XIII. *On Repulsion resulting from Radiation.*—Parts III. & IV.

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Contents.

PART III.

125. In my previous papers on this subject* the experiments described have had for their object the demonstration of the broad facts of repulsion resulting from radiation. In Part I., after satisfying myself that the action was not due to air-currents or electricity, I went rapidly over bodies of the most diverse chemical and physical characters, organic and inorganic, metallic and non-metallic, dense and light, in spheres, disks, and thin plates, endeavouring to find, from their behaviour when free to move in a vacuum, what conditions were necessary to obtain the strongest movement under the influence of radiation, and what were unnecessary. I ascertained that chemical constitution had little or nothing to do with the action. I said (par. 75) "the law appears to be that the force exerted is in proportion to the extent of surface exposed, rather than in proportion to the mass. Much surface and extreme lightness are the requisites in selecting materials for the beam, index, or gravitating mass; and when the masses have the same specific gravity and extent of surface, their position in respect to the source of heat determines the extent of movement. Thus a cylinder of pith is more sensitive when arranged for the heat to act on its side than on its end." I tried many experiments on the circumstances governing the position of the neutral point during exhaustion, and I proved that, within experimental limits, the nearer the vacuum approached perfection the stronger was the movement due to radiation.

In Part II. I described many improved forms of apparatus by which the movements due to radiation could be studied in a more complete manner and numerical results be obtained; the action of the various kinds of radiation, from the obscure heat-rays emitted by copper at 100° C. to the blue and ultra-violet rays of the spectrum, was examined, the interference caused by passing the rays through various screens was shown, and the phenomena of the neutral point were further discussed. Experiments were described which satisfied me that the hypothesis of the movements being due to evaporation and condensation at the surface would not account for all the facts of the case; and ample proof was afforded that "to get the greatest delicacy in these apparatus there is required large surface with a minimum of weight," an apparatus for the quantitative examination of this law being described.

126. Nearly all the experiments described in Parts I. and II. were made with the

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* Philosophical Transactions, vol. clxiv. (for 1874) p. 501, and vol. clxv. (for 1875) p. 519.

dark or slightly luminous heat-rays—the fingers, a hot glass rod, hot copper, or a candle-flame being used as the source of radiation. I quote the following sentence from par. 94:—"Although I most frequently speak of repulsion by *heat*, and in illustrating any of the results obtained I generally use either the fingers or the flame of a spirit-lamp as a convenient source of radiation, it must be clearly understood that these results are not confined to the heating-rays of the spectrum, but that any ray, from the ultra-red to the ultra-violet, will produce repulsion in a vacuum. I have already mentioned this fact in my first paper (58, 68)."

A few experiments were tried on the effect of radiation on surfaces the reflecting or radiating power of which was modified by coating them with various substances. In par. 102, after describing a torsion-apparatus for quantitative work, I mention that the surfaces of pith, as thin as possible, may be coated with lampblack or silver, or may retain their natural surface; in par. 108 I state, as the result of a long series of experiments with this apparatus, that "the conducting-power for heat and condition of the surface (whether coated with lampblack or consisting of polished metal) of the body on which radiation falls materially influence the movements." In par. 112 I again refer to the effect caused by the physical condition of the surface; and further on, in par. 116, I say, "A series of experiments have been tried with a view to ascertain what influence the state of the surface of the substance submitted to radiation has on the amount or the direction of its movement." After describing one in which white ivory was compared with lampblacked ivory without giving very striking results, I continue:—"These experiments were, however, tried in 1873, when I had not succeeded in getting any thing like the delicacy I now obtain in the apparatus; and I propose to repeat them under varied conditions, before employing the results to found any arguments upon."

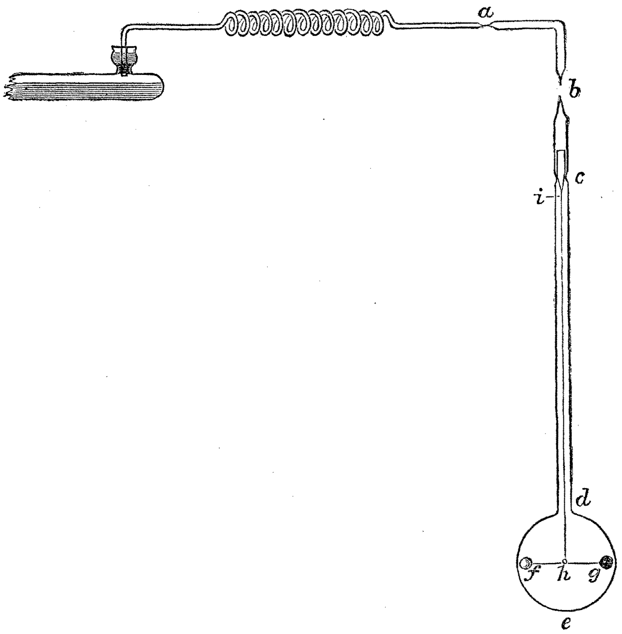
The present paper contains an account of these experiments on the action of radiation on bodies the surfaces of which have their radiating and absorbing powers modified by various coatings. The surfaces examined in this way are of the most diverse character, the incident rays have been selected of all refrangibilities from ultra-red to ultra-violet, the radiation has been sifted through liquid, solid, and gaseous screens, the degree of exhaustion and the sensitiveness of the apparatus have been brought to a state of perfection undreamed of in my earlier experiments, and the results, I venture to state, are of a correspondingly striking character.

127. The results which I obtained on comparing the action of radiation on thin substances, plain and lampblacked, were at first very anomalous. As already stated (116) the movement of lampblacked ivory under the influence of radiation was only a little more than that of plain white ivory. On the other hand, coating platinum with lampblack produced a very marked effect on its movement (114).

Pith coated with lampblack was generally found to have its sensitiveness heightened; but this was not always the case, and the following experiments were tried for the purpose of clearing up these discrepancies.

128. An instrument was made similar to the one described and figured in pars. 84, 85,

Fig. 1.



consisting of a glass bulb on the end of a tube, and having suspended in it, by means of a silk fibre, a horizontal glass stem with a disk of pith at each end. For a detailed description and the mode of exhaustion I refer to my last paper, the only point of difference being that in the present case one of the pith disks was coated with lampblack, the other remaining white.

Before exhausting the apparatus I found that the white and the black disk were attracted about equally by the fingers, a bulb of warm water, or a hot glass rod.

After exhausting it I tried the action again. The fingers repelled either disk strongly, and in about an equal degree; and the same result was obtained with other sources of heat of low intensity. If the finger, a bulb of warm water, or a warm piece of glass or metal is held for some time close to the glass bulb, the two disks are repelled, and the rod connecting them sets equatorially, showing that the repulsion is equal on the black and the white surface.

The bulb of water with enclosed thermometer (28) was raised to 100° C., and brought close to the bulb of the apparatus. The black and white disks were equally repelled, the connecting rod setting equatorially.

A bath of fusible metal was prepared. In this a small copper ball was heated to different temperatures, and the action on the black and white disks noted.

At 100° C. the repulsion of the two was equal.
150° ,, ,,
200° ,, ,,
250° ,, ,,
300° the black was slightly more repelled than the white disk, the rod setting about five degrees from the equatorial position.

The fusible metal bath was gradually increased in temperature up to dull redness, and the action of the copper ball heated in it was tested from time to time; the temperatures were not ascertained, as they were above the boiling-point of mercury. The repulsion of the black disk increased until at dull redness the copper ball caused the rod joining the two disks to make an angle of about 40 degrees. At a full red heat the ball repelled the black disk very strongly, causing the rod to oscillate violently, and sometimes even to pass the axial position.

129. A candle brought near the apparatus acted on the disks even more energetically than the red-hot copper. At a little distance off the movable rod set at an angle of 45 degrees; and by causing the candle to approach or recede, the angle formed by the rod varied in a corresponding manner, the torsion of the suspending fibre balancing the varying force of radiation.

130. During the exhaustion of one of these pieces of apparatus, an action of aqueous vapour was observed which explained some of the anomalies I had met with in the course of this investigation. The apparatus had a little water in it; and although the mercury-pump brought the gauge to within about 8 millims. of the barometric height in the course of ten minutes, the tension of the aqueous vapour prevented it from rising higher. After working the pump for several hours, and gently warming the different parts of the apparatus, the liquid water was evaporated, and only aqueous vapour remained. The gauge now rapidly rose to the height of the barometer, the apparatus necessarily being filled with the residual aqueous vapour. On bringing a lighted candle near the disks I expected to see the black one violently repelled; but instead of that the connecting-arm set equatorially, showing that the radiation from the candle within a few inches of the disks repelled the white one as strongly as it did the black. The pump was kept in action, and oil of vitriol was passed through it once or twice (44). This was continued for about four hours; and on testing the apparatus from time to time with a candle the repulsion of the black disk gradually increased, the arm setting at a greater and greater angle from the equatorial position, but at no time getting very strongly deflected.

An accident happening to one of the tubes of the pump, it was necessary to let air into the apparatus; it was passed in slowly over oil of vitriol. As soon as the pump was mended exhaustion of the apparatus was recommenced. As soon as the gauge rose within 6 millims. of the barometric height the candle was seen to repel the black disk. At 3 millims. the superior repulsion of the black over the white disk was sufficient to cause the arm to set 45°; and as the exhaustion got better the repulsion of the black disk increased, until at the point when the gauge and barometer were level the candle exerted a strong action many feet off, and when brought close to the instrument set the bar and disks in most violent agitation, the black disk being driven violently away, and the connecting-arm swinging rapidly on each side of the axial position.

This experiment shows that the presence of even a small quantity of aqueous vapour in the exhausted apparatus almost, if not quite, neutralizes the more energetic action which luminous rays appear to exert on a blackened surface. In the first case, even when the gauge and the barometer were appreciably level, and the pump had been working for some hours, the superior repulsion of the black over the white was not so strong as it was in the second case when the gauge was several millims. below the barometer.

131. These two experiments, the one showing a marked difference of action on a black surface between heat of low intensity and luminous rays, and the other showing that this difference may be neutralized by aqueous vapour, explain most of the anomalies I have met with; and especially they prove how it was that my earlier experiments with black and white surfaces failed to show much difference. They also prove that still further improvement in the vacuum-producing apparatus would be advisable. I accordingly adopted Dr. ANGUS SMITH'S and Professor DEWAR'S plan of absorbing the residual gas by means of cocoanut-shell charcoal; and I found that after a little experience this, although somewhat tedious, left little to be desired in the perfection of the vacuum. A glass tube about 6 inches long is tightly packed with small pieces of freshly ignited cocoanut-shell charcoal; it is then drawn narrow at each end and sealed on to the apparatus, between it and the spiral glass tube*. The exhaustion proceeds as usual till the gauge and barometer are appreciably level; the charcoal-tube is then heated to a temperature well within the softening point of the glass, when the occluded gases are given off from the charcoal and depress the mercurial gauge 30 or 40 millims. The pump is now worked rapidly until the gauge is brought up again; the heating of the charcoal is repeated, when more gas is given off and the gauge is again depressed, although not so much as before. The pump is again set going, and these operations are repeated until heating the charcoal ceases to depress the gauge. The effect of this has been to repeatedly wash out the residual atmospheric air and aqueous vapour from the interior of the apparatus, and replace it by gas or vapour which has been occluded by the charcoal, and which we are justified in supposing will be again occluded by it even when very highly exhausted. When these operations are finished, and no more gas is carried down by the mercury, the apparatus is removed from the pump by sealing off the tube at the narrow part between the charcoal and the spiral, so as to leave the charcoal still in connexion with the apparatus. The two together are now set aside for some weeks, when the charcoal will gradually absorb the whole of the residual gas and leave the vacuum so nearly perfect that it will not conduct an induction-current of electricity. In most of my experiments this refinement is not necessary; but in some, especially when working with the apparatus subsequently described, I prefer to adopt it. When it is considered that the charcoal has exerted its full action the tube containing it may be drawn off before the blowpipe, and the apparatus left ready for use.

132. The repulsion being due to the action of radiation on the surface of bodies, it became of interest to ascertain whether doubling the amount of incident radiation would produce double the movement. In my earlier apparatus I could not detect any

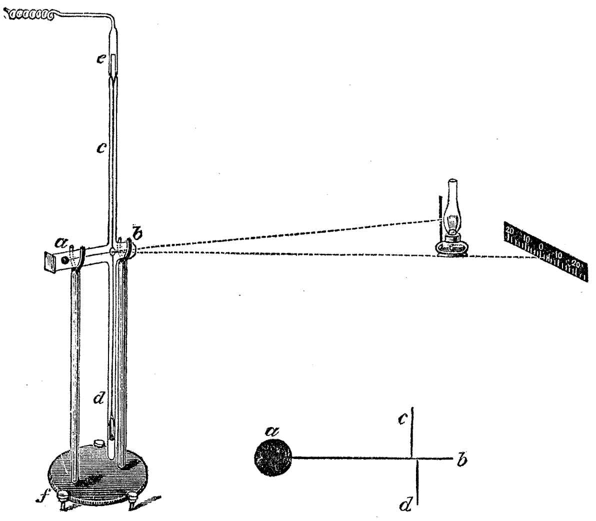
* In some of the subsequent woodcuts of apparatus (135, 145) this charcoal-tube is shown in its place.

such action as would show that it followed the law of inverse squares (109). There were, however, many reasons why this might not have come out with the apparatus then used; the glass torsion-thread might have been too stiff, or the source of light too near; the pith surfaces were white instead of black, and the vacuum was by no means so good as I have subsequently been able to obtain. The experiment described in par. 129, where the angle formed by the arm carrying the black and white disks was found to vary as the light approached or receded, appeared to me likely to afford valuable information on this point; and I accordingly fitted up more delicate apparatus on the same principle.

133. I wished to suspend the arm carrying the blackened pith in such a manner that it should move to the very slightest force, and still return accurately to zero when the force ceased to act on it. The principle of Professor ZÖLLNER'S horizontal pendulum* seemed well adapted for this; and I accordingly fitted up an apparatus shown in the annexed figure.

A tube (*a b*) about an inch in diameter has two narrower tubes (*c d*) blown on to it near one end, so that they shall be at right angles to the large tube, but not quite in the same straight line, the upper tube (*c*) being about a quarter of an inch nearer the end *a* of the wide tube. In the wide tube is a straw beam, carrying at the *a* end a disk of lampblacked pith, and at the other end a silvered glass mirror. At *e* is a plug of glass, firmly fixed in the tube *c*, and carrying a very fine glass thread. In the tube *d* is another similar thread of glass, having at the end a weight made of glass tube and mercury. The two threads are firmly fastened to the straw beam, behind the mirror, in such a manner that the upper thread in *c* holds the beam a quarter of an inch nearer the pith end than the lower thread in *d* holds it, as shown in the enlarged view. By adjusting the tension on the glass fibres, the beam can be kept in a horizontal position

Fig. 2.



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* POGG. Ann. 1873, vol. cl. pp. 131, 134.

along the axis of the tube *a b*. The whole is supported on a stand furnished with finely cut levelling-screws, and, according to the principle of the horizontal pendulum, the sensitiveness of the beam to any force applied at the pith end can be increased or diminished at pleasure by tilting the end *a* of the apparatus up or down; this can be easily effected by turning the milled head of the screw *f*. A ray of light from a lamp is reflected from the mirror to a graduated scale, and appropriate screens are used to cut off from the pith disk all radiation, except that being experimented on. The apparatus is connected to the pump by means of the glass spiral shown at the upper part of the tube *c*. On lowering the end *a* of the horizontal tube, by means of the screw *f*, the oscillation of the beam becomes very rapid, and its sensitiveness diminishes. On raising the end *a* the time of oscillation can be increased to any desired amount, with corresponding increase in sensitiveness. The other levelling-screws are for the purpose of bringing the beam into the centre of the horizontal tube. If the tube is too much tilted up, the centre of gravity gets too high, and the pith falls to one side or the other of the tube. The most convenient degree of sensitiveness I found to be that accompanying an oscillation at the rate of one per minute.

The ray of light used as an index of movement was reflected to a graduated scale 4 feet off. The instrument, mounted and adjusted as above described and highly exhausted, was found to be very sensitive. A ray of light from a candle 10 feet off, falling on the pith, would cause the index ray to move through 15 divisions; when 5 feet off the index moved about 60 divisions, and when 20 feet off the index moved between 3 and 4 divisions. These movements were sufficient to show that the motion of the pith was in inverse proportion to the square of the distance the candle was from it.

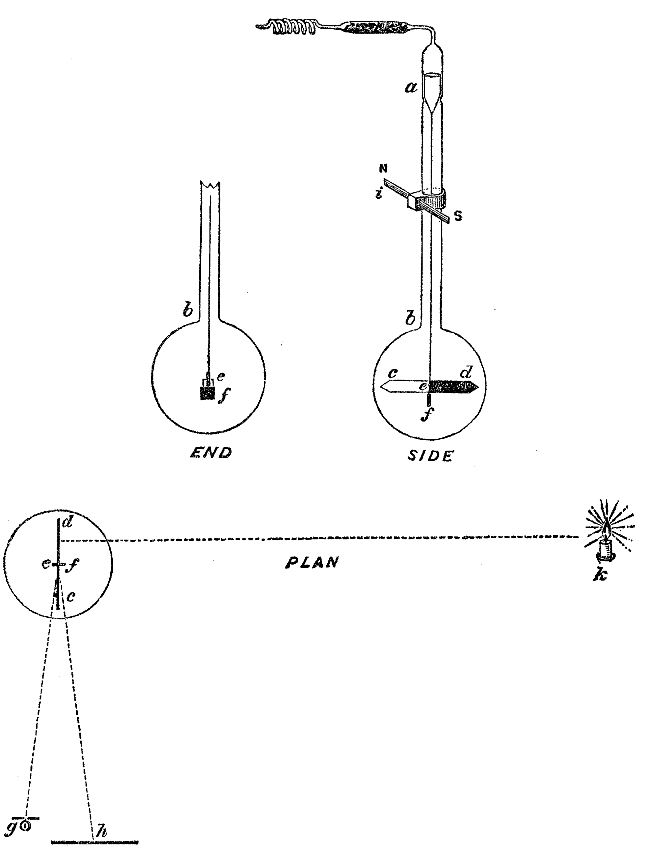
I tried numerous experiments with this apparatus, and verified the law perfectly; but there were difficulties connected with working with it which induced me to devise another instrument, free from the objections attending the use of the horizontal pendulum, and at the same time simpler to make and equally sensitive to faint radiation.

134. The objections to the use of the horizontal pendulum were the following:—When sufficiently sensitive to indicate readily the action of faint light, I found it almost impossible to bring the index to zero; the oscillations were so slow, and, taking place in a vacuum, kept on for so many minutes that my patience became exhausted with waiting for the next observation. But if I ventured to move away, or, when standing close to the apparatus, even to shift the weight of the body from one leg to the other, that was sufficient to alter the level of the floor, and therefore of the horizontal beam; the spot of light would suddenly fly ten or twelve degrees in another direction, and all the tedious waiting had to be gone over again, and possibly another zero had to be taken. A person running up stairs, a child playing in the adjoining room, a passing carriage, or a railway-train, all had their influence on the level of the laboratory floor. I tried fixing the apparatus to a main wall of the house, but this did little good. When the instrument was brought to its highest pitch of sensitiveness, to watch the move-

ments of the index ray when it should have pointed to zero gave one the impression that my house rested on an india-rubber cushion, so sensitively did it shift its level in obedience to a passing vehicle; and yet it is very well built, and the part where my work is mostly done was erected by myself some years ago, and was made of extra strength for the purpose of physical research. An incredibly small angular movement of the base of the instrument is, however, sufficient to cause the luminous index to move. In a paper by Professor O. N. Rood*, "On the application of the Horizontal Pendulum to the measurement of minute changes in the dimensions of Solid Bodies," the author illustrates his method of determining the change of volume of bodies. The levelling-screw of his instrument, corresponding to screw *f* in my apparatus (fig. 2), rests on the body the change in whose dimensions is the subject of study (such as a bar of iron about to undergo magnetization). Professor Rood gives experiments which show that an increase of thickness under the screw equal to the $\frac{1}{36,204,000}$ of an inch is an appreciable quantity!

135. The following apparatus (fig. 3) is much simpler than the horizontal pendulum,

Fig. 3.



and is free from the objections noted above; whilst its available sensitiveness is almost

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* Read before the National Academy of Sciences, November 4th, 1874, and published in 'Silliman's Journal' for June 1875.

as great, and has the advantage of being capable of being increased or diminished within very wide limits.

A glass tube (*a b*), 16 inches long and 1 inch diameter, has a 4-inch bulb blown on to the lower end. *c d* is a bar of pith $\frac{3}{4}$ inch wide, $3\frac{1}{4}$ inches long, and $\frac{1}{16}$ inch thick. One half (*d*) is coated with lampblack, and the other half left white, as shown in the figure. The pith bar is suspended in the bulb by a very fine cocoon fibre. Through the centre of the pith bar, at *e*, and at right angles to it, is passed a magnet (101) about $\frac{1}{4}$ inch long, made out of a fine steel sewing-needle. To the ends of this magnet are attached cocoon fibres, which support a small square of silvered glass (*f*), hanging freely below the pith bar and at right angles to it; a reference to the *end* view will show the arrangement. At the upper part of the tube (*a b*) are seen the tube filled with cocoa-nut-shell charcoal, and the spiral glass tube for connexion with the mercury-pump. The arrangement for an experiment is shown in fig. 3, *plan*. A ray of light (*g f h*) from a slit in front of a lamp falls on the mirror (*f*), and is thence reflected on to the scale (*h*). The apparatus is so placed that the index ray falls near zero when the magnet (*e*) has assumed its normal north-south position. It may be brought accurately to zero, and the sensitiveness increased or diminished at will, even during an experiment, by means of a control-magnet on a cork sliding up and down the tube, as shown at *i*, either close to the bulb or at some distance off, and acting with or contrary to the earth's magnetism, according to the sensitiveness required.

The instrument was exhausted and reexhausted, with repeated heatings of the charcoal-tube, in the manner already described (131). It was finally sealed off from the pump, the charcoal still remaining attached to it, and it was set aside for some months. The following experiments were tried with it after it had arrived at its maximum sensitiveness:—

136. The bulb was placed in a box lined with black velvet, apertures being cut to allow the index ray to pass in and out and the experimental light to fall on it. The index ray was passed through diaphragms in cards and a cell of water, to keep the heat from the lamp from acting on the pith. The face of the pith was also protected by black screens from all side radiation, and the path of the experimental ray of light was guarded on each side by a double row of bottles filled with water, and packed at the top and bottom with cotton-wool. Without this precaution I was unable to go sufficiently near the apparatus to observe the movement, without introducing irregularities from the heat of my body. The light was only allowed to shine on the black surface of the pith, a screen shading it from the white half.

The scale (*h*) on which the index ray of light (*g f h*) fell was 5 feet 6 inches from the hanging mirror (*f*). It was divided into millimetres; the measurements given below are the actual movements of the index ray of light along this millimetre-scale. The candle (*k*) was a "parliamentary standard" (109). It was surrounded on three sides with black velvet screens, and an assistant, standing close to it, raised or depressed a black shade in front of it, as I called "light" or "dark," watching the index ray of light at the same time.

No one moved during the experiment, and the room was in perfect darkness (except from the candle) and was of a uniform temperature.

Each recorded observation is the mean of three or four. I did not carry the series beyond 35 feet, as that was the greatest distance I could get in my laboratory.

Distance between standard candle and pith bar of instrument.	Movement of luminous index on millimetre-scale, 5 feet 6 inches from the hanging mirror, in millimetres.	
	With no screen interposed.	With a glass screen, 2 millims. thick, interposed.
feet.	millims.	millims.
35	9·0	6·0
34	13·0	8·0
33	14·0	9·5
32	11·5	7·5
31	13·5	9·0
30	13·5	8·5
29	16·0	10·5
28	14·0	9·0
27	16·5	11·0
26	23·5	15·5
25	18·0	11·5
24	19·5	13·0
23	23·5	15·5
22	23·5	15·0
21	26·0	17·5
20	28·5	19·0
19·5	31·0	20·5
19	32·5	21·5
18·5	33·0	22·0
18	37·5	24·5
17·5	39·5	26·5
17	43·0	28·5
16·5	43·5	28·5
16	45·5	30·5
15·5	50·5	34·0
15	52·5	35·0
14·5	56·0	37·5
14	63·5	42·5
13·5	66·0	44·5
13	71·0	47·5
12·5	78·0	51·5
12	82·5	54·0
11·5	87·5	58·5
11	96·5	64·0
10·5	108·5	72·0
10	114·5	77·0
9·5	133·0	89·5
9	147·0	97·5
8·5	165·0	111·5
8	190·0	125·0
7·5	210·0	138·0
7	244·0	162·5
6·5	279·5	187·0
6	325·0	218·0

I could not take measurements with the candle nearer than 6 feet, as the index went off the scale. The diagram fig. 4, Plate 35, shows graphically the above series. The isolated dots show the experimental observations, whilst the continuous lines show the curves which the observations ought to have taken according to the law of inverse squares. The agreement is sufficiently close to prove that the force of radiation varies inversely with the square of the distance of the source. The discrepancies, especially at the greater distances, are considerable. Some are doubtless due to irregular torsion of the silk fibre, to interfering heat which penetrated the screens, to some of the observations following too closely those preceding them, but chiefly to the irregular burning of the standard candle. Indeed this cause alone is sufficient to account for all the discrepancies between theory and experiment; and it would appear to be very active in some cases, as a reference to the diagram will show. The observations with the glass plate in front followed immediately after the corresponding observation with the naked flame, so that if the candle were burning irregularly in one instance it would probably be burning irregularly in the other. The diagram shows the observations to agree pretty well with theory from 6 feet off to 9·5 feet. At 10 feet the action of the naked flame is less than it ought to be, and this is repeated when the sheet of glass is interposed. At 14 feet off the naked-flame observation shows more action than is required by theory, and the observation behind the glass plate is also in excess. The dots at 16, 17, 18·5, 22, 24, and 25 feet follow the same rule; where one is in excess or deficient the corresponding one repeats the error. At 26 feet off the candle must have been burning with extra brilliancy, for the action on the pith is as strong as it was when the candle was only 23 feet off; and almost identically the same thing is noticed when the plate of glass is interposed and the corresponding observation taken; at 33 and 34 feet off the same discrepancies occur. Altogether I consider that the comparison of these curves shows that unequal burning of the candle must be credited with most of the discrepancies.

137. This apparatus was now placed so that I could put a candle or other source of light on each side of it; and its sensitiveness was greatly diminished by lowering the controlling magnet. A thin glass screen was placed on each side of the black velvet box containing the bar-apparatus. The scale, divided into millimetres, was placed 5 feet 6 inches from the bar. No screen was put in front of the white half of the pith bar, the movement, under the influence of radiation, being a differential one, due to the superior sensitiveness of the black over the white surface:—

1 candle,	48	inches from	bar, deflected	the luminous	index	. 90	millims.
2 candles,	48	„	„	„	„	. 177	„
2 „	72	„	„	„	„	. 98	„
1 candle,	72	„	„	„	„	. 50	„
1 „	36	„	„	„	„	. 180	„
3 candles,	72	„	„	„	„	. 160	„

These results are sufficiently close to theory for the differences to be accounted for by variations in the light of the candle used.

138. A candle was placed 36 inches from the bar, and the deflections of the index were taken, after various screens were interposed in the path of the light (109):—

Candle, naked flame			. . . .	180 millims.
Do.	shining through	yellow glass	. . . .	161 „
Do.	„ „	blue glass	. . . .	102 „
Do.	„ „	green glass	. . . .	101 „
Do.	„ „	red glass	. . . .	128 „
Do.	„ „	40½ millims. greenish glass	. . .	125 „
Do.	„ „	81 „ „	. . .	99 „
Do.	„ „	3½ millims. of water in cell	. .	48 „
Do.	„ „	7½ „ „	. . .	47 „
Do.	„ „	alum plate 5 millims. thick	. . .	27 „

139. A candle was now placed on the left side of the bar, 48 inches off. The luminous index moved 95 millimetres. Another candle was placed on the right side of the bar, 48 inches off. It drove the index back to zero, and, after a few oscillations, kept it stationary a few millimetres the other side of it. I moved the right-hand candle 49 inches off, and the index soon stood steadily at zero. By shading off either of the candles the index ray instantly moved 95 millimetres one side or the other. This gives a ready means of balancing two sources of light one against the other. Thus, retaining the standard candle 48 inches off on the left of the bar (deflection of index=95 millims.), the index was brought to zero by

2 candles, on the right	67 inches off.
1 candle, behind solution of sulphate of copper 7½ millims. thick	6 „
1 „ „ alum plate 5 millims. thick	14 „
A small gas-flame (bat's-wing)	113 „

140. These experiments show how conveniently and accurately this instrument can be used as a photometer. By balancing a standard candle on one side against any source of light on the other the value of the latter, in terms of a candle, is readily shown; thus, in the last experiment, the standard candle 48 inches off was balanced by a small gas-flame 113 inches off. The lights were therefore in the proportion of 48^2 to 113^2; or as 2304 : 12,769, or as 1 : 5·5. The gas-burner was therefore equal to 5½ candles.

By interposing screens of water or plates of alum, and so cutting off all the dark heat, the actual luminosity is measured. In addition to this, by interposing coloured glasses or solutions, any desired colours can be measured, either against the total radiation from a candle, its luminous rays, or any desired colour. One coloured ray can be balanced against another coloured ray by having differently coloured screens on either side. If one screen is a cell of iodine in disulphide of carbon, dark heat can be balanced on one side against light and colour on the other side (109, 110).

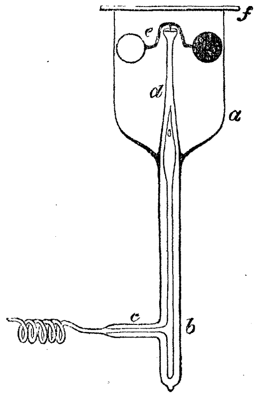
Again, the variations in the luminosity of a "standard" candle will cease to be of importance. Any candle may be taken, and if it be placed at such a distance from the bar as to give a uniform deflection (say 100 millims.), the standard can be reproduced at any subsequent time; and the burning of the candle may be tested during the photometric experiments by taking the deflection it causes from time to time, and altering its distance, if needed, to keep the index at 100 millims.

141. When a strong light is brought near this apparatus the bar receives an impulse which, unless the magnetic control is very strong, spins it round and round several times. If two strong lights are presented to it on opposite sides the bar oscillates rapidly from one to the other. As the lights are withdrawn to a greater distance the oscillations get smaller, until the bar settles down to a fixed position, dependent on the relative intensities of the lights shining on it.

142. Another instrument was constructed like the one last described (135), but the pith bar was blacked on alternate halves, instead of having the same half blacked on each side. By this construction an impetus given to the bar by a beam of radiation would always act in the same direction of movement, the right half of the pith surface presented to the light being always black, and the left half of the pith always white, so that, if the impulse were strong enough to carry the bar beyond the dead centre, continual rotation would be produced. Experiment fully confirmed this supposition. When even imperfectly exhausted, the suspended bar rotated when a candle was brought near it; and after more complete exhaustion it spun round rapidly, under the influence of radiation, so that the suspending fibre was twisted up, and ultimately stopped the movement by the accumulated torsion.

143. Were the black and white surfaces mounted on a pivot, like a compass-needle, instead of being suspended on a silk fibre, the movement would not be stopped by torsion. The friction, however, would possibly interfere. To test this an apparatus was fitted up, as shown in fig. 5. *a* is a glass vessel open at the top, and attached to a hollow glass stem (*b*), which is sealed up at the lower end. At the side of *b* a tube (*c*) is attached, which is connected by the glass spiral to the mercury-pump. To the hollow stem a piece of glass tube (*d*) is cemented by fusion so as to remain fixed in the position shown. The upper part of *d* is drawn somewhat narrow before the blowpipe, and in it is cemented a small cup-shaped ruby. The top of the vessel *a* is ground quite flat, and a ground-glass cover (*f*) can be cemented on (83). The movable part of the apparatus is shown at *e*; it consists of a fine curved brass wire with a needle-point soldered to the centre, and having a very thin disk of pith, half an inch in diameter, cemented on to each end. Each disk of pith is lampblacked on one side and plain white on the other, and they are fastened on so that one black and one white surface is always visible. The movable arms are balanced so that they turn easily to the slightest

Fig. 5.



impulse when the needle rests in the cup. The apparatus being arranged as shown, the cap is cemented on and the whole is exhausted.

144. When the vacuum is within a few millimetres of being perfect, the arms of this instrument move when a candle is brought near; as the pump continues working rotation commences, which gets more and more rapid, until, with the candle close to the glass, several revolutions are made per second. When well exhausted, the following experiments were tried :—

A flask of boiling water, placed 1 inch from the outer glass, caused the arms to set at right angles to the line joining the flask and the pivot, showing that the heat from boiling water acts on black and white surfaces equally (128).

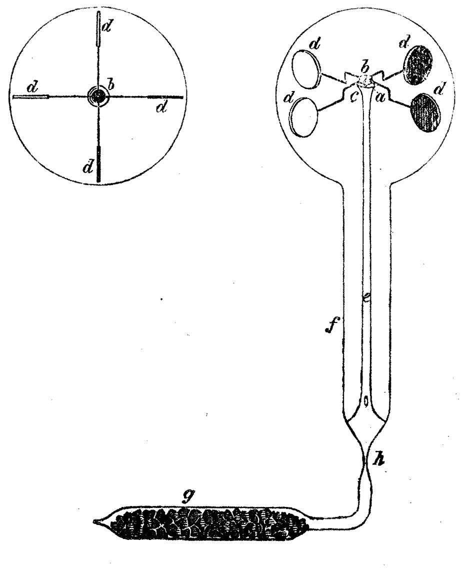
Copper at 400° C. kept the arms revolving, at first quickly, then slowly, until, as the copper cooled, the rotation stopped, and the black and white surfaces ultimately set equidistant from the hot metal (128).

A candle always set the arms revolving, when it was near enough for the force to overcome the friction.

This showed that rotation was possible, and that it would be kept up as long as the radiation lasted; and I accordingly devised a form of apparatus which would enable this action to be shown with greater facility. Owing to there being only two disks, the action of light was not uniform, as if it struck the arms at the end, instead of at the side, movement would not be commenced. Also the cement joint rendered it impossible to get the vacuum very good, whilst it took away from the permanent character of the instrument. After many trials of different arrangements, an instrument was made which had none of these defects, whilst it showed the movement of rotation in a very convenient manner.

145. The apparatus is shown in fig. 6. It consists of four arms, of very fine glass, passing horizontally through pieces of pith (*b*), and afterwards bent twice at right angles, as shown in the figure. Through the centre of the pieces of pith (*b*) is passed vertically the point of a very fine sewing-needle (*a*), which rests in a glass cup (*c*) blown on to the end of the glass tube *e*. At the end of each glass arm is fastened a thin disk of pith, white on one side and lampblacked on the other, the black surfaces of all the disks facing the same way. The whole is enclosed in a glass bulb blown on to the end of a wide tube. *f* is a piece of cement to keep the support (*e*) in its place. *g* is the tube containing cocoanut-shell charcoal; the other end is sealed on to the mercury-pump. The exhaustion is effected as already described (131); and the apparatus is then sealed off, with the char-

Fig. 6.



coal-tube still attached to it. Ultimately, when all the residual gas has been absorbed by the charcoal, a flame is applied to the contracted part of the tube at *h*, and the charcoal-tube is disconnected.

146. Before adopting the above method of making these instruments many experiments were tried, both to secure ease of manipulation and greater delicacy of action. The cup supporting the needle-point was made of ruby, sapphire, chrysolite, aquamarine, and agate; it was, however, found that these offered no advantage over glass, as the friction was not sufficient to produce any abrasion of the glass by the steel point. The disks at the end of the arms were made of every imaginable substance which was likely to answer. Among these I may mention wood, paper, flies' and butterflies' wings, talc, mica, selenite, thin glass, metals of various kinds, ivory, cork, and pith (86). For general purposes I prefer pith, as it is easily cut into slices, is extremely light, dries readily in a vacuum, and does not evolve vapour subsequently; besides which its natural white surface is almost as insensitive to radiation as any substance I have yet examined.

The number of disks has been varied from ten, the maximum which can follow one another without available surface being uselessly obscured, to two, or even one, which latter form has been experimented with, and possesses some advantages. Six disks are a useful number; but as the difficulty of making these instruments increases with the number of arms and disks to be got into the bulb, I prefer four disks for ordinary purposes.

The material of which the arms are made has also been the subject of experiment. My earlier instruments (exhibited at the Soirée of the Royal Society on the 7th of April, 1875) had straw arms. These are, however, too heavy, and are liable to evolve vapour after being kept in the vacuum for some time. An inorganic body is preferable; and I have finally adopted either thin rolled brass or fine glass thread drawn from thermometer tubing.

The colour of the disks has also been experimented on. During this part of the inquiry many curious results have been obtained, which will be described further on. At present, however, I have found nothing better than lampblack for the black surface and the freshly cut pith for the white surface. In working with cork, metals, &c., where the natural surface is not white enough, oxide of zinc may be used as a coating for the white surface.

147. The lampblack is best applied to the pith surface in the following way:—Camphor is burnt, and a sheet of glass is held close over the flame. An abundant deposit of lampblack takes place. A brush dipped in alcohol is then rubbed over the deposit, and the surface is painted over with the mixture. The lampblack adheres very well to pith, and in a few hours the alcohol and moisture have dried off, and a dead black, very even surface is the result. In some cases I smoke this again over burning camphor; but this is not of much use, unless the first coating shows glistening patches or is not laid on evenly.

148. I have proposed for this instrument the name of the *Radiometer*, as it serves to

measure the amount of radiation falling upon it by the velocity with which it revolves. It may also be called the *Light-Mill.* The rapidity of revolution is directly proportional to the intensity of the incident rays. Several radiometers, of various constructions, were exhibited at the Soirée of the Royal Society on April 7th, 1875. The following experiments have been tried with radiometers of different kinds and very varying sensitiveness. I could easily have obtained better curves and closer accordance with theory by repeating some of the observations with more recent instruments; but the results already obtained are sufficient to prove the laws, and I could do no more than this were I to repeat the experiments.

As soon as the radiometer was seen to revolve it was apparent that the stronger the light the more rapid was the movement. The second instrument which was made, the vacuum being very imperfect, the moving parts (straw arms and pith surfaces) heavy, and the instrument accordingly comparatively insensitive, was mounted for the purpose of testing its action at different distances.

The radiometer was covered with a thin glass shade, and in front of this was a large sheet of plate glass. The whole was covered on three sides and the top and bottom with black velvet, the fourth side admitting the light from the lamp. The source of light was one of DIETZ's paragon lamps, burning paraffin-oil. This lamp I find gives the brightest light and steadiest flame of any I have tried. Black velvet screens were put round the lamp, except on the side facing the radiometer. The room was darkened, and the temperature was kept uniform. The radiometer was kept fixed, and the lamp was moved backwards and forwards along a graduated scale, the number of seconds required for the radiometer to make one revolution being recorded by a chronograph watch. The following Table gives the results:—

Distance between Radiometer and centre of lamp-flame, in millimetres.	Number of seconds of time required for the revolution of the Radiometer.
150 millims.	6 seconds.
200 „	8, 9 „
250 „	11 „
300 „	15, 16 „
350 „	20 „
375 „	21 „
400 „	23, 24 „
450 „	29, 31 „
500 „	34, 36 „
550 „	40, 42, 44 „
600 „	52 „
650 „	60 „
700 „	65 „
750 „	74 „
800 „	82, 84 „
850 „	93, 95 „
900 „	100, 102 „
950 „	116 „
1000 „	129 „
1050 „	140 „
1100 „	158 „
1150 „	170 „
1200 „	184, 188 „

The diagram Plate 36. fig. 7 shows the curve formed by these observations. The isolated dots show the experimental observations, and the continuous line gives the theoretical curve which ought to have been followed according to the law of inverse squares. They are sufficiently concordant to show that this is the law governing the movements of the radiometer. The diagram illustrating this was laid before the Royal Society on April 22, 1875; I therefore prefer to retain it rather than prepare another one with a more sensitive instrument.

149. I next wished to ascertain if the speed of rotation would increase directly with the number of candles, the same distance off, shining on the instrument.

The same radiometer that was used in the last experiment was placed in the centre of a circle, 2 feet diameter, having 24 standard candles arranged symmetrically round the circumference. All the candles were lighted at first, and the times of revolution taken as they were removed one by one.

Number of candles burning 1 foot off.	Number of seconds required for one revolution of Radiometer.
24	6·4 mean.
23	7 „
22	7·5 „
21	8·5 „
20	9·5 „
19	10 „
18	11 „
17	11·3 „
16	12 „
15	13 „
14	13·3 „
13	14·5 „
12	16 „
11	17 „
10	18·5 „
9	19·7 „
8	21 „
7	23·5 „
6	28 „
5	35·5 „
4	44·5 „
3	59 „
2	92 „
1	180 „

The diagram shown in Plate 36. fig. 8 gives these observations, with the theoretical curve. Like the last one, this diagram was handed in to the Royal Society on April 22nd, 1875.

With a recently made instrument I should have been able to obtain better results. A radiometer now before me will revolve once in eight seconds to the light of a candle 1 foot off, whilst 24 candles make it spin with such velocity as to become almost invisible.

150. From the construction of the radiometer it is evident that the position of the light in the horizontal plane is of no consequence, provided the distance is not altered. This was tested during the last-described experiment. When a candle had to be removed, it was found to make no difference from what part of the circle it was taken. The following experiments were tried to further verify this result, the radiometer being a different one from that last used:—

	seconds.
1 candle, placed 1 foot from centre of radiometer, gave 1 revolution in 78 seconds $(78\times 1=)$	78
2 candles, placed 1 foot from centre of radiometer and put close together, gave 1 revolution in 39·5 seconds $(39{\cdot}5\times 2=)$	79
2 candles, placed opposite to each other, gave 1 revolution in 39 seconds $(39\times 2=)$	78
3 candles, close together, gave 1 revolution in 26·5 seconds $(26{\cdot}5\times 3=)$.	79·5
3 candles, spread round circumference, gave 1 revolution in 26 seconds $(26\times 3=)$	78
4 candles, close together, gave 1 revolution in 19 seconds $(19\times 4=)$ . .	76
5 candles, close together, gave 1 revolution in 16 seconds $(16\times 5=)$ . .	80
5 candles, spread round circumference, gave 1 revolution in 15·5 seconds $(15{\cdot}5\times 5=)$	77·5

151. I wished now to ascertain what would be the effect of bringing a radiometer into a uniformly lighted space, so that there should be no difference of action on any side.

A radiometer was covered over the top with a large sheet of paper, and the light from an argand gas-burner was reflected vertically downwards on to the paper. The apparatus was arranged so that, as near as possible, exactly the same amount of light should illuminate the instrument all round. The arms revolved at a uniform speed of one revolution in six seconds, and kept on at this rate as long as the experiment lasted.

A radiometer was taken on to the roof of the house, where there was an almost uninterrupted view all round. The sky was of a uniform dull leaden colour, a cold north-east wind was blowing, and, as far as the eye could judge, there was no difference in the amount of light received from any quarter of the sky. The radiometer was covered with a white handkerchief, to still further diffuse the light. In this condition the arms made one revolution in an average of 1·9 second. On shading the light from the south the time of revolution was 2·7 seconds. On shading it from the north the time was one revolution in 2·9 seconds. With the west shaded off it was one in 2·3 seconds; and with the east shaded off, the rate was one in 2·9 seconds.

The same radiometer, exposed near a south-east window in a room in the afternoon of the same dull April day, revolved once in 16 seconds.

[The radiometer shows a striking difference between heat and light, as commonly expressed. Brought into a uniformly *heated* space, the instrument comes to rest as soon as it has acquired the temperature of the space; but brought into a uniformly *lighted* space (151) it continues revolving as long as the light lasts.—Received January 10, 1876.]

152. The following experiments were tried with a very sensitive radiometer in a 2-inch bulb. The moving part (the "fly"), consisting of glass arms, pith disks, and steel point, weighed only 0·8 grain. It was exhausted with a charcoal reservoir attached (131).

A standard candle, placed 2 inches from the centre, made the arms spin with a velocity of 4 revolutions per second; with the candle 4 inches off the velocity was 10 revolutions in 11 seconds. In the full sunshine of a November day the speed was too great to count. Nothing was visible but an undefined nebulous ring, which became more or less distinct as the sunlight increased and diminished owing to passing clouds. This speed was kept up for more than an hour; indeed there appears no reason why it should ever diminish as long as light of uniform intensity shines on it.

153. The same radiometer was tried by the light of a candle, 4 inches off, behind different screens, with the following results:—

1 candle,	4 inches off,	naked flame		1·1	sec.	for 1 revolution.
,,	,,	behind	thin white glass	1·3	,,	,,
,,	,,	,,	thick plate glass	1·4	,,	,,
,,	,,	,,	purple glass	1·5	,,	,,
,,	,,	,,	dark red glass	1·5	,,	,,
,,	,,	,,	pink glass	1·6	,,	,,
,,	,,	,,	light yellow glass	2·1	,,	,,
,,	,,	,,	blue glass	2·5	,,	,,
,,	,,	,,	orange glass	2·7	,,	,,
,,	,,	,,	green glass	3·0	,,	,,
,,	,,	,,	"eclipse" glasses (blue and orange, almost opaque to daylight)	4·0	,,	,,
,,	,,	,,	7½ millims. of water in cell	6·0	,,	,,
,,	,,	,,	solution chromate of potash, 7½ millims. thick	6·0	,,	,,
,,	,,	,,	solution bichromate of potash, 7½ millims. thick	7·0	,,	,,
,,	,,	,,	clear plate of alum, 5 millims. thick	9·0	,,	,,
,,	,,	,,	solution chloride of cobalt, 7½ millims. thick	12·0	,,	,,
,,	,,	,,	sol. ferrocyanide of potassium, 7½ millims. thick	16·0	,,	,,

1 candle, 4 inches off, behind	sol. ammonio-sulphate of copper, 7½ millims. thick	20·0	secs. for 1 revolution.
" " "	sol. ferricyanide of potassium, 7½ millims. thick	30·0	" "
" " "	sol. sulphate of nickel, 7½ millims. thick . . .	35·0	" "
" " "	sol. sulphate of copper, 7½ millims. thick . .	39·0	" "

154. The instrument is thus seen to be capable of very extended use as a measurer of radiation of any desired kind. Unlike the instrument described in paragraph 135, it cannot be used for actually balancing one quality of light against another; and the method of taking an observation is not so accurate, for it is less easy to count revolutions per second or per minute than to observe the movement of a spot of light along a graduated scale. There are besides many causes which tend to interfere with the accuracy of the indications of this form of instrument. But, notwithstanding these drawbacks, I think the radiometer is likely to be a more popular form of light-measurer. It requires no adjustment, and is always ready to be observed, whilst there is a peculiar charm in using an instrument which is constantly in active work. With the exception of the comparison by balancing one light against another, all the observations mentioned in paragraph 140 can be taken with the radiometer, and it is besides capable of applications of its own. I will mention one, although others easily suggest themselves.

As the radiometer will revolve behind the orange-coloured glass used by photographers for admitting light into their so-called dark room, it is only necessary to have one of these instruments in the window to enable the operator to see whether the light entering his room is likely to injure the sensitive surfaces there exposed; thus, having ascertained by experience that his plates are fogged or his paper injured when the revolutions exceed, say, one in three seconds, he will take care to draw down an extra blind when the revolutions approach that number. In photographic operations a radiometer may be placed in some convenient spot near the object to be copied. Having ascertained, once for all, how many revolutions the instrument makes whilst a good negative is being taken, the operator need in future take no account of the variation of light, but simply expose for the same number of revolutions, with a certainty that his negatives will all be of the same quality.

For the more important work of gas-testing probably the bar-instrument already described (135) will be more valuable; although, even for this purpose, the radiometer will be found to give very rapid and trustworthy indications.

155. I have already mentioned that the motion of the radiometer depends on a differential action of radiation on the black and white surfaces. To obtain rotation in the ordinary way the black must be repelled with more energy than the white; and this appears to be the case with all the luminous rays. In the case of dark heat, however,

this difference of action is not apparent (128). The following experiments were tried with various radiometers:—

A candle was placed at such a distance from a radiometer that the fly would make one revolution a minute. A small glass flask of boiling water was then placed half an inch from the bulb. The revolutions instantly stopped, two of the arms setting equidistant from the hot-water flask. The candle was kept in the same position, and the flask of water was removed. As the portion of the bulb which had been heated by the hot water cooled, the white surface gradually crept nearer and nearer to it, the superior repulsion of the candle on the black disks urging the arms round, and acting in opposition to the repulsion of the hot glass to the white disk. At last the force of the light drove the white disk with difficulty past the hot spot of glass. Rotation then commenced, but for some revolutions there appeared to be a difficulty in the white disks passing the spot of glass which had been warmed by the hot water.

156. The flask of boiling water was then replaced in its position half an inch from the bulb of the radiometer. The rotation immediately stopped. The candle was then brought gradually nearer and nearer to the instrument, but with no particular effect. As it came very near the arms vibrated to and fro, and appeared to make violent efforts to get round, but no force of the light seemed sufficient to overcome the repugnance of the white disk to pass the heated portion of the glass.

157. The radiometer was allowed to cool, and the candle was again placed in the first position, where it produced one revolution in a minute. The finger was pressed against the side of the bulb. As the spot of glass got warm the white surface experienced more and more difficulty in getting past it, until at last one disk refused to pass, and the arms came to rest.

The instrument was again allowed to cool, and the revolutions recommenced at the usual speed (the laboratory in which this was tried was somewhat cold). I then came from a warm room, and stood a foot from the radiometer, watching it. In about a minute the radiant heat from my body had warmed the side of the bulb nearest to me sufficiently to cause an appreciable difficulty in the movement, and soon the revolutions stopped. The same effect has been observed if the radiometer is brought into a very warm room, and placed near a cold window. If the daylight is feeble, the instrument not very sensitive, or an observer stands near the instrument, an appreciable sticking is observed as the white disks come near that part of the bulb which is the warmest.

These experiments show that dark heat has quite a different action from that of the luminous rays. They also show that many precautions are necessary to guard against the interfering action of unequal heating of the radiometer when it is being used for accurate measurements.

158. Having found such an antagonistic action of dark heat, I tried the action of ice. This, I have already shown (33, 88), is equivalent to warming the opposite side of the instrument. A piece of ice brought near the radiometer on one side cuts off the influx

of heat to it from that side, and therefore allows an excess of heat to fall upon it from the opposite side.

The same radiometer that I used in the experiments with boiling water (155) was mounted with a candle the same distance off as before, so that one revolution took place in one minute. A lump of ice was now brought within half an inch from the bulb on the opposite side to the candle. The revolutions got slower, each arm as it passed seeming drawn towards the ice, and having a difficulty in moving away from it. At last the movement stopped altogether, an arm pointing direct to the ice, and being apparently held there by a powerful attractive force. Bringing the candle nearer caused the arms to oscillate a little; and when it was almost close to the bulb the force of the light overcame the action of the ice, and the arms revolved again, but irregularly and with jerks, the disks moving quickly to the ice and leaving it with difficulty. In this action of ice no preference was noticed for either the black or white surface.

159. A very delicate radiometer, in 2-inch bulb (152), was placed in a light just sufficient to see it distinctly by, but not enough to cause it to move. I then came out of a warm room and stood near it. In a few seconds it began to move slowly round, *but the motion was negative*, i. e. the black disks advanced instead of retreated—the action of the radiation of low intensity from my body being apparently to repel the white surface more than the black. On moving away from the instrument the rotation gradually stopped. I now came near it again, and held one hand an inch from the bulb. Rotation soon commenced, but still in the reverse way. These experiments were repeated several times and on different evenings with the same results.

160. When the instrument was at rest I came quickly to it, and gently breathed on the bulb. There was a slight movement in the normal direction, but this stopped directly, and the arms commenced to revolve the negative way, and kept on in the same direction for more than a minute, performing three or four complete revolutions.

161. A glass shade 4 inches diameter was held over a gas-flame till the air inside was warm and the inner surface dim with steam. It was then inverted over the radiometer. Negative rotation commenced, and kept up for several minutes.

The glass shade was then dried inside, and heated uniformly before a fire, until it had a temperature of about 50° C. It was then inverted over the radiometer. Negative rotation instantly commenced, and kept up with some vigour for more than five minutes, diminishing in speed until the shade had cooled down to the temperature of the surrounding air.

162. The same experiment was repeated, and whilst the arms were in full rotation a lighted candle was slowly brought near it. When 3 feet off the negative rotation slackened. When the candle was about 2 feet off the arms became still, and when nearer than 2 feet the instrument rotated normally. The antagonism between the action of the hot shade and the lighted candle was perfect; by moving the candle to and fro it was easy to cause the radiometer to move in one direction or the other, or to become still. These experiments were repeated many times, always with the same result. The perfect

obedience of the instrument to the opposing forces, according as one or the other was in excess, was very striking. I may mention that only some of my radiometers act in this manner. It seems to require extreme lightness and great perfection of vacuum. The movable parts of the radiometer which shows this action best only weigh 0·55 grain.

163. These experiments had all been tried with surfaces made of pith, a very bad conductor of heat. It became of interest to ascertain what would be the action of a radiometer the fly of which was made of a good conductor, such as a metal. Experiments already recorded show that metals behave generally like pith. This has been proved in the case of magnesium (99, 100), aluminium (122), silver and bismuth (63), copper (64), brass (37–40, 61), and platinum (55, 62, 113, 114, 115); but none of these experiments have been tried under the different conditions to which I have lately submitted the radiometers.

164. I selected thin rolled brass as the material wherewith to make the fly of a radiometer. The parts were all fastened together with hard solder, and no cement or organic matter was used, so that if necessary the radiometer could be submitted to a high temperature without injury. In general appearance when finished it resembles the instrument shown in fig. 6. The moving portion weighed 13·1 grains. One side of the disks was silvered and polished, the other side being coated with lampblack. The apparatus was exhausted with a charcoal reservoir attached. When exhausted it proved to be very sensitive, considering its weight, a candle $1\frac{1}{2}$ inch from the bulb causing it to revolve about once a second, the black surface being repelled in the normal manner.

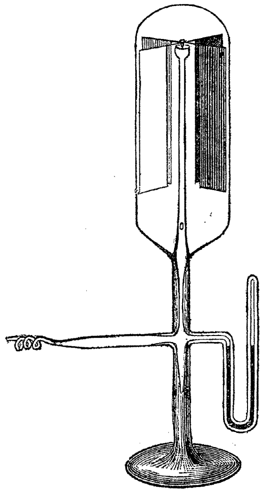
165. The apparatus, standing motionless in a rather dark cold room, was covered with a warm glass shade. It immediately commenced to revolve the negative way, viz. silver side repelled, but very slowly.

A few drops of ether poured on the bulb caused the arms to move rather rapidly the normal way. A hot shade put over whilst it was thus moving caused it to stop, and then begin moving the negative way.

A small non-luminous gas-flame was held vertically beneath the apparatus, so that hot air should ascend and wrap round the bulb on all sides. The arms now revolved the negative way.

166. The brass radiometer being somewhat heavy, one was made of aluminium, of the shape represented in fig. 9. The surfaces were made large, and the whole moving parts were hard-soldered together. A siphon-gauge was attached, and the apparatus was connected direct on to the pump by a spiral, no charcoal-tube being used. One side of the wings was bright aluminium and the other was lampblacked. When exhausted the fly revolved very quickly to a candle a few inches off, the black being repelled.

Fig. 9.



167. On removing the candle a remarkable phenomenon was observed. The arms stopped and immediately commenced revolving the negative way, keeping up rotation for more than ten minutes, and being little inferior in speed to what it was when the candle shone on it.

The whole of the bulb was heated with a BUNSEN burner; whilst it was getting hot the aluminium arms revolved rapidly in the normal direction; but as soon as the source of heat was removed and cooling commenced, negative rotation set up, and continued with great energy till the whole thing was cold. It appeared as if the negative movement during cooling was equal in amount to the positive movement as it was being heated.

168. The very sensitive pith radiometer used in experiments 152 *et seq.* was now experimented with. A little ether was dropped on the bulb as it was standing still in a faint light. The evaporation of the ether caused a chilling of the instrument and a rapid abstraction of heat from the fly. It commenced to move in the positive direction, and increased quickly in speed until it revolved at a rate of one in four seconds. This movement kept up for several minutes, and as it slackened it could at any time be revived by a few drops of ether on the bulb.

When in rapid positive movement, produced in the above manner, a hot glass shade (161, 165) was placed over the radiometer. The movement slackened, the arms quickly came to rest, and then immediately revolved in the negative direction, acquiring a speed of about two revolutions a minute, and keeping up this negative movement for more than ten minutes.

169. The radiometer was again set in rapid positive rotation by dropping ether on the top of the bulb. I applied the tip of one finger to the side of the bulb for ten seconds. The rotation stopped, and I could not start it again for some minutes, although I dropped ether on the bulb several times in the interval.

When the radiometer had once more acquired the temperature of the air, I dropped ether on the bulb, not in cethe ntre, but so that the ether wetted only half of the bulb. The arm which was nearest to the part most wetted by the ether rushed towards that part and remained, as it were, fixed opposite to it, refusing to move away, although I tried to equalize the temperature by dropping ether on the other parts of the bulb, and to drive it round by bringing a candle near. Not until the candle came within 6 inches of the bulb did the arms begin to rotate, which they then did with a rush, as if suddenly relieved from a state of tension.

170. These results appear at first sight anomalous. I think, however, they admit of an explanation which is in keeping with the facts, if I may make one supposition. The great difference between a lampblacked and a white surface is only an optical one. Pith reflects a considerable amount of light, and lampblack absorbs a large quantity of light, but it is unsafe to carry the analogy into the ultra-red region of the spectrum. We know of many white powders, optically identical, which in their thermic relations are as wide apart as pith and lampblack (*e.g.* powdered alum and

powdered rock-salt); and it is therefore reasonable to suppose that other substances may exist which, whilst they are very different to the eye, may have the same action on dark radiant heat. We may also fairly assume that a substance may exert a considerable selection on the rays which it absorbs and reflects—that, in fact, there may be, in the ultra-red region of the spectrum, *thermic* colours, as in the visible spectrum we have *optical* colours; so that whilst two substances may absorb to the same extent heat-rays of one refrangibility, they may be quite different in their actions on heat-rays of another refrangibility. These suppositions are not only resonable but very probable: let us see how they account for the facts. Light falls on the black and white surfaces of a radiometer, or other similar instrument. That which falls on the white surface is nearly all reflected back again. Were the surface perfectly white *all* the force which went into the bulb would be reflected out again; the incident ray would contain in itself a certain amount of potential work; but as the emergent beam would come out with no loss of intensity, no work could have been done on the reflecting surface. In practice this does not quite hold good. Pith is not a perfect reflector, some light stops behind, that which comes from it is not quite equal to that which it receives, and the balance makes itself evident by causing the pith to move to a slight extent.

171. But in the case of light falling on the lampblacked surface the result is very different. Here, practically, the whole of the light is quenched by the lampblack. Force is poured into the bulb, but none comes out. What, then, becomes of it? It is changed into motion, and becomes evident in the strong repulsion which is exerted on the black surface.

This I think is clear in the case of light. We can see that there is an enormous difference in the absorbing powers of white and black pith for light, and we can also see that there is an equally marked difference between the motive power which light exerts on them. But with the heat from boiling water or from a hot copper ball our eyes cannot tell us whether the same difference obtains or not, and we must use other and less direct means of finding out what takes place.

Let me direct attention to the experiments described in paragraphs 128 & 144. Here red-hot copper was seen to repel the black surface with violence, and the white surface only moderately. As the copper ball cooled, the repulsion on each surface became more nearly equal. At 400° C. the differential action was decided, though faint. At 300° C. the black surface was still repelled slightly more than the white surface, but at 250° C. down to 100° C. the repellent action of the radiant heat was the same on the white as on the black surface. The two surfaces were then *thermically* of the same colour.

The fact that the work done on each surface was equal, is, I think, proof that the absorption of the incident rays was equal.

172. Let me now carry the reasoning a step further. Experiments described in pars. 159 to 168 show that when heat of low refrangibility—from the body (159), the breath (160), hot air, or a warm glass shade (161, 165, 168)—falls on the white and

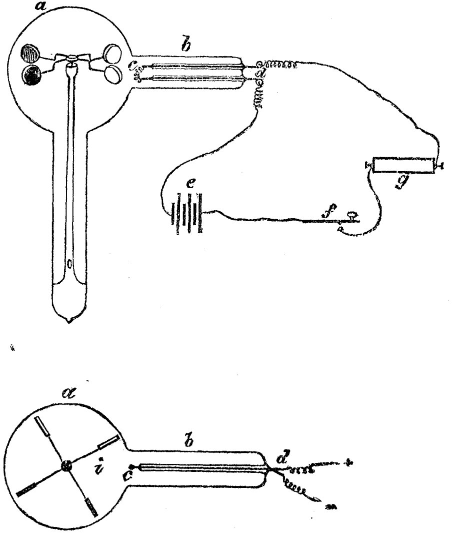
black surfaces, the white is repelled more than the black, rotation of the radiometer taking place in the negative direction. The same rays falling on the two surfaces do more work on the white than on the black; and this, to my mind, appears sufficient to make it almost certain that the white pith absorbs more of these low rays than does the lampblack.

173. Let us imagine that surfaces of lampblack and pith are carried along the spectrum from the blue to the ultra-red. As long as they are in the visible portion we observe an enormous difference between them. In the extreme red we can actually see that this difference is becoming less. In my mind's eye I picture the progress being continued along the whole length of the ultra-red spectrum. I can see, by the light of the above-quoted experiments, that the absorptive action of the two surfaces gradually gets more equal. Soon they become identical in their action on the incident rays, and after that they enter a portion of the spectrum whose rays are no longer absorbed by lampblack, whilst they are quenched by the pith. Lampblack and pith have now changed places; the latter is black, whilst lampblack has become a white substance.

174. The normal rotation of the radiometer caused by dropping ether on it (163) is perfectly well explained by the above hypothesis. If heat in the act of absorption produces motion in one direction, in the act of radiation it produces motion in the opposite direction (167). Heat of low refrangibility falling on the radiometer repels the white more than it does the black, and produces negative rotation. When the same kind of heat is drawn out of the black and white surfaces by the chilling action of the ether, movement takes place in an opposite direction, and the arms rotate normally. On stopping this efflux of heat by covering the instrument with a hot shade (163), I changed the direction of movement by causing the surfaces to absorb instead of emit heat.

An irregular emission or absorption of heat (164) stops the movement altogether, for the reasons given in pars. 155 to 158.

Fig. 10.



175. I have made an apparatus by means of which I hoped to put the above theory to accurate test. The results are not so definite as they ought to be in order to settle the question; but they are worth giving in detail, as some novel facts have been elicited by them.

Fig. 10 shows the instrument: *a* is the bulb of a radiometer of the usual construction, having pith disks blacked on one side. *b* is a tube sealed into one side of the bulb, and having two stout platinum wires passing along it, sealed their whole length in glass to prevent leakage of air into the interior of the apparatus. At the ends *c* of the wires, a spiral of fine platinum wire is fastened, and the other ends (*d*) terminate in loops outside. *e* is a battery, *f* a contact-key, and *g* a resistance-coil, which I can vary at will. The bulb was perfectly exhausted, and the following experiments were tried:—

176. The resistance-coil was so adjusted that the battery would keep the platinum spiral (*c*) at a bright red heat. The arms of the radiometer, which were before quite still, moved rapidly until two of the disks were one on each side of the hot spiral, the black disk being further off than the white disk, as shown at *i*. The resistance was then gradually increased, and as the temperature of the spiral diminished, the black disk gradually approached the spiral, until, when the temperature was just at the point of visible redness in a dark room, the black and white disks were practically equidistant from the spiral. On diminishing the resistance, the same phenomena took place in inverse order.

177. The resistance was adjusted to give a bright red spiral, and the contact-key kept pressed down. The disks stood as at *i*. A lighted match was momentarily brought near the bulb, so as to start a movement. Rotation of the arms commenced, and kept up, with some energy, at the rate of about 1 revolution in five seconds, equal to that given by a candle 8 inches off. There was some little hesitation as the white side came up to the spiral, but this was scarcely noticed when the speed had become steady.

The resistance was slightly increased. The speed became slower as the temperature of the spiral diminished, and the hesitation as the white approached the spiral became more apparent. The resistance was further increased, with the effect of making rotation still slower. I now brought the temperature of the spiral down to just visible redness in the dark. The speed of rotation again slackened; at each approach of the white surface to the spiral it stopped, hesitated, and then got past with a rush. Thus it went on for a few revolutions, until one white disk, a little nearer perhaps than the others, was not able to pass, and the arms after a few oscillations came to rest, the black and white surfaces being, as near as I could judge, equidistant from the hot spiral.

These results fully confirm those obtained in experiments 128 & 144, and I think justify the conclusions arrived at in my discussion of them at par. 171—that at temperatures between 250° and 100° the repellent action of radiant heat is about equal on black and on white surfaces.

178. I now wished to ascertain whether the continuation of the reasoning (172) was correct—whether at temperatures lower than 100° C. the white would be repelled most.

The resistance of the coil was increased again, and the position of the arms in respect to the spiral noticed. When so much resistance was offered to the passage of the current that the spiral would only be just warm, I fancied the white set further from it than the black; but the observation was not satisfactory at higher temperatures; up to visible redness the repulsion was equal for each.

The breath sent the arms rapidly round the negative way (160).

179. The battery was disconnected from the instrument, and one end of a wire was attached to one of the platinum loops, *d*, the other end of the wire being connected to the prime conductor of a frictional electrical machine. A few turns of the handle sent the arms flying about wildly; sometimes they spun round violently in one direction, then they stopped and went round the other way, finally one pointed steadily to the platinum spiral and refused to move. A candle was brought near, and all means were tried to discharge the disk, but with no effect. When the candle was quite close it overcame the interference, and the disks revolved in an irregular jerky manner.

The spiral was ignited by a battery, in the hope that this would discharge the electricity, but with no avail, and there was nothing to be done but stop the experiments and put the apparatus in water.

In three or four days the electrical disturbance was sufficiently diminished to enable me to proceed experimenting; but I could detect the influence for weeks after.

180. One pole of a small induction-coil capable of giving half-inch sparks in air was fastened to the platinum loops *d*, the other pole being held by an insulating handle. The loose pole was then brought near the bulb. The nearest disk rushed round to it and followed it a little, then it stuck as if the glass were electrified. By gently moving the loose pole round I could get the arms to rotate in either direction with a little practice, and they would keep on for five minutes or more when once started. It seemed a matter of indifference whether the black or the white surface went first. The results with the induction-coil were only a little more under control than those with the friction machine. The movements appear all to be explained by the known laws of static electricity; the rotations have no connexion with the instruments under the influence of radiation, but are of the "electrical fly" kind (34, 35, 36).

181. Before leaving the subject of the radiometer, it may be of interest if I describe a few forms of this instrument which I have made for special purposes.

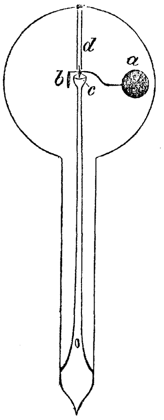
It is easy to get rotation in a radiometer without having the surfaces of the disks differently coloured. A radiometer was made similar to the one described in par. 152, but somewhat larger, and having the pith disks lampblacked on both sides. Its weight was 1·25 grain. It was exhausted with a charcoal-tube attached. When it was exhausted and a candle was brought near it, the arms moved until two of the disks were equidistant from the flame, and no amount of initial impulse in one or the other direction would set it in rotation. A piece of ice caused it to move until one disk pointed to the ice, when it also stopped. By shading the candle with a screen, so that the light shone on only one half of the fly, rapid rotation commenced, which was instantly stopped, and changed into as rapid rotation in the opposite direction, by altering the position of the screen to the other side.

182. It is difficult to exhibit the movement of a radiometer to any large number of people at once. To enable me to do this I have made an instrument, the disks of which are thin glass, silvered and polished on one side, and coated with lampblack on the other. This, owing to its great weight (65 grains), is somewhat slow; but in the

sun, or with the electric light shining on it, the movement is very striking, as it shows four disks of light chasing each other round the room.

183. A radiometer was made of the following construction (fig. 11). *a* is the disk of pith, black on one side; it is attached to a thin brass arm revolving on a needle-point; *b* is a mirror, seen in section, hanging from the other side of the brass arm, and having its plane perpendicular to the plane of the pith disk *a*. The needle-point works in a jewel cup *c*, and is prolonged upwards into the tube *d*, which is sealed into the bulb, and in which the needle fits loosely. Behind the mirror *b* is a very small magnet, to give direction to the arm. The object of having the upper tube (*d*) is to prevent the arm from coming off in carriage: with the four, or more, armed radiometers it is easy to get the movable part on when it falls off, but with this one-armed instrument it would be an almost impossible feat. (This artifice of an upper protecting tube is one I have had occasion to adopt on many occasions, and I find it very convenient.) The moving part weighs 2·42 grains; it revolves somewhat slowly when a candle is brought near, owing to the interference of the magnet. When the magnet is rendered nearly astatic by another magnet near it, and an index ray of light is reflected from the mirror, this radiometer is sensitive to a candle several yards off. It is a more convenient instrument for measuring different kinds of radiation than is the one on a similar principle described in par. 135, but, owing to the friction on the needle-point, it is not so sensitive.

Fig. 11.



184. A large radiometer in a 4-inch bulb was made with ten arms, eight of them being of brass, and the other two being a long watch-spring magnet. The disks are of pith, blackened on one side. The weight of the fly is 11·87 grains. This moves very rapidly for so heavy an instrument. The power of the earth on the magnet is too great to allow the arms to be set in rotation, unless a candle is brought very near; but once started it will continue to revolve with the light some distance off. This was made to enable me to communicate motion from the interior of the bulb to the outside. By suspending a magnet near the bulb, it oscillates to and fro with every revolution of the radiometer. The movement can thus either be projected on a screen or it may work a telegraphic instrument, and thus give a visible demonstration or a permanent record of the revolutions caused by any source of light under examination. As a self-registering photometric instrument this form of radiometer would be of considerable value.

185. A large six-disk radiometer was made in a 4-inch bulb. Immediately over the needle support a silvered glass mirror was fixed almost, but not quite, horizontal. By throwing a beam of light vertically downwards on this mirror it is reflected upwards at a slight angle, and as the radiometer revolves the movement can be seen by an audience as a spot of light traversing in a circle around the ceiling. The effect of various lights, coloured screens, &c. in modifying the rapidity of movement can be well illustrated in this manner.

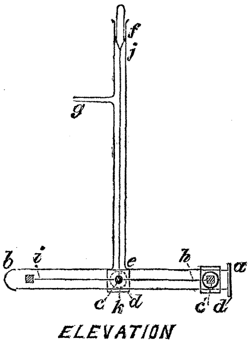
In a subsequent paper, which I hope soon to have the honour of laying before the Society, I propose to give the results of my experiments on the different rays of the solar spectrum, on the action of light and heat on various surfaces other than black and white, and on some attempts I have made to measure the force of radiation.

PART IV.

186. In a former paper on this subject, communicated to the Royal Society March 20, 1875, I gave some rough observations (110, 111) on the effect of the different rays of the electric and solar spectrum on the horizontal torsion-balance (102); and in a note (111) I said, "Every thing is ready to try a series of experiments with the solar spectrum, as soon as sunshine is available. The results shall be communicated in a subsequent paper."

The apparatus which I have now used for this purpose is shown in figs. 12 & 13. Fig. 12 shows the horizontal torsion-balance; it is similar in appearance to the one described in par. 102. *a b* is a piece of thin glass tubing, sealed off at the end *b*, and ground perfectly flat at the end *a*. In the centre a circular hole (*c*) is blown, and another one (*c'*) at the end, the centre hole being at the back, and the one at the end in front. The edges of these holes are ground quite flat. *a*, *c*, and *c'* can therefore be sealed up by cementing flat transparent pieces of plate glass, quartz, rock-salt, &c. (*a*, *d*, and *d'*) on them. To the centre of *a b* an upright tube (*e f*) is sealed, having an arm (*g*) blown on it for the purpose of attaching the apparatus to the pump. *h i* is a glass index drawn from glass tubing, and as light as possible consistently with the needful strength. A long piece of this tube is first drawn out before the blowpipe, and it is then calibrated with mercury until a piece is found having the same bore throughout; the necessary length is then cut from this portion. *j k* is a very fine glass fibre, cemented at *j* to a piece of glass rod, and terminating at *k* with a stirrup, cut from aluminium foil, in which the glass index (*h i*) rests. In front of the stirrup is a thin concave glass mirror, shown at *k*, silvered. The suspending thread is selected of the proper stiffness by the method given in par. 103. The small glass rod hung on to the end of the fibre to test its torsion weighs 15·46 grains; its length is 90 millims., and its external diameter 3 millims. The selected fibre, having this glass rod suspended to it in air, was found to vibrate half oscillations in 35 seconds.

Fig. 12.



The weight of the beam with the blackened pith ends is 0·891 grain; the mirror and stirrup by themselves weigh 0·87 grain; therefore the whole beam, as suspended, weighs 1·761 grain. The length of the beam from centre to centre of the pith squares is 147·5 millims. This beam is so light, and the pith surfaces are so large, that its vibration in air, when suspended from the glass fibre, cannot be timed. Therefore to ascertain what the torsion of the fibre is with that weight suspended on it, I cemented a piece of platinum weighing 1·543 grain (1-10th gramme) to the fibre, cut to the proper length, and timed its oscillations. 10 half-vibrations were taken by a chronograph. The times recorded during three experiments were

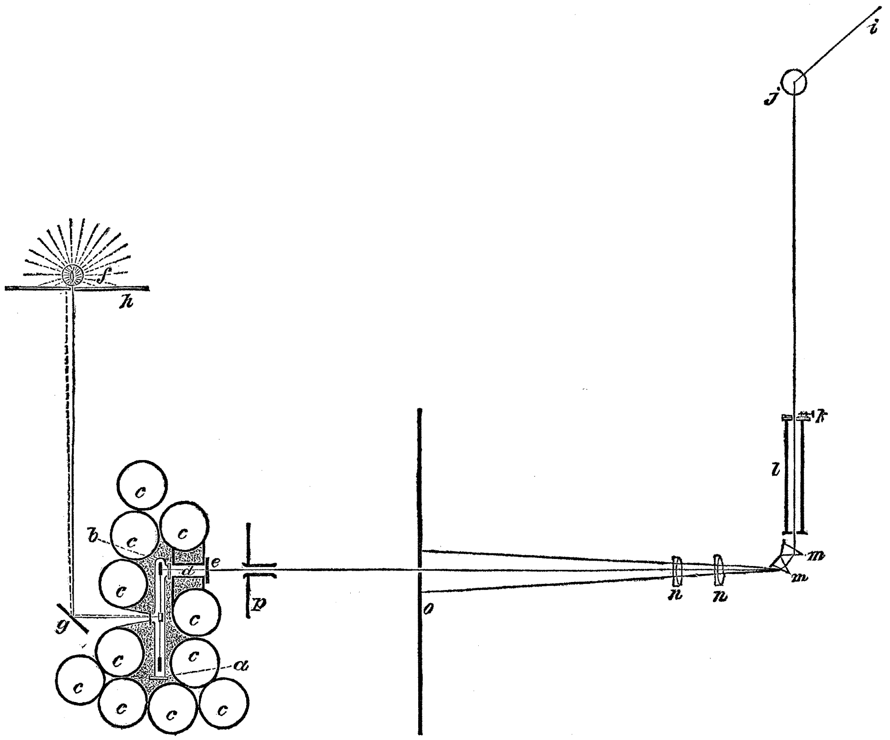
9·5 seconds, 9·6 seconds, 9·6 seconds;

so that *in vacuo* the beam ought to take about two seconds for each complete oscillation.

The pith surfaces at the ends of the beam are 13 millims. square; they are very thin, and are lampblacked on the surface. The window in the centre (*d*) is of plate glass, the window at *d'* is of quartz. They are on opposite sides of the apparatus, as will be better seen by referring to fig. 13.

187. When fitted up for spectrum observations the whole arrangement is shown in fig. 13. *a b* is the torsion-apparatus, shown in plan, the pith disks being represented by black lines at the ends of the central fine line representing the beam. The suspended mirror is shown in the centre of the beam. The quartz window is shown at the end *b*, and the other window opposite the central mirror. *c*, *c*, *c* are Winchester quart bottles full of water, and each encased in brown paper to prevent it accidentally acting as a lens, and condensing light on any part of the apparatus. Between the bottles, and surrounding the apparatus on all sides, as well as above and below, cotton-wool is well packed, spaces being left only for the rays of the spectrum to pass to the pith disk, and for the index ray of light to pass to and from the mirror. The cotton-wool acts as an excellent non-conductor of heat, and also prevents air-currents. The water in the bottles keeps the apparatus of a nearly uniform temperature, and entirely prevents sudden

Fig. 13.



changes. *d* is a cardboard tube, blackened inside, for the light to pass along; it has a movable shutter (*e*) at the outer end, which can be opened or closed by a touch of the finger without shaking the apparatus. The torsion-balance is firmly fastened to the walls of the room, which are very thick and firm, whilst the bottles and rest of the apparatus are supported by the floor; vibration caused by walking about or touching any of the other pieces of apparatus is therefore not communicated to the torsion-beam. *f* is a small lamp, a ray from which, passing through a narrow slit, falls on the inclined mirror (*g*), whence it is reflected to the suspended mirror of the torsion-apparatus. The light is now reflected back again to the mirror (*g*) and the graduated scale (*h*), where its position indicates the movements of the torsion-beam. The mercury-pump (not shown in the figure) is at some distance from the apparatus, so that the radiation from my body might not affect the apparatus when the pump was set working.

The ray of sunlight (*i*) falls first on the silver mirror (*j*) of a heliostat moving by clockwork; thence it is reflected to the slit *k*, along the tube *l*, through the prisms *m*, and the lenses *n*. *o* is a large screen, with a narrow vertical slit in it, so as to allow only the part of the spectrum I wished to experiment with to pass on to the apparatus. *p* is another screen extending for a considerable distance, and intended to prevent extraneous light from entering the apparatus when the shutter (*e*) is opened. It has a square aperture of such a size that a beam of light passing through it will just cover the pith surface (13 millims. square). The slit was kept half a millimetre wide during the experiments; the focus of the lenses was so adjusted as to form a sharp image of the spectrum lines at the place occupied by the square of pith on the torsion-beam. The slit and prisms are on a firm stand, capable of rotating through a small angle on a centre near the prisms. By this means any desired portion of the spectrum can be thrown on the pith without disturbing the focus. This necessitates an alteration in the adjustment of the heliostat, but that is soon effected. Slight alterations in the position of the spectrum can be made by moving one or both of the lenses sideways.

The distance between the slit and prisms is 16 inches; from the prisms to the pith surface is 7 feet 8 inches. The length of the spectrum here is 200 millims. from the lines A to G. The apparatus was fitted up in a room which admitted the sun in the right direction from about 10 A.M. to half-past 1 P.M. The heliostat was sufficiently good to keep a beam of light on the apparatus the whole of that time.

188. The past summer and autumn have been very unfavourable for spectrum researches of this character. My first accurate experiments with the above described apparatus were tried on July 26, and between that date and the middle of September the apparatus was kept in good adjustment, so that use could be made of the comparatively few occasions when the sun was sufficiently clear. I find that, owing probably to a variation in the aqueous vapour in the atmosphere or to slight haze, the observations of one day are not readily compared with those of another. Isolated experiments on one part of the spectrum are therefore of slight value, and my endeavour has been to embrace as wide an extent of spectrum each morning as I was able. A cloudless sky is not always the

clearest. The best results seem to be obtained when there is a moderate amount of wind, and great white clouds are floating about. The method of observation was as follows:—Having adjusted the scale so that the index ray of light pointed to zero, and having brought the particular part of the spectrum I wished to examine opposite the aperture in the screen, I opened the shutter and watched the progress of the luminous index until it reached its furthest point, when the shutter was closed. As the scale was divided into millimetres, the number of these traversed by the index was taken as the value of the part of the spectrum which shone on the pith. The piece of pith was 13 millims. square; consequently each number so obtained must be considered the average of a portion of the spectrum 13 millims. long.

189. I give below the actual results as they were obtained.

Date.	Portion of spectrum thrown on to pith*.	Deflection of index ray of light. millims.	Observations.
July 26.	C	25	
"	D	19	
"	E	12	
"	b	8	
"	F	5	
"	between F and G†	2	
29.	C	61	
"	D	34	
"	b	12	
"	F	9	
Aug. 4.	A	23	Sky hazy, and light varying very much.
"	B	24	
"	C	35	
"	between C and D	27	
"	D	15	
"	b	10	
5.	between B and C	40	
"	D	29	
"	between D and E	24	
"	b	17	
"	F	10	
"	between F and G	6	
"	G	3	
"	H_1	2	
13.	ultra-red	147	The sun was very bright and powerful. All the observations were taken between 12 noon and 1 P.M.
"	"	121	
"	B	105	
"	between C and D	75	
"	" "	65	
16.	between A and B	96	Sun very bright. No clouds.
"	D	80	
"	between D and E	57	
"	b	33	
"	F	25	
"	between F and G	16	
"	" "	12	
"	G	5	

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[*] The lines were caused to fall on the exact centre of the pith. Consequently the action is caused by the portion of the spectrum 6½ millims. on each side of the portion here designated.

[†] The exact position of the central line falling on the pith was in this and similar cases carefully taken and marked on a diagram (see Plate 35. fig. 14).

TABLE (continued).

Date.	Portion of spectrum thrown on to pith.	Deflection of index ray of light. millims.	Observations.
Aug. 17.	just below A	90	Sun very bright, but small hazy clouds floating about.
,,	C	65	
,,	just above C	64	
,,	D	63	
,,	b	48, 42	
,,	F	35	
,,	between F and G	17	
,,	G	11	
,,	H	9	
31.	just below A	205	White clouds in patches. Sun occasionally obscured. Could not work after noon.
,,	C	155	
,,	between D and E	110	
,,	,, ,,	85	
,,	E	67	
,,	F	40	
,,	between F and G	13	
Sept. 1.	ultra-red	35	Sun very bright, but large white clouds floating about. Observations taken during clear intervals.
,,	,,	133	
,,	,,	170	
,,	,,	190	
,,	,,	127	
,,	A	113	
,,	B	102	
,,	between C and D	79	
,,	,, ,,	77, 75	
,,	between D and E	59	
,,	b	34	
,,	F	23	
,,	between F and G	14	
,,	,, ,,	13	
,,	,, ,,	12	
,,	H	9	
10.	ultra-red	21	Sun quite bright up to 12.30 P.M., then the sky became rather hazy.
,,	,,	100	
,,	,,	169	
,,	,,	215	
,,	C	149	
,,	E	82	
,,	F	29	
16.	E	88	Perfectly clear sky.
,,	F	47	
,,	G	18	
,,	H	13	
,,	ultra-violet	11	

190. In fig. 14, Plate 35, which is reduced to half the linear scale, I have attempted to show the above results graphically. The horizontal band, crossed by vertical lines, at the lower part of the figure represents the solar spectrum. The vertical lines to which letters are attached are the FRAUNHOFER lines. The other lines do not represent spectrum-lines, but are put there to mark the parts of the spectrum at which observations were taken. The spectrum is of half the length which I used in the experiments, and the lines are also to scale. The square black portion at the left extremity shows the relative size of the pith surface in the torsion-apparatus.

The dots scattered about the upper portion of the figure, when measured from the upper horizontal line bounding the spectrum, give the millimetres traversed by the index ray of light when the portion of the spectrum corresponding to the dot fell on the black pith. Observations taken the same day are connected by lines; the date of observation is written at the beginning and end of the line. The curves thus formed may be regarded, therefore, as a measure of the intensity of the radiation.

Although there is a general resemblance between the curves taken on separate days, inasmuch as they all approach a maximum at a point somewhat below A, and then diminish on each side, the incline being steeper on the ultra-red than on the blue side, yet there is scarcely any resemblance between the heights of the curves on separate days. There are two causes for this. The first is that the weather was not always so favourable as I could wish; but having waited so long, I took observations at first whenever I could get an opportunity. Thus the first four days, July 26 and 29, and August 4 and 5, were not quite clear, and the curves consequently have but slight gradients; they form a group by themselves. Afterwards I became more critical, and would not attempt spectrum observations unless there was a good chance of a very bright sun. Consequently the curves on the next three days, August 13, 16, and 17, show an improvement in altitude. Having got these results, I determined not to try any more unless the weather were exceedingly favourable, and then to work principally at the extreme ends of the spectrum. The curves of August 31, September 1, 10, and 16 show, in consequence, much greater elevations.

The second cause which may possibly account in some measure for the differences in the curves, is that, as the apparatus was kept exhausted week after week with the pump working almost daily, the pith may have become drier, the aqueous vapour may have become more perfectly removed, and the vacuum consequently more nearly absolute*.

191. To obtain the nearest approach to the theoretical curve of intensity from my results, it will not be right to take the mean of all my observations. The error can only be on one side—that of deficiency. Therefore the lower observations must be rejected, and the highest results only taken.

Bearing in mind that the spectrum formed with glass prisms is condensed at the red end and expanded at the blue end, it would appear from an inspection of the curves, that, with a normal spectrum, such as a diffraction-grating would give, the maximum of action should be at a little below A in the ultra-red, and that the curve should descend equally on each side.

192. This appears to be the most appropriate place to discuss the question which, from its being almost invariably asked the first, seems to be of the greatest interest to most inquirers:—"Is the effect due to *heat* or to *light*"?

I cannot answer this question. The terms heat and light are not definite enough. The physicist has no test for light independent of heat. Light and colour are physiological accidents, due to the fact that a small portion near the middle of the spectrum

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* I could not exhaust this apparatus with charcoal (131) owing to the cement joints.

happens to be capable of affecting the retina of the human eye. There is no real distinction between heat and light; all we can take account of is difference of wave-length; and all we can see in the spectrum is one continuous series of vibrations, longer at the red end than at the violet end, but extending in an unbroken series for an unknown distance on each side. I say unknown, for it is probable that the whole spectrum, as we know it, is limited by the imperfect transparency of the atmosphere, or of the refracting medium, for the extreme ultra-red and ultra-violet rays.

Take a ray of the spectrum of a definite wave-length (the line B for instance), and allow it to fall on a thermometer; the mercury rises, showing the action of *heat*; concentrate it on the hand by a lens, it raises a blister accompanied with pain; let it fall on a bismuth and antimony couple, the galvanometer is deflected; and this action we also call one of *heat*. Let the ray fall on the eye, and it produces the sensation of *light* and *colour*. Let it fall on a collodion plate prepared in a particular manner, and it gives a permanent image, showing that it can cause *chemical action*. Lastly, throw the ray on a portion of matter free to move in a vacuum, and it makes itself evident as *motion*. Now these actions of *heat*, *light*, *colour*, *chemical action*, and *motion* are inseparable attributes of the ray of that particular wave-length; and to consider that there can be a splitting-up of this ray into two or more rays of the same refrangibility, one having the property of light, the other of heat, &c., is to my mind an absurdity.

The longer waves of the spectrum are those most able to produce heating-effects, the shorter waves best cause chemical action, and the intermediate waves easiest excite the sensation of vision; but although the maxima of these actions are at different parts of the spectrum, each effect can be detected at any part.

In a similar way the production of motion has its maximum in the waves situated at the ultra-red part of the spectrum, whilst it is capable of being rendered evident in all parts. This at first sight would favour the supposition that the action was due to the heating power of the waves.

193. How far this is really the case may be seen by the following Table, in which I have reduced the maximum to 100, and given the motion-producing value of the different colours of the spectrum, reduced in the same proportion:—

Ultra-red	100
Extreme red	85
Red	73
Orange	66
Yellow	57
Green	41
Blue	22
Indigo	$8\frac{1}{2}$
Violet	6
Ultra-violet	5

A comparison of these figures with those usually given in text-books to represent the distribution of heat in the spectrum will be a sufficient proof that the mechanical action of radiation is as much a function of the luminous rays as it is of the dark heat-rays.

194. In the intervals of spectrum work I tried many other experiments with the apparatus. I was anxious to get the exact time of the oscillations of the beam in a vacuum, and tried many ways of starting the initial impulse.

A candle held close to the screen, and the shutter momentarily opened and closed, sent the index with some violence to the extreme limit of the scale. It then slowly came back to zero and there stopped. Magnesium wire used in the same way produced the same effect. There was no oscillation, as there would have been if the impulse had been given by a material blow. The movement of the beam, as shown by the spot of light, seemed as if it were held in check by a force acting the whole time of its movement, and not only for the time the light acted. The impression conveyed was that the beam was swinging in a viscous fluid, and the more perfect the vacuum the greater appeared to be the viscosity (107). Thinking that the heat-rays from the candle might be absorbed by the black pith and so raise its temperature, I interposed screens of water, alum, and thick plates of glass, so as to cut off the ultra-red rays. Still the apparent resistance to free oscillation continued.

I then, without interfering with the vacuum, and without letting radiation fall on the pith surface, gave the apparatus a sudden twist round, so as to cause the beam to knock against the side of the tube. This set it swinging through a large arc, and the oscillations kept up with perfect freedom for several minutes, declining in amplitude at each oscillation till the beam ultimately came to zero. This perfectly free movement is in strong contrast to the constraint under which the beam moves when the initial blow is given by a ray of light instead of by a mechanical push.

The same effect was noticed during the experiments with the spectrum. A ray in the blue, falling on the pith, would drive the index twenty divisions along the scale. It would then gently come back to zero, where it would stop, occupying the same time to come back as it did to go forward. If, however, after the action of the light had entirely ceased, I gave the tube a slight jerk, so as to cause the beam to swing through the same arc, the index on returning to zero would pass perhaps 15 degrees the other side, and would thus oscillate for some time from one side to the other of zero, taking many minutes to come to rest.

195. This phenomenon enables me to advance a step towards an explanation of the mechanical action of radiation, although I fear I shall have to make some assumptions which are scarcely yet proved.

A ray of light falls on a white surface and is reflected back again; it does no work there (170, 171); but if the ray falls on a black surface it is absorbed and quenched. What becomes of it? It seems to me probable that the ray becomes converted into thermometric heat, and that its energy is in whole or in great part used up in raising the temperature of the dark body. But having thus become warm, the powerful radiating action of the surface for heat comes into play, and the heat, which has just been engendered and absorbed, is quickly radiated back again. It would appear as if this radiation of heat from the surface of a body caused the latter to retreat backwards, and so produced the motion. This would account for the apparent viscosity of the vacuum; for the heat radiating from the black surface of the pith would act in opposition to the torsion, and hold the latter force in check till it was itself all dissipated. The superiority of pith over metal is also accounted for. Pith is one of the worst conductors of heat, and thus allows all the heat to radiate from the same surface which absorbed it; whilst metals, being the best conductors of heat, allow it to pass through and radiate almost as much from one surface as the other.

The slight action of the blue rays is thus due to their short vibrations not being capable of transmutation into so much thermometric heat as are the longer rays; whilst the strong action of the red rays is owing to the degradation necessary to convert them into heat being but slight.

This action is parallel to that of the production of phosphorescence. A ray of such high refrangibility as to be invisible falls on a suitable surface; it is there absorbed, degraded in refrangibility, and radiated out again in the form of visible rays of longer wave-length. We have only to imagine our eyes to be unaffected by what we now call light, but capable of responding to an octave lower in the spectrum, and we should see the same thing when the blue ray falls on the blackened pith. In such a case an invisible beam would be thrown on a suitable surface of lampblack; the latter would instantly respond, lowering the refrangibility and increasing the wave-length to the point of visibility; the ray so generated would be absorbed and then radiated back again, the lampblacked surface glowing with light for some time after the original ray had ceased to fall on it.

196. Making use of the property discovered by Dr. TYNDALL of the almost perfect transparency for the invisible heat-rays of iodine dissolved in disulphide of carbon, and its opacity to the luminous rays, experiments were instituted with a view to obtain a numerical comparison of the mechanical action which was due to the invisible rays and that due to the visible rays.

The apparatus was used as fitted up for spectrum observations (187), the prisms and lenses being removed. A ray of sunlight was reflected from the heliostat, then reflected by means of a right-angled prism (placed in the usual position of the refracting prisms) into the apparatus.

The action of the sunlight was far too powerful for the apparatus, and I accordingly passed it through a plate of alum, a thick piece of glass, and an empty glass cell.

On opening the shutter the pith was powerfully repelled, the index ray moving 300 divisions. The cell was filled with disulphide of carbon, and the experiment again tried. The index moved to the same point.

The clear disulphide of carbon was removed, and it was replaced by a strong solution of iodine in disulphide of carbon. This was opaque to the sun's ray. On opening the shutter the deflection amounted to 79°.

This experiment shows that the total radiation from the sun, passing through alum and glass screens, produced a deflection of 300°, whilst if the whole of the light was cut off by interposing a solution of iodine in disulphide of carbon, there was still a movement of 79°. This 79° was the effect due to dark heat which penetrated the alum, the difference (221°) being due to light.

I endeavoured to cut off the whole of the dark heat, so as to work with the luminous portion only of the solar radiation. The ray of sunlight reflected from the heliostat was accordingly passed through the following screens, placed one behind the other, as shown in Plate 36. fig. 15:—

A lens.
A thick, total-reflection, right-angled prism.
Three thin plates of glass.
A plate of alum 7½ millims. thick.
Two thick glass plates.
Another plate of alum, 5 millims. thick.
A glass cell full of saturated solution of alum.
An empty glass cell.

It was expected that these numerous cells would effectually cut off the dark heat-rays. To prove this the empty cell was filled with opaque disulphide[*]. On opening the shutter the deflection of the index was 2° only.

What came through the alum, glass, and water screens was therefore pure light, practically free from the dark rays which are called heat.

The opaque disulphide was then replaced by clear disulphide. The deflection was 105°.

	Action of filtered sunlight.
Opaque disulphide	2 degrees.
Clear disulphide	105 ,,

Deducting the 2° as representing the trace of dark heat which escaped the alum, glass, and water screens, the difference (103°) represents the action of the luminous portion of solar radiation and of that small quantity of the ultra-violet rays which would pass the screens; for had the effect of the sun's radiation after passing through the screens been due to *heat*, on cutting off the *light* by means of opaque disulphide, the deflection should have been practically undiminished. But experiment shows that, after passing through the screens, the repulsion due to heat is less than 2 per cent. of the total action of the solar ray.

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[*] For the sake of brevity I call the solution of iodine in disulphide of carbon *opaque disulphide*; the disulphide of carbon alone I call *clear disulphide*.

The screens, whilst diminishing the heat almost to nothing, also cut off a considerable quantity of the light.

197. A similar series of experiments was tried with the radiation from a candle. No alum, glass, or water screens were at first interposed, and the deflections were taken with the clear and opaque disulphide, alternately put in the path of the ray. The candle was 3 feet off. The mean of several experiments was as follows:—

Opaque disulphide	28 degrees.
Clear disulphide	130 „

This shows that much of the action of a candle is due to rays which pass through iodine, *i. e.* to the ultra-red rays.

The candle was now brought 2 feet from the apparatus, and the alum and glass screens were interposed. On repeating the experiments the mean result was as follows:—

Opaque disulphide	5 degrees.
Clear disulphide	37 „

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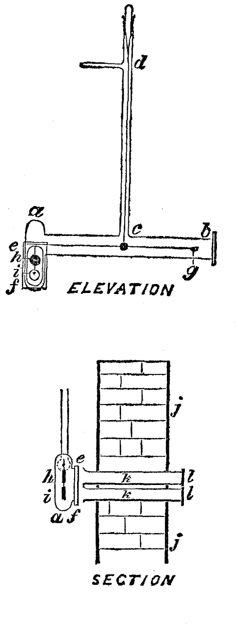
198. I have hitherto taken it for granted that a lampblacked surface is the most repelled by radiation, and that a white surface, such as that of freshly cut pith, is the least repelled. Experiments tried repeatedly with other surfaces abundantly confirm this supposition. It was necessary, however, to get accurate data on this point; and I have accordingly fitted up an apparatus which will enable me to measure the force of radiation and its action on disks of various materials of the same size, compared with a standard black disk.

The apparatus is represented in fig. 16. It is similar in principle to the torsion-apparatus already described (186). *a b* is the horizontal tube containing the glass torsion-beam; *c d* is the suspending fibre, also of glass. In the centre of the beam is a mirror, from which an index ray of light is reflected. The end *a* of the horizontal tube is sealed on to a wider piece of tube in a vertical position, and having in front of it a large opening (*e f*) occupying the whole of one side of the piece of tube; this opening has the edges ground perfectly flat, and is closed with a piece of plate glass cemented on. The object of the opening is to enable the disks to be changed. At the end (*b*) of the horizontal tube is another opening, closed in like manner with a plate of glass. This is to give access to the pan (*g*) of the beam, so as to counterpoise the disks, as they are not all of the same weight. At the other end of the beam a light aluminium bar hangs, on which is cemented the standard disk *h* and the movable disk *i*. The standard disk is of pith, coated with lamp-

Fig. 16.



black by holding it over the flame of burning turpentine. The movable disk may be of any substance.

The apparatus was fitted up in a recess built of brick, and closed in front with a glass window. In the brick wall at the side *j* holes were pierced opposite the disks and the central mirror. These were lined with card tubes (*k*) blacked inside. The interstices were packed with cotton-wool, and the apparatus was closely surrounded with Winchester quart-bottles filled with water. In front of the card tubes wooden shutters (*l*) were fastened, so that either one could be opened independently of the other. The apparatus was sealed on to the pump by means of the arm shown at the upper part of the torsion-apparatus.

With nothing in the pan, and only the standard black disk on, the beam is in equilibrium; consequently each new disk requires a special counterpoise.

199. The following weights and measurements of the different parts of the apparatus were taken:—

Weight of glass beam, central stirrup, and mirror	3·0485 grains.
Standard black disk and aluminium bar	0·4635 grain.
Pan at other end of glass beam, acting as counterpoise for above.	0·5263 „
Weight of white pith disk and support	0·2670 „
Counterpoise for ditto	0·3085 „
Length of arm from centre of support to centre of disk . . .	99 millims.
Length of arm from centre of support to centre of counterpoising pan	84 „
Diameter of disks	17·25 „
Torsion of suspending fibre, in air, with glass rod (186) hanging to it	½ oscillation in 15·75 seconds.

200. The experiments were tried as follows:—The exhaustion having been carried to the utmost point, so that no increase in sensitiveness was produced by further working the pump, a standard candle was adjusted opposite the black disk and at a definite number of millimetres off. The deflection of the index ray of light was then taken on opening the shutter. After completing this observation, the beam was allowed to come to rest; the candle was then lowered till it was opposite the lower disk, and the deflection caused by it was again taken. These were repeated several times. The mean results of the first series are given in the following Table (the lower disk being plain white pith):—

Distance of candle from disks.	Screen interposed.	Deflection of index ray of light on millimetre-scale 1100 millims. from mirror.			
		Black disk.	White disk.	Reduced to Black=100.	
				Black.	White.
800 millims......	Nothing	192	32	100	16·7
900 „	„	122	21	100	17·1
1200 „	„	62	10	100	16·1
500 „	Cell of water	80	7	100	8·7
500 „	Alum plate.....................	100	8	100	8·0
500 „	„ solution	76	7	100	9·2
500 „	Ammonia gas, 6 in. thick, and cell of water...........	79	7	100	8·8
800 „	Ammonia gas alone	190	31	100	16·3

201. The lower disk was removed and replaced by a disk of pith thickly coated on one side with pure precipitated carbonate of lead. The disk weighed 0·499 grain, the counterpoise weighing 0·530 grain.

After complete exhaustion, the results of various experiments are shown in the following Table:—

Distance of candle from disks.	Screen interposed.	Deflection of index ray of light on millimetre-scale 1100 millims. from mirror.			
		Black.	Carb. Lead.	Reduced to Black=100.	
				Black.	Carb. Lead.
800 millims.	Nothing	130	17	100	13·0
500 „	Iodine in disulphide of carbon	127	9·5	100	7·5

Instead, therefore, of carbonate of lead being a good absorber of the rays which produce motion, it is a better reflector than a plain white pith surface, owing probably to its superior whiteness.

202. Another black surface was now sought for to compare with the standard disk. Pith coated with precipitated iodide of palladium was employed. The disk weighed 0·460 grain, and the counterpoise 0·491 grain. The results were:—

Standard Black.	Iodide of Palladium.	Reduced to Black=100.	
		Black.	Iodide of Palladium.
70	61	100	87·3

203. Plates of alum and of rock-salt were successively introduced into the apparatus, to be compared with the standard black disk. The apparatus was, however, not sufficiently sensitive to enable me to make satisfactory comparisons. The average of

several observations (which, however, were not so concordant as I should have liked) were—

Standard Black.	Rock-salt.	Reduced to Black=100.	
		Black.	Rock-salt.
131	4	100	3

Standard Black.	Alum.	Reduced to Black=100.	
		Black.	Alum.
120	6	100	5

There was no action on either the alum or the rock-salt when a screen of water or of alum was interposed.

204. In consequence of some experiments tried by Professors TAIT and DEWAR, and published in 'Nature,' July 15th, 1875, I fitted up a more sensitive apparatus for the purpose of carefully examining the action of radiation on alum, rock-salt, and glass. The apparatus was similar to the one described in par. 186, there being, however, no window at either end. To the horizontal beam suspended by the glass fibre were attached a plate of alum at one end and a plate of rock-salt at the other. Each plate was perfectly polished and transparent, and measured 12·5 by 13·5 millims., and was 1·5 millim. thick. The deflection was produced by a candle placed opposite the crystalline plate under examination, and it was measured in the usual way by a reflected ray of light. The following were the results:—

Distance of candle from plate.	Deflection observed.		Reduced to alum=100.	
	Alum.	Rock-salt.	Alum.	Rock-salt.
150 millims.	21	17	100	81
" "	22	17	100	77·3
" "	24	17	100	71
100 "	48	30	100	62·5
" "	43	26	100	60·4

The action on the alum was found to increase at each observation. A glance at the plate showed the reason. When it was first put in it was perfectly smooth and transparent. Before it had been long in the vacuum efflorescence commenced, and when the first observation was taken the surface of the alum plate was dotted over with small white specks, which increased in size and number as the experiments were continued. The opacity thus caused was apparently sufficient to account for the increased action of radiation upon the alum plate.

The pump was kept going the whole time, so that the water vapour evolved from the dehydrating alum might be carried away and prevented from interfering with the results, as it otherwise would have done (130). The last two experiments, however, show the effect of aqueous vapour.

205. To test the accuracy of the explanation that the opacity caused increased action, I coated two disks of pith, one with powdered rock-salt and the other with powdered alum, and tested them against lampblacked pith in a similar apparatus to the one described in par. 198. The deflections were—

	Black pith.	Powdered alum.	Powdered rock-salt.
	110	38	18
or reduced,	100	34·5	16·3

As will be seen on reference to par. 203, the ratio between the black disk and the plate of rock-salt was 100 : 3. Powdering the rock-salt has therefore increased the action 13·3 per cent. The much larger action of the powdered alum is probably due to the fact that crushing the crystals facilitates efflorescence *in vacuo.*

206. The alum and rock-salt plates were removed, a fresh alum plate ground and polished, and this and the rock-salt were coated with lampblack. They were then put into the apparatus as before, the black side being away from the source of radiation, so that the rays would have to pass through the crystal plates before meeting with the lampblack. The deflections were taken as soon as the vacuum was good. The deflections were—

	Blackened alum.	Blackened rock-salt.
	26	19
or reduced,	100	73

The rock-salt was more slow in its movements under the influence of radiation than the alum was, but they both returned to zero equally well.

207. A very sensitive apparatus, similar to the torsion-apparatus described in par. 198, fig. 5, was now employed, and a clear polished disk of rock-salt and a thin disk of glass of the same size were placed therein. The apparatus was very well exhausted, and the deflections taken when the radiation from a candle was allowed to fall on either disk. The mean of several concordant observations was—

Rock-salt.	Glass.
39	40

I quote the following from the article in ‘Nature’ already referred to:—“Prof. DEWAR then proceeded to show that the heating of the disk was the efficient cause of the action. Two equal disks, one of rock-salt, the other of glass, were attached to the glass fibre. The rock-salt was inactive when the beam [from a candle] was thrown on it; the glass disk was active. The reason is evidently that the rock-salt is not heated, being transparent to heat, whereas the glass is opaque, absorbs the heat and is heated.” It will be seen that I have failed to obtain this marked difference in action between rock-salt and glass, although the glass shell of the apparatus was as thin as was consistent with strength to resist the atmospheric pressure.

208. The action of radiation on surfaces of pith coated with thin layers of different substances is deserving of considerable attention. I have had an apparatus at work for several months past, in which six disks can be experimented with on the same beam and during the same exhaustion (similar to the arrangement described in par. 198, which held two disks). With this I have tried many hundred experiments, using the flame of a candle direct, or shaded by screens of water, alum, &c. The results are of much value, as showing that there is no definite connexion between the colour of a body and the mechanical action of radiation upon it. For instance, taking the movement of the lampblacked pith, under the influence of a standard candle, as 100°, I find that under the same conditions

		°
Precipitated silver	moves	56
Amorphous phosphorus	„	40
Sulphate of baryta	„	37
Red oxide of iron	„	28
Scarlet iodide of mercury and copper	„	22
Lampblacked silver	„	18
White pith	„	18
Rock-salt	„	6·5
Glass	„	6·5

These are only a few of the results I have obtained. The experiments will occupy some time to carry out with the completeness which they deserve, and I therefore propose to defer any further mention of them to a subsequent paper.

The Measurement of the Force.

209. I have long endeavoured to devise some means of measuring the amount of force exerted by radiation, from a standard candle for instance at a foot off, on a measured surface of matter. The data given in pars. 199 and 200 are sufficient to enable the amount of force acting on the pith disks to be calculated indirectly; but I wished to have a means of measuring the force by as direct a method as we have of getting the weight of a ponderable body. I wanted an apparatus which will give me, at once, the pressure in grains which a ray of light exerts on a surface on which it may fall. Such an apparatus is shown in fig. 17.

The principle of the construction is that of the torsion-balance first described by W. Ritchie, F.R.S., in 1830*. *a b* is a glass tube 13·5 inches long, 1 inch wide as far as *a c*, and 1·2 inch wide at *c b*. It is closed at the end *a*, and ground flat and polished at the end *b*, so as to be capable of being closed by a plate of glass cemented on. *d e* and

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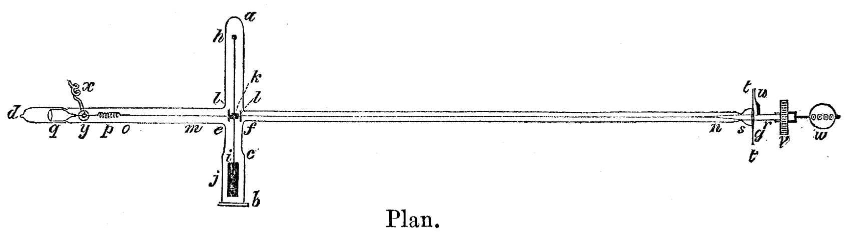
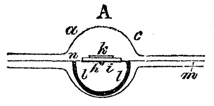
* Phil. Trans. vol. 120 (for 1830), p. 215.

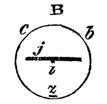
Fig. 17.



Plan.



Elevations and details.



Vertical section of cross tube at the centre.

Vertical section of cross tube at the end containing the pith.

f g are two narrower tubes sealed into *a b*, as shown, the part *d e* being 17 inches long, and *f g* 38 inches long. *d e* is $\frac{1}{2}$ an inch in diameter, and is closed at the end; *f g* is a $\frac{1}{4}$ of an inch diameter. *h i* is a thin glass beam, having a glass weight at the end *h*, and a flat surface of lampblacked pith (*j*) at the end *i*. The pith (*j*) exposes exactly 2 square inches of surface. It is prevented from curling up in the vacuum by cutting it partly through at intervals, as shown. *k* is a silvered mirror, cemented on to the centre of the glass beam; *l l* are two knife-edges of glass, finely ground and polished; *m n* is a very fine fibre of glass cemented to the beam (*h i*) beneath the mirror (*k*). The end (*n*) of the glass torsion-fibre is attached to the solid stopper (*r*), which is carefully ground and polished into the contracted part of the tube (*s*). The other end of the torsion-fibre (*m*) is cemented to a filament of silk (*m o*); this silk is attached to one end of a steel spring (*p*), which is held firmly at the other end by the solid rod (*q*) cemented to the glass tube (*d e*). The torsion-fibre (*m n*) passes over the knife-edges (*l l*), which thus support the beam. The tension of the spring (*p*) is so adjusted that the glass fibre shall remain stretched under a constant pull of about 100 grains. *t t* is a circular card cemented to the end of the tube (*g*) and divided into 360 degrees. On the stopper (*r*) is fixed a pointer (*u*), which revolves with it, and marks the degrees through which it has turned. The complete revolutions are recorded on a "counter" (*w*). Motion is given to *r* by a torsion-handle (*v*). The apparatus is connected to the pump by the spiral (*x*), which works in a stopper tap (*y*) most ingeniously devised by my friend and assistant Mr. C. H. Gimingham, so as to enable the instrument to be disconnected from the pump and attached to it again without interfering with the exhaustion*.

The stopper (*r*) is very accurately ground and polished in the tube at *s*, as long a surface as possible being in contact. It should be lubricated by setting fire to a piece of plain india-rubber, and allowing the melted drops to fall on the contact surfaces.

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* I have asked Mr. Gimingham to send a description of this tap, and some useful improvements he has introduced in the mercury-pump, to the Royal Society.

This is a nearly perfect lubricant, allowing very free movement and preventing any access of air.

210. The torsion-fibre must be selected with great care. Ten threads were drawn (103) and were suspended from a horizontal beam. Weights were then gradually hung on to the lower ends. Only two were found strong enough, the others having broken before 450 grains had been added. The one selected stood 450 grains without breaking. Its diameter is less than ·001 inch.

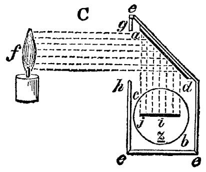
The torsion of the glass fibre was taken by the method given in par. 186. With the weight of 15·46 grains hanging on to it half an oscillation took 30 seconds.

A fellow thread, selected of as nearly as possible the same strength and tension, and having a weight of about 100 grains at the end, broke when it was twisted 36 times. The actual thread used in the balance has been tested up to 30 turns without breaking.

211. A flat oblong piece of soft iron, weighing accurately 0·01 grain, is put loose into the cross tube under the pith surface (see *z*, fig. 17, vertical section of cross tube). This weight can be picked up by a horseshoe magnet outside the tube, and dropped on any part of the pith. A mark is made at the exact centre of the pith surface, and by moving the magnet about, it is easy to place the iron weight accurately on this mark.

212. A silvered glass mirror is supported at an angle of 45° over the pith surface, and so that the centre of the mirror is 2 inches from the pith when the beam is in equilibrium. The whole is enclosed in a blackened box, in such a manner that when a candle is placed a few inches from the mirror in a horizontal line with its centre, no direct ray, but only the reflected ray, falls on the pith. Fig. 18 shows the arrangement: *a d* is the mirror; *e e e e* is the wooden frame with the aperture (*g h*) in front to allow the flame of the candle (*f*) to fall on the mirror and thence be reflected on to the pith without illuminating the pith with direct rays. *b c* is the cross tube, *j* the pith, *i* the beam, and *z* the iron weight.

Fig. 18.



213. A ray of light from a lamp is directed on the small central mirror (*k*, fig. 17) of the beam, whence it is reflected back to a millimetre scale 4 feet off, forming a sharply defined image, and making evident by its movement the slightest angular motion of the beam. When the reflected ray points to zero on the scale, it is evident that a turn of the torsion-handle (*v*) in one or the other direction will raise or depress the pith end of the beam, and thus cause the index ray to travel along the scale to the right or to the left. It is also evident that if a small weight is placed on one end of the beam so as to depress it, and the torsion-handle be then turned, the tendency of the glass fibre to untwist itself will ultimately balance the downward pressure of the weight, and (provided the glass torsion-fibre does not break) will bring the beam to a horizontal position, the index ray again pointing to zero. The object of the spring *p* is to keep the torsion-thread always stretched; and the silk fibre (*m o*) connecting the torsion-fibre and the spring is to allow the whole of the torsion of the fibre to be utilized in moving the beam, as the filament of silk may be considered practically free from torsion.

214. The first operation was to ascertain the number of degrees of torsion which were equal to the $\frac{1}{100}$ of a grain weight. The apparatus being well exhausted*, the index ray of light being at zero, and the pointer of the torsion-handle standing at 0° on the divided circle, the iron weight was picked up by a magnet, and placed exactly on the centre of the pith surface. The end of the beam instantly fell down, and I had to turn the torsion-handle 27 complete revolutions and 353° in addition, or 10073°, before the beam became horizontal and the index ray again stood at zero†. The downward pressure of $\frac{1}{100}$ of a grain was therefore equivalent to the force of torsion of the glass thread when twisted through 10073°.

215. My next operation was to find out the degree of delicacy of the balance. The law of torsion is that the force with which the glass fibre tends to untwist itself is directly proportional to the number of degrees through which it has been twisted ‡. I can therefore find out the smallest amount of weight which the balance will indicate by ascertaining what is the smallest angular movement of the torsion-handle which will cause an appreciable movement of the index ray of light.

I found that a movement of three degrees of torsion sent the index ray a considerable distance. One degree of torsion gave a very decided movement, whilst half a degree displaced the index ray to a sufficient extent to be easily seen. I believe less than half a degree could have been detected had the scale been further off; but not to run any risk of over-estimating the delicacy of the balance, I will take one degree of torsion as its ordinary working limit.

To what fraction of a grain will this torsion of one degree be equivalent? This is easily calculated. A twist through 10,073° balances the $\frac{1}{100}$ of a grain; a twist of 10,074° overbalances it.

$$\begin{aligned} &10{,}073^\circ : 0{\cdot}01 \text{ grain} :: 10074^\circ : 0{\cdot}01000099 \text{ grain};\\ \therefore\ &10{,}074^\circ - 10{,}073^\circ = 0{\cdot}01000099 \text{ grain} - 0{\cdot}01 \text{ grain},\\ \therefore\ &1^\circ = 0{\cdot}00000099 \text{ grain}. \end{aligned}$$

The balance will therefore turn to the $\frac{99}{100{,}000{,}000}$ of a grain.

Divide a grain weight into a million parts, place one of them on the pan of my balance, and the beam is instantly depressed!

216. The balance was exhausted up to the highest point, the index ray of light was projected on to the scale, and the apparatus was kept in darkness, well protected from external influences by screens around it. The index ray soon became stationary; it was then brought to zero, and the pointer of the divided circle set to 0°, the counter also being at 0.

A standard candle was then adjusted 10 inches from the centre of the mirror, and

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* This preliminary testing the value of the $\frac{1}{100}$ grain weight can be equally well performed in air.

† This is the mean of several concordant experiments.

‡ BIOT, Traité de Physique, tom. i. p. 486; RITCHIE, Phil. Trans. vol. 120. p. 215.

therefore 12 inches from the surface of the pith. The screens were removed, and the reflected rays of the candle were allowed to fall perpendicularly on to the pith surface. The pith instantly sank to the bottom of the tube, and the torsion-handle had to be turned through 442° to restore equilibrium.

The $\frac{1}{100}$ of a grain required 10,073° of torsion to restore equilibrium (214); and the ratio between the weights being the same as that between the degrees of torsion, the mechanical force of the radiation from the candle is easily calculated:—

10,073° : 0·01 grain : : 442° : 0·0004387 grain.

Other experiments were tried, the candle being blown out and the apparatus allowed to cool in the dark between each. The following Table gives the results:—

Mechanical Force of Radiation from a candle on 2 square inches of blackened pith.

Distance of candle from pith.	Degrees of Torsion.	Mechanical Pressure.	Difference of last column from mean.
12 inches	442°	0·000438 grain.	−0·000006 grain.
,, ,, ...	449	0·000445 ,,	+0·000001 ,,
,, ,, ...	452	0·000448 ,,	+0·000004 ,,
Mean	448	0·000444 ,,	
6 inches	1815	0·001801 ,,	+0·000029 ,,
,, ,, ...	1800	0·001787 ,,	+0·000015 ,,
,, ,, ...	1740	0·001727 ,,	−0·000045 ,,
Mean	1785	0·001772 ,,	
6 ins., with water-cell interposed .	235	0·000233 ,,	

The pressure at 12 inches off is 0·000444 grain, whilst that at 6 inches is 0·001772 grain. At half the distance the pressure should be four times, or 0·001776 grain. The difference between theory and experiment, being only 4 millionths of a grain, is a sufficient proof that the indications of this instrument, like those of the previously described apparatus, follow the law of inverse squares.

The last column in this Table, the "difference from mean," shows that my estimate of the sensitiveness of this balance is not excessive, and that in practice it will safely indicate the millionth of a grain.

217. I have tried in vain to get a good observation with sunlight. On the very rare occasions within the last few months on which the sun has been shining brightly my balance has not been in adjustment, or I have been away from home. I was able, however, on December 13th last to get a few observations. The sun was obscured by thin clouds and haze, and its rays were but faint. The pressure of its radiation was, on this occasion, only equal to that of 10·2 candles, six inches off, pressing down the pith, therefore, with a weight of 0·018074 grain.

218. But the result of my observations of the sun on Dec. 13th being only equal to 10·2 candles 6 inches off, is of course far below the real power of the unclouded mid-summer sun. I propose trying this experiment under more favourable circumstances. Meanwhile I have endeavoured to find what results in this direction have been obtained by other observers. The data given by different authorities vary considerably, as will be seen by the following Table:—

BAUGEE[*] found that sun = 62,280 candles 1 metre off.
WOLLASTON[†] „ „ = 59,830 „ „ „
BECQUEREL[‡] „ „ = 50,000 „ „ „
ZÖLLNER[§] „ „ = 154,500 „ „ „

In these cases the sun was measured when at the highest point in a clear sky, and the *optical* difference alone was taken. In my case the light was very faint and hazy, and the total radiation, both of the sun and of the candle, was measured. I do not give my results as attaching the least importance to the actual figures, but simply as an illustration of the marvellous sensitiveness of the instrumental means at my disposal. I hope during the forthcoming summer to work out the subject more fully, and to be in a position to communicate to the Society many observations obtained with the torsion-balance, not only in photometry and the repulsion caused by radiation, but in other branches of science in which the possession of a balance of such incredible delicacy is likely to give valuable results.

POSTSCRIPT.—January 17, 1877.

In the foregoing paper, pars. 126, 128, 155, 156, 157, 158, 159, 170, and 171, experiments are referred to which show that the repelling force appears to be different on a white or a black surface according as the radiation causing the movement is dark heat (from the fingers, hot water, hot glass, or copper below 250° C.) or the luminous rays. In commenting on these results, I gave what appeared at the time to be the most reasonable explanation. Twelve months' research, however, has thrown much light upon these actions; and the explanation afforded by the dynamical theory of gases makes what was a year ago obscure and contradictory, now reasonable and intelligible.

In a preliminary notice submitted to the Royal Society, Nov. 16, 1876, and published in No. 175 of the 'Proceedings,' I gave the explanation of the movements of repulsion under the influence of radiation according to the dynamical theory of gases, first, I believe, used in this connexion by Mr. JOHNSTONE STONEY. In this preliminary notice I brought forward experimental proof that the presence of residual gas is the cause of

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[*] Essai d'optique sur la gradation de la lumière, 1729, p. 30.

[†] Phil. Trans. vol. 89, 1799.

[‡] Ann. de Chim. et de Phys. 3 série, t. lxii. p. 34, 1861.

[§] Private letter to the author.

the movement of the radiometer, and generally of the repulsion resulting from radiation, the maximum effect being at a pressure of about 50 millionths of an atmosphere. According to the dynamical theory of gases, the repulsion is due to the internal movements of the molecules of the residual gas. When the mean length of path between successive collisions of the molecules is small compared with the dimensions of the vessel, the molecules rebounding from the heated surface, and therefore moving with an extra velocity, help to keep back the more slowly moving molecules which are advancing towards the heated surface; it thus happens that though the individual kicks against the heated surface are increased in strength in consequence of the heating, yet the number of molecules struck is diminished in the same proportion, so that there is equilibrium on the two sides of the disk, even though the temperatures of the faces are unequal. But when the exhaustion is carried to so high a point that the molecules are sufficiently few and the mean length of path between their successive collisions is comparable with the dimensions of the vessel, the swiftly moving, rebounding molecules spend their force, in part or in whole, on the sides of the vessel, and the onward crowding, more slowly moving molecules are not kept back as before, so that the number which strike the warmer face approaches to, and in the limit equals, the number which strike the back, cooler face; and as the individual impacts are stronger on the warmer than on the cooler face, pressure is produced, causing the warmer face to retreat.

This theory explains very clearly how it was that I obtained such strong actions in my earlier experiments when using white pith as the material to be repelled, and employing the finger as a source of heat, and how it happened that I did not discover for some time that dark heat and the luminous rays were essentially different in their actions on black and white surfaces. The explanation of this is as follows:—Rays of high intensity (light) pass through the wall of the glass vessel without warming it; they then, falling on the white surface, are simply reflected off again; but falling on the black surface they are absorbed, and, raising its temperature, produce the molecular disturbance which causes motion. Rays of low intensity (dark heat) do not, however, pass through the glass to any great extent, but are absorbed and raise its temperature. This warmed spot of glass now becomes the repelling body, through the intervention of the molecules rebounding from it with a greater velocity than that at which they struck it. The molecular pressure, therefore, in this case streams from the inner surface of the warm spot of glass on which the heat-rays have fallen, and repels whatever happens to be in front of it, quite irrespective of the colour of its surface.

FIG. 4.

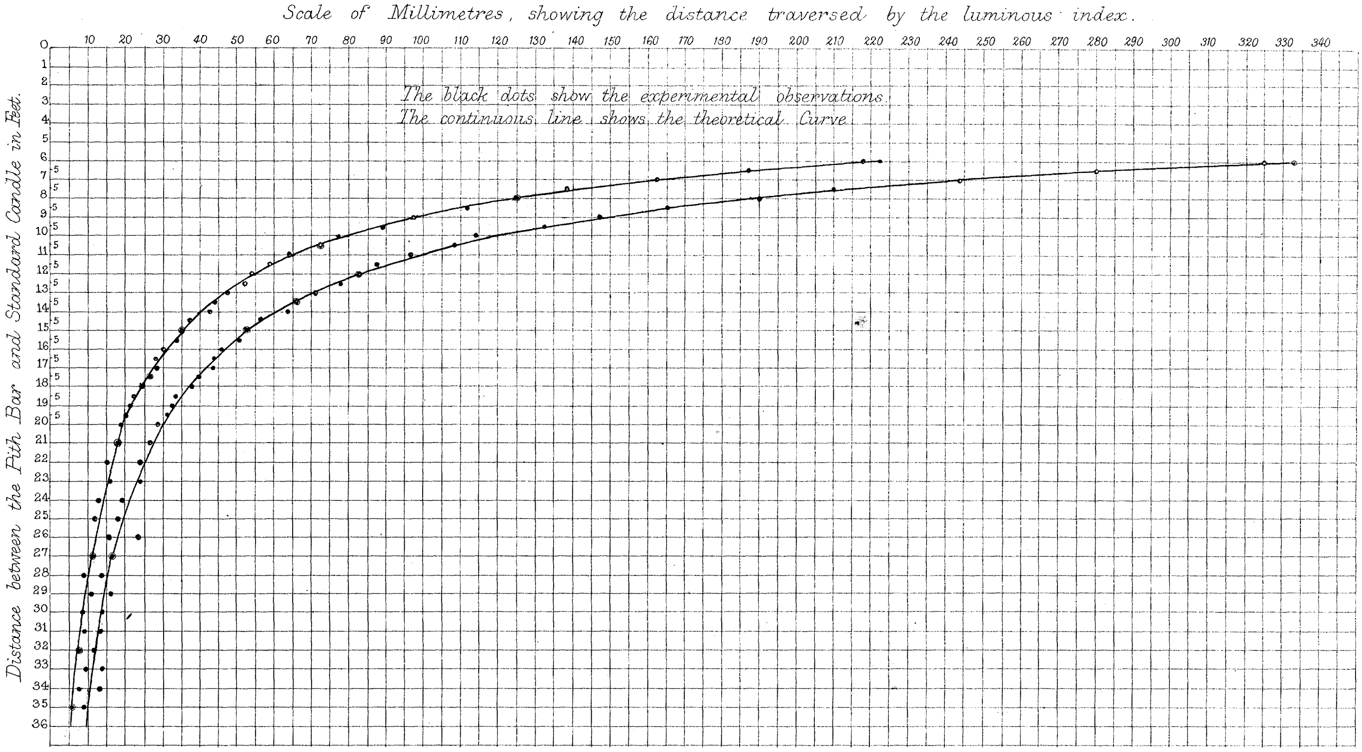
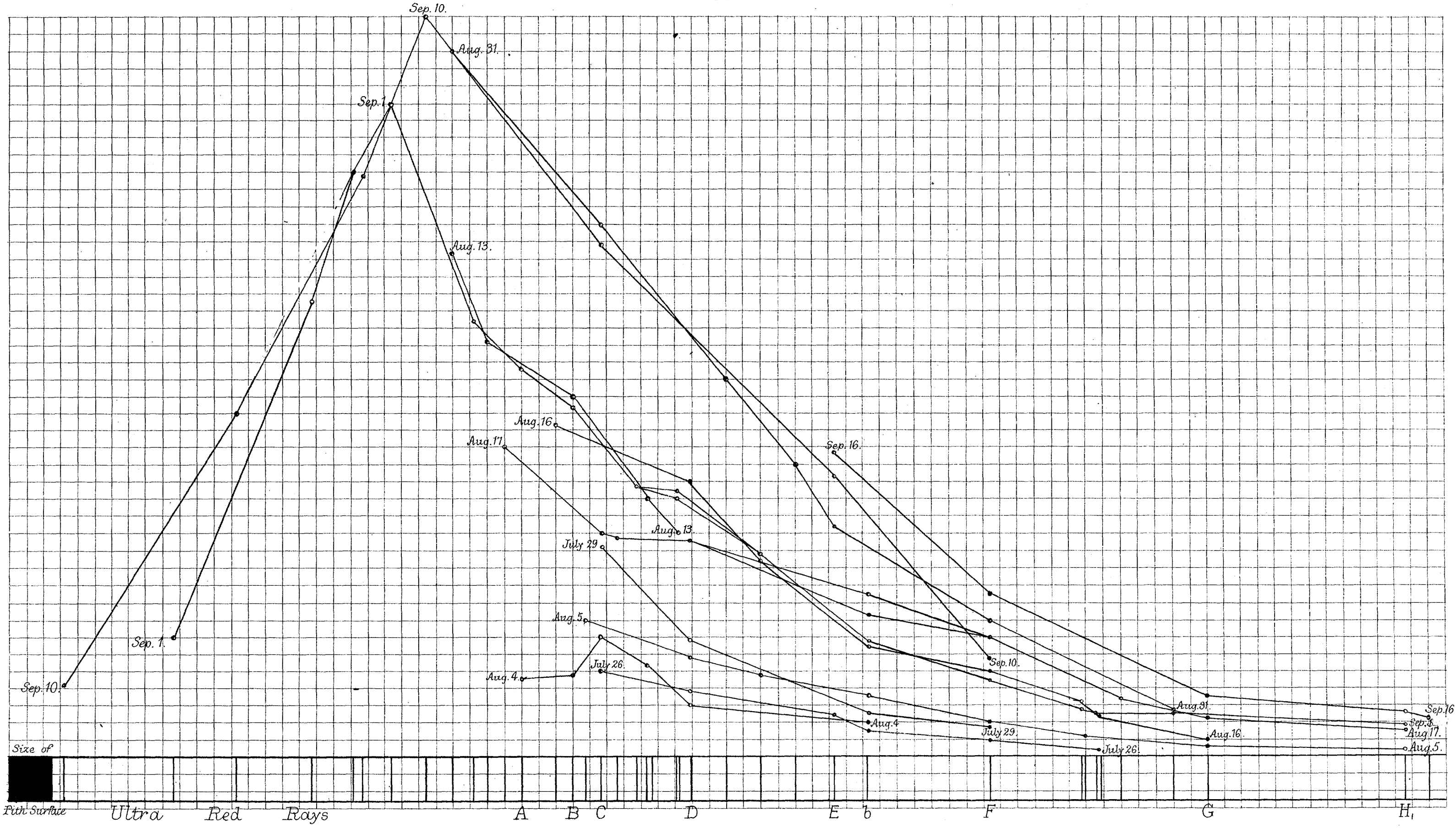


FIG. 14.



(*Reduced to one-half the linear Scale.*)

W. West & C^o, lith.

FIG. 7.

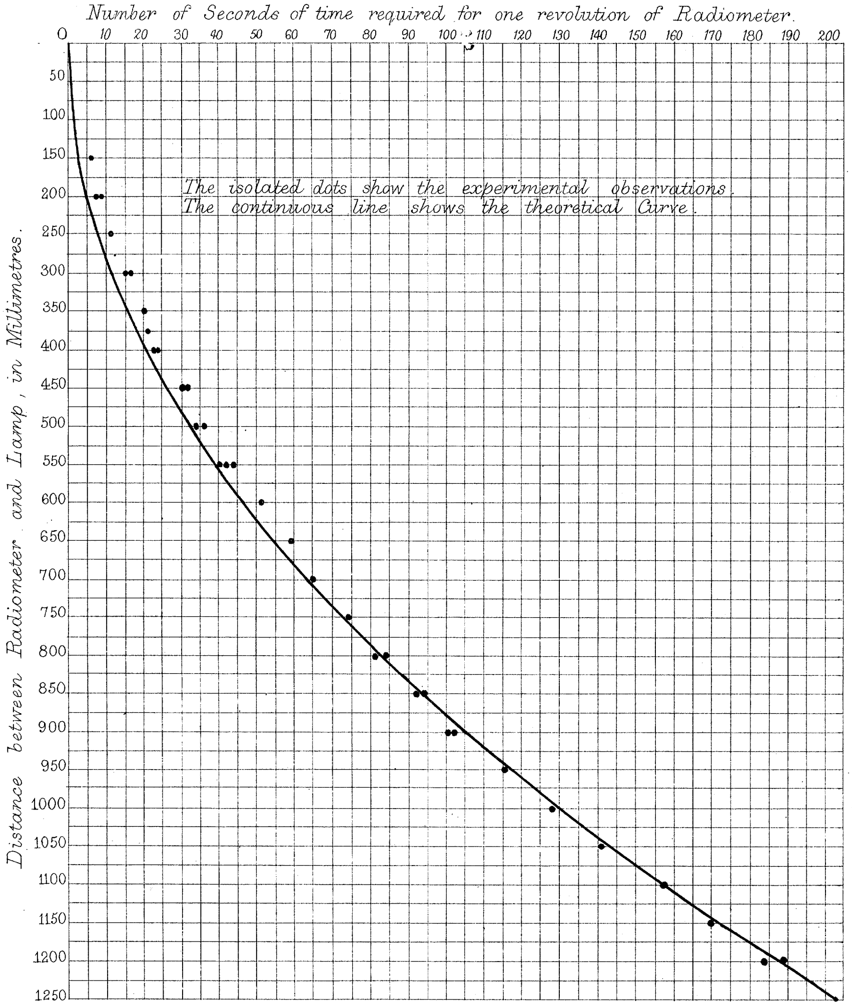


FIG. 15.

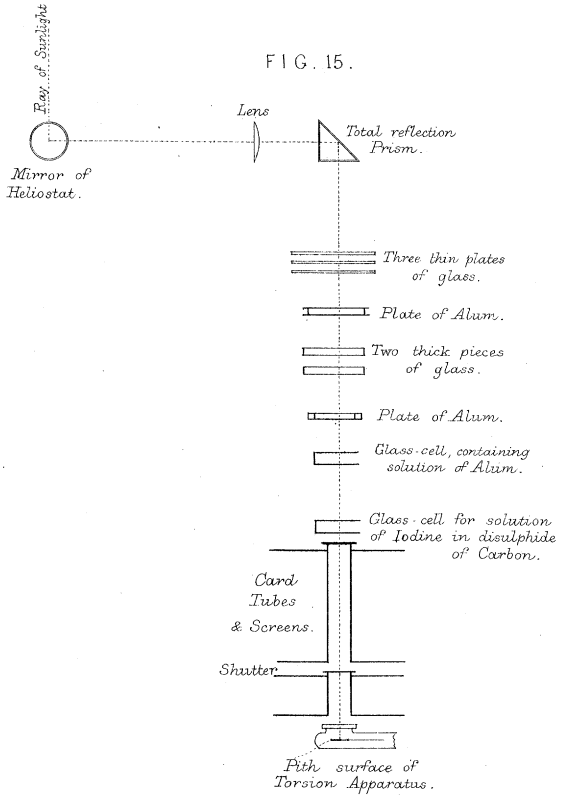


FIG. 8.