by Larmor

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burgh, 1868. 2. 'Burns in Drama, together with Saved Leaves,' Edinburgh. 1878, a collection of literary writings. 3. 'Darwinianism: Workmen and Work,' Edinburgh, 1894, an acute criticism of the Darwinian theory of evolution. 4. 'What is Thought?' Edinburgh, 1900. 5. 'The Categories,' Edinburgh, 1903; 2nd edit. 1907; an appendix to the former book, both further elucidating the Hegelian position.

A painted portrait by Stirling's daughter Florence is in the possession of the family. There is also a black-and-white drawing, of which a replica is in the philosophy classroom of St. Andrews University.

[A biography of Stirling, by his daughter Amelia, is in course of publication.]

E. S. H.

STOKES, Sir GEORGE GABRIEL, first baronet (1819–1903), mathematician and physicist, born at Skreen, co. Sligo, 13 Aug. 1819, was youngest son of Gabriel Stokes, rector of Skreen, by his wife Elizabeth, daughter of John Haughton, rector of Kilrea, co. Derry. First educated at Dr. Wall's school in Dublin from 1831, he proceeded in 1835 to Bristol college under Dr. Jerrard, the mathematician, and entered Pembroke College, Cambridge, in 1837, becoming senior wrangler, first Smith's prizeman, and fellow of his college in 1841.

In his early Cambridge years he established a close scientific friendship with William Thomson (afterwards Lord Kelvin) [q. v. Suppl. II], which gathered force throughout their long lives. Both were impelled by the keenest interest in the advance of scientific discovery, but their endowments were in some respects complementary. Stokes remained a student throughout his life, closely pondering over mathematical questions and the causes of natural phenomena, perhaps over-cautious in drawing conclusions and in publication of his work, remarkable for his silence and abstraction even in crowded assemblies, but an excellent man of affairs, inspiring universal confidence for directness and impartiality in such administration as came to him. Thomson, during all his career, took Stokes as his mentor in the problems of pure science which he could not find leisure to probe fully for himself; and, though their opinions sometimes clashed, yet in the main no authority was with him more decisive or more venerated than that of his friend. In 1845, at the end of his undergraduate course, Thomson took over the editorship of the 'Cambridge Mathematical Journal' from Robert Leslie Ellis [q. v.], and for the following ten years his own contributions and those which he obtained from Stokes made that journal a classic. In 1849 Stokes was appointed Lucasian professor of mathematics at Cambridge, and he held the post till his death.

In his early years of residence as a graduate Stokes promoted most conspicuously the development of advanced mathematical knowledge at Cambridge. His own earliest work was mainly on the science of the motion of fluids, which he found in the preliminary stage in which it had been left by Lagrange, notwithstanding some sporadic work done by George Green [q.v.], then resident at Cambridge; in a few years he developed it into an ordered mathematical and experimental theory. To this end, in addition to a very complete discussion of the phenomena of waves on water, he created, in two great memoirs of dates 1845 and 1850, the modern theory of the motion of viscous fluids, a subject in which some beginnings had been made by Navier. In the later of these memoirs the practical applications, especially to the important subject of the correction of standard pendulum observations for aerial friction, led him into refined extensions of mathematical procedure, necessary for the discussion of fluid motion around spheres and cylinders; these, though now included under wider developments in pure analysis, have remained models for physical discussion, and have been since extensively applied to acoustics and other branches of physical science.

In the science of optics he had already in 1849 published two memoirs on Newton's coloured rings, treated always with dynamical implications; one appeared in 1851 establishing on a firm physical basis the explanation of Newton's colours of thick plates; and he had elucidated the principles of interference and polarisation in many directions. In 1849 a new path was opened in the great memoir on 'The Dynamical Theory of Diffraction,' which deals with the general problem of propagation of disturbances spreading from vibrating centres through an elastic æther, and in which mathematical expressions were developed wide enough to include the Hertzian theory of electrical vibrations and other more recent extensions of the theory of radiation. A side problem was the experimental investigation of the displacement of the plane of polarisation of light by diffraction, in order, by comparison with the theory, to ascertain the relation of the plane of its vibration to that of its polarisation. Such a determination, though fundamental for a purely dynamical view, is not essential to the construction of an adequate formal account of the phenomena of radiation, and the workers in the modern electric theory have been content in the main to stop short of it.

The calculations relating to corrections for pendulums had led him into pure analysis connected with Bessel functions and other harmonic expansions; in various subsequent memoirs he established and justified the semi-convergent series necessary to their arithmetical use over the whole range of the argument, thus making practical advances that were assimilated only in later years into general analysis. Likewise the discrepancies which he encountered in practical applications of Fourier's theory led him as early as 1847 to a reasoned exposition of doctrines, now fundamental, relating to complete and limited convergence in infinite series. Here and elsewhere, however, his work developed rather along the path of advance of physical science than on the lines of formal pure analysis; and the recognition of its mathematical completeness was in consequence delayed.

In 1859 great interest was excited by the announcement of the discovery and development of spectrum analysis by Kirchhoff and Bunsen, and its promised revelations regarding the sun and stars by means of the Fraunhofer lines, an advance which was introduced to English readers by Stokes's translation of their earlier papers. It was soon claimed by William Thomson (Lord Kelvin) that he had been familiar with the scientific possibilities in this direction since before 1852, having been taught by Stokes the dynamical connection between the opacity of a substance to special radiation and its own power of emitting radiation of the same type. The theoretical insight thus displayed, on the basis of the interpretation of isolated observations, was, of course, no detraction from the merit of the practical establishment of the great modern science of spectrum analysis by the former workers: yet the feeling in some circles, that such a claim for Stokes was not quite warranted, was only set at rest by the posthumous discovery, among his papers, of a detailed correspondence with Lord Kelvin on this subject, mainly of date 1854, which is now printed in vol. iv. of his 'Collected Papers' (cf. pp. 126–36 and 367–76).

But in fact it was hardly necessary to wait for this evidence: for the same general considerations had already entered essentially into Stokes's discussion of one of his most refined and significant experimental discoveries. Shortly after he entered on the study of optics as a subject for his activity in the Lucasian chair at Cambridge, his attention was attracted to the blue shimmer exhibited by quinine in strong illumination, which had been investigated by Sir John Herschel [q. v.] in 1845. He soon found (1852) that the phenomenon was at variance with the Newtonian principle of the definite prismatic analysis of light, as the blue colour appeared when it was not a constituent of the exciting radiation. He discovered that this emission of light, called by him fluorescence from its occurrence in fluor-spar, was provoked mainly by rays beyond the violet end of the visible spectrum; and as a bye-product he thus discovered and explored the great range of the invisible ultra-violet spectrum, having found that quartz prisms could be used for its examination, though glass was opaque. Discussion of the exceptional nature of this illumination, created by immersion of the substance in radiation of a different kind, necessarily led him into close scrutiny of the dynamics of ordinary absorption and radiation; and the idea of a medium absorbing specially the same vibrations which it could itself spontaneously emit was thus fully before him (cf. § 237 of the memoir).

Another mathematical memoir (1878), suggested by the feeble communication of sound from a bell to hydrogen gas, elucidated the circumstances which regulate the closeness of the grip that a vibrating body gets with the atmosphere; and its ideas have also wider application, to the facility for emission and absorption of radiations of all kinds from and into the vibrating bodies which are their sources.

In two memoirs of date 1849 (*Papers*, ii. 104–121), on the variation of gravity over the earth's surface, he became virtually the founder of the modern and more precise science of geodesy. The fundamental proposition was there established, as the foundation of the subject, that the form of the ocean level determines by itself the distribution of the earth's attraction everywhere outside it, without requiring any reference to the internal constitution of the earth, which in this regard must remain entirely unknown.

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from the *à priori* method depending on laws of attraction, which was inherited from the astronomers; for this there was substituted a combination of the powerful analysis by partial differentials, already cultivated by Laplace and Fourier, with close attention to the improvement of physical ideas and modes of expression of natural phenomena. The way was thereby prepared for Clerk Maxwell's interpretation of Faraday, and for the modern wide expansion of ideas.

The copious early output of Stokes's own original investigation slackened towards middle life. In 1851 he had been elected F.R.S., and next year was awarded the Rumford medal for his discovery of the nature of fluorescence. In 1854 he became secretary of the Royal Society, and the thirty-one years of his tenure of this office (1854–85) were devoted largely to the advancement of science in England and the improvement of the publications of the Royal Society. There were few of the memoirs on physical science that passed to press through his hands that did not include valuable extensions and improvements arising from his suggestions. When the Indian geodetic survey was established, he was for many years its informal but laborious scientific adviser and guide. The observatory for solar physics, which was founded in 1878, was indebted to him in a similar manner. His scientific initiative as a member of the meteorological council, who managed from 1871 the British weather service, was a dominant feature of their activity. During these years the imperfect endowment of his chair at Cambridge made it necessary for him to supplement his income from other sources: thus he was for some time lecturer at the School of Mines, and a secretary of the Cambridge University Commission of 1877–81. He had vacated his fellowship at Pembroke on his marriage in 1857, but was re-elected under a new statute in 1869.

In 1883 Stokes was appointed, under a new scheme, Burnett lecturer at Aberdeen, and delivered three courses of lectures on 'Light' (1883–5), which were published in three small volumes (1884–7). In 1891 he became Gifford lecturer at Edinburgh, and delivered other three courses on the same general subject (1891–3). The theme in all these courses was treated from the point of view of natural theology, as the terms of the foundations required. His interests as a churchman and theologian were strong through life, and found occasional expression in print. He often took part in the proceedings of the Victoria Institute in London, which was founded for inquiry into Christian evidences.

Stokes received in his later years nearly all the honours that are open to men of science. He was president of the British Association at the Exeter meeting in 1869. In 1885 he succeeded Professor Huxley as president of the Royal Society, holding the office till 1890, when he was himself succeeded by his friend Lord Kelvin; he remained on the council as vice-president two years longer, and on his retirement he was immediately awarded in 1893 the society's Copley medal. On the death of Beresford-Hope in 1887, he was elected without opposition, in the conservative interest, one of the members of parliament for Cambridge University, and he sat in the House of Commons till 1891. He was a royal commissioner for the reform of the University of London (1888–9). In 1889 he was created a baronet (6 July). In 1899 the jubilee of his tenure of the Lucasian chair was celebrated at Cambridge by a notable international assembly. Through the friendship of Hofmann, Helmholtz, Cornu, Becquerel, and other distinguished men, he became in his later years widely known abroad; and the Prussian order *pour le mérite* and the foreign associateship of the Institute of France were conferred on him. At his jubilee celebration the Institute of France sent him the special Arago medal; and he was one of the early recipients of the Helmholtz medal from Berlin. He received honorary doctor's degrees from Edinburgh, Dublin, Glasgow, and Aberdeen, as well as from Oxford and Cambridge. In October 1902 his colleagues of Pembroke College, of which he had long been fellow and of late years president, elected him Master. He died at Cambridge on 1 Feb. 1903, and was buried there at the Mill Road cemetery.

Stokes married on 4 July 1857 Mary (*d.* 30 Dec. 1899), daughter of Thomas Romney Robinson, the astronomer [q. v.], and left issue two sons and one daughter. His elder son, Arthur Romney Stokes succeeded him as second baronet.

Stokes's writings have been collected into five volumes of 'Mathematical and Physical Papers' (Cambridge, 1880–1905) of which the first three were carefully edited by himself, and the other two were prepared posthumously by Sir Joseph Larmor, his successor in the Lucasian chair. Two volumes of his very important 'Scientific Correspondence' were published in 1907 under the same editorship, and include a biographical memoir (pp. 1–90) prepared mainly by his daughter, Mrs. Laurence Humphry.

There is a portrait by G. Lowes Dickinson in Pembroke College, and one by Sir Hubert von Herkomer at the Royal Society; marble busts by Hamo Thornycroft were presented to the Fitzwilliam Museum and to Pembroke College on the celebration of his jubilee as Lucasian professor in 1899, and a memorial medallion bust by the same sculptor is in Westminster Abbey.

[Mrs. Humphry's memoir mentioned above; notice by Lord Rayleigh in Proc. Royal Soc. 1903, and reprinted in Papers, vol. v. pp. ix–xxv; cf. also Silvanus Thompson's Life of Lord Kelvin, 1910.] J. L.

STOKES, Sir JOHN (1825–1902), lieutenant-general, royal engineers, born at Cobham, Kent, on 17 June 1825, was second son in a family of three sons and three daughters of John Stokes (1773–1859), vicar of Cobham, Kent, by his wife Elizabeth Arabella Franks (1792–1868). Educated first at a private school at Ramsgate, then at the Rochester Proprietary School, Stokes passed into the Royal Military Academy at the head of the list in the summer of 1841. On leaving he was awarded the sword of honour and received a commission as second lieutenant in the royal engineers on 20 Dec. 1843. After professional instruction at Chatham, he was posted in February 1845 to the 9th company of royal sappers and miners at Woolwich, with which he proceeded in June to Grahamstown, South Africa. He was promoted lieutenant on 1 April 1846.

In Cape Colony he spent five adventurous years, taking part in the Kaffir wars of 1846–7 and of 1850–1. In the first war he was deputy assistant quartermaster-general on the staff of Colonel Somerset commanding a column of the field force in Kaffraria. He was particularly thanked by the commander-in-chief, General Sir Peregrine Maitland [q. v.], for his conduct in the action of the Gwanga on 8 June 1846, and on 25 July following, when he opened communications through the heart of the enemy's country. In the war of 1850–1 he was again on the staff as a deputy assistant quartermaster-general to the 2nd division of the field force; he was in all the operations of the division from February to July 1851, and helped to organise and train some 3000 Hottentot levies. He was repeatedly mentioned in general orders, and was thanked by the commander-in-chief, Sir Harry Smith [q. v.].

Returning home from the Cape in October 1851, Stokes became instructor in surveying at the Royal Military Academy at Woolwich. He was promoted captain on 17 Feb. 1854, and in March 1855 was appointed to the Turkish contingent, a force of 20,000 men raised for service in the war with Russia and commanded by Sir Robert John Hussey Vivian [q. v.]. Stokes sailed at the end of July after raising and organising a nucleus for the contingent's corps of engineers, to be supplemented by Turks on the spot. He was given the command of the corps, and arriving in the Crimea in advance, witnessed the final assault on Sevastopol on 8 Sept. 1855. The Turkish contingent was sent to Kertch, where Stokes employed his corps in fortifying the place and in building huts for the troops during winter. When peace was concluded in March 1856 Stokes was made British commissioner for arranging the disbandment of the contingent. For this work he received the thanks of the government, and for his services in the Crimea a brevet-majority on 6 June 1856, the fourth class of the Mejidie, and the Turkish medal.

In July 1856 Stokes was nominated British commissioner on the European commission of the Danube, constituted under the treaty of Paris to improve the mouths and navigation of the Lower Danube. The commission, at first appointed for two years, became a permanent body, with headquarters at Galatz. Stokes's colleagues were often changed, but he held office for fifteen years, and thus came to exert a commanding influence on the commission's labours. By Stokes's advice (Sir) Charles Hartley was appointed engineer and the Sulina mouth of the Danube was selected for experimental treatment. The waterway was straightened and narrowed so as to confine and accelerate the current and thus concentrate its force to scour away the bar. In 1861 it was decided to replace the temporary constructions by permanent piers which should extend into the deeper water of the Black Sea. In order to obtain the necessary funds small loans were raised on the shipping dues, but these proved insufficient for the larger scheme. Stokes devoted himself to the finances and at the same time suppressed disorders on the river, and regulated the navigation and pilotage. The fixing of a new scale of dues involved a thorough investigation into the mode of measuring ships, as to which all nations then differed. In 1865 the 'Public Act' was promulgated, embodying the decision *punkt des Ingenieurs* (1931), which went through several editions.

BIBLIOGRAPHY

I. Original Works. Stodola's publications are listed in Poggendorff, VI, 2551, and VIIa, pt. 4, 550; in his *Festschrift* (see below), xxi–xxiii; and in *Schweizerische Bauzeitung*, **121** (1943), 77–78. His major book is *Die Dampfturbinen und die Aussichten der Wärmekraftmaschinen* (Berlin, 1903), 5th ed. retitled *Dampf- und Gasturbinen* (Berlin, 1922; 6th ed., 1925); 1st ed. translated by Louis C. Lowenstein as *Steam Turbines, With an Appendix on Gas Turbines, and the Future of Heat Engines* (New York, 1905; 2nd ed., 1906), and the 5th ed. by Lowenstein as *Steam and Gas Turbines* (New York, 1927) and by E. Hahn as *Turbines à vapeur et à gaz*, 2 vols. (Paris, 1925). Other books are *Gedanken zu einer Weltanschauung vom Standpunkt des Ingenieurs* (Berlin, 1931); and *Geheimnisvolle Natur: Weltanschauliche Betrachtungen* (Zurich, 1937).

II. Secondary Literature. The most useful biographical treatments of Stodola are the following, listed chronologically: W. G. Noack, "Prof. Dr. Aurel Stodola," in E. Honegger, ed., *Festschrift Prof. Dr. A. Stodola zum 70. Geburtstag* (Zurich–Leipzig, 1929), ix–xx; G. Eichelberg, "Aurel Stodola," in *Schweizerische Bauzeitung*, **121** (1943), 73–74; H. Quiby, "Aurel Stodola, sein wissenschaftliches Werk," *ibid.*, 74–77; E. Sörensen, "Aurel Stodola," in *Zeitschrift des Vereins deutscher Ingenieure*, **87** (1943), 169–170; Anton Turecký, ed., *Aurel Stodola 1859–1942, pamiatke storočnice narodenia* (Bratislava, 1959); C. Keller, "Zum 100. Geburtstag von Aurel Stodola am 10. Mai 1959," in *Zeitschrift des Vereins deutscher Ingenieure*, **101** (1959), 558–560; and A. Sonntag, "Aurel Stodola 1859/1942," in *Brennstoff-Wärme-Kraft*, **11** (1959), 211–212.

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

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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

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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

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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 $\int_0^\infty \cos \frac{\pi}{2}\left(x^3 - mx\right)dx$, 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 $\frac{d^2w}{dz^2} - 9zw = 0$ 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, $\frac{d^2y}{dx^2} + \frac{1}{x}\frac{dy}{dx} - \frac{n^2}{x^2}y = y$, 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.

BIBLIOGRAPHY

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. The Gifford Lectures . . . 1893* (London, 1893), and *Conditional Immortality. A Help to Sceptics. A Series of Letters Addressed . . . to James Marchant (With a Prefatory Note by the Latter)* (London, 1897).

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 elektrostatiki i privedenie ee k