38 / Big Bang Versus Steady State

Astronomy's understanding of the structure and behavior of the universe underwent its most dramatic revision in the 1920s. Edwin Hubble confirmed, once and for all, that the Milky Way was but one of a multitude of other galaxies spread throughout the vast gulfs of space. He later enhanced the discovery in 1929 by proving that the very fabric of space-time was expanding, with galaxies continually riding the wave outward (see Chapters 51 and 52). Theorists such as Aleksandr Friedmann and Georges Lemaître, working on solutions to the equations of general relativity, already accounted for this motion in the light of Einstein's new law of gravitation (see Chapter 37). With theory and observation working hand in hand, astronomers could at last contemplate the universe's very creation, the unique moment when it all began. No longer was our cosmic origin a matter of metaphysics; it was a scientific theory that could be tested.

Soon after he introduced his model of an expanding universe, Lemaître was the first to contemplate in a scientific manner what that beginning might have been like. He mentally put the expansion of space-time into reverse and imagined the galaxies moving ever closer to one another, until they ultimately merged and formed a compact fireball of dazzling radiance. Boldly picturing the cosmos at earlier and earlier moments, Lemaître suggested that the universe emerged from a "primeval atom." Today's stars and galaxies, he surmised, were constructed from the fragments blasted outward from this original superatom. "The evolution of the world can be compared to a display of fireworks that has just ended: some few red wisps, ashes, and smoke," wrote Lemaître. "Standing on a well-chilled cinder, we see the slow fading of the suns, and we try to recall the vanished brilliance of the origin of the worlds."[15] From this poetic scenario arose the vision of the Big Bang, the cosmological model that shapes and directs the thoughts of cosmologists today as strongly as Ptolemy's crystalline spheres influenced natural philosophers in the Middle Ages.

For many, though, the contemplation of a singular moment of creation was philosophically distasteful. "The notion of a beginning of the present order of Nature is repugnant to me," said the British theorist Arthur Eddington. "By sweeping it far enough away from the sphere of our current physical problems, we fancy we have got rid of it. It is only when some of us are so misguided as to try to get back billions of years into the past that we find the sweepings all piled up like a high wall and forming a boundary—a beginning of time—which we cannot climb over."[16] There were scientific hurdles, too: estimates of the universe's age based on early (and incorrect) measurements of its rate of expansion were initially suggesting that the universe was younger than the stars, a paradox that posed a dilemma to Big Bang cosmologists for a while.

The notion of an evolving universe faced other challenges as well before it could be fully accepted. The most notable was the steady-state model of the universe. A group of young scientists at Cambridge University in the 1940s, contemplating a universe expanding and the density of matter thinning out, was concerned that the physical laws of nature would also change over time, making it impossible to compute anything about the universe's future or past. Mathematician Hermann Bondi and astrophysicist Thomas Gold (later joined by astrophysicist Fred Hoyle) figured this dire fate could be avoided if the density of matter did not change over time.[17] They conceded that the universe was eternally expanding (the observational evidence couldn't be denied), but it was an expansion with neither a beginning nor an end. It was in a "steady state." From wherever one viewed the universe, it always looked the same, because matter was continually and spontaneously being created to fill in the gaps opened up by the cosmic expansion. Galaxies were endlessly forming out of the new material to replace those that receded beyond our view, which meant the universe of the past would look very much like the universe of today. The Cambridge group estimated that to keep this process going, only one atom of hydrogen needed to be created each hour in roughly every cubic mile of intergalactic space.

For many years the steady-state universe was a potent competitor to the Big Bang theory. Ironically it was Hoyle, the ardent steady-stater, who gave his rivals a name for their cosmological model. During a British radio series on cosmology in 1949, Hoyle offhandedly and derisively described the explosive version of creation as the "big bang idea."[18] The adjective stuck and turned into a noun. The rivalry between the two models inspired astronomers throughout the 1950s and into the 1960s to seek the observational evidence to decide the universe's true nature. The Big Bang was triumphant in 1964 with the discovery that the universe was awash in a sea of microwave radiation, the remnant echo of its thunderous conception (see Chapter 63).

"The Beginning of the World from the Point of View of Quantum Theory." *Nature*, Volumes 127 (May 9, 1931) and 128 (October 24, 1931)

by Georges Lemaître

First Paper

Sir Arthur Eddington states that, philosophically, the notion of a beginning of the present order of Nature is repugnant to him.* I would rather be inclined to think that the present state of quantum theory suggests a beginning of the world very different from the present order of Nature. Thermodynamical principles from the point of view of quantum theory may be stated as follows: (1) Energy of constant total amount is distributed in discrete quanta. (2) The number of distinct quanta is ever increasing. If we go back in the course of time we must find fewer and fewer quanta, until we find all the energy of the universe packed in a few or even in a unique quantum.

Now, in atomic processes, the notions of space and time are no more than statistical notions; they fade out when applied to individual phenomena involving but a small number of quanta. If the world has begun with a single quantum, the notions of space and time would altogether fail to have any meaning at the beginning; they would only begin to have a sensible meaning when the original quantum had been divided into a sufficient number of quanta. If this suggestion is correct, the beginning of the world happened a little before the beginning of space and time. I think that such a beginning of the world is far enough from the present order of Nature to be not at all repugnant.

It may be difficult to follow up the idea in detail as we are not yet able to count the quantum packets in every case. For example, it may be that an atomic nucleus must be counted as a unique quantum, the atomic number acting as a kind of quantum number. If the future development of quantum theory happens to turn in that direction, we could conceive the beginning of the universe in the form of a unique atom, the atomic weight of which is the total mass of the universe. This highly unstable atom would divide in smaller and smaller atoms by a kind of super-radioactive process. Some remnant of this process might, according to Sir James Jeans's idea, foster the heat of the stars until our low atomic number atoms allowed life to be possible.*

Clearly the initial quantum could not conceal in itself the whole course of evolution; but, according to the principle of indeterminacy, that is not necessary. Our world is now understood to be a world where something really happens; the whole story of the world need not have been written down in the first quantum like a song on the disc of a phonograph. The whole matter of the world must have been present at the beginning, but the story it has to tell may be written step by step.

Second Paper

. . . If I had to ask a question of the infallible oracle . . . , I think I should choose this: "Has the universe ever been at rest, or did the expansion start from the beginning?" But, I think, I would ask the oracle not to

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* "*Nature*, March 21, 1931, p. 447."

* Jeans was a British mathematician and astrophysicist.

give the answer, in order that a subsequent generation would not be deprived of the pleasure of searching for and of finding the solution.

If the total time of evolution did not exceed, say, ten times the age of the earth, it is quite possible to have a variation of the radius of the universe going on, expanding from zero to the actual value. I would picture the evolution as follows: At the origin, all the mass of the universe would exist in the form of a unique atom; the radius of the universe, although not strictly zero, being relatively very small. The whole universe would be produced by the disintegration of this primeval atom. It can be shown that the radius of space must increase. Some fragments retain their products of disintegration and form clusters of stars or individual stars of any mass. When the stars are formed, the process of formation of the extragalactic nebulae out of a gaseous material, proposed by Sir James Jeans, could be retained for the star-gas filling the space. The numerical test works out equally well for this case.

Whether this is wild imagination or physical hypothesis cannot be said at present, but we may hope that the question will not wait too long to be solved. . . .

"The Steady-State Theory of the Expanding Universe." *Monthly Notices of the Royal Astronomical Society,* Volume 108 (1948)

by Hermann Bondi and Thomas Gold

. . . Any interdependence of physical laws and large-scale structure of the universe might lead to a fundamental difficulty in interpreting observations of light emitted by distant objects. For if the universe, as seen from those objects, presented a different appearance, then we should not be justified in assuming familiar processes to be responsible for the emission of the light which we analyze. This difficulty is partly removed by the "cosmological principle." According to this principle all large-scale averages of quantities derived from astronomical observations (i.e. determination of the mean density of space, average size of galaxies, ratio of condensed to uncondensed matter, etc.) would tend statistically to a similar value independent of the positions of the observer, as the range of the observation is

increased; provided only that the observations from different places are carried out at equivalent times. This principle would mean that there is nothing outstanding about any place in the universe, and that those differences which do exist are only of local significance; that seen on a large scale the universe is homogeneous.

This principle is widely recognized, and the observations of distant nebulae have contributed much evidence in its favor. An analysis of these observations indicates that the region surveyed is large enough to show us a fair sample of the universe, and this sample is homogeneous. . . .

We shall proceed quite differently at this point. As the physical laws cannot be assumed to be independent of the structure of the universe, and as conversely the structure of the universe depends upon the physical laws, it follows that there may be a stable position. We shall pursue this possibility that the universe is in such a stable, self-perpetuating state, without making any assumptions regarding the particular features which lead to this stability. We regard the reasons for pursuing this possibility as very compelling, for it is only in such a universe that there is any basis for the assumption that the laws of physics are constant; and without such an assumption our knowledge, derived virtually at one instant of time, must be quite inadequate for an interpretation of the universe and the dependence of its laws on its structure, and hence inadequate for any extrapolation into the future or the past.

Our course is therefore defined not only by the usual cosmological principle but by that extension of it which is obtained on assuming the universe to be not only homogeneous but also unchanging on the large scale. This combination of the usual cosmological principle and the stationary postulate we shall call the *perfect cosmological principle,* and all our arguments will be based on it. The universe is postulated to be homogeneous and stationary in its large-scale appearance as well as in its physical laws.

We do not claim that this principle must be true, but we say that if it does not hold, one's choice of the variability of the physical laws becomes so wide that cosmology is no longer a science. . . .

For the perfect cosmological principle to apply, one might at first sight expect that the universe would have to be static, i.e. to possess no consistent large-scale motion. This, however, would conflict with the observations of distant galaxies, and it would also conflict with the thermodynamic state which we observe. For such a static universe would be very different indeed from the universe we know. A static universe would clearly reach thermodynamical equilibrium after some time. An infinitely old universe would certainly be in this state. There would be complete equilibrium between matter and radiation, and (apart possibly from some slight variations due to gravitational potentials) everything would be at one and the same temperature. There would be no evolution, no distinguishing features, no recognizable direction of time. That our universe is not of this type is clear not only from astronomical observations but from local physics and indeed from our very existence. Accordingly there must be large-scale motions in our universe. The perfect cosmological principle permits only two types of motion, viz. large-scale expansion with a velocity proportional to distance, and its reverse, large-scale contraction.

In a contracting universe there would be even more radiation compared with matter than in a static universe. Therefore we reject this possibility and confine our attention to an expanding universe.

The observations of distant galaxies, which are now capable of a more rigorous interpretation by means of the perfect cosmological principle, inform us of the motion of expansion. This motion in which the velocity is proportional to the distance (apart from a statistical scatter) is well known to be of the only type compatible with homogeneity; but the compatibility with the hypothesis of a stationary property requires investigation. If w considered that the principle of hydrodynamic continuity were valid ove large regions and with perfect accuracy then it would follow that the mea density of matter was decreasing, and this would contradict the perfect cosmological principle. It is clear that an expanding universe can only be st tionary if matter is continuously created within it. The required rate o creation, which follows simply from the mean density and the rate o expansion, can be estimated as at most one particle of proton mass per lit per 10^9 years. . . .

We can now examine the requirements which the perfect cosmologic principle places on the evolution of stars and galaxies. The mean ratio o condensed to uncondensed matter has to stay constant, and for this reaso new galaxies have to be formed as older ones move away from eac other. . . . In opposition to most other theories we should hence expect find much diversity in the appearance of galaxies, as they will be of great different ages. . . . Furthermore the age distribution of galaxies in any vo ume will be independent of the time of observation, and it will hence be th same for distant galaxies as for near ones. . . .

45 / Cosmic Microwave Background Predicted

Working as a consultant at the Applied Physics Laboratory of Johns Hopkins University in Maryland in the late 1940s, the Russian-American theorist George Gamow came to work closely with Ralph Alpher and Robert Herman, two young employees at the lab who eagerly joined Gamow's crusade to study the physics of the Big Bang model of the cosmos. The trio were particularly interested in seeing if the elements were generated all at once out of the primordial plasma of the universe's fiery birth (see Chapter 44).

Along the way, Alpher and Herman came to predict that the present-day universe should be bathed in a uniform wash of radiation. The flood of highly energetic photons released in the aftermath of the Big Bang, they figured, should cool down with the expansion of the universe and appear today as centimeters-long microwaves. This momentous prediction had a curious debut. It was tucked away in a short *Nature* note, written to correct some errors that Gamow had made in a paper published two weeks earlier on the universe's evolution. In the very last sentence Alpher and Herman reported that the present-day microwave background should register a temperature of 5 K, five degrees on the Kelvin scale above absolute zero. (Today, it is measured at 3 K.) Over the next few years, the two young physicists went on to develop a detailed evolution of the newborn universe, work described as "the first thoroughly modern analysis of the early history of the universe."[51]

No one at the time did anything about their fascinating forecast of a cosmic microwave background or seemed to take note, despite its usefulness as a tool for deciding between the steady-state and Big Bang models of the universe then being debated (see Chapter 38). Perhaps it was because cosmology was still a young discipline skeptically regarded by mainstream astronomers, and radio astronomy, also in its infancy in 1948, had other pressing concerns. Gamow, Alpher, and Herman never pushed to make a search for the remnant echo of the primeval blast, and so the prediction fell into obscurity. Most astronomers forgot it altogether. The idea did not resurface until the 1960s and came to be verified serendipitously (see Chapter 63).

"Evolution of the Universe." *Nature*, Volume 162 (November 13, 1948)

by Ralph A. Alpher and Robert Herman

In checking the results presented by Gamow in his recent article on "The Evolution of the Universe" [*Nature* of October 30, p. 680], we found that his expression for matter-density suffers from the following errors: (1) an error of not taking into account the magnetic moments in Eq. (7) for the capture cross-section, (2) an error in estimating the value of α by integrating the equations for deuteron formation (the use of an electronic analogue computer leads to $\alpha = 1$), and (3) an arithmetical error in evaluating ρ_0 from Eq. (9). In addition, the coefficient in Eq. (3) is 1.52 rather than 2.14. Correcting for these errors, we find

$$\rho_{\text{mat.}} = \frac{4.83 \times 10^{-4}}{t^{3/2}}$$

The condensation-mass obtained from this corrected density comes out not much different from Gamow's original estimate. However, the intersection point $\rho_{\text{mat.}} = \rho_{\text{rad.}}$ occurs at $t = 8.6 \times 10^{17}$ sec. $\cong 3 \times 10^{10}$ years (that is, about ten times the present age of the universe). This indicates that, in finding the intersection, one should not neglect the curvature term in the general equation of the expanding universe. In other words, the formation of condensations must have taken place when the expansion was becoming linear with time.

Accordingly, we have integrated analytically the exact expression:

$$\frac{dl}{dt} = \left[\frac{8\pi G}{3}\left(\frac{aT^4}{c^2} + \rho_{mat}\right) l^2 - \frac{c^2 l_0{}^2}{R_0{}^2}\right]^{1/2}$$

with T $\propto$ $1/l$ and $R_0 = 1.9 \times 10^9 \sqrt{-1}$ light-years. The integrated values of $\rho_{\text{mat.}}$ and $\rho_{\text{rad.}}$ intersect at a reasonable time, namely, 3.5×10^{14} sec. $\cong 10^7$ years, and the masses and radii of condensations at this time become, according to the Jeans' criterion, $M_c = 3.8 \times 10^7$ sun masses, and $R_c = 1.1 \times 10^3$ light-years. The temperature of the gas at the time of condensation was 600° K., and the temperature in the universe at the present time is found to be about 5° K. . . .

63 / Evidence for the Big Bang

Casual readers of the July 1, 1965, issue of the *Astrophysical Journal* could easily have missed the article. Its title was fairly prosaic ("A Measurement of Excess Antenna Temperature at 4080 Mc/s"), and it was tucked away at the very end of the journal. Yet the one-page report was conveying one of the most important discoveries in twentieth-century astronomy. In their eight short paragraphs plus a note, Bell Telephone Laboratory researchers Arno Penzias and Robert Wilson were announcing the first definitive evidence for the Big Bang. The excess energy they had detected with their radio antenna—a background of microwaves filling the celestial sky—unexpectedly turned out to be the remnant echo of the explosive creation of our universe.

After Edwin Hubble discovered in 1929 that the cosmos was expanding (see Chapter 52), attention was soon focused on its origin. The expansion implied a beginning, a unique moment when space and time first emerged. Some scientists were unsettled by this notion of an initial cosmic bang and so offered an alternative cosmological theory: a universe in steady-state expansion, with neither a beginning nor an end (see Chapter 38). As the galaxies receded from one another, matter was spontaneously generated to form new galaxies, which meant the universe of the past would look very much like the universe of today. This was in stark contrast to the predicted behavior of a Big Bang universe, where galaxies would age and evolve over the eons. Moreover, a primeval explosion would have released a flood of energetic photons that eventually cooled down with the expansion and would currently appear as a faint glow of microwave radiation.

Ralph Alpher and Robert Herman, while working with George Gamow in the 1940s on models of element production in the Big Bang, were the first to suggest the presence of a cosmic microwave background. They figured that the overall temperature of the waning cosmic fire would by now have dropped to within several degrees of absolute zero (see Chapter 45). But no one followed up on the prediction, even though it provided a clear-cut means of deciding between the two opposing theories of creation. Cosmological tests were not a high priority in radio astronomy at the time, and so their calculation was eventually forgotten.

The idea did not resurface until the 1960s, when Robert Dicke and P. James E. Peebles at Princeton University, as well as Yakov Zel'dovich in the Soviet Union, again reasoned that residual heat from the Big Bang must be permeating the universe. Peebles figured it was "as low as 3.5° K."[33] Dicke and several colleagues began constructing the equipment to measure this radiation, but in the process of setting up their antenna on a campus rooftop they learned that they had been scooped; by chance, two radio astronomers with Bell Labs had already been listening to the weak cosmic hiss.

In 1964 Penzias and Wilson had begun to calibrate a massive horn-shaped antenna, three stories high, located in Holmdel, New Jersey, not far from the site where Karl Jansky first detected celestial radio waves. They were converting the receiver, originally used for satellite communications, into a radio telescope to study our galaxy. During their initial tests, they consistently registered an excess signal, no matter where the instrument was pointed. They spent months investigating possible sources, from atmospheric radiation to electromagnetic noises emanating from nearby New York City. They even cleaned up pigeon droppings within the antenna to rule out biological interference.

Despairing that he and Wilson would ever locate the origin of the noise, Penzias chanced to mention the problem to a friend, who knew of the plan under way at Princeton to search for a cosmic microwave background. Penzias soon invited the Princeton group to visit the Holmdel installation, just a few dozen miles from the university, whereupon it was confirmed that Penzias and Wilson had indeed been listening to the faint reverberation of the Big Bang all along. Their initial report focused solely on all the possible sources contributing to their reception. They refer to a companion article by Dicke and his colleagues in the same journal issue for an explanation of the cosmological consequences of "the remaining unaccounted-for antenna temperature."

Others had actually detected the cosmic noise earlier. In 1941 the Canadian astronomer Andrew McKellar recognized that cyanogen (CN) molecules in space were being energized by a thermal background of about 2.3 K, but he failed to understand the implications of his find.[34] Others wrote off the extra heat as a systematic error in their instrumentation.

Since Penzias and Wilson's discovery, the cosmic microwave background has been measured from both the ground and space with ever finer precision. The Cosmic Background Explorer satellite (COBE), launched by NASA in 1989, detected a Big Bang afterglow of 2.7 degrees above absolute zero on the Kelvin scale, with an uncertainty of only 0.01 K.[35]

"A Measurement of Excess Antenna Temperature at 4080 Mc/s." *Astrophysical Journal*, Volume 142 (July 1, 1965)

by Arno A. Penzias and Robert W. Wilson

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s [million cycles per second] have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson in a companion letter in this issue.[36]

The total antenna temperature measured at the zenith is 6.7° K of which 2.3° K is due to atmospheric absorption. The calculated contribution due to ohmic losses in the antenna and back-lobe response is 0.9° K.

The radiometer used in this investigation has been described elsewhere.[37] It employs a traveling-wave maser, a low-loss (0.027-db) comparison switch, and a liquid helium-cooled reference termination. Measurements were made by switching manually between the antenna input and the reference termination. The antenna, reference termination, and radiometer were well matched so that a round-trip return loss of more than 55 db existed throughout the measurement; thus errors in the measurement of the effective temperature due to impedance mismatch can be neglected. The estimated error in the measured value of the total antenna temperature is 0.3° K and comes largely from uncertainty in the absolute calibration of the reference termination.

The contribution to the antenna temperature due to atmospheric absorption was obtained by recording the variation in antenna temperature with elevation angle and employing the secant law. The result, 2.3° ± 0.3° K, is in good agreement with published values.

The contribution to the antenna temperature from ohmic losses is computed to be 0.8° ± 0.4° K. In this calculation we have divided the antenna into three parts: (1) two non-uniform tapers approximately 1 m in total length which transform between the 2⅛-inch round output waveguide and the 6-inch-square antenna throat opening; (2) a double-choke rotary joint located between these two tapers; (3) the antenna itself. Care was taken to clean and align joints between these parts so that they would not significantly increase the loss in the structure. Appropriate tests were made for leakage and loss in the rotary joint with negative results.

The possibility of losses in the antenna horn due to imperfections in its seams was eliminated by means of a taping test. Taping all the seams in the section near the throat and most of the others with aluminum tape caused no observable change in antenna temperature.

The back-lobe response to ground radiation is taken to be less than 0.1° K for two reasons: (1) Measurements of the response of the antenna to a small transmitter located on the ground in its vicinity indicate that the average back-lobe level is more than 30 db below isotropic response. The horn-reflector antenna was pointed to the zenith for these measurements, and complete rotations in azimuth were made with the transmitter in each of ten locations using horizontal and vertical transmitted polarization from each position. (2) Measurements on smaller horn-reflector antennas at these laboratories, using pulsed measuring sets on flat antenna ranges, have consistently shown a back-lobe level of 30 db below isotropic response. Our larger antenna would be expected to have an even lower back-lobe level.

From a combination of the above, we compute the remain unaccounted-for antenna temperature to be 3.5° ± 1.0° K at 4080 Mc/s. connection with this result it should be noted that DeGrasse *el al.*[38] Ohm[39] give total system temperatures at 5650 Mc/s and 2390 Mc/s, resp tively. From these it is possible to infer upper limits to the background te peratures at these frequencies. These limits are, in both cases, of the sa general magnitude as our value.

Note added in proof.—The highest frequency at which the ba ground temperature of the sky had been measured previously was 4 Mc/s, where a minimum temperature of 16° K was observed. Combin this value with our result, we find that the average spectrum of the ba ground radiation over this frequency range can be no steeper than $\lambda^{0.7}$. T clearly eliminates the possibility that the radiation we observe is due radio sources of types known to exist, since in this event, the spectr would have to be very much steeper.

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Note added in proof.—The highest frequency at which the background temperature of the sky had been measured previously was 404 Mc/s, where a minimum temperature of 16° K was observed. Combining this value with our result, we find that the average spectrum of the background radiation over this frequency range can be no steeper than $\lambda^{0.7}$. This clearly eliminates the possibility that the radiation we observe is due to radio sources of types known to exist, since in this event, the spectrum would have to be very much steeper.

64 / Pulsars

The first neutron star was found in 1967, a discovery that came as a complete surprise. No one had ever imagined that a compact star—a mere dozen miles wide—would be emitting clocklike radio pulses. "No event in radio astronomy seemed more astonishing and more nearly approaching science fiction," said the British radio-astronomy pioneer James S. Hey.[40]

That neutron stars might exist was not unforeseen. Theorists had been contemplating their creation since the 1930s; they were pictured as the compressed stellar cores left behind after supernova explosions (see Chapter 41). But no one seriously thought neutron stars would be detected, since calculations showed them to be so small. In a 1966 paper on such "superdense stars," general relativist John Archibald Wheeler figured the only opportunity to catch sight of this "nuclear matter in bulk" would be immediately after a stellar explosion (a rare event in our galaxy), when the remnant core was still hot and fiercely emitting a host of electromagnetic radiations.[41]

But within a year this opinion was completely overturned by British radio astronomers, who stumbled upon a neutron star by accident. Their report in the journal *Nature*, terse and dense with scientific data, offers few details on the serendipity that led to their finding. A small platoon of students and technicians, led by Cambridge University radio astronomer Antony Hewish, had just completed the construction of a sprawling radio telescope near the would certainly be in this state. There would be complete equilibrium between matter and radiation, and (apart possibly from some slight variations due to gravitational potentials) everything would be at one and the same temperature. There would be no evolution, no distinguishing features, no recognizable direction of time. That our universe is not of this type is clear not only from astronomical observations but from local physics and indeed from our very existence. Accordingly there must be large-scale motions in our universe. The perfect cosmological principle permits only two types of motion, viz. large-scale expansion with a velocity proportional to distance, and its reverse, large-scale contraction.

In a contracting universe there would be even more radiation compared with matter than in a static universe. Therefore we reject this possibility and confine our attention to an expanding universe.

The observations of distant galaxies, which are now capable of a more rigorous interpretation by means of the perfect cosmological principle, inform us of the motion of expansion. This motion in which the velocity is proportional to the distance (apart from a statistical scatter) is well known to be of the only type compatible with homogeneity; but the compatibility with the hypothesis of a stationary property requires investigation. If we considered that the principle of hydrodynamic continuity were valid over large regions and with perfect accuracy then it would follow that the mean density of matter was decreasing, and this would contradict the perfect cosmological principle. It is clear that an expanding universe can only be stationary if matter is continuously created within it. The required rate of creation, which follows simply from the mean density and the rate of expansion, can be estimated as at most one particle of proton mass per liter per 10^9 years. . . .

We can now examine the requirements which the perfect cosmological principle places on the evolution of stars and galaxies. The mean ratio of condensed to uncondensed matter has to stay constant, and for this reason new galaxies have to be formed as older ones move away from each other. . . . In opposition to most other theories we should hence expect to find much diversity in the appearance of galaxies, as they will be of greatly different ages. . . . Furthermore the age distribution of galaxies in any volume will be independent of the time of observation, and it will hence be the same for distant galaxies as for near ones. . . .

39 / White Dwarf Stars

By the early decades of the twentieth century, astronomers had come to recognize a wide range of stellar sizes and types—from the large, white-hot O and B stars to the smaller and cooler M dwarf stars. What they didn't anticipate was a star the size of the Earth.

The first clue toward this revelation emerged between 1834 and 1844 when Friedrich Wilhelm Bessel, who also measured the first distance to a star (see Chapter 19), noticed that the bright star Sirius had a wavelike motion as it journeyed through the heavens. He reasoned that Sirius had an unseen companion that was gravitationally tugging on it. In 1862 the American telescope maker Alvan Clark Jr., while testing a new refractor, finally saw this dim companion. From its orbital movements, astronomers were able to determine that Sirius B weighed a solar mass, even though its light output was less than a hundredth of our Sun's. At the time they just figured it was a sunlike star cooling off at the end of its life.

That assessment would dramatically change in 1915 when Walter Adams at the Mount Wilson Observatory in California at last secured a spectrum of the faint light emanating from Sirius B, a difficult task due to the overwhelming brightness of the primary star. Even though the companion star was very dim, Adams was surprised to see that it displayed the spectral features of an intensely hot A star—at 25,000 K far hotter than our Sun. Adams knew that it wasn't