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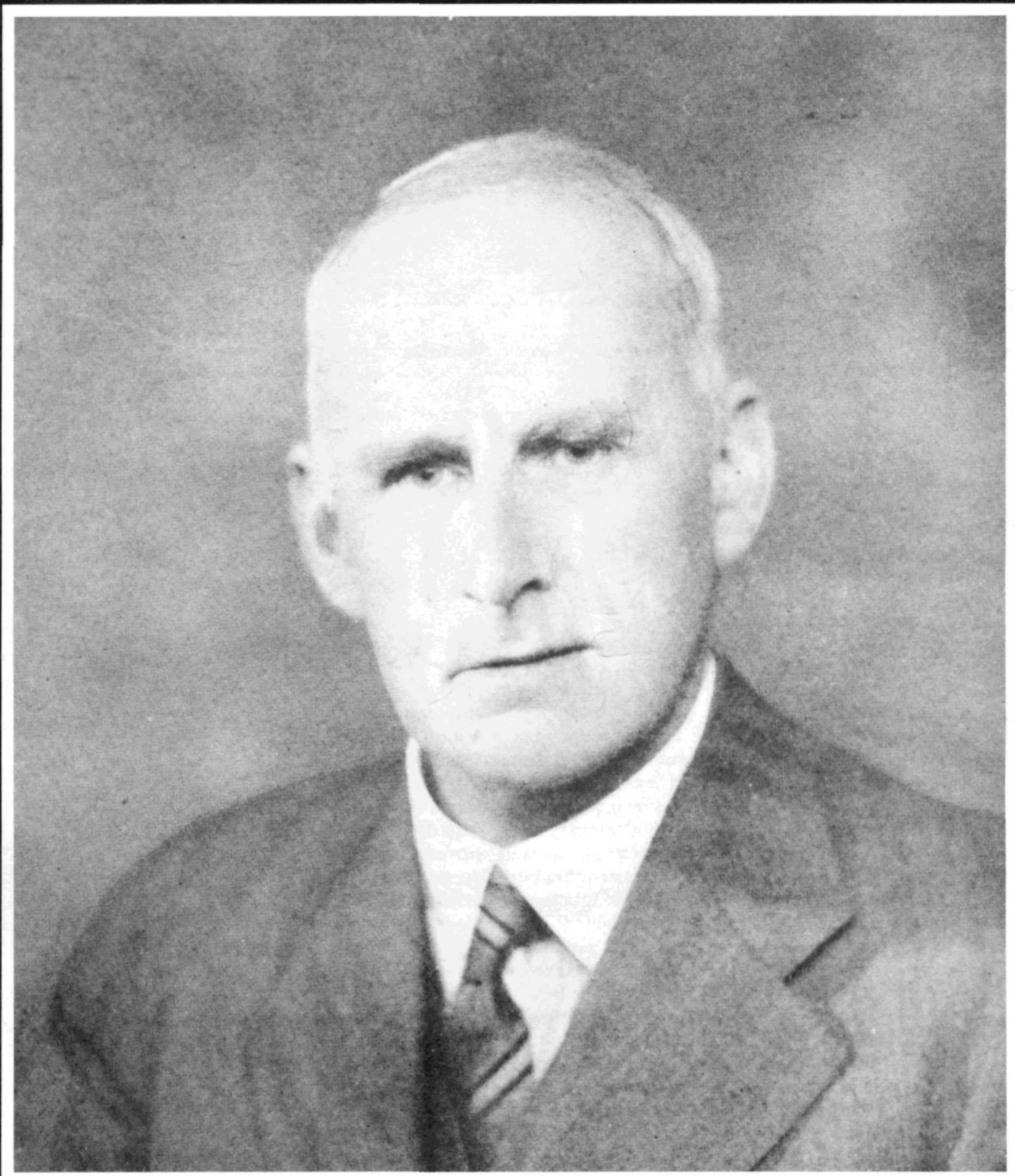


In this issue: The Eddington Centennial
and Clumpy, Irregular Galaxies

Arthur Stanley Eddington

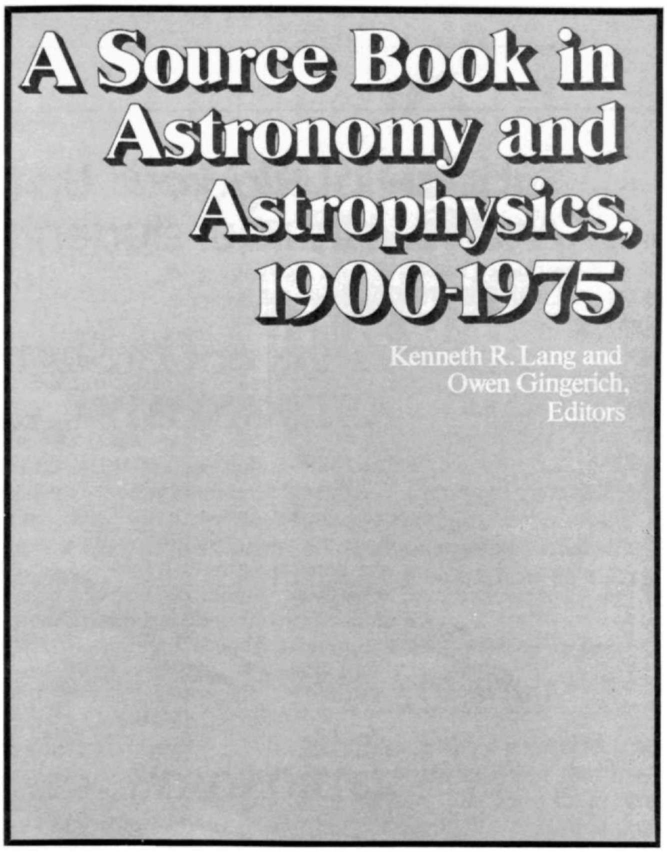
Joe S. Tenn
Sonoma State University

In the preface to *A Source Book in Astronomy and Astrophysics* (1975, Harvard U. Press), editors Kenneth R. Lang and Owen Gingerich note, "The 132 selections that make up this *Source Book* represent the seminal contributions to twentieth century astronomy and astrophysics through the year 1975."

The 132 selections reprinted in the book actually include 160 articles by approximately 200 important astronomers.[1] Researchers represented by two or more papers in the collection may be considered particularly noteworthy. Among those with two articles in the *Source Book* are such famous astronomers from the past as George Ellery Hale, Alfred H. Joy, J.C. Kapteyn, Henry Norris Russell, Harlow Shapley, and Fritz Zwicky, as well as such prominent scientists of today as Viktor A. Ambartsumian, Hans Bethe, Fred Hoyle, Maarten Schmidt, and Hendrik van de Hulst. Four astronomers—Walter S. Adams, Jesse L. Greenstein, Rudolph Minkowski, and Allan Sandage—each have three articles in the collection, and five more—Walter Baade, George Gamow, Edwin Hubble, Jan Oort, and Albert Einstein—are represented by four.

Only one astronomer had more than four of his works chosen as among the "seminal contributions to twentieth century astronomy and astrophysics." Arthur Stanley Eddington was the sole author of five and coauthor of a sixth paper in the collection. Perhaps more remarkable, his articles appear in five of the eight fields of astronomy into which the *Source Book* is divided.

1. Copies of this *Source Book* are available at a discount through the A.S.P. *Selectory*. —*Ed.*



A Source Book in Astronomy and Astrophysics, *compiled by Kenneth Lang and Owen Gingerich, contains more than a hundred selections considered to be "the seminal contributions to twentieth century astronomy and astrophysics." Only Eddington wrote more than four of the selections.*

Who was this man who made so many important contributions to so many areas of astronomical research? He was born one hundred years ago, on December 28, 1882, in England, the son of a Quaker schoolmaster who died when Stanley was two.[2] From earliest childhood he gave evidence of two characteristics: unusual mathematical ability and an intense interest in the stars. He learned the multiplication tables up to 24 x 24 before he could read. At age four he tried to count the stars; at ten he was observing regularly with a three-inch telescope. As a schoolboy he won numerous mathematics contests. After studying physics at Manchester he won a scholarship to Cambridge University. There he would earn his degree in mathematics and finish first in the famed Mathematical Tripos contest, the first to do so in his second year of study. Thus he won the coveted title of Senior Wrangler.

Eddington spent seven years at the Royal Observatory at Greenwich. There he performed observations—one of his first tasks was to check the places of 12,000 stars for a new catalog—and began his important work on the motions of stars. He took part in expeditions to Malta and Brazil to measure the longitude of a geodetic station and to attempt (unsuccessfully) to observe a solar eclipse.

Star Motions

The distribution and motions of the stars in space was the most controversial issue in astronomy in the first two decades of this century. Astronomers throughout the world, under the leadership of the Dutch astronomer Kapteyn, were counting stars to various magnitudes (brightnesses). Proper motions were being measured, and statistical studies were being made. How were the stars organized and how did they move?

After Kapteyn discovered (1904) that stellar motions were not random but that the stars appeared to be moving in two streams, young Eddington analyzed the problem. His first paper, "The Systematic Motions of the Stars" gave strong support to the two star-stream model. In 1914 his first book, *Stellar Movements and the Structure of the Universe,* (Macmillan) reviewed the various models of star-streaming and provided a foundation for subsequent research in this field. As was to be the case for most of his thirteen books, it was written for the general scientific reader, not just the specialist. By this time the controversy that was eventually to reach its peak in the Shapley-Curtis debate of 1920 and its resolution with the work of Hubble in the mid-1920's, was heating up: Were all stars part of the Milky Way system, or did the "spiral nebulae" represent other, similar systems?[3] Eddington favored the view that the spiral nebulae were external star systems. As he put it in his 1911 British Association Lecture:

> "If confirmed, the hypothesis opens up to our imagination a truly magnificent vista of system beyond system . . . in which the great stellar system of hundreds of millions of stars (our galaxy) . . . would be an insignificant unit."

2. Most of the biographical information in this article is from Douglas, A.V.: *The Life of Arthur S. Eddington* (1956, Thomas Nelson and Sons.)

3. For more on the Shapley-Curtis debate, see the article by D. Seeley and R. Berendzen in the Jul/Aug 1978 issue of *Mercury*.

The spiral galaxy NGC 6744 in Pavo. Eddington's early work on the motions of nearby stars led him to believe that our Milky Way Galaxy is but one of a multitude of galaxies — more than a decade before Hubble finally proved that spiral "nebulae" such as this one are indeed other galaxies. (CTIO 4-meter photograph courtesy of Kitt Peak National Observatory.)

He forsaw quite early the ultimate explanation for the star streaming phenomenon: the rotation of our Galaxy, a phenomenon that was to be proved by Oort and Bertil Lindblad some two decades later.

Eddington's book on stellar motions was published after he had left Greenwich. In 1913 he was appointed Plumian Professor of Astronomy at Cambridge, a position he would hold for four decades.

Relativity

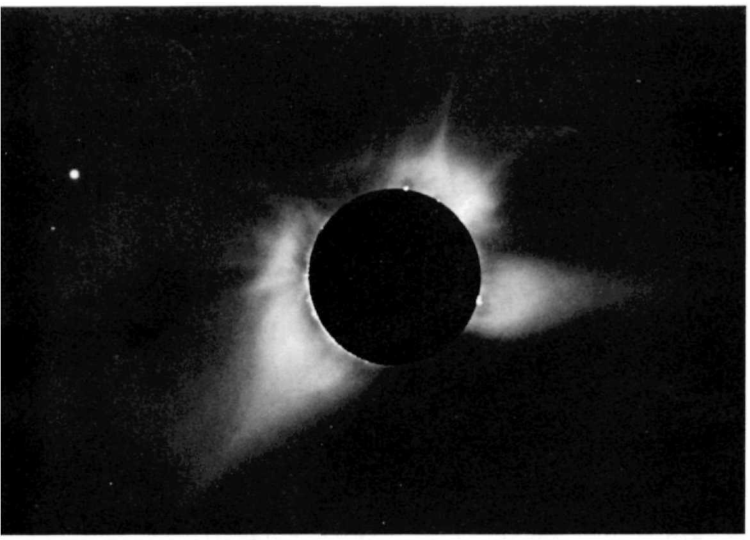
While World War I paralyzed Europe, Einstein completed the general theory of relativity in Berlin. There was no communication between enemy nations, but Einstein's papers reached neutral Holland. The Dutch astronomer Willem de Sitter, a man destined to make important contributions to relativity and cosmology, sent copies to his friend Eddington. Thus Eddington was for a while the only man in Britain or the U.S. to know about the revolutionary new theory. He immediately saw the importance of Einstein's new work and, expert mathematician that he was, mastered its techniques. In 1918, with the war still on, he published the first complete account of the theory in English, called *Report on the Relativity Theory of Gravitation* (1918, Fleetway Press.) In the preface he wrote:

"Whether the theory ultimately proves to be correct or not, it claims attention as being one of the most beautiful examples of the power of general mathematical reasoning . . . It further leads to interesting conclusions with regard to the deflection of light by a gravitational field, and the displacement of spectral lines of the sun, which may be tested by experiment."

The first of these tests, the deflection of light by a gravitational field, was to be one of Eddington's most famous contributions to science.

The story of how the expedition to make this test (during a total eclipse of the Sun) came about is told in a delightful reminiscence by a leading astrophysicst of today, Eddington's former student, S. Chandrasekhar:

"Let me go back a little to tell you about the circumstances which gave rise to the planning of the British expeditions. I learned of the circumstances from Eddington (in 1935) when I expressed to him my admiration of his scientific sensibility in planning the expeditions during 'the darkest days of the war.' To my surprise, Eddington disclaimed any credit on that account—indeed he said that, left to himself, he would not have planned the expeditions since he was fully convinced of the truth of the general theory of relativity! And he told me how the expeditions came about.



A total eclipse of the Sun. During such an event, background stars close to the Sun on the sky can be photographed without interference from the glare of the Sun's bright disk, and their apparent positions can be measured. Einstein's general relativity theory predicted that the light beams from such stars would be deflected slightly by the Sun's gravity, and Eddington confirmed the phenomenon. His analysis of photographs taken during the May 29, 1919, total eclipse constituted the first direct test of Einstein's theory and provided Eddington with what he later called the greatest moment of his life. (Photograph of the November 12, 1966, total eclipse courtesy of the High Altitude Observatory. The overexposed dot at left is Venus.)

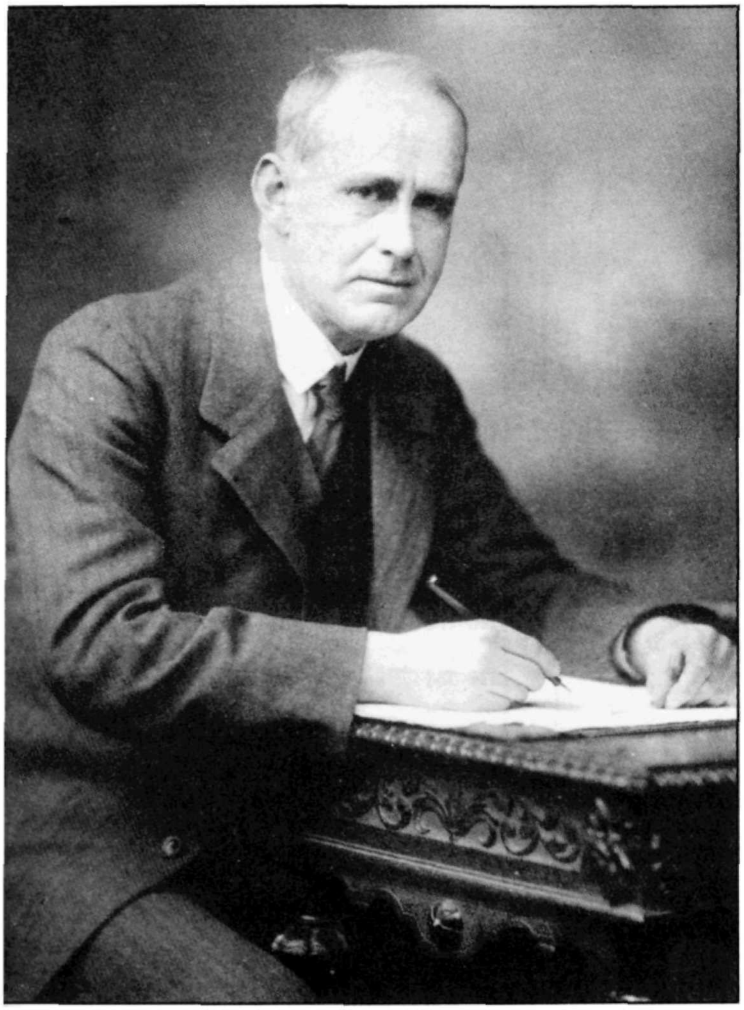
"In 1917, after more than two years of war, England enacted conscription for all able-bodied men. Eddington, who was then 34, was eligible for draft. But as a devout Quaker, he was a conscientious objector; and it was generally known and expected that he would claim deferment from military service on that ground. Now the climate of opinion in England during the war was very adverse with respect to conscientious objectors; it was, in fact, social disgrace to be even associated with one. And the stalwarts of Cambridge of those days—Sir Joseph Larmor (of the Larmor precession), Professor H.F. Newall, and others—felt that Cambridge University would be disgraced by having one of its distinguished members a declared conscientious objector. They, therefore, tried through the Home Office to have Eddington deferred on the grounds that he was a most distinguished scientist and that it was not in the long-range interests of Britain to have him serve in the army. (The case of H.G.J. Moseley, who discovered the concept of atomic number and who was killed in action at Gallipoli, Turkey, was very much in the minds of the British scientists at that time.) And Larmor and others nearly succeeded in their efforts.

"A letter from the Home Office was sent to Eddington; and all he had to do was to sign his name and return it. But Eddington added a postscript to the effect that, if he were not deferred on the stated grounds, he would claim it on conscientious objection any way. This postscript, naturally, placed the Home Office in a logical quandary: a confessed conscientious objector 'had to be sent to a camp.' Larmor and others were much annoyed. Eddington told me that he could not understand their annoyance; and as he expressed himself, many of his Quaker friends found themselves in camps in Northern England 'peeling potatoes' for holding the same convictions and he saw no reason why he should not join them. In any event, at Sir Frank Dyson's intervention—as the Astronomer Royal, he had close connections with the Admiralty—Eddington was deferred with the express stipulation that if the war should have ended by 1919, he should lead one of two expeditions that were being planned for the express purpose of verifying Einstein's prediction with regard to the gravitational deflection of light."[4]

Eddington headed the team which went to Principe; Frank Dyson, the Astronomer Royal, took another team to Brazil. In her biography of Eddington, A.V. Douglas quotes from his notebook:

"On May 29 a temendous rainstorm came on. The rain stopped about noon and about 1.30 when the partial phase was well advanced, we began to get a glimpse of the sun. We had to carry out our programme of photographs in faith. I did not see the eclipse, being too busy changing plates, except for one glance to make sure it had begun and another half-way through to see how much cloud there was. . .

4. Passage from Chandrasekhar, S.: *Bulletin of the Atomic Scientists*, June 1975, p. 17. (Reprinted with permission.)



Eddington in 1931 when he was Plumian Professor at Cambridge. (From A.V. Douglas's The Life of Arthur Stanley Eddington.*)*

"June 3. We developed the photographs, 2 each night for 6 nights after the eclipse, and I spent the whole day measuring. The cloudy weather upset my plans and I had to treat the measures in a different way from what I intended, consequently I have not been able to make any preliminary announcement of the result. But the one plate that I measured gave a result agreeing with Einstein."

Shortly afterward the eclipse results were presented to the Royal Society. According to Aflred North Whitehead:

"The whole atmosphere of tense interest was exactly that of the Greek drama: we were the chorus commenting on the decree of destiny as disclosed in the development of a supreme incident. There was dramatic quality in the very staging: — the traditional ceremonial, and in the background the picture of Newton to remind us that the greatest of scientific generalisations was now, after more than two centuries, to receive its first modification. Nor was the personal interest wanting: a great adventure in thought had at length come safe to shore."

From that moment on scientists knew that they would have to get over their Newtonian world-view and learn the new Einsteinian one, the public knew that great changes were occurring in science, and Einstein knew no peace — he was to be a celebrity for the remainder of his life.

Both the scientists and the public were helped considerably by Eddington. His book, *Space, Time, and Gravitation,* published in 1920 by Cambridge University Press, is still one of the best introductions to the subject. Translated into several languages, it is still in print.

After a Lick Observatory expedition confirmed the Einstein deflection of sunlight in 1922, Eddington remarked:

"I think it was the Bellman in *The Hunting of the Snark* who laid down the rule 'when I say it three times, it is right.' The stars have now said it three times to three separate expeditions, and I am convinced that their answer is right."

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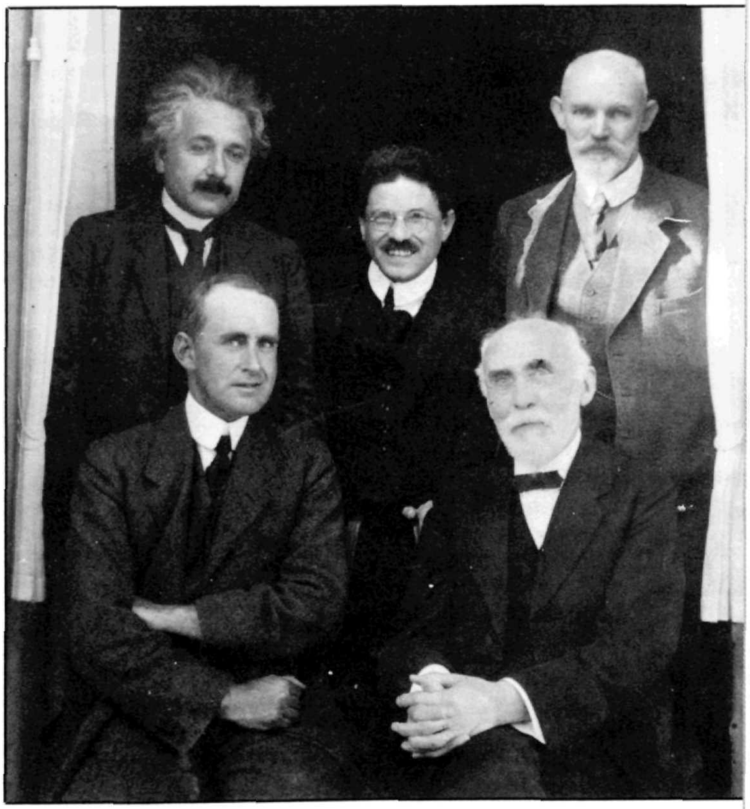

Five pioneer "relativists" in 1923. From left to right, they are Albert Einstein, Eddington, Paul Ehrenfest, H.A. Lorentz, and Willem de Sitter. During World War I, while Einstein was completing the general theory of relativity in Germany, de Sitter — in neutral Holland — was able to send copies of Einstein's work to his friend Eddington in England. (Yale University photograph.)

Eddington *continued from p. 181*

Besides testing the general theory of relativity, and popularizing it, Eddington also contributed to its application to cosmology. He found alternate ways of obtaining some of Einstein's results, and he brought out some of the theory's implications for the study of the properties of the universe for the first time.

Chandrasekhar tells a famous anecdote about the meeting where the eclipse results were presented.

> "The meeting of November 6, 1919, of the Royal Society also originated a myth that persists even today (though in a very much diluted version): "Only three persons in the world understand relativity." Eddington explained the origin of this myth during the Christmas recess conversation with which I began this account.
>
> "Sir J.J. Thomson, as President of the Royal Society at that time, concluded the meeting with the statement, 'I have to confess that no one has yet succeeded in stating in clear language what the theory of Einstein's really is.' And Eddington recalled that as the meeting was dispersing, Ludwig Silberstein (the author of one of the early books on relativity) came up to him and said, 'Professor Eddington, you must be one of three persons in the world who understands general relativity.' On Eddington demurring to this statement, Silberstein responded, 'Don't be modest, Eddington.' And Eddington's reply was, 'On the contrary. I am trying to think who the third person is!' "[4]

By 1922 Eddington was telling his students:

> "The real three-dimensional world is obsolete, and must be replaced by the four-dimensional space-time with non-Euclidean properties . . . But the four-dimensional world is no mere illustration; it is the real world of physics, arrived at in the recognized way by which physics has always (rightly or wrongly) sought for reality."

Eddington published his book *The Mathematical Theory of Relativity* in 1923. In various editions and translations it helped teach a generation of scientists the new physics and contains a number of Eddington's own contributions to the subject.

The study of general relativity led naturally to cosmology. Eddington's most important role here may have been his seeing to it that an obscure paper by his one-time student Georges Lemaître was translated and published in the *Monthly Notices of the Royal Astronomical Society*. This led to general dicussion of non-static cosmological models, and the concept of an expanding universe that has dominated cosmology ever since.

Stars and Atoms

Eddington's greatest achievements were not in stellar motions or in relativity theory, but in the physics of stars. In a long series of papers, and in his important book, *The Internal Constitution of the Stars*, (1926, 1930; Cambridge U. Press) he discovered and explained the importance of radiation pressure inside stars, derived the relation between the mass of a star and its luminosity, treated pulsations in Cepheid variable stars, advanced the idea that white dwarf stars are enormously dense, and made an early attempt to understand the opacity of stellar interiors.

Let us read about it in his own words:

> "Between 1916 and 1924 I was very much occupied trying to understand the internal constitution of the stars, for example, finding the temperature in the deep interior, which is usually ten million degrees, and making out what sort of properties matter would have at such high temperatures. Physicists had recently been making great advances in our knowledge of atoms and radiation; and the problem was to apply this new knowledge to the study of what was taking place inside a star. In the end I obtained a formula by which, if you knew the mass of a star, you could calculate how bright it ought to be. An electrical engineer will tell you that to produce a certain amount of illumination you must have a dynamo of a size which he will specify; somewhat analogously I found that for a star to give a certain amount of illumination it must have a definite mass which the formula specified. This formula, however, was not intended to apply to all stars,but only to diffuse stars with densities coresponding to a gas, because the problem became too complicated if the material could not be treated as a perfect gas.
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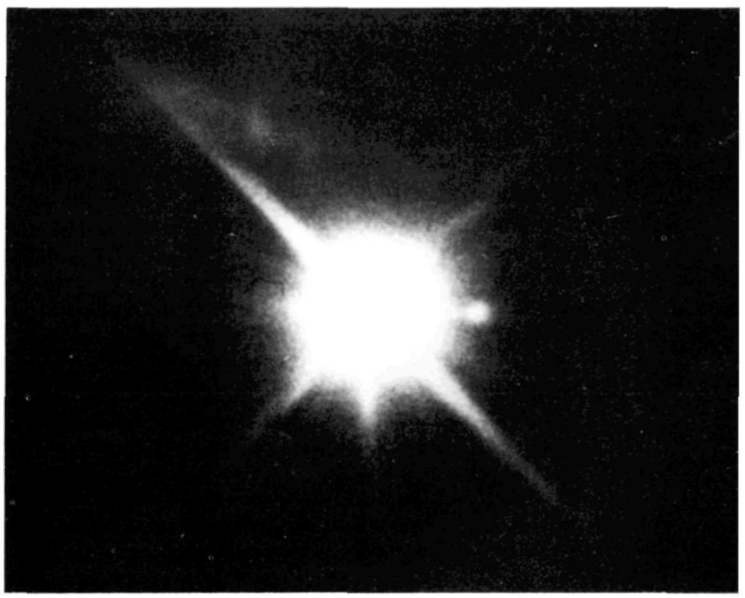
> "Having obtained the theoretical formula, the next thing was to compare it with observation. That is where the trouble often begins. And there was trouble in this



Eddington's greatest accomplishments were in the physics of stars. For example, he was the first to realize that stars like the white dwarf Sirius B — seen here as a small dot just to the right of the overexposed image of brilliant Sirius A — could have enormous densities. Eddington noted in a popular-level article in 1937 that a matchbox full of Sirius B's material would weigh a ton. (Photograph courtesy Lick Observatory.)

case; only it was not of the usual kind. The observed masses and luminosities agreed with the formulae all right; the trouble was that they would not stop agreeing! The dense stars for which the formula was *not* intended agreed just as well as the diffuse stars for which the formula was intended. This surprising result could only mean that, although their densities were as great as that of water or iron, the stellar material was nevertheless behaving like a gas; in particular, it was compressible like an ordinary gas.

"We had been rather blind not to have foreseen this. Why is it that we can compress air, but cannot appreciably compress water? It is because in air the ultimate particles (the molecules) are wide apart, with plenty of empty space between them. When we compress air we merely pack the molecules a bit closer, reducing the amount of vacant space. But in water the molecules are practically in contact and cannot be packed any closer. In all substances the ordinary limit of compression is when the molecules jam in contact; after that we cannot appreciably increase the density. This limit corresponds approximately to the density of the solid or liquid state. We had been supposing that the same limit would apply in the interior of a star. We ought to have remembered that at the temperature of millions of degrees there prevailing the atoms are highly ionized, i.e. broken up. An atom has a heavy central nucleus surrounded by a widely extended but insubstantial structure of electrons—a sort of crinoline. At the high temperature in the stars this crinoline of electrons is broken up. If you are calculating how many dancers can be accommodated in a ball-room, it makes a difference whether the ladies wear crinolines or not. Judging by the crinolined terrestrial atoms we should reach the limit of compression at densities not much greater than water; but the uncrinolined stellar atoms can pack much more densely, and do not jam together until densities far beyond terrestrial experience are reached.

"This suggested that there might exist stars of density greater than any material hitherto known, which called to mind a mystery concerning the Companion of Sirius. The dog-star Sirius has a faint companion close to it, visible in telescopes of moderate power. There is a method of finding densities of stars which I must not stop to explain. The method is rather tentative; and when it was found to give for the Companion of Sirius a density 50,000 times greater than water, it was naturally assumed that it had gone wrong in its application. But in the light of the foregoing discussion, it now seemed possible that the method had not failed, and that the extravagantly high density might be genuine. So atronomers endeavoured to check the determination of density by another method depending on Einstein's relativity theory. The second method confirmed the high density, and it is now generally accepted. The stuff of the Companion of Sirius is 2000 times as dense as platinum. Imagine a match-box filled with this matter. It would need a crane to lift it—it would weigh a ton."[5]

A field of spicules on the surface of the Sun. Eddington was among the first astronomers to become convinced that the source of the Sun's enormous and long-sustained energy output must be "subatomic" (that is, nuclear) reactions. (Photograph © 1979, Sacramento Peak Observatory.)

Eddington showed that stellar interiors are composed of ionized gases. With their electrons removed, the atoms are so small that they can crowd close together. Thus matter denser than lead can be as compressible as the air in a balloon. This was one of many topics over which Eddington clashed with his rival in astrophysics, Sir James Jeans. The two held lively debates at meetings of the Royal Astronomical Society. To Jeans the fact that the Sun's average density is greater than that of water meant that the solar interior had to be as incompressible as a liquid. As was often the case, Eddington was right.

Work on stellar physics led naturally to the question of the source of stellar energy. In 1900 Lick Observatory astronomer (and the founder of the A.S.P.) Edward S. Holden had written:

> "The sun can not have existed in the past more than fifteen million or twenty million years, not can its heat support life on the globe more than ten million years in the future. The immense periods of past time called for

5. From an article by Eddington entitled "The Milky Way and Beyond," published in 1937.

by the geologist, and especially by the biologist, to account for observed changes in strata and in the species of animals, are thus denied to them by the mathematical astronomer."

Holden here was referring to the calculations of Kelvin and Helmholtz as to how long the Sun could shine if its energy source were gravitational contraction or meteoritic infall.

As early as 1919 Eddington was convinced that the source of stellar energy lay not in those two processes, but rather in "sub-atomic" reactions and the conversion of matter into energy in accordance with the Einstein equation, $E = mc^2$. In a famous address to the British Association for the Advancement of Science the following year he made the point again. Jeans and others had objected,claiming, in accordance with the physics of the times, that the stars were not hot enough for positively charged particles to approach each other closely enough for "sub-atomic" reactions to occur. Eddington retorted:

> "We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find a hotter place."[6]

In a few years quantum mechanics would make possible a resolution of the argument. The quantum mechanical tunnelling described by Gamow and by Condon and Gurney to explain radioactive decay provided the necessary explanation of how what is now called nuclear fusion could occur in the relatively cool stellar interiors.

In the address quoted above, twelve years before the discovery of the neutron and twenty-five years before Hiroshima, Eddington noted:

> "If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fullfillment our dream of controlling this latent power for the well-being of the human race—or for its suicide."

By 1934 he was telling an audience at Cornell that the stars *must* get their energy from nuclear reactions:

> "To the engineer the prolific liberation of subatomic energy is a Utopian dream; to the physicist it is a pleasant speculation; but to the astronomer it is just a common well-recognised phenomenon which it is his business to investigate."

Again he was prophetic:

> "I have referred to the practical utilisation of subatomic energy as an illusive hope which it would be wrong to encourage; but in the present state of the world it is rather a threat which it would be a grave responsibility to disparage altogether. It cannot be denied that for a society which has to create scarcity to save its members from starvation, to whom abundance spells disaster, and to whom unlimited energy means unlimited power for war and destruction, there is an ominous cloud in the distance though at present it be no bigger than a man's hand."

6. See *Observatory*, Vol. 43, page 341.

Fundamental Theory

Eddington was, at heart, a physicist. One of the first to apply the great twentieth century physical theories—relativity and quantum mechanics—to astronomical problems, he was eager to extend the theories and to make breakthroughs in fundamental physics. In his later years he became convinced that he could solve many problems of physics by pure reasoning, an idea for which Aristotle is frequently ridiculed. In particular Eddington attempted to calculate the values of such constants of nature as the fine structure constant, the ratios of the masses of the fundamental particles, and the number of particles in the universe. His last book, *Fundamental Theory*, published posthumously, is filled with "mystical" numbers.

Some scientists derided this direction of Eddington's work; the theoretical physicist Freeman Dyson said a few years ago:

> "The crazy ideas about calculating the constants of nature from first principles had roughly the same place in Eddington's life that alchemy had in Newton's . . . Unfortunately Eddington spoilt his reputation by publishing his crazy ideas; in this respect Newton was wiser."

The Man

Eddington was a loner. According to his biographer, A.V. Douglas, herself a one-time post-doctoral student of his:

> ". . . to a most unusual extent, his work was his life and his life was his work.
>
> "His need for relaxation after long periods of intensive mental concentration found its outlet only rarely in social intercourse and then to a limited extent. He never married nor did he ever wish to marry. Apart from his mother and sister who were the homemakers, his interest in women was simply and solely as acquaintances or, in the case of the very few women astronomers in various countries, as friendly colleagues."

He read, bicycled, walked, and hiked. He lectured on four continents. He was a conscientious teacher and administrator, a tireless popularizer of science through books, articles, and lectures, a serious philosopher of science, and a religious man. He was also something of a mystic.

He served as secretary and president of the Royal Astronomical Society, and as president of the Physical Society and of the International Astronomical Union. Among his many honors were the Gold Medal of the Royal Astronomical Society and the Bruce Medal of the Astronomical Society of the Pacific (1924). He was knighted in 1930 and received one of his country's highest honors, the Order of Merit, in 1938.

After his death November 22, 1944, an obituary in the *Publications of the Astronomical Society of the Pacific* concluded:

> "A great master is gone, and a master in many fields, but most of all in astrophysics." ■