

## CROOKES'S RADIOMETERS: A TRAIN OF THOUGHT MANIFEST

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The Royal Society is to exhibit its collection of original radiometers by William Crookes in the 350th anniversary re-display, thus providing an opportune moment to study the instruments in some detail. This paper attempts to trace Crookes's line of enquiry as described in a series of papers in *Philosophical Transactions*, linking the individual objects with the particular experiments in which they participated. From these accounts of painstaking technical endeavours, involving the construction of these exquisite objects, we gain an insight into the challenges, both physical and intellectual, posed by the exploration of new extremes of sensitivity and pressure. The radiometer's charm has been lasting, and Crookes's legacy is to allow us to follow a train of thought through a series of beautiful artefacts.

**Keywords:** William Crookes; radiometers; classical physics; scientific instruments; kinetic theory of gases

In July 1911 Sir William Crookes donated 26 of his original radiometers and otheoscopes (figure 1) to the Royal Society in appreciation of the support and encouragement he had received during 55 years of scientific work. During the 1870s his line of questioning had led him to devise the simple and elegant radiometer, which, in his own words, would be popular because 'there is a peculiar charm in using an instrument which is constantly in active work'.<sup>1</sup>

Crookes's work is not easily compartmentalized, as one line of enquiry followed on from another seamlessly.<sup>2</sup> Having won a reputation for the spectroscopic discovery of thallium in 1861,<sup>3</sup> he devoted the next few years to verifying its atomic mass. At the end of this period he became interested in psychic phenomena, in part because of the attractive and repulsive forces encountered in the thallium experiments.<sup>4</sup> Spiritualism was widely practised and Crookes wrote, 'I consider it the duty of scientific men who have learnt exact modes of working to examine phenomena which attract the attention of the public.'<sup>5</sup> This led to questions concerning a possible previously unrecognized attractive power, which Crookes had referred to as 'psychic power',<sup>6</sup> which in turn resolved into a study of attraction or repulsion resulting from radiation.<sup>7</sup> It was during this considerable piece of work that Crookes introduced the radiometer (figures 2 and 3). The experiments were described in a

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Figure 1. The Royal Society's collection of Crookes's radiometers and otheoscopes. (Copyright © Science Museum, London; reproduced with permission.) (Online version in colour.)

series of abstracts in *Proceedings of the Royal Society*,<sup>8</sup> and produced in full slightly later in *Philosophical Transactions*.<sup>9</sup> His work on cathode rays followed directly.<sup>10</sup>

Crookes first demonstrated the radiometer to the Royal Society at a soir e on 7 April 1875.<sup>11</sup> The report lists simply: 'Radiometer: showing phenomena of Repulsion under the influence of Radiation'.<sup>12</sup> The first published description appears as a supplement submitted on 20 April of that year to a paper originally submitted on 20 March, so the invention of the radiometer can be dated fairly precisely.<sup>13</sup>

Although there is now a Platonic ideal radiometer, Crookes was to devise a range of diverse instruments. He was asking a battery of questions and working with a large array of variables that sometimes seemed overwhelming. His assistant, the master glass-blower Charles Gimmingham, was responsible for many evacuated vessels.<sup>14</sup> While Crookes undoubtedly imposed post-hoc order on his thoughts and experiments for his publications, it is instructive to follow the methodical exposition in *Philosophical Transactions* and link each of the individual instruments with the experiment in which they participated. The notebooks and letters held by the Science Museum have also been studied, although access was limited because they have been found to be radioactive.<sup>15</sup> Labels on the instruments in varying conditions were sometimes helpful, although there were various numbering systems.<sup>16</sup> Identification has been largely possible, and it is not often that historians are so fortunate as to see how a line of enquiry was pursued through surviving artefacts. Crookes had some inkling of the legacy he was leaving: 'It has been my

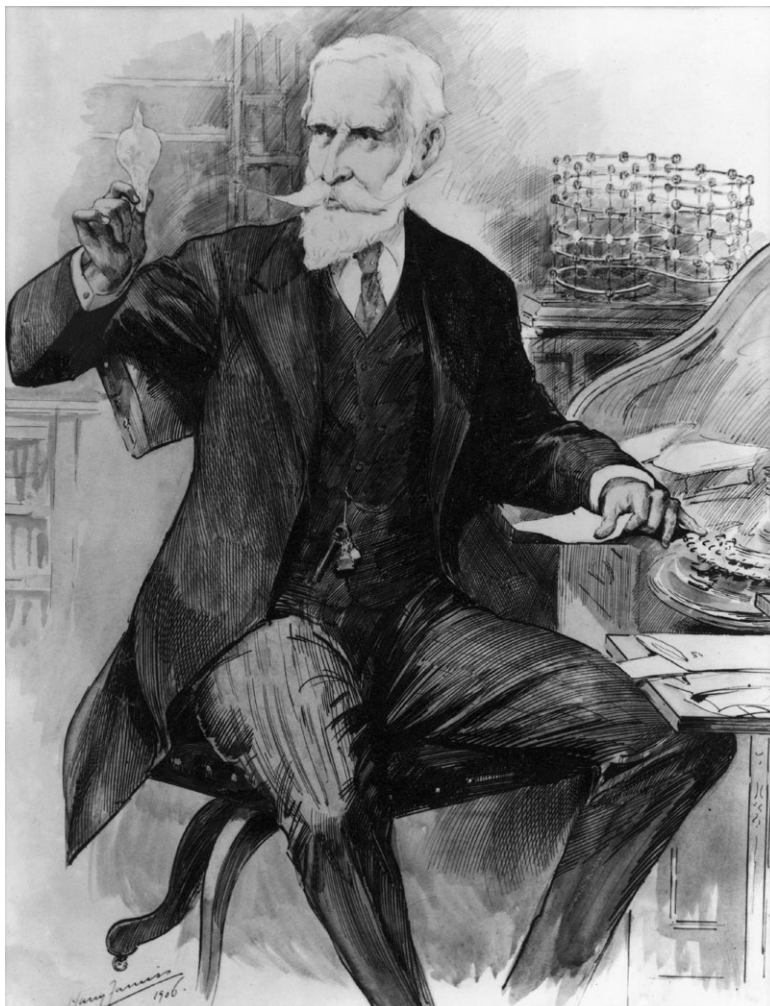


Figure 2. Portrait of Crookes with radiometer, by Harry Jarvis, 1906. (Copyright © SSPL/Science Museum, London; reproduced with permission.)

endeavour to permanently record such experimental proof in the convenient form of an instrument . . .'<sup>17</sup>

In his work on the atomic mass of thallium, Crookes had noticed that hot bodies weigh less than cold ones, and that the accepted interpretation could not hold in a near vacuum.<sup>18</sup> Because of these results he was hoping to find a connection between heat and the force of gravity that had been suspected by previous experimenters but required more delicate apparatus to confirm.<sup>19</sup> Referring to Cavendish's well-known experiments,<sup>20</sup> he found that, by eliminating any extraneous factors, in normal pressure, a heavy metallic mass will attract a light ball if the mass is hotter than the ball, and repel it if colder. However, in an evacuated vessel, the situation was reversed. Crookes could only speculate as to the cause: 'in the radiant molecular energy of solar masses may at last be found . . .



Figure 3. Miniature radiometer on a pin.<sup>63</sup> (Science Museum inventory number 1920-392. Copyright © Science Museum, London; reproduced with permission.) (Online version in colour.)

that agent acting constantly according to certain laws which Newton held to be the cause of gravity.’<sup>21</sup>

In the second paper of the series, published a year later, Crookes modified his apparatus. He allowed possible movement in a horizontal rather than a vertical plane, using a torsion balance with the lightweight balls suspended with a long silk fibre inside a glass globe. The apparatus began to resemble a radiometer but the crucial characteristic of permanent motion was not yet established. This torsion balance was so sensitive that when it was demonstrated at the Royal Society in December 1873 and April 1874 it ‘followed a piece of ice as a needle follows a magnet’.<sup>22</sup>

Crookes had noticed that optimum effects were achieved with greater surface areas, so he substituted discs for balls in some experiments. He now started to experiment more widely with the material of the discs and also with blackened and silvered surfaces. The radiant sources were burning magnesium wire, standard candles, copper balls at various temperatures, light of various wavelengths, or simply human fingers. The effect of pressure, surface area, and distance of the source on the amplitude of swing was noted. Crookes asserted that by these experiments he had eliminated air currents, electricity and condensation as the cause of the motion.<sup>23</sup> He ended the paper by avoiding theorizing and

instead quoted Humphry Davy: 'One good experiment is of more value than the ingenuity of a brain like Newton's.'

In the third paper in the series, Crookes took an important step towards the radiometer when 'the pith bar was blacked on alternate halves, instead of having the same half blacked on each side'. In the presence of a candle the bar 'spun round rapidly so the suspending fibre was twisted up'. Then came the crucial step: 'Were the black and white surfaces mounted on a pivot, like a compass needle, the movement would not be stopped by torsion'.<sup>24</sup> This was the first true radiometer. The example exhibited in April 1875 had straw arms but these were now rejected as being too heavy. Crookes chose glass arms and pith vanes, each blackened on one side.

Whereas the first radiometer had two vanes, following on from the torsion balance, Crookes was quick to experiment with different numbers. On 2 June 1875 he wrote to Gimingham: 'I am glad you have a six-armed radiometer to work. Is it quicker than a four armed one?'<sup>25</sup> He reported in the paper that ten was 'the maximum which can follow one another without available surface being uselessly obscured' and 'Six discs are a useful number.' The earliest identifiable Royal Society radiometer (figure 4) exactly matches the diagram provided.

Crookes then confirmed the inverse square law with respect to the velocity of motion and distance of the source. He had to concede that the rapidity of movement and inability to balance light sources acted against its efficacy as a photometer, but he believed that the instrument had a peculiar charm. He noted the difference between the reaction to heat and to light, sometimes using the human body as a heat source. He experimented with heat conductors as vanes, questioning the relationship between the optical and thermic properties of the surfaces.

Towards the end of this paper Crookes described some radiometers for special purposes, and some of the Royal Society instruments seem to be these. The first is a radiometer with ten pith vanes, blackened on one side, with two of the arms comprising a watch-spring magnet. This was used to show that motion could be communicated outside the bulb. Suspending a magnet near the bulb gave rise to oscillations, which Crookes suggested could be used in a telegraphic instrument or projected on a screen.<sup>26</sup>

The difficulties associated with making these instruments are well documented in the notebooks and letters. One note from Gimingham to Crookes reads, 'After you were gone the whole thing came to grief, the cup fell out and then I went mad for a few minutes and tortured myself to what I deemed a sufficient extent.'<sup>27</sup> Crookes devised a method of retaining the fly in position by including an upper tube, and all subsequent radiometers have had this.<sup>28</sup>

In the fourth paper Crookes explored differences in the effects of heat and light, not directly involving the radiometer. The fifth paper concerned his considerable output during late 1876 and early 1877. He had looked at the effect of repulsion due to radiation on chemical precipitates, varied the characteristics of the radiation, investigated conductors and experimented with the presentation of surfaces. He decided to compare the reactions of various substances by using radiometers. The first two tested were chromic oxide and precipitated selenium, with the use of a particularly beautiful radiometer in the Royal Society collection.<sup>29</sup> Unfortunately the selenium surface has now lost its 'bright scarlet' colour. Crookes found that this radiometer was so sensitive that it would turn in opposing directions depending on whether he used a sperm oil candle or a wax candle, as the ratio of heat to light differed.<sup>30</sup>



Figure 4. Early radiometer with six vanes.<sup>64</sup> (Science Museum inventory number 1920-412. Copyright © Science Museum, London; reproduced with permission.) (Online version in colour.)

After experimenting with polarized light, Crookes again returned to the radiometer. An accidental anomaly with a crumpled vane set him investigating the variations attributable to inclination.<sup>31</sup> A lengthy series of trials varying the position of the radiant source, and considerations concerning lines of molecular force, led Crookes to vary the shape of the vanes, not merely their inclination. At first he used cones, but ‘cones being inconvenient in shape’ he substituted hemi-cylinders. Aluminium was one material chosen because it was a good conductor of heat.<sup>32</sup>

Crookes replaced hemi-cylinders with cups, because the latter were more responsive. He proceeded to perform experiments on eight radiometers with cup-shaped vanes: four gold, four aluminium, one of each bright on both sides, black on the inside, black on the outside, and black on both sides, respectively. One of the Royal Society instruments is the example made from aluminium bright on both sides.<sup>33</sup> The experiment involved the use of hot rings

at the 'pole' and 'equator' of the radiometer bulbs, alternately shielding the convex and concave sides of the vanes, and immersion in hot water. Crookes then considered viscosity of the residual gas, and one of the Royal Society instruments is associated.<sup>34</sup>

The sixth paper in the series refers to a large number of radiometers in the Royal Society collection. Crookes was now considering the lines of pressure inside the bulb. His notebooks tell us that in September and October 1877 he spent some time studying electrical discharge in a partial vacuum, in what would become a major area of his research.<sup>35</sup> In these experiments he considered 'an instrument of some sort... that could be used to detect variations in the force at different points inside an apparatus.' He then described 'a little turbine radiometer not blacked at all' and called it a 'tell-tale'.<sup>36</sup> He used these tiny radiometers initially to compare the forces at different points within his evacuated tubes, and later to study radiometer theory.<sup>37</sup>

The investigation of the lines of pressure had led Crookes to experiment with screens to direct the force. He described a radiometer with two vanes, each blackened on one side but with that side screened by a sheet of clear mica, and then a radiometer with both sides of the vanes screened by clear mica. Two radiometers were obviously related to this set of experiments.<sup>38</sup> Crookes then moved on to suggest allowing freedom of movement for the screens. The two hypotheses tested were that 'radiation passes through the clear mica screen and generates molecular disturbance on the black surface' and 'molecular pressure is exerted on that side which is most easily warmed'.<sup>39</sup> Crookes believed that the results of this experiment, showing an optimum distance of separation for effect, confirmed the second of the two hypotheses; however, he wished to eliminate complications arising from different absorbing powers. The next instrument to be devised had the screens set at right-angles to the vanes.<sup>40</sup>

There followed a long and complex series of experiments that are beyond the scope of this paper, before Crookes described the turbine radiometer. These have inclined vanes and respond to radiation from above or below rather than from the horizontal plane. Experiments with the lower part of the radiometer at different temperatures from the upper part caused varying motion.<sup>41</sup>

While considering the effect of the size of the bulb on the speed of rotation of the vanes, Crookes invented the spiral form of the instrument. It had advantages over the ordinary radiometer in that it could present a surface to the source of radiation constantly and could be made with the reacting surface as close to the glass as desired, a feature under investigation. Crookes warned that the surfaces of the spiral and the bulb must always be at an angle or 'there will be no tangential action of the molecular pressure'. Two examples of spiral radiometers are in the collection; one is shown in figure 5.<sup>42</sup>

Crookes became increasingly interested in the role of the bulb, coating it with aluminium and blackened aluminium. He recalled experiments that he had performed early in 1876 showing that the motion of the fly could be transferred to the bulb if the radiometer was floated in water.<sup>43</sup> Using an instrument that bears some resemblance to one in the collection,<sup>44</sup> he tried to ascertain what sort of fly produced the best results when turning the bulb while the instrument is in water. The experiment involved a radiometer carrying a magnetized needle that was set in motion by a candle flame. The fly was then brought to a halt by a magnet outside, when the glass bulb began to rotate in the opposite direction. The instrument he described had lead shot as ballast, a totally blackened fly and screens. The label on the Royal Society instrument, giving a legible phrase of 'fixed by a magnet', further suggests that this radiometer was involved at this point.

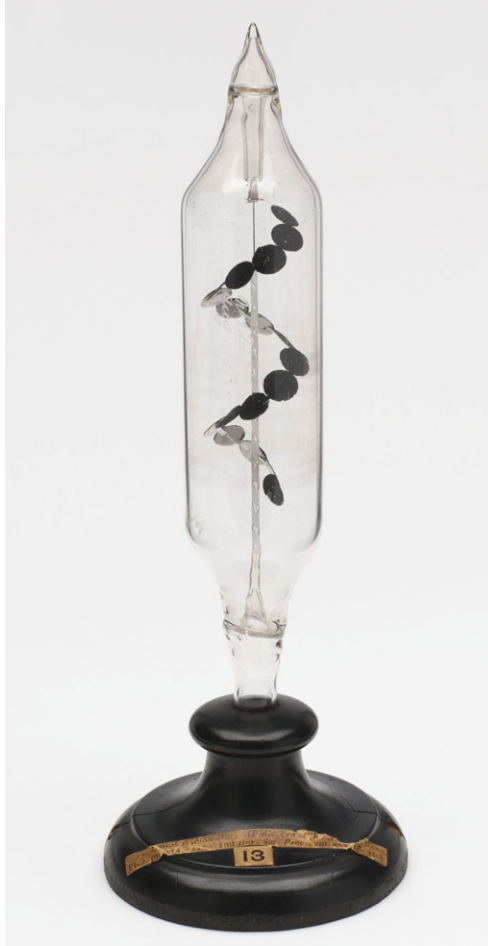


Figure 5. Spiral radiometer. (Science Museum inventory number 1920-409. Copyright © Science Museum, London; reproduced with permission.) (Online version in colour.)

After a suggestion from George Stokes, Crookes then experimented with obtaining rotation with flat vanes, polished on both sides, with the obliquity provided by three clear mica surfaces attached to the bulb and set at an angle to the vanes. Crookes did obtain rotation, which led him to believe the mica screens, rather than the vanes, were providing the motive force. One of the Royal Society radiometers exactly matches this description and diagram.<sup>45</sup>

Crookes then put forward the argument that the radiometer, as a heat engine, could be improved if the driving surface did not move. It would then not be so restricted in size and weight. Calling the driving surface the ‘heater’, and the corresponding surface, which is the bulb in a radiometer, the ‘cooler’, he argued that the instrument would be more efficient if the heater could be separated from the moving part. He called an instrument that used a stationary ‘heater’ an otheoscope.<sup>46</sup> ‘The glass envelope is an essential part of the machinery of a radiometer, without which the fly would not move, but in the otheoscope the glass vessel simply acts as a preserver of the requisite amount of rarefaction.’





Figure 6. Otheoscope operating a Newton's disc. (Science Museum inventory number 1920-403. Copyright © Science Museum, London; reproduced with permission.) (Online version in colour.)

In the otheoscope then described, the driving surface is a disc blackened on the upper surface, with a fly above consisting of vanes at  $45^\circ$  to obtain the maximum rotational effect.<sup>47</sup> To avoid any perceived loss through tangential action, Crookes devised an instrument that had the driving disc, blackened on the upper surface, bent into the form of vanes positioned to face the fly vanes.<sup>48</sup> Another (figure 6) ran a Newton's disk: 'When exposed to sunshine the speed was so great as to cause the colours to blend together in a neutral grey.'<sup>49</sup>

A ‘twin’ radiometer featuring in the collection is referred to in the notebooks<sup>50</sup> but not in *Philosophical Transactions*. It consists of two flies, one above the other, with the standard blackened and silver square metallic vanes, which would turn in opposite directions when illuminated.

Crookes finished this series of papers without attempting to provide an overall explanation for his many findings relating to repulsion due to radiation.<sup>51</sup> In his notebook he headed a series of experiments ‘Radiometer Theory’,<sup>52</sup> but his experimental work was his strength and he seems to have been a follower rather than a leader in this aspect. William Brock relates Crookes’s reluctance to move from the idea of radiation pressure to a kinetic explanation involving the molecules in the vessel.<sup>53</sup> However, his instrument had stimulated research into an already active field.<sup>54</sup> In Crookes’s words, ‘The radiometer is now so much occupying the attention of scientific men.’<sup>55</sup>

Brock gives a detailed description of the theoretical arguments surrounding the radiometer.<sup>56</sup> In brief, it is this: the initial hypothesis that radiation pressure, a result of James Clerk Maxwell’s recently published electromagnetic theory,<sup>57</sup> could explain the reaction of the blackened surfaces, was seen to be fallacious because the silvered surfaces should have been repulsed more strongly. The issue was taken up, shortly after Crookes began publishing, by Osborne Reynolds, Arthur Shuster and Johnstone Stoney,<sup>58</sup> the first two of whom obtained ‘light mills’ from Heinrich Geissler of Bonn. Reynolds was working towards his substantial paper describing his theory of ‘thermal transpiration’.<sup>59</sup> This work was refereed by Clerk Maxwell, who, with acknowledgement, took up Reynolds’s as yet unpublished ideas and provided a quantitative explanation.<sup>60</sup>

Reynolds suggested that the focus of attention in a radiometer should be the edges of the vanes rather than the surfaces. The faster molecules from the warmer (blackened) side hit the edges obliquely with a larger force than the colder molecules from the silvered side, so the net movement is away from the warmer side, while the gas creeps around the edges from the cooler to the hotter side. This is the same principle as the thermal transpiration that Reynolds discussed in connection with porous plates. This is now the agreed interpretation.<sup>61</sup>

Scientific interest in the radiometer diminished after this explanation had been widely accepted. William Sutherland summed it up: ‘the new conquest was simply an outlying part of the Kinetic Theory of Gases.’<sup>62</sup> However, the radiometer has retained its presence as a talking point and toy up to the present day. Its popularity as such can mislead us into forgetting that it was once at the cutting edge of scientific debate, taxing the experimental skills of Crookes, the technical skills of Gimmingham, and the analytical and mathematical skills of leading physicists. The Royal Society’s collection has survived to give us an insight into a series of beautifully crafted experiments central to mainstream physics in the 1870s.

#### NOTES

- 1 W. Crookes, ‘On Repulsion from Radiation, parts III and IV’, *Phil. Trans. R. Soc.* **166**, 325–376 (1876), at p. 345. An unpublished thesis by Lina Hakim (of the London Consortium), *Scientific playthings: the play of things and with things in the creation of scientific knowledge* (2009) discusses the charm of the radiometer on p. 21.
- 2 W. H. Brock, *William Crookes (1832–1919) and the commercialization of science* (Ashgate, Aldershot, 2008). Brock’s recent book gives an exhaustive and clear account of Crookes’s life and work.

- 3 See F. A. J. L. James, 'Of "medals and muddles" the context of the discovery of thallium: William Crookes's early spectro-chemical work', *Notes Rec. R. Soc.* **39**, 65–90 (1984).
- 4 Brock, *op. cit.* (note 2), p. 124.
- 5 W. Crookes, 'Spiritualism viewed by the Light of Modern Science', *Q. J. Sci.* **7** (July), 316–321 (1870); reprinted in W. Crookes, *Researches in the Phenomena of Spiritualism* (J. Burns, London, 1874), p. 3.
- 6 W. Crookes, 'Some Further Experiments on Psychic Force', *Q. J. Sci.* **8** (October), 471–493 (1871). Also R. Noakes, 'Instruments to Lay Hold of Spirits', in *Bodies/machines* (ed. I. R. Morus), pp. 125–163 (Berg, Oxford, 2002); Brock, *op. cit.* (note 2), p. 144.
- 7 In a letter to his technician and associate Charles Gimmingham dated 10 October 1871, Crookes wrote: 'I am sorry the experiments seem to show that heat is the active agent in the movement (of a torsion balance apparatus). Try and get a better vacuum.' Science Museum Library 1997-1694. W. Crookes, 'On The Action of Heat on Gravitating Masses', *Proc R. Soc.* **22**, 37–41 (1873), at p. 41; Brock, *op. cit.* (note 2), pp. 163 and 170.
- 8 The *Proceedings* series consists of the following: W. Crookes, 'On the Attraction and Repulsion Resulting from Radiation, part II' [abstract], *Proc. R. Soc.* **23**, 373–378 (1874); W. Crookes, 'On the Repulsion Resulting from Radiation, part III' [abstract], *Proc. R. Soc.* **24**, 276–279 (1875); W. Crookes, 'On Repulsion Resulting from Radiation: Influence of the Residual Gas', *Proc. R. Soc.* **25**, 136–140 (1876–77); W. Crookes, 'On the Repulsion Resulting from Radiation, part IV' [abstract], *Proc. R. Soc.* **24**, 279–283 (1875); W. Crookes, 'On the Repulsion Resulting from Radiation, part V' [abstract], *Proc. R. Soc.* **27**, 29–38 (1878); W. Crookes, 'On the Repulsion from Radiation, part VI' [abstract], *Proc. R. Soc.* **28**, 35–41 (1878).
- 9 The *Philosophical Transactions* series consists of the following: W. Crookes, 'On Attraction and Repulsion Resulting From Radiation', *Phil. Trans. R. Soc.* **164**, 501–527 (1874); W. Crookes, 'On Repulsion Resulting From Radiation, part II', *Phil. Trans. R. Soc.* **165**, 519–547 (1875); W. Crookes, 'On Repulsion Resulting from Radiation, parts III and IV', *Phil. Trans. R. Soc.* **166**, 325–376 (1876); W. Crookes, 'The Bakerian Lecture: On Repulsion Resulting from Radiation, part V', *Phil. Trans. R. Soc.* **169**, 243–318 (1878); W. Crookes, 'On Repulsion Resulting From Radiation, part VI', *Phil. Trans. R. Soc.* **170**, 87–134 (1879).
- 10 Brock, *op. cit.* (note 2), p. 235.
- 11 List of exhibits of the Royal Society Conversatione, 7 April 1875. Crookes demonstrated the torsion balance to the Royal Society in April 1874, and the radiometer in the following year.
- 12 Crookes, *op. cit.* (note 8), part II, p. 377.
- 13 There is a reference to an instrument in a letter to Gimmingham of September 1874: 'You had better now put a standard candle at a fixed distance from it and time the revolutions.' However, revolutions were timed with the torsion balance and the dated publications above seem definitive. Science Museum Library, 1997-1674.
- 14 Crookes acknowledges Gimmingham's work at the end of the series of papers. 'It is a pleasure for me to state that in the six years [the experiments] have been in progress I have been materially aided by my assistant Mr. C. H. Gimmingham whose extraordinary mechanical dexterity and skill in glass manipulation have been called almost daily into service.' Crookes, *op. cit.* (note 9), part VI, p. 134; also Brock, *op. cit.* (note 2), pp. 156–157.
- 15 The notebooks (Science Museum Library 1997-1673, parts 1–5) and letters (Science Museum Library 1997-1674).
- 16 See, for example, W. Crookes, 'On Repulsion Resulting From Radiation—Preliminary Note on The Otheoscope', *Proc. R. Soc.* **26**, 176–179 (1877); also J. A. Chaldecott, *Handbook of the collection relating to heat and cold* (HMSO, London, 1954), pp. 38–39. The references are not always reliable.
- 17 Crookes, *op. cit.* (note 9), part V, p. 244.
- 18 Crookes, *op. cit.* (note 9), part I, p. 501; Brock, *op. cit.* (note 2), p. 162.

- 19 Crookes, *op. cit.* (note 9), part I, p. 509. Much was organic; see, for example, letter to Gimingham, 5 November 1872: ‘pith ball terminals silk sewing thread stiffened by shellac’. Science Museum Library 1997-1674 and ‘dragon flies’ wings’, ‘spiders’ thread’, ‘thistledown’ and ‘down of dandelion’. Crookes, *op. cit.* (note 8), part I, p. 502.
- 20 H. Cavendish ‘Experiments to Determine the Density of the Earth’, *Phil. Trans. R. Soc.* **88**, 469–526 (1798).
- 21 Crookes, *op. cit.* (note 9), part I, p. 527. Brock, *op. cit.* (note 2), p. 165.
- 22 Brock, *op. cit.* (note 2), part II, p. 522.
- 23 Brock, *op. cit.* (note 2), pp. 166–167.
- 24 Crookes, *op. cit.* (note 9), part III, p. 338.
- 25 Science Museum Library 1997-1674.
- 26 Science Museum inventory number 1920-407. W. Crookes, ‘On the Movement of the Glass Case of a Radiometer’, *Proc. R. Soc.* **24**, 409–410 (1875). This instrument has labels reading ‘7’ and ‘Radiometer having ten arms and a light magnet used to communicate motion from the interior to the outside of the case and record the revolutions per minute for photometric purposes Philosophical Transactions vol 166 p. 354’.
- 27 Science Museum Library 1997-1673 part 2, 24 July 1878.
- 28 Science Museum inventory number 1920-397. This instrument has a label reading ‘3 Radiometer . . . upper . . . falling off cup Philosophical Transactions . . . p. 35 . . .’ Another radiometer whose label claims it belongs here, but whose precise use has not been ascertained, is Science Museum inventory number 1920-393.
- 29 Crookes, *op. cit.* (note 9), part V, p. 266 and in particular p. 270.
- 30 Science Museum inventory number 1920-413. This instrument has labels: ‘18’ and ‘chromic oxide one side, selenium the other. Moves in different directions to heat and light Philosophical Transactions vol 169? p266–272’.
- 31 Science Museum inventory number 1920-401. Crookes, *op. cit.* (note 8), part V, p. 281. This instrument has a label reading ‘radiometer with sloping vanes . . . incident radiation . . . but filled with mercury vapour Philosophical Transactions vol 169 p. 281’.
- 32 Science Museum inventory number 1920-414. The label on it reads ‘Radiometer with hemispherical aluminium vanes bright on both sides Philosophical Transactions vol 169 p. 294–295’. Brock, *op. cit.* (note 2), p. 233.
- 33 Science Museum inventory number 1920-393. The label reads ‘cup shaped vanes bright on both sides Philosophical Transactions vol 169 p. 296’ The base is slightly radioactive.
- 34 Science Museum inventory number 1920-395. Crookes, *op. cit.* (note 8), part V, pp. 309–312. The label gives the best information available: ‘Instrument for showing the viscosity of the residual gas in a radiometer. The lower disc of mica is connected to a magnet and when this is put into rotation by means of an outside magnet the upper mica disc revolves in the same direction.’
- 35 Science Museum Library 1997-1673 part 4, 28 September 1877. See F. Müller, *Gasentladungsforschung im 19. Jahrhundert* (GNT-Verlag, Diepholz, 2004) for an excellent and comprehensive account of this work.
- 36 Science Museum Library 1997-1673 part 4, p. 499, 2 October 1877. Müller, *op. cit.* (note 35), pp. 221–227.
- 37 Science Museum inventory number 1920-392, although miniature, has the standard blackened and silvered vanes and is enclosed; the tell-tales consist of clear mica vanes. Science Museum Library 1997-1673 part 5, p. 104, 15 June 1878.
- 38 Science Museum inventory numbers 1920-396 and 1920-408. They are both dated 1 January 1878, and both carry the number 1338; in the four-vaned example the number is etched onto the glass bulb. Their labels read, respectively, ‘5’, ‘Radiometer with two aluminium? vanes coated on one side with clear mica. 1338’, and ‘4’ ‘Radiometer with four aluminium vanes coated on one side and with clear mica on the other. Jan 1st 1878’.

- 39 Science Museum inventory number 1920-399. Crookes, *op. cit.* (note 9), part VI, p. 90. This instrument has labels reading '11', '1043' and 'Radiometer with two aluminium vanes and two screens of clear mica. Philosophical Transactions vol 170 p89–93'.
- 40 Science Museum inventory number 1920-400. This instrument has labels reading '11', '1285' and 'Radiometer with two aluminium vanes and moveable... of clear mica Philosophical Transactions vol 170 pp89–93'.
- 41 Science Museum inventory number 1920-398. Crookes, *op. cit.* (note 9), part VI, p. 112. This instrument has a damaged label but the words 'tilted' 'cup-shaped' and 'bright' can be made out, and a reference 'p. 112', which must refer to this paper.
- 42 Science Museum inventory numbers 1920-394 and 1920-409. The first is a simple example with the blackened surface uppermost as described, and the second consists of flat discs suspended on a spiral aluminium wire. The labels read, respectively, '19' and 'Spiral... no 2045 Philosophical Transactions vol 170 p114–115', and '13', 'spiral radiometer Philosophical Transactions R S vol 170 p114–115'. 1920-409 also has '1245 Aug 1877' etched on the glass bulb.
- 43 W. Crookes, 'On the Movement of the Glass Case of a Radiometer', *Proc. R. Soc.* **24**, 409–410 (1876). Brock, *op. cit.* (note 2), p. 227.
- 44 Science Museum inventory number 1920-405. The label is partly illegible but includes 'fixed by a magnet' and on the glass '1354 Feb 7th 1878'. Another radiometer involved in this set of experiments, but not corresponding exactly to one described in the paper, is Science Museum inventory number 1920-411.
- 45 Science Museum inventory number 1920-418. Crookes, *op. cit.* (note 9), part VI, p. 120. The label reads 'metallic rectangular vanes Philosophical Transactions vol 170 p 120'.
- 46 Crookes, *op. cit.* (note 9), part VI, p. 121. Brock, *op. cit.* (note 2), p. 232: Brock cites Crookes's friend Alexander Constantine Ionides as having recommended this name.
- 47 Science Museum inventory number 1920-417. The label reads 'Otheoscope having four armed fly pivoted above a disc of bright aluminium. Philosophical Transactions vol 170 p. 120'.
- 48 Science Museum inventory number 1920-416. Crookes, *op. cit.* (note 9), part VI, p. 122. The labels read '23' and 'Otheoscope inclined vanes. Philosophical Transactions vol 170 123'.
- 49 Science Museum inventory number 1920-403. Crookes, *op. cit.* (note 9), part VI, p. 123. The labels read '21' and 'Otheoscope'. Two other unidentified otheoscopes exist, namely Science Museum inventory numbers 1920-402 and 1920-415. The first has labels reading '21' and 'vol... p. 121, 122, 123'. It could correspond to an instrument described in Crookes, *op. cit.* (note 16), which had a large horizontal disc and inclined metallic vanes blackened on both sides. The second has labels reading '24' and '... no 23 but having mica vanes...'.  
50 Science Museum inventory number 1920-410. Science Museum Library 1997-1673 part 1, 5 August 1876. This radiometer has a base made to resemble the others, but is not mahogany and has no labels other than the number '10'.
- 51 Crookes, 'On Repulsion Resulting from Radiation', *op. cit.* (note 8), p. 140, in which Crookes moves from the radiation's being the direct cause to its being the indirect cause, and recognizes the effect of the residual gas. Crookes, *op. cit.* (note 8), part V, p. 35; Crookes, *op. cit.* (note 8), part VI, p. 37.
- 52 Science Museum Library 1997-1673 part 5, p. 104, 15 June 1878.
- 53 Brock, *op. cit.* (note 2), p. 168.
- 54 This has been well documented by S. G. Brush and C. W. F. Everitt, 'Maxwell, Osborne Reynolds and the radiometer', *Hist. Stud. Phys. Sci.* **1**, 105–125 (1969).
- 55 W. Crookes, 'Experimental Contributions to the Theory of the Radiometer', *Proc. R. Soc.* **25**, 303–314 (1876–77).
- 56 Brock, *op. cit.* (note 2), pp. 172–176 and 217–235. Also A. E. Woodruff, 'William Crookes and the radiometer', *Isis* **57**, 188–198 (1966).
- 57 J. C. Maxwell, *A Treatise on Electricity and Magnetism* (Clarendon Press, Oxford, 1873).

- 58 O. Reynolds, 'On the Force Caused by the Communication of Heat Between a Surface and a Gas' [abstract], *Proc. R. Soc.* **24**, 387–391 (1875–76); Arthur Shuster, 'On the Nature of the Force producing the Motion of a Body Exposed to Rays of Heat and Light', *Proc. R. Soc.* **24**, 391–392 (1875–76); G. J. Stoney and R. J. Moss, 'On Crookes's Force', *Proc. R. Soc.* **25**, 553–559 (1876–77).
- 59 O. Reynolds, 'On Certain Dimensional Properties of Matter in a Gaseous State . . .', *Phil. Trans. R. Soc.* **170**, 727–845 (1879).
- 60 J. C. Maxwell, 'On Stresses in Rarefied Gases Arising from Inequalities of Temperature' [abstract], *Proc. R. Soc.* **27**, 304–308 (1878); *idem*, 'On Stresses in Rarefied Gases Arising from Inequalities of Temperature', *Phil. Trans. R. Soc.* **170**, 231–256 (1879).
- 61 See, for example, Philip Gibbs, 'How does a light mill work?' (1996) at <<http://www.corepower.com:8080/~relfaq/light-mill.html>>.
- 62 W. Sutherland, 'Thermal Transpiration and Radiometer Motion', *Phil. Mag.* (5) **42**, 373–391 (1896).
- 63 Hakim, *op. cit.* (note 1), p. 33; Hakim quotes from Fournier D'Albe, *The life of Sir William Crookes* (T. Fisher Unwin, London, 1923), p. 261. Brock, *op. cit.* (note 2), p. 177, remarks that Crookes used a radiometer as an icon after 1875.
- 64 This instrument has labels reading '2' and 'Early radiometer with glass arms and pith vanes Philosophical Transactions vol 166 p. 339'.