CHAPTER XIII.

RADIATION.

182. **Radiation distinct from Conduction.**—When two bodies at different temperatures are placed opposite to each other, with nothing between them but air or some other transparent medium, the hotter body gives heat to the colder by *radiation*. It is by radiation that the earth receives heat from the sun and gives out heat to the sky; and it is by radiation that a fire gives heat to a person sitting in front of it.

Radiation is broadly distinguished from conduction. In conduction, the transmission of heat is effected by the warming of the intervening medium, each portion of which tends to raise the succeeding portion to its own temperature.

On the other hand heat transmitted from one body to another by radiation does not affect the temperature of the intervening medium. The heat which we receive from the sun has traversed the cold upper regions of the air; and paper can be ignited in the focus of a lens of ice, though the temperature of ice cannot exceed the freezing-point.

Conduction is a gradual, radiation an instantaneous process. A screen interposed between two bodies instantly cuts off radiation between them; and on the removal of such a screen radiation instantly attains its full effect. Radiant heat, in fact, travels with the velocity of light, and it is subject to laws similar to the laws of light; for example, it is usually propagated only in straight lines.

Strictly speaking, radiant heat, like latent heat, is not heat at all, but is a form of energy which is readily converted into heat. Its nature is precisely the same as that of light, the difference between them being only a difference of degree, as will be more fully explained in treating of the analysis of light by the prism and spectro-

scope. The present chapter will contain numerous instances of the analogy between the properties of non-luminous radiant heat and well-known characteristics of light.

183. **A Ponderable Medium not Essential.**—The transmission of the sun's heat to the earth shows that radiation is independent of any ponderable medium. But since the solar heat is accompanied by light, it might still be questioned whether dark heat could be propagated through a vacuum.

This was tested by Rumford in the following way:—He constructed a barometer (Fig. 114), the upper part of which was expanded into a globe, and contained a thermometer hermetically sealed into a hole at the top of the globe, so that the bulb of the thermometer was at the centre of the globe. The globe was thus a Torricellian vacuum-chamber. By melting the tube with a blow-pipe, the globe was separated, and was then immersed in a vessel containing hot water, when the thermometer was immediately observed to rise to a temperature evidently higher than could be due to the conduction of heat through the stem. The heat had therefore been communicated by direct radiation through the vacuum between the sides of the globe and the bulb *a* of the thermometer.

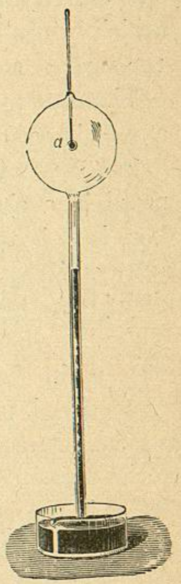

Fig. 114.—Rumford's Experiment.

184. **Radiant Heat travels in Straight Lines.**—In a uniform medium the radiation of heat takes place in straight lines. If, for instance, between a thermometer and a source of heat, there be placed a number of screens, each pierced with a hole, and if the screens be so arranged that a straight line can be drawn without interruption from the source to the thermometer, the temperature of the latter immediately rises; if a different arrangement be adopted, the heat is stopped by the screens, and the thermometer indicates no effect.

Hence we can speak of *rays* of heat just as we speak of rays of light. Thus we say that rays of heat issue from all points of the surface of a heated body, or that such a body emits rays of heat. The word *ray* when thus used scarcely admits of precise definition. It is a popular rather than a scientific term; for no finite quantity of heat or light can travel along a mathematical line. In a mere geometrical sense the rays are the lines which indicate the direction of propagation.

It is now generally admitted that both heat and light are due to a vibratory motion which is transmitted through space by means of a fluid called ether. According to this theory the rays of light and heat are lines drawn in all directions from the origin of motion, and along which the vibratory movement advances.

185. Surface Conduction.—The cooling of a hot body exposed to the air is effected partly by radiation, and partly by the conduction of heat from the surface of the body to the air in contact with it. The activity of the surface-conduction is greatly quickened by wind, which brings continually fresh portions of cold air into contact with the surface, in the place of those which have been heated.

The cooling of a body *in vacuo* is effected purely by radiation, except in so far as there may be conduction through its supports.

186. Newton's Law of Cooling.—In both cases, if the body be exposed in a chamber of uniform temperature, the rate at which it loses heat is approximately proportional to the excess of the temperature of its surface above that of the chamber, and the proportionality is sensibly exact when the excess does not exceed a few degrees. If the body be of sensibly uniform temperature throughout its whole mass, as in the case of a thin copper vessel full of water which is kept stirred, its fall of temperature is proportional to its loss of heat, and hence the rate at which its temperature falls is proportional to the excess of its temperature above that of the chamber. Practically if the body be a good conductor and of small dimensions—say a copper ball an inch in diameter, or an ordinary mercurial thermometer—the fall of its temperature is nearly in accordance with this law, which is called *Newton's law of cooling.* The observed fact is that when the readings of the thermometer are taken at equal intervals of time, their excesses above the temperature of the inclosure (which is kept constant) form a diminishing geometrical progression.

To show that this is equivalent to Newton's law, let θ denote the excess of temperature at time t; then, in the notation of the differential calculus, $-\frac{d\theta}{dt}$ is the rate of cooling; and Newton's law asserts that this is proportional to θ, or that

$$-\frac{d\theta}{dt}=A\theta, \qquad (1)$$

where A is a constant multiplier. This is equivalent to

$$-\frac{d\theta}{\theta}=A\,dt, \qquad (2)$$

which asserts that for equal small intervals of time the differences between the temperatures are proportional to the temperatures. But if the differences between the successive terms of a series are proportional to the terms themselves, the series is geometrical; for if we have

$$\frac{\theta_1-\theta_2}{\theta_1}=\frac{\theta_2-\theta_3}{\theta_2}=\frac{\theta_3-\theta_4}{\theta_3},$$

we obtain, by subtracting unity from each member,

$$\frac{\theta_2}{\theta_1}=\frac{\theta_3}{\theta_2}=\frac{\theta_4}{\theta_3};$$

that is, $\theta_1, \theta_2, \theta_3, \theta_4$ are in geometrical progression.

The expression $-\frac{d\theta}{\theta}$ in equation (2) is, by the rules of the differential calculus, equal to $-d\log\theta$; hence equation (2) shows that $\log\theta$ diminishes by equal amounts in equal times. Log θ here denotes the Napierian logarithm of θ; and since common logarithms are equal to Napierian logarithms multiplied by a constant factor, the common logarithm of θ will also diminish by equal amounts in equal times. The constant A in equation (1) or (2) will be determined from the experimental results by dividing the decrement of $\log\theta$ by the interval of time.

We have been assuming that the body is hotter than the chamber or inclosure; but a precisely similar law holds for the warming of a body which is colder than the inclosure in which it is placed.

187. Dulong and Petit's Law of Cooling.—Newton's law is sensibly accurate for *small* differences of temperature between the body and the inclosure. Dulong and Petit conducted experiments on the cooling of a thermometer by radiation in vacuo with excesses of temperature varying from 20° to 240° C., from which they deduced the formula

$$-\frac{d\theta}{dt}=ca^{v}(a^{\theta}-1);$$

or, as it may be otherwise written,

$$-\frac{d\theta}{dt}=c(a^{v+\theta}-a^{v}),$$

where v denotes the temperature of the walls of the inclosure, which was preserved constant during each experiment, $v+\theta$ the temperature of the thermometer, and $-\frac{d\theta}{dt}$ the rate of cooling. The other letters, c and a, denote constants. When the temperatures are Centi-

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grade, the constant a is 1·0077; when they are Fahrenheit it is 1·0043, the form of the expression for the rate of cooling being unaffected by a change of the zero from which temperatures are reckoned. The value of c depends upon the size of the bulb and some other circumstances, and is changed by a change of zero.

188. **Consequences of this Law.**—The formula in its first form shows that, for the same excess θ, the cooling is more rapid at high than at low temperatures.

Employing the Centigrade scale, we have $a=1{\cdot}0077$, whence $\log a = {\cdot}0077$ nearly, and since

$$a^\theta = 1 + \theta \log a + \tfrac{1}{2}(\theta \log a)^2 + \tfrac{1}{6}(\theta \log a)^3 + \text{\&c.},$$

Dulong and Petit's formula, in its first form, gives

$$-\frac{d\theta}{dt} = c\,(1{\cdot}0077)^v \{{\cdot}0077\,\theta + \tfrac{1}{2}({\cdot}0077\,\theta)^2 + \text{\&c.}\};$$

which shows that, for a given temperature of the inclosure, the rate of cooling is not strictly proportional to θ, but is equal to θ multiplied by a factor which increases with θ, this factor being proportional to $1 + \tfrac{1}{2}({\cdot}0077\,\theta) + \tfrac{1}{6}({\cdot}0077\,\theta)^2 +$ &c.

When θ is small enough for ·0077 θ to be neglected in comparison with unity, the factor will be sensibly constant, in accordance with Newton's law.

189. **Theory of Exchanges.**—The second form of Dulong and Petit's formula, namely

$$-\frac{d\theta}{dt} = c(a^{v+\theta} - a^v),$$

suggests that an unequal *exchange* of heat takes place between the thermometer and the walls, the thermometer giving to the walls a quantity of heat $ca^{v+\theta}$ (where $v+\theta$ denotes the temperature of the thermometer), and the walls giving to the thermometer the smaller quantity ca^v.

This is the view now commonly adopted with respect to radiation in general. It has been fully developed by Professor Balfour Stewart under the name of the *theory of exchanges*. Its original promulgator, Prévost of Geneva, called it the theory of *mobile equilibrium of temperature.*

The theory asserts that all bodies are constantly giving out radiant heat, at a rate depending upon their substance and temperature, but independent of the substance or temperature of the bodies which surround them; and that when a body is kept at a uniform temperature, it receives back just as much heat as it gives out.

According to this view, two bodies at the same temperature, exposed to mutual radiation, exchange equal amounts of heat; but if two bodies have unequal temperatures, that which is at the higher temperature gives to the other more than it receives in exchange.[1]

190. **Law of Inverse Squares.**—If we take a delicate thermometer and place it at successively increasing distances from a source of heat, the temperature indicated by the instrument will exceed that of the atmosphere by decreasing amounts, showing that the intensity of radiant heat diminishes as the distance increases. The law of variation may be discovered by experiment. In fact, when the excess of temperature of the thermometer becomes fixed, we know that the heat received is equal to that lost by radiation; but this latter is, by Newton's law, proportional to the excess of temperature above that of the surrounding air; we may accordingly consider this excess as the measure of the heat received. It has been found, by experiments at different distances,[2] that the excess is inversely proportional to the square of the distance; we may therefore conclude that *the intensity of the heat received from any source of heat varies inversely as the square of the distance.*

The following experiment, devised by Tyndall, supplies another simple proof of this fundamental law:—

The thermometer employed is a Melloni's pile, the nature of which we shall explain in § 197. This is placed at the small end of a hollow cone, blackened inside, so as to prevent any reflection of heat from its inner surface. The pile is placed at S and S′ in front of a vessel filled with boiling water, and coated with lamp-black on the side next the pile. It will now be observed that the temperature indicated by the pile remains constant for all distances. This result proves the law of inverse squares. For the arrangement adopted prevents the pile from receiving more heat than that due to the area of A B in the first case, and to the area A′ B′ in the second. These are the areas of two circles, whose radii are respectively proportional to S O and S′ O; and the areas are consequently proportional to the squares of S O and S′C. Since, therefore, these two areas communi-

[1] For a full account of this subject see "Report on the Theory of Exchanges," by Balfour Stewart, in *British Association Report*, 1861, p. 97; and *Stewart on Heat*, book ii. chap. iii.

[2] The dimensions of the source of heat must be small in comparison with the distance of the thermometer, as otherwise the distances of different parts of the source of heat from the thermometer are sensibly different. In this case, the amount of heat received varies directly as the solid angle subtended by the source of heat.

cate the same quantity of heat to the pile, the intensity of radiation must vary inversely as the squares of the distances S O and S′O.

The law of inverse squares may also be established *a priori* in the following manner:—

Suppose a sphere of given radius to be described about a radiating particle as centre. The total heat emitted by the particle will be received by the sphere, and all points on the sphere will experience

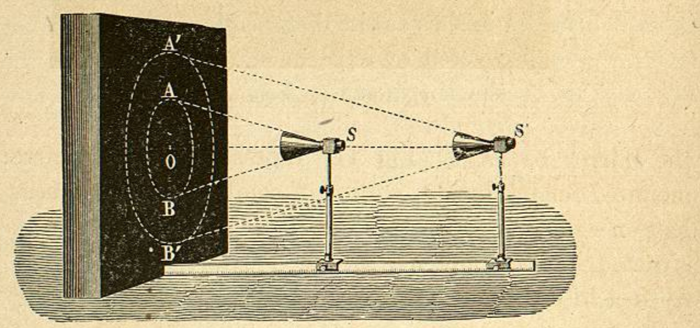

Fig. 115.—Law of Inverse Squares.

the same calorific effect. If now the radius of the sphere be doubled, the surface will be quadrupled, but the total amount of heat remains the same as before, namely, that emitted by the radiating particle. Hence we conclude that the quantity of heat absorbed by a given area on the surface of the large sphere is one-fourth of that absorbed by an equal area on the small sphere; which agrees with the law stated above.

This demonstration is valid, whether we suppose the radiation of heat to consist in the emission of matter or in the emission of energy; for energy as well as matter is indestructible, and remains unaltered in amount during its propagation through space.

191. Law of the Reflection of Heat.— When a ray of heat strikes a polished surface, it is reflected according to the same law as a ray of light.

192. Burning Mirrors.—All rays, either of heat or light, falling on a parabolic mirror in directions parallel to its axis (AC, Fig. 116) are reflected accurately to its focus F, and all rays from F falling on the mirror are reflected parallel to the axis. A spherical concave mirror is a small portion of a sphere, and rays parallel to its axis are reflected so as approximately to pass through its "principal focus" F (same figure), which is midway between A, the central point of the mirror, and C, the centre of the sphere.

When the axis of a concave mirror, of either form, is directed towards the sun, intense heat is produced at the focus, especially if

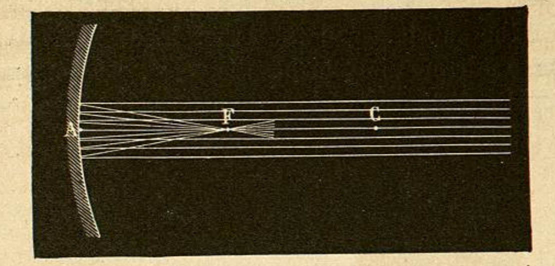

Fig. 116.—Focus of Concave Mirror.

the mirror be large. Fig. 117 represents such a mirror suitably mounted for producing ignition of combustible substances. Tschirnhausen's mirror, which was constructed in 1687, and was about $6\frac{1}{2}$ feet in diameter, was able to melt copper or silver, and to vitrify brick. Instead of curved mirrors, Buffon employed a number of movable plane mirrors, which were arranged so that the different pencils of heat-rays reflected by them converged to nearly the same point. In this way he obtained an extremely powerful effect, and was able, for instance, to set wood on fire at a distance of between 80 and 90 yards. This is the method which Archimedes is said to have employed for the destruction of the Roman fleet in the siege of Syracuse; and though the truth of the story is considered doubtful, it is not altogether absurd.

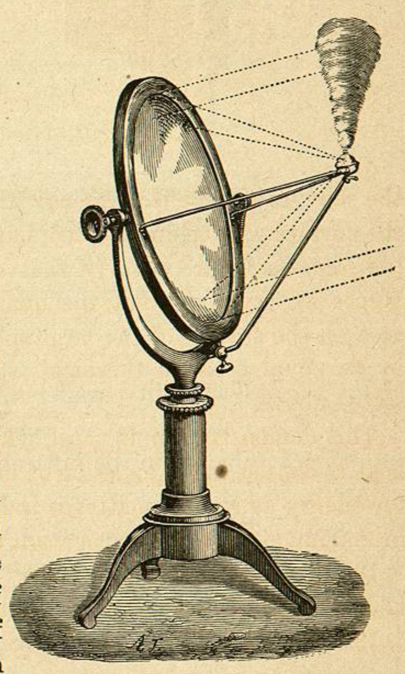

Fig. 117.—Burning Mirror.

193. Conjugate Mirrors.—Fig. 118 represents an experiment which is said to have been first performed by Pictet of Geneva.

Two large parabolic mirrors are placed facing each other, at any convenient distance, with their axes in the same straight line. In the focus of one of them is placed a small furnace, or a red-hot cannon-ball, and in the focus of the other some highly inflammable material, such as phosphorus or gun-cotton. On exciting the furnace with bellows, the substance in the other focus immediately takes fire. With two mirrors of 14 inches diameter, gun-cotton may thus be set on fire at a distance of more than 30 feet. The explanation is very easy. The rays of heat coming from the focus of the first

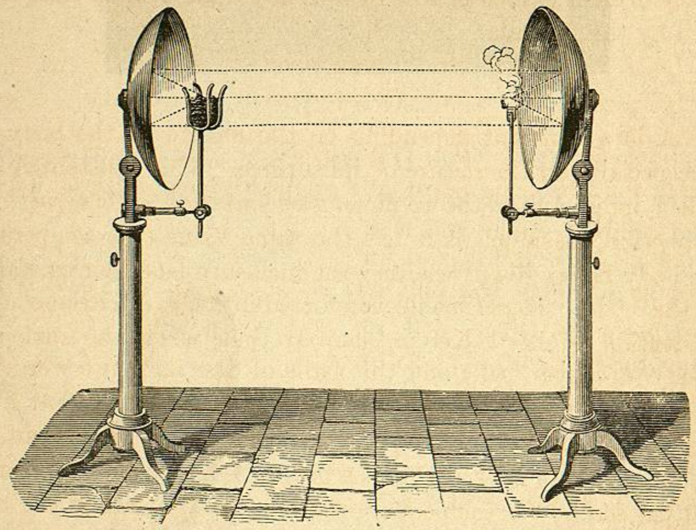

Fig. 118.—Conjugate Mirrors.

mirror are reflected in parallel lines, and, on impinging upon the surface of the second mirror, converge again to its focus, and are thus concentrated upon the inflammable material placed there.

Careful adjustment is necessary to the success of the experiment, and the adjustment is most easily made by first placing a source of light (such as the flame of a candle) in one focus, and forming a luminous image of it in the other. We have thus a convincing proof that heat and light obey the same law as regards direction of reflection.

194. Reflection, Diffusion, Absorption, and Transmission.—When radiant heat is incident upon the surface of a body it is divided into several distinct parts. A portion is *regularly reflected* according to the law given above. A portion is irregularly or *diffusely reflected* and is scattered through space in all directions. A portion penetrates into the body so as to be *absorbed* by it, and to contribute to

raise its temperature; and in some cases a fourth portion passes through the body without contributing to raise its temperature. This portion is said to be *transmitted.*

195. Coefficient of Absorption and Coefficient of Emission.—Applying Newton's law (§186), let θ be the small difference of temperature between the surface of the body and the inclosure, and S the area of this surface, which we suppose to have no concavities, then the quantity of heat gained or lost by the body per unit of time is expressed by the formula

$$AS\theta,$$

where A is a constant depending on the nature of the body and more especially on the nature of its surface. This constant A may be called indifferently the *coefficient of emission* or the *coefficient of absorption*, inasmuch as it has the same value (the temperature of the body being given) whether the inclosure be colder or warmer than the body. Experiments conducted by Mr. M'Farlane under the direction of Lord Kelvin, showed that when the surface of the body (a copper ball) and the walls of the inclosure were both covered with lamp-black, the inclosure being full of air at atmospheric pressure, the value of the coefficient A in C.G.S. units is about $\frac{1}{4000}$, that is to say $\frac{1}{4000}$ of a gramme-degree of heat is gained or lost per second for each square centimetre of surface of the body, when there is 1° of difference between its temperature and that of the walls of the inclosure. When the surface of the body (the copper ball) was polished, the walls of the inclosure being blackened as before, the coefficient had only $\frac{7}{10}$ of its former value. It was estimated that of the value $\frac{1}{4000}$ for blackened surfaces, one-half is due to atmospheric contact and the other half to radiation. As the excess of temperature of the body above that of the walls increased from 5° to 60°, the quantity of heat emitted, instead of being increased only twelve-fold, was increased about sixteen-fold for the blackened and fifteen-fold for the polished ball.

When air is excluded, and the gain or loss of heat is due to pure radiation between the body and the walls, the coefficient A represents, according to the theory of exchanges, the difference between the absolute emission at the temperature of the body and at a temperature 1° higher or lower.

196. Limit to Radiating Power.—It is obviously impossible for a body to absorb more radiant heat than falls upon it. There must, therefore, be a limiting value of A applicable to a body which would absorb all the heat that falls upon it and not absorb or transmit any. Such a body would possess perfect emissive power for radiant heat. Hence it appears that good radiation depends rather upon defect of resistance than upon any positive power. A perfect radiator would be a substance whose surface offered no resistance to the passage of radiant heat in either direction; while an imperfect radiator is one whose surface allows a portion to be communicated through it, and reflects another portion regularly or irregularly.

The reflecting and diffusive powers of lamp-black are so insignificant, at temperatures below 100°, that this substance is commonly adopted as the type of a perfect radiator, and the emissive and absorptive powers of other substances are usually expressed by comparison with it.

CHAPTER XIV.

RADIATION (CONTINUED).

197. Thermoscopic Apparatus employed in researches connected with Radiant Heat.—An indispensable requisite for the successful study of radiant heat is an exceedingly delicate thermometer. For this purpose Leslie, about the beginning of the present century, invented the differential thermometer, with which he conducted some very important investigations, the main results of which are still acknowledged to be correct. Modern investigators, as Melloni, Laprovostaye, &c., have exclusively employed Nobili's thermo-multiplier, which is an instrument of much greater delicacy than the differential thermometer.

The thermo-pile, invented by Nobili, and improved by Melloni, consists essentially of a chain (Fig. 119) formed of alternate elements of bismuth and antimony. If the ends of the chain be connected by a wire, and the alternate joints slightly heated, a thermo-electric current will be produced, as will be explained hereafter. The amount of current increases with the number of elements, and with the difference of temperatures of the opposite junctions.

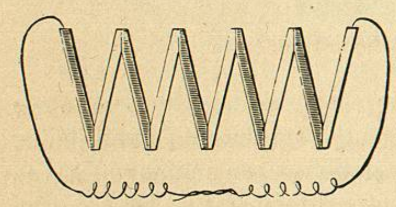

Fig. 119.—Nobili's Thermo-electric Series.

In the pile as improved by Melloni, the elements are arranged side by side so as to form a square bundle (Fig. 120), whose opposite ends consist of the alternate junctions. The whole is contained in a copper case, with covers at the two ends, which can be removed when it is desired to expose the faces of the pile to the action of heat. Two metallic rods connect the terminals of the thermo-electric series