

punkt des Ingenieurs (1931), which went through several editions.

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OTTO MAYR

STOKES, GEORGE GABRIEL (*b.* Skreen, County Sligo, Ireland, 13 August 1819; *d.* Cambridge, England, 1 February 1903), *physics, mathematics*.

Stokes was born into an Anglo-Irish family that had found its vocation for a number of generations in the established Church of Ireland. His father, Gabriel Stokes, was the rector of the parish of Skreen in County Sligo. His mother, Elizabeth Haughton, was the daughter of a rector. The youngest of six children, Stokes had three brothers, all of whom took holy orders, and two sisters. He received his earliest education from his father and the parish clerk in Skreen. Stokes then attended school in Dublin before going to Bristol

College in Bristol, England, to prepare to enter university. Later in life Stokes recalled that one of his teachers at Bristol, Francis William Newman, a classicist and mathematician, had influenced him profoundly. In 1837 Stokes entered Pembroke College, Cambridge, where during his second year he began to read mathematics with William Hopkins, an outstanding private tutor whose influence on Stokes probably far outweighed that of the official college teaching. When he graduated as senior wrangler and first Smith's prizeman in 1841, Pembroke College immediately elected him to a fellowship.

Stokes became the Lucasian professor at Cambridge in 1849, rescuing the chair from the doldrums into which it had fallen, and restoring it to the eminence it had when held by Newton. Since the Lucasian chair was poorly endowed, Stokes taught at the Government School of Mines in London in the 1850's to augment his income. He held the Lucasian chair until his death in 1903. In 1857 he married Mary Susanna, daughter of the Reverend Thomas Romney Robinson, the astronomer at Armagh Observatory in Ireland. Stokes had to relinquish his fellowship to marry, but under new regulations he held a fellowship again from 1869 to 1902. A very active member of the Cambridge Philosophical Society, he was president from 1859 to 1861. Always willing to perform administrative tasks, Stokes became a secretary for the Royal Society of London in 1854, conscientiously carrying out his duties until 1885 when he became president of the society, a post he held until 1890. The society awarded him the Copley Medal in 1893. From 1887 to 1891 he represented the University of Cambridge in Parliament at Westminster; and from 1886 to 1903 he was president of the Victoria Institute of London, a society founded in 1865 to examine the relationship between Christianity and contemporary thought, especially science. Stokes was universally honored, particularly in later life, with degrees, medals, and membership in foreign societies. He was knighted in 1889. The University of Cambridge lavishly celebrated his jubilee as Lucasian professor in 1899, and three years later Pembroke College bestowed on him its highest honor by electing him master.

As William Thomson commented in his obituary of Stokes, his theoretical and experimental investigations covered the entire realm of natural philosophy. Stokes systematically explored areas of hydrodynamics, the elasticity of solids, and the behavior of waves in elastic solids including the diffraction of light, always concentrating on physically important

problems and making his mathematical analyses subservient to physical requirements. His few excursions into pure mathematics were prompted either by a need to develop methods to solve specific physical problems or by a desire to establish the validity of mathematics he was already employing. He also investigated problems in light, gravity, sound, heat, meteorology, solar physics, and chemistry. The field of electricity and magnetism lay almost untouched by him, however; he always regarded that as the domain of his friend Thomson.

After graduating, Stokes followed Hopkins' advice to pursue hydrodynamics, a field in which George Green and James Challis had recently been working at Cambridge. Thus in 1842 Stokes began his investigations by analyzing the steady motion of an incompressible fluid in two dimensions. In one instance, for motion symmetrical about an axis, he was able to solve the problem in three dimensions. In the following year he continued this work. Some of the problems that Stokes tackled had already been solved by Duhamel in his work on the permanent distribution of temperature in solids. Despite this duplication, which Stokes mentioned, he deemed the application of the formulas to fluid flow instead of heat flow sufficiently different to warrant publication. Stokes had not yet analyzed the motion of a fluid with internal friction, later known as viscosity, although references to the effects of friction continually appear in his papers. The problem, however, of the motion of a fluid in a closed box with an interior in the shape of a rectangular parallelepiped, which Stokes solved in 1843, was attacked partly with an eye to possible use in an experiment to test the effects of friction. By 1846 he had performed the experiment, but to Stokes's disappointment the differences between the experimental results and the theoretical calculations that excluded friction were too small to be useful as a test of any theory of internal friction.

Stokes's analysis of the internal friction of fluids appeared in 1845. Navier, Poisson, and Saint-Venant had already derived independently the equations for fluid flow with friction, but in the early 1840's Stokes was not thoroughly familiar with the French literature of mathematical physics, a common situation in Cambridge. Stokes said that he discovered Poisson's paper only after he had derived his own equations. He insisted, however, that his assumptions differed sufficiently from Poisson's and Navier's to justify publishing his own results. One novel feature of Stokes's derivation was that instead of using the Frenchmen's ultimate molecules he assumed that the fluid was infinitely

divisible, for he was careful not to commit himself to the idea that ultimate molecules existed. Another novel feature was his treatment of the relative motion of the parts of the fluid. He was able also to use these equations and the principles behind them to deduce the equations of motion for elastic solids, although he introduced two independent constants for what were later called the moduli of compression and rigidity, instead of one independent constant to describe elasticity as Poisson had. Stokes noted that the equations of motion he obtained for an elastic solid were the same as those that others had derived for the motion of the luminiferous ether in a vacuum. He then justified the applicability of these equations to the ether partly on the basis of the law of continuity, which permitted no sharp distinction between a viscous fluid and a solid, and which he believed held throughout nature.

Stokes became well known in England through a report on recent developments in hydrodynamics, which he presented in 1846 to the British Association for the Advancement of Science. So perceptive and suggestive was his survey that it immediately drew attention to his abilities and further enhanced his reputation as a promising young man. The report shows Stokes's increasing familiarity with the French literature on hydrodynamics and reveals his admiration for the work of George Green.

Stokes then pursued (1847) the topic of oscillatory waves in water, which he had suggested in his report merited further investigation. Poisson and Cauchy had already analyzed the complicated situation in which waves were produced by arbitrary disturbances in the fluid, but Stokes ignored the disturbances to examine the propagation of oscillatory waves the height of which is not negligible compared with their wavelength. Much later, in 1880, Stokes examined the shape of the highest oscillatory waves that could be propagated without changing their form. He showed that the crest of these waves enclosed an angle of 120° , and proposed a method for calculating the shape of the waves.

In one of his most important papers on hydrodynamics, presented in 1850, Stokes applied his theory of the internal friction of fluids to the behavior of pendulums. Poisson, Challis, Green, and Plana had analyzed in the 1830's the behavior of spheres oscillating in fluids, but Stokes took into account the effects of internal friction, including both spherical bobs and cylindrical pendulums. He then compared his theoretical calculations with

the results of experiments conducted by others, including Coulomb, Bessel, and Baily. In the same paper he showed that the behavior of water droplets in the atmosphere depended almost completely on the internal friction of air and so explained how clouds could form in the atmosphere of the earth.

On account of his theoretical analysis and experimental observations of pendulums combined with his study of gravity at the surface of the earth, Stokes became the foremost British authority on the principles of geodesy. In his study of 1849 he related the shape of the surface of the earth to the strength of gravity on it without having to adopt any assumptions whatsoever about the interior of the earth. He obtained Clairaut's theorem as a particular result. Stokes assumed merely that the earth has a surface of equilibrium, one perpendicular to the gravity on it, whereas previously assumptions about the distribution of matter in the earth were always introduced to derive Clairaut's theorem. One result of his analysis was an explanation of the well-known observation that gravity is less on a continent than on an island. When the pendulum observations for the Great Trigonometrical Survey of India were conducted from 1865 to 1873, his expertise, together with his position as secretary to the Royal Society, made him an obvious person for the surveyors to turn to for advice, even though numerical calculations based on some of Stokes's own formulas would have been too laborious to carry out.

Occasionally Stokes studied problems in sound, which he considered a branch of hydrodynamics. In 1848 and 1849 he replied to Challis' claim of a contradiction in the commonly accepted theory, and in doing so Stokes introduced surfaces of discontinuity in the velocity and density of the medium. But later, on the basis of the argument by William Thomson and Lord Rayleigh that the proposed motion violated the conservation of energy, he retracted the idea that such motion, later called shock waves, could take place. (Stokes frequently crossed swords with Challis publicly in the *Philosophical Magazine*. They disagreed over the basic equations of fluid flow [1842, 1843, 1851], the theory of aberration [1845, 1846, 1848], and the theory of colors [1856].) In 1857 Stokes explained succinctly the effect of wind on the intensity of sound. Also, using a sphere to represent a bell and an infinite cylinder to represent a string or wire, he analyzed mathematically the production of sound by the transmission of motion from a vibrating body to a surrounding gas (1868). Poisson had already solved the case of the sphere, but Stokes

was quick to point out that Poisson had examined a different problem. Stokes's analysis explained John Leslie's observation that hydrogen or a mixture of hydrogen and air transmitted the sound of a bell feebly, and why sounding boards were necessary for stringed instruments to be heard, the vibrations being communicated to the board and then to the air. In a manner typical of Stokes, he then proceeded to explain how sound was produced by telegraph wires suspended tightly between poles.

The wave theory of light was well established at Cambridge when Stokes entered the university, and he seems to have embraced it right from the beginning of his studies. His earliest investigations in this field centered on the nature of the ether, beginning in 1845 with a proof that the wave theory was consistent with a theory of aberration in which the earth dragged along the ether instead of passing freely through it, as Fresnel had suggested. In 1846 Stokes showed that when the motion of the earth through the ether was not ignored, the laws of reflection and refraction remained unchanged in his own theory as well as in Fresnel's theory, thus offering no way to decide between the two theories of the interaction of the ether with the earth. In 1848 Stokes examined mathematically the properties of the ether, and by analogy with his own theory of the motion of fluids with internal friction he combined in his ether the seemingly contradictory properties of fluidity and solidity. He maintained that to examine the motion of the earth, the ether must be viewed as a very rarefied fluid, but to examine the propagation of light the same ether must be regarded as an elastic solid. To illustrate his view Stokes suggested that the ether is related to air in the same way as thin jelly is to water. Also in 1848 Stokes employed the wave theory of light to calculate the intensity of the central spot in Newton's rings beyond the critical angle of the incident light at which the rings vanish, leaving only the central black spot. He also examined the perfectly black central spot that results when the rings are formed between glasses of the same material. Fresnel had already analyzed this phenomenon, but Stokes's assumptions and derivation differed from his.

In a major paper on the dynamical theory of diffraction (1849), Stokes treated the ether as a sensibly incompressible elastic medium. Poisson had already calculated the disturbance at any point at any time resulting from a given initial disturbance in a finite portion of an elastic solid; but Stokes presented a different derivation, which he deemed

simpler and more straightforward than Poisson's. Stokes also determined the disturbance in any direction in secondary waves, upon which the dynamical theory of diffraction depends, not limiting himself, as others had, to secondary waves in the vicinity of the normal to the primary wave. Moreover, by comparing his theory with the results of diffraction experiments that he conducted with a glass grating, Stokes answered the vexing question about the direction of vibrations of plane-polarized light by concluding that they were perpendicular to the plane of polarization.

At this time, both Stokes's theoretical analyses and his experiments covered a broad area of optics. In addition to his experiments on diffraction, he conducted experiments on Talbot's bands (1848), on the recently discovered Haidinger's brushes (1850), on phase differences in streams of plane-polarized light reflected from metallic surfaces (1850), and on the colors of thick plates (1851). Occasionally he invented and constructed his own instruments, as he did to facilitate measurements of astigmatism in the human eye (1849). In 1851 Stokes devised and largely constructed an instrument for analyzing elliptically polarized light. Here we see an excellent example of his theoretical studies complementing his experimental and instrumental work. In 1852 he published a mathematical analysis of the composition and resolution of streams of polarized light originating from different sources; the four parameters by which he characterized polarized light in this study became known as the Stokes parameters.

Stokes's explanation of fluorescence, published in 1852, for which the Royal Society awarded him the Rumford Medal, arose from his investigations begun the previous year into the blue color exhibited at the surface of an otherwise colorless and transparent solution of sulfate of quinine when viewed by transmitted light. Sir John Herschel had described this phenomenon in 1845, and Sir David Brewster had also examined it. Stokes, who had started by repeating some of Herschel's experiments and then had devised his own, rapidly concluded that light of a higher refrangibility, which corresponded to light of a higher frequency, produced light of lower refrangibility in the solution. Thus the invisible ultraviolet rays were absorbed in the solution to produce blue light at the surface. Stokes named this phenomenon fluorescence. Always looking for applications of optics, he quickly devised a method for exhibiting the phenomenon that did not require direct sunlight and so would render a chemist independent of the fickle

British weather in utilizing fluorescence to distinguish between various chemicals. In opening up the entire field of fluorescence to investigation, Stokes showed how it could be used to study the ultraviolet segment of the spectrum. By 1862 Stokes was using the spark from an induction coil to generate the spectra of various metals employed as electrodes. The invisible rays of the spectra were then examined and recorded systematically by means of fluorescence, although Stokes knew that photography was already beginning to replace fluorescence as a tool for mapping out spectra. Through his studies on fluorescence Stokes in 1862 began to collaborate with the Reverend W. Vernon Harcourt, who was one of the few people at that time attempting to vary the chemical composition of glass to produce new glasses with improved optical properties. Hoping to make glasses that would allow them to construct a perfectly achromatic combination, they collaborated until Harcourt's death in 1871.

While studying spectra by means of fluorescence, Stokes speculated on the physical principles of spectra, a topic of growing interest in the 1850's. Although Stokes always disclaimed priority in developing the principles of spectrum analysis, William Thomson insisted vigorously that Stokes taught him the principles in their conversations no later than 1852. They were discussing the topic in their correspondence in 1854 and speculating on the possibility of employing spectra to identify the chemical constituents of the sun. But Stokes did not publish anything on these ideas at that time, so the credit for the development of the principles of spectrum analysis went later to Kirchhoff and Bunsen.

Stokes's use of fluorescence in the 1850's as a tool for investigation typified his increasing emphasis on the exploitation of light to study other aspects of nature than light itself. In the 1860's, for instance, he drew the attention of chemists to the value of optical properties such as absorption and colored reflection as well as fluorescence in discriminating between organic substances. He was also a pioneer in combining spectrum analysis with chemical reactions to study blood.

Stokes's final major mathematical study on light was his classic report of 1862 on the dynamical theory of double refraction, presented to the British Association. He reviewed the theories of Fresnel, Cauchy, Neumann, Green, and MacCullagh, showing his preference for the ideas of Green and pointing out that he thought the true dynamical theory had not yet been discovered. Continuing his

study of the dynamical theories, Stokes later showed experimentally that double refraction could not depend on differences of inertia in different directions, an idea W. J. M. Rankine, Lord Rayleigh, and Stokes had all entertained. He concluded that Huygens' construction for the wave fronts should be followed. A very brief summary of his experiments and conclusion was published in 1872, but a detailed account that he promised to present to the Royal Society was never published.

Stokes's papers on pure mathematics were tailored to his requirements for solving physical problems. His paper on periodic series (1847) consisted of an examination of various aspects of the validity of the expansion of an arbitrary function in terms of functions of known form. The expansions are now called Fourier series. In the paper Stokes applied his findings to problems in heat, hydrodynamics, and electricity. In 1850 he calculated the value

of $\int_0^\infty \cos \frac{\pi}{2} (x^3 - mx) dx$, when m is large and real,

an integral that had arisen in the optical studies of G. B. Airy. The method employed by Stokes for expanding the integral in the form of power series that initially converge rapidly and ultimately diverge rapidly was the one he afterward used in 1850 to determine the motion of a cylindrical pendulum in a fluid with internal friction. In 1857 he solved the equation $\frac{d^2 w}{dz^2} - 9zw = 0$ in the complex z -plane,

which was equivalent to calculating the definite integral above. He also showed that the arbitrary constants forming the coefficients of the linear combination of the two independent asymptotic solutions for large $|z|$ were discontinuous, changing abruptly when the amplitude of z passed through certain values. The discontinuous behavior became known as the Stokes phenomenon, and the lines for which the amplitude of z has a constant value at which the discontinuities occur became known as the Stokes lines. He later examined (1868) a method of determining the arbitrary constants for the asymptotic solutions of the Bessel

equation, $\frac{d^2 y}{dx^2} + \frac{1}{x} \frac{dy}{dx} - \frac{n^2}{x^2} y = y$, where n is a real

constant. These studies in mathematics, however, formed only one small area of Stokes's publications.

In the early years of his career, through the Cambridge Philosophical Society, his teaching, and the examinations he composed, Stokes was a pivotal figure in furthering the dissemination of French mathematical physics at Cambridge. Partly because of this, and because of his own researches,

Stokes was a very important formative influence on subsequent generations of Cambridge men, including Maxwell. With Green, who in turn had influenced him, Stokes followed the work of the French, especially Lagrange, Laplace, Fourier, Poisson, and Cauchy. This is seen most clearly in his theoretical studies in optics and hydrodynamics; but it should also be noted that Stokes, even as an undergraduate, experimented incessantly. Yet his interests and investigations extended beyond physics, for his knowledge of chemistry and botany was extensive, and often his work in optics drew him into those fields.

Stokes's output of papers dropped rapidly in the 1850's, while his theoretical studies gradually gave way to experimental investigations. This occurred partly when he became a secretary to the Royal Society in 1854 and partly after he married in 1857. He often took on heavy administrative duties, which prevented him from conducting any research; and so from the 1860's many of his publications related to points arising from his official duty of reading papers submitted to the Royal Society. Stokes's papers eventually became a guide to other people's problems and interests. This is also seen in his correspondence with Thomson, for whom Stokes was a lifelong sounding board.

Throughout his life Stokes invariably took time to reply in detail to private as well as official requests for aid in solving problems, a frequent occurrence. A good example is his paper (1849) on the solution of a differential equation representing the deflection of iron railroad bridges, which Robert Willis, who was on a royal commission looking into the behavior of iron in various structures, had asked him to examine.

Although Stokes never fulfilled the expectations of his contemporaries by publishing a treatise on optics, his Burnett lectures on light, delivered at the University of Aberdeen from 1883 to 1885, were published as a single volume. The Gifford lectures on natural theology, which he delivered at Edinburgh in 1891 and 1893, were also published. A devoutly religious man, Stokes was deeply interested in the relationship of science to religion. This was especially true toward the end of his life, although he did not feel qualified to do justice to his Gifford lectureship.

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I. ORIGINAL WORKS. A comprehensive list of Stokes's papers appears in the *Royal Society Catalogue of Scientific Papers*, V, 838–840; VIII, 1022–1023;

XI, 505–506; XVIII, 977. Almost all of his published papers are included in *Mathematical and Physical Papers*, 5 vols. (Cambridge, 1880–1905); vols. I–III were edited by Stokes, and vols. IV–V posthumously by Sir Joseph Larmor. Vol. V also contains a previously unpublished MS on waves in water, as well as Smith's Prize examination papers and mathematical tripos papers set by Stokes at Cambridge.

A list of lectures and addresses on scientific topics, which were not printed in *Mathematical and Physical Papers*, is included in Larmor's preface to vol. V. A second ed. with a new preface by C. Truesdell appeared as *Mathematical and Physical Papers by the Late Sir George Gabriel Stokes, Bart. . . . Second Edition, Reprinting the Former of 1880–1905, Prepared by the Author (Volumes 1–3) and Sir J. Larmor (Volumes 4–5). With Their Annotations and the Obituary Notices by Lord Kelvin and Lord Rayleigh, and Also Including the Portions of the Original Papers Which Were Omitted From the Former Edition . . .*, 5 vols. (New York–London, 1966). *Memoirs and Scientific Correspondence of the Late Sir George Gabriel Stokes . . . Selected and Arranged by Joseph Larmor . . .*, 2 vols. (Cambridge, 1907; repr., New York–London, 1971), contains selected correspondence of Stokes, memoirs by his daughter Mrs. Laurence Humphrey and some of his colleagues, and miscellaneous material about Stokes's life and work.

Cambridge University Library, England, holds an extensive collection of Stokes's MSS, especially the Stokes Papers, which include his scientific, miscellaneous, family, Royal Society, and religious correspondence; notes for lectures; notes taken in lectures; and material concerning university administration. Add. MS 7618 at Cambridge contains the Stokes-Kelvin correspondence. The Scientific Periodicals Library, Cambridge, holds a number of Stokes's notebooks, some containing records of his experiments.

From the journal's inception in 1857 to 1878, Stokes, with A. Cayley and M. Hermite, assisted editors J. J. Sylvester and N. M. Ferrers of the *Quarterly Journal of Pure and Applied Mathematics* (London). He contributed articles, mostly on physical optics, and revised others on physical topics taken from the *Penny Cyclopaedia*, for *The English Cyclopaedia. A New Dictionary of Universal Knowledge. Conducted by Charles Knight. Arts and Sciences*, 8 vols. (London, 1859–1861). The three series of Burnett lectures were issued separately, and then published together as *Burnett Lectures. On Light. In Three Courses Delivered at Aberdeen in November, 1883, December, 1884, and November, 1885* (London–New York, 1887; 2nd ed., 1892), with a German trans. by O. Dziobek appearing as *Das Licht* (Leipzig, 1888).

Apart from his contributions to the *Journal of the Transactions of the Victoria Institute* (London), Stokes's principal writings on religion and on aspects of its relationship to science are *Natural Theology. The Gifford Lectures Delivered Before the University of Edinburgh in 1891* (London, 1891), *Natural Theology.*

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The *Transactions of the Cambridge Philosophical Society*, 18 (1900), consists of memoirs presented to the society to celebrate Stokes's jubilee as Lucasian professor.

II. SECONDARY LITERATURE. The two most important obituaries assessing Stokes's scientific work are Lord Kelvin, in *Nature*, 67 (1903), 337–338, also in *Mathematical and Scientific Papers*, 2nd ed., V, xxvii–xxxii, and Lord Rayleigh, *Proceedings of the Royal Society*, 75 (1905), 199–216, repr. in both eds. of *Mathematical and Physical Papers*, V, ix–xxv.

Since these obituaries and Larmor's *Memoir and Scientific Correspondence . . .*, little has been published on Stokes's scientific work. A few recent accounts are Truesdell's preface to the *Mathematical and Physical Papers*, 2nd ed., I, IVA–IVL; I. Grattan-Guinness, *The Development of the Foundations of Mathematical Analysis From Euler to Riemann* (Cambridge, Mass.–London, 1970), 113–120; and David B. Wilson, "George Gabriel Stokes on Stellar Aberration and the Luminiferous Ether," in *British Journal for the History of Science*, 6 (1972–1973), 57–72.

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STOLETOV, ALEKSANDR GRIGORIEVICH (*b.* Vladimir, Russia, 10 August 1839; *d.* Moscow, Russia, 27 May 1896), *physics*.

Stoletov came from a merchant family that had been exiled to Vladimir for sedition by Ivan the Terrible. His father, Grigory Mikhailovich, owned a small grocery store and a tannery; his mother, Aleksandra Vasilievna, was intelligent and well-read. While still a schoolboy he studied French, English, and German.

In 1856 Stoletov entered the Faculty of Physics and Mathematics at Moscow University as one of the first students from the merchant class to receive a government scholarship. His instructors in physics were M. F. Spassky and N. A. Lyubimov; and he received solid mathematical preparation under N. E. Zernov and N. D. Brashman. After graduating in 1860, he remained in the physics department to prepare for an academic career.

In 1862 Stoletov traveled abroad on a fellowship and spent three and a half years in Germany, where he attended the lectures of Helmholtz, Kirchhoff, and Wilhelm Weber and worked in H. G. Magnus' laboratory. At the end of 1865 he became a physics teacher at Moscow University. Four years later he defended his master's thesis, "Obshchaya zadacha elektrostati i privedenie ee k