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EDWIN POWELL HUBBLE

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A Biographical Memoir by

N. U. MAYALL

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EDWIN HUBBLE, by his inspired use of the largest telescope of his time, the 100-inch reflector of the Mount Wilson Observatory, revolutionized our knowledge of the size, structure, and properties of the universe. He thus became the outstanding leader in the observational approach to cosmology, as contrasted with the previous work that involved much philosophical speculation. Although he regarded himself primarily as an observational astronomer assembling and analyzing empirical data, Hubble, from the very beginning of his astronomical career, took the widest possible view of the relationship of his investigations to the general field of cosmology. Indeed, Edwin Hubble advanced the astronomical horizon on the universe by steps relatively as large in his time as those taken by Galileo in his studies of the solar system, and by the Herschels in their investigations of our own Milky Way stellar system.

PERSONAL HISTORY

In a conversation with the author Bernard Jaffe, Hubble is reported to have said that the best biographical memoir of a scientist would be written if each man set down, as well as he could, the way he came to do the work he did. In this way his work would be separated completely from the man's own personal history, which Hubble thought need not enter the picture. Jaffe is reported to have replied that the personal side also had value, possibly in reflecting the effect of the man's times and environment in determining what he went about doing.

Since Hubble firmly kept his personal history in the background, there is little about it in the literature of astronomy. Through the generosity of Mrs. Hubble, however, the present writer was given access to her journals, which form an important part of the collection of biographical materials in the Huntington Library, San Marino, California. These journals contain a wealth of information, enough for a biography of much greater scope than this memoir. From the many events and experiences described so perceptively and understandingly in the journals, a selection has been made of some that seem especially revealing of Hubble's character and philosophy. In many cases the wording follows closely that of the journal entries, particularly when they quote Hubble's remarks. The verbatim record should be accurate, since Hubble himself read, corrected, and made suggestions, such as, for example, "The next time at camp there should be more about fish."

The Hubble family for many generations produced pioneering and patriotic individuals. Hubble's ancestors were from the British Isles; Richard Hubble, an officer in the Royalist army, came to the United States in the seventeenth century. About him Hubble remarked, "I was always glad that he waited until after the king was beheaded . . . whenever there was trouble in England someone of the family left in a hurry." Richard settled in Connecticut, prospered, and left five thousand dollars to each of his eleven children, "a good deal of money in the seventeenth century," Hubble commented. Justus Hubble, one of Edwin's forefathers, fought in the Revolutionary War and later settled in Virginia. At the time of the Civil War the family was divided in its loyalty. Edwin's paternal grandfather joined the Union army, while other members of the family fought for the Confederates. Edwin's mother was Virginia Lee James, from Virginia City, Nevada, and his father was John Powell Hubble, from Missouri, where Edwin himself was born in Marshfield on November 20, 1889, during a visit of the parents to his grandparents. Hubble, however, said later that he would rather have been born in Kentucky, where his relatives had been living and where his ancestors had established themselves. There were seven children in the family, three brothers and four sisters; Edwin was the fifth child and the second son.

Among the many pleasant childhood memories Hubble recalled were long country wanderings spent in watching birds and animals, swimming, and ice skating. He was expected to obey at once, without questioning. He was spanked when small, and had "good lickings" when older. In later years he approved of this discipline, saying, "It did me a lot of good." He liked and read many books, such as novels by Jules Verne and H. Rider Haggard, especially *King Solomon's Mines*. His father was connected with an insurance company; he had his office in Chicago and settled his family in suburban Wheaton, where many years later Grote Reber carried out his pioneering research in radio astronomy. Young Edwin corresponded with his grandfather, who once wrote to his twelve-year-old grandson to ask some questions about Mars. The reply so pleased the grandfather that he had it printed in a Springfield newspaper.

Like many other youngsters, Edwin earned his first money by delivering morning papers in Wheaton. At Wheaton High School he participated actively in athletics, with football as his favorite game, although he also entered many track events. In a later year Mrs. Hubble once was surprised by her husband's exact estimate of her height of 5 feet 4 inches. Hubble's explanation was, "I was a high jumper, my dear." On his high school commencement day in 1906, the principal said, "Edwin Hubble, I have watched you for four years and I have never seen you study for ten minutes." He then paused for what was an awful moment for Edwin, and continued, "Here is a scholarship to the University of Chicago."

By a mistake, this high school scholarship was also awarded to another student, thus the money had to be halved, and Edwin had to supply the rest. He paid his expenses by tutoring, by summer work, and, in his junior year, by a scholarship in physics and by working as a laboratory assistant to Robert Millikan. When Edwin left home his mother asked him to give up football. Instead he played basketball, and in 1909 was on the team that won the championship of the West. He also took up college boxing and was so successful that promoters urged him to turn professional and train to fight the heavyweight champion, Jack Johnson. He received a college letter in athletics for his participation in track, boxing, and basketball.

During summer vacations he worked as a surveyor and civil engineer in the woods around the Great Lakes, in the regions where railroads were competing for rights-of-way to iron mines. At that time the border towns were very rough; one evening when walking through the railroad yards, Edwin was held up by two ruffians. He laughed at them, walked on past, but was stabbed in the back below his shoulder. He turned and knocked one man out, while the other ran away. Another time, two girls stopped him to ask help in getting a drunken lumberjack from a bridge. Edwin's friendly words changed the drunken man's challenging mood to one of affection, so he was able to get the lumberjack home, where the man's wife thought Edwin was responsible for her husband's state. At the end of one summer he and another worker were the last to leave, but by a change of schedule they were left waiting in vain at the railroad station, without provisions. They walked out of the woods in three days, without food, although Edwin said, "We could have killed a porcupine or small game, but there was no need, and anyway, there was plenty of water." The experience gained from his work as a surveyor later served him well during World War II at Aberdeen, where he laid out the firing and bombing ranges for ballistic research.

In 1910 Hubble received his B.S. degree from the University of Chicago, and in the same year was awarded a Rhodes Scholarship, under which he read Roman and English Law at Queen's College, Oxford. In athletics he was an Oxford Blue, taking part in track and boxing and rowing stroke in the Queen's boat. Some years later he was made an Honourary Fellow of Queen's College. He returned to the United States in 1913, passed the bar examination September 2, and practiced law halfheartedly for a year thereafter in Louisville, Kentucky. He reported that at this time he "chucked the law for astronomy, and I knew that even if I were second-rate or third-rate, it was astronomy that mattered." Thus in 1914 he returned to the University of Chicago for postgraduate work leading to his doctoral degree in astronomy. He found congenial men among the faculty—Millikan, Gale, Michelson, Breasted, and Moulton. Hubble's undergraduate experiences were helpful to him when he was asked to serve as head of Snell Hall, which had the reputation of housing the toughest campus elements. "They never gave any trouble," Hubble recalled, "partly perhaps because I had been a C man and because I boxed." He had, in fact, appeared in an exhibition bout with the French champion, Carpentier.

During his graduate student days at Yerkes Observatory he once strolled down to a lakeside pier, where a professor and his wife also were walking. She fell in and Edwin dived in to help her out. She struggled and grabbed him, but Hubble related that "I didn't like to knock her out, so as the water was not too deep, I set her on my shoulders, which just brought her head above the surface while I walked underwater until it became shallow and I could put her down on the shore. I thought it odd," he added reflectively, "that her husband showed no warmth in his thanks, nor did he seem particularly glad to see her."

While finishing work for his doctorate early in 1917, Hubble was invited by Hale to join the staff of the Mount Wilson Observatory, Pasadena, California. Although this was one of the greatest of astronomical opportunities, it came in April of that fateful year. After sitting up all night to finish his Ph.D. thesis, and taking the oral examination the next morning, Hubble enlisted in the infantry and telegraphed Hale, "Regret cannot accept your invitation. Am off to the war."

Hubble was commissioned a captain in the 343d Infantry, 86th Division, and later became a major. His first assignment was to take discards (many of whom were AWOL's), called "replacements," to camp. An armed guard brought two men to the station in handcuffs. Edwin said, "I have enough to do without looking after you. Take the handcuffs off these men." In return the grateful men offered to inspect food supplies for bulged tins (of spoiled food), since they were experts after so much KP. The result was that there were no food-poisoning cases on the long, slow train trip. The train arrived with no deserters, no sick men, and no men unaccounted for.

The official history of the 86th Division relates the following story. One of the commanding general's standing orders was that, when he met an officer, the latter should stop work, stand at attention, salute, give his name and rank, and account for the activities of the moment. One morning Edwin was riding a bicycle on the drill field and saw the general. He dismounted, saluted, and said, "Good Morning, General, nice day, sir." The general snapped, "Major, can it be that you do not know what my orders stipulate on the procedure to be taken by an officer whom I meet?" The major looked the general squarely in the eyes, saluted, hopped on the bike, and said, "Sir, Major Hubble, 86th Infantry, getting on his bicycle and riding away." On another occasion at a dinner of civilians in Rockford, his hostess challenged him to inspect her kitchen for cleanliness, because he had said army standards were very high. He reluctantly agreed, so with guests and hostess looking on, he took out a white handkerchief and wiped the inside of a stove leg, the joint between blade and handle of a knife, and the electric light cord, all of which produced black marks. "This," he said, "is a test for army kitchens," and afterwards doubted if his hostess ever forgave him.

Hubble was sent to France where he served as a field and line officer. Early in November 1918 he was injured by a bursting shell, from which he suffered a concussion and some damage to his right elbow. After the armistice he was called to serve as a judge advocate on courts-martial because of his Oxford law degree, and later he became administrative head of the American officers assigned to the universities of Oxford, Cambridge, and Wales.

He returned to the United States in the summer of 1919, was mustered out in San Francisco, and went immediately to Pasadena, California. Although he deplored the evils of war, he nevertheless admitted enjoying army life. He liked the plain hard living under campaign conditions, the simple rations, the discipline and adventure, and the living and working together with fighting men. He took no war insurance, no pensions, no wound remuneration, or allowance of any kind. He kept only his tin hat, the crossed rifles of the 343d Infantry, the gold maple leaves of a major, and a German trench dagger "to cut the pages of French books."

On February 26, 1924, Edwin Hubble and Grace Burke were married in Pasadena, California. Mrs. Hubble recalls that the first description of her future husband was given to her by W. H. Wright, at that time Astronomer in the Lick Observatory. "He is a hard worker," he said, "he wants to find out about the universe; that shows how young he is."

Hubble worked at the Mount Wilson Observatory until the summer of 1942, when he left to do war work at the Aberdeen Proving Ground. He has described his assignment in the following manner: "Some time after Pearl Harbor, while I was trying to get back into the Infantry, I was called in by Army Ordnance and told, in effect, to stop that nonsense, that I had been ear-marked long before for a job in Ordnance. . . . My name, they told me, was top of the list because ballistics had a curious affinity with astronomy, and, moreover, as a line officer in the last war I might appreciate the significance of some of the problems as viewed from positions in front of the guns as well as behind the guns. . . . I rushed to a dictionary. Ballistics, it seemed, is the science of hurling missiles against an enemy. This seemed a trifle thin so I turned to the encyclopaedia; there I found a long article, but it puzzled me. Ballistics was either underdeveloped or highly classified. So I went to Aberdeen, partly to find out. . . . I found out. . . . Ballistics was both underdeveloped and highly classified." At the Ballistics Research Laboratory, Aberdeen Proving Ground, Hubble was Chief of Exterior Ballistics and Director of the Supersonic Wind Tunnel. In a letter to Mrs. Hubble, September 2, 1942, Hubble wrote: "I am more and more impressed with the place. It is not the home of genius but it knows the answers to many problems and how to get the answers for others. And best of all, it fights for high standards—when a conclusion is reached and a statement formulated, you treat it with respect or get into trouble." For his valuable service to his country during the war he was awarded the Medal of Merit in 1946.

After World War II Hubble returned to his position at the Mount Wilson Observatory where his research, so brilliantly carried out between two world wars, had provided strong evidence of the need for a telescope larger than the 100-inch reflector. He had assisted greatly in the design of the 200-inch Hale telescope, and had served on the Mount Wilson Observatory Advisory Committee for building the Mount Palomar Observatory. "With the 200-inch," he said in a BBC broadcast in London, "we may grasp what now we can scarcely brush with our fingertips." As Chief of Research, he planned in advance a broad program for this great instrument. "What do you expect to find with the 200-inch?" he was asked, and he replied, "We hope to find something we hadn't expected."

Hubble was also active in his community. He was elected to the Board of Trustees of the Huntington Library, as successor to George Ellery Hale, and he served on this Board from 1938 until his death. He organized the Los Angeles Committee on Foreign Relations and served as a member and its chairman.

He was elected to the National Academy of Sciences in 1927.

Hubble had considerable foresight not only in matters pertaining to astronomy but also in political and international affairs. He recognized very early that the European policy of appeasement in the 1930s was doomed to failure, and that this country would again be drawn into war. When Germany committed her first acts of aggression, he said, "This is a world war and we are in it." In the months preceding the U.S. entry into the war, he made many speeches throughout the country, and he advocated immediate participation by the United States as an ally of Great Britain. In October 1941 Hubble was introduced to two visiting Englishmen as "Pro-British," to which he replied, "Hell, I'm for civilization."

Hubble was an accomplished and eloquent speaker, well able to hold the attention of his audience. An interesting example of this ability occurred in Pasadena after a very damaging earthquake in March 1933. The guests at the Huntington Hotel had panicked and were agitatedly canceling their reservations and trying to leave as soon as possible. The hotel manager, a friend of Hubble, called him to come over in order to try to calm the guests. Hubble suggested getting a man from the Cal Tech Seismology Laboratory, but the manager insisted that he wanted Hubble because he "could give them confidence." Hubble agreed and told his audience they were fortunate to have experienced an earthquake without suffering any damage. He described the geological history of southern California, the locations of the major faults, and explained that damage occurred in poorly planned and constructed buildings. He told his audience that they need have no fear about the hotel falling down, because he and the manager had inspected it that morning. What he did not tell them was that his own house and the hotel were built on an earthquake fault, later named the "Huntington-Hubble" fault by a geologist at Cal Tech. Hubble's talk at the hotel saved the season.

Hubble had a deep interest in science and philosophy, and he gave his library to the Mount Wilson Observatory. He had collected many books covering his three principal interests: Nicolas de Cusa (1401-1464), Giordano Bruno (1548-1600), and selections from Chinese science and philosophy.

Hubble was a very skillful dry-fly fisherman and did much fishing in this country in the Rockies, in England on the River Test at Longstock, and at Bossington House near Stockbridge. In July 1949, while fishing in the Rockies, he suffered an attack of coronary thrombosis. In May 1953 Hubble went to England, where he gave the George Darwin Lecture, the Cormac Lecture of the Royal Society of Scotland, and a lecture before the Royal Institution of Great Britain. In Paris he attended a meeting of the Institut de France, of which he was a member. He came back to Bossington House, the residence of his friend Sir Richard Fairey. Upon his return home, he continued his researches at the Mount Wilson and Palomar Observatories, where he was active until the time of his death, from a cerebral thrombosis, on September 28, 1953.

RÉSUMÉ OF RESEARCH

In order truly to appreciate the remarkable contributions to the field of extragalactic research made by Edwin Hubble, it is necessary to review briefly the state of this knowledge in the early part of the twentieth century. About 1900 only speculation as to the nature of the thousands of faint nebulous objects was available. Nebular research in the eighteenth and nineteenth centuries was restricted primarily to the cataloguing of these faint objects. With the application of photography, spectrographs, and telescopes of increasingly larger size to the study of the nebulae, several different types of objects were differentiated. A large number of these made up the group called "extragalactic nebulae" by Hubble, who never accepted the term "galaxy" to describe them. These small, usually symmetrical objects, found everywhere in the sky, except in the plane of the Milky Way, were beyond the limit of detailed study with small or moderate-sized telescopes in operation during the first two decades of the twentieth century.

Toward the end of 1923, Hubble, using the 100-inch reflecting telescope on Mount Wilson, was able to resolve several of the largest spiral nebulae into stars. In particular, among the brighter resolved stars Hubble was able to identify some having characteristics identical to a type of variable stars called Cepheids. These objects had been recognized and carefully studied in our own galaxy and in the Magellanic Clouds, and their intrinsic brightnesses, or luminosities, were known with order-of-magnitude accuracy. Thus, by measuring the apparent brightnesses of these Cepheids in a few of the largest extragalactic nebulae, and by knowing the luminosities of these variables, Hubble determined the first reliable extragalactic distances, which were of the order of a million light-years—far greater than any previously measured. He then extended this research to determinations of secondary distance criteria, such as estimates of luminosities of the brightest nonvariable stars in spiral nebulae, and finally of the total luminosities of the nebulae themselves, which provided a distance indicator so bright as to be useful for distances hundreds of times greater than those measurable by Cepheids. With these observationally developed methods of distance measurement, he was able to sound the depths of space to distances out to 500 million light-years.

Hubble combined his results on extragalactic distances with the radial velocities from the pioneering spectroscopic work of V. M. Slipher on bright nebulae, and with those from the work on fainter ones by his colleague Milton Humason, to develop a relationship between distance and velocity of recession for these extragalactic nebulae. The straight line relationship between these observational quantities, now known as Hubble's law of red-shifts, had immediate and far-reaching influence on all subsequent cosmological theories, particularly those given by Einstein's theory of relativity.

Hubble's observational approach to the study of extragalactic nebulae is set forth in his classical book *The Realm of the Nebulae,* based on his Silliman Lectures given at Yale in 1935. This monograph, first published in 1936, met with immediate acclaim from both scientific and lay readers. Sir James Jeans's review of Hubble's book, the first review he had consented to write in ten years, states: "The author sets to work to record, in simple language and with much charm, the story of the recent enlargement of the visible universe. . . . It is a chapter of scientific history which has stirred the imagination not only of professional astronomers but also of the public at large. . . . Such is the arresting feast of 'plums' which Dr. Hubble might have served up in sensational setting had he elected to play the sensation-monger. He has preferred, and we will all thank him, to give a straight-forward record of patient and often laborious work, carried through with a skill, persistence and flair which often reminds us of Faraday. He sees the whole exploration as 'a case history of scientific research in a rather simple form,' and this determines the style of his record."

In the preface to a 1958 reprint of this book, Allan R. Sandage wrote: "*The Realm of the Nebulae* is important because it is still a source of inspiration in the scientific methods in this field. . . . Of course many of the details of the subject have changed since 1936 . . . but these are changes in numerical detail and not in fundamental philosophy or direction of attack. Hubble's original approach to observational cosmology remains."

In addition to his renowned study of the red-shifts of nebulae, Hubble undertook a detailed and comprehensive study of the nebulae as individuals, and he set up in 1926 a classification system generally used as the standard to the present time. A revision of this system based on manuscript notes left by Hubble has recently been included by Allan Sandage in his discussion of the magnificent collection of photographs reproduced in *The Hubble Atlas of Galaxies* (Carnegie Institution of Washington, Publication No. 618, 1961).

SCIENTIFIC WORK

In addition to being an active observer in astronomical research, Hubble also was a keen student of the history of science. He collected many books on this subject, because he held the opinion that, whenever possible, one should go to the original source materials; books written by the men themselves were of greater interest and significance than books written about them. In deference to his opinion, this account of his multifarious contributions to astronomy will consider chronologically his most outstanding papers, with copious use of his own words because they are so well chosen.

1920: "Photographic Investigations of Faint Nebulae." "Extremely little is known of the nature of nebulae, and no significant classification has yet been suggested; not even a precise definition has been formulated. The essential features are that they are situated outside our solar system, that they present sensible surfaces, and that they should be unresolved into separate stars. . . . Some at least of the great diffuse nebulosities . . . lie within our stellar system; while others, the great spirals, with their enormous radial velocities and insensible proper motions apparently lie outside our system." Thus Hubble summarized the state of knowledge of nebulae in the year 1920. This paper, based on his doctoral dissertation, deals with a statistical study of the "numerous small faint nebulae, vague markings on the photographic plate, whose very forms are indistinct." Hubble studied several clusters of these small, faint nebulae that he had discovered by photographing fields with the 24-inch reflector of the Yerkes Observatory. Until this time only 76 nebulae were known in clusters; Hubble added 512 more in seven well-defined clusters. These objects he classified according to form, brightness, and size, and he measured their positions accurately.

Hubble went on to estimate the minimum sizes of these objects by reasoning that "the spirals form a continuous series from the great nebula of Andromeda to the limit of resolution, the small ones being much more numerous. Considering them to be scattered at random as regards distance and size, some conception may be formed of their dimensions from the data at hand. The average radial velocity of those so far observed is about 400 km/sec, while the proper motion is negligible. Putting the annual proper motion at 0″.05 the lower limit of the average distance is found to be 7500 light years. If they are within our sidereal system, then, as they are most numerous in the direction of its minimum axis, the dimensions of our system must be much greater than commonly supposed." Hubble continued with an estimate of the velocity of escape from a spiral, which he found to be comparable to that of the galaxy. Thus he concluded, "Considering the problematic nature of the data, the agreement is such as to lend some color to the hypothesis that the spirals are stellar systems at distances to be measured often in millions of light years."

1922: "A General Study of Diffuse Galactic Nebulae." This paper contains a wealth of information concerning the galactic nebulae, obtained by Hubble with the Mount Wilson telescopes. In it Hubble laid the cornerstone upon which rest many contemporary theories of the nature of galactic nebulae. By first setting up an unambiguous classification system of nebulae "based upon the fundamental differences between galactic and non-galactic nebulae," and by subdividing the galactic nebulae into planetary and diffuse (in turn subdivided into luminous and dark), Hubble paved the way to a piercing analysis of both the distribution of galactic nebulae and the origin of their luminosity. The following excerpt is quoted not only for its basic importance in the study of galactic nebulae but also because it is a typical example of the mastery of scientific thought, ease, and clarity of style characteristic of all of Hubble's writings.

"Association of Galactic Nebulosity with Stars—This intimate relation between spectral type of nebula and of involved stars raises a presumption that one is a consequence of the other. It seems more reasonable to place the active agency in the relatively dense and exceedingly hot stars than in the nebulosity, and this leads to the suggestion that nebulosity is made luminous by radiation of some sort from stars in certain physical states. The necessary conditions are confined to certain ranges in stellar spectral type and hence are possibly phenomena of effective temperature. The nebulous material itself must be in a physical state sensitive to the stellar radiation, and close enough for the density of radiation to be effective. The abrupt transition from emission to 'continuous' nebulosity between spectral type B0 and B1 suggests a critical point in the spectral sequence or possibly effective temperature below which stellar radiation is incapable of exciting nebulous material to emission luminosity. From thence down the spectral sequence the luminosity gives a continuous spectrum and probably partakes more and more of the nature of reflected light." More than forty years later, this conclusion still stands, except that the large amount of subsequent work indicates the division into emission and reflection nebulae is not so sharp.

1922: "The Source of Luminosity in Galactic Nebulae." Hubble continued his study of galactic nebulae in this paper, and he presented the observational evidence necessary to support his theory of the source of luminosity of galactic nebulae described in the above quotation. To test his theory he obtained for 82 nebulae data on angular extent of the nebulosity as a function of the apparent brightness of the stars associated with them. For nebulae showing continuous spectra, Hubble reported the general conclusion from this investigation: "Within the errors of observation, the data can be represented on the hypothesis that diffuse nebulae derive their luminosity from involved or neighboring stars and that they re-emit at each point exactly the amount of light radiation which they receive from the stars. Where stars of sufficient brightness are lacking in the neighborhood, or, if present, are not properly situated to illuminate the nebula as seen from the earth, the clouds of material present themselves as dark nebulosity." The second section of this paper is devoted to a study of planetary nebulae, for which he shows that the luminosities of planetaries do not follow the relation found for galactic nebulae.

1925: "NGC 6822, a Renote Stellar System." With this paper Hubble returned to the field of extragalactic nebulae. In this "faint irregular cluster of stars with several small nebulae involved," Hubble was able to identify eleven variables as Cepheids. By using the period-luminosity relation, he found a distance of 214,000 parsecs for this object. From star counts and measurements of surface brightnesses he determined the absolute luminosity and the mean density of the system, and compared it with the Magellanic Clouds. The importance of this study for the extragalactic distance scale is clearly stressed by Hubble himself in his conclusion:

"The present investigation identifies NGC 6822 as an isolated system of stars and nebulae of the same type as the Magellanic Clouds, although somewhat smaller and much more distant. A consistent structure is thus reared on the foundation of the Cepheid criterion, in which the dimensions, luminosities and densities, both of the system as a whole and of its separate members, are of orders of magnitude which are thoroughly familiar. The distance is the only quantity of a new order.

"The principle of the uniformity of nature thus seems to rule undisturbed in this remote region of space. This principle is the fundamental assumption in all extrapolations beyond the limits of known and observable data, and speculations which follow its guide are legitimate until they become self-contradictory. It is therefore a matter of considerable importance that familiar relations are found to be consistent when applied to the first system definitely assigned to the regions outside the galactic system.

"Of especial importance is the conclusion that the Cepheid criterion functions normally to this great distance. Cepheid variables have recently been found in the two largest of the spiral nebulae, and the period-luminosity relation places them at distances even more remote than NGC 6822. This criterion seems to offer the means of exploring extra-galactic space; NGC 6822 furnishes a critical test of its value for so ambitious an undertaking and the results are definitely in its favor."

1926: "A Spiral Nebula as a Stellar System: Messier 33." Hubble continued his study of the nearest nongalactic nebulae by using "the highest resolving power available—the full aperture of the 100-inch reflector working under exceptionally fine conditions of mirror surface and seeing." His results, as presented in this paper and the following one, were epoch-making. A study of the plates clearly established the stellar appearance of the images of the condensations: "They are as small and as sharp as those of ordinary stars of the same magnitude. The two most successful plates, each of 30 minutes exposure . . . show images with angular diameters smaller than any previously obtained on any astronomical photograph." On the collection of photographs available to him, Hubble was able to identify forty-five variables and two novae. Thirty-five of the variables were shown to be typical Cepheids; using the period-luminosity relation, Hubble found a distance about 8.1 times that of the small Magellanic Cloud. Hubble emphasized that "hitherto, wherever Cepheids have been found in isolated systems, the criterion has led to distances entirely consistent with other characteristics that could be observed. . . . Here also, the period-luminosity relation functioned normally and the order of resulting distances was confirmed by several independent criteria. A presumption is thus raised in favor of the general validity of the Cepheid criterion, which only strong and cumulative evidence to the contrary will destroy."

1926: "Extra-Galactic Nebulae." In Part I of this paper

Hubble set forth his classification of nebulae, with detailed discussion of his classification of extragalactic nebulae. He emphasized that "the basis of the classification is descriptive and entirely independent of any theory." The photographs of typical elliptical, irregular, normal, and barred spirals appearing in this paper are perhaps the most familiar set of photographs in present-day astronomy books. This classification system, later revised by Hubble, and completed by Sandage after Hubble's death, is the standard system used today.

Part II of this paper contains a statistical study of some 400 extragalactic nebulae. Hubble reported that "the various types are homogeneously distributed over the sky, their spectra are similar, and the radial velocities are of the same general order. These facts, together with the equality of the mean magnitudes and the uniform frequency distribution of magnitudes, are consistent with the hypothesis that the distances and absolute luminosities as well are of the same order for the different types. This is an assumption of considerable importance, but unfortunately it cannot yet be subjected to positive and definite tests."

Hubble next proceeded to give detailed analyses of the relations between luminosities and diameters of spiral and elliptical nebulae. He reported that "among the nebulae of each separate type are found linear correlations between total magnitudes and logarithms of diameters. . . . The residuals without regard to sign average 0.87 mag., and there appears to be no systematic effect due either to type or luminosity. The scatter, however, is much greater for the spirals, especially in the later types, than for the elliptical nebulae. The limiting cases are explained by peculiar structural features. The nebulae which fall well above the line usually have bright stellar nuclei, and those which fall lowest are spirals seen edge-on in which belts of absorption are conspicuous."

In those extragalactic systems in which individual stars had been resolved, Hubble used them as distance criteria to make estimates of the total absolute magnitudes of the parent nebulae, because from the Cepheid criterion "the number of nebulae of known distance is too small to serve as a basis for estimates of the range in absolute magnitude among the nebulae in general. Further information, however, can be derived from a comparison of total apparent magnitudes with apparent magnitudes of the brightest stars involved, on the reasonable assumption, supported by such evidence as is available, that the brightest stars in isolated systems are of about the same intrinsic luminosity." Finally, using what observational evidence was available, he determined the mean density of nebulae in space, and applied this result in the theory of general relativity to get the radius of curvature of the finite universe —"600 times the distance at which normal nebulae can be detected with the 100-inch reflector." This calculation represented the boldest probe of the universe yet made, and it greatly stimulated theoretical work in cosmology.

1929: "A Spiral Nebula as a Stellar System, Messier 31." This paper, 55 pages long, contains a detailed discussion of the Andromeda nebula, the first giant spiral nebula for which Hubble was able to get a reliable distance, by use of the period-luminosity relation for Cepheids. "The present discussion," Hubble wrote, "is based on the study of about 350 photographs taken with the 60- and 100-inch reflectors, distributed over an interval of about eighteen years. Two-thirds of the total number were obtained by the writer during the five years 1923-1928." The same procedure used by Hubble in his 1926 paper on M33 was adopted in his study of M31, with the result that forty Cepheids were identified and used to construct the period-luminosity relation for this great stellar system. "The distance of M31 has been derived by comparing Figure 2 [the period-luminosity relation for M31] with corresponding diagrams for Cepheids in M33 and in the Small Magellanic Cloud. . . . The distance of M31 is about 0.1 mag., or 5 percent, greater than that of M33, and 8.5 times the distance of the Small Cloud. Using Shapley's value for the Cloud ($m - M = 17.55$) we find for M31 . . . Distance = 900,000 light years. . . . The accuracy of the relative distances is very satisfactory. . . . The accuracy of the distances in parsecs or light-years, however, depends largely upon the accuracy of the zero-point of the period-luminosity curve. Accumulating evidence indicates that Shapley's value is certainly of the right general order of magnitude, but there still remains the possibility of a considerable correction when more data on galactic Cepheids become available."

The extensive amount of observational data assembled by Hubble enabled him to make a detailed study of the characteristics of the 85 novae observed photographically in the Andromeda nebula. He reported that "their mean light-curve is of the same general character as that for galactic novae," and that the distribution of novae in M31 "follows the distribution of luminosity in the nebula."

Hubble was unable to resolve the nuclear region of M31 with the 100-inch reflector, but he summarized what evidence he was able to obtain regarding this particularly interesting portion of the nebula: "The observational data bearing on the composition of the nuclear region are: (1) the lack of absorption, (2) the infrequency of very bright giants, (3) the appearance of novae, and (4) the characteristic dwarf-solar-type spectrum with broad, fuzzy lines. A superficial interpretation of these data suggests a star cloud in which bright giants are rare, in contrast with the outer arms of the spiral, where giants are abundant. The Cepheids would then follow the distribution of the giants, while the novae would follow that of the faint stars, or possibly that of the stars in general."

Finally, Hubble estimated the mass, luminosity, and density distribution in M31, and concluded that "the galactic system is five or six times the diameter of the spiral." This disparity in size nearly vanished when, within a year, Trumpler demonstrated the existence of interstellar absorption of light in the galaxy—a phenomenon that gave too large a measure of distance.

1930: "Distribution of Luminosity in Elliptical Nebulae." This paper is concerned with "a preliminary attempt to determine the actual luminosity distribution in the images of a selected list of elliptical nebulae. The results emphasize the dynamical pattern on which they are constructed." Hubble photographed 15 of these nebulae at the Newtonian focus of the 100-inch reflector. From these plates he then derived the distribution of luminosity within the nebulae, i.e., the spatial light density, and compared the results with the distribution in density of the Emden isothermal gaseous sphere. From the comparison he concluded: "The nuclei of the nebulae appear to be relatively more concentrated, and in the outer regions the luminosity falls off faster than the density, as would be expected in the case of finite rotating bodies such as the nebulae." At the time, no elliptical nebula had been resolved into stars, and this result was available for consideration by rival theories of ellipticals as gaseous or stellar systems. Hubble did not venture an interpretation in this respect in the present paper. He was content to offer the new data with the hope "that they may furnish an observational basis for the dynamical study of elliptical nebulae."

1931: "The Velocity-Distance Relation among Extra-Galactic Nebulae" (with Milton L. Humason). In Part I, "Distances of Nebulae," Hubble and Humason listed the 10 nebulae in which types of stars were identified, which enabled them to determine the individual distances of the nebulae from the criterion of brightest-star absolute magnitude. They stated:

"The range in the magnitudes of the brightest stars is about 1.8, with an average residual of 0.4 around the mean value —6.1. . . . These facts lend color to the assumption of a fairly uniform upper limit to the luminosity of stars in the great isolated systems, which may be used as a criterion of distance where stars can be seen but no types identified." Thus they derived a formula for the distance of a nebula, "as indicated by the brightest stars involved," as

$$\log D = 0.2\ m_s + 2.2,$$

where D = distance in parsecs and m_s = photographic magnitude of the brightest star. For the restricted types of objects studied, they found the mean absolute total magnitude, or luminosity, of these 10 extragalactic nebulae to be —14.9.

The measurement of total apparent magnitudes of nebulous objects is, however, a very difficult technical problem of photographic photometry. In this paper, therefore, the authors described in detail the method developed and adopted at Mount Wilson. Based upon extra-focal exposures, this method gave results of improved accuracy mainly for distances of clusters of nebulae, because "the luminosity criterion is purely statistical and is reliable only when large numbers of nebulae are available. One direct application concerns the great clusters of nebulae. The mean or most frequent apparent magnitude of the many members is a good indicator of the distance of the cluster, and hence clusters offer the greatest distances that can definitely be assigned to individual objects. If observations of very remote objects are desired, the brightest members of very faint clusters may be selected."

In Part II, "The Velocity-Distance Relation," the writers compiled data on 26 new velocities of nebulae belonging to 8 clusters or groups, together with 14 new velocities for isolated objects. These highly significant results were summarized as follows: "The relation [between radial velocity and distance] is a linear increase in the velocity amounting to about +500 km/sec per million parsecs of distance." The cosmological consequences and implications of this simple statement have had enormous influence on astronomical and philosophical thought.

The authors pointed out, nevertheless, that "the interpretation of red-shifts as actual velocities does not command the same confidence, and the term 'velocity' will be used for the present in the sense of 'apparent' velocity, without prejudice as to its ultimate significance."

1932: "Nebulous Objects in Messier 31 Provisionally Identified as Globular Clusters." Hubble continued his detailed studies of the nearer spiral systems, and in this paper he reported the discovery of 140 "nebulous objects" in and around the Andromeda nebula. These objects he described as "nebulous stars—small, highly concentrated, round and perfectly symmetrical. . . . The observed characteristics of the objects appear to admit of but one interpretation. On the basis of structure, luminosity, diameters and colors, the objects are provisionally identified as globular star clusters. Their absolute magnitudes are systematically fainter by one or two magnitudes than the absolute magnitudes of the globular clusters in the galactic system derived from Shapley's distances." Hubble lived to learn the reason for this discrepancy: the Cepheid distance criterion as formulated by Shapley gave distances too small by a factor of two, as reported in 1952 by Baade.

1932: "The Surface Brightness of Threshold Images." The problem of the measurement of apparent total magnitudes of nebulae is difficult photographically, because it involves the comparison of surfaces (nebulae) with point sources (stars). Since Hubble's greatest distance criteria were based on such measurements, and since he himself was engaged in extensive counts of faint nebulae, he was naturally concerned to develop as accurate a method as possible for detemining nebular magnitudes. This paper discusses one practical aspect of the problem: "The photographic photometry of threshold images involves an effect depending on the areas. It is well known that the photometry of surfaces differs from that of point-source images, but the manner in which one merges into the other is seldom discussed in the literature. The question bears on the estimates of limiting magnitudes of nebulae recorded under given exposure conditions."

The results of Hubble's studies of both nebular and stellar images produced under threshold conditions with the 100- and 60-inch reflectors resulted in "a relation between surface brightness and size of image, according to which the surface brightness diminishes as the size increases, at first rapidly and then more and more slowly. . . . For very small images the total magnitudes are independent of the size; for very large images the surface brightness is independent of the size. The observed relation is a smooth transition between these limiting conditions." With this relationship he was able to obtain more accurate magnitudes of nebulae from those of stars used as standards.

1934: "Red-Shifts in the Spectra of Nebulae." In this beautifully written paper, the Halley Lecture of the Royal Astronomical Society delivered in London on May 8, 1934, Hubble discussed "some of the more recent explorations in the realm of the nebulae which bear more or less directly on the structure of the universe." Here he invoked the "Principle of the Uniformity of Nature, which supposes that any other equal portion of the universe, chosen at random, will exhibit the same general characteristics. As a working hypothesis, serviceable until it leads to contradictions, we may venture the assumption that the realm of the nebulae *is* the universe—that the Observable Region is a fair sample, and that the nature of the universe may be inferred from the observable characteristics of the sample." After a condensed description of observational techniques for determining the velocity-distance relation, Hubble considered briefly its significance: "The significance of this strange characteristic of our sample of the universe depends upon the interpretation of red-shifts. The phenomena may be described in several equivalent ways—the light from distant nebulae is redder than normal, the light waves are longer, the vibrations are slower, the light quanta have lost energy. Many ways of producing such effects are known, but of them all, only one will produce large red-shifts without introducing other effects which should be conspicuous but actually are not found. This one known permissible explanation interprets red-shifts as due to actual motion away from the observer. . . . We may say with confidence that red-shifts are due either to actual motion or to some hitherto unrecognized principle of physics. Theoretical investigators almost universally accept the red-shifts as indicating motion of recession of the nebulae, and they are fully justified in their position until evidence to the contrary is forthcoming."

1934: "The Distribution of Extra-galactic Nebulae." In an introduction to this long paper containing an immense amount of new material, Hubble referred to his work on distance estimates of the nebulae as giving a "hasty sketch of some of the general features of the Observable Region as a unit. The next step," he said, "was to follow the reconnaissance with a survey —to repeat carefully the explorations with an eye to accuracy and completeness. The program, with its emphasis on methods, will be a tedious series of successive approximations, but the procedure is necessary, since extrapolations beyond the frontiers will be significant only in proportion to the accuracy with which the trend of correlations has been established out to the frontier itself." These words were prophetic, for the remainder of Hubble's research reflected his belief expressed in these thoughts. This paper, 69 pages in length, incorporates counts of about 80,000 nebulae identified on photographs taken with the Mount Wilson 60- and 100-inch reflectors. In this work, generally recognized as a classic, Hubble obtained on a firm quantitative basis, for the first time, information on the large-scale occurrence of obscuring matter along the plane of the galaxy, on the numbers of the nebulae to successively fainter magnitude limits, on the tendency of nebulae to cluster, and on the average density of matter in extragalactic space. The impact of these new data on cosmology and galactic structure investigations can hardly be overestimated. There are innumerable references to this work in many subsequent papers by theorists and observers.

1935: "Two Methods of Investigating the Nature of Nebular Red-Shift" (with Richard C. Tolman). Although Hubble had no official connection with the California Institute of Technology until he served on the Advisory Committee for the construction of the large Palomar telescopes, he had many friends and colleagues on its faculty. In particular, he enjoyed many scientifically productive associations with H. P. Robertson and R. C. Tolman, and this paper is an example of the cooperative spirit that existed between Hubble and these theoreticians at Cal Tech.

In Part I of the paper, their empirical approach to the analysis of the nebular red-shift was stated as follows: "Until further evidence is available, both the present writers wish to express an open mind with respect to the ultimately most satisfactory explanation of the nebular red-shift and, in the presentation of purely observational findings, to continue to use the phrase 'apparent' velocity of recession." Surely this seems a warning for some not to "rush in where angels fear to tread."

On the basis of (*a*) an expanding cosmological model using relativistic mechanics and (*b*) the case in which "the red-shift is due to some cause other than recession," the authors derived a theoretical relation between locations in space and photographic magnitudes of nebulae, for tests of the nature of the red-shift. The derived formula contained the distance to a nebula as an unobservable quantity. It was eliminated by connecting "either nebular dimensions with observed luminosities, or nebular counts with observed luminosities."

Part II of the paper presented the existing status of the observational work pertinent to the problem. The authors concluded: "In the case of the relation between nebular dimensions and luminosities, the observations are such as to confirm our general ideas as to the extra-galactic character of the objects in question, but are not yet sufficient to permit a decision between recessional or other causes for the red shift."

They next considered in some detail the uncertainties in the counts of galaxies, such as the difficulties in determining the number of nebular images per plate, in measuring the limiting magnitudes, in evaluating the fractional red-shift, and in determining the spectral energy correction term K. They concluded finally that "the observations now available show a rate of increase in counts with distance which seem rather large compared with what would be expected for a homogeneous distribution of nebulae on the basis of either a recessional or a non-recessional theory."

1936: "Effects of Red Shifts on the Distribution of Nebulae." In this paper Hubble added two additional groups of nebular counts to the three groups already discussed in his 1935 paper with Tolman. After a detailed analysis of the observational data, and a comparison with the theoretical models computed with Tolman, Hubble found that "the observations may be fitted into either of two quite different types of universes. If the red-shifts are velocity shifts, the model is closed, small and dense. It is rapidly expanding, but over a long period the rate of expansion has been steadily diminishing. Existing instruments range through a large fraction of the entire volume and, perhaps, through a considerable fraction of past time since the expansion began.

"On the other hand, if red-shifts are not primarily due to velocity shifts, the Observable Region loses much of its significance. The velocity-distance relation is linear; the distribution of nebulae is uniform; there is no evidence of expansion, no trace of curvature, no restriction to the time scale. The sample, it seems, is too small to indicate the particular type of universe we inhabit.

"Thus the surveys to about the practical limits of existing instruments present as alternatives a curiously small-scale universe, or a hitherto unrecognized principle of nature. A definitive choice, based upon observational criteria that are well above the threshold of uncertainty may not be possible until results with the 200-inch reflector become available."

1936: "The Luminosity Function of Nebulae." "Consider all the nebulae *in a given volume of space*," Hubble wrote in *The Realm of the Nebulae* (p. 59). "The relative numbers of giants and dwarfs and normal objects—more precisely, the frequency-distribution of absolute magnitudes (candle powers) among these nebulae—form the 'luminosity-function.' It was assumed that the luminosity-function remains constant throughout the regions covered by the surveys—that the function is independent of distance or direction—that the giants do not tend to congregate in one region and the dwarfs in another region. The assumption has not been fully established by direct observations, but it seems reasonable and it is consistent with all information available at the present time."

In this paper Hubble attempted to estimate the luminosity function for the nebulae, and he did so by two separate methods: (1) the luminosity function of resolved nebulae as indicated by their brightest stars, and (2) the luminosity function as indicated by residuals in velocity-magnitude relations. The first of these methods utilizes the criterion of the brightest star in a nebula, "which is arbitrarily defined as the mean of the three or four brightest objects which are judged to be individual, non-variable stars situated in a nebula." Hubble pointed out the observational pitfalls in identifying these stars, and added: "Regardless of their true nature, the objects selected as brightest stars . . . form a homogeneous group in which the absolute magnitudes do not vary systematically with apparent magnitudes (or distances)." Therefore, the difference in the apparent magnitude of the brightest star within the nebula and the magnitude of the nebula itself should give an indication of the intrinsic luminosity of the nebula; and the compilation of a large number of such differences for many nebulae should give a reasonable evaluation of the luminosity function of the nebulae. Hubble listed about 125 nebulae in which stars were identified "with some confidence." From these he determined the frequency distribution of the differences between apparent magnitudes of nebulae and of their brightest stars. His general conclusion was that the luminosity function of nebulae approximates a normal error-curve.

The second method used by Hubble in determining the nebular luminosity function employed the velocity-distance relation. He pointed out that this relation furnishes individual distances of unresolved field nebulae, and that the percentage errors actually diminish as distances increase. Following a new evaluation of the velocity-magnitude relation, Hubble derived the residuals from the relation for 109 field nebulae. Of these objects, 29 are resolved nebulae included in the first method, and Hubble found that the luminosity function derived from their residuals agrees closely with that determined in the first method from the brightest stars in resolved nebulae alone.

1939: "The Motion of the Galactic System among the Nebulae." In this paper Hubble analyzed the residual radial motions of the nebulae, after removing the systematic red-shifts. His analysis of these residual motions of many nebulae well distributed over the sky assumed that the peculiar motions tend to cancel out, since they are presumably distributed at random in all directions; thus there was left only the reflection of the motion of the galactic system. Hubble concluded: "A relatively small velocity and a high inclination to the plane of the Milky Way seem to be definitely indicated, although precise numerical values cannot be derived from the data now available."

1943: "The Direction of Rotation in Spiral Nebulae." Hubble's survey of the nearby nebulae led him to the recognition of four spirals in which the direction of rotation could be determined unambiguously from the silhouetting of absorption lanes against the bright nuclear regions. For fifteen other spirals for which spectrographic rotation had been observed, spiral arms could be traced, and the dissymmetry of obscuration offered a general criterion of tilt. He found that the consistent application of this general criterion indicated all these nebulae appear to be rotating in the same direction; the sense of this direction could be found from the four spirals for which the tilt could be determined without ambiguity. By this process he found that in all these nebulae the arms are trailing—the outer parts lag behind as the inner regions rotate faster.

1949: "First Photographs with the 200-inch Hale Telescope." Here Hubble reported that the photographs taken while testing the 200-inch telescope recorded stars and nebulae fully 1.5 magnitudes fainter than the extreme limit of the 100-inch reflector on Mount Wilson, and that at high galactic latitudes the 200-inch telescope records many more nebulae than stars, as he had predicted about fifteen years earlier. This paper also contains a reproduction of the first photograph taken with the

Hale Telescope on January 26, 1949, about 10:00 P.M. (after waiting more than a week for a break in the weather). The object was NGC 2261, a well-known galactic nebula, now generally known as Hubble's Variable Nebula because of the remarkable changes in its brightness that he discovered.

1951: "Explorations in Space: The Cosmological Program for the Palomar Telescope." Few astronomers have equaled Hubble's impressive eloquence in popular lectures. This paper, presented as the Penrose Memorial Lecture to the American Philosophical Society, is a prime example of such talks. It contains a résumé of extragalactic research already done, and then concentrates on the program for Palomar: "The cosmological program for the Palomar telescope has been formulated to get new answers to the observational problems, free from systematic errors and with the accidental errors sufficiently small to be unimportant. Specifically, the problems are, first, to find the mean density of matter in space, and the rate of increase of red-shifts in our immediate vicinity—say within 50 million light-years of our own system—and second, to determine whether or not there are any appreciable systematic changes with distance or direction in either of the two data."

1954: "The Law of Red-Shifts." This paper, the George Darwin Lecture delivered by Hubble on May 8, 1953, in London, was edited by Sandage, and published after Hubble's death. In it, he discussed the emergence of the law of red-shifts, first in its discovery phase, which ended with a crude formulation in 1928-1929, then its rapid extension and improved formulation out to the limit of the 100-inch reflector in 1929-1936, and finally the recent attempts to reach the limit of the 200-inch reflector with the definite formulation of the law. He discussed in some detail the current efforts at this definitive formulation with the 200-inch reflector, including the problems of magnitude standards, measurement of nebular magnitudes, and effects of red-shifts on apparent magnitudes. He concluded by reporting the latest evaluation of the red-shift magnitude relation, stating that the correlation is linear within the uncertainties of the data, and that the residuals are surprisingly small.

It seems fitting to conclude this memoir with Hubble's own words, to indicate how he viewed the continuation of extragalactic research in a field he had made so much his own:

"As for the future, it is possible to penetrate still deeper into space—to follow the red-shifts still farther back in time—but we are already in the region of diminishing returns; instruments will be increasingly expensive, and progress increasingly slow. The most promising programmes for the immediate future accept the Observable Region as presently defined, hope for only modest extensions in space, but concentrate on increased precision and reliability in the recorded description. The reconnaissance is being followed by an accurate survey; the explorations are pushed towards the next decimal place instead of the next cipher. This procedure promises to reduce the array of possible worlds as surely as did the early inspections of the new territory. And later, perhaps in a happier generation, when the cost of a battleship can safely be diverted from insurance of survival to the consolations of philosophy, the march outward may be resumed.

"For I can end as I began. From our home on the Earth, we look out into the distances and strive to imagine the sort of world into which we are born. Today we have reached far out into space. Our immediate neighborhood we know rather intimately. But with increasing distance our knowledge fades, and fades rapidly, until at the last dim horizon we search among ghostly errors of observations for landmarks that are scarcely more substantial. The search will continue. The urge is older than history. It is not satisfied and it will not be suppressed."

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KEY TO ABBREVIATIONS

Am. Astron. Soc. Publl. = American Astronomical Society Publications
Astrophys. J. = Astrophysical Journal
Carnegie Inst. Wash. News Serv. Bull. = Carnegie Institution of Washington News Service Bulletin
Contrib. Mt. Wilson Obs. = Contributions from the Mount Wilson Observatory
Leaflet Astron. Soc. Pacific = Leaflet of the Astronomical Society of the Pacific
Monthly Notices Roy. Astron. Soc. = Monthly Notices of the Royal Astronomical Society
Mt. Wilson Obs. Commun. = Mount Wilson Observatory Communications
Mt. Wilson Palomar Obs. Reprint = Mount Wilson and Palomar Observatories Reprint
Popular Astron. = Popular Astronomy
Proc. Nat. Acad. Sci. = Proceedings of the National Academy of Sciences
Publ. Astron. Soc. Pacific = Publications of the Astronomical Society of the Pacific
Sci. Monthly = Scientific Monthly
Smithsonian Inst. Ann. Rept. = Smithsonian Institution, Annual Report

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