La química en la historia, para la enseñanza.

John James Waterston A pioneer of the kinetic theory of gases

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Resumen
John James Waterston (1811-1883) puede ser considerado el último de los pioneros de la teoría cinética. El mejoró en forma notable la teoría desarrollada por Herapath y demostró que la velocidad cuadrática media de las moléculas de un gas, puro o mezclado, está conectada directamente con su temperatura absoluta. Fue el primero en publicar el teorema de equipartición de la energía y demostró cómo su teoría podía ser utilizada para calcular la velocidad del sonido así como el diámetro de una molécula. Lamentablemente su publicación fundamental sufrió el mismo destino que la de Herapath: su rechazo por la Sociedad Real y, por tanto, desconocida por el mundo científico. Afortunadamente, Lord Rayleigh la encontró y publicó años después de la muerte de Waterston.

Abstract
John James Waterston (1811-1883) may be considered the last of the pioneers of the kinetic theory. He improved substantially the theory developed by Her - path and demonstrated that the mean square velocity of the molecules of a gas, in the pure state or mixed, is directly connected to the absolute temperature of the same. He was the first to establish the theorem of equipartition of energy. He showed how his theory could be used to calculate the velocity of sound, as well as the diameter of a molecule. Regrettably his basic publication suffered the same fate as that of Herapath: rejection by the Royal Society and thus unknown to the scientific world. Fortunately Lord Rayleigh found it and had it published, years after Waterston's death.

The kinetic theory regards a mass of gas as a collection of a great number of independently moving minute solid particles, molecules, or atoms, separated by spaces relatively large in comparison with the diameter of the particles, These entities move mostly in straight lines, except when deflected with occasional collisions with the walls of the containing vessel and with each other. The colliding particles are supposed to act upon each other only within very small distances and for very short times before and after collision, their motion being free in the intervals between such distances and times (free path). The duration of free paths are assumed to be indefinitely large as compared to the durations of the encounters and of the mutual actions. The motion as a whole is conserved by reason of the absolute elasticity of the moving particles, while the directions of the movements of the individual particles are persistently changed by their mutual collisions. Molecules of different gases differ in mass, but all molecules of the same gas have the same mass. The everlasting motion of the particles can be explained assuming that the rebound by collision occurs without loss of kinetic energy or momentum. The kinetic theory interprets the pressure, or elasticity of a gas, as the aggregate of the pressures exerted by the various molecules when they collide with the boundary; only at relatively high pressures does the effect of intermolecular forces become important. The ideal gas laws are easily deduced from this model by Newtonian mechanics, and the temperature is identified with the mean-square velocity

One of the original assumptions of the kinetic theory is the perfect elasticity of the molecules, a fact that was not clearly understood and gave place to much discussion. Inasmuch as no perfectly elastic solid is known, there is no basis in experience for this assumption. In actual solids part of the kinetic energy of colliding spheres is transformed into heat due to friction in the deformation of the bodies. Nevertheless, the kinetic theory develops the notion that heat is the energy of molecules in motion.

The ideas current at Waterston's time, and almost universally accepted, were that the particles of gases were stationary, being held in position by repulsive forces that were thought to exist between them. These repulsive forces were themselves attributed to the presence, either round or between the gas particles, of the subtle, weightless and highly elastic fluid of heat that was known to most scientists as *caloric*, as Antoine-Laurent Lavoisier (1743-1794)

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named it in 1787. The theory negated that atomic vibrations alone could account for the phenomena of heat; the role of the æther was essential. In addition, atoms in a gas could not move freely through space, they were constrained to vibrate about fixed equilibrium positions. Caloric was characterized by the following attributes: (a) it was an elastic fluid, the particles of which repelled one another strongly, (b) the particles of caloric were attracted by particles of ordinary matter, the magnitude of the attraction being different for different substances and for different states of aggregation, (c) caloric was indestructible and uncreatable, (d) caloric could be either sensible or latent, and in the latter state was combined chemically with the particles of matter to form the liquid or vapour. Sensible caloric was supposed to form an atmosphere around the particles of the body, and (e) caloric did not have appreciable weight (Roller, 1950). Manifest caloric was assumed to possess the peculiar property of being attracted by ordinary matter, but repelled by itself in inverse proportion to distance. Hence the molecules of a gas or other substance containing manifest caloric repelled one another in direct proportion to their concentration, while they also repelled one another in proportion to the amount of manifest caloric they contained. Absolute zero on this theory would represent a state in which there is no manifest caloric in the molecules. It was further assumed that when the rise of temperature is produced by friction or compression, this was due to the liberation of latent caloric, while the cooling which accompanied expansion and other processes was due to caloric becoming latent. The caloric theory also lent itself admirably to mathematical treatment.

Leonhard Euler (1707-1783), Daniel Bernouilli (1700-1782), John Herapath (1790-1868), and John James Waterston (1811-1883) may be considered the principal scientists who prior to 1850 attempted a more or less complete mathematical treatment of gases based on a set of molecular postulates. He we describe the contribution of Waterston, which would lead to the seminal contribution of James Clerk Maxwell (1831-1879).

Life and career

Most of the details available about the personal life of John Jaime Waterston (1811-1883) appear in the book by Haldane, which also carries most of Waterston's publications (published and unpublished) (Haldane, 1928).

John James Waterston was born in Edinburgh, Scotland on 1811, the sixth of a family of nine, who remained deeply attached to one another throughout their lives. His father was George Waterston, originally a schoolmaster and later an Edinburgh manufacturer of sealing wax and other stationery requisites. George Waterston was greatly interested in literature, science, and music. His family thus grew up in an atmosphere of culture and often came into contact with young literary men, such as John Hill Burton (1809-1881), the future historian of political and social economy, Thomas De Quincey (1785-1859), an essayist and critic, and George Combe (1788-1858), the apostle of phrenology (Haldane, 1928).

The Waterston firm was founded in 1752 by William Waterston, grandfather of John James. Originally a schoolmaster in East Lothian, William established a business in Edinburgh as a wax chandler and for the manufacture and supply of sealing wax and the flambeaus or links used in those days before public lighting of the streets. William Waterston married Catherine Sandeman, daughter of a Perth merchant, and a woman of great character and ability, who after her husband's death, carried on the business vigorously. Catherine was the niece of Robert Sandeman (1718-1771), a well-known religious leader, and with her there came into the family, not only an additional tradition of culture, but also the religious teaching of his uncle Robert and his father-in-law John Glas (1695-1773). Sandeman and Glas were the originators of the religious body known as Glasites or Sandemanians, active in England and America. Glas was a Forfarshire Prebysterian minister who objected to State interference with Church, and was therefore deposed, but continued to act on his convictions, together with members of his congregation and others who held similar opinions (Haldane, 1928).

One of the English Sandemanians was Michael Faraday's (1791-1867) father. Michael Faraday himself remained throughout his life an active member of the Sandemanian Church in London. The principles of Glas and Sandeman were closely akin to those requisite in a real leader in pure science, and it is significant that two such men such as Faraday and John James Waterston were connected in their upbringing with this very small religious body (Haldane, 1928).

All the Waterston children were educated at the Edinburgh High School, then the leading school in

Scotland. On leaving the High School, Waterston became an apprentice with Messrs Grainger and Miller, civil engineers, and at the same time attended lectures at the University and took a very active part in the student's Literary Society. He studied mathematics under John Leslie (1766-1832), and was a medallist of his year in Leslie's class. Waterston also attended lectures on anatomy under Alexander Monroe (tertius,1773-1859), as well as on chemistry and surgery. This somewhat remarkable choice of subjects was doubtless connected with the fact that both his father and he were much influenced by the physiological and educational teaching of George and Andrew Combe(1797-1847) (Haldane, 1928).

Like most of the scientists of his time Waterston wanted to prove that all the different forces of nature are only different manifestations of one or two basic forces. Like other early kinetic theorists such as George-Louis Le Sage (1724-1803) and John Herapath (1790-1868), he was hopeful that he could construct a mechanical explanation of gravity, without invoking action at a distance. At the age of 19 he published a paper in *Philosophical Magazine* in which he discussed the properties of a system of small colliding cylindrical particles, arguing that these could generate a gravity-like force between larger bodies immersed in the system (Waterston, 1831). Some of the ideas developed in this paper were later utilized in his kinetic theory, in particular the idea that collisions would result in a transfer of energy from the rectilinear to the rotatory modes of motion. Here too Waterston enunciated the basic goal of mechanistic physics: "that matter and motion alone will be found sufficient to explain all the phenomena attending the grand cycle of nature's operations" (Brush, 1961).

At the age of 21 Waterston moved to London, with a view of prosecuting his intended career as a civil engineer. There he became a pupil of James Walker (1781-1862), a leading civil engineer and President of the Institution of Civil Engineers. For two or three years he was employed in drawing and surveying work in connection with the rapidly developing railway system of England, and with docks, lighthouses, etc. He became an associate of the Institution of Civil Engineers, and contributed a paper to the first volume of the *Transactions* of that body on a graphical method of estimating the earthwork en embankments and cuttings (Haldane, 1928).

In order to follow his scientific interests, he applied for and obtained a post in the hydrographer's department of the Admiralty. The head of the Department was Captain (afterwards Admiral) Francis Beaufort(1744-1857), who subsequently communicated Waterston's paper on kinetic theory to the Royal Society. On Beaufort's suggestion, and with his support, Waterston obtained in 1839 a position as naval instructor to the East India Company's cadet college at Bombay. He found this appointment very rewarding, he was making good money and in addition had enough free time to make use of the scientific books and journals at the library of Grant College, Bombay. He taught the different aspects of such subjects as navigation and gunnery (Haldane, 1928).

Waterston carried out at Bombay a series of experiments on the relation between capillarity or surface tension and latent heat of vaporization of liquids at different temperatures. He also worked at Bombay on solar radiation, and at certain astronomical subjects.

In 1857, then 46 years old, Waterston resigned his appointment at Bombay and returned to Scotland, having saved enough money to be able to devote all his time to his scientific interests. He lived in Edinburgh for about eight years, and then moved to Inverness, near his brother Charles, who was a banker there. Afterwards he moved to Dunkeld where his mother lived, but soon he returned to Edinburgh and remained there until his death in 1883. A main reason for his resignation was probably the difficulty in getting his scientific work published. In one of his letters he alludes to the possibility of getting a professorship, possible at the Addiscombe College of the East India Company (Haldane, 1928).

In Scotland he did additional experimental work on liquids and between 1857 and 1868 he published twenty papers in all in the *Philosophical Magazine*, including four on electrical matters in 1865 and three on astronomical subjects. Some of these papers were on the experimental measurement of solar radiation, yielding an estimate of about 13 million degrees for the sun's temperature; this figure was frequently quoted in the debate on the sun's temperature during the 1870's. Apparently, he never met any of the scientists who might have recognized the value of his work on the kinetic theory, with the possible exception of William John Macquorn Rankine (1820-1872) who spoke at the same session of the British Association for the Advancement of Science meeting at which Waterston presented a paper on gases in 185 (Waterston, 1851). According to a memoir by his nephew, Waterston "would not attend the meetings of the Royal Society of Edinburgh though some friends sent him billets, and rather avoided the society of scientific men We could never understand the way in which he talked of the learned societies, but any mention of them generally brought out considerable abuse without any definite reason assigned" (Haldane, 1928).

In 1878 the Royal Astronomical Society rejected two papers by Waterston. A few months later, he resigned, having been a member since 1852. The event reinforced his isolation from the scientific world.

During his stay in India, Waterston send home the manuscript of a short book and several scientific papers. His book bore the somewhat unappealing title of *Thoughts in the Mental Functions* (Waterston, 1843), and is an essay on the physiology of the central system. Oliver & Boyd published it anonymously in Edinburgh in 1843. It contains the first sketch of Waterston's views on molecules, and corresponding theory of gases and heat, on the possible application of molecular theory to biology, and includes some basic principles of the kinetics theory (see below).

Waterston's paper on the theory of sound (Waterston, 1858), published in *Philosophical Magazine* in 1858, was the ultimate reason for his posthumous recognition by the scientific community. In 1876. Samuel Tolver Preston (1844-) wrote to Maxwell about this paper, noting that Waterston had investigated the kinetic theory of gases as early as 1845, although his work had not been yet published. But Maxwell apparently took no interest in this matter and it was not until 1891, eight years after Waterston's death, that Lord Rayleigh (John William Strutt, 1842-1919), who was then Secretary of the Royal Society, rediscovered the 1858 paper on sound because of his interest in another of Waterston's paper cited in it. The paper was published in the *Philosophical Transactions* for 1892 (Waterston, 1846), with an introduction by Rayleigh, according to whom "It is difficult to put oneself in imagination into the position of the reader of 1845, and one can understand that the circumstance of the memoir should have appeared speculative and that its mathematical style should have failed to attract. But it is startling to find a referee expressing the opinion that the "paper is nonsense, unfit even for reading before the Society." A second referee wrote, "That the whole investigation is confessedly founded on a principle entirely hypothetical, from which it is the object to deduce a mathematical representation of the phenomena of elastic media. It exhibits much skill and many remarkable accordances with the general facts, as well as numerical values furnished by observation…The original principle itself involves an assumption which seems to me difficult to admit, and by no means a satisfactory basis for a mathematical theory, viz., that the elasticity of a medium is measured by supposing its molecules in vertical motion, and making a succession of impacts against an elastic gravitating plane." The history of this paper suggests that highly speculative investigations, particularly by an unknown author, are best brought before the scientific world through some other channel that a scientific society, which naturally hesitates to admit into its printed records matter of uncertain value. Perhaps one may go further and say that a young author who believes himself capable of great things would usually do well to secure the favourable recognition of the scientific world by work whose scope is limited, and whose value is easily judged, before embarking on greater flights".

Waterston argued that in mixed media the mean square molecular velocity is inversely proportional to the specific weight of the molecules. This leads to the result that in equal volumes of gas, at the same temperature and pressure, there is equal number of molecules, independently of the size and weight of the molecules (Avogadro's law). Another consequence is that the mean velocities of the molecules of different kinds of gas vary inversely as the square roots of their molecular weights. This corresponds to Thomas Graham's (1805-1869) empirically discovered law of diffusion in different gases. Within fifteen years of the rejection of Waterston's first paper, the reasoning which had led him to the dynamical explanation of the gas laws had been independently rediscovered piecemeal by August Karl Krönig (1822-1879), Rudolf Julius Emanuel Clausius (1822-1888), and Maxwell; and long before the end of the nineteenth century the kinetic theory of gases and a dynamical conception of heat and temperature had become a common place in ordinary text books (Haldane, 1928).

In his calculation of the ratio c_P/c_V Waterston made an unfortunate algebraic error that led him to believe that the energy of rotation could be neglected in the kinetic theory of gases. This error also led him to underestimate the mechanical equivalent of heat (673 lb of water descending the height of one foot will increase the temperature of water one degree), by about one seventh below James Prescott Joule's

(1818-1889) experimental result (800 lb of water). Waterston believed Joule's value to be too high.

Waterston never married, he lived the life of a very popular bachelor, fond of the best music, billiards, a cigar, or chess, and the idol of children who knew him. He took great interest in all the members of his family, and particularly in his nephews and nieces, to whom he used to teach mathematics and other subjects in which they showed interest. He was also keenly interested in contemporary literature and politics, and was strongly liberal in his political sympathies. Although he was living in Edinburgh in the midst of a Glasite community, he was never a member of the Glasite Church, either there or in London. Waterston was very critical of William Thomson, Lord Kelvin (1824-1907), owing to what he considered the latter's connection with commercial applications of science (Kelvin became very rich for his participation in the laying of the transatlantic submarine cable between Ireland and Newfounland in 1850). Waterston, like Faraday, carried Glasite principles into science and held that scientific men should support themselves in other ways, for instance by teaching, than by practical applications of their scientific investigations (Haldane, 1928).

During an experiment on solar radiation in Bombay he had a severe attack of heat stroke and his native assistant, not knowing what to do, left him for some time unconscious in the sun. The effects of the accident affected seriously his health. He was subject to sudden attacks of dizziness, particularly in crowded rooms and on railway journeys. It is very probable that his death was indirectly caused by one of these attacks (Haldane, 1928).

On June 18, 1883, he went one morning from his home for one of his ordinary walks. He did not return and the most efforts were made to discover what had become of him, with no success. It seems practically certain that he fell in the water of a new breakwater under construction and that his body was carried out to sea by the tide, which was high at that time. He probably had an attack of giddiness or loss of conscious, which resulted in his falling in the water (Haldane, 1928).

Scientific work

Book (Waterston, 1846)

The general philosophical standpoint adopted by Waterston appears explicitly in the Preface and Introduction of the book and in the sub-title "An attempt to treat metaphysics as a branch of the physiology of the central nervous system". Waterston, tried to work out the implications of this scientific and philosophical assumption when applied to human behaviour He believed that this trait could only express itself in material changes, which must be dependent on previous material changes (Haldane, 1928).

A whole chapter of his book is devoted to phrenology, which at that time was very popular. Phrenology was a science of character divination, faculty psychology, theory of brain, and what the 19th-century phrenologists called "the only true science of mind." Phrenology was derived from the theories of the Viennese physician Franz Joseph Gal**l** (1758-1828), which claimed the brain is the organ of the mind, each faculty has a separate seat in it, and the surface of the skull can be read as an accurate index of psychological aptitudes and tendencies of the individual. As believed by Waterston, the characteristics of the head could be used to distinguish, for example, a clever person from a dull one. He went further on and suggested a new classifications of the attributes which would be sitted in different locations of the brain. For example, the seat of the apetites was located in the interior surface of the cerebellum.

Waterston believed that: "The faculty of association has been elaborately treated and reduced to the single principle of simultaneousness of excitement. Every exertion was made to penetrate this apparently simple law, but without success. It involves a power of registering successive action, which, as there is nothing in physics the least analogous, must be viewed as a primary organic principle, a characteristic of organization." He remarked that: "we are led to expect that if molecular philosophy is ever destined to advance into the region of organization the phenomena of perceptive consciousness will admit of being applied to illustrate the physical aspect of the elementary powers of matter." According to Haldane (Haldane, 1928) these words were almost prophetic of relativity physics.

Waterston saw clearly that the problems of life and conscious behaviour are bound up in those of molecular or atomic behaviour. It was from molecular adaptations that the amazing monuments of creative intelligence had emanated. Organization was to be viewed, in connection with the chemical relations of bodies, as a magnificent exhibition of the capabilities of the elements of matter. Assimilation, reproduction, perceptive and motor intelligence, bounded together by association, the grand principle of organic attraction, were enclosed in forms which were circles of molecular action, where the divine spirit, the omnipotent principle of adaptation, had been exerted with infinite and perfect display. The constitution of animals and vegetables demonstrated an exact knowledge of the intensity of the force of gravity and of the heat and light of the sun.

Waterston's book ends on a chapter called *Note on Molecularity*, in which he gives the first expression of his views on molecules and on the possible application of molecular theory to biology. It is of interest to quote in full its most important assumptions and conclusions because they constitute the building stones of Waterston's dynamical theory of gases: (a) "Hypothesis - The molecular forces of bodies are derived from media, consisting of atoms perfectly elastic and endowed with momentum, which exists in them in either or all the preceding modes (rectilineal, vibrational, and rotational). The evolution or absorption of molecular momentum, or change of molecular conditions and relations, is caused by a transference of momentum from one mode of existence to another, (b) By the continued impact of the spherical atoms of such a medium, part of their rectilinear momentum will be absorbed and converted into momentum of rotation (of which billiard balls are a familiar example)…The proportion of the whole rectilineal to the whole rotatory momentum of the medium is probably constant, and might be found perhaps by calculation; it cannot be less than $(\sqrt{5/2} - 1)$ to 1, (c) A medium constituted of elastic spherical atoms that are continually impinging against each other with the same velocity, will exert against a vacuum an elastic force that is proportional to the square of this velocity and to its density. To maintain the same elasticity with atoms of different size, their velocity must be inversely as the mass of the atom, (d) If an elastic force is introduced into the medium, the atoms by impinging upon it, will lose rotatory momentum and gain rectilineal; consequently, their angle of reflection will be less than that of incidence; hence, there will be a deficiency of centripetal elasticity in a direction perpendicular to the surface, and an excess of centrifugal elasticity in directions oblique to the surface. If a slender, elastic rigid cylinder is introduced into the medium and if it is indefinitely longer that the mutual distance of atoms, similar changes of elasticity will be established as in the case of the elastic surface, (e) Two such lines will be subject to the influence of mutual attractive and repulsive forces, which tend to bring them into one position of equilibrium with regard to each other…A medium constituted of such rigid lines would exhibit a polar arrangement, and the parts would be held together by a force similar to that of cohesion, which does not extend beyond the adjacent lines, (f) It is of little use of pursuing this further, unassisted by mathematics; but there is perhaps enough to show, that media present great capabilities of explaining molecularity, and in the hands of a mathematician might lead to interesting results. If we view the molecules of bodies as consisting of clusters of rigid lines, the forces which they eliminate from the media may be sufficient to bind them together in various modes of arrangements, each mode having a corresponding peculiarity in its habitudes with the media, from which may arise its particular molecular powers and chemical qualities, (g) If these hypothetical views of the elastic constitution of the elements of matter are consistent with truth, then heat is evolved by gravitation (!) as well as by chemical action. The greater the load a molecule has to bear, the greater will be its temperature; hence the equilibrium of heat in a planetary body requires that the temperature should increase towards the centre and in the atmosphere that it should diminish as we ascend".

In a memoir written after the book was sent to the printers (*Physical Constitution of Gaseous Fluids and a Theory of Heat*) Waterston adds some additional comments related to the properties of gases, suggesting that increase in temperature might correspond to increase in molecular *vis viva* and that the square of the velocity of the molecules represent the temperature. He shows that the distance traveled by a molecule, after hitting one and before encountering another, is inversely as the density of the medium and also inversely as the square of the diameter of the molecules. He then discusses the constitution of the earth's atmosphere and mentions that if the atomic weight of air were as small as hydrogen, the Earth's attraction could not retain it, it would evaporate in space, just as the moon's atmosphere as already done. The mean velocity of air at 60°F is calculated to be 2822 feet per second. The velocity of sound is just half, according to Waterston.

Kinetic theory

Waterston's propositions about the dynamical theory of gases, presented in his book, along with other far-fetched notions, attracted little attention at that time. In December 1845,Waterston presented a mor systematic exposition of his theory of gases in a paper entitled "On the Physics of Media that are Composed of Free and Elastic Molecules in a State of Motion" (Waterston, 1846). In the introduction he mentions that the experiments by James David Forbes (1828-1876) and Macedonio Melloni (1798-1854) on radiant heat have led to a wider acceptance of the wave theory of light. The ondulatory theory leads to the conclusion that the temperature of a body is a persistent quality due to the motion of its molecules and thus it seems impossible to escape from the conclusion that heat is essentially kinetic energy. As mentioned before, one of Waterston's main conclusions was that "in a mixed media the mean square molecular velocity is inversely proportional to the specific weight of the molecules"; this was the first statement of the "equipartition theorem" of statistical mechanics (for translational motion only). Since this conclusion was printed in an Abstract of the British Association meeting in 1851,Waterston seems to have established his priority in announcing the theorem even though the rest of his paper was not published until much later (Brush, 1957).

Waterston submitted his paper for publication in the *Philosophical Transactions of the Royal Society* of London. At that time it was the practice of the Society that a paper submitted by someone not a fellow of the Society could be read (officially presented) if it were communicated by a fellow, but it then became the property of the Society and would not be returned to the author even if it was not published. The two referees who examined Waterston's manuscript recommended that it should not be published (the same negative decision that was adopted in 1815 with regards to Herapath's paper on kinetic theory). It was first sent to Baden Powell(1796-1860), Savilian Professor of Geometry at Oxford, who said that Waterston's basic principle, that the pressure of a gas is due to the impacts of molecules against the sides of the container, was "very difficult to admit, and by no means a satisfactory basis for a mathematical theory." Although he objected to Waterston's fundamental hypothesis he admitted that the paper "exhibits much skill & many remarkable accordances with the general facts as well as numerical values furnished by observation." He did not think it should be published in the *Philosophical Transactions*, but suggested that the final decision should be made by an expert in the field such as the astronomers John William Lubbock (1803-1865) or Philip Kelland (1808-1879). The paper was then sent to Lubbock, who wrote that "the paper is nothing but nonsense, unfit even for reading before the Society." These judgments seem rather harsh, not because Waterston's theory was essentially the same as the one proposed in the 1850's by Rudolf Julius Emanuel Clausius (1822-1888 and Maxwell, but because even by 1845 the physical basis for such a theory, the relation between heat and mechanical energy, was accepted by a substantial portion of the scientific community (Haldane, 1928).

The paper was read in March 1845 (before Lubbock had given his opinion) and although a brief abstract of it appeared in the *Abstracts of the Papers Printed in the Philosophical Transactions of the Royal Society* in 1846, the Society refused to print the paper itself. It seems that Waterston was not aware that a paper was not be returned to the author even if it was read and not published. Since he did not keep a copy for himself he was unable to publish it elsewhere. He tried to overcome this limitation by privately printing and circulating a twelve long summary of his paper and by raising the subject in later papers presented at the British Association meetings and in *Philosophical Magazine*. He sent one copy of the summary to John Herschel (1792-1891; the famous astronomer known for his work on double stars) and other scientists, but did not get any encouragement from any of them. The paper remained unpublished in the archives of the Royal Society until Rayleigh discovered it in 1891 and had it reprinted with his own comments and corrections (as explained above) (Waterston, 1831, 1846; Brush, 1957).

The only immediate responses came from Rankine (Rankine, 1853) and from Helmholtz (Helmholtz, 1855). Rankine criticized Waterston's theory on the basis that the total heat of a gas could not be accounted for by translational motion of the particles and suggested remedying this defect with his own theory of rotating molecular vortices. Later, Clausius noted the same difficulty and suggested instead that the molecules of gases are composed of two or more atoms. In general, although the total kinetic energy would be distributed in some way between the translational motion of the whole molecules and the internal vibratory or rotary motion of the constituents of the molecules, the translational motion of the whole molecules would always have a constant relation to the internal movements of the constituents. These comments may have had some influence on August Karl Krönig (1822-1879) revival of the kinetic theory in 1856.

Waterston was aware of Herapath's basic mistake. He wrote: "Mr. Herapath unfortunately assumed heat or temperature to be represented by the simple ratio of the velocity instead of the square of the velocity, being in this apparently led astray by the definition of motion generally received, and thus he was baffled in his attempts to reconcile his theory with observation. If we make this change in Mr. Herapath's definition of heat or temperature, viz., that it is proportional to the *vis viva* or square velocity of the moving particle, not to the momentum or simple ration of the velocity, we can without much difficulty deduce, not only the primary laws of elastic fluids, but also the other physical properties of gases" (Waterston, 1858).

Waterston's statement of his kinetic theory was more careful that that of Herapath, he realized that his was an idealized mathematical model, which might have some relation to the physical world. At the beginning of his paper he stated very firmly that he intended to discuss the properties of "a hypothetical condition of matter", that is, "a hypothetical medium, which we have carefully to refrain to assimilating to any known form of matter until, by synthetical reasoning, circumstantial evidence has been accumulated sufficient to prove or render probable its identity." Thus, he did not claim to develop the kinetic theory of a gas, but rather the theory of a medium "composed of free and perfectly elastic molecules in a state of motion which we have carefully to refrain from assimilating to any known form of matter until, by synthetical reasoning, circumstantial evidence has been accumulated sufficient to prove or render probable its identity".

Waterston assumed the existence of a "vast multitude of small particles of matter, perfectly alike in every respect, perfectly elastic as glass or ivory, but of size, form and texture that requires not to be specified further that that they are not liable to change by mutual action, to be enclosed by elastic walls or surfaces in a space so much greater that their aggregate bulk as to allow them freely to move amongst each other in every direction. As all consideration of attractive forces is left out at present, it is obvious that each particle must proceed on a straight line until it strikes against another, or against the sides of the enclosure; that it must then be reflected and driven into another line of motion, traversing backwards and forwards in every direction, so that the intestine condition of the multitude of those that form the medium may be likened to the familiar appearance of a swarm of gnats in a sunbeam The quality of perfect elasticity being common to all the particles, the original amount of *vis viva*, or living, acting force, of the whole multitude must for ever remain the same. If undisturbed by external action it cannot, of itself, diminish or increase, but must forever remain as unchanged as the matter that is associated with it and that it endows with activity. Such is the case if we view the whole mass of moving particles as one object, but each individual of the multitude must at every encounter give or receive, according to the ever changing angle and plane of impact, some portion of its force, so that, considered separately, they are ever continually changing the velocity and direction of their individual motions, striking against and rebounding from each other, they run rapidly in their zig-zag conflict through every possible mode of occurrence, and at each point of the medium we may thus conceive that particles are moving in every possible direction and encountering each other in every possible manner during so small an elapsed interval of time that it may be viewed as infinitesimal in respect to any sensible period This medium must in this way become endowed with a permanent state of elastic energy or disposition to expand, uniformly sustained in every part and communicating to it the physical character of an elastic fluid."

"The simplicity of this hypothesis facilitates the application of mathematics in ascertaining the nature and properties of such a media, and the study acquires much interest from the analogies that it unfolds. For if the reasoning is correct, the physical laws common to all gases and vapours, those laws, namely, that concern heat and pressure, do actually belong to such media, and may be synthetically deduced from the constitution which has now assigned to them".

Waterston used his theory to derive Boyle's law and the perfect gas equation. In contrast to Herapath, he identified absolute temperature with the mean square molecular velocity and defined a correct absolute temperature scale. He considered a mixture of gases and deduced that the average molecular *vis viva* of all species was equal under equilibrium conditions.

In order to derive the gas laws, Waterston considered how an elastic plane, having a weight the weight n times that of a molecule, could be supported by the successive impacts of such molecules striking it with a velocity *v*. He proceeded as follows: If two masses *B* and *D* with initial velocities and meet in an intermediate point and strike each other, the velocities after impact are, respectively:

$$\beta' = -\beta + \frac{2(\delta+\beta)D}{B+D} \tag{1}$$

$$v = \delta' = \delta - \frac{2(\delta+\beta)B}{B+D} \tag{2}$$

the direction for *D*'s motion being reckoned positive. Now let *B*= *nD* be the mass of the upper place surface of the container and assume that both the particle *D* and the plane *B* reverse their velocities on impact. Then β′ = β and v = δ *and:*

$$\beta = -\beta + \frac{2(v+\beta)}{n+1} \tag{3}$$

and therefore $\beta = v / n$ (Brush, 1957, 1961).

As a result of the impacts the plane will ascend or descend. The time between successive impacts will be that required by the force of gravity to destroy and reproduce the velocity v/n, namely $2v/ng$, where *g* is the acceleration of gravity For a very large number of molecules (impacts) the plane will change its height by an infinitesimal distance, that is, the net result will correspond to a continuous force of upward pressure. To sustain a static equilibrium the number of impacts per unit time, *A*, must be

$$A = \frac{gn}{2v} \tag{4}$$

Further analysis leads to the conclusions that (a) the elastic force of a medium, *e*, as represented by weight or pressure required to confine it, is directly proportional to the number of molecular impacts that take place against a unit surface in a unit time with constant velocity, or $e \propto A$, if *v* is constant, and (b) the elastic force of a medium with a constant mean molecular velocity is proportional to its density Δ^3, or $e \propto \Delta^3$, if *v* or v^2 is constant.

Waterston's next step was to calculate the change on the elasticity produced by a change in the velocity from *v* to *mv (e.g, of A* to *mA)*, at constant density. In this situation *2Av/g* becomes:

$$\frac{2Avm^2}{g} = nm^2 \tag{5}$$

Equation (5) means that the elasticity of a medium having a constant density is proportional to the mean square velocity, or *vis viva* of the medium, that is, $e \propto v^2$ when Δ^3 is constant. Therefore, when both the density and the *vis viva* are changed the elasticity will be proportional to their product, or be absent, that is, $e \propto \Delta^3 v^2$. At constant pressure the density is inversely proportional as the *vis viva* mean square velocity, or $\Delta^3 \propto v^{-2}$, if *e* is constant.

Comparison with the ideal gas laws requires that the square of the velocity, v^2, represent the temperature of the gas. Unlike Herapath, Waterston's theoretical model did not have a conflict with the possibility of perfectly elastic atoms. This possibility gave a sounder basis for his calculations.

Waterston derived the above result by considering the head-on collision of two molecules having masses *B* and *D* and approaching each other with velocities β and δ. If the direction of *D* is considered positive the velocities after impact are respectively:

$$\beta_0 = -\beta + \frac{2(\delta+\beta)D}{B+D} \tag{6}$$

$$\delta_0 = \delta - \frac{2(\delta+\beta)B}{B+D} \tag{7}$$

On the other hand, if both molecules are moving in the same direction and *D* overtakes *B* the velocities after impact will be

$$\beta_1 = \beta + \frac{2(\delta-\beta)D}{B+D} \tag{8}$$

$$\delta_1 = \delta - \frac{2(\delta-\beta)B}{B+D} \tag{9}$$

To preserve an equilibrium state it is necessary that the average value of $(\beta_0^2 + \beta_1^2)$ for many collisions be equal to 2^2 and that the average value of $(\delta_0^2 + \delta_1^2)$ must be $2\delta^2$, since otherwise there would be a continual transfer of *vis viva* from the molecules *B* to the molecules *D*, or from *D* to *B* and vice versa. Hence squaring eqs. (8) and (9) we get

$$\beta_0^1 + \beta_1^2 = 2[\beta^2 - \frac{4D}{B+D}\beta^2 + \frac{4D^2}{(B+D)^2}(\delta^2+\beta^2)] \tag{10}$$

and

$$\delta_0^1 + \delta_1^2 = 2[\delta^2 - \frac{4D}{B+D}\delta^2 + \frac{4D^2}{(B+D)^2}(\delta^2+\beta^2)] \tag{11}$$

If in any case it happens that $\beta_0^1 + \beta_1^2 = 2\beta^2$ we shall have

$$\beta^2 \frac{4D}{B+D} = \frac{4D^2}{(B+D)^2}(\delta^2+\beta^2) \qquad (12)$$

or $\beta^2 B = \delta^2 D$. Hence, if the squares of the impinging velocities turn out to be in the inverse ratio of their molecular weights, then in either molecule the sum of the *vis viva* of the twofold encounter before impact, or $2\beta^2$, is equal to the sum after impact, or to $\beta_0^2 + \beta_1^2$ (in mixed media the mean square molecular velocity is inversely proportional to the specific weight of the molecules). In simple words, the mean kinetic energy of the two molecules is equal.

In this paper Waterston derived the ratio of the specific heats at constant pressure and constant volume but because of a numerical error he obtained the result $c_P/c_V = 4/3$ instead of 5/3. The former value was in fair agreement with the experimental data then available so that the failed to encounter the discrepancy, which plagued later theorists. He first calculated the amount of *vis viva* expended in raising a gravitating plane, weighing n times as much as one molecule, in the case of a head-on encounter.Putting $B = nD$ and assuming that the plane is initially at rest ($\beta = 0$) he found that the velocity upwards of the plane after the shock is

$$\beta = \frac{2w}{n+1} \qquad (13)$$

[The symbol in eq. (1) has now been replaced by w]. Waterston makes now the unexpected mistake of writing that the velocity downwards of the molecules after the shock is

$$w_0 = \delta_0 = w - \frac{2wn}{n+1} = -w + \frac{2wn}{n+1} = w - \frac{2w}{n+1} \qquad (14)$$

instead of

$$w_0 = \delta_0 = w - \frac{2wn}{n+1} = -(-w + \frac{2wn}{n+1}) = -w + \frac{2w}{n+1} \qquad (15)$$

leading to the erroneous relation

$$w_0 = +w - \frac{w}{n+1} \qquad (16)$$

and not

$$w_0 = -(w - \frac{w}{n+1}) \qquad (17)$$

Since the number of molecules n is larger than one, the gravitating plane ascends with velocity $2w/n$ to the height

$$2\frac{w}{gn})^2(\frac{g}{2}) = \frac{2w^2}{gn^2} \qquad (18)$$

This ascent has been accomplished at the expense of a change in the molecular velocity of

$$w - w_0 = \frac{2w}{n} \qquad (19)$$

so that the differential change in the square of the velocity (*vis viva*) is thus $4w^2/n$. (Waterston's result was $2w^2/n$) (Brush, 1957, 1961).

Since the frequency of impacts A, is proportional to the velocity w and the density Δ^3, one can write

$$A = cw\Delta^3 \qquad (20)$$

where c is a constant factor that has to be determined. Waterston now combined eqs. (4) and (20) to determine n, which could then be eliminated To get the ratio c_P/c_V it is necessary to determine the ratio between w^2, the mean impinging velocity, and v^2, the mean square absolute velocity (Brush, 1957, 1961).

Replacing v by w in eq. (4) and combining with (20), it is found that

$$n = \frac{2}{g}cw\Delta^3 \qquad (21)$$

Assuming now that the medium is confined to a cube of unit volume, the upper side of which is the plane n, and adding up the mean square velocities of all the molecules, the total at all times is $\Delta^3 v^2/6$. Resolving the motion of each molecule at any instant into the six rectangular directions parallel to the side of the cube and adding up the square of the resolved velocities, it is evident that this sum must be $\Delta^3 v^2/6$. If the width of the layer is considered to be D^2 then the mean square velocity perpendicular to a given wall is $v^2/3$, which is directed towards the wall half the time and away from it half the time. Waterston now calculated the effect on this wall of impacts from molecules, which are, at a given instant, found in a stratum adjacent to the wall. This calculation gave

$$A = \frac{\Delta^3}{2}\sqrt{\frac{v^2}{3}} \qquad (22)$$

and

$$v = \sqrt{\frac{3gn}{\Delta^3}} \qquad (23)$$

Now suppose at constant pressure that the volume is increased by a factor $(1 + \frac{2w^2}{gn^2} 1 +)$. Then according to the last statement above, the molecular *vis viva* must be increased in the same ratio, that is, from to

$$\Delta^3 v^2 \left(1 + \frac{2w^2}{gn^2}\right) = \Delta^3 v^2 + \frac{2v^2}{n} \tag{24}$$

The increment of *vis viva* required to support the increased volume, $2v^2/n$, is now compared with the *vis viva* expended in the act of increasing the volume by this amount, which was found before to be $4w^2/n$, or $4v^2/3n$ since by eq. (21) $w^2 = v^2/3$ (Brush, 1957, 1961).

If, on the other hand, the volume is kept constant, while the *vis viva* increases, no force will be expended and the contribution of $4v^2/3n$ will be absent. Therefore Waterston's derivation, with the numerical value corrected, shows that the ratio of the specific heats at constant pressure and constant volume is

$$\frac{c_P}{c_V} = \gamma = \frac{\frac{2v^2}{n} + \frac{4v^2}{3n}}{\frac{2v^2}{n}} = \frac{5}{3} \tag{25}$$

Unlike Herapath, Waterston seemed to find no philosophical difficulty in the concept of perfectly elastic atoms. This was perhaps because he did not, like Herapath, believe that the atoms are really hard elastic spheres; he simply recognized that this hypothesis provided a convenient model for his calculations. Waterston's own views on the nature of atoms can perhaps be inferred from the following passage in his book (Waterston, 1843): "Perhaps the most interesting attempt of this kind is that of Ottaviano Fabrizio Mossotti (1791-1863), who derives from the electric theory of Franz Maria Ulrich Theodosius Aepinus (1724-1802) alternations of attractive and repulsive forces which have all the character of molecularity, and leave a residual attraction that exactly represents gravitation. A medium is suppose to pervade space, consisting of atoms that have an intense mutual repulsion and an intense attraction for the molecules of matter; while these also have a mutual repulsion and a reciprocal attraction to the atoms. It follows, that each molecule will be surrounded with an atmosphere of that medium condensed toward its center; and between adjacent molecules there will be a single attraction by means of the reciprocal atmospheres on the molecules, and a double repulsion from the direct mutual action of the molecules themselves, and indirectly from the mutual attraction of the atmospheres. At small distance the latter forces greatly exceed the former; but there is a point where they mutually balance, and beyond which the attraction preponderates and increases for a short space, and then subsides rapidly…Thus all the variety of chemical phenomena may be illustrated. If these curves and the law of their changes could be determined from simple and invariable principles, then the theory of molecularity would be complete and their would be no necessity for inquiring into the cause of these powers…"

Physical chemistry

Waterston's first paper published after his return from India was on deviations from the gas laws (Waterston, 1857) as demonstrated by Victor Regnault's (1810-1878) extensive experiments (Regnault, 1847) and Benjamin Thomson (Count Rumford, 1753-1814) and Joule's famous porous experiments (Joule and Thomson, 1852). In 1846 Regnault measured the compressibility of air, N_2, CO_2, and H_2 at different temperatures and pressures and found that air, N_2 and CO_2 presented a similar compressibility, which not only was larger than the one predicted by Mariotte-Boyle's law, but also increased with increased pressure. The results for H_2 were surprising in that they presented the opposite behavior. From these results Regnault concluded that the compressibility of a gas depended not only on the pressure and the temperature, but also on the nature of the gas. Joule and Thomson had shown that when certain gases are compressed the heat produced is greater than corresponds to the work done in compression. Joule and Thomson had shown that when air and CO_2 were compressed the heat evolved was larger than the mechanical equivalent of the work of compression (Joule and Thomson, 1854).Waterston criticized Thomson and Joule's mode of stating their results pointing out that the external work done is not the whole of work, and showed how the whole work may be estimated from the data, and brought into accordance with the conception of a perfectly definite mechanical equivalent of heat.

In a paper published in 1852 on the calculated relative densities (molar concentration) of vapours, which are saturated in presence of their liquids at different temperatures(Waterston, 1852). Waterston looked for the possibility of finding a quantitative law connecting the liquid with the gaseous state. According to Waterston, the relation between pressure and temperature in saturated vapours had been expressed by many empirical formulae, which did not claim to represent any general law. For this reason he used data published by Académie des Sciences to find if the density of a vapour in contact with its liquid followed any distinct law with the temperature measured from the zero of gas pressure (which he assumed to occur at –273.89°C, and designed by the letter *G*). Since his kinetic theory assumed that the *vis viva* was connected with the square root of the absolute temperature, he first plotted the experimental data as the ratio of *P/t* (density) against $\sqrt{G}$. The resulting curve was of parabolic nature, but of higher power. To reduce the curvature he used the fact that density is a cubic quantity. Hence he now drew the cubic root of the density against $\sqrt{G}$ as abscissa and found that the curve approximated a cubic parabola. This led him to draw a third graph, this time using as ordinate the sixth root of the density. To his satisfaction he found that the data plotted as almost straight lines, which he could express analytically as

$$P = t\left[\frac{\sqrt{t} - g}{h}\right]^6 \qquad (26)$$

where *g* and *h* are constants, characteristic of the compound in question. For example, for water $g = 22.606$ and $h = 20.00$.

This paper was first sent to the British Association (which did not publish it) and then to the Royal Society in 1851. It appeared in the *Philosophical Transactions* of 1852 (Waterston, 1852). The paper contains the results of a number of experiments made by Waterston himself, using a new method, which is not affected by the fact that at high temperatures the saturated vapours do not conform with the ideal gas law, and which gives the densities of both liquid and vapour. The experimental procedure consisted on observing the change in liquid volume in two sealed graduated glass tubes, filled with a given liquid in different proportions, and heated by means of a Bunsen flame. In spite of the high pressures achieved, he seems, however, to have had no serious accident, though he mentions that a glass tube containing water burst at a temperature of 330°C owing to corrosion of the glass. Corrosion with water begun at 350°C where a small amount of water was adsorbed and an opaque white crust was formed that prevented visual observation above 400°C (Waterston, 1861, 1863a, 1864a, 1868).

Afterwards he published a paper on a method of correcting the indications of a thermometer between the fixed points of 0°C and 100°C. To introduce the necessary corrections Waterston proposed to make use of a law, for which he had given the evidence in his second unpublished Royal Society paper, that the six root of the density of a saturated vapour varies as the absolute temperature minus a constant (Waterston, 1858b).

Another of Waterston's papers is on capillary and latent heat where he reports a calculation of the diameter of the water molecules from surface tension and latent heat (Waterston, 1858a). In the introduction to this paper he wrote that the experiments were "suggested by the modern view of the dynamical or work value of molecular force". The argument kept in view is that "if the capillarity of a liquid is the exhibition of part of the forces of the superficial stratum of its molecules, numerical calculations with the latent heat of its vapour ought to be demonstrable if latent heat is a measure of liquid cohesion." He then discusses observations by himself and others on capillary phenomena at temperatures close to the critical temperature, and concludes that both surface tension and latent heat of vaporization must diminish rapidly as the neighborhood of the critical temperature is approached. He identified surface tension (γ) as the energy per unit area, and latent heat as the energy per unit volume, associated with the intermolecular force. He deduced that the molecular volume was $(6\gamma/\rho L)^3$, where ρ is the liquid density and L the latent heat. For water he found the length $6\gamma/\rho L$ to be 1.17×10^{-8} cm and for alcohol 1.74×10^{-8}, values very similar to the ones calculated in 1816 by Thomas Young (1773-1829), based on the ratio of surface tension to tensile strength (Young, 1855). This estimate was published seven years before Joseph Loschmidt's (1821-1895) determination of molecular sizes from the densities of liquefied gases and the mean free paths of molecules in the gaseous state (Loschmidt, 1866).

Chemical notation

In 1863 and 1864 Waterston published two papers on chemical notation (Waterston, 1863b, 1864b). According to him, the dynamical theory of heat and gases required that equal volumes of gases at the same temperature and pressure contain the same number of separate parts. This did not mean that these parts could not be in all cases the atoms that entered into chemical union. Hence, it we were to view the ultimate part of all gases as consisting of at least two atoms, then the same chemical symbols would express not only the combining proportions of all bodies entering into union, but the actual composition of a volume (today, one mole) of the compound. This would eliminate all the ambiguity and difficulties in the arithmetic of combining proportions. Hence, instead of writing the chemical formula of methane CH_4, Waterston suggested that it be $C^{1/2}H^2$, meaning that one gas molecule of methane is composed of half a molecule of carbon and two molecules of hydrogen. Waterston understood that analytical chemists would at first object to his proposition, from the preconceived notion that a gas molecule should be viewed as a combination of two or more indestructible atoms and not of fractions of the same. He believed that if this feeling could be overcome the advantage would fully repay the effort.

Waterston's first paper on the subject included a list of nearly two hundred gases and their proposed formulas. He actually used this form of notation in his papers, with the result that the substances to which he refers are at first hard to identify.

Astronomy

The teaching work at Bombay brought Waterston into contact with astronomy, and from 1852 onwards he was a life member of the Royal Astronomical Society. His first astronomical paper appeared in 1843 (Waterston, 1843-1845), and this brought him into communication with John Couch Adams (1819-1892) and James Challis (1803-1882), the discoverer of Neptune. In their account of Waterston in the *History of the Royal Astronomical Society* (1923) Herbert Hall Turner (1861-1930) and John Louis Emil Dreyer (1852-1926) refer to this contribution in June 1844 of "as a short note on a graphical method by which with ten to fifteen minutes work an occultation could be predicted within one minute, and in the January following some good observations of the comet." In 1850 h published a paper on "A Graphical Method of Computing the Excentric Anomaly" (Waterston, 1849 1859)

At the 1853 meeting British Association, Waterston read a paper "On Dynamical Sequences in Kosmos" where he suggested that significant amounts of heat could be generated by the fall of matter into the sun. He thought that the earth might have grown in size over long periods of time by the accumulation of such meteoric material, and mentioned other possible astrophysical applications of the theory that heat is equivalent to mechanical energy and may be simply the motion of the elementary parts of bodies. He drew a careful distinction between the case of a large body like the earth and a single free molecule but unfortunately had not good enough data to quantify the consequences.

In his article "Thoughts on the Formation of the Tail of a Comet" published in the *Monthly Notices of the Royal Astronomical Society* in 1859 (Waterston, 1859), Waterston suggested an explanation for the fact that a comet's tail points away from the sun. He wrote: "If we view the tail as composed of molecules as free from the force of cohesion as the molecules of an incondensable gas, and raised from the nucleus by the heat of the sun; and the heat as it strikes upon each molecule is converted into a force centrifugal, that not only effectually counteracts the force centripetal of the sun's gravity, but that greatly exceeds it; such molecules will be quickly removed from the feeble attraction of the nucleus, and assume the motion of bodies entirely free from its influence" (Waterston, 1859).

He then computed the acceleration, which could be imparted to a molecule by the complete conversion of the heat energy, which falls on a given area of the earth's surface. He obtained an acceleration of 800 miles per second per second, which, he remarked, was based on the incorrect assumption of complete conversion of heat into mechanical energy, but might suggest the proper order of magnitude (Waterston, 1859).

In a comment about this paper Herbert Hall Turner (1861-1930) wrote, "Waterston's ideas are surprisingly suggestive of modern views of light pressure. He shows himself aware of the difficulties in converting a vibratory movement into a translatory, but he is impressed by the fact that if the whole heating power of the sun's rays could be converted into a centrifugal force, the acceleration would be 800 mile/s^2, and he is tempted to think that even a fraction of this might serve."

In 1878, Waterston send a paper to the Royal Astronomical Society, on a procedure for measuring the temperature of the sun. This paper was rejected (Waterston, 1878) and a few months later Waterston resigned from the Society, from which he had been a member since 1852. In this paper Waterston described a very simple instrument to measure a precise value of the radiant force of the sky, including clouds and sun. The apparatus was made of two thermometers, one with black bulb and the other with the bulb uncoated, each enclosed in a glass receptacle, which had been sealed after exhausting the air. When the thermometers where exposed to the same radiant force, the lecture in the uncoated one was always nearly one-third the lecture in the coated one. Hence, the difference in readings indicated the amount of radiant force delivered on a constant surface in a given period of time. Waterston calculated that if a black bulb thermometer would circulate around the sun in the earth's orbit it would record a reading of 67° above absolute zero. Hence, since the sun occupies 1/183960 of the spherical concave, this result meant that if the whole concave was occupied by suns, the thermometer would rise to 183,960 times 67°C, or 12,325,320°C, a figure which indicates the potential temperature of the sun's radiant surface (Waterston, 1860).

In another paper Waterston discussed gravitation (Waterston, 1858c) and at the end of which he again expressed his fundamental belief in mechanical principles: "It would be taking too narrow a view if we limited the function of the luminiferous æther to be conveying of physical pulses only. The atmosphere also conveys physical pulses, but that is the least important of its functions in the economy of nature. There is nothing that should hinder us attributing to the media concerned in the radiation of light and heat the higher functions of electric polarity and gravitation. The special dynamic arrangements by which this is effected may ever elude research, but as there is no limit to the *vis viva*, which such a media may conserve in their minutest parts, so there is no physical impossibility in that *vis viva* being suddenly transferred to the molecules of ordinary matter in the proportions and sequence required to carry out the order and system of nature. The fundamental principle of action in such media must be in accordance with elastic impact, for upon that the dynamical theory of heat and conservation of force rests as a foundation" (Waterston, 1858c). ◩

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