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DAYLIGHT.*

BY

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LADIES AND GENTLEMEN: Shortly after I sent in my subject to Dr. Owens, in response to his kind invitation to me to speak here this evening, I chanced to discover that a lecture on an almost identical topic had been given before the Franklin Institute by the late Henry Morton. His theme was "Sunlight and Moonlight." This, however, was some forty years ago, and most of what I shall have to say to-night is based on newer work, and will not greatly infringe on this earlier paper.

Daylight is simply the light of the sun, modified by its passage through our atmosphere, and further modified by the addition of light, which, having reached the atmosphere, is reflected back and forth and reaches us in the form of skylight. The light from the sky differs from direct sunlight because of the selective reflection to which it has been subjected at the surface of cloud masses and of the earth itself and from particles of dust and moisture in the air.

The effect of the selective absorption of the atmosphere is very marked, as may be seen from the curve in Fig. 1, which is plotted from data given by Dr. Abbot, of the Astrophysical Observatory of the Smithsonian Institution. The values were obtained by making use of numerous sets of observations of the sun's spectrum taken at various localities.

At $.8\mu$, or just beyond the red end of the visible spectrum, about eight per cent. of the sun's rays are cut off by the atmos-

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phere, whereas in the violet at least half the light is absorbed, and the sharp downward trend of the curve would seem to indicate complete opacity of the air for a greater portion of the ultra-violet rays. It is on this account that the spectrum of sunlight ends so soon after the boundary of the visible spectrum is passed, and that many rays which appear in the spectra of artificial sources of light near at hand are absent from the spectrum of the sun.

In clear weather, daylight is nearly all direct sunlight. A white surface exposed to the sun and to the whole sky receives about eighty-five per cent. of the light which illuminates it directly from the sun, and only about fifteen per cent. from the other portions of the dome of the sky. In cloudless weather, therefore,

FIG. 1.

Selective absorption of light by the atmosphere.

daylight differs but little from sunlight, for even marked changes in the reflected light from the sky would produce but little effect upon the blended illumination from sun and sky.

To tell what sunlight is like, outside of our atmosphere, is not a very simple matter, but by going to greater and greater heights above the sea, and making observations upon its constitution, we can estimate its original character as it reaches the upper limits of the earth's atmosphere. By such methods we can indeed form a very good idea of what sunlight would be like if we could entirely remove this blanket or sea of vapor at the bottom of which we live, and could see the sun as it really is.

Daylight, as we get it after its passage through this great atmospheric filter, is of very great importance and interest to us,

because mankind has been brought up in it and, by long exposure to this particular form of illumination, has become thoroughly adapted to it. Daylight, in spite of the increasing use of artificial illumination, is still the normal stimulus of the human eye. The eye is most sensitive to those rays which in the spectrum of sunlight are of maximum energy.

How exact the coincidence is may be seen from Fig. 2, in which L is the ordinary luminosity curve of the eye and E is a portion of the curve giving the distribution of energy in sunlight.

Coincidence of maximum of the sensitiveness of the eye and of the sun's energy.

Doubtless this is not a mere coincidence, but the result of gradual adaptation of the race to the particular stimulus to which the human eye has so long been subjected.

On the surface of a planet with an atmosphere as transparent to the violet and ultra-violet as to the longer wave-lengths of the visible spectrum we should expect to find beings the maximum sensitiveness of whose eyes would be considerably displaced towards the violet, so as to correspond to the crest of the curve E^1 in Fig. 2, which is the energy curve of sunlight before its passage through the earth's atmosphere.

The eye, in order to meet all the demands upon it, must of necessity have an extremely wide working range. It has to serve not only at noonday, but also at morning and at evening, and within doors and at night. It is never normally exposed to anything of greater intensity than full daylight, and we find, accordingly, that its range of sensitiveness is such that broad daylight represents the upper limit of what we can endure without danger. We feel no discomfort out of doors when the sun is at its highest, but, under a very slight further increase of intensity, the eye does begin to suffer. Upon a snow field in the summer time, for example, in mountain climbing, the eye is overpowered, and, unless protected, is in danger of serious damage. Proper snow-goggles are recognized as an imperative necessity, even by those who, like the mountain guides, are most inured to such exposure.

How very near we are to the upper limit of endurable brightness appears from the discomfort suffered from the glare of an unshaded street in summer time. The light of the open is pleasurable only when it comes chiefly from above and the eye is relieved by the presence of large, dark, absorbent areas in the line of sight. This has been ingeniously demonstrated in a recent and skilful study of the distribution of luminosity in nature by Drs. Ives and Luckiesh.¹ They show, by many actual measurements made in town and country, that to be pleasing a landscape must be lighted mostly from above the horizon and have a certain abundance of contrast.

The brightness of out-of-doors, even without snow underfoot, is really almost incredibly great as compared with what we use in artificial lighting. The illumination of a surface, exposed to sunlight and skylight, in midsummer has been found to reach 100,000 hefner-meters or 90,000 candle-meters in midsummer.² In the suburbs of Berlin, another estimate, by Vogel, was 78,000 hefner-meters, and even in the smoky city of Chicago, in the month of June, Dr. Basquin found 33,000 hefner-meters. When we consider that about 12 hefner-meters, or a candle-foot, is sufficient illumination for easy reading of ordinary print, we realize

¹ Ives and Luckiesh: *Transactions of the Illuminating Engineering Society*, p. 687 (1911).

² Occasional isolated values run even higher, and Weber, the inventor of the Weber photometer, gives as the highest record 154,300 hefner-meters. (See Pernter and Exner, "Meteorologische Physik," p. 712.)

what an enormous step down it is from the maximum of full daylight to the minimum which we find necessary for our uses. The sensitiveness of the eye, however, has by no means reached its lowest limit here. All sense of light is not lost until we have descended to an illumination of about $1/1,000,000$ of a hefner-meter. From broad daylight, which represents the upper limit, to the almost utter darkness in which we can still see our way about we have a range of usefulness in the human eye for which it is hard to find a parallel.

It is not in the matter of intensity only that the eye exposed to ordinary daylight is near the danger line. Such light contains very nearly the maximum amount of ultra-violet rays that can be borne with impunity.

Sunlight of the sort which exists above the earth's atmosphere, even if the total energy of radiation were not increased, would probably soon destroy the eyesight of an inhabitant of the earth's surface. Even in climbing the higher snow mountains (4,500 to 5,500 meters) where the barometric pressure falls to about half an atmosphere it is necessary to protect the eyes, by means of colored spectacles, quite as much against the excessive amount of ultra-violet radiation as on account of the glare. The extraordinary blue-violet sky at such altitudes, described by Tyndall and other observant mountaineers, and familiar to all climbers, is indicative of the change in composition of daylight due to the greatly reduced thickness of the atmospheric light filter.

The other end of spectrum, where the energy is thousands of times as great as in the ultra-violet, has no such effect. One may sit by the firelight until he burns the skin without hurting his eyes, but a mere glance at the mercury arc in a quartz tube or at certain flaming arcs without the protection of an intervening screen of glass may endanger the eyesight.

Daylight, of course, varies in brightness with the height of the sun above the horizon, and, in the temperate zones, the annual range is much greater than most people, excepting, perhaps, the photographers, are apt to suppose. Fig. 3 contains a curve from observations taken in Germany³ by L. Weber.

The curve is irregular on account of the occurrence of a long period of dark weather in June. If measurements were made in

³ For these and further European data see Pernter and Exner: *l. c.*

some cloudless region, such as Arizona or the Desert of Sahara, the curve would probably be quite symmetrical with the maximum at midsummer.

Observations made by Basquin⁴ in Chicago entirely confirm Weber's values, and he also finds that the average brightness of daylight in midwinter is only one-tenth⁵ of that in June, and that the ratio between winter and summer in this respect is nearly the same in the United States as in Europe.

One might naturally expect that the daily range of the intensity of daylight would be expressed by a somewhat similar curve having a maximum precisely at noon, but this is not strictly the case, as will be seen from Fig. 4, which contains a set of curves

Annual range in the brightness of daylight (measured at Kiel, Germany, by L. Weber).

taken by the author on a cloudless day in Switzerland. In all of these curves, which show the variation in the brightness of four regions of the spectrum from dawn until dusk, there is pronounced dissymmetry; the light in the afternoon being brighter than that at the corresponding time before noon. The ordinate for 4 P.M. of the curve marked "Green .530 μ " corresponds, for example, to that for 9.30 A.M.; that is to say, four hours after the sun had passed the meridian the amount of daylight was as great as at two and a half hours before noon. Similarly, the

⁴ Basquin: *l. c.*

⁵ The range between the very brightest day in summer and the darkest in December is vastly greater; the ratio, according to Weber, being nearly 300:1.

brightness for 6 P.M. was equal to that at 7 A.M. This excess of brightness in the later portions of the day is common to all portions of the spectrum. Observations by Basquin, in which the light was measured without dispersion, exhibit the same characteristics.

In unsettled weather the changes in the course of a day may naturally be much more erratic. Even when there is no very obvious variation in the appearance of the sky, the various portions of the visible spectrum may undergo very different sorts of

variation, as may be seen from the curves in Fig. 5, which are from observation made during an April day at Palermo, Italy.

In this case the range was nearly normal for the red, but the preponderance of green and blue in the early afternoon was very marked, and the maximum was not reached until about 2 P.M. The violet decreased steadily in amount throughout the day. To what this lack of symmetry in the curves for the daily range in daylight is due will be considered in a later paragraph of this paper.

A point about which there is apt to be misconception on the

part of those who have not paid particular attention to the subject concerns the relative brightness of clouded and unclouded skies. We think of the unclouded sky as bright, but, in point of fact, it is just about as bright as a densely clouded sky, and all the intervening stages of cloudiness are brighter than either. I had an opportunity, a few years ago, of measuring the brightness of the sky in the zenith on an afternoon during which, in the course of a few minutes, as sometimes happens in mountainous regions, the sky passed from an unclouded condition to that of being densely

FIG. 5.

Variations in brightness during April day in Palermo, Italy.

overcast. The observations were made in a high valley in the Tyrol, where, as frequently happens in summer, showers come up with great suddenness. The results of my measurements, which are given in Fig. 6, cover a time interval of only ten minutes, from 5.30 to 5.40 P.M. The sky at 5.30 was cloudless, but it began very rapidly to thicken up with mist. Two minutes later the brightness had materially increased, as shown in the curve. It then remained almost stationary for two minutes, after which it became rapidly brighter and brighter as shreds of sunlit clouds appeared and gathered into shining masses of cumulus.

Then quite suddenly after eight minutes of observations the clouds closed in, the sun disappeared, and it began to rain. Just before I was driven from my post by the downpour, namely, at 5.40, the brightness of the sky in the zenith was almost exactly what it had been ten minutes before, when no cloud in that portion of the sky was visible.

Daylight under the conditions of overcast sky consists of all skylight and no direct sunlight, whereas with unclouded sky, as has already been pointed out, 85 per cent. comes directly from the sun and only 15 per cent. from the sky. The intensity of

FIG. 6.

Variations of brightness with state of sky.

daylight under these conditions, although the sky in the two cases is equally bright, would obviously be quite different.

Of the various theories concerning what we call the color of the sky, an interesting one is that of Spring,^o the Belgian physicist, who pointed out that both oxygen and ozone in the liquid form are blue when viewed by transmitted light; also, that water when pure is blue, although not to the same extent. He regarded the blue color of these components of the atmosphere as the main cause of the color of the sky, since those rays which reach the eye after reflection, and perhaps after multiple reflections within the atmosphere, will have passed over a longer path in this absorb-

^o Spring: Bulletin de l'Academie de Bruxelles, 1898, p. 504.

ing medium than the direct rays from the sun. Whatever effect this color of the atmosphere itself may have, it is certain that the sky would have a blue color aside from any effect of selective absorption in passing through it.⁷ The atmosphere is a turbid medium, and selective reflection from minute particles suspended in it, in accordance with Rayleigh's formula, would produce what may be called the ideal sky. These actual skies sometimes approach, but they never quite correspond to, it. In general we may say that the effect of reflection by the particles of the atmosphere is to give us light, which is distinctly bluer than that transmitted directly from the sun, but which is rarely or ever as blue as the ideal sky. Daylight, being a mixture of this bluer light from the sky with direct sunlight in varying proportions, will therefore be intermediate in quality.

In the study of daylight or of the light from the sky the only really definite and satisfactory method is that of the spectrophotometer, by means of which instrument it is possible to measure as many of the separate wave-lengths of the visible spectrum of which the light to be studied is composed as one may desire. The measurements consist in the comparison, wave-length by wave-length, of the spectrum of the light to be described with the corresponding wave-lengths of the spectrum of some source of known composition. For this purpose sunlight itself will hardly do for a standard, because the rays from the sun at different times of day and in different atmospheric conditions vary very greatly both in intensity and in composition. It is better, therefore, to make comparisons with some standard source of artificial light, and the best available source is the acetylene flame, the composition of which is very nearly uniform, while it possesses the valuable property of relatively great strength in the blue and violet as compared with incandescent lamps or with the flames of ordinary illuminating gas or petroleum.

With a special form of spectrophotometer, one collimator of which points toward the zenith or towards some other selected region of the sky, while the other collimator is illuminated by means of an acetylene lamp properly regulated and adjusted, it is possible to study the composition of the light from the sky very

⁷ For an excellent and judicious discussion of the various theories of the color of the sky see Chr. Jensen, "Das Weltall," p. 37, 1904-1905.

conveniently and rapidly. If with such an instrument we begin at dawn and work at intervals through the day, we find certain progressive changes occurring in addition to the increase and decrease in total brightness. These changes, which depend upon the weather, are not the same every day, but on bright mornings, before sunrise, the type of curve which one gets, and which I have called the typical dawn curve, is almost always the same, and this curve comes closer to that which would be obtained from observations of the ideal sky of Rayleigh than anything which

FIG. 7.

Relative qualities of daylight at dawn and after sunrise.

one gets later in the day. The form of these typical dawn curves and of the corresponding curve after sunset may be seen in Fig. 7 (curve *d*), in which ordinates are the ratio of the brightness of the spectrum of the sky to that of the acetylene flame used for comparison, and abscissæ are wave-lengths. Curves taken on any clear morning or evening when the sun is below the horizon will be found to approximate very closely to this example.

After sunrise there is a rapid increase in the brightness of all portions of the spectrum of skylight, but the brightness of different wave-lengths does not increase at the same rate. In other

words, it is not a mere brightening of the sky we observe, but a change in its color as the day progresses. How great this change is can be seen from curve *n* as compared with the typical dawn curve *d*. Curve *n* was taken in the middle of the morning of the same day. The scales chosen are such as to make the two curves cross each other in the red. It will be seen, however, that this equality does not persist throughout the spectrum, but that the relative brightness in the yellow and green is greater and in the blue and violet less than before sunrise. On exceptional days the red and

FIG. 8.

blue may remain of the same relative brightness, as shown in curve *b*, the middle of the spectrum showing greater increase; but in general, when the sun is well above the horizon, the sky is less blue than in the morning, and its light approaches more closely to that of direct sunlight.

This modification in the light of the sky is probably due in great part to a gradual gathering of particles of moisture, and the changes in the curves as the day progresses will often enable one to predict what kind of an afternoon is to be expected, especially whether there will be a gathering of cumulus and perhaps

showers in the afternoon. I found in the mountain valleys of Switzerland, where many measurements were made, a very peculiar development in the violet of the spectrum of the sky occurring gradually during the later morning and lasting late into afternoon which seemed to be an almost certain forerunner of the gathering of cumulus clouds. On such occasions, beginning about 9 o'clock in the morning, an emission band appears with its maximum in the blue, which increases steadily in intensity until after mid-day and then gradually disappears as evening approaches. Unless the sky becomes overcast it is possible to follow the accession and diminution of this phenomenon and its final disappearance at sunset. A characteristic curve for this type of sky is given in Fig. 8.

Professor Very⁸ has discussed these measurements which I first described in two papers before the American Physical Society,⁹ to which the reader is referred for further details, and has offered a very suggestive explanation. He says:

"I suggest that the growth of this band is possibly connected with the formation of the complex water molecules described in my 'Atmospheric Radiation' (p. 100), to which Sutherland has given the name hydrols. Increasing ionization of the upper air by the sun's ultra-violet rays lead to the formation of nuclei of condensation, and this, combined with the mid-day upward movement of aqueous vapor at considerable altitudes, conduces to the formation of an exceptional amount of peculiar diffracting particles in the upper air during the middle of the day."

On misty days, or when the collimator of the spectrophotometer is directed towards masses of cumulus cloud illuminated by the sun, the intensity of the green, yellow, and red rays of the spectrum is further greatly increased. As may be seen in Fig. 9, which contains a group of curves showing the character of the light of the sky during a time of light mist or fog (curve *A*), the light from cumulus clouds (curve *C*), and, for purposes of comparison, the light of an overcast sky (curve *O*), it will be seen that these three curves differ chiefly in that the two first, *A* and *C*, show the maximum in the blue already described, whereas the same is nearly or quite absent in curve *C*. Curve *C*

⁸F. W. Very: *Astrophysical Journal*, xxxiv, p. 372, 1911.

⁹Nichols: *Physical Review*, xxvi, p. 498, and xxviii, p. 123.

rises to higher ordinates towards the red end of the spectrum, indicating that sunlit cumulus is less blue than fog or overcast sky.

A comparison of curves made during the day, when the sun shines on the surface of the earth and is reflected back, shows that the earth has also had a modifying influence. Measurements taken at sea are entirely different from those made on shore, especially in the summer time, when the surrounding country is clothed with green foliage. In the latter case we have actually reflected back from the green leaves a weak but unmistakable

FIG. 9.

Characteristic curves for Mist (A), Cumulus (C), and Overcast Sky (O).

absorption spectrum containing the bands of chlorophyl. In Fig. 10 a curve is presented which may suffice to illustrate this effect. In it the ratio between the intensities of a daylight spectrum at 8.25 A.M. to that of the corresponding wave-lengths in the typical dawn curve is plotted. The positions of the maximum and the minimum intensities are such as to indicate that the selectivity is partly due, as has already been hinted, to the absorption of light by green leaves. Measurements made at sea or over a sufficiently large snow field in winter do not show these peculiarities.

A sufficient number of examples of the spectrum of daylight under various conditions has been given to indicate the very considerable range of brightness and composition according to the locality, the time of year, the time of day, and the condition of the sky which one meets with in the study of this subject. These fluctuations are much greater than the fluctuations of any given type of artificial light. Our sources of artificial illumination, from the candle to the tungsten lamp, represent a comparatively small range of temperature, and these temperatures are

FIG. 10.

Ratios of daylight to dawn, curves showing selective reflection by the surface of the earth.

so much lower than that of the sun that the distribution of intensities in all such sources is necessarily of an entirely different character from that of the spectrum of daylight. In the former case we have to do with continuous spectra emanating from glowing carbon or from incandescent metals, such as tantalum or tungsten heated to temperatures lying, approximately, between 1500° C. and 2200° C. Even the carbon arc-light, in spite of the high temperature of the crater (3600° C.), can hardly be assigned a temperature above 2500° for the aver-

age of its radiation. As to the sun, whose temperature was in earlier days variously estimated by indirect and inadequate methods as between 5000° and $100,000^{\circ}$, the development of our knowledge of the laws of radiation and the perfecting of the art of optical pyrometry afford the means of making fairly accurate determinations.

The problem, stated in its simplest terms, consists in reducing the visible radiation from the sun, which is enormous when compared with that of a black body of measurable temperature with which it must be compared, to something like the same brightness. For this purpose the sun's light must be diminished to about .00002 of its original value, for which purpose none of the ordinary methods employed in photometry suffice. This has recently been accomplished by Professor Kurlbaum,¹⁰ of Charlottenburg, Germany, in the following ingenious manner. Instead of attempting to measure the brightness of the sun itself, he observes a diffusely reflecting surface obtained by depositing magnesium oxide upon metal, this surface being exposed to sunlight. The illumination of such a surface will be directly proportional to the brightness of the sun multiplied by the ratio of the square of the sun's radius to the square of the distance of the earth from the sun. This ratio happens to give just the proper reduction demanded. The reflecting power of the magnesium oxide being known, its brightness compared to that of the sun which illuminates it can be computed from the quantities mentioned above; and by the comparison of the brightness of this sunlit surface with that of an artificially-heated black body of measurable temperature the temperature of the sun may thus be computed with an accuracy which depends only upon our knowledge of certain distances and constants and of the laws of radiation. Kurlbaum estimates by this method that the temperature of the sun lies between 6002° and 6023° , an uncertainty which arises chiefly from the inaccuracy of our scales of measuring temperature. Now, between 2000° and 6000° radiation differs so greatly, both in intrinsic brightness and in composition, that sunlight or daylight is in an entirely different class from ordinary artificial illuminants; and, since we cannot, at present, produce incandescence approaching that at 6000° , we are unable to imitate sunlight, except in two

¹⁰ Kurlbaum: *Berichte der Preussischen Akademie der Wissenschaften*, p. 541 (1911).

ways. Certain bright line spectra of glowing vapors, the composition of whose light is really altogether different from the continuous spectrum of the sun, may have the power of stimulating the three primary sensations of red, green, and violet in nearly the same proportions; and thus, as in the case of CO_2 in vacuum tubes under certain conditions, may be made to simulate sunlight in some respects. All known solids, at temperatures of incandescence attainable in practice, are, however, relatively much stronger in red and weaker in the violet than daylight.

Candles, oil and gas flames; the Nernst filament and mantle burner; glow-lamps, whether with filaments of carbon, tantalum or tungsten, are all intermediate as regards the distribution of intensities in their visible spectra between the Hefner standard lamp and the acetylene flame.

How small a range of variation they cover as regards quality of light, and how different they are from daylight, may be seen from Fig. 11, in which the spectrophotometric curves for the Hefner lamp and the acetylene flame are drawn.¹¹ In this diagram, ordinates are values for each wave-length of the ratios Hefner/daylight or acetylene/daylight.

The brightness of the spectra is so chosen for ease of comparison that these ratios are unity in the yellow region (0.590μ). The standard for daylight used in this comparison is from the average of numerous measurements taken in all sorts of weather, during what I have since learned from European meteorologists was an abnormally dull or gray season. Had the observations been confined to the sort of day which one would naturally select on which to sample daylight, the contrast with these artificial sources would have been much more striking.

Now, while we cannot increase the degree of incandescence of these sources of low temperature so as to make them approach appreciably nearer to sunlight, it is possible to change the quality of their light by the use of properly selected color screens, and this is the second of the two possible methods to which reference is made above.

When we try the experiment by placing over half of the field of the lantern a blue screen which gives a fair match as

¹¹ Nichols: "Daylight and Artificial Light," *Transactions of the Illuminating Engineering Society*, 1908 (May).

to color with daylight, and, by means of a carefully-chosen amber screen, reduce the other half to the color of candle-light, we get, as you see, by direct appeal to the senses, a telling realization of the significance of these curves in Fig. 11, and we have brought home to us the very great difference between the light of the heavens and that by which the greater part of our indoor work is done.

Fortunately the preponderance of the longer wave-lengths in artificial light is one which is restful rather than harmful

FIG. 11.

The distribution of intensities in the spectra of the Hefner lamp and the acetylene flame compared with daylight.

to the eye (which bears excess of violet and ultra-violet so ill), and it is doubtless more healthful to work under a ruddy illumination of fifty candle-meters than to strain the eyes with the two or three candle-meters of cold daylight, which, according to recent measurements,¹² is all that reach the pages of readers in the rooms of many public libraries.

¹² "Nature," 88, p. 600, an abstract of L. Weber's recent Study of Daylight in *Schriften des Naturwissenschaftlichen Vereins für Schleswig-Holstein*, xv, i.