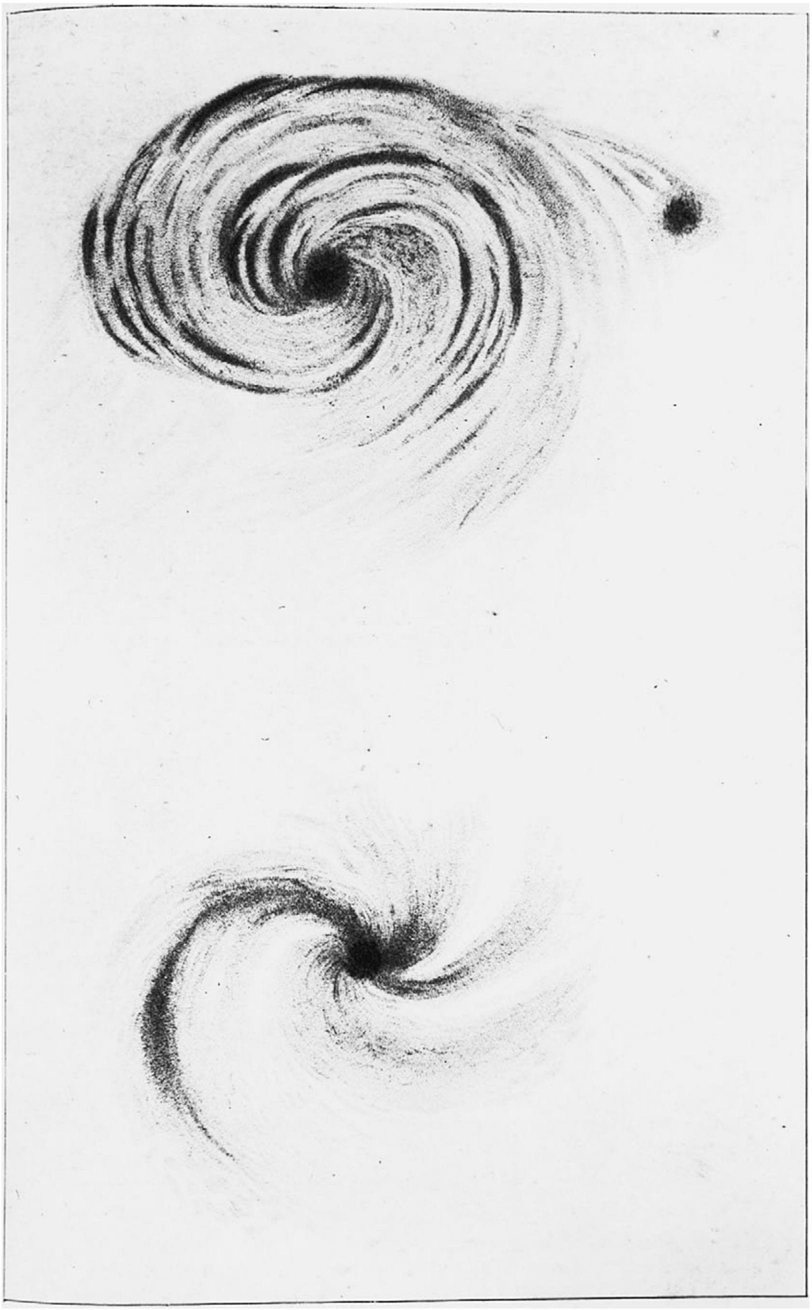

Fig. 13.1. Lord Rosse's depiction of a spiral nebula as seen through the Leviathan of Parsonstown.

were moving through the heavens. By the beginning of the twentieth century, photography and spectroscopy were standard tools of observational astronomy, vital to the task of distinguishing different kinds of objects in the night skies (Becker 2011).

During the first few decades of the twentieth century, there were two dominant and competing theories concerning the nature of nebulae, both of which had important implications for astronomers' views concerning the size and shape of the universe. According to one view, at least some nebulae—particularly spiral nebulae—were galaxies similar to our own Milky Way. According to the other view, nebulae were dense clusters of stars or gaseous clouds within the confines of the Milky Way. In deciding between these two opposing views, much rested on astronomers' differing views concerning the size of the Milky Way, the solar system's position within it, and the distances between the solar system and the various nebulae. Matters came to a head in a famous encounter in Washington, DC, in 1920—the so-called great debate—between Harlow Shapley of the Mount Wilson Observatory and Heber D. Curtis of the Lick Observatory. Shapley argued that our own galaxy was of a massive size, about 300,000 light years in diameter, with the galactic center about 65,000 light years from Earth. Globular star clusters and spiral nebulae were part of the galaxy and did not constitute separate systems of stars. Curtis, in contrast, argued for a considerably smaller local galaxy (about 30,000 light years in diameter) and suggested that spiral nebulae were best understood as distant galaxies. The "great debate" did little to resolve the issue. Debate concerning the size and structure of the universe continued throughout the 1920s and beyond (Smith 1982).

Both sides in the debate could point to quantities of observational evidence supporting their respective positions. Much depended on various estimates of the distances of the different celestial features from Earth. There was, of course, no direct way of measuring such distances, so astronomers typically made use of a range of approximations based on features such as the apparent magnitude (brightness) of stars of different types and the appearance of their spectra. In the early 1920s it did look, however, as if the key piece of evidence was in the hands of those who opposed the theory that nebulae (or at least some nebulae) were separate galaxies. The Dutch astronomer Adriaan van Maanen claimed that he could identify "proper motion" on the part of components of spiral nebulae. Van Maanen was a highly respected observational astronomer working at the prestigious Mount Wilson Observatory (fig. 13.2) and had come to the conclusion that

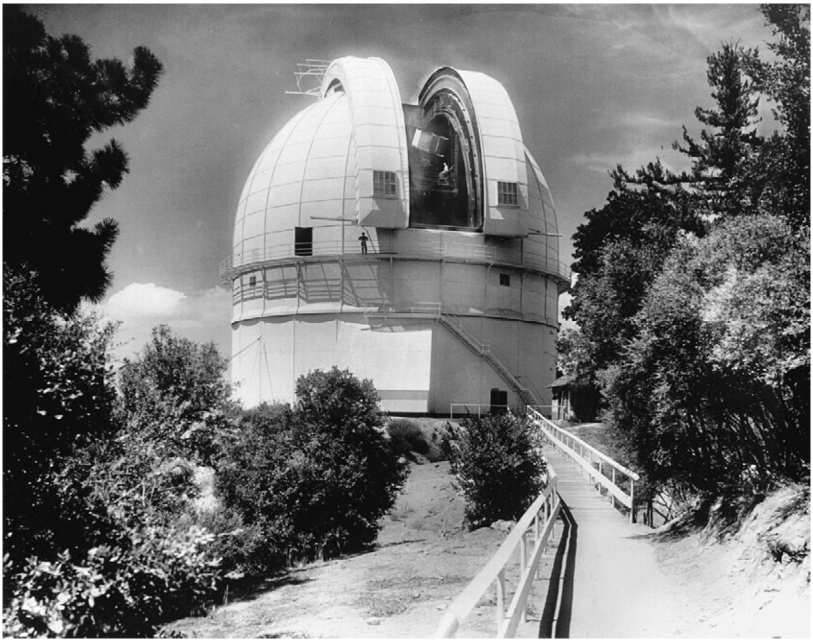

Fig. 13.2. Mount Wilson Observatory as it appeared in the early twentieth century. This is where many of the astronomical observations used to decide the size of the universe were made.

proper motion was detectable in the arms of spiral nebulae on the basis of careful comparison of nebular photographs taken over long periods. Opponents of the separate galaxies theory argued that if proper motions of this magnitude were detectable in objects as far away as the spiral nebulae were supposed to be by proponents of the theory, then the spirals' arms must be moving at speeds in excess of the speed of light. Such a proposition was clearly ridiculous, and the nebulae must therefore, in fact, be considerably closer, as required by those who argued that they were within the Milky Way itself.

Despite van Maanen's apparently conclusive evidence, proponents of the separate galaxies theory by and large stuck to their guns. In 1923, a new observation by the young American astronomer Edwin Hubble seemed to provide decisive evidence in their favor. Working at Mount Wilson Observatory (like van Maanen) and using what was then the world's most powerful telescope, Hubble identified a Cepheid variable star in the Andromeda Nebula. Previous studies of Cepheid variables by the Harvard astronomer Henrietta Swan Leavitt in 1908 had identified a constant relationship between the period of a Cepheid variable (the time between its moments of highest luminosity) and its luminosity. That meant that measurements of a Cepheid variable star's period could be used to gauge its absolute luminosity. Its absolute luminosity compared with its apparent luminosity (how bright it appeared in the night sky) could then be used to approximate its distance since different objects with the same absolute levels of brightness appear relatively less bright the further away they are. Hubble could therefore use his discovery of a Cepheid variable in the Andromeda Nebula to calculate its approximate distance. He calculated this distance as about 300,000 parsecs (a parsec being 3.26 light years)—much farther than van Maanen or Shapley argued. At distances like these it seemed inconceivable that nebulae like the Andromeda Nebula could be part of the Milky Way galaxy (fig. 13.3).

Astronomers were left with two apparently highly trustworthy sets of observations that were nevertheless contradictory. If van Maanen was to be believed, his measurements of the internal proper motions of spiral nebulae indicated that they must be relatively nearby (fig. 13.4). If Hubble, on the contrary, were to be believed, spiral nebulae like the Andromeda Nebula were well outside the plausible boundaries of the Milky Way. By the end of the 1920s, most astronomers agreed that the separate galaxy theory—the "island universe" hypothesis, as it was known—had won the day. They found Hubble's Cepheid variables more convincing than van Maanen's photographic evidence of proper motions. In the end, it was a matter of deciding what kind of observational evidence—and which individual astronomers—was to be considered most trustworthy.

The island universe model was also used as the foundation for yet another transformation of the traditional worldview. In studying the light coming from distant galaxies, astronomers noticed that the spectral lines (described above) were shifted toward the red end of the spectrum. The most obvious explanation of this was in terms of the Doppler effect, in which the frequency of a wave motion is affected by the velocity of the body emitting the wave (in the case of sound, this produces the familiar drop in tone when a whistling train passes by an observer standing by the track). This explanation of the "red shift" implied that galaxies are receding from us. In 1929, Hubble went further by proposing a law governing the relationship between the distance of a galaxy from the earth and its velocity of recession. Not only did we live in an expanding universe, but the more distant are the galaxies we see, the faster they are moving away from us.

By the 1930s, astronomers were therefore largely agreed about the size

Fig. 13.3. An early twentieth-century photograph of a distant nebula.

and shape of the universe and had begun to see it as a dynamic, not a static, system. The Milky Way was recognized as being only one among a huge number of similar galaxies, with the earth and its solar system located near the outer rims of one of its spiral arms. Not even the galaxy that human beings inhabited was any longer to be considered as the center of the universe. From that perspective, the transformation might certainly be regarded as truly revolutionary in the same sense that the Copernican revolution was. Whether the participants in the debate saw matters in the same apocalyptic terms is another question.

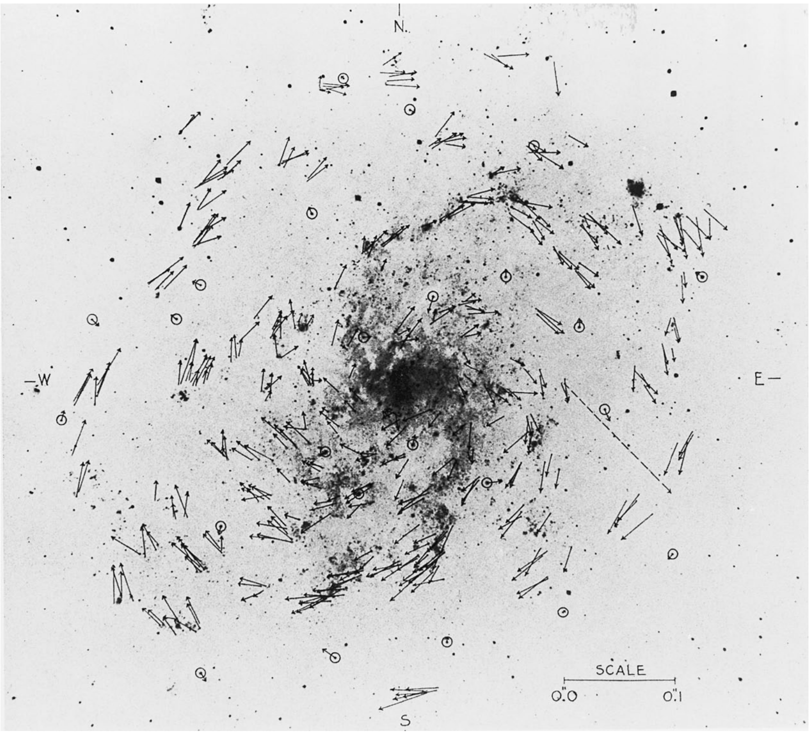

Fig. 13.4. Van Maanen's observations of internal nebular motions.

Einstein's Universe

New observational technologies and techniques were not the only source of insight into the shape of the universe. New theoretical developments in physics at the beginning of the twentieth century also had a major impact on the way in which astronomers understood the cosmos. As we have already seen, many historians of physics have characterized the changes that took place in physics at the beginning of the twentieth century as being revolutionary. The traditional worldview associated with Newton was swept away and replaced with a new, relativistic physics (see chap. 11, "Twentieth-Century Physics"). The view of space and time as being absolute regardless of the observer's position and velocity was abandoned and replaced with the standpoint that time and space were relative to the position and velocity of the observer. The key figure in this transformation was the German physicist Albert Einstein. Einstein's special theory of relativity, published in 1905, and the general theory of relativity (dealing with accelerating systems) published a decade later had a profound impact on the new discipline of theoretical physics. The implications of Einstein and his followers' views for understanding the structure of the universe were quickly recognized by astronomers (Pais 1982). After all, two of the key pieces of evidence for the theory of general relativity—the anomalous shift in the perihelion (nearest point to the sun) of the planet Mercury and the observed bending of light during an eclipse found by the astronomer Arthur Eddington—were themselves astronomical in nature.

Einstein himself quickly recognized that his theories had important implications for the ways in which astronomers understood the universe. In the years following his announcement of the general theory of relativity, he worked at finding solutions to his relativistic field equations that would provide a stable description of the universe's structure. The universe as described in Einstein's field equations had a non-Euclidean geometry. In other words, it did not follow the classical geometric laws whereby, for example, a straight line is always the shortest distance between two points. Einstein's space was curved. The solution to Einstein's field equations was a finite, unbounded four-dimensional space. This can be understood by analogy with a three-dimensional sphere. An entity living on the surface of such a sphere would, if it traveled for long enough in the same direction, arrive back at its point of origin. It would also be possible, in principle, to traverse every point on the sphere's surface. That surface must therefore be finite. At the same time, at no stage would the entity encounter a boundary, so the surface is also unbounded. According to Einstein, this was the way the universe was in four dimensions. Einstein was also firmly convinced that the universe must be static—unchanging in its structure. He therefore introduced an extra component—the cosmological constant—into his field equations to ensure this feature. Einstein famously later described the cosmological constant as the greatest mistake he had made in physics.

Not everyone was satisfied with Einstein's solution to his field equations. In 1917, the Dutch astronomer Willem de Sitter proposed an alternative geometric model of the universe but one that also obeyed Einstein's relativistic field equations. After studying at the University of Groningen, de Sitter had spent several years working at the Royal Observatory at the Cape of Good Hope in South Africa before returning to the Netherlands and eventually becoming professor of astronomy at Leiden University in 1908. His main research interests lay in celestial mechanics, but from 1911 on, he became increasingly interested in the astronomical implications of the theory of relativity. Unlike Einstein's universe, the model that de Sitter proposed was infinite. Its equivalent in three dimensions would be a saddle shape stretching to infinity in each direction. Like Einstein, de Sitter was convinced that any model of the universe must be static. In order to maintain this characteristic in his model he had to assume that the universe contained no matter. Clearly, the real universe did not obey this assumption, but de Sitter argued that the overall density of matter in the universe was sufficiently low for his model to provide a reasonable approximation. Einstein was particularly worried by this feature of de Sitter's solution to his equations. The suggestion that a massless universe was possible seemed to him to imply that space itself had absolute properties — a view at odds with his own interpretation of relativity theory.

De Sitter's model of the universe had one feature in particular that caught the interest of some astronomers, particularly the British astronomer Arthur Eddington. If atoms were introduced into this mathematical model at large distances from each other, it seemed that, as a result of time dilation, any light emitted by them would appear to an observer as being of lower frequency than it actually was. Translating this into the real universe, the suggestion was that light from distant sources would appear to be shifted toward the red end of the spectrum. Similarly, it seemed that point masses inserted into this hypothetical mathematical universe would spontaneously begin to accelerate away from each other as a result of the cosmological constant that de Sitter, like Einstein, had inserted into his equations. In his *Mathematical Theory of Relativity* published in1923, Eddington suggested that these features of de Sitter's model might be useful in solving the problem of the large radial velocity (apparent velocity away from the earth) of many spiral nebulae. In the first place, de Sitter's model would explain the apparent movement as the result of the general tendency of matter in his model to move away from each other. In the second place, estimates of radial velocity were usually based on measurements of the shift toward the red end of the spectrum (red shift) of distant objects as the result of velocity. If de Sitter was right, then some, at least, of that observed red shift was the result of distance and time dilation, rather than velocity, so the spiral nebulae were not really moving away at such large velocities after all (Smith 1982).

Eddington also made another observation on de Sitter's model: "It is sometimes urged against de Sitter's world that it becomes non-statical as soon as any matter is inserted in it. But this property is perhaps rather in favor of de Sitter's theory than against it." Eddington was starting to move toward the position that the universe might be expanding rather than static. In 1929, the American astronomer Edwin Hubble (fig. 13.5) presented a

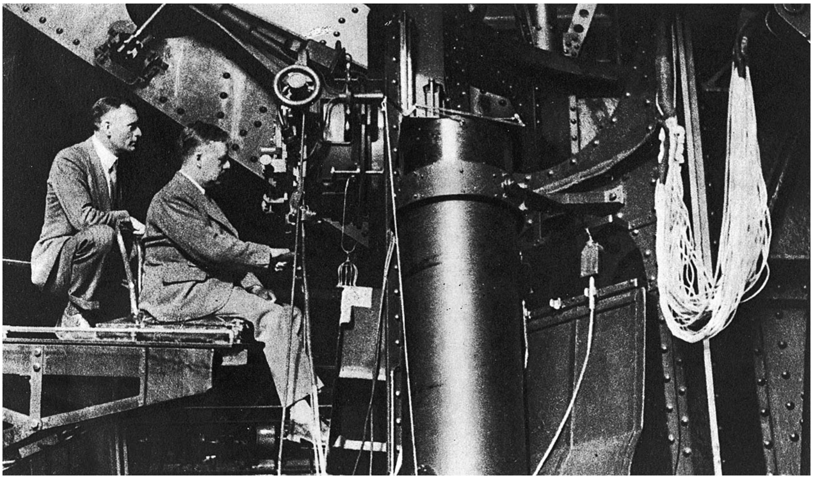

Fig. 13.5. Edwin Hubble and James Jeans making astronomical observations. From *Fortune* (July 1932).

paper before the National Academy of Sciences demonstrating, on the basis of observations, a straightforward linear relationship between the radial velocity and the distance of spiral nebulae, the relationship now known as Hubble's Law. According to Hubble, he had embarked on the research leading to the new generalization at least partly as an attempt to test de Sitter's model of the universe. Most astronomers interpreted Hubble's Law as strong evidence in favor of an expanding rather than a static universe (Crowe 1994). Einstein was sufficiently concerned to visit Hubble at the Mount Wilson Observatory before announcing in 1930 that he had given up on the static universe and the cosmological constant that went with it. According to one story, when Einstein and his wife visited the observatory they were shown the telescopes, and it was explained to Einstein's wife that they were used to discover the structure of the universe. Elsa Einstein responded, "Well, well, my husband does that on the back of an old envelope" (Berendzen et al. 1976). The story may well be apocryphal, but it demonstrates nonetheless the growing intellectual and professional differences between theoreticians and observational astronomers and the different techniques they adopted to approach the same questions.

Big Bang or Steady State?

By the 1930s, astronomers and physicists increasingly agreed that the universe appeared to be expanding. This was what Einstein's relativistic field equations, shorn of the cosmological constant, appeared to suggest. It was also the conclusion that many drew from Hubble's observations of the relationship between the velocity and distance of spiral nebulae. Some theorists started suggesting that if the universe was expanding, then it must have had a discrete beginning. They argued that by extrapolating backward through time the universe's current rate of expansion it would be possible to arrive at a time when all the matter at the universe was concentrated at one point (Kragh 1996). The explosion of this point represented the origins of the universe. A mathematical model of a universe expanding from a single point had been put forward by the Soviet physicist Alexander Friedmann in the early 1920s. Neither its author nor anybody else suggested, however, that the model was anything other than a mathematical curiosity. In 1927, the Belgian astronomer Georges Lemaître, a student of the British astronomer Arthur Eddington at Cambridge, before studying for a PhD at the Massachusetts Institute of Technology, did come up with a physical model of an expanding universe. It was not until the 1930s, however, that Lemaître's model was taken seriously. Lemaître suggested that the universe had started as a massive single atom. This single atom would have been highly unstable and would have broken up "by a kind of super-radioactive process" producing an expanding universe (Kragh 1996).

During the 1940s, another Soviet scientist, the nuclear physicist George Gamow, started working on his own version of the Big Bang theory of the universe and its origins. Gamow's interest in cosmology was prompted by his researches in quantum mechanics and nuclear physics. Gamow had made a name for himself in 1928 with his theory of quantum tunneling, explaining the emission of alpha particles from radioactive matter. Along with colleagues such as Fritz Houtermans and Robert Atkinson, Gamow soon concluded that his quantum tunneling theory could also be used to help understand nuclear processes taking place inside stars. Particularly after the discovery of new subatomic particles during the early 1930s, the stars increasingly came to be regarded as testing grounds for new theories in nuclear physics (see chap. 11, "Twentieth-Century Physics"). During the 1940s, Gamow was concerned to produce a theory that would account for the origins of the heavy elements, and since it seemed increasingly unlikely that they could have been produced inside stars, he turned to the Big Bang for an alternative scenario. Gamow first suggested that the universe had originally consisted of a cold (comparatively speaking) and thick soup of neutrons that expanded, forming more complex configurations that eventually produced the known chemical elements through the emission of beta radiation. In 1948, along with Ralph Alpher and Hans Bethe, Gamow submitted a revised version of his Big Bang theory to the *Physical Review* (the so-called *αβγ* paper). Bethe had in fact not made a significant contribution to the paper—his name was included in order to preserve the *αβγ* "joke." In this new version, the universe had started life as a hot and highly compressed neutron gas that had started decaying into protons and electrons, eventually producing the modern universe.

As far as many of its early promoters were concerned, one good reason for supporting the Big Bang theory of the universe's origins was its theological significance. While some, like Gamow himself, explicitly avoided theological arguments, others embraced them. Edward Arthur Milne, professor of mathematics at Manchester University and inveterate opponent of Einstein's theory of relativity, argued in 1947 that anything other than a universe created from a single point was a logical contradiction. Similar claims were made by the mathematician and historian of physics Edmund Whittaker, who argued that knowing that the universe had a distinct beginning in time proved the existence of God as the first cause of the universe. It is worth noting that Georges Lemaître, one of the first astronomers to produce a physical Big Bang theory, was himself a Catholic priest. In 1951, Pope Pius XII delivered an address to the Pontifical Academy of Sciences in which he explicitly appealed to the Big Bang theory of the universe as a scientific endorsement of the Catholic Church's position. According to the pope, there was nothing new for Christians in the latest cosmological theories. They were simply a restatement of the opening sentence of Genesis: "In the beginning God created heaven and earth" (quoted in Kragh 1996).

This kind of explicit linking of cosmological theory with religion provided at least one reason for the discomfort with the Big Bang theory felt by the advocates of an increasingly powerful alternative—the so-called steady state theory of the universe. Steady state theory was first put forward by three Cambridge graduates, Hermann Bondi, Thomas Gold, and Fred Hoyle, during the late 1940s, just as Gamow's theories concerning the Big Bang were taking shape. Hoyle, in particular, was an outright atheist who felt that religious views had no place in scientific discussions, and he argued that Big Bang theory only made sense in a religious context. According to Bondi, Gold, and Hoyle's new theory, the universe had always existed and always would. As the universe expanded, new matter was continually created to fuel the expansion. In two papers in the *Monthly Notices of the Royal Astronomical Society* in 1948, one by Hoyle and the other jointly authored by Bondi and Gold, they set out the principles of their new theory. In particular, they introduced what Hoyle called the "wide cosmological principle" and Bondi and Gold called the "perfect cosmological principle," stating that the universe was homogenous and unchanging on the large scale through both space and time. In 1949, Hoyle gave a series of radio broadcasts to the BBC in which he expounded his steady state theory. In 1950, the talks were published as a book, *The Nature of the Universe*, which sparked widespread controversy. Many astronomers felt that Hoyle's representation of the state of cosmology had been far too partial and favorable to his own steady state theory (Gregory 2005).

The controversial new steady state theory gathered only a few new supporters throughout the 1950s, particularly outside its promoters' own close-knit Cambridge circle. At the same time, supporters of the Big Bang theory found few new theoretical arguments that they could use to argue for their own theory's superiority. Many astronomers took little interest in these kinds of grand cosmological theories, taking the view that they had little relevance to the everyday astronomical business of observing and cataloging. Observationally, it seemed that there was little evidence available to help choose between the two theories. In the early 1960s, however, new measurements of the universe's background radiation seemed to Big Bang theorists to give their views of the universe's origins a decided edge. In 1961, the Cambridge radio astronomer Martin Ryle presented the results of the latest survey of extragalactic radio sources, suggesting that their range of energies supported a Big Bang rather than steady state view of the universe. Many supporters of the Big Bang (including Ryle himself) regarded this as the decisive nail in the coffin of the steady state theory. The steady state theory's advocates disagreed, suggesting that further refinement of Ryle's result would bring them back into line with steady state theory predictions. The discovery of quasars during the first half of the 1960s also seemed to pose a problem for the steady state theory. These stellar objects only seemed to exist at huge distances away in time and space—an observation at variance with steady state theory's assumption of the universe's homogeneity in time and space.

Textbook histories of astronomy and cosmology often present these observations from the 1960s as decisive refutations of steady state theory and triumphant vindications of the Big Bang. Historical reality is, of course, rather more complex. Most of the steady state theory's adherents—certainly its founding fathers—remained convinced that these were no more than local difficulties that would eventually be solved by way of further observational and theoretical refinements. Hoyle, for example, put forward an alternative theory concerning the physical nature of quasars that would allow them to be understood as local rather than distant objects. By the second half of the 1960s, however, steady state theory was an increasingly marginalized area with its proponents seeming increasingly at odds with the mainstream of their profession. The controversy has still not disappeared entirely. Hoyle and his advocates continued and still continue to argue in favor of the steady state. This episode is an instructive example of the historical and philosophical difficulties involved in identifying decisive events that exclusively determine the outcome of scientific debate. What Big Bang theorists regarded as increasingly desperate ad hoc measures to defend a bankrupt theory were regarded by their steady state opponents as simply further refinements of a highly productive and powerful theoretical framework and suggestions for further elaboration. By the end of the twentieth century, new and more refined observations of the universe's rate of expansion led Big Bang theorists to postulate the existence of "dark matter" and "dark energy" to account for the apparent mismatch between theory and observation. The term "dark matter," or *Dunkle Materie,* had been introduced as early as 1933 by the Swiss astronomers Fritz Zwicky in an effort to account for this sort of anomaly.

Black Holes and the Modern Cosmos

During the last quarter of the twentieth century, cosmologists succeeded in transforming their discipline into a popular science, though of course a strong tradition of popular cosmology had existed since at least the beginning of the century as well (see chap. 17, "Popular Science"). The process culminated in many ways with the publication of the theoretical physicist Stephen Hawking's *Brief History of Time* in 1988. For much of the century, even, most astronomers regarded cosmology—and theoretical cosmology in particular—as a highly esoteric subject, far divorced from the concerns of mainstream astronomy. According to one eminent astronomer during the early 1960s, "there are only 2½ facts in cosmology" (quoted in Kragh 1996). The two he had in mind were the observation that the night sky is dark and Hubble's observation of the recession of the galaxies. The half fact was that the universe was evolving. The joke was symptomatic of a widespread view among astronomers that the theoretical models hypothesized by cosmologists were based on very little hard astronomical evidence, and were therefore of little use in understanding known astronomical phenomena. From the early 1960s, there were an increasing number of new astronomical phenomena to understand, too, as astronomers turned to new technologies to examine the night skies. New techniques such as radio astronomy, itself based on surveillance and early warning systems developed during World War II, produced large amounts of novel information in need of theoretical interpretation (see chap. 21, "Science and War"). By the 1980s, the new view of a cosmos composed of various bizarre and hitherto unknown objects and areas where the known laws of physics came apart at the seams was catching the public imagination. It was helped on by a renewed vogue for popular TV science fiction such as the *Star Trek* series.

During the late 1950s and early 1960s, a number of astronomers reported observations of unusual starlike objects that appeared to have peculiar properties. In 1963, the Dutch astronomer Maarten Schmidt studied the spectrum of one of these objects and concluded that its light was redshifted to a high degree, indicating that it was at an immense distance. This also meant that the object must be putting out an enormous amount of energy. Further observations suggested the same to be the case with others of these "radio stars" that were soon renamed "quasi stellar sources," or "quasars" for short. The fact they all seemed to be at immense distances was itself, as we have seen, of theoretical significance, casting doubt on the viability of the steady state theory of the universe. Cosmologists also set about trying to understand what could be the source of the massive amounts of energy given off by these quasars. During the late 1960s another mysterious set of energetic objects was added to the cosmic population. In 1967 the Cambridge graduate Jocelyn Bell, working at Cambridge's radio astronomy observatory, noticed a series of regular but intermittent signals coming from an unknown source. She described them as flashing like a "Belisha Beacon" (the popular term for the flashing orange light at a British pedestrian crossing). After excluding all possible terrestrial sources of contamination (and some extraterrestrial ones, including the possibility of little green men), she and her PhD supervisor Anthony Hewish concluded that a hitherto unknown kind of stellar object, which they dubbed a "pulsar," emitted the signals. In 1974 Hewish and Martin Ryle, the head of Cambridge's radio astronomy observatory, received a Nobel Prize for their contribution to the discovery.

In 1968 the steady state theorist Thomas Gold suggested that pulsars could be explained as being rapidly spinning neutron stars. Theoretical cosmologists had predicted that entities such as neutron stars might exist as the result of stars of a certain size collapsing in on themselves under the influence of gravity as the outward push of their radiation was reduced over time. It was starting to look as if some of the stranger objects postulated by cosmologists might have observational equivalents in the real astronomical universe. In 1916 the German mathematician Karl Schwartzchild had proposed a solution to Einstein's relativistic field equations in which there were points where the curvature of space-time became infinite. At such points the force of gravity would also become infinite and no light could escape. Schwartzchild's speculations were regarded as interesting mathematical curiosities for the next several decades until, during the 1960s, the American physicist John Wheeler set out to investigate the circumstances in which they might exist in the real universe. In 1968, Wheeler coined the phrase "black hole" to describe a massive star that had hypothetically collapsed under the force of its own gravity and been compressed to such a degree that it formed a singularity of the kind described by Schwartzchild. The properties of such black holes became an increasingly important topic of theoretical research for a new generation of theoretical cosmologists such as Stephen Hawking, who first postulated the hypothesis that black holes might emit radiation in 1973 (Hawking 1988).

By the end of the 1980s, not only professional astronomers but large sections of the public as well were increasingly familiar with the cosmological menagerie of black holes, neutron stars, white dwarfs, and wormholes. Stephen Hawking's bestselling *Brief History of Time* was a major factor in this rise in public interest in cosmological theorizing. Hawking's bestseller was only the crest of a wave of similar titles, such as John Gribbin's *In Search of the Edge of Time* and P. C. W. Davies's *God and the New Physics*. Another factor was the (eventual) success of the Hubble space telescope, named after the pioneering astronomer Edwin Hubble and designed to transmit images of the distant universe of hitherto unparalleled clarity back to planet Earth. When the space telescope was first launched in 1990 by the American space agency NASA, astronomers soon realized that major design flaws in the reflecting mirror (it was the wrong shape) rendered it largely useless for the purposes for which it had been originally designed. Once those faults had been corrected, however, TV viewers in the Western world were bombarded by spectacular images of the faraway cosmos comparable to the fictional space vistas seen through the bridge viewer of *Star Trek*'s Starship Enterprise (Smith 1993, DeVorkin and Smith 2011)). The result was to make large parts of the once esoteric lexicon of theoretical cosmology part of the everyday vocabulary of significant sections of at least the European and North American public.

Conclusions

The universe was transformed beyond recognition during the course of the twentieth century. At the end of the nineteenth century, space and time were generally understood to be absolute categories, unchangeable and unvarying in their properties regardless of the position and speed of the observer. Few if any astronomers seriously considered the possibility of an universe that—in terms of its observable contents, at any rate—extended very far beyond those visible using the then existing technology. For all intents and purposes, the universe was synonymous with the Milky Way galaxy. This understanding changed radically during the twentieth century's opening decades. New techniques and technologies—as well as new theoretical worldviews—made it possible for astronomers to produce convincing estimates of stellar distances. The end result was a view of the Milky Way as only one relatively undistinguished galaxy among an innumerable host of others. Einstein's theory of general relativity brought new meaning to the question of the shape of the universe. Considerations drawn from Einstein's theories led theoretical cosmologists to think about the age and duration of the universe in novel ways. At about the same time, new observational evidence led astronomers to rethink their view of the universe as an unchanging, largely static entity. The universe as it entered the twenty-first century was a very different place, inhabited by very different beasts, from the one that began the twentieth century.

So to pose our familiar question, was this a revolution? In many ways it seems difficult to avoid the conclusion that, yes, it was. There can certainly be no doubt that a thoroughgoing overhaul of astronomers' understanding of the nature of the universe and humanity's physical place in it took place during the twentieth century. At the same time, however, the complexities of the history summarized here are an indication of the difficulties involved in imposing such a category on the past. While it may seem relatively obvious that a significant change did take place over the century or so covered in this chapter, it would be far harder to pinpoint any particular episode or point in time as the decisive moment. It would be just as difficult to identify any particular new theoretical insight or observational discovery or technique as being the decisive trigger for such a transformation in worldview as well. A full account of the transformation in cosmological understanding we have outlined here would need to look at developments in the institutions and professional structures of astronomy and physics as well as at changes in ideas and practices. We would need to look at the kind of training new generations of astronomers received and the material and cultural resources available to them. In short, if there was a cosmological revolution at all, we would need to understand it as a revolution in the culture of cosmology as much as a revolution in its content.

References and Further Reading

Barnes, Barry. 1974. *Scientific Knowledge and Sociological Theory*. London: Routledge.

Becker, Barbara J. 2011. *Unravelling Starlight: William and Margaret Huggins and the Rise of the New Astronomy*. Cambridge: Cambridge University Press.

Berendzen, R., R. Hart, and D. Seeley. 1976. *Man Discovers the Galaxies*. New York: Science History Publications.

Collins, Harry. 1985. *Changing Order*. London: Sage.

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

DeVorkin, David, and Robert Smith. 2011. *Hubble: Imaging Space and Time*. Washington: National Geographic.

Gregory, Jane. 2005. *Fred Hoyle's Universe*. Oxford: Oxford University Press.

Hawking, Stephen. 1988. *A Brief History of Time*. London: Bantam.

Hoskin, Michael. 1964. *William Herschel and the Construction of the Heavens*. New York: Norton.

———. 2011. *Discoverers of the Universe: William and Caroline Herschel*. Princeton, NJ: Princeton University Press.

Jackson, M., 2000. *Spectrum of Belief: Joseph von Fraunhofer and the Craft of Precision Optics*. Cambridge, MA: Harvard University Press.

Jaki, Stanley. 1978. *Planets and Planetarians: A History of Theories of the Origins of Planetary Systems*. Edinburgh: Scottish Academic Press.

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

Kuhn, Thomas S. 1962. *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press.

———. 1966. *The Copernican Revolution*. Chicago: University of Chicago Press.

North, John. 2008. *Cosmos: An Illustrated History of Astronomy and Cosmology*. Chicago: University of Chicago Press.

Pais, Abraham. *Subtle Is the Hand: The Science and the Life of Albert Einstein*. Oxford: Clarendon Press.

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

———. 1993. *The Space Telescope*. Cambridge: Cambridge University Press.

Winterburn, Emily. 2017. *The Quiet Revolution of Caroline Herschel: The Lost Heroine of Astronomy*. Stroud, UK: History Press.