

# Crookes' Radiometer and Otheoscope

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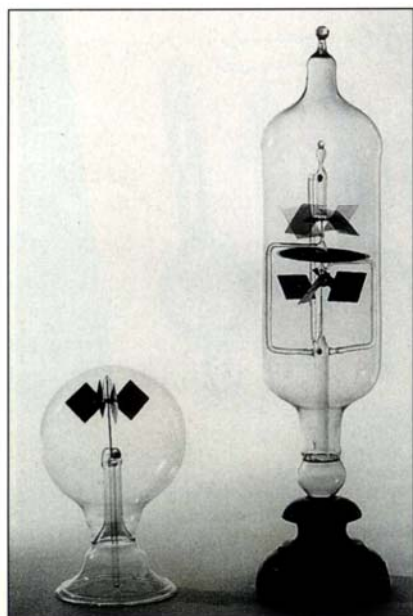


Fig. 1 Left: Modern radiometer, and right: Three element radiometer/ otheoscope.

Crookes' radiometer is one nineteenth century scientific instrument still widely available today. The most common form consists of a glass bulb a few centimetres in diameter, evacuated to a pressure of about 50 mtorr, containing an arrangement of four vanes (or 'fly') pivoted on a vertical axis. Normally, one side of each vane is blackened and the other made white or reflective. When it is illuminated by visible or infrared radiation, the fly rotates. Such a device is more a toy or demonstration device than a quantitative measuring instrument but the motion of the hermetically sealed fly with its overtones of perpetual motion or action at a distance has caught the attention and imagination not only of countless window shoppers but also of scientists of the calibre of Maxwell and Einstein.

Its inventor, William Crookes (1832-1919), was one of the most prominent English scientists of his day. Like his mentor, Michael Faraday, he had no mathematical training and relied on intuitive models for guidance. Although most of these turned out to be incorrect, they and his great experimental skill led him to remarkable discoveries, which overshadowed a notorious involvement with spiritualism at one stage of his career.<sup>2</sup> When he was knighted in 1897 in recognition of his work in chemistry and physics, he incorporated a radiometer in his arms.

His invention of the radiometer grew out of studies of discrepancies he observed when weighing hot samples under vacuum. His first device was in the form of a balance with a vane at each end, but by 1873 he was using a 'mill' with pith vanes blackened on one side.<sup>3</sup> This device, which is the direct ancestor of our toy, and which he named 'radiometer', is among a number of his instruments on display, still working<sup>4</sup> in the Science Museum, London.

Figure 1 shows, at left, the typical form of Crookes' radiometer still available today in educational toy shops as a 'solar engine', 'space age sphere'. An evacuated glass bulb encloses a fly of four vanes, each white on one side and blackened on the other. The fly is supported by a glass cup on a needle-point to give a low friction pivot. When illuminated with visible or infrared light, the fly begins to rotate with the white sides leading. Most older examples have mica vanes with lampblack on one side. They usually have a turned wooden foot. There is rarely any marking or maker's name.

Radiometers are easily made, especially with the aid of modern vacuum pumps, and have appeared in the catalogues of instrument suppliers ever since Crookes' time. However, the theory of their operation has been controversial from the beginning and is still too complicated to be worked out in complete detail.

At first Crookes suspected some link between heat and gravity but later came to believe that the incident radiation was exerting a pressure on the absorbing elements. This explanation is sometimes still advanced today<sup>5,6</sup>, because a celebrated consequence of Maxwell's electromagnetic theory of radiation (1873) is that light waves can exert a pressure. However, radiation pressure would actually be greater on the reflective surface where photon momentum is reversed rather than merely absorbed so that the black surfaces should lead in the rotation. In fact, the opposite is observed, consistent with an interaction between the surfaces heated by the radiation and the residual gas. Besides, experiments by Arthur Schuster<sup>7</sup> and Augusto Righi<sup>8</sup> in 1876 showed that there was a reaction force on the vessel walls in the opposite sense to the vane rotation showing that a force was being transmitted through the gas.

A simple explanation, advanced by Osborne Reynolds<sup>9</sup> in 1874 and usually

given to students today, is that gas molecules rebound from the black surface with high velocities characteristic of its high temperature so that the net recoil force is greater than on the cold side.

Such an explanation is satisfactory only when the molecular mean free path is so large that collisions between the molecules can be neglected. If the pressure in a radiometer of normal construction is reduced to this point, the fly will cease to turn.<sup>10</sup> In fact the actual radiometer force is much larger at higher pressures where the mean free path is less than a millimetre. Here the situation is far more complex and an explanation in terms of Maxwell's 'thermal creep' is more appropriate.<sup>11</sup>

Here one must consider what happens when a temperature gradient exists along a surface. Molecules striking the surface at an angle, and coming from the hot end, bring with them more tangential momentum, on account of their greater speeds, than those coming from the colder end. As a result, the gas exerts a force on the surface towards the colder region and in return the surface exerts a reaction force on the gas which causes a thermal creep towards the hotter area. Since the force is parallel to the surface, not normal to it, only at the vane edges will the force be in a direction able to turn the fly. Thermal creep explains the action of several variants of radiometer which use unpainted metal cups, half cylinders or cones, instead of vanes. When illuminated, the fly rotates with the cooler open edges of the cups leading. Figure 2 (after Kennard<sup>11</sup>) shows flow patterns driven by thermal creep in normal (a) and cup (b) radiometers. Since the flow is hindered by viscosity, pressure builds up in regions of convergence, providing the observed force. Further, molecular flow patterns set up by thermal creep on an absorbing but fixed element can move a non-absorbing but mobile element mounted nearby. Crookes wrote 'the heater, or driving surface, acts as if a molecular wind were blowing from it, principally in a direction normal to the surface'.<sup>12</sup>

Two nice examples illustrating this effect are in the collection of the Museo di Fisica at the Università di Bologna (Fig. 3). In one (130 STAN), a fly with transparent angled mica vanes is pivoted above a fixed disc, blackened on its upper side. In the other (131 STAN) a transparent disc is pivoted above a set of four angled vanes, blackened on both sides, and fixed in place. In both cases,

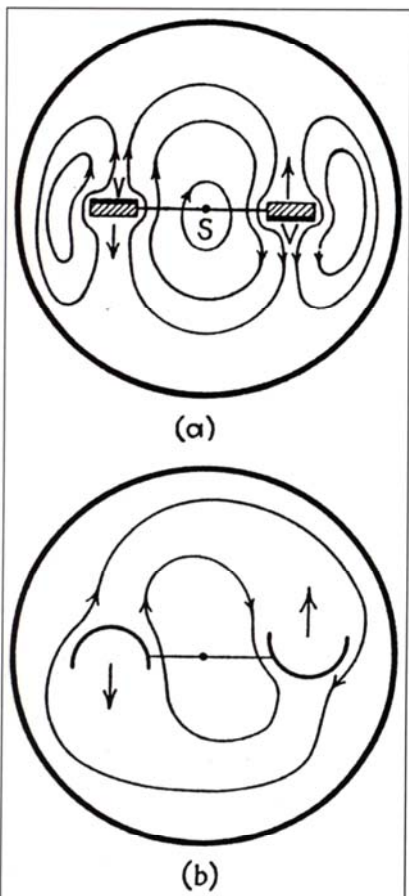


Fig. 2 Thermal creep flow patterns in (a) normal and (b) cup radiometers (after Kennard<sup>11</sup>).

when the fixed black element is illuminated, the transparent element rotates. This should put to rest any lingering desires to see radiation pressure as the motive force.

Crookes called such devices 'otheoscopes', from the Greek for 'I propel'.<sup>12</sup> Although many details were to be worked out, Osborne Reynolds and Maxwell had identified the basic operating mechanism by 1879.<sup>13</sup> Crookes however became convinced that he could trace 'lines of increased molecular pressure' to explain his results. These radiated perpendicular to a heated surface and when they reached the vessel walls caused the vane to recoil. He carried this simplistic idea over into his new work on cathode rays in gas discharges where he made a number of important discoveries. Among several 'Crookes' tubes' he used were 'electrical radiometers' where the fly acted as an electrode and rotated under the influence of the discharge.

A quantitative theory of the basic radiometer remained a challenge to believers

in the kinetic theory of gases well into this century. Knudsen<sup>14</sup> worked out the theory for the low pressure limit and used it as the basis of an absolute pressure gauge, insensitive to gas composition. The pressure range normally used in demonstration radiometers was more difficult to treat and even attracted the interest of Einstein.<sup>15</sup>

At the turn of the century, scientific instrument suppliers such as Baird and Tatlock, Griffin, and Leybold's Nachfolger listed a variety of such tubes carrying the names of Crookes, Puluj and Zölner according to illustrations which had appeared in their papers. A long paper by J. Puluj, which appeared in English translation<sup>16</sup> in 1889 as 'Radiant Electrode Matter and the so-called Fourth State' seems to have been influential in this respect. Zölner's name is especially associated with radiometer tubes with angled vanes above a loop of heating wire, while 'Puluj radiometers' were driven by electrical discharges, and therefore have electrical feedthroughs, and often had fluorescent coatings on the vanes.

In spite of its name, the radiometer with its friction limited rotating fly is not well adapted for quantitative measurement of radiation intensity. However, devices based on the same principle but with the force acting on a vane twisting a torsion fibre through a measurable angle, similar to Crookes' earliest devices, were used in the 1880-1900 period for infrared radiation measurements. A similar geometry was adopted later for measurements made by Lebedew<sup>17</sup> and Nichols and Hull<sup>18</sup> of the much smaller true radiation-pressure force which remains at extremely low pressures. Observation of anything more than these most subtle effects of radiation pressure had to wait until well into the twentieth century. Its effects on the trajectories of spacecraft can be important. More recently, it has been found that if a laser beam, even one of low power, is focused to a spot only a few micrometres across, the pressure of radiation on tiny particles floating in liquid can be sufficient to trap them and move them around.<sup>19</sup> This principle is now being introduced to laboratories around the world to manipulate cells and bacteria.

Figure 1 also shows a second, more complex, device, from the collection of the Physics Museum at The University of Queensland in Brisbane, Australia. Its provenance is unknown but the details of its construction show it to be from the same workshop as the otheoscopes in Bologna. It is the most complex non-electrical radiometer device yet seen by the author. It stands 300 mm high on its

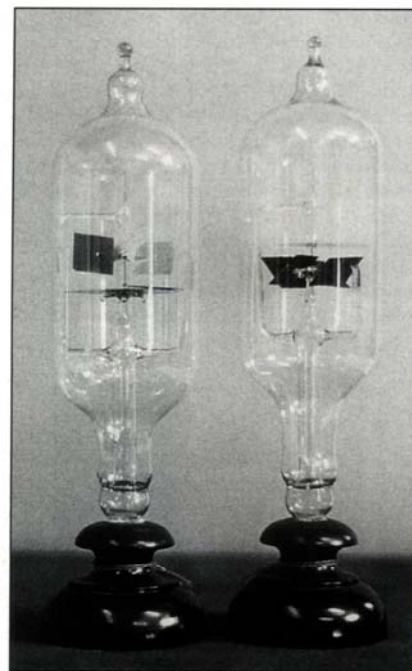


Fig. 3. Two otheoscopes at the University of Bologna (inv. 130 STAN and 131 STAN).

lead-weighted wooden foot. There are three moving parts pivoted on glass cup/needle bearings: at the bottom is a 'mill' of mica vanes, angled at 45° to the vertical and blackened on the upper sides. Above that is a mica disc, blackened on the upper side, and at the top is a second mill of mica vanes angled in the opposite sense to those below, and left transparent. When lit with a lamp or sunlight, the two mills rotate in the same direction, with the black surfaces on the lower mill following as expected. Meanwhile, the disc rotates in the opposite direction, in accordance with an arrow scratched into the blackening.

Using a collimated light beam, one can separately illuminate each element in turn. If the upper mill is illuminated, nothing happens. If the lower mill is illuminated, it turns as expected, but the disc also turns, in the opposite direction, presumably as a result of drag from the thermal creep flow over the tops of the vanes, illustrating the reaction force demonstrated by Schuster and Righi. If the disc is lit, one would expect the device to act like an otheoscope where the flow pattern set up by thermal creep to the hot upper side of the disc would set the upper fly into motion. This is indeed the case, but there is also a reaction back on the disc, which rotates in the opposite direction.

A century after its invention, Crookes' radiometer remains a fascinating toy, demonstrating in the most striking way

the conversion between two apparently rather different forms of energy - light and mechanical energy. However, the implication that the conversion is direct, which follows from the fact that the bulb has been evacuated, is a red herring. The 'radiometer effect' is not radiation pressure but a gas heating effect which acted as a touchstone in the development of the kinetic theory of gases. This fact is brought out most clearly in the related device, also invented by Crookes, the 'othescope', which separates the radiation heated surface from the moving one.

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