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Author: Percy Phillips

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RADIATION

BY P. PHILLIPS

D.Sc. (B'HAM), B.Sc. (LONDON), B.A. (CANTAB.)

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INTRODUCTION

We are so familiar with the restlessness of the sea, and with the havoc which it works on our shipping and our coasts, that we need no demonstration to convince us that waves can carry energy from one place to another. Few of us, however, realise that the energy in the sea is as nothing compared with that in the space around us, yet such is the conclusion to which we are led by an enormous amount of experimental evidence. The sea waves are only near the surface and the effect of the wildest storm penetrates but a few yards below the surface, while the waves which carry light and heat to us from the sun fill the whole space about us and bring to the earth a continuous stream of energy year in year out equal to more than 300 million million horsepower.

The most important part of the study of Radiation of energy is the investigation of the characters of the waves which constitute heat and light, but there is another method of transference of energy included in the term Radiation; the source of the energy behaves like a battery of guns pointing in all directions and pouring out a continuous hail of bullets, which strike against obstacles and so give up the energy due to their motion. This method is relatively unimportant, and is usually treated of separately when considering the subject of Radioactivity. We shall therefore not consider it in this book.

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RADIATION

CHAPTER I

THE NATURE OF RADIANT HEAT AND LIGHT

Similarity of Heat and Light.—That light and heat have essentially the same characters is very soon made evident. Both light and heat travel to us from the sun across the ninety odd millions of miles of space unoccupied by any material.

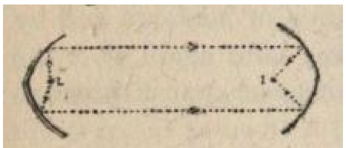

Fig. I.

Figure 1

Both are reflected in the same way from reflecting surfaces. Thus if two parabolic mirrors be placed facing each other as in the diagram (Fig. 1), with a source of light L at the focus of one of them, an inverted image of the light will be formed at the focus I of the other one, and may be received on a small screen placed there. The paths of two of the rays are shown by the dotted lines. If L be now replaced by a heated ball and a[1] blackened thermometer bulb be placed at I, the thermometer will indicate a sharp rise of temperature, showing that the rays of heat are focussed there as well as the rays of light.

[1] See page 37.

{10} Both heat and light behave in the same way in passing from one transparent substance to another, *e.g.* from air into glass. This can be readily shown by forming images of sources of heat and of light by means of a convex lens, as in the diagram (Fig. 2).

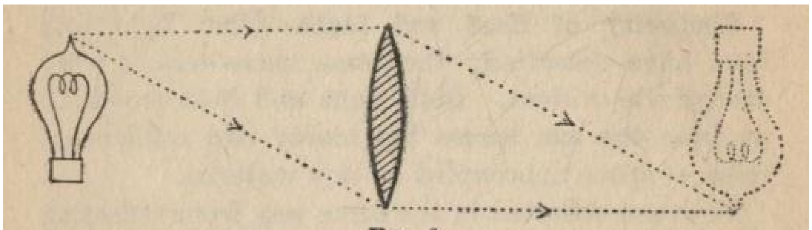

Fig. 2.

FIG. 2.

The source of light is represented as an electric light bulb, and two of the rays going to form the image of the point of the bulb are represented by the dotted lines. The image is also dotted and can be received on a screen placed in that position.

If now the electric light bulb be replaced by a heated ball or some other source of heat, we find by using a blackened thermometer bulb again that the rays of heat are brought to a focus at almost the same position as the rays of light.

The points of similarity between radiant heat and light might be multiplied indefinitely, but as a number of them will appear in the course of the book these few fundamental ones will suffice at this point.

The Corpuscular Theory.—A little over a century ago everyone believed light to consist of almost inconceivably small particles or corpuscles shooting out at enormous speed from every
{11} luminous surface and causing the sensation of sight when impinging on the retina. This was the corpuscular theory. It readily explains why light travels in straight lines in a homogeneous medium, and it can be made to explain reflection and refraction.

Reflection.—To explain reflection, it is supposed that the reflector repels the particles as they approach it, and so the path of one particle would be like that indicated by the dotted line in the diagram (Fig. 3).

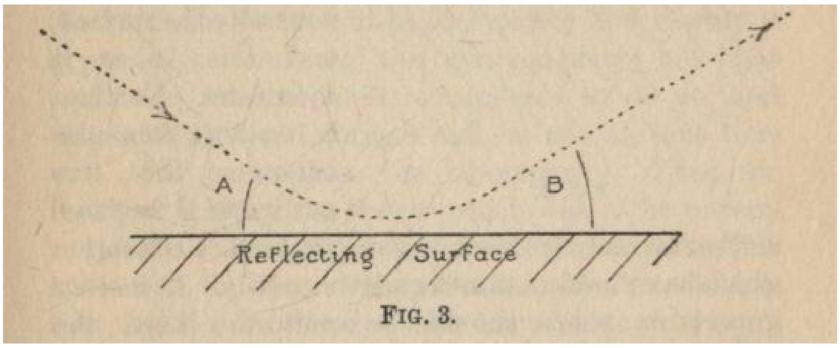

FIG. 3.

Until reaching the point A we suppose that the particle does not feel appreciably the repulsion of the surface. After A the repulsion bends the path of the particle round until B is reached, and after B the repulsion becomes inappreciable again. The effect is the same as a perfectly elastic ball bouncing on a perfectly smooth surface, and consequently the angle to the surface at which the corpuscle comes up is equal to the angle at which it departs.

Refraction.—To explain refraction, it is supposed that when the corpuscle comes very close to the surface of the transparent substance it is attracted by the denser substance, e.g. glass, more than by the lighter substance, e.g. air. Thus a particle moving along the dotted line in air
{12} (Fig. 4) would reach the point A before the attraction becomes appreciable, and therefore would be moving in a straight line. Between A and B the attraction of the glass will be felt and will therefore pull the particle round in the path indicated. Beyond B, the attraction again becomes inappreciable, because the glass will attract the particle equally in all directions, and therefore the path will again become a straight line. We notice that by this process the direction of the path has become more nearly normal to the surface, and this is as it should be. Further, by treating the angles between the two paths and the normal mathematically we may deduce the laws of refraction which have been obtained experimentally. One other important point should be noticed. Since the surface has been attracting the particle between A and B the speed of the particle will be greater in the glass than in the air.

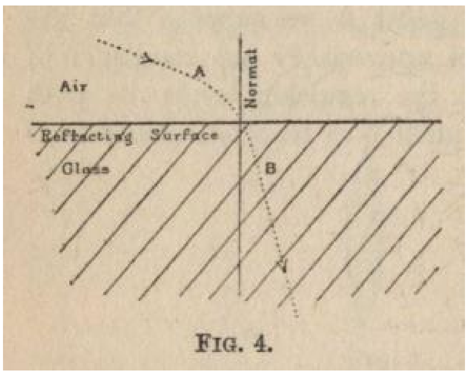

FIG. 4

Ejection and Refraction at the same Surface.—A difficulty very soon arises from the fact that at nearly all transparent surfaces some light is reflected and some refracted. How can the same surface sometimes repel and sometimes attract a corpuscle? Newton surmounted this difficulty by attributing a polarity to each particle, so that one end was repelled and the other
{13}

attracted by the reflecting and refracting surface. Thus, whether a particle was reflected or refracted depended simply upon which end happened to be foremost at the time. By attributing suitable characteristics to the corpuscles, Newton with his superhuman ingenuity was able to account for all the known facts, and as the corpuscles were so small that direct observation was impossible, and as Newton's authority was so great, there was no one to say him nay.

Wave Theory. Rectilinear Propagation.—True, Huyghens in 1678 had propounded the theory that light consists of waves of some sort starting out from the luminous body, and he had shown how readily it expressed a number of the observed facts; but light travels in straight lines, or appears to do so, and waves bend round corners and no one at that time was able to explain the discrepancy. Thus for nearly a century the theory which was to be universally accepted remained lifeless and discredited. The answer of the wave theory to the objection now is, that light does bend round corners though only slightly and that the smallness of the bend is quite simply due to the extreme shortness of the light waves. The longer waves are, the more they bend round corners. This can be noticed in any harbour with a tortuous entrance, for the small choppy waves are practically all cut off whereas a considerable amount of the long swell manages to get into the harbour.

Interference of Light. Illustration by Ripples.—The revival of the wave theory dates from the discovery by Dr. Young of the phenomenon of interference of light. In order to understand
{14} this we will consider the same effect in the ripples on the surface of mercury. A tuning-fork, T (Fig. 5), has two small styles, S S, placed a little distance apart and dipping into the mercury contained in a large shallow trough. When the tuning-fork is set into vibration, the two styles will move up and down in the mercury at exactly the same time and each will start a system of ripples exactly similar to the other. At any instant each system will be a series of concentric circles with its centre at the style, and the crests of the ripples will be at equal distance from each other with the troughs half-way between the crests.

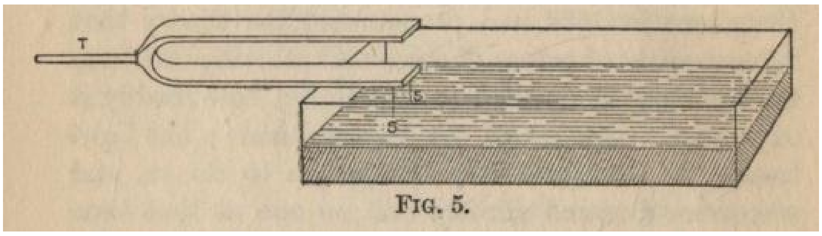

FIG. 5.

The ripples from one style will cross those from the other, and a curious pattern, something like that in Fig. 6, will be formed on the mercury. S S represents the position of the two styles, while the plain circles denote the positions of the crests and the dotted circles the positions of the troughs at any instant. Where two plain circles cross it is evident that both systems of ripples are producing a crest, and so the two produce an exaggerated crest. Similarly where two dotted circles cross an exaggerated trough is produced. Thus in the shaded portions of the diagram we get more violent ripples than those due to a single style. Where a plain circle cuts a dotted one,
{15} however, one system of ripples produces a crest and the other a trough, and between them the mercury is neither depressed below nor raised above its normal level. At these points, therefore, the effect of one series of ripples is just neutralised by the effect of the other and no ripples are produced at all. This occurs in the unshaded regions of the diagram.

The mutual destruction of the effects of the two sets of waves is "Interference."

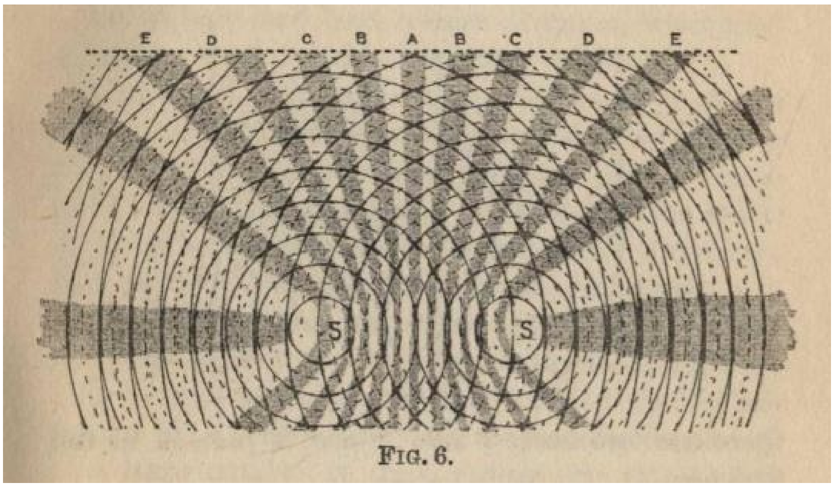

FIG. 6.

Now imagine a row of little floats placed along the line EDCBABCDE. At the lettered points the floats will be violently agitated, but at the points midway between the letters they will be unmoved. This exactly represents the effect of two interfering sources of light S, S, sending light which is received by a screen at the dotted line EDCBABCDE. The lettered points will be brightly illuminated while the intermediate points will be dark.

{16} In practice it is found impossible to make two sources of light whose vibrations start at exactly the same time and are exactly similar, but this difficulty is surmounted by using one source of light and splitting the waves from it into two portions which interfere.

Young's Experiment.—Dr. Young's arrangement is diagrammatically represented in Fig. 7.

Light of a certain wave length is admitted at a narrow slit S, and is intercepted by a screen in which there are two narrow slits A and B parallel to the first one.

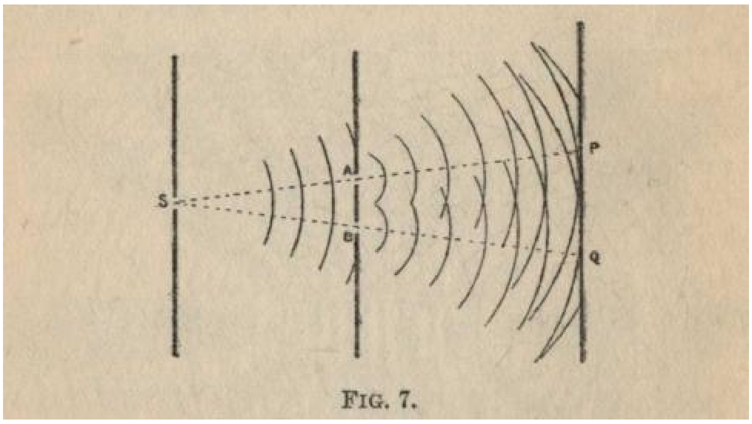

FIG. 7.

A screen receives the light emerging from the two slits. If the old corpuscular theory were true there would be two bright bands of light, the one at P and the other at Q, but instead Dr. Young observed a whole series of parallel bright bands with dark spaces in between them. Evidently the two small fractions of the original waves which pass through A and B spread out from A and B and interfere just as if they were independent sources like the two styles in the mercury ripples experiment.

{17} **Speed of Light in Rare and Dense Media.**—The discovery of interference again brought the wave theory into prominence, and in 1850 the death-blow was given to the corpuscular theory by Foucault, who showed that light travels more slowly in a dense medium such as glass or water than in a light medium such as air. This is what the wave theory anticipates, while the reverse is anticipated by the corpuscular theory.

But if light and heat consist of waves, what kind of waves are they and how are they produced?

Elastic Solid Theory.—In the earlier days of the wave theory it was supposed that the whole of space was filled with something which acted like an elastic solid material in which the vibrations of the atoms of a luminous body started waves in all directions, just as the vibrations of a marble embedded in a jelly would send out waves through the jelly. These waves are quite easily imagined in the following way.

If one end of an elastic string be made to oscillate to and fro a series of waves travels along the string. If a large number of these strings are attached to an oscillating point and stretch out in all directions, the waves will travel along each string, and if the strings are all exactly alike will travel at the same speed along all of them. Any particular crest of a wave will thus at any instant lie on the surface of a sphere whose centre is the oscillating point. If now we imagine that the strings are so numerous that they fill the whole of the space we have a conception of the transmission of waves by an elastic solid.

{18} **Electromagnetic Waves.**—Since Maxwell published his electromagnetic theory in 1873 it has been universally held that heat and light consist of electro-magnetic waves.

These are by no means so easy to imagine as the elastic waves, as there is no actual movement of the medium; an alternating condition of the medium is carried onward, not an oscillation of position.

When a stick of sealing-wax or ebonite is rubbed with flannel it becomes possessed of certain properties which it did not have before. It will attract light pieces of paper or pith that are brought near to it, it will repel a similar rubbed piece of sealing-wax or ebonite and will attract a rod of quartz which has been rubbed with silk.

The quartz rod which has been rubbed with silk has the same property of attracting light bodies which the ebonite and sealing-wax rod has, but it repels another rubbed quartz rod and attracts a rubbed ebonite or sealing-wax rod.

Positive and Negative Electrification.—The ebonite is said to be negatively electrified and the quartz positively electrified.

When the two rods, one positively and the other negatively electrified, are placed near to one another, we may imagine the attraction to be due to their being joined by stretched strings filling up all the space around them. If a very small positively electrified body be placed between the two it will tend to move from the quartz to the ebonite, *i.e.* in the direction of the arrows.

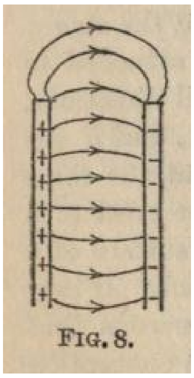

FIG. 8.

{19} **The Electric Field. Lines of Force.**—The space surrounding the electrified sticks in which the forces due to them are appreciable is called the electric field, and the direction in which a small positively electrified particle tends to move is called the direction of the field. The lines along which the small positive charge would move are called lines of force.

The conception of the electric field as made up of stretched elastic strings is, of course, a very crude one, but there is evidently some change in the medium in the electric field which is somewhat analogous to it.

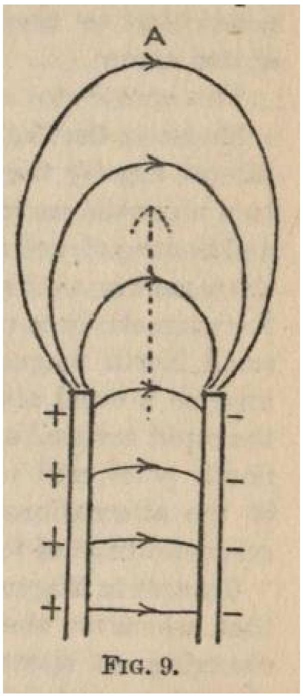

FIG. 9.

Electric Oscillations.—If the position of the two rods is reversed, then of course the direction of the field at a point between them is reversed, and if this reversal is repeated rapidly, we shall have the direction of the field alternating rapidly. If these alternations become sufficiently rapid they are conveyed outwards in much the same way as the oscillations of position are conveyed in an ordinary ripple. Thus suppose the two rods are suddenly placed in the position in the diagram. The field is not established instantaneously, the lines of force taking a short time to establish themselves in their ultimate positions. During this time the lines of force
{20} will be travelling outwards to A in the direction of the dotted arrow. Before they reach A let us suppose that the position of the rods is reversed. Then the direction of the lines is reversed and these reversed lines will travel outwards towards A, following in the track of the original lines. Thus a continuous procession of lines of force, first in one direction and then in the opposite direction, will be moving out perpendicular to themselves in the direction of the dotted arrow.

This constitutes an electric wave.

Magnetic Oscillation, Lines of Force, and Field.—Almost exactly the same kind of description applies to a magnetic wave. The space near to the North and South poles of a magnet is modified in somewhat the same way as that between the electrified rods, and the magnetic lines of force are the lines along which a small North magnetic pole would move. We may imagine a rapid alternation of the magnetic field by the rapid reversal of the positions of the

North and South poles, and we may imagine the transmission of the alternations by means of the procession of magnetic lines of force.

Changes in Magnetic Field.—But experiment shows that whenever the magnetic field at any place is changing an electric field is produced during the alteration, and *vice-versa*. Electric and magnetic waves must therefore always accompany one another, and the two sets of waves together constitute electro-magnetic waves.

These are the waves which a huge amount of experimental evidence leads us to believe
{21} constitute heat, light, the electric waves used in wireless telegraphy, and the invisible ultraviolet waves which are so active in inducing chemical action.

Oscillation of Electric Charges within the Atom.—We have seen how these waves might be produced by the oscillation of two electrified rods, and it is supposed that the light coming from luminous bodies is produced in a similar way. There are many reasons for believing that there exist in the atoms of all substances, minute negatively electrified particles which may rotate in small orbits or oscillate to and fro within the atom. There also exists an equal positive charge within the atom. As the negative particles rotate or oscillate in the atom, it is evident that the field between them and the positively electrified part of the atom alternates, and so electro-magnetic waves are sent out.

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CHAPTER II

GRAPHIC REPRESENTATION OF WAVES

A system of ripples on the surface of water appears in vertical section at any instant somewhat as in Fig. 10. The dotted line AB represents the undisturbed surface of the wafer, and the solid line the actual surface. If the disturbance which is causing the ripples is an oscillation of perfectly regular period the individual ripples will be all alike, except they will get shallower as they become more remote from the disturbance.

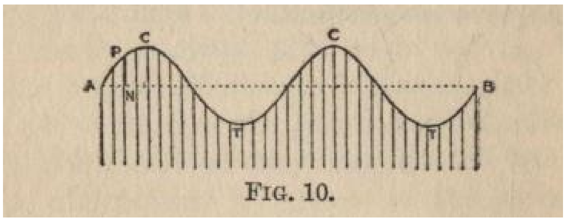

FIG. 10.

Wave-length.—The distance between two successive crests will be the same everywhere, and this distance or the distance between any two corresponding points on two successive ripples is called the wave-length. Evidently, the wave-length is the distance in which the whole wave repeats itself.

Phase.—The position of a point in the wave is called the phase of the point. Thus the
{23} difference of phase between the two points A and C is a quarter of a wave-length. As the waves move on along the surface it is evident that each drop of water executes an up and down oscillation, and at the points C, C the drop has reached its highest position and at the points T, T its lowest.

Amplitude.—The largest displacement of the drop, *i.e.* the distance from the dotted line to C or to T, is called the amplitude of the wave. The time taken for a drop to complete one whole oscillation, *i.e.* the time taken for a wave to travel one whole wave-length forward, is called the period of the wave. The number of oscillations in one second, *i.e.* the number of wave-lengths travelled in one second, is called the frequency.

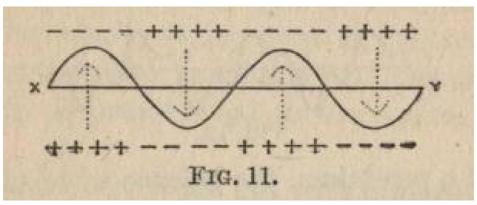

FIG. 11.

Although there is no visible displacement in the waves of light and heat, yet we may represent them in much the same way. Thus if AB, Fig. 10, represents the line along which a ray of light is travelling, the length NP is drawn to scale to represent the value of the electric field at the point N, and is drawn upwards from the line AB when the field is in one direction and downwards when it is in the opposite direction.

Thus the direction of the field at different points in the wave XY, Fig. 11, is shown by the dotted arrows as if due to electrified rods of quartz and ebonite placed above and below XY.

{24} In the case of the electromagnetic wave, the amplitude will be the maximum value to which the electric field attains in either direction, and the other terms—wave-length, phase, period and frequency—will have the same meaning as for water ripples.

Wave Form.—Waves not only differ in amplitude, wave-length, and frequency, but also in wave form. Waves may have any form, *e.g.* Fig 12. Or we may have a solitary irregular disturbance such as is caused by the splash of a stone in water.

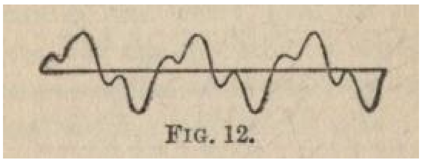

FIG. 12.

But there is one form of motion of a particle in a wave which is looked upon as the simplest and fundamental form. It is that form which is executed by the bob of a pendulum, the balance wheel of a watch, the prong of a tuning-fork, and most other vibrations where the controlling force is provided by a spring or by some other elastic solid.

It is called "Simple Harmonic Motion" or "Simple Periodic Motion," and the essential feature of it is that the force restoring the displaced particle to its undisturbed position is proportional to its displacement from the undisturbed position. A wave in which all the particles execute simple harmonic motion has the form in Fig. 10 or Fig. 11, which is therefore looked upon as the fundamental wave form or simple wave form.

Simple waves will vary only in amplitude, wave-length, and frequency, and the energy in the wave will depend upon these quantities.

{25} **Energy in a Simple Wave.**—If the velocity is the same for all wave-lengths, then the frequency will evidently be inversely proportional to the wave-length and the energy will depend upon the amplitude and the wave-length. The kinetic energy of any moving body, *i.e.* the energy due to its motion, is proportional to the square of its velocity, and we may apply this to the motion of the particles in a wave and to show how the energy depends upon the amplitude and wave-length.

Since the distance travelled by a particle in a single period of the wave will be equal to four times the amplitude, the velocity at any point in the wave must be proportional to the amplitude and therefore the kinetic energy is proportional to the square of the amplitude.

With the same amplitude but with different wave-lengths, we see that the time in which the oscillation is completed is proportional to the wave-length and that the velocity is therefore inversely proportional to the wave-length. The kinetic energy is therefore inversely proportional to the square of the wave-length.

Addition of Waves.—The superposition of two waves so as to obtain the effect of both waves at the same place is carried out very simply. The displacements at any point due to the two waves separately are algebraically added together, and this sum is the actual displacement. In Fig. 13 the dotted lines represent two simple waves, one of which has double the wave-length of the
{26} other. At any point P on the solid line, the displacement PN is equal to the algebraic sum of the displacement NQ due to one of the waves and NR due to the other. The solid line, therefore, represents the resulting wave. We may repeat this process for any number of simple waves, and by suitably choosing the wave-length and amplitude of the simple waves we may build up any desired form of wave. The mathematician Fourier has shown that any form of wave, even the single irregular disturbance, can thus be expressed as the sum of a series of simple waves and that the wave-lengths of these simple waves are equal to the original wave-length, one-half of it, one-third, one-quarter, one-fifth, and so on in an infinite series. Fourier has also shown that only one such series is possible for any particular form of wave.

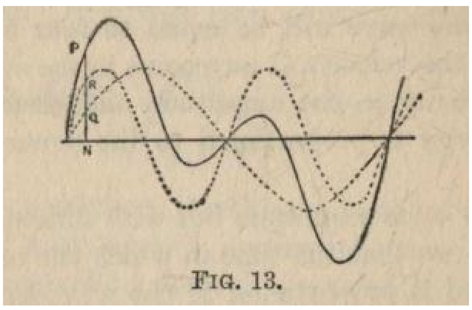

FIG. 13.

The importance of this mathematical expression lies in the fact that in a number of ways Fourier's series of simple waves is manufactured from the original wave and the different members of the series become separated. Thus the most useful way in which we can represent any wave is, not to draw the actual form of a wave, but to represent what simple waves go to form it and to show how much energy there is in each particular simple wave.

{27} **Energy—Wave-length Curve.**—This can be done quite simply as in Fig. 14. The distance PN from the line OA being drawn to scale to represent the energy in the simple wave whose length is represented by ON.

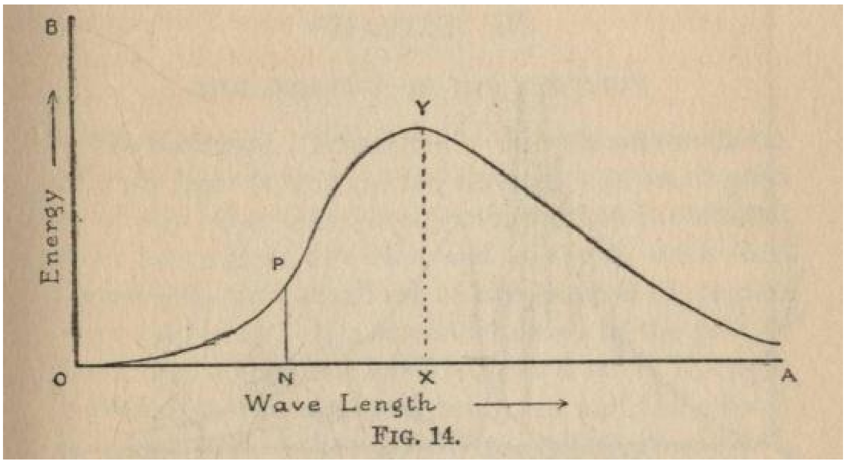

FIG. 14.

Thus the simple wave of length OX has the greatest amount of energy in it.

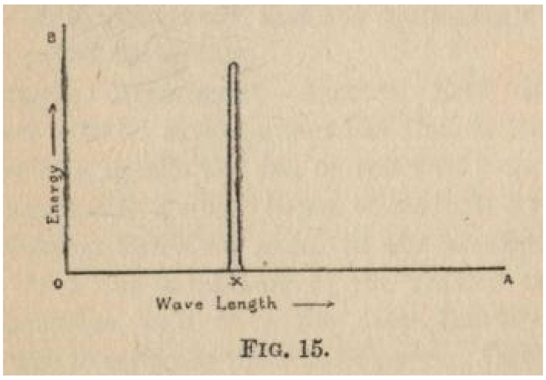

FIG. 15.

Fig. 15 wall represent a simple wave of wave-length OX, the energy in all the other waves being zero.

{28} The three curves given in Fig. 16 give a comparison of the waves from the sun, an arc lamp, and an ordinary gas-burner.

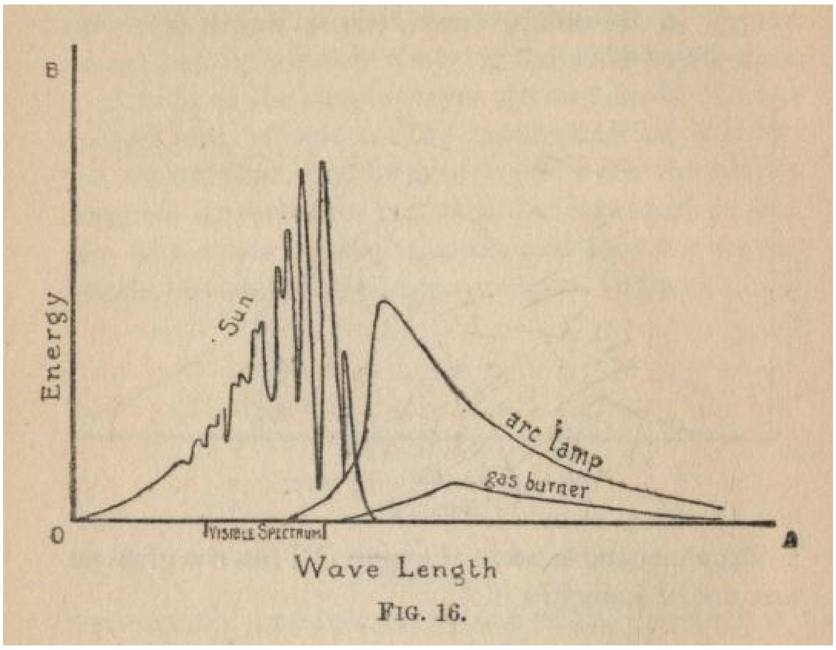

FIG. 16.

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CHAPTER III

THE MEANING OF THE SPECTRUM

The Spectrum. Dispersion.—When a narrow beam of white light is transmitted through a prism of glass or of any other transparent substance, it is deflected from its original direction and is at the same time spread out into a small fan of rays instead of remaining a single ray. If a screen is placed in the path of these rays a coloured band is formed on it, the least deflected part of the band being red and the colours ranging from red through orange, yellow, green, blue, and indigo, to violet at the most deflected end of the band. This band of colours is called the spectrum of the white light used, and the spreading out of the rays is called dispersion.

Newton's Experiment.—Newton first discovered this fact with an arrangement like that in Fig. 17.

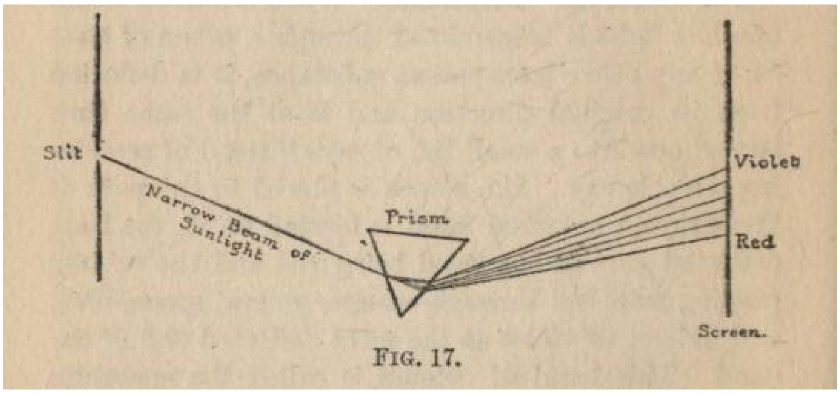

FIG. 17.

If by any means the fan of coloured rays be combined again into a single beam, white light is reformed, and Newton therefore came to the conclusion that white light was a mixture of the various colours in the spectrum, and that the only function of the prism was to separate the constituents. Of the nature of the constituents Newton had little knowledge, since he had rejected the wave theory, which could alone give the clue.

{30} We now believe that white light is an irregular wave, and that the prism manufactures from it the Fourier's series of waves to which it is equivalent. It is supposed that the manufacture is effected by means of the principle of resonance. As an example of resonance let a small tap be given to a pendulum just as it commences each swing. Then because the taps are so timed that each of them increases the swing of the pendulum by a small amount, they will very soon cause the pendulum to swing very violently even though the effect of a single tap can scarcely be detected at all.

Thus when any body which has a free period of vibration is subject to periodic impulses of the same period as its own, it will vibrate very vigorously and absorb nearly all the energy of the impulses.

Electrons and their Vibrations.—There is conclusive evidence to show that in the atoms of all substances, and therefore of the glass of which the prism is composed, there are a number of minute negatively electrified particles which are called electrons. These are held in position by a
{31} positive charge on the rest of the atom, and if they are displaced from their usual positions by any means they will vibrate about these positions. The time of vibration of the electron will depend upon its position in the atom and upon the position of neighbouring atoms. In solid or liquid bodies the neighbouring atoms are so near that they have a considerable influence in modifying the period of an electron or a system of electrons, and consequently we may find almost any period of vibration in one or other of these electrons or systems.

As the wave of light with its alternating electric fields comes up to the prism, the field will first displace the electrons in one direction and then in the other, and so on. If the period of one particular type of electron happens to coincide with the period of the wave, that electron will vibrate violently and will in its turn send out a series of waves in the glass. If the wave is an irregular one it will start all the electrons vibrating, but those electrons will vibrate most violently whose periods are equal to the periods of the Fourier's constituents which have the greatest energy. Thus we shall actually have the Fourier's constituent waves separated into the vibrations of different electrons. But the speed with which any simple wave travels in glass or in any transparent medium, other than a vacuum, is dependent upon its period.

The shorter the period, *i.e.* the shorter the wave-length, the slower is the speed in most transparent substances. But the slower the speed in the prism the more is the ray deviated, and therefore we conclude that the violet end of the spectrum consists of the shortest waves while {32} the red end consists of the longest waves, and that the different parts of the spectrum are simple waves of different period.

The Whole Spectrum.—The visible spectrum is by no means the whole of the series of Fourier's waves, however. The eye is sensitive only to a very small range of period, while there exists in sunlight a range many times as great.

Those waves of shorter period than the violet end of the visible spectrum will be deviated even more than the violet, and will therefore be beyond the violet. They are called the ultra violet rays, and can easily be detected by means of their chemical activity. They cause a number of substances to glow, and therefore by coating the screen on which the spectrum is received with one of these substances, the violet end of the spectrum is extended by this glow.

The waves of longer period than the red rays will be deviated less than the red, and will therefore lie beyond the red end of the visible spectrum. They are called the infra-red rays, and are chiefly remarkable for their heating effect.

All the rays are absorbed when they fall on to a perfectly dull, black surface, and their energy is converted into heat. This heating effect provides the best way of measuring the energy in the different parts of the spectrum, and of thus constructing curves similar to those given in Fig. 16. The instrument moat commonly used is called Langley's bolometer. It consists of a fine strip of blackened platinum, which can be placed in any part of the spectrum at will and thus absorb the {33} waves over a very small range of wave-length. It is heated by them, and the rise in temperature is found by measuring the electrical resistance of the strip. The electrical resistance of all conductors varies with the temperature, and since resistance can be measured with extreme accuracy this forms a very sensitive and accurate method.

Spectrum of an Incandescent Solid or Liquid.—The spectra given by different sources of light show certain marked differences.

An incandescent solid or liquid gives a continuous spectrum, *i.e.* all the different wave-lengths are represented, but the part of the spectrum which has the greatest energy is different for different substances and for different temperatures: cf. arc and gas flame in Fig. 16. This is quite in keeping with the idea already suggested that in solids and liquids there are electrons of almost every period of vibration. When they are agitated by being heated, a mixture of simple waves of all periods will be sent out giving a very irregular wave.

Gases may also become incandescent. Thus when any compound of sodium is put into a colourless flame the flame becomes coloured an intense yellow. This is due to the vapour of sodium, and the agitation of the electrons in it is probably due to the chemical action in which the compound is split up into sodium and some other parts.

We may also make the gas incandescent by enclosing it at low pressure in a vacuum tube and passing an electrical discharge through it. The glow in the tube gives the spectrum of the gas. {34} Incandescent gases give a very characteristic kind of spectrum. It consists usually of a limited number of narrow lines, the rest of the spectrum being almost perfectly dark. The light therefore consists of a few simple waves of perfectly definite period. This would suggest that in the atom of a gas there are only a few electrons which are concerned in the emission of the light waves.

Thus the spectra of gases and of incandescent solids are represented in character by the curves in Fig. 18.

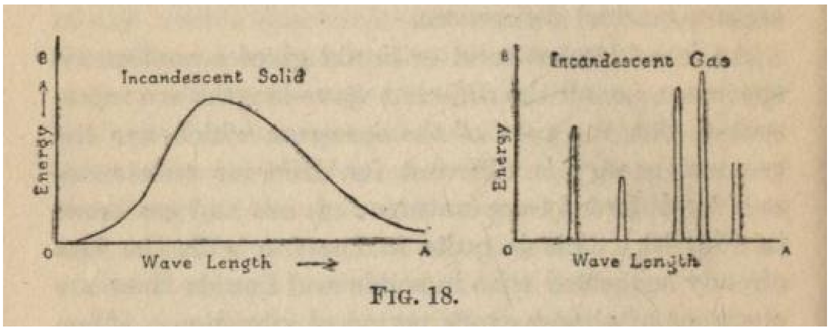

FIG. 18.

Spectrum Analysis.—The lines in a gas spectrum are so sharply defined and are so definitely characteristic of the particular gas that they serve as a delicate method of detecting the presence of some elements. These spectra which are emitted by incandescent bodies are called emission spectra. But not only do different materials emit different kinds of light when raised to incandescence, but they also absorb light differently when it passes through them.

When white light is passed through some transparent solids or liquids and then through a prism, it is found that whole regions of the spectrum are absent. Thus a potassium permanganate {35} solution which is not too concentrated absorbs the whole of the middle part of the spectrum, allowing the red and blue rays to pass through. Since with solids and liquids the absorbed regions are large and somewhat ill-defined, the absorption spectra are not of any great use in the detection of substances.

The absorption spectra of gases show the same sharply defined characteristics as the emission spectra. Thus if white light from an arc lamp passes through a flame coloured yellow with sodium vapour, the spectrum of the issuing light has two sharply defined narrow dark lines close together in the yellow part of the spectrum in exactly the same position as the two bright yellow lines which incandescent sodium vapour itself gives out. The flame has therefore absorbed just those waves which it gives out. This is perfectly general, and applies to solids and liquids as well as to gases. It is perfectly in keeping with our view of the refraction of light by the resonance of electrons to the Fourier's constituents which have the same period. For if the electrons have a certain period of vibration they will resound to waves of that period and therefore absorb their energy.

Spectrum of the Sun.—One of the most interesting examples of the absorption by incandescent gases of their own characteristic lines is provided by the sun. The spectrum of the sun is crossed by a large number of fine dark lines which were mapped out by Fraunhöfer and are therefore called Fraunhöfer lines. These lines are found to be in the position of the
{36} characteristic lines of a number of known elements, and therefore we assume that these elements are present in the sun. The interior of the sun is liquid or solid owing to the pressure of the mass round it. It therefore emits a continuous spectrum. But the light has to pass through the outer layers of incandescent vapour, and these layers absorb from the light their characteristic waves and so produce the dark lines in the spectrum.

The spectra of stars show similar characters to those of the sun, and therefore we assume them to be in the same condition as the sun.

The spectra of nebulæ consist only of bright lines, and we therefore assume that nebulæ consist of incandescent masses of gas which have not yet cooled enough to have liquid or solid nuclei.

{37}

CHAPTER IV

THE LAWS OF RADIATION

Absorbing Power.—A perfectly dull black surface is simply one which absorbs all the light which is falling on it and reflects or diffuses none of it back. If the surface absorbs the heat as well as the light completely, it is called a perfect or full absorber. Other surfaces merely absorb a fraction of the heat and light falling on them, and this fraction, expressed usually as a percentage, is called the absorbing power of the surface. The absorbing powers of different kinds of surfaces can be measured in a great many ways, but the following may be taken as fairly typical. A perfectly steady beam of heat and light is made to fall on a small metallic disc, and the amount of heat which is absorbed per second is calculated from the mass of the metal and the rate at which its temperature rises. The disc is first coated with lamp-black, and the rate at which it then receives heat is taken as the rate at which a full absorber absorbs heat under these conditions. The disc is then coated with the surface whose absorbing power is to be measured, and the experiment is repeated. Then the rate at which heat is received in the second case divided by the rate at which it is received in the first is the absorbing power of the second
{38} surface. Experiments with a large number of surfaces show that the lighter in colour and the more polished is the surface, the smaller is its absorbing power.

Radiating Power.—But the character of the surface affects not only the rate at which heat and light are absorbed, but also the rate at which they are emitted. For example, if we heat a fragment of a willow pattern china plate in a blowpipe flame until it is bright red hot, we shall notice that the dark pattern now stands out brighter than the rest. Thus the dark pattern, which absorbs more of the light which falls on it when it is cold, emits more light than the rest of the plate when it is hot. This is one example of a general rule, for it is found that the most perfect absorbers are the greatest radiators, and *vice-versa*. The perfectly black surface is therefore taken as a standard in measuring the heat and light emitted by surfaces, in exactly the same way as for heat and light absorbed. Thus the emissive or radiating power of a surface is defined as the quantity of heat radiated per second by the surface divided by the amount radiated per second by a perfectly black surface under the same conditions. As it is somewhat paradoxical to call a surface a perfectly black surface when it may even be white hot, the term "a full radiator" has been suggested as an alternative and will be used in this book.

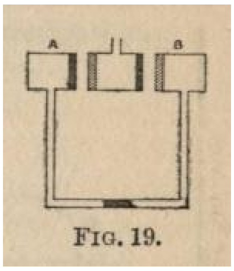

FIG. 19

Relation between Absorbing and Radiating Powers.—The exact relation between the absorbing and radiating powers of a surface was first determined by Ritchie by means of an ingenious experiment. Two equal air-tight metal chambers A and B were connected by a glass
{39} tube bent twice at right angles as in Fig. 19. A drop of mercury in the horizontal part of this tube acted as an indicator. When one of the vessels became hotter than the other, the air in it expanded and the mercury index moved towards the colder side. Between the two metal chambers a third equal one was mounted which could be heated up by pouring boiling water into it and could thus act as a radiator to the other two. One surface of this radiator was coated with lamp-black and the opposite one with the surface under investigation, *e.g.* cinnabar. The inner surfaces of the other two vessels were coated in the same way, the one with lamp-black, the other with cinnabar. The middle vessel was first placed so that the lamp-blacked surface was opposite to a cinnabar one, and *vice-versa*. In this position, when hot water was poured into it no movement of the mercury drop was detected, and therefore the amounts of heat received by the two outer vessels must have been exactly equal. On the one side the heat given out by the cinnabar surface of the middle vessel is only a fraction, equal to its radiating power, of the heat given out by the black surface. All the heat given out by the cinnabar surface to the black surface opposite to it is absorbed, however, while of the heat given out by the black surface to the cinnabar surface opposite it only a fraction is absorbed equal to the absorbing power of the cinnabar surface. Thus on the one side only a fraction is sent out but all of it is absorbed, and on
{40} the other side all is sent out and only a fraction absorbed. Since the quantities absorbed are exactly equal, it is obvious that the two fractions must be exactly equal, or the absorbing and radiating powers of any surface are exactly equal. This result is known as Kirchoff's law, and it applies solely to radiation which is caused by temperature. Later experiments have shown that it applies to each individual wave-length, *i.e.* to any portion of the spectrum which we isolate, as well as to the whole radiation. Thus at any particular temperature let the dotted line in Fig. 20 represent the wave-length—energy curve for a full radiator, and let the solid line represent it for the surface under investigation. Then for any wave-length, ON, the radiating power of the surface would be equal to QN divided by PN.

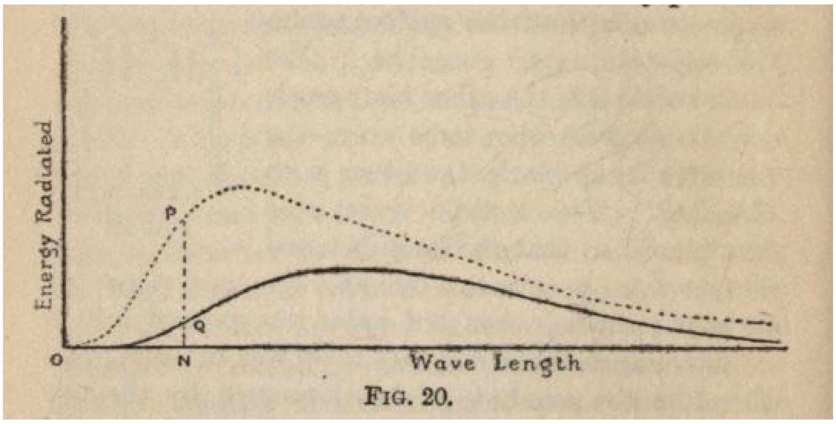

FIG. 20.

Now a wave-length—energy curve may be as easily constructed for absorbed as for emitted radiation by means of a Langley's bolometer. The strip of the bolometer is first coated with lamp-black and the spectrum of the incident radiation is explored in exactly the same way as is
{41} described in Chapter III. The strip is then coated with the surface under investigation and the spectrum is again explored. Since the incident radiation is exactly the same in the two experiments, the differences in the quantities of heat absorbed must be due solely to the difference in the absorbing powers of the two surfaces. In Fig. 21 the dotted line represents the wave-length—energy curve for the radiation absorbed by the blackened bolometer strip, and the solid line the curve for the strip coated with the surface under investigation.

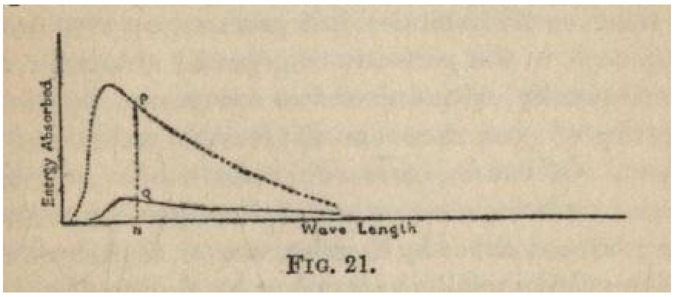

FIG. 21.

The actual form of the curves may and probably will be quite different from the form in Fig. 20, but it will be found for the same wave-length ON that PN/QN is exactly the same in the two figures.

It has already been mentioned that dull, dark-coloured surfaces radiate the most heat, and that polished surfaces radiate the least. A radiator for heating a room should therefore have a dull, dark surface, while a vessel which is designed to keep its contents from losing heat should have a highly polished exterior.

A perfectly transparent substance would radiate no energy, whatever the temperature to
{42} which it is raised, for its absorbing power is zero and therefore its radiating power is also zero. No perfectly transparent substances exist, but some substances are a very near approach to it. A fused bead of microcosmic salt heated in a small loop of platinum wire in a blowpipe flame may be raised to such a temperature that it is quite painful to look at the platinum wire, yet the bead itself is scarcely visible at all. Any speck of metallic dust on the surface of the bead will at the same time shine out like a bright star.

Gases as Radiators.—Most gases are an even nearer approach to the perfectly transparent substance, and consequently, with one or two exceptions, the simple heating of gases causes no appreciable radiation from them. Of course, gases do radiate heat and light under some circumstances, but the radiation seems to be produced either by chemical action, as in the flames coloured by metallic vapours, or by electric discharge, as in vacuum tubes, the arc or the electric spark.

The agitation of the electrons is thus produced in a different way in gases, and we must not apply Kirchoff's law to them, although at first sight they appear to conform to it. We have seen that the particular waves which an incandescent gas radiates are also absorbed by it. This we should expect, because the particular electron which has such a period of vibration that it sends out a certain wave-length will naturally be in tune to exactly similar waves which fall on it, and will so resound to them, and absorb their energy. The quantitative law, however, that the absorbing power is exactly equal to the radiating power, is not true for gases.

{43} **Emission of Polarised Light.**—One very interesting result of Kirchoff's law is the emission of polarized light by glowing tourmaline and by one or two other crystal when they are heated to incandescence. In ordinary light the vibrations are in all directions perpendicular to the line along winch the light travels, that is, the vibrations at any point are in a plane perpendicular to this line. Now any vibration in a plane may be expressed as the sum of two component vibrations, one component in one direction and the other in a perpendicular direction. If we divide up the vibrations all along the wave in this way we shall have two waves, one of which has its vibrations all in one direction and the other in a perpendicular direction. Such waves, in which the vibrations all lie in one plane, are said to be plane polarised.

Tourmaline is possessed of the curious property of absorbing vibrations in one direction of the crystal much more rapidly than it does those vibrations perpendicular to this direction, and therefore light which passes through it emerges partially, or in some cases wholly, plane polarised.

Since the absorbing power of tourmaline is different for the two components, the emissive power should also be different, and that component which was most absorbed should be radiated most strongly. This was found to be true by Kirchoff himself, who detected and roughly measured the polarised light emitted. Subsequently in 1902, Pflüger carried out exact experiments which gave a beautiful confirmation of the law.

{44}

CHAPTER V

FULL RADIATION

The Full Radiator.—We have assumed that a lamp-blacked surface is a perfect absorber, and consequently a full radiator, but although it is a very near approach to the ideal it is not

absolutely perfect. No actual surface is a perfectly full radiator, but the exact equivalent of one has been obtained by an ingenious device. A hollow vessel which is blackened on the inside has a small aperture through which the radiation from the interior of the vessel can escape. If the vessel is heated up, therefore, the small aperture may act as a radiator. The radiation which emerges through the aperture from any small area on the interior of the vessel is made up of two parts, one part which it radiates itself, and the other part which it scatters back from the radiation which it receives from the other parts of the interior of the vessel. These two together are equal to the energy sent out by a full radiator, and therefore the small aperture acts as a full radiator: *e.g.* suppose the inner surface has an absorbing power of 90 per cent., then it radiates 90 per cent. of the full radiation and absorbs 90 per cent. of the radiation coming up to it therefore scattering back 10 per cent. We have therefore coming from the inner surface 90 per
{45} cent. radiated and 10 per cent. scattered, and the radiated and scattered together make 100 per cent.

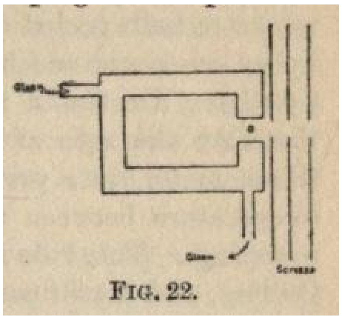

FIG. 22.

One form in which such radiators have been used is shown in section in Fig. 22. A double walled cylindrical vessel of brass has a small hole, *a*, in one end. Steam can be passed through the space between the double walls, thus keeping the temperature of the inner surface at 100° C. A screen with a hole in it just opposite to the hole in the vessel, or rather several such screens, are placed in front of the vessel in order to shield any measuring instrument from any radiation except that emerging through the hole.

The Full Absorber.—In an exactly similar way an aperture in a hollow vessel will act as a full absorber, for the fraction of the incident radiation which is scattered on the inner surface again impinges on another portion of the surface and so all is ultimately absorbed except a minute fraction which is scattered out again through the aperture.

The variation in the heat radiated by a full radiator at different temperatures forms a very important part of the study of radiation, and a very large number of experiments and theoretical investigations have been devoted to it. These investigations may be divided into two sections: those concerned with the total quantity of heat radiated at different temperatures and those concerned with the variation in the character of the spectrum with varying temperatures.

{46} The experiments in the first section have been carried out mainly in two ways. In the first, the rate of cooling of the full radiator has been determined, and from the rate of cooling at any temperature the rate at which heat was lost by radiation was immediately calculated. Newton was the first to investigate in this way by observing the rate at which a thermometer bulb cooled down when it was surrounded by an enclosure which was kept at a uniform temperature. He found that the rate of cooling, and therefore the rate at which heat was lost by the thermometer, was proportional to the difference of temperature between the thermometer and its surroundings. This rule is known as Newton's Law of Cooling, and is still used when it is desired to correct for the heat lost during an experiment where the temperature differences are small. It is only true, however, for very small differences of temperature between the thermometer and its surroundings, and as early as 1740 Martine had found that it was only true for a very limited range of temperature.

Prévost's Theory of Exchanges.—In 1792, Prévost of Geneva, when endeavouring to explain the supposed radiation of cold, introduced the line of thought, that any body is not to be regarded as radiating heat only when its temperature is falling, or absorbing heat only when its temperature is rising, but that both processes are continually and simultaneously going on. The amount of heat radiated will depend on the temperature and character of the body itself, while the amount absorbed will depend upon the condition of the surroundings as well as upon the
{47} nature of the body. If the amount of heat radiated is greater than the amount absorbed the body will fall in temperature, and *vice-versa*. This view of Prévost's is called the Theory of Exchanges, and we can see that it is a necessary consequence of our ideas as to the production of heat and light waves by the agitation of electrons in the radiating body.

If the rate of cooling of a body at a certain temperature is measured when it is placed in an enclosure at a lower temperature, it must be borne in mind that the rate of loss of heat is equal to the rate at which heat is radiated minus the rate at which it is absorbed from the enclosure.

A second way in which the heat lost by a body has been measured at different temperatures is by heating a conductor such as a thin platinum strip by means of an electric current, and measuring the temperature to which the conductor has attained. When its temperature is steady, all the energy given to it by the current must be lost as heat, and therefore the electrical energy, which can very easily be calculated, must be equal to the heat radiated by the body minus the heat received from the enclosure.

So many attempts have been made to establish, by one or other of these two methods, the relation between the quantity of heat radiated and the temperature, that it is impossible to give even a passing reference to most of them. Unfortunately, the results do not show the agreement with one another which we would like, but probably the most correct result is that stated by
{48} Stefan in 1878, after a close inspection of the experimental results of Dulong and Petit. He stated that the quantity of heat radiated per second by a full radiator is proportional to the fourth power of its absolute temperature.[1] Thus the quantity of heat radiated by one square centimetre of the surface of a full radiator whose absolute temperature is T, is equal to ET^4, where E is some constant multiplier which must be determined by experiment and which is called the radiation constant. If the absolute temperature of the enclosure in which the surface is placed is T, then the rate at which the surface is losing heat will be $E(T^4-T_1^4)$, for it will receive heat at the rate ET_1^4 and will radiate it at the rate ET^4.

[1] See page 56.

Stefan's fourth power law has been verified by a number of good experiments, notably those of Lummer and Pringsheim (*Congrés International de Physique*, Vol. II. p. 78), so that although some experiments do not agree with it, we are probably justified in taking it as correct.

In 1884 Boltzmann added still further evidence in support of this law by deriving it theoretically. He applied to a space containing the waves of full radiation the two known laws which govern the transformation of energy, by imagining the space to be taken through a cycle of compressions and expansions in just the same way as a gas is compressed and expanded in what is known as Carnot's cycle.

Variation of Spectrum with Temperature.—The variation of the character of the spectrum of a full radiator has been determined mainly by the use of Langley's bolometer, but the general nature of the change may be readily observed by the eye.

{49} As the temperature of a full radiator rises it first gives out only invisible heat waves; as soon as its temperature exceeds about 500° C. it begins to emit some of the longest visible rays; and as the temperature rises further, more and more of the visible rays in the spectrum are emitted until, when the radiator is white hot, the whole of the visible spectrum. is produced. Thus the higher the temperature of the radiator the more of the shorter waves are produced.

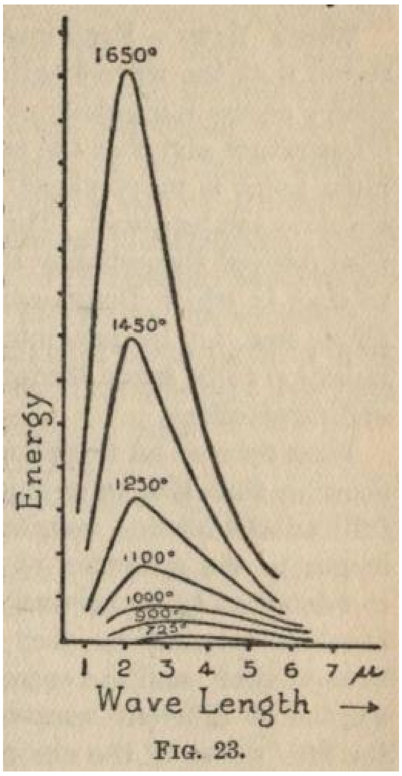

FIG. 23.

By means of Langley's bolometer the distribution of energy in the spectrum has been measured accurately, with the results of confirming and amplifying the general results just stated. The energy in the spectrum of even the hottest of terrestrial radiators is mostly in the longer waves of the infra-red, but the position of the maximum of energy moves to shorter and shorter wave-lengths as the temperature rises, and so more of the shorter waves make their appearance. The sun is not a full radiator, but is nearly so, and its temperature is so high that the maximum of energy in its spectrum is in the visible part near to the red end.

{50} Fig. 23 shows the results obtained by Lummer and Pringsheim, and brings out clearly the shift of the maximum with rising temperature and also the position of the greatest part of the energy in the infrared region.

Wien's Laws.—Examination of the results also shows that the wave-length at which the maximum energy occurs is inversely proportional to the absolute temperature and that the actual energy at the maximum point is proportional to the fifth power of the absolute temperature. These two results have both been derived theoretically by Wien[2] in a similar way to that in which Boltzmann derived Stefan's fourth power law, *i.e.* by imagining a space filled with the radiation to be taken through a cycle of compressions and rarefactions.

[1] *Wied. Ann.*, 46, p. 633; 52, p. 132.

Wien derived an amplification of the last result by showing that if a wave-length in the spectrum of a full radiator at one temperature and another wave-length in the spectrum at another temperature are so related as to be inversely proportional to the two absolute temperatures, they may be said to correspond to each other, and the energy in corresponding wave-lengths at different temperatures is proportional to the fifth power of the absolute temperature.

We see therefore that if the distribution of energy in the spectrum of the full radiator be known at any one temperature it may be calculated for any other temperature by applying these two laws of corresponding wave-lengths and the energy in them.

{51} Neither of them give us any information, however, about the actual distribution of energy at any one temperature from which we may calculate that at any other temperature. For that, some relation must be found between the energy and the wave-length. Planck, by reasoning founded on the electromagnetic character of the waves, derived such a relation, but both his reasoning and his results are a little too complicated to be introduced here. His results have been confirmed in the most striking manner by experiments carried out by Rubens and Kurlbaum (*Ann. der Physik*, 4, p. 649, 1901). They measured the energy in a particular wave-length (.0051 cms., *i.e.* nearly 100 times the wave-length of red light) in the radiation of a full radiator from a temperature of 85° up to 1773° absolute, and their results are given in the following table:

Absolute Temperature.	Observed Energy.	Energy calculated from Planck's Formula.
85	-20.6	-21.9
193	-11.8	-12
293	0	0
523	+31	+30.4
773	64.6	63.8
1023	98.1	97.2
1273	132	132
1523	164	160
1773	196	200

We have therefore the means of calculating both the total quantity and the kind of radiation given out by any full radiator at any temperature, and a number of very interesting problems may be solved by means of the results.

{52} **Efficiency in Lighting.**—One very simple problem is concerned with efficiency in lighting. We see by reference to Fig. 16, that in the radiation from the electric arc very little of the energy is in the visible part of the spectrum even though the temperature in the arc is the highest yet obtained on the earth, whereas the energy in the visible part of the spectrum from a gas flame is almost wholly negligible. The problem of efficient lighting is to get as big a proportion as possible of the energy into the visible part of the spectrum, and therefore the higher the temperature the greater the efficiency. This is the reason of the greater efficiency of the incandescent gas mantle over the ordinary gas burner, for the introduction of the air into the gas allows the combustion to be much more complete, and therefore the temperature of the mantle becomes very much higher than that of the carbon particles in the ordinary flame. The modern metallic filament electric lamps have filaments made of metals whose melting point is extremely high, and they may therefore be raised to a much higher temperature than the older carbon filaments. The arc is even more efficient than the metallic filament lamps, because its temperature is higher still; and we must assume that the temperature of the sun is very much higher even than the arc, since its maximum of energy lies in the visible spectrum.

Temperature of the Sun.—The actual temperature of the sun may be calculated

approximately by means of Stefan's fourth power law. We will first assume that the earth and the
{53} sun are both full radiators, and that the earth is a good conductor, so that its temperature is the same all over. The first assumption is very nearly true, and we will make a correction for the small error it introduces; and the second, although far from true, makes very little difference to the final result, for it is found that the values obtained on the opposite assumption that the earth is an absolute non-conductor differ by less than 2 per cent. from those calculated on the first assumption. We will further assume that the heat radiated out by the earth is exactly equal to the heat which it receives from the sun. This is scarcely an assumption, but rather an experimental fact, for experiment shows that heat is conducted from the interior of the earth to the exterior, and so is radiated, but at such a small rate that it is perfectly negligible compared with the rate at which the earth is receiving heat from the sun.

The sun occupies just about one 94,000th part of the hemisphere of the heavens or one 188,000th part of the whole sphere. If the whole sphere surrounding the earth were of sun brightness, the earth would be in an enclosure at the temperature of the sun, and would therefore be at that temperature itself. The sphere would be sending heat at 188,000 times the rate at which the sun is sending it, and the earth would be radiating it at 188,000 times its present rate. But the rate at which it radiates is proportional to the fourth power of its absolute temperature, and therefore its temperature would be the fourth root of 188,000 times its present temperature, *i.e.* 20.8 times. If the radiating or absorbing power of the earth's surface be taken
{54} as 9/10, which is somewhere near the mark, the calculation gives the number 21.5 instead of 20.8. The average temperature of the earth's surface is probably about 17° C. or 290° absolute, and therefore the temperature of the sun is 290 x 21.5, *i.e.* about 6200° absolute.

It is easy to see that if we had known the temperature of the sun and not of the earth, we could have calculated that of the earth by reversing the process.

By this means we can estimate the temperatures of the other planets, at any rate of those for which we may make the same assumptions as for the earth. Probably those planets which are very much larger than the earth are still radiating a considerable amount of heat of their own, and therefore to them the calculation will not apply; but the smaller planets Mercury, Venus and Mars have probably already radiated nearly all their own heat and are now radiating only such heat as they receive from the sun. The temperatures calculated in this way are—

	Average Absolute Temperature
Mercury	467°
Venus	342°
Earth	290°
Mars	235°

Since the freezing point of water is 273° absolute, we see that the average temperature of Mars is 38° C. below freezing, and it is almost certain that no part of Mars ever gets above freezing point.

In a very similar way we may find the temperature to which a non-conducting surface reaches when it is exposed to full sunlight by equating the heat absorbed to the heat radiated, and the
{55} result comes to 412° absolute, *i.e.* 139° C., or considerably above boiling point. This would be the upper limit to the temperature of the surface of the moon at a point where the sun is at its zenith.

On the surface of the earth the sunlight has had to pass through the atmosphere, and in perfectly bright sunshine it is estimated that only three-fifths of the heat is transmitted. Any surface is also radiating out into surroundings which are at about 300° absolute. Taking into account these two facts, we find that the upper limit to a non-conducting surface in full sunshine on the earth is about 365° absolute, or only a few degrees less than the boiling point of water.

Effective Temperature of Space.—The last problem we will attack by means of the fourth power law is the estimation of the effective temperature of space, *i.e.* the temperature of a full absorber shielded from the sun and far away from any planet.

It is estimated by experiment that zenith sun radiation is five million times the radiation from the stars. This estimate is only very rough, as the radiation from the stars is so minute. As the sun only occupies one 94,000th part of the heavens, the radiation from a sunbright hemisphere would be five million times 94,000 times starlight, *i.e.* 470,000,000,000 times. The temperature of the sun is therefore the fourth root of this quantity times the effective temperature of space, *i.e.* about 700 times. Since the temperature of the sun is about 6200°, the temperature of space is a little under 10° absolute; *i.e.* lower than -263° C.

{56} **Note on Absolute Temperature.**—It is found that, if a gas such as air has its temperature raised or lowered while its pressure is kept uniform, for every one degree centigrade rise or fall its volume is increased or decreased by one two hundred and seventy-third of its volume at freezing point, *i.e.* at 0° centigrade. If therefore it continued in the same way right down to -273° centigrade, its volume would be reduced to zero at this temperature. This temperature is therefore called the absolute zero of temperature, and temperatures reckoned from it are called absolute temperatures. To get absolute temperatures from centigrade temperatures we evidently need to add 273°.

{57}

CHAPTER VI

THE TRANSFORMATION OF ABSORBED RADIATION

No account of radiation would be complete without mentioning what becomes of the radiation which bodies absorb, but a good deal of the subject is in so uncertain a state that very little space will be devoted to it.

Absorbed Radiation converted into Heat.—The most common effect of absorbed radiation is to raise the temperature of the absorbing body, and so cause it to re-emit long heat-waves. As the usual arrangement is for the absorbing body to be at a lower temperature than the radiating one, the waves given out by the absorber are longer than those given out by the radiator, and so the net result is the transformation of shorter waves into longer ones. But we have seen by Prévost's theory of exchanges that radiator and absorber are interchangeable, and therefore we see that those waves which are emitted by the absorber and absorbed by the radiator are re-emitted by the latter as shorter waves.

The mechanism by means of which the waves are converted into heat in the body is still a mystery. That the waves should cause the electrons to vibrate is perfectly clear, but how the {58} vibrations of the electrons are converted into those vibrations of the atoms and molecules which constitute heat is still unsolved, and the reverse process is, of course, equally puzzling.

The heating of the body and the consequent re-emission of heat-waves is not, however, the only process which goes on. In a large number of substances, waves are given out under the stimulus of other waves without any heating of the body at all. In most of these cases the emission stops as soon as the stimulating waves are withdrawn, and in these cases the phenomenon has been called fluorescence. The name has been derived from fluor spar, the substance which was first observed to exhibit this peculiar emission of waves.

A familiar example of fluorescence is provided by paraffin-oil, which glows with a blue light when it is illuminated with ordinary sunlight or daylight. Perhaps the easiest way to view it is to project a narrow beam of light through the paraffin-oil contained in a glass vessel and view the oil in a direction perpendicular to the beam. The latter will then show up a brilliant blue.

A water solution of sulphate of quinine, made acid by a few drops of sulphuric acid, also exhibits a blue fluorescence, while a water solution of æsculin (made by pouring hot water over some scraps of horse-chestnut bark) shines with a brilliant blue light.

Some lubricating oils fluoresce with a green light, as does also a solution in water of fluorescene, named thus because of its marked fluorescence.

A solution of chlorophyll in alcohol, which can be readily prepared by soaking green leaves in alcohol, shows a red fluorescence; uranium glass—the canary glass of which small vases are very {59} frequently made—exhibits a brilliant green fluorescence, as does also crystal uranium nitrate.

It is found, on observing the spectrum of the fluorescent light, that a fairly small range of waves is emitted showing a well-marked maximum of intensity at a wave-length which is characteristic of the particular fluorescing substance.

There also seems to be a limited range of waves which can induce this fluorescence, and this range also depends upon the fluorescing substance. As a rule, the inducing waves are shorter in length than the induced fluorescence, but this rule has some very marked exceptions.

The fact that only a limited range of waves produces fluorescence explains a noticeable characteristic of the phenomenon. If the fluorescing solutions are at all strong the fluorescence is confined to the region close to where the light enters the solution, thus showing that the rays which are responsible for inducing the glow become rapidly absorbed, whereas the remainder of the light goes on practically unabsorbed.

Phosphorescence.—Sometimes the emission of the induced light continues for some time after the inducing waves are withdrawn, and then the phenomenon is termed phosphorescence, since phosphorus emits a continuous glow without rise of temperature.

Sometimes the glow will continue for several hours after the exciting rays have been cut off, a good example of this being provided by Balmain's luminous paint, which is a sulphide of calcium. With other substances the glow will only continue for a very small fraction of a second, {60} so that it is impossible to say where fluorescence ends and where phosphorescence begins.

In order to determine the duration of the glow in the case of these small times, an arrangement consisting of two rotating discs, each of which have slits in them, is set up. Through the slits in one of them the substance is illuminated, and through the slits in the other the substance is observed while the light is cut off. By adjusting the position of the discs with regard to each other the slits may be made to follow one another after greater or shorter intervals, and so the time of observation can be made greater or smaller after the illumination is cut off.

All the bodies which have been observed to exhibit phosphorescence are solid.

Theory of Fluorescence.—It is fairly simple to imagine a mechanism by which fluorescence might be brought about, as we might assume a relation between the periods of oscillation of certain types of electron in the substance and the period of the stimulating waves. Thus resonance might occur, and the consequent vibrations of the electrons would start a series of secondary waves.

If, however, we assume resonance, it is difficult to see why there is a range of wave-lengths produced and another range of wave-lengths which may produce them. We should have expected one definite wave-length or a few definite ones producing one or a few definite wave-lengths in the glow, while if a whole range of waves will produce the effect it is difficult to see why all bodies do not exhibit the phenomenon.

{61} But the phenomenon of phosphorescence finally disposes of any such description, for the two phenomena have no sharp distinction between them. Some substances are known in which the phosphorescence lasts for such an extremely small fraction of a second after the stimulating waves are withdrawn that it is difficult to know whether to call the effect fluorescence or phosphorescence. It is probable, therefore, that both are due to the same action. Now a wave of orange light completes about five hundred million million vibrations in one second, and therefore if an orange-coloured phosphoresence were to last for only one five-hundredth of a second it would mean that the electrons responsible for it vibrate one million million times after the stimulus is removed. This is hardly credible, and becomes more credible when we remember that in some phosphorescent substances the effect lasts for many hours.

Chemical Theory of Phosphoresence.—It is more probable that the stimulating rays produce an actual chemical change in the phosphorescent substance. For instance, it is possible that the vibrations of a certain type of electron in one kind of atom become so violent as to detach it from the atom and the temporarily free electron attaches itself immediately to another kind of atom.

The new arrangement may be quite stable; it is so in the action of light on a photographic plate, but it may only be stable when the electrons are being driven out of their original atoms, and in this case the electrons will begin to return to their old allegiance as soon as the stimulus is
{62} withdrawn. In the return process the electrons will naturally be agitated, and will therefore emit waves having their characteristic period. The rate at which the return process takes place will evidently depend upon the stability of the new arrangement. If it is extremely unstable, the whole return may only occupy a fraction of a second, but if it is nearly as stable as the original arrangement the return may be extremely slow.

On this view, then, those substances will phosphoresce which have an electron which is fairly easily detached from its atom and which will attach itself to another atom, forming an arrangement which is less stable than the original.

Temperature and Phosphorescence.—A confirmation of this chemical view is provided by the effect of temperature on phosphorescence. The rate of a chemical change is usually very largely increased by rise of temperature, and further, at very low temperatures a large number of chemical changes which take place quite readily at ordinary temperatures do not take place at all.

Similarly at very low temperatures the action of the light may be more or less stable. For example, Dewar cooled a fragment of ammonium-platino-cyanide by means of liquid hydrogen, and exposed it to a strong light. After removing the light no phosphorescence was observed, though at ordinary temperatures a brilliant green phosphorescence is exhibited, but on allowing the fragment to warm up it presently glows very brightly.

A partial stability is shown by Balmain's luminous paint, for if it be kept in the dark until it
{63} becomes quite non-luminous it will begin to glow again for a short time if warmed up in any way. By means of this property the infra-red region of the spectrum may be made visible. For this purpose a screen is coated with the paint, exposed to strong sunlight, and then placed so as to receive the spectrum. The first effect of the invisible heat rays is to make the portions of the screen on which they fall brighter than their surroundings; but this causes the phosphorescence to be emitted more rapidly, and soon it is all emitted, leaving a dark region where the heat has destroyed the phosphorescence.

On the whole, then, those substances which phosphoresce at ordinary temperatures do so more rapidly as the temperature rises.

But Dewar has found a number of substances which phosphoresce only at low temperatures, *e.g.* gelatine, celluloid, paraffin, ivory and horn. This is not a fatal objection to the idea of chemical change, as some chemical actions will only take place at low temperatures, but it is an objection as quite a large number of substances only phosphoresce at low temperatures, whereas there are not many chemical reactions which will only take place there.

As a matter of fact, even if the idea of a chemical change be the true one, it is not a very satisfactory one, as chemical changes are undoubtedly very complicated ones, and it would be too difficult to trace the change from the vibration of an electron to the chemical change, and *vice-versa*.

No satisfactory theory therefore exists to account for the absorption and the remission of the waves, whether accompanied or unaccompanied by a rise in temperature of the absorbing body.

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CHAPTER VII

PRESSURE OF RADIATION

Prediction of Pressure by Maxwell.—Had the fact that light exerts a pressure been known in Newton's time there is no doubt that it would have been hailed as conclusive proof of the superiority of the corpuscular theory over the wave theory. Yet, ironically enough, it was reserved for James Clerk Maxwell to predict its existence and calculate its value on the assumption of his electromagnetic wave theory; and further, the measurement of its value has given decisive evidence in favour of the wave theory, for the value predicted by the latter is only one-half that predicted by the corpuscular theory, and the measurements by Nicholls and Hull agree to within 1 per cent. with the wave theory value.

Maxwell showed that all waves which come up to and are absorbed by a surface exert a pressure on every square centimetre of the surface equal to the amount of energy contained in one cubic centimetre of the beam.

If the surface is a perfect reflector, the reflected waves produce an equal back pressure, and therefore the pressure is doubled. As the waves are reflected back along their original direction,
{65} the energy in the beam will also be doubled, and so the pressure will still be equal to the energy per cubic centimetre of the beam.

As the energy which is received in one second from the sun on any area can be measured by measuring the heat absorbed, and since the speed of light is known, we can calculate the energy contained in one cubic centimetre of full sunlight, and hence the pressure on one square centimetre of surface. For the energy received on one square centimetre of surface in one second must have been spread originally over a length of beam equal to the distance which the light has travelled in one second, *i.e.* over a length equal to the speed of light. If we divide that energy, therefore, by the speed of light, we shall get the energy in a one-centimetre length of the beam, and therefore in one cubic centimetre.

This turns out to be an extremely small pressure indeed, being only a little more than the weight of half a milligram, on a square metre of surface.

Maxwell suggested that a much greater energy of radiation might be obtained by means of the concentrated rays of an electric lamp. Such rays falling on a thin, metallic disc delicately suspended in a vacuum might perhaps produce an observable mechanical effect.

Nearly thirty years after Maxwell's suggestion it was successfully carried out by Prof. Lebedew of Moscow, who used precisely the arrangement which Maxwell had suggested.

Measurement of the Pressure.—A beam of light from an arc lamp was concentrated on to a
{66} disc suspended very delicately in an exhausted glass globe about 8 inches across. Actually four discs were suspended, as in Fig. 24, and arrangements were made to concentrate the beam on to either side of any of the four discs.

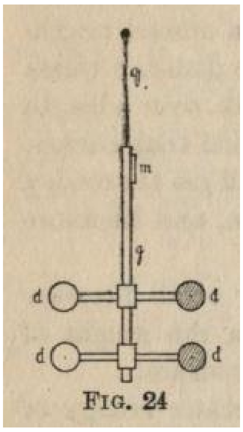

FIG. 24.

The suspension was a very fine quartz fibre *q*. The discs *d*, *d*, *d*, *d*, were half a centimetre in diameter and were fixed on two light arms, so that their centres were one centimetre from the glass rod, *g*, which carried them. A mirror, *m*, served to measure the angle through which the whole system was twisted owing to the pressure of the beam on one of the discs. In order to measure the angle a telescope viewed the reflection of a scale in *m*, and as *m* turned different divisions of the scale came into view.

The two discs on the left were polished and therefore the pressure on them should be about twice that on the blackened discs on the right.

Having measured the angle through which a beam of light has turned the system, it is a simple matter to measure the force which would cause this twist in the fibre q. In order to test whether the pressure agrees with the calculated value, we must find the energy in the beam of light. This was done by receiving the beam on a blackened block of copper and measuring the rate at which its temperature rose. From this rate and the weight of copper it is easy to calculate the amount of heat received per second, and therefore the amount of energy received per second
{67} on one square centimetre of the area. Knowing the speed of the light we can, as suggested above, calculate the energy in one cubic centimetre of the beam.

Lebedew's result was in very fair accord with the calculated value. The chief difficulty in the experiment is to eliminate the effects due to the small amount of gas which remains in the globe. Each disc is heated by the beam of light, and the gas in contact with it becomes heated and causes convection currents in the gas. At very low pressures a slightly different action of the gas becomes a disturbing factor. This effect is due to the molecules which come up to the disc becoming heated and rebounding from the disc with a greater velocity than that with which they approached it. The rebound of each molecule causes a backward kick on to the disc, and the continual stream of molecules causes a steady pressure.

This would be the same on both sides of the disc if both sides were at the same temperature, but since the beam of light comes up to one side, that side becomes hotter than the other and there will be an excess of pressure on that side. This action is called "radiometer" action, because it was first made use of by Crookes in detecting radiation.

Between the Scylla of convection currents at higher pressures and the Charybdis of radiometer action at lower pressures, there seems to be a channel at a pressure of about two or three centimetres of mercury. For here the convection currents are small and the radiometer action has scarcely begun to be appreciable.

{68} By working at this pressure and using one or two other devices for eliminating and allowing for the gas action, Professors Nicholls and Hull also measured the pressure of light in an exceedingly careful and masterly way. Their results were extremely consistent among themselves, and agreed with the calculated value to within one per cent. Those who know the difficulty of measuring such minute forces, and the greatness of the disturbing factors, must recognise in this result one of the finest experimental achievements of our time.

Effect of Light Pressure in Astronomy.—Forces due to light pressure are so small that we should not expect to be able to detect their effects on astronomical bodies, and certainly we cannot hope to observe them in the large bodies of our system.

The pressure of the sunlight on the whole surface of the earth is about 75,000 tons weight. This does not sound small until we compare it with the pull of the sun for the earth, which is two hundred million million times as great.

When we consider very small bodies, however, we find that the pressure of the light may even exceed the gravitational pull, and therefore these small particles will be driven right away from our system.

In order to show that the light pressure becomes more and more important, let us imagine two spheres of the same material, one of which has four times the radius of the other.

Then the weight of the larger one, that is its gravitational pull, will be sixty-four times as great as that of the smaller one, while the area, and therefore the light pressure, will be sixteen times as great.

{69} The light pressure is therefore four times as important in the sphere of one-quarter the radius. For a sphere whose radius is one two hundred million millionth of the radius of the earth and of the same density, the pressure of the light would equal the pull of the sun, and therefore such a sphere would not be attracted to the sun at all.

This is an extremely small particle, much smaller than the finest visible dust, but even for much larger things the light pressure has an appreciable effect.

Thus for a sphere of one centimetre radius and of the same density as the earth, the pressure due to the sunlight is one seventy-four thousandth of the pull due to gravitation. It therefore need not move in its orbit with quite such a high speed in order that it may not fall into the sun, and its year is therefore lengthened by about three minutes. The lengthening out of comets' tails as they approach the sun, and the apparent repulsion of the tail by the sun, has sometimes been attributed to pressure of sunlight, but it is pretty certain that the forces called into play are very much greater than can be accounted for by the light.

Doppler Effect.—The Doppler effect also has some influence on the motion of astronomical bodies. When a body which is receiving waves moves towards the source of the waves, it receives the waves more rapidly than if it were still, and therefore the pressure is greater. When the body is moving away from the source it receives the waves less rapidly, and hence the pressure of light on it is less than for a stationary body. If a body is moving in an elliptical orbit, it is moving
{70} towards the sun in one part of its orbit and away in another part; it will therefore be retarded in both parts, and the ultimate result will be that the orbit will be circular.

The Doppler effect can act in another way. A body which is receiving waves from the sun on one side is thereby heated and emits waves in all directions. As it is moving in its orbit it will crowd up the waves which it sends out in front of it and lengthen out those which it sends out behind it. But the energy per cubic centimetre will be greater where the waves are crowded up than where they are drawn out, and therefore the body will experience a retarding force in its orbit. As the body tends to move more slowly it falls in a little towards the sun, and so approaches the sun in a spiral path.

Three Effects of Light Pressure.—We thus have three effects of light pressure on bodies describing an orbit round the sun. The first effect is to lengthen their period of revolution, the second is to make their orbits more circular, and the third is to make them gradually approach the sun in a spiral path. These effects are quite inappreciable for bodies anything like the size of the earth, but for small bodies of the order of one centimetre diameter or less the effects would be quite large. Our system is full of such bodies, as is evidenced by the number of them which penetrate our atmosphere and form shooting stars. The existence of such bodies is somewhat of a problem, as whatever estimate of the sun's age we accept as correct, he is certainly of such an age that if these bodies had existed at his beginning they would all have been drawn in to him
{71} long ago. We must therefore suppose that they are continually renewed in some way, and since we can see no sufficient source inside the Solar system, we must come to the conclusion that they are renewed from outside. There is every reason to believe that some of them originate in comets which have become disintegrated and spread out along their orbits. These form the meteoric showers.

Thus the very finest dust is driven by the sun right out of our system, and all the rest he is gradually drawing in to himself.

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CHAPTER VIII

THE RELATION BETWEEN RADIANT HEAT AND ELECTRIC WAVES

In this concluding chapter it is proposed to show how the wave-lengths of radiant heat have been determined and to state what range of wave-lengths has been experimentally observed. It is then proposed to show how electromagnetic waves have been produced by straightforward electrical means and how their wave-lengths have been measured. The similarity in properties of the radiant heat and of the electric waves will be noted, leading to the conclusion that the difference between the two sets of waves is merely one of wave-length.

Diffraction Grating.—The best method of measuring the wave-lengths of heat and light is by means of the "Diffraction Grating." This consists essentially of a large number of fine parallel equidistant slits placed very close to one another. For the measurement of the wave-lengths of light and of the shorter heat waves, it is usually produced by ruling a large number of very fine close equidistant lines on a piece of glass or on a polished mirror by means of a diamond point. The ruled lines are opaque on the glass and do not reflect on the mirror, and consequently the spaces in between act as slits.

{73} **Rowland's Gratings.**—The ruling of these gratings is a very difficult and tedious business, but the difficulties have been surmounted in a very remarkable manner by Rowland, so that the gratings ruled on his machine have become standard instruments throughout the world. He succeeded in ruling gratings 6 inches in diameter with 14,000 lines to the inch, truly a remarkable performance when we remember that if the diamond point develops the slightest chip in the process, the whole grating is spoilt.

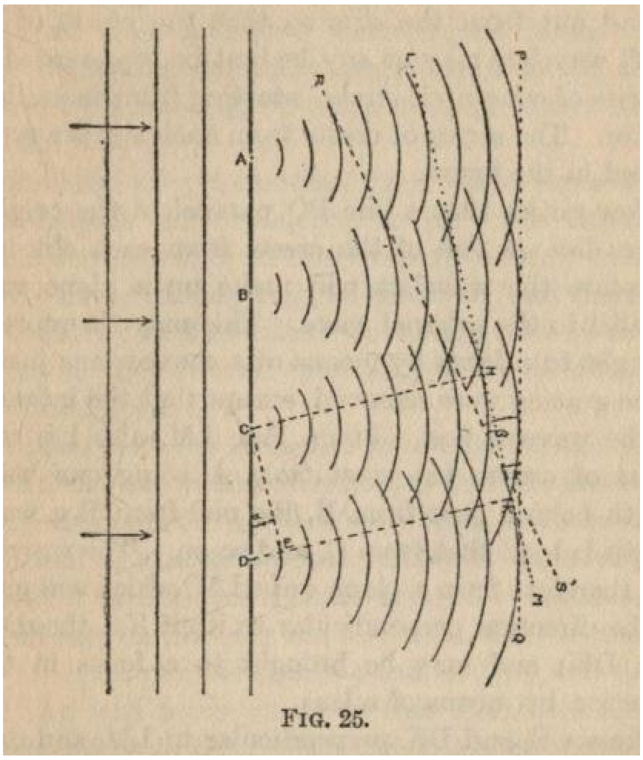

FIG. 25.

{74} The action of the grating can be made clear by means of Fig. 25. Let A, B, C, D represent the equidistant slits in a grating, and let the straight lines to the left of the grating represent at any instant the crests of some simple plane waves coming up to the grating. The small fractions of the original waves emerging from the slits A, B, C, D will spread out from the slits so that the crests of the small wavelets may at any instant be represented by a series of concentric circles, starting from each slit as centre. The series of crests from each slit are represented in the figure.

Now notice that a line PQ parallel to the original waves lies on one of the crests from each slit, and therefore the wavelets will make up a plane wave parallel to the original wave. This may therefore be brought to a focus by means of a convex lens just as if the grating were removed, except that the intensity of the wave is less. But a line, LM, also lies on a series of crests, the crest from A being one wave-length behind that from B, the one from B a wave-length behind that from C, and so on. The wavelets will therefore form a plane wave LM, which will move in the direction perpendicular to itself (*i.e.* the direction DK) and may be brought to a focus in that direction by means of a lens.

Draw CH and DK perpendicular to LM, and draw CE perpendicular to DK, *i.e.* parallel to LM. The difference between CH and DK is evidently one wave-length, *i.e.* DE is one wave-length. If α is the angle between the direction of PQ and LM, DE is evidently equal to CD sin α and therefore one wave-length=CD sin α.

{75} From the ruling of the grating we know the value of CD, and therefore by measuring α we can calculate the wave-length.

We find that a third line RS also lies on a series of crests, and therefore a plane wave sets out in the direction perpendicular to RS. We notice here that the crest from A is two wave-lengths behind that from B, and so on, and therefore if β is the angle between RS and PQ, CD sin β is equal to two wave-lengths.

Similarly we get another plane wave for a three wave-lengths difference, and so on. The intensity of the wavelets falls off fairly rapidly as they become more oblique to their original direction, and therefore the intensity of these plane waves also falls off rather rapidly as they become more oblique to the direction in which PQ goes.

We see that the essential condition for the plane wave to set out in any direction, is that the difference in the distances of the plane wave from two successive slits shall be exactly a whole number of wave-lengths. Should it depart ever so little from this condition we should see, on drawing the line, that there lie on the line an equal number of crests and troughs, and therefore, if a lens focus waves in this direction, the resulting effect is zero. The directions of the waves PQ, LM, RS, &c., will therefore be very sharply defined and will admit of very accurate determination.

Dispersion by Grating.—Evidently the deviations α, β will be greater the greater is DE, *i.e.* the greater the wave-length, and therefore the light or heat will be "dispersed" into its different
{76} wave-lengths as in the prism; but in this case the dispersion is opposite to that in the normal prism, the long waves being dispersed most and the short waves least.

Evidently, too, the smaller the distance CD the greater the angle, and therefore for the extremely short wave-lengths of light and of ultraviolet rays we require the distance between successive slits to be extremely small.

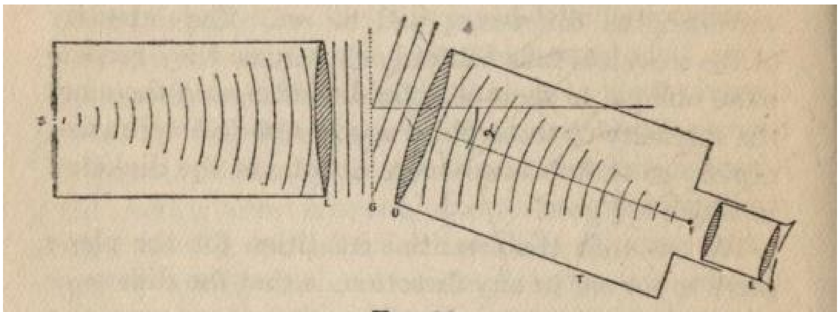

FIG. 26.

The Spectrometer.—The grating is usually used with a spectrometer, as shown in plan diagrammatically in Fig. 26. The slit S from which the waves radiate is placed at the principal focus of the lens L, and therefore the waves emerge from L as plane waves which come up to the grating G. The telescope T is first turned until it views the slit directly, *i.e.* until the plane waves like PQ in Fig. 25 are brought to a focus at the principal focus F of the objective of the telescope. The eyepiece E views the image of the slit S which is formed at F. The telescope is then turned through an angle, α, until it views the second image of the slit which will be formed by the plane waves similar to LM in Fig. 25. The angle α is carefully measured by the graduated circle on the
{77} spectrometer, and hence the wave-length of a particular kind of light, or of a particular part of the spectrum, is measured.

This spectrometer method is exactly the method used for measuring the wave-lengths in the visible part of the spectrum.

For the ultraviolet rays, instead of viewing the image of the slit by means of the eyepiece of the telescope, a photographic plate is placed at the principal focus F of the objective of the telescope, and serves to detect the existence and position of these shorter waves. For the heat rays a Langley's bolometer strip is placed at F, in fact the bolometer strip might be used throughout, but it is not quite so sensitive for the visible and ultraviolet rays as the eye and the photographic plate.

Absorption by Glass and Quartz.—Two main difficulties arise in these experiments. The first one is that although glass, or better still quartz, is extremely transparent to ultraviolet, visible, and the shorter infra-red waves, yet it absorbs some of the longer heat waves almost completely.

For these waves, therefore, some arrangement must be devised in which they are not transmitted through a glass diffraction grating or through glass or quartz lenses. To effect this, the convex lenses are replaced by concave mirrors and the ruled grating is replaced by one which is made of very fine wires, which are stretched on a frame parallel to and equidistant from each other. The wire grating cannot be constructed with such fine or close slits as the ruled grating, but for the longer waves this is unnecessary.

{78} **Reflecting Spectrometer.**—An arrangement used by Rubens is represented roughly in plan in Fig. 27. L represents the source of heat, the rays from which are reflected at the concave mirror M, and brought to a focus on the slit S. Emerging from S the rays are reflected at M_2 and are thereby rendered parallel before passing through the wire grating G. After passing through the grating, the rays are reflected at M_3 and are thereby focussed on to a bolometer strip placed at B. Turning the mirror M_3 in this arrangement is evidently equivalent to turning the telescope in the ordinary spectrometer arrangement.

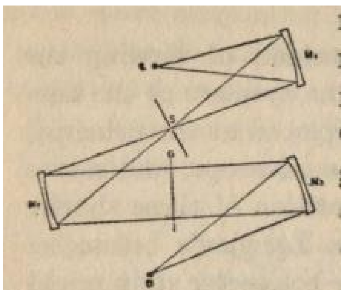

FIG. 27.

Absorption of Waves by Air.—By using a spectrometer in an exhausted vessel Schumann discovered that waves existed in the ultraviolet region of much smaller wave-length than any previously found, and that these waves were almost completely absorbed on passing through a few centimetres of air. To all longer waves, however, air seems to be extremely transparent.

The second difficulty arises from the fact, already explained, that a diffraction grating produces not one, but a number of spectra. If only a small range of waves exists, this will lead to no confusion, but if a large range is being investigated, we may get two or more of these spectra overlapping.

Suppose, for example, we have some waves of wave-length DE (in Fig. 25), some of wave-
{79} length one-half DE and some of one-third DE. Then in the direction DK we shall get plane waves of each of these wave-lengths setting out and being brought to a focus in the same place. This difficulty can be fairly simply surmounted where the measurement of wave-length alone is required, by placing in the path of the rays from the source of light, suitable absorbing screens, which will only allow a very small range of wave-lengths to pass through them. There will then be no overlapping and no confusion.

Where the actual distribution of energy in the spectrum of any source of heat is to be determined the difficulty becomes more serious, and probably there is some error in the determinations, especially in the longest waves, which are masked almost completely by the overlapping shorter waves.

Rest-Strahlen or Residual Rays.—A very beautiful method of isolating very long heat waves, and so freeing them from the masking effect of the shorter waves, was devised by Rubens and Nichols.

It is found that when a substance very strongly absorbs any waves that pass through it, it also strongly reflects at its surface the same waves. For example, a sheet of glass used as a fire-screen will cut off most of the heat coming from the fire, although it is perfectly transparent to the light. If, now, it is placed so as to reflect the light and heat from the fire, it is found to reflect very little light but a very large proportion of the heat.

Some substances have a well-defined absorption band, *i.e.* they absorb a particular wave-
{80} length very strongly, and these substances will therefore reflect this same wave-length strongly. If instead of a single reflection a number of successive reflections be arranged, at each reflection the proportion of the strongly reflected wave-length is increased until ultimately there is practically only this one wave-length present. It can therefore be very easily measured. These waves resulting from a number of successive reflections, rest-strahlen or residual rays as they have been named, have been very largely used for investigating long waves. Quartz gives rest-strahlen of length .00085 centimetres and very feeble ones of .0020 centimetres long. Sylvite gives the longest rays yet isolated, the wave-length being .006 centimetres.

Range of the Waves.—The lengths of the waves thus far measured are:—

Schumann waves	.00001 to .00002	cms.
Ultraviolet	.00002 to .00004	"
Violet	.00004	"
Green	.00005	"
Red	.00006 to .000075	"
Infra-red	.000075 to about .0001	"
Rest-strahlen from quartz . . .	.00085 and .0020	"
Rest-strahlen from Sylvite . .	.0060	"

Thus the longest waves are six hundred times the length of the shortest.

The corresponding range of wave-lengths of sound would be a little more than eight octaves, of which the visible part of the spectrum is less than one.

Electromagnetic Induction.—In the attempt to explain the nature of an electromagnetic wave (pp. 17-21) it was stated that an electric wave must always be accompanied by a magnetic wave.
{81} In order to understand the production of these waves, the relation between electric and magnetic lines of force must be stated in more detail. A large number of quite simple experiments show that whenever the electric field at any point is changing, *i.e.* whenever the lines of force are moving perpendicular to themselves, a magnetic field is produced at the point, and this magnetic field lasts while the change is taking place. An exactly similar result is observed when the magnetic field at a point is changing—an electric field is produced which lasts while the magnetic field is changing. When the electric field changes, therefore, there is both an action and a reaction—a magnetic field is produced and this change in magnetic field produces a corresponding electric field. This induced electric field is always of such a kind as to delay the change in the original electric field; if the original field is becoming weaker the induced field is in the same direction, thus delaying the weakening, and if the original field is becoming stronger the induced field is in the opposite direction, thus delaying the increase.

Momentum of Moving Electric Field.—Imagine now a small portion of an electric field moving at a steady speed; it will produce, owing to its motion, a steady magnetic field. If now the motion be stopped, the magnetic field will be destroyed, and the change in the magnetic field will produce an electric field so as to delay the change, *i.e.* so as to continue the original motion. The moving electric field thus has momentum in exactly the same way as a moving mass has. The
{82} parallel between the two is strictly accurate. The mass has energy due to its motion, and in order to stop the mass this energy must be converted into some other form of energy and work must therefore be done. The electric field has energy due to its motion—the energy of the magnetic

field—and therefore to stop the motion of the electric field, the energy of the magnetic field must be converted into some other form, and work must therefore be done. One consequence of the momentum of a moving mass is well illustrated by the pendulum. The bob of the pendulum is in equilibrium when it is at its lowest point, but when it is displaced from that point and allowed to swing, it does not swing to its lowest point and stay there, but is carried beyond that point by its momentum. The work done in displacing the bob soon brings it to rest on the other side, and it swings back again only to overshoot the mark again. The friction in the support of the pendulum
{83} and the resistance of the air to the motion makes each swing a little smaller than the one before it, so that ultimately the swing will die down to zero and the pendulum will come to rest at its lowest point. The graph of the displacement of the bob at different times will therefore be something like Fig. 28. Should the pendulum be put to swing, not in air, but in some viscous medium like oil, its vibrations would be damped down very much more rapidly, and if the medium be viscous enough the vibrations may be suppressed, altogether, the pendulum merely sinking to its lowest position.

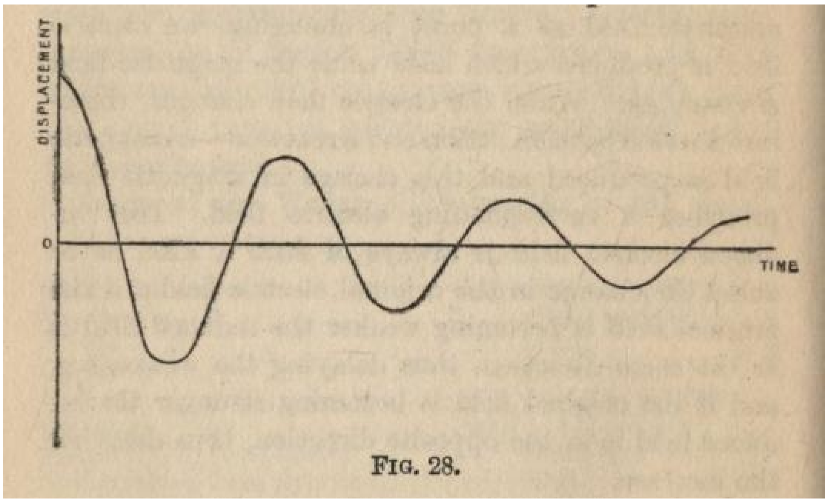

FIG. 28.

Electric Oscillation.—These conditions have their exact counterpart in the electric field. To understand them, three properties of lines of force must be borne in mind: (i.) lines of force act as if in tension and therefore always tend to shorten as much as possible; (ii.) the ends of lines of force can move freely on a conductor; (iii.) lines of force in motion possess momentum. Now imagine two conducting plates A and B, Fig. 29, charged positively and negatively, and therefore connected by lines of force as indicated. Let the two plates be suddenly connected by the wire *w*, so that the ends of the lines of force may freely slide from A to B or *vice-versa*, and therefore all the lines will slide upwards along A and B, and then towards each other along *w*, until they shrink
{84} to zero somewhere in *w*. The condition of equilibrium will evidently be reached when all the lines have thus shrunk to zero, but the lines which are travelling from A towards B will have momentum and will therefore overshoot the equilibrium condition and pass right on to B. That is, the positive ends of the lines will travel on to B, and similarly the negative ends will pass on to A. The lines of force between A and B will therefore be reversed. The tension in the lines will soon bring them to rest, and they will slide back again, overshoot the mark again, reach a limit in the original direction and still again slide back. The field between A and B will therefore be continually reversed, but each time its value will be a little less, until ultimately the vibrations will die down to zero. Thus if we were to replace the displacement in Fig. 29 by the value of the field between A and B we should have an exactly similar graph.

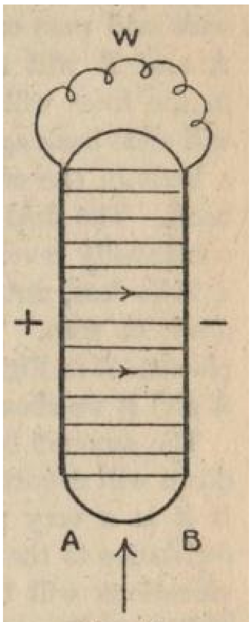

FIG. 29.

The amount by which the oscillations are damped down will depend upon the character of the wire *w*. If it is a very poor conductor it will offer a large resistance to the sliding of the lines along it, and the vibrations will be quickly damped down or, if the resistance is great enough, be suppressed altogether.

This rapid alternation of the electric field will send out electromagnetic waves which die down as the oscillations decrease.

The Spark Discharge.—In practice the wire *w* is not actually used, but the air itself suddenly becomes a conductor and makes the connection. When the electric field at a point in
{85} the air exceeds a certain limiting strength, the air seems to break down and suddenly become a conductor and remains one for a short time. This breaking down is accompanied by light and heat, and is known as the spark discharge or electric spark.

Experiments of Hertz.—In the brilliant experiments carried out by Hertz at Karlsruhe between 1886 and 1891, he not only demonstrated the existence of the waves produced in this way, but he showed that they are reflected and refracted like ordinary light, he measured their wave-length and roughly measured their speed, this latter being equal to the speed of light within the errors of experiment.

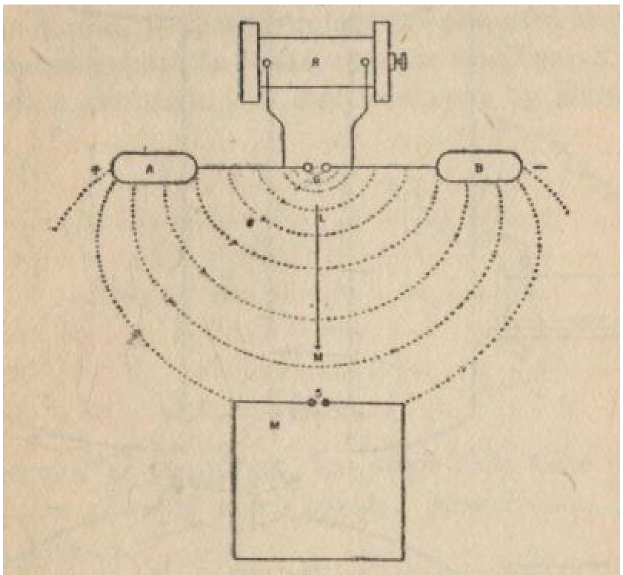

FIG. 30.

One arrangement used by Hertz is shown in plan in Fig. 30. A Ruhmkorff coil R serves to charge the two conductors A and B until the air breaks down at the gap G, and a spark passes.
{86} Before the spark is produced, the lines of force on the lower side of AB will in form be something like the dotted lines in the figure, but as soon as the air becomes a conductor, the positive ends of the lines will surge from A towards B and on to B, and the negative ends will surge on to A. These to and fro surgings will continue for a little while, but will gradually die out. As the surgings are
{87} all up and down AB, the electric vibrations in the electromagnetic waves sent out will all be

parallel to AB, and therefore they will be polarised.

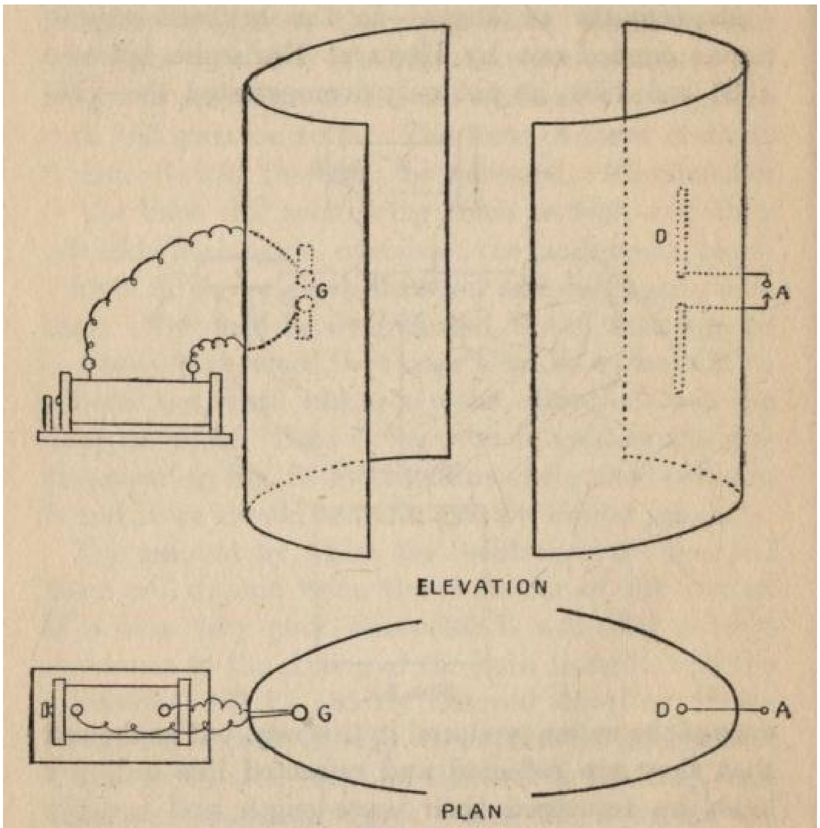

FIG. 31.

FIG. 31.

This is characteristic of all electric waves, as no single sparking apparatus will produce anything but waves parallel to the spark gap. The electric vibrations coming up to a conductor placed in the position of the wire rectangle, M, will cause surging of the lines along it, and, if these surgings are powerful enough, will cause a spark to pass across the small gap S.

Such a rectangle was therefore used by Hertz as a detector of the waves, but since that time many detectors of very much greater sensitiveness have been devised.

Reflection.—In order to show that these waves are reflected in the same way as light waves, Hertz placed the sparking knobs, G, at the focus of a large parabolic metallic reflector, and his detector, D, at the focus of a similar reflector placed as in Fig. 31, but much farther away (cf. Fig. 1). In this position sparking at G produced strong sparking in the detector, although the distance was such that no sparking was produced without the reflectors.

{88} **Refraction.**—The refraction of the waves was shown by means of a large prism made of pitch. This had an angle of 30° and was about 1.5 metres high and 1.2 metres broad.

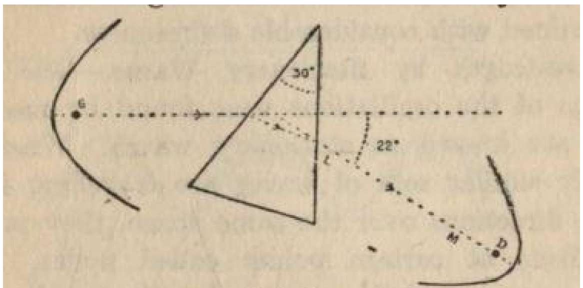

FIG. 32.

FIG. 32.

Setting it up as shown in plan in Fig. 32, strong sparking was produced in the detector, thus showing that the rays of electric waves were deflected by 22° on passing through the prism.

Moving the mirror and detector in either direction from the line LM, made the sparks decrease rapidly in intensity, so that the exact position of LM can be determined with considerable definiteness.

Wave-length, by Stationary Waves.—The wave-lengths of the oscillations were found by means of what are known as stationary waves. When two exactly similar sets of waves are travelling in opposite directions over the same space, they produce no effects at certain points called nodes. These nodes are just half a wave-length apart. Their production can be understood by reference to Fig. 33. The dotted lines represent the two waves which are travelling in the direction indicated by the arrows. In A the time is chosen when the waves are exactly superposed, and the resultant displacement will be represented by the solid line. The points marked with a cross will be points at which the displacement is zero.

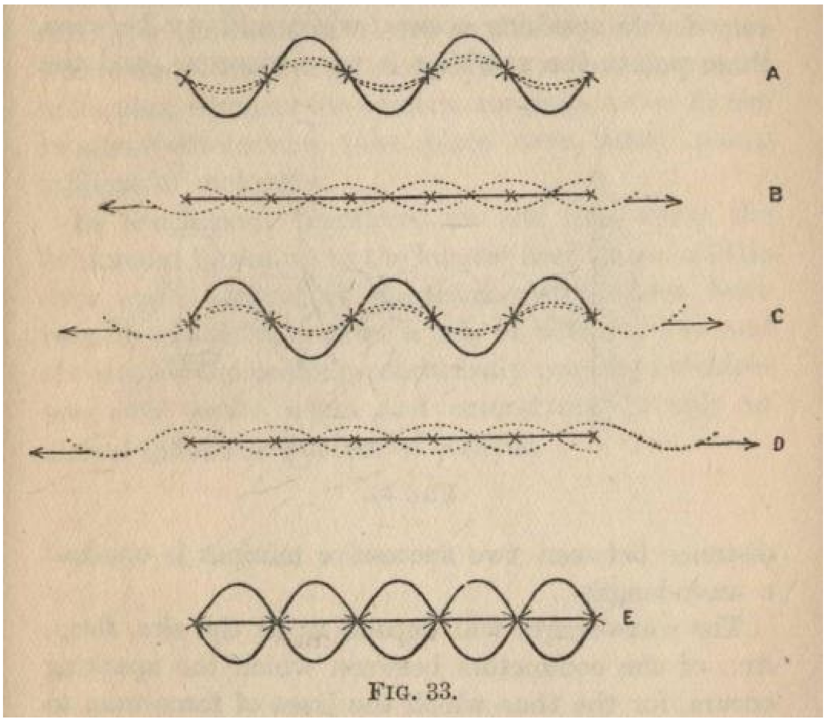

FIG. 33.

In B each wave has travelled a distance equal to a quarter of a wave-length, and it will be seen that the two sets of waves cause equal and opposite displacements. The resulting displacement is therefore zero, as indicated by the solid line. In C the waves have travelled
{89} another quarter of a wave-length and are superposed again, but in this case the displacements will be in the opposite directions from those in A. In D, still another quarter wave-length has been traversed by each wave, and another quarter wave-length would bring back the position A.

In E, we have the successive positions of the wave drawn in one diagram, and we notice that the points indicated by a cross are always undisplaced and their distance apart is one-half a wave-length.

Hertz produced these conditions by setting up his coil and sparking knobs at some distance from a reflecting wall, Fig. 34. Then the waves which are coming up to the wall and those which
{90} are reflected from the wall will be travelling in opposite directions over the same space. True, the reflected waves will be rather weaker than the original ones, so that there will be a little displacement even at the nodes, but there will be a well-marked minimum. Thus when the detector is placed at A, B, C or D no sparking or very feeble sparking occurs, while midway between these points the sparking is very vigorous, and the distance between two successive minima is one-half a wave-length.

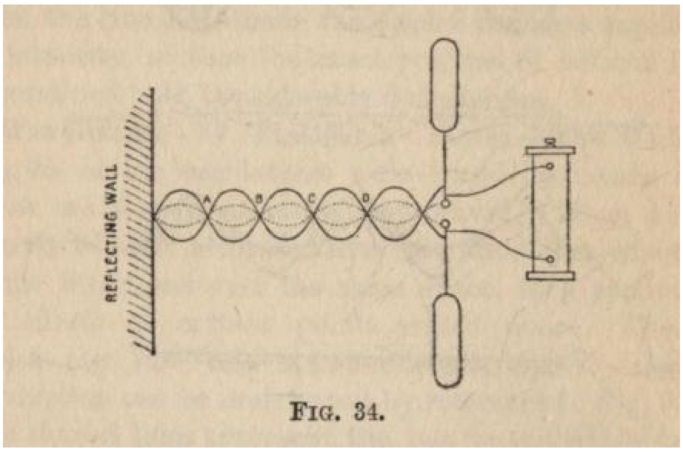

FIG. 34.

The wave-length will depend upon the size, form, &c., of the conductors between which the sparking occurs, for the time which the lines of force take to surge backwards and forwards in the conductors will depend upon these things. Other things being equal, the smaller the conductors the smaller the time and therefore the shorter the wave-length. The shortest wave which Hertz succeeded in producing was 24 centimetres long, but since then waves as little as 6 millimetres long have been produced.

{91} The waves which are produced in a modern wireless telegraphy apparatus are miles in length.

We thus see that there is rather a large gap between the longest heat waves which have been isolated, .006 cms., and the shortest electric waves, .6 cms. The surprising fact, however, is that this gap is so small, for the heat waves are produced by vibrations within a molecule, or at most within a small group of molecules, whereas the electric surgings, even in the smallest conductors, take place over many many millions of molecules.

In conclusion, therefore, we see that from the Schumann waves up to the longest heat waves a little over eight octaves of electromagnetic waves have been detected, then after a gap of between five and six octaves the ordinary electrically produced electromagnetic waves begin and extend on through an almost indefinite number of octaves.

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