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approach Earth more closely than any heavenly body except for the Moon. Observations of Eros enabled astronomers to compute more precise distances of the Sun and the planets. In the same manner, William Pickering (1858–1938) discovered the ninth satellite of Saturn.

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Astronomy and Cosmology: Twentieth Century

Craig Fraser

Cosmology and the Island-Universe Hypothesis

Scientific thinking in 1900 about the large-scale structure of the universe was concerned primarily with the status of something known as the *island-universe hypothesis*. With the advent of telescopic astronomy in the seventeenth century, observers began to detect many small cloudy or fuzzy objects in the sky called *nebulae* (from the Latin word *nebula*, cloud). In 1784, the French astronomer Charles Messier (1730–1817) made a systematic catalog of the nebulae and star clusters. He was interested in finding comets—objects in our solar system—and compiled his list so that comet hunters would not waste their time on the nebulae, which were frequently confused with comets. In 1755, Immanuel Kant (1724–1804), following the lead of Thomas Wright (1711–86), had suggested that the nebulae constituted countless island universes, such as our Milky Way system, but much more distant. Although Kant's writings were only speculative, he provided the first clear statement of the island-universe theory, and the idea of extragalactic nebulae was implanted in the minds of astronomers.

The construction of large telescopes in the nineteenth century brought new information about the detailed structure of nebulae. In 1850, the Irish astronomer and aristocrat William Parsons, the third earl of Rosse (1800–67), discerned with his large reflecting telescope (the "Leviathan of Parsonstown") that many of the very white nebulae possessed a definite spiral structure. One example is an object close to the Big Dipper numbered 51 in the Messier catalog. This object is observed from Earth face-on, and M 51 is sometimes called the *Whirlpool nebula*. Another very bright nebula that is observed more obliquely is M 31 in the constellation of Andromeda, often referred to as the great Andromeda nebula (see Figure 1). It may be sighted easily with the naked eye in the autumn from locations in the Northern Hemisphere. It turned out that the class of whitish nebulae possessing an oval or

Figure 1. Photograph of the Andromeda nebula M 31. © *Roger Ressmeyer/CORBIS*

spiral shape was very large indeed, involving myriad objects distributed throughout the sky in regions away from the band of the Milky Way.

Although the island-universe hypothesis continued to attract occasional adherents, it largely lost favor among astronomers as the nineteenth century came to a close. Several pieces of evidence counted against the hypothesis. First, as was noted above, the nebulae are not distributed randomly in the sky, but conglomerate in regions away from the band of the Milky Way. This *zone of avoidance* seemed to indicate that the nebulae were systemically connected to the Milky Way galaxy and were not independent objects distributed in distant space. In 1885, a new star, or *nova*, observed in the Andromeda nebula outshone the entire nebula for a short period of time. It was later realized that this star was a supernova, an incredibly energetic and short-lived event in which a massive star explodes. At the time, astronomers reasoned that the brightness of the Andromeda nova meant that it must be nearby, celestially speaking, certainly within the near vicinity of the Milky Way system. A final piece of evidence against the island-universe hypothesis emerged with the invention of stellar spectroscopy and the discovery that several of the nebulae showed prominent absorption lines, indicating that they were composed primarily of gas. It was later determined that such nebulae were of a special sort, called *planetary nebulae*, which are in fact the gaseous remnants of exploded stars fairly close to the Sun in the Milky Way galaxy. However, it was not apparent at the time that the nebulae were of such radically different types, and the existence of absorption lines in some of them was regarded as evidence that the nebulae as a class were not distant objects composed of an immense number of stars.

In 1887, Agnes Clerke (1842–1907), an influential American writer on astronomy, published *A Popular History of Astronomy during the Nineteenth Century*, in which she confidently rejected the island-universe hypothesis: "There is no maintaining nebulae to be simply remote systems of stars . . . . It becomes impossible to resist the conclusion that both nebular and stellar systems are parts of a single scheme." This conclusion was reiterated in 1907 by the German astronomer Max Wolf (1863–1932), who wrote: "The nebulae and clusters of stars represent an essential part of our star-island and perhaps lie relatively close to us. They all form, together with the stars of the Milky Way, an organic whole. Distant, isolated Milky Ways have never been sighted by man."

Observational discoveries in the first two decades of the twentieth century contributed to a revival of interest in the island-universe hypothesis. Curtis Heber (1872–1942) was an American classicist turned astronomer who carried out stellar research at the Lick Observatory in California. In studying photographs of nebulae, he noticed that many of those that were observed edge-on possessed an equatorial band of obscuring matter. If the Milky Way were such a system and itself possessed this obscuring matter, this fact would explain why no distant nebulae were observed in the band of the galaxy. The discovery by Vesto Slipher (1875–1969) in 1916 of very large radial velocities of spiral nebulae [discussed in more detail below] indicated to some astronomers that these objects were unlike anything within the Milky Way galaxy and must be extragalactic in nature.

Harlow Shapley (1885–1972) was a prominent U.S. astronomer who opposed the island-universe hypothesis. He believed that the visible universe was composed essentially of the Milky Way galaxy, which he reasoned was a very large object indeed, as many as 250,000 light-years across. Although many of Shapley's views were later shown to be in error, he made one fundamental and enduring discovery. Globular clusters, compact conglomerations of thousands of stars, are an important class of celestial object. One of these, Messier 13 (M 13) in Hercules, is visible to the naked eye in the summer sky from the Northern Hemisphere. Shapley reasoned on various grounds that the galaxy is framed symmetrically by globular clusters. Since most of these clusters are in fact observed on one side of the sky, it followed that Earth is not at the center of the Milky Way system but is located a considerable distance away from this center. This result, which turned out to be correct, was a striking confirmation of the principle that Earth occupies no special place in the universe.

At a meeting of the American Astronomical Society in April 1920, Shapley and Curtis engaged in a debate on the island-universe hypothesis and the status of the nebulae. Curtis staked out the claim that the white nebulae are autonomous distant galaxies of stars, much like Earth's own galaxy. In opposing this view, Shapley appealed to the work of the Mount Wilson astronomer Adriaan van Maanen (1884–1946). The latter had investigated spiral nebulae that we view face on. A prominent example is Messier 101 (M 101) in the constellation of Ursa Major. Van Maanen took photographs of M 101 and similar objects over successive periods of time and superimposed the resulting images. He was an expert in precision photographic measurement and believed that he had detected a rotational motion in the spiral arms, a result that would certainly be possible only if these objects were relatively close and relatively small. It would later be shown that the motions that van Maanen identified were illusory, a mistake in observation that arose because he was working at the very limits of measurement. Nevertheless, he was a prominent astronomer and a friend of Shapley's, and his conclusions were cited at the time as evidence against the island-universe theory.

Hubble and Extragalactic Nebulae

Although many people were impressed by Curtis's arguments in the debate with Shapley, there was no definite winner, and the question of the island-universe hypothesis was an open one in the early 1920s. The victory of this hypothesis followed from a new method of measuring celestial distances and from the construction of powerful telescopes that enabled this method to be applied to stars in distant space. In the period 1880–1910, a group of researchers at the Harvard Observatory under the direction of Edward Pickering (1846–1919) carried out an extensive program of photographic photometry, involving the measurement of the brightness of stars from the images they produced on photographic plates. Included in this survey were stars in the Magellanic

Clouds, which are visible as two patches of light in the southern sky and are resolved by telescope into two closely related systems of stars. The Harvard researchers, most of whom were women, measured the brightness of Magellanic stars recorded on photographic plates exposed at regular intervals at the Harvard observatory in Peru. A distinct class of these stars consisted of what are known as *Cepheid variables*, so-named after the prototype δ Cephei in the northern constellation of Cepheus. Such stars vary in brightness by about 0.5 to 2 magnitudes, with a period of anywhere from 1 to 15 days. One of the Harvard researchers, Henrietta Swan Leavitt (1868–1921), computed the relationship between period and brightness for a group of Magellanic Cepheid variables. She noticed that there was a direct relationship between period and brightness in which brightness increased with period according to a simple mathematical law. Leavitt's finding, which was published by Pickering in 1912, ranks as one of the signal discoveries in the history of observational astronomy.

The observed brightness of a star gives one no clear indication of its intrinsic or "absolute" brightness; it could be a luminous object that is very distant or a dim object that is very close. To determine the distance to a given star, one must know both its observed brightness and how bright or luminous it really is, its absolute luminosity. The stars in the Magellanic Clouds belong to a localized group all of which are at the same approximate distance from Earth. Viewed from Earth, the relative differences in their distances are very minor, so that the apparent brightness of a given star in the cloud compared to other stars in the cloud is also an indication of its relative absolute brightness. It follows that the relationship between period and observed brightness detected by Leavitt is also a relationship between period and absolute luminosity, how bright the star really is. In light of this fact, the German-Danish astrophysicist Ejnar Hertzsprung (1873–1967) pointed out that Leavitt's result could in principle be used to determine the distance to Cepheid variables located anywhere in the universe. From observations over time of a given Cepheid variable star, one could measure its period, and by means of the period-luminosity relationship, one then knew the star's absolute luminosity. Knowing this quantity, and knowing the observed brightness of the star, one could compute its distance. Cepheid variables therefore provided a yardstick to measure stellar distances. It was necessary to calibrate this yardstick, which meant knowing the distance to at least one Cepheid variable. In addition, it was later revealed that there are different types of Cepheid variables, and it was necessary to ensure that the Cepheid variable in question belonged to the class for which the yardstick was calibrated. Despite the sizable uncertainties introduced by these considerations, the discovery of the Cepheid distance method was a major leap forward in the scientific project of mapping the universe.

During the nineteenth century, the refracting telescope was the supreme instrument of astronomical investigation. In such a telescope, the image is formed through refraction of the light through a primary lens known as the *objective lens*. Although refractors provided very good resolution and were excellent for precision measurement, they were inherently limited in size, and their capacity to gather light was consequently restricted. In a reflecting telescope, by contrast, the light entering the telescope passes to a ground mirror, where it is reflected and focused to an image, which is then examined by a secondary lens system. The size of a reflecting telescope is typically designated by the diameter of its mirror. Reflectors could be built much larger, since one entire surface of the primary mirror could be supported structurally within the telescope assembly. In the period from 1900 to 1920, large reflectors were built on mountaintops in California and several other locations around the globe. A 36-inch (91.4-centimeter) reflector was established in 1898 at Lick Observatory on Mount Hamilton south of San Francisco and proved to be very effective for stellar photography. In 1908, a 60-inch (152.4-centimeter) reflector was built on Mount Wilson near Pasadena in southern California; this was followed in 1917 at the same location by a larger 100-inch (254-centimeter) reflector, the Hooker telescope. Financial support for the Mount Wilson facility was obtained by astronomer George Ellery Hale (1868–1938) from the philanthropist Joseph Hooker (and from the Carnegie Institution). In 1918, a 74-inch (188-centimeter) reflector was built at the Dominion Astrophysical Laboratory near Victoria, British Columbia, in Canada. The large reflectors benefited from improvements in glass technology and superior mounts. They were well suited to deep-space observation, in which the objects are very faint, and soon achieved complete dominance as the instrument of choice in stellar astronomy.

One astronomer to benefit from the expanding availability of powerful reflecting telescopes was Edwin Powell Hubble (1889–1953). Hubble was born into a middle-class American family, the son of a lawyer who worked in the insurance business. Upon completing high school in Chicago, he entered the University of Chicago, where he studied mathematics and astronomy. One of his professors was Hale, whose efforts had led in 1897 to the establishment of the Yerkes Observatory at Williams Bay, Wisconsin. Upon graduation, Hubble went as a Rhodes scholar to Oxford, where he studied law, excelling as well as a heavyweight boxer and track-and-field athlete. He returned to the United States in 1913 and, after a brief period as a practicing lawyer, went to the Yerkes Observatory to do graduate research in astronomy. His doctoral thesis in 1917 was titled "Photographic Investigations of Faint Nebulae." Following service in World War I, in 1919 he was offered a position as staff astronomer at Mount Wilson. There he trained the 100-inch (254-centimeter) reflector on the Andromeda Nebula [Messier 31 (M 31)] and was able to resolve a multitude of stars within it. Such was the power of this telescope that Hubble was able to identify a group of Cepheid variables within M 31 and accurately measure their periods of variation. These data immediately provided an indication of the distance of M 31 relative to nearby galactic Cepheid stars. By late 1924, Hubble had established that M 31 was an object outside our Milky Way, indisputably an extragalactic nebula. His discovery was announced at a historic meeting of the American Astronomical Association in early January 1925.

With Hubble's result, the astronomical community was largely won over to the island-universe hypothesis. For a time, Shapley still adhered to a modified version of his earlier position, the "big galaxy" model, in which the Milky Way was regarded as much larger than the spiral nebulae, the latter being exterior but essentially satellite-objects to it. Eventually, he abandoned even this claim, accepting the fact that the Milky Way is only one among the vast multitude of galaxies in the cosmos. He attributed his earlier belief to a misguided faith in van Maanen's measurements of spiral rotation.

Figure 2. Photograph of Arthur Eddington. © Hulton-Deutsch Collection/CORBIS

General Relativity

The theory of general relativity is a theory of gravitation; the gravitational force, being the only fundamental force that acts effectively over large distances, is of paramount interest for the science of astronomy. General relativity has proved to be the most successful theory for describing the large-scale gravitational interaction of matter in the universe. It originated during the years 1905 to 1916 as a mathematical attempt by Albert Einstein (1879–1955) and Marcel Grossmann (1878–1936) to extend the special theory of relativity, published by Einstein in 1905, to inertial and gravitational physics. The basis of the theory consists of what are known as the *field equations*, describing gravity in terms of the geometrical properties of space and time. One of the predictions of the theory is that light should bend near massive bodies, a prediction that was apparently confirmed in 1919 by the British astronomer Arthur Eddington (1882–1944).

Scientific Method: Eddington's 1919 Eclipse Expedition

One of the predictions of Einstein's general theory of relativity concerned the bending of light in a gravitational field. Light coming from a star near the edge of the Sun will experience a small deflection as a result of the Sun's gravitation. Newtonian theory also predicted such an effect, but according to relativity theory the deflection is larger, about twice the Newtonian value. Observations of stars near the Sun should therefore provide a crucial test to distinguish between the two theories. Unfortunately, the only time it is possible to see stars close to the Sun is during a total eclipse.

In 1919, the English astronomer Arthur Stanley Eddington led an expedition to test Einstein's prediction. The path of totality of the eclipse on May 29 passed from West Africa southwest to South America. Eddington and a colleague voyaged to the island of Principe in the Gulf of Guinea off the coast of Africa, while another team of scientists travelled to Sobral in northern Brazil. Photographic plates were exposed during the eclipse and compared with nighttime plates of the same star field taken at a different time of the year. By comparing the relative positions of the stars on the two plates, Eddington obtained an estimate of the deflection resulting from the Sun's gravitation.

At a historic joint meeting of the Royal Society and the Royal Astronomical Society in November 1919, Eddington reported that the results of the expedition confirmed Einstein's theory. Alfred North Whitehead (1861–1947) described the mood of the meeting as follows:

"The whole atmosphere of tense interest was exactly that of the Greek drama. We were the chorus commenting on the decree of destiny as disclosed in the development of a supreme incident. There was dramatic quality in the very staging—the traditional ceremonial, and in the background the picture of Newton to remind us that the greatest of scientific generalizations was now, after more than two centuries, to receive its first modification." Eddington's confirmation was reported widely in the press, and Einstein became a famous figure in Britain and North America.

There were, nonetheless, curious questions about Eddington's original report. One of the instruments used to record the star images was an astrograph, a photographic instrument with large light-gathering capacity that could record a large field in a single exposure. The 12 astrographic plates exposed at Sobral confirmed the Newtonian prediction, but Eddington chose to disregard these data. His interpretation of the two inferior astrographic plates at Principe involved assumptions that reflected his commitment to Einstein's theory. A commentator pointed out in 1923 that "the logic of the situation does not seem entirely clear." Eclipse expeditions carried out for the next 30 years failed to replicate his results. It was Eddington's authority as a scientist rather than the observations themselves that led the 1919 eclipse expedition to be perceived as a decisive confirmation of the general theory of relativity.

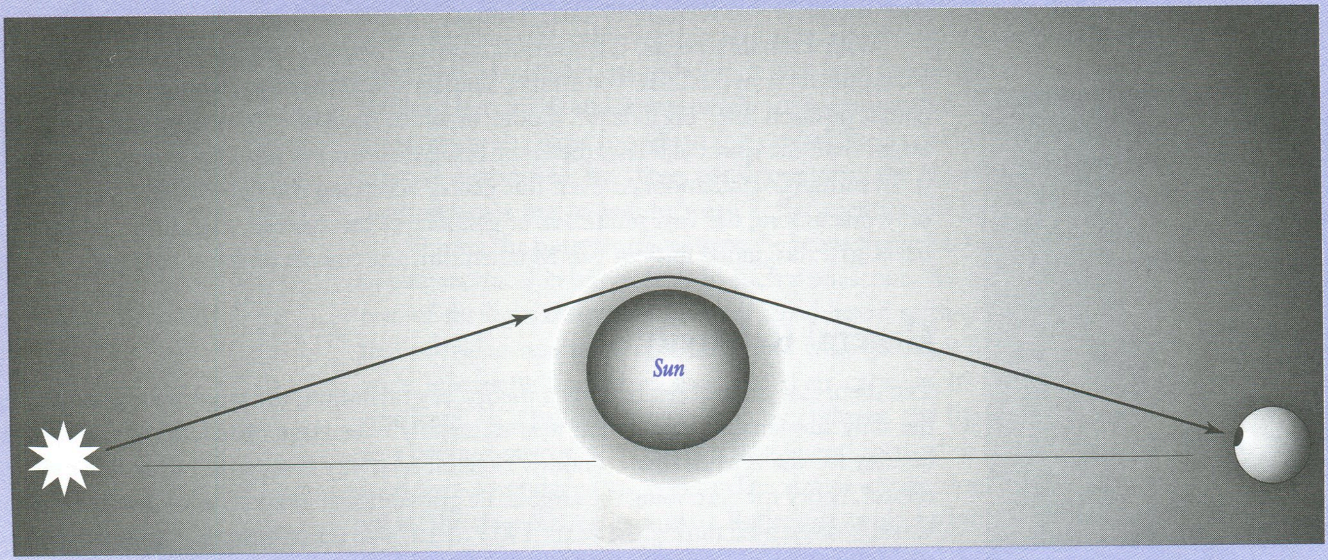

Figure 3. Diagram of light bending (greatly exagerated here). During a total eclipse, it is possible to see stars in the field of the view of the Sun during the daytime. The light from such a star travels close to the Sun and should be deflected. Eddington's expedition photographed this deflection during a total eclipse, producing a result that was in agreement with Einstein's theory of relativity.

In 1917, Einstein published a paper titled "Cosmological Considerations of General Relativity" in which he constructed models for the whole universe on the basis of a few simple principles. He supposed that there was no special vantage point within the universe, that it looks on a large scale the same from every point within it. This became known as the *cosmological principle*. He also assumed that the world was more or less static, an assumption that seemed consistent with what was known at the time about the distant universe. To ensure that the world was static and that it was not subject to gravitational implosion, Einstein found it necessary to introduce a kind of cosmic repulsion into his model, corresponding to the appearance of a certain term λ in the field equations. This term would become known as the *cosmological constant*.

Models different from Einstein's based on general relativity were devised by the Dutch astronomer Willem de Sitter (1872–1934) in 1917 and the Russian physicist Aleksandr Friedmann (1888–1925) in 1924. In 1927, the Belgian astrophysicist Georges Lemaître (1894–1966) recognized the cosmological implications of general relativity and independently duplicated some of Friedmann's results. With the discovery of universal expansion in 1929 [see below], a range of models based on general relativity were advanced to describe this phenomenon.

Until the 1960s, general relativity was a rather esoteric branch of theoretical physics, of interest primarily to a few mathematical specialists and to cosmologists. After 1960, there was a huge increase of interest in the subject, and today it is a prominent field of research. With the development of **radar** technology, researchers were able to bounce radar beams off nearby planets and measure the influence of the planetary and solar **gravitational fields** on the radar trajectories. A pioneer in this investigation was the Jet Propulsion Laboratory in Pasadena, California, which first made radar contact with the planets in the early 1960s. The predictions of general relativity could be subjected to direct experimental tests, and these have largely confirmed its predictions. With the discovery in 1965 of the microwave background radiation, described below, cosmology took on a new respectability as a subject of research. General relativity has provided a very successful mathematical formalism to describe models of the universe. Finally, a range of astronomical phenomena, from extremely dense stellar objects to the gravitational lensing of distant galaxies, has been explained using Einstein's theory.

* **Radar.** A technology employing radio-frequency energy to detect objects, measure distance or altitude, and navigate, among other things.

* **Gravitational field.** A region of space with the property that a test body of unit mass placed at any point within the region will experience a definite gravitational force.

Hubble's Law

The Flagstaff Observatory in Arizona housed a powerful 24-inch (61-centimeter) refractor installed in 1896. The director of the Flagstaff facility, Percival Lowell (1855–1916), was interested primarily in planetary astronomy and, more particularly, in the planet Mars; Lowell was among those who believed that Martian surface features were possible evidence of an advanced civilization. One of Lowell's assistants, Vesto Slipher, was given the secondary job of stellar spectroscopy. The Flagstaff refractor was fitted with a state-of-the-art spectroscope that allowed clear spectra of fairly faint objects to be recorded. In the years 1913 to 1915, Slipher obtained spectra from a number of the spiral nebulae and was surprised to find that they possessed very large spectral shifts. The spectral lines were shifted away from their normal position by a sizable amount, indicating a quite large radial velocity with respect to Earth.

Slipher initially identified in his group of nebulae a symmetrical pattern of blue and red spectral shifts, indicating that some nebulae were moving toward Earth and some away. He interpreted this as evidence of the Sun's motion relative to the more-or-less stationary system of nebulae; as the Sun moved through space, it was moving away from some of the nebulae and approaching others. A similar technique of spectroscopic

The Doppler Effect

In 1842, the Austrian physicist Christian Doppler (1803–53) reasoned that the frequency of light should change depending on the motion of the source relative to the observer. As the source approaches the observer, the frequency will increase; as it moves away, the frequency will decrease. Such an effect was observed for sound waves and waves in water, and Doppler suggested that it is also present in light. He believed variable stars were double-star systems, and the variation in their brightness resulted from the shift of the starlight in and out of the visible range as the stars revolved about each other.

Doppler's explanation of variable stars was in error, but he was correct in assuming that the frequency shift in question was real. With the advent of stellar spectroscopy, it was possible to measure the spectral lines of sunlight and starlight precisely. A change in the position of such a line meant that the light had undergone a shift: an increase in frequency if the line was shifted toward the blue, a decrease if the line was shifted to the red. The shift indicated that the source was in motion along the line or radius from it to the observer: It possessed a radial velocity. In 1871, Hermann Vogel (1841–1907) was able to calculate the rate of solar rotation by measuring the shifts in solar lines at the east and west limbs (edges) of the Sun. He also identified a small periodic spectral shift in starlight emanating from certain double-star systems called *eclipsing binary stars*. As the two stars rotate about each other, they experience periodic changes in radial velocity that show up as a fixed cycle of spectral shifts. The size of the shift was much smaller than Doppler had predicted, but it was real. Vogel developed the use of photography to measure stellar spectra, pioneering a method that would transform stellar astronomy.

In 1913, when Vesto Slipher first detected the large spectral shifts of spiral nebulae, it was assumed that they were standard Doppler shifts arising from the motions of the nebulae relative to the observer. Although this interpretation has been challenged by some astronomers, the majority of researchers today believe that galactic red shifts represent real motions arising from the expansion of the universe.

examination of stars in the vicinity of the Sun had enabled astronomers to calculate the Sun's motion with respect to other stars in its neighborhood of the Milky Way.

As a much larger group of spectra was accumulated, it became clear that the overwhelming majority of the spiral nebulae display substantial red spectral shifts, indicating velocities of recession away from Earth. This fact seemed to invalidate Slipher's initial drift explanation, which required approximate parity between red and blue shifts. With the consolidation of the island-universe hypothesis after 1925, the phenomenon of nebular red shifts took on significance for cosmology, since it seemed to indicate a fundamental fact about the motions of galaxies in the universe relative to the Milky Way system.

The project of recording spectra of very faint objects was taken up by researchers in the late 1920s using the much more powerful 100-inch (254-centimeter) telescope at Mount Wilson. An important contributor to this endeavor was Milton Humason (1891–1972), who had worked his way up to the position of astronomer from a beginning as a mule driver. In 1928, Hubble and Humason embarked on a systematic study of the spiral nebulae. Humason concentrated on measuring nebular spectral shifts, while Hubble took up the theoretically more difficult task of estimating the nebular distances. Hubble was by this time the undisputed world leader in this field of astronomy. The method he followed was to use the brightest object in a given formation as a kind of "standard candle." He assumed on average that each of the brightest stars in nearby spiral nebulae possessed the same intrinsic luminosity; for more distant formations, he assumed that on average each of the brightest galaxies in clusters of galaxies possessed the same absolute luminosity. By comparing apparent and absolute luminosities, he was led directly to an estimate of the distance to the nebula. These assumptions provided a rather crude but statistically valid yardstick for very distant objects.

Although Hubble was first and foremost an observationalist, he was also aware to some extent of contemporary research on relativistic world models, in particular of de Sitter's 1917 model, which predicted an increase in red shifts with increase in distance. In 1929, he was able to infer from his data that there was a rough linear relationship between distance and red shift: the farther away the nebula or galaxy, the greater the red shift. He suggested that this was evidence of the *de Sitter effect* and pointed out the need to investigate its validity for more distant nebulae. The proportionality of red shift to distance, which became known as *Hubble's law*, has come to be seen as one of the greatest discoveries in the history of observational astronomy, if not in all of science. In 1929, Hubble verified the law out to a distance of 6 million light-years, a result that he and Humason subsequently extended to a distance of 100 million light-years. In 1948, a giant 200-inch (508-centimeter) telescope was installed at Mount Palomar Observatory in southern California, and observations with this instrument confirmed the validity of Hubble's relation for objects out to the farthest reaches of the universe.

An important historical question related to Hubble's momentous discovery concerns its relationship to contemporary work in the general theory of relativity. It was a strange and remarkable coincidence that the invention of cosmological models based on general relativity occurred at precisely the same time that Slipher and Humason were beginning to detect large systematic nebular red shifts. The two developments were largely independent. The advances in telescopic instrumentation that made the nebular research possible followed from improvements in engineering and the increased financial support for astronomy in the United States from government and philanthropists. General relativity, by contrast, developed within a central European scientific culture with a strong emphasis on abstract mathematics and pure theory. In retrospect, it seems that Hubble's relation would inevitably have been detected with improvements in the size, quality, and location of observing facilities; it could well have been discovered earlier. It is, nonetheless, a fact that throughout the decade leading up to the 1929 breakthrough, speculation about the red shifts was often tied in with theorizing about relativistic models in cosmology. Hubble was motivated in part by de Sitter's writings and cited the de Sitter effect explicitly in the 1929 paper. It was also the case that general relativists such as Eddington were among the first to explore the implications of Hubble's discovery in terms of mathematical world models.

Expansion of the Universe

A natural explanation of the nebular red shifts is that they result from radial velocities of motion away from the Sun and the galaxy, according to the well-documented Doppler principle. As early as the 1930s, some astronomers proposed alternative theories in which the red shift was attributed to a "tired-light" effect, a kind of dissipation in energy that was linearly proportional to the distance traveled. According to this conception, the red shifts did not arise from the motion of the nebulae but were the result of some other effect. For some time, Hubble himself entertained the possibility of such an idea. However, proponents of tired-light theories were not able to provide a satisfactory physical explanation for the effect, and the majority of astronomers accepted the standard interpretation in terms of recessional motions. It also seemed clear that the Milky Way does not occupy a highly privileged place in the universe and that the phenomenon described in Hubble's law would be observed from any other point in the universe. Given these facts, Hubble's law indicates that the universe is expanding: Any two objects in it are steadily moving apart with a speed that is proportional to their distance. The two-dimensional analogy that is usually introduced to help picture this situation involves an inflating balloon dotted with spots. The surface of the balloon represents the universe and the dots on the surface, the galaxies in the universe. As the balloon expands, any two dots move apart from each other, and the speed of the separation along the surface increases with the distance between the dots.

* **Megaparsec.** One million parsecs. A parsec is a unit of distance equal to 3.2616 light years.

The expansionist interpretation of Hubble's law was popularized by Arthur Eddington in his 1933 book *The Expanding Universe*. The law is given in the very simple mathematical form $v = Hd$, asserting that an object at a distance d from the Sun will have a radial velocity v away from the Sun equal to Hd. The constant H is given in terms of units of kilometers per second per **megaparsec** (km/s^{-1}/Mpc^{-1}). (Radial velocity is velocity along the line or radius joining the Sun and the object and is expressed in kilometers per second. A star 1 parsec from the Sun exhibits a parallax of 1 second of arc; a parsec is approximately 3.26 light-years. A megaparsec is 1 million parsecs.) The constant H is known as *Hubble's constant* and is a measure of the rate at which the universe is expanding. According to the relation $v = Hd$, the radial velocity increases by the amount H for each increase of 1 megaparsec. For nearby galaxies, the Hubble velocity is masked by local or peculiar motions resulting from their gravitational interaction with the Milky Way galaxy. The Andromeda galaxy, for example, is actually moving toward the Milky Way, and its spectrum exhibits a blue shift. After a certain distance from the galaxy, one encounters what is known as pure *Hubble flow,* where the Hubble recessional velocity becomes the dominant component in an object's motion relative to the galaxy.

From 1929 to the present, the exact value of H has been the subject of detailed study and disagreement. Its value depends very sensitively on distance measurements, and these have undergone continuous refinement since the 1920s. According to the big-bang model of the universe [discussed below], the value of the constant is closely tied to the age of the universe and to the question of its ultimate fate. Hubble calculated that H was about 550 km/s^{-1}/Mpc^{-1}, a value that was widely accepted in the 1930s and 1940s but was later downgraded substantially. The leader in the attempts to nail down the value of H has been Allan Sandage (b. 1926), a student of Hubble's and an astronomer at Mount Palomar since 1954. In the 1980s and early 1990s, Sandage and many other cosmologists favored a value of H of around 50 to 55, a rate of expansion that seemed consistent with an older universe. The current value (2001) of H is estimated to be 70 km/s^{-1}/Mpc^{-1}, with an uncertainty of around 10 percent.

The expansionist interpretation of Hubble's relation is the cornerstone of modern theories of the universe. In 1972, cosmologist Gerald J. Whitrow (1912–2000) wrote: "This result has come to be generally regarded as the outstanding discovery in twentieth-century astronomy. It made as great a change in man's conception of the universe as the Copernican revolution 400 years before. For, instead of an overall static picture of the cosmos, it seemed that the universe must be regarded as expanding, the rate of the mutual recession of its parts increasing with their relative distance."

It is now customary to speak of what happened in cosmology after 1920 as a scientific revolution and to compare it to the change in worldview initiated by Copernicus. It is nonetheless important to appreciate the very different historical character of the two events. Copernicus worked in relative isolation without advanced technology and succeeded in reconceptualizing a body of astronomical phenomena that had been familiar to astronomers for 1500 years. Perhaps his greatest achievement was to possess the independence of mind to recognize that heliocentric astronomy was a feasible conceptual alternative to the traditional view. The discovery of universal expansion, by contrast, emerged as the direct result of advances in viewing capability afforded by new instruments and mountaintop observatories. Hubble himself suggested modestly but accurately in 1936 that "the conquest of the Realm of the Nebulae is an achievement of great telescopes."

Big-Bang Theory

Both Friedmann and Lemaître had devised cosmological models on the basis of general relativity, which hypothesized that the universe had expanded outward from an initial singular state. Friedmann died in 1925, quite unaware of any of the new developments in nebular astronomy. Lemaître, by contrast, was present in January 1925 at the meeting of the American Astronomical Society where Hubble's discovery of extragalactic nebulae was announced. With the discovery of Hubble's relation in 1929, his relativistic models became something more than mathematical curiosities; the very real possibility existed that they described the physical universe in which one lived.

Lemaître observed that if the expansion of the universe is extrapolated backward in time, one is led, other things being equal, to an initial moment of creation involving conditions of extremely high density. He proposed that the universe began in the radioactive disintegration of a "primeval atom," a large explosion that propelled the subsequent expansion of the universe. Like many cosmological theorists in the 1930s, Lemaître also believed that the expansion might be assisted by a kind of repulsive cosmic force corresponding to the cosmological constant in the field equations of general relativity. With the discovery of the expanding universe, Einstein himself rejected the cosmological constant, stating that its earlier introduction by him—done so as to preserve a static cosmos—was a blunder.

Lemaître is regarded as the father of modern physical cosmology. His idea that the universe began with an explosive event in conditions of high density attracted the attention of many theorists in the two decades following 1931. This idea formed the basis for what became known as the *big-bang theory* of the universe. The name itself was coined by British scientist Fred Hoyle (1915–2001) in 1949 in a BBC radio lecture. Ironically, Hoyle was a proponent of an alternative cosmology (the steady-state theory, discussed below), and used the phrase *big bang* in a rather disparaging way to criticize his scientific opponents.

A key idea of the big-bang theory is that the universe is evolutionary. It originated at a finite time in the past, believed by current estimates to be around 12 or 13 billion years ago, and has undergone a steady expansion and decrease in density since then. As one looks out in space, one looks back in time; it follows according to the big-bang theory that the universe should look less evolved the farther that one looks out. The theory is an essentially historical one, since its account of the large-scale structure of the universe is also an account of the temporal origins of the universe. In this respect, the big-bang theory stands in striking contrast to the heliocentric cosmology of the period 1550 to 1700, which involved no assumptions about the origins of the Sun's planetary system.

Lemaître's notion of a disintegrating primeval atom was an interesting idea, but it proved difficult to develop it into a consistent quantitative model describing conditions in the very early universe. The modern "hot" big-bang theory has its origins in the writings during the 1940s and early 1950s of three American specialists in nuclear physics: George Gamow (1904–68), Ralph Alpher (b. 1921), and Robert Herman (b. 1914). Of the three, Gamow was the most vigorous in promoting big-bang cosmology, which he did in research papers as well as in popular writings aimed at a broad scientific audience.

Gamow was initially concerned with the problem of stellar nucleogenesis, that is, the process by which heavier elements are synthesized from lighter elements in the interiors of stars. This problem was closely connected to the question of how stars evolve. By the 1930s, it was recognized that a star's source of energy involved

thermonuclear fusion in its hot and dense core. A major breakthrough occurred in 1938 when Hans Bethe (b. 1906) in the United States explicitly identified the chain of reactions by which hydrogen is converted to helium, called the ***carbon-nitrogen cycle***. Carl Von Weizäcker (b. 1912) in Germany obtained a similar result at roughly the same time. Serious problems arose when physicists tried to derive corresponding reaction cycles for the heavier elements. Gamow and others were attracted to cosmology and the big-bang idea because it allowed in principle for the possibility of prestellar synthesis of the heavier elements.

The essential conception as it emerged in the work of Gamow, Alpher, and Herman in the late 1940s was that the very early universe was dominated by radiation; matter was present at this time in the form of a soup consisting of protons, neutrons, and electrons. As the universe expanded, thermonuclear processes produced helium nuclei from the protons and neutrons. Further element formation followed, although the precise mechanisms for this were not spelled out. At a certain time, the universe had expanded and cooled to such a degree that the matter density exceeded the radiation density; at this moment, later referred to as the *decoupling time*, the universe as we know it was born. In a quantitative paper in 1948, Alpher and Herman carried out some computations and concluded that "the temperature in the universe at the present time is found to be about 5°K." No one at the time viewed this as a serious empirical prediction subject to testing, and the work of Gamow, Alpher, and Herman failed to attract much interest.

* **Thermonuclear fusion.** In conditions of extremely high temperature, the fusing of the nuclei of two atoms together to form a heavier nucleus, releasing a substantial amount of energy in the process.

* **Carbon-nitrogen cycle.** A sequence of nuclear reactions in which hydrogen is converted to helium in the cores of stars. Carbon plays the role of a catalyst in the cycle of reactions. The carbon-nitrogen cycle is the main source of stellar energy.

Steady-State Theory

In 1946, three young scientists in England proposed a model for an expanding universe that was radically different from the class of models to which Lemaître's and later big-bang theories belonged. Fred Hoyle, Herman Bondi (b. 1919), and Thomas Gold (b. 1920) had worked together on war-related projects at Cambridge University; Bondi and Gold were physicists and refugees from Hitler's Europe, while Hoyle had studied stellar physics at Cambridge as a scholarship student. In analyzing the phenomenon of universal expansion formulated in Hubble's law, Bondi and Gold were influenced by what is known as the *perfect cosmological principle*. The cosmological principle, which had been at the base of world models since Einstein and before, posits that there is no privileged point of reference in the universe: The world on a large scale looks the same from every point within it. The perfect cosmological principle extends this idea to the temporal dimension, asserting that there is also no privileged point of reference in time: The universe on a large scale looks the same at all points in space and in time.

The perfect cosmological principle amounted to a philosophical tenet, but it was also motivated in the 1940s by empirical considerations. The distance scales that were employed by astronomers at this time implied very high values for Hubble's constant, as high as 500 to 600 $km/s^{-1}/Mpc^{-1}$. According to big-bang models, this in turn seemed to imply that the age of the universe was quite small, certainly no more than 1 or 2 billion years. It was unclear how the evolution of the stars and the development of the solar system and Earth itself could have occurred within such a narrow time frame. The "age paradox" would be resolved in the 1950s by sharply revised distance scales introduced by Walter Baade (1893–1960) of the Mount Palomar Observatory. However, the paradox has arisen again more recently in cosmology and has proved to be a recurring difficulty for big-bang models of the universe.

Bondi, Gold, and Hoyle proposed that the universe is in a steady state. As the galaxies recede outward from each other, matter in the form of hydrogen atoms is created spontaneously at a very low rate in the resulting void. Out of this matter, new stars and galaxies form, so the large-scale density of the universe remains constant in time. The spontaneous creation of matter generates pressure, which propels the expansion of the universe; the galaxies are thrust outward at an ever-increasing rate. Hoyle, who was a gifted popular expositor of astronomy and the steady-state theory, explained the mechanism in the following way: "Each new object makes room for itself among the previously existing units, forcing the previously existing units to move apart from each other, and so providing a physical *raison d'être* for the expansion of the universe. . . . Think of the creation as being driven by ascertainable physical processes, and of the inexorable introduction of new units of creation as forcing the others apart, much as the introduction of new guests into a cocktail party forces earlier guests to move outwards from the initial gathering point, although as always in cosmology this concept has to be formulated without reference to any particular spatial center."

In its detailed form there were two versions of the steady-state theory, one advanced by Bondi and Gold and the other by Hoyle. The former stressed the philosophical basis of the theory and its independence from general relativity; the latter tried to develop the theory using relativity in a way that was consistent with physical cosmology. Hoyle proved to be the most persistent and enduring defender of the steady-state world picture. He cited the problem of galaxy formation in the universe. As one looks out in very distant space, galaxies are sighted; according to the big-bang theory, they must have been around quite early in the universe. It is not at all clear how compact gravitationally bound objects such as galaxies could have formed out of diffuse matter in these conditions of very high energy, so close in time to the initial explosion that created the world. The problem of galaxy formation is today a very thorny one for the big-bang theory. In a steady-state model, by contrast, matter is formed in the void opened up between the separating galaxies; in these rather placid conditions, the formation of galaxies would seem to be a fairly natural event.

Adherents of the big-bang idea, unable to account for the production of heavy elements in the interior of stars, had supposed that these elements were synthesized in the conditions of extreme temperature and density in the early universe. Such a solution was not possible for Hoyle and he was thus motivated to investigate more seriously the basic problem of stellar nucleogenesis. During the 1950s, Hoyle, William Fowler (1911–95), Margaret Burbidge (b. 1919), and Geoffrey Burbidge (b. 1925) successfully developed a theory to explain the synthesis of elements in stars and supernovae. Similar results were obtained independently at this time by Alastair Cameron (b. 1925), a physicist at a nuclear facility in Canada. According to the resulting theory of stellar evolution, which is now widely accepted, supernovae scatter the heavier elements throughout space, and it is from this debris and existing interstellar matter that a later generation of stars is born. It is believed that the Sun and its planetary retinue were born of such a process.

Emergence of Radio Astronomy

A very significant development in twentieth-century astronomy was the invention beginning in the 1930s of radio telescopes that permitted the detection of low-frequency radiation from celestial sources. Radio astronomy did not originate as a concerted program by astronomers, but rather, emerged by chance in the course of attempts by electrical engineers to identify sources of noise in radio communication. Karl Jansky (1905–50) was an engineer at Bell Telephone Laboratories in the 1930s, working on the problem of interference in transatlantic telephone communication. In 1932, using a rotating radio receiver, he detected "a steady hiss type static of unknown origin," which he was able to show was astronomical in nature and emanated from the band of the Milky Way. He published his results in a journal for radio engineers, although his findings were also reported in popular astronomical periodicals of the day.

During the years 1932 to 1937, Jansky worked alone on the problem of "star static." If modern science has any heroes, Jansky's efforts at this time cast him among them. His radio astronomical researches were sometimes acknowledged by professional astronomers but failed to excite serious interest in the research community. After 1937, he returned to work on problems of terrestrial noise in radio communication. He suffered from a debilitating kidney ailment that led to his death in 1950. His pioneering astronomical efforts were continued by Grote Reber (b. 1911), another radio engineer, who in the 1940s used a backyard paraboloidal dish in a suburb of Chicago to create the first map of celestial radio emissions. It would later be established that the radiation detected by Jansky and Greber was the result of a blending of a large number of galactic sources of what is known as *synchrotron radiation*. The latter is emitted by particles moving in very strong magnetic fields and typically is associated with the remnants of supernovae.

The event that led to radio astronomy on a large organized scale was the intensive development of radio and electronic technology during World War II. After the war, many of the scientists who had been involved in military projects retooled their radar equipment and receivers and began to carry out research in radio astronomy. Pioneers were J. Stanley Hey (b. 1909) and his colleagues in Britain's Army Operational Research Group, Bernard Lovell (b. 1913) at Jodrell Bank (near Manchester); Martin Ryle (1918–84) and Francis Graham Smith (b. 1923) at Cambridge's Cavendish Laboratories, John Bolton (1922–93), Gordon J. Stanley (1921–2002), and Bernard Y. Mills (b. 1920) in Sydney, Australia, and Harold I. Ewen (dates unknown) at Harvard. Several areas of investigation emerged. One involved the analysis of solar radiation and the investigation of radio waves emitted by the **solar corona**. Another was initiated by work in 1944 of the Dutch theorist H. C. Van de Hulst (1918–2000), who predicted that neutral hydrogen atoms in space should emit radiation at the 8.27-inch (21-centimeter) wavelength. In 1951, this radiation was detected by Ewen and the Harvard researchers. Jan Oort (1900–1992) in Holland established a program of research in the 1950s that was successful in using the 21-centimeter band to map out the arms of the Milky Way galaxy.

* **Solar corona.** A wispy atmosphere that extends from the Sun millions of miles into space. The temperature of the corona is very high, up to 1 million kelvin.

A third area of research focused on objects with very small angular diameters that were strong emitters of radio waves. The first of these powerful discrete sources was identified in 1946 by Hey and his collaborators in the constellation Cygnus and designated as Cygnus A. Another such source, Cassiopeia A, was discovered in 1948 by Ryle and Smith. In the early 1950s, Walter Baade (1893–1960) and Rudolph Minkowski (1895– 1976), working with the 200-inch (508-centimeter) Mount Palomar telescope, established that Cassiopeia A was a galactic nebula with unusual filamentary structure. It would later be determined that it was the remnant of a supernova in the Milky Way system. Cygnus A was found to be a seventeenth-magnitude galaxy with a substantial red shift, indicating that it was a very distant and very energetic source of radio waves. It was the first of the so-called *radio galaxies* to be discovered. The collaboration between optical and radio astronomers would prove to be very fruitful—among the immense number of nebular objects, the radio data enabled the observer to identify particular ones for detailed optical investigation.

As the resolution of radio receivers improved, astronomers began to detect many more very localized or discrete sources of emission. A project to compile a systematic catalog of discrete radio sources was established in the 1950s at Cambridge University under the direction of Ryle. From 1950 to 1955, the Cambridge group carried out several detailed surveys. Radio objects are typically known by their designation in the Cambridge catalogs; for example, 3C 273 is the 273rd object in the third Cambridge survey. The Cambridge group also pioneered methods of interferometry, in which the same source is observed simultaneously from two separate locations. The two signals are relayed to a receiver and the interference between the two enables one to determine the position of the object with improved accuracy.

Examination of the optical counterparts of discrete radio sources had revealed that many of them were distant galaxies. Ryle came to believe that the majority of these sources were extragalactic. He became interested in the cosmological implications of radio astronomy and carried out counts of discrete radio sources by distance. In 1955, he announced that his results indicated a statistically anomalous increase of faint sources with distance and therefore with earlier time, a crucial piece of evidence against the steady-state theory, which required uniformity in both space and time. Ryle's claims were controversial and were criticized both by Australian researchers in radio astronomy and by the founders of the steady-state theory itself. Nevertheless, as Ryle himself observed, his research seemed to show that it was possible in principle to distinguish empirically among the competing predictions of the different world pictures, an exciting fact in itself. Ryle's contributions to science were recognized in 1974 when he and his Cambridge colleague Antony Hewish (b. 1924) became the first astronomers to receive a Nobel prize.

With further advances in interferometry, the resolution of radio receivers improved. By the early 1960s, fairly accurate coordinates for a large number of discrete sources were available. Examined in the great California reflectors, some of these objects appeared to be starlike, with extremely unusual spectra. Two examples were the sources 3C 48 and 3C 273. Jesse Greenstein (b. 1909) and Maarten Schmidt (b. 1929) were astronomers at the California Institute of Technology (Caltech) involved in the analysis of their spectra. In 1963, Schmidt realized that the unusual character of 3C 273's spectrum was a result of the fact that its hydrogen emission lines were shifted by an extremely large amount to the red; the red shift was so large that the spectrum had appeared unrecognizable. The huge red shift implied that it must be extremely distant in space, a very compact and incredibly powerful source of energy. A similar conclusion followed for 3C 48. These objects became known as *quasars*, short for *quasi-stellar radio sources*; the name proved to be somewhat misleading, since it was soon discovered that many of the starlike sources with large red shifts are radio silent. Nevertheless, the name stuck, and quasar astronomy developed into an important field of research.

The discovery of quasars seemed to provide evidence for the big-bang theory, since it apparently showed that the more distant universe was different from the nearer universe, as one would expect in an evolving cosmology. Astronomers hypothesized that quasars are the active centers of galaxies, possibly associated with the collision of two galaxies. Because the earlier universe was denser and more crowded, such collisions would have been more frequent. These considerations did not impress opponents of the big-bang theory, who reasoned that as one looks out into the distant universe it is natural to encounter diversity; the identification of unusual objects is to be expected. Supporters of the steady-state theory also questioned the "cosmological" interpretation of the quasar red shifts as arising from the expansion of the universe according to Hubble's relation. They suggested that they may result instead from objects thrust out with great velocity from relatively nearby galactic cores. Although the discovery of quasars was an important event, the debate in cosmology continued and no consensus was forthcoming.

Triumph of the Big-Bang Theory

The event that clinched victory for the big-bang theory in the minds of most astronomers was the detection in 1965 of the microwave background radiation. Like many of the major discoveries of twentieth-century astronomy, this event occurred more or less by accident in the course of a project devoted to another purpose. Arno Penzias (b. 1933) and Robert Wilson (b. 1936) were working in the early 1960s at Bell Laboratories in Holmdel, New Jersey, on the problem of satellite communication (see Figure 4). Penzias had a doctorate in physics from Columbia University, and Wilson a doctorate in astronomy from Caltech. They were granted permission by Bell to devote some of their time to astronomical research. They worked with a horn-shaped receiver that had been surplused following Bell's termination of its involvement with the Echo satellite communications project. They set about preparing the instrument for a program to study sources of microwave emission in the Milky Way galaxy. The intensity of radiation picked up by a radio receiver at a given wavelength is typically measured in terms of the temperature of a **blackbody** that emits the radiation at this wavelength. Penzias and Wilson were interested in radiation of very low intensity. They fitted the receiver with a liquid helium load that could be used as a comparison to measure accurately a low-noise signal coming into the horn.

* **Blackbody**. An idealized body that absorbs all radiation that falls on it. The radiation emitted by a blackbody depends only on its temperature and is characterized by a graph relating wavelength and intensity.

Penzias and Wilson possessed a directional instrument of unprecedented sensitivity, capable of making accurate measurements of low-intensity radiation. They picked up a steady 3-kelvin noise in the microwave band that seemed to emanate from all parts of the sky. To make refined observations of galactic sources, it was first necessary to identify the source of this radiation. Despite repeated attempts over a one-year period, they were unable to trace it to any of the likely sources: nearby New York City, contamination on the surface of the receiver, or even radiation from within the galaxy.

At the same time that Penzias and Wilson were working on this problem, a group of astronomers at nearby Princeton University under the direction of Robert Dicke (1916–97) was investigating models of the early universe. A former student of Dicke's, James Peebles (b. 1935), had discussed the "cosmic electromagnetic radiation" associated with the early universe in a paper delivered at Johns Hopkins University early in 1965. In effect, Dicke and Peebles were duplicating the research of

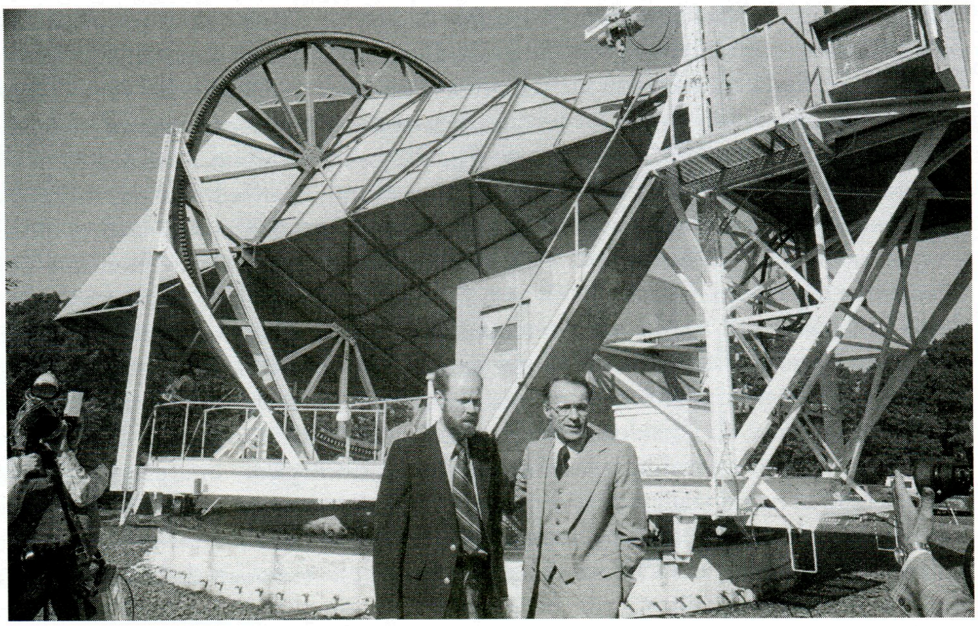

Figure 4. Photograph of Wilson and Penzias in front of the radio astronomy antenna at Bell Laboratories in Holmdel, New Jersey. © Bettmann/ CORBIS

Gamow, Herman, and Alpher from over 15 years earlier, which had largely been forgotten. Through their contacts in the astronomical community, Penzias and Wilson became aware of the work of Dicke, and a meeting was arranged between the Bell scientists and the Princeton group. Dicke realized that the 3-kelvin excess noise in the Holmdel horn receiver was consistent with the radiation that would have been emitted following the big bang. The radiation appeared to be a fossil relic left over from the initial cataclysm that created the world.

The discovery of microwave background radiation turned out to be a turning point in the history of cosmology, comparable to Hubble's 1929 discovery of the red shift relation. It provided concrete physical evidence for the big-bang theory. There was no immediate explanation for its existence in steady-state or other alternative cosmologies, and the majority of the scientific community was won over to the big-bang idea. After 1965, cosmology began to be taken much more seriously, both scientifically and institutionally. High-energy physicists became interested in the subject, and graduate courses in it became a regular part of astronomy programs in universities. Financial support for research in extragalactic radio and optical astronomy increased. In 1978, Penzias and Wilson were awarded the Nobel Prize in Physics for their discovery.

The standard cosmological model accepted today by the astronomical community is the big-bang theory. Further evidence for this theory emerged in the 1960s and 1970s from estimates of the frequency of helium in the universe. Surveys of near and distant regions indicate a constant ratio of helium to hydrogen: For every 10 atoms of hydrogen, there is one atom of helium. It is believed that this amount of helium could not have been produced in stars, and that some of it must have resulted from fusion in the primordial conditions of high temperature and density following the initial bang. The frequency of **isotopes** of such light elements as hydrogen and lithium also appears to point to a prestellar origin in the big bang.

➢ **Isotope.** One of two or more species of atoms of the same element having different atomic masses due to variations in the number of neutrons in their nuclei.

Stellar Astronomy Since 1965

In the past 40 years, technological advances in Earth- and satellite-based instrumentation have led to unprecedented opportunities for both galactic and extragalactic observation. Replacement of the photographic plate by the **charge-coupled device** has increased the sensitivity of telescopes many times over. *Adaptive optics*, a system for canceling the disturbing effect of the atmosphere within a telescope, has dramatically enhanced the resolution of images. These advances have been introduced into a new generation of gigantic telescopes situated high on mountaintops in Hawaii and Chile. Instruments attached to high-altitude balloons, airborne observatories, and orbiting satellites have enabled detailed observations in the infrared, ultraviolet, and x-ray bands not possible from Earth's surface. The Cosmic Background Explorer (COBE), launched into Earth orbit in 1990, mapped minute changes in the intensity of the microwave background radiation. In the 1990s, the Hubble Space Telescope, equipped with a 7.9-foot (2.4-meter) reflector, relayed back to Earth a succession of stunning images of the cosmos. In radio astronomy, very long baseline interferometry (VLBI) using continent-sized baselines has enabled researchers to construct radio maps of unprecedented resolution, up to a thousandth of a second of arc.

* **Charge-coupled device.** A device containing a light-sensitive chip that stores incoming light from a source as an electrical charge.

The period since 1965 has witnessed the discovery of several new objects in the universe. In 1967, Susan Jocelyn Bell (b. 1943), a graduate student of Antony Hewish's at Cambridge University, detected a celestial source emitting a rapid series of radio pulses at extremely regular intervals. Other such pulsating sources were soon found. Although these radio pulsars were initially seen as an enigma, Thomas Gold arrived in

1968 at the explanation that is now generally accepted. A star more than about eight times the mass of the Sun ends its life as a type of supernova in which a large explosion is accompanied by the collapse of the star's core to a very compact and dense object, so dense that the protons and electrons are fused together as neutrons. Neutron stars possess extremely powerful magnetic fields, which result in the emission of radio waves from the ends of a magnetic axis through the star that is inclined to the star's axis of rotation. The star rotates very rapidly, and as it does so the beam of radiation crosses the observer's line of sight periodically, resulting in the detection of a regular sequence of radio pulses.

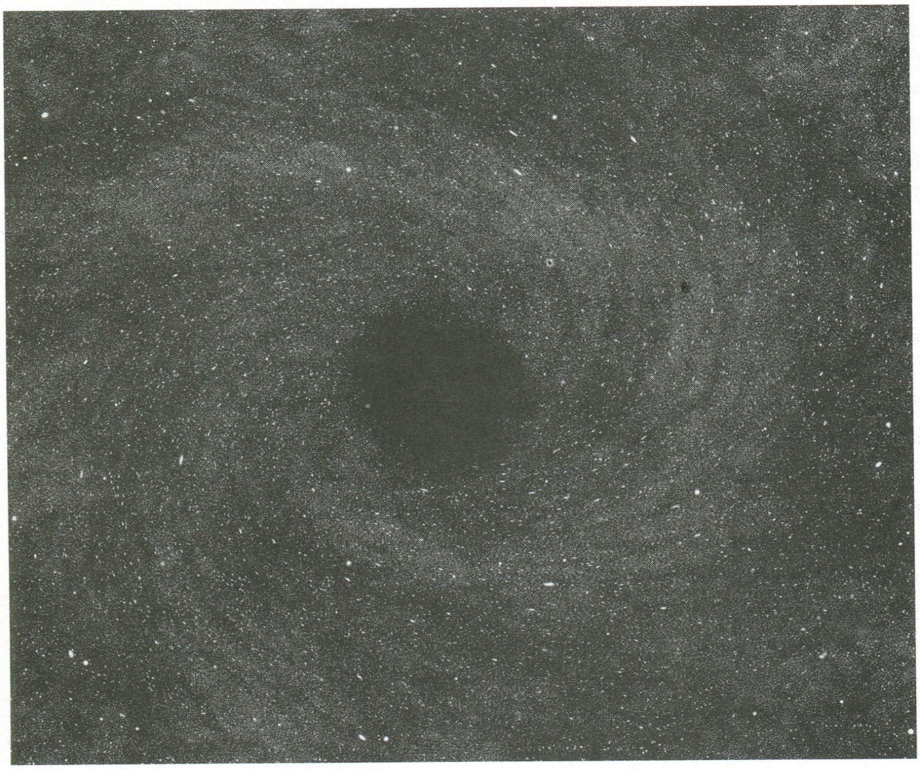

Figure 5. Photograph of a black hole. © *Aaron Horowitz/CORBIS*

Neutron stars are the last stage in the evolution of a star more than eight times the mass of the Sun and less than about 20 solar masses. (The precise limits vary somewhat according to the theoretical model adopted.) A star more massive than this is believed to end its life as a black hole (see Figure 5). The term was introduced by John Archibald Wheeler (b. 1911) in 1968 and refers to an object that is so dense and massive that no electromagnetic radiation can escape from its gravitational field. Although once viewed almost as part of science fiction, black holes have proved to be a sound and important theoretical concept. Observations made with the Hubble Space Telescope indicate that large black holes lie at the center of most galaxies. The mathematics of such objects has been studied extensively by, among others, distinguished Cambridge theorist Stephen Hawking (b. 1942), who has shown that black holes are not entirely black: They interact thermodynamically with their environment, emitting energy. Hawking has carried out his scientific work despite being afflicted by amyotrophic lateral sclerosis, a serious degenerative disorder.

Challenges in Cosmology

In the 1970s and 1980s, scientists at the Harvard-Smithsonian Center for Astrophysics measured the distances to over 30,000 galaxies in selected sectors of the sky. Distances were calculated from red shift data using Hubble's relation. The plan was to construct a three-dimensional map of the universe out to several hundred light-years. Leadership in this venture was provided first by Marc Davis (b. 1947) and later by John Huchra (b. 1948), Margaret Geller (b. 1947), and Valerie de Lapparent (dates unknown). The CFA surveys came as a major surprise. Instead of being distributed more or less uniformly in space, galaxies lie along long sheets and walls that surround large voids. The universe possesses a soap-bubble structure characterized by considerable local unevenness in the distribution of galaxies. Beginning with the uniform conditions indicated by the cosmic background radiation, the universe has evolved into a rather lumpy place. The task of explaining this fact in terms of relativistic models of galaxy formation in an expanding universe has not proven an easy one.

A major ongoing challenge to astronomy that has emerged in the last 50 years is the problem of dark matter. As early as the 1930s, the Mount Wilson astronomer Fritz Zwicky (1898–1974) had observed that the rotational characteristics of galaxies in the Coma cluster implied that the galaxies must be embedded in a larger dark mass. In the 1960s, Vera Rubin (b. 1928) and her associates at the Carnegie Institution in Washington, D.C., carried out detailed spectroscopic studies of individual galaxies. They measured the angular rate of rotation as a function of distance from the center of the galaxy. They found that beyond a certain distance from the center the curve became flat, indicating that the galaxy was rotating very much like a rigid body. The visible galaxy was apparently contained within a larger halo of dark matter. The discovery of the Great Attractor in the 1980s revealed a region of generalized high mass density in intergalactic space detectable only by its gravitational attraction. Evidence on many different fronts has accumulated to indicate that a very considerable percentage of the universe is present in a "dark" form, emitting no electromagnetic radiation but interacting gravitationally with visible matter.

In considering what dark matter is made of, it is customary to distinguish between *baryonic* and *nonbaryonic* matter. Baryonic matter, which consists of ordinary protons, neutrons, and electrons, would be present in dark form in **brown dwarfs**, black holes, and other objects that are known to exist but emit little or no radiation (see Figure 6). This class of sources consists of *massive compact halo objects* (MACHOS), so-named because they are believed to populate the outer region or halo of the galaxy. Unfortunately, it is believed that MACHOS could provide only a small fraction of the dark matter in the universe. Candidates for nonbaryonic dark matter include something known as *weakly interacting massive particles* (WIMPS), none of which have been detected so far. Another more popular candidate is the *neutrino*, a particle whose existence was predicted in 1931 but was first detected in 1956. Neutrinos are small chargeless particles that travel at velocities close to the speed of light and are produced in nuclear reactions. When a neutron decays into

* **Brown dwarfs.** Very small stars, less than about 8 percent the mass of the Sun, too small to generate energy through nuclear reactions in their cores. They emit some energy as the result of gravitational contraction.

Scientific Practice: The Great Attractor

During the 1980s, astronomers embarked on an international collaborative project to investigate a particular class of galaxies, the elliptical galaxies. These are galaxies that lack spiral arms, are free of gas, and are predominantly oval or round in shape. The astronomers, led by Sandra Faber (b. 1944) of the Lick Observatory and Trevor Lynden-Bell (b. 1935) of Cambridge University, were interested in the problem of galactic evolution and concentrated on the ellipticals because they are as a class quite uniform in their properties. To map the galaxies, they measured their red shifts and used Hubble's relation to estimate their distances. In the course of their investigation they derived an indicator that appeared to correlate very well with absolute luminosity. The indicator was the velocity dispersion of the galaxy, a quantity that measures the speed of a typical star in the galaxy. Its correlation with luminosity allowed a measure of distance that could be used independent of the Hubble relation. Much to their surprise, the astronomers discovered that the galaxies they were studying possessed large and systematic "peculiar motions," velocities independent of universal expansion arising from the gravitational attraction of neighboring galaxies and matter.

The Milky Way galaxy is part of a larger collection of galaxies known as the *Local Group*. The Local Group, in turn, belongs to a system of clusters known as the *Local Supercluster.* The data of Faber, Lynden-Bell, and their associates indicated that the Local Group, the Supercluster, and several other clusters are streaming toward a more distant concentration of mass. Dubbed the *Great Attractor* in 1986 by Alan Dressler (b. 1948), one of the investigators in the project, this mass consists of a large swell in the density of matter arising from a high concentration of galaxies and dark matter in the direction of the constellation Virgo. The discovery of the Great Attractor showed that there is considerable local inhomogeneity in the distribution of matter in the universe.

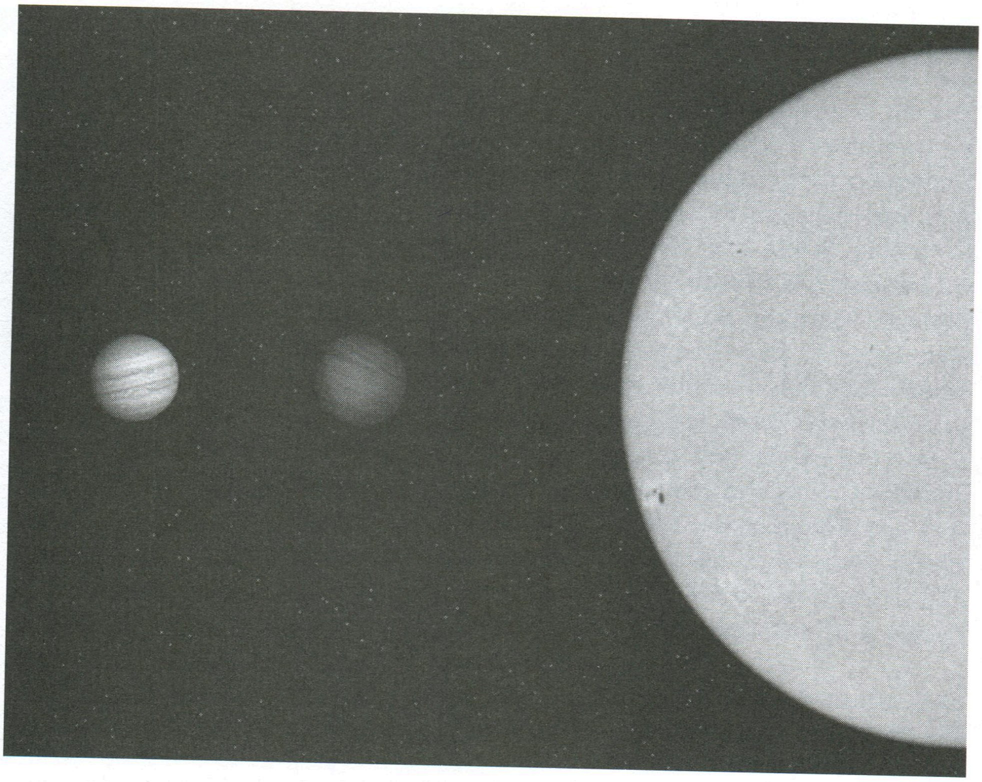

Figure 6. Illustration of a brown dwarf (center) compared to Jupiter and the sun. © Reuters New Media Inc./CORBIS

a proton and electron, it emits an antineutrino. It is not known conclusively if any of the different types of neutrino possess mass, although experiments in the late 1990s indicated that some types may have a slight mass. Because there are so many neutrinos in the universe, even a very small nonzero mass would result in a significant contribution to the total bulk of the cosmos.

Theoretical cosmology has recently been dominated by a new conception of the very early universe first advanced by Massachusetts Institute of Technology physicist Alan Guth (b. 1947) in 1981. A remarkable characteristic of the cosmic background radiation is its uniformity—points on the sky 180° apart possess the same temperature to an accuracy of 1 part in 100,000. These temperatures correspond to parts of the universe that can have had no contact since the initial big bang. Using general relativity, thermodynamics, and particle physics, Guth devised a theory known as *inflation* to explain this fact. According to this conception, at the very beginning of its history the universe underwent a **phase transition**, resulting in a period of exponentially accelerated expansion lasting only a tiny fraction of a second—in an instant the universe inflated, creating the homogeneity and isotropy (uniformity in different directions) that we observe today in the cosmic background radiation. A major difficulty of inflation is that it requires the universe to be much more massive than it apparently is. Indeed, if inflation in its original form is correct, 99 percent of the universe must consist of dark matter. In recent years, theorists have been hard at work developing low-density versions of inflationary cosmology, with no clear results forthcoming so far.

It was generally assumed until recently that as the universe expanded following the initial bang, the gravitational attraction of all the mass within it acted as a brake, causing a slight deceleration in the rate of expansion. As the twentieth century came to a close, two teams of astronomers announced a discovery that, if confirmed by more research, could rank with Hubble's relation and the cosmic background radiation in its importance for cosmology. In certain double-star systems containing a **white dwarf**, matter accretes from the second member to the dwarf, until the latter reaches a critical

* **Phase transition.** A process in which a physical system suddenly changes from one state to another. For example, when water freezes, it passes from liquid to solid.

* **White dwarf.** A very dense hot star the size of a planet that has exhausted its supply of nuclear fuel and is at the final stage of its evolution.

mass that causes the system to explode as a supernova. Such events are known as *type IA supernovae*. Their intrinsic luminosity is roughly equal, allowing them to be used as standard candles to determine distance. Separate teams of astronomers at Harvard University and the University of California at Berkeley used IA supernovae to calculate the way in which the value of Hubble's constant correlates with distance. They discovered that distant galaxies (i.e., those created early in the history of the universe) appear to recede more slowly than they should according to the conventional Hubble relation. According to the data gathered, the expansion of the universe appears to be accelerating in time. It would be an understatement to say that this result came as a surprise. The immediate fallout from the supernovae studies has been to renew interest in relativistic world models in which the cosmological constant λ is positive. Few scientific subjects today are as exciting as cosmology, and few hold greater promise than it does for fundamental surprises in the future.

Planetary Astronomy

The past 100 years have been an interesting time for planetary astronomy, as new instruments and space probes have spectacularly extended our knowledge of the solar system. Except for the American trips to the Moon between 1969 and 1972, exploration has consisted of probes and robotic craft that are controlled from Earth. Viewed in light of the grand plans of human colonization of space envisaged by futurists 30 or 40 years ago, the cessation of manned missions beyond Earth orbit in the early 1970s was a somewhat surprising development.

DISCOVERY OF PLUTO

The identification of the last planet in the solar system actually occurred before the era of space exploration. Following the discoveries of Uranus and Neptune, astronomers in the late nineteenth century analyzed their orbits and looked for possible variations that would indicate the influence on them of another more distant planet. Some irregularities were found, and the search began for "Planet X." A leader in this venture was the Flagstaff astronomer Percival Lowell, who carried out calculations of X's position and searched for it at his observatory in Arizona. The hunt was continued following his death in 1916, but nothing was found.

In 1929, a young amateur astronomer named Clyde Tombaugh (1906–97) was brought to Flagstaff to look for Planet X. For this purpose he used a blink comparator, an instrument that alternately displayed in rapid succession two photographic plates of the same star field taken at different times; small movements in a planet or an asteroid would show up immediately. Tombaugh examined photographs of a region of the ecliptic in the constellation of Gemini near where Lowell predicted that Planet X would be located. In February 1930, he discovered an unknown moving object there. Further observation of its orbit indicated that it was indeed a trans-Neptune object, apparently the ninth planet of the solar system. It was given the name Pluto by an 11-year-old English schoolgirl, after the Greek god of the underworld.

Subsequent analysis of Pluto's orbit indicated that its mass was much too small to have caused the irregularities in the orbits of Uranus and Neptune used by Lowell to predict the position of Planet X. It seemed that Tombaugh's discovery was fortuitous and did not depend in an essential way on Lowell's calculations. In 1978, astronomers at the U.S. Naval Observatory found that Pluto has a satellite, subsequently named Charon after the ferryman of the underworld, which orbits Pluto at a distance of only 12,000 miles (19,000 kilometers) and is one-half of Pluto's diameter. Because of its diminutive size (smaller than five of the satellites in the solar system), eccentric orbit, and rocky constitution, some astronomers have suggested that Pluto is not a planet at all but should be regarded as an outer asteroid, possibly a member of the family of cometlike objects that populate the outer reaches of the solar system.

MOON AND MARS

Exploration of the Moon began with a series of probes launched by the Soviets and Americans and culminated with the Apollo manned missions during the years 1969 to 1972. The far side of the Moon was first photographed by the Soviet probe *Luna 3* in 1959 and found to possess more craters and fewer dark seas than the near side. Analysis of seismic and heat flow data as well as rock samples returned by Apollo and by Soviet robotic missions advanced understanding of the Moon's internal constitution. In the 1980s, a new theory of the Moon's origin was proposed. Now widely accepted, the theory holds that Earth was grazed about 4 1/2 billion years ago by a Mars-sized object, which lifted up a ring of debris that coalesced into the Moon. The colliding body contributed some of the debris, while the remaining part of this body fused with the primordial Earth. This account has displaced various older theories that held the Moon to be a passing planetoid captured by Earth, something that was formed very early from Earth as a result of rotational fissure, or a body formed in a process of co-accretion with Earth from the gas and dust in the original solar nebula.

The *Mariner* and *Viking* missions explored Mars between 1965 and 1978. Guided from the Jet Propulsion Laboratory in California, the *Mariner* spacecraft flew by Mars and returned photos, while the two *Viking* missions landed craft on the surface of the planet and carried out analyses of Martian soil. The question of intelligent life on Mars debated so vigorously by astronomers 100 years ago was definitely settled by these missions. The Martian surface is cold, barren, and possesses a thin atmosphere, consisting mostly of carbon dioxide gas. It is certain that intelligent life forms are not found there and were never present in the past.

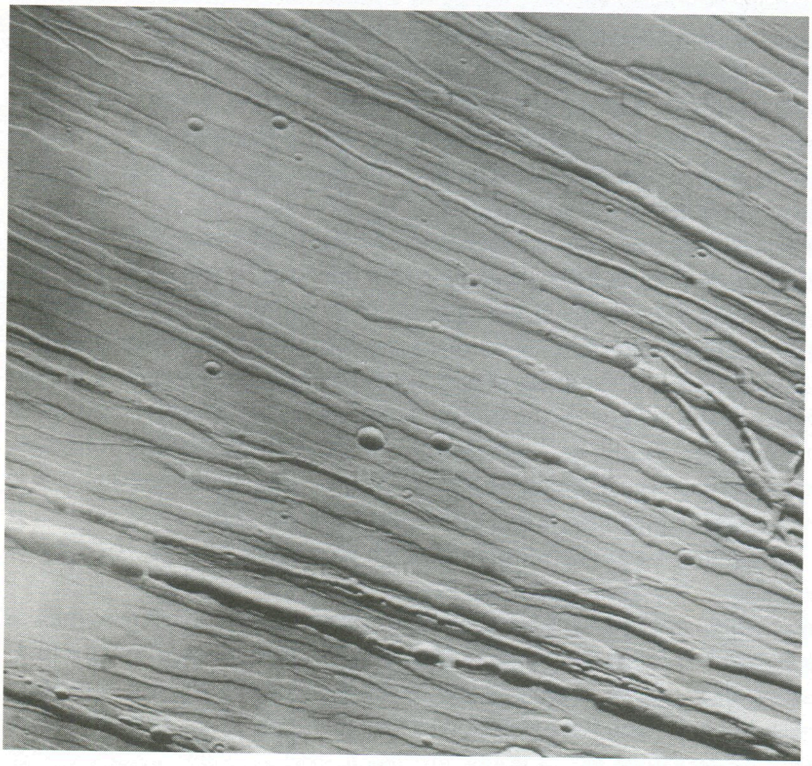

Figure 7. Photograph of channels on Mars from Viking Orbiter. *© Roger Ressemeyer/CORBIS*

Exploration of Mars languished in the 1980s and early 1990s, but two important missions were launched at the end of the century. In 1997, the *Pathfinder* mission landed a small robotic rover named *Sojourner*, which ventured out several meters over the Martian surface. Launched in 1996, the *Mars Global Surveyor*, equipped with a full array of instruments, went into orbit around Mars and is currently carrying out a detailed examination of its surface features, atmosphere, and magnetic field. Despite some mission failures, further exploration of Mars is planned, and the planet is the probable eventual target of a manned expedition in the twenty-first century.

INNER SOLAR SYSTEM

The planet Venus had always been an enigma to astronomers because it is shrouded in thick clouds. Radar probing in 1964 established that Venus has a retrograde rotation on its axis of 225 days. Unlike Earth, which rotates on its axis in the same direction as it revolves about the Sun, Venus rotates in a direction opposite to its revolution about the Sun. Several missions were launched to Venus; the Soviet *Venera* missions extended from 1972 to the 1980s, and included craft that landed on the surface and for a short time returned photographs and data. The U.S. *Magellan* probe went into orbit around Venus in 1990 and carried out an extensive radar mapping of the Venusian surface. Venus has a much denser atmosphere than Earth, consisting of carbon dioxide gas and sulfuric acid droplets. Its surface temperature varies from 500° to 800°C, the lower range of a pottery kiln. Atmospheric and temperature conditions would certainly preclude any form of life, so confidently predicted to exist by nineteenth-century astronomers. Tectonic activity that is so basic to the formation and evolution of Earth's features appears to be absent on Venus, or at least the core-crust mechanism there is quite different.

The secrets of Mercury, the closest planet to the Sun, have been disclosed by radar probing since the 1960s and by one spacecraft, *Mariner 10,* which executed three flybys of the planet in 1974 and 1975. Radar contact established that Mercury has a rotational period of 59 days. Photographs taken by *Mariner 10* revealed a highly cratered surface similar to the Moon's, indicating that Mercury is a geologically quiet and probably very old body. The gravitational pull exerted by Mercury on *Mariner 10* enabled controllers to calculate its mass. It turns out that it is much denser than previously thought and must be composed of an iron core surrounded by a thin shell of rock.

OUTER SOLAR SYSTEM

With the exception of Pluto, the basic orbital parameters and dimensions of the outer planets had been identified before the twentieth century. They are much larger than Earth and rotate rapidly on their axes—a day on Jupiter and Saturn lasts 10 hours, and only a few hours longer on Uranus and Neptune. Spectroscopic examination from the 1930s indicated that Jupiter and Saturn possess extended atmospheres consisting of methane, ammonia, and molecular hydrogen. The currently accepted model for the internal constitution of the outer planets, essentially a development of one first proposed by Rupert Wildt (1905–76) in 1938, consists of a small rocky core surrounded by a layer of condensed hydrogen so dense that it possesses metallic properties, followed by a layer of liquid hydrogen, and ending with the extended atmosphere itself.

Jupiter and Saturn were explored by the spacecraft *Pioneers 10* and *11* between 1973 and 1979 and by *Voyagers 1* and *2* between 1979 and 1981. *Voyager 2* benefited from a rare alignment of the planets to slingshot out to Uranus and Neptune, which it flew by in 1986 and 1989. In 1995, the *Galileo* spacecraft went into orbit around Jupiter and launched a small suicide probe into the Jovian atmosphere that managed to send back data for an hour before it was crushed by the atmosphere. The *Galileo* orbiter continues to send back data from Jupiter. The *Cassini* mission, launched in 1997, will reach Saturn in 2004 and is scheduled to release a probe that will parachute to the surface of Titan, Saturn's largest moon.

Immanuel Kant had reasoned that the inhabitants of Jupiter were of a superior temperament, their distance from the Sun's heat bestowing on them a sense of equilibrium and freedom from decay. One suspects, however, that the placid outlook of Jovians—who surely lived only in Kant's imagination—would be perturbed in no small part by the great storms swirling about the surface, not to mention magnetic fields 20,000 times stronger than Earth's and deadly radiation belts. According to infrared analysis of Jupiter, it generates nearly twice as much heat as it receives from the Sun.

Some of the most interesting discoveries of the space probes have been of the satellites of the outer planets. Many small new moons have been found, and the structure of the rings of Saturn and Uranus—the latter first detected by Earth-based telescopes in 1977—has been studied closely. Considerable attention has centered on the four large Galilean satellites (i.e., those first discovered by Galileo in the early seventeenth century). In order of increasing distance from Jupiter they are Io, Europa, Ganymede, and Callisto. All orbit Jupiter in nearly circular orbits. Io is caught in a gravitational tug of war between Jupiter on one side and Europa on the other and is very active volcanically, spewing hot sulfur gas that then condenses in large splotches on its surface. Europa is covered with a smooth sheet of ice and displays a complex system of superficial linear features. It is conjectured that a subsurface ocean of water exists on Io, heated by the immense tidal forces of Jupiter; it is even possible that life forms are present there. Ganymede, the largest satellite in the solar system, and Callisto are heavily cratered low-relief bodies, probably unchanged for billions of years. Each of the four satellites has a captured rotation with respect to Jupiter. The period of rotation of each is equal to its period of revolution about the giant planet. Saturn's moon Titan was found by *Voyager* to possess a thick orange atmosphere, a unique feature among the satellites of the solar system.

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