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ON THE PHYSICAL NATURE OF THE SOLAR CORONA

In a paper on "The 1900 Solar Eclipse"* Langley and Abbot published some measurements on the heat radiation of the solar corona. This was found to be "unexpectedly feeble." Therefore the authors oppose the view, that the "main source of the light from the corona is the incandescence of its particles, due to the proximity of the hot photosphere." Instead of this they suppose that the "principal source of its radiations is of the nature of an electrical discharge." The example used by the authors for such light caused by electrical discharge, namely, the light of the aurora, seems to me not to be a good one, for the aurora has a bright-line spectrum and the corona mainly a continuous one. Again, the phosphorescent glow under the influence of cathode or Röntgen—or ultraviolet rays seems to give a nearer approximation to the continuous spectrum of the corona. But the spectra of the coronas of 1898 and 1901, as given by Campbell and Perrine, are not very similar to that of a phosphorescent substance, so that this modification of Langley and Abbot's views has also to struggle with rather great difficulties.

Mr. Campbell drew my attention to the conclusion of Langley and Abbot. As will be seen from the following considerations the heat—and light—effects of the corona agree very well with the assumption that its radiation is due to the incandescence of its particles. The special difficulty of Langley and Abbot is given in the following words: "Why should the coronal radiation, of equal apparent brightness to that of the full moon, be comparatively so feeble in heating effect?" This effect was measured by five scale-divisions on a bolometer, whereas a (black) body of the room's temperature under similar conditions gave eighteen divisions.

* Washington, 1904, page 26.

Now I shall show that the brightness and the heat-effect of the corona are just such as we might expect from dust-particles heated by the radiation from the photosphere of the Sun.

The image of the Sun was produced by a concave mirror of 1 m. focal length. It had therefore a diameter of 9 mm. The part of the corona observed was 0.2 mm. from the limb of the Sun. I assume that this means the edge of the photosphere. From this I calculate that the photosphere of the Sun, seen from the observed point of the corona, would fill an angle of sight equal to $2 \cdot 73^\circ$, corresponding to a spherical angle equal to $2\pi \cdot 0.708$. A spherical particle in the corona at this point radiates to space through an angle of $1.292 \cdot 2\pi$, and to the Sun through an angle of $0.708 \cdot 2\pi$. Equilibrium of heat is soon reached and gives, in accordance with Stefan's law, if t is the absolute temperature of the particle, T that of the Sun (6000° absolute),

$$1.292 t^4 + 0.708 (t^4 - T^4) = 0;$$

from which $t^4 = 0.354 T^4$, and as T is assumed to be 6000° , t is found to be 4620° absolute.

According to the law of Wien (or Planck) we may now calculate the relative strength of the radiations E_1 and E_2 of two bodies at the temperatures 6000° and 4620° for different wave-lengths (λ). Thus we find:

λ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
E_1	0.0041	2.0	142	248	270	245	202	162
E_2	0.0000033	0.052	13.2	41.7	64.9	74.7	73.0	66.1

Taking the sum of the radiations in the visible spectrum from $\lambda = 0.4$ to $\lambda = 0.8$, we find $\Sigma E_2 : \Sigma E_1 = 0.289$. If we only regard the physiologically most effective part in the spectrum, for $\lambda = 0.55$ we find $\Sigma E_2 : \Sigma E_1 = 0.271$, which falls very close to the first figure. We may use the mean of them, 0.28, as lying very near to the true figure.

A body of the temperature 4620° abs. would therefore radiate a quantity of light equal to 0.28 times that radiated from the Sun, if they took up equal spherical angles of sight. The same would be the case if the body of 4620° were composed of little particles in such numbers that the background (the sky) could not be seen between them. Now, instead of this, Langley and Abbot indicate that the brightness of the corona was only equal to that of the full moon, which in accordance with the measurements of Zöllner is supposed to be about 1:618000 of that of the Sun. Therefore we must conclude that only $(1:618000) : (0.28) = 1:173000$ of the angle of sight to the corona is filled by the radiating particles of the corona, in the case of Langley and Abbot's observations.

In this calculation we have neglected the sunlight reflected from the particles in the corona. If we had not done so, we would have found a number somewhat, but not much, less than 1:173000.

Let us now make an analogous calculation for the radiation of heat from the corona. Langley and Abbot compare this with the radiation of heat from the moon. Langley found* that the radiation of the moon in the middle of the earth's umbra is equal to 1.3, whereas the radiation from the middle of the full moon is equal to 180 scale divisions. Now the middle of the full moon has a temperature of about 419° abs. Calculating the temperature of the middle of the umbra according to Stefan's law, we find 122° abs. As the temperature of the moon sinks from 419° abs. to 122° abs. in about three hours, it will be quite near to the truth to suppose that at the solar eclipse the center of the moon will be very near to absolute zero, so that its radiation may be neglected. Now we will suppose that the temperature of the cardboard, used for screening the bolometer in the experiment, was $+27^{\circ}C = 300^{\circ}$ abs., which will not be far from the truth. Further, we will suppose with Very† that the sky acts as a screen, sending back fifty per cent of the radiation from the bolometer. Then the radiation from the bolometer to free space being $-y$,‡ it is to space with the intervening atmosphere of the earth, $-\frac{1}{2}y$. This radiation gives a deviation of -18 divisions.

Now the bolometer was directed to the corona and the deviation found to be -13 divisions. The loss of heat to space through the atmosphere was as before $-\frac{1}{2}y$. To this came the radiation from the corona, which is supposed to be absorbed by the atmosphere (or reflected by its dust-particles) to a degree of 50 per cent. Call it therefore $\frac{1}{2}y$, so that we have

$$-\frac{1}{2}y + \frac{1}{2}y = -13,$$

* *Memoirs Nat. Acad. of Sciences*, Vol. IV, Part II, page 159.

† *The Astrophysical Journal*, 1898, December.

‡ The sign $-$ indicates loss of heat from the bolometer.

or $z = 10$. Now we have $y = 36$ as a measure of the radiation of a black body of 300° abs. If we suppose, as before, that the particles of the corona radiate as a black body, the effective temperature of the corona is found to be $\sqrt[4]{\frac{10}{36}} \cdot 300 = 217^{\circ}.75$ abs.

We have above deduced the temperature of the particles in the corona to be 4620° abs.; that is, the radiation should be $\left(\frac{4620}{217.75}\right)^4 = 2.02 \cdot 10^5$ stronger than it is found, provided that space would not be seen through the corona. Therefore we conclude that the particles of the corona do not fill more than the 202000-part of the angle of sight. This figure agrees excellently with that, 173000, calculated for the light, as evidently the measurements of Langley and Abbot are not claimed to give more than the order of magnitude. Also, the neglect of the sunlight reflected from the corona and the deviation of the small coronal particles from the laws of radiation valid for absolutely black bodies, would well account for the discrepancy, if the measurements were absolutely correct.

The difficulty which Langley and Abbot found, as stated above, is discussed in the following quotation (l. c. p. 251). "If the brightnesses of the full moon and of the solar corona are to the eye the same, why should they be different in heating effect? Obviously a natural explanation would be the comparative absence of some invisible radiations in the case of the inner corona, which are present in the case of the moon, such as would be due to the absence of infrared rays."

We will analyze this point a little more closely. If we regard the radiation of the Sun as like that of a body with a temperature of 6000° abs., and count radiation between 0.4μ and 0.8μ as luminous, and the rest as non-luminous radiation, the proportion of luminous to the total radiation is as 0.45 : 1, calculated from Wien's law. If we now regard a point in the middle of the full moon we find that it reflects diffusely 12 per cent of the Sun's light falling upon it (Zöllner), while the rest is transformed into heat. For the non-luminous radiation the moon is supposed to be a nearly opaque body, and it reflects diffusely perhaps two per cent of the incident non-luminous radiation and absorbs the rest. Now all the absorbed radiation is (as equilibrium of heat is reached) radiated out as heat.* The proportion of the luminous and total radiation from the moon is therefore in the proportion

$$\frac{0.12 \cdot 0.45}{1} = 0.054 : 1.$$

For the particles of the corona Wien's law gives the proportion of luminous to the total energy as 0.36 : 1, neglecting the sunlight reflected from the

* Therefore it is for our calculation immaterial whether the non-luminous radiation is partially reflected or not.

corona. We may therefore say that the luminous energy is more than 6.7 times stronger in the coronal light than in the moonlight, compared with the total energy. It is this distribution of the radiation which makes the corona appear so luminous and so "cold" compared with the moon.

By help of the measurements of Abbot it is possible to form an idea of the mass of the coronal dust. The dust-particles in the inner corona are heated to 4620° abs., and may therefore be drops of liquid metal. It is not probable that the dust is of carbon, for carbon seems to have a rather high vapor-pressure at this temperature, and the gaseous pressure in the corona is extremely low. We may, for example, suppose that the dust-particles are molten iron-drops (melting point of iron about 1600°C.). The specific weight of iron is 7.9 at 0°C. , of molten iron 6.9 (at 1600°C.), and if its cubical dilatation is like that of cast-iron (0.000053 between 0° and 1000° , according to Le Chatelier), its specific weight at 4620° abs. will be about 6 (probably it is lower). If the iron-drops reflected the incident light totally, they would be driven away by the radiation-pressure from the Sun with the same force as they would be attracted to the Sun if their diameters were $250\ \mu\mu$. According to Schwarzschild's calculations for the influence of diffraction and the deficiency of the total reflection, this figure may be changed to about $350\ \mu\mu$.

It is very probable that those drops for which gravitation is just compensated by the pressure of radiation will be the chief material of the inner corona. For drops of other sizes are selected out, the heavier ones by falling back to the sun, the lighter ones by being driven away by the pressure of radiation, so that just the drops which, so to say, swim under the equal influence of gravitation and pressure of radiation will accumulate in the corona. The mass of such a drop is $m = \frac{4}{3} \pi (175)^3 \cdot 10^{-21} \cdot 6 = 0.135 \cdot 10^{-12}$ grammes. Their cross-section is $a = \pi (175)^2 \cdot 10^{-14} \text{ cm}^2 = 9.62 \cdot 10^{-10} \text{ cm}^2$. Now we know that the particles in the corona fill about $\frac{1}{190000}$ of the angle of sight. Therefore a column of 1 m.^2 cross-section through the corona at the point of observation of Abbot will contain $\frac{1}{190000} \cdot \frac{10^4}{9.62 \cdot 10^{-10}} = 54.7 \cdot 10^6$ particles of a total mass equal to $7.37 \cdot 10^{-6}$ grammes.

According to a formula by Turner the brightness of the corona decreases, in moving from the photosphere, inversely as the sixth power of the distance from the Sun's center. This may be due to a decrease of the temperature, but certainly the quantity of reflecting particles exerts the chief influence, and therefore I have supposed as a first approximation that the number of particles in a volume of 1 m.^3 is inversely proportional to the sixth power of the dis-

tance from the Sun. Then, according to Turner's formula, the concentration of matter in the innermost part of the corona would be 1.3 times greater than that calculated above. The total quantity of particles that we observe in the corona would, according to Turner's formula, be half as great as the quantity of particles in 1 m.^2 at the innermost part of the corona, multiplied by the cross-section of the Sun in m^2 . It would therefore be $\frac{1.3}{2} \cdot 54.7 \cdot 10^6 \cdot (108.56)^2 \cdot \frac{5.1}{4} \cdot 10^{14} = 62.8 \cdot 10^{24}$ particles with the total mass $8.6 \cdot 10^{12}$ grammes.*

Now the mass of the corona will be a little greater than this figure shows, for what we see is the total corona diminished by the part of it lying before and behind the Sun. I have executed a mechanical integration of the formula for this case, and found that the total mass of the corona is $\frac{6.67}{3.99}$ times greater than of that part calculated above, that is $14.7 \cdot 10^{12}$ grammes. If we had supposed that another material than iron composes the corona, we would have found nearly the same total weight; so, for instance, if the specific weight had been one, the total weight had been about $11 \cdot 10^{12}$ grammes. If the diffraction did not disturb, and the reflecting and absorbing power were always the same, then the calculated weights would be independent of the specific weight of the material of which the drops consist. For the total of the cross-sections of the drops, determined by the radiation, is an experimental constant, and the diameter of the drops would under these conditions be inversely proportional to their density. Now the total mass is proportional to (total cross-section) $\cdot$ (diameter) $\cdot$ (specific weight) and as the first value is constant, and likewise the product of the last two, then the total product, *i.e.*, the calculated mass, is independent of the assumed specific weight. For different metals, that may be supposed to enter into the corona, the specific weight is also but little variable, and therefore also the condition for diffraction, according to Schwarzschild, is nearly the same for them all. Likewise their reflecting and absorbing power cannot be very different, so that the calculation given above may be regarded as very reliable concerning the order of magnitude.

As now the brightness of the corona seems to vary between the single and the double brightness of the full moon, the total weight of it may vary in the same proportions, or approximately between 13 and $26 \cdot 10^{12}$ grammes.

It is also easy to make a calculation of the probable number of drops in a cubic meter at the densest part of the corona. The number of drops in a cross-section of 1 m.^2 was found to be $54.7 \cdot 10^6$. The number of particles in a column of 1 m.^2 cross-section,

* The surface of the earth is $5.1 \cdot 10^{14} \text{ m.}^2$ and the radius of the Sun 108.56 times greater than the earth's radius.

and the Sun's diameter as height, would be 1.82 times greater (found by mechanical integration), if the number of particles per cubic meter were the same as in the innermost part of the corona. The total number of particles would be then $1.3 \cdot 54.7 \cdot 10^6 \cdot 1.82 = 130 \cdot 10^6$ in $108.56 \cdot 12740 \cdot 10^3 = 138 \cdot 10^7 \text{ m.}^3$, or every particle would take up a space of 10.7 cubic meters. This space would increase proportionately to the sixth power of the distance from the Sun's center, and in a distance of one solar radius would therefore be $64 \cdot 10.7 = 685$ cubic meters. If we had calculated with a substance having n times greater specific weight than the iron, we would have found a volume about n^2 times less, so for particles of the specific weight 12, the volume would have been only 2.7 cubic meters for every particle in the innermost part of the corona.

As a comparison with the corona we may use a dense fog. Conrad determined the quantity of water in a fog, in which one could see 26 steps (equal to about 20 m.) to be 4.4 grammes per cubic meter. For water drops of 20μ diameter (probable value) 1 cubic meter of this contains $1050 \cdot 10^6$ drops, with a total cross-section of 0.33 m.^2 . According to this it is easy to calculate that a thin layer of 0.015 millimeter of this fog would look just as bright as the corona, if the drops consisted of molten iron. Through a wall of such a fog 20 meters thick only the 630th part of an incident light-ray would pass unreflected and unbroken, which agrees well with the assertion that it is impossible to discriminate objects at 20 meters distance through such a fog.

It is often supposed that the outermost layers of the Sun are of an exceedingly low temperature, due to the adiabatic dilatation of the Sun's gases from their vertical circulation. Just in the same manner one calculates that the highest strata of the earth's atmosphere should have an exceedingly low temperature.

The spectroscopic evidence for the Sun gives a totally different idea of the temperature in its upper strata. This depends upon two circumstances. The

radiation of the Sun is extraordinarily strong. In the higher strata the density and consequently the heat-capacity of the gases sink to the lowest limit. Therefore their expansion, with the lowering of the temperature in ascending, is wholly overwhelmed by the strong radiation, and we may calculate the temperature as determined by the radiation alone, as we have done above, without committing any sensible error.

This probably also holds good for the uppermost extremely thin strata of the earth's atmosphere, especially on the insolated side of the earth. These highest strata contain particles of cosmical dust, supposed to swim by help of the repulsion of their negative electric charges from the electric charge of lower strata. On account of the insolation the temperature of these dust-particles reaches about 57°C , if the temperature of the soil below is about 30°C ,* as is easily calculated by the formula of Stefan. Also, on the night side of the earth, by the radiation of the earth, these particles will get a temperature $\sqrt{2}$ times lower than that of the soil. If this is assumed to be 15°C , one finds for the dust-particles in the highest strata -31°C . Now one has observed much lower temperatures in lower strata up to about 20 km. It is therefore probable that our atmosphere at a certain height reaches a minimum of temperature, and that at higher strata the temperature again increases. Especially is this valid for the insolated part of the earth, on which the highest temperatures according to this opinion occur in the highest strata of the atmosphere and not, as is generally supposed, in the lowest layers of it.

These conclusions are in excellent agreement with the results of the most modern researches, by Teisserenc de Bort and Assmann, of the temperature of the highest investigated strata of the air.

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* Above a soil of 0°C it would be 47°C .

END OF VOLUME II.