

ART. XL.—*The Radiation and Absorption of Heat by Leaves*; by ALFRED GOLDSBOROUGH MAYER, M. E.  
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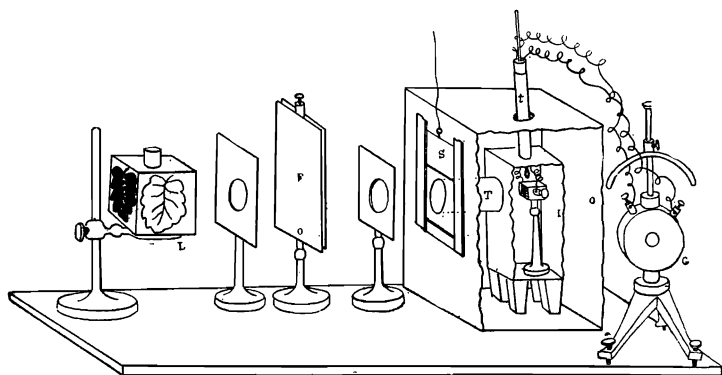
THE present research was commenced in the Physical Laboratory of the University of Kansas in the autumn of 1890, and continued in the Jefferson Physical Laboratory of Harvard University.

As plants must necessarily receive a considerable portion of their energy by the absorption of the sun's heat during the daytime, and then lose some of this heat by radiation during the night, it becomes of some interest to the physiological botanist to determine what may be the laws of this periodical gain and loss. Furthermore as by far the greater portion of the land surface of the globe is covered by vegetation, the laws of its radiation would become an important factor in a determination of the radiation of heat by the earth.

*Apparatus.*—In the research use was made of a highly sensitive thermopile in connection with a low resistance, reflecting astatic Thomson galvanometer. As it was feared that heating the leaves to abnormal temperatures might alter the coefficients of radiation of their surfaces, the form of apparatus shown in fig. 1 was devised, by means of which the radiation from leaves at the temperature of the air of the laboratory might

be determined. The essential parts consisted of two concentric boxes made of sheet tin (O I, fig. 1), drawn with their sides nearest the observer torn away in order to show the

Fig. 1.



internal parts. The two boxes were connected by means of the tin tube (T) soldered into a perforation in the middle of a side of each.

The inner box which contained the thermopile was mounted upon wooden legs, and running out from its top and also through the top of the larger box was the tube (*t*). The wires which connected the thermopile with the galvanometer (G), ran through this tube (*t*), as did also a very delicate thermometer giving the temperature of the air surrounding the thermopile. The sliding metallic screen (S) could be dropped down over the opening of the tube T, thus shielding the thermopile from all radiant heat. The capacity of the larger box was about 850 cubic inches, that of the inner one being 150. The outer box was jacketed with a two-inch layer of cotton wool.

By filling the space between the two concentric boxes with cracked ice, the temperature of the thermopile, and of the air in the inner box which surrounded it, could be lowered, so that one might determine the radiation from leaves at the temperature of the air of the laboratory. This apparatus possessed also the very great advantage that there were no air currents impinging upon the thermopile, and as a consequence its readings were remarkably concordant.

Many determinations both of radiation and absorption of heat were made by the aid of this apparatus, but in the excellent constant-temperature room of the Jefferson Physical Laboratory it was found unnecessary to inclose the thermopile, and therefore it was mounted upon an ordinary Melloni's bench.

Of course, as the thermopile was then at the temperature of the air of the room it became necessary to raise the temperature of the leaves which radiated to it. It was found, however, by numerous experiments, that the temperature of the leaves might be raised to 45° C. without altering in the least the coefficient of radiation from their surfaces.

### *Methods of Experimenting.*

I. *Radiation of Leaves*.—Two leaves of the same species of plant and as nearly alike as possible were procured, and each was glued, flat, upon one of the polished tin sides of the Leslie cube (L, fig. 1). One of the leaves was then painted over with lampblack in alcohol, which caused it to present a dull, dead black appearance. The Leslie cube was then filled with water which was heated to about 40° C., at which temperature it was maintained constantly by means of a low luminous flame of a Bunsen burner. A side of the cube bearing a leaf was turned so as to face the thermopile, and after the temperature of the water had become steady, the falling screen (F, fig. 1) was lowered, the slider S raised, and the deflection of the galvanometer after five minutes exposure to the radiant heat carefully observed. An exactly similar experiment was then gone through with, upon the lampblack leaf, in order that the radiation from the green leaf might be accurately compared with that from a similar surface of lampblack. Great care was taken in these experiments that the thermopile cooled completely, so as to cause the galvanometer to return to its zero reading before another experiment was performed. As the deflections of the galvanometer were small the radiation was assumed to be proportional to the deflection produced.

II. *The Effect of Dew upon the Radiation of Leaves*.—As a copious film of dew commonly forms upon the leaves of plants during summer nights, it occurred to me to ascertain whether their radiating ability was thereby altered to any perceptible degree.

The experiments were conducted as follows:—A leaf was glued to the polished side of the Leslie cube as in experiments upon radiation. The cube was then filled with finely cracked ice. This soon caused a film of dew to form upon the surface of the cooled leaf. The temperature of the air of the room and of the melting ice in the cube was then determined. The leaf was placed facing the thermopile, the shielding screens removed and the deflection of the galvanometer after five minutes exposure observed. The Leslie cube was then filled with water which was heated up and maintained at a tempera-

ture, as nearly as possible, as much *higher* than the temperature of the room as the melting ice was *lower* than that temperature. A five minute exposure was again given and the reading of the galvanometer taken. From the results of these two experiments it became possible to compare the radiation of the dewed leaf with the heated one. For example: let  $t_1$  represent the temperature of the air of the room, supposed constant,  $t_0$  that of the melting ice,  $T$  that of the heated water in the Leslie cube,  $d_0$  the deflection produced by the dewed leaf, and  $d_1$  that caused by the dry heated leaf. Then assuming the deflections of the galvanometer to be proportional to the radiation's we would have

$$(T - t_1) : (t_1 - t_0) = d_1 : x$$

Instead of  $x$  coming out equal to  $d_0$  as it would do if the coefficient of radiation of the dewed surface were equal to that of the heated surface, it was always greater than  $d_0$ ; thus proving that the coefficient of radiation of the leaf was *lowered* by the dew which had collected upon it.

III. *Absorption of Heat by Leaves.*—In performing these experiments the side of the Leslie cube was lampblackened, and the cube filled with water which was kept gently boiling. The reading of the galvanometer produced by five minutes exposure to the hot lampblackened surface of the Leslie cube was taken and compared with that produced when the heat from the Leslie cube was obliged to pass through a leaf, placed over a diaphragm, between the cube and the thermopile. Great care was taken to insure that all the heat which reached the thermopile had passed through the leaf. From the results of these two experiments it became a simple matter of ratio to calculate the percentage of heat absorbed by the leaf. Thus: Let  $D$  be the deflection produced when the heat passed uninterruptedly from the cube to the thermopile, and  $d$  that produced when the path of the heat was intercepted by a leaf, placed between the cube and the thermopile. Then the percentage of heat transmitted by the leaf would evidently be given by the expression  $\frac{d \times 100}{D}$  = per cent transmitted. To find the

per cent absorbed we have merely to subtract the per cent transmitted from 100. By causing the heat to pass through successively, one, two, and three leaves placed in its path, some facts relative to the selective absorption of leaves were obtained. By determining the heat-absorbing ability of a fresh green leaf, and then dissolving out its chlorophyll in alcohol or ether and testing the same leaf again, it became possible to ascertain how much of the absorption was due to the chlorophyll of the leaf.

*Results of the Experiments.*

In conducting the experiments upon radiation it was deemed wise to select leaves of widely different genera of plants; accordingly the leaves of a few forest trees, bushes, weeds living in both sunny and shady places, aquatic plants, cultivated plants and grasses were chosen. The results of a series of experiments upon the following leaves demonstrated that the coefficient of radiation of dark heat from both their upper and lower surfaces was *exactly* the same as that of lampblack.

The leaves tested were elm, oak, maple, horse chestnut, basswood (*Tilia Americana*), silver poplar, beech, lilac, mullein (*Verbascum thapsus*), plantain (*P. major*), lilly pads (*Nuphar advena*), cultivated grape, blackberry and clover. A single interesting exception, however, was discovered. The upper surface of burdock leaves (*Arctium lappa*) radiates exactly as do all other leaves, but the *under* surface radiates only 81 per cent of this amount.

These leaves are very broad and thick, and as they lie for the most part spread out horizontally very near the ground, the under surface is largely shaded from the sun's rays, and therefore receives but little direct heat. Moreover it is probable that being so near to the ground less dew would form upon the under surface than upon the upper. Both of these causes would combine, as we shall see later, to make it very advantageous to such leaves to possess a poorly radiating lower surface.

Of course, as leaves radiate exactly as lampblack surfaces, they also possess correspondingly good absorbing surfaces. Numerous experiments were made by the method already described to ascertain the effect of dew upon the radiation of leaves. If we call the radiation from a dry leaf 100, that from a leaf covered by a thin film of dew is about 78, and if the dew stand out in beads over the surface the radiation is reduced to 66.

A polished tin surface which only radiated 14 per cent as much heat as a lampblack surface, radiated 96·8 per cent of the lampblack one when both were covered with beads of dew. The coefficient of radiation of the lampblack surface was lowered, and that of the polished one raised until the radiation was nearly the same from both. So potent is a film of dew in altering the nature of a radiating surface.

Upon the importance of this remarkable fact we need hardly dwell. The surface of leaves being one of the best known radiators of heat, is therefore an equally good absorber of that heat. If then we imagine a forest in the tropics where the days and nights are of almost equal length the whole year round, very much of that heat which had been absorbed by the leaves during the day, would be lost by their great radiation

during the night, were it not for the fact that the blanket of dew which covers them cuts down this radiation to two thirds of its former value.

In the experiments upon the absorption of heat by the leaves, considerable individual difference was found in different specimens of the same species of leaf. In stating the results therefore I shall give the range of variation, where necessary. The following table gives the percentages of heat absorbed and transmitted by single leaves of the species named.

Name of Leaf.	Transmits	Absorbs
Ash .....	19·7 per cent	80·3 per cent
Elm .....	18-23	77-82
Maple .....	16-20	80-84
Wild Cherry .....	15-18	82-85
Horse Chestnut .....	19	81
Lilac .....	14-18	82-86
Mullein ( <i>V. thapsus</i> ) .....	17	83
Burdock ( <i>A. lappa</i> ) .....	14	86
Chicory ( <i>Chicorium intybus</i> ) .....	17	83
Rose leaves .....	28-31	69-72
Petals of red rose (cultivated)	33	67
“ “ White rose .....	27	73
“ “ Yellow rose .....	24	76
“ “ <i>Oenothera speciosa</i> .	28	73
“ “ <i>Tradescantia</i> Vir- ginica .....	31	69

The above table would seem to indicate that if dark heat be allowed to pass through a leaf, rather more than 80 per cent is absorbed by the leaf and somewhat less than 20 per cent transmitted. The heat passes through exactly as readily when it enters by the lower surface, as when it enters the upper.

The absorption of heat by leaves is highly selective. Thus a single elm leaf in the path of the dark radiant heat transmits 20 per cent of the heat which entered it. If now the heat which has passed through the first leaf be allowed to fall upon a second, it will be found that only 78 per cent of it will be transmitted. A third leaf will transmit over 83 per cent of the heat which passed through the second, and the effect of a fourth leaf is hardly noticeable. This may in some measure account for the somewhat remarkable fact that there is no very great difference between the absorbing abilities of such leaves as mullein and wild cherry, although the former are thick tough leaves and the latter very thin. By dissolving the chlorophyl out of leaves and again testing them, as has been explained under methods of experimenting, it was found that this substance absorbs but little of the dark heat. Thus, wild cherry leaves transmitted 9· per cent and chicory (*C. intybus*.)

4 per cent more heat when their chlorophyl was abstracted by ether or alcohol. In thick tough leaves such as lilac or elm, however, I was unable to detect its influence. It will be seen upon referring to the table that rather more heat seemed to be transmitted by the petals of flowers than by leaves. Natural selection has forced all leaves to the optimum as regards transmission and absorption of heat, and hence we find but little difference in the behavior of leaves of widely different genera of plants in this respect. Their surfaces have become the best known absorbers of heat, and in order to counterbalance the consequent disadvantage of being the best of radiators, the dew, which collects upon them at night, cuts that radiation down.

In conclusion, it gives me pleasure to acknowledge my great indebtedness to Professor Trowbridge, who kindly placed at my disposal the excellent apparatus and facilities of the Jefferson Physical Laboratory.

Cambridge, October, 1892.

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There appears to be no bibliography relating directly to the whole subject of the above paper. For reference to some of the few works relating more or less directly to it, I am indebted to the kindness of Professor Goodale.

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