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RADIATION AND THE TEMPERATURE OF THE SUN[1]

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THE temperature of the sun cannot be measured by the methods with which we are familiar in our every day life; some other method must be devised. The heat and light of the sun reach us by a process which we call radiation. Of the three processes by which heat may be transmitted from one place to the other *conduction* and *convection* are well known, and instances abound of the part they play in heat transference; but we are not so familiar with the method of *radiation*. How does the energy from the sun reach us across the ninety-two million miles of so-called empty space between earth and sun? The view that the sun could give us heat and light without anything happening in the space between us was abhorrent to experimental philosophers and a theory was promulgated that this so-called empty space is filled with a medium called 'ether.' The only laws which this ether obeys are the laws which are necessary for the passage of transverse wave-motion through it. The solar radiant energy is brought to us by this motion. The same laws apply to radiation as to light.

[1]Substance of a lecture given to the Society on Dec. 10th, 1918

In fact, the physical processes of radiation and light are identical, light being just that portion of the radiation which excites the sensation of vision. There is a complete parallelism of experiments on 'light' and 'radiation' as far as propagation, reflection, refraction, dispersion, diffraction and polarization are concerned. We usually do the experiments with the 'light' because we can 'see' the results. In the case of reflection by a concave reflector, the 'light' focus is also the 'heat' focus. In the case of an ordinary burning glass the same identity occurs, except in so far as chromatic aberration pushes the 'heat' focus a little farther away from the lens than the light focus. By using a prism and one or more lenses we can throw a spectrum of the sun's radiation upon the screen. We only see a band of colors on the screen, ranging from violet to red, but it is important to remember that what we see is but a small portion of the whole of the spectrum. If we use lenses and prisms which do not absorb the radiation, and also suitable detectors, it is possible to observe the presence of radiation beyond the violet, and also beyond the red. All the waves which fall upon the screen have the same mechanical basis; the only difference is that of wave-length. We have an analogy in sound, where all the sound waves given out by a musical band travel with the same velocity, but our ears distinguish one from the other by the difference in pitch. There is a wide variation of wave length in the radiation from a body like the sun, and the spectrum looks almost continuous. Some heated vapors, however, give out radiation of definite wave-lengths and in these cases the spectrum consists of a number of bright lines, each bright line being the image of the illuminated slit, produced by radiation of some definite wave-length. The red rays have a wave-length of about seven ten-thousands of a millimetre, or .7 micron, while for the violet the wave-length is about .4 micron.

The other colors range in between these. Waves of length less than that of violet light are called ultra-violet waves. They do not excite vision, but they are chemically active and affect photographic plates. Waves longer than seven-tenths of a micron are known as infra-red. They extend over a very wide range; they have little chemical activity, but some have considerable heating effect. Of course, all the waves carry energy; it is only their manifestations that differ. Whenever the energy of the waves (whether ultra-violet, lumionus, or infra-red) is absorbed, heat is developed and by the theorem of the conservation of energy the heat developed is a measure of the energy in the waves. This gives us the basis of the usual method of measuring radiant energy.

It was found in the early days of science that black surfaces, e.g., one covered with lamp-black, absorbed practically all the wave-energy incident on them, and most of the measuring instruments have their sensitive receiver coated with a dead-black surface. One of the first experimenters was Leslie, who used his differential thermoscope for this purpose. This consisted of two glass bulbs connected by a U-tube containing a liquid index. One bulb was blackened and when the instrument was exposed to a stream of radiant energy, the blackened bulb became the warmer of the two and the index moved away from it. Good work was done by Leslie with this instrument. In time it was superseded by Nobili's thermopile, in which was used the principle discovered by Seebeck, that, if a circuit is made of two metals and one junction is heated to a higher temperature than the other, a current of electricity flows around the circuit. This current can be measured by inserting a delicate galvanometer in the circuit. It may be increased by using many junctions, exposing alternate ones to the radiation and keeping the others cold. The current is proportional to the difference of temperature between the hot and cold junctions as long as this difference is small. Also the difference of temperature is proportional to the heat absorbed by the junctions from the stream of radiation, and hence the current is proportional to the intensity of the radiation. This method of measuring energy streams has been widely used and can be made very sensitive. D'Arsonval and Boys used it in the radiomicrometer to measure total energy. In conjunction with a large mirror, Boys used this apparatus to measure the radiation from a candle three miles away. Rubens, by using a number of tiny junctions in a row, has measured the energy sent into the different 'lines' of the spectrum.

Another measuring device is based upon the alteration of the electrical resistance of metals, usually platinum, by a change of temperature. This alteration is about one-third of one per cent. per degree Centigrade. Langley made up a grid of very fine platinum strips and used a Wheatstone bridge arrangement to measure the resistance. The apparatus was sensitive enough to measure a rise of temperature of 1/10000° C. Lummer and Kurlbaum have increased the sensitiveness by using a differential arrangement of grids, and have also modified the construction to measure the radiation sent into a spectrum line.

The first man to show that the sun's radiation extended beyond the range of the visible spectrum was W. Herschel. He threw a solar spectrum on the screen and by moving a thermometer from one end to the other, he showed by the heating effect on the thermometer the existence of the infra-red rays. Later work has shown that this infra-red radiation vastly extends the solar spectrum. In the case of a line spectrum such as is observed with a mercury lamp, one must remember that each spectrum line on the screen is an image of the illuminated slit produced by radiation of some definite wave-length, the wave-length corresponding to the position of the line on the screen. A continuous spectrum means that the light going through the slit has an infinite gradation of wave length. A dark line in a spectrum, e.g., in the solar spectrum, indicates the absence of radiation of some particular wave-length, or rather the very low intensity of such radiation, so low that in comparison with its surroundings the line appears dark. The low intensity is due to absorption by the outer and therefore colder layers of the solar atmosphere. By taking a linear thermopile or bolometer through the spectrum from end to end, the distribution of energy in the spectrum can be measured. This has been done by Langley, Lummer and Kurlbaum, and others, and by adding up all the energy, the total energy has been obtained, which should, of course, check up with the measurement of total energy made when the dispersing prism is not interposed. There are corrections to be applied for absorption and reflection by parts of the apparatus, and by the medium through which the radiation has passed. Before we can take up the study of the temperature of the sun, we must also consider what is called the *Theory of Exchanges.* Enunciated by Prevost towards the end of the eighteenth century and later elaborated by Balfour Stewart and Kirchhoff, the theory tells us (1) that any thermal equilibrium of an isolated body simply means equal giving and taking going on at the same time, (2) that good absorbers are good radiators, and so on. One branch of the theory deals with constant temperature enclosures. A body placed in a constant temperature enclosure acquires the temperature of the enclosure. The radiation in the enclosure has its energy distributed amongst the different waves in a certain definite way, dependent only on the temperature and independent of the nature of the enclosure. Such a stream of radiation is said to be 'full' radiation. It is identical in nature with the radiation from a heated lampblack surface at the same temperature, and hence was at one time called 'black body' radiation. Bodies differ much in their radiating power; thus a polished platinum surface emits much less radiation than lampblack surface at the same temperature, but if a constant temperature enclosure were made of platinum or any other body and a narrow tunnel were made through the walls to let some of the radiation out, that radiation would be practically 'black body' or 'full' radiation and would equal that from a lampblack surface of the same size as the tunnel and raised to the same temperature. Much work has been done with black bodies of this construction to see how the intensity of full radiation depends upon the temperature of the radiator. A body placed in a constant temperature enclosure not only acquires the same temperature as the enclosure, but also absorbs and emits radiation in such a way that the quality of the radiation in all parts of the enclosure is kept absolutely uniform, and the amount per unit volume the same all over the enclosed space, this amount depending only on the temperature of the enclosure; and sometimes we even speak of the temperature of full radiation meaning the temperature of the lampblacked surface or of the constant temperature enclosure which would supply exactly that same quality of radiation.

We have now to enquire into the relation between the amount of radiation from a surface and the temperature of that surface. The first law is due to Newton, who found out that the intensity of the stream of radiation from a hot body was proportional to the difference between the temperatures of the body and the surroundings; but it was soon found that this law was only approximately true. Dulong and Petit showed that a higher power of the temperature than the first was essential. Rosetti used nearly the third power, and in 1879 Stefan, working on some observational results of Tyndall's, showed that the radiation from a surface can be expressed by the formula

$$S = a\ T^4,$$

where T is the absolute temperature and a is a factor depending on the surface and the temperature. This law is known as the *Law of Radiation* or the *Fourth Power Law.* If the radiation is black-body radiation, a is a constant, and this constant has been evaluated most carefully by a large number of most refined experiments. Its value is 5.3×10^{-5} erg per sq. cm. per second per (degree)^4. In the case of a platinum surface, the a is much smaller than the a of the lampblack surface, but if the temperature of the platinum is greatly increased the a of the platinum increases, and at very high temperatures, say, nearly two or three thousand degrees Centigrade, the a of the platinum approaches the black body a. In other words, all bodies tend to become 'full radiators' at high temperatures, a proceeding which is of great value in practical work on the measurement of the temperature of very hot bodies.

The radiating stream from a black body being given as aT^4, the absorption of the black body from its surroundings is given by $aT_0{}^4$, where T_0 is the temperature of the surroundings. The rate of cooling of the body is therefore given by $a(T^4 - T_0{}^4)$. In the case of bodies of very high temperature, T^4 is much greater than $T_0{}^4$, so that the formula aT^4 can be used indiscriminately for the total stream and the balance of the output.

This fourth power law has been applied to the measurement of temperature by the aid of a simple radiation measurer known as Fery's Radiation Pyrometer. The stream of radiation from the black body, or from a tunnel dug into the mass of any body, is focussed by a gold-plated concave mirror upon a little thin blackened copper disc. The disc is warmed. Its temperature is measured by a delicate thermocouple, soldered to the back of the disc, and if readings are taken with two bodies at temperatures T_1 and T_2, then obviously the galvanometers' readings C_1 and C_2 are in the ratio

$$\frac{C_1}{C_2} = \frac{T_1^4}{T_2^4};$$

hence, if T_1 is known, T_2 can be found. The galvanometer scale can even be graduated to read 'black body' temperatures directly. In another form of the instrument, the copper disc is replaced by a spiral of compounded gold and silver strips, and the heating of the strips causes the spiral to wind or unwind, and the motion of a pointer fastened to the free end of the spiral indicates temperatures on a previously constructed scale. In both forms the instrument can be used by an ordinary workman, and one advantage that it has is, that its indications are independent, within wide limits, of the distance the pyrometer is away from the source of radiaion, as long as the image of the radiating source focussed by the mirror is larger than that of the copper disc or spiral upon which it falls. Thus the temperature of the sun may be taken by simply directing the instrument at the sun. At the same time, it may be necessary to introduce sector-diaphragms to cut down the amount of the radiation received, so that the pointer does not fly off the scales.

The distribution of the energy of a very hot body at some one temperature is shown in Fig. 1, and that through the spectrum of an incandescent gas in Fig. 2.

Lummer and Pringsheim investigated the energy distribution in the spectrum of a black body at different temperatures. The area under the intensity curve (Fig. 1) is a measure of the total

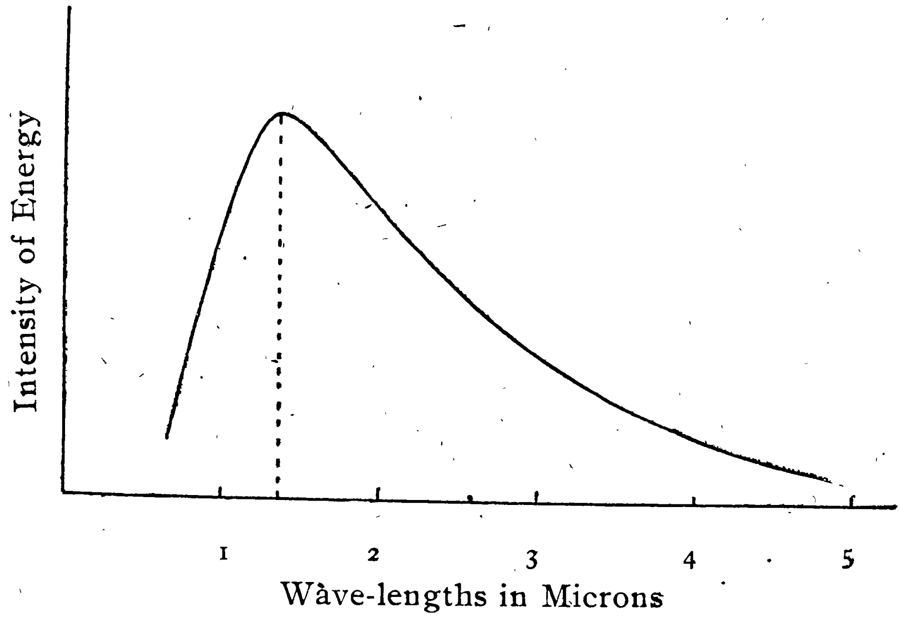

FIG. 1.

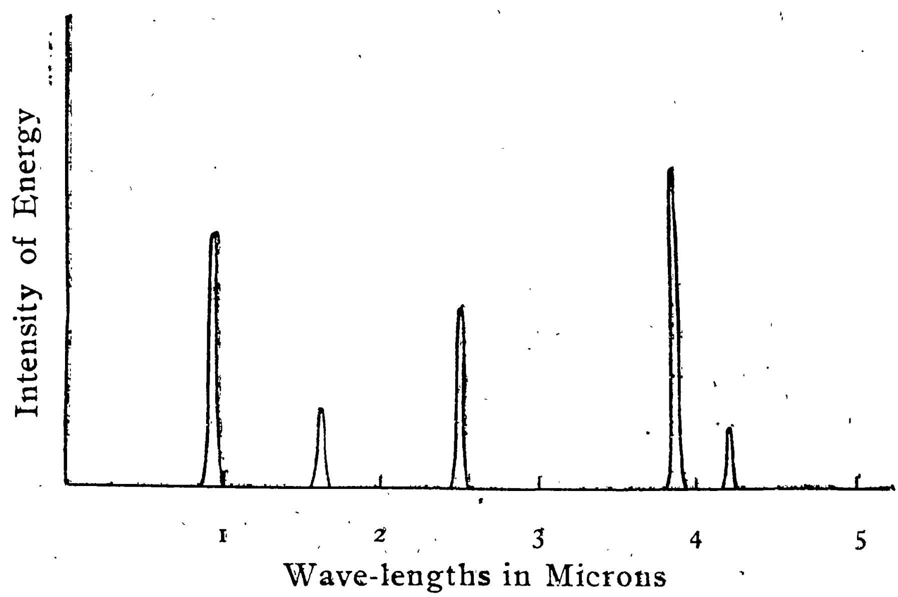

FIG 2.

energy output, and they showed that this area was proportional to the fourth power of the absolute temperature, thus confirming Stefan's Law. If we draw the tallest ordinate in Fig. 1, the corresponding abscissa gives us the wave-length of the particular waves which carry the maximum amount of energy. This wave-length is called λ_m. When they investigated the energy distribution for black bodies of different temperatures they got curves like Fig. 3. Here each curve of a higher temperature lies wholly above the curve of a lower temperature. The areas under the curves are proportional to T^4, and the next fact deduced was that

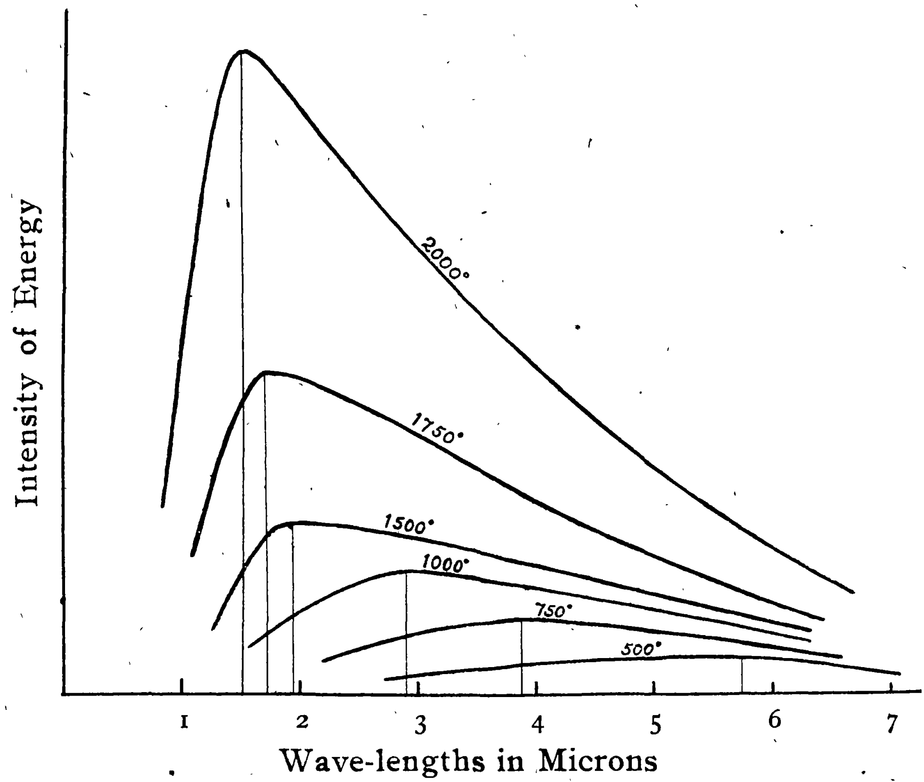

FIG. 3

as the temperature went up the wave-length of maximum energy decreased and decreased in such a way that the product, λ_m absolute temperature, was constant and equal to 2910, if λ_m is in microns and T in absolute degrees Centigrade. This law is known as *the displacement law*. It is important, for it affords a means of finding the temperature of the black body. For if in the energy distribution of any black body we find by some means the λ_m, we can get at once the temperature of the body by simple division.

We will now take up what is called the *solar constant*. The solar constant is the amount of energy which the sun sends per second to every sq. cm. on the earth which is exposed normally to its rays. To measure this quantity, the energy is absorbed by a blackened surface and thus converted into heat, which is measured directly by a rise of temperature in water or some other body, or else compared to an equal emission of heat from a source of known output. The great problem in the measurement of the solar constant was to correct for the absorption in the atmosphere. This was done by Langley and Abbot, who have compared readings on the surface of the earth with readings on the tops of high mountains. The final value obtained for the constant is .033 calories per sq. cm. per second, or $.033 \times 4.2 \times 10^7$ ergs per sq. cm. per second.

We have now all the material to hand for calculating the effective temperature of the sun. We do not say the actual temperature of the sun, because there may be considerable variation in temperature throughout the sun's mass. The solar disc, however, radiates energy, and when we speak of the effective temperature of the sun, we mean the temperature of a full radiator which, if placed in the position of the sun, would radiate just the same amount of energy that is given out by the real sun.

METHOD 1. USING THE DISPLACEMENT LAW.

Langley and Abbot have measured the distribution of the energy throughout the solar spectrum very carefully and found that the waves of wave-length about .490 micron carry the maximum amount of energy.

Putting $\cdot 490 \times T = 2910$
we get $T = 5940°$C. absolute

as the effective temperature of the sun.

METHOD 2. USING THE SOLAR CONSTANT.

The energy sent out by the sun = the energy received on the interior of a sphere whose equator is the orbit of the earth. Therefore, area of sun's surface $\times\ aT^4$ = area of the given sphere $\times$ solar constant.

Hence

$$T^4 = \left(\frac{\text{distance of earth from sun}}{\text{sun's radius}}\right)^2 \times \frac{\text{solar constant}}{a}$$

$$= \left(\frac{9{\cdot}28 \times 10^7 \text{ miles}}{4{\cdot}33 \times 10^5 \text{ miles}}\right)^2 \times \frac{{\cdot}033 \times 4{\cdot}2 \times 10^7}{5{\cdot}3 \times 10^{-5}}$$

$$= 5890°\text{C. absolute.}$$

METHOD 3. USING THE THEORY OF EXCHANGES.

Let us assume that the sun and the earth are full radiators, that the temperature of the crust of the earth is nearly the same all over the earth, and the loss of heat from the earth by radiation equals that gained from the sun by radiation. These assumptions are very nearly true; even if not true, the errors involved are small.

What is the ratio of the size of the disc of the sun to the whole area of the celestial sphere?

The angular semi-diameter of the sun is approximately 16′ 1″, which is

$$\frac{961}{206265} \text{ radians}$$

Therefore the fraction of area of celestial sphere occupied by disc of sun

$$= \frac{\pi \left(r \dfrac{961}{206,265} \right)^2}{4 \pi r^2}$$

where r may have any value,

$$\text{This} = \frac{1}{4}\left(\frac{961}{206,265}\right)^2 = \frac{1}{184,300}$$

Now, imagine the celestial sphere to be coated with solar discs. The number required would be 184,300, and the earth at the centre of such a sun-lit sky would receive 184,300 times as much radiation as it does at present. The earth would then be in a 'fully-radiating' enclosure and the temperature would rise until it became equal to that of the sun. When this was attained, the earth would be radiating 184,300 times as much radiation as it is at present. But the amount of radiation from a body is proportional to the fourth power of the absolute temperature of the body.

Hence, taking the average temperature of the crust of the earth as 290° absolute, we see that, if T is the temperature of the sun,

$$\frac{T^4}{290^4} = 184{,}300$$

$$T = 290 \sqrt[4]{184300} = 300 \times 20.72 = 6000°\text{C. absolute.}$$

A slight correction may be made to this, but it is hardly worth while bothering about it.

We have thus deduced the effective temperature of the sun by three methods and the three results agree fairly well. We may therefore conclude that the effective temperature of the sun is in the neighborhood of 5900 or 6000 degrees absolute.

We might have reversed the arithmetic in the last method quoted above, and, having assumed the temperature of the sun, deduced the temperature of the earth. We should have got somewhere near 290° absolute. Making like assumptions for the other planets, we could work out their temperatures in much the same way. This has been done by the late Professor Poynting, who arrives at the following temperatures: Mercury, 467°A; Venus, 342°A; Mars, 235°A. It is interesting to note that the average temperature of Mars' crust is nearly 40° C. below the freezing point of water. In the same way the effective temperature of space has been found to be 7° C. above the absolute zero.

In 1899, Professor Callendar, in a lecture to the Royal Institution on the temperature of the sun, quoted some of the results obtained by early workers on this subject. Dulong and Petit, in 1817, from a knowledge of the rate of cooling of a body in vacuo, deduced 1900° C. Rosetti, in 1878, using a radiation formula of his own, deduced 12,700° C. Bottomley in 1888 and Paschen in 1893, using a radiation law involving a power of temperature higher than the fourth, both deduced 4000° C. Early workers, using the fourth power law, obtained 6900°, and as late as 1897, Wilson and Gray, from results of experiments with a radiomicrometer, and using heated platinum as a comparison object, deduced 6900°. But we may safely conclude that the results given by the three methods outlined above are much nearer the mark.

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