ON RADIATION.

THE "REDE" LECTURE, DELIVERED IN THE SENATE-HOUSE, BEFORE THE UNIVERSITY OF CAMBRIDGE, ENGLAND, ON TUESDAY, MAY 16, 1865.

BY

JOHN TYNDALL, F.R.S.,

PROFESSOR OF NATURAL PHILOSOPHY IN THE ROYAL INSTITUTION AND IN THE ROYAL SCHOOL OF MINES.

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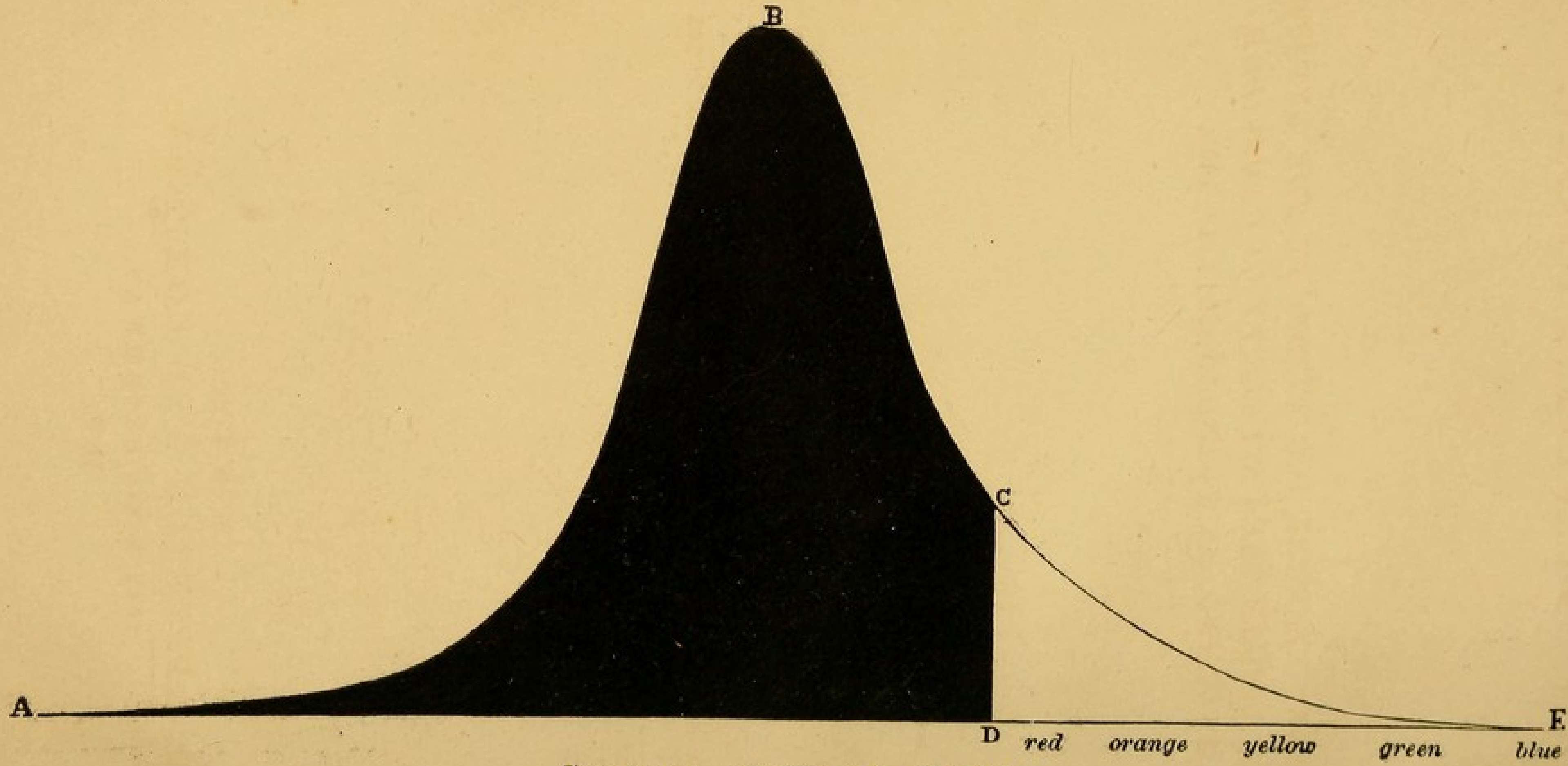

Spectrum of Electric Light.

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CONTENTS.

ON RADIATION.

1. *Visible and Invisible Radiation.*

BETWEEN the mind of man and the outer world are interposed the nerves of the human body, which translate, or enable the mind to translate, the impressions of that world into facts of consciousness and thought.

Different nerves are suited to the perception of different impressions. We do not see with the ear, nor hear with the eye, nor are we rendered sensible of sound by the nerves of the tongue. Out of the general assemblage of physical actions, each nerve, or group of nerves, selects and responds to those for the perception of which it is specially organized.

The optic nerve passes from the brain to the back of the eye-ball and there spreads out, to form the retina, a web of nerve filaments, on which the images of external objects are projected by the optical portion of the eye. This nerve is limited to the apprehension of the phenomena of radiation, and notwithstanding its marvellous sensibility to certain impressions of this class, it is singularly obtuse to other impressions.

Nor does the optic nerve embrace the entire range even of radiation. Some rays, when they reach it, are incompetent to evoke its power, while others never reach it at all, being absorbed by the humours of the eye. To all rays which, whether they reach the retina or not, fail to excite vision, we give the name of invisible or obscure rays. All non-luminous bodies emit such rays. There is no body in nature absolutely cold, and every body not absolutely cold emits rays of heat. But to render radiant heat fit to affect the optic nerve a certain temperature is necessary. A cool poker thrust into a fire remains dark for a time, but when its temperature has become equal to that of the surrounding coals it glows like them. In like manner, if a current of electricity of gradually increasing strength be sent through a wire of the refractory metal platinum, the wire first becomes sensibly warm to the touch; for a time its heat augments, still, however, remaining obscure; at length we can no longer touch the metal with impunity; and at a certain definite temperature it emits a feeble red light. As the current augments in power the light augments in brilliancy, until finally the wire appears of a dazzling white. The light which it now emits is similar to that of the sun.

By means of a prism, Sir Isaac Newton unravelled the texture of solar light, and by the same simple instrument we can investigate the luminous changes of our platinum wire. In passing through the prism all its rays (and they are infinite in variety) are bent or refracted from their straight course; and as different rays are differently refracted by the prism, we are by it enabled to separate one class of rays from another. By such prismatic analysis Dr. Draper has shown, that when the platinum wire first begins to glow, the light emitted is a pure red. As the glow augments the red becomes more brilliant, but at the same time orange rays are added to the emission. Augmenting the temperature still further, yellow rays appear beside the orange, after the yellow, green rays are emitted, and after the green come, in succession, blue, indigo, and violet rays. To display all these colours at the same time the platinum wire must be *white-hot:* the impression of whiteness being in fact produced by the simultaneous action of all these colours on the optic nerve.

In the experiment just described we began with a platinum wire at an ordinary temperature, and gradually raised it to a white heat. At the beginning, and before the electric current had acted at all upon the wire, it emitted invisible rays. For some time after the action of the current had commenced, and even for a time after the wire had become intolerable to the touch, its radiation was still invisible. The question now arises: What becomes of these invisible rays when the visible ones makes their appearance? It will be proved in the sequel that they maintain themselves in the radiation; that a ray once emitted continues to be emitted when the temperature is increased, and hence the emission from our platinum wire, even when it has attained its maximum brilliancy, consists of a mixture of visible and invisible rays. If, instead of the platinum wire, the earth itself were raised to incandescence, the obscure radiation which it now emits would continue to be emitted. To reach incandescence the planet would have to pass through all the stages of non-luminous radiation, and the final emission would embrace the rays of all these stages. There can hardly be a doubt that from the sun itself, rays proceed similar in kind to those which the dark earth pours nightly into space. In fact, the various kinds of obscure rays emitted by all the planets of our system are included in the present radiation of the sun.

The great pioneer in this domain of science was Sir William Herschel. Causing a beam of solar light to pass through a prism he resolved it into its coloured constituents; he formed what is technically called the solar spectrum. Exposing thermometers to the successive colours he determined their heating power, and found it to augment from the violet or most refracted end, to the red or least refracted end of the spectrum. But he did not stop here. Pushing his thermometers into the dark space beyond the red, he found that, though the light had disappeared, the radiant heat falling on the instruments was more intense than that at any visible part of the spectrum. In fact, Sir William Herschel showed, and his results have been verified by various philosophers since his time, that besides its luminous rays, the sun pours forth a multitude of other rays more powerfully calorific than the luminous ones, but entirely unsuited to the purposes of vision.

At the less refrangible end of the solar spectrum, then, the range of the sun's radiation is not limited by that of the eye. The same statement applies to the more refrangible end. Ritter discovered the extension of the spectrum into the invisible region beyond the violet; and, in recent times, this ultra-violet emission has had peculiar interest conferred upon it by the admirable researches of Professor Stokes. The complete spectrum of the sun consists, therefore, of three distinct parts:—1° Of ultra-red rays of high heating power, but unsuited to the purposes of vision; 2° Of luminous rays which display the following succession of colours: red, orange, yellow, green, blue, indigo, violet; 3° Of ultra-violet rays which, like the ultra-red ones, are incompetent to excite vision, but unlike them possess a very feeble heating power. In consequence, however, of their chemical energy these ultra-violet rays are of the utmost importance to the organic world.

2. *Origin and Character of Radiation. The Ether.*

When we see a platinum wire raised gradually to a white heat, and emitting in succession all the colours of the spectrum, we are simply conscious of a series of changes in the condition of our eyes. We do not see the actions in which these successive colours originate, but the mind irresistibly infers that the appearance of the colours corresponds to certain contemporaneous changes in the wire. What is the nature of these changes? In virtue of what condition does the wire radiate at all? We must now look from the wire as a whole to its constituent atoms. Could we see those atoms, even before the electric current has begun to act upon them, we should find them in a state of vibration. In this vibration indeed consists such warmth as the wire then possesses. Locke enunciated this idea with great precision, and it seems placed beyond the pale of doubt by the excellent quantitative researches of Mr. Joule. "Heat," says Locke, "is a very brisk agitation of the insensible parts of the object, which produce in us that sensation from which we denominate the object hot: so what in our sensation is *heat* in the object is nothing but *motion*." When the electric current, still feeble, begins to pass through the wire, its first act is to intensify the vibrations already existing, by causing the atoms to swing through wider ranges. Technically speaking, the *amplitudes* of the oscillations are increased. The current does this, however, without altering the *period* of the old vibrations, or the time in which they were accomplished. But, besides intensifying the old vibrations, the current generates new and more rapid ones, and when a certain definite rapidity has been attained the wire begins to glow. The colour first exhibited is red, which corresponds to the lowest rate of vibration of which the eye is able to take cognizance. By augmenting the strength of the electric current, more rapid vibrations are introduced, and orange rays appear. A quicker rate of vibration produces yellow, a still quicker green, and by further augmenting the rapidity we pass through blue, indigo, and violet, to the extreme ultra-violet rays.

Such are the changes which science recognizes in the wire itself, as concurrent with the visual changes taking place in the eye. But what connects the wire with this organ? By what means does it send such intelligence of its varying condition to the optic nerve? Heat being, as defined by Locke, "a very brisk agitation of the insensible parts of an object," it is readily conceivable that on *touching* a heated body the agitation may communicate itself to the adjacent nerves, and announce itself to them as light or heat. But the optic nerve does not touch the hot platinum, and hence the pertinence of the question, By what agency are the vibrations of the wire transmitted to the eye?

The answer to this question involves, perhaps, the most important physical conception that the mind of man has yet achieved; the conception of a medium filling space and fitted mechanically for the transmission of the vibrations of light and heat, as air is fitted for the transmission of sound. This medium is called the *luminiferous ether.* Every shock of every atom of our platinum wire raises in this ether a wave, which speeds through it at the rate of 186,000 miles a second. The ether suffers no rupture of continuity at the surface of the eye, the inter-molecular spaces of the various humours are filled with it; hence the waves generated by the glowing platinum can cross these humours and impinge on the optic nerve at the back of the eye. Thus the sensation of light reduces itself to the communication of motion. Up to this point we deal with pure mechanics; but the subsequent translation of the shock of the ethereal waves into consciousness eludes the analysis of science. As an oar dipping into the Cam generates systems of waves, which, speeding from the centre of disturbance, finally stir the sedges on the river's bank, so do the vibrating atoms generate in the surrounding ether undulations, which finally stir the filaments of the retina. The motion thus imparted is transmitted with measurable, and not very great velocity to the brain, where, by a process which science does not even tend to unravel, the tremor of the nervous matter is converted into the conscious impression of light.

Darkness might then be defined as ether at rest; light as ether in motion. But in reality the ether is never at rest, for in the absence of light-waves we have heat-waves always speeding through it. In the spaces of the universe both classes of undulations incessantly commingle. Here the waves issuing from uncounted centres cross, coincide, oppose, and pass through each other, without confusion or ultimate extinction. The waves from the zenith do not jostle out of existence those from the horizon, and every star is seen across the entanglement of wave motions produced by all other stars. It is the ceaseless thrill which those distant orbs collectively create in the ether, which constitutes what we call *the temperature of space.* As the air of a room accommodates itself to the requirements of an orchestra, transmitting each vibration of every pipe and string, so does the inter-stellar ether accommodate itself to the requirements of light and heat. Its waves mingle in space without disorder, each being endowed with an individuality as indestructible as if it alone had disturbed the universal repose.

All vagueness with regard to the use of the terms *radiation* and *absorption* will now disappear. Radiation is the communication of vibratory motion to the ether, and when a body is said to be chilled by radiation, as, for example, the grass of a meadow on a starlight night, the meaning is, that the molecules of the grass have lost a portion of their motion, by imparting it to the medium in which they vibrate. On the other hand, the waves of ether once generated may so strike against the molecules of a body exposed to their action as to yield up their motion to the latter; and in this transfer of the motion from the ether to the molecules consists the absorption of radiant heat. All the phenomena of heat are in this way reducible to interchanges of motion; and it is purely as the recipients or the donors of this motion, that we ourselves become conscious of the action of heat and cold.

3. *The Atomic Theory in Reference to the Ether.*

The word "atoms" has been more than once employed in this discourse. Chemists have taught us that all matter is reducible to certain elementary forms to which they give this name. These atoms are endowed with powers of mutual attraction, and under suitable circumstances they coalesce to form compounds. Thus oxygen and hydrogen are elements when separate, or merely *mixed*, but they may be made to *combine* so as to form molecules, each consisting of two atoms of hydrogen and one of oxygen. In this condition they constitute water. So also chlorine and sodium are elements, the former a pungent gas, the latter a soft metal; and they unite together to form chloride of sodium or common salt. In the same way the element nitrogen combines with hydrogen, in the proportion of one atom of the former to three of the latter, to form ammonia, or spirit of hartshorn. Picturing in imagination the atoms of elementary bodies as little spheres, the molecules of compound bodies must be pictured as groups of such spheres. This is the atomic theory as Dalton conceived it. Now, if this theory have any foundation in fact, and if the theory of an ether pervading space, and constituting the vehicle of atomic motion be founded in fact, we may assuredly expect the vibrations of elementary bodies to be profoundly modified by the act of combination. It is on the face of it almost certain that both as regards radiation and absorption, that is to say, both as regards the communication of motion to the ether and the acceptance of motion from it, the deportment of the uncombined will be different from that of the combined atoms.

4. *Absorption of Radiant Heat by Gases.*

We have now to submit these considerations to the only test by which they can be tried, namely, that of experiment. An experiment is well defined as a question put to Nature; but to avoid the risk of asking amiss we ought to purify the question from all adjuncts which do not necessarily belong to it. Matter has been shown to be composed of elementary constituents, by the compounding of which all its varieties are produced. But besides the chemical unions which they form, both elementary and compound bodies can unite in another and less intimate way. By the attraction of cohesion gases and vapours aggregate to liquids and solids, without any change of their chemical nature. We do not yet know how the transmission of radiant heat may be affected by the entanglement due to cohesion, and as our object now is to examine the influence of chemical union alone, we shall render our experiments more pure by liberating the atoms and molecules entirely from the bonds of cohesion, and employing them in the gaseous or vapourous form.

Let us endeavour to obtain a perfectly clear mental image of the problem now before us. Limiting in the first place our enquiries to the phenomena of absorption, we have to picture a succession of waves issuing from a radiant source and passing through a gas; some of them striking against the gaseous molecules and yielding up their motion to the latter; others gliding round the molecules, or passing through the inter-molecular spaces without apparent hindrance. The problem before us is to determine whether such free molecules have any power whatever to stop the waves of heat, and if so, whether different molecules possess this power in different degrees.

The source of waves which I shall choose for these experiments is a plate of copper, against the back of which a steady sheet of flame is permitted to play. On emerging from the copper, the waves, in the first instance, pass through a space devoid of air, and then enter a hollow glass cylinder, three feet long and three inches wide. The two ends of this cylinder are stopped by two plates of rock salt, this being the only solid substance which offers a scarcely sensible obstacle to the passage of the calorific waves. After passing through the tube, the radiant heat falls upon the anterior face of a thermo-electric pile, where it is instantly applied to the generation of an electric current. This current conducted round a magnetic needle deflects it, and the magnitude of the deflection is a measure of the heat falling upon the pile. This famous instrument, and not an ordinary thermometer, is what we shall use in these enquiries, but we shall use it in a somewhat novel way. As long as the two opposite faces of the thermo-electric pile are kept at the same temperature, no matter how high that may be, there is no current generated. The current is a consequence of a *difference* of temperature between the two opposite faces of the pile. Hence, if after the anterior face has received the heat from our radiating source, a second source, which we may call the compensating source, be permitted to radiate against the posterior face, this latter radiation will tend to neutralize the former. When the neutralization is perfect, the magnetic needle connected with the pile is no longer deflected, but points to the zero of the graduated circle over which it hangs.

And now let us suppose the glass tube, through which pass the waves from the heated plate of copper, to be exhausted by an air-pump, the two sources of heat acting at the same time on the two opposite faces of the pile. Perfectly equal quantities of heat being imparted to the two faces, the needle points to zero. Let the molecules of any gas be now permitted to enter the exhausted tube; if these molecules possess any sensible power of intercepting the calorific waves, the equilibrium previously existing will be destroyed, the compensating source will triumph, and a deflection of the magnetic needle will be the immediate consequence. From the deflections thus produced by different gases, we can readily deduce the relative amounts of wave motion which their molecules inteceupt.

In this way the substances mentioned in the following table were examined, a small portion only of each being admitted into the glass tube. The quantity admitted was just sufficient to depress a column of mercury associated with the tube one inch: in other words, the gases were examined at a pressure of one-thirtieth of an atmosphere. The numbers in the table express the relative amounts of wave motion absorbed by the respective gases, the quantity intercepted by atmospheric air being taken as unity.

Radiation through Gases.

Name of Gas.	Relative Absorption.
Air	1
Oxygen	1
Nitrogen	1
Hydrogen	1
Carbonic Oxide	750

Name of Gas.	Relative Absorption.
Carbonic Acid	972
Hydrochloric Acid	1005
Nitric Oxide	1590
Nitrous Oxide	1860
Sulphide of Hydrogen	2100
Ammonia	5460
Olefiant Gas	6030
Sulphurous Acid	6480

Every gas in this table is perfectly transparent to light, that is to say, all waves within the limits of the visible spectrum pass through it without obstruction; but for the waves of slower period, emanating from our heated plate of copper, enormous differences of absorptive power are manifested. These differences illustrate in the most unexpected manner the influence of chemical combination. Thus the elementary gases, oxygen, hydrogen, and nitrogen, and the mixture atmospheric air, prove to be practical vacua to the rays of heat; for every ray, or more strictly speaking, for every unit of wave motion, which any one of them is competent to intercept, perfectly transparent ammonia intercepts 5460 units, olefiant gas 6030 units, while sulphurous acid gas absorbs 6480 units. What becomes of the wave motion thus intercepted? It is applied to the heating of the absorbing gas. Through air, oxygen, hydrogen, and nitrogen, on the contrary, the waves of ether pass without absorption, and these gases are not sensibly changed in temperature by the most powerful calorific rays. The position of nitrous oxide in the foregoing table is worthy of particular notice. In this gas we have the same atoms in a state of chemical union, that exist uncombined in the atmosphere; but the absorption of the compound is 1800 times that of the air.

5. *Formation of Invisible Foci.*

This extraordinary deportment of the elementary gases naturally directed attention to elementary bodies in another state of aggregation. Some of Melloni's results now attained a new significance; for this celebrated experimenter had found crystals of the element sulphur to be highly pervious to radiant heat; he had also proved that lamp black and black glass (which owes its blackness to the element carbon) were to a considerable extent transparent to calorific rays of low refrangibility. These facts, harmonizing so strikingly with the deportment of the simple gases, suggested further enquiry. Sulphur dissolved in bisulphide of carbon was found almost perfectly transparent. The dense and deeply coloured element bromine was examined, and found competent to cut off the light of our most brilliant flames, while it transmitted the invisible calorific rays with extreme freedom. Iodine, the companion element of bromine, was next thought of, but it was found impracticable to examine the substance in its usual solid condition. It however dissolves freely in bisulphide of carbon. There is no chemical union between the liquid and the iodine, it is simply a case of solution, in which the uncombined atoms of the element can act upon the radiant heat. When permitted to do so, it was found that a layer of dissolved iodine, sufficiently opaque to cut off the light of the mid-day sun, was almost absolutely transparent to all invisible calorific rays.

By prismatic analysis, Sir William Herschel separated the luminous from the non-luminous rays of the sun, and he also sought to render the obscure rays visible by concentration. Intercepting the luminous portion of his spectrum he brought, by a converging lens, the ultra-red rays to a focus, but by this condensation he obtained no light. The solution of iodine offers a means of filtering the solar beam, or failing it, the beam of the electric lamp, which renders attainable more powerful foci of invisible rays than could possibly be obtained in the above experiment by Sir William Herschel. For to form his spectrum he was obliged to operate upon solar light which had passed through a narrow slit or through a small aperture, the amount of the obscure heat admitted being limited by this circumstance. But with our opaque solution we may employ the entire surface of the largest lens, and having thus converged the rays, luminous and non-luminous, we can intercept the former by the iodine, and do what we please with the latter. Experiments of this character, not only with the iodine solution, but also with black glass and layers of lamp black, were publicly performed at the Royal Institution in the early part of 1862, and the effects at the foci of invisible rays then obtained were such as had never been witnessed previously.

In the experiments here referred to, glass lenses were employed to concentrate the rays. But glass, though highly transparent to the luminous, is in a high degree opaque to the invisible heat-rays of the electric lamp, and hence a large portion of those rays was intercepted by the glass. The obvious remedy here is to employ rock salt lenses instead of glass ones, or to abandon the use of lenses wholly, and to concentrate the rays by a metallic mirror. Both of these improvements have been introduced, and, as anticipated, the invisible foci have been thereby rendered more intense. The mode of operating remains however the same, in principle, as that made known in 1862. It was then found that an instant's exposure of the face of the thermo-electric pile to the focus of invisible rays, dashed the needles of a coarse galvanometer violently aside. It is now found that on substituting for the face of the thermo-electric pile a combustible body, the invisible rays are competent to set that body on fire.

6. *Visible and Invisible Rays of the Electric Light.*

We have next to examine what proportion the non-luminous rays of the electric light bear to the luminous ones. This the opaque solution of iodine enables us to do with an extremely close approximation to the truth. The pure bisulphide of carbon, which is the solvent of the iodine, is perfectly transparent to the luminous, and almost perfectly transparent to the dark rays of the electric lamp. Through the transparent bisulphide the total radiation of the lamp may be considered to pass, while through the solution of iodine only the dark rays are transmitted. Determining, then, by means of a thermo-electric pile, the total radiation, and deducting from it the purely obscure, we obtain the amount of the purely luminous emission. Experiments, performed in this way, prove that if all the visible rays of the electric light were converged to a focus of dazzling brilliancy, its heat would only be one-ninth of that produced at the unseen focus of the invisible rays.

Exposing his thermometers to the successive colours of the solar spectrum, Sir William Herschel determined the heating power of each, and also that of the region beyond the extreme red. Then drawing a straight line to represent the length of the spectrum, he erected, at various points, perpendiculars to represent the calorific intensity existing at those points. Uniting the ends of all his perpendiculars, he obtained a curve which showed at a glance the manner in which the heat was distributed in the solar spectrum. Professor Müller, of Freiburg, with improved instruments, afterwards made similar experiments, and constructed a more accurate diagram of the same kind. We have now to examine the distribution of heat in the spectrum of the electric light; and for this purpose we shall employ a particular form of the thermo-electric pile, devised by Melloni. Its face is a rectangle, which, by means of moveable side pieces, can be rendered as narrow as desired. We can, for example, have the face of the pile the tenth, the hundredth, or even the thousandth of an inch in breadth. By means of an endless screw, this *linear* thermo-electric pile may be moved through the entire spectrum, each of its rays being selected in succession, the amount of heat falling upon the pile at every point of its march being declared by an associated magnetic needle.

When this instrument is brought up to the violet end of the spectrum of the electric light, the heat is found to be insensible. As the pile gradually moves from the violet end towards the red, heat soon manifests itself, augmenting as we approach the red. Of all the colours of the visible spectrum the red possesses the highest heating power. On pushing the pile into the dark region beyond the red, the heat, instead of vanishing, rises suddenly and enormously in intensity, until at some distance beyond the red it attains a maximum. Moving the pile still forward, the thermal power falls, somewhat more suddenly than it rose. It then gradually shades away, but for a distance beyond the red greater than the length of the whole visible spectrum, signs of heat may be detected. Drawing, as Sir William Herschel did, a datum line, and erecting along it perpendiculars, proportional in length to the thermal intensity at the respective points, we obtain the extraordinary curve which exhibits the distribution of heat in the spectrum of the electric light. In the region of dark rays beyond the red the curve shoots up in a steep and massive peak—a kind of Matterhorn of heat, which dwarfs by its magnitude the portion of the diagram representing the luminous radiation. Indeed, the idea forced upon the mind by the inspection of this diagram is that the light rays are a mere insignificant appendage to the dark ones, thrown in as it were by nature for the purposes of vision. (See Frontispiece, where the space *ABCD* represents the non-luminous, and *CDE* the luminous radiation.)

The diagram drawn by Professor Müller to represent the distribution of heat in the solar spectrum is not by any means so striking as that just described, and the reason, doubtless, is that prior to reaching the earth the solar rays have to traverse our atmosphere. The aqueous vapour there diffused acts very energetically upon the ultra red rays, and by it the summit of the peak representing the sun's invisible radiation is cut off. A similar lowering of the mountain of invisible heat is observed when the rays from the electric light are permitted to pass through a film of water, which acts upon them as the atmospheric vapour acts upon the rays of the sun.

7. *Combustion by Invisible Rays.*

The sun's invisible rays transcend the visible ones in heating power, so that if the alleged performances of Archimedes during the siege of Syracuse had any foundation in fact, the dark solar rays would have been the philosopher's chief agents of combustion. On a small scale we can readily produce with the purely invisible rays of the electric light all that Archimedes is said to have performed with the sun's total radiation. Placing behind the electric light a small concave mirror, the rays are converged, the cone of reflected rays and their point of convergence being rendered clearly visible by the dust always floating in the air. Interposing, between the luminous focus and the source of rays, our solution of iodine, the light of the cone is entirely cut away, but the intolerable heat experienced when the hand is placed, even for a moment, at the dark focus, shows that the calorific rays pass unimpeded through the opaque solution.

Almost any thing that ordinary fire can effect may be accomplished at the focus of invisible rays; the *air* at the focus remaining at the same time perfectly cold, on account of its transparency to the heat-rays. An air thermometer, with a hollow rock salt bulb, would be unaffected by the heat of the focus: there would be no expan sion, and in the open air there is no convection. The ether at the focus, and not the air, is the substance in which the heat is embodied. A block of wood, placed at the focus, absorbs the heat, and dense volumes of smoke rise swiftly upwards, showing the manner in which the air itself would rise, if the invisible rays were competent to heat it. At the perfectly dark focus dry paper is instantly inflamed: chips of wood are speedily burnt up: lead, tin, and zinc are fused: and discs of charred paper are raised to vivid incandescence. It might be supposed that the obscure rays would show no preference for black over white; but they do show a preference, and to obtain rapid combustion, the body, if not already black, ought to be blackened. When metals are to be burned, it is necessary to blacken or otherwise tarnish them, so as to diminish their reflective power. Blackened zinc foil, when brought into the focus of invisible rays, is instantly caused to blaze, and burns with its peculiar purple flame. Magnesium wire flattened, or tarnished magnesium ribbon, also bursts into splendid combustion. Pieces of charcoal suspended in a receiver full of oxygen are also set on fire: the dark rays after having passed through the receiver still possessing sufficient power to ignite the charcoal, and thus initiate the attack of the oxygen. If, instead of being plunged in oxygen, the charcoal be suspended in vacuo, it immediately glows at the place where the focus falls.

8. *Transmutation of Rays:** *Calorescence.*

Eminent experimenters were long occupied in demonstrating the substantial identity of light and radiant heat, and we have now the means of offering a new and striking proof of this identity. A concave mirror produces beyond the object which it reflects an inverted and magnified image of the object; withdrawing, for example, our iodine solution, an intensely luminous inverted image of the carbon points of the electric light is formed at the focus of the mirror employed in the foregoing experiments. When the solution is interposed and the light is cut away, what becomes of this image? It disappears from sight, but an invisible thermograph remains, and it is only the peculiar constitution of our eyes that disqualifies us from seeing the picture formed by the calorific rays. Falling on white paper, the image chars itself out: falling on black paper, two holes are pierced in it, corresponding to the images of the two coal points: but falling on a thin plate of carbon in vacuo, or upon a thin sheet of platinized platinum, either in vacuo or in air, radiant heat is converted into light, and the image stamps itself in vivid incandescence upon both the carbon and the metal. Results similar to those obtained with the electric light have also been obtained with the invisible rays of the lime light and of the sun.

Before a Cambridge audience, it is hardly necessary to refer to the excellent researches of Professor Stokes at the opposite end of the spectrum. The above results consti-

* I borrow this term from Professor Challis, *Philosophical Magazine*, Vol. xii., p. 521.

tute a kind of complement to his discoveries. Professor Stokes named the phenomena which he has discovered and investigated, *Fluorescence;* for the new phenomena here described, I have proposed the term *Calorescence.* He, by the interposition of a proper medium, so lowered the refrangibility of the ultra-violet rays of the spectrum as to render them visible; and here, by the interposition of the platinum foil, the refrangibility of the ultra-red rays is so exalted as to render them visible. Looking through a prism at the incandescent image of the carbon points, the light of the image is decomposed, and a complete spectrum obtained. The invisible rays of the electric light, remoulded by the atoms of the platinum, shine thus visibly forth; ultra-red rays being converted into red, orange, yellow, green, blue, indigo, and ultra-violet ones. Could we, moreover, raise the original source of rays to a sufficiently high temperature, we might not only obtain from the dark rays of such a source a single incandescent image, but from the dark rays of this image we might obtain a second one, from the dark rays of the second a third, and so on—a series of complete images and spectra being thus extracted from the invisible emission of the primitive source.*

* On investigating the calorescence produced by rays transmitted through glasses of various colours, it was found that in the case of certain specimens of blue glass the platinum foil glowed with a *pink* or *purplish* light. The effect was not subjective, and considerations of obvious interest are suggested by it. Different kinds of black glass differ notably as to their power of transmitting radiant heat. In thin plates some descriptions tint the sun with a greenish hue; others make it appear a glowing red without any trace of green. The latter are by far more diathermic than the former. In fact, carbon, when perfectly dissolved, and incorporated with a good white glass, is highly transparent to the calorific rays, and by employing it as an absorbent, the phenomena of "calorescence" may be obtained, though in a less striking form than with the iodine. The black glass chosen for thermometers, and intended to absorb completely the solar heat, may en-

9. *Deadness of the Optic Nerve to the Calorific Rays.*

The layer of iodine used in the foregoing experiments, when placed before the eye, intercepted the light of the noonday sun. No trace of light from the electric lamp was visible, even in the darkest room, when a white screen was placed at the focus of the mirror. It was thought, however, that if the retina itself were brought into the focus the sensation of light might be experienced. The danger of this experiment was twofold. If the dark rays were absorbed in a high degree by the humours of the eye, the albumen of the humours might coagulate along the line of the rays. If, on the contrary, no such high absorption took place, the rays might reach the retina with a force sufficient to destroy it. To test the likelihood of these results, experiments were made on water and on a solution of alum, and they showed it to be very improbable that in the brief time requisite for an experiment any serious damage could be done. The eye was, therefore, caused to approach the dark focus, no defence, in the first instance, being provided; but the heat acting upon the parts surrounding the pupil could not be borne. An aperture was therefore pierced in a plate of metal, and the eye, placed behind the aperture, was caused to approach the point of convergence of invisible rays. The focus was attained, first by the pupil and afterwards by the retina.

tirely fail in this object, if the glass in which the carbon is incorporated be colourless. To render the bulb of a thermometer a perfect absorbent, the glass with which the carbon is incorporated ought in the first instance to be green. Soon after the discovery of fluorescence, Dr. W. A. Miller pointed to the lime light as an illustration of exalted refrangibility. Direct experiments have since entirely confirmed the view expressed at page 210 of his work on *Chemistry*, published in 1855.

Removing the eye, but permitting the plate of metal to remain, a sheet of platinum foil was placed in the position occupied by the retina a moment before. The platinum became red hot. No sensible damage was done to the eye by this experiment; no impression of light was produced; the optic nerve was not even conscious of heat.

But the humours of the eye are known to be highly impervious to the invisible calorific rays, and the question therefore arises, "Did the radiation in the foregoing experiment reach the retina at all?" The answer is that the rays were in part transmitted to the retina, and in part absorbed by the humours. Experiments on the eye of an ox showed that the proportion of obscure rays which reached the retina amounted to eighteen per cent. of the total radiation; while the luminous emission from the electric light amounts to no more than ten per cent. of the same total. Were the purely luminous rays of the electric lamp converged by our mirror to a focus, there can be no doubt as to the fate of a retina placed there. Its ruin would be inevitable; and yet this would be accomplished by an amount of wave motion but little more than half of that which the retina bears without being conscious of it, at the focus of invisible rays.

This subject will repay a moment's further attention. At a common distance of a foot the visible radiation of the electric light is 800 times the light of a candle. At the same distance, that portion of the radiation of the electric light which reaches the retina but fails to excite vision, is about 1,500 times the luminous radiation of the candle.* But a candle on a clear night can readily be seen at a distance of a mile, its light at this distance being less than one 20,000,000th of its light at the distance of

* It will be borne in mind that the heat which any ray, luminous or non-luminous, is competent to generate, is the true measure of the energy of the ray.

a foot. Hence to make the former equal in power to the non-luminous radiation received from the electric light at a foot distance, its intensity would have to be multiplied by 1,500 × 20,000,000, or by thirty thousand millions. Thus the thirty thousand millionth part of the radiation from the electric light, received unconsciously by the retina at the distance of a foot, would, if slightly changed in character, be amply sufficient to provoke vision. Nothing could more forcibly illustrate that special relationship supposed by Melloni and others to subsist between the optic nerve and the oscillating periods of luminous bodies. Like a musical string, the optic nerve responds to the waves with which it is in consonance, while it refuses to be excited by others of almost infinitely greater energy, whose periods of recurrence are not in unison with its own.

10. *Persistence of Rays.*

At an early part of this Lecture it was affirmed that when a platinum wire was gradually raised to a state of high incandescence, new rays were constantly added, while the intensity of the old ones was increased. Thus in Dr. Draper's experiments the rise of temperature that *generated* the orange, yellow, green, and blue rays *augmented* the intensity of the red ones. What is true of the red is true of every other ray of the spectrum, visible and invisible. We cannot indeed *see* the augmentation of intensity in the region beyond the red, but we can measure it and express it numerically. With this view the following experiment was performed: A spiral of platinum wire was surrounded by a small glass globe to protect it from currents of air; through an orifice in the globe the rays could pass from the spiral and fall afterwards upon a thermo-electric pile. Placing in front of the orifice an opaque solution of iodine, the platinum was gradually raised from a low dark heat to the fullest incandescence, with the following results:

Appearance of Spiral.	Energy of Obscure Radiation.
Dark	1
Dark, but hotter	3
Dark, but still hotter	5
Dark, but still hotter	10
Feeble red	19
Dull red	25
Red	37
Full red	62
Orange	89
Bright Orange	144
Yellow	202
White	276
Intense White	440

Thus the augmentation of the electric current, which raises the wire from its primitive dark condition to an intense white heat, exalts at the same time the energy of the obscure radiation, until at the end it is fully 440 times what it was at the beginning.

What has been here proved true of the totality of the ultra-red rays is true for each of them singly. Placing our linear thermo-electric pile in any part of the ultra-red spectrum, it may be proved that a ray once emitted continues to be emitted with increased energy as the temperature is augmented. The platinum spiral so often referred to being raised to whiteness by an electric current, a brilliant spectrum was formed from its light. A linear thermo-electric pile was placed in the region of obscure rays beyond the red, and by diminishing the current the spiral was reduced to a low temperature. It was then caused to pass through various degrees of darkness and incandescence, with the following results:

Appearance of Spiral.	Energy of Obscure Rays.
Dark	1
Dark	6
Faint Red	10
Dull Red	13
Red	18
Full Red	27
Orange	60
Yellow	93
Full White	122

Here, as in the former case, the dark and bright radiation reached their maximum together; as the one augmented, the other augmented, until at last the energy of the obscure rays of the particular refrangibility here chosen, became 122 times what it was at first. To reach a white heat the wire has to pass through all the stages of invisible radiation, and in its most brilliant condition it still embraces, in an intensified form, the rays of all those stages.

And thus it is with all other kinds of matter, as far as they have hitherto been examined. Coke, whether brought to a white heat by the electric current, or by the oxyhydrogen jet, pours out invisible rays with augmented energy as its light is increased. The same is true of lime, bricks, and other substances. It is true of all metals which are capable of being heated to incandescence. It also holds good for phosphorous burning in oxygen. Every gush of dazzling light has associated with it a gush of invisible radiant heat, which far transcends the light in energy. This condition of things applies to all bodies capable of being raised to a white heat, either in the solid or the molten condition. It would doubtless also apply to the luminous fogs formed by the condensation of incandescent vapours. In such cases when the curve representing the radiant energy of the body is constructed, the obscure radiation towers upwards like a mountain, the luminous radiation resembling a mere spur at its base.

What, then, is the real origin of the luminous radiation? We find it appearing when the radiating body has attained a certain temperature; or, in other words, when the vibrating atoms of the body have attained a certain width of swing. In solid and molten bodies a certain amplitude cannot be surpassed without the introduction of periods of vibration, which provoke the sense of vision. If permitted to speculate, one might ask, are not these more rapid vibrations the product of the slower? Is it not really the mutual action of the atoms, when they swing through very wide spaces, and thus encroach upon each other, that causes them to tremble in quicker periods? If so, it matters not by what agency the large swinging space is obtained; we shall have light-giving vibrations associated with it. It matters not whether the large amplitudes are produced by the strokes of a hammer, or by the blows of the molecules of a non-luminous gas, such as the air at some height above a gas-flame; or by the shock of the ether particles when transmitting radiant heat. The result in all cases will be incandescence. Thus, the invisible waves of our filtered electric beam, with which incandescence has been produced, may be regarded as generating synchronous vibrations in the platinum on which they impinge; but once these vibrations attain a certain amplitude, the mutual jostling of the atoms would produce quicker tremors, and the light-giving waves would follow as the necessary progeny of the heat-giving vibrations. From the very brightness of the light of some of the fixed stars we may infer the intensity of the dark radiation, which is the precursor and inseparable associate of thelr luminous rays.

11. *Absorption of Radiant Heat by Vapours and Odours.*

We commenced the demonstrations brought forward in this Lecture by experiments on permanent gases, and we have now to turn our attention to the vapours of volatile liquids. Here, as in the case of the gases, vast differences have been proved to exist between various kinds of molecules, as regards their power of intercepting the calorific waves. While some vapours allow the waves a comparatively free passage, in other cases the minutest bubble of vapour, introduced into the tube already employed for gases, causes a deflection of the magnetic needle. Assuming the absorption effected by air at a pressure of one atmosphere to be unity, the following are the absorptions effected by a series of vapours at a pressure of $\frac{1}{60}$th of an atmosphere:

Name of Vapour.	Absorption.
Bisulphide of Carbon	47
Iodide of Methyl	115
Benzol	136
Amylene	321
Sulphuric Ether	440
Formic Ether	548
Acetic Ether	612

Bisulphide of carbon is the most transparent vapour in this list, and acetic ether the most opaque; $\frac{1}{60}$th of an atmosphere of the former, however, produces 47 times the effect of a whole atmosphere of air, while $\frac{1}{60}$th of an atmosphere of the latter produces 612 times the effect of a whole atmosphere of air. Reducing dry air to the pressure of the acetic ether here employed, and comparing them then together, the quantity of wave-motion intercepted by the latter would be many thousand times that intercepted by the air.

Any one of these vapours discharged in the free atmosphere, in front of a body emitting obscure rays, intercepts more or less of the radiation. A similar effect is produced by perfumes diffused in the air, though their attenuation is known to be almost infinite. Carrying, for example, a current of dry air over bibulous paper moistened by patchouli, the scent taken up by the current absorbs 30 times the quantity of heat intercepted by the air which carries it; and yet patchouli acts more feebly on radiant heat than any other perfume yet examined. Here follow the results obtained with various essential oils, the odour, in each case, being carried by a current of dry air into the tube already employed for gases and vapours:

Name of Perfume.	Absorption.
Patchouli	30
Sandal Wood	32
Geranium	33
Oil of Cloves	34
Otto of Roses	37
Bergamot	44
Neroli	47
Lavender	60
Lemen	65
Portugal	67
Thyme	68
Rosemary	74
Oil of Laurel	80
Camomile Flowers	87
Cassia	109
Spikenard	355
Aniseed	372

Thus the absorption by a tube full of dry air being 1, that of the odour of patchouli diffused in it is 30, that of lavender 60, that of rosemary 74, while that of aniseed amounts to 372. It would be idle to speculate on the quantities of matter concerned in these actions.

12. *Aqueous Vapour in Relation to Terrestrial Temperatures.*

We are now fully prepared for a result which, without such preparation, might appear incredible. Water is, to some extent, a volatile body, and our atmosphere, resting as it does upon the surface of the ocean, receives from it a continual supply of aqueous vapour. It would be an error to confound clouds of fog or any visible mist with the vapour of water: this vapour is a perfectly impalpable gas, diffused, even on the clearest days, throughout the atmosphere. Compared with the great body of the air, the aqueous vapor it contains is of almost infinitesimal amount, 99½ out of every 100 parts of the atmosphere being composed of oxygen and nitrogen. In the absence of experiment, we should never think of ascribing to this scant and varying constituent any important influence on terrestrial radiation; and yet its influence is far more potent than that of the great body of the air. To say that on a day of average humidity in England, the atmospheric vapour exerts 100 times the action of the air itself, would certainly be an understatement of the fact. The peculiar qualities of this vapour, and the circumstance that at ordinary temperatures it is very near its point of condensation, render the results which it yields in the apparatus already described, less than the truth; and I am not prepared to say that the absorption by this substance is not 200 times that of the air in which it is diffused. Comparing a single molecule of aqueous vapour with an atom of either of the main constituents of our atmosphere, I am not prepared to say how many thousand times the action of the former exceeds that of the latter.

These large numbers depend in part upon the extreme feebleness of the air; the power of aqueous vapour seems vast, because that of the air with which it is compared is infinitesimal. Absolutely considered, however, this substance exercises a very potent action. Probably a column of ordinary air ten feet long would intercept from 10 to 15 per cent. of the heat radiated from an obscure source, and I think it certain that the larger of these numbers fails to express the absorption of the terrestrial rays, effected within ten feet of the earth's surface. This is of the utmost consequence to the life of the world. Imagine the superficial molecules of the earth trembling with the motion of heat, and imparting it to the surrounding ether; this motion would be carried rapidly away, and lost forever to our planet, if the waves of ether had nothing but the air to contend with in their outward course. But the aqueous vapour takes up the motion of the ethereal waves, and becomes thereby heated, thus wrapping the earth like a warm garment, and protecting its surface from the deadly chill which it would otherwise sustain. Various philosophers have speculated on the influence of an atmospheric envelope. De Saussure, Fourier, M. Pouillet, and Mr. Hopkins have, one and all, enriched scientific literature with contributions on this subject, but the considerations which these eminent men have applied to atmospheric air have now to be transferred to aqueous vapour.

The observations of meteorologists furnish important, though hitherto unconscious, evidence of the influence of this agent. Wherever the air is dry we are liable to daily extremes of temperature. By day, in such places, the sun's heat reaches the earth unimpeded and renders the maximum high; by night, on the other hand, the earth's heat escapes unhindered into space and renders the minimum low. Hence the difference between the maximum and minimum is greatest where the air is driest. In the plains of India, on the heights of the Himalaya, in Central Asia, in Australia—wherever drought reigns, we have the heat of day forcibly contrasted with the chill of night. In the Sahara itself, when the sun's rays cease to impinge on the burning soil, the temperature runs rapidly down to freezing, because there is no vapour overhead to check the calorific drain. And here another instance might be added to the numbers already known, in which nature tends as it were to check her own excess. By nocturnal refrigeration, the aqueous vapour of the air is condensed to water on the surface of the earth, and as only the superficial portions radiate, the act of condensation makes water the radiating body. Now experiment proves that to the rays emitted by water, aqueous vapour is especially opaque. Hence the very act of condensation, consequent on terrestrial cooling, becomes a safeguard to the earth, imparting to its radiation that particular character which renders it most liable to be prevented from escaping into space.

It might, however, be urged that, inasmuch as we derive all our heat from the sun, the self-same covering which protects the earth from chill must also shut out the solar radiation. This is partially true, but only partially; the sun's rays are different in quality from the earth's rays, and it does not at all follow that the substance which absorbs the one must necessarily absorb the other. Through a layer of water, for example, one-tenth of an inch in thickness, the sun's rays are transmitted with comparative freedom; but through a layer half this thickness, as Melloni has proved, no single ray from the warmed earth could pass. In like manner, the sun's rays pass with comparative freedom through the aqueous vapour of the air: the absorbing power of this substance being mainly exerted upon the heat that endeavours to escape from the earth. In consequence of this differential action upon solar and terrestrial heat, the mean temperature of our planet is higher than is due to its distance from the sun.

13. *Liquids and their Vapours in Relation to Radiant Heat.*

The deportment here assigned to atmospheric vapour has been established by direct experiments on air taken from the streets and parks of London, from the downs of Epsom, from the hills and sea-beach of the Isle of Wight, and also by experiments on air in the first instance dried, and afterwards rendered artificially humid by pure distilled water. It has also been established in the following way: Ten volatile liquids were taken at random and the power of these liquids, at a common thickness, to intercept the waves of heat was carefully determined. The vapours of the liquids were next taken, in quantities proportional to the quantities of liquid, and the power of the vapours to intercept the waves of heat was also determined. Commencing with the substance which exerted the least absorptive power, and proceeding upward to the most energetic, the following order of absorption was observed:

Liquids.	Vapours.
Bisulphide of Carbon.	Bisulphide of Carbon.
Chloroform.	Chloroform.
Iodide of Methyl.	Iodide of Methyl.
Iodide of Ethyl.	Iodide of Ethyl.
Benzol.	Benzol.
Amylene.	Amylene.
Sulphuric Ether.	Sulphuric Ether.
Acetic Ether.	Acetic Ether.
Formic Ether.	Formic Ether.
Alcohol.	Alcohol.
Water.	

We here find the order of absorption in both cases to be the same. We have liberated the molecules from the bonds which trammel them more or less in a liquid condition; but this change in their state of aggregation does not change their relative powers of absorption. Nothing could more clearly prove that the act of absorption depends upon the individual molecule, which equally asserts its power in the liquid and the gaseous state. We may assuredly conclude from the above table that the position of a vapour is determined by that of its liquid. Now, at the very foot of the list of liquids stands *water*, signalizing itself above all others by its enormous power of absorption. And from this fact, even if no direct experiment on the vapour of water had ever been made, we should be entitled to rank that vapour as the most powerful absorber of radiant heat hitherto discovered. It has been proved by experiment that a shell of air two inches in thickness surrounding our planet, and saturated with the vapour of sulphuric ether, would intercept 35 per cent. of the earth's radiation. And though the quantity of aqueous vapour necessary to saturate air is much less than the amount of sulphuric ether vapour which it can sustain, it is still extremely probable that the estimate already made of the action of atmospheric vapour within ten feet of the earth's surface, is altogether under the mark; and that we are indebted to this wonderful substance, to an extent not accurately determined, but certainly far beyond what has hitherto been imagined, for the temperature now existing at the surface of the globe.

14. *Reciprocity of Radiation and Absorption.*

Throughout the reflections which have hitherto occupied us, the image before the mind has been that of a radiant source generating calorific waves, which, on passing among the scattered molecules of a gas or vapour, were intercepted by those molecules in various degrees. In all cases it was the transference of motion from the ether to the comparatively quiescent molecules of the gas or vapour. We have now to change the form of our conception, and to figure these molecules not as absorbers but as radiators, not as the recipients but as the originators of wave motion. That is to say, we must figure them vibrating and generating in the surrounding ether undulations which speed through it with the velocity of light. Our object now is to inquire whether the act of chemical combination, which proves so potent as regards the phenomena of absorption, does not also manifest its power in the phenomena of radiation. For the examination of this question it is necessary, in the first place, to heat our gases and vapours to the same temperature, and then examine their power of discharging the motion thus imparted to them upon the ether in which they swing.

A heated copper ball was placed above a ring gas-burner, possessing a great number of small apertures, the burner being connected by a tube with vessels containing the various gases to be examined. By a gentle pressure the gases were forced through the orifices of the burner against the copper ball, where each of them, being heated, rose in an ascending column. A thermo-electric pile, entirely screened off from the hot ball, was exposed to the radiation of the warm gas, and the deflection of a magnetic needle connected with the pile, declared the energy of the radiation.

By this mode of experiment it was proved that the self-same molecular arrangement which renders a gas a powerful absorber, renders it in the same degree a powerful radiator—that the atom or molecule which is competent to intercept the calorific waves is, in the same degree, competent to generate them. Thus, while the atoms of elementary gases proved themselves unable to emit any sensible amount of radiant heat, the molecules of compound gases were shown to be capable of powerfully disturbing the surrounding ether. By special modes of experiment the same was proved to hold good for the vapours of volatile liquids, the radiative power of every vapour being found proportional to its absorptive power. These experiments were based upon the fact that atoms, such, for example, as those of air, which glide through the ether without sensible resistance, cannot thus glide among the molecules of another gas. When mixed with such molecules, the heated atoms communicate their motion to the molecules by direct collision, and if these be of a complex chemical character, they instantly disturb the ether which surrounds them, and thus lose their heat. Hence the motion possessed in the first instance by the atoms, and which the atoms are incompetent to discharge directly upon the ether, may, by the intervention of more complex molecules, be thus discharged. Suppose, then, a small quantity of any vapour to be introduced into an exhausted tube, and air to be subsequently allowed to rush in and fill the tube. By its impact against the sides of the tube the air is heated; the motion of heat is instantly imparted, by collision, to the molecules of the vapour, and they in their turn impart it to the ether, or, in other words, reduce it to the radiant form. By this process, which has been called Dynamic Radiation, the radiative power of both vapours and gases has been determined, and the reciprocity of their radiation and absorption proved.* In the excellent researches of Leslie, De la Provostaye, and Desains, and Mr. Balfour Stewart, the reciprocity of radia-

* When heated air imparts its motion to another gas or vapour, the transference of heat is accompanied by a change of vibrating period. The Dynamic Radiation of vapours is rendered possible by the transmutation of vibrations.

tion and absorption in the case of solid bodies has been variously illustrated; while the labours, theoretical and experimental, of Kirchhoff have given this subject a wonderful expansion, and enriched it by applications of the highest kind. To their results are now to be added the foregoing, whereby a vast class of bodies hitherto thought inaccessible to experiment, are proved to exhibit the duality of radiation and absorption, the influence on both of chemical combination being exhibited in the most decisive and extraordinary way.

15. *Influence of Vibrating Period and Molecular Form. Physical Analysis of the Human Breath.*

In the foregoing experiments with gases and vapours we have employed throughout invisible rays; some of these bodies are so impervious that in lengths of a few feet only, they intercept every ray as effectually as a layer of pitch would do. The substances, however, which show themselves thus opaque to radiant heat are perfectly transparent to light. Now the rays of light differ from those of invisible heat only in point of period, the former failing to affect the retina because their periods of recurrence are too slow. Hence, in some way or other, the transparency of our gases and vapours depends upon the periods of the waves which impinge upon them. What is the nature of this dependence? The admirable researches of Kirchhoff help us to an answer. The atoms and molecules of every gas have certain definite rates of oscillation, and those waves of ether are most copiously absorbed whose periods of recurrence synchronize with the periods of the molecules among which they pass. Thus, when we find the invisible rays absorbed and the visible ones transmitted by a layer of gas, we conclude that the oscillating periods of the gaseous molecules coincide with those of the invisible, and not with those of the visible spectrum.

It requires some discipline of the imagination to form a clear picture of this process. Such a picture is, however, possible. When the waves of ether impinge upon molecules whose periods of vibration coincide with the recurrence of the undulations, the timed strokes of the waves cause the motion of the molecules to accumulate, as a heavy pendulum is set in motion by well-timed puffs of breath. Thousands of millions of shocks are received every second from the calorific waves, and it is not difficult to see that every wave, arriving just in time to repeat the action of its predecessor, the molecules must finally be caused to swing through wider spaces than if the arrivals were not so timed. In fact, it is not difficult to see that an assemblage of molecules, operated upon by contending waves, might remain practically quiescent, and this is actually the case when the waves of the visible spectrum pass through a transparent gas or vapour. There is here no sensible transference of motion from the ether to the molecules; in other words, there is no sensible absorption.

One striking example of the influence of period may be here recorded. Carbonic acid gas is one of the feeblest of absorbers of the radiant heat emitted by solid sources. It is, for example, extremely transparent to the rays emitted by the heated copper plate already referred to. There are, however, certain rays, comparatively few in number, emitted by the copper, to which the carbonic acid is impervious; and could we obtain a source of heat emitting such rays only, we should find carbonic acid more opaque than any other gas to the radiation from that source. Such a source is actually found in the flame of carbonic oxide, where hot carbonic acid constitutes the main radiating body. Of the rays emitted by our heated plate of copper, olefiant gas absorbs ten times the quantity absorbed by carbonic acid. Of the rays emitted by a carbonic oxide flame, carbonic acid absorbs twice as much as olefiant gas. This wonderful change in the power of the former as an absorber is simply due to the fact, that the periods of the hot and cold carbonic acid are identical, and the waves from the flame freely transfer their motion to the molecules which synchronize with them. Thus it is that the tenth of an atmosphere of carbonic acid, enclosed in a tube four feet long, absorbs 60 per cent. of the radiation from a carbonic oxide flame, while one-thirtieth of an atmosphere absorbs 48 per cent. of the heat from the same origin.

In fact the presence of the minutest quantity of carbonic acid may be detected by its action on the rays from the carbonic oxide flame. Carrying, for example, the dried human breath into a tube four feet long, the absorption there effected by the carbonic acid of the breath amounts to 50 per cent. of the entire radiation. Radiant heat may indeed be employed as a means of determining practically the amount of carbonic acid expired from the lungs. My assistant, Mr. Barrett, has, at my request, made this determination. The absorption produced by the breath, freed from its moisture, but retaining its carbonic acid, was first determined. Carbonic acid, artificially prepared, was then mixed with dry air in such proportions that the action of the mixture upon the rays of heat was the same as that of the dried breath. The percentage of the former being known immediately gave that of the latter. The same breath, analyzed chemically by Dr. Frankland, and physically by Mr. Barrett, gave the following results:

Percentage of Carbonic Acid in the Human Breath.

Chemical Analysis.	Physical Analysis.
4·66	4·56
5·33	5·22

It is thus proved that in the quantity of ethereal motion which it is competent to take up, we have a practical measure of the carbonic acid of the breath, and hence of the combustion going on in the human lungs.

Still this question of period, though of the utmost importance, is not competent to account for the whole of the observed facts. The ether, as far as we know, accepts vibrations of all periods with the same readiness. To it the oscillations of an atom of oxygen are just as acceptable as those of a molecule of olefiant gas; that the vibrating oxygen then stands so far below the olefiant gas in radiant power must be referred not to period, but to some other peculiarity of the respective molecules. The atomic group which constitutes the molecule of olefiant gas, produces many thousand times the disturbance caused by the oxygen, because the group is able to lay a vastly more powerful hold upon the ether than the single atoms can. The cavities and indentations of a molecule composed of spherical atoms may be one cause of this augmented hold. Another, and possibly very potent one may be, that the ether itself, condensed and entangled among the constituent atoms of a compound, virtually increases the magnitude of the group, and hence augments the disturbance. Whatever may be the fate of these attempts to visualize the physics of the process, it will still remain true, that to account for the phenomena of radiation and absorption we must take into consideration the shape, size, and complexity of the molecules by which the ether is disturbed.

16. *Summary and Conclusion.*

Let us now cast a momentary glance over the ground that we have left behind. The general nature of light and heat was first briefly described: the compounding of matter from elementary atoms and the influence of the act of combination on radiation and absorption were considered and experimentally illustrated. Through the transparent elementary gases radiant heat was found to pass as through a vacuum, while many of the compound gases presented almost impassable obstacles to the calorific waves. This deportment of the simple gases directed our attention to other elementary bodies, the examination of which led to the discovery that the element iodine, dissolved in bisulphide of carbon, possesses the power of detaching, with extraardinary sharpness, the light of the spectrum from its heat, intercepting all luminous rays up to the extreme red, and permitting the calorific rays beyond the red to pass freely through it. This substance was then employed to filter the beams of the electric light, and to form foci of invisible rays so intense as to produce almost all the effects obtainable in an ordinary fire. Combustible bodies were burnt and refractory ones were raised to a white heat by the concentrated invisible rays. Thus, by exalting their refrangibility, the invisible rays of the electric light were rendered visible, and all the colours of the solar spectrum were extracted from utter darkness. The extreme richness of the electric light in invisible rays of low refrangibility was demonstrated, one-tenth only of its radiation consisting of luminous rays. The deadness of the optic nerve to those invisible rays was proved, and experiments were then added, to show that the bright and the dark rays of a body raised gradually to intense incandescence, are strengthened together; that to reach intense white heat, intense dark heat must be generated. A sun could not be formed, or a meteorite rendered luminous, on any other conditions. The light-giving rays constitute only a small fraction of the total radiation, their unspeakable importance to us being due to the fact that their periods are attuned to the special requirements of the eye.

Among the vapours of volatile liquids vast differences were also found to exist, as regards their power of absorption. We followed, moreover, various molecules from a state of liquid to a state of gas, and found, in both states of aggregation, the power of the individual molecules equally asserted. The position of a vapour as an absorber of radiant heat was proved to be determined by that of the liquid from which it is derived. Reversing our conceptions, and regarding the molecules of gases and vapours not as the recipients, but as the originators of wave motion; not as absorbers but as radiators; it was proved that the powers of absorption and radiation went hand in hand, the self-same chemical act which rendered a body competent to intercept the waves of ether, rendering it competent in the same degree to generate them. Perfumes were next subjected to examination, and notwithstanding their extraordinary tenuity, were found vastly superior, in point of absorptive power, to the body of the air in which they were diffused. We were led thus slowly up to the examination of the most widely diffused and most important of all vapours—the aqueous vapour of our atmosphere, and we found in it a potent absorber of the purely calorific rays. The power of this substance to influence climate, and its general influence on the temperature of the earth, were then briefly dwelt upon. A cob-web spread above a blossom is sufficient to protect it from nightly chill; and thus the aqueous vapour of our air, attenuated as it is, checks the drain of terrestrial heat, and saves the surface of our planet from the refrigeration which would assuredly accrue were no such substance interposed between it and the voids of space. We considered the influence of vibrating period and molecular form on absorption and radiation, and finally deduced from its action upon radiant heat the exact amount of carbonic acid expired by the human lungs.

Thus, in brief outline, have I placed before you some of the results of recent enquiries in the domain of Radiation, and my aim throughout has been to raise in your minds distinct physical images of the various processes involved in our researches. It is thought by some that natural science has a deadening influence on the imagination, and a doubt might fairly be raised as to the value of any study which would necessarily have this effect. But the experience of the last hour must, I think, have convinced you that the study of natural science goes hand in hand with the culture of the imagination. Throughout the greater part of this discourse we have been sustained by this faculty. We have been picturing atoms and molecules and vibrations and waves which eye has never seen nor ear heard, and which can only be discerned by the exercise of imagination. This, in fact, is the faculty which enables us to transcend the boundaries of sense, and connect the phenomena of our visible world with those of an invisible one. Without imagination we never could have risen to the conceptions which have occupied us here to-day; and in proportion to your power of exercising this faculty aright, and of associating definite mental images with the terms employed, will be the pleasure and the profit which you will derive from this

Lecture. The outward facts of nature are insufficient to satisfy the mind. We cannot be content with knowing that the light and heat of the sun illuminate and warm the world. We are led irresistibly to enquire what is light, and what is heat? and this question leads us at once out of the region of sense into that of imagination.

Thus pondering, and asking, and striving to supplement that which is felt and seen, but which is incomplete, by something unfelt and unseen which is necessary to its completeness, men of genius have in part discerned, not only the nature of light and heat, but also, through them, the general relationship of natural phenomena. The power of nature is the power of motion, of which all its phenomena are but special forms. It manifests itself in tangible and in intangible matter, being incessantly transferred from the one to the other, and incessantly transformed by the change. It is as real in the waves of the ether as in the waves of the sea; the latter being in fact nothing more than the heaped-up motion of the former. For it is the calorific waves emitted by the sun which heat our air, produce our winds, and hence agitate our ocean. And whether they break in foam upon the shore, or rub silently against the ocean's bed, or subside by the mutual friction of their own parts, the sea-waves finally resolve themselves into waves of ether, and thus regenerate the motion from which their temporary existence was derived. This connection is typical. Nature is not an aggregate of independent parts, but an organic whole. If you open a piano and sing into it, a certain string will respond. Change the pitch of your voice; the first string ceases to vibrate, but another replies. Change again the pitch; the first two strings are silent, while another resounds. Now in altering the pitch you simply change the form of the motion communicated by your vocal chords to the air, one string responding to one form, and another to another. And thus is sentient man sung unto by Nature, while the optic, the auditory, and other nerves of the human body are so many strings differently tuned and responsive to different forms of the universal power.

THE END.