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William Thomson: Smoke Rings and Nineteenth-Century Atomism

By Robert H. Silliman *

I

ON February 18, 1867, Sir William Thomson, later to be Lord Kelvin, read before the Royal Society of Edinburgh a paper entitled "Vortex Atoms." [1] Supported in a sketchy manner, the central assertion of the paper was that the theory of vortex motion, a recent development in theoretical hydrodynamics, "inevitably suggests the idea that Helmholtz's rings are the only true atoms." According to this view, atoms are nothing more than loci of a special type of rotary motion within a homogeneous aether pervading space, and matter, then, simply "a mode of motion." In the months and years that followed, Thomson developed the mathematical basis of his theory and, at the same time, was able to enlist in its behalf the support of many of his most distinguished colleagues.

While seriously entertained as a credible scientific hypothesis in some circles as late as 1906, the year before Thomson's death, the vortex atom was eventually forgotten in the wake of achievements associated with the names of J. J. Thomson, Ernest Rutherford, and Niels Bohr and today has no value as a representation of the ultimate nature of matter. Nevertheless, the theory was not without permanent value and merits a more detailed historical notice than it has received.[2] Though as a model of microcosmic reality the vortex atom proved untenable, the mathematical theory of vortex motion — from which it derived and the further development of which it, in turn, greatly stimulated — served to broaden the scope of theoretical hydrodynamics in the late nineteenth century and still retains a prominent place in standard textbooks on that subject.[3] The historian of

* Princeton University. Awarded the 1962 Henry Schuman Prize.

1 A stenographic report of the paper appears in Thomson's *Mathematical and Physical Papers* (6 vols.; Cambridge: at The University Press, 1882-1911), IV, pp. 1-12.

2 Accounts of the vortex atom theory by Pierre Duhem, *L'Évolution de la mécanique* (Paris: Libraire Scientifique, A. Hermann, 1905), pp. 169-176; Florian Cajori, *A History of Physics* (New York: Dover Publications, 1962), pp. 146-147; Sir Edmund Whittaker, *A History of the Theories of Aether and Electricity* (2 vols.; New York: Harper & Brothers, 1960), I, pp. 293-295; and J. C. Gregory, *A Short History of Atomism from Democritus to Bohr* (London: A. & C. Black, 1931), pp. 159-162, are very brief, mainly expository, and except for Gregory's somewhat derisive treatment fail to set the theory in any detailed historical perspective. Two works which one might expect to have treated the theory, van Melsen's *From Atomos to Atom. The History of the Concept Atom* (New York: Harper & Brothers, 1960) and L. L. Whyte's *Essay on Atomism: From Democritus to 1960* (Middletown, Conn.: Wesleyan University Press, 1961), make no mention of it.

3 See, for example, Horace Lamb, *Hydrodynamics* (New York: Dover Publications, 1945). This is a reprint of the sixth edition of 1932.

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science may consider the vortex atom theory worthy of attention on still other grounds, for the proposal of the concept of matter as a "mode of motion" suggests that "classical" physics did not deal exclusively with billiard table mechanics or always uphold a sharp distinction between matter and energy. Perhaps the twentieth-century revolution in physics has not been quite as radical as we sometimes like to think. In any case, the theory is of interest because of the scientific stature of its propounder and the long span of time during which it enjoyed a following. In this context it provides an arresting focal point for examining several aspects of the character and orientation of nineteenth-century science. In what follows, the background, original statement, and subsequent impact of the theory will be discussed in the light of some of the broader features of Thomson's thought and the scientific milieu in which he worked.

II

As Thomson acknowledged, it was the work of Hermann von Helmholtz that provided the suggestion for his atomic model. More precisely, the source of inspiration was a pioneering mathematical investigation in hydrodynamics published by the great German physicist in *Crelle's Journal* in 1858.[4] A mathematical theory of fluid motion had been worked out by Leonhard Euler, Joseph Louis Lagrange, and others during the eighteenth and early nineteenth centuries, but the theory took the form of a series of differential equations which had been solved for only a few cases of what came to be called "irrotational" motion.[5] Accordingly, the whole question of rotational motion remained open, and it was to this that Helmholtz directed his attention. His findings were unexpected and quite remarkable.

Theoretical in intent and mathematical in form, the investigation made the assumption of a homogeneous, incompressible, frictionless fluid and turned on the concept of vortex lines (*Wirbellinien*). If u, v, w be the components of the velocity of the fluid at the point (x, y, z) and

$$\alpha = \frac{dv}{dz} - \frac{dw}{dy}, \quad \beta = \frac{dw}{dx} - \frac{du}{dz}, \quad \gamma = \frac{du}{dy} - \frac{dv}{dx},$$

then α, β, γ are the components of the rotational velocity of the fluid at the point (x, y, z). The axis of rotation of the fluid is in the direction of the resultant of α, β, γ, and the velocity of rotation, ω, is measured by this resultant. A line drawn in the fluid so that at every point of the line

$$\frac{1}{\alpha}\frac{dx}{ds} = \frac{1}{\beta}\frac{dy}{ds} = \frac{1}{\gamma}\frac{dz}{ds} = \frac{1}{\omega},$$

[4] "Ueber Integrale der hydrodynamischen Gleichungen, welche den Wirbelbewegungen entsprechen," *Journal für die reine und angewandte Mathematik*, 1858, *55*: 25-55.

[5] The motion of a fluid is said to be irrotational when it is such that if a spherical portion of the fluid were suddenly solidified, the solid sphere so formed would not be rotating about any axis. The motion is rotational when a *small* solidified sphere is in rotation about some axis passing through it.

where s is the length of the line up to the point (x, y, z), is called a vortex line; its direction coincides at every point with the axis of rotation. Now if vortex lines be drawn through every point of the boundary of an infinitely small closed curve, these lines will form a tubular surface called a vortex tube or vortex filament (*Wirbelfaden*). Proceeding from these definitions and the fundamental equations of fluid motion,[6] Helmholtz demonstrated in a series of theorems that in a perfect fluid, infinite in extent, vortex filaments turn upon themselves, forming closed rings, and that these vortex rings are totally immune to destruction or dissipation, invariable as to strength (a quantity representing the product of the cross section of the filament into the angular velocity), and subject to specified rules of rotational and translational motion.

Vortex rings, Helmholtz pointed out, exist in nature, and when examined experimentally — by drawing a circular disk or spoon across the surface of a liquid, for example — exhibit the properties required by the mathematical theory. A more dramatic method of demonstrating the vortex theory, however, suggested itself to a Scottish professor, into whose hands a version of this important paper eventually fell.

On a day in mid-January, 1867, Peter Guthrie Tait set up some homely apparatus in his lecture room at Edinburgh and proceeded to create a "magnificent display" of smoke rings. Expelled from two boxes situated at varying angles from one another, the smoke rings behaved in a most curious manner. When two rings were made to travel in the same direction with their centers in the same line and their planes perpendicular to this line, the leading ring expanded and moved more slowly; the pursuing ring contracted and moved faster; and each in turn passed through the other. When, however, two rings were made to approach each other from opposite directions, both of them expanded and moved more and more slowly, never quite touching. Propelled toward each other at oblique angles, the rings glanced off each other without coming into actual contact and thereafter went into a state of violent vibration. No less remarkable was the fact that individual smoke rings resisted all efforts to cut them with a knife. No matter how vigorous the slicing motions, the rings simply moved away from, or wriggled around, the sharp instrument. Conceived and executed as an illustration of the vortex theory, this demonstration was frequently to be repeated.[7] This particular performance, however, is significant for the effect

[6] At a point (x, y, z) in a fluid let p be the pressure, u, v, w the rectangular components of the velocity, X, Y, Z the components of external forces acting on unit mass, and h the density, all at time t. Then the equations of motion for the particles within the fluid are:

$$X - \frac{1}{h}\frac{dp}{dx} = \frac{du}{dt} + u\frac{du}{dx} + v\frac{du}{dy} + w\frac{du}{dz},$$

$$Y - \frac{1}{h}\frac{dp}{dy} = \frac{dv}{dt} + u\frac{dv}{dx} + v\frac{dv}{dy} + w\frac{dv}{dz},$$

$$Z - \frac{1}{h}\frac{dp}{dz} = \frac{dw}{dt} + u\frac{dw}{dx} + v\frac{dw}{dy} + w\frac{dw}{dz},$$

$$0 = \frac{du}{dx} + \frac{dv}{dy} + \frac{dw}{dz}.$$

[7] See Tait's commentary accompanying a demonstration performed in 1874, *Lectures on Some Recent Advances in Physical Science* (2nd ed.; London: Macmillan, 1876), pp. 290-300. Other observations on smoke rings made at this time by Robert Ball are reported in his

it had on the chief witness for whom it was arranged, Sir William Thomson.[8] Highly impressed by what he saw, Tait's counterpart in the chair of natural philosophy at Glasgow promptly reread the memoir of Helmholtz and consigned himself to an intense study of *Wirbelbewegung*.[9] A month later he read the paper on vortex atoms.

III

It is easy to conceive of Thomson's interest in atoms and the nature of matter as just another preoccupation of an extremely fertile and active mind which ranged over nearly every aspect of physical science.[10] Yet, in fact, this interest was fundamental to all his theoretical concerns. His scientific papers, from the beginning of his career in the eighteen-forties to the end in the first decade of this century, abound with theories, assertions, and speculations on the nature of matter and its connection with the aether. Behind this abiding interest was the firm persuasion that a completely satisfactory explanation of any natural phenomenon presupposed an understanding of its ultimate mechanism at the atomic level. As expressed in a textbook written in collaboration with Tait, his position is that "until we know thoroughly the nature of matter and the forces which produce its motions, it will be utterly impossible to submit to mathematical reasoning the *exact* conditions of any physical question."[11] It is clear that his atomic viewpoint was enforced by the desire to lay bare the mainsprings of not only individual phenomena, but also, what for him was especially important, the precise connection between related phenomena, such as electricity, magnetism, and light. A true insight into this connection could only be acquired by reference to the lowest common denominator of all natural forces, to the ultimate properties of matter and space. In Thomson's mind the final goal of scientific inquiry was to work out "a great chart, in which all physical science will be represented with every property of matter shown in dynamical relation to the whole."[12]

The term "dynamical" is commonly encountered in Thomson's work

"On Vortex-rings in Air," *The Philosophical Magazine*, 1868, *36*: 12-14. A long list of the characteristics of smoke rings produced according to Tait's method is given in A. E. Dolbear, *Modes of Motion or Mechanical Conceptions of Physical Phenomena* (Boston: Lee and Shepard, 1897), pp. 28-33.

[8] Thomson and Tait were collaborating on a physics textbook at this time, and while much of the work was carried on through the mail, it was Thomson's practice to journey to Edinburgh on weekends. See W. E. Aryton, "Kelvin in the Sixties," *The Popular Science Monthly*, March, 1908, *72*: 259 f. The textbook appeared under the title *A Treatise on Natural Philosophy* (Oxford: Clarendon Press, 1867).

[9] See Silvanus P. Thompson, *The Life of William Thomson, Baron Kelvin of Largs* (2 vols.; London: Macmillan, 1910), I, p. 512, and Thomson's letter to Helmholtz quoted in *ibid.*, pp. 513-516. Thomson had originally read the paper in the fall of 1858, but apparently without the enthusiasm it later inspired. See *ibid.*, p. 403.

[10] The fertility and diversity of Thomson's mind is strikingly apparent from the bibliography of his printed books, scientific communications, and addresses, and the list of his patents given in *ibid.*, II, pp. 1223-1277.

[11] *Elements of Natural Philosophy. Part I* (2nd ed.; Cambridge: at the University Press, 1879), p. 136.

[12] "Address," *British Association Report*, 1871, *41*: xciii. See also Thomson's *Popular Lectures and Addresses* (3 vols.; London: Macmillan, 1889), I, pp. 231-233.

and, as it is intimately bound up with his entire conception of scientific explanation, constitutes an important element in his theory of matter. It is only a slight exaggeration to say that Thomson and, indeed, that whole school of distinguished British mathematical physicists to which he belonged, equated physics with dynamics and sought as far as possible to reduce all natural phenomena to the laws of motion and impact.[13] In fact, in Thomson's case, theories were occasionally put forth in the form of crude mechanical models replete with springs, pulleys, and flywheels. With these models he sought to find some arrangement or configuration of moving parts that would reproduce all the observable attributes of the phenomenon to be explained, and when this was found, and not until then, a sufficient explanation would be at hand. " It seems to me that the test of ' Do we understand a particular point in physics? ' is ' Can we make a mechanical model of it? ' " [14] The requirement for mechanical or dynamical models, in fact, played such a large role in Thomson's thought that he could never bring himself fully to accept Maxwell's electromagnetic theory of light: " I firmly believe in an electromagnetic theory of light, and that when we understand electricity and magnetism and light we shall see them all together as parts of a whole. But I want to understand light as well as I can, without introducing things we understand even less of. That is why I take plain dynamics; I can get a model in plain dynamics; I cannot in electromagnetics." [15] When Thomson witnessed the smoke ring demonstration, his conception of what constitutes a scientific explanation had already predisposed his mind toward atomic considerations and toward mechanical models to which any theory, including an atomic theory, would have to conform.

IV

In the decades prior to the announcement of the vortex atom theory, atoms or ultimate corpuscles had played a prominent role in two separate lines of scientific investigation, chemistry and the kinetic theory of gases. In the former the laws of definite and multiple proportions led directly to atomic considerations and to extensive efforts to determine relative atomic weights; in the latter the behavior of gases under varying conditions of pressure, volume, and temperature suggested the existence of minute elastic corpuscles whose velocities and masses were fit subject for study. Neither of these lines of investigation, however, led to any new comprehensive theory of the nature of matter. Accordingly, in the decade of the sixties speculations on this subject were usually centered around two theories inherited from the past, the ancient theory of Democritus in the form transmitted by

[13] In a formal definition in the *Elements of Natural Philosophy*, p. 1, Thomson and Tait include *statics* as well as *kinetics* under the term *dynamics*, which then becomes equivalent to our *mechanics*, a term they reserve for " the Science of Machines, and the art of making them." See Maxwell's comments on the distinction between dynamical and chemical reasoning in his article " Atom," *Encyclopedia Britannica* (9th ed., 1878), III, p. 40.

[14] Quoted in Silvanus P. Thompson, *op. cit.*, II, p. 830.

[15] *Ibid.*, pp. 835-836.

Lucretius and revived in the late Renaissance, and that of Roger Boscovich, an eighteenth-century Jesuit priest.

The older theory, which conceived of atoms as hard, elastic bodies moving in empty space, maintained its currency primarily because it proved useful in understanding the behavior of gases. In Thomson's mind, however, the theory had little to recommend it. It was conceptually barren and in reality explained nothing. His objection, as stated in the initial paper on vortex atoms, was that the proponents of the Lucretian atom arbitrarily endowed it with exactly those characteristics it was supposed to account for on the molar level: " Lucretius's atom does not explain any of the properties of matter without attributing them to the atom itself. Thus the ' clash of atoms,' as it has been well called, has been invoked by his modern followers to account for the elasticity of gases. Every other property of matter has similarly required an assumption of specific forces pertaining to the atom."[16] The hard, elastic bodies singularly failed to explain the findings of spectrum analysis, unless vibration was simply assigned to the atom as one of its properties.

The theory of Boscovich, set forth in his *Theoria Philosophiae Naturalis*, first published just a hundred years before the Helmholtz memoir, depicted atoms as indivisible points of force which at vanishing distances repel each other; at insensible distances, alternately attract and repel; and at sensible distances, attract according to the inverse square law.[17] In the eighteenth century, this theory had a wide following, especially in Great Britain, ostensibly because of its Newtonian orientation, and in the nineteenth, it remained a worthy alternative to the Lucretian theory due, most probably, to the hope that in some way it could account for electrical and magnetic phenomena, which the other theory could accommodate only with contrived auxiliary hypotheses.[18] Thomson's paper on vortex atoms does not make any allusion to the theory of Boscovich, but it may be surmised from other writings of this period that he was not completely unsympathetic with it. Indeed, in later years, when his enthusiasm for the vortex atom waned, he was to devote considerable effort to the further development of the Boscovichian theory.[19] Nevertheless, in the sixties his position was probably little different from that taken by J. Clerk Maxwell in his article on the atom written for the ninth edition of the *Encyclopedia Britannica*. After leveling

[16] " On Vortex Atoms," *Mathematical and Physical Papers*, IV, pp. 1-2.

[17] See Ruggiero G. Boscovich, J. M. Child (ed.), *A Theory of Natural Philosophy. Latin-English Edition from the First Venetian Edition, Published under the Personal Superintendence of the Author is 1763. With a Short Life of Boscovich* (Chicago: Open Court, 1922).

[18] J. T. Merz discusses the influence of Boscovich in France, Germany, and Great Britain in the eighteenth and nineteenth centuries, and for the earlier century speculates that the theory found favor " because it seemed to give support to the prevalent corpuscular theory of light." See *A History of European Thought in the Nineteenth Century* (4 vols.; Edinburgh and London: Blackwood & Sons, 1896-1914), I, p. 357, n. 2.

[19] Noting his change in attitude toward this theory and selecting appropriate phrases from his writings, Thomson's biographer comments: " And so Father Boscovich, judged obsolete in 1884, and his theory pronounced ' infinitely improbable ' in 1893, was in 1900 ' reinstated as guide.' " Silvanus P. Thompson, *op. cit.*, II, p. 107, n. 2.

against the Lucretian atom the same criticism that is found in Thomson's paper of 1867, Maxwell writes:

> The massive centers of force imagined by Boscovich may have more to recommend them to the mathematician, who has no scruple in supposing them to be invested with the power of attracting and repelling according to any law of distance which it may please him to assign. Such centers of force are no doubt in their own nature indivisible, but they are also, singly, incapable of vibration.[20]

Unsatisfied with current theories of the atom and yet anxious to have a mechanical model of the molecular bases of all phenomena, Thomson was prepared to entertain novel ideas and even to abandon the orthodox notion of a sharp distinction between matter and its surroundings.

It is an interesting commentary on the orientation of nineteenth-century physics that the aether should have provided the focus for Thomson's model. Precisely those phenomena whose connections he was most anxious to elucidate were of a type that ostensibly involved action at a distance. Now since action at a distance was philosophically unacceptable — matter cannot act where it is not — the satisfactory theory of the ultimate mechanism of phenomena had to comprehend not only matter, considered in the usual sense, but also the intervening space. Certain phenomena, light in particular, suggested that space was not empty and featureless, but indeed, had certain properties which could be investigated.[21] The reality of the aether and its manifest interaction with ponderable matter tended to weaken the position of matter as an ordering principle in physical science and even to blur the distinction between matter and space. Here was another reason for rejecting the theory of the atoms and the void, and in fact the inability of Michael Faraday to account for electrical conduction and insulation on this model led him to advocate something like the atom of Boscovich, an atom which effectively abolished the boundary between matter and space:

> The view now stated of the constitution of matter would seem to involve necessarily the conclusion that matter fills all space, or, at least, all space to which gravitation extends (including the sun and its system); for gravitation is a property of matter dependent on a certain force, and it is this force which constitutes the matter. In that view matter is not merely mutually penetrable, but each atom extends, so to say, throughout the whole of the solar system, yet always retaining its own center of force.[22]

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[20] III, p. 45.

[21] "It seems to me that we must know a great deal more of the luminiferous ether than we do. But instead of beginning with saying that we know nothing about it, I say that we know more about it than we do about air or water, glass or iron — it is far simpler; there is far less to know. That is to say, the natural history of the luminiferous ether is an infinitely simpler subject than the natural history of any other body." Thomson in the *Baltimore Lectures* (1884), quoted in Silvanus P. Thompson, *op. cit.*, II, pp. 818-819. See Maxwell's article "Ether," *Encyclopedia Britannica* (9th ed.; 1878), VIII, pp. 568-572.

[22] "A Speculation Touching Electric Conduction and the Nature of Matter," *The Philosophical Magazine*, February, 1844, *24*, no. 157: 143.

It is very likely that considerations of this kind prepared Thomson's mind for the aether-centered theory, even if, as his biographer states, it were clearly perceived " by a flash of inspiration."

While the aether occupied a prominent place in scientific thought from the establishment of the wave theory of light, an interest in vortices seems always to have been in the air, and as Helmholtz's paper shows, this interest was still alive after the disappearance of Cartesianism.[23] In fact, a thin line of " vortical " thought can be traced from the late seventeenth to the mid-nineteenth century, where something like a full revival took place. In the eighteenth century a Cartesian, John Bernoulli, the younger, accounted for the propagation of light by postulating a fluid aether which owed its elasticity to an immense number of small whirlpools situated within it. While this theory enjoyed almost no favor in the years that followed, James MacCullagh, in 1839, resolved a perplexing discrepancy in current optical theory by developing a new type of " rotationally elastic " aether.[24] The idea next figured prominently in a series of papers on thermodynamics delivered before the Royal Society of Edinburgh by W. J. M. Rankine in 1849-1850.[25] Based on an hypothesis of " molecular vortices," these papers came to the notice of Thomson and inspired a new interpretation of magnetism which he set forth in 1856. From a study of the rotation of the plane of polarized light, he came to the conclusion that magnetism possesses a rotary character and suggested that the resultant angular momentum of the thermal motions of a body might be taken as the measure of the magnetic moment.[26] The paper embodying these conclusions, in its turn, inspired a mechanical model of the aether devised by Maxwell in 1861, in which the energy of a magnetic system was represented by the rotation of fluid about the lines of magnetic force, each unit tube of force being depicted as a vortex.[27] Thomson's interest in vortices, then, predated the smoke ring demonstration and was part of a general fascination with various types of rotational motion.

[23] For a comment on the " perennial " and " unprofitable " fascination for vortices, see H. T. Pledge, *Science Since 1500. A Short History of Mathematics, Physics, Chemistry, Biology* (New York: Harper & Brothers, 1959), pp. 134-135.

[24] " An Essay Towards a Dynamical Theory of Crystalline Reflection and Refraction," *The Collected Works of James MacCullagh*, edited by John H. Jellett and Samuel Haughton (Dublin: Hodges Figgis and Co., 1880), pp. 145-193. The discrepancy involved the fact that while prevailing conceptions of the aether allowed for the transverse waves necessary for the representation of light, they did not provide for the exclusion of longitudinal waves, which were undetectable in reflection and refraction. Later Thomson was to design a mechanical model of MacCullagh's aether. See " Exhibition of a Gyrostatic Model of a Medium capable of Transmitting Waves of Transverse Vibration," *Proceedings of the Royal Society of Edinburgh*, 1889, *16*: 811.

[25] " On the Mechanical Action of Heat," *Transactions of the Royal Society of Edinburgh*, 1853, *20*: 147-210.

[26] " Dynamical Illustrations of the Magnetic and Heliocoidal Rotary Effects of Transparent Bodies on Polarized Light," *The Philosophical Magazine*, March, 1857, *13*, no. 85: 198-204.

[27] " On Physical Lines of Force," *The Philosophical Magazine*, 1861, *21*: 161, 281, 338; 1862, *23*: 12, 85. See " The Origins of Clerk Maxwell's Electric Ideas, as Described in Familiar Letters to W. Thomson," *Proceedings of the Cambridge Philosophical Society*, 1936, *32*, part 5: 695-750.

V

The notion that atoms are centers of vortex motion in a fluid aether pervading space had value for Thomson, of course, only insofar as these atoms "explained" something and actually conformed to nature. In the middle of the nineteenth century an atomic theorist had a fairly large fund of experimental data to contend with, especially if his theory were to be as comprehensive as Thomson wished it to be. Even so, as late as 1878 Maxwell could limit the essential conditions an atom must satisfy to three: "permanence in magnitude, capability of internal motion or vibration, and a sufficient amount of possible characteristics to account for the difference between atoms of different kinds." [28] For Thomson, likewise, these three conditions seem to have served as a minimum standard by which to judge the adequacy of an atomic theory.

The first general condition imposed on the atom was that it had to account for permanence, that is, for "the unalterable distinguishing qualities of different kinds of matter." [29] That permanence in this sense was a characteristic of matter was so undeniable as to be almost an axiom of science. The entire experience of the scientific laboratory showed that each of the elements retained at all times and in all places the same physical and chemical properties. Thus the chemical laws of constant and multiple proportions were explained on the assumption of different kinds of atoms, each of a characteristic, invariable weight. Likewise, the kinetic theory of gases was developed partly on the basis that molecules of the same kind could be taken to have the same mass. The possibility remained, however, that the correct explanation of these phenomena involving the invariability of mass was not that small particles of the same kind were of the same mass, but only that their mean mass was a statistical constant of great stability. Nevertheless, this possibility could practically be discounted due to the results of dialysis experiments. The method for separating particles of different mass by diffusing them through a membrane — a method developed by Thomas Graham — could not succeed in separating particles of one and the same gas.[30] All evidence pointed to the conclusion that a primary characteristic of the atom was its permanence, invariability, and stability. Consequently, Thomson can recommend the vortex ring as "the only true atom" partly on the ground that vortex motion has "infinitely perennial specific quality." The generation of vortex rings requires an "act of creative power," and once generated in a perfect fluid, these rings can never be altered or destroyed.[31]

A second condition imposed on the atom was that it account for manifestations of inertia and elasticity. These two characteristics of matter were, of course, fundamental to all of physics, but at this time they derived their prominence largely from their role in the kinetic theory of gases. Helmholtz

[28] "Atom," *Encyclopedia Britannica*, III, p. 45.

[29] *Mathematical and Physical Papers*, IV, p. 1.

[30] See Maxwell, "Atom," *Encyclopedia Britannica*, III, pp. 40-41.

[31] *Mathematical and Physical Papers*, IV, p. 1.

had not extended his theory to the problem of what would happen if two vortex rings approached each other obliquely on a collision path. Thomson felt this was " a perfectly solvable mathematical problem," but since his first paper on vortices was delivered only a month after the original inspiration, there had been insufficient time to work it out. Nevertheless, the behavior of smoke rings upon collision made him confident that a vortex ring in a perfect fluid would possess perfect elasticity. Furthermore, vortex rings, " without requiring any other property in the matter whose motion composes them than inertia and incompressible occupation of space," could account for the thermodynamic properties of gases revealed by the investigations of Rudolf Clausius, Maxwell, and their predecessors. Indeed, the mathematical solution to the problem of two closely approaching vortex rings " will become the basis of the proposed new kinetic theory of gases." What is more, he felt that a theory of elastic solids and liquids based on the dynamics of more closely packed vortex atoms could be " reasonably anticipated." [32]

Another general condition was that the atomic model possess a sufficient number of possible characteristics to account for different kinds of matter. The tremendous variety of substances encountered in the chemical laboratory indeed required a versatile atom. Not only were there some sixty different elements, but an inexhaustible number of compounds whose characteristics, since they were not simple combinations of those of the constituent elements, required a separate explanation in atomic terms. Here the vortex rings admirably met the test. This is not to say that specific types of vortex rings could be set in a one to one correspondence with specific substances, but only that vortex theory provided for an endless possible variety of atoms. The sole requirement imposed on the configuration of the vortex filament was that its ends must meet, and therefore it was possible to find the required variety in any number of linked and knotted rings. Thomson illustrated this at the reading of his paper by showing the audience diagrams and wire models representing knotted atoms, " the endless variety of which is infinitely more than sufficient to explain the varieties and allotropies of known simple bodies and their mutual affinities." [33]

A final general condition imposed upon any atomic model claiming plausibility was that it provide the " capability of internal motion or vibration." This was made necessary by the wave theory of light and, in particular, the phenomena of spectra. Thomson, by his own statement, learned the " dynamical " theory of spectra from George Gabriel Stokes and was teaching it to his classes at Glasgow as early as 1852.[34] However, it was not until 1859 that Gustav Kirchoff and Robert Bunsen succeeded in showing that there existed an invariable connection between certain rays of the spectrum and certain kinds of matter. The fact was that spectra required the assump-

[32] *Ibid.*, pp. 2-3.

[33] *Ibid.*, p. 3. Tait tried unsuccessfully to establish a relation between the numbers of knots of different orders of " knottiness " and the chemical elements. See " Knots," *Scientific Papers of Peter Guthrie Tait* (2 vols.; Cambridge: Cambridge University Press, 1898-1900), I, pp. 273-347.

[34] *Mathematical and Physical Papers*, IV, p. 3.

tion of one or more fundamental periods of vibration within the recesses of matter, and now the conclusion could be drawn that the atom — that which distinguishes one kind of matter from another — constitutes the source of vibration. In any case, vibration had to be accounted for. Again, as in the case of elasticity, Thomson had had insufficient time to make a proper mathematical analysis, which he deemed "formidable," and had to rely on the analogy of the smoke rings. Choosing an example, he states that "it is probable that the vibrations which constitute the incandescence of sodium vapour are analogous to those which the smoke rings had exhibited." If this is true, then, the period of each vortex rotation of the atoms of sodium vapour is "much less than $\frac{1}{525}$ of the millionth of the millionth of a second," the period of vibration of the yellow sodium light. Since, however, sodium light shows two sets of vibrations with slightly different periods and about equal intensity, the sodium atom must have two fundamental modes of vibration, and therefore it seems probable that the sodium atom may not consist of a single vortex line, but of two approximately equal vortex rings passing through one another like two links in a chain. "It is, however, quite certain that a vapour consisting of such atoms, with proper volumes and angular velocities in the two rings of each atom, would act precisely as incandescent sodium-vapour acts — that is to say, would fulfill the 'spectrum test' for sodium." [35]

After indicating the conformity of the vortex ring to the essential conditions which any adequate atomic model must meet, Thomson in his initial paper went on to discuss the translational velocity of a vortex ring, an analogy between the momentum of vortex rings and the magnetic moment of a circular electro-magnet, and, finally, the conditions which determine the size of a ring. In a subsequent paper [36] read on April 29, 1867, he worked through the entire theory of vortex motion, simplifying Helmholtz's proofs and adding a few theorems of his own, and in a note [37] appended to Tait's translation of the Helmholtz memoir made for the *Philosophical Magazine*, he gave the formula for the translational velocity of a vortex ring in terms of its dimensions and velocity of rotation.

In the years that followed, the general theory of vortex motion and suggestions for its application to a theory of matter were discussed by Thomson in a score of papers and notes, the most important of which were "Vortex Statics" (1875), "On Vortex Sponges" (1881), "Steps Toward a Kinetic Theory of Matter" (1884), and "The Vortex Theory of Luminiferous Ether" (1887). For the most part this later work considered vortex theory mathematically and abstractly, and the theory was extended not by reference to experimental data or specific facts of physical reality, but by recourse to definitions and theorems. Only occasionally — when, for example, he showed that the pressure exerted by a gas composed of vortex atoms exactly matches the requirements of the kinetic theory of gases under the assumption of

[35] *Ibid.*, p. 5.

[36] "On Vortex Motion," *Mathematical and Physical Papers*, IV, pp. 13-66.

[37] "The Translatory Velocity of a Circular Vortex Ring," *The Philosophical Magazine*, 1867, *33*: 511-512.

hard, elastic spheres [38] — did Thomson relate the theory to potentially observable phenomena.

VI

Around 1883, Thomson began to be assailed by doubts about his theory, and in 1886, he told Theodore Merz that the vortex atom did not realize his expectations, inasmuch as it did not explain inertia or gravitation. Worst of all, about 1887, he came to the conclusion that the Helmholtz circular ring was, after all, essentially unstable and that " its fate must be to become dissipated." [39] Finally in 1898, he wrote to Silas Holman, emeritus professor of physics at the Massachusetts Institute of Technology:

> I am afraid it is not possible to explain all the properties of matter by the Vortex-atom Theory alone, that is to say, merely by motion of an incompressible fluid; and I have not found it helpful in respect to crystalline configurations, or electrical, chemical, or gravitational forces. . . . We may expect that the time will come when we shall understand the nature of an atom. With great regret I abandon the idea that a mere configuration of motion suffices.[40]

For a period of thirty to forty years the vortex atom theory maintained a prominent position in British and American thinking on atomism. In 1874, Tait called it " the most fruitful in consequences of all the suggestions that have hitherto been made as to the ultimate nature of matter " [41] and for years did much to popularize it through his dramatic smoke ring demonstrations. Maxwell, writing for the *Encyclopedia Britannica* in 1878, singled out the vortex atom for special attention and described it as satisfying more essential conditions " than any atom hitherto imagined." [42] In 1883, J. J. Thomson published an essay on " Vortex Atom Rings " and twenty years later spoke of his own corpuscular atomic model as " not nearly so fundamental as the vortex-atom theory of matter." [43] In the same year that William Thomson definitively repudiated the vortex atom, Holman discussed its applications to the explanation of the phenomena of gas pres-

[38] " On the Average Pressure Due to Impulse of Vortex-Rings on a Solid," *Mathematical and Physical Papers*, IV, p. 188.

[39] " Deep Water Ship-Waves," *Proceedings of the Royal Society of Edinburgh*, 1904, *25*: 565, n.

[40] Quoted in Silas W. Holman, *Matter, Energy, Force and Work. A Plain Presentation of Fundamental Physical Concepts and of the Vortex Atom and Other Theories* (New York: Macmillan, 1898), p. 226.

[41] *Lectures on Some Recent Advances in Physical Science*, pp. 290-291.

[42] III, p. 45.

[43] *The Corpuscular Theory of Matter* (New York: Charles Scribner's Sons, 1907), p. 2. In 1898, he wrote to Holman: " With reference to the Vortex-atom Theory, I do not know of any phenomenon which is manifestly incapable of being explained by it; and personally I generally endeavor (often without success) to picture to myself some kind of vortex-ring mechanism to account for the phenomenon with which I am dealing. In lectures and papers, however, I generally content myself with an illustration which, though it has no claim to the fundamental character of one based on vortex motion, is easily conceived and handled by the mind, and so is more adapted as a guide to research.

" I regard, however, the vortex-atom explanation as the goal at which to aim, though I am afraid we know enough about the properties of molecules to feel sure that the distribution of vortex motion concerned is very complex." Quoted in Holman, *op. cit.*, p. 226.

sure, chemical valence, dissociation, cohesion, elasticity, and gravitation and remarked that these applications "and their concordance with observed facts indicate for this hypothesis far greater prominence than attends the former, kinetic, theory or any of the other suggestions yet made." [44] One year later A. A. Michelson asserted that the vortex atom was "one of the most promising hypotheses," and added:

> Suppose that an ether strain corresponds to an electric charge, an ether displacement to the electric current, these ether vortices to the atoms — if we continue these suppositions, we arrive at what may be one of the grandest generalizations of modern science — of which we are tempted to say that it ought to be true even if it is not — namely, that all phenomena of the physical universe are only different manifestations of the various modes of motion of one all-pervading ether.[45]

Despite the almost universal acknowledgment of the "suggestiveness" of the vortex atom theory, no one — including, perhaps, Thomson himself — was thoroughly persuaded that vortex rings were "the only true atoms," and, in fact, throughout this period there was a considerable reluctance in some circles even to admit that atoms had a real existence in nature.[46] Accordingly, the relatively long history of the vortex theory constitutes something of a problem. No doubt, the scientific reputation of its propounder had much to do with its viability, and certainly the absence of a thoroughly persuasive alternative theory was not inconsequential. Nevertheless, the theory in its own right was highly seductive. Due to a long-standing canon of science, simple hypotheses were always favored, and nothing appeared simpler, and therefore more likely true, than the notion that matter is merely a locus of rotary motion in an all-pervading aether. Previously it had been shown that heat is nothing more than motion. Might not this also be true of matter, since smoke rings and spinning tops provided clear evidence that mere motion can produce the elasticity and rigidity associated with sensible matter? Supported by crude analogies, the vortex atom theory remained pretty much free from refutation because of the physical minuteness of its object and the mathematical complexity of its statement, which severely restricted the possibility of experimentally verifiable deductions. When, in 1897, J. J. Thomson came to the conclusion that cathode rays were made up of particles sub-atomic in size, the fate of the vortex atom was sealed. Four years later William Thomson (now Lord Kelvin) suggested an entirely new atomic model to accommodate the electrons [47] and this model, further developed by J. J. Thomson, initiated the train of concepts which led ultimately to our current view of the atom.

As time was to show, the atom is no mere configuration of vortex motion, and the aether — the incompressible, homogeneous fluid in which this motion was supposed to take place — does not exist. Nevertheless, the efforts

[44] *Ibid.*, p. 219.

[45] *Light Waves and Their Uses* (Chicago: University of Chicago Press, 1903), pp. 161-162.

[46] See van Melsen, *op. cit.*, pp. 149-153; Cajori, *op. cit.*, pp. 147-148.

[47] See "Aepinus Atomized," *The Philosophical Magazine*, 1902, *3*: 257; 1904, *8*: 528; and 1905, *10*: 695.

of Thomson and his followers to develop the vortex atom theory led them to an intensive study of fluid motion, and the results of this study were of permanent value, even if applications had to be made to fluids less exalted than a universal aether. While Helmholtz established the fundamental laws of vortex motion, William Thomson extended them and laid down the theory of the steady motion and stability of vortices. J. J. Thomson added to the theory of the single vortex ring, worked out the mutual interaction of two rings, and contributed to the further development of the theory of knotted and linked vortices.[48] Other contributions to the general theory of vortex motion, largely inspired by a desire to extend the vortex atom theory, were made by William Mitchinson Hicks, Alfred George Greenhill, M. J. M. Hill, Alfred Barnard Basset, and C. V. Coates.[49] Made in pursuit of a fantasy, the achievements of these men helped to shape modern hydro- and aerodynamics.

[48] See J. J. Thomson, *A Treatise on the Motion of Vortex Rings* (London: Macmillan, 1883).

[49] See A. E. H. Love, "On Recent English Researches in Vortex-Motion," *Mathematische Annalen*, 1887, *30*: 326-344.