The Radiometer and how it does not work

Arthur E. Woodruff

The radiometer now is a little toy. Anyone who, passing by an optician's shop, has seen the vanes spinning merrily in the sunlight will know the delight and wonder it inspires, usually momentarily. Most physicists think they know how it works, and a few really do. The phenomena involved have by now passed well within the expanding research frontiers of physics. The heyday of the radiometer, the decade of the 1870's, has long vanished, and the scientific excitement it caused is gone.

Yet much can be learned from the lessons of the radiometer. Besides being a valuable instructional device, it has a fascinating history. It is a beautiful example of how science develops—not in the logical, almost inevitable, sequence of the textbook, but by chance discoveries, false hypotheses and false reasoning, and gradual, hard-won understanding and incorporation into the body of the known.

Early research into the force conceivably exerted on tiny bodies by light produced negative results. Late in the 18th century Abraham Bennet illuminated a paper vane in a crude vacuum, but concluded that he could not "perceive any motion distinguishable from the effects of heat."[1] Newton's corpuscularian ideas as to the nature of light still dominated optics. Bennet and, later, Thomas Young,[2] the founder of the periodic wave theory of light, used Bennet's results as an argument against the particle theory in favor of waves. Even in 1866 Balfour Stewart cited the same results as support for the wave theory,[3] claiming (certainly incorrectly) that the recoil effect of the vane on being struck by light corpuscles should have been detected by Bennet if it had existed.

A true radiometric force was first observed in 1825 by Augustin Fresnel,[4] who had independently discovered and greatly developed the periodic wave theory of light. By varying the pressure in the evacuated chamber, Fresnel concluded that this force was not caused by the convection currents in the residual air, or by evaporation of vapor from the heated surfaces. However, Fresnel was at this time mortally ill, and his initial work was not significantly developed by others.

By the 1870's vacuum techniques had improved, chiefly with the introduction of the Geissler mercury pump (a manometric device, *not* the later mercury diffusion pump). Still, it required a chance observation by William Crookes to rediscover the radiometer force, which, through Crookes' enthusiastic and extensive investigations, then became permanently incorporated into the awareness of physicists.

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William Crookes was educated at the newly-founded Royal College of Chemistry in London.[5] Besides his important work in chemistry and on cathode radiation, he was deeply interested in photography, and was involved as a writer for and editor of chemical and photographic journals. He also did practical work as a chemical engineer and would-be industrialist, attempting to stem the English cattle plague (Rinderpest) of the 1860's, developing a process of gold amalgamation, and involving himself in other engineering and business ventures, in which he did not succeed in realizing his financial hopes. Although he was never academically employed, he was made a Fellow of the Royal Society in 1863, becoming its president in 1913. Besides receiving various scientific honors, he was knighted in 1897 for his scientific research; he chose arms depicting, in part, a radiometer, and the motto: *Ubi Crux Ibi Lux* ["Where the Cross (or Crookes) is, there is light"].

Crookes had discovered a new element, thallium, in 1861, by use of the spectroscope.[6] This was the third element so to be detected. Like rubidium and cesium, both discovered by Bunsen and Kirchhoff, it was named for the color of the line by which its presence was made manifest (the Greek word *thallos* means green twig.) A decade later, Crookes turned his efforts to determining the atomic weight of the new element.[7] He endeavored to obtain an accuracy sufficient to test Prout's hypothesis that all atoms were composed of hydrogen atoms and therefore had integer atomic weights. This was a difficult task, because thallium is heavy, and although Crookes believed he had given a new example to add to the work of Stas in refuting the hypothesis, he did not actually attain a sufficient accuracy to accomplish this. In the course of his delicate determinations, Crookes had occasion to weigh warm samples in an evacuated chamber. He found, to his surprise, that warm samples appeared to weigh less than cold ones. This could not be attributed to convection currents in the residual air, since, he believed, there was too little gas left in the chamber to produce such an effect. Was there perhaps a connection between gravitation and heat?

When he had completed the work on thallium, Crookes turned to investigate the exciting new effect.[8] He placed crude balances, with pith balls at the ends, into evacuated tubes. When a warm body was brought underneath the tube close to one of the balls, it rose, but when the warm body was placed above a ball, it fell. The initial speculation relating heat and gravitation had to be dropped. Perhaps, though, he had discovered a repulsion caused by the heat radiation from the warm body, a prospect certainly little less exciting.

In 1874, Crookes exhibited his discovery at a soirée of the Royal Society. A pith ball was fixed to the end of a horizontal arm suspended by a fiber in a vacuum. When a candle was brought near, the ball was repelled. Osborne Reynolds, whose name we perpetuate in the "Reynolds number" of fluid dynamics, was present. He noted an interesting aspect of the phenomenon, that is, when the candle flame was left near the apparatus, the oscillations of the arm were not damped, but increased in amplitude.[9] This suggested to Reynolds that a direct radiative repulsion was not involved, but rather a delayed effect, such as might depend on the gradual heating of the nearer side of the ball. He wrote a paper in which he hypothesized that water was evaporating from the near side of the ball, causing it to recoil. Crookes, however, was quite sure that there was very little water vapor present. Reynolds had second thoughts which he incorporated into the last paragraphs of his paper, and here, for the first time, appeared the explanation usually accepted today.

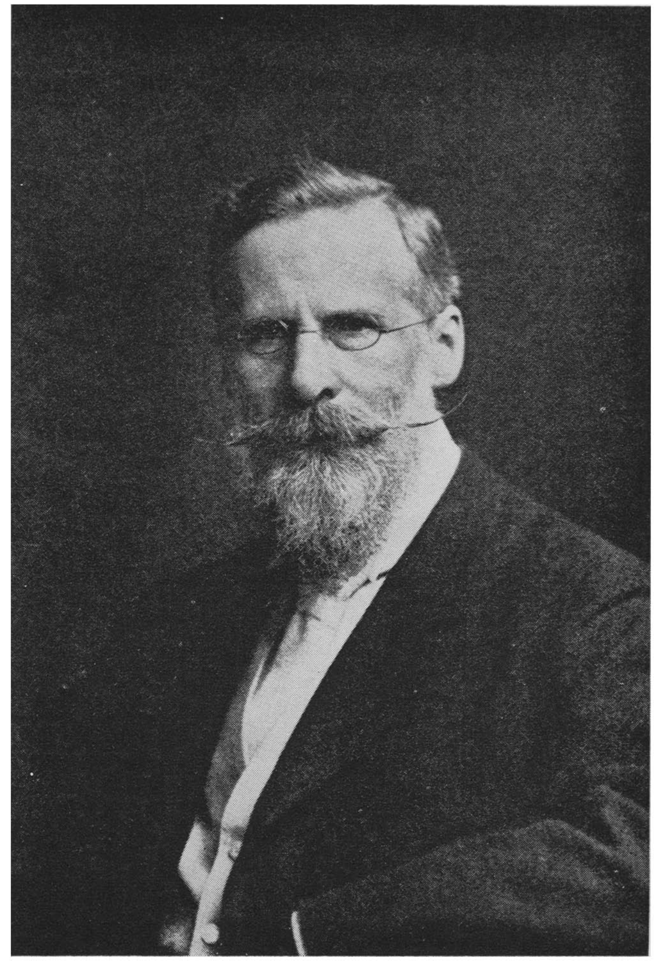

Fig. 1. William Crookes in 1889. [From E. E. Fournier d'Albe, *The Life of Sir William Crookes* (See Ref. 5).]

According to this explanation, which appears in the following form in Reynold's paper of 1876,[10] the molecules of the residual gas which bombard the warmer surface of the ball rebound with increased vigor, and so impart a greater recoil to the warm surface. If a molecule collides head-on with a surface and rebounds elastically, the momentum change of the molecule is $2mv$, and by momentum conservation, this amount of momentum is transferred to the surface, contributing to the pressure exerted on that surface. But if in rebounding the molecule gains in speed, so that the new speed is $v+dv$, the momentum transferred to the surface by the collision is $m[v+(v+dv)] =2mv+m\,dv$. The average kinetic energy of the molecules

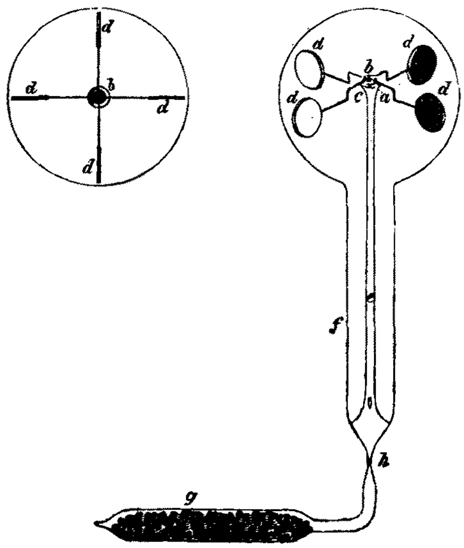

Fig. 2. Crookes' original radiometer [from Phil. Trans. Roy. Soc. London, Ser. A **166**, 339 (1876)].

is proportional to the absolute temperature of the gas:

$$\frac{1}{2}mv^2 = aT,$$

where a is a proportionality constant. If the molecule colliding with the warm surface picks up, on the average, a speed $v+dv$ appropriate to the temperature $T+dT$ of the surface, the two quantities are related by the same rule:

$$\frac{1}{2}m(v+dv)^2 = a(T+dT).$$

Let us assume for simplicity that the temperature of the surface does not greately exceed that of the surroundings, so that $dT<<T$. Then, subtracting the two equations from each other and neglecting dv^2, we obtain

$$mvdv = adT.$$

Division of this by the former of the two equations yields

$$2dv/v = dT/T.$$

Now the pressure on a surface is proportional to the average momentum transfer per molecule, so that, if $p+dp$ represents the increased pressure on the warm surface,

$$\frac{p+dp}{p} = \frac{2mv+mdv}{2mv} = 1 + \frac{1}{4}\frac{dT}{T}.$$

The ratio of the pressure increase dp on the warm surface to the normal pressure in the gas p is, therefore,

$$\frac{dp}{p} = \frac{1}{4}\frac{dT}{T}.$$

I believe that this, or something close to it, is the argument which the average physicist would present today, if asked how the radiometer works. It is wrong. Tait and Dewar pointed this out (rather obscurely, from the published reports) in 1875.[11] The pressure on a surface is not only proportional to the momentum transferred by the individual molecular impacts, it depends as well on the rate at which the molecules are impinging on the surface. The rapidly rebounding molecules from the warmer surface are more effective in stopping other molecules from approaching and hitting the surface. If the surface is extensive, so that we are mainly concerned with areas not near its edge, the two factors exactly compensate one another. How can we know this, without analyzing the collisions of the molecules? Because pressure differences set up over extended surfaces are very quickly equilibrated in a gas—as in a pulse of sound. The equilibrium of a gas is an equilibrium of pressure, so that if the temperature is artificially raised in a region of the gas, its density will decrease proportionately.

Reynolds came to appreciate the cogency of Tait and Dewar's argument, and himself supplied an example which may be instructive.[12] Imagine two parallel plates of indefinite extent, arranged as in a parallel plate capacitor and connected to each other, with gas in the space between. If we naively accept the argument Reynolds originally gave, then, if one of the plates is warmer on its inner surface than the other, the entire apparatus should accelerate with the warmer plate leading, without any external forces. This, of course, contradicts the fundamental principles of mechanics.

In the meantime, Crookes continued his experiments on the new force. He found that if a blackened and a white surface, at the two ends of a torsion balance, were equally illuminated, the black surface suffered a greater repulsion. The force was sometimes sufficient to spin the arm about the fiber. This suggested to Crookes the construction of the radiometer, or "light mill," with its vanes alternately blackened and whitened, pivoted as a fly to be able to rotate freely[13] (see Fig. 2). Crookes was still holding to the hypothesis of a direct radiation repulsion rather than a gas effect. He held that the black surface absorbed the force of the radiation incident upon it, while the white surface simply threw it back, so that the black surface would recoil.[14] This argument confused the energy absorbed or reflected by the surfaces with the force exerted upon them or the momentum transferred to them.

To settle the question as to whether radiation repulsion or a gas phenomenon was involved, Arthur Schuster, who had joined Reynolds on the faculty at Manchester, performed an ingenious experiment in 1876.[15] He hung Reynolds' radiometer case from two parallel fibers (bifilar suspension), and observed the direction the *case* twisted when light was shone onto the vanes. If a direct repulsion were exerted by the light on the vanes, a small amount of torque should be exerted by the spinning vanes on the pin supporting them, and the casing should twist in the same sense as the rotation of the vanes. On the other hand, if the more rapid heating of the blackened vanes somehow caused an increased pressure from the neighboring gas, the gas should receive an angular momentum opposite to that of the vanes, so that the net angular momentum would be conserved. The gas would communicate some of this angular momentum to the walls of the radiometer, and the case should twist in the opposite sense to the rotation of the vanes. In this neat crucial experiment, the latter effect was observed, confirming those who believed that the heated gas played the crucial role.

As a result, Crookes changed his mind about radiation repulsion and accepted an explanation propounded at this time by Johnstone Stoney.[16] Stoney attempted to save the type of argument initially presented by Reynolds. Making use of an incorrect relation between the pressure of a gas and the mean free path of the molecules of the gas between their mutual collisions, he concluded that in the radiometer, the mean free path of the molecules was so great that they would generally traverse the distance from the vanes to the walls without colliding with other molecules. Then the number of incoming molecules impinging on the warm (blackened) surfaces would not be cut down, and Reynolds' original argument would apply.

This explanation was enthusiastically taken up by Crookes, who devoted himself to tracing the "lines of increased molecular pressure" extending perpendicularly from the heated surfaces in the radiometer. It was to serve Crookes well. By a chance observation of a radiometer with a crumpled vane spinning the wrong way, he developed the cup radiometer.[17] This device resembles an anemometer or wind gauge, with unpainted cups replacing the radiometer vanes. When exposed to radiation, it spins in the opposite direction of an anemometer, the open ends of the cups leading. The explanation seemed simple on the basis of Stoney's theory (see Fig. 3). The rays of increased molecular pressure from the outside of the cup nearest the casing would reach the wall of the casing before being stopped by the intervening gas, while the rays from the inside of the cup would have farther to go, and might not reach the wall. So the Stoney force would be exerted only on the outsides of the cups, pushing them forwards.

It is amazing to see how this idea led Crookes into his famous cathode ray research, and how it led him astray in interpreting the nature of the cathode rays. The last paper on the radiometer was immediately followed by the first on cathode rays, significantly entitled "On the Illumination of Lines of Molecular Pressure, and the Trajectory of Molecules."[18] Crookes constructed both ordinary and cup radiometers in which the moving fly was a cathode. He interpreted the dark space around the cathode as delimiting the extent of the lines of increased molecular pressure, believing that the cathode rays were ionized gas molecules. When the dark space from one side of the vanes, or the outside of the cups, extended to the wall, the fly rotated in the expected sense, as though being pushed forward by the dark space. Rather than electrons, Crookes conceived of a "fourth state of matter" in which the mean free molecular paths were comparable to the size of the apparatus, a designation now aptly applied in plasma physics.

But Stoney had argued from an incorrect relation between gas pressure and mean free path. Actually, pressure and mean free path are inversely proportional to each other. At a typical radiometer pressure of 1/10 mm of mercury, the mean free path of air molecules is only 6/10 mm, and Crookes had observed radiometric effects at 35 mm of mercury, where the path is 1/500 mm. Although an occasional molecule will go a good deal farther than the mean value, these lengths are too small in comparison with the dimensions of a typical radiometer for Stoney's explanation to hold up.

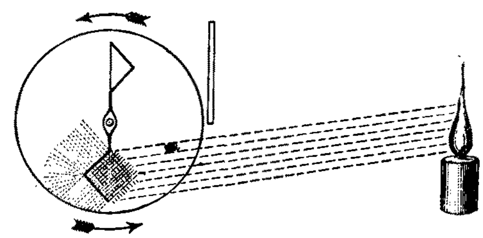

Fig. 3. Crookes' cup radiometer, showing the lines of molecular pressure [from Phil. Trans. Roy. Soc. London, Ser. A **169**, 293 (1878)].

And yet it moves! The foundations for a correct explanation of the motion of a radiometer were laid in two difficult papers by Maxwell[19] (shortly before his death) and Reynolds,[12] both of which appeared in 1879. They realized that the argument which invalidates Reynold's original explanation, and shows that a pressure differential cannot be maintained over an extended surface, breaks down near the edges of the vanes. But these papers were not exclusively devoted to the radiometer, and the arguments given have had to be modified and extended in more recent times. In Crookes' work, the temperature of the surfaces were not known, so that qualitative explanations sufficed. This defect was largely remedied by experiments performed in the 1920's.[20] These experiments demonstrated that the radiometer force occurred at the edges of the vane. Theoretical work was pursued by various researchers, particularly Martin Knudsen;[21] this work also includes a short but typically fascinating paper by Einstein.[22] The phenomena involved in the radiometer are complex, but a simplified account of *one* of them (the "Einstein effect") is in order.

We learned above that, though the molecules make more vigorous collisions with the warmer side of the vane, they are held back more effectively from the vane by the recoiling molecules, so that the pressure over most of the vane is the same as the pressure on the cooler side. But for molecules impinging near the edge of the vane, onto a strip of the order of the mean free path in from the edge, the situation differs. They are held back in part by molecules rebounding from the vane and in part by molecules passing the edge of the vane from the cooler side. But the latter are less efficient in stopping incoming molecules. So while the individual collisions with the vane may be on the average just as vigorous as nearer the center of the hot surface, more such collisions will occur in a unit area in a given time. The pressure near the edge, then, will be greater than at the center of the warm side, and therefore also greater than the pressure on the other side. It is this excess pressure at the edge which is responsible, at least in part, for the motion of the vanes.

Crookes, we noted, had suspected that the radiometer was run by a direct repulsion due to the radiation, until Arthur Schuster performed his crucial experiment. Although Crookes was not at first aware of it when he began his work on the radiometer force, Maxwell had just presented the expression for the pressure of electromagnetic radiation in his *Treatise*. . . (1873), and suggested that it might be detected by an experiment very like those Crookes was setting out to perform.[23] It does not take Schuster's experiment to convince us that radiation pressure does not run the radiometer. It turns the wrong way. The black vanes, which absorb the light, obtain a momentum transfer equal to that of the incident radiation, but the white vanes reflect the light and so obtain twice as much momentum, just as a wall does when a molecule collides with it and rebounds elastically rather than sticking to it. The black vane gets the energy and heats up faster, but the white one experiences twice as much direct radiation pressure given the same light intensity. Light pressure would cause the vanes to rotate the opposite way from that in which they actually do. The gas forces predominate, and must be removed by obtaining a much higher vacuum than Crookes used if the radiation pressure is to be detected. This was done by Lebedev[24] and by Nichols and Hull,[25] who independently found the radiation pressure. For example, while evacuating the chamber of his apparatus, which contained radiometer vanes at the end of a torsion balance, Lebedev flushed the chamber with mercury vapor, afterwards freezing out the residual vapor.

How does the ordinary radiometer *not* work?

It does *not* work by radiation pressure, because the vanes turn the wrong way, and also because, when the case is suspended, it twists the wrong way. The existing radiation pressure is masked by the forces exerted by the gas.

It does *not* work simply by an overall pressure increase of the gas against the warmer surfaces, because such pressure differentials very quickly resolve themselves. The usual argument, the one which Reynolds introduced in 1874, fails to take into consideration the fact that, while the individual collisions of the molecules against the hot side tend to be more vigorous, the rate at which these collisions occur is reduced.

However, the radiometer *does* work by forces exerted by the residual gas. These forces are exerted along the *edges* of the vanes. In part, at least, the usual argument does apply here, because the greater vigor of the collisions on the hot edge is not fully compensated for by a reduced rate of collision.

The usual argument, though strictly incorrect, certainly contains essential elements of the truth. When the radiometer is used as an illustration for students being initiated into the ideas of the kinetic gas theory, this argument is probably the best one to introduce. It leads correctly to other qualitative results. Put a radiometer into a cold and dark place, for example, a refrigerator. The black surfaces, being good absorbers of light and heat radiation, are therefore also good radiators (by Kirchhoff's law). They cool down more rapidly than the white surfaces, and the vanes will spin in the reverse to the usual sense. This spinning will come to a halt as both surfaces of the vane approach a new thermal equilibrium. So, too, a radiometer run by a heater will gradually cease its rotation as the vanes attain the same overall temperature. The radiometer run by sunlight, which is converted to heat by the black surface, does not stop since it never comes to equilibrium with the temperature of the incident radiation, that is, the temperature of the sun's surface.

On the other hand, the usual argument involving an excess pressure over the entire hot surface does not serve to explain why the radiometer works only at reduced pressures. The unbalanced force is exerted only on a strip along the edges of the vanes, which strip becomes thinner as the pressure rises. At intermediate pressures, convective currents in the unevenly heated gas dominate the true radiometer force and generally tend to move the vanes in the opposite sense, while at atmospheric pressure both effects are so diminished that the vanes do not respond.

Since I have concentrated on the explanations of radiometer action, rather than on the experimental work, I fear to have given a poor impression of the quality of William Crookes' research. Crookes was no mathematical physicist, but a first-rate experimentalist. It is fitting that I allow him the last words in this article, and by so doing also illuminate another aspect of his fascinating personality and of his times.

When he was working on the weight of thallium, Crookes had also been investigating spiritualism, which was much in vogue at the time. For a while, at least, he had convinced himself that spiritualism was valid, though in later years he dropped the subject completely. In 1877 the biologist, W. B. Carpenter, published an article entitled "The Lessons of the Radiometer" in the first volume of the Nineteenth Century Review of London.[26] Six years before, Crookes had identified Carpenter as the author of an anonymous attack on his own researches into spiritualism.[27] In this later, signed review, Carpenter contrasted Crookes' open-minded inquiry into the radiometer phenomenon, and his willingness to relinquish his early hypotheses on fresh evidence, with his apparent credulity in connection with spiritualism. Carpenter concluded: "The lesson which this curious contrast seems to me most strongly to enforce is, that of the importance of training and disciplining the *whole* mind during the period of its development, of cultivating scientific habits of thought (by which I mean nothing more than strict reasoning based on exact observation) in regard to *every* subject, and of not allowing ourselves to become 'possessed' by any ideas or classes of ideas that the common sense of educated mankind pronounces to be irrational."

Although Crookes was no longer actively supporting spiritualism, he was an ardent polemicist, and "Another Lesson from the Radiometer" appeared in the same journal three months later.[28] (Further "Lessons" reverberated through the pages of Nature for the following year.) After a detailed defense, or really, counterattack, Crookes stated:

"One most significant conclusion which might be drawn, and which must surely suggest itself to every man of science who reads the history of the Radiometer, is the importance of *residual phenomena*. . .If we carefully scrutinize the processes either of the laboratory or of nature, we may occasionally detect some slight anomaly, some excess or deficiency of action, some unanticipated phenomenon, which we cannot account for, and which, were received theories correct and sufficient, ought not to occur. Upon undrilled men these possibilities are simply thrown away. The untrained physicist or chemist fails to catch these suggestive glimpses. . . .Take the very subject which suggests the text for Dr. Carpenter's article. Can the wildest dreams of the spiritualist ask credence to anything more repugnant to 'common sense' than the hypotheses imagined by science, and now held to account for the movements of the Radiometer? In the glass bulb which has been exhausted to such a degree that 'common sense' would pronounce it to be quite empty, we must conceive there are innumerable smooth elastic spheres, the molecules of the residual gas, dashing about in apparent confusion, with sixty times the velocity of an express train, and hitting each other millions of times in a second. Will the 'common sense of educated mankind' consider this rational doctrine?. . .Doubtless in the processes of scientific evolution in the coming times many a discovery will be brought to light to give a sharp shock to 'the common sense of educated mankind.' "

Works on the History of the Radiometer

This article incorporates much of the material appearing in my article, "William Crookes and the Radiometer" [Isis **57**, 188 (1966)]. I am indebted to unpublished papers by Stephen Brush of Harvard Project Physics ("The Radiometer and the Origins of Rarified Gas Dynamics," which will appear as part of a forthcoming book by Dr. Brush on the *History of Statistical Mechanics*, to be published by Gordon and Breach) and by Brush and C. W. F. Everitt of Stanford ("Maxwell, Osborne Reynolds, and the Radiometer"). The more recent history is discussed by Loeb, in *The Kinetic Theory of Gases* (Dover, New York, 1961), 3rd ed., Sec. 84.

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[1] Abraham Bennet, Phil. Trans. Roy. Soc. London, Ser. A **82**, 81 (1792).

[2] Thomas Young, Phil. Trans. Roy. Soc. London, Ser. A **92**, 12 (1802); see p. 46.

[3] Balfour Stewart, *An Elementary Treatise on Heat* (Oxford University Press, London, 1866), pp. 161, 352.

[4] Augustin Fresnel, Ann. Chim. Phys. (Paris) **29**, 57, 107 (1825).

[5] The biography of Crookes: E. E. Fournier d'Albe, *The Life of Sir William Crookes* (T. Fisher Unwind Ltd., London, 1923).

[6] William Crookes, Phil. Mag. **21**, 301 (1861).

[7] William Crookes, Phil. Trans. Roy. Soc. London, Ser. A **163**, 277 (1873).

[8] William Crookes, Phil. Trans. Roy. Soc. London, Ser. A **164**, 501 (1874); followed by **165**, 519 (1875); **166**, 325 (1876); **169**, 243 (1878); **170**, 87 (1879).

[9] Osborne Reynolds, Proc. Roy. Soc. (London) Ser. A **22**, 401 (1874).

[10] Osborne Reynolds, Phil. Trans. Roy. Soc. London, Ser. A **166**, 725 (1876).

[11] P. G. Tait and J. Dewar, Nature **12**, 217 (1875).

[12] Osborne Reynolds, Phil. Trans. Roy. Soc. London, Ser. A **170**, 727 (1879).

[13] William Crookes, Phil. Trans. Roy. Soc. London, Ser. A **166**, 338–341 (1876). Research into the radiometer force had also been begun in Germany, by Bergner and Neesen, and it has been stated that Geissler had already been making light mills in Bonn. I have been unable to verify this last statement. The major point is, however, that the British experimental and theoretical work was far superior in this period, and led us to a basic understanding of the radiometer.

[14] William Crookes, Phil. Trans. Roy. Soc. London, Ser. A **166**, 350 (1876).

[15] Arthur Schuster, Phil. Trans. Roy. Soc. London, Ser. A **166**, 715 (1876).

[16] Johnstone Stoney, Phil. Mag. (5) **1**, 177, 305 (1876).

[17] William Crookes, Phil. Trans. Roy. Soc. London, Ser. A **169**, 278-302 (1878).

[18] William Crookes, Phil. Trans. Roy. Soc. London, Ser. A **170**, 135 (1879).

[19] J. C. Maxwell, Phil. Trans. Roy. Soc. London, Ser. A **170**, 231 (1879).

[20] Particularly, H. E. Marsh, L. B. Loeb, and E. Condon, J. Opt. Soc. Amer. **11**, 257 (1925); I. Bleibaum, Z. Phys. **49**, 590 (1928); M. Knudsen, Ann. Phys. **6**, 129 (1930).

[21] See the article by Knudsen cited in Ref. 20. Knudsen had previously developed Stoney's ideas, which apply at lower pressures, in connection with his absolute manometer [Ann. Phys. **32**, 809 (1910)].

[22] Albert Einstein, Z. Phys. **27**, 1 (1924).

[23] J. C. Maxwell, *Treatise on Electricity and Magnetism* (Oxford University Press, London, 1873) (Sect. 793 in the third edition, which is the most available).

[24] P. N. Lebedev, Arch. Sci. Phys. Nat. **8**, 184 (1899); Ann. Phys. **6**, 433 (1901).

[25] E. F. Nichols and G. F. Hull, Phys. Rev. **13**, 307 (1901).

[26] W. B. Carpenter, The Nineteenth Century **1**, 242 (1877).

[27] Anon., Quart. Rev. **131**, 301 (1871). Crookes replied in a pamphlet quoted by Fournier d'Albe (Ref. 5, p. 213).

[28] William Crookes, The Nineteenth Century **1**, 879 (1877).