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(*b*. Kendal, England, 28 December 1882; *d*. Cambridge, England, 22 November 1944)

astronomy, relativity.

Eddington was the son of a Somerset Quaker, Arthur Henry Eddington, headmaster of Stramongate School in Kendal from 1878 until his death in 1884, and of Sarah Ann Shout, whose forebears for seven generations had been north-country Quakers. Following the death of her husband, Mrs. Eddington took Arthur Stanley, not yet two, and her daughter Winifred, age six, back to Somerset, where they made their home at Weston-super-Mare. In the atmosphere of this quiet Quaker home, the boy grew up. He remained a Quaker throughout his life.

Eddington's schooling was fortunate. Brynmelyn School, to which he went as a day boy, had three exceptionally gifted teachers who imparted to him a keen interest in natural history, a love of good literature, and a splendid foundation in mathematics. Reserved and studious by nature, Eddington was also physically active, playing on the first eleven at both cricket and football and enjoying long bicycle rides through the Mendip Hills. Before he was sixteen, he won an entrance scholarship to Owen's College (now the University of Manchester), where again he was fortunate in his teachers—Arthur Schuster in physics and Horace Lamb in mathematics. In the autumn of 1902, with an entrance scholarship, Eddington went into residence at Trinity College, Cambridge.

After two years of intensive concentration on mathematics under the guidance of the distinguished coach R. A. Herman, who stressed both the logic and the elegance of mathematical reasoning, Eddington sat the fourteen papers of the tripos examinations in 1904. He won the coveted position of first wrangler, the first time that a second-year man had attained this distinction. In 1905 he gained his degree and proceeded to coach pupils in applied mathematics and to lecture in trigonometry during the following term.

In February 1906 Eddington took an appointment as chief assistant at the Royal Observatory, Greenwich, where he remained until 1913. Here he obtained thorough training in practical astronomy and began the pioneer theoretical investigations that placed him in the forefront of astronomical research in a very few years. Besides his participation in the regular observing programs, Eddington had two special assignments: he went to Malta in 1909 to determine the longitude of the geodetic station there, and to Brazil in 1912 as leader of an eclipse expedition. Two further tests of his ability as a practical astronomer came after his return to Cambridge as Plumian professor of astronomy and director of the observatory. During the war years Eddington completed single-handed the transit observations for the zodiacal catalog. In 1919 he organized the two eclipse expeditions that provided the first confirmation of the Einstein relativity formula for the deflection of light in a gravitational field.

During these years Eddington was elected to fellowships in the Royal Astronomical Society (1906) and the Royal Society (1914). He was knighted in 1930, and his greatest honor, the Order of Merit, was conferred on him eight years later.

Eddington was president of the Royal Astronomical Society from 1921 to 1923 and of the Physical Society and the Mathematical Association from 1930 to 1932. In 1938 he became president of the International Astronomical Union. After his death an annual Eddington Memorial Lectureship was established and the Eddington Medal was struck for annual award, the first recipient being a former pupil of Eddington's, Canon Georges Lemaître of Louvain.

Eddington never married. After his appointment in 1913 to the Plumian professorship in Cambridge, he moved into Observatory House as director of the observatory and brought his mother and sister to live with him. Here he remained until the autumn of 1944, when he underwent a major operation from which he did not recover.

Of Eddington's scientific work, particularly in the field of stellar structure, E. A. Milne wrote in 1945 that he "brought it all to life, infusing it with his sense of real physics and endowing it with aspects of splendid beauty.... Eddington will always be our incomparable pioneer." His intuitive insight into the profound problems of nature, coupled with his mastery of the mathematical tools, led him to illuminating results in a wide range of problems: the motions and distribution of the stars, the internal constitution of the stars, the role of radiation pressure, the nature of white dwarfs, the dynamics of pulsating stars and of globular clusters, the sources of stellar energy, and the physical state of interstellar matter. In addition, he was the first interpreter of Einstein's relativity theory in English, and made his own contributions to its development; and he formulated relationships between all the principal constants of nature, attempting a vast synthesis in his provocative but uncompleted *Fundamental Theory*.

It is important to remember how rudimentary was much of our knowledge of astrophysics and of stellar movements at the beginning of this century. Proper motion or transverse motion had been known since the time of Halley and radial velocity since Doppler, but the assumption of William Herschel of random motion of the stars relative to the sun had been abandoned of necessity by Kapteyn in 1904. Schwarzschild attempted to show that the radial velocity vectors could be represented as forming an ellipsoid. This problem of the systematic motions of the stars was the subject of Eddington's first theoretical investigations. He chose to work with proper motions and isolated two star streams or drifts. In 1917 he compared the two theories thus:

The apparent antagonism between the two-drift and the ellipsoidal hypotheses disappears if we remember that the purpose of both is descriptive. Whilst the twodrift theory has often been preferred in the ordinary proper motion investigations on account of an additional constant in the formulae which gives it a somewhat greater flexibility, the ellipsoidal theory has been found more suitable for discussions of radial velocities and the dynamical theory of the stellar system [*Monthly Notices of the Royal Astronomical Society*, **77** , 314].

Eddington's remarkable statistical analyses of proper-motion data fully confirmed the existence of the two star streams, and he was able to determine their directions and relative numbers. He went on to other problems, such as the distribution of stars of different spectral classes, planetary nebulae, open clusters, gaseous nebulae, and the dynamics of globular clusters. In his first book, *Stellar Movements and the Structure of the Universe* (1914), Eddington brought together all the material of some fifteen papers, most of which had been published in the *Monthly Notices of the Royal Astronomical Society* between 1906 and 1914. The cosmological knowledge of the period was summarized and the most challenging problems were delineated, and he clearly declared his preference for the speculation that the spiral nebulae were other galaxies beyond our Milky Way, which was itself a spiral galaxy.

Eddington's great pioneer work in astrophysics began in 1916. His first problem was radiation pressure, the importance of which had been pointed out a decade earlier by R. A. Sampson. A theory of the radiative equilibrium of the outer atmosphere of a star was subsequently developed by Schwarzschild in Germany. Eddington delved deeper, in fact to the very center of a star, showing that the equation of equilibrium must take account of three forces— gravitation, gas pressure, and radiation pressure. Replacing the assumption of convective equilibrium of Lane, Ritter, and Emden with radiative equilibrium, he developed the equation that is still in general use. At that time he felt justified in assuming that perfect gas conditions existed in a giant star, and he adopted Emden's equation for a polytropic sphere with index $n = 3$. This is still referred to as Eddington's model of a star. Not until 1924 did he realize that this assumption and, therefore, this model were also applicable to dwarf stars.

That matter under stellar conditions would be highly ionized had been recognized by several astronomers, but it was Eddington who first incorporated this into the theory of stellar equilibrium by showing that high ionization of a gas reduced the average molecular weight almost to 2 for all elements except hydrogen.

Finding that the force of radiation pressure rose with the mass of the star, and with startling rapidity as the mass exceeded that of our sun, Eddington concluded that relatively few stars would exceed ten times the sun's mass and that a star of fifty times the solar mass would be exceedingly rare. To obtain a theoretical relation between mass and luminosity of a star, some assumption was necessary about internal opacity. At first he regarded opacity as mainly a photoelectric phenomenon, a view that drew strong criticism; but when Kramers' theory of the absorption coefficient became available, Eddington adapted it to the stellar problem, introducing his "guillotine" factor, and obtained his important mass-luminosity relation, announced in March 1924. Since the observational data for dwarf stars, as well as for giant stars, closely fitted the theoretical curve, he announced that dwarfs also must be regarded as gaseous throughout, in spite of their densities exceeding unity. He realized that the effective volume of a highly or fully ionized atom is very small, and hence deviations from perfect gas behavior will occur only in stars of relatively high densities. The mass-luminosity relation has been widely used and is still of immense value, although its applicability has been somewhat limited in recent years by the more detailed classification of both giants and dwarfs and by the recognition of the distinctive characteristics, for example, of subdwarfs, which do not conform to the mass-luminosity relation.

Eddington had calculated the diameters of several giant red stars as early as the summer of 1920. In December, G. E. Hale wrote him of the Pease and Anderson interferometer measurement of α Orionis on 13 December "in close agreement with your theoretical value and probably correct within about 10 per cent." Later Eddington applied his calculations to the dwarf companion of Sirius, obtaining a diameter so small that the star's density came out to 50,000 gm./cc., a deduction to which he said most people had mentally added "which is absurd!" However, in the light of his 1924 realization of the effects of high ionization, he claimed these great densities to be possible and probably actually to exist in the white dwarf stars. He therefore wrote W. S. Adams, asking him to measure the red shift in the Mount Wilson spectra of Sirius B, since, if a density of 50,000 or more did exist, then a measurable Einstein relativity shift to the red would result. Adams hastened to comply, and wrote Eddington that the measured shifts closely confirmed the calculated shift and, hence, confirmed both the third test of relativity theory and the immense densities that Eddington had calculated. (This exchange of historic letters in 1924 and 1925 is recorded in *Arthur Stanley Eddington*, pp. 75–77.)

A direct consequence of this work was the challenge it presented to physicists, a challenge taken up in 1926 by R. H. Fowler, who achieved a brilliant investigation of the physics of super-dense gas, afterward called "degenerate" gas, by employing the newly developed wave mechanics of Schrödinger.

A consequence of Eddington's mass-luminosity relation was his realization that a time scale of several trillion (i.e., 10^{12}) years was essential for the age of stars if the then current Russell-Hertzsprung sequence of stellar evolution was to be retained. Except in the rare case of a nova or supernova that hurls out much of its matter, the loss of mass by a star is due to radiation. For a massive O or B class star to radiate itself down to a white dwarf, at least a trillion years would be required. This brought into the limelight the theory of conversion of matter into radiation by annihilation of electrons and protons, a hypothesis that appears to have been first suggested by Eddington in 1917. For seven years, in spite of severe criticism in Great Britain, he defended the general idea that the chief source of stellar energy must be subatomic. After 1924 many astronomers and physicists turned their attention to this. In 1934, after the discovery of the positron, Eddington urged abandonment of the electron-proton annihilation theory, on the ground that electron-positron annihilation was not only a more logical supposition but also an observed fact. In 1938 came the famous carbon-nitrogen-oxygen-carbon cycle of Hans Bethe, elegantly solving some of the problems of stellar energy and invoking the electronpositron annihilation hypothesis.

In 1926 Eddington published his great compendium, *The Internal Constitution of the Stars* (reprinted in 1930). In this book he drew attention to the unsolved problems partially treated in his investigations, among them the problem of opacity and the source or sources of stellar energy, which he called "two clouds obscuring the theory." Another obstinate problem was the phase relation of the light curve and the velocity curve of a Cepheid variable. In 1918 and 1919 he had published papers on the mathematical theory of pulsating stars, explaining many observed features of Cepheid variables but not the phase relation. He returned to this problem in 1941, when more was known about the convective layer and he could apply the physics of ionization equilibrium within this layer with encouraging results.

Other problems dealt with in these years were the central temperatures and densities of stars and the great cosmic abundance of hydrogen (recognized independently by Strömgren). Eddington developed a theory of the absorption lines in stellar atmospheres, extending earlier work of Schuster and Schwarzschild. This made possible the interpretation of many observed line intensities. When the "nebulium" lines were identified by Bowen in 1927 as the result of so-called forbidden transitions in ionized nitrogen and oxygen atoms, Eddington explained how and why these emission lines can be produced within the highly rarefied gases that constitute a nebula. Another line of adventurous thinking concerned the existence, composition, and absorptive and radiative properties of interstellar matter. He calculated the density and temperature and showed that calcium would be doubly ionized, with only about one atom in 800 being singly ionized. He discussed the rough measurement of the distance of a star by the intensity of its interstellar absorption lines, a relation soon confirmed by O. Struve and by J. S. Plaskett

In the field of astrophysics Eddington undoubtedly made his greatest—but by no means his only—contributions to knowledge. Here he fashioned powerful mathematical tools and applied them with imagination and consummate skill. But during these same years his mind was active along other lines; thus we have his profound studies on relativity and cosmology, his herculean but unsuccessful efforts to formulate his *Fundamental Theory*, and his brilliant, provocative attempts to portray the meaning and significance of the latest physical and metaphysical thinking in science.

Einstein's famous 1915 paper on the general theory of relativity came to England in 1916, when deSitter, in Holland, sent a copy to Eddington, who was secretary of the Royal Astronomical Society. Immediately recognizing its importance and the revolutionary character of its implications, Eddington threw himself into a study of the new mathematics involved, the absolute differential calculus of Ricci and Levi-Civita. He was soon a master of the use of tensors and began developing his own contributions to relativity theory. At the request of the Physical Society of London, he prepared his *Report on the Relativity Theory of Gravitation* (1918), the first complete account of general relativity in English. He called it a revolution of thought, profoundly affecting astronomy, physics, and philosophy, setting them on a new path from which there could be no turning back. A second edition (1920) contained the results of the eclipse expeditions of 1919, which had appeared to confirm the bending of light in a gravitational field, as predicted by Einstein's theory; it also contained a warning that the theory must meet the test of the reddening of light emitted from a star of sufficient density. This test was met when the measurements on Sirius B made by W. S. Adams at Eddington's request were announced in 1924.

Eddington published a less technical account of relativity theory, *Space, Time and Gravitation*, in 1920. This book brought to many readers at least some idea of what relativity theory was and where it was leading in cosmological speculation. It showed, too, how Eddington's mind had already entered philosophical grooves in which it continued to run—his selective subjectivism, almost universally repudiated, and his logical theory of structure, "a guiding illumination," in the words of Martin Johnson, who added, "As elucidator of the logical status of physics, Eddington led well his generation."

In 1923 came Eddington's great book, *Mathematical Theory of Relativity*. Einstein said in 1954 that he considered this book the finest presentation of the subject in any language, and of its author he said, "He was one of the first to recognize that the displacement field was the most important concept of general relativity theory, for this concept allowed us to do without the inertial system."

In this book Eddington gave the substance of the original papers of Einstein, deSitter, and Weyl but departed from their presentations to give a "continuous chain of deduction," including many contributions of his own, both in interpretation and in derivation of equations. With intuitive brilliance he modified Weyl's affine geometry of world structure by means of a new mathematical procedure, parallel displacement, which in itself was a not unimportant contribution to geometry. This led to his explanation of the law of gravitation ($G_{\mu\nu} = \lambda g_{\mu\nu}$) as implying that our practical unit of length at any point and in any direction is a definite fraction of the radius of curvature for tha point and direction, so that the law of gravitation is simply the statement of the fact that the world radius of curvature everywhere supplies the standard with which our measure lengths are compared.

This led subsequently to his theoretical determination of the cosmic constant λ. Assuming the principle that the wave equation determining the linear dimensions of an atomic system must give these dimensions in terms of the standard world radius, he obtained a value for λ in terms of the atomic constants that appear in the ordinary form of the wave equation.

This fascination with the fundamental constants of nature—the gravitation constant, the velocity of light, the Planck and Rydberg constants, the mass and charge of the electron, for example—and the basic problem of atomicity had driven Eddington to seek this bridge between quantum theory and relativity. Having found it, he eventually established relationships between all these and many more constants, showing their values to be logically inevitable. From seven basic constants Eddington derived four pure numbers, including the famous 137 forever associated with his name. This is the fine structure constant. He evolved the equation $10m^2 - 136m + 1 = 0$, the coefficients of which are in accordance with the theory of the degrees of freedom associated with the displacement relation between two charges and the roots of which give the ratio of masses of proton and electron as 1847.60. He showed that the packing factor for helium should be 136/137. Later Eddington identified the total number of protons and electrons in the universe with the number of independent quadruple wave functions at a point; he evaluated this constant as $3/2 \times 136 \times 2^{256}$, which is a number of the order of 10^{79}. In all, he evaluated some twenty-seven physical constants.

As all this work proceeded, Eddington published a succession of books, both technical and nontechnical, dealing with the above problems and also with the new problems that were arising in cosmological theories. The spherical Einstein universe was found to be unstable, and in 1927 Georges Lemaître published in an obscure journal his cosmology of an expanding universe, the result of the catastrophic explosion of a primeval atom containing all the matter of the universe. He sent a reprint to Eddington only in 1930. Immediately his own modification of this became the basis of all of Eddington's further work in this field. In 1928 Dirac published his new interpretation of the Heisenberg symbols q and p, an approach to a recondite subject that sent Eddington's mind racing off in a new direction. He developed a theory of matrices providing "a simple derivation of the first order wave equation, equivalent to Dirac's but expressed in symmetrical form" and also "a wave equation which we can identify as relating to a system containing electrons with opposite spin." He then developed his *E*-number theory, which proved to be a powerful tool in much subsequent work.

The Nature of the Physical World (1928) and *The Expanding Universe* (1933) deal with the above ideas and his, epistemological interpretation. *New Pathways in Science* (1935) and *The Philosophy of Physical Science* (1939) carried his ideas further. All these books are rich in literary excellence and in the sparkle of his imagination and humor, as well as being gateways to new ideas and adventures in thinking.

His technical book *The Relativity Theory of Protons and Electrons* (1936), based almost wholly on the spin extension of relativity, spurred Eddington to evolve a statistical extension. Thus, during his last years he worked indomitably toward his dream—"Bottom's dream," he called it—his vision of a harmonization of quantum physics and relativity. The difficulties were immense and, as we now know, the greatest complexities of nuclear physics and subatomic particles were not yet discovered. But he took hurdle after hurdle as he saw them, with daring leaps, always landing, as he believed, surefootedly on the far side, even though he could not demonstrate his trajectories with mathematical rigor.

The obscurities and gaps in logical deduction in *Fundamental Theory* have discouraged most scientists from taking it seriously, but a few able men— Whittaker, Lemaître, Bastin, Kilmister, Slater—have seen Eddington's vision and have felt it worthwhile to explore further. Slater isolated an erroneous numerical factor in Eddington's work, a factor of 9/4 which modified the calculated recessional constant that had agreed reasonably well with the Mount Wilson observed value. Thus, in 1944, although he did not realize it himself, Eddington's theory had really demanded the change in the distance scale of the universe that Baade announced in 1952 from observational studies of the Cepheid variables in the Andromeda galaxy.

Eddington's biographer has referred to *Fundamental Theory* as an "unfinished symphony" standing as a challenge to "the musicians among natural philosophers of the future." His mystical approach to all experience necessarily embraced the sensual, the mental, and the spiritual. He believed that truth in the spiritual realm must be directly apprehended, not deduced from scientific theories. His Swarthmore Lecture to the Society of Friends, published as *Science and the Unseen World* (1929), and his chapter entitled "The Domain of Physical Science" in *Science, Religion and Reality* (1925), as well as passages throughout his books, reveal a deeply sincere, mystical, yet essentially simple, approach to consideration of the things of the spirit. In the search for truth, whether it be measurable or immeasurable, "It is the search that matters," he wrote. "You will understand the true spirit neither of science nor of religion unless seeking is placed in the forefront."

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A. Vibert Douglas